ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV002

EX-SITU INVESTIGATION OF THE EFFECTS OF HEATING RATE ON THE RECRYSTALLIZATION IN ROLLED POLYCRYSTALS OF HIGH-PURITY NIOBIUM*

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Abstract

The consistent production of high-purity niobium cavities for superconducting radio frequency (SRF) applications is crucial for enabling improvements in accelerator performance. Recent work has shown that dislocations and grain boundaries trap magnetic flux which dissipates energy and degrades cavity performance. We hypothesize that the current heating rate used in production is too slow and therefore facilitates recovery rather than recrystallization. Recovery, unlike recrystallization, does not reduce the number of geometrically necessary dislocations (GNDs) that are strongly correlated to trapped magnetic flux. Using excess high-purity niobium saved from the production of a cavity, the material was divided into two groups and rolled to ~30% reduction with half rolled parallel to the original rolling direction, and the other half rolled perpendicular. To examine the effect of heating rate, samples were encapsulated in quartz tubes and placed into either a preheated furnace or a cold furnace to allow for heat treatments at different rates. Then using ex-situ electron backscatter diffraction (EBSD) mapping, the extent of recrystallization was determined.

INTRODUCTION

Ensuring that the SRF cavities produced from high-purity niobium have a high Q value is of great importance in the production of the cavities. Degradation in the Q value is associated with a number of factors: such as the introduction of new dislocation substructures due to the deformation required to form the cavities; the possibility of introducing impurities (specifically hydrogen and the resulting niobium hydrides) through the necessary cryo-temperature cooling of the cavities; as well as recovery, recrystallization, and grain growth due to the heat treatments imposed on the cavity post production. There is significant current interest in the impact of trapped flux which is associated with defects in the metal such as dislocations [1–4]. With current heat treatment schedules, dislocation recovery (reduction in dislocation density with formation of low energy low angle grain boundaries within in the deformed grains) may occur as much as recrystallization (motion of high angle grain boundaries that result in a nearly perfect crystal structure behind them) [5]. As low angle boundaries have been shown to trap flux as effectively as high angle grain boundaries when they are parallel to the magnetic field, it is reasonable to expect that the probability of a boundary being parallel to a magnetic field will be much greater if grains have a network of low angle boundaries within them. Consequently, recrystallization is highly desirable. Recent work has shown that higher temperature heat treatments reduce flux pinning losses in cavities, and as this higher temperature favors more grain growth, fewer low angle boundaries are present. On the other hand, the cavities require sufficient strength as a pressure vessel [6], so the grain size should not become too large. Therefore, a more complete understanding of recrystallization in deformed high-purity niobium and its ties to the dislocation substructure resulting from forming, specifically the geometrically necessary dislocations (GNDs) that become low angle boundaries, it will be possible to identify production specifications for both cost-effective and high Q niobium SRF cavities [7].

Furthermore, the variability of rolled niobium sheet metal is know to be large, as microstructures and local texture gradients are highly variable from one batch of material to the next even for the same product from the same supplier. Thus, the current acceptance criteria based upon grain size and yield strength may not be sufficient to ensure that recrystallization occurs in formed cavities in a predictable way. Therefore, it would be valuable to determine if a small sample of a batch of material will meet a minimum recrystallization threshold. One of the simplest ways to do this is with small samples that are deformed in a easily reproducible way, to determine the fraction recrystallized in a reproducible and robust manner. To this end, this paper examines a particular deformation history of sheet using a ~30% reduction, and different heat treatment strategies are compared. An operating hypothesis examined in this paper is that a slow heating rate facilitates recovery that removes excess dislocations by the time that the heat treatment temperature is reached. Therefore, if the material is heated faster, there may be more dislocations still present by the time the heat treatment temperature is reached, such that the driving force for recrystallization may be increased, and hence the fraction recrystallized is increased. A critical enabling metric to assess this hypothesis is the measurement of the fraction recrystallized, and this paper compares several thresholds and methods to make this assessment.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV003

DYNAMIC TEMPERATURE MAPPING OF Nb_3Sn CAVITIES*

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Abstract

Niobium-3 Tin (Nb_3Sn) is the most promising alternative material to niobium for SRF accelerator cavities. The material promises nearly twice the potential accelerating gradients ($\approx$ 100 MV/m in TESLA elliptical cavities), increased quality factors, and 4.2 K operation. Current state of the art Nb_3Sn cavities reach quality factors of $2 \cdot 10^{10}$ at 4.2 K and have reached 24 MV/m. Determining the cause of the premature field limitation is the topic of ongoing research. Cornell University has recently developed a high-speed temperature mapping system that can examine cavity quench mechanisms in never before achieved ways. Here we present high-speed temperature map results of Nb_3Sn cavities and examine the quench mechanism and dynamic heating. We show an initial multipacting quench and sudden temperature jumps at multiple locations on the cavity.

INTRODUCTION

Niobium-3 Tin (Nb_3Sn) is the most promising alternative material for superconducting radiofrequency (SRF) accelerator cavities. Nb_3Sn has nearly twice the critical temperature (T_c = 18 K vs T_c = 9.2 K [1]) and nearly twice the superheating magnetic field ($H_{sh} \approx 425$ mT vs $H_{sh} \approx= 220$ mT [2]) compared to niobium. This allows Nb_3Sn cavities to operate at 4.2 K (where refrigeration is more efficient) at high quality factors $> 2 \cdot 10^{10}$ (at 1.3 GHz) and potentially reach 96 MV/m in TELSA elliptical geometry cavities.

Cornell University has a leading program to create Nb_3Sn accelerator cavities [3–7]. Nb_3Sn is very brittle and must be formed in the final cavity shape. To accomplish this we utilize Sn vapor deposition: a fully formed Nb cavity is placed in an ultra-high vacuum furnace where $SnCl_2$ and Sn is vaporized, allowed to absorb into the surface and forms Nb_3Sn [6, 8]. Additional fabrication techniques such at Chemical Vapor Deposition, Sn-electroplating with thermal conversion, and Nb_3Sn sputtering are being pursued but have not reached the same level of performance [9–15]. After the Sn vapor deposition process our cavities are coated in 2 – 3 µm of Nb_3Sn.

Current Nb_3Sn cavities at Cornell University achieve a quality factor of $2 \cdot 10^{10}$ at 4.2 K and a maximum accelerating gradients of $\approx$ 17 MV/m in 1.3 GHz TESLA elliptical cavities. The high quality factor at 4.2 K enables 4.2 K operation and even cryocooler operation [16–18]. The 17 MV/m maximum accelerating gradient is usable, but far below the theoretical limit. Similar accelerating gradients have been reached at JLab [19] and IMP [20], and recently reached 24 MV/m at FNAL [21]. The cause of premature Nb_3Sn cavity quench is the subject of ongoing research [4, 22, 23].

Temperature mapping has been used to examine quench. Figure 1 shows a quench map of a Nb_3Sn cavity indicating that quench is occurring at a localized spot. This cavity was cut up and the quench site was examined using microscopy, but no obvious quench candidate was observed. Nb_3Sn is sensitive to small defects and temperature maps only have a resolution of $\approx$ 1 cm making quench identification difficult.

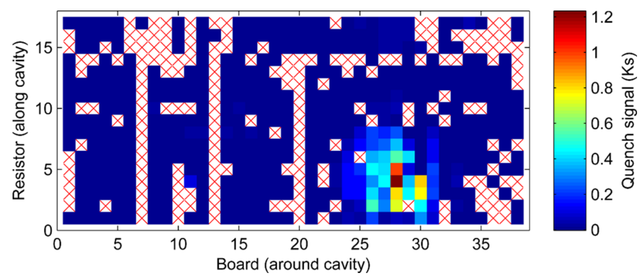

Figure 1: A quench map of a Nb_3Sn cavity taken with the old temperature mapping system [4, 5]. The hot spot in the lower right indicates a localized thermal quench. Quench maps are acquired by allowing the cavity to quench many times and measuring each thermometer in series. Places that are on average hotter are likely the quench site. The plot is displayed as integrated temperature. White squares with red x's indicate non-functional thermometers.

Additional experiments were conducted by D. L. Hall *et al.* where the quench site temperature alone was measured at 25 ksps as the cavity was charged and discharge. The results can be seen in Fig. 2. As the cavity charges we first see Ohmic heating, as expected, but then the temperature suddenly jumps up [5]. When the cavity discharges there are jumps back down, but there is hysteresis between the charge and discharge cycles. The cavity does not quench during the cycle. Furthermore, the jumps appear to be quantized. There has been much speculation as to the cause of the these jumps and how they might be related to quench [4, 23].

These experiments suggest valuable information about the Nb_3Sn quench mechanism could be revealed by time-resolved temperature mapping. The additional information could inform theoretical models of quench or rule out certain quench mechanisms.

Recently, Cornell University has developed a new high-speed temperature mapping system that can resolve the dynamics of RF dissipation [24]. This system samples the entire temperature map 50 ksps, fast enough to resolve cav-

* This work was supported by U.S. DOE award DE-SC0008431 (hardware development, construction, and cavity tests.). This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams (software development, firmware development, and data analysis).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV005

CURRENT STATUS OF THE ALPI LINAC UPGRADE FOR THE SPES FACILITIES AT INFN LNL

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Abstract

The SPES (acronyms for “Selective Production of Exotic Species”) project is based at INFN LNL and covers basic research in nuclear physics, radionuclide production, materials science research, nuclear technology and medicine. The Radioactive Ion Beam (RIB) produced by SPES will be accelerated by ALPI (acronyms for “Acceleratore Lineare Per Ioni” in italian), which is a linear accelerator, equipped with superconducting quarter wave resonators (QWRs) and operating at LNL since 1990. For RIB acceleration it is mandatory to perform an upgrade of ALPI which consists of the implementation of two additional cryostats, containing 4 accelerating cavities each, in the high-ß section. The QWRs production technology is well established [1]. The production technology of Nb/Cu QWRs should be adjusted for high-ß cavities production. In the framework of the upgrade, several vacuum systems were refurbished, optimal parameters of the biased sputtering processes of copper QWR cavities and plates were defined. The process of mechanical and chemical preparation, sputtering and cryogenic measurement of the high-ß Nb/Cu QWR cavities were adjusted. Several QWR cavities were already produced and measured. Currently, the production of the Nb/Cu sputtered QWR cavities and plates is ongoing.

INTRODUCTION

SPES is a new ISOL facility, dedicated to the production of neutron-rich beams. The main aim of the SPES Project is to provide high intensity and high-quality beams of neutron-reach nuclei for the performing of the research activity in nuclear physics, reacting beams and interdisciplinary fields like medical, biological and material science [2].

The SPES facility starts with proton cyclotron by producing exotic species via the nuclear fission. The beam is delivered after, through the Wien filter and a high-resolution mass separator to the charge breeder (CB). The CB, followed by the Continuous Wave RFQ is the front-end part of the radioactive ion beam injector, after which the ion beam is delivered to the superconducting linac ALPI for acceleration. After the acceleration, RIB species of interest are delivered into three experimental halls of LNL. For accelerating RIB species of interest to the experimental halls, the ion beam should gain final energy $E_f \sim 10$ MeV/A [3].

The ALPI LINAC is a superconductive accelerator, based in Legnaro National Laboratories from the early 1990s. The linac is combined from three sections (low-β, medium-β and high-β branches) of the superconductive quarter wave resonators (QWRs) depending on the different velocity of the beam on its path. From the operation with lead electroplated QWRs at the beginning, ALPI linac was under continuous upgrade of the number of cavities and of the replacing of lead electroplated QWRs with sputtered niobium [4]. Upgrades in the numbers and performances of the ALPI cavities were made to increase the accelerating energy of the linac [2].

For its use as RIB accelerator for the SPES facility, an ALPI linac upgrade is required in transition and final energy. Part of the total ALPI upgrade is the upgrade of the high-β section, concerned the implementation of 2 new cryostats (4 QWRs each) in the end of the branch. Increasing of the QWRs number in high-β section will optimise the accelerating energy for the lightest ions and increase the final energy of the linac in total [5].

To perform the ALPI linac upgrade in the high-β section 8 new Nb/Cu superconductive QWR cavities are in production. The ALPI linac operates at the working power 7 W. The target performance of the produced QWRs is the following: quality factor (Q_0) is 10^9, energy of the acceleration field (E_{acc}) at 7 W higher than 4.5 MeV/m with quality factor at 7 W in the order of magnitude 10^8. The current status of production and low-temperature measurement of the high-β Nb/Cu superconducting ALPI QWR cavities for the ALPI linac upgrade will be described in this paper.

EXPERIMENTAL PART

Mechanical and Chemical Treatment

A Copper substrate for different QWR cavities was machined with two different techniques: lathing from bulk copper billet (cavities № HB5, HB6, HB7 and HB8) and deep drawing technique (cavities № DD0 and DD1).

The R&D activity on the deep drawing technique for the cavity substrate preparation is ongoing because of the possible advantages of this method. With the deep drawing technique, indeed, a seamless copper substrate can be produced with lower amount of copper material and easier machining process in general. Nevertheless, the influence of the copper substrate, machined by the deep drawing technique, on the performance of the Nb/Cu QWR cavity should be evaluated.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV006

CAVITY DESIGNS FOR THE CH3 TO CH11 OF THE SUPERCONDUCTING HEAVY ION ACCELERATOR HELIAC

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Abstract

In collaboration of GSI, HIM and the Goethe University Frankfurt, the superconducting linear accelerator Helmholtz Linear Accelerator (HELIAC) is being built at GSI in Darmstadt. The cw-mode operated linac with a final energy of 7.3 MeV/u at a mass-to-charge ratio of $A/q = 6$ and a frequency of 216.816 MHz is intended for various experiments, especially with heavy ions at energies close to the Coulomb barrier for the research of superheavy elements. The entire planned linac consists of four cryostats, four superconducting buncher, four solenoids and twelve superconducting CH-cavities. After successful beam tests with CH0 and successful high frequency tests with CH1 and CH2, CH3 to CH11 will be designed. Based on previous experience and successful test results, individual optimizations of the cavity design will be performed. Among other things, attention has been paid to reducing production costs by designing as many components as possible, such as spokes or the tank caps with the same geometries. Despite this cost reduction, it was possible to improve the theoretical performance in the simulations.

INTRODUCTION

The HELIAC is a cw-operated superconducting linear accelerator to be built at GSI in collaboration between IAP, GSI and HIM. It will replace UNILAC, which is currently under reconstruction as part of the FAIR project, in the experiments on the synthesis of superheavy elements (SHE) [1]. Within the demonstrator project, a sc CH cavity (CH0) has already been successfully tested with beam in a prototype cryostat with two superconducting solenoids [2]. While the demonstrator project was still in progress, work began on designing and building the identical CH1 and CH2 cavities. These two cavities were successfully realized and tested under cold conditions [3]. The entire sc accelerator will consist of four cryomodules (CM), each with three sc CH cavities, two solenoids (S) and a buncher (B) (see Fig. 1).

In Summer 2018 the design of nine 216.816 MHz sc CH-cavities (CH3 to CH11) for the cw-mode operated HELIAC at GSI in Darmstadt has started [4]. The design for these cavities is based on the design of the previously successfully tested CH1 and CH2 [3]. During the design progress several new optimizations and modifications were done. A new design for the dynamic bellow tuner has been developed, which has been examined for its influence on the frequency and for its mechanical properties. This new design of the dynamic tuner was compared with the design of the tuner of the CH1 and CH2 cavities [5]. In addition, the new designs focused on reducing peak electric and magnetic fields within the cavity.

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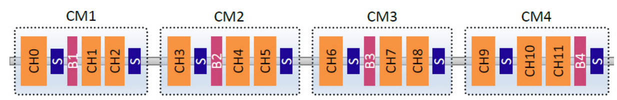

Figure 1: Layout of sc HELIAC.

CAVITY DESIGN

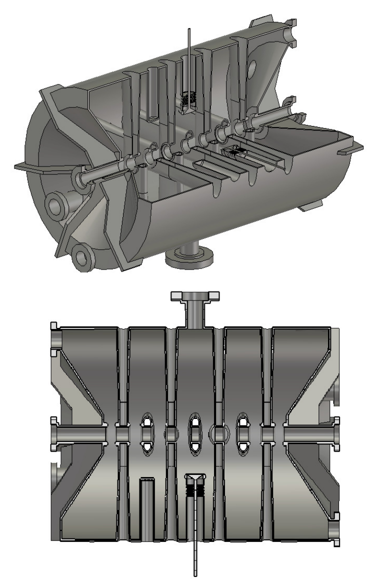

Figure 2: Layout of the 216.816 MHz sc CH-cavity CH3 with new bellow tuner design. The basic design of all cavities from CH3 to CH11 is the same except for the number of gaps, the gap lengths, the radius and the length. Here CH3 is shown as an example.

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV007

THICK FILM MORPHOLOGY AND SC CHARACTERIZATIONS OF 6 GHz Nb/Cu CAVITIES

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Abstract

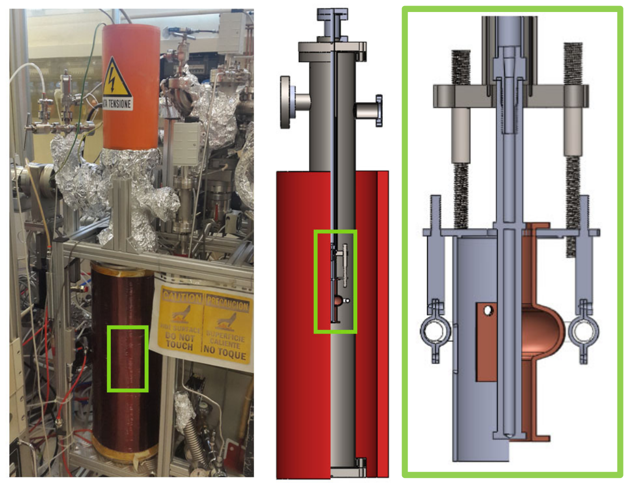
Thick films deposited in long pulse DCMS mode onto 6 GHz copper cavities have demonstrated the mitigation of the Q-slope at low accelerating fields. The Nb thick films (~40 microns) show the possibility to reproduce the bulk niobium superconducting properties and morphology characterizations exhibited dense and void-free films that are encouraging for the scaling of the process to 1.3 GHz cavities. In this work a full characterization of thick films by DC magnetometry, computer tomography, SEM and RF characterizations are presented.

INTRODUCTION

At Legnaro National Laboratories (INFN), an innovative approach for prototypes cavities has represent an important part of the SRF research. The approach includes high temperature coatings, by placing the substrates inside the vacuum chamber, and depositing thick films (<100 μm). These films, promote a structure that pushes the superconducting properties and performances close to the niobium bulk ones. In this work will be shown different characterizations on prototype cavities and samples that support the hypothesis mentioned before, as well as the last results on a QPR sample deposited with similar conditions to the 6 GHz cavities.

COATING TECHNIQUE

For the deposition of the thick films (~45μm), post magnetron configuration has been used (Fig. 1). The source of the magnetic field that allows the sputtering process to develop, is located outside the vacuum chamber. The copper substrates (cavities or samples) are deposited by long pulse DC magnetron sputtering. Single layers of hundreds of nanometres grow consecutively in order to avoid stress in the thick film that might affect the adhesion of the niobium to the copper and reduce the film performances. The coating technique includes also the high-temperature coating at 550°C in ultra-high vacuum conditions. The substrates are located inside a vacuum chamber, this permits the implementation of a heating system for the baking and coating processes [1].



(a) (b) (c)

Figure 1: (a) Deposition system by post-magnetron sputtering technique. (b) Design of system. (c) Cavity and sample coating configuration inside the system.

THICK FILM MORPHOLOGY

Thorough analysis by Scanning Electron Microscopy (SEM) and Electron Backscatter Diffraction (EBSD) characterizations were made at STFC to samples from cut 6 GHz cavities coated at LNL. The thick film approach was studied in two different deposition modes: long pulse and one-shot (coating without any pauses in the process) modes. The coating technique by long pulse deposition showed a higher grain structure than the one-shot deposition. Furthermore, the dispersion of the histograms representing the grain sizes, was also lower. In the Fig. 2, it is possible to observe the EBSD characterization for cavity 16 deposited by long pulse mode where each pulse thickness is 500 nm (a), and cavity 7 deposited in one pulse mode (one-shot).

It is evident that close to the Cu-Nb interface, the grain size is small and gradually the size increased with thickness. After approximately 30 μm, the structure is homogeneous with a columnar growth of the Nb grains.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV008

DESIGN AND CONSTRUCTION OF Nb_3Sn VAPOR DIFFUSION COATING SYSTEM AT KEK

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Abstract

The vapor diffusion Nb_3Sn coating system was developed at KEK. At most, it can be used to coat a 1.3 GHz 3-cell cavity. The coating system comprises a coating chamber made of Nb, vacuum furnace for heating the Nb chamber, and Sn heating device in the crucible. The Nb chamber vacuum and furnace vacuum are isolated to prevent contamination from the furnace. Heating device for increasing the Sn vapor pressure was installed for the coating system. This paper reports the details of the Nb_3Sn coating system at KEK.

INTRODUCTION

Nb_3Sn cavities have a smaller heat load at approximately 4.2 K, and they have a higher efficiency than Nb cavities [1]. Therefore, Nb_3Sn cavities are anticipated to be operated at 4.2 K by using a small refrigerator with a cryocooler. Studies have carried out cooling tests and cavity performance tests by a small refrigerator [2–4].

Several methods have been investigated for Nb_3Sn coating. Among them, coating via the vapor diffusion method has exhibited the best cavity performance [5]. The performance of Nb_3Sn coating cavities by vapor diffusion was evaluated in many laboratories. In FNAL, a cavity performance test of a 1.3 GHz single-cell cavity was carried out at 4.2 K. The results were as follows: the Q-value in the low accelerating field was 3×10^{10} and the maximum accelerating field reached 22.5 MV/m. [6].

KEK has undertaken Nb_3Sn cavity R&D, and its final goal is to realize Nb_3Sn cryomodule, which is cooled by small refrigerators.

A Nb_3Sn film coating system using the vapor diffusion method was constructed for developing Nb3Sn coating cavities. The coating system comprises a heating vacuum furnace, coating chamber, Sn crucible, and heater for Sn crucible. This system is designed for Nb_3Sn coating on up to a 1.3 GHz 3-cell cavity.

REQUIREMENT FOR Nb_3Sn COATING SYSTEM

The Nb_3Sn vapor diffusion coating system at KEK was constructed based on the system at Cornell University [7]. Figure 1 shows a schematic of the Nb_3Sn coating system at KEK. The coating system comprises a furnace for heating, coating chamber made of Nb, Sn and $SnCl_2$ crucibles, and Sn crucible heater.

The conditions of the coating temperature and coating time for Nb_3Sn coating are described below. Nb_3Sn is

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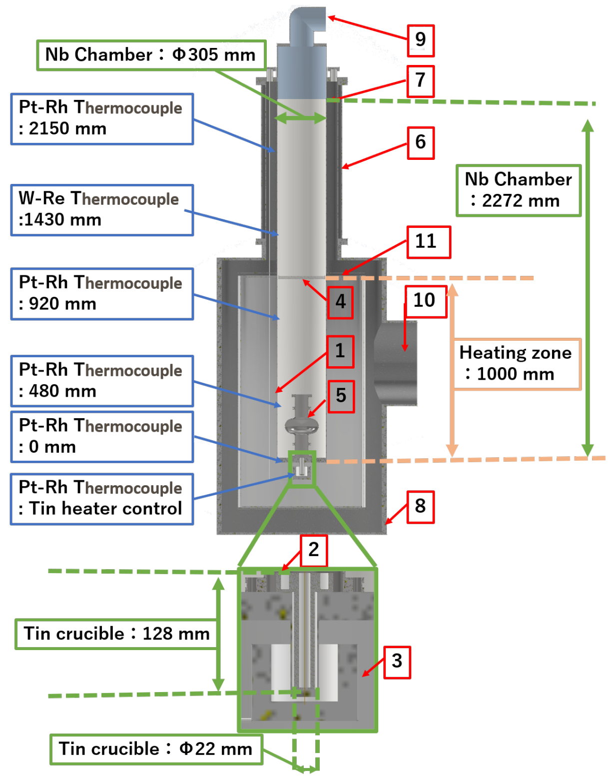

Figure 1: Design of the coating system at KEK: **1** Nb chamber, **2** Sn crucible, **3** Heater for Sn, **4** Mo reflectors inside Nb chamber, **5** Nb cavity, **6** SUS extension tube, **7** Nb-SUS conversion flange, **8** Vacuum furnace, **9** Pumping port for Nb chamber, **10** Pumping port for vacuum furnace, **11** Mo reflectors in vacuum furnace.

coated at approximately 1100°C to avoid the growth of Nb-Sn compounds, other than Nb_3Sn, which have a lower superconducting transition temperature. Nb_3Sn is formed when the Sn composition is between 17 and 25 at%, and the temperature is above 930 °C in the Nb-Sn reaction. Nb-Sn compounds with a low superconducting transition temperature are formed depending on the Sn composition of the reaction below 930 °C [8]. In general, Nb_3Sn is coated at 1100 °C for approximately 3 h to maintain sufficient thickness [1].

Next, the clean requirements are described below. Impurities that contaminate the Nb_3Sn film during the coating process can degrade the cavity performance. Therefore, impurities need to be prevented from contaminating the coating chamber during Nb_3Sn coating. The coating chamber and furnace are possible sources of impurities. The material of the chamber should be Nb to avoid any impurities from the coating chamber. A double vacuum structure with an

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV009

FIRST Nb_3Sn COATING AND CAVITY PERFORMANCE RESULT AT KEK

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Abstract

At the High Energy Accelerator Research Organization (KEK), Nb_3Sn vapor diffusion R&D for high-Q performance has just commenced. A coating system via vapor diffusion was constructed, and the samples were coated using the system. The cavity-coating parameters were determined based on the results of the evaluated sample. A TESLA-like single-cell cavity was applied to coat the Nb_3Sn film, and its performance was evaluated by a vertical test. In this paper, we report on the cavity coating process and the result of cavity performance test.

INTRODUCTION

Nb_3Sn cavities have a high Q-value at a temperature of 4.2 K, which is almost equal to that of Nb cavity at 2 K; cryocoolers can be used to achieve the operating temperature of 4.2 K. Therefore, a small superconducting radio frequency (SRF) accelerator using a Nb_3Sn cavity is expected to be applied in various fields, such as RI production and water purification. Nb_3Sn vapor diffusion R&D for high-Q has just started at KEK, where Nb_3Sn films were coated on Nb substrates using the constructed coating system.

COATING SYSTEM

At KEK, a Nb_3Sn coating system via vapor diffusion was constructed [1]. It is a vertical-type coating system capable of coating a 1.3 GHz 3-cell cavity. Tin and tin chloride crucibles were used for the sample and cavity coating. Both crucibles were made of tungsten. A sample holder made of Nb was used for the sample coating. Figure 1 shows the coating parameters.

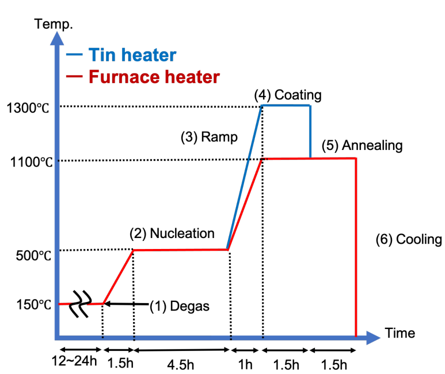

Figure 1: A typical coating process at KEK.

The coating process at KEK comprises a nucleation process, coating process, and annealing process, similar to that at Cornell University [2]. All nucleation processes described in this paper were performed at 500 °C for 4.5 h.

SAMPLE COATING

The coating parameters for the cavity were determined using samples: Two types of Nb substrates, Nb plates, and Nb foils, were used for the coating experiments. The Nb plates were cavity-grade Nb with a size of 7 mm × 7 mm and a thickness of 2.7 mm. The Nb plates were used to observe the surface condition. The Nb foil size was 4 mm × 50 mm with a thickness of 0.1 mm, and its RRR was approximately 30. The Nb foils were used to evaluate the Nb_3Sn film thickness and transition temperature (T_c). The samples were coated under several coating parameters, where the temperature and time of the coating and annealing process were changed. After coating, the surface condition, composition ratio of the tin, Nb_3Sn film thickness, and superconducting temperature, T_c, were evaluated. Surface observation and composition ratio measurements were performed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). The Nb foils were embedded in a resin and polished, and the cross-sections were evaluated using SEM. The T_c of the samples was evaluated by measuring the temperature versus anti magnetization for each applied magnetic field using a magnetic property measurement system. Table 1 shows the typical sample coating result. Figure 2 shows the surface SEM images of the 9th and 23rd sample in Table 1.

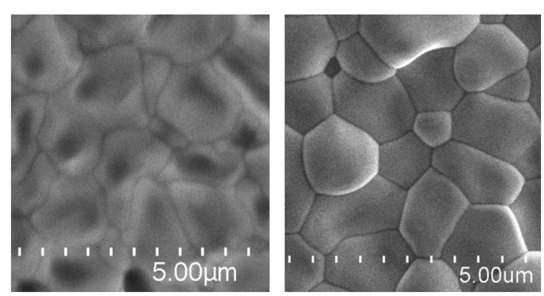

Figure 2: SEM image of the samples' surface. Left: the 9th sample; Right: the 23rd sample.

The T_c and tin composition ratio of the 4th sample were lower than that of the 9th and 23rd samples. The coating temperature of the 4th sample was 1200 °C; therefore, the diffusion rate of tin was faster in this sample than in the others. The tin diffused deep into the Nb substrate of the 4th sample, and consequently, the tin composition ratio on the surface became lower than that in the other sample. The T_c was lower than 18 K when the tin composition ratio was lower than 25 atomic percent (at %). Therefore, the T_c of the 4th sample with a low tin composition ratio was also

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV010

DESIGN OF THIRD-HARMONIC SUPERCONDUCTING CAVITY FOR SHEN-ZHEN INDUSTRY SYNCHROTYON RADIATION SOURCE *

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Abstract

Shenzhen industry synchrotron radiation source is the fourth generation of medium energy light source with beam energy of 3GeV. It has the characteristics of low emittance and high brightness. In the design, the beam lifetime is one of the most important parameters. The main factor that affects its beam lifetime is the scattering of electron collisions inside the beam. To solve this problem, a harmonic radio frequency system is used. The third harmonic superconducting elliptical cavity is designed to stretch beam length to improve beam quality and beam lifetime. The present work is mainly about the shape optimization of 1.5 GHz 2-cell third harmonic superconducting elliptical cavity. Firstly, the principle of harmonic cavity in dual high frequency system is introduced, and the resonant frequency and acceleration gradient of superconducting cavity are given. Then, CST, electromagnetic field simulation software is used to optimize the cavity parameters to obtain the high performance and high frequency parameters that meet the requirements.

INTRODUCTION

The beam lifetime in low-medium energy third and fourth generation synchrotron light sources is typically dominated by large-angle intrabeam (Touschek) scattering. Much attention has been paid to the use of harmonic rf systems to lengthen the bunches and improve the lifetime [1, 2]. Under ideal conditions, one expects lifetime improvements of a factor of 2–4, depending on the machine parameters. As shown in Fig 1, the high-order harmonic cavity is a high-frequency cavity whose resonant frequency is a multiple of the main high-frequency cavity. The addition of a high-order harmonic cavity can make the slope of the cavity pressure encountered by the center of the cluster zero, which makes the cluster elongated longitudinally, reduces the cluster charge density, thereby reducing Toschek scattering and increasing beam life. At the same time, the high-order harmonic cavity can cause frequency dispersion in the beam cluster, which can suppress the longitudinally coupled beam instability through Landau damping [3, 4]. For synchrotron radiation light source, a second high-frequency system is added to make the high-frequency accelerating electric field seen by the beam cluster superposition of the main high-frequency cavity pressure and the harmonic cavity pressure, and the electron density and length of the beam cluster are changed, thereby modulating and improving the beam quality and life .

At present work, we have studied the high-frequency cavity used in the third harmonic cavity system of Shenzhen Light Source. The content of this article is the design and optimization of the 1.5 GHz superconducting third harmonic cavity.

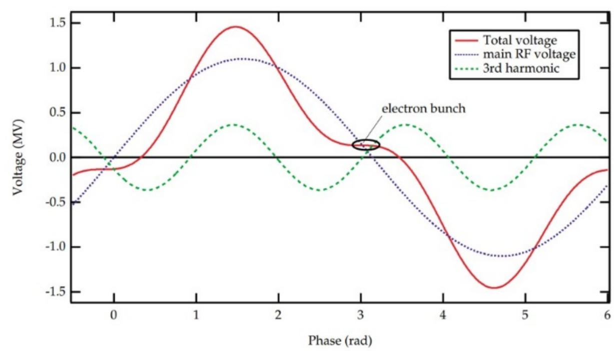

Figure 1: RF voltage seen by the bunch for main rf and higher harmonic cavity.[3]

PERFORMANCE PARAMETERS OF SRF CAVITY

Accelerating Gradient

The ratio of the accelerating voltage of the resonant cavity to the effective length d of the cavity is defined as the accelerating gradient (*E*acc). The accelerating gradient characterizes the energy gain per unit length of charged particles. The accelerating gradient is defined as follows:

$$E_{acc} = \frac{V_{acc}}{d}. \tag{2.1}$$

In accelerators, the definition of the effective length of the resonant cavity is different. The usual definition is:

$$d = \frac{N}{2}\beta\lambda\,, \tag{2.2}$$

where N is the number of acceleration gaps, β is the relative velocity of the particles, and λ is RF wavelength.

Quality Factors

The intrinsic quality factor of the resonant cavity can be used to reflect the power loss of the resonant cavity, which is defined as:

$$Q_0 = \frac{\omega \cdot W}{P_c}, \tag{2.3}$$

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV011

THIRD HARMONIC SUPERCONDUCTIVE CAVITY FOR BUNCH LENGTHENING AND BEAM LIFETIME INCREASE OF SIRIUS SYNCHROTRON LIGHT SOURCE

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Abstract

Sirius is a 4th generation synchrotron light source currently under comissioning at the Brazilian Center for Research in Energy and Materials in Campinas, Brazil. A passive third harmonic superconductive cavity is planned to be installed in the storage ring in order to lengthen the bunches and increase beam lifetime by reducing Touschek scattering while keeping its high brightness. This paper presents the analysis of the longitudinal bunch lengthening in the optimal case of a quartic potential well and the discussion of results considering shunt impedances and quality factors of known higher harmonic cavities (HHC) designs.

INTRODUCTION

New generation synchrotron light sources require low-emittance storage rings in order to increase radiation brightness, which reduces beam lifetime due to Touschek scattering. A common approach to increase beam lifetime without affecting the brightness is to include a higher harmonic cavity in the system in order to lengthen the bunches and reduce the longitudinal bunch density [1]. For Sirius, which has a natural emittance of 0.250 nm−rad and a fundamental RF frequency of 500 MHz, a 1.5 GHz passive third harmonic superconductive cavity is planned to be installed and a beam lifetime increase around 4.5 times the current value is expected. As a result of passive operation, voltages across the cavity are due only to beam loading, meaning that the induced fields depend on the bunch distribution, which depends on the cavity fields. This self dependence requires an iterative process to find steady state bunch distribution, as will be discussed further on.

In this paper, logitudinal beam dynamics is reviewed, flat potential conditions for Sirius' parameters are found and corresponding bunch length, energy acceptance, synchrotron oscillation frequency and lifetime increase are calculated. A full self-consistent approach is adopted in order to obtain the equilibrium bunch distribution as described in [2]. Fundamental cavity beam loading is then studied in order to find the optimal detune that minimizes power input in the presence of the harmonic cavity. At last, a few considerations regarding the current spectrum and operation stability are briefly discussed.

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LONGITUDINAL DYNAMICS

The longitudinal motion of a particle in a storage ring is represented by the set of differential equations given by Eq. (1) and Eq. (2).

$$\frac{d\tau}{dt} = -\alpha\frac{\epsilon}{E_0} \tag{1}$$

$$\frac{d\epsilon}{dt} = \frac{eV(\tau) - U_0}{T_0} \tag{2}$$

where E_0 is the nominal beam energy, α is the moment compaction, ϵ is the energy deviation with relation to the synchronous electron, e is the magnitude of the electron charge, $V(\tau)$ is the total voltage, U_0 is the energy loss per revolution in the ring and T_0 is the revolution period. The time deviation with relation to the synchronous electron, given by τ, is defined by Eq. (3), being $s(t)$ the position of the electron with relation to an arbitrary reference, $s_c(t)$ the position of the synchronous electron and c the relativistic speed of the synchronous electron.

$$\tau = \frac{s(t) - s_c(t)}{c} \tag{3}$$

Substituting Eq. (1) into Eq. (2) it is possible to write the second order differential equation shown in Eq. (4), which is analogous to a harmonic oscillator and motivates the definition of the potential function given by Eq. (5).

$$\frac{d^2\tau}{dt^2} = -\frac{\alpha}{E_0}\left[\frac{eV(\tau) - U_0}{T_0}\right] \tag{4}$$

$$\Phi(\tau) = \frac{\alpha}{E_0 T_0}\int_0^\tau [eV(\tau) - U_0]d\tau \tag{5}$$

From the potential function it is possible to find the electron distribution of a bunch through Eq. (6), where ρ_0 is a normalization constant and σ_e is the energy spread.

$$\rho(\tau) = \rho_0 e^{-\frac{\Phi(\tau)}{\alpha^2\sigma_e^2}} \tag{6}$$

Continuing with the harmonic oscillator analogy, the total energy of the system given by the sum of kinetic and potential energy must be constant and equal to Φ_0, as shown in Eq. (7). Substituting Eq. (1) into Eq. (7), it is possible to obtain the energy deviation as a function of the time deviation as in Eq. (8), which gives the phase portrait of the longitudinal dynamics.

$$\frac{1}{2}\left(\frac{d\tau}{dt}\right)^2 + \Phi(\tau) = \Phi_0 \tag{7}$$

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV013

MULTIPACTING ANALYSIS OF THE QUADRIPOLAR RESONATOR (QPR) AT HZB

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Abstract

Multipacting (MP) is a resonating electron discharge, often plaguing radio-frequency (RF) structures, produced by the synchronization of emitted electrons with the RF fields and the electron multiplication at the impact point with the surface structure. The electron multiplication can take place only if the secondary emission yield (SEY, i.e. the number of electrons emitted due to the impact of one incoming electron), is higher than 1. The SEY value depends strongly on the material and the surface contamination. Multipacting simulations are crucial in high frequency (HF) vacuum structures to localize and potentially improve the geometry. In this work, multipacting simulations were carried out on the geometry of the Quadrupole Resonator (QPR) in operation at HZB using the Spark 3D module in Microwave Studio suite (CST). These simulations helped to understand a particular behavior observed during the QPR tests, and furthermore made it possible to suggest enhancement ways in order to limit this phenomenon and facilitate its operation.

INTRODUCTION

The Quadrupole resonator at HZB is a device developed measure the surface resistance of superconducting samples. It is based on a design from CERN [1]. The structure of the quadrupole resonator is based on the theory of transmission lines. Four rods are connected to each other with a pair of loops. The magnetic field is maximum at both ends of the resonator. The sample is at the bottom of the loop where the magnetic field is maximum (see Fig. 1). The fundamental operating frequency is 427 MHz, other harmonics can be excited such as 868 MHz and 1310 MHz. The measurement of the surface resistance is done by a calorimetric method. As all RF structures, the phenomenon of multipacting can exist and potentially hinder the operation at several field levels.

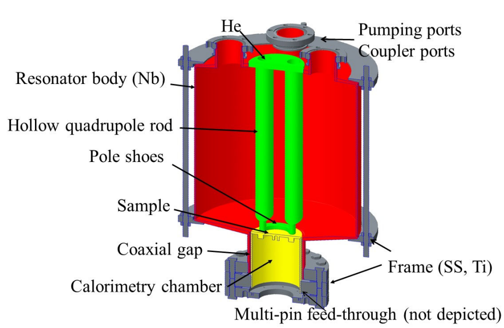

Figure 1: Schematic view of the QPR, taken from [2].

Multipacting is a resonant secondary electron emission phenomenon that is generated in an RF structure (see Fig. 2). When a primary electron collides with the surface after an RF or multiple period, secondary electrons reemitted by the surface could be accelerated again and so on at each period. Some conditions are necessary for multipacting to develop [3]: A synchronization between the RF period and the electron trajectory is given by the RF field distribution and thus the geometry and the electronic multiplication can only take place if the secondary emission yield (SEY), depending on the material and its surface, is greater than 1.

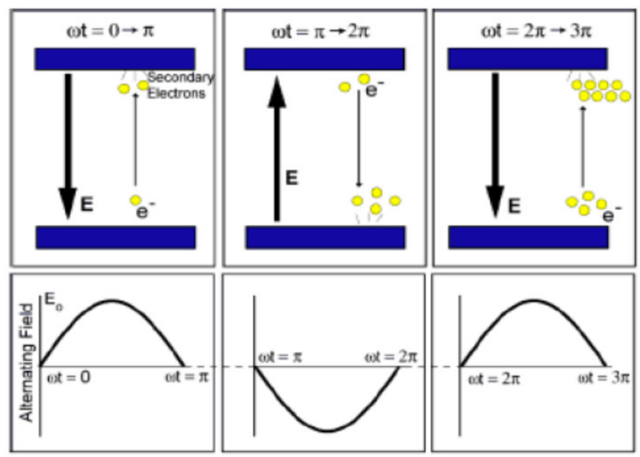

Figure 2: Multipacting phenomenon.

The collision of the electrons with the RF surface produces important heating. As the measurement of the surface resistance in the QPR is done by the calorimetric method, anomalous heating triggered by multipacting can bias the measurement of the surface resistance.

So as to ensure a reliable measurement of the surface re-sistance, multipacting simulation is necessary.

SIMULATION RESULTS

The multipacting simulations were done with SPARK3D module included in CST Microwave Studio [4]. At the beginning of the simulation, primary electrons are generated all over the surface. Trajectories of secondary electrons are tracked over several RF periods. The main input parameters for SPARK3D are:

- Frequency and electromagnetic field distribution are imported from CST.
- RF power level.
- Electron parameters: Initial electron number, simulation time (related to period number) and secondary emission coefficient (SEY) curve of niobium (Fig. 3).

SPARK3D allows to identify multipacting region. The simulations are done on three QPR regions; around coupler, rods and on the coaxial line (see Fig. 4).

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV014

DESIGN AND SIMULATION OF 500 MHz SINGLE CELL SUPERCONDUCTING CAVITY*

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Abstract

The Shenzhen Industrial Synchrotron Radiation Light Source is a fourth-generation medium-energy light source with a 3GeV storage ring electron energy and an emittance less than 100 pm·rad. In order to ensure the long-term stable and efficient operation of the light source, a new type of 500 MHz single-cell superconducting cavity was designed in this study to be used as a pre-research superconducting cavity for the Light Source. The 500 MHz superconducting cavity has a large beam aperture and low high order modes (HOMs) impedance, which can be used in accelerators with larger currents. In this design, we simply adopted the same design scheme as the KEKB-type and CESR-type superconducting cavity. Using CST electromagnetic field simulation software to calculate and simulate the characteristics of the cavity, the results show that the designed 500 MHz single-cell cavity can meet the requirements of a high acceleration gradient, a high r/Q value, and a low peak surface field.

INTRODUCTION

With the development of superconducting radio frequency technology, the superconducting cavity has been proven to be the best solution for compact, high-power and high-current accelerators. The application of single-cell superconducting radio frequency cavities in synchrotron radiation sources has also been widely recognized. The 500 MHz single-cell superconducting cavity has been successfully applied to major synchrotron radiation sources in the world. The most representative one should be the CESR and KEKB 500 MHz single-cell superconducting cavities developed by Cornell University and KEK in the 1990s. The KEKB type superconducting cavity has a cylindrical large beam tube (LBP), which is designed to 1) propagate the high-order modes (HOMs) along the beam axis; 2) Damping the HOMs through the ferrite absorber pasted on the inner surface of the beam tube on both sides of the cavity [1]. The ferrite absorber damps the HOMs. The CESR cavity uses a fluted beam tube (FBT) to propagate HOMs. It has four special grooves that can reduce the cut-off frequency of the dipole mode and the round beam tube (RBT), and its cut-off frequency is high enough to exceed the resonance of the fundamental mode Frequency, but less than the resonant frequency of the HOMs of the second magnetic monopole [2].

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In addition, due to the large beam aperture of the superconducting cavity, the use of low-frequency resonant superconducting cavities in high current accelerators can suppress wake field effects and HOMs losses. Compared with a cavity that resonates at a higher frequency, a 500 MHz single-cell superconducting cavity has a lower surface resistance in the BCS theory [3]. The use of a low-frequency cavity can solve the challenge of low-temperature power loss of continuous wave high-current accelerators [4]. However, due to the large size of the low-frequency superconducting cavity, manufacturing and surface treatment will also bring another challenge [5]. What is exciting is that, through continuous in-depth research in recent years, Chinese researchers have realized the localization of all processes including the manufacturing and surface treatment of superconducting cavities. However, the prepared superconducting cavity type still belongs to the existing design cavity type abroad [6, 7]. Therefore, in order to realize the localization of superconducting cavities, an optimized state-owned superconducting cavity structure is proposed [8].

In this thesis, a new type of 500 MHz single cell superconducting cavity is proposed based on the development of the international 500 MHz single cell superconducting cavities in recent years. Through a large amount of simulation design and calculation, the spare superconducting cavity of Shenzhen Industrial Synchrotron Radiation Light Source was designed. This research provides the preliminary structure design and simulation calculation of various performance parameters. The optimization goals of this design include, for example, lower surface electromagnetic fields (E_p/E_{acc}, H_p/E_{acc}), lower low temperature loss, stronger HOMs damping, or lower loss factor. Some of these goals are mutually exclusive, so in the actual design, we have carried out comprehensive considerations to achieve the best results. The innovation of this design lies in the combination of the advantages of the two cavities, the LBT of KEKB and the FBT of CESR.

CAVITY DESIGN

The new superconducting cavity combines the FBT of the CESR cavity and the LBT of the KEKB cavity. Its obvious advantages are: large beam aperture, small beam loss, good electron acceleration, HOMs suppression and power transmission effects. A typical cavity shape is shown in Fig. 1, where l is the length of the cell, R_{eq} is the equatorial radius, R_{ir} is the iris radius, b_1/a_1 is the aspect ratio of the equatorial ellipse, and b_2/a_2 is the aspect ratio

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV016

STUDIES ON THE FUNDAMENTAL MECHANISMS OF NIOBIUM ELECTROPOLISHING

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Abstract

To improve the superconducting performance of niobium SRF cavities, electropolishing (EP) with a sulfuric and hydroflouric acid mixture is used. The chemistry of this reaction is complex due to the interactions between diffusion mechanisms, surface oxide structure, and multiple chemical species. Past studies on the EP process have produced a certain set of optimum parameters that have been used successfully for a long time. However, two recent developments have called the efficacy of the existing EP process into question. Since the introduction of nitrogen doping the surface quality of some cavities has been very poor. Also, EP performed at colder than standard temperatures leads to an increase in the cavity performance. To understand these questions, we perform a multivariate study on the EP process using niobium test samples electropolished at different temperatures and potentials. We find that electropolishing at lower potentials leads to rough surface features such as pitting and grain etching. Some of the surface features show similarities to features seen in niobium cavities. The effect of electropolishing temperature is not clear based on the results of this study.

INTRODUCTION

Electropolishing is a well-established process for smoothing the inside surface of niobium SRF cavities. Despite this, the scientific knowledge regarding this process is lacking in many areas. This is because the chemistry of the electropolishing reaction is highly complex due to the interactions between diffusion mechanisms, surface oxide structure, and multiple chemical species. Electropolished cavities sometimes end up with a rough surface finish or surface defects without any explanation. To improve the quality and repeatability of the electropolishing process we polish niobium samples at different potentials and temperatures.

BACKGROUND AND MOTIVATION

Niobium is a passivating metal, meaning that when an electric potential is applied, a protective oxide layer is formed on the surface preventing the metal from being dissolved. In HF containing solutions, the oxide is chemically dissolved by the HF allowing more of the metal to be oxidized. The metal is dissolved through this two step reaction. The mechanism for how this reaction occurs is dependent on many variables such as the electrode potential, the temperature, and the amount of electrolyte mixing. The dissolution mechanisms can be broken down into two main types: active dissolution and diffusion limited dissolution. In the active region, the reaction rate is limited by the electrode potential dependent kinetics of the niobium dissolution reaction. In this region the current increases with the potential, since the reaction is driven by the electric potential. In the diffusion limited region, the current is limited by the diffusion of HF to the surface of the Niobium. The current remains constant even with increasing potential in this region, since diffusion is not affected by the electrode potential. Separating these two regions is a region of instability where the current spontaneously oscillates (see Fig. 1).

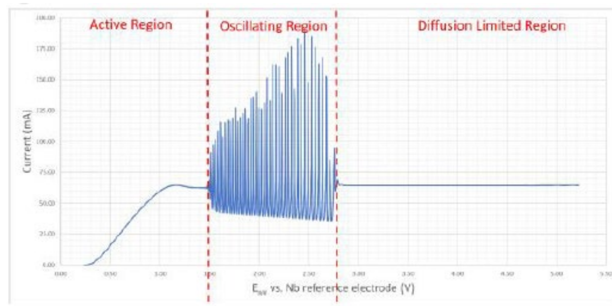

Figure 1: The etching current as a function of the electrode potential of niobium electropolished in an HF containing electrolyte. The current response is divided into the active, oscillating, and diffusion limited regions.

EXPERIMENTAL

Samples were polished two at a time in a 1:9 mixture of 48% hydrofluoric acid and 99% sulfuric acid. The electropolishing potential is applied between the niobium working electrode and an aluminum counter electrode. The electrolyte is circulated by a pump and cooled by a heat exchanger to control sample temperature. The surface temperature of the niobium samples is monitored by a thermocouple attached directly to the surface. The sample surface temperature is controlled by changing the acid temperature using a chiller.

Before the experiment, the samples were prepared by removing 100 microns of material from the surface at 18 volts to ensure an equal starting point. During the experiment five microns of material was removed with the experimental electropolishing conditions. The amount of material removal is measured through three separate methods: integrating the etching current, measuring the change in sample thickness with a gauge, and measuring the change in weight of the sample. All three methods show good agreement.

After the EP, the surface roughness of the samples is measured using an interferometric white light optical microscope and the surface is imaged using scanning electron microscopy.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPCAV018

FIRST N-DOPING AND MID-T BAKING OF MEDIUM-β 644 MHz 5-CELL ELLIPTICAL SUPERCONDUCTING RF CAVITIES FOR MICHIGAN STATE UNIVERSITY'S FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

Two hadron linacs currently under development in the US, the PIP-II linac at Fermi National Accelerator Laboratory (FNAL) and the upgrade for Michigan State University's Facility For Rare Isotope Beams (FRIB), will employ 650 and 644 MHz $\beta \approx 0.6$ elliptical superconducting cavities respectively to meet their design energy requirements. The desired CW operational mode of these two linacs sets the cavity Q_0 requirements well above any previously achieved at this operating frequency and velocity, driving the need to explore new high-Q_0 treatments. The N-doping technique developed at FNAL and employed at an industrial scale recently to deliver the LCLS-II cryomodules [1,2] is a strong candidate for high-Q_0 treatments, but investigation is required to understand how to translate and optimize N-doping to the lower operating frequency and velocity regime. Herein we present the results of the first high-power RF tests of (2/0) (2 min N profusion 0 min annealing) N-doped and medium-temperature "Mid-T" baking tests [3-5] of the prototype FRIB400 644 MHz $\beta = 0.65$ 5-cell elliptical cavities [6]. Investigations of modifications to the electropolishing (EP) cathode required to accommodate the eccentric medium-beta cavity geometry in the post N-doping EP are also presented.

INTRODUCTION

The upgraded FRIB400 linac [7] aims to double the FRIB baseline end-energy from 200 to 400 MeV/u for the heaviest uranium ions, which equates to 1 GeV for protons. FRIB conventional facilities incorporated 80 meters of space in the linac tunnel reserved for energy upgrade cryomodules. Several SRF cavity designs were studied for their potential to meet this energy requirement in the available space in the most economical fashion, and it was ultimately concluded that a 5-cell 644 MHz cavity with $\beta_{opt} = 0.65$ is optimal for the energy upgrade [6]. Essentially, this design meets energy upgrade performance targets while minimizing heat load, number of additional cavities, and number of additional cryomodules. Two 5-cell prototypes of this design, serialized as S65-001 and S65-002, were ordered by FRIB and built at RI in Germany. These were delivered to FRIB/MSU in the fall of 2018, where preliminary RF testing commenced. This testing encompassed the following three "conventional" recipes: Buffered chemical polishing + 120°C baking (BCP+baking), electropolishing +120°C baking (EP+baking) and electropolishing without any baking (EP-only). The results of these tests have been reported previously [8, 9]. In summary, the EP-only trial delivered the best results, achieving $Q_0 = 2.3 \times 10^{10}$ at the desired operating gradient of 17.5 MV/m, achieving FRIB400 baseline requirements by 1.3 times. While these results are encouraging, we remain motivated to explore the application of novel N-doping recipes to these cavities, given the potential for significant gains in Q_0 that N-doping, or mid-T baking, offers [1, 3]. Gains in Q_0 by as much as a factor of two would significantly reduce the dynamic heat load, and in general, would further future, and wider, applications of medium- β superconducting RF cavities in science and industry.

RF SURFACE PROCESSING

S65-001 baseline EP consisted of a 150 μm bulk EP that was carried out at Argonne National Laboratory (ANL). The cavity was then baked FRIB's high-vacuum furnace for hydrogen degassing: first at 350°C for 12h, then at 600°C for 10 hours. After 20 μm EP, the cavity was used to test EP+120°C 48-hour bake. After this test, the cavity was "reset" with 30 μm EP plus 10 μm cold EP at ANL. S65-002 was similarly prepared to initially test the BCP+120°C 48-hour bake, and was similarly reset with 20 μm EP plus 10 μm cold EP at ANL. These EP preparations served as the baseline of comparison for each cavity to their future N-doped and mid-T baked performance.

After the EP baseline tests were conducted, S65-001 and S65-002 were then N-doped at FNAL facilities (2/0 doping at 800°C followed by 7 μm cold EP). Based on the initial performance of S65-001, it was suspected that post-doping EP had been incomplete, and an additional 5 μm of EP was conducted, which somewhat improved Q_0.

After the conclusion of the N-doping test, S65-001 was then EP-reset, and re-baselined. The cavity then underwent a further light EP at ANL, high pressure water rinse (HPR), 3 h 300°C "mid-T" bake in the FNAL vacuum furnace, then another HPR in the FNAL vacuum furnace, before final clean assembly to the vertical test insert at FNAL.

EP CATHODE MODIFICATION

Medium-β cavities have a relatively eccentric shape characterized by a high aspect ratio between the equator standoff distance (197 mm) and the cell length (142 mm). Equivalently, the sidewalls of this cavity type are relatively steep. The mechanical implications of steep sidewalls have been previously reported [1, 8, 9]. The implications of the

* This work is supported by the award of the DOE-SCGSR grant, 2020, Solicitation 1, the Accelerator Stewardship (US Department of Energy, Office of Science, High Energy Physics under Grant award number DE-SC0020371) and PIP-II. Further support provided by the US Department of Energy, Office of Science, High Energy Physics under Cooperative Agreement award number DE-SC0018362.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV001

UPDATE ON NITROGEN INFUSION SAMPLE R&D AT DESY

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Abstract

Many accelerator projects, such as the European XFEL cw upgrade or the ILC, would benefit from cavities with reduced surface resistance (high Q-values) while maintaining a high accelerating gradient. A possible way to meet the requirements is the so-called nitrogen-infusion procedure on Niobium cavities. However, a fundamental understanding and a theoretical model of this method are still missing. The approach shown here is based on R&D using small samples, with the goal of identifying all key parameters of the process and establishing a stable, reproducible recipe. To understand the underlying processes of the surface evolution that give improved cavity performance, advanced surface-analysis techniques (e.g. SEM/EDX, TEM, XPS, TOF-SIMS) are utilized and several kinds of samples are analyzed. Furthermore, parameters such as RRR and the surface critical magnetic field denoted as H_{c3} have been investigated. For this purpose, a small furnace dedicated to sample treatment was set up to change and explore the parameter space of the infusion recipe. Results of these analyses and their implications for the R&D on cavities are presented.

NITROGEN INFUSION IN A DEDICATED SAMPLE FURNACE

The so-called "Nitrogen Infusion" [1] process applied to 1.3 GHz TESLA-type cavities was reported to achieve higher Q-values compared to the standard surface treatments as shown in Fig. 1. The recipe consists of a heat treatment at 800°C for 3 h under vacuum conditions typically $\sim 10^{-7}$ mbar followed by a ramping down to 120°C. During the hold time of 48 h at 120°C a partial pressure ($3.3 \cdot 10^{-2}$ mbar) of nitrogen is applied. The reproducibility among other laboratories has proven difficult so far since it is very sensitive to furnace cleanliness. It is our goal to find the key parameter for a stable and reproducible recipe. An extensive sample study with a dedicated sample furnace as shown in Fig. 2 is carried out and the results are presented here. The furnace has a ceramic tube with a diameter of 80 mm. A Residual Gas Analyzer (RGA) and a mass-flow controller for nitrogen inlet are installed. The maximum achievable, stable temperature is 1350°C. The pump system saturates at an end pressure of $p < 5 \cdot 10^{-8}$ mbar at room temperature. The furnace has been setup for explicit nitrogen-infusion studies on niobium samples. Data from the RGA during a nitrogen infusion is shown in Fig. 3.

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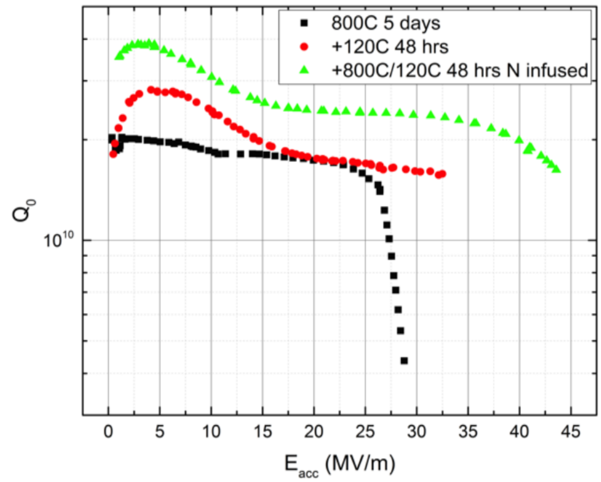

Figure 1: Q vs. E comparison between nitrogen infusion and standard EP-treated cavities [1].

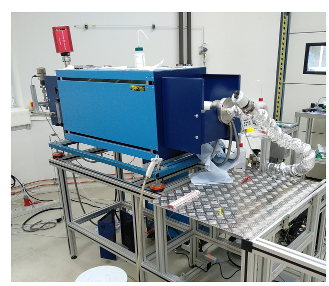

Figure 2: Image of the small sample furnace.

RESIDUAL RESISTIVITY RATIO (RRR)

RRR is the ratio of electrical resistance $\rho(T)$ at room temperature to the residual one at 4.2 K: RRR $= \frac{\rho(295\,\mathrm{K})}{\rho(4.2\,\mathrm{K})}$. However, since for niobium $T_c = 9.2$ K the RRR at nearly 9.2 K is used or extrapolated down to 4.2 K. As the phonon-electron interaction can be neglected for very low temperatures (but above 4 K), the electrical resistivity then starts to depend only on impurities and lattice defects. The higher the RRR, the fewer defects and interstitials in the material. Thus the RRR characterizes the purity of a metal and is sensitive to changes in impurities due to diffusion during treatments such as heat treatments in vacuum or under certain gas atmospheres and after chemical surface treatments. Therefore, this parameter is particularly interesting for niobium cavities and especially treatments such as nitrogen infusion, which will be discussed in more detail in the following chapters.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV002

AB INITIO THEORY OF THE IMPACT OF GRAIN BOUNDARIES ON THE SUPERCONDUCTING PROPERTIES OF Nb_3Sn*

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Abstract

Grain boundaries significantly affect the superconducting properties of Nb_3Sn, and for SRF applications, grain boundaries can provide weak points for vortex entry and ultimately limit the efficiency of Nb_3Sn SRF cavities. Here we use density functional theory (DFT) to investigate the physics of different grain boundary types in Nb_3Sn and distinguish the properties of clean grain boundaries from grain boundaries containing tin antisite defects. Clean grain boundaries reduce the Fermi-level density of states by over a factor of two, and the bulk electronic structure is recovered $\sim$1 nm from the boundary plane. We use atomic concentration measurements of an SRF cavity to determine the effects of tin-segregation on grain boundaries and find that tin-rich boundaries widen the reduction in the Fermi-level density of states out to $\sim$1.5 nm from the boundary plane, producing a full width of $\sim$3 nm. Finally, we introduce a model for a local superconducting transition temperature T_c as a function of distance from the boundary plane, and provide a new estimate for flux-pinning forces based on our DFT calculations.

INTRODUCTION

Nb_3Sn is a type-II superconductor with a critical temperature of 18 K and is a promising material for next-generation SRF cavities [1, 2]. The $\sim$3 nm coherence length of Nb_3Sn is considerably shorter than the $\sim$50 nm coherence length of elemental superconductor Nb, making the material much more sensitive to defects such as grain boundaries [3–5].

For SRF applications, grain boundaries can provide nucleation sites for flux to penetrate and lead to significant dissipation. [6–9]. In particular, strong Q-slopes have been observed in SRF cavities with prominent tin segregation at grain boundaries [10]. Furthermore, studies of superconducting wires show that strong gradients of tin composition at grain boundaries can reduce the critical current density, the flux pinning force, and flux pinning scaling field [11–13].

Despite many experimental and numerical studies pointing out the importance grain boundaries in Nb_3Sn, only recently has a study thoroughly investigated the physics of grain boundaries in Nb_3Sn using first principles calculations [14].

Here we study the influence of grain boundaries on the properties of Nb_3Sn from first principles using density functional theory (DFT). We calculate the impact of grain boundaries on the material's electronic structure, and go on to calculate the effect of grain boundaries containing atomic concentrations corresponding to measurements of Nb_3Sn SRF cavities exhibiting strong Q-slopes [10]. Finally, we provide estimates for local superconducting properties including a model for a local T_c and flux-pinning force.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams.
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METHODS

We perform DFT calculations with open-source plane wave software JDFTx using the pseudopotential framework [15]. The electronic states are calculated for the valence and semi-core electrons of niobium ($4p^6 5s^2 4d^3$) and tin ($4d^{10} 5s^2 5p^2$), and the atomic cores are approximated using ultrasoft pseudopotentials [16]. We use the Perdew-Burke-Ernzerhof (PBE) approximation to the exchange-correlation functional and employ a 12 Hartree planewave cutoff energy [17]. We calculated zero-temperature effects using the cold-smearing method developed by Marzari with a smearing width of 5 mH [18]. For cubic A15 Nb_3Sn, we sample 6^3 k-points in the Brillouin zone and its density of states is calculated with a dense Monte Carlo sampling in a maximally localized Wannier function basis [19]. The k-point meshes for the grain-boundary cells contain comparable sampling densities as the unit cell calculation, and their densities of states are calculated with tetrahedral interpolation. The lattice parameter for cubic A15 Nb_3Sn is calculated to be 5.271 Å, agreeing well with its measured value of 5.289 Å [20, 21]. We allow the lattices of the grain-boundary cells to relax along the boundary plane normal but find that the lattice relaxations do not produce any significant changes, and consequently, we choose to report results calculated at the bulk lattice constant. All the boundary cells reported in this paper contain fully relaxed internal atomic coordinates.

SUPERCONDUCTIVITY IN THE A15 STRUCTURE

Nb_3Sn is part of the A15 class of conventional superconductors which held the record for highest T_c from 1954–1986 [22, 23]. The A15 structure is shown in Fig. 1(a), with tin atoms in red forming a BCC lattice and niobium atoms in blue forming long chains that span the faces of the cubic unit cell.

A common feature of the A15 superconductors is their high Fermi-level density of states. The total density of states for Nb_3Sn is plotted in 1(b). The value at the Fermi-level is indeed high and also sharply drops by nearly a factor of 5 within $\sim$0.2 eV. The shape of the density of states in Nb_3Sn is attributed to the d-orbitals of the chains of Nb atoms in the A15 phase. Figure 1(c) demonstrates this relationship by displaying the partial projected density of states along d-orbitals of the Nb atoms.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV003

EFFECT OF MEAN FREE PATH ON NONLINEAR LOSSES OF TRAPPED VORTICES DRIVEN BY A RF FIELD*

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Abstract

We report extensive numerical simulations on nonlinear dynamics of a trapped elastic vortex under rf field, and its dependence on electron mean free path l_i. Our calculations of the field-dependent residual surface resistance $R_i(H)$ take into account the vortex line tension, the linear Bardeen-Stephen viscous drag and random distributions of pinning centers. We showed that $R_i(H)$ decreases significantly at small fields as the material gets dirtier while showing field independent behavior at higher fields for clean and dirty limit. At low frequencies $R_i(H)$ increases smoothly with the field amplitude at small H and levels off at higher fields. The mean free path dependency of viscosity and pinning strength can result in a nonmonotonic mean free path dependence of R_i, which decreases with l_i at higher fields and weak pinning strength.

INTRODUCTION

RF losses in SRF cavities are quantified by the quality factor Q_0 which is inversely proportional to the surface resistance R_s. The surface resistance consists of two parts, $R_s = R_{BCS} + R_i$, where $R_{BCS} \propto \omega^2 \exp(-\Delta/T)$ comes from thermally activated quasiparticles while R_i quantified a weakly-temperature dependent residual resistance. The temperature independent R_i can produce a large fraction of the total dissipation about $\approx$ 20% for Nb and $\approx$ 50% for Nb_3Sn at 2 K and 1-2 GHz [1]. So the dependence of R_i on the magnetic field H, frequency f and mean free path (l_i) is of much interest. The main contributions to R_i comes from trapped vortices generated during the cavity cool down through the critical temperature T_c at which the lower critical field $H_{c1}(T)$ vanishes [2–10]. In this case even small stray fields $H > H_{c1}(T)$ such as unscreened earth magnetic field can produce vortices in the cavity. During the subsequent cooldown to $T \simeq 2$ K some of these vortices exit the cavity but some get trapped by the material defects such as non-superconducting precipitates, network of dislocations or grain boundaries.

Low-field rf losses of pinned vortices have been calculated by many authors [3, 11–15]. Nonlinear quasi-static electromagnetic response of perpendicular vortices has been addressed both for weak collective pinning [1], and strong pinning [16, 17]. The extreme nonlinear dynamics of a vortex under a strong ac magnetic field at which $R_i(H)$ decreases with H because of the decrease of vortex viscosity with the velocity was addressed in [18]. The dissipation of vortices under a strong magnetic field in the cases of mesoscopic pinning has been calculated recently by [19]. The nonlinear dynamics of the trapped vortex and the field dependence R_i can also be tuned by nonmagnetic impurities. Yet, the mean free path dependency of the rf power generated by flexible oscillating vortex though a random pinning potential remains poorly understood. In this work, we calculate field dependent $R_i(H)$ and its dependencies on the mean free path, frequency and the pinning strength due to a trapped vortex line under rf magnetic field. Our calculation take into account the vortex line tension, pinning force, and Bardeen-Stephen viscous drag force.

DYNAMIC EQUATIONS

Consider a single vortex pinned by materials defects as shown in the Fig. 1. Here the vortex is driven by the ac

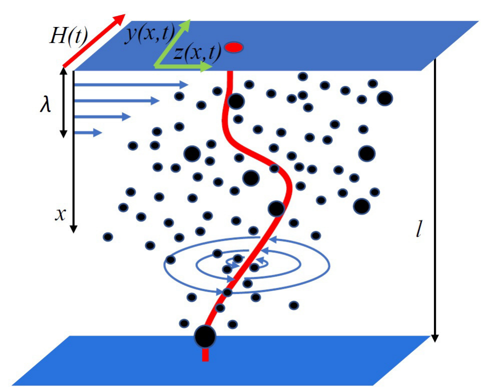

Figure 1: A flexible vortex shown by the read line driven by the rf surface current. The black dots represent pinning centers such as non-superconducting precipitates. Green arrows show vortex tip displacement on the YZ plane.

Meissner currents flowing in a thin layer of $\sim\lambda$ at the surface. The ac displacement of the vortex $\mathbf{R} = [Y(X,t), Z(X,t)]$ is mainly confined within the elastic skin depth [3] so that the vibrating vortex segment interacts only with a few pins while the rest of the vortex does not move. In this situation, the electromagnetic response of a perpendicular vortex becomes dependent on its position and the statistical distribution of random pinning potentials. For instance, Fig.1 shows a representative case of bulk pinning by small, randomly-distributed non-superconducting precipitates. The dynamic equation for trapped vortex shown in the Fig. 1 is given by:

$$M\frac{\partial^2 \mathbf{R}}{\partial t^2} + \eta\frac{\partial \mathbf{R}}{\partial t} = \epsilon\frac{\partial^2 \mathbf{R}}{\partial X^2} - \nabla U(X,\mathbf{R}) - \hat{y} f_L(X,t), \quad (1)$$

$$f_L(X,t) = (\phi_0 H/\lambda)e^{-X/\lambda}\sin\omega t, \quad (2)$$

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV006

INVESTIGATION OF SIS MULTILAYER FILMS AT HZB

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Abstract

The systematic study of multilayer SIS films (Superconductor-Insulator-Superconductor) is being conducted in Helmholtz-Zentrum Berlin. Such films theoretically should boost the performance of superconducting cavities, and reduce some problems related to bulk Nb such as magnetic flux trapping. Up to now such films have been presented in theory, but the RF performance of those structures has not been widely studied. In this contribution we present the results of the latest tests of AlN-NbN films, deposited on micrometer-thick Nb layers on copper. It has, also, been shown previously at HZB that such SIS films may show some unexpected behaviour in surface resistance versus temperature parameter space. In this contribution we continue to investigate those effects with the variation of different parameters of films (such as insulator thickness) and production recipes.

INTRODUCTION

Previous measurements [1, 2] of the first SIS structure at HZB with the Quadrupole Resonator (QPR) [3] have shown unusual behaviour of the surface resistance in temperature dependant parameter space. To study this effect further 3 more SIS layered samples have been coated by the University of Siegen [4] within the ARIES program [5]. The samples are listed in the Table 1. The first SIS sample measured at HZB, prior to ARIES, was prepared at Jefferson Lab (JLab) using DC MS sputtering technology [1, 2]. It is included in the table as well for comparison.

The ARIES SIS samples were the consequent study of the niobium films on copper [5]. Partially due to this reason the structure of the samples was chosen to be NbN-AlN-Thick Nb layer on copper (see Fig. 1). The copper surface of all substrates for the ARIES samples was prepared by INFN with electropolishing (see Fig. 2) [6].

The reasoning behind the choice of the respective layer thicknesses was initially based on Kubo's paper [7]. Moreover, the choice of NbN layer thickness was based on results from the VSM measurements performed within ARIES [8] and then thirdly, we did variations in the thin AlN layer according to advice and feedback session with Gurevich.

First ARIES sample was coated with the DC MS sputtering technology (similar to the SIS films described in [8]). For this sample prior to NbN-AlN coating the RF test of the base Nb layer was performed. The sample with 4 µm Nb layer on copper was transported to HZB from Siegen in a sealed container with a neutral gas (Argon). Then the sample was tested with the QPR, and sent back to Siegen for the subsequent NbN-AlN coating. As a result the Nb layer was exposed to air between the coatings.

The second and third ARIES samples were coated in one run with HiPIMS method [4].

Table 1: SIS Samples Structure

Sample	Sample structure	Layers thickness [nm]
J-Lab SIS [1]	NbTiN/AlN/Nb(bulk) DC MS	75/15/bulk Nb
ARIES 1st SIS	NbN/AlN/Nb/Cu DC MS	197/35/3000 Nb
ARIES 2nd SIS	NbN/AlN/Nb/Cu HiPIMS	180/8/4000 Nb
ARIES 3ed SIS	NbN/AlN/Nb/Cu HiPIMS	180/24/4000 Nb

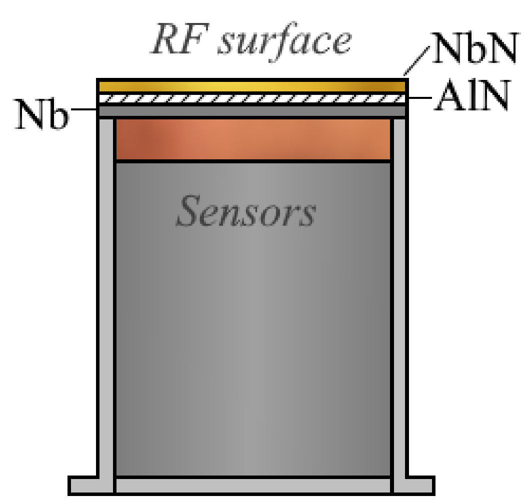

Figure 1: Structure of ARIES samples.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV007

MAGNETIC FIELD PENETRATION OF NIOBIUM THIN FILMS PRODUCED BY THE ARIES COLLABORATION*

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Abstract

Superconducting (SC) thin film coatings on Cu substrates are already widely used as an alternative to bulk Nb SRF structures. Using Cu allows improved thermal stability compared to Nb due to having a greater thermal conductivity. Niobium thin film coatings also reduce the amount of Nb required to produce a cavity. The performance of thin film Nb cavities is not as good as bulk Nb cavities. The H2020 ARIES WP15 collaboration studied the impact of substrate polishing and the effect produced on Nb thin film depositions. Multiple samples were produced from Cu and polished with various techniques. The polished Cu substrates were then coated with a Nb film at partner institutions. These samples were characterised with surface characterisation techniques for film morphology and structure. The SC properties were studied with 2 DC techniques, a vibrating sample magnetometer (VSM) and a magnetic field penetration (MFP) facility. The results conclude that both chemical polishing and electropolishing produce the best DC properties in the MFP facility. A comparison between the VSM and the MFP facility can be made for 10 μm thick samples, but not for 3 μm thick samples.

INTRODUCTION

The current material used in superconducting radio frequency (SRF) cavities is bulk Nb which is reaching its theoretical limits. Superconducting (SC) thin film cavities are a good alternative to bulk Nb cavities. Copper is a preferable substrate to Nb for machining due to being more frequently used and being less brittle. Polishing Cu also uses less harmful chemistry than polishing Nb. Another advantage of Cu is its good thermal conductivity, providing better thermal stability and uniformity in comparison to Nb. Thin films reduce the amount of Nb used to make accelerating structures.

Systematic studies of SC thin films were performed by an international collaboration funded by H2020 ARIES project. These studies included the effect of substrate preparation[1] on the growth of Nb thin films. The SC properties of the Nb thin films were measured in RF conditions and in a DC magnetic field using a vibrating sample magnetometer (VSM) and a magnetic field penetration (MFP) facility.

Polishing of Cu Substrates

The condition of the substrate surface is critical for the quality of thin film growth, therefore attention must be paid to surface cleanliness and flatness prior to deposition. After the Cu substrates were cut, they were cleaned and polished with[1] [2]: Chemical polishing (SUBU5), Electropolishing (EP), EP + SUBU5, Tumbling. Once the Cu substrates had been polished and characterized, 15 substrates were equally distributed between INFN, Siegen and STFC for Nb deposition described in [1][2]. After deposition, the Nb thin films were characterized using AFM in non-contact mode. The SC properties of the Nb were then tested in a VSM, with the samples tested in both perpendicular and parallel orientation to the applied magnetic field (B_{app}). This paper is reporting the results of these samples obtained with a new MFP method.

It should be noted that the Nb deposited at STFC were 10 μm thick whilst the samples at Siegen and INFN are 3 μm. Before these samples were tested in the field penetration facility described in the next section, the samples from INFN were laser treated post Nb deposition described in [1].

FIELD PENETRATION FACILITY

Method

In an accelerating cavity the magnetic field induced by the RF wave is applied parallel to the surface of the cavity,

* This research has been supported by European Commission's ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV009

THERMAL ANNEALING OF SPUTTERED Nb_3Sn AND V_3Si THIN FILMS FOR SUPERCONDUCTING RF CAVITIES*

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Abstract

Nb_3Sn and V_3Si thin films are alternative material candidates for the next-generation of superconducting radio-frequency (SRF) cavities. However, past sputtered films suffer from stoichiometry and strain issues during deposition and post annealing. As such, we aim to explore the structural and chemical effects of thermal annealing, both in-situ and post-sputtering, on DC-sputtered Nb_3Sn and V_3Si with varying thickness on Nb or Cu substrates. We successfully enabled recrystallization of 100 nm thin Nb_3Sn films with stoichiometric and strain-free grains at 950 °C annealing. For 2 µm films, we observed removal of strain and slight increase in grain size with increasing temperature. A phase transformation from unstable to stable structure appeared on thick V_3Si samples, while we observed significant Sn loss in thick Nb_3Sn films at high temperature anneals. For films on Cu substrates, we observed similar Sn and Si loss during annealing likely due to Cu-Sn and Cu-Si phase generation and subsequent Sn and Si evaporation. These results encourage us to refine our process to obtain high quality films for SRF use.

INTRODUCTION

As niobium-based superconducting radio-frequency (SRF) cavities are reaching the theoretical limits, alternative materials are of great interest to continue the quest of increasing quality factors, accelerating gradients, and efficiency. A-15 superconductors Nb_3Sn and V_3Si are promising candidates for this role, used as thin films inside either Nb or Cu cavities [1, 2]. Both candidates have relatively high critical temperatures ($T_{c,Nb3Sn}$=18.3K and $T_{c,V3Si}$=17.1K), and Nb_3Sn is predicted to yield a superheating field of ~400 mT that doubles the Nb limit of ~200 mT [2-4]. These properties could allow cavity operation at an elevated temperature of 4.2K and the potential for increased accelerating gradients [5]. Due to their brittle nature and low thermal conductivity, Nb_3Sn and V_3Si are best suited for use as a thin film inside a host cavity with better thermal conductivity, such as Nb or Cu [2, 6, 7]. Here, we investigated Nb_3Sn and V_3Si films of different thickness on both Nb and Cu substrate to optimize the best conditions that overcome cracking while producing required stoichiometry and properties.

Sputtering that utilizes high-energy plasma to eject target materials is a promising technique for deposition of these films onto the substrates [1]. The film properties can be tailored via controlling the Ar plasma pressure, substrate temperature, sputtering voltage, sputtering current, and rate of deposition. In literature, sputtered Nb_3Sn films have been demonstrated on Nb and Cu surfaces either using direct a Nb_3Sn target or through annealing a sputtered Nb/Sn multilayer, and achieved T_c above 17 K [1, 4, 5, 8], while V_3Si has not yet been extensively studied for SRF use [6, 7]. One goal of this work is to optimize the sputtering capability of these alternative SRF materials at Cornell and compare our results with existing efforts in the SRF field.

Thermal annealing of the sputtered films, either in-situ or post deposition, is required to minimize the internal stress induced by the sputtering process and improve the stoichiometry and grain structures, which are critical to their critical temperature and cavity RF performance. However, during annealing of sputtered Nb_3Sn or Nb/Sn multilayers, the films suffer from issues such as the Sn loss, Cu incorporation into the film for Cu substrates, and lattice mismatch at the substrate-film boundary [1, 4, 8]. Thus, we aim to systematically investigate the effect of thermal annealing on the sputtered Nb_3Sn and V_3Si thin films in order to better understand these observed issues and design an optimal process for SRF use.

METHODS

In this study, Nb_3Sn and V_3Si thin films were deposited using a DC-sputtering system at the Cornell Center for Materials Research. These films varied in thickness, substrate, and heating in-situ. In the sputtering process, bulk Nb_3Sn and V_3Si targets were used, and all depositions were performed at 5 mTorr Ar pressure. The substrates were square-shape samples of Nb (1 cm x 1 cm x 3 mm) and Cu (1 cm x 1 cm x 2 mm). Before deposition, Nb substrates were electropolished and Cu substrates were chemically polished to ensure a smooth surface.

The sputtering parameters studied are the film material (Nb_3Sn vs. V_3Si), substrate material (Nb vs. Cu), deposition temperature (room temperature vs. 550 °C in-situ heating), and film thickness (100 nm, 300 nm, and 2 µm). After the sputtering process, films were annealed under different temperatures (600 °C - 950 °C) for 6 hours in a Lindberg high-vacuum (10^{-7} Torr) furnace. Structural and chemical analysis were conducted between anneals to characterize the films. These analysis methods included scanning electron microscope (SEM) to observe the grain structure and size, energy dispersive X-ray spectroscopy (EDS) to calculate the atomic composition, and X-ray diffraction (XRD) to gain insight about the crystal structure of the film and calculate the strain. In this analysis, the key features we are looking for are the quality of the film surfaces (smoothness, uniformity, grain shape/size), the stoichiometry of the films, and the existence and strain of Nb_3Sn and V_3Si diffraction planes.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. This work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV012

THE DEVELOPMENT OF HiPIMS MULTILAYER SIS FILM COATINGS ON COPPER FOR SRF APPLICATIONS

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Abstract

In recent years, the use of alternatives to bulk Nb in the fabrication of SRF cavities, including novel materials and/or fabrication techniques, have been extensively explored by the SRF community. One of these new methodologies is the use of a superconductor-insulator-superconductor (SIS) multilayer structure. Typically, these have been envisaged for use with bulk Nb cavities. However, it is conceivable to combine the benefits of SIS structures with the benefits of coated Cu cavities, such as operation at 4.2 K. It is also clear that the use of, so-called, energetic deposition techniques such as high power impulse magnetron sputtering (HiPIMS), provide significant benefits over typical DC magnetron sputtering (MS) coatings, in terms of SRF performance.

In light of this, two series of multilayer SIS film coatings, with a Nb-AlN-NbN structure, were deposited onto electropolished OFHC Cu samples, with the use of HiPIMS, in order to determine the efficacy of this approach. This contribution details the development of these coatings and the required optimization of the coating parameters of the separate material systems, through the use of multiple material and superconducting characterization techniques. This research culminated in the deposition of two SIS-film quadrupole resonator (QPR) samples, using the final optimized coating process.

INTRODUCTION

The ever-increasing performance of bulk Nb cavities is pushing them towards their theoretical limits. The use of superconductor-insulator-superconductor (SIS) film structures has been proposed as one of the main pathways to overcome this [1]. Initial trials of this approach have indicated its potential for enhancing the penetration field above the H_{c1} of Nb [2]. These structures were originally envisaged for use with bulk Nb cavities. However, it is conceivable to combine the benefits of SIS structures with the benefits of coated Cu cavities, such as operation at 4.2 K. The use of SIS film coatings can also potentially delay the onset of the Q-slope typically observed with coated Cu cavities.

It is also clear that the use of, so-called, energetic deposition techniques such as high power impulse magnetron sputtering (HiPIMS), provide significant benefits over typical DC magnetron sputtering (MS) coatings, in terms of SRF performance, as has been shown for NbN thin films [3].

The results of investigations into HiPIMS-deposited multilayer SIS films are presented in this contribution. Each of the individual layers were previously optimised in separate studies. Given the predictions for an optimum shielding layer thickness [4] and feedback on initial quadrupole resonator (QPR) sample results [5], both the AlN and NbN layer thicknesses were adjusted during this study.

EXPERIMENTAL

Two series of multilayer SIS film coatings, with a Nb-AlN-NbN structure, were deposited onto electropolished OFHC Cu substrates and Si witness samples with HiPIMS, using a Nb (RRR 300) target in a commercial, high-volume, fully automated coating tool (CemeCon CC800). The HiPIMS parameters were kept constant at 1000 Hz and 120 µs for both the deposition of Nb and NbN in all coatings, in conjunction with a constant DC substrate bias. The AlN layer was deposited with DC MS, similar to the films detailed in [6]. A substrate temperature of 180°C was maintained during the coating of all three layers. The Nb and AlN layers were deposited with 100 % Ar (99.999 Vol-%) and N_2 (99.999 Vol-%) gas respectively, while the NbN layer was deposited with a mixture of Ar and N_2 with the N_2/Ar gas ratio maintained by flow rate control. A schematic of the film coating is shown in Fig. 1.

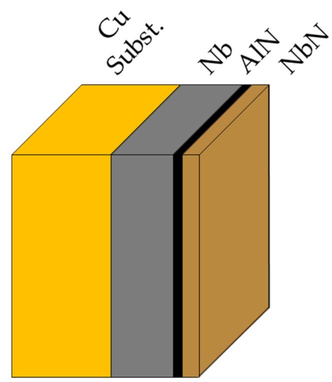

Figure 1: Schematic representation of the SIS film coating.

Prior to deposition, the system was baked at 650°C for 6 hours, to assist in removing any built up adsorbents, and thereafter evacuated to a base pressure of 6 x 10^{-7} mbar. The system was then backfilled with Ar to a pressure of

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV013

HiPIMS NbN THIN FILM DEVELOPMENT FOR USE IN MULTILAYER SIS FILMS

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Abstract

As part of efforts to improve the performance of SRF cavities, the use of alternative structures, such as superconductor-insulator-superconductor (SIS) film coatings have been extensively investigated. Initial efforts using DC magnetron sputtering (MS) deposited NbN films showed the efficacy of this approach. The use of energetic condensation methods, such as high power impulse magnetron sputtering (HiPIMS), have already improved the performance of Nb thin films for SRF cavities and have already been used for nitride film coatings in the tool industry.

In this contribution, the results from the deposition of HiPIMS NbN thin films onto oxygen free high conductivity (OFHC) Cu substrates are presented. The effects of the different deposition parameters on the deposited films were elucidated through various characterisation methods, resulting in an optimum coating procedure. This allowed for further comparison between the HiPIMS NbN films and the previously presented DC MS NbN films. The results indicate the improvements offered by HiPIMS deposition, most notably, the significant increase in the entry field, and its applicability to the deposition of SIS films on Cu.

INTRODUCTION

Bulk Nb cavities are reaching their theoretical limits of operation. As such, new approaches are required in order to enhance the performance of future SRF cavities. One of the approaches currently being investigated is the use of superconductor-insulator-superconductor (SIS) film structures, as first proposed by A. Gurevich [1]. Initial trials of this approach have indicated its potential for enhancing the penetration field above the H_{c1} of Nb [2].

With its high T_c and high H_c, NbN stands as one of the prime candidates for use in SIS structures, even though its H_{c1} is lower than Nb [3]. One of the issues facing NbN however, is ensuring the formation of the high T_c (17.3 K [4]), δ-NbN phase. This was successfully accomplished during previous DC magnetron sputtering (MS) studies, however, the resultant film possessed a relatively low film density, resulting in decreased penetration fields compared to the theoretical value and penetration of oxygen between the NbN grains [5]. In light of this, and given the improvements offered by the use of high power impulse magnetron sputtering (HiPIMS), a series of investigations looking at the potential to deposit denser NbN films using HiPIMS were completed. The foremost aim of the investigations was to improve the field of first flux penetration (H_{en}) of the NbN films, to better serve as a shielding layer in the deposition of SIS film coatings.

The effects of the deposition parameters on the film growth, phase formation and superconducting properties were investigated in order to realise an optimum parameter set for high performance films. The results of these investigations are detailed in this contribution.

EXPERIMENTAL

A series of NbN thin films were deposited onto electropolished OFHC Cu substrates and Si witness samples with HiPIMS, using a 100.0 x 88.0 mm Nb (RRR 300) target in a commercial, high-volume, fully automated coating tool (CemeCon CC800). The HiPIMS parameters were kept constant at 1000 Hz and 120 µs for all coatings, in conjunction with a constant DC substrate bias and a substrate temperature of 180°C. A gas mixture of Ar (99.999 Vol-%) and N_2 (99.999 Vol-%) was used for all coatings, with the N_2/Ar gas ratio maintained by flow rate control.

Prior to deposition, the system was baked at 650°C for 6 hours, to assist in removing any built up adsorbents, and thereafter evacuated to a base pressure of 6 x 10^{-7} mbar. The system was then backfilled with Ar to a pressure of 1.5 x 10^{-3} mbar for target plasma cleaning and MF etching of the substrates.

The films were deposited with a range of different deposition parameters in order to identify those that most significantly influence the NbN phase formation and subsequent superconducting performance. Based on previous experience [5], this included the cathode power, the N_2 content in the gas and the deposition pressure. With the increased ionisation ratio of the sputtered material and the resultant densification of the deposited films offered by HiPIMS, a range of substrate bias values was also included. The high and low limits of the varied parameters are detailed in Table 1.

Table 1: Set Point Ranges for the Varied Deposition Parameters Used for the NbN Film Coatings

Parameter Boundary	Cathode Power (W)	Deposition Pressure (mbar)	Substrate Bias (V)	N_2 Content (%)
High	600	2.4×10^{-2}	100	22
Low	300	1.2×10^{-2}	0	5

Following the deposition of the films, the samples were analysed with a number of characterisation methods, including: AFM, CLSM, EDX, SEM, XRD and VSM magnetisation measurements. Specific results of interest are detailed here.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV015

PRELIMINARY RESULTS FROM MAGNETIC FIELD SCANNING SYSTEM FOR A SINGLE CELL NIOBIUM CAVITY*

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Abstract

One of the building blocks of modern particle accelerators is superconducting radiofrequency (SRF) cavities. Niobium is the material of choice to build such cavities, which operate at liquid helium temperature (2 - 4 K) and have some of the highest quality factors found in Nature. There are several sources of residual rf losses, one of them is trapped magnetic flux, which limits the quality factor in SRF cavities. The flux trapping mechanism depends on different niobium surface preparations and cool-down conditions. Suitable diagnostic tools are not yet available to study the effects of such conditions on magnetic flux trapping. A magnetic field scanning system (MFSS) for SRF cavities using Hall probes and fluxgate magnetometer has been designed, built, and it is commissioned to measure the local magnetic field trapped in 1.3 GHz single-cell SRF cavities at 4 K. In this contribution, we will present the preliminary results from MFSS for a single cell niobium cavity.

INTRODUCTION

Modern particle accelerators depend more and more on superconducting radio frequency (SRF) cavities because of their excellent efficiency, compared to the normal-conducting cavities. More than four decades of research and development has proven that bulk Niobium is the material of choice to build SRF cavities, which are used in modern particle accelerator. With the advancement in research and development of SRF cavities, the quality factor (Q_0) of SRF cavities is now routinely in range of 10^{10} to 10^{11} at 2 K with peak surface magnetic field of up to ≈200 mT [1, 2]. For high energy particle accelerator, we would like to have SRF cavities with higher accelerating gradient > 50 MV/m and a higher quality factor of >10^{10}. It is really challenging to fabricate a cavity with both high-quality factor and accelerating gradient due to RF losses in SRF cavities. Theoretically, when a superconducting cavities cool-down through the critical temperature (T_c), all magnetic flux lines should be expelled from the cavity. However, material defects such as dislocation, impurity precipitates, and grain boundaries are effective pinning sites where magnetic flux lines could get trap during cool-down through T_c.

Magnetic flux trapping is a leading cause of residual losses in superconducting Nb cavities, and it depends on cool-down conditions, surface preparation and ambient magnetic field [3-6]. Suitable diagnostic tools are in high demand to study the effects of such conditions on magnetic flux trapping to enhance cavity performance [7, 8]. We have designed, developed, and commissioned a magnetic field scanning system (MFSS) to detect trapped flux over a large fraction of the surface of 1.3 GHz single-cell cavities. In this contribution, we report initial results of the newly commissioned MFSS, which used cryogenic Hall probes (HP) and fluxgate magnetometers (FGM) to measure the trapped flux on the cavity surface at different cool-down conditions and different ambient magnetic field.

EXPERIMENTAL SETUP AND PROCEDURE

Experimental Setup

Figure 1 shows the assembled MFSS on a 1.3 GHz niobium SRF cavity. This setup consists of four HPs in one bracket and four FGMs in another bracket, 180° apart. The setup is developed in such a way that both brackets along with sensors can move from 0° to 360° in azimuthal direction, around the cavity axis. More detail about the magnetic field scanning system setup can be found in reference [9]. Figure 2 shows the orientation of the sensors with respect to the cavity axis. In order to measure the external applied magnetic field, we installed three fluxgate magnetometers FGMA, FGMB and FGMC. We used four Cernox temperature sensors, two at top beam tube labelled *a* and *b*, and two at the bottom beam tube labelled *c* and *d*, to measure the temperature at the cavity surface at four locations, T_a, T_b, T_c, T_d.

Experimental Procedure

A single-cell TESLA-shape 1.3 GHz niobium cavity labelled PJ1-1 was used for this study. The cavity, under vacuum, with the MFSS was inserted in a vertical cryostat at Jefferson Lab. We applied the certain amount of external magnetic field along the cavity axis using the compensation coils around the Dewar and we measured the applied field using three fluxgate magnetometers. We performed the experiment in two modes: “monitor mode” and “scan mode”.

In monitor mode, we kept all the sensors at a fixed location (no movement in the azimuthal direction) and performed a “fast cool-down” (⇆T across the cavity of ~20 K) through T_c. During fast cool-down, we recorded the magnetic field measured by four Hall probes using Aeropoc’s data acquisition module USB2ad. We also recorded the magnetic field measured by four fluxgate magnetometers

* Work supported by NSF Grant 100614-010. Work at Jefferson Lab is supported by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV016

A LOW POWER TEST FACILITY FOR SRF THIN FILM TESTING WITH HIGH SAMPLE THROUGHPUT RATE

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Abstract

A low-power SRF test facility is being upgraded at Daresbury Laboratory as part of the superconducting thin film testing programme. The facility consists of a bulk niobium test cavity operating at 7.8 GHz, surrounded by RF chokes, and can be run with input RF powers up to 1 W. It is housed within a liquid helium free cryostat and is able to test thin film planar samples up to 100 mm in diameter with a thickness between 1 and 20 mm. The RF chokes allow the cavity to be physically and thermally isolated from the sample, thus reducing the need for complicated sample mounting, whilst minimising field leakage out of the cavity. This allows for a fast turnaround time of two to three days per sample. Initial tests using a newly designed sample holder have shown that an RF-DC compensation method can be used successfully to calculate the surface resistance of samples down to 4 K. Potential upgrades include a pick-up antenna for direct measurements of stored energy and the addition of a self-excited loop to mitigate the effects of microphonics. Details of this facility and preliminary results are described in this paper.

INTRODUCTION

The main aim for the thin film SRF programme at Daresbury Laboratory is to have a simple system able to measure samples under RF conditions with a quick turnaround time between tests. A vertical test facility able to achieve this is in the final stages of commissioning.

After commissioning of the system has been completed, it is expected that two to three samples can be fully characterised under RF conditions per week. This is made possible because of a simple sample mounting procedure that requires little time and effort to perform as it does not require welding.

The ultimate aim is to have the system running in tandem with both a magnetic field penetration facility [1] and a RRR facility [2] operating at Daresbury Laboratory. In doing so, a full picture can be built up of how well each sample performs under both RF and DC conditions. This can then be compared with deposition/preparation parameters used as well as results from surface analysis techniques in order to inform future full cavity depositions.

This paper reports on upgrades made to the test facility as well as RF testing and preliminary measurements of the surface resistance of a bulk niobium sample.

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THE FACILITY

The facility consists of a bulk-niobium choked cavity as described in [3–5]. There are two versions of the cavity design available to use. Both consist of an identical cylindrical half cell, with one surrounded by two chokes and the other surrounded by three chokes. These are both able to test planar samples up to 100 mm in diameter with variable thicknesses between 1 and 20 mm. The resonant frequency of the cavities is 7.8 GHz. This frequency was chosen due to the requirement of chokes surrounding the half cell, thus limiting its size. This, along with to the maximum size of planar samples able to be manufactured, result in a higher resonant frequency compared with most other test facilities.

Planar samples are used because they are easy to deposit on and can be manufactured at low cost unlike full sized cavities. Preparation and deposition of thin film samples of niobium, as well as other superconducting compounds, by members of ASTeC are detailed in [6–8].

The choke cavity is housed in a two-stage LHe-free cryostat. This system is described fully in [5]. The system allows for a simple, fast sample changeover, justifying the decision to switch from using a previous LHe cryostat [4]. The facility contains a laminar air flow providing cleanliness to ISO 6 standard, though moving to a cleaner environment might be required in the future.

There have since been some modifications to this dry system. The main upgrade has been to the sample mounting system. The previous design was deemed to provide poor thermal control of the sample. In order to improve on this, the sample holder that mounts the sample to the system was redesigned. The new sample holder, made from OFHC copper is brazed at 160 °C with indium foil to the sample prior to installation in the cryostat. This is carried out in a separate facility, either under vacuum or in the presence of an inert gas, to ensure that there is minimal contamination of the sample. The high thermal conductivity of indium provides a strong thermal contact between the sample holder and sample allowing for more accurate temperature measurements and optimal thermal control. Since it is not possible to attach thermometers directly to the sample, two silicon diode thermometers are mounted to the sample holder. The sample holder also has two 10 Ω heaters attached as well as copper heat links connected to the cold head for cooling.

Another upgrade was made to improve the thermal isolation between the sample and cavity. To maintain a 1mm vacuum gap between the two, aluminium spacers were previously used. However, these spacers were later replaced

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV018

CERN BASED T_C MEASUREMENT STATION FOR THIN-FILM COATED COPPER SAMPLES AND RESULTS ON RELATED STUDIES

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Abstract

In the framework of the Future Circular Collider (FCC) Study, the development of thin-film coated superconducting radio-frequency (SRF) cavities capable of providing higher accelerating fields (10 to 20 MV/m against 5 MV/m of LHC) represents a major challenge. The development of a test stand commissioned at CERN for the inductive measurement of the critical temperature (T_cc) of SC thin-film deposited on copper samples for SRF application is presented in this work. Based on new studies for the production of Non Evaporable Getters (NEG) coated chambers, the first results of an alternative forming method for seamless copper cavities with niobium layer integrated in the production process are also presented.

INTRODUCTION

The station for the measurement of the T_c of SC thin films deposited on copper substrate presented in this paper was commissioned at the Central Cryogenic Laboratory (Cryolab) at CERN. A consistent R&D program for the development of SC thin-film coated copper cavities is ongoing at CERN, which implies the synergy of the Vacuum, Surfaces and Coatings, Radio Frequency, Cryogenics and Mechanical and Materials Engineering groups. The measurement of the T_c is needed as first assessment of the film quality, and can turn out to be costly in terms of both time and financial resources. Hence the measurement station at the Cryolab has the role of providing a service with fast feedback in the initial part of the production process. The test station is described in "T_c MEASUREMENT". The results obtained with the first reproduction of the procedure described in "REVERSE COATING STUDY" for the production of NEG coated chambers, although applied to niobium and copper to investigate the effectiveness of the *reverse coating* concept for the production of niobium-coated seamless copper cavities, are then presented. Additional measurement series were performed on niobium and A15 films deposited on copper with the T_c measurement station, according to methods established by addressing different goals (which were to study the optimisation Nb film quality for ion incidence at grazing angles, find the optimal recipe for A15 coatings and understand the influence of the substrate preparation on the film quality) and in cooperation with other institutes such as INFN-LNL (Italy) [1], HZB and University of Siegen (Germany).

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T_C MEASUREMENT

The measurement station consists of a contactless two-coil system operated inside a large neck, liquid helium vessel cryostat. The samples[1] to be measured can be inserted and extracted via a dip stick into a chamber that lies above a helium bath, in helium vapour environment. The vapour can flow into the chamber (and hence thermalise the sample) thanks to an inlet at the bottom of the chamber. The temperature of the vapour is adjusted via a heater wound around the inlet and connected to the temperature sensor through a PID feedback loop.

The measurement principle is based on an inductive technique sensitive to the magnetic field expulsion occurring in the film when it turns superconducting, due to Meissner effect. As depicted in Fig. 1.1, the system consists of two coils arranged in front of each other, with the coil planes being parallel but having opposite orientations. The sample is placed between the coils so that its faces are also parallel to the coil planes. The geometry of the system requires the sample to have the standard size and shape of $11 \times 35 \times 1\ \mathrm{mm}^3$, as Fig. 2 shows. The coil facing the film, namely the *drive* coil, is excited with a sinusoidal AC current which in turn generates an alternating magnetic field that can be measured as a voltage induced across the coil facing the sample substrate, addressed in this context as *pickup* coil, which remains passive throughout the measurement. Before the *drive* coil is turned on, the sample is cooled down below its critical temperature to avoid magnetic flux trapping. When the magnetic field is turned on, the film is in the SC state, the screening currents prevent the field lines from entering the film, and a base background signal is detected in the *pickup* coil to which both external noise and the field leaking around the sample contribute. Starting from this initial state, a temperature ramp is run until the sample turns normal conducting. The data acquisition system logs the temperature and voltage amplitude data during the ramp. The transition of the sample to the normal conducting state results into a step-like voltage signal in the *pickup* coil, due to the increased amount of magnetic field crossing the sample and reaching the *pickup* coil as superconductivity breaks and the screening currents cease to exist.

Figure 1.2 shows a schematics of the complete experimental apparatus, including the generator for the drive current (I_D), the controller to set and read the temperature of the vapour, the lock-in amplifier for the measurement of the am-

[1] In this context, by the term "sample" we refer to the "copper substrate *plus* SC film" system.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPFDV020

ALD-BASED NbTiN STUDIES FOR SIS R&D

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Abstract

Superconductor-Insulator-Superconductor (SIS) multilayers improve the performance of superconducting radio frequency (SRF) cavities providing magnetic screening of the bulk cavity and lower surface resistance. In this framework NbTiN alloys stand as a potential material of interest. Atomic layer deposition (ALD) allows for uniform coating of complex geometries and enables tuning of the stoichiometry and precise thickness control in sub-nm range. HERE, we report about NbTiN thin films deposited by plasma-enhanced ALD (PEALD) on insulating AlN buffer layer. Post-deposition rapid thermal annealing (RTA) studies with varying temperatures, annealing times, and gas atmospheres have been performed to further improve the thin film quality and the superconducting properties. Based upon the promising results obtained by RTA, high vacuum annealing has been also investigated in order to stablish the recipe to obtain SIS multilayer for SRF cavities by plasma-enhanced ALD and subsequent annealing.

INTRODUCTION

Over the past decades, the RF performance of bulk Nb cavities has continuously improved with material and surface developments. Meanwhile we are approaching the theoretical limits of bulk niobium and long-term solutions for further SRF performance improvements need to be pursued. A potential solution was proposed by A. Gurevich [1], namely Superconductor – Insulator – Superconductor multilayers (SIS structures). The idea is to coat the internal surface of the SRF cavities with alternating superconducting and insulating layers taking in advantage of superconductors with higher Tc than niobium (see Fig. 1).

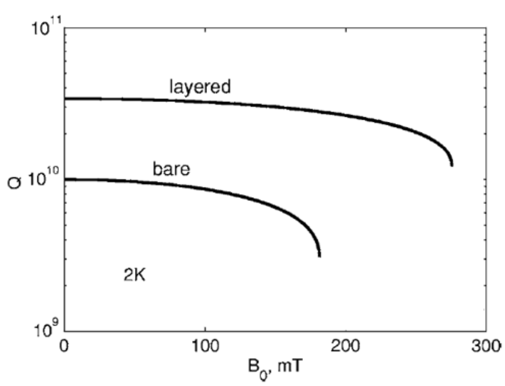

Figure 1: Q vs B curve calculated by A. Gurevich [1] for bare and layered cavity, which shows the significative improvement in the RF cavity performance due to the multilayer S-I-S coating.

The strong increase of Hc1 in films allows to operate at RF fields higher than the Hc1 of the bulk niobium cavity since the multilayers provide magnetic screening of the bulk cavity preventing vortex penetration. Moreover, the use of higher Tc superconductors reduces the surface resistance. Therefore, the SIS structures improve the SRF cavity performance, increasing the accelerating field and reducing the losses.

In this framework NbTiN alloys stand as a potential material of interest. While NbN has a high Tc of 17.3 K, it contains a high normal conducting resistivity, which is significantly reduced with the incorporation of Ti into NbN. NbTiN alloys can be deposited by physical vapor deposition (PVD), chemical vapor deposition (CVD) and atomic layer deposition (ALD). The latter provide conformal coatings on high aspect ratio structures at low deposition temperatures, which makes it particularly interesting for coating the internal surface of SRF cavities. The deposition of NbTiN by thermal ALD, generally using chlorinated precursors [2] can introduce chlorine contamination on the deposited films while plasma-enhanced ALD (PEALD) enables metalorganic precursors, improving the quality of the deposited films.

To further improve the superconducting properties of the NbTiN films post-deposition rapid thermal annealing (RTA) and high vacuum annealing have been studied.

EXPERIMENTAL DETAILS

We investigate the deposition of superconducting films of $Nb_xTi_{1-x}N$ grown on Si wafer by plasma enhanced atomic layer deposition (PEALD) using metalorganic precursors and H_2/N_2 plasma. The precursors used were (t-Butylimido)tris(diethylamino)niobium(V) (TBTDEN) and tetrakis(dimethylamino)titanium(IV) (TDMAT), which were maintained at 90 ºC and 70 ºC respectively. The deposition temperature was kept at 250 ºC and the plasma power at 300 W. The deposition process consists in an PEALD supercycle which alternates the PEALD cycles for the deposition of NbN (alternation of TBTDEN pulse and plasma exposure) with TiN cycles (alternation of TDMAT pulse and plasma exposure). Thus, the composition of the deposited $Nb_xTi_{1-x}N$ films can be modified varying the ratio of NbN cycles to TiN cycles run inside the ALD supercycle. Eight different Nb:Ti composition ratios were studied. As insulator the material selected was AlN since it enhances the Tc of NbTiN [3]. The precursor used was Trimethylaluminum (TMA) and was kept at room temperature. Both layers, AlN and NbTiN were deposited within the same PEALD process on Si wafer.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV001

MAGNETIC FIELD PENETRATION TECHNIQUE TO STUDY FIELD SHIELDING OF MULTILAYERED SUPERCONDUCTORS*

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Abstract

The SIS structure which consists of alternative thin layers of superconductors and insulators on a bulk niobium has been proposed to shield niobium cavity surface from high magnetic field and hence increase the accelerating gradient. The study of the behavior of multilayer superconductors in an external magnetic field is essential to optimize their SRF performance. In this work we report the development of a simple and efficient technique to measure penetration of magnetic field into bulk, thin film and multilayer superconductors. Experimental setup contains a small superconducting solenoid which can produce a parallel surface magnetic field up to 0.5 T and Hall probes to detect penetrated magnetic field across the superconducting sample. This system was calibrated and used to study the effect of niobium sample thickness on the field of full magnetic flux penetration. We determined the optimum thickness of the niobium substrate to fabricate the multilayer structure for the measurements in our setup. This technique was used to measure penetration fields of Nb_3Sn thin films and Nb_3Sn/Al_2O_3 multilayers deposited on Al_2O_3 wafers. The system was optimized to mitigate thermomagnetic flux jumps at low temperatures.

INTRODUCTION

For decades, bulk Nb has been the material of choice for SRF accelerator cavities due to its machinability and desirable superconducting properties. With continues progress in SRF technology, the performance of Nb cavities has steadily improved and approach theoretical limits. Best Nb cavity can reach breakdown field up to the thermodynamic critical field, B_c~200 mT which corresponds to accelerating gradient ~40-50 MVm^{-1}[1-4]. Further significant increase of accelerating gradients in the SRF cavities requires superconductors with superheating fields and critical temperatures higher than those for Nb to provide lower surface resistance R_s (high quality factor) and higher breakdown fields (high accelerating gradient) in the Meissner state [5,6]. Since clean Nb has the highest lower critical field $B_{c1} \simeq 180$ mT among type-II superconductors, all other alternative materials have B_{c1} lower than B_{c1}^{Nb}. To address this problem S-I-S multilayer structures with thin superconductors (S) with $B_c > B_c^{Nb}$ separated by dielectric (I) layers deposited on bulk Nb (Fig. 1) have been proposed to enhance the peak surface magnetic field by increasing the field onset of penetration of vortices [7,8]. Surface materials and topographic defects can cause premature local penetration of vortices resulting in hot spots on the cavity surface [9]. The insulating layers block propagation of vortices to the bulk of Nb cavity and increases the breakdown field of the cavity. By developing the S-I-S coating technology, we would be able to achieve high thermal stability to operate cavity at 4.2 K to reduce the operating costs.

The study of SIS multilayers is important to optimize their SRF performance. Many such investigations are going on to study technological issues and SRF characteristics of SIS multilayers [10-17]. This work is based on investigation of the behavior of S-I-S multilayer structures in an external dc magnetic field. Since, maximum accelerating gradient is determined by the peak surface magnetic field at the inner cavity surface, the field onset of magnetic flux penetration is a key characteristic of the breakdown field and the high-field performance of SRF cavities. To measure the field of flux penetration in SRF materials, we developed a simple and efficient technique.

This measurement system was used to investigate bulk Nb, Nb_3Sn thin films and multilayer structure which consists of Nb_3Sn thin films. Nb_3Sn is an attractive choice for the next generation coating materials which could nearly double the maximum accelerating gradient as compared to the best Nb cavities [5].

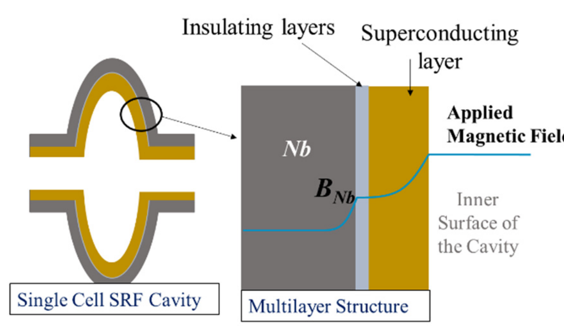

Figure 1: SIS multilayers fabricated on niobium cavity enhances peak surface magnetic field at inner cavity surface.

MEASUREMENT TECHNIQUE

This technique is designed to efficiently measure full flux penetration across the superconducting sample using a simple methodology. To mimic the field configuration in SRF cavities, the magnetic field from the magnet should be applied to the one side of the sample so that the field lines are parallel to the surface, as shown in Fig. 2. Here a NbTi superconducting magnet is placed above the flat sample to produce parallel magnetic field on the surface of the sample up to 500 mT. The magnet is small enough compared to the sample diameter to prevent penetration of magnetic

*Work supported by NSF Grants PHY-1734075 and PHY-1416051, and DOE Awards DE-SC0010081 and DE-SC0019399.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV002

APPLICATION OF PLASMA ELECTROLYTIC POLISHING ONTO SRF SUBSTRATES*

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Abstract

A new promising approach of SRF substrates surface treatment has been studied - Plasma Electrolytic Polishing (PEP). The possible application of PEP can be used not only on conventional elliptical resonators, but also on other components of SRF such as, for example, couplers or the Quadrupole resonators (QPRs). However, SRF application of PEP represents a challenge since it requires a different approach to treat the inner surface of elliptical cavities compared to electropolishing. In this work, the main problematics and possible solutions, the equipment, and the polishing system requirements will be shown. A proposed polishing system for 6 GHz elliptical cavities and QPRs will be shown and discussed.

INTRODUCTION

The PEP processing is a potent method to treat metal surfaces for various purposes: fast cleaning, derusting, polishing, surface preparation for the film deposition, etc. It is wide use for the dental implants treatment field [1]. Thus, being significantly known in some particular industrial fields, the technology it is not well studied and requires additional investments for even more potential benefits. The scalability from the laboratory technology to the needs of SRF is not a trivial task. The possibility of Nb and Cu PEP has been already demonstrated for SRF and published earlier [2], and further studies are being shown in detail [3]. The aim of this work is to share the obtained experience regarding the application of the PEP technology for the SRF needs with the community. A list of possible setups is discussed.

EXPERIMENTAL SETUPS

All the processes were carried out at the facility of Materials Science and Technology Service for Nuclear Physics at Legnaro National Laboratories (LNL) of INFN. The PEP is a technology, that is very similar to EP in terms of the equipment requirements: DC power supply, two electrode system (anode and cathode), the electrolytic solution and connection. However, additional requirements are necessary, such as more powerful power supplies, with high current and high voltage output. At LNL, two DC power supplies of 16 kW, 500V, 90A each, are currently available. They are connected in series, to gain additional current values.

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The different polishing object may require different setups, that is why this study is aimed to demonstrate the comparison and basic schemes of possible setups during PEP processing.

Generic Laboratory Setup "EP-like"

The "EP-like" setup was developed and currently is operation at LNL due to its simplicity and convenient usage in the laboratory environment. It consists of a 5 L beaker, a metallic stand (for electrical connection), and a custom cathode (planar, cylindrical, mesh-type shape). The connection is done similarly as in EP, where the electrodes are defined according to the polarity of the DC power supply (negative – cathode, positive – anode, a sample). The process is carried out at 60℃ with an agitation by magnetic stirrer to improve heat dissipation. The average temperature of the solution is constantly controlled, to avoid low or too high temperature regime. This setup can treat relatively small pieces, depending on the metal nature and composition of the solution (up to 70 cm^2). A scheme of the current setup is shown below (e.g. Fig. 1). An Additional cooling for continuous treatments is necessary and it can be achieved by using jacketed beakers or nitrogen fluxing.

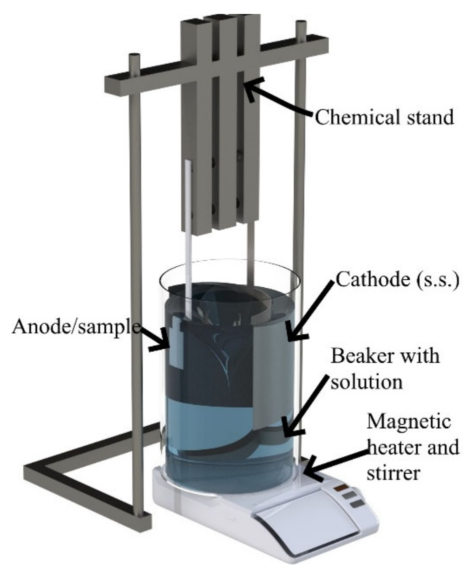

Figure 1: Generic laboratory setup "EP-like".

PROS: Simplicity, fast installation, low volume of solution allow faster studies of possible solution composition. Faster pre-heating. Glass transparency permit observation of the discharge process.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV003

Cu/Nb QPR SURFACE PREPARATION PROTOCOL IN THE FRAMEWORK OF ARIES PROJECT*

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Abstract

The Quadrupole Resonator is a powerful tool for SRF R&D on thin films. It allows to perform Q vs Eacc measurements on flat samples rather than a curved surface of a cavity. For the investigation of super conductive (SC) coatings on copper substrates, e-beam welded Cu/Nb samples have been prepared for the QPR. However, the presence of two metals, in particular at the interface, makes proper polishing of both surfaces challenging, due the different chemical behaviour of both components. In this work we present the protocol developed for the surface preparation of the coexisting Cu and Nb phases and the results obtained for 5 different samples. The work was performed in the framework of the ARIES project.

INTRODUCTION

ARIES is an international collaboration between research groups from CEA (France), CERN (Switzerland), INFN/LNL (Italy), HZB and USI (Germany), IEE (Slovakia), RTU (Latvia) and STFC/DL (UK) that are working on the improvement of the superconductive thin films for SRF cavities [1]. The work package 15, and in particular task 15.2, is focused on the substrate surface preparation.

After a study of electropolishing, chemical polishing (SUBU5), tumbling and its combination on the planar samples [2, 3], the protocol had to be adjusted for the QPR samples preparation. Subsequently, five Cu/Nb QPR samples were treated to study then SC thin films, described in detail in [1, 4-9]. In this work, the optimized protocol of the QPR samples is shown, and a brief description of all treatments and some variable parameters are given.

SURFACE PREPARATION PROTOCOL

A protocol consists of a series of steps, described below in the Table 1. Initially, the protocol included either electropolishing or chemical polishing (SUBU5) treatments as a main polishing step. In the last version, it was decided to do only electropolishing, as it is a more stable and potent technique. For the new QPR sample, the protocol starts from the 1a step and do not include step 3*- Indium removal process. Instead, for the previously sputtered QPR samples, no machining is done, but the stripping process that removes Nb thin film from the Cu disk part of the QPR sample. Some of the samples after measuring process had residuals of Indium. To remove it, relatively fast treatment was done, that chemically pills the Indium material from the flange after 5-10 minutes, and then can be easily removed with a plastic object.

Table 1: Complete Protocol of the Cu/Nb QPR Samples Treatment

#	Step	Solution	Parameters	Time
1a	Lathe machining	-	270 RPM, 40 µm a time	
1b	Stripping	100 g/l powder in $HF:HFB_4$	Applied only locally on the SC film	<30 min
2	Ultrasound cleaning	GP-1740 10g/l soap solution	40°C	1 h
3*	Indium removal	20% HCl	Until In detach	5-30 min
4	Etching	20 g/l $(NH_4)_2S_2O_8$		15 min
5	EP	3:2 v.r. H_3PO_4:n-Butanol	2-3 V, 40°C	15-30 min
6	Rinsing, Ultrasound	Distilled water		30 min
7	Passivation	10 g/l Sulfamic acid		1-3 min
8	High Pressure rinsing	Distilled water	150 atm	1 min
9	Rinsing, drying	Distilled water, ethanol, Nitrogen		2 min
10	Vacuum chamber transfer	-	Vacuuming, Ar fluxing up to the 1,1 atm	

Lathe Machining

The initial roughness of the commercially produced samples after milling was too high (Ra ~1.6 µm, Rz ~ 12 µm) to apply polishing recipes. That is why it was decided to do a uniform polishing by lathe machine at LNL mechanical workshop using a diamond tool that should not contaminate the surface. The first machining processes were optimized later, as initially processing caused troubles on the surface due to the low removing thickness (1 µm) (e.g. Fig. 1). Only an average removal of 40 µm has led to defect-free surface.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV006

COMMISSIONING OF A CALIBRATION DEVICE FOR SECOND SOUND QUENCH DETECTION

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Abstract

An important part of research and development in the field of superconducting radio frequency technology is the quench detection since these breakdowns of superconductivity often limit the cavity performance. Although the second sound based quench detection is widely used, only few studies dealing with its systematic uncertainties exist. Hence, the vertical test stands at the cavity test facility of DESY were extended by calibration device prototypes in order to estimate the accuracy of this method. For the first time at DESY, artificial signals have been generated and reconstructed by heating power film resistors. These second sound signals are determined using noise canceling algorithms and the existing reconstruction software. To evaluate the reconstructed positions, the absolute distance between reconstructed and true coordinates is calculated. Thus, a first uncertainty map of the cavity surface is created to quantify the reconstruction results of actual cavity quenches including systematic effects of the quench positioning like the varying sensor coverage around the cavity.

SECOND SOUND BASED QUENCH DETECTION

Superconducting radio frequency (SRF) cavities made of niobium play a pivotal role in particle acceleration, but their performance is often limited by quenches. These local breakdowns of superconductivity are mainly caused by exceeding the critical temperature or the critical magnetic field of the material.

Due to the heat dissipation during a quench, a temperature-driven entropy wave is generated which propagates through the liquid helium used to cool the cavity. These so-called second sound signals are detected by oscillating superleak transducers (OSTs) [1] based on a capacitor microphone. Utilizing the running times of the detected second sound signals, the wave origin (quench) is reconstructed via trilateration [2] or ray-tracing [3] algorithms.

In order to quantify the reconstruction quality of the second sound method, a device for external calibration was commissioned. As a summary of a recently finished bachelor thesis [4], the commissioning and the calibration results are presented in the following.

At DESY, the quench localization based on second sound waves is performed in vertical test stands. First, the cavity is mounted into an insert supporting up to 16 OSTs. As shown in Fig. 1, four layers of sensors are attached at four metal rods around the cavity.

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Within the cryostats, the insert (including the cavity and sensors) is then cooled with liquid helium to a temperature of about 1.8 K. As helium partly condensates into its superfluid state below the lambda-point of 2.17 K, the propagtion of second sound waves is enabled.

Figure 1: Oscillating superleak transducers (here with white cover caps) mounted on an insert supporting a TESLA-shape single cell SRF cavity with a resonant frequency of 1.3 GHz.

The OSTs consist of a capacitor with parallel plates; one rigid and the other flexible and porous. Whereas the superfluid He-II can pass the porous membrane due to its vanishing viscosity, the normal fluid He-I is blocked and exerts pressure onto the flexible plate during a second sound wave [1]. This causes a shift of the capacitor plates distance and changes thereby its capacity. Since the charge is held constant, the change of capacity is measured via the amplified voltage across the OST.

TRILATERATION ALGORITHM FOR QUENCH RECONSTRUCTION

Using the already existing reconstruction software [2], the quench spot is located via trilateration based on the running times between the signal generation and its detection by OSTs in direct line of sight to the wave origin. In order to locate the quench position in three dimensions, three or more

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV007

DEVELOPMENT OF A SYSTEM FOR COATING SRF CAVITIES USING REMOTE PLASMA CVD*

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Abstract

Next-generation, thin-film surfaces employing Nb_3Sn, NbN, NbTiN, and other compound superconductors are destined to allow reaching superior RF performance levels in SRF cavities. Optimized, advanced deposition processes are required to enable high-quality films of such materials on large and complex-shaped cavities. For this purpose, Cornell University is developing a remote plasma-enhanced chemical vapor deposition (CVD) system that facilitates coating on complicated geometries with a high deposition rate. This system is based on a high-temperature tube furnace with a clean vacuum and furnace loading system. The use of plasma alongside reacting precursors will significantly reduce the required processing temperature and promote precursor decomposition. A vacuum quality monitor (VQM) is used to characterize the residual gases before coating. The CVD system has been designed and is currently under assembly and commissioning.

INTRODUCTION

Niobium-3 tin (Nb_3Sn) is the most promising alternative material to niobium for SRF accelerator cavities. The material has the potential to double accelerating gradients and operating temperature of SRF cavities, decreasing costs and increasing efficiency of future accelerators, see [3]- [7]. The dominant process currently used at Cornell University and elsewhere to coat Nb_3Sn films is based on vaporizing tin in a vacuum furnace and allowing the tin on the surface of an Nb substrate cavity to form Nb_3Sn. This vapor diffusion growth process creates films of good quality, but defects and surface roughness still limit these films well below the ultimate potential of this material. Exploring alternative Nb_3Sn growth methods is therefore of importance, and might offer more control over the growth process. Very thin (tens of nm) films of Nb_3Sn, NbN, NbTiN, and other compound superconductors might also promise superior RF performance levels in SRF cavities, but growing these will require advanced deposition processes to achieve high-quality, uniform films of such materials on large and complex shaped cavity surfaces. Cornell University is therefore developing a dedicated cavity CVD growth system as described in the following sections.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams
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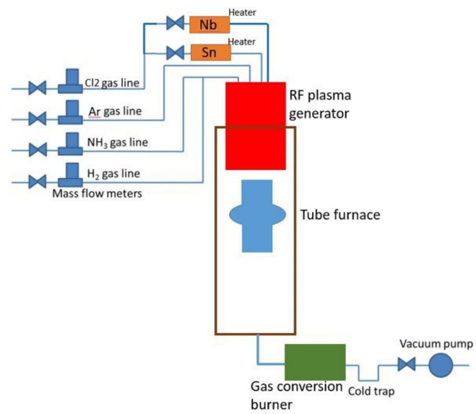

Figure 1: Schematic of the CVD system.

DESCRIPTION OF SYSTEM

The schematic of the system is shown in Fig.1 and a picture of the system in Fig. 2. The tube furnace contains a quartz tube, that can be heated safely up to 1100 C.

The furnace can be used for annealing and CVD work. A branch of the vacuum system contains a roughing pump used for CVD and another branch that contains a turbo-pump, which allows for smaller pressures to be achieved for annealing processes.

Near the gas input side of the tube furnace, there is an RF(Radio Frequency) plasma generator used in the plasma-enhanced CVD process.

The system contains a Vacuum Quality Monitor (VQM) for monitoring possible contamination, as it has the advantage of not over-representing hydrogen when compared to a classical RGA.

On the side for loading cavities, we have a clean room to maintain the cavities and samples free of contamination as seen in Fig. 2.

Chemical Vapor Deposition (CVD)

CVD is a vacuum deposition method and it offers a potential path to grow high-quality films of Nb_3Sn, NbN, NbTiN on various substrates including niobium and copper. An example of the use of CVD is given in [2], and a paper detailing RF results for CVD on a cooper substrate is given in [1] .

A substrate is heated up and exposed to precursors. Figure 1 shows a cavity that is heated, representing the substrate. Nb and Sn precursors decompose at the surface of the cavity and nucleate to Nb3Sn grains. The chemical equation describing the deposition of a film of Nb_3Sn is:

$$3NbCl_x+SnCl_y+(3x+y)/2H_2 \rightarrow Nb_3Sn+(3x+y)HCl \quad (1)$$

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV008

CW OPERATION OF CONDUCTION-COOLED NB_3SN SRF CAVITY*

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Abstract

The substantial development of Nb_3Sn for use in SRF cavities has enabled reliable RF operation at 4.2 K rather than 2 K while maintaining comparable cavity performance. This reduction in required cooling power makes novel cooling schemes possible. New studies have examined the use of commercialized cryocoolers in conduction-cooling based test assemblies for Nb_3Sn SRF cavities. Cornell University has developed and tested a 2.6 GHz Nb_3Sn cavity assembly which utilizes such cooling methods. RF tests in early 2020 resulted in the first-ever demonstration of stable CW operation at 10 MV/m for a conduction-cooled cavity. Our studies also revealed the importance of re-cooling the cavity with more controlled methods in order to improve cavity performance. This finding is connected to the reduction of thermal gradients across the cavity during the superconducting transition.

INTRODUCTION

National studies and workshops have found that a wide range of fields benefit from the use of accelerators at different energy scales, some of them around a few MeV. Some notable examples include: radioisotope production for medical imaging and treatment, material processing and e-beam lithography for integrated circuit printing in industry, wastewater treatments for environmental impacts, and cargo scanning for national defense. Such applications, along with many others, are examined in detail in reports from the DOE and national labs [1, 2]. In many cases, switching to SRF technology could pose a significant advantage thanks to the massive increase in cavity efficiency compared to normal conducting cavities. However, the cooling requirements for SRF cavities present a substantial obstacle, as they require complex and expensive cryogenic infrastructure for efficient operation. This makes SRF technology inaccessible to small-scale operations, as they may not have the resources or space needed for such systems.

There are two significant developments in recent years which could enable the widespread use of SRF technology in industry. First is the improvement of Nb_3Sn as a new material for use in SRF cavities. Nb_3Sn has a critical temperature of just over 18 K which allows for efficient cavity operation at temperatures of 4.2 K [3]. This is a marked improvement over pure niobium, which requires temperatures around 2 K for comparable efficiency [4]. Steady improvements in the performance of Nb_3Sn cavities [3, 5–10] have resulted in cavities capable of reliable operation at accelerating gradients relevant to the various applications described above. Second is the recent development of commercial cryocoolers which are capable of dissipating a couple watts of heat at 4.2 K while providing robust, turn-key operation. Thus, the demonstration of stable RF operation using Nb_3Sn cavities cooled by such cryocoolers can play a significant role in making SRF technology more accessible.

We would like to acknowledge that both FermiLab [11] and Jefferson Lab [12] have performed their own studies on conduction cooling setups with commercial cryocoolers. Those studies involved lower-frequency Nb_3Sn cavities which showed limitations at lower accelerating gradients.

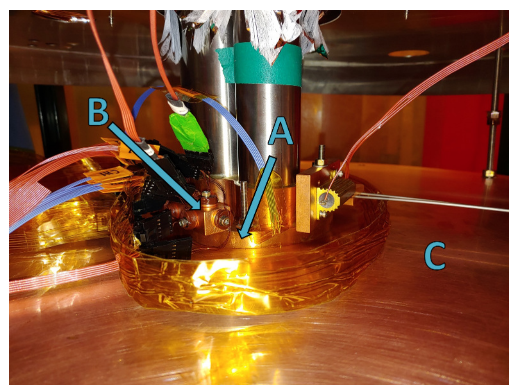

Figure 1: Close-up of the 1st stage cold head portion of the test assembly. (A) indicates the cold head itself. (B) indicates the heat sink used to intercept room-temperature heat loads from the various sensor cabling. (C) indicates the top surface of the copper thermal shield which is used to protect the primary cavity assembly from any room-temperature thermal radiation.

ASSEMBLY

The assembly built at Cornell uses a Cryomech PT420-RM cryocooler, which is capable of dissipating a maximum of 1.8 W at 4.2 K at the 2nd stage cold head. This cooling capacity is maximized when the 1st stage cold head is intercepting 55 W which results in a temperature of 45 K [13]. The 1st stage is primarily used to intercept heat loads from room temperature. This helps reduce static heat at the 4.2 K portion of the assembly, which leaves more room for dynamic heat dissipation during RF operation. Figure 1 shows a close-up image of the 1st stage cold head and surrounding components in our test assembly. The cold head itself is

* This work was supported by the U.S. Department of Energy (DOE). U.S. DOE award DE-SC0008431 supports Nb3Sn cavity coating and RF testing R&D, including the initial development of a conduction cooling assembly. U.S. DOE award DE-SC0021038 "Next Steps in the Development of Turn-Key SRF Technology" supports the full development of the conduction cooling concept.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV009

DEVELOPMENT OF A NEW B-MAPPING SYSTEM FOR SRF CAVITY VERTICAL TESTS*

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Abstract

Magnetic flux trapped in the Niobium bulk material of superconducting radio frequency (SRF) cavities degrades their quality factor and the accelerating gradient. The sensitivity of the cavity to trapped magnetic flux is mainly determined by the treatment, the geometry and the Niobium grain size and orientation. To potentially improve the flux expulsion characteristics of SRF cavities and hence the efficiency of future accelerator facilities, further studies of the trapping behavior are essential. For this purpose a so-called B-mapping system to monitor the magnetic flux along the outer cavity surface of 1.3 GHz TESLA-Type single-cell SRF cavities is currently under development at DESY. Contrary to former approaches, this system digitizes the sensor signals already inside of the cryostat to extensively reduce the number of required cable feedthroughs. Furthermore, the signal-to-noise ratio (SNR) and consequently the measuring sensitivity can be enhanced by shorter analog signal lines, less thermal noise and the Mu-metal shielding of the cryostat. In this contribution the design, the development process as well as first performance test results of the B-mapping system are presented.

B-MAPPING SYSTEM DESIGN

Based on the first magnetometric-mapping approach at Helmholtz-Zentrum Berlin (HZB) [1] a B-mapping system using Anisotropic MagnetoResistive (AMR) sensors of type Sensitec AFF755B [2] is currently under development at DESY. These single-axis AMR-sensors are arranged in groups of three to enable spatial magnetic flux measurements. To hold the sensor-groups in a desired position, nine groups each are mounted on a so-called sensor-board shown in Fig. 1. In the final setup 48 sensor-boards will surround the cell of a 1.3 GHz TESLA-Type single-cell SRF cavity. Thus, in total, the magnetic flux distribution of the outer cavity surface can be mapped by 432 sensor-groups or 1296 sensors. This system will be included in the vertical test stand environment at DESY to continue former studies [3–7] investigating the impact of the cavity geometry, the field orientation, the pre-treatment and the material grain size on the quality factor and the gradient of SRF cavities. To measure the magnetic flux directly on the cavity surface, a preferably low distance between the sensor-groups and the surface was pursued during the design phase. Consequently, a gap width between the sensor-boards and the cavity of only 1.5 mm was chosen. This minimal distance is required due to cavity comprehensive mechanical deviations of the cell. The measurement uncertainties caused by this minor offset compared to the desired sensor position directly at the cavity surface is approximated by a simulation model. For this purpose, the magnetostatic solver Pandira of the LAACG Poisson Superfish collection of programs for an applied stray field by a Helmholtz coil with a radius of 150 mm is used. For the equator (Group 5) a deviation of measurement results between the actual sensor-group position and the nearest cavity surface of about 6 % is predicted by the model.
To identify and solve possible technical issues of the system before the series production of the sensor-boards starts, two prototypes of the sensor-board printed circuit boards (PCB) were manufactured. During the PCB assembly of the first sensor-board (sensor-board I) a ferromagnetic material was identified in the selected Ceramic and Tantalum capacitors. Therefore, only one backup capacitor pair at the upper-right board-corner was populated during the assembly of the second PCB (sensor-board II) to prevent a parasitic drag of the later measurements.

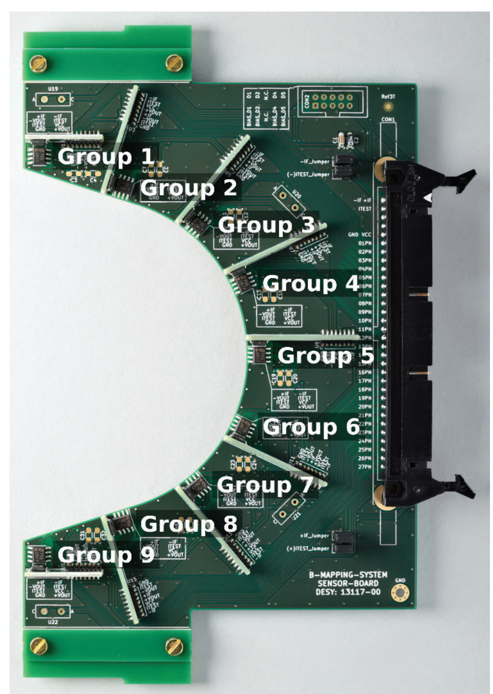

Figure 1: Second prototype of the DESY sensor-board design. The backup capacitors of each individual sensor are not populated due to a contained ferromagnetic material.

* This work was supported by the Helmholtz Association within the topic Accelerator Research and Development (ARD) of the Matter and Technologies (MT) Program.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV010

ELECTRICAL AND THERMAL PROPERTIES OF COLD-SPRAYED BULK COPPER AND COPPER-TUNGSTEN SAMPLES AT CRYOGENIC TEMPERATURES*

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Abstract

The development of high thermal conductivity coatings with pure copper or copper-tungsten alloy could be beneficial to improve the heat transfer of bulk Nb cavities for conduction cooling applications and to increase the stiffness of bulk Nb cavities cooled by liquid helium. Cold spray is an additive manufacturing technique suitable to grow thick coatings of either Cu or CuW on a Nb cavity. Bulk (~5 mm thick) coatings of Cu and CuW were deposited on standard 3 mm thick, high-purity Nb samples and smaller samples with 2 mm × 2 mm cross section were cut for measuring the thermal conductivity and the residual resistivity ratio. The samples were subjected to annealing at different temperatures and a maximum RRR of ~130 and ~40 were measured for the Cu samples and CuW samples, respectively.

INTRODUCTION

The development of metallic coatings with high thermal conductivity in liquid He temperatures may be beneficial for application to the superconducting radiofrequency (SRF) cavity technology [1]. The deposition of such bulk (a few millimeter thick) coatings on the cavity outer surface could result in niobium material cost saving, increased stiffness and increased heat conductance.

Recent research on SRF cavities cooled by conduction with a commercial cryocooler, instead of liquid He, utilized electroplating to grow a high-purity Cu layer on the outer surface of a Nb cavity with a Nb_3Sn film on the inner surface [2]. A drawback of the electroplating is the low deposition rate and the difficulty of achieving good bonding to the Nb substrate.

Cold-spray consists of accelerating solid powders with a carrier gas through a de Lavalle nozzle at high-enough speed such that the particles endure plastic deformation and adhere to the surface [3, 4]. This technique can be used to deposit many different types of materials. Cu and CuW were considered as candidate materials for cold-spray deposition in this study, aiming at producing samples with thermal conductivity of ~1 kW/(m K) at 4 – 7 K.

SAMPLE PREPARATION

The substrates used for this study were high-purity, fine-grain Nb plates cut from ~3 mm thick Nb used for SRF cavity fabrication. The cold spray was done at Concurrent Technologies Corporation, Johnstown, PA.

Copper Samples

For the Cu deposition, two 45 × 70 mm^2 and three 50 mm diameter Nb coupons were used. Cu powder with 99.95% purity and 325 mesh was used for the deposition. The substrate surface was grit blasted with aluminum oxide, followed by cleaning with isopropyl alcohol. A raster program was used to coat entire surface with a 1 mm step, speed of 200 mm/sec, and 1 inch standoff. The first 2 layers were applied with helium gas at 600 PSI and 400 °C. The next 4 layers were deposited with nitrogen gas at 950 PSI and 650 °C. The remainder of the deposition was done using nitrogen gas at 600 PSI and 400 °C to achieve a target thickness of ~3 mm. Helium gas was used for the first two layers as it allows for the Cu particles to be deposited at higher speed than nitrogen, therefore increasing the adhesion. The adhesion was measured to be ~33 MPa using a pull-off adhesion tester (PosiTest AT, DeFelsko), in accordance with ASTM D4541.

Figure 1 shows a picture of the samples, whereas Fig. 2 shows an optical microscopy image of the cross-section of a sample coated with similar deposition parameters as those used for this study. The microscopy images show some delaminations between the deformed Cu grains but a relatively small amount of coarse porosity.

The impurities content was measured on samples taken from the Cu powder and from the cold-sprayed coupon, as listed in Table 1. The concentration of Ag, Be, Cd, Co, Li, Mg, Mn, P, Pb, S, Se, V, Zn, and Zr was measured to be ≤ 1 ppm. The Cu concentration was measured to be 99.93% and 99.96% for the cold-sprayed and powder samples, respectively.

Samples 2 × 2 mm^2 in cross section were cut by wire electro-discharge machining (EDM) and were subjected to vacuum annealing in the temperature range 300 °C – 1000 °C for 3 h. The annealing of one sample at 900 °C and the one at 1000 °C was done in dry air, at ~10^{-2} Pa.

Figure 1: Picture of Nb coupons with 3 mm Cu deposited by cold spray.

* Work supported by the U.S. Department of Energy, Office of Science, SBIR grant DE-SC00195589.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV011

Nb_3Sn COATING OF TWIN AXIS CAVITY FOR SRF APPLICATIONS*

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Abstract

The twin axis cavity with two identical accelerating beams has been proposed for energy recovery linac (ERL) applications. Nb_3Sn is a superconducting material with a higher critical temperature and a higher critical field as compared to Nb, which promises a lower operating cost due to higher quality factors. Two niobium twin axis cavities were fabricated at JLab and were proposed to be coated with Nb_3Sn. Due to their more complex geometry, the typical coating process used for basic elliptical cavities needs to be improved to coat these cavities. This development advances the current coating system at JLab for coating complex cavities. Two twin axis cavities were coated recently for the first time. This contribution discusses initial results from coating of twin axis cavities, RF testing and witness sample analysis with an overview of the current challenges towards high performance Nb_3Sn coated twin axis cavities.

INTRODUCTION

In the high-intensity Energy-Recovery Linac (ERL) beam transits through the cryomodule at least twice with one pass for accelerating a high-quality beam and the other for decelerating the used beam to recover the beam energy [1]. Most of the ERL designs use standard TM010-type accelerating structures, in which the beam must pass along the same accelerating axis and thus occupy the same transverse position. Therefore to improve the performances of the ERL, the idea of using two beam-axis structures was first proposed by Noguchi and Kako in 2003 [2]. Then the similar concept was suggested again by Wang, Noonan and Lewellen in 2007 [1] with a proposal of superconducting cavity with two equivalent but separate axes for accelerating and decelerating beams while energy recovery is still performed within the same physical cavity and interact with the same rf dipole mode [3].

As proposed by Jefferson Lab (JLab) and designed by the Center for Accelerator Science (CAS) at Old Dominion University (ODU), two elliptical twin axes single cell cavities have been fabricated [4] with the intention of later growing a Nb_3Sn layer inside. Nb_3Sn is a potential alternative material with a higher critical temperature T_c close to 18 K, higher critical field, and lower surface resistance compared to Nb to replace Nb in SRF cavities, promising cost reduction and better performance. This Nb_3Sn gives a lower dissipation than that of niobium at the same temperature. Its superheating field of about 400 mT suggests a higher breakdown field is possible [5].

Among the methods used to coat thin films on niobium cavities, the vapor diffusion technique is used at Jefferson Lab to deposit Nb_3Sn thin layers on SRF cavities [6]. Although several basic elliptical cavity models have been coated and tested using this method, it has not yet been applied to coat cavities with complex geometries like the twin axis cavity. This paper discusses the recent Nb_3Sn coating of twin axis cavities at Jefferson Lab.

JLAB/ODU TWIN AXIS CAVITY

The new cavity designed by ODU CAS, was optimized to minimize the peak RF surface fields while providing the same longitudinal electric field profile in both beam tubes by operating in the TM110 rf dipole mode with 1497 MHz frequency [4] using CST Microwave Studio (Fig. 1). Making the cavity compatible with the Jefferson lab Nb_3Sn deposition system was also a goal of the mechanical design. Since the deposition chamber does not allow niobium-titanium inside the furnace, cavity flanges were made of niobium [7]. Two completed cavities are shown in Fig. 2. The cavity parameters and RF properties are given in Table 1.

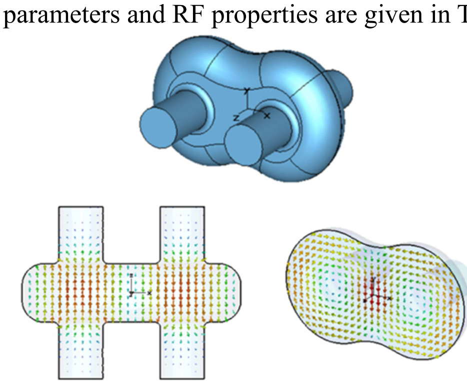

Figure 1: Twin axis cavity model (top) and electric (left) and magnetic (right) field profile at the twin cavity cross section (bottom) from CST microwave studio [3].

Figure 2: Twin axis cavities.

* Research supported by DOE Office of Science Accelerator Stewardship Program Award DE-SC0019399. Partially authored by Jefferson Science Associates under contract no. DEAC0506OR23177. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and Office of High Energy Physics .
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV013

VALIDATION OF THE 650 MHz SRF CAVITY TUNER FOR PIP-II AT 2 K*

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Abstract

The PIP-II linac will include thirty-six β_G=0.61 and twenty-four β_G=0.92 650 MHz 5-cell elliptical SRF cavities. Each cavity will be equipped with a tuning system consisting of a double lever slow tuner for coarse frequency tuning and a piezoelectric actuator for fine frequency tuning. One cavity equipped with an SRF tuner has been tested in the horizontal test stand at Fermilab. Results of testing the cavity-tuner system will be presented.

INTRODUCTION

The proton improvement plan (PIP)-II linac section being built at Fermilab will consist of five classes of superconducting RF (SRF) cavities made of niobium. Two types of elliptical cavities, the low beta (LB) cavity at β_G= 0.61 and the high beta (HB) cavity at β_G= 0.92, are used to accelerate the proton beam from 185 MeV to 800 MeV. The beam then will be injected into the booster synchrotron at 800 MeV and will exit with a beam energy of 8 GeV. Lastly, the proton beam goes into the main injector ring resulting in a proton beam energy of 120 GeV and power of 1.2 MW. The proton beam will hit a target producing a secondary kaon beam which decays into neutrinos. The proton beam will also be used for experiments in the g-2 and mu2e collaborations at Fermilab. The neutrino beams travel 800 miles through the earth from Fermilab to an underground detector in Sanford, South Dakota [1].

The prototype HB 650 cryomodule (CM) will have a mix of the β_G= 0.92 and legacy β_G =0.90 cavities. The legacy cavity was jacketed first and was tested in the horizontal configuration The double lever arm tuner was tested at room temperature on a $\beta_G = 0.9$ five cell 650 MHz elliptical cavity [2]. In this paper the testing of the double lever arm tuner on the cavity at 2 K is presented. The cavity was placed in the recently upgraded cryostat [3] at the Meson Detector Building (MDB) at Fermilab, pictured in Fig. 1. This double lever tuner will be used for both the HB and LB 650 MHz elliptical cavities. The tuner specifications for the HB and LB 650 MHz cavities are shown in Table 1. The SRF cavity tuner has three roles. It is needed for active microphonics compensation. It is also used for moving the cavities to the nominal frequency after cooling to 2 K. Lastly, it is used for protecting the cavity during pressure tests. There are two components to the tuner, one is the slow and coarse frequency tuning component consisting of a stepper motor. The other is the fast and fine frequency tuning component composed of piezoelectric actuators.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support provided by award number DE-SC0018362 and Michigan State University.
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The slow and coarse electromechanical component of the double lever arm tuner consists of a stepper motor manufactured by Phytron. The stepper motor has been tested in ultra-high vacuum and at cryogenic temperature in the cryomodule environment. Accelerated lifetime tests done at Fermilab demonstrate that this stepper motor will survive prolonged operation for the typical linac lifetime of 25 years [4, 5]. The cavity in the cryomodule with beam and high power is expected to produce field emissions and other radiation which can be detrimental to the stepper motor. No performance degradation was observed after an irradiation hardness test (gamma rays) with a dose level of 5×10^8 Rad, demonstrating that the stepper motor can survive under these operating conditions [5].

The fast and fine tuner component consists of two piezoelectric actuator capsules. The piezoelectric actuators are used for fast and fine frequency tuning control of microphonics. The piezoelectric actuators are designed and fabricated by Physik Instrumente (PI) per Fermilab specifications. The design consists of two 10×10×18 mm PICMA lead zirconate titanate (PZT) ceramics glued together and encapsulated in a stainless-steel cylindrical shell.

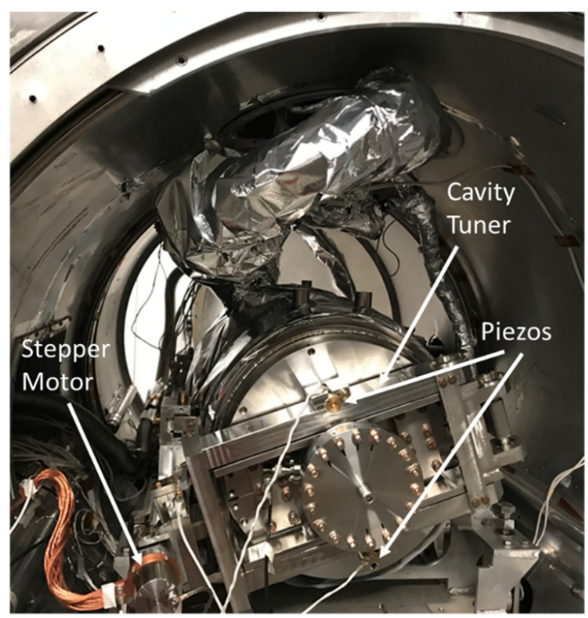

Figure 1: 650 MHz $\beta_G = 0.90$ with tuner and other ancillaries inside the STC cryostat at the MDB facility in Fermilab.

The accelerated lifetime test demonstrates that the piezo can sustain 2×10^{10} pulses with a peak-to-peak amplitude of 2 V, which is equivalent to 25 years of operation of the LCLS-II linac. The same number of cycles are expected for the PIP-II linac. The irradiation test, with same parameters as the stepper motor test, also showed minimal degradation

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV014

SRF CAVITY TUNERS FOR 3.9 GHz CRYOMODULES FOR LCLS-II PROJECT*

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Abstract

Fermilab conducted testing of three 3.9 GHz cryomodules for the LCLS-II project that will operate in continuous wave mode. A fast/fine tuning component was added to the LCLS-II 3.9 GHz tuner design due to the cavity bandwidth of 180 Hz which consists of two encapsulated piezos. Several cavities faced problems with fast-tuner operations after cooldown to 2 K and tuning the cavities to 3.9 GHz in cryomodule 2. All the piezo actuators were in working conditions, but the slow tuner ranges required to stretch some of the cavities to the operational 3.9 GHz frequency were too small to deliver the required preload on the piezos. This behavior can be attributed to several factors: setting the initial warm cavity frequency during production too high, pressure tests of the warm cryomodule could have changed cavity frequency; and the small bending and twisting of the cavity-tuner system during the cooldown and warmup of the cavities. A decision was made to inelastically retune the warm cavities to decrease the unrestrained frequency by 130-500 kHz, this was done via the slow tuner. The major challenge was to conduct this procedure without disassembling cryomodule and without any access to the tuner and cavities systems. The results for this retuning method of three 3.9GHz cryomodules will be discussed.

INTRODUCTION

The LCLS-II linac features a third harmonic section to generate an electron beam for the production of short-wavelength FEL operation. This section will have two cryomodules each consisting of eight 3.9 GHz elliptical cavities for the linearization of the beam phase space before the longitudinal bunch compression to increase the peak beam current [1]. The cavities and cryomodules designs were optimized from the Eu-XFEL linac and are discussed in [2]. The half-bandwidth of the cavity is 90 Hz, the peak frequency detuning (with resonance control) must be less than 30 Hz based on the design specifications [2]. Each cavity employs a slim blade tuner based on the INFN design for the Eu-XFEL 3.9 GHz cavities [3]. Two piezo actuator encapsulations were added to this design for fast/fine tuning. These tuners were tested on the cavities in the cryomodule setting at Fermilab. When moving the cavities to the nominal frequency after cooldown it was discovered that some of the piezo encapsulations were not engaging since no frequency change was observed when a voltage was applied to the piezos. This paper will detail the results of the tuner operation, unravel why the piezos were not engaging, and provide a solution to make the piezos engage with the tuner.

SLIM BLADE TUNER

The slim blade tuner is installed coaxially on the cavity helium vessel. The tuner can compress and stretch the cavity via the slow/coarse frequency component. Compression of the cavity decreases the frequency while stretching the cavity increases the frequency. The slow-coarse component consists of a Phytron stepper motor which is also used for the 1.3 GHz cavities [4, 5]. This component is used to tune the cavity to the nominal frequency after cooldown. The second frequency tuning component consists of two piezo actuator encapsulations used for fast-fine frequency compensation which can only stretch the cavity. The fast-fine component is used for resonance control of microphonics. The piezo encapsulations are made from two 10 × 10 × 18 mm PICMA butted piezo stack manufactured by Physik Instrumente (PI) [5]. The slim blade tuner and the two components are shown installed on the 3.9 GHz cavity in Fig. 1. Kinematic model of the slim blade tuner presented in Fig. 2.

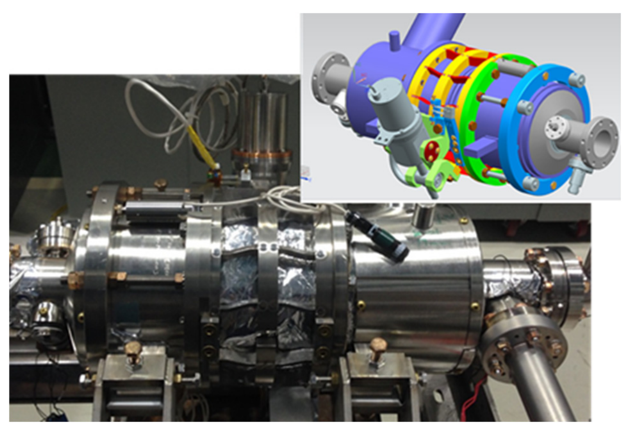

Figure 1 : Slim blade tuner installed on a 3.9 GHz cavity.

The kinematics of the bladed tuner movement are described in Ref. [3]. Four safety rods are located downstream of the blades (see Fig. 2). These safety rods protect the cavity during transportation and from non-elastic deformation during cavity/helium vessel system pressure tests. A safety gap is set on all the safety rods so that the piezos do not lock when the cavity-tuner system is cooled down to 2 K.

*This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support provided by award number DE-SC0018362 and Michigan State University.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV015

MITIGATION OF DIELECTRIC HEATING OF PIEZOELECTRIC ACTUATORS AT CRYOGENIC TEMPERATURES*

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Abstract

The new generation of low beam intensity superconducting linacs will require high accelerating gradients for new scientific discoveries. The high accelerating gradient cavities in pulsed SRF linacs will experience large (~1000's of Hz) detuning caused by Lorentz force detuning (LFD). The piezo actuators that will be used to compensate large LFD must operate at a nominal voltage of 120V to 150V to deliver the required stroke to the cavity. In this high voltage range, the piezo is expected to warm up drastically due to its location in an insulating vacuum environment. Overheating of the piezo will significantly decrease the longevity of the actuator. A collaboration between FNAL and Physik Instrumente (PI) developed a novel piezo actuator design that mitigates piezo overheating. The design consists of using a metal foam in contact with the piezoelectric ceramic stack for heat removal. The second solution used lithium niobite as an alternative material. A comparison of the temperature stability will be presented and discussed. This study characterizes the dielectric properties of both materials. The results obtained are in the temperature range of 10 K to 300 K.

INTRODUCTION

Piezoelectric (piezo) actuators are used for resonance control of superconducting radio frequency (SRF) cavities in linacs. Linacs with cavities of narrow bandwidth caused by low beam current are especially dependent on the reliability and lifetime of piezo actuators. Piezo actuators exhibit the piezoelectric effect which occurs below the Curie temperature. Materials exhibiting this effect experience a mechanical deformation when an electric field is applied to the material. The opposite effect is also possible where a mechanical deformation of the material will induce an electric field. For resonance control of a cavity, a voltage is applied to the piezo to deform the cavity which results in a change of frequency. The amount of frequency shift depends on the voltage that is applied, a higher voltage will lead to a larger frequency shift of the cavity. The amount of voltage needed for resonance control depends on the linac operation.

During CW operation the main source of vibration noise is caused by microphonics which can result in a detuning of the cavity of ~10-20 Hz and the worst-case scenario 100-150 Hz [1, 2]. The frequency of the microphonics vibration sources is found to be less than 100 Hz. This level of detuning can be compensated with a low voltage on the piezo and by driving it at a frequency less than 100 Hz. The reliability and lifetime of the encapsulated piezo stacks PI PICMA® were tested at Fermilab. During these tests it was shown that the piezo sustained 2×10^{10} cycles (equivalent to 20 years of LCLS-II operation) with a peak-to-peak voltage (V_{pp}) of 2 V on the piezo [3]. During this study, the temperature rise of the piezo was on the order of 5 K. In the case of a linac in pulsed operation a larger voltage is needed to compensate the detuning of the cavities.

For a linac in pulse operation the main source of detuning is caused by radiation pressure known as Lorentz force detuning (LFD). The detuning is given by $\Delta f = k_L E_{acc}^2$ where k_L is the Lorentz force detuning and E_{acc} is the accelerating gradient. This can result in a frequency shift of --500 Hz to -3 kHz depending on the cavity [4-6]. To compensate for this type of detuning a larger voltage must be used. The RF pulse will also excite the mechanical frequencies of the cavity which can be greater than 100 Hz. To compensate for pulse linac operation detuning a larger V_{pp} on the order of 120 V-150 V and frequencies of 200-300 Hz is needed [4-6].

At large V_{pp} and high driving frequency the piezo actuator heats up drastically as shown in Ref. [7]. The piezo actuators are made from lead zirconate titanate (PZT). PZT has a thermal conductivity of 4 W/(m·K) at room temperature and this drops to 0.02 W/(m·K) at 20 K [8] which makes heat transfer difficult. In this paper a novel design for heat dissipation demonstrates that large temperature fluctuations are prevented. Additionally, a lithium niobate ($LiNbO_3$) which has small permittivity was tested for the first time for use in resonance control of SRF cavities. This material exhibits small temperature increases at high voltage.

DIELECTRIC HEATING

The study of dielectric heating of the piezoelectric material is important since large temperature fluctuations can affect the coercive field (the critical electric field that changes the polarization of the material). Additionally, the effects of large temperature fluctuations can cause stress on the ceramic which can result in piezo failure. The first material to be discussed is PZT since this is the most widely used material for actuators due to the large stroke it provides. At room temperature, the PI piezo actuator can operate from -20 V to 120 V (unipolar operation). Below 77 K the voltage range of operation can go down to -120 V. The displacement stroke of the piezo can be doubled when the piezo is operated in the bipolar regime, but the heating

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support provided by award number DE-SC0018362 and Michigan State University.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-SUPTEV016

SAMPLES FOR 3RD HARMONIC MAGNETOMETRY ASSESSMENT OF NbTiN-BASED SIS STRUCTURES*

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Abstract

In the quest for alternative superconducting materials to bring accelerator cavity performance beyond bulk niobium (Nb) intrinsic limits, a promising concept uses superconductor-insulator-superconductor (SIS) thin film structures that shields accelerator cavities from magnetic flux at higher fields [1]. Candidate materials for such structures are NbTiN as the superconductor and AlN as the insulator. We have demonstrated high quality NbTiN and AlN deposited by reactive DC magnetron sputtering (DCMS), both for individual layers and multilayers. Interface quality has been assessed for bi-layer stacks with 250 nm NbTiN layers and AlN thicknesses from 30 nm down to 1 nm. These SIS structures show continued sharp interfaces with total average roughness under 2 nm.

The H_{fp} enhancement of the films will be examined with a 3rd harmonic magnetometry. The system is being designed and built in a continuing collaboration with CEA Saclay. It can measure 25 to 50 mm samples on a temperature controlled stage. This contribution presents an overview of the design of the 3rd harmonic magnetometer and the material properties assessment of standalone films and multilayer nanostructures.

INTRODUCTION

In the search for a superconductor capable of surpassing the theoretical material limits of Nb, Gurevich [1] proposed the use of SIS layers to reach fields beyond the material limits of bulk Nb. When a superconducting layer S is thinner than its London penetration depth, it sees an enhancement of its lower critical magnetic field H_{c1}, causing the applied field to be attenuated as it passes through the layer. The insulating layer I needs to be thick enough to inhibit Josephson coupling. Then, the layered SIS structure attenuates the magnetic flux into the underlying superconductor. This may allow reaching higher cavity accelerating gradients.

NbTiN and AlN are promising materials for the SIS structures. NbTiN has a superconducting transition temperature (T_c) of 17.3 K for bulk like films. AlN has a lattice parameter of 4.08 Å which is close to NbTiN (4.34 Å). This paper discusses the properties of monolayers of NbTiN and SIS structures with AlN deposited by reactive DC magnetron sputtering. Also, the 3rd harmonic magnetometer is described .

SIS THEORY

SIS structures shield SRF cavities from vortex penetration generated by high magnetic fields. The penetration of a vortex can return the superconductor to its normal state by creating a thermomagnetic avalanche. The insulating layer in the SIS structure helps to disconnect magnetic vortices in the superconducting layer from the bulk superconductor.

The magnetic penetration shielding of SIS structures can be measured by magnetometry. The shielding is dependent on the thickness of the superconducting layer. A thinner superconducting layer can withstand higher fields but more of the applied field will reach the bulk superconductor. A thicker superconducting layer can not withstand high fields but will attenuate the applied field more before it reaches the bulk superconductor. The optimum thickness of the superconducting layer and the insulating layer can be extracted from the contour plot of the achievable peak surface-field without vortex dissipation for NbTiN-AlN on Nb (see Fig. 1). The contour plot was calculated using the equations from [2] and assumes for NbTiN a London penetration depth of 240 nm [3] and a coherence length of 2.2 nm.

DEPOSITION

The films are deposited on different substrates in a UHV system with a base pressure of 10^{-10} Torr. During deposition, the working gas is a mixture of Ar and N. The system is equipped with several DC magnetron sputtering guns with rotatable shutters. A 80/20 (at. wt.%) NbTi target and a pure Al target are used to deposit the SIS structures. The sample stage rotates to face each magnetron for sequential depositions of the different layers.

The substrates used are MgO, Nb and AlN ceramic. MgO is a single crystal with a lattice parameter of 4.36 Å which closely matches NbTiN (4.34 Å). This substrate provides an excellent surface for film growth, yielding high quality NbTiN films. Nb is the substrate of choice for the SRF application of SIS structures. The Nb surfaces are prepared by buffered chemical polishing (BCP) or electropolishing (EP). Films on AlN ceramic represent a worst case scenario

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. NSF Grants PHY-1734075 and PHY-1416051, and DOE Awards DE-SC0010081 and DE-SC0019399.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOOFAV01

SUCCESSFUL BEAM COMMISSIONING OF HEAVY-ION SUPERCONDUCTING LINAC AT RIKEN

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Abstract

A new superconducting booster linac, called SRILAC, has been constructed at the RIKEN Nishina Center to upgrade the acceleration voltage of the existing linac to enable investigation of new super-heavy elements and production of useful radioactive isotopes. The SRILAC consists of 10 superconducting (SC) TEM quarter-wavelength resonators made from pure niobium sheets which operate at 4.5 K. We successfully developed high performance SC-cavities which satisfy the required Q_0 of 1×10^9 with a wide margin. Installation of the cryomodule and He refrigerator system was completed at the end of FY2018 and the first cooling test was performed in September 2019. After various preparations and tests, beam acceleration was successfully commissioned on January 28th, 2020. The project was successfully completed on schedule and the beam supply to experiments was started in June 2020. This paper reports on the beam commissioning of the SRILAC and the preparation and testing of the components for the commissioning.

INTRODUCTION

The RIKEN Nishina Center for Accelerator-Based Science promotes heavy-ion beam science through basic research, such as elucidating the origin of elements, and developing new nuclear models, synthesizing superheavy elements (SHEs) using high-intensity primary beams, by applying research such as nuclear transmutation, and industrial applications such as biological breeding and producing useful radio isotopes (RIs). The Radioactive Isotope Beam Factory (RIBF) [1, 2], the main facility at the RIKEN Nishina Center, started operation in 2006 and provides the world's most intense RI beam by accelerating heavy-ion beams with a cascade of four ring cyclotrons. Among them, the heavy-ion linac, RILAC, plays an important role as an injector for RIBF cyclotrons and also supplies a high intensity beam for SHE experiments and has been in operation since 1982. Figure 1(a) shows a schematic of the RILAC facility prior to 2017.

The RILAC was initially designed to have six drift-tube-linac (DTL) tanks with a total acceleration voltage of 16 MV [3]. Each DTL tank is a room-temperature (RT) quarter-wavelength resonator (QWR) which can vary its resonant frequency from 17 to 45 MHz in continuous wave

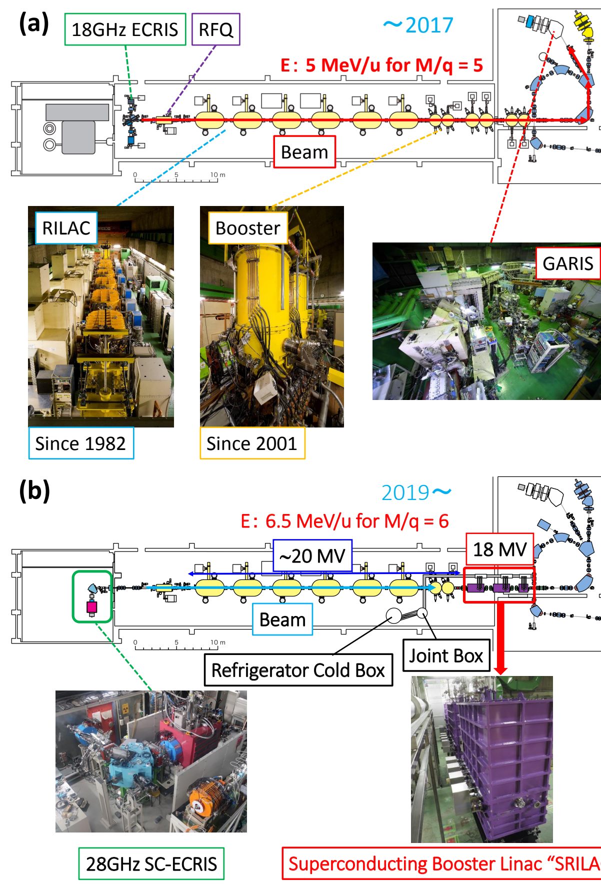

Figure 1: Schematic of the previous heavy-ion linac facility at RIKEN in 2017 (a) and the upgraded facility (b).

operation. In 1996, the front end of the RILAC, consisting of a combination of an 8 GHz electron-cyclotron-resonance ion source (ECRIS) and a 500 kV Cockcroft–Walton electrostatic accelerator was replaced with an 18 GHz ECRIS and a variable frequency RFQ linac [4] to increase the beam intensity. In order to increase the beam energy for SHE synthesis experiments, etc., six DTL cavities (A1–A6) with twice the resonant frequency of the RILAC were newly added downstream of the RILAC as a booster linac in 2001 [5]. The first two cavities, A1 and A2, have variable frequencies in the range 36–76.4 MHz, while the latter four cavities, A3–A6, have fixed frequencies of 75.5 MHz. With this modification, the RILAC was able to accelerate heavy ions with $m/q = 5$

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOOFAV02

STATUS OF THE RAON SUPERCONDUCTING LINEAR ACCELERATOR*

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Abstract

RAON, being constructed as the Rare Isotope Science Project (RISP) by the Institute for Basic Science (IBS) since 2011 is a flagship heavy ion accelerator facility in Korea to promote fundamental science and application of isotope nuclei and related science. The installation of the heavy ion accelerator systems including injector, rare isotope (RI) production systems, and experimental systems are currently being progressed toward to commissioning of RAON, while the civil construction of the RAON site in Shindong, Daejeon of Korea, is completed in May 2021. The superconducting LINAC with low energy, so-call SCL3 as the 1st phase will be commissioned on the December of 2021. The overview RAON accelerator facility and status of RISP are provided.

MANUSCRIPTS PROJECT OVERVIEW

The RAON heavy ion accelerator facility is to accelerate both stable and isotope beams up to the power of 400 kW with an energy higher than 200 MeV/u and to produce rare isotopes [1]. The rare isotope (RI) production system of RAON is to have both Isotope Separation On-Line (ISOL) and In-Flight (IF) fragmentation method combined to produce rare isotope beams far from the valley of stability. The construction project for RAON facility, which is located at Shindong area near the city of Daejeon, is progressed with expectation on the commissioning of low energy facilities including injector, SCL3 and KoBRA. The SCL3 (Superconducting LINAC 3) in Fig. 1 is the post-accelerator of ISOL, which is to produce high-intensity and high-quality beams of neutron-rich isotopes with masses in the range of 80-160 by means of a 70 MeV proton beam directly impinging on uranium-carbide thin-disc targets. It accelerates ions or rare isotopes drawn from ISOL up to about 20 MeV/nucleon for low-energy experiments at Korea Broad Acceptance Recoil spectrometer and Apparatus (KoBRA).

The injector system comprises 14.5 GHz and 28 GHz electron cyclotron resonance ion source (ECR-IS), a low energy beam transport (LEBT), a radio frequency quadrupole (RFQ), and a medium energy beam transport (MEBT).

The SCL3 uses two different families of superconducting resonators, i.e., a quarter wave resonator (QWR) and a half wave resonator (HWR). The SCL31 consists of 22 QWRs with geometrical β of 0.047 and resonance frequency of 81.25 MHz. Each QWR cryomodule bears one superconducting cavity. Meanwhile, SCL32 consists of 102 HWRs with 0.12 of β and 162.5 MHz of frequency. All 102 HWRs are installed in two different cryomodules depending on the number of cavities in a cryomodule, where the 13 Type-A cryomodules bear two cavities each as the 19 Type-B cryomodules with 4 cavities each.

The SCL2 accepts a beam with energy 18.5 MeV/u and accelerates it to 200 MeV/u, with two types of single spoke resonators, as SSR1 and SSR2. The SCL2 consists of the SCL21 and the SCL22, each single spoke resonator with geometric β of 0.3 and 0.51, respectively, with same resonance-frequency of 325 MHz. The SSR1 for SCL21 is chosen mainly because it can have a larger beam radius compared to that of HWR without sacrificing accelerating efficiency. Another consideration for SSR is the robust design of mechanical structure and less severe multipaction in principle. They would provide the advantages during beam operation. The numbers of cavities of the SSR1 and the SSR2 is 69 and 150, and the cryomodules bear 3 and 6 cavities, respectively. The SCL2 provides a beam into the in-flight fragmentation (IF) system via a high-energy beam.

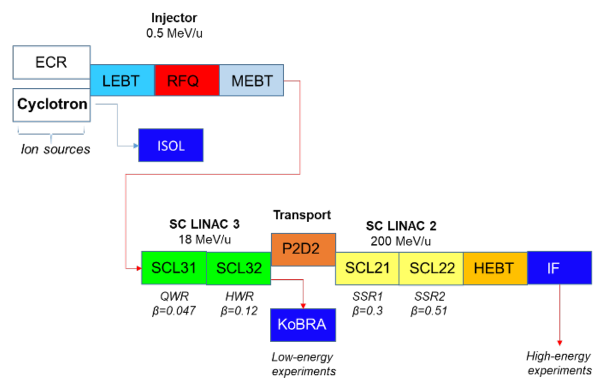

Figure 1: The schematic configuration of RAON complex.

According to the project plan, the accelerator part for low-energy accelerator SCL3 and high-energy accelerator SCL2 should be completed in 2021. But it is changed as SCL3 will be commissioned in December 2021, while the plan for SCL2 is under re-scheduling.

PREPARATION OF INJECTOR

The injector [2] as normal conducting accelerator produces ion beam bunches and accelerated to the design beam structure for SCL3 as shown in Fig. 1. The 14.5 GHz, ECR-IS is a compact permanent magnet ion source. The superconducting 28 GHz, ECR-IS, which is dedicated to extract Uranium ion beam, is under performance test. The RFQ accelerates ion beams from proton to uranium from 10 to 500 keV/u through the LEBT. One feature is that this RFQ can accelerate two different charge states, for example, of uranium beams ($^{238}U^{33+}$ and $^{238}U^{34+}$ of 12 pμA) for high-intense ion beams, simultaneously (see Fig. 2). The MEBT is designed to transport and match ion beams to the SCL3. It consists of four 81.25 MHz re-bunching cavities and eleven quadrupoles.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOOFAV05

PROTON IMPROVEMENT PLAN – II: OVERVIEW OF PROGRESS IN THE CONSTRUCTION*

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Abstract

The Proton Improvement Plan II (PIP-II) project is an essential upgrade to Fermilab's particle accelerator complex to enable the world's most intense neutrino beam for LBNF/DUNE and a broad particle physics program for many decades to come. PIP-II will deliver 1.2 MW of proton beam power from the Main Injector, upgradeable to multi-MW capability. The central element of PIP-II is an 800 MeV superconducting radio frequency (SRF) Linac, which comprises a room temperature front end followed by an SRF section. The front end has been constructed and operated with beam in the PIP-II Injector Test facility (PIP2IT). The SRF section consists of five different types of cavities/cryomodules, including Half Wave Resonators (HWR), Single Spoke and elliptical resonators operating at state-of-the-art parameters. The first two PIP-II cryomodules, Half Wave Resonator (HWR) and Single Spoke Resonator 1 (SSR1) are installed in PIP2IT and have accelerated beam to above 17 MeV. PIP-II is the first U.S. accelerator project that will be constructed with significant contributions from international partners, including India, Italy, France, United Kingdom and Poland. The project was recently baselined, and site construction is underway

INTRODUCTION

The Fermi National Accelerator Laboratory (Fermilab) accelerator complex powers research into the fundamental nature of the universe and is the only one in the world to produce both low- and high-energy neutrino beams for science. The Strategic Plan for U.S. Particle Physics in the Global Context [1] by the Particle Physics Project Prioritization Panel (P5) calls for a performance upgrade of the Fermilab accelerator complex to support a world-leading neutrino program, while maintaining high-reliability operations through the rejuvenation of aging systems within this complex and providing a platform for future enhancements.

The Proton Improvement Plan II, or PIP-II, Project is an essential enhancement to the Fermilab accelerator complex to deliver higher-power proton beams to the neutrino-generating target that serves the Deep Underground Neutrino Experiment (DUNE) that will be located within the Long-Baseline Neutrino Facility (LBNF). It also provides a more capable and reliable front end to the Fermilab accelerator complex to support the future scientific efforts of the high energy physics community [2].

PIP-II is the first particle accelerator on U.S. soil built with significant in-kind contributions from international partners. Institutions in France, India, Italy, Poland and the U.K. are contributing to the project, bringing specific expertise and capabilities in accelerator technologies and established track records in international accelerator projects.

OVERVIEW OF THE PIP-II IN-KIND CONTRIBUTION

PIP-II benefits from in-kind contribution by many partners. International partnerships have been formed with the following institutions for in-kind contributions of radio frequency (RF), superconducting radio frequency (SRF), cryogenic infrastructure and other significant components:

- Department of Atomic Energy (DAE) in India
- Istituto Nazionale di Fisica Nucleare (INFN) in Italy
- Science and Technology Facilities Council as part of UK Research Innovations (STFC-UKRI) in the United Kingdom
- Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) and Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules (CNRS/IN2P3) in France
- Wroclaw University of Science and Technology (WUST)

All agreements with international partners are bilateral and all contributions are in-kind. The scope of in-kind deliverables is included in two of the five technical systems that make up the PIP-II project: Superconducting Radio Frequency and Cryogenics, and Accelerator Systems. The division of scope during the construction phase with all international partners was determined by the collaborating parties based on capabilities and interests of the collaborating institutions and maturity of negotiations towards formal agreements. PIP-II international partners contribute world-leading expertise and capabilities which are essential for the success of PIP-II.

PERFORMANCE GOALS

Design criteria for PIP-II are established on the basis of the P5 report [1] as follows:

- Deliver >1 MW of proton beam power from the Fermilab Main Injector, over the energy range of 60 - 120 GeV, at the start of operations of the LBNF/DUNE program
- Provide a platform for eventual extension of beam power to LBNF/DUNE to >2 M@

* Work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under U.S. DOE Contract No. DE-AC02-07CH11359.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOOFAV06

FOUR YEARS OF SUCCESSFUL OPERATION OF THE EUROPEAN XFEL

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Abstract

The European X-Ray Free-Electron Laser (EuXFEL) has been successfully operating for almost 4 years, and routinely delivering 6- to 14-KeV X-rays to users (30 KeV photon energy was demonstrated). At the heart of the machine is the 1.3-km-long 1.3-GHz superconducting radio-frequency linac which can reach a maximum electron energy of 17.6 GeV, and is capable of accelerating up to 2700 bunches per RF pulse at a repetition rate of 10 Hz, delivering beam to 6 experiments via 3 SASE undulator sections. In this contribution, we present the linac operational experience and highlight some recent developments towards monitoring and improving operations and linac availability.

THE EUROPEAN XFEL

The EuXFEL comprises a normal conducting gun, a first 1.3 GHz and third-harmonic accelerating modules (A1 and AH1), a dogleg and chicane; the first linac L1 consists of one RF station (A2) with 32 SRF cavities housed in 4 cryomodules, followed by the first bunch compressor (BC1), the second linac L2 consists of three RF stations (A3-A5); the beam energy at the exit of the second bunch compressor (BC2) is 2.4 GeV going into the main linac L3 with stations A6 to A25. A26 was planned but not installed. The collimator section is followed by three undulator lines. Beam dumps are located at the end of the injector (I1D), after each bunch compressor (B1D, B2D), at the end of the linac (XTD) and at the end of the photon beam lines. A facility overview is presented in [1].

Since the main linac cool down end of 2016, the European XFEL (EuXFEL) has reached several important milestones. In April 2017, the first beam was delivered to the main dump; in May 2017, the first self-amplified spontaneous emissions (SASE) were demonstrated; in September 2017, the first user run took place. The maximum linac energy (17.5 GeV) was reached in July 2018; in October 2018, all three undulator lines (SASE1/2/3) were in operation. In November of the same year, the maximum number of bunches (2699) was accelerated. In January 2019, piezo operation was fully automated (to compensate for Lorentz force detuning), in October of the same year, beam-based feedback demonstrated a beam arrival time stability better than 10 fsec rms [2]. 2019 has also marked the start of parallel user operation in all three beam lines. In February 2020, despite the covid-19 lock down, a 30-keV world record photon energy was achieved, while in May of 2021, the linac RF demonstrated an availability of 100% for a whole week.

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This contribution gives a general status report on the operation of the accelerator since its start in 2017, with an emphasis on the superconducting linac and its availability. Machine operating hours are introduced in the introduction. The following section exposes the linac configuration strategy to deliver the various beam energies requested by users. The next section gives a short report on some key components of the accelerator. Section four presents the linac availability and is followed by an outlook on the future of the accelerator.

Overview of Machine Operating Hours

Figure 1 summarizes the machine operating hours since start-up in 2017. The last column depicts the typical or target time distribution. With the exception of 2020, where the global covid pandemic forced a shutdown longer than anticipated, the photon delivery hours have been steadily increasing, the target being around 4400 hours (i.e. ≈ 183 days). The scheduled down time (≈ 10 weeks) would be difficult to reduce further. It includes winter and summer shutdowns, mandatory for the yearly operation approval from the German safety authority (TÜV), routine maintenance activities as well as bank holidays. The increased photon delivery time over the years has been enabled by the reduced commissioning or machine development time. The category labeled "Access, Set-up, Tuning" corresponds to machine setup or tuning after an operation interruption, or between different machine settings, as well as unscheduled access time (whether remote or in-situ tunnel interventions) required to fix faulty subsystems.

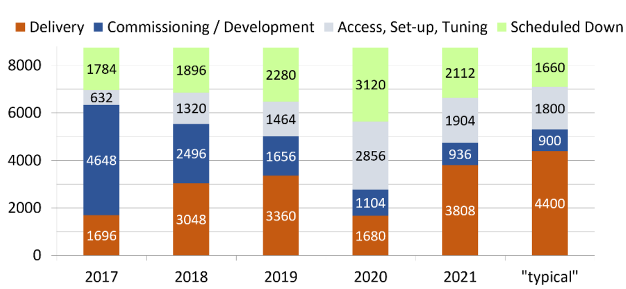

Figure 1: Operation hours distribution from the start-up in 2017. The last column, "typical", shows the target hour distribution.

LINAC OPERATION CONFIGURATION

Typical user runs require linac energies ranging from 11.5 to 16.5 GeV. The injector section mode of operation is usually kept constant to match the 2.4 GeV energy required at the second bunch compressor. Therefore, the main energy

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOOFAV10

COMPLETION OF THE FRIB SUPERCONDUCTING LINAC AND PHASED BEAM COMMISSIONING*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is an accelerator-based facility funded by the US Department of Energy for nuclear physics research. FRIB is nearing the end of technical construction, with first user beams expected in Summer 2022. Key features are the delivery of a variety of rare isotopes with a beam energy of ≥ 200 MeV/u and a beam power of up to 400 kW. The facility is upgradable to 400 MeV/u and multi-user capability. The FRIB driver linac consists of 324 superconducting resonators and 69 superconducting solenoids in 46 cryomodules. FRIB is the first linac to deploy a large number of HWRs (220) and the first heavy ion linac to operate at 2 K. We report on the completion of production and installation of the FRIB cryomodules and phased beam commissioning results.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) has been a US Department of Energy Office of Science (DOE-SC) User Facility since September 2020. The FRIB superconducting driver linac (Fig. 1, bottom) can accelerate ion species up to ^{238}U to energies of ≥ 200 MeV per nucleon for rare isotope production; a beam power of up to 400 kW is planned [1]. FRIB will use existing beam lines and experimental areas for fast, stopped, and reaccelerated beams of the Coupled Cyclotron Facility (CCF), outlined in blue in Fig. 1.

Figure 2 shows the time line of the project. In August 2013, DOE-SC approved the project baseline and start of civil construction (CD2-3a) with a total project cost of $730M, funded by DOE, MSU and the State of Michigan. FRIB obtained CD-3b approval from DOE in August 2014, and technical construction began in October 2014. The project is on track to be completed by January 2022, with the first user experiments expected in Summer 2022.

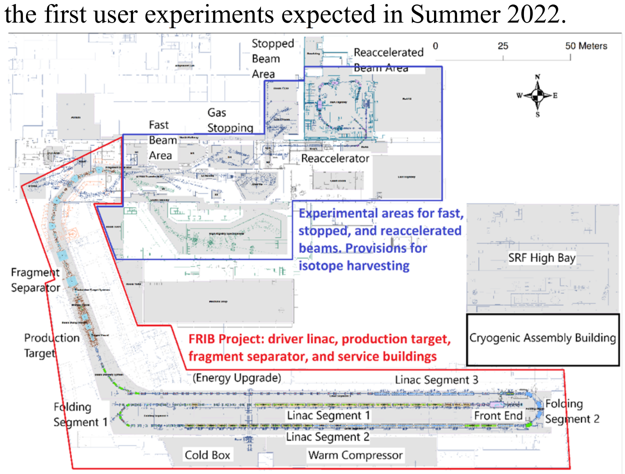

Figure 1: Layout of the FRIB linac, target, fragment separator, and experimental areas.

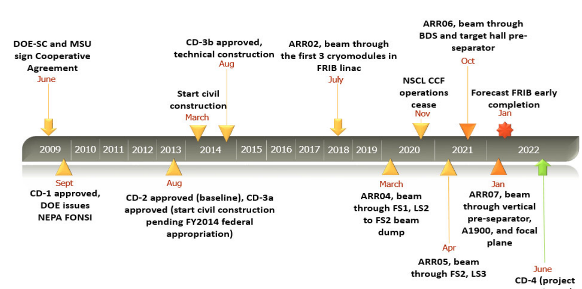

Figure 2: Time line of the FRIB project.

The driver linac technical construction has been completed. The system utilities were ready in June 2017 and the Li Stripper was installed in March 2021, marking the

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV002

EXTENDED RANGE SRF CAVITY TUNERS FOR LCLS-II HE PROJECT*

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Abstract

The off-frequency detune method is being considered to be applied in the LCLS-II-HE superconducting linac to produce multi-energy electron beams for supporting multiple undulator lines simultaneously [1]. To deliver off-frequency operation (OFO) requirements for SRF cavity tuner must be changed. Tuner design modifications and results of the testing new tuner installed on the single dressed cavity and eight cavity/tuner system, deployed in verification cryomodule (vCM), will be presented.

INTRODUCTION

Tuner for LCLS II project developed as part of broad R&D program [2,3]. 250 units have been built, installed in into more than 40 cryomodules [4]. All tuners successfully tested as part of cryomodule qualification program [5]. LCLS II HE project is considering option for multi-energy operation that call for much more demanding parameters for SRF cavity tuners.

SRF tuners, that will be deployed into LCLS-II-HE linac, must be capable to bring 100% cavities to operational frequency 1.3GHz and at least 62% of the cavities of the linac need to be retuned to 1.299,535kHz (F_{OFO}=1.3GHz-465kHz) [6]. One more demanding requirement is regularity of cavity re-tuning from 1.3GHz to F_{OFO}=1.3GHz-465kHz. It must be done approximately twice a month, that will be required exceptional longevity for SRF cavity tuner.

TUNER MODIFICATIONS

Tuner Frame

To deliver OFO specification required to increase slow tuner range must be increase in almost 2,5 times. During LCLS II cryomodules testing, as first step after cooling-down CM to T=2K frequency of each cavity was measured. We called this frequency $F_{T=2K\_Landing}$. Cavity frequency $F_{T=2K\_Landing}$ is different from frequency $F_{T=2K\_non\text{-}restrained}$ on ~150kHz, that could be explained by initial preload of the cavity by tuner during installation and different thermo-contractions of the dressed cavity/tuner system components. Distribution of the $F_{T=2K\_Landing}$ for 160 cavities (20 CMs) equipped with tuner and tested at FNAL presented on the Fig. 1. Average of this distribution is Fig. 1. The LCLS II tuner range, required to bring cavities after cool-down to T=2K, is from 30kHz up to 250kHz. We are expecting that vendor will use similar procedure for LCLS II HE cavities during production and distribution of the $F_{T=2K\_Landing}$ will be similar. To tune LCLS II HE cavities to OFO slow tuner range need to be increase from 250kHz to 720kHz (or ~3 times).

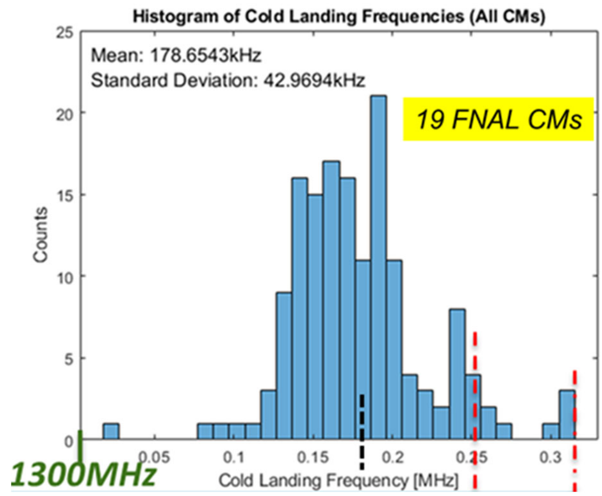

Figure1: Distribution of the values $F_{T=2K\_Landing}$ for 152 cavities assembled into 19 FNAL's cryomodules. Mean value is 1.3GHz+178kHz. 95% of the cavities have value of $F_{T=2K\_Landing}$ <1.3GHz+250kHz.

To be tuned to OFO cavity (with $F_{T=2K\_Landing}$ =1.3GHz+250kHz) must be compressed on 2.7mm from non-restrained position. LCLS II Tuner is double lever tuner with lever ratio 1:20 [2]. Review of the 3D model of the tuner and experience of tuner installation on the dressed cavity demonstrated that LCLS II tuner "as is" could not deliver required stroke/cavity compression.

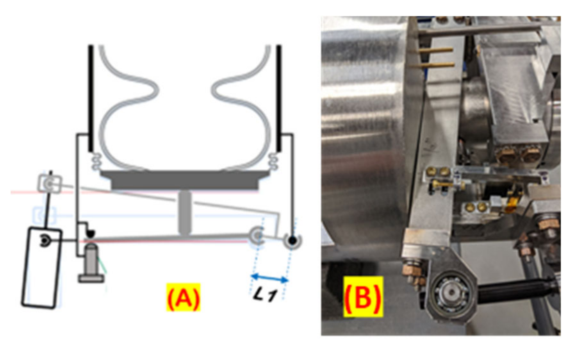

Figure 2: (A) Kinematic model of the double lever tuner. For demonstration purposes motor arm fully open/maximum compression of the cavity (up to limit by hard stop on the dressed cavity). (B) Close up picture of tuner/motor arms and cavity's endcap magnetic shield. This picture of the LCLS II, before arms extension on 7mm.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV005

COMMISSIONING OF RF POWER COUPLER FOR BISOL R&D RESEARCH

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Abstract

RF power coupler is a key component of superconducting accelerating system. For the pre-research of BISOL, we designed a 162.5 MHz RF power coupler which can transmit CW 20 kW power for HWR cavities. It can also transmit 1-5 kW 81.25MHz power for QWR cavity horizontal test study. Two prototype couplers have been fabricated and proceeded the high power conditioning.

INTRODUCTION

Beijing isotope separation on line type rare ion beam facility (BISOL) is a proposed facility which has an intense deuteron driver superconducting linac and a post-accelerator [1]. For the first stage of BISOL, the beam load reaches 10 mA of 162.5MHz HWR cavities for deuteron beams and 0.4 uA of 81.25MHz QWR cavities for secondary heavy ion beams. For the pre-research of BISOL, a cryomodule which can provide the horizontal test of both 81.25 MHz QWR for the post-accelerator and 162.5 MHz HWR for the driver accelerator with the proper external quality factor was designed and fabricated under the collaboration between Peking University (PKU) and China Institute of Atomic Energy (CIAE). In order to reduce expenses, we designed a RF power coupler which could transmit both CW 20 kW162.5MHz for HWR cavities and 1-5 kW 81.25MHz power for QWR cavities [2].

Figure 1 shows the cross section of the coupler. The parameters of coupler are listed in Table 1. The coupler consists of two cylindrical ceramic windows, adjusting bellows, coaxial lines and T-box. Although T-box has frequency selectivity, we can adjust the size of outside box and the position of short-circuit face to guarantee the impedance matching for the whole coupler transmitting both 162.5MHz and 81.25MHz frequency.

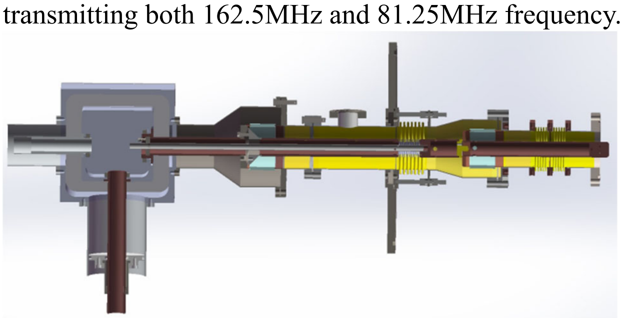

Figure 1: Cross section of the coupler.

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Table 1: Parameters of the Coupler

Parameter	Value
Frequency	162.5MHz/81.25MHz
Impedance	50ohm
Structure type	Coaxial
Window type	Double, cylinder ceramic
Coupling method	Antenna coupling
Power level	20kW@162.5MHz, 1kW@81.25MHz

FABRICATION AND ASSEMBLY

The outer conductor is made of SS316L and the surface is coated with about 15 μ m copper. The inner conductor is oxygen free copper or stainless steel coated with 50 μ m copper. The ceramic windows are made of Al_2O_3 with purity of 97.6%.

A nitrogen air pipe inserted inside the inner conductor to cool the inner part of the coupler. Polyimid film is used to isolate the inner conductor and the inner part of the T-box. We fabricated two prototype couplers. Figure 2 shows the parts of the couplers. After ultrasonic cleaned, all the parts were assembled in the class 100 clean room and the two couplers had leak check.

The commissioning of the couplers was done at Institute of High Energy Physics (IHEP). They have a 166MHz 50kW cw amplifier and the test stand. It can provide at least 20kW 162.5 MHz power. To do the commissioning of the couplers, a connecting cavity is used. Figure 3 shows the structure of the connecting cavity with flanges of 100 mm diameter. For the impedance matching, we designed and fabricated two transition parts to connect the cavity and the two couplers. The antenna length was optimized to get the right coupling between the connecting cavity and the coupler at 162.5 MHz.

Figure 2: Parts of the coupler.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV006

SYNCHROTRON XPS STUDY OF NIOBIUM TREATED WITH NITROGEN INFUSION*

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Abstract

Processing of niobium cavities with the so-called nitrogen infusion treatment demonstrates the improvement of efficiency and no degradation of maximal accelerating gradients. However, the chemical composition of the niobium surface and especially the role of nitrogen gas in this treatment has been the topic of many debates. While our study of the infused niobium using synchrotron X-ray Photoelectron Spectroscopy (XPS) showed modification of the surface sub-oxides surprisingly there was no evidence of nitrogen concentration build up during the 120°C baking step, irrespectively of N_2 supply. Noteworthy, that the niobium contamination with carbon and nitrogen took place during a prolonged high-temperature anneal even in a high vacuum condition (10^{-8}-10^{-9} mbar). Evidently, the amount of such contamination appears to play a key role in the final cavity performance

INTRODUCTION

Vacuum thermal processing is a key technological step in the cavity production technology. It has been established that a low-temperature baking at 120°C/48 h eliminates a so-called Q_0-slope and provides more stable accelerating gradients [1]. In the last years new treatments, nitrogen doping [2] and infusion [3], have been elaborated. The $Q_0(E_{acc})$ curve demonstrated anti-Q slope which has not been previously observed. With these treatments improving of the efficiency up to three times and moderate maximal accelerating fields is possible to obtain.

Evidently, the increased interstitial content in the near-surface Nb region upon such treatments is leading to coupled effects associated with the modulation of electron mean free path and "dirty superconductivity" [4], suppression of hydride formation by hydrogen trapping [5] and as a consequence a reduction of residual resistance. In order to find a possible origin of anti-Q slope, determine a role of nitrogen supply in the chamber during the low-temperature baking step and further optimize the Nb surface treatment procedure extensive studies of chemical composition and crystal structure are required. Here we are exploring the "classic" infusion recipe by synchrotron radiation XPS using small Nb samples, study the effect of N_2 supply during 120°C baking step, and explore the Nb surface in a high vacuum environment immediately after the high-temperature anneal step.

EXPERIMENTAL DETAILS

The samples were cut by electro-erosion from 2.8 mm-thick large-grain Nb sheets (Heraeus) followed by buffered chemical polishing (BCP), water and ethanol rinsing. The annealing experiments were performed in a furnace consisting of a ceramic tubular chamber (7 cm in diameter, 1.5 m in length) with a three-zone temperature control providing a base pressure of 10^{-6} mbar at 800°C. The titanium polycrystalline tubular holder covered with Nb foil was used both as a getter material and a sample support. Several treatments were tested on samples. Here we present the results on the 800°C vacuum anneal (800°C/2–3·10^{-6} mbar/3h), nitrogen infusion (800°/3h + 120°C/4·10^{-2} mbar of N_2/48h), and infusion without N_2 supply (800°/3h, 2-3·10^{-6} mbar + 120°C/7.5·10^{-7} mbar/48h). After the treatment, the samples were subjected to ambient atmosphere for a couple of days and transferred to XPS set up for further investigation. The samples are compared to the same large-grain Nb chemically pre-treated in a same way but thermally annealed in high-vacuum (800-950°C/2·10^{-8} – 2.5·10^{-9} mbar/11h) in the preparation chamber of the XPS set-up. The sample was studied immediately after the annealing upon cooling to room temperature in ultra-high vacuum (without air exposure).

Investigation of the chemical composition of the first set of samples was performed using synchrotron radiation XPS at the end-station based on Argus analyzer with the 128-channel high sensitive detector and integrated to P04 beamline, PETRAIII. Several photon energies (PEs) of the incident beam in the range of 800-1500 eV and at an angle close to normal emission (72°) were used. The latter sample was measured at dipole RGBL, BESSYII synchrotron radiation facility (HZB, Berlin) at PE 450-1000eV, normal emission geometry at 55° angle between the incident beam and an analyzer aperture. The binding energies were calibrated using Au $4f_{7/2}$ core level peak from a metal foil. Nb 3d, Nb 3p, O 1s, C 1s, N 1s, and in some cases Ti 2p core-level spectra have been analysed using the CasaXPS software package. The samples were additionally characterized by SEM, XRD (Bruker D8 Advance, Cu kα), and Raman spectroscopy (MonoVista SP-2500i, 532 nm DPSS-laser, 5 mW).

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV007

RF CONDITIONING OF 120 KW CW 1.3 GHz HIGHPOWER COUPLERS FOR THE bERLinPro ENERGY RECOVERY LINAC*

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Abstract

This year, the commissioning of the 50 MeV, 100 mA bERLinPro Energy Recovery Linac test facility [1] will resume. For the Booster cryo-module of the injector line, operated with three modified 1.3 GHz Cornell style 2-cell SRF cavities, a new type of power coupler was developed, based on KEK's C-ERL injector coupler. Modifications were made for a stronger coupling and lower emittance diluting coupler tip variant, a so-called Golf Tee shape and the cooling concept was redesigned based on KEK's first experiences. For the final stage, the injector needs to deliver a low emittance beam of 100 mA average beam current at 6.5 MeV. That results in a traveling and continuous wave forward power requirement of up to 120 kW for each coupler of the twin setup feeding one Booster cavity. In this contribution we will give a short overview of the RF design and its impact on the beam's emittance, give an overview of the conditioning teststand and the results achieved with the first pairs of couplers.

INTRODUCTION

For the bERLinPro ERL [1] the Booster module housing three two cell SRF cavities needs to accelerate the beam from about 2.3 MeV of the SRF photo-injector [2] to 6.5 MeV, whereas the first cavity will be used in zero-crossing mode to allow bunch shortening for the injection into the merger/recirculator section. See Figure 1 for an overview of the coupler-coldstring assembly. Besides transmitting in total 420 kW power to the beam, the acceleration process in the Booster needs to preserve the low beam emittance from the photo-injector. Thus, a coupler design had to be optimized in withstanding the high thermal load by this power level and also minimize any influence on the beam by transverse field components of the geometry variation caused by the coupler arrangement to the field symmetry.

Figure 2 depicts a schematic of the coupler design and how it is attached to the cavity. To minimize the power load per coupler and to mitigate kicks by the field distorted by the coupler as well as emittance increase, two couplers power one cavity. The coupler design is a modification of the C-ERL injector cryo-module coupler [3] and features a single window, fixed coupling and avoids such any bellows exposed to RF. Mechanical variations during e.g. cool-down are compensated by the doorknob part itself and bellows outside the module in the waveguides. Cooling is provided by 5 K and 80 K helium heat intercepts. The major heat transfer is by water cooling of the inner conductor, the outer conductor of the warm part, the doorknob section and the ceramic window by a copper sleeve. More information on the RF and mechanical design can be found here [4] and here [5, 6]. The antenna tip is designed such, that at full

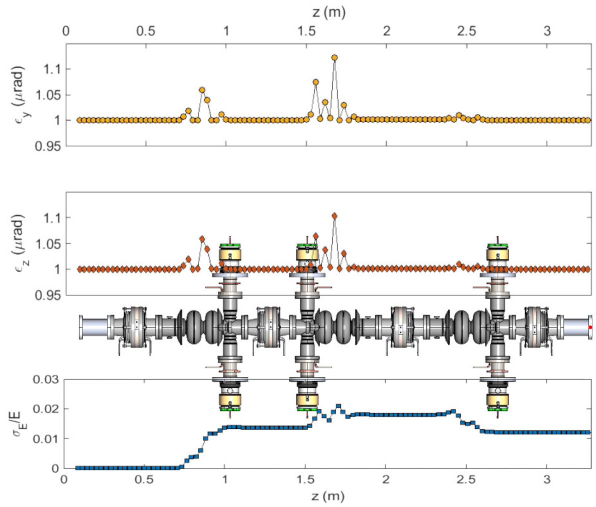

Figure 1: Booster SRF injector cold string layout with attached coupler cold parts and SiC HOM loads between adjacent cavities and exit beam tube. The three plots show the relative energy spread (bottom) and transverse normalized emittance for both planes without space charge calculated by 3DS CST PIC tracking. The emittance increases by 0.3% in both planes is caused by coupler kicks due to port variations as measured with a CMM tool.

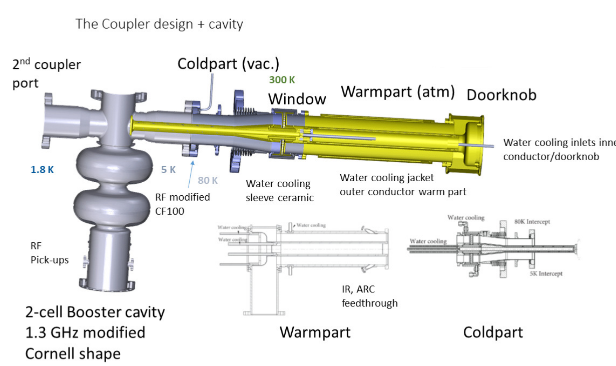

Figure 2: Schematic overview of the bERLinPro Booster injector coupler. The insert gives an better view on the water cooling channels and the diagnostic port observing the ceramic window.

* Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin, and grants of Helmholtz Association
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV009

A METHOD FOR IN-SITU Q0 MEASUREMENTS OF HIGH-QUALITY SRF RESONATORS*

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Abstract

Accelerator projects such as LCLS-II naturally require low-loss superconducting (SRF) cavities. Due to strong demand for improving intrinsic quality factor (Q0), importance of accurate cavity characterization increases. We propose a method to measure Q0 in situ for an SRF resonator installed in its cryogenic module and connected with a RF feed source via a fixed RF coupler. The method exploits measurements of a response for an SRF resonator fed by an amplitude-modulated signal. Such a signal can be synthesized as a beat-wave composed of two frequencies that are close to the resonant frequency. Analyzing the envelope of the reflected signal, one can find the difference in reflection for the chosen frequencies and use them to compute the intrinsic Q. We also develop the methodology to carry out measurements of Q0 at the nominal cavity operating voltage. We verified our method in experiments with a room temperature copper resonator and with two SRF resonators including Fermilab's 650 MHz cavity and JLab's 1500 MHz cavity.

INTRODUCTION

Although SRF resonators have extremely high Q-factors (10^6–10^7 loaded quality factor, and 10^{10}–10^{11} unloaded quality factor, Q0) there are well-developed methods to measure these values. However, problems arise when an SRF resonator installed in a cryogenic module is connected to a feeding RF source via a fixed RF coupler. In this case, there are no direct ways to measure the degradation of Q_0 in situ. Measurement of the cryogenic heat load is the only method that can be used in this case. However, when several cavities are housed in a common cryomodule, measuring individual Q_0 values can be time consuming, since each cavity needs to be operated individually in order to identify the heat load increase produced by that particular cavity. The method proposed in this paper circumvents this drawback by offering a direct and faster measurement for each individual cavity. We also propose a methodology to carry out the measurements of Q_0 at high accelerating voltages, or even at the nominal cavity operating voltage. These measurements are most beneficial, because Q_0 at the nominal accelerating voltage can differ considerably from the low-field value of Q_0. Therefore, there is a particular need for accurate and fast in situ Q-factor measurements. The procedure should not require removing the RF coupler, which introduces additional loss that interferes with the direct measurements.

We suggest the generation of a beat wave, which introduces the superposition of two frequencies. One frequency is to be tuned exactly to the test cavity resonance, and the second shifted off of the resonance. The beat wave provides information on the difference in reflection (or transmission) on resonance and off resonance. In case of the reflected beat-wave measurements, this difference is inversely proportional to the intrinsic Q-factor and can be used to retrieve it. In the case of transmitted signal measurements at a pick-up, the mentioned difference depends on Q_0 in a more complicated form, but still can be used to retrieve Q_0.

A CONCEPT FOR Q0 MEASUREMENTS

The reflection of a monochromatic signal from a resonator having high beta factor ($\beta=Q_0/Q_{ext}$ – ratio of intrinsic and external Q-factors) is very close to unity. That is why direct measurement of the resonant reflection curve of such cavities requires the use of modern network analyzers with a very large dynamic range [1]. The loaded Q-factor is frequently measured as the inverse decay time of the stored energy in a radiating resonator that has been previously energize at the resonant frequency [2].

The measurement procedure can be simplified if one makes use of a reference signal, so that the reflected signal can be measured relative to the reference signal (Fig. 1a). Reformulating the problem, in this case it is only the difference between these two signals that needs to be measured (Fig. 1b). Let us consider the superposition of two frequency components, f_0 and $f_0+\Delta f$, with equal amplitudes and closely spaced frequencies (Fig. 1a). The mentioned superposition of the two frequencies is the beat-wave signal, where the beat frequency corresponds to the frequency difference between these two components. Each frequency component will be reflected from the high-Q resonator with close to unity reflection (Fig. 2a), but with slightly different amplitudes and essentially different phases (Fig. 2b). Using a broadband oscilloscope, one can measure the beat wave with high accuracy. Assuming that the amplitudes of the components of the incident beat wave were selected to be equal to each other, the minimum of the incident wave envelope will be exactly zero. For the reflected beat wave, the minimum will become greater than zero, and the greater the difference in the reflection coefficients for the selected test frequencies, the greater the value of the

* This work was supported by DoE SBIR grant # DE-SC0019687.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV010

RF SYSTEM EXPERIENCE FOR FRIB HALF WAVE RESONATORS*

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Abstract

The installation and commissioning of the Facility for Rare Isotope Beams (FRIB) superconducting linac adopts a phased strategy. In SRF'19 we reported the progress on the commissioning of the linear segment 1 (LS1) which contains mainly the quarter wave resonators (QWRs). In this paper, we will report the recent progress on the commissioning of the remainder of the linac, including linear segment 2 (LS2), folding segment 2 (FS2) and linear segment 3 (LS3), focusing on the RF system experience for the half wave resonators (HWRs). Compared to the QWRs, the HWRs have a different type of tuner, run at higher power levels and have additional components (for example, high voltage bias tee for multipacting suppression and spark detector). Topics such as nonlinear tuner control for the pneumatic tuners, auto turn on/off implementation, and early issues and failures will be discussed in more detail.

INTRODUCTION

As presented previously, the Facility for Rare Isotopes Beams (FRIB) adopts a phased commissioning strategy [1, 2]. Table 1 shows the FRIB accelerator readiness review (ARR) schedule. The linear segment 1 (LS1) and folding segment 1 (FS1) were commissioned by February 2019 when all quarter wave resonators (QWRs) were commissioned. In the past two year, FRIB has made significant progress on the linac commissioning even under the effect of the COVID-19 pandemic. The ARR4 was completed by March 2020 and ARR5 was completed by April 2021 during which all half wave resonators (HWRs) were successfully commissioned.

Table 1: FRIB ARR Phases

ARR Phase	Area with beam	Energy MeV/u	Date
1	Front end	0.5	07/2017
2	+ β = 0.041	2	05/2018
3	+ β = 0.085 (LS1, FS1)	20	02/2019
4	+ β = 0.29, 0.53 (LS2)	200	03/2020
5	+ β = 0.53 (FS2, LS3)	>200	04/2021
6	+ target, beam dump	>200	09/2021
Final	integration with NSCL	>200	06/2022

As shown in Table 2, HWRs with 220 cavities in total make up two thirds of the FRIB Linac. Compared to the QWRs, the HWRs have a different type of tuner and run at higher frequency and higher power levels [3]. HWRs also have additional components such as high voltage bias tee for coupler multipacting (MP) suppression and spark detectors.

Table 2: FRIB Superconducting Cavity Types

Cavity Type	Freq. (MHz)	Power (kW)	Tuner	Qty
β=0.041 QWR	80.5	0.7	Stepper	12
β=0.085 QWR	80.5	2.5	Stepper	92
β=0.29 HWR	322	3.0	Pneumatic	72
β=0.53 HWR	322	5.0	Pneumatic	148

For the rest part of the paper, several topics that are related to the RF system for the HWRs will be discussed, including resonance control, automation, HWR specific components and issues encountered.

PNEUMATIC TUNER CONTROL

The HWRs use pneumatic tuners in comparison to the stepper tuners used by the QWRs. The pneumatic tuner control has evolved significantly over the years since HWR integrated test, cryomodule bunker test and test in the linac tunnel trying to improve the tuner control performance.

The main challenge can be explained with the valve characteristic curve as shown in Figure 1. First, the valve does not give any flow if the control signal is less than certain amount (typically 30~40%); second, the point where flow begins is uncertain (due to static friction, pressure operating point, thermal effect of the coil in the valve, etc.); third, the flow needed for tuning is less than 15% which means the valve operates mostly in the nonlinear region.

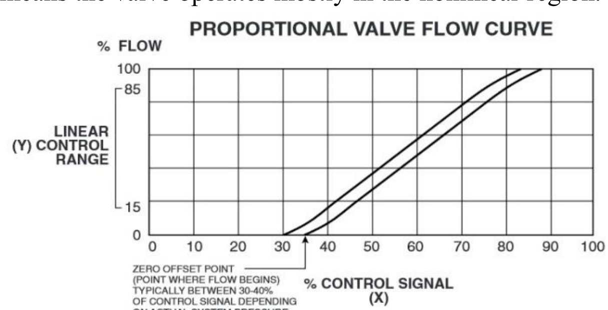

Figure 1: Valve characteristic.

The "static" deadzone mentioned in the first point can be easily addressed by calibrating the valve close voltage (vClose). Due to the uncertainty mentioned in the second point, however, a "dynamic" deadzone of around 10% (or 0.5 V for 0 ~ 5 V control signal) is unavoidable. The maximum flow is limited by calibrating the valve open voltage (vOpen) to around 0.15 ~ 0.2 psi/s which correspond to a maximum cavity tuning rate of 150 ~ 200 Hz/s.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV012

EXTRA-COLD EP PROCESS AT FERMILAB*

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Abstract

FNAL has established a Cold Electro-Polishing (EP) method which maintains the outer surface temperature of cavity cell around 12~15 degC during EP process. Cold EP has been applied on the various SRF cavities as the final removal of 10 µm or less and contributed to achieve high RF performances with them. To investigate more feasibility and capability of EP at lower temperature, the FNAL EP temperature control system was recently upgraded. Extra-cold EP process below zero-degC at cavity cell region was successfully performed on 1.3GHz 1-cell cavity. A compatible RF performance with cold EP method was also demonstrated during the cavity vertical testing. Here we report details of extra-cold EP process and the cavity test results in this paper.

INTRODUCTION

Electro-Polishing (EP) is one of key techniques for niobium SRF cavity treatment to remove materials from its surface. FNAL EP processes have two different temperature conditions depends on removal range. Precise temperature control over the cavity is established by applying cooling shower on cavity outer surface and controlling EP acid temperature. “Hot EP” is applied on the removal more than 10 µm. During this process, the cavity outer cell surface is maintained around 32 degC, and the cavity beam tubes are maintained around 5 degC. “Cold EP” is applied on the removal below 10 µm, which maintains the cavity outer cell surface around 12~15 degC and the cavity beam tubes around 0 degC. An example, when we do bulk removal of 120 µm, 110 µm is removed with hot conditions, then last 10 µm was removed with cold conditions. For the removal 10 µm or below, whole process is done with cold conditions. Cold EP was established at FNAL with the motivation of precise temperature control to achieve continues large current oscillations during the EP process which would provide better surface finish [1]. Cold EP method has been successfully applied on single-/multi-cell niobium SRF cavities with elliptical shape at FNAL EP facility and ANL EP facility and contributed to the cavities achieved high-Q and/or high gradient performances. As one of new challenges in EP R&D at FNAL is investigating impacts of EP process with much lower temperature conditions. The first challenge is seeking the lowest temperature FNAL EP tool can run and control the process. The second challenge is applying that “Extra-Cold” EP conditions to the cavity and perform cryogenic testing.

*Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.
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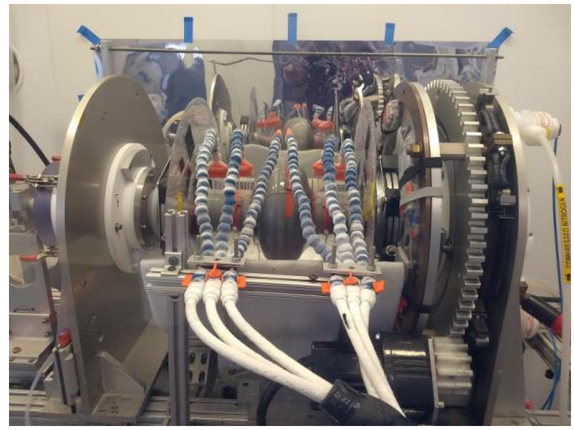

Figure 1: 1.3GHz 1-cell on FNAL EP tool.

EP TOOL AT FERMILAB

Figure 1 shows 1.3 GHz TESLA shape single cell cavity on FNAL EP tool at CPL (Cavity Processing Laboratory). Six cooling shower line for cavity outer surface also can be seen. This EP tool is capable for single cell cavities with frequency of 1.3~3.9 GHz.

Electrolyte

EP electrolyte is the mixtures of sulfuric acid (H_2SO_4) and hydrofluoric acid (HF). Fermilab uses EP electrolyte with the ratio of H_2SO_4 : HF = 13.5 : 1 by volume. Concentration of each acid Fermilab uses are H_2SO_4 > 96 % and HF ~70 % by weight. The electrolyte was pre-mixed by the company and delivered to Fermilab (~110 L/drum). A fresh electrolyte of 10 L was transferred from the EP electrolyte drum to the acid tank of EP tool. This 10 L of electrolyte was circulated during EP process and dumped to the waste drum after the process, no electrolyte was reused even if the removal was small. The administrative removal limit with 10 L of electrolyte is 80 µm on 1.3 GHz single cell cavity; this corresponds to the niobium concentration of about 11 g/L.

Temperature Control

Two chiller units and flow adjust valves in acid line and cooling lines control the EP process temperature (Fig.2 top). The 30 % propylene glycol is used to achieve below 0 degC without freezing. Temperature monitoring during EP process is done with six thermocouples. One is on cavity equator, two are on cavity beam tubes, another two are on the acid drain lines. The last one is in the acid tank of EP tool. Thermocouples, except the one in acid tank, are covered with insulator to avoid the impact from cooling shower or room temperature. Wireless thermocouple system is applied on the rotating cavity and the drain lines.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV013

THE VSR DEMO MODULE DESIGN – A SPACEFRAME-BASED MODULE FOR CAVITIES WITH WARM WAVEGUIDE HOM ABSORBERS

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Abstract

The VSR (Variable pulse length Storage Ring) demo module is a prototype for the superconducting upgrade of HZB's BESSY II. The module, shown in Fig. 1, houses two 1.5 GHz superconducting cavities operated at 1.8K in continuous wave (CW) mode. Each cavity has five water cooled Waveguide HOM Absorbers with high thermal load (450 W), which requires them to be water cooled. This setup introduces several design challenges, concerning space restriction, the interconnection of warm and cold parts and the alignment. In order to provide support and steady alignment an innovative space frame was designed. The transition from cold to warm over the partially superconducting waveguides made a more complex design for shielding and cooling system necessary. With the design close to completion, we are now entering the purchase phase.

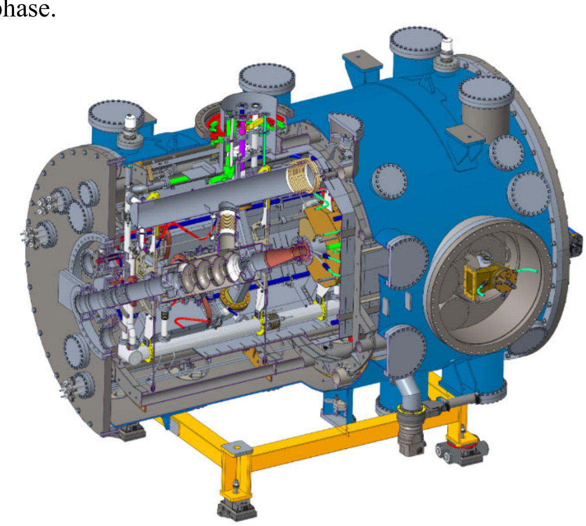

Figure 1: VSR DEMO module.

VSR DEMO PROJECT

Bunch length manipulation is mandatory in modern storage ring light sources and CW SRF provides the required high voltage in a compact system to reach this goal [1]. One possible technique as proposed in [1] is to combine higher harmonic SRF cavities (3 and 3.5 harm.) with the fundamental frequency of the BESSY II storage ring (500 MHz). This corresponds to a setup of 1.5 GHz-Cavities and 1.75 GHz-Cavities.

VSR DEMO seeks to develop and demonstrate the required SRF technology to achieve this by means of "offline" testing at HZB SupraLab facilities of a setup comprising two 1.5 GHz SRF cavities.

If successful, the two-cavity module would be ready for commissioning in the storage ring of BESSY II. This will represent the final step towards validating the proposed technology.

In perspective the module is prepared to accommodate also one or two 1.75 GHz or a subsequent module with four cavities (2x 1.5 GHz cavities 2x 1.75 GHz cavities) as presented in [2] offering the beam flexible dynamics could be built.

VSR DEMO MODULE DESIGN

The VSR module design is defined by some boundary conditions and demands originated from the SRF setup.

Space Restriction

The VSR DEMO module should be able to be installed in the storage ring of BESSY II and at HZB SupraLab. This means there are space restriction.

At Supralab there is main constrain is the ceiling height therefore the module's support structure is lowered and the Multi-transfer-line (MTL) which supplies the Module with Helium does not come from above like at the BESSY II site but from the right side.

At the Bessy II the module should be integrated in the storage ring this means that the possible straight also has space restrictions in axial direction and radial direction. While the axial restriction is relaxed for the two cavities module the radial restrictions are still strictly defined by the distance between beam and radiation protection wall. This also means that the module is only good accessible from the front.

Waveguide and HOMs

Due to the beam-cavity interaction high HOM power is expected. To damp this high loads in an axial space saving way the cavities are equipped with water cooled waveguides HOM absorbers (s. Fig. 2) [3].

Due to the high field strength leaping into the Waveguide the lower part of the waveguide (outside of the helium bath) must kept superconducting. Since the HOM loads are water cooled quite long Waveguides are required to deal with temperature gradient with acceptable headloads. Due to radial space restrains, warm HOM absorbers are on the same radial plane like the cold part of the waveguide. As a

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV014

NEW IMPROVED HORIZONTAL ELECTROPOLISHING SYSTEM FOR SRF CAVITIES*

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Abstract

The best performance of niobium SRF accelerating cavities is obtained with surfaces smoothed with electropolishing chemical finishing. Jefferson Lab has recently specified, procured, installed, and commissioned a new versatile production electropolishing (EP) tool. Experience with EP research and operations at JLab as well as vendor interactions and experience guided development of the system specification. Detailed design and fabrication was awarded by contract to Semiconductor Process Equipment Corporation (SPEC). The delivered system was integrated into the JLab chemroom infrastructure and commissioned in 2020. The new EP tool provides much improved heat exchange from the circulating H_2SO_4/HF electrolyte and also the cavity via variable temperature external cooling water flow, resulting in quite uniform cavity wall temperature control and thus improved removal uniformity. With the JLab infrastructure, stabilized process temperature as low as 5 °C is available. We describe the system and illustrate operational modes.

BACKGROUND

Bulk Nb SRF cavities are almost always fabricated via sheet metal forming and machining techniques and integrated by electron beam welding. Because clean, crystallographic niobium is essential for best superconducting properties, of order 200 µm of surface material is typically chemically removed from the RF surface to remove any surface damage or fabrication contamination. To support the highest surface magnetic fields, surfaces additionally need to be smooth at the submicron level to avoid local field enhancements approaching critical field amplitudes.

The community has developed the H_2SO_4/HF (10:1 using US standard reagent HF) electrolyte based diffusion-limited electropolishing that is now employed generally for at least the final chemical finishing steps [1-4]. As experience has been gained and process refinements realized, the lessons learned are now being integrated into the specifications of new production processing tools. Jefferson Lab has recently completed this process and has commissioned a new production horizontal cavity electropolishing (EP) system. The system is now in regular routine use.

There are inherent limitations if one uses the acid solution as both the chemical agent and the process coolant. The best one can do to establish reproducible process conditions is to regulate the supply acid temperature and flow rate and take pains to ensure symmetric outflow of acid from the cavity. One may then attempt to reduce smaller diameter surface heating by increasing the distance of these surfaces from the cathode by masking portions of the cathode, but this has the offsetting effects of increasing cathode current density (increasing sulfur precipitation rates) and increasing likelihood of etching roughing in beampipe appendages (HOM cans or coupler structures). For some structures this is doable when the resulting non-uniform removal still meets requirements. Changing process conditions or rates then involves changing the temperature of the supplied acid/coolant, the convenience of which depends strongly on the details of all of the infrastructure systems involved.

The most robust process control solution is to separate the chemical agent role from the process coolant role. This is accomplished via provision of external temperature-controlled water to essentially define the process temperature with flow adequate to remove any heat produced with negligible temperature rise in the cavity and near-surface solution. How well and flexibly this functions in reality depends on the available infrastructure systems.

SYSTEM SPECIFICATION

As a part of the JLab TEDF Project 2012-13 [5], a flexible support infrastructure was set up to accommodate the evolution of process tooling. This infrastructure provides generous capacity of ultrapure water (UPW) and process cooling water at various temperatures. The project also included a clean cavity chemistry processing room which has been used to house the JLab cavity EP system. The EP system originally set up in the old facility and largely commissioned to support the ILC R&D activity 2008-2012 and then the CEBAF 12 GeV Upgrade was relocated here into the new facility in 2013 and recommissioned. As system components were aging and process improvement lessons had been learned, a specification for a new system was developed.

Several key features were sought from the new system:

- Locate the electrolyte sump below grade and in an adjoining service space for enhanced safety.
- Arrange cavity setup for improved ergonomics and reduced assembly labor.
- Improved external cavity cooling.
- Upgraded and serviceable PLC control with contemporary user interface.
- Increased capacity to handle larger cavities.

A functional specification was developed in 2015. When enabling funds were identified, a solicitation of corresponding proposals was posted in 2017. After refinement of the specification, a contract was awarded in

* This manuscript has been authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OThR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV015

SPOKE TUNER FOR THE MINERVA PROJECT

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Abstract

In the framework of the MINERVA construction (MYRRHA Isotopes productioN coupling the linEar acceleRator to the Versatile proton target fAcility), a fully equipped prototype cryomodule is being developed. In order to control the resonance frequency of the cavities during operation, a deformation tuner has been studied. The kinematic model is based on a double lever system coupled with a screw nut linear actuator. The motion is generated by a stepper motor and two piezoelectric actuators working at low temperatures within the thermal insulation vacuum of the cryomodule. Key parameter of this work is the high tuning speed which is required to fulfil the fault tolerance strategy. This paper reports the design study and first tests of the built tuners at room temperature and in vertical cryostat configuration.

INTRODUCTION

The tuner experimentations described in this paper were made using one prototype tuner designed for the MYRRHA project with one prototype cavity, in the continuity of the work done on pre-prototype tuners [1, 2]. The main goals of this experimentation were to qualify the tuner performances, the compatibility with cavity, and verify the capability for fault tolerance feature of the linac [3, 4] which represent a key challenge of this tuner.

TUNER DESCRIPTION

The tuner is based on a double lever deformation system, which induce resonant cavity shift by mechanical deformation of one cavity end cup. This deformation can be obtained by pulling the cavity beam pipe flange while the tuner structure is fixed on the cavity helium vessel. Different types of actuators are used to adjust de cavity resonant frequency: one stepper motor and two piezo actuators. The stepper motor represent the slow tuner. It can be used to adjust the frequency over a wide range in order to compensate uncertainties on the cavity resonant frequency shift occurring during the preparation of the cavity itself and the cool down. The piezo actuators represent the fast tuner. They are useful for fine and fast tuning, when the stepper motor find its limit.

ROOM TEMPERATURE TEST

Cavity was installed in horizontal position and connected to a VNA to track its resonant frequency by looking at S21 parameter. A laser sensor was used to observe micro displacement of the beam pipe (see Fig. 1). The motor position is controlled by steps, which is converted into linear displacement by using an equation that is coming from the tuner kinematic model. This value is equivalent to the linear displacement of the beam flange, in the case that the tuner is infinitely stiff, relatively to the cavity stiffness.

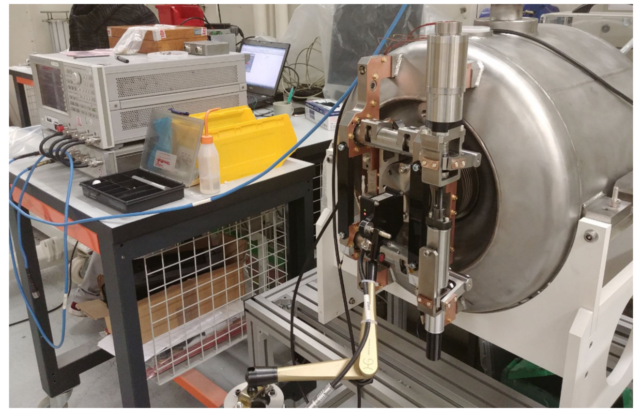

Figure 1: Room temperature setup.

Motor Test

The test routine is a simple back and forth, starting at a point where the cavity is nearly no stressed, and with limited forward displacement in order to not exceed the elasticity limit of the niobium.

Results show a linear action of the tuner on the cavity above 0.12 mm motor position, where the tuner get strongly connected to the cavity. Tuning sensitivity resulting on this region is 112 kHz/mm (see Fig. 2).

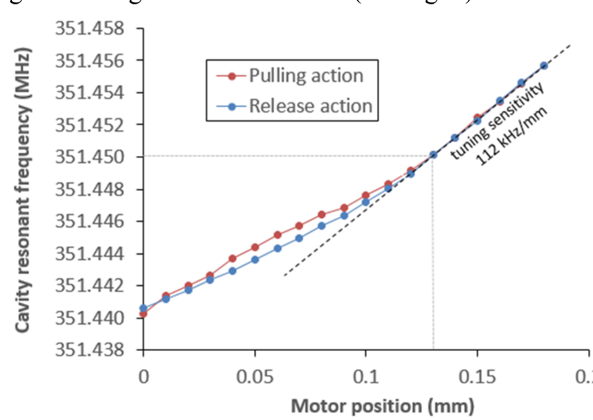

Figure 2: Complete motor run at room temperature.

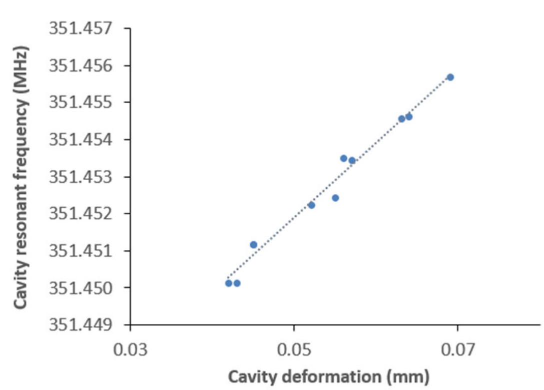

Figure 3: Cavity sensitivity measurement.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPTEV017

DEVELOPMENT AND OPERATION OF PIP-II INJECTOR TEST, SSR1 CRYOMODULE, 325 MHz AMPLIFIERS

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Abstract

The PIP-II Injector Test (PIP2IT) [1] has successfully accelerated ionized hydrogen up to 17 MeV through a superconducting, single spoke resonator (SSR1) Cryomodule at Fermi National Accelerator Laboratory (FNAL). Each of the SSR1 cavities is tuned to 325MHz and requires up to 6 kW of RF power to accelerate 2mA of ionized hydrogen at the design gradients. RF power amplifiers, specialized for SRF cavity beam operations, were designed by Bhabha Atomic Research Center (BARC) and constructed in a collaboration between the BARC in Mumbai, India and the Electronics Corporation of India Limited (ECIL) in Hyderabad, India. The RF amplifiers meet the specifications and requirements mutually approved between BARC and FNAL. They operate at 325 MHz with a linear power output of 7 kW in both CW and pulse mode. The amplifiers are compatible with the FNAL accelerator personnel safety system and the cavity protection interlocks. Access to controls and internal diagnostic instrumentation are compatible with EPICS control standards. This paper gives details about RF power amplifier development within the Department of Atomic Energy (DAE), India and the operational details with PIP2IT at FNAL.

INTRODUCTION

Charged particle accelerators were developed for pursuing research in frontier areas of physics. Their scope and usefulness has been extended to a variety of applications like food industry, health care, agriculture, environment, archaeology industry, national security, and waste management.

Advance technology development in cryogenic and super conducting RF (SCRF) resonating cavities has led to a new era in modern RF accelerators. SCRF cavities have reduced the RF power requirement by orders of magnitude for achieving the same accelerating potentials.

High power radio frequency (HPRF) system is one of the most important and critical technologies in an SCRF accelerator. HPRF needs to demonstrate of high performance amplifiers to achieve higher power levels with improved efficiency. The cost of such amplifiers is comparable to vacuum tube based amplifiers. Hence, the solid-state RF power amplifiers have become increasingly suitable for the super conducting accelerator applications.

These RF systems are developed using innovative designs / techniques with their experimental validation, application of stringent qualification standards during their development, and earlier operational experience with accelerators.

State-of-art solid state radio frequency power amplifiers (RFPAs), designed and developed by Bhabha Atomic Research Centre (BARC) and productionized at ECIL, are now a part of Fermilab's beam facility in USA.

INTERNATIONAL COLLABORATION

The Science and Technology (S&T) Cooperation agreement was signed between Department of Atomic Energy (DAE), India and Department of Energy (DOE), USA. Radio Frequency Power is one among the sixteen technologies listed under Technical Cooperation. Due to the similar interests in accelerator technology, a collaboration named as Indian Institutes and Fermilab Collaboration (IIFC) has been established to design and develop the superconducting radio frequency accelerators for both the Indian and Fermilab programs.

Fermilab is upgrading its accelerator complex to deliver high intensity neutrino beams as well as to provide beams for a broad range of experiments.

The 800 MeV, 2 mA Superconducting (SC) linear accelerator (LINAC) named PIP-II [2] is being developed at Fermilab. In the PIP II Injector Test (PIP2IT) - a technology demonstration part of PIP II, single spoke resonator (SSR1) cavities with β 0.22 utilizes 325 MHz RF power. Under IIFC, BARC has designed and developed the solid-state RF power amplifier at 325 MHz for its proton accelerator [3] and for Fermilab, USA.

DEVELOPMENT OF RF POWER SYSTEMS FOR SUPER CONDUCTING SPOKE RESONATORS OF PROTON ACCELERATORS

High power RF (HPRF) systems provide power to normal conducting (NC) or superconducting LINAC for beam acceleration. HPRF systems must be reliable, rugged, with

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV001

CAVITY PRODUCTION AND TESTING OF THE FIRST C75 CRYOMODULE FOR CEBAF*

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Abstract

The CEBAF cryomodule rework program was updated over the last few years to increase the energy gain of refurbished cryomodules to 75 MeV. The concept recycles the waveguide end-groups from original CEBAF cavities fabricated in the 1990s and replaces the five elliptical cells in each with a new optimized cell shape fabricated from large-grain, ingot Nb material. Eight cavities were fabricated at Research Instruments, Germany, and two cavities were built at Jefferson Lab. Each cavity was processed by electropolishing and tested at 2.07 K. The best eight cavities were assembled into "cavity pairs" and re-tested at 2.07 K, before assembly into the cryomodule. All but one cavity in the cryomodule were within 10% of the target accelerating gradient of 19 MV/m with a quality factor of 8×10^9. The performance limitations were field emission and multipacting.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab has forty 8-cavity cryomodules (CMs) originally built in the 1990s [1]. Field emission is the main limitation for the operation of the cryomodules and results in a steady beam energy loss over time [2]. A refurbishment program was started in 2006 to remove the lowest-performing CMs from the accelerator, at a rate of about one CM per year, and reprocess the cavities to increase the energy of the CM to 50 MeV, from the original ~20 MeV [3]. The rework program was updated in 2016 to further increase the energy of the CMs to 75 MeV, at the lowest possible cost. The proposed concept was to reuse the waveguide end-groups of the old cavities and replace the 5-cells with new ones with a more efficient shape and with low-cost large-grain, ingot Nb [4]. Three prototypes of such "C75" cavities were built, processed and tested at Jefferson Lab in 2016 and two of them were installed in the last C50 CM, which has been operating in CEBAF since December 2017 [5]. The current plan requires nine C75 reworked CMs to be installed in CEBAF over the next 5 years.

CAVITY FABRICATION, TREATMENT AND VERTICAL TEST RESULTS

Two C75 cavities, 5C75-J-004 and -005 were fabricated at Jefferson Lab in 2018 and eight cavities, 5C75-RI-001 to -008 were built at Research Instruments (RI), Germany in 2018-19. The Nb material used for the elliptical cells was obtained from ingots from CBMM, Brazil, sliced into 3.155 mm thick discs by multi-wire slicing at Slicing Tech, USA. The ingots' Ta content was 923 wt.ppm and 139 wt.ppm for the cavities built at JLab and RI, respectively. The RRR measured on samples cut from the discs was 165 and 203 for the material used at JLab and RI, respectively. The cost of the Nb discs was ~1/3 of the cost that was quoted for the conventional fine-grain, high-RRR, low-Ta Nb disc.

The cavity fabrication followed conventional methods such as deep-drawing of the Nb discs and electron-beam welding of parts. A re-shaping tool was used at the dumbbell stage, both at JLab and RI, to correct the shape. The cavities were received tuned and with >95% field flatness from RI. One of the cells of cavity 5C75-RI-008 had a narrow underbead at one of the equator welds, the joint was missed at two locations and had to be sent back to RI for a partial re-weld. Figure 1 shows a picture of a C75 cavity built at RI.

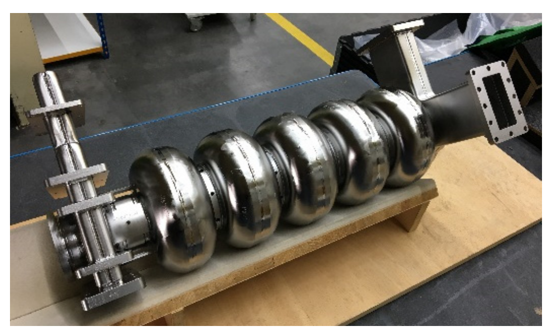

Figure 1: Picture of a C75 cavity built at RI.

All of the surface treatments were done at JLab and can be summarized as:

- 100 μm removal by electropolishing (EP)
- Vacuum annealing at 800 °C/3 h
- 30 μm removal by EP
- Dimensional check/adjustment and RF tuning
- Lapping and buffered chemical polishing of Nb flanges
- High-pressure rinse with ultra-pure water
- Assembly of ancillary components in an ISO Class 4 cleanroom
- Slow evacuation on a vertical test stand and leak check.

The amount of material removal was calculated from the total charge during EP and confirmed by measuring the wall thickness at the equator using an ultrasonic probe.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV002

SHAPE EVOLUTION OF C75 LARGE-GRAIN NIOBIUM HALF-CELLS DURING CAVITY FABRICATION*

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Abstract

The largely anisotropic deformation of large-grain Nb discs during deep drawing into half-cells poses a challenge for achieving a desired shape accuracy. Two 5-cell cavities for the C75 CEBAF cryomodule rework program have been fabricated at Jefferson Lab from large-grain Nb discs directly sliced from an ingot. The shape of the inner surface of eight half-cells has been inspected using a FARO Edge laser scanner during the fabrication process and compared to the reference shape. On average, approximately 63% of the half-cell inner surface was found to be within 0.1 mm of the reference shape and ~90% to be within 0.2 mm, after the final equator machining. Several 5-cell C75 cavities have also been fabricated at Research Instruments, Germany, and measurements of the shape accuracy using a Zeiss 3D coordinate measuring machine gave similar results. One half-cell was measured both at Research Instruments and Jefferson Lab for comparison.

INTRODUCTION

Large-grain Nb technology is a viable alternative to the use of standard fine-grain, high-RRR, Nb material for SRF cavity production [1]. Nb discs are directly sliced from a Nb ingot and deep-drawn into half-cells of the required cell shape. Because of the presence of several cm^2-size grains, large-grain half-cells have a larger deviation from the ideal shape than fine-grain ones, after deep-drawing. Additional steps in the cavity fabrication, such as welding of stiffening rings, can also alter the cell shape.

Maintaining an accurate cell shape of the cavity is important to assure that the spectra of higher-order modes is consistent with what has been calculated using 3D electromagnetic solvers, at the cavity design stage. During the production of 1.3 GHz, 9-cell cavities for E-XFEL, a maximum deviation from the ideal cell shape of ±0.2 mm for 90% of the measured data and up to ±0.25 mm for the remaining 10% had to be maintained throughout the cavity fabrication steps [2, 3].

The availability of fast, non-contact, 3D coordinate measuring machines (CMM), allows for more detailed 3D shape measurements than it is possible with traditional CMM. In this contributions we present the 3D shape evolution of several large-grain Nb half-cells during the fabrication of two 1.5 GHz, 5-cell cavities for the C75 cryomodule rework program at Jefferson Lab [4]. The same type of cavities have also been built at RI Research Instruments GmbH, Germany, using the same type of material. The shape accuracy requested throughout the cavity fabrication was ±0.2 mm for 80% of the data within ±0.4 mm for the remaining 20%.

EXPERIMENTAL RESULTS

A FARO Edge ScanArm® laser line scanner [5] along with Geomagic® Control X 3D metrology software [6] were used throughout this study to measure the shape of half-cells and compare it to the ideal shape. The nominal accuracy of the laser line scanner is ±0.029 mm.

C75 Large-Grain Half-Cells

The large-grain discs of RRR ~ 165, 3.155 mm thick, were sliced from a Nb ingot produced by CBMM, Brazil. Figure 1 shows a shape comparison for the male and female dies used for deep-drawing C75 half-cells, showing that ~72% of the data points from the female die and ~48% of the data points from the male die are within ±0.1 mm from the ideal shape. About 96% of the data points and ~83% of the data points are within ±0.2 mm from the ideal shape for the female and male die, respectively. The die set, made of Al 7075, had been already used several times to fabricate C75 cavities in the past and was designed for 3.175 mm thick discs.

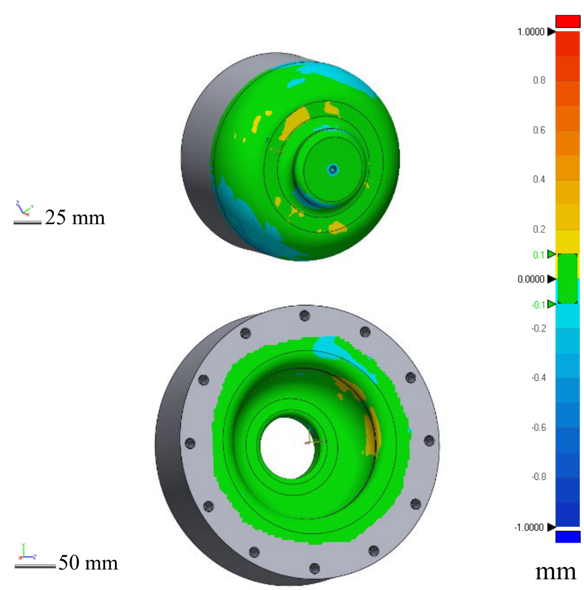

Figure 1: 3D shape comparison of the male (top) and female (bottom) dies used for the deep-drawing of C75 half-cells.

3D CMM data were acquired after the following fabrication steps:

1. First deep-drawing at 100 ton, iris coining at 25 ton, re-stamping at 100 ton

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV004

MECHANICAL PROPERTIES OF DIRECTLY SLICED MEDIUM GRAIN NIOBIUM FOR 1.3 GHZ SRF CAVITY

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Abstract

At KEK, research is being conducted to manufacture cost-effective 1.3 GHz superconducting radio frequency cavities based on the fine grain (FG) and large grain (LG) Niobium (Nb) materials. Medium grain (MG) Nb has been proposed and developed as an alternative to the FG and LG Nb, being expected to have better mechanical stability with a cost-effective and clean manufacturing approach. MG Nb has an average grain size of 200 - 300 µm, which is approximately 100 times smaller than the LG Nb, however, there are occasional grains as large as 1-2 mm. As such, it is expected to have isotropic properties rather than the anisotropic properties of LG Nb. In this paper, we will outline the mechanical properties of the directly sliced high RRR MG Nb material (manufactured by ATI), and a comparative study will be presented with respect to FG and LG Nb. Moreover, the viability of MG Nb for the global high-pressure regulation for 1.3 GHz SRF cavity will be presented.

INTRODUCTION

The International Linear Collider (ILC) is an electron-positron collider accelerator, that requires approximately 7800 1.3 GHz Niobium 9-cell cavities to attain 250 GeV centre-of-mass energy and is extendable up to 1 TeV [1, 2]. The ILC design update for the ILC-250 (GeV) has been already published [2] but the cost of its construction is a major hindrance. Cost reduction studies are being carried out at KEK and other facilities all over the world for the realization of ILC. A part of the cost-reduction studies at KEK is to research on various grades of Niobium, to reduce the manufacturing cost of the SRF cavity. P. Kneisel et al. reviewed the Niobium Ingot material for SRF cavities and has detailed the Niobium Ingot manufacturing for various grades of Niobium [3]. In this paper, we would like to introduce a cost-effective alternative grade of Niobium for the SRF cavity manufacturing.

Various Grades of Nb for 1.3 GHz SRF Cavities

The operational requirement for the ILC's 1.3 GHz 9-cell cavities is E_{acc} > 31.5 MV/m with Q_0 > 1E10, such specification generally requiring Niobium with high purity (RRR >300). However, the mechanical strength of Nb generally deteriorates with higher purity. The Niobium material in SRF community is usually classified in two categories:

1. Residual Resistivity Ratio – Low (< 100), Medium (100 to 300) and High (> 300).
2. Grain Size – Fine Grain (< 50 µm) and Large grain (few millimetres to centimetres).

After the Nb is extracted from mines, it is melted by electron beam melting method under vacuum to remove interstitial impurities such as H, C, O and N to form it in an ingot, which is largely in LG Nb form [1]. The fine grain (FG) Nb is then manufactured by a series of forging, rolling, annealing and etching process reducing the ingot in sheet forms, producing grains with size < 50 µm, hence it has isotropic mechanical properties [1]. Research on SRF cavities manufactured with FG Nb has been carried out extensively but the cost of the material is high due to its manufacturing process. Some of the renowned research on determining the mechanical properties of FG Nb has been conducted by G. R. Myneni et al., Nakai et al. etc [4, 5].

Large Grain (LG) Nb was developed as a clean and low-cost alternative, where the LG Nb Ingot is directly sliced into disks. Its grain size usually varies from a few mms to several cms, due to which it has anisotropic mechanical properties causing its 0.2% Yield Strength (Y.S) and Tensile Strength (T.S) to sometimes fall short of the mechanical property requirement set for 9-Cell 1.3 GHz SRF cavities. W. Singer et al., Zhao et al., Enami et al., Yamanaka et al., has conducted in depth research on determining the mechanical properties of the LG Nb at various temperatures and strain rate ranges [6-9].

ATI MG Nb

There is another type of material that the authors would like to introduce in the second category called as Medium Grain (MG) Niobium [1, 10]. It has an average grain size of 200 - 300 µm with occasional grains as large as 1-2 mm and was manufactured by ATI in 2020 as a potential alternate to both FG and LG Nb, with better formability than LG Nb and potential cost reduction compared to FG Nb. It is formed by forging and annealing of the LG Nb ingot to a billet to achieve smaller grain sizes, as shown in Fig. 1. The forged billet is then directly sliced in disk forms, which lowers the number of manufacturing steps that are involved with FG Nb, such as rolling, etching, annealing etc, elimination of these steps having the potential to reduce material cost. The MG Nb billet manufactured by ATI and delivered to KEK is a high RRR Nb and its specifications are given in Table 1. At KEK, we have been conducting tensile tests to characterize the mechanical properties of this material at room and in liquid helium temperatures.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV005

STATUS OF SNS PROTON POWER UPGRADE SRF CAVITIES PRODUCTION QUALIFICATION*

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Abstract

The Proton Power Upgrade project at Oak Ridge National Lab's Spallation Neutron Source (SNS PPU) currently being constructed will double the proton beam power from 1.4 to 2.8 MW by adding 7 additional cryo-modules, each contains four six-cell high beta (β= 0.81) superconducting radio frequency cavities. The cavities were built by Research Instruments, Germany, with all the cavity processing done at the vendor site, including electropolishing as the final active chemistry step. All 28 cavities needed for 7 cryomodules were delivered to Jefferson Lab, ready to be tested. The cryogenic RF qualifications and helium vessel welding were done at Jefferson Lab. The performance largely exceed the requirements, and greatly exceeded the performance of the original SNS cavity production series. Here, we present the summary of RF test on production cavities to this date.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is the world's first megawatt class pulsed neutron source with the proton power of 1 GeV. The Proton Power Upgrade (PPU) project will double the proton beam power from 1.4 to 2.8 MW by adding 7 additional cryomodules each contains four six cell high beta (HB) β= 0.81 superconducting radio frequency cavities. Some modification were made to both cavities and helium vessels based on the operating experience of earlier SNS cryomodules and one of the prototypes currently installed in the linac [1]. Additionally, some modification were made in the cavity fabrication. The end groups of the cavities were made from high purity niobium whereas the original SNS cavities were fabricated from reactor grade niobium. Cooling blocks were added to the end groups to increase the thermal contact between the end group and the helium bath. Based on the operational experience of machine, the high order mode couplers aren't necessary and those were removed from the PPU cavity design. This removes a complex geometry to chemically process and rinse during the cavity processing reducing the possibility for early field emission and multipacting. Furthermore, some modifications were made to the fundamental power couplers and cryomodule end cans based on the operational experience of the original SNS project [1].

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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All the PPU cavities were built by Research Instruments, Germany, with all the cavity processing done at the vendor site, including electropolishing as the final active chemistry step. An improvement in performance of the cavities was expected due to electropolishing compared to buffered chemical polishing that was applied to the original SNS cavities. To this date, all cavities needed for 7 cryo-modules were delivered at Jefferson Lab, ready for RF test. The cavities go through incoming mechanical and RF inspection followed by the RF test at 2.1 K. Figure 1 summarize the cavity processing flow chart.

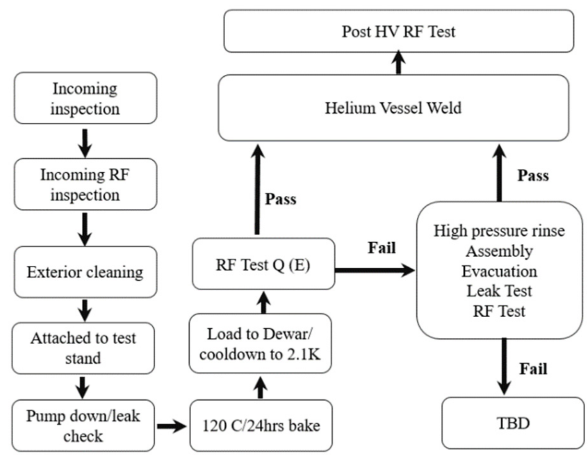

Figure 1: Flow chart of cavity qualification prior to cryo-modules assembly.

RF TEST RESULTS

The design modification to PPU cavities were based on the operational experience of original SNS HB cryo-modules as well as the results of prototype cryomodules installed in the SNS tunnel. A quality assurance plan was put in place to ensure the optimal performance of PPU cavities from production steps at vendor sites to the cavity qualification at Jefferson Lab [2]. The incoming cavities are checked for RF and mechanical issues followed by a wipe down to ensure no particulates are transferred into the clean room. While in the clean room each cavity was attached to a vertical test stand using clean assembly procedures, followed by a leak check. Once on the test stand the cavity is transferred to a bake box, where all cavities were baked at 120°C for 24 hours. The analog scans of the residual gas analyzer before and after baking were recorded. Also, the partial pressure of various gas species were recorded during the low temperature baking. The cavity was cooled down to 2.1 K in a vertical Dewar

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV006

HIGH-Q/HIGH-G R&D AT KEK USING 9-CELL TESLA-SHAPED NIOBIUM CAVITIES

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Abstract

Since April 2019, we have evaluated the performance of three TESLA-shaped niobium superconducting radio-frequency cavities at the vertical test facility of KEK-STF. These cavities were made of fine grain niobium materials with residual resistivity ratio > 300 and were annealed at 900 °C for 3 h. All cavities achieved a Q_0-value > 2 $\times 10^{10}$ and a maximum accelerated gradient of >35 MV/m when the standard process for International Linear Collider was applied. Then, additional surface treatments and experimental techniques for enhancing cavity performance were applied to the three cavities as follows: (i) 2-step baking at 70–75 °C for four hours followed by 120 °C for 48 h (ii) electropolishing process at a lower temperature than the standard condition (iii) cooling procedure to increase the cooling speed and the temperature gradient between cells before the vertical test. We herein report on these additional surface treatments and experimental techniques and the cavity performance after applying them.

HIGH-Q/HIGH-G R&D AT KEK

The International Linear Collider (ILC) project has been proposed as a next-generation collider experiment for elementary particle physics [1]. Therein, electron and positron beams are accelerated to a center of mass energy greater than 250 GeV in linac and head-on collisions. Several 1.3 GHz elliptical shaped 9-cell niobium SRF cavities are used for the main accelerator component. The ILC experiment has the capability to precisely verify the standard model in elementary particle physics and also search for various results indicating theoretical models beyond the standard model. In recent years, the consensus that cost reduction is essential for realizing an ILC project in the future has been formed. The major cost of an ILC is the preparation cost for about over 8000 SRF cavities. Improvements in maximum accelerating gradients decrease the number of cryomodules and shorten the length of the tunnels. Improvements in the RF surface resistance reduce the RF power and refrigerator power otherwise lost during operation. Thus, High-Q/High-G R&D of SRF niobium cavities is thought to be the most effective approach for cutting ILC costs. According to this consensus, KEK have proceeded with high-Q/high-G R&D for ILC-cost reduction, such as nitrogen infusion [2–4]. In this study, we tried to evaluate the effectiveness of methods regarded as promising in High-Q/High-G R&D by performing a vertical test at KEK STF.

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MOTIVATION FOR THIS STUDY

A summary of our study on improvements in the cavity performance of three TESLA-shaped niobium superconducting radio-frequency (SRF) 9-cell cavities performed at KEK-STF from the beginning of 2019 to date is presented in this paper. Theses cavities are 1.3 GHz elliptical shaped SRF cavities made of fine grain niobium material with residual resistivity ratio (RRR) > 300 and manufactured by Mitsubishi Heavy Industries Mechanical Systems Co. The cavities are referred as to MT-3, MT-5 and MT-6. The surface treatments applied to these cavities include electropolish (EP) and heat treatment at 900 °C for 3 h at KEK. As a result, we achieved Q_0-values greater than 2 $\times 10^{10}$ and the maximum accelerating gradient > 35 MV/m for the three SRF cavities using a standard surface treatment processes developed for ILC. In this study, we applied new surface treatments in order to enhance the cavity performance and compared the results with those of cavities to which ILC standard recipes had been applied; the following treatments were first examined at KEK: (i) EP method at a lower temperature than the KEK-standard condition (ii) two-step baking that has been reported to improve the Q_0-value by 15% and the achievable electric field by 20% [5]. In addition, we newly adopted an experimental technique for cooling the cavity faster than usual. This is the first case where a fast-cooling method was applied at KEK. We performed a vertical test measurement at KEK-STF to evaluate the efficacy. We report on the obtained results.

METHOD

We evaluated the cavity performance of three SRF cavities (MT-3, MT-5, and MT-6) to which cold EP, 2-step baking, and original cooling procedures (KEK-fast cooling and additional cooling methods) were applied. The conditions adopted in this study are summarized in Figure 1. 2-step baking is a surface treatment consisting of a pre-baking procedure for four hours at about 75 °C and thereafter, another baking procedure at 120 °C for 48 h, which has been the de-facto standard surface treatment to date. Literature [5] describes an example in which the maximum accelerating gradient and the Q_0-value of a 1.3 GHz TESLA-shaped niobium SRF cavity were increased by 20% and 15% by applying 2-step baking, respectively. In contrast, in this study EP was applied to cavities at a lower temperature condition than the KEK-standard. Usually, at KEK EP as KEK standard is performed at a temperature of 25–30 °C, whereas cold EP at KEK is performed at a temperature of 14-15 °C. Generally, cold EP has the effect of suppressing hydrogen

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV008

CiADS AND HIAF SUPERCONDUCTING CAVITY DEVELOPMENT STATUS AND THE TRANSITION TO PRODUCTION STAGE*

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Abstract

Two accelerator facilities, China initiative Accelerator Driven Sub-critical System (CiADS) and High Intensity heavy-ion Accelerator Facility (HIAF) are co-funded by the China central and local government are being designed and constructed in Huizhou city, Guangdong Province, China. The Institute of Modern Physics (IMP), Chinese Academy of Science responded to construct and operate both accelerator facilities. CiADS's mission is to demonstrate the principle and technical of employing high power protons to transit fission nuclear plant wastes. HIAF is defined as a nuclear structure research facility. Seven types of Superconducting Radio Frequency (SRF) cavities with a total number of 233, will be constructed in the coming three years for the both linacs. Stable production rate and reliable surface processing will be the main challenges. This paper reports the cavity design, prototype status and massive production plan and status.

INTRODUCTION

The HIAF project will be a scientific user facility, which is aim to expand nuclear structure understanding. The facility contains a superconducting driver linac, a accumulation ring, and a booster Ring [1].

HIAF driver linac has the capability to accelerate uranium ion beams to energies up to 17 MeV/u. Two types of SRF cavities are used for the acceleration. Five Quarter Wave Resonators (QWRs), with an optimal beta of 0.007, are assembled in one cryomodule. There are a total of six QWR cryomodules in the linac. Eleven Half Wave Resonators (HWRs) cryomodules are followed by the QWR cryomodules to accelerate the beam. Each HWR cryomodule contains six cavities with an optimal beta of 0.15. The HWR015 cavity is a mature superconducting cavity in IMP, as the IMP has developed twelve cavities of this type for the demo linac of CaFe. The HIAF linac including the cryogenic system layout is shown in Fig. 1.

CiADS project are located in the same area with HIAF facility. It's a demo facility for showing the technology of transit fission nuclear plant wastes by high power proton beam [2]. The construction started in 2021 by the IMP, at Huizhou city.

* Work supported by the Large Research Infrastructures "China initiative Accelerator Driven System"(Grant No. 2017-000052-75-01-000590).
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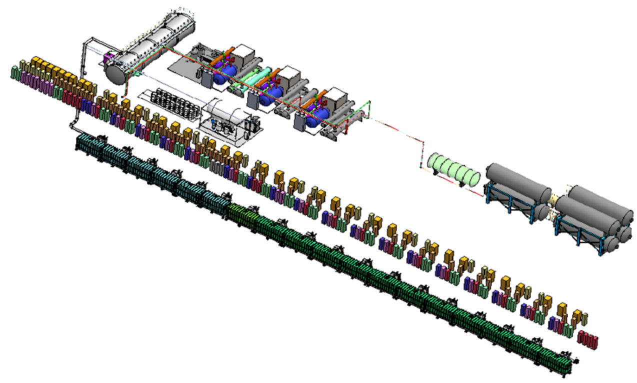

Figure 1: HIAF linac layout, six QWR007 cryomodules and eleven HWR015 cryomodules have capability to accelerate U^{35+} to 17MeV/u.

The CiADS facility contains a driver Linac, a spallation target and a sub-critical reactor. The superconducting linac accelerates the proton beam to higher energies to collide with the spallation target, then produces neutron. The sub-critical reactor employs the produced neutrons to occur nuclear reactions.

CiADS linac utilizes 162.5 MHz with β=0.1 and 0.19 HWR cavities, 325 MHz β=0.42 double Spoke cavity, 650 MHz with β=0.62 and 0.82 elliptical cavity to accelerate the proton beam to 500 MeV. In addition, this linac has the potential to accelerate the proton higher energies up to 1 GeV. The linac's nominal beam current is 5 mA [3]. The layout of CiADS linac is shown as follow Fig. 2.

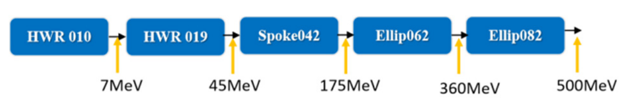

Figure 2: CiADS linac layout, the output energy is 500 MeV.

There are a total of 233 SRF cavities will be fabricated in the coming three years for both projects CiADS and HIAF. The cryomodule configurations and parameters are summarized in Table 1. Cryomodule length is limited to less than 6m, due to the linac tunnel entrance design. The low beta cavity have superconducting solenoid for beam control, which is located inside cryomodule. The elliptical cavity have no solenoid inside cryomodule.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV009

A NEW PROCESS FOR NITROGEN DOPING OF NIOBIUM CAVITIES

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Abstract

The author presents a process for Nitrogen doping of Niobium cavities based on ion beam implantation, with a description of equipment needed and beam parameters.

EXISTING DOPING PROCESSES

Nitrogen doping to improve quality factor of Niobium SRF cavities has been widely investigated over the past years [1-10]. Several doping processes based on thermal diffusion has been defined experimentally and their results were confirmed by different research teams.

Although some of the mechanisms explaining how Nitrogen improves quality factor are understood, like the reduction of mean free path in Niobium [7], many questions remain open.

The multiple experimental attempts with the aim to obtain the best cavity (changing infusion temperature from 90 °C to 800 °C from 20 hours to 300 hours [8-10]) reveal that the current empiric approach is more likely a cooking recipe [2, 10] than a mastered process.

The existing Nitrogen doping processes for Niobium cavities have several drawbacks, either regarding the processing point of view, or regarding the accuracy to control key parameters.

First, we can wonder how efficient it is to bake cavities during tens or hundreds of hours in a Nitrogen gaseous solution, to finally remove by electro-polishing 50 to 100 µm of material of the inner cavity surface to remove unwanted intermetallic compound (Niobium Nitride and Oxide). Besides the necessity for a furnace large enough to welcome multiple-cell cavities, the process is clearly far from being environment-friendly.

Then, the thermal diffusion process can be simulated, but by removing some of the inner cavity surface where Nitrogen diffused, we complicate the prediction of Nitrogen depth and stoichiometry.

As previous studies showed, the quality factor improvement may be linked to the presence of Nitrogen as interstitial sites, hence the necessity to know and master the Nitrogen stoichiometry in Niobium.

A more precise Nitrogen doping process is obviously needed to master and tune each parameter. This will allow to understand fully the role of each parameter (such as Nitrogen doped stoichiometry, penetration depth, created phases, ...) on the Niobium cavity quality factor improvement.

This work proposes such doping process, with the possibility to answer all issues highlighted previously.

PROPOSED PROCESS

Ion beam implantation is a well-known process used in semiconductor industry and metals modification for decades, and this process coupled with a custom-made cavity implanter allows to achieve an accurate Nitrogen doping of Niobium cavities.

This custom-made implanter, shown in Fig. 1, will include an ion source, preferably ECR type to have multicharged Nitrogen ions, a small electrostatic acceleration system, a spectrometer such as Wien filter or dipole magnet, and a support where the cavity to be doped will be installed. This mechanical support allows the rotation of the cavity. It is important to highlight that no large vacuum furnace is needed as flanges of the cavity are used for vacuum sealing.

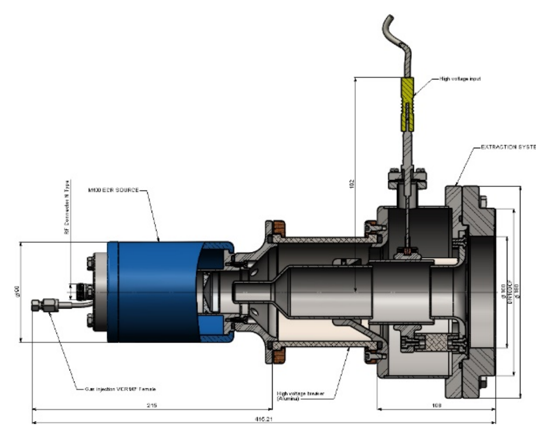

Figure 1: Possible ECR ion source and acceleration system for Nitrogen ion implantation (courtesy of Pantechnik).

Skin depth in superconducting cavities is known to be less than 50 nm [10, 11], therefore a SRIM calculation (see Fig. 2) allows to estimate the maximum energy that Nitrogen ions must have to implant on all this thickness: 25 keV.

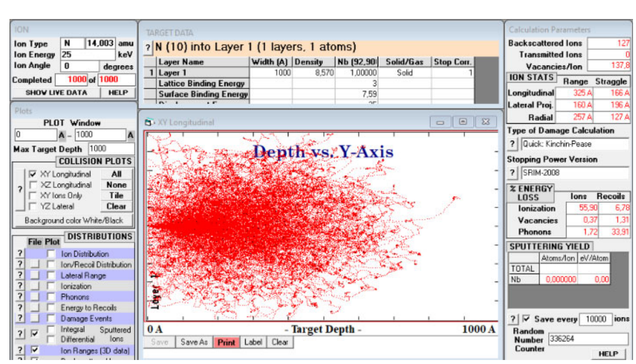

Figure 2: SRIM simulation of Nitrogen implanted into Niobium at 25 keV.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV010

DESIGN OF A HOM-DAMPED 166.6 MHz COMPACT QUARTER-WAVE BETA=1 SUPERCONDUCTING CAVITY FOR HIGH ENERGY PHOTON SOURCE

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Abstract

Superconducting cavities with low RF frequencies and heavy damping of higher order modes (HOM) are desired for the main accelerator of High Energy Photon Source (HEPS), a 6 GeV synchrotron light source promising ultralow emittance currently under construction in Beijing. A compact 166.6 MHz superconducting cavity was proposed adopting a quarter-wave beta=1 geometry. Based on the successful development of a proof-of-principle cavity, a HOM-damped 166.6 MHz compact superconducting cavity was subsequently designed. Ferrite damper was installed on the beam pipe to reduce HOM impedance below stringent threshold of coupled-bunch instabilities. Being compact, RF field heating on the cavity vacuum seal was carefully examined against quenching the NbTi flange. The cavity was later dressed with helium vessel and the tuning mechanism was also realized. Excellent RF and mechanical properties were eventually achieved. Finally, the two-cavity string was designed to ensure smooth transitions among components and proper shielding of synchrotron light. This paper presents a complete design of a fully dressed HOM-damped low-frequency beta=1 superconducting cavity for HEPS.

INTRODUCTION

High Energy Photon Source (HEPS) is 6 GeV diffraction limited synchrotron light source under construction in Beijing [1]. Its main parameters of HEPS storage ring are listed in Table. 1. A modified hybrid seven-bend achromat (7BA) lattice has been designed to push the natural beam emittance down to 34 pm while preserving a high brightness of the X-ray synchrotron light. For the storage ring with a circumference of 1360.4 m, five 166.6-MHz superconducting cavities have been adopted as fundamental rf accompanied by two 499.8-MHz superconducting cavities as third harmonic. This configuration is to accommodate a novel injection scheme for the future while considering the technology readiness of both the rf cavity and the fast kicker [2]. The choice of frequency was extensively elucidated elsewhere from both physics [1] and technology aspects [3]. The fundamental cavity makes use of a superconducting quarter-wave beta=1 structure due to a low operating frequency.

A proof-of-principle (PoP) cavity has been previously developed between 2016 and 2019 and its performances have been extensively studied in both vertical tests and horizontal tests [3–6]. The development of the PoP cavity explored the design of the cavity's main body, verified the feasibility of manufacturing and related processes, transformed and developed a post-processing system, and analyzed the test results. This provided a lot of experience and lessons for us. Based on the successful development of a proof-of-principle cavity, a HOM-damped 166.6 MHz compact superconducting cavity was subsequently designed.

Table 1: Main Parameters of the HEPS Storage Ring

Parameter	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Energy loss per turn (w/IDs)	4.4	MV
Total beam power	900	kW
Fundamental RF frequency	166.6	MHz
Total RF voltage	5.4	MV
3^{rd} harmonic rf frequency	499.8	MHz

The electromagnetic (EM) design, multipacting (MP), mechanical design, fabrication, and layouts of cavity string of the HOM-damped cavity are described in the following sections.

THE CAVITY DESIGN

The specifications of HEPS 166.6 MHz HOM-damped superconducting cavities are listed in Table. 2. The design will focus on the HOM damped design, meanwhile, the successful part of the PoP cavity should be kept as much as possible, and the problems found in the test should be improved.

The EM Design

Since the cavity frequency is only 166.6 MHz, the most compact quarter-wave cavity structure is uesed as the main body of the cavity to reduce the size to the processable. The success of the PoP cavity test indicates that the cavity structure has excellent rf performance. The optimized cavity geometry is shown in Fig. 1, and the parameter differences with the PoP cavity are listed in Table. 3.

The main body of the cavity was basically the same as that of the PoP. Only the diameter of the cavity (Φ_cav) has

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV011

FABRICATION PROCESS OF SINGLE SPOKE RESONATOR TYPE-2 (SSR2) FOR RISP*

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Abstract

Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS), South Korea, is now constructing superconducting linear accelerator 3 (SCL3) for low-energy beam experiment and also making prototypes of superconducting cavity, RF power coupler, tuner, and cryomodule of superconducting (SC) linear accelerator 2 (SCL2) for high-energy beam experiment. Single spoke resonator type-1 (SSR1) and type-2 (SSR2) superconducting cavities are now on the prototyping stage, which is applied a "balloon-variant" concept invented by TRIUMF. This paper explains about SSR2 fabrication process from press-forming to electron beam welding (EBW) with RRR300 niobium sheets.

INTRODUCTION

RISP linac is composed with two sections, one is the low-energy acceleration region which includes the low-beta SC cavity – QWR and HWR - and the other is high-energy acceleration region which includes high-beta SC cavity – SSR1 and SSR2 [1]. SSR1/2 have each 0.3/0.51 beta and both single-spoke type, made by high-purity niobium material and covered by STS316L material liquid helium (LHe) jacket. This paper explains about the fabrication process of SSR2 SC cavity.

SSR2 DESIGN MODEL AND MANUFACTURING DRAWING

The design concept of SSR2 is based on the "balloon-variant" concept which is proceeded by the prototyping contract between RISP and TRIUMF [2]. TRIUMF invented the balloon-variant concept which has higher multipacting suppression performance with the expected acceleration gradient over 9MV/m and target Q value over 5E9 [3]. The SC cavity development engineers of RISP have developed the engineering design of SSR2 since 2017 [4], and RISP contracted with domestic vendor for making six SSR2 SC cavity prototypes. Figure 1 shows the exploded view of SSR2 SC cavity, and Table 1 shows the design specifications of SSR2 SC cavity.

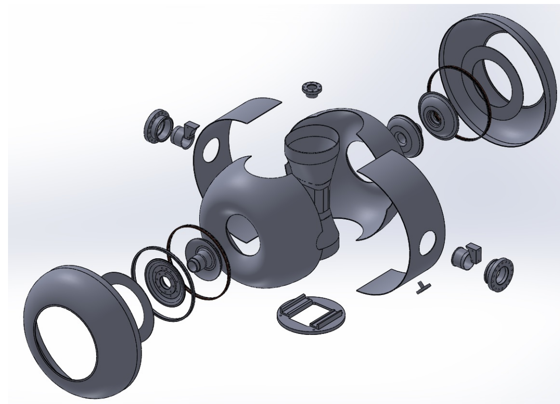

Figure 1: SSR2 dressed cavity exploded view.

Table 1: SSR2 Design Parameters

Parameters	Values	Units
Operating Frequency	325	MHz
Beta	0.51	-
Operating Temperature	2	K
Quality Factor	5E9	-
Epeak	35	MV/m
Vacc	4.1	MV
df/dP	10	Hz/mbar
Tuning Range	180	IkHz
External Q	6E6	-
RF Bandwidth	40	Hz
Beam Aperture	50	Imm
Pressure Envelop 300K	2	bar
Pressure Envelop 5K	5	bar

SSR2 HALF SHELL AND SPOKE PRESS

Engineering design of SSR2 SC cavity was evaluated through the technical advisory committee (TAC) by 2018, and TAC suggested to proceed the prototyping of SSR2 SC cavity [5]. Fabrication process of SSR2 SC cavity applied some modifications of SSR1 SC cavity fabrication process [6], changing half shell production from spinning to press-forming. SSR2 bare cavity is divided into four subcomponents, half shell, beam port, RF port, and spoke. Both the half shell and spoke has been made by press-forming. Comparing with SSR1, SSR2 half shell has almost 70mm deeper shape so the forming process is more difficult than SSR1. After many trial and error, SSR2 half shell press-forming is finished. Figure 2 shows the shape of press die, and Figures 3–5 show the forming shape of SSR2 half shell with different evaluation materials, AL6061T0, oxygen free high conductivity copper (OFHC), and RRR300 niobium. RISP usually uses AL6061T0 for the first forming test, and uses OFHC for the second forming test. After checking first/second forming test results and modifying forming con-

* Work supported by Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS) which is funded by the Ministry of Science and ICT, Republic of Korea
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV012

FABRICATION OF 1.3GHz SRF CAVITIES USING MEDIUM GRAIN NIOBIUM DISCS DIRECTLY SLICED FROM FORGED INGOT*

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Abstract

Medium grain (MG) niobium disc which is directly sliced from forged ingot is newly investigated for the cavity material. An effective cost reduction can be achieved using MG niobium since rolling process which is necessary for typical niobium sheet can be skipped during MG niobium production. An average grain size of MG niobium is 200-300 μm with occasional grains as large as 1-2 mm which is much smaller than large grain (LG) niobium directly sliced from melted niobium ingot. Hence, the formability of MG niobium is expected to be much better than LG niobium. KEK has fabricated two single cell cavities using MG niobium and RF tested one of them. In this study, the characteristics of MG niobium during fabrication and RF test result are discussed here.

INTRODUCTION

In a large accelerator experiment which uses large amount of SRF cavities such as international linear collider (ILC), reducing material cost for cavity is one of the big issues. Typical SRF cavities were made by forged and rolled niobium sheets called fine grain (FG) niobium. KEK has been trying to reduce material cost using several materials such as LG niobium [1]. Using LG niobium discs for cavity can reduce the material cost since it is directly sliced from melted niobium ingot and enables to skip forge and rolling process. The risk of contamination of foreign material on the niobium surface which occur during rolling step can be also reduced using LG niobium. On the other hand, LG niobium has large anisotropy since it has large crystals. This large anisotropy leads shape distortion of formed disc which makes fabrication process more difficult. Moreover, LG discs have different mechanical properties even in the same disc. Hence it is difficult to guarantee certain mechanical strength of cavity made by LG discs against high pressure air or helium.

MG niobium discs are directly sliced from forged niobium ingot called "billet". Using MG niobium discs as cavity material is suggested in [2, 3]. The MG niobium discs have much smaller grain size than LG discs. Hence MG niobium discs are expected to have more uniform mechanical properties and better formability. Furthermore, an effective cost reduction and reduced chance of contamination can be expected because the rolling process is not used.

MATERIAL

In the MG niobium production process, a melted ingot was forged into columnar shape billet. This billet is then sliced into 2.8 mm thickness discs by multi-wire saw for the cavity material. Figure 1 shows one of the sliced MG discs which diameter is 260 mm. Several patterns which consist of small grains can be seen in the disc. Figure 2 shows the zoomed view of MG disc. Measured average

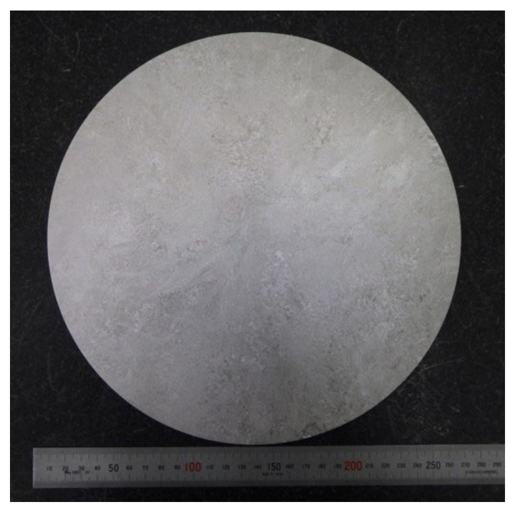

Figure 1: Sliced MG disc.

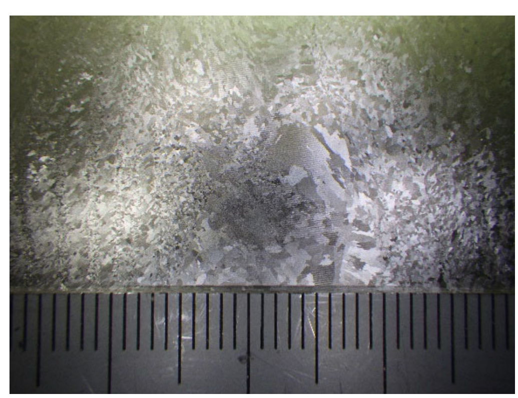

Figure 2: Zoomed view of MG disc.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV013

LCLS-II-HE VERTICAL ACCEPTANCE TESTING PLANS*

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Abstract

LCLS-II-HE has performance requirements similar to but generally more demanding than those of LCLS-II, with an operating gradient of 21 MV/m (up from 16 MV/m in LCLS-II) and tighter restrictions on field emission and multipacting. In this paper, we outline the requirements for the 1.3 GHz cavities and the plans for qualification of these cavities by vertical test. We discuss lessons learned from LCLS-II and highlight the changes implemented in the vertical test procedure for the new project.

INTRODUCTION

LCLS-II-HE is a new electron linac being built at SLAC. The LCLS-II-HE accelerating cavities are fundamentally similar to those in LCLS-II: they are mechanically identical niobium 1.3 GHz TESLA-style 9-cell cavities, they are built using a vendor supply chain also used for LCLS-II, and they will be prepared using nitrogen doping. However, the LCLS-II-HE cryomodules have higher performance requirements than those in LCLS-II, with a target cryomodule gradient of 20.8 MV/m at an average Q_0 of $2.7{\times}10^{10}$ [1]. Through R&D efforts the nitrogen doping protocol has been improved in order to achieve these performance goals [2]. Further, lessons learned from LCLS-II have been implemented to counter multipacting and field emission, both of which affected many cavities in LCLS-II and will pose a problem for LCLS-II-HE if unaddressed, as noted elsewhere [3].

As in LCLS-II, the cavities will be studied under vertical test at the partner laboratories Jefferson Lab (JLab) and Fermilab (FNAL), with each lab testing approximately half of the cavities. LCLS-II-HE has established the cavity technical board (CTB), a body of SRF experts representing SLAC, JLab, and FNAL; the CTB will examine the test results of each cavity and accept or reject the cavities for assembly into cryomodule strings based on these results.

The criteria and procedures described here have been reported previously in internal project documentation [4] and are largely based on those developed for LCLS-II [5].

VERTICAL TEST ACCEPTANCE CRITERIA

Table 1 summarizes the performance criteria that the cavities must meet in vertical test (VT) in order to qualify for string assembly. In cases where cavities do not meet the requirements, the CTB will deliberate to decide on any remedial action required. The exception to this is in cases of only minor and common light reprocessing tasks, such as a routine re-rinse if field emission is detected.

Resonant Frequency

The resonant frequency of the accelerating π mode of the cavities is required to be 1300.25 ± 0.10 MHz in the vertical test. This is slightly higher than the operating frequency in the cryomodules, 1300.00 MHz, to allow for preloading of the compressive tuners in the cryomodule. The lack of tuners in VT also drives the larger acceptance range for f_0. This is the same acceptance condition as in LCLS-II.

Peak Accelerating Gradient

Cavities tested in VT are required to reach a peak accelerating gradient (*i.e.* the ultimate quench gradient after all field emission and multipacting processing is finished) of at least 23 MV/m. This is larger than the cryomodule peak gradient requirement of 20.8 MV/m. The difference allows for a conservative margin of measurement uncertainty of 10% and mitigates risk of gradient degradation due to field emission or other factors introduced between VT and cryomodule installation.

In addition, the CTB will have the option of establishing a variable peak gradient acceptance threshold (see also [3] in these proceedings). Aided by a statistical model [6] of cavity gradient performance, the CTB may raise or lower the 23 MV/m threshold in order to ensure cryomodule requirements are met while also maximizing cavity yield. As an example of a situation where this might be used, if the cavity gradients and quality factors were routinely exceeding performance thresholds, the CTB might decide to lower the gradient threshold and accept cavities with lower peak gradients so long as cryomodules would still meet the average E_{acc} and Q_0 requirements.

Intrinsic Quality Factor

The intrinsic quality factor Q_0 measured in VT is required to exceed 2.5×10^{10} measured at $T = 2$ K and $E_{\mathrm{acc}} = 20.8$ MV/m. This corresponds to a microwave surface resistance $R_s = 11.1$ nΩ. This Q_0 acceptance threshold is slightly lower than the average quality factor of 2.7×10^{10} required in the cryomodule; the difference is due to the RF losses caused by the stainless steel end flanges installed on the cavity beam tubes during vertical test. These flanges, removed before cryomodule assembly, dissipate power with an equivalent Q of 3.6×10^{11}, or 0.75 nΩ of residual resis-

* Work supported by the United States Department of Energy through the LCLS-II-HE project.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV014

THE DEVELOPMENT OF A PROTOTYPE FUNDAMENTAL POWER COUPLER FOR CiADS AND HIAF HALF WAVE RESONATORS

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Abstract

More than 100 Half-wave resonators (HWR) will be adopted for China Initiative Accelerator Driven System (CiADS) [1] and High Intensity heavy-ion Accelerator Facility (HIAF) [2] at IMP. Each HWR cavity equips with one variable coupling, dual-warm-ceramic fundamental power coupler (FPC). The FPC should be able to transmit up to 30 kW in CW mode. This paper will give an overview of the RF design of the 162.5 MHz CW power coupler. The coupler employs two warm ceramics in a 50 Ohm coaxial line to ensure operation reliability. The results of thermal and thermo-mechanical will also be reported. Two prototype couplers have been fabricated and the RF measurements with low RF power were carried out.

INTRODUCTION

The fundamental power coupler is the critically important component of a superconducting (SC) accelerator. The primary function of the coupler is to delivery RF power from RF source, which located at room temperature and at atmospheric pressure, to a superconducting cavity sat at cryogenic temperature and vacuum. In consequence, the fundamental power couplers for these cavities should be carefully designed.

The superconducting ion Linac accelerator (iLinac) of HIAF is designed to accelerate ions with the charge-mass ratio Z/A=1/7 (e. g. $^{238}U^{34+}$) to the energy of 17 MeV/u. The CiADS makes use of superconducting RF cavities to accelerate H^- ions to over 500 MeV in the first phase.

HIAF and CiADS accelerators desire not only high accelerating gradient, but also high operating efficiency and reliability. Based on the operation experience of China ADS, two-ceramic coupler for SC cavities is the higher safety margin against ceramic failure during operation [3]. Consequently, the dual-warm-ceramic coupler will be adopted for the two SC linear accelerators. The beam current of CiADS will be less than 2.5 mA in the first phase, and it will be upgraded to more than 10 mA in the future. The coupler should be variable to accommodate diverse beam loading at different phase to reduce the cost of power source. The main specifications of power coupler for CiADS and HIAF are listed in the Table 1. It was decided that only one coupler design will be used for all the HWR cavities in face of their diverse power needs. The prototype coupler should be able to test up to 30 kW CW RF power at 162.5 MHz in travelling wave, but it should also be RF conditioned in total reflection mode.

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Table 1: Margin Specifications

	HIAF				CiADS		
	QWR007	HWR015	HWR010	HWR019	DSR042	Ellip062	Ellip082
Frequency (MHz)	81.25	162.5	162.5	162.5	325	650	650
Quality	30+5	66+6	9	24+6	40+4	40+4	24
Qe(10^6)	0.18~0.61	0.36~0.92	0.36~1.02	0.54~1.18	1.08~5.17	2.17~6.64	2.95~5.61
stroke(mm)	-	6	6	6	6	6	10
Operation power (kW)	3	4	7	24	42	88	92
Power at Test Stand (kW)	6	6	10	30	60	100	110

THE PROTOTYPE POWER COUPLER DESIGN

The electromagnetic design and thermal-mechanical simulation of the 162.5MHz prototype coupler will be presented in this section.

EM Design

A general overview of the coupler set is shown in Fig. 1. The coupler has a coaxial geometry, which is connected between the HWR and a "T" transition box. It constituted of a dual-warm-ceramic part, a bellow for adjusting coupling coefficient and an antenna. The RF transmission of the coupler was optimized by CST Studio Suite with its intrinsic optimizer [4].

The coaxial windows are planar annular disk-type made of AL300 alumina ceramic. Bigger out conductor and smaller inner conductor are used to match the two ceramics in the coaxial line.

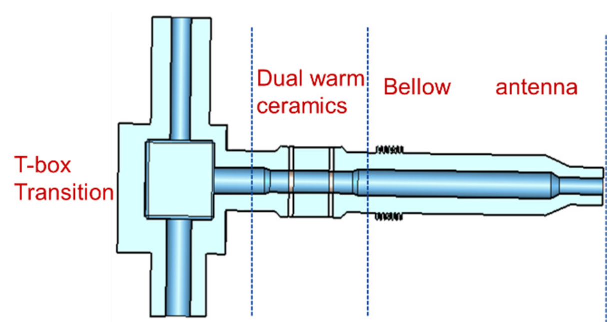

Figure 1: RF model of the coupler.

After a series of optimization, a good S parameter result has been found. As shown in Fig. 2, the coupler presents a minimum of reflexion parameter of -49 dB at a frequency of 162.5 MHz. The simulation results show that the coupler has good transmission properties for broad transition at operation frequency, thereby allowing standard fabrication tolerances.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV015

DEVELOPMENT OF QWRS FOR THE FUTURE UPGRADE OF JAEA TANDEM SUPERCONDUCTING BOOSTER

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Abstract

The Japan Atomic Energy Agency (JAEA) tandem booster is one of the pioneering superconducting heavy ion linac in the world. It consists of 40 QWRs with an operation frequency of 130 MHz and $\beta_{opt} = 0.1$, and has potential to accelerate various ions up to Au to10 MeV/u. The user operation was started in 1994, however, it has been suspended since the Great East Japan Earthquake in 2011. Recently, in addition to the efforts to restart the tandem booster, activities to develop new lower-beta cavities to improve the acceleration efficiency of heavier ions such as Uranium has been launched. In this work, the current status of the design study of the QWRS for the JAEA tandem facility is presented.

INTRODUCTION

The JAEA tandem accelerator is a 20-MV tandem Van de Graaff accelerator which provides heavy ion beams for various kinds of studies such as low energy nuclear physics experiments and irradiation to reactor materials [1]. To obtain enough energy for the nuclear reaction of heavy ions with mass numbers of more than 70, the JAEA tandem facility is also equipped with a superconducting booster linac [2, 3]. Figure 1 shows the schematic layout of the JAEA tandem accelerator and the superconducting booster.

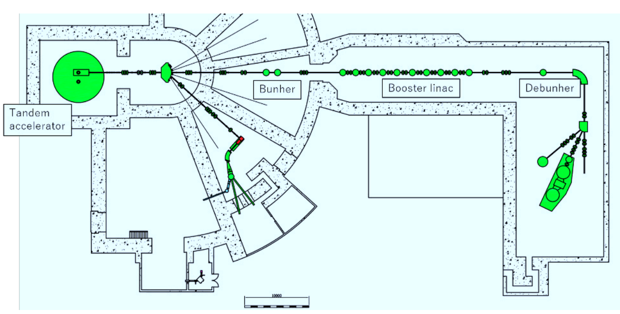

Figure 1: Schematic layout of the JAEA tandem accelerator and the superconducting booster.

With this booster, ions up to Au can be accelerated to 10 MeV/u. The tandem booster consists of 40 129.8 MHz quarter-wave resonators (QWRs) with an optimum β of 0.1. The total acceleration voltage is 30 MV. Since this QWR was developed at the very early stage of the low-β superconducting resonator progress, it has unique structure. The outer conductor of this QWR is made of explosively bonded niobium(Nb)-copper bi-metal sheets, which is indirectly chilled by the liquid helium filled at the top of the cavity. The drift tube made of pure Nb is suspended from the top plate bolted to the outer conductor via a flange. They are operated with 4.5 K, and the typical acceleration field E_{acc} is 4~5 MV/m, with input power of 4 W. Table 1 is main parameters of this QWR.

Table1: Main Parameters of the JAEA Tandem Booster QWR.

Resonant frequency f_0	129.8 MHz
Duty	100%
Optimum beta β_{opt}	0.1
Inner diameter on beam axis	150 mm
Aperture	30 mm
Gap length	40 mm
$G = Q_0 \cdot R_s$	26 Ω
P_0	4 W
E_{acc}	4~5 MV/m
E_{pk}/E_{acc}	4.6
B_{pk}/E_{acc}	7.5 (mT/(MV/m))

To improve the acceleration efficiency of heavier ions such as Uranium, development of lower β cavity had been proceeded [4], but unfortunately, the operation of the superconducting booster has been suspended since the Great East Japan Earthquake in 2011. The upgrade project was also postponed. Recently, we launched activities towards the restart of the tandem booster operation. The project is including the low energy extension of the booster, moreover, the future replacement of the tandem Van de Graaff accelerator with a superconducting linac is in the scope.

Using the same frequency as the existing booster is a natural choice for the low β extension of the booster. In the previous development, replacement of only the drift tube part of the existing cavity with a low-β one was assumed. To this end, a twin drift tube (twin-DT) QWR had been developed [4] to obtain higher energy gain per cavity. The current R&D program is based on this development. However, more recent superconducting cavity technology using sheet-forming of pure Nb is assumed. Therefore, a ordinary single-DT resonator is also considered in addition to the twin-DT QWR. Assumed β range for these QWRs is from 0.048 (1.1 MeV/u) to 0.075 (2.7 MeV/c).

For the replacement of the tandem accelerator, acceleration of A/q=7 particles such as $^{238}U^{34+}$ is assumed. In this case, 130 MHz is too high because the focusing force

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV016

HOM COUPLERS AND RF ANTENNAS FOR HL-LHC CRAB CAVITIES: DEVELOPMENTS FOR MANUFACTURING

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Abstract

Superconducting RF crab cavities are being manufactured as part of the High-Luminosity LHC project at CERN. Amongst its related ancillaries, radiofrequency HOM (High Order Modes) couplers and field antennas are essential for reaching nominal performance during operation with high energy beams, as they monitor and control the electromagnetic fields in the cavities. Several concepts of such equipment have been engineered and manufactured, for both design validation and RF performance assessment.

The following paper highlights manufacturing process definition, its challenges and the assembly strategies focusing on the ongoing RFD prototypes for the SPS beam tests. Specific tooling development and test campaigns are also described.

INTRODUCTION

In the scope of the HL-LHC project [1], compact crab cavities will be installed in the LHC during the Long Shutdown 3. The purpose of such equipment is to increase the integrated luminosity of the LHC machine, through a reduction of the beam crossing angles at the interaction points [2].

Two cavity types have been developed and prototyped [3] at CERN main workshop for SPS beam tests, the Double Quarter Wave (DQW) cavities for ATLAS and the Radiofrequency Dipole (RFD) cavities for CMS. Each version comes with bespoke RF devices: the so-called High Order Modes (HOM) couplers and field antennas, designed to sustain the required high-power electromagnetic fields in the cavities. Whereas the HOM couplers (or suppressors) are essential to damp the detrimental resonance modes generated by the passage of the LHC beams, the field antenna is an acquisition device which allows precise control and feedback on the RF field quality during operation.

Specific variants of such equipment have been engineered [4] for the DQW and RFD cavities, as shown in Fig. 1. Each system features 3D shapes with demanding manufacturing and assembly tolerances. SRF requirements impose tight precision on the final assemblies, in the order of a few tenths of millimetres (up to ±0.2 mm). Fabrication is also rendered more complex by the intricate shape of the couplers, which calls for an elaborate assembly sequence.

Figure 1: 3D views of the DQW (top) and RFD (bottom) dressed crab cavities with RF couplers and antennas.

Such a manufacturing endeavour requires a well-defined strategy for definition of sub-assemblies' cut-out, implementation of advanced fabrication and joining techniques, down to an extended development campaign and quality assurance. All these aspects are presented in this paper.

EXAMPLE OF MANUFACTURING STRATEGY AND CUT-OUT

The complexity of the HOM couplers' shape imposes to find a good compromise between attainable geometrical tolerances, ease of manufacturing and material cost. To answer this problematic, the following strategy, shown in Fig. 2, was employed in the case of the RFD H-HOM coupler:

- Step 1: RRR300 niobium tubes are brazed [5] to 1.4429 stainless steel (316LN) flanges, while maintaining both niobium and stainless-steel components in a rough shape. After brazing, these subassemblies are machined to their final shape (with anticipation of welding shrinkage).

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFAV002

COMMISSIONING OF THE UKRI STFC DARESBURY VERTICAL TEST FACILITY FOR JACKETED SRF CAVITIES

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Abstract

A novel vertical test facility has been developed at the STFC Daresbury Laboratory. The VTF is designed to test 3 jacketed SRF cavities in a horizontal configuration in a single cool-down run at 2 K. Cavities were tested at low power levels for HOMs and passband modes, and Q vs E field measurements at high power levels. The specification requires an unloaded Q of 5E9 at a field gradient of 19.9 MV/m. The cavities are cooled with superfluid helium filled into their individual helium jackets. This reduces the liquid helium consumption by more than 70% in comparison with the conventional facilities operated elsewhere. The facility will be used to conduct a 2-year program to qualify 84 high-beta SRF cavities for the European Spallation Source as part of the UK's in-kind contribution. This paper reports on the commissioning program, along with a detailed discussion of the RF and cryogenic operations and performance of the facility.

INTRODUCTION

A new Superconducting Radio Frequency Lab (SuRF Lab) which includes a Vertical Test Facility (VTF) and Reprocessing Facility (Cleanroom and High Pressure Rinse) is currently in the commissioning phase at the UKRI STFC Daresbury Laboratory. An internal operational readiness review has been completed for the requirements of the ESS High Beta Cavity Project.

The VTF supports 2 K characterisation of three jacketed SRF cavities in a single cool-down run. Measurements of HOMs and passband modes are made at low power. Q vs E field measurements are made at high power levels (up to 200 W). A novel cryogenic architecture is used to significantly reduce the liquid helium (LHe) consumption compared with conventional facilities.

VTF CRYOSTAT DESIGN

The conventional method for VTF SRF cavity testing is to fully immerse the cavities in a large LHe bath, and then cool to 2 K using a cold compressor/vacuum pump to reduce the vapour pressure over the bath. RF testing is then carried out with the cavities at 2 K. This approach has been used successfully for many programs, including XFEL cavity testing at DESY [1]. Whilst well-proven, this technique requires both a large cryoplant and, for this activity, would require ~8500 L of LHe per test cycle.

Given the diminishing global supply of He, and associated rise in cost, an alternative cryostat architecture has been developed for vertical testing of jacketed SRF cavities which requires significantly less LHe and a much smaller cryoplant throughput [2–4]. The cryostat is based on a cavity support insert (CSI) where three cavities are mounted horizontally inside LHe jackets below a header tank, each fed by a common fill/pumping line; this may be seen in Figs. 1 and 4 which show a photograph and a CAD model of an assembled insert respectively. By using this design approach, far less LHe is required per testing run (~1500 L, all of which is recovered) compared with the conventional designs.

Figure 1: Photograph of CSI on stand with three jacketed cavities installed (top and middle cavities dressed in MLI jackets).

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFAV004

FIRST VERTICAL TEST OF A PROTOTYPE CRAB CAVITY FOR HL-LHC AT FREIA LABORATORY IN UPPSALA UNIVERSITY

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Abstract

We developed and commissioned a new vertical test stand at FREIA Laboratory for the High-Lumi LHC (HL-LHC) project. The first cold test was performed with a prototype crab cavity and the obtained result met the project specification. This opened a new opportunity at Uppsala University for superconducting radiofrequency (SRF) science and engineering. In this paper, the result of the first cold test and plans for future experiments are presented.

INTRODUCTION

The FREIA laboratory is a leading facility for accelerator development in Sweden. It actively supports the development of the European Spallation Source, CERN, and MAX IV, among others [1]. In particular, the HL-LHC project is presently one of the core projects and we contribute to testing corrector dipole magnets and crab cavities. The main objective of this paper is to qualify the newly commissioned vertical test-stand GERSEMI for the Double-Quarter-Wave (DQW) crab cavity testing [2], using a prototype cavity as shown in Fig. 1.

Figure 1: photograph of a prototype DQW cavity.

EXPERIMENTAL

GERSEMI is a general-purpose cryostat for testing both superconducting magnets and cavities and was cooled down to 2 K, for the first time, at the end of 2019 [3, 4]. Figure 2 shows a schematic of GERSEMI and a photograph of a cavity insert. The cryostat has large active diameter of 1106 mm and 2860 mm long filled with liquid helium volume of 2650 L. Thanks to these large dimensions, GERSEMI can accommodate different types of cavities and potentially multiple cavities at the same time. An insert dedicated to superconducting cavities was developed by using non-magnetic materials. Depending on the purpose and size of each cavity, the volume of the cryostat can be flexibly decreased with cryogenic foams to reduce the helium amount.

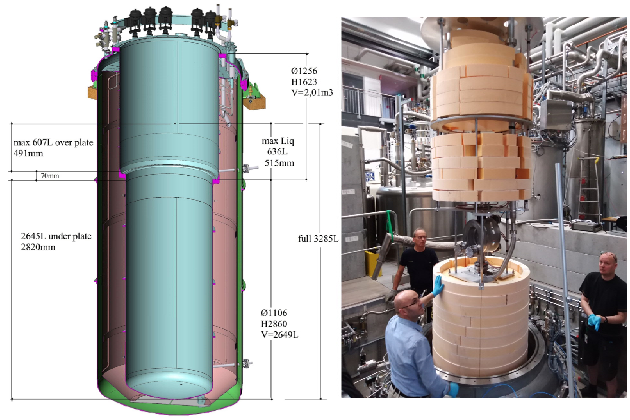

Figure 2: GERSEMI cryostat and a cavity insert.

The cryostat is equipped with active compensation coils without magnetic shields. We showed [5] that a very uniform (1.2%) and weak (<1 µT) field around SRF cavities can be achieved in a systematic way. A prototype 3-axis fluxgate sensor [6] was installed on a cavity and the magnetic field was monitored during cooling down. Figure 3 shows temperature history during cooling down monitored by four CERNOX sensors on the cavity, and 3-dimensional magnetic field components. The temperature gradient of the cavity was controlled to be below 60 K when the average temperature was above 120 K. All the components of the magnetic field were kept below 0.6 µT to avoid flux pinning at the superconducting transition.

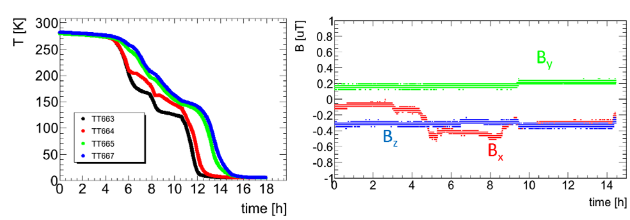

Figure 3: cooling down curve and magnetic fields.

After the cryostat was filled with liquid helium and well thermalized at 4.2 K, it was pumped down to 2 K and then 1.8 K. Figure 4 shows the stability of pressure at 2K. This very stable (standard deviation 4.7 µbar) allowed a conventional analogue phase-lock-loop (PLL) circuit to lock the cavity at resonant frequency as shown in Figure 5. This PLL circuit was originally developed for the LHC project at CERN and was used for this project with a 400 MHz solid state amplifier. In the future, digital self-excited-loop (SEL), which is currently in use for ESS cryomodule testing, will be deployed for cavity experiments at GERSEMI.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFAV005

OPERATION EXPERIENCE OF THE SUPERCONDUCTING LINAC AT RIKEN RIBF

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Abstract

Construction and hardware commissioning of the RIKEN superconducting linac (SRILAC) [1] based on 10 SC-QWRs (Superconducting Quarter-Wave-length Resonators) (73 MHz, C.W.) was completed in the end of 2019 and beam acceleration test was succeedingly conducted in January 2020 for the first time. After beam commissioning in the end of FY2019 [2], user service was started. So far argon and vanadium ions were accelerated to the energy from 4.2 to 6.3 MeV/u. In the user-service phase one of the most important issues for superconducting cavity (SC) is how to preserve their original performance, such as acceleration gradient, Q_0, field emission (FE), radiation onset voltage and so on. Recently the average beam power reached 1 kW. It is becoming more important to keep the beam losses at SCs as small as possible. In this paper operation history, control of the beam losses, and radiation monitoring are reported.

RILAC UPGRADE AT RIKEN

The RIKEN Heavy-Ion Linac (RILAC) [3] upgrade was performed to allow it to further investigate super-heavy elements. The new element Nh was synthesized by bombarding a ^{209}Bi target with an intense ^{70}Zn^{14+} beam with an energy of 5 MeV/u accelerated by the RILAC, which was upgraded by adding a booster linac comprising six DTLs. The SRILAC was introduced by replacing the latter four DTLs of the booster linac as shown in Fig. 1 so that ions (A/q=6) are accelerated to 6.5 MeV/u [4]. This upgrade corresponds to an increase of the total acceleration voltage by 14 MV.

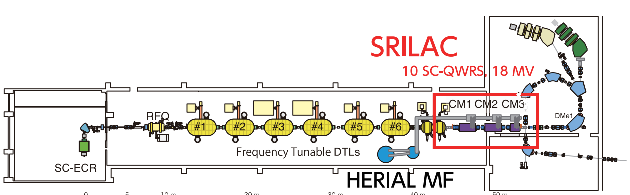

Figure 1: Layout of RILAC and SRILAC.

Construction of the SRILAC started in the middle of FY2016 and installation to the accelerator cave was finished in the end of FY2018. First cool-down with He refrigerator was successfully performed in October 2019 and radio-frequency (RF) commissioning was succeedingly made [5]. On January 28, 2020, ^{40}Ar^{13+} beam was successfully accelerated with to 6.2 MeV/u for the first time. Due to the vacuum leak from the coupler ceramic window of SC05, beam commissioning was accomplished using 9 SCs. After acceleration tests, additional NEG pumps and high pumping-speed Ion-pumps were installed to improve the vacuum pressure of MEBT to several times 10^{-8} Pa during a long-term shutdown due to COVID-19. From June 2020, after the shutdown, user beam-service restarted. By choosing the number of SCs and their gap voltages, the beams with energy from 4.2 MeV/u to 6.3 MeV/u were accelerated. Beam power was being slightly increased reached 1 kW keeping the MEBT vacuum level below 1×10^{-7} Pa and in this year.

SUPERCONDUCTING LINAC BOOSTER

The SRILAC consists of three cryomodules (CMs) and a beam transport line connecting CMs. Design parameters are summarized in Table 1.

Table 1: Design Parameters of SRILAC

Parameters	Value
Frequency (MHz)	73.0 (c.w.)
E_{inj} (MeV/u)	3.6
E_{out} (MeV/u)	6.5
Maximum gap voltage (MV)	2.4
Synchronous phase (°)	-25
Number of cavities	10
Cavity type	QWR(TEM)
β_{opt}	0.078
TTF	0.9
R_{sh}/Q_0 (Ω)	579
G	22.4
E_{acc} (MV/m)	6.8
E_{peak}/E_{acc}	6.2
B_{peak}/E_{acc} (mT/(MV/m))	9.6
Operating temperature (K)	4.5
Target Q_0	1×10^9
Q_{ext}	$1 - 4.5 \times 10^6$
Amplifier output (kW)	7.5
Beam current (µA)	~100

Three Cryomodules host 10 SC-QWRs. The SC-QWRs are made from pure Nb sheets with a residual resistivity ratio of 250, and their inner surfaces are processed by buffered chemical polishing (BCP1) with 100 µm, annealing at 750°C for 3 h, light etching (20 µm, BCP2), and 120°C baking for 48 h. The operating temperature is 4.5 K, not 2 K, and all the cavities achieved fairly large Q_0 that exceeded the target value of 1×10^9 at an E_{acc} of 6.8 MV/m in the cavity

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV001

INVESTIGATION OF AN ALTERNATIVE PATH FOR SRF CAVITY FABRICATION AND SURFACE PROCESSING

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Abstract

The preparation of SRF cavities includes a lengthy, costly, and safety issued electrochemical polishing (EP or BCP) step to remove the damaged layer coming from the cavity fabrication. We have shown that most of the damage layer is originated from the rolling process during the preparation of the sheet material, while subsequent deep drawing tends to leave only µm thick damage layer. We propose a 2-steps mechanical process that allows us to easily get rid of the thick damage layer on the sheets before cavity forming. The process has been established on samples and extended to large disks ready for 1.3 GHz half-cell forming. The polished sheets will be then sent to KEK for half-cell forming and subsequent surface and material analysis before proceeding to half-cell welding. Former studies on the sample demonstrated that damages induced by forming can successfully be removed by recrystallization and less than 10 µm final chemistry.

INTRODUCTION

During the production of the superconducting radiofrequency (SRF) cavities made of Niobium (Nb), the inner surface is significantly damaged. To recover the surface properties and obtain optimal performances in term of quality factor and accelerating field, a layer of 150-200 µm has to be removed [1]. Regarding the order of magnitude and comparing it with the value of the standard surface processing, we can conclude that the damaged layer is caused mainly by the preparation of 3.5 mm sheets from 1 cm diameter rolls (rolling process), see Fig. 1. The following cavity forming steps (deep-drawing, EB welding) leave significantly thinner damaged layer [2].

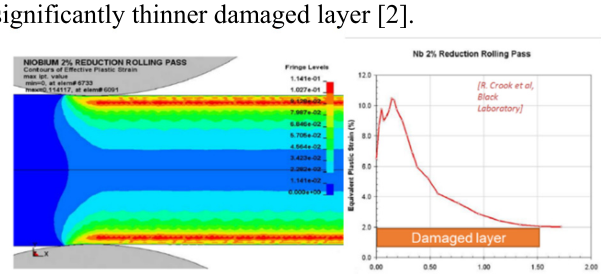

Figure 1: Finite element simulation of rolling process [3].

* Part of this work supported by the European Nuclear Science and Applications Research-2 (ENSAR-2) under grant agreement N°654002.
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Nowadays, buffered chemical polishing (BCP) and electropolishing (EP) are the main techniques used for surface processing. However, the increased demand for the number of SRF units for the future large-scale accelerators (FCC, ILC), see Fig. 2, requires higher performances, higher reliabilities, and higher repeatability to initiate the construction. For such ambitious goals, traditional surface processing needs new strategies, due to issues with safety regulations, environmental impacts, and limitations in the quality of the final surface state (level of roughness, remaining defects),

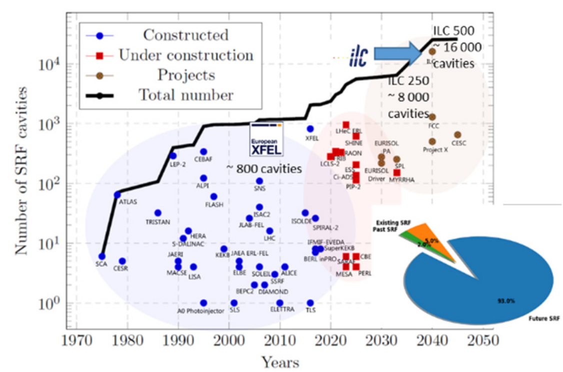

Figure 2: Number of SRF cavities versus year [4].

Metallographic polishing (MP) is a possible candidate as an alternative surface processing not only for bulk Niobium, but also to prepare the substrate for thin film deposition. Thin films seem to be a future path of SRF due to their potential to show higher performances, whereas the bulk Nb approaches his theoretical limit. This new surface preparation technique has the potentials for cost savings, smooth surface preparation, and improved reliability and repeatability of the process, compared to the standard treatment of the bulk Niobium. However, instead of polishing complex geometries, metallographic polishing can only be applied on flat surfaces. Hence, based on such limitations we have to perform the polishing on Niobium sheets before forming. An alternative path of SRF cavity fabrication is thus required and is composed of several steps as depicted in Fig. 3.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV002

HIGH DENSITY MAPPING SYSTEMS FOR SRF CAVITIES

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Abstract

High density mapping systems for superconducting RF cavities are prepared. They include sX-map, XT-map, and B-map, which can be used to detect the distribution of X-ray, temperature, and magnetic flux. sX-map is a strip shape detector for X-ray that can be set under stiffener rings of superconducting cavities. Each strip of the sX-map system has 32 X-ray sensors approximately 10 mm apart, which can be inserted under the stiffener rings to show uniform higher sensitivities. This is suitable to get X-ray distribution around iris areas. The XT-map system enables temperature distribution mapping of cavity cells with high spatial resolution at approximately 10 mm intervals in both azimuth and latitude. It also gives X-ray distribution on cells, as well. Magnetic field distributions can be obtained by the B-map system using AMR sensors. Since all these systems are based on the technology of multiplexing at the cryogenic side, fewer wires can carry the huge number of signals. Among the systems, sX-map system is reported.

INTRODUCTION

Inspection equipment for SRF (Superconducting Radio Frequency) cavities during vertical tests is important to evaluate the characteristics of cavities. Active researches are being conducted to achieve high-Q or high-gradient cavities [1], measurement devices with high sensitivity and high positional resolution are needed for us to observe various physical quantities such as local temperature increase, X-ray emission, and trapped magnetic flux [2]. Utilizing high density mapping systems with high sensitivity sensors, source spot of quench or field emission X-ray can be identified with high accuracy. In this article, an overview of the mapping systems and recent results of test experiments on sX-map, an X-ray mapping system for stiffener region, are reported.

HIGH DENSITY MAPPING SYSTEM

Sensors of temperature, X-ray, and trapped magnetic flux are widely used to locate the positions where quench or field emitted X-rays are generated. While a large number of sensors are required to raise the positional resolution of the measurement, the number of lines to read out the signals tends to increase with the number of sensors. As the number of the wires increases, the experimental setup becomes more complicated, and the heat intrusion into the cryostat through the wires increases, which disturb the efficient operation of cavity tests and raise the cost. In order to simplify the connection scheme and to reduce the wires for readout, mapping systems with multiplexers are developed, which can scan a large number of the sensor signals inside the cryogenic dewar. All the active (semiconductor) devices to multiplex, amplify, and convert the signals are CMOS circuits that can work even at the cryogenic temperature. The devices include digital logics and analog multiplexers.

We picked up RuO (Ruthenium Oxide) chip resistors as the cryogenic temperature sensors, infrared photo-diodes as the X-ray sensors, and AMR (Anisotropic Magneto Resistance) flux sensors. Starting from the high-density temperature mapping system [3], 3 types of mapping systems are under development; X-ray mapping system in stiffener region (sX-map), X-ray and Temperature mapping system (XT-map), and magnetic flux mapping system (B-map) [4]. Figure 1 shows prototype systems of sX-map and XT-map. In vertical tests, the equipment shown in Fig. 1 is installed in a cryogenic dewar and communicates with a PC outside of the dewar via small numbers of ribbon cables (Fig. 2).

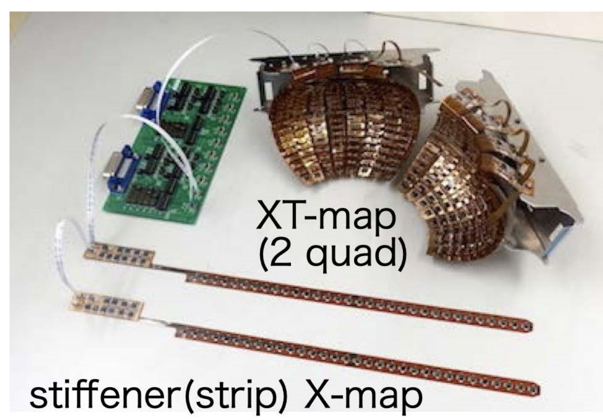

Figure 1: Photo of sX-map and XT-map.

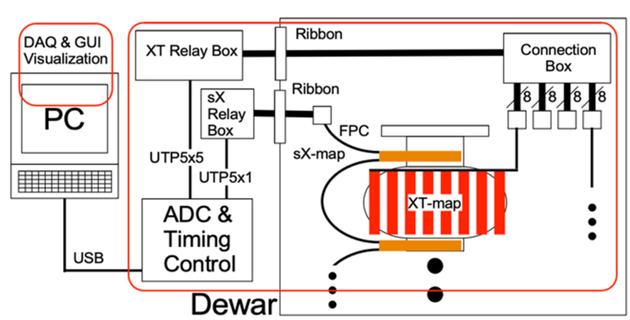

Figure 2: Typical experimental setup of mapping system.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV003

MEASURING FLUX TRAPPING USING FLAT SAMPLES

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Abstract

With modern superconducting cavities flux trapping is a limiting factor for the achievable quality factor. Flux trapping is influenced by various parameters such as geometry, material, and cooldown dynamics. At SRF2019 we presented data showing the magnetic field surrounding a cavity. We now present supplemental simulations for this data focusing on geometric effects. As these simulations are inconclusive, we have designed a new setup to measure trapped flux in superconducting samples which is presented as well. The advantages compared to a cavity test are the simpler sample geometry, and quicker sample production, as well as shorter measurement times. With this setup we hope to identify fundamental mechanisms of flux trapping, including geometry effects, different materials, and different treatments. First results are presented along with the setup itself.

INTRODUCTION

In superconducting cavities operating in the radio frequency (RF) range, losses occur. As the cavities are operated at a temperature around 2 K, 1 W of dissipated power in the cavities requires close to 1 kW of wall plug power to keep the temperature stable. Therefore, it is critical to reduce losses in the cavities, especially when accelerators are operated in continuous wave (CW) mode. The losses stem from the non-vanishing surface resistance of superconductors in RF fields. Part of this surface resistance is caused by trapped magnetic flux and since it is impossible to completely shield the earth's or other stray magnetic fields it is necessary to understand the fundamental flux trapping mechanism to increase cavity performance further.

In this paper we will first compare measured magnetic field surrounding a superconducting cavity with two simulations to investigate whether all components of magnetic flux are trapped or only the component perpendicular to the cavity's surface. In the simulations only a simple static model was assumed and the analysis showed that with the data set at hand no definite statement can be made.

To better understand the flux trapping mechanism we designed a new experiment that is presented in this paper. The new setup is intended to increase the accuracy of the magnetic field data as well as decrease the geometric complexity of the superconductor. The sample is a (100 x 60 x 3) mm Niobium sheet. The magnetic field ist measured by 45 anisotropic magnetoresistive (AMR) sensors mounted on a custom printed circuit board (PCB) just above the sample. Additionally the temperature can be controlled with heaters at either end of the sample. We hope that the small distance of the sensors to the sample, the high density of sensors and the simple geometry helps to overcome the problems we faced with the measurements conducted with the cavity. In addition to the setup we present data from commissioning.

FLUX TRAPPING MEASUREMENTS WITH CAVITIES

In this section we analyse data showing the magnetic field surrounding a superconducting cavity already presented SRF 2019 [1]. However, since then we performed more detailed simulations with which we want to investigate how the magnetic field gets trapped inside the cavity: In particular the question whether all components of magnetic flux are trapped within the superconductor or only components perpendicular to the surface are trapped. The analysis reveals that neither of the two static models that were assumed in the simulations can describe the measured data with high accuracy. We, therefore, conclude that with the data set at hand it is not possible to make a definite statement of how the flux is trapped.

Experimental Setup

Here we only give a brief overview of the setup. A more detailed description can be found in [2]. A schematic view is shown in Fig. 1 Measurements are conducted on a 1.3 GHz

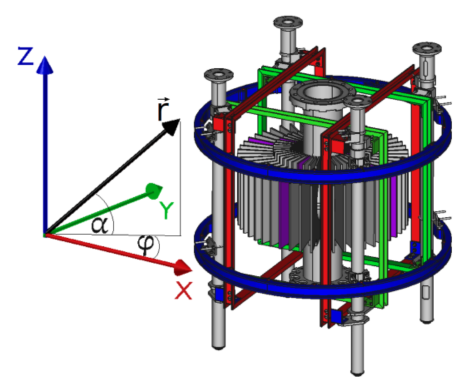

Figure 1: CAD rendering of the measurement setup consisting of a cavity in the middle, circuit boards measuring the temperature and B-field around it, and three Helmholtz coils. The blue, red, and green coils generate a field in z, x, and y directions respectively. Boards for measuring the magnetic field are highlighted purple.

TESLA single cell cavity. 48 PCBs are spaced evenly around the cavity, four of which are used to measure magnetic field. The remaining 44 are used to measure the surface temperature of the cavity. The four magnetic field mapping cards are highlighted purple, and are spaced 90° apart. On each board 15 single-axis AMR sensors are installed, forming five

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV008

SRF LEVITATION AND TRAPPING OF NANOPARTICLES*

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Abstract

A proposal has been conceived to levitate and trap mesoscopic particles using radio frequency (RF) fields in a superconducting RF (SRF) cavity. Exploiting the intrinsic characteristics of an SRF cavity, this proposal aims at overcoming a major limit faced by state-of-the-art laser trapping techniques. The goal of the proposal is to establish a foundation to enable the observation of quantum phenomena of an isolated mechanical oscillator interacting with microwave fields. An experiment supported by LDRD funding at JLab has started to address R&D issues relevant to these new research directions using existing SRF facilities at JLab. The success of this experiment would establish its ground-breaking relevance to quantum information science and technology, which may lead to applications in precision force measurement sensors, quantum memories, and alternative quantum computing implementations with promises for superior coherence characteristics and scalability well beyond the start-of-the-art. In this contribution, we will introduce the proposal and basic considerations of the experiment.

INTRODUCTION

While levitation and trapping have always attracted attention and found applications such as for containerless processing and spectroscopy of microparticles [1], recent developments in the field of optomechanics have brought about levitation of nanoparticles enabling observation of quantum phenomena in the context of quantum science and technology.

Quantum properties occur when a macroscopic matter particle, being trapped in an optical field and behaving like a mechanical oscillator, is further cooled, either by the same trapping optical field or by an external laser, to its fundamental quantum ground state. Coherent control of a macroscopic quantum system has potentially game-changing implications for fundamental physics as well as technology. It could allow the exploration of the classical-to-quantum boundary, the development of precision force measurement sensors, and could provide a fundamental building block for quantum information [2]. The motion of a "membrane" type mechanical oscillator, embodied by a compliant capacitor in an LC resonator, has been demonstrated to entangle with a propagating electrical signal, with one half of the entangled state being stored in the mechanical oscillator [3]. That result highlighted the potential for the mechanical oscillators to serve as quantum memories for microwave signals and to allow information retrieval from the memory on demand.

Levitated nanoparticles offer the unique and appealing feature of being highly decoupled from the environment, allowing the observation of extremely high quality factors (theoretically expected up to 10^{12}) in a mechanical oscillator. As the main source of heating is avoided by being free from mechanical attachment to other mechanical objects, reaching the quantum ground state of the mechanical motion of levitated particles is hence greatly facilitated. Recent experiments obtaining optical trapping of a dielectric silica sphere of ~140 nm in diameter at ambient temperature in vacuum, have demonstrated the realization of the quantum ground state [4, 5].

Four current challenges are identified for nanoparticle trapping and cooling with light fields in an optical cavity [6]: (1) stable trapping at high vacuum; (2) minimizing the mechanical occupation; (3) minimizing the photon shot noise; (4) maximizing the optomechanical coupling.

We proposed an experiment on levitation and trapping mesoscopic particles by RF fields in an SRF cavity, SRF levitation and trapping of nanoparticles, aimed at enabling the ultimate observation of quantum phenomena in the context of quantum science and technology. Our approach is expected to bring a new tool that is unfamiliar to the field of optomechanics. Most critically, by virtue of much longer wavelength (factor of 10^5), ultra-high vacuum (down to 10^{-10} - 10^{-11} mbar), and cryogenic temperatures (1-4 K), it addresses three of the four currently identified challenges faced by optomechanical nanoparticle levitation, therefore promises to advance nanoparticle levitation well beyond the state of the art demonstrated by optical cavities. Expected gains in other metrics:

- Photon scattering, $P_{scat} = |\alpha|^2 k_L^4 I_{opt}/6\pi\varepsilon_0^2$, to be reduced by 10^{20}.
- Mechanical phonon occupation, $n_m = k_B T_{env}/\hbar\omega_q$, to be reduced by 10^2.
- Cavity internal loss k_{cav} to be reduced by a factor of 10^4.

SRF LEVITATION AND TRAPPING

Theory

The gradient force is the major driving force behind the SRF levitation and trapping. Such a force arises in an EM field where a spatial variation in the field amplitude, electric or magnetic, exists. For a dielectric particle in air or vacuum, in the Rayleigh regime with the particle radius, r, being sufficiently smaller than the wavelength of the electromagnetic field λ, $r < \lambda/20$, the time-averaged gradient force arises from spatial variation of the electric field amplitude,

* Authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy and by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV009

ON THE NATURE OF SURFACE DEFECTS FOUND IN 2/0 N-DOPED 9-CELL CAVITIES*

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Abstract

In this contribution, we present a surface characterisation on the microstructure of 1.3 GHz 9-cell TESLA type SRF cavity, processed with 2/0 Nitrogen-doping surface treatment, to explain the premature quench phenomenon observed in cavities that were submitted to this treatment. The microstructure was characterised using secondary electron images and advanced metallurgical techniques such as EBSD in parallel with chemical information obtained from spectroscopic techniques. The most remarkable difference was observed in the ends-cavities (one and nine), which showed roughening on the surface, revealing a series of morphologies associated with Nb cubic phase. The cell-to-cell analysis also showed standard pits with different geometry and distribution, located in grains and grain boundaries. The surface defects found in the multicell suggest that during the electropolishing process, the parameters such as temperature (T), current (I) and time (t), shown deviation from the standard procedure, insufficient to generate a smooth surface without discarding the role of the impurities, N and O, that could have induced the growth of these features.

INTRODUCTION

Niobium is the material of choice for SRF technology used in particle accelerators. Under operation conditions, the RF penetration depth is about 100 nm. From this fact, the local chemical composition and structural defects in that near-surface region are relevant for the cavity's performance. Different cavity treatments have been evaluated in the past to improve the cavity quality factor (Q0), among them the N-doping, which results in a significant increase in the value of Q0. Since a decrease in the structural defects in the near-surface region results in a better cavity performance, in this study, we are evaluating a 9-cell cavity processed with 2/0 N-doping treatment, which shows an unexpected early quench.

EXPERIMENTAL STUDIES

Cavity Preparation

The samples under study were extracted from all cells of the Nb 9-cell cavity (CAV018) processed with 2/0 N-doping surface treatment. The process stages are shown in Fig. 1. In addition, the surface of the cut-out was examined as received, using an EBSD/SEM instrument and Laser Confocal Scanning Microscopy.

The surface chemical composition of these cut-outs was evaluated from XPS spectra recorded with an ESCALAB 250Xi from Thermo-Fisher spectrometer equipped with an AlKα source.

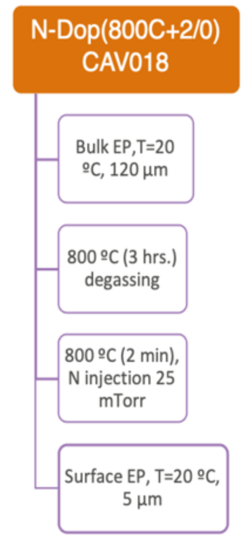

Figure 1: Process stages to evaluate the surface chemical composition.

RF Results

The 9-cell cavity shown an early quench during the RF test, locating the inducer region in cell 1, Fig. 2.

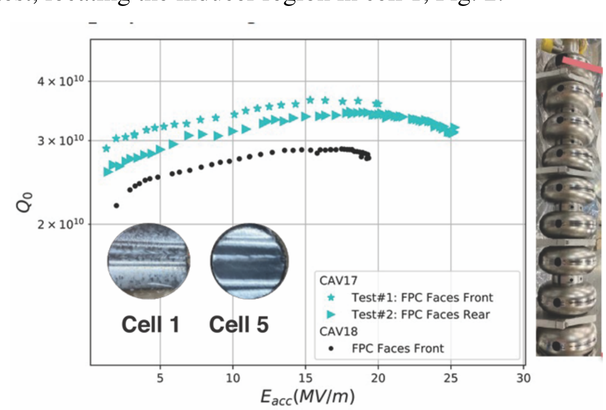

Figure 2: Q_0 vs E_{acc} curve of the 9-cell cavity (CAV018). The plot took from reference [1].

RESULTS AND DISCUSSION

Characterisation with XPS

XPS is a surface analysis technique that explores the near-surface region to a depth of about 7 nm using AlK(radiation)

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPFDV010

MICROSTRUCTURE CHANGES OBSERVED IN THE NEAR-SURFACE REGION OF SRF Nb CAVITIES CUTOUTS UPON COOLING/HEATING CYCLES USING GI-SYNCHROTRON XRD

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Abstract

This contribution discusses the results of a structural study of the near-surface region from GIXRD data on cutouts from cavities treated with RF state-of-the-art surface treatments such as: N-doping, low-T bake (75/120C), and standard-T EP. For N-doping, the main phase found was $Nb(NH_x)$ solid solution where the N atoms occupy the interstitial octahedral sites of Nb, trapping hydrogen atoms located in the tetrahedral sites. This avoids the formation of Nb-hydrides upon cooling. A similar effect appeared with the existence of oxygen as an absorbed species in Nb, particularly in the low-T baking cutout. Interestingly, the Nb-hydride formation on the sample cooling was detected only for the standard T-EP cutout, which is related with an ordered solid solution of Nb, α-Nb(H). The recorded GIXRD patterns provided a conclusive clue on such phase composition.

INTRODUCTION

Niobium is the metal superconductor of choice for SRF cavity technology because of its high surface superconducting properties and formability, which facilitates the cavities manufacture. Nb is a highly reactive metal, particularly for hydrogen, nitrogen, oxygen, and carbon, and these elements can be found in the near-surface region forming hydrides, nitrides, oxides, carbides, or forming solid solutions. That region is relevant for the cavity's performance because the superconducting current flows through a thin surface layer, of about 100 nm thick, and from this fact, the presence of structural defects, secondary phases, species dissolved the Nb structure, etc. could have a detrimental effect on their functional properties. During the manufacture, the cavity is submitted to several thermal and chemical surface treatments which remove the oxide layer, mainly formed by Nb_2O_5/NbO. The oxide layer passivates the surface and behaves as a barrier for hydrogen absorption. When it is removed, the naked Nb surface facilitates the uptake of hydrogen, which is finally found occupying the tetrahedral and octahedral interstitial sites in the Nb bcc unit and precipitates as hydrides upon cooling. These niobium hydride precipitates have a detrimental effect on the cavity quality factor, Q_0, known as High Field Q-Slope, due to proximity effect by normal conducting state of Nb-hydrides. This study reports a phase analysis for the near-surface region on cutouts from cavities treated with RF state-of-the-art surface treatments such as: N-doping, low-T baking (75/120C), and standard-T EP as function of cryogenic cooling and warming cycle. The results herein discuss the mechanism by which N and O as dissolved species in the Nb matrix minimize the detrimental effect of hydrogen in the cavity performance.

EXPERIMENTAL

The cutouts herein studied were obtained from the cavity after the corresponding surface treatment. In that sense, the recorded GIXRD patterns are representative of the crystalline phase composition and microstructural features for the near-surface region of these samples. The GIXRD patterns were acquired at the 33-BM-C beamline at the Advanced Photon Source facilities at ANL., using a double crystal monochromator with $\lambda = 0.7749$ Å with an incidence angle of 1°, with a step size of 0.001°. For that radiation energy and incidence angle, the estimated penetration depth in Nb is no deeper than 1 μm. The diffraction patterns were recorded by cooling from 300 to 30 K, at temperature intervals of 25 K, for every 10 min at each temperature, and then, the patterns were recorded again while the sample was warming up to 300 K. For GIXRD data processing, the background was removed first, and the qualitative phase analysis was carried out based on the ICDD and ICSD database, and an exhaustive patterns evaluation was performed in terms of their matching with the expected crystalline phases. Once the potential phases were identified, their cell and cell parameters were checked using DicVol and Le Bail programs available in the FullProf suite package [1].

RESULTS AND DISCUSSION

Tetrahedral and Octahedral Interstitial Sites in the Nb bcc Unit Cell

The Nb bcc unit cell has small available spaces with four and six Nb atoms as first neighbors, known as interstitial tetrahedral and octahedral sites, respectively (Fig. 1). The tetrahedral site has the smaller free volume related to a minor distance between neighboring Nb atoms. These sites are appropriate to accommodate small atoms, like hydrogen. The octahedral site has a relatively larger available volume for the absorption of bulky atoms, e. g. N, and O. The covalent radius of H, N, and O is 0.037, 0.077, and 0.066 nm, respectively. The distance between the centers of the neighboring tetrahedral and octahedral and tetrahedral sites is about ~0.019 and ~0.024 nm. This suggests that when the Nb metal has N or O as absorbed species, it could have a high ability to stabilize H atoms in the neighboring tetrahedral site, through a covalent interaction between them, N-H, or O-H. This occupying mechanism suggests

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUOFDV03

VACANCY-HYDROGEN DYNAMICS AND MAGNETIC IMPURITIES DURING MID-T BAKE

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Abstract

Positron annihilation measurements allow to study the hydrogen interaction with vacancies in a crystal lattice. Furthermore, the $3\gamma/2\gamma$ ratio of the positronium annihilation showed local magnetic impurities in the native niobium-oxide layers. Dynamic studies of these properties in annealing studies up to 300° C will be presented. The discussion is accompanied by X-ray reflectivity studies performed on single crystal samples to study the niobium oxide dissolution and structural reorganization. The dynamics of magnetic impurities during a Mid-T bake will be presented, put into the context of cavity studies and a potential link to rf properties will be presented.

INTRODUCTION

Annealing procedures to tailor the chemical composition of superconducting radio-frequency (SRF) cavities made out of niobium have been applied for decades. But only recently, a 300 – 400° C anneal for 3 h in UHV was studied (the newly dubbed "Mid-T Bake") and showed very high quality factors of $Q_0 \approx 5 \times 10^{10}$ at already 2 K [1]. In addition, a behavior called "anti-Q-slope", a positive slope in the Q_0 vs. applied accelerating field E_{acc} representation, was observed. This behavior was only observed on doped cavities so far [2, 3]. As been reported by He et al. and Ito et al [4, 5], this anneal was successfully reproduced at other labs rather fast, even relaxing the annealing conditions (using furnaces and cavities with caps rather than in-situ annealing of cavities while still under vacuum as been done by Posen et al.). Similar studies were pursued by Palmer et al. [6], in which observations in agreement with the recent Mid-T bake were already described (increase of the sensitivity to ambient magnetic field, reduction of the critical temperature, decrease of the BCS resistance).
In this paper, we will present the results of the first application of the Mid-T bake in the industry and discuss another similarity of the Mid-T bake with the doping procedure, besides the anti-Q-slope. Furthermore, we will show that a reorganization of a lower niobium-oxide, NbO, takes place at 300° C which has a significant impact on the overall properties of the near-surface region and its interfaces of the niobum rf surface.

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CAVITY STUDIES

Four 1.3 GHz single-cell cavities were sent for a 300° C anneal for 3 h to Zanon R.I.. Each cavity underwent a baseline rf test before shipment. The standard surface preparation was applied, but two cavities got a final electropolishing (EP) as last treatment step (namely 1DE9 and 1AC2), while the other two cavities underwent a subsequent low-temperature anneal, the so called 120° C bake, as last treatment step (namely 1DE5 and 1DE7). The decision was, that one of each cavities with the different final surface treatment were annealed together in one furnace run. The first furnace run (cavities 1AC2 and 1DE7) was done without caps installed, while the second run (cavities 1DE9 and 1DE5) was done with caps installed. Up to now, only the cavities from the first furnace run were tested, and the rf tests at 2 K before and after the treatment are shown for 1AC2 in Fig. 1 and for 1DE7 in Fig. 2. Besides the shown test results, R_s versus temperature measurements were done. The residual resistance R_{res} of 1AC2 increased from 1.9 nΩ before the treatment to 8.5 nΩ after the treatment. The residual resis-

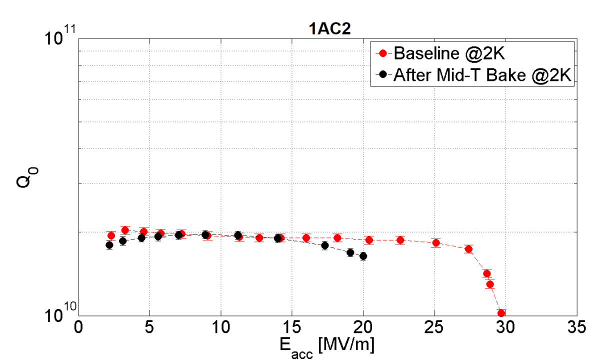

Figure 1: Quality factor versus applied accelerating field for 1AC2 at 2 K. The measurement before (red) and after (black) the Mid-T bake is shown. An anti-Q-slope is not observed. The cavity is quench limited without field emission.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUOFDV05

DYNAMICS OF RF DISSIPATION PROBED VIA HIGH-SPEED TEMPERATURE MAPPING*

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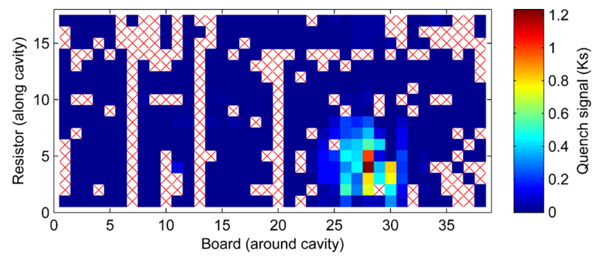
Abstract

Recently, Cornell University has developed a new high-speed, high-resolution temperature mapping system that can resolve the time dynamics of RF dissipation, i.e., provide high-speed videos of the surface heating across the entire surface of the cavity. This new powerful tool allows to observe rapid changes in the local RF dissipation, as well as to resolve the dynamics of quenches, field emission processing, and other cavity events, giving new insights into these. This contribution presents the development of this new high-speed temperature mapping system, discusses its commissioning and extensive performance testing (e.g., demonstrating micro-Kelvin resolution), as well as show intriguing high-speed temperature mapping results from multiple Nb_3Sn cavities.

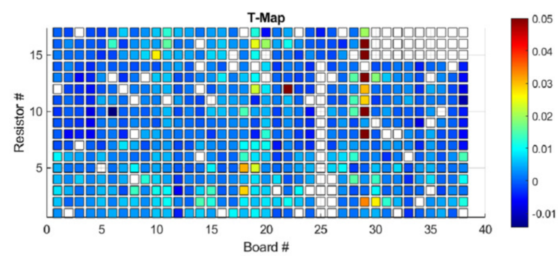
INTRODUCTION

Temperature mapping is a useful tool in understanding Superconducting Radiofrequency (SRF) cavity performance and limitations. This diagnostic technique involves placing numerous thermometers (often 100's) on the outside of an SRF cavity and measuring the heating of the outer cavity wall during operation. Areas of increased temperature can reveal the location of cavity quench or areas of increased resistance that lowers the cavities quality factor. These locations can then be investigated to determine what is responsible. In addition, temperature maps can reveal important information about the quench source or even identify the problem without subsequent measurements: the heat shape/distribution itself can indicate the quench culprit or heating source and heating distributions of many common problems are known [1]. Figure 1 show several examples of temperature maps and their culprits. The understanding provided helps overcome limitations in SRF cavities.

Temperature mapping of SRF cavities can be traced back to the 1980's when Cornell University developed a temperature map for 1.5 GHz cylindrical pill-box cavity [2]. Subsequently, Cornell and other institutions developed temperature maps elliptical cavities and other geometries [1, 3–5]. Temperature mapping has become a key tool in SRF and new systems continue to be developed [6, 7].



(a) A quench map of a Nb_3Sn cavity taken with the old temperature mapping system [8, 9]. The hot spot in the lower right indicates a localized thermal quench. Quench maps are acquired by allowing the cavity to quench many times and slowly measuring each sensor so that several quenches are measured on each channel. Places that are on average hotter are likely the quench site. The plot is displayed as integrated temperature. White squares with red x's indicate non-functional thermometers.



(b) A temperature map of a Nb_3Sn cavity with field emitter. The field emitter is indicated by the vertical line of heating seen in the upper right. White squares indicate non-functional thermometers.

Figure 1: Example temperature maps. These maps are read like a map of the world. The horizontal middle line is the equator of the cavity, and the top and bottom are the irises of the cavity.

Current temperature mapping systems take several minutes to read out the temperature of the entire array. This makes the systems effectively capable of only taking long exposure pictures and they cannot resolve dynamic effects. Many SRF cavity processes are dynamic: charging a cavity takes ~ 1 s, cavity quench takes place on time-scale of 0.1 – 10 ms, and D. L. Hall et. al. observed sudden, fast temperature jumps at the quench site of Nb_3Sn cavities that are speculated to be related to cavity quench [8, 9]. Measuring dynamic processes may provide important insights into the cause of quench or other performance problems in SRF cavities.

* This work was supported by U.S. DOE award DE-SC0008431 (hardware development, construction, and cavity tests.). This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams (software development, firmware development, and data analysis).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUOFDV07

SAMPLE TEST SYSTEMS FOR NEXT-GEN SRF SURFACES*

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Abstract

With the increasing worldwide focus on the development of new surfaces for SRF cavities, exploring alternative materials and multilayer structures, test systems that allow measuring the RF performance of simple sample geometries (e.g., flat samples) become increasingly essential. These systems provide RF performance results that are needed to guide the development of these surfaces. This contribution gives an overview of sample test systems currently available, including the improved Cornell sample host cavity. Recent advances in this important technology, performance specifications, and current limitations are discussed. In addition, an overview is given of interesting recent RF performance results on samples coated with non-niobium bulk and multilayer films.

INTRODUCTION

The use of three dimensional microwave electromagnetic resonators with superconducting surfaces for accelerating charged particles has a long and successful history [1]. In contrast to normal conductors a superconducting surface exposed to a microwave field will dissipate far less energy. For accelerator applications this propagates into two major advantages. First, a reduction of overall power cost, coming from a net gain of low dissipation in the electromagnetic resonator requiring low input powers to reach a given stored energy (proportional to the square of field magnitude) versus higher refrigeration costs to reach the cryogenic temperatures required for the low T_c superconducting phases employed for this application. Second, less dissipation corresponds to less heating which can be more efficiently removed allowing for continuous wave operation. On the other hand, superconducting RF surfaces are limited to a critical magnetic field above which the low dissipation flux-free Meissner state can no longer be maintained. The optimization of these key metrics; minimizing dissipation (surface resistance) and maximizing accelerating field limitation (quench field) are paramount for advancing SRF accelerator technology.

This regime of minimum dissipation and maximum RF field is unique to the SRF accelerator application and poses major challenges theoretically. At low RF fields accurate estimates of surface resistance can be obtained [2, 3]. Lowering the expected dissipation will increase the role of any defects or material features making accurate estimation increasingly difficult. As the RF field strength is increased dissipation becomes difficult to model as more sources may become relevant and complicated nonequilbrium effects may become important. Unfortunately this regime is of the most practical importance since higher field cavity operation is desired. Thus it is important not only to maximize the limiting field and minimize surface resistance but to do so in the poorly understood high field regime.

The elemental superconductor niobium was a clear initial choice since its properties, compared to other elemental superconductors available at the time, minimize surface resistance and maximize the ideal quench field (superheating field). Over decades niobium processing was advanced to optimize it for accelerator applications [1]. Surface processing techniques have been developed to routinely reduce the surface resistance at high fields in addition to reaching higher quench fields [4, 5]. With cutting edge techniques niobium has been extended further than low-field BCS predictions for surface resistance and very close to predictions for the theoretical superheating field [6]. As such its utility for continuing to meet the ever-rising demands of the future accelerators may be approaching an end.

The potential limits of niobium have refreshed efforts to search for materials or metamaterials that could surpass the capabilities of niobium [7]. Nb_3Sn has emerged as the most successful candidate explored though its measured performance is far below theoretical expectations [8]. At this time it appears that none of the superconducting alloys have demonstrated naive expectations of dissipation or quench field. To assist with field limitations superconductor-insulator-superconductor (SIS') multilayers were proposed [9]. Recently RF measurements have been performed on these metamaterials but benefits have not yet been observed in the presence of an RF field [10].

A major problem with advancing beyond niobium is a lack of measurement of these materials in relevant RF fields. Niobium optimization followed from innumerable and extremely costly RF tests and surface processing trials. In many situations performance improvements are reproducible but the physical mechanisms are not clear. Understanding and identifying positive and negative features will require improved capabilities for measuring surface resistance, quench fields, or other relevant metrics with more diverse samples as a function of more variables. Measurement of flat samples is important for probing more diverse materials and structures without significant investment in specialized deposition systems. Though exposing these surfaces to significant RF fields and obtaining relevant metrics is nontrivial. The purpose of this writing is to present existing systems and methods attempting to perform field-dependent surface resistant measurements on flat samples.

COMPLICATIONS AND STRATEGIES FOR FLAT SAMPLE RF CHARACTERIZATION

The primary difficulty of experimentally probing materials for SRF accelerator application is exposing them to

* Work supported by Center of Bright Beams from the National Science Foundation under Grant No. PHY-1549132
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUOFDV08

FIRST βNMR RESULTS ON SRF SAMPLES AT TRIUMF

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Abstract

The βNMR (β-detected nuclear magnetic resonance) facility at TRIUMF offers the possibility of depth-resolved probing of the Meissner state over the first 100 nm below a sample surface. The measurement can give the attenuation of the applied magnetic field, as a function of depth. The technique can be especially important when probing layered systems like the dirty/clean S-S (superconductor-superconductor) bilayer and S-I-S (Superconductor-Insulator-Superconductor) structures. The TRIUMF SRF (Superconducting RF) group has recently completed first measurements at beta-NMR on Nb samples with various treatments. The results and method will be reported.

MOTIVATIONS FOR βNMR SRF STUDIES

Superconducting RF (SRF) cavity performance, characterized by the Q_0 (intrinsic quality factor) vs. E_{acc} (accelerating gradient) curve, is fundamentally limited by superconducting quench at high RF magnetic fields where the SRF cavity undergoes transition from the Meissner state to the highly dissipative vortex state. In the Meissner state, magnetic fields are screened within the so-called *London layer*, and therefore RF dissipation is contained only within a tens of nm from the inner SRF cavity surface. As the fields are increased, however, the surface barrier to magnetic flux penetration can be overcome and the magnetic flux penetrates into the bulk of the SRF cavities, which quenches the superconductivity due to high dissipation from rapidly oscillating flux vortices in the RF fields. In Niobium (Nb), the theoretical limiting RF magnetic field for an ideal surface is on the order of the superheating field, $\mu_0 H_{sh}$ ~240 mT at 0 K [1]. In the presence of surface defects, however, the limiting field is reduced towards the lower superconducting critical field, $\mu_0 H_{c1}$ (~174 mT at 0 K [2]).

In practice, the Q_0 vs. E_{acc} degrades at much lower fields due to a phenomenon called the *Q-slope*. The complete picture of the *Q-slope* is not yet fully understood but it is clearly related to the detailed material properties in the vicinity of the surface. Practical remedies have been developed in the form of low/medium temperature heat treatment (e.g., 120 °C bake which cures the *high-field Q-slope*). Various impurity doping recipes (e.g., nitrogen doping [3] and infusion [4]) have also been developed in the production of high-performance SRF cavities. A novel approach using thin film coating of higher H_c superconductors on Nb cavities for bilayer S-S (superconductor-superconductor) [5] and multilayer S-I-S (superconductor-insulator-supeconductor) [6] on Nb SRF cavities have also been proposed to further increase the limiting field beyond that of bulk Nb, as well as providing additional barriers to flux penetration at much higher fields.

Various surface studies of SRF cavity cut-outs and SRF Nb samples have elucidated the important role of the nm RF surface. The aforementioned heat treatment and impurity doping recipes have been shown to alter the impurity concentration profile near the surface, but a direct correlation on how they affect the Meissner state at high magnetic fields is not fully understood (though a detailed theoretical framework has been proposed [7]). An ideal characterization technique would allow for a direct measure of the magnetic field screening in the Meissner state in a the depth-resolved manner within the nm *London layer*, especially at high-parallel magnetic fields (fields parallel to the sample surface). The depth-resolved capabilities would allow a better understanding of how to engineer surface impurity concentrations via various heat-treatment/doping recipes in order to obtain custom SRF performance. The parallel magnetic field configuration is usually used to simulate the orientation of rf magnetic fields in SRF cavities.

A powerful technique to measure the local magnetic field is by implanting spin-polarized probes which interact with local electromagnetic fields inside a host material, wherein the local field is quantified by monitoring the time evolution of the probe's nuclear spin polarization. TRIUMF host two

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFAV001

PROGRESS ON SRF LINAC DEVELOPMENT FOR THE ACCELERATOR-DRIVEN SUBCRITICAL SYSTEM AT JAEA*

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Abstract

To overcome the nuclear waste problem, the Japan Atomic Energy Agency (JAEA) has been developing an accelerator-driven subcritical system (ADS) since the late 1980s. In the JAEA-ADS proposal, an 800 MWth subcritical reactor is driven by a 30 MW cw proton linear accelerator (linac). The biggest challenges for the ADS machines are the high reliability and availability required for their operations. To this end, the present JAEA-ADS linac was redesigned by adopting the current developments in Superconducting Radio-Frequency (SRF) technology. Additionally, we developed a robust lattice to control the beam loss and implemented a fault-tolerance scheme for the fast recovery of SRF cavity failures. This work presents the latest results of the R&D of the JAEA-ADS superconducting linac.

INTRODUCTION

The Japan Atomic Energy Agency (JAEA) is designing an Accelerator Driven Subcritical System (ADS) to deal with nuclear waste by transmuting minor actinides. Figure 1 presents the general scheme for the JAEA-ADS. The project consists of a 30 MW cw proton accelerator, a Spallation target, and an 800 MW thermal power subcritical reactor [1]. Table 1 provides a summary of the specifications for the JAEA-ADS linac.

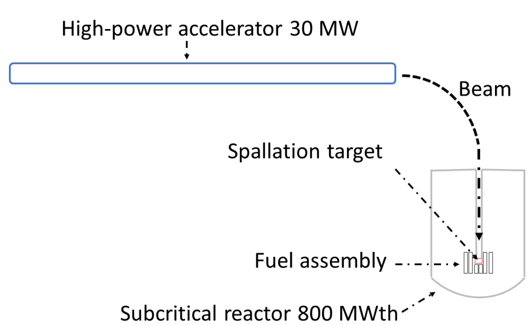

Figure 1: General scheme for the ADS.

The accelerator for the JAEA-ADS requires to operate in cw to be compatible with the reactor operation and accelerates a 20 mA proton beam up to an energy of 1.5 GeV. In addition, high reliability in the accelerator is demanded to avoid thermal stress in the subcritical reactor elements. Thus, the previous requirements indicate a Superconducting Radio-Frequency (SRF) linear accelerator (linac) is the most suitable candidate for this task. From the specifications presented in Table 1, reliability is the biggest challenge. The reliability for the ADS is higher than the achieved in the present high-intensity linacs [2, 3]; to this end, the JAEA-ADS SRF linac pursues a robust beam optics design and fault-tolerance capabilities to become a reliability-oriented accelerator [4].

Table 1: Main Characteristics of the JAEA-ADS Accelerator

Parameter		Beam trip duration
Particle	Proton	
Beam current (mA)	20	
Beam energy (GeV)	1.5	
Duty factor (%)	100 (cw)	
Beam loss (W/m)	< 1	
Beam trips per year [5]	$2{\times}10^4$	≤ 10 s
	$2{\times}10^3$	from 10 s to 5 min
	42	> 5 min

BEAM OPTICS DESIGN

To achieve a robust beam optic design: the lattice must have strict control of beam loss, have a simple configuration, and operates with de-rated SRF cavities to reduce the failure probabilities. Moreover, we want to reduce the number of cavities and the linac length to minimize the operational cost.

Our linac starts with a normal conducting injector up to an energy of some MeVs, following to the state of the art of high-intensity SRF linacs [6–8]. Then, an SRF section, the so-called main linac, provides the rest of the acceleration. The main linac supplies most of the beam energy and represents the largest part of the linac length. Thus, we designed the main linac lattice to satisfies the above conditions.

To achieve an efficient design in terms of the numbers of cavities and length, we use three different types of SRF cavities: Half Wave Resonator (HWR), Single Spoke Resonator (SSR), and five-cell Elliptical Resonator (EllipR). The main linac is divided into five sections and operates with three different frequencies, as is shown in Fig 2. Table 2 presents a description of the section layouts using the following notation: C= cavity, S= solenoid, DQ= doublet quadrupole.

Table 2: Lattice Configuration in the Main Linac

Section	Layout	Period (m)	Total cavities
HWR	S-C	0.7	25
SRR1	S-C^2	1.7	66
SSR2	S-C^3	3.4	72
EllipR1	DQ-C^3	5.7	60
EllipR2	DQ-C^5	9.9	70

* Work supported by Subvention for ADS development.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFAV002

CALIBRATION OF SRF CAVITY VOLTAGE BY MEASUREMENT OF SYNCHROTRON FREQUENCY IN SuperKEKB

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Abstract

Eight SRF cavity modules, which have been operated in KEKB for more than ten years, are stably operating also in SuperKEKB. As for calibration of the cavity voltage V_c, non-negligible discrepancy was observed between the results obtained from two different methods: one is using external Q value (Q_{ext}) of pickup ports, and the other is using loaded Q value (Q_L) of the cavities. The discrepancy comes from inaccuracy of power measurement in high power RF system and uncertainty of the Q_{ext} or Q_L values. In order to solve the discrepancy by improving the accuracy of the calibration for each individual cavity, we investigated a method by measuring synchrotron frequency f_s of stored beam. With this method, V_c calibration can be performed without affected by inaccuracy of high-power measurement or uncertainty of the Q_{ext} or Q_L values. The f_s measurement studies were carried out in SuperKEKB. With these studies, V_c calibration was obtained with a high accuracy of about 1%. The results are applied to the SuperKEKB operation.

INTRODUCTION

The SuperKEKB accelerator [1] is an electron-positron asymmetric energy collider that aims for a luminosity of 8×10^{35} /cm^2/s, which is 40 times higher than that of the KEKB accelerator. SuperKEKB main ring consists of a 7 GeV electron ring (high energy ring, HER) and a 4 GeV positron ring (low energy ring, LER). In order to achieve high luminosity, the stored beam currents are designed as 2.6 A for HER and 3.6 A for LER, which are twice those achieved in KEKB. After Phase-1 commissioning beam operation in 2016, the Belle II detector has been rolled in and the operation of the positron damping ring has started. Phase-2 operation started in 2018, and the first beam collision event was observed at Belle II in April [2, 3]. A full-scale collision experiment (Phase-3) started in March 2019 [4], and a peak luminosity of 2.96×10^{34} /cm^2/s was recorded in May 2021 with the beam currents of 680 mA for HER and 840 mA for LER.

The eight superconducting accelerating cavities (SCC) and eight normal-conducting accelerating cavities (ARES) [5] are operating in HER. The SCC is a higher-order-mode (HOM) damped cavity [6-9] developed for KEKB. Despite more than 20-years of usage, the SCC operation has maintained stable by keeping good performance with help of horizontal high pressure water cleaning [10, 11] and regular RF aging. The cavity voltage V_c of each SCC has been kept at 1.35 MV. The frequency of beam abort caused by cavities, so-called the trip rate, has been less than 0.1/day/eight cavities in recent operation.

An issue is related to calibration of V_c for each individual cavity with a sufficiently high accuracy. For SCCs, two independent methods are usually used: one is use of monitor power at the pickup port of cavity with the external Q value (Q_{ext}) of the pickup port. The other is use of cavity input power with the loaded Q value (Q_L) of cavity. In some cases, such as for some of the SCCs in SuperKEKB, non-negligible discrepancy is observed between the results obtained from the two methods. One reason is inaccuracy of power measurement in high power RF system. Another reason is uncertainty of the Q_{ext} or Q_L values. In order to improve the accuracy of the calibration, measurements using beams can give powerful information to correct these calibrations by eliminating inaccuracy of high-power measurement. In DESY, V_c calibration based on measurement of beam-induced voltage was performed [12]. In SuperKEKB, a different approach based on f_s measurement is investigated. A benefit of our approach is that the calibration is performed without affected by an error of Q_L. With this method, V_c calibration can be performed without affected by inaccuracy of high-power measurement or uncertainty of the Q_{ext} or Q_L values.

In this report, we will present the method of V_c calibration for each independent cavity using f_s measurement as well as results of studies of this method applied to SuperKEKB operation.

STATUS OF SCC IN SuperKEKB

A cross-sectional view of the SCC in SuperKEKB is shown in Fig. 1. It is a 509-MHz single-cell HOM damped cavity made of niobium. The HOM power is damped by a pair of ferrite absorbers [9] attached at beam pipes outside

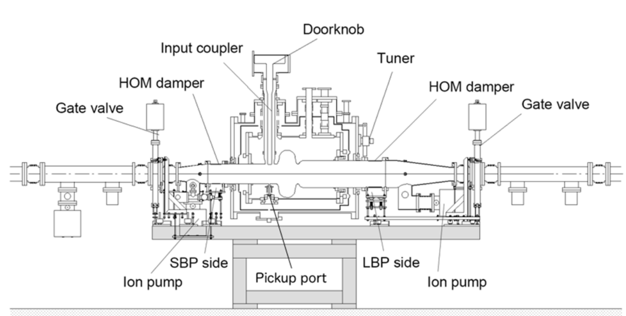

Figure 1: Cross-sectional view of the SCC module of SuperKEKB.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFAV003

STABLE BEAM OPERATION AT 33 MV/m IN STF-2 CRYOMODULES AT KEK

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Abstract

In STF at KEK, as the operational demonstration of the SRF accelerator for ILC, the STF-2 cryomodules (CM1+CM2a: one and half size CM with 12 cavities) have achieved 33 MV/m as average accelerating gradient with 7 cavities in Mar/2019. After that, one cavity with the lowest performance installed in CM2a was replaced with one N-infused cavity developed for High-Q/High-G R&D between Japan and US. From Apr/2021, the beam operation started again and those CMs achieved 33 MV/m as average accelerating gradient with 9 cavities including one N-infused cavity again. This is remarkably important milestone for the ILC project. In this report, the detailed results will be presented.

INTRODUCTION

In the Superconducting RF Test Facility (STF) of the High Energy Accelerator Research Organization (KEK), research and development of superconducting cavities and cryomodules (CMs), which are the core technologies for the International Linear Collider (ILC) project [1, 2], has been promoted since 2006. There are four experimental projects that have been implemented so far, as shown in Table 1. In STF-2, a total of 6 cooldown tests have been conducted, and only the low power test was carried out in the 1st and 5th cooldown tests.

Table 1: Four Projects Performed in STF

Project	Experimental period
STF Phase-1 (STF-1) [3]	F.Y. 2008~2009
S1-Global [4]	F.Y. 2010~2011
Quantum Beam [5]	F.Y. 2012~2013
STF Phase-2 (STF-2, 1st) [6]	F.Y. 2014
STF-2, 2nd	F.Y. 2015
STF-2, 3rd [7]	F.Y. 2016
STF-2, 4th [8]	F.Y. 2018
STF-2, 5th	F.Y. 2020
STF-2, 6th [9]	F.Y.2020~2021

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Since the ILC is an energy frontier machine, it is required to operate at the highest accelerating gradient possible, and STF has been developing superconducting cavities that can reach the higher accelerating gradient. Nine 9-cell cavities that reached the ILC spec of 35 MV/m or higher in vertical test (VT) were installed in the STF-2 CMs, which started experiments in 2014 (12 cavities for the entire cryomodule), and from February to March 2019. In the 4th cooldown test conducted, beam operation was performed with a high accelerating gradient exceeding the ILC specifications. Table 2 shows the ILC specifications for beam operation. In the Quantum Beam project shown in Table 1, one small CM with two cavities was developed and operated for beam acceleration. This CM is used as Capture CM (CCM) in the STF-2 accelerator.

Table 2: ILC Specification in Beam Operation [9]

Item	Specification
Accelerating gradient	31.5 MV/m
Q_0	1.0×10^{10}
Drive Frequency, Mode	1.3 GHz, TM_{010}, π-mode
Cavity fill time	924 μsec
Beam pulse length	727 μsec
Total RF pulse length	1650 μsec
Pulse repetition rate	5 Hz
Beam current	5.8 mA
Operational temperature	2 K

CAVITY REPLACEMENT

After the 4th cooldown test, CAV#9 with the lowest performance in the STF-2 CMs was replaced with a new cavity. This new cavity experienced nitrogen infusion (N-infusion) process as a new surface treatment recipe for the higher performance. This is the plan being promoted by Japan-US collaboration since 2017. This cavity replacement work was the first time in STF (not ever done in the past projects). From mid. of Aug/2019, the disassembly work of CM2a started, pulled out of the tunnel, and cavity string

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFAV004

SURFACE POLISHING FACILITY FOR SUPERCONDUCTING RF CAVITIES AT CERN

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Abstract

A new SRF cavity polishing facility which covers the needs for present projects like the HL-LHC and its CRAB cavities as well as ongoing and future activities in the frame of the FCC study was commissioned at CERN in 2019. This facility can handle chemical and electrochemical polishing baths, can process both niobium and copper-based cavities on a wide range of geometries, starting at 400 MHz up to 1.3 GHz for elliptical type of cavities and more complex shapes as defined by the DQW and RFD CRAB design. The main subassemblies of this facility are presented. Some important design details and materials choices of the facility will be briefly discussed together with the range of operational parameters. First results on different substrates and geometries are discussed in terms of surface finishing and polishing rate uniformity.

INTRODUCTION

CERN new facility for polishing SRF cavities was assembled and commissioned in 2019 with the purpose of covering the treatment of a wide range of accelerating structures. To fulfil this objective, the facility is composed of three main assemblies: two independent chemical plants and one cavity handling equipment. Altogether, the facility can process all foreseen accelerating cavities, independently of the nature of the substrate, for HL-LHC, like DQW and RFD CRAB cavities, with and without their helium tank; as well as the cavities defined within the FCC study, including the 400 MHz monocell elliptical structures. In Fig.1 are the 3D representation of the listed cavities and their overall dimensions. The main requirement is that the cavity holding frame is equipped with compatible supports and interfaces.

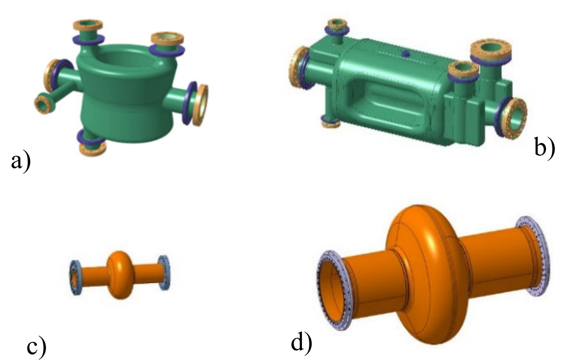

Figure 1: a) DQW, 497 mm diameter by 660 mm in length; b) RFD, 412 mm diameter by 919 mm in length; c) 1.3 GHz, 216 mm diameter by 414 mm in length; d) 400 MHz, 693 mm diameter by 1095 mm in length.

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The facility concept was entirely designed internally, and the main assembly fabrications, as listed previously, were outsourced.

FACILITY DESCRIPTION

The new facility was installed in an existing building, which had already all necessary services to house chemicals handling equipment, namely wastewater and fumes extraction as well as the supply of demineralised water (up to 60 l/minute at >10 MOhm.cm). The footprint of the installation, 45 m^2, was optimised to cope with space constraints inside the building such as the existing hydrofluoric acid compatible basin and fumes extraction ducts.

The facility is composed by three main subassemblies. A first chemical plant to handle copper electropolishing bath (H_3PO_4 (85% w/w) 55% v/v + n-butanol (99% w/w) 45% v/v), a second chemical plant to handle niobium Buffered Chemical Polishing (BCP): H_3PO_4 (85% w/w) 50% v/v + HNO_3 (65% w/w) 25 % v/v + HF (40% w/w) 25% v/v) or electrochemical (H_2SO_4 (95% w/w) 90% v/v + HF (40% w/w) 10% v/v) polishing baths, and a cavity handling device, which has a useful working volume of 1000 mm in diameter by 1500 mm in length and can handle charges up to 300 kg. The following subsections present a detailed description of the subassemblies shown in Fig. 2.

Figure 2: a) copper chemical plant; b) niobium chemical plant; c) cavity handling device.

Chemical Plants

Each plant was assembled as an enclosed independent unit including its own retention and extraction to create a first confinement and reduce the impact of any chemical incident. This separation provides more flexibility for future modifications and improves the safety of the installation as it hinders any accidental mixes of different baths in case of a leak or mishandling. As example, Fig. 3 presents a 3D drawing of the copper chemical plant module.

All pipes, valves and instrumentation were from off-the-shelf PVDF (Polyvinylidene fluoride) parts and, where

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFAV006

THE SUPERCONDUCTING RADIO FREQUENCY SYSTEM OF SHENZHEN INDUSTRIAL SYNCHROTRON RADIATION SOURCE FACILITY*

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Abstract

Shenzhen industrial synchrotron radiation source is a 3 GeV synchrotron radiation diffraction-limited source. It consists of three parts, linear accelerator, booster, and storage ring. As a basic part of the storage ring, the superconducting radio frequency system provides energy for the beam to supplement the beam power loss caused by synchrotron radiation and higher-order modes, and provide the longitudinal bunch for electron beam. The superconducting radio frequency cavity of the storage ring consists of two 500 MHz single-cell cavities and a third harmonic 1500 MHz double-cell cavity. This paper will introduce the superconducting cavity, radio frequency amplifier, and low-level radio frequency system in the Shenzhen industrial synchrotron radiation source facility.

INTRODUCTION

Synchrotron radiation light source has become the most advanced and irreplaceable tool in the basic and applied research of materials science, life science, environmental science, physics, chemistry, medicine, geology and other disciplines, and has important and extensive applications in electronic industry, pharmaceutical industry, petroleum industry, chemical industry, bioengineering and micro processing industry [1]. At present, the synchrotron radiation light source device is developing from the mature third generation to the fourth generation marked by diffraction limit storage ring. The Table 1 shows the announced situation of the fourth generation synchrotron radiation light sources being proposed or under construction by various countries in the world, which has reached 12, and 8 of them are under design.

Shenzhen industrial synchrotron radiation source facility (SZISRF), a high performance medium energy synchrotron radiation diffraction limited light source with circumference 696 m, storage ring electron energy of 3.0 GeV and emittance 81 pm·rad, is designed and constructed. The light source adopts the diffraction limited storage ring technology based on 7BA magnetic focusing unit, which can produce synchrotron radiation with wide spectrum and high brightness (10^{21} phs/s/mm^2/mrad^2/0.1%BW) from 4 meV to 160 keV. SZISRF will plan, design and build 50 beamline stations. The Layout of SZISRF is as shown in Fig. 1.

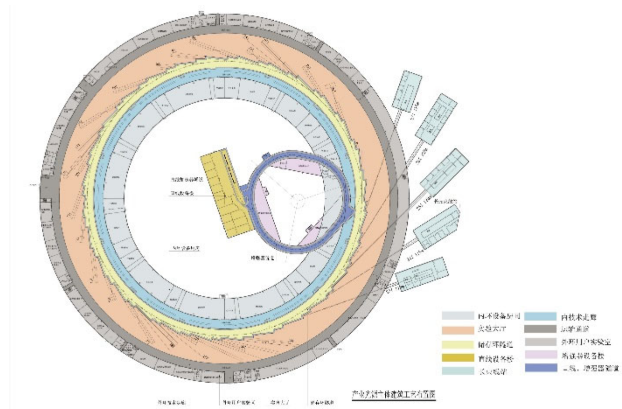

Figure 1 : The layout of the Shenzhen industrial synchrotron radiation source.

The radio frequency system of the storage ring has three main functions: provideing accelerating voltage for the beam to ensure sufficient momentum acceptance, longitudinal quantum lifetime and Toschek lifetime of the storage ring; providing energy for the beam to supplement the energy loss when it moves in the storage ring, such as the radiation loss in the deflection magnet and the insert-device, the parasitic mode loss caused by the impedance of the vacuum chamber, etc; providing the lowest possible high-order mode environment for the beam, so as to reduce the multi bunch coupling instability. During the operation of the system, the frequency of the high frequency cavity is locked by feedback control, so that the amplitude and phase of the high frequency acceleration voltage in the cavity are stable and correct, and the safety interlock ensures the safety of personnel and equipment.

The main beam parameters related to the radio frequency system of the storage ring of SZISRF are listed in Table 2. Here, it is considered that SZISRF will build about 50 beam line stations, and the design of the radio frequency system is based on the parameters in this table. The main parameters are as following : the beam energy is 3 GeV, the circumference is 696 m, the maximum beam current is 300 mA, the radiation energy loss by deflection magnet and insert-devices are about 318.4 keV and 600 keV, respectively.

The radio frequency system consists of three parts as superconducting cavity, amplifier and low level radio frequency (LLRF) control system.

* Work supported by Shenzhen Development and Reform Commission
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV001

EFFECT OF HEATING RATE ON RECRYSTALLIZATION IN ROLLED MULTICRYSTALS OF PURE NIOBIUM*

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Abstract

The performance of niobium cavities in superconducting radio frequency particle accelerators requires nearly defect free inner surfaces. While methods to obtain smooth inner surfaces are in place, the role of metallurgical defects on superconducting performance is less known, as defects such as grain boundaries and dislocations can trap flux that dissipates energy and reduces efficiency. Variable microstructure and texture gradients may account for the observed variability in cavity performance, so it is hypothesized that the texture and microstructure gradients originate from the large grain size of ingots, whose influence is not completely erased in the process of making sheet metal. To examine the evolution of microstructure and texture gradients, the crystal orientations present in a cylindrical cap rolled to ~90% reduction were heat treated. Initial crystal orientations were measured before rolling, and before and after slow and rapid heating rate vacuum heat treatments.

INTRODUCTION

In the past decade, high Q values have been achieved in high purity Niobium SRF cavities. Trapped flux is a significant factor that degrades Q, which is associated with defects such as impurities, dislocations, and grain boundaries [1–7]. With a better understanding of the effects of dislocation substructure evolution and recrystallization on electron and phonon transport, as well as the subsurface and surface states, it will be possible to design optimal processing paths for cost effective and high-performance accelerator cavities [8]. Recent experience with cavity production for the LCLS-II has shown that heat treatments at higher temperatures than 800°C are sometimes required to achieve acceptable cavity performance [9]. The higher heat treatment temperatures enhance flux expulsion during the transition to the superconducting state, so that less trapped flux leads to higher Q, and lower cryogenic costs.

As higher heat treatment temperatures lead to more recrystallization and/or grain growth, and as grain boundary motion leaves a less defective crystal structure in its wake, the ability to achieve microstructures with fewer defects leads to better performance. More importantly, the ability to obtain microstructures that consistently result in sufficient recrystallization and/or grain growth during the final heat treatment of cavities is important, so that the variability in cavity performance can be reduced. It is well known that the microstructure and properties of the same sheet metal product from the same supplier can vary significantly [8]. To this end, it is important to examine how the path from ingot to sheet metal leads to the variable microstructures and properties that affect cavity forming and subsequent changes during heat treatment.

Prior examination of the deformation characteristics of pure niobium single and multicrystals shows that some crystal orientations result in uniform deformation at the microscale while others lead to very heterogeneous deformation [10–14]. In these investigations, the recrystallization was very sensitive to the both the crystal orientation and the heat treatment temperature. An important factor to consider is that recovery (reduction of dislocation density and formation of stable low-angle grain boundaries) takes place both during plastic deformation and during heat treatment [4–6]. If too much recovery takes place, the driving force for recrystallization is reduced, i.e. if high-angle grain boundaries do not move, the stable low angle boundaries are retained. As both low angle and high angle boundaries can trap flux [3–7], it is strategic to minimize both without compromising the strength required to maintain the cavity shape.

This paper focuses on the relationship between the amount of rolling reduction, crystal orientation and heat treatment parameters and their effect on recrystallization in order to improve our general understanding of why microstructures are so variable in rolled sheet metal. With improved understanding, it may be possible to identify better processing paths that will lead to more meaningful acceptance criteria for sheet metal that will lead to consistent recrystallization during heat treatments such that cavity performance will be more consistent.

EXPERIMENTAL PROCEDURES

A cylindrical cap in Fig. 1 of high RRR niobium was obtained from an ingot (Niowave Inc., Lansing MI). Prior to rolling, two slices were cut off the edges to measure the orientation of grains on each side of the sample using Laue X-ray diffraction (Fig. 2), indicating that the grain orientations on both sides were different. About 25 passes were used with 10% reduction of the current thickness per pass, resulting in about 90% reduction. The orientations near the surface experience a greater amount of shear than the interior, as indicated by the sketch on the left side of Fig. 1. The rolling process led to one side of the strip being more reduced than the other, causing a curve in the rolled strip, such that it had

* This work is supported by US Dept. of Energy award DE-SC0009960. Some of this work was conducted during a sabbatical leave of TRB that was supported by the Talent Attraction program of the Comunidad de Madrid (reference 2016-T3/IND-1600).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV002

SIMS SAMPLE HOLDER AND GRAIN ORIENTATION EFFECTS *

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Abstract

SIMS analyses for "N-doped" materials are becoming increasingly important. A major hurdle to acquiring quantitative SIMS results for these materials is the uncertainty of instrument calibration due to changes in sample height either from sample topography or from the sample holder itself. The CAMECA sample holder design allows for many types of samples to be analyzed. However, the cost is that the holder faceplate can bend, introducing uncertainty into the SIMS results. Here we designed and created an improved sample holder which is reinforced to prevent faceplate deflection and thereby reduce uncertainty. Simulations show that the new design significantly reduces deflection from 10 µm to 5 nm. Measurements show a reduction of calibration (RSF) uncertainty from this source from 4.1% to 0.95%. Grain orientation has long been suspected to affect RSF determination as well. A bicrystal implant standard consisting of [111] and [001] grains was repeatedly rotated 15° in between analyses. It was observed that 20% of the analyses performed on [111] grains exhibited anomalously high RSF values likely due to the changing of the grain normal with respect to the primary Cs^+ beam.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are particle accelerating structures renowned for their extreme efficiency. Nb SRF cavities rely on maintaining the superconducting state in the extreme conditions of high peak magnetic fields. Therefore, great care has been taken to avoid contaminants like carbon, nitrogen and oxygen [1]. Interestingly, over the last decade it was discovered that intentionally "doping" these cavities with nitrogen (interstitial alloying of the surface Nb) can improve the quality factor (Q_0) by a factor of three with continual improvements being made [2].

Today, ongoing research is performed by scientists globally to further improve the performance of SRF cavities, with great attention directed towards nitrogen doping [3]. Changing N-doping diffusion times and temperatures can substantially influence the interstitial N concentration and affect the superconducting properties. Because the RF penetration layer is ~100 nm, determination of nitrogen concentration is needed with high depth resolution.

Secondary Ion Mass Spectrometry (SIMS) is the ideal choice to quantify the concentration of nitrogen. SIMS utilizes a primary ion beam, such as Cs^+, to bombard the surface of a sample, causing the surface to sputter away at a controlled rate[4]. The removed material is also ionized and extracted into a secondary ion beam where the contents are detected over time by the mass spectrometer. Initially, the intensity of the secondary ions is given as the output for detection. Implantation standards are used to convert the intensity to concentration. These standards are materials of the identical matrix as the experimental samples, i.e niobium, which have been dosed with a known amount of impurity atoms by ion implantation. Analysis of the implant standard generates the relative sensitivity factor (RSF) which acts as a calibration factor to determine concentration of impurities, i.e. nitrogen [4-7].

Commercial/traceable implant standards do not exist for niobium-based materials and must be fabricated by ion implantation labs. Virginia Tech and JLab undertook a major study to evaluate factors which lead to uncertainty of RSF determination [7]. It was determined that sample topography had the most profound effect in increasing RSF uncertainty. The sample topography effects were found to be mitigated by adjusting the dynamic transfer contrast aperture (DTCA) in between analytical scans. This change alone, decreased RSF uncertainty from 40% to 10% with large grain single crystals exhibiting values from 2-8%.

Another major finding was that the sample holders were sensitive to the loading force. Variations in the loading force causes uncertainty in RSF determination by changing the working distance between sample and secondary ion extraction optics. Samples loaded into the sample holder are held in place by friction by compressing copper springs between the sample and a backing plate (Fig. 1). Varying the number of springs causes the faceplate to deflect differently which changes the working distance of the sample, subsequently changing the focal point and extraction of the primary and secondary beam, respectively [7, 8]. The observable effect is the change in the detection of the matrix signal which adversely affects the RSF determination. Depending on the significance of this effect, altering the DTCA in between scans will not solve this problem. Therefore, a new SIMS holder was designed and machined to limit working distance variation to generate the most accurate quantitative SIMS results for N-doped niobium.

It has been hypothesized that grain orientation could also affect the determination of the RSF as well as quantitation of nitrogen in niobium [9]. However, it has been observed that the effect is more likely to occur in [111] grains with respect to normal and tends to coincide with increased matrix counts. The effect which causes the RSF values to shift in niobium matrices has yet to be properly documented.

* Work supported by U.S. DOE Contract No. DE-AC05-06OR23177 and grant DE-SC0018918
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV004

A SIMS APPROACH FOR THE ANALYSIS OF FURNACE CONTAMINATION *

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Abstract

Detection of surface contamination for SRF material is difficult due to the miniscule quantities and near atomic resolution needed. Visual inspection of samples known to have experienced surface contamination indicated inconsistent nitride coverage after nitrogen doping. EBSD analysis suggested that nitride suppression tends to be most prevalent when deviating from the [111] and [001] zone axes. XPS suggested that tin was present as a contaminant on the surface with SIMS mass spectra also confirming its presence. SIMS depth profiles show a depletion of nitrogen content as well as an increase in carbon content for contaminated samples.

INTRODUCTION

Superconducting radiofrequency (SRF) cavities are critical components of particle accelerators and responsible for propelling charged particles to relativistic energies which are essential to probe the most fundamental laws of physics. Historically, niobium cavities cooled to 2ºK have been used for these applications. Next generation machines, like SLAC's LCLS-II HE will use niobium cavities "doped" with low levels of nitrogen which allows for the instrument to operate more efficiently [1] .

Nitrogen "doping", a process discovered at Fermilab in 2013, has yielded highly efficient ($Q_0 = 3.5 \times 10^{10}$ at 16 MV/m) SRF cavities [2]. N-doping is the process in which a small concentration of nitrogen is thermally diffused into interstitial sites of the niobium cavities (properly termed "surface alloying"). During this process, niobium's surface also becomes decorated with lossy nitrides which subsequently must be removed by electropolishing [3, 4].

These N-doped niobium cavities are fabricated with meticulous attention to detail to avoid a premature reduction in efficiency with increasing power (quenching) [5]. Avoiding contamination throughout the fabrication process is critical. It is suspected that metallic contamination can occur during the furnace heat treatment of the cavities. To guard against this, cavities are capped to prevent metallics from depositing on the interior cavity surface which may limit the performance of the cavities [6].

Mitigation of furnace contamination by capping the cavities prophylactically solves the contamination issue, rather than seeks to understand it. Characterization of the contaminated cavities may lead to further understanding of the doping process and additionally act as a quality assurance check to prevent costly loss of materials. Here we use SEM, SIMS and XPS to investigate the cause of contamination.

Furnace Cap Design and Procedure

The furnace caps are designed not to be gas tight, as the cavity must be allowed to absorb significant gas quantity during the doping process (Fig. 1). RRR grade niobium was machined to include small pores to allow for gas transfer. Two holes on the edge of the caps are also included to attach the caps to the cavities with molybdenum bolts. Prior to assembly, all hardware associated with the caps is precleaned by buffer chemical polishing (BCP). The etch rate for molybdenum is significantly higher than niobium. The molybdenum components are rapid dipped in the BCP solution for ~2 seconds and then rinsed with deionized water. Ultrasonication in detergent and subsequent rinsed with deionized water are repeated and then blown dry with nitrogen. The caps are attached to the cavity in a clean room by tightening the molybdenum bolts finger tight. Overtightening will lead to cold welding during the high-temperature run.

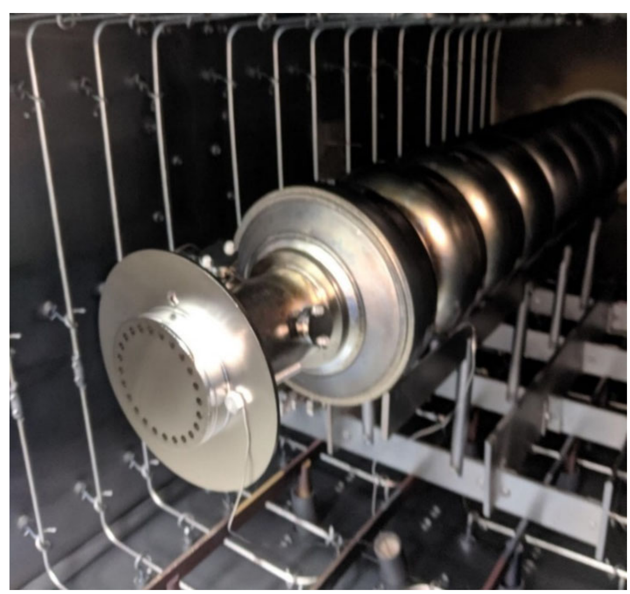

Figure 1: Depiction of a 9-cell cavity with furnace caps attached, loaded in N-doping furnace.

* Work supported by U.S. DOE Contract No. DE-AC05-06OR23177 and grant DE-SC0018918
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV006

DYNAMICS OF ONE-SIDE MULTIPACTOR ON DIELECTRIC*

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Abstract

Breakdown of dielectric RF windows is an important issue for particle accelerators and high-power RF sources. One of the generally considered reasons for the RF windows failure is the multipactor on dielectric surface. The multipactor may be responsible for excessive heating of dielectric and discharge of charges that accumulated in ceramic due to secondary emission. In this study the comprehensive self-consistent PIC simulations with space charge effect were performed in order to better understand the dynamic of one-side multipactor development and floating potential on dielectric induced by the emission. The important correlations between the multipactor parameters at saturation and the secondary emission properties of dielectric and the applied RF field parameters were found and are reported in the paper.

INTRODUCTION

One side multipactor, which is typical for RF windows, requires a returning force to develop. In case of isolated metal or dielectric body the returning force can be a result of floating potential which is due to charging of the isolated body by emission current. Also, an inhomogeneous RF field can by itself ensure the return of the emitted electrons to the body surface, but this case is not considered here. Buildup in the surface charge starts with random colliding electrons that come from other processes and sources with energy enough to generate larger number of secondary electrons. If the certain conditions are met, then, at early stage of multipactor development, the emission current (the secondary electrons that leave the body) is larger than the collision current (the electrons that return to and hit the body), so the surface charge buildup continues, and positive electric charge is accumulated on the body. With increasing of the returning force more and more of the secondary electrons start to return to the emitting surface and contribute to the floating potential. This stochastic process requires sufficiently high secondary emission yield of material (SEY) to be realized, and, unfortunately, the dielectric materials of RF windows typically have very high secondary emission yield (SEY=8-10 for alumina). Obviously that this charging cannot continue indefinitely and eventually the process comes to saturation at some equilibrium floating potential on dielectric.

The time-dependent physics of the one-side multipactor was studied in detail with self-consistent particle in cell (PIC) numerical simulations using CST Particle Studio. The main advantages of this PIC solver are true multiparticle dynamic, 3D space charge distribution, RF and static fields distortion due to impact from the space charge and the surrounding, advanced secondary emission models. It turned out that besides space charge effect the realistic energy spread of the secondary electrons to a large extent defines the dynamic of this type multipactor.

Particle-in-Cell Model

The principal PIC model is simple: it is a dielectric plate 40x20x0.2 mm placed in the static and radiofrequency (RF) electric fields. Uniform electrostatic electric field is perpendicular to the plate surface and acts as a returning force in the simulations without space charge effect, and it is disabled in simulations with space charge effects. With space charge effect a returning force is generated by a positive charge accumulated on the dielectric plate. Uniform RF electric field is parallel to the dielectric surface in both cases and provides the electrons with energy for the secondary electron generation. The equations of the electron motion in this case are as follows:

$$m\ddot{y} = -eE_{DC}; \quad m\ddot{x} = -eE_{rf0}\sin(2\pi f t + \theta) \qquad (1)$$

where x and y are respectively horizontal and vertical coordinate of the electron; m – electron mass; e – electron charge; E_{DC} – static electric field (external or induced by MP); E_{rf0} – amplitude of RF electric field; f – frequency of the RF field; θ – phase of the RF field at the moment of electron emission (initial phase of the emitted particle).

The emission property of plate's material is provided by assigned secondary emission model. Because of several reasons it was decided not to use the advanced probabilistic Furman emission model from CST library, and the dielectric plate was provided with the imported Vaughan emission model. The important incident energies of its SEY function are threshold energy W_t (SEY=0 below W_t), first crossover W_1 (SEY=1), W_{max} (SEY is maximal) and second crossover W_2 (SEY=1). The maximums of SEY functions varied from 1.5 to 3, which is much lower than a maximal real emission of dielectrics can be. The SEY was lowered in the simulations to avoid excessive number of particles being tracked and reduce time of simulation.

The only random gamma distributed initial energy of secondary electrons W_0 with maximum of probabilistic density function at 7.5 eV was used in all simulations.

The source of initial particles was placed in the center of the plate. It emitted particles at start of the simulations during one RF period T=1/f to cover all possible initial phases of particles. Total number of initial electrons was typically large ~10^4-10^5 since most of them usually are lost after emission ends without multiplication. For easier interpretation of starting stage of simulation, the initial electrons were monoenergetic with fixed energy of 7.5 eV and did not have angular spread – they all were emitted perpendicularly to the surface. Note, that this setting worked for initial particles only – during further simulations the parameters of secondary electrons were governed by chosen emission model.

* Operated by Fermi Research Alliance, LLC under contract No .DE-AC02-07CH11359 with the United States Department of Energy
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV007

SURFACE IMPEDANCE OF Nb_3Sn AND $YBa_2Cu_3O_{7-\delta}$ IN HIGH MAGNETIC FIELDS

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Abstract

New potential rf applications of superconductors are emerging with the need to operate in high dc magnetic fields (up to 16 T) where vortex motion dictates the response: the beam screen coating of the Future Circular Collider (FCC) and haloscopes, i.e. rf cavities for the axions detection. We present in this work measurements of the surface impedance Z_s up to 12 T on bulk Nb_3Sn and $YBa_2Cu_3O_{7-\delta}$ thin films by means of a dielectric loaded resonator operating at 15 GHz. We obtained the vortex motion resistivity and extracted the depinning frequency, the flux-flow resistivity and the pinning constant. Substantial differences are highlighted in the high frequency pinning properties of the studied materials, providing useful information on possible improvements in view of applications.

INTRODUCTION

Particle accelerators have for a long time benefited by the application of superconducting materials at radio frequency (rf) in zero static magnetic fields, allowing for resonant cavities with very high quality factors Q and thus providing very intense accelerating electric fields. Recently, a new field for the application of superconductors (SC) at microwave and radio frequencies opened up, namely the search for low surface resistance in high or very high dc magnetic fields. Examples are the beam screen in the Future Circular Collider project at CERN (frequencies up to f ~1.5 GHz [1], in static magnetic fields up to B =16 T at temperature $T = 50$ K), and haloscopes in dark matter research (high Q cavities operating in static magnetic B of the order of a few tesla [2]).

In the foreseen operating conditions the main source of losses in the superconductor arises from the dissipative motion of quantized magnetic flux lines (called fluxons or vortices) under the action of the alternating currents, making the zero-field surface resistance completely irrelevant. Minimization of these losses involves the reduction of fluxon motion by introducing suitable defects (vortex pinning centers). Engineered pinning centers in $YBa_2Cu_3O_{7-\delta}$ (YBCO) were found to strongly improve the performances in d.c. [3,4]. Moreover, it was shown long since [5] that the same nano-engineered defects are effective in reducing the microwave surface resistance $R_s := \mathrm{Re}(Z_s)$ of YBCO in moderate fields ($B \lesssim 1$ T), by increasing the pinning efficiency (measured by the so-called pinning constant k_p) also in the high frequency dynamics regime, although through a different pinning mechanism [6]. This effect was also observed in YBCO coated conductors (CC) [7,8], and regardless of the pristine material anisotropy [9]. Very recently, studies up to 9 T [10] in YBCO CC and up to 12 T [11] in YBCO thin films showed the effectiveness of artificial pinning centers (APC) at high fields, too.

With respect to the studies in YBCO, very little is known about the rf behaviour in the mixed state of Nb_3Sn, the workhorse of superconducting materials, promising as a successor of Nb in rf accelerating cavities [12], in moderate static magnetic fields.

Aim of this work is to present and compare sample studies on Nb_3Sn and YBCO. We report on microwave measurements at high magnetic fields ($\mu_0 H \leq 12$ T) of the surface impedance Z_s, and extract the relevant fluxon parameters through the established model for vortex motion, which is discussed in the following.

MODEL AND METHODS

The high frequency complex resistivity $\tilde{\rho}$ in the mixed state in the linear regime is [13]

$$\tilde{\rho} = \frac{\rho_{vm} + \mathrm{i}/\sigma_2}{1 + \mathrm{i}\sigma_1/\sigma_2} \tag{1}$$

where $\sigma = \sigma_1 - \mathrm{i}\sigma_2$ is the two fluid conductivity and ρ_{vm} is the vortex motion resistivity. The vortex motion resistivity depends on three physical mechanisms: the free motion of vortices, leading to dissipation in the vortex core, the vortex pinning, leading to elastic recall of the vortex with pinning constant k_p, and finally the thermally activated jumps from one pinning site to another, called flux creep. These mechanisms are built in the following expression:

$$\rho_{vm} = \rho_{vm,1} + \mathrm{i}\rho_{vm,2} = \rho_{ff}\frac{\chi + \mathrm{i}\nu/\nu_c}{1 + \mathrm{i}\nu/\nu_c} \tag{2}$$

where $\rho_{ff} = \Phi_0 B/\eta$ is the free-flux flow resistivity (as in absence of pinning), η is the so-called vortex viscosity, $\chi \in [0,1]$ is an adimensional creep factor (where $\chi = 0$ means no creep and $\chi = 1$ denotes maximum creep, condition in which creep completely washes out the pinning potential yielding $\rho_{vm} = \rho_{ff}$). The characteristic frequency ν_c is a combination of the creep factor and of the pinning frequency $\nu_p = k_p/(\eta 2\pi)$, and it is $\nu_c(\chi = 0) = \nu_p$ (the $\chi = 0$ model has been worked out longtime ago [14]). ν_c represents a synthetic evaluation of the (relative) amount of losses, as depicted in the plot of $\rho_{vm}(\nu)$ in Fig. 1.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV008

INSTRUMENTATION R&D FOR THE STUDIES OF SRF THIN-FILM STRUCTURES AT KEK AND KYOTO UNIVERSITY

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Abstract

We have been developing SRF instrumentations by which the effective lower critical magnetic field $H_{c1,eff}$ of superconducting-material sample is evaluated through the method of the third-order harmonic voltage measurement mainly for the studies of new SRF thin-film structures. Recently, the quad coil system, which enables us to measure four samples simultaneously in a single batch of an experiment, has been developed. In order to study the creation of thin-film structures inside the SRF cavity, we developed 3 GHz-shaped coupon cavities and an XT-map system for the performance tests of 3 GHz cavities. This article reports the details of these works.

INTRODUCTION

KEK and Kyoto University collaborate for the research to improve the performance of SRF cavities. Starting from a high-resolution camera system for defect detection in SRF cavities [1], various studies such as non-destructive inspection systems for SRF cavities [2], theoretical research on multilayer thin-film structures for high-Q/high-gradient SRF cavities [3-7], are conducted. One of the focused topics is the experimental investigation of thin-film superconducting structures, especially on superconductor-Insulator-Superconductor (S-I-S) structures, for performance enhancement of SRF cavities. In this article, we will report on the recent update result for studies of multilayer structure conducted by KEK and Kyoto University.

QUAD THIRD-ORDER HARMONIC DISTORTION MEASUREMENT SYSTEM

The measurement of effective lower critical magnetic field ($H_{c1,eff}$) for S-I-S thin-film structure is one of the important topics in the SRF community. Recently, it has been pointed out that the $H_{c1,eff}$ of a superconducting RF cavity might be increased by coating the inner surface of the cavity with a multilayer thin-film structure consisting of alternate insulating and superconducting layers [4, 5]. Generally, the $H_{c1,eff}$ of a superconducting material can be evaluated by applying an AC magnetic field to the material with a small coil and detecting the third-harmonic component in the coil voltage. This third-harmonic voltage component rises when the phase transition from the full Meissner state to the vortex-penetrating state happens. Hereafter, this method is called the third-harmonic voltage method. The measurement systems for third-harmonic voltage have been developed in CEA Saclay [8, 9], and later in Kyoto University [10] and KEK [11] in collaboration with CEA/Saclay. We have verified that the $H_{c1,eff}$ is enhanced for a sample with S-I-S structure that consists of NbN (200 nm) and SiO_2 (30 nm) formed on a pure Nb substrate that has an RRR of >250 [10, 11]. Recently, we have developed a new experimental setup for the third-harmonic voltage measurement system which allows us to measure four samples simultaneously in a single batch of the experiment. This feature can enhance the efficiency of the measurement cycle when the measurement is semi-automatic, as will be explained later. Figure 1 shows the 3D schematic view of the new experimental setup, consisting of four coil plates and a base plate made of aluminum. Four samples are mounted on the base plate (see Fig. 2). The coil plate is pressed down against each sample with a spring of appropriate pressure, and the distance between the coil plate and the sample is ensured by three ceramic balls embedded in the coil plate. Each coil plate has a cooling tab made of aluminum whose bottom area is immersed in liquid He (LHe). The temperature of the sample is controlled by a balance between the heater power and the heat flow through the cooling aluminum tab.

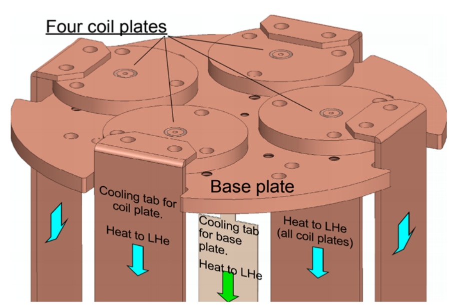

Figure 1: 3D schematic view of the third-harmonic voltage measurement system to measure four samples in a single batch of experiment.

Figure 2: Four coil plates on a base plate.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPFDV010

NEW RECIPES TO OPTIMIZE THE NIOBIUM OXIDE SURFACE FROM FIRST-PRINCIPLES CALCULATIONS*

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Abstract

The properties of niobium oxide are of critical importance for a wide range of topics, from the behavior of nitrogen during infusion treatments, to the nucleation of Nb_3Sn, to the superconducting properties of the surface. However, the modeling of the oxide is often much simplified, ignoring the variety of niobium oxide phases and the extremely different properties of these phases in the presence of impurities and defects. We use density functional theory (DFT) to investigate how electrochemical treatments and gas infusion procedures change the properties of niobium oxide, and to investigate how these properties could be optimized for Nb_3Sn nucleation and for niobium SRF performance.

INTRODUCTION

The niobium oxide system, which in general may include nitrogen, hydrogen, and other species, is extraordinarily complex, both in the sheer number of phases which may exist and in the wide variety of properties these phases can have. Therefore it is no surprise that modern cavity recipes which alter the oxide surface have been fertile ground for record-breaking niobium and Nb_3Sn SRF cavities, in particular 120C nitrogen-infused niobium cavities and Nb_3Sn cavities grown on pre-anodized niobium [1, 2]. However, we still lack a fundamental understanding of how different chemical conditions affect the composition of the surface oxide, and of how these changes result in improved SRF properties, or improved Nb_3Sn nucleation. If merely scratching the surface, so to speak, of surfaces-by-design has yielded such impressive advances in cavity performance, it behooves us to investigate the oxide surface in detail. Here we present density functional theory (DFT) calculations on niobium oxide; taken together with experimental measurements, they bring us closer to an understanding of the physical mechanisms at hand and potential avenues toward further improvement [3–6].

METHODOLOGY

All calculations are performed within a density-functional theory plane-wave pseudopotential framework using the open-source plane wave software JDFTx [7, 8]. To treat electron exchange and correlation, we use the Perdew-Burke-Ernzerhof (PBE) version of the generalized gradient approximation [9] to the exact density functional. To represent the effects of the atomic cores we employ ultrasoft pseudopotentials [10]. Solvated-surface calculations use the CANDLE polarizable continuum model [11]. To balance charge when calculating energy differences involving the removal of an OH- ion, the initial and final surface state are calculated with excess charge -0.5 and +0.5 respectively. Tc calculations use Eliashberg theory [12] for strong-coupled superconductors within a DFT framework, calculating electron-phonon matrix elements and employing Wannier function methods to integrate smoothly over all scattering processes on a dense momentum-space grid in order to precisely determine phonon linewidths [13, 14]. These linewidths are themselves smoothly interpolated in reciprocal space and integrated to calculate the phonon spectral function, which we then use to estimate T_c using the McMillan formula [15].

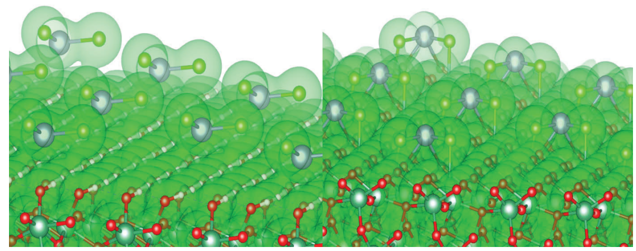

Figure 1: $SnCl_2$ molecules on a Nb_2O_5 surface with (left) and without (right) passivating OH groups covering the surface. An electron density contour is plotted in green.

NUCLEATION OF NB_3SN

Experiments have consistently shown that anodization of the niobium surface produces a thick oxide layer, and that nucleation of Nb_3Sn on this thick oxide results in much more uniform films and higher-performing cavities compared to nucleation on the thin, native niobium oxide surface [16]. Very recently, further experiments have shown that additional modifications to the nucleation step can further improve film uniformity, to the point that it has a shiny appearance as opposed to the usual matte, and a significantly higher quench field than previous Nb_3Sn cavities [2].

It is straightforward to show that the bulk reaction between the Nb_2O_5 oxide and the $SnCl_2$ nucleation agent is not energetically favorable. This immediately makes clear that a more nuanced picture, accounting for surface effects and defects in Nb_2O_5, is necessary in order to adequately describe the nucleation process. Fortunately, an extraordinary amount of research has been done on the low-temperature amorphous phase of Nb_2O_5 with the goal of characterizing its catalytic properties [17]. Our work builds on this research to understand how $SnCl_2$ interacts with a realistic niobium oxide surface.

* Work supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV001

VERTICAL ELECTRO-POLISHING OF 704 MHz RESONATORS USING NINJA CATHODE: FIRST RESULTS

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Abstract

Vertical Electro-Polishing (VEP) of elliptical cavities using rotating Ninja cathodes (Marui Company patented technology) has continually been improved since 2012 and successfully applied for 1300 MHz multi-cell ILC-type resonators. The goal of the presented study is to apply this technology to 704 MHz European Spallation Source (ESS)-type resonators with both better Q_0 and accelerating gradients in mind. We intend to demonstrate the superiority of VEP compared to standard Buffer Chemical Polishing (BCP), for possible applications such as MYRRHA accelerator. We describe here the promising results achieved on β = 0.86 single-cell cavity after 200 µm uniform removal. The cavity quenched at 27 MV/m without any heat treatment. The surface resistance achieved was less than 5 nΩ at 1.8 K. Substantial performance improvement is expected after heat treatment of the cavity and additional 20 µm VEP sequence. A cathode for 5-cell ESS cavity is concomitantly under design stage.

INTRODUCTION

CEA Saclay has been developing Vertical Electro-Polishing (VEP) since 2012 [1, 2] and a collaboration has been strengthened between KEK, Marui Galvanizing Co. Ltd and CEA Saclay. The goal of this collaboration is to demonstrate the feasibility of the VEP process as a key technology and its scalability to industry mass production of SRF cavities. Marui Galvanizing Co. Ltd has developed and continuously improved the design of a rotating cathode "i-cathode Ninja" for ILC shape configuration. Extensive parameter investigation is presented in [3, 4]. For the first time, this technology is developed for a lower frequency geometry: we intend to demonstrate that VEP using a Ninja cathode can be efficiently applied in 704 MHz configuration, which is presently used for ESS linac. With this purpose in mind, a specific cathode was designed to electropolish vertically a single-cell ESS cavity, with β = 0.86. RF results as well as surface aspects will be presented. Such a study might be useful for increased performance of 704 MHz resonators for linacs such as MYRRHA [5].

EXPERIMENTAL DETAILS

Cavity

The single cell cavity (EH101) has been manufactured by Zanon Research&Innovation using fine grain high purity niobium (RRR > 300) from Tokyo Denkai. The cell shape is the same as the end cell of high beta elliptical cavities for European Spallation Source (ESS) linac [6]. In Table 1 are summarized some relevant cavity parameters.

Table 1: Cavity Parameters

Parameter	Value
R/Q [Ω] @β=0.86	113
G [Ω]	250
E_{pk}/E_{acc}	1.88
B_{pk}/E_{acc} [mT/(MV/m)]	3.86
Inner surface [m^2]	0.55
Volume [l]	14.6

VEP Set-up

The VEP set-up operated at Saclay has been described in details in a previous publications [1]. To prevent from risks of explosion, nitrogen is flown in the acid tank and in the top of the set-up. The set-up has been upgraded with water sprays dedicated to the cooling of the external surface of the cavity. Four water sprays equipped with ten nozzles each are used (see Fig. 1). The temperature at the cavity surface was recorded at three locations (middle of the top beam pipe, top iris and equator). It was less than 17 °C at the three locations during all sequences.

For the experiments presented here, 200L of HF(40%) – H_2SO_4(96%) mixture with ratio 1-9 were used. Because of a modification of the fabrication process by our electrolyte supplier (increased venting during mixing), the HF concentration is lower compared to the standard one (HF mass concentration is approximately 0.5%). As shown in [7] where similar mixture was used, a decreased hydrogen incorporation in niobium might be achieved using this lower HF concentration. Complementary experiments are necessary to confirm that point.

Ninja Cathode

The core of the cathode is a hollow 70 mm diameter aluminium cylinder. A large diameter was chosen in order to increase as much as possible the cathode area so as to optimize the electrical field during the process and reduce sulphur contamination [8]. The cathode/cavity surface ratio is approximately 0.2. The aluminium cylinder is surrounded by a 114 mm diameter PVC cylinder which aims to guide the hydrogen bubbles along the cathode and prevents them to reach the cell surface. Four Teflon wings are used to stir

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV002

HOM EXCITATION IN SPOKE RESONATOR FOR SRF STUDIES

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Abstract

The excitation of Higher Order Modes (HOM) or Lower Order Modes (LOM) has been performed for years on multi-cell superconducting accelerating cavities as a mean to coarsely locate a quench, a defective area or ignite a plasma for surface cleaning. Moreover, such multi-mode testing is very useful to understand more accurately the frequency dependence of the surface resistance in a wide range of surface magnetic fields (0<B<150mT). In that sense, several type of dedicated non-accelerating resonators like Quadrupole Resonator (QPR), Half- or Quarter-Wave resonators have been built to specifically study new superconducting materials or new surface or heat treatments. What is proposed in this paper is to perform such multi-mode analysis (352 MHz, 720 MHz and 1300 MHz) in an existing accelerating cavity, in particular a Spoke Resonator. Baseline results will be presented and perspectives of such technique will be discussed.

INTRODUCTION

SRF cavities are nominally operated between 50 MHz and 4 GHz depending on their position in accelerators and on their mode of operation (accelerating, bunch corrections, crabbing, …). The most used frequency for particle acceleration and R&D purposes corresponds to the Tesla type 1.3 GHz elliptical cavity developed for light sources like the EU-XFEL and LCLS-II, and eventually used for next generation linear colliders like ILC. Years of intense R&D have been carried out worldwide through the Tesla Technology Collaboration (TTC) to reach the very ambitious specifications in term of accelerating gradient (Eacc) and quality factor (Qo). Most of models on surface resistance, optimization of surface treatment recipe is based on data collected at 1.3 GHz. However, the growing business of low beta structures for ion accelerators tends to show that recipes optimized at 1.3 GHz structures is not necessarily optimal at lower or higher frequencies [1]. More importantly, the field dependence of the surface resistance appears to be very dependent on the frequency. In an attempt to gain more insight in the frequency dependence, several studies [2, 3] have been performed and new dedicated SRF structures [4, 5] have been built. These studies are very delicate to carry out and interpret as the frequency dependence is studied in multiple cavity geometries requiring to proceed with identical surface treatments to be representative. On the other hand, the fabrication of dedicated SRF structures in which multiple modes can be excited is very expensive, time consuming and risky. Only one structure is built with no guarantee that it will be suitable for this kind of studies. What is suggested in this paper is to perform multi frequency analysis in low-beta accelerating cavities built during prototyping phase for accelerator projects. These cavities are typically numerous, not used on the linac and thus available for further studies.

At IJCLab, several Spoke resonators have been developed, built and optimized for Spiral2, ESS and MYRRHA projects. Multi-mode testing has been developed for MYRRHA prototypes as these cavities are easy to process and show very good performances like high achievable accelerating gradient, low surface resistance and low field emission. The cavity is externally coupled with a movable antenna with a stroke of 50 mm. The pick-up antenna is however fixed.

This paper aims at describing firstly all the RF simulations performed to characterize suitable modes and obtain important parameters. Secondly, all necessary room temperature measurements prior to cold test will be presented. Finally results of first cryogenic tests will be shared and discussed.

SIMULATIONS

RF Simulations

RF Simulations have been performed with CST Microwave Studio. The main goal of the simulations is to identify which modes could be easily operated with regular RF system. First the mode would need to be easily coupled with an antenna with a simple geometry and critical coupling at 2K should be achieved within the 50-mm stroke of the system. Moreover, the fixed pick-up antenna should show coupling factors, denoted Qt, compatible with Qo of all operational modes (typically $Qt > 10 \cdot Qo$). Secondly, the frequencies of modes should be close to standard frequencies like 700 MHz and 1.3 GHz so as to be compatible with existing RF equipment.

At the sight of all these constraints, several modes have been identified by simulation, important parameters are shown in Table 1 and field distributions in Fig. 1. So as to evaluate the peak magnetic field in the cavity during vertical testing, the specific parameter U/Bpk^2 can be used to translate the stored energy into peak magnetic field.

Table 1: Modes Parameters Estimated by Simulation

Id	Frequency (MHz)	U/Bpk^2 (J/mT^2)	G (Ohms)	Bpeak @1J (mT)
1	353	8.9e-3	109	15.8
2	719	7.75e-4	255	36.1
3B	1300	1.8e-3	396	24
3D	1312	6.6e-4	431	40
3E	1333	1.6e-3	483	25.4

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV003

1.3 GHz SEAMLESS COPPER CAVITIES VIA CNC SPINNING TECHNIQUE

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Abstract

The spinning process is an established technology to produce seamless resonant cavities. The main drawback is that, so far, a manual process is adopted, so the quality of the product is subject to the worker's skills. The Compute Numerical Controlled (CNC) applied to the spinning process can be used to limit this problem and increase the reproducibility and geometrical accuracy of the cavities obtained. This work reports the first 1.3 GHz SRF seamless copper cavities produced by CNC spinning at the Laboratori Nazionali di Legnaro of INFN. For this purpose, metrological analysis were conducted to verify the geometrical accuracy of the cavities after different steps of forming and thermal treatments; axial profile and wall thickness measurements were carried out, investigating different zones of the cavity profile. The cavities were also characterized through mechanical and microstructural analysis, to identify the effect of the automatic forming process applied to the production process of the 1.3 GHz SRF seamless copper cavities.

INTRODUCTION

In the last decade seamless cavities were investigated to limit the decreasing of the Quality Factor at high accelerating fields given by the welded cavities [1]. The study of new sheet forming techniques has been a fundamental part of the research at LNL. This was made possible thanks to the European Social Fund (FSE), project in which this activity is part of. The pursuit to produce seamless cavities is a current challenge to face the problem of the cost and possible mass production. There are different techniques to produce a seamless cavity, as for example spinning, hydroforming, explosive forming, electroforming etc [2]. The spinning process for a single cell cavity starts with a circular disk of a certain diameter and thickness and consists in four steps. In the first step the sheet metal blank is clamped against a mandrel on a spinning lathe, and gradually preformed onto a frustum-shaped mandrel. In the second step the first half-cell is formed, and a cylindrical shape is given to the remaining part of the piece, by means of a second pre-mandrel. In the third step the second half-cell is obtained through the spinning of the manufact onto a collapsible mandrel, that has the same shape of the cavity interior to guide the material in the fourth stage of the spinning process [2] (Fig. 1).

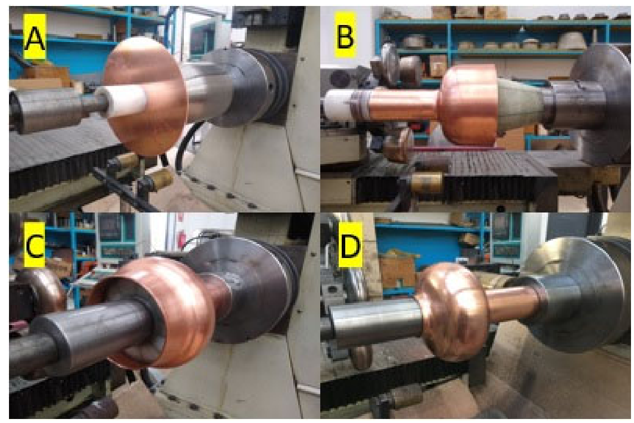

Figure 1: Spinning of a 1.3 GHz copper cavity via CNC A) Step 1, B) Step 2, C) Step 3, D) Step 4.

To reduce the variability due to the manual process of the operator and improve the reproducibility and geometrical accuracy of the cavities, the Compute Numerical Controlled (CNC) spinning process was applied.

The work shown in this document will deal with the study of the 1.3 GHz seamless copper cavities, through metrological and microstructural analysis, investigating the respect of dimensional tolerance, that is one of the challenges of this research for a large-scale production.

MATERIALS AND METHOD

The forming process starts from a 330 [mm] circular blank obtained from an Oxygen Free High Conductive (OFHC) Copper plate (Vickers micro hardness of 82±3 $HV_{0,5}$) through Wire EDM. Before the cold work, each blank is subjected to a first annealing in Ultra High Vacuum Furnace, to increase the ductility and reduce the contamination of the plate. To reach a desired vacuum value, a slow increasing temperature was applied to gradually degas the chamber. The thermal annealing was provided in the LNL UHV furnace following the thermal cycle reported in Table 1.

* Work supported by POR-FSE project, INFN CSNV group experiment TEFEN and performed under the CERN-INFN-SEFC Agreement
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV004

DEFLECTING CAVITIES FOR PROTON BEAM SPREADER IN CiADS PROJECT*

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Abstract

Chinese initiative Accelerator Driven Subcritical System (CiADS) is supposed to accelerate continuous 162.5MHz, 10 mA (or higher) proton beam to 500 MeV (or higher energy) with a superconducting driver linac. More application scenarios based on this high power intensity proton linac are now under considerations. Beam spreader system based on deflecting cavities for multiple users simultaneous operation are discussed in this paper, as well as the RF structure options for the equal eight- and nigh- beam-line split schemes.

INTRODUCTION

Deflecting cavities for beam separation were originally proposed at CEBAF and SLAC [1, 2]. With proper RF cavity resonant frequency, and appropriate bunch phase, the incoming bunch train could be separated to two ways or there ways equally, as shown in Fig. 1.

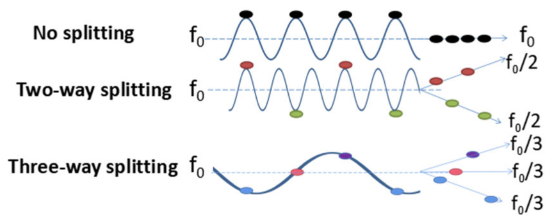

Figure 1: Two-way and three-way equal splitting scheme with deflecting cavities.

More beam lines could be achieved by repeating this process on each split beam line, with the second and the third class of deflecting cavities [3], as shown in Fig. 2 and Fig. 3. With seven cavities classified into three categories, the incoming bunch train with repetition frequency f_0 could be separated to eight bunch trains with equal repetition frequency $f_0/8$. With four cavities classified into two categories, the original bunch train f_0 could be split ted to nine $f_0/9$ bunch trains.

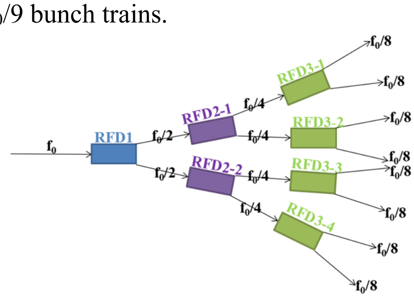

Figure 2: Eight beam lines with seven deflecting cavities classified into three categories.

*Work supported by Large Research Infrastructures "China initiative Accelerator Driven System"(Grant No.2017-000052-75-01-000590) and National Natural Science Foundation of China (Grant NO. 11805249)
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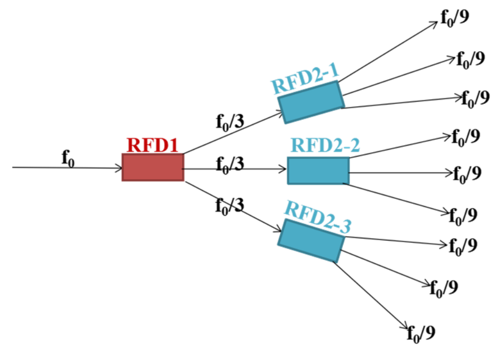

Figure 3: Nine beam lines with four deflecting cavities classified into two categories.

RF FREQUENCY OF THE DEFLECTING CAVITY

For the two-way splitting scheme, the RF frequency of the deflecting cavity (RFD1) could be $f_0/2$, $3f_0/2$, 5f0/2, and higher, as shown in Fig. 4. For the three-way splitting scheme, the RF frequency of the deflecting cavity (RFD1) could be $f_0/3$, $4f_0/3$, $7f_0/3$, and higher, as shown in Fig. 5. Here f_0 is the incoming bunch repetition frequency.

For the second class cascading deflecting cavities (RFD2), the incoming bunch repetition is $f_0/2$ and $f_0/3$ for the two-way and three-way splitting scheme, separately. For 162.5 MHz proton bunches, RF frequencies of the deflecting cavities in each cascading scheme for the eight-beam-line scheme and nigh-beam-line scheme are summarized in Table 1.

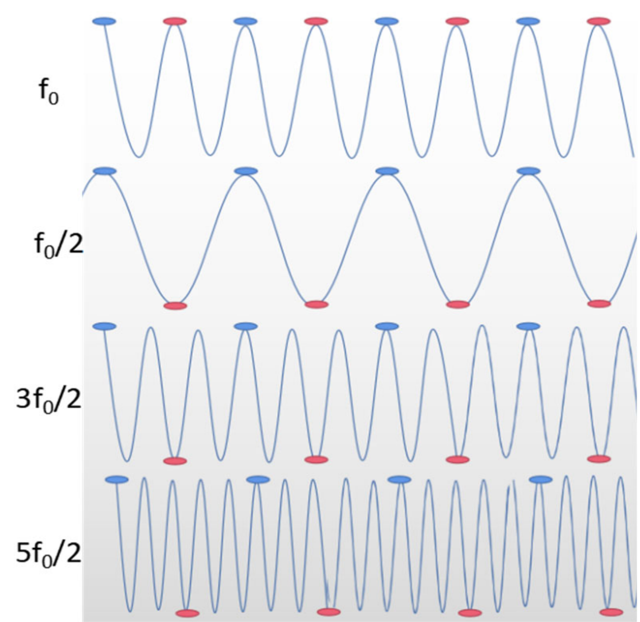

Figure 4: Two-way splitting scheme with RF deflecting cavity frequency equal to $f_0/2$, $3f_0/2$,$5f_0/2$.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV005

TOWARD QUALIFICATIONS OF HB AND LB 650 MHz CAVITIES FOR THE PROTOTYPE CRYOMODULES FOR THE PIP-II PROJECT *

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Abstract

High-beta (HB) and low-beta (LB) 650 MHz cryomodules are key components of the Proton Improvement Plan II (PIP-II) project. In this contribution we present the results of several 5-cell HB650 cavities that have been processed and tested with the purpose of qualifying them for the prototype cryomodule assembly, which will take place later this year. We also present the first results obtained in LB650 single-cell cavities process optimization. Taking advantage of their very similar geometry, we are also analyzing the effect of different surface treatments in FRIB's 5-cell medium-beta 644 MHz cavities. Cavities processed with N-doping and mid-T baking showed very promising results in term of both Q-factors and accelerating gradient for these low-beta structures.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) project aims to upgrade the Fermilab accelerator complex to power the world's most intense high-energy neutrino beam for the Deep Underground Neutrino Experiment (DUNE). The high-power proton beam will also enable muon-based experiments and a broad physics research program [1].

PIP-II includes the construction of a 215 m superconducting linear accelerator that will accelerate protons up to 800 MeV by using 5 different types of superconducting cavities: Half-Wave-Resonators (HWR), Single-Spoke-Resonators (SSR1 and SSR2), low- and high-beta 650 MHz elliptical cavities (LB650 and HB650) [2]. The project relies on significant international contributions, from cavities to cryomodule assembly for many of these sections [3].

* Work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under U.S. DOE Contract No. DE-AC02-07CH11359
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This proceeding focuses on the status of 650 MHz cavities qualification for which Fermilab partners with RRCAT (India), VECC (India), UKRI (United Kingdom) and INFN (Italy) [4, 5].

Several HB650 pre-production bare cavities have been qualified in vertical tests at Fermilab and are being jacketed, awaiting now for qualification for the prototype-CM assembly which will start in fall this year. LB650 cavities are currently undergoing a processing optimization phase, currently involving both single-cell and 5-cell cavities.

We are also studying the effect of different surface treatments in FRIB 644 MHz medium-beta cavities which show very similar design. This effort started in the framework of an Accelerator Stewardship in collaboration between Fermilab, Michigan State University (MSU) and Argonne National Laboratory (ANL) and is now being carried out in collaboration with the PIP-II project.

HB 650 MHz CAVITIES: QUALIFICATION FOR pCM ASSEMBLY

After a first phase of processing optimization that involved a large number on single-cell high-beta 650 MHz cavities [6], the processing was then transferred to bare 5-cell cavities that were tested in the Vertical Test Stand (VTS) at Fermilab. Cavities that met PIP-II specifications ($Q_0 = 3.3 \times 10^{10}$ at 18.8 MV/m) were jacketed with He-vessel and tested again for the final qualification for cryomodule assembly. Some of the cavities were also instrumented with temperature and magnetic sensors before being jacketed in order to allow for the monitoring of temperature and magnetic field during the cryomodule testing. Some of the cavities are also tested horizontally in the Spoke Test Cryostat (STC) which has been modified to allow for 650 MHz cavities testing [7].

Fermilab has a total of seven HB650 prototype cavities: four $\beta = 0.9$ that were procured several years ago and three $\beta = 0.92$ that were recently received from RRCAT (India).

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV006

Nb_3Sn FILMS DEPOSITIONS FROM TARGETS SYNTHESIZED VIA LIQUID TIN DIFFUSION

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Abstract

The deposition of Nb_3Sn on copper cavities is interesting for the higher thermal conductivity of copper compared to common Nb substrates. The better heat exchange would allow the use of cryocoolers reducing cryogenic costs and the risk of thermal quench [1]. Magnetron sputtering technology allows the deposition of Nb_3Sn on substrates different than Nb, however the coating of substrates with complex geometry (such as elliptical cavities) may require targets with non-planar shape, difficult to realize with classic powder sintering techniques. In this work, the possibility of using the Liquid Tin Diffusion (LTD) technique to produce sputtering targets is explored. The LTD technique is a wire fabrication technology, already developed in the past at LNL for SRF applications [2], that allows the deposition of very thick and uniform coating on Nb substrates even with complex geometry [3]. Improvements in LTD process, proof of concept of a single use LTD target production, and characterization of the Nb_3Sn film coated by DC magnetron sputtering with these innovative targets are reported in this work.

INTRODUCTION

The thin film technology deposition of Nb_3Sn represents an interesting perspective for superconducting radio frequency (SRF) applications. Nb_3Sn shows potential limits, as critical temperature and theoretical accelerating gradient, that are higher with respect to Nb. The Nb_3Sn thin films on Nb bulk cavities produced by Vapor Tin Diffusion (VTD) show excellent performances, but there is a strong interest in growing Nb_3Sn on a Cu substrate ,because of its higher thermal conductivity, by PVD techniques [1].

The features required for the cylindrical cathode cooling related to the fragility of the material, make the classic sintering from powders difficult to implement.

One possible solution is the production of the targets by growing thick films of Nb_3Sn on a niobium substrate with Liquid Tin Diffusion (LTD) technique [3].

Along the years, different coating methods for Nb_3Sn have been developed and in particular, LTD has been deeply studied at LNL from 2005 to 2009 [2]. The LTD allows the formation of thick films on niobium substrates by direct immersion in molten tin. The films deposited with DC magnetron sputtering are analysed and the characteristics are correlated with the synthesis process via LTD.

The LTD technique allows the coating on substrates with complex geometry. The synthesis of cylindrical targets for 6 GHz and 1.3 GHz cavities at industrial level is relatively easy to scale.

EXPERIMENTALS

The material under study is Nb_3Sn synthetised on bulk Nb substrate. Two types of samples are studied: 37 small Nb bulk samples (30x15x3 mm) and 5 one-inch planar targets 3 mm thick. The niobium substrates are subjected to ultrasonic bath and subsequent BCP (Buffer Chemical Polishing) HF: HNO_3: H_3PO_4 in a 1:1:2 ratio from five to ten minutes. The substrates prepared for pre-nucleation are subsequently anodized at 20 V for one minute in NaOH solution to form a 70 nm Nb_2O_3 layer. For each run, 2 samples at a time have been used: one anodized and one just polished with BCP to evaluate possible change in the film growth.

The LTD system consists of an ultra-high vacuum pumping system, a linear manipulator, a furnace used for heating the crucible containing the tin, a furnace used for annealing of the samples, and a water jacket. The main chamber is made of Inconel. The samples are fixed to the manipulator by niobium wires. The system is heated and evacuated to a base pressure of 10^{-8} mbar. The dipping process is divided into various steps as described in Fig. 1 and Fig. 2. The total protocol is summarized below [4].

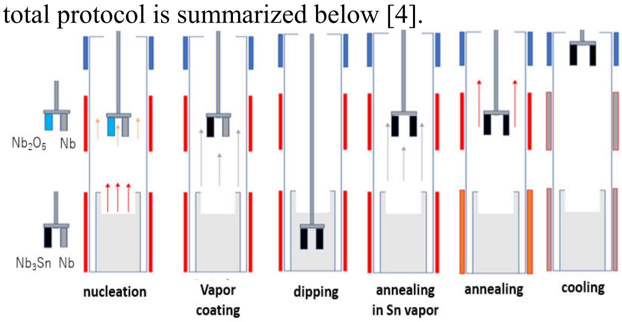

Figure 1: Samples position in the chamber in the dipping "hybrid" process with nucleation.

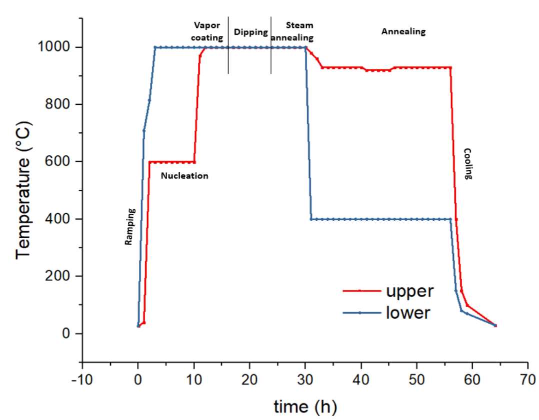

Figure 2: Temperature profiles of furnaces in the "hybrid" process with nucleation step for targets synthesis.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV009

AMR SENSORS STUDIES AND DEVELOPMENT FOR CAVITIES TESTS MAGNETOMETRY AT CEA

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Abstract

Studying flux expulsion during superconducting cavities test increases the need for exhaustive magnetometric cartography. The use of Anistropic Magneto Resistance (AMR) sensors, much cheaper than commercial fluxgates, allows the use of tens of sensors simultaneously. Such sensors are developed and sold for room temperature application but are resistant to cryogenic temperatures. However, they need proper calibration, which is more difficult at cryogenic temperature. Actually, this calibration uses the flip of the magnetization of the anisotropic ferromagnetic element, which coercitive field is increased at low temperature. We will present the development of method and software carried out at CEA for the use of such sensors, as well as the preliminary design of a rotating magnetometric device destined to elliptical cavities.

AMR SENSORS CHARACTERIZATION

In order to achieve high performances for superconducting cavities it is necessary to control their material behavior and their environment during operation. In our laboratory we are currently designing a suite of detectors that will focus on superconducting cavities diagnostic during their test in liquid helium bath.

The magnetic field, even if lower than the earth magnetic field, increases the Joule losses, thus it is important to control it. We are currently developing detectors able to map the magnetic field around the cavity at cryogenic temperature. The sensors are AFF755 from Sensitec. They exploit the anisotropic magnetoresistance (AMR) of a ferromagnetic material at their core. They are much cheaper than the current standard for this kind of measures (Fluxgate) and should enable to equip a cavity cryostat or even a cryomodule with more detectors.

However, they need a calibration step to get their sensitivity, which is the relationship between the voltage measured by the sensor and the magnetic field, and which varies with temperature. Our calibration procedure uses two specific coils already implemented in the sensors: the flip coil, which magnetizes the ferromagnetic material, made of permalloy, and the test coil, which generates a controlled magnetic field. This calibration can be achieved in situ, when the sensors are placed inside a cryostat, and in an unknown magnetic field.

We defined a calibration procedure that allows calibration even in an unknown ambient magnetic field. The first step is to characterize the test coil (TC) for each sensor by the relationship between the coil current and the coil generated magnetic field. To this intend, the sensor response to the test coil is compared to the sensor response to a reference Helmholtz coil and the α coefficient is deduced:

$$B_{TC} = \alpha I_{TC}$$

We have verified that α does not change at cold temperatures. Actually the only effect of the temperature change on the coil is thermal shrinkage, which is very small.

The second step is to apply a set of TC field after a positive flip coil $B_{TC}(Flip_+)$ and after a negative flip coil $B_{TC}(Flip_-)$, and to measure the corresponding voltages $U(Flip_+)$ and $U(Flip_-)$.

We get two curves with B_{TC} vs U, one for Flip+ and one for Flip-,

$$B_{TC}(Flip_+) = a_1 U(Flip_+) + B_1$$

$$B_{TC}(Flip_-) = a_2 U(Flip_-) + B_2$$

From which we extract a_1, a_2, B_1 and B_2.

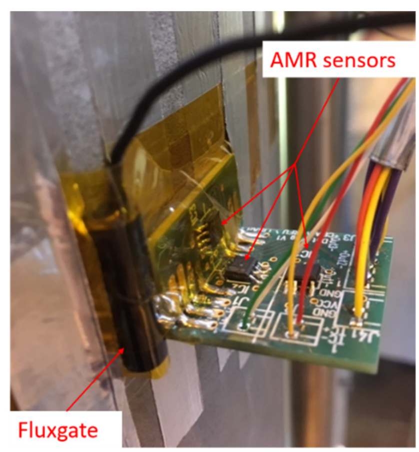

Figure 1: Set of three AMR sensors (X, Y and Z) and fluxgate installed on a cavity.

The slopes, a_1 and a_2, are opposite to each other. The offsets B_1 and B_2 contain both the electrical offset of the sensor and the ambient magnetic field, which are unknown. In order to get rid of the ambient field, we calculate the electrical offset, which is supposed to be the same for both flips:

$$B_{OFF} = \frac{B_{Flip-} + B_{Flip+}}{2} = \frac{B_1 + B_2}{2}$$

And then the real magnetic field:

$$B = a_2 U + B_2 - B_{OFF} = a_2 U + \frac{B_2 - B_1}{2}$$

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV010

APPLICATION OF THE ASME BOILER AND PRESSURE VESSEL CODE IN THE DESIGN OF SRF CAVITIES AT FERMILAB*

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Abstract

Jacketed Superconducting Radio Frequency (SRF) cavities structurally comprise of an inner niobium vessel surrounded by a liquid helium containment vessels. The pressure of the helium bath and/or its volume might be such that a jacketed SRF cavity shall be considered a system of pressure vessels. Thus, methods described in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) should be used to analyze the structural soundness of jacketed SRF cavities. This paper will report the use of the set of rules developed at Fermilab for the design of SRF cavities, such as jacketed 1.3 GHz cavities for LCLS-II HE and jacketed Single Spoke Resonator type 2 (SSR2) for PIP-II, to ensure a similar level of safety as prescribed by the ASME BPVC.

INTRODUCTION

Jacketed Superconductiong Radio Frequency (SRF) Cavities are designed, manufactured, and used at Fermi National Accelerator Laboratory for a variety of research purposes. SRF cavities have multiple pressure retaining volumes that bring them within the scope of the Boiler and Pressure Vessel Code (The Code) [1]. There are multiple issues inherent in the design of SRF Cavities that prevent an acceptable Code design such as using materials not accepted into The Code. As required by the Department of Energy (DOE) directive 10 CFR 851, an equivalent level of safety is required for the vessels as the The Code, so to ensure an equivalent level of safety, internal documentation has been defined [2]. Additional documentation needed for acceptance is defined in the Guidelines for Design, Fabrication, Testing and Installation of SRF Nb Cavities (SRF Guidelines) [3].

The SRF guidelines provides additional requirements to The Code such as material properties, allowable weld documentation, and analysis methods. Details of these processes will be discussed as they relate to the LCLS-II HE [4] and SSR2 Cavities [5] [6].

The LCLS-II HE and SSR2 cavities serve as an intermediary point between design methods at Fermilab. Starting with the SSR1 Cavities [7], the elastic-plastic method of analysis has been used to verify the safety of the cavities. Cavities previously designed at Fermilab have been analyzed using primarily design by rule and elastic material methods. The LCLS-II HE, SSR1, SSR2 are the beginning of cavities designed using primarily elastic-plastic material methods. The successful design of cavities using the elastic-plastic material methods may lead to more optimized cavity designs in the future.

CAVITY DESIGNS

There are two general designs for SRF cavities made at Fermilab, Elliptical Cavities and Spoke Cavities.

Elliptical cavities are generally designed as a two part structure comprised of a Cavity and Jacket. The cavity is a convoluted niobium structure. The Jacket is a cylindrical helium vessel, usually made of Titanium, and joined to the cavity through conical transition rings. The frequency of each cavity is controlled with a tuner. The tuner serves as a way to finely tune the frequency of the cavity during operation. Details of the effects of the tuner on their cavities can be seen in their respective engineering notes [8]. One example of a dressed cavity designed at Fermilab is the LCLS-II HE 1.3 GHz Cavity seen in Figure 1.

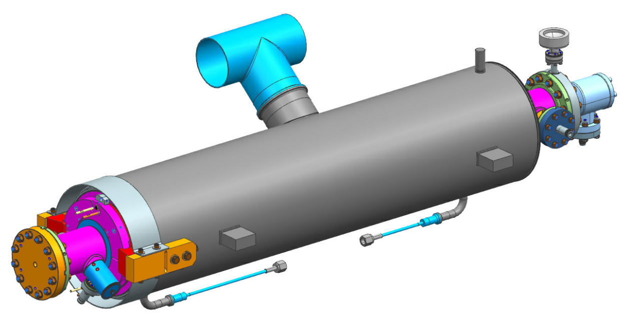

Figure 1: LCLS-II HE Cavity Assembly.

Spoke cavities are designed as a niobium cylindrical shell surrounded by the metallic jacket. The cavity addressed in this report is the SSR2 cavity for use in the PIP-II project and can be seen in Figure 2.

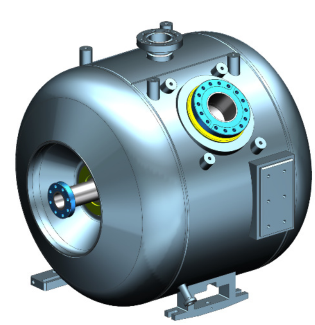

Figure 2: SSR2 Cavity Assembly.

* Work supported by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV013

STC QUALIFICATION TESTS OF PIP-II HB650 CAVITIES

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Abstract

Design of the high beta 650 MHz prototype cryomodule for PIP-II is currently undergoing at Fermilab. The cryomodule includes six 5-cell elliptical SRF cavities with accelerating voltage up to 20 MV and low heat dissipation ($Q_0 > 3.3 \cdot 10^{10}$). Characterization of performance of fully integrated jacketed cavities with high power coupler and tuner is crucial for the project. Such a characterization of jacketed cavity requires a horizontal test cryostat. The Fermilab Spoke Test Cryostat (STC) has been upgraded to accommodate testing of 650 MHz cavities. Commissioning of upgraded STC has been reported at SRF'19 conference. In this paper we present results of testing of the prototype HB650 cavity in upgraded STC facility. We characterize cavity performance and qualify it for the prototype HB650 cryomodule assembly.

INTRODUCTION

Ongoing upgrade of the Fermilab proton source, Proton Improvement Plan II (PIP-II), aimed to deliver intense neutrino beam to LBNF/DUNE and support frontier particle physics experiments [1, 2]. Major part of PIP-II accelerator is a Superconducting RF (SRF) linac, accelerating 2 mA beam of H^- ions up to 800 MeV. To optimize performance, the SRF linac employs five different types of cryomodules. The last section of linac has four cryomodules, containing six 5-cell elliptical high-beta ($\beta = 0.92$) 650 MHz (HB650) cavities providing accelerating voltage up to 20 MV with low heat dissipation, $Q_0 > 3.3 \cdot 10^{10}$. Design of the prototype HB650 cryomodule is completed and cryomodule assembly will start soon. Successful cryomodule construction requires characterization of performance of fully dressed HB650 cavities assembled with high power coupler and tuner in a horizontal test facility. Earlier we described the upgrade of the Fermilab Spoke Test Cryostat (STC) which included installation of the STC vacuum vessel extension with magnetic and thermal shields, modifications of cryogenic connections and RF infrastructure to accomodate testing of 650 MHz cavities, while also retaining capability of testing SSR1 and SSR2 cavities [3]. First cold test of HB650 cavity in STC was performed in 2020. The goals of the test were threefold: 1) Commissioning of STC for 650 MHz testing, including facilities (mechanical, instrumentation, vacuum, cryogenic, RF systems, safety/interlocks), procedures, documentation; 2) Validation of 650 MHz high power coupler and tuner design; 3) Qualification of the prototype HB650 cavity (s/n `B9A-AES-010`, $\beta = 0.9$). Here we report results of this test.

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CAVITY PREPARATION AND INSTALLATION TO STC

Standard procedure for HB650 cavities processing before testing at STC and/or assembly in cryomodule includes bulk material removal with electropolishing (EP), high temperature bake with N-doping option, tuning cavity frequency and field flatness, light EP, HPR, and assembly for vertical testing in cleanroom [4]. After jacketing of cavity `B9A-AES-010` its field flatness degraded, which required additional re-tuning. This jacketed cavity hasn been tested at the Fermilab Vertical Test Stand (VTS) and achieved $Q_0 \approx 2 \cdot 10^{10}$ at 20 MV/m.

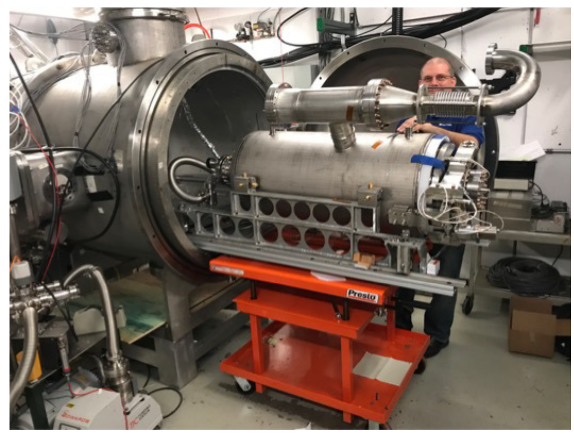

Figure 1: HB650 $\beta = 0.9$ cavity assembled with the cold part of the high power coupler, tuner, LHe fill line and the interface elbow.

Following VTS testing, cold part of the power coupler was installed on the cavity. After installation of safety brackets, which prevent cavity without tuner from movement and deformation, cavity was evacuated and moved for the installation to the STC facility building. In order to move cavity into the STC enclosure, two concrete blocks were removed from the enclosure roof, the cavity was lifted from its transportation crate and lowered to the insertion cart at the assembly table inside enclosure using building crane. Since this was the first HB650 cavity in STC, after alignment of the cavity inside cryostat with respect to the coupler port, the elbow interfacing the cavity 2-phase pipe and the cryostat 2 K helium header was field fitted. For tuner installation cavity beam line vacuum space had to be backfilled to 1 atm. We modified STC vacuum system to accomodate slow backfill with dry nitrogen and slow evacuation. Figure 1 shows cavity ready for insertion to STC cryostat.

STC cryostat, cavity and coupler are instrumented with temperature and magnetic field sensors. `B9A-AES-010` has additional sensors installed inside helium vessel, as shown in Fig. 2.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV014

DESIGN OF A THIRD HARMONIC CAVITY WITH LOW R/Q FOR THE ESR IN BNL EIC*

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Abstract

For the electron Storage Ring (ESR) of Brookhaven National Lab Electron Ion Collider (BNL EIC), beam loading is a great concern due to the high beam current together with abortion gap, especially for harmonic cavities due to higher operational frequency. There were attempts to use feedback/feedforward control, using multiple cavities with counter-phasing [1]. A straightforward way to lower beam loading effect is to design a cavity with low *R/Q*. In this paper, we show such a design for the 3rd harmonic cavity for BNL EIC ESR.

INTRODUCTION

In the BNL EIC ESR, counter-phasing was studied to be used to fight against beam loading of the 1st harmonic and possible 3rd harmonic accelerating cavities. There are drawbacks of using this technique, such as higher RF power, higher power dissipation on cryo system, limited working conditions, etc. A better way to ease the beam loading effect, is to design a cavity with lower *R/Q* while maintaining the other RF parameters. In this paper, we describe cavity designs with effective length longer than half of the working mode's wavelength, and with large beampipes that connected to the cavity with chokes, so that peak fields can be controlled at certain cavity voltage while *R/Q* can be lowered, and higher order modes (HOMs) can be damped using beampipe absorber. We also present the multipacting analysis, as well as a special fundamental power coupler (FPC) design.

CAVITY DESIGN

We start from the design in the pre-conceptual design report (pCDR) [2] see Fig. 1. It is a 1-cell elliptical cavity with λ/2 cavity length, with λ the wavelength of the working mode with resonance frequency f_0. Two half-cells of this cavity are identical, with the iris of each half choked and connected to the enlarged beam pipe using a taper. An FPC port is located on the right side of the cavity. SiC absorbers are used on both sides as HOM absorbers. There will be 5 cavities in the ESR providing up to 7.8 MV accelerating voltage. Each cavity is designed to provide 1.6 MV. Some of the RF parameters of this cavity are shown in Table 1. The *R/Q* of the pCDR design is 51.5 Ω, with all impedances in circuit definition in this paper, and the design goal is to lower it to 1/3 of the original value.

There are two convenient approaches to achieve a lower *R/Q*: enlarged beampipe diameter, and a cavity either longer or shorter than λ/2. With enlarged beampipe or shorter cavity, however, normally has enhanced peak electric field E_{pk} and peak magnetic field B_{pk} while maintaining its accelerating voltage V_{acc}. For a longer cavity, the lowest HOM frequency will be closer to, or even smaller than the working mode frequency at 1.7736 GHz. We explore the possibility of the cavity design with longer length together with large beampipe in this paper.

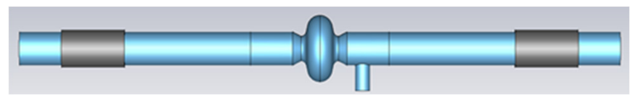

Figure 1: pCDR design of the 3rd harmonic cavity. It is a 1-cell λ/2 elliptical cavity, with an FPC port on the right side and two SiC HOM absorbers on the beampipes.

Table 1. RF parameters of the 3rd harmonic cavity of BNL EIC ESR at 1.7736 GHz. Peak fields are normalized to 1.6 MV accelerating voltage.

	pCDR design	Design goal	New 1-cell design	New 2-cell design
R/Q [Ω]	51.5	17.0	20.7	15.9
B_{pk} [mT]	82.4	80.0	115.6	81.0
E_{pk} [MV/m]	37.4	40.0	19.1	24.3

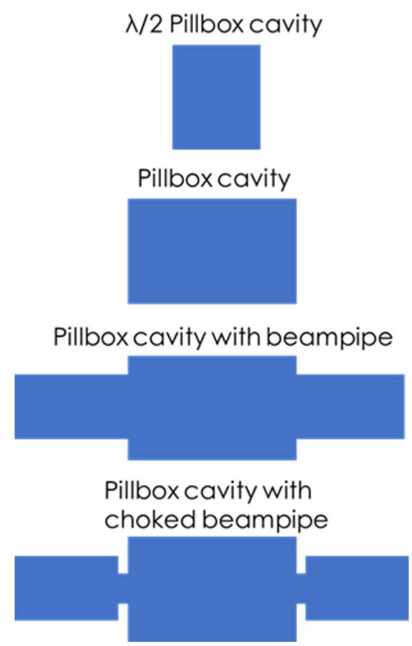

Figure 2: Design towards a longer cavity with low R/Q.

The design should adopt a simple damping scheme that is able to handle high HOM power. There are three candidates: 1, beampipe absorber, as shown in pCDR; 2, on cell damping with rectangular or ridged waveguide; and 3,

* Work supported by Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the US DOE.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPCAV015

PERFORMANCE OF A LOW FREQUENCY QWR-BASED SRF GUN*

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Abstract

Superconducting radio-frequency (SRF) electron guns are generally considered to be an effective way of producing beams with high brightness and high repetition rates (or continuous wave). In this work, the 199.6 MHz quarter wave resonator (QWR)-based Wisconsin Free Electron Laser (WiFEL) superconducting electron gun was recently refurbished and tested at Argonne (ANL). The field performance of the e-gun was fully characterized. During this time, multipacting (MP) conditioning was performed for over 20 hours to overcome the hard MP barrier observed in the accelerating voltage range of 8 to 40 kV; the presence of multipacting is expected to operationally important for future e-guns. Here we simulated and studied the effect using CST [1] Microwave Studio and Particle Studio and compare with the measured data.

INTRODUCTION

For the next generation light source (such as for the LCLS-II project at SLAC) or the instruments for ultrafast electron diffraction or microscopy, high brightness electron beams are of the high importance, where beam brightness is related to the ratio of the beam current to the emittance. The electron beam source should also achieve high repetition rates (up to continuous wave CW operation), and very short pulses. A promising solution uses a quarter wave superconducting electron gun, which could provide electrons in continuous wave mode, and the cryogenic environment may reduce the normalized transverse emittance of the beam [2].

The 199.6 MHz quarter wave resonator (QWR)-based Wisconsin Free Electron Laser (WiFEL) gun cavity was originally designed and fabricated by University of Wisconsin and NIOWAVE Inc. The cavity was transported and arrived at Argonne for additional tests in December 2019. Due to a damaged coupler bellows and contamination in the cavity, the gun was dissembled and cleaned by high pressure rinsing (HPR), followed by clean re-assembly after the cavity had been fully dried.

The cavity geometry together with the electromagnetic field distributions are presented in Fig. 1. In this work, the MP conditioning process (in CW mode) of the WiFEL cavity was experimentally measured and its behavior was then studied using CST simulations. After breaking through the MP barrier, a sequence of rf cold tests were performed after individual rounds of pulsed conditioning with up to 4 kW of available power. An intrinsic cavity factor Q_0 was found to be 2.3×10^8 at the highest stable CW peak field level of 15 MV/m.

* This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
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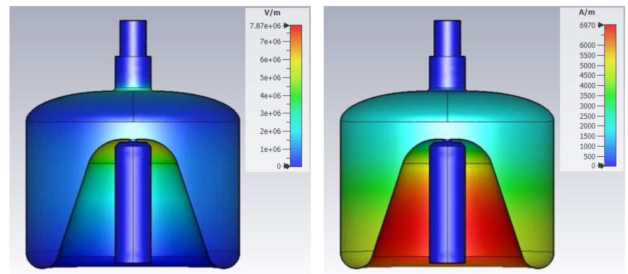
The geometry of the WiFEL cavity together with the electromagnetic field distribution is shown in Fig. 1, which is simulated by using the CST Microwave Studio's Eigenmode solver.



(a) Electric field (b) Magnetic field

Figure 1: Simulated electromagnetic field distribution of the cavity.

CAVITY COLD TESTS

The experimental setup for the cold tests is shown in Fig. 2, where the cathode stalk was replaced by a capacitive cavity field probe with a simulated Q_{ext} of $\sim 1 \times 10^{11}$. The cold tests were started with a 3-day CW MP conditioning until the MP barrier 'broke though'. More studies on the WiFEL cavity's MP behavior will be presented in the next section. Then the cavity Q-curve was determined from the direct measurements of the forwarded (V_F), the reflected (V_R) and the transmitted (V_T) signal voltage in CW mode; two systematic readout errors of ± 0.08 dB from the oscilloscope (Tektronix TDS-7404B) and ± 0.05 dB from the power meter were considered in all measurements.

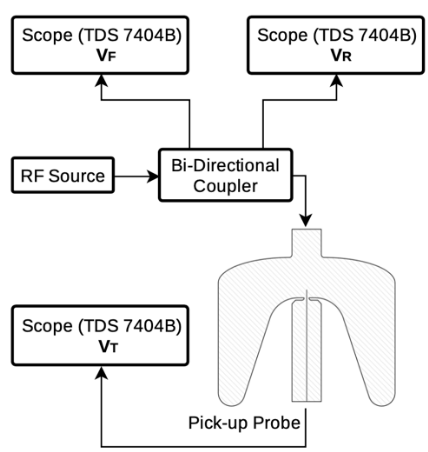


Figure 2: Simplified schematic diagram of the experimental setup.

Figure 3 shows the four Q-curve measurements as a function of the peak gradient (E_{peak}). The first Q-curve was obtained after breaking though the MP barrier. Then

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV001

RF EXPERIENCE FROM 6 YEARS OF ELBE SRF-GUN II OPERATION

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Abstract

At the electron accelerator for beams with high brilliance and low emittance (ELBE), the second version of a superconducting radio-frequency (SRF) photoinjector was brought into operation in 2014. After a period of commissioning, a gradual transfer to routine operation took place in 2017 and 2018, so that now more than 3400h of user beam have already been generated since 2019. During this time, a total of 20 cathodes (2 Cu, 12 Mg, 6 Cs2Te) were used, but no serious cavity degradation was observed. In this paper, we summarize the operational experience of the last 6 years of SRF gun operation, with special emphasis on main RF properties of the gun cavity.

INTRODUCTION

At the superconducting (SC) electron linear accelerator of the ELBE radiation facility [1] a new superconducting electron photo injector has been installed in May 2014. This SRF gun II is replacing the previous one which had been in successful test operation from 2007 until April 2014. Although SRF gun I could not reach the design specifications, it was successfully operated for R&D purposes and also some dedicated user experiments at the ELBE accelerator had been done [2].

For SRF gun II a new niobium cavity has been built, treated and tested at JLab [3]. At the same time a new cryomodule has been designed and built at HZDR. In November 2013, the cavity was shipped to HZDR and assembled into the cryomodule. About half a year later, the gun was installed into the ELBE accelerator hall and transferred into routine operation. The main task of SRF gun II is to demostrate an average current up to 1 mA as well as to serve as an electron source for user operation (e.g. THz generation with 200 pC and some 100 kHz of rep. rate).

CRYOMODULE DESIGN

The design of the SRF gun II cryomodule is shown in Fig. 1. Most of the components are similar or even identical to the previous gun [4].

The cryomodule is designed for CW operation of a superconducting Nb cavity cooled down to 2K. For this purpose, the helium vessel is equipped with a 2-phase helium pipe that can handle a heat load of 40 W (or 2g/s). This value is composed by 7 W static loss and up to 33 W dynamic loss. Since the latter is determined by the electrical field inside the cavity in addition an electric heater is used to operate the cryomodule always at the same helium load (or mass flow) regardless of the cavity gradient. This has been proven to be advantageous to achieve a pressure stability of down to 0.1 mbar rms in the whole helium system.

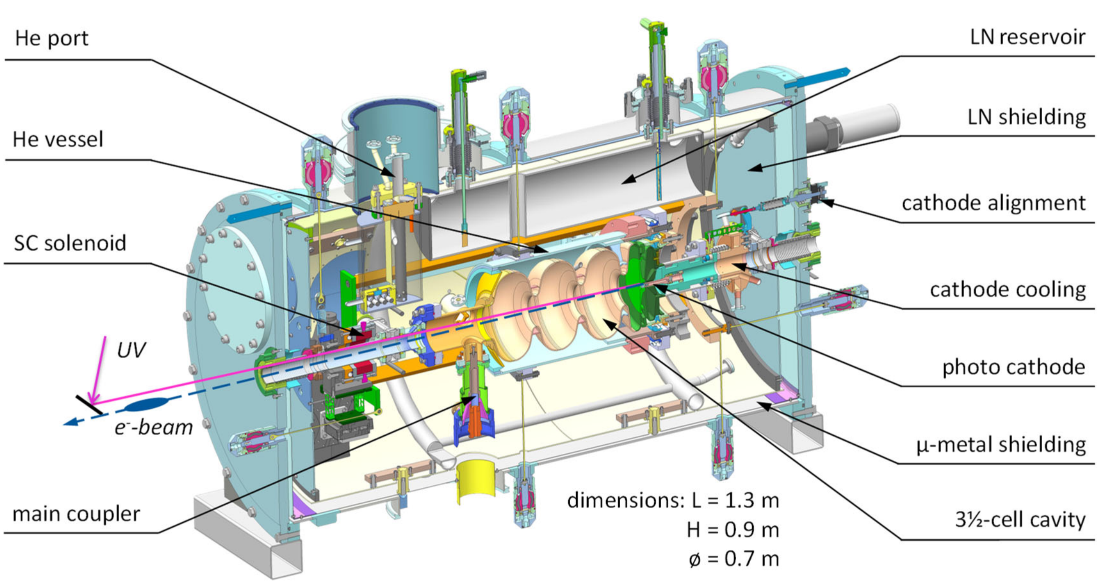

Figure 1: Cross section of the ELBE SRF gun II cryomodule, holding a 3.5 cell gun cavity and a superconducting solenoid at about 70 cm in front of the cathode.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV003

PROGRESS OF MgB_2 DEPOSITION TECHNIQUE FOR SRF CAVITIES AT LANL

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Abstract

Since its discovery in 2001, Magnesium Diboride (MgB_2) has had the potential to become a material for cavity manufacturing. Having a transition temperature (Tc) at ~39 K, there is a potential to operate the cavity at ~20 K with cryocoolers. This will open up a variety of applications that benefit from compact high-efficiency superconducting accelerators. We have found a 2-step deposition technique as a viable technique for cavity coating, i.e., coating of a pure boron layer with chemical vapor deposition using a diborane gas in the first step and react it with Mg vapor in the second step. In this paper, we will show some recent results with up to Tc ~38 K using a small furnace and describe a new coating system under construction with a new 3-zone furnace to coat a 1.3-GHz single-cell cavity.

INTRODUCTION

Niobium superconducting radio frequency (SRF) cavities have been used in particle accelerators for a long time and thanks to research and technological effort they are now approaching their theoretical gradient limit of 50 MV/m [1, 2]. The raw material cost has also quadrupled over the last 20 years, leading to a substantial increase in costs for new SRF particle accelerators. Another large cost for an SRF particle accelerator comes from the cryoplant, necessary to cool down Nb cavities at ~2 K by immersing the cavity in superfluid helium. To address these issues alternative materials with a higher transition temperature (T_c), such as Nb_3Sn [3, 4], are being explored: operating at a higher temperature would remove the need of superfluid helium, simplifying the cryoplant and driving down cost.

Another material of interest is magnesium diboride, MgB_2: discovered in 2001 [5], it exhibits superconductivity below ~39 K, four times the T_c of niobium and twice the T_c of Nb_3Sn. If cooled to 20 K the theoretical highest acceleration field that a MgB_2 cavity would produce is approximately 50 MV/m for a typical electron accelerator, comparable to Nb at 2 K. These properties make MgB_2 a very attractive material for SRF cavities, since operating a facility at 10 times today's temperatures could lead to replacing liquid helium cooling with closed-circuit cryocoolers.

As of the writing of this paper, very few MgB_2 full SRF cavities have been manufactured [6]. This could be due to the fact that one of the reagents (B_2H_6) required to obtain a boron film is toxic, which may discourage its use. The current research approach is to deposit MgB_2 via a co-deposition process [7] where a substrate is exposed to carefully controlled B_2H_6 gas and Mg vapour quantities, leading to the deposition of the superconductor. While this approach has proven successful on flat samples it is still not perfected to deposit on 3D surfaces, like a cavity.

In this paper we present the more recent results of the two-step deposition technique developed at LANL, with T_c and chemical composition results. We will also describe briefly a new MgB_2 coating facility for 1.3-GHz cavities under construction and scheduled to be completed by the end of September 2021.

EXPERIMENTAL SETUP

We restarted our experiments to react B films with Mg vapor. Some details of the experiment are written in [8]. The B films used for these experiments were prepared by flowing B_2H_6 gas through a 1.3-GHz cavity in the previous project that ended in 2015. Figure 1 shows the locations of the samples we used for these experiments.

The B and Mg reaction procedure is similar to the work of Hanna [9].

Since the new deposition facility that will be used to coat a full-size cavity won't easily allow a fast cooling step like the small tubular furnace in Fig. 2 tests were performed with a slow cooling step after the Mg evaporation. Since the highest value of T_c was obtained by depositing Mg at 700 °C this was the temperature chosen for the Mg reaction.

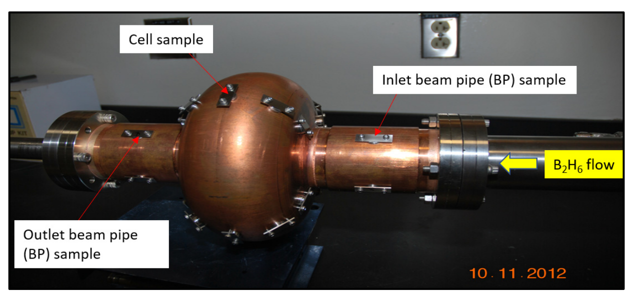

Figure 1: The location of B samples that were taken from the previous project that ended in 2015.

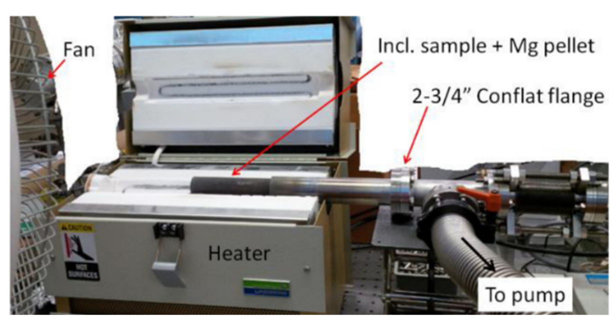

Figure 2: Experimental setup.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV004

IN SITU PLASMA PROCESSING OF SUPERCONDUCTING CAVITIES AT JEFFERSON LAB*

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Abstract

Jefferson Lab began a plasma processing program starting in the spring of 2019. Plasma processing is a common technique for removing hydrocarbons from surfaces, which increases the work function and reduces the secondary emission coefficient. Unlike helium processing which relies on ion bombardment of the field emitters, plasma processing uses free oxygen produced in the plasma to break down the hydrocarbons on the surface of the cavity. The residuals of the hydrocarbons in the form of water, carbon monoxide and carbon dioxide are removed from the cryomodule as part of the process gas flow. The initial focus of the effort is processing C100 cavities by injecting RF power into the HOM coupler ports. We will then start investigating processing of C50 cavities by introducing RF into the fundamental power coupler. The plan is to start processing cryomodules in the CEBAF tunnel in the mid-term future, with a goal of improving the operational gradients and the energy margin of the linacs. This work will describe the systems and methods used at JLab for processing cavities using an argon oxygen gas mixture. Before and after plasma processing results will also be presented.

BACKGROUND

The main accelerator at Jefferson Lab is the Continuous Electron Beam Accelerator Facility (CEBAF), which is a continuous wave 5-pass recirculating accelerator that uses 418 superconducting cavities to accelerate electrons to a maximum design energy of 12 GeV. The cavities are configured into 52-1/4 cryomodules. Twelve of the cryomodules are known as C100 style cryomodules which use TESLA-style HOM coupler antennas. The remaining 40-1/4 cryomodules are known as C20, C50 and C75 style cryomodules. These cryomodules have internal ceramic HOM loads, which are waveguide coupled to the beam line and are operated at 2K, with no RF connections outside of the cryomodule.

Many of the cavities in CEBAF suffer from field emission due to particulates on the surface of the cavities. While some of these particles originate from the production processes, which have improved substantially in the past 30 years, a fraction of the particles is assumed to be transported into the cavities via the beamline during normal operation and maintenance. These introduced particles can cause new field emitters to “turn on” which further degrades machine operation [1]. For the most recent C100 rebuild, which was installed in the fall of 2019, seven of the eight cavities had no field emission and the rebuilt module has been routinely operated at 100 MeV with no measurable radiation.

In the C100 cryomodules and most of the C50/C75 cryomodules, while field emission does not cause frequent arcing, it does cause extra heat load to the helium system. Unfortunately, due to physics needs for higher energy, the cavities are normally operated at relatively high levels of field emission. This causes significant radiation primarily at the ends of the cryomodule which, in addition to activating beam line hardware, damages components such as O-ring seals and instrumentation cables.

Plasma Processing of SRF Cavities

Plasma processing using argon/oxygen gas mixtures is used in a number of industrial applications for removing hydrocarbons from the surfaces prior to the application of thin films or performing surface analysis [2]. Unfortunately, due to the size and shape of the SRF structures in a cryomodule, the gas pressure and the free oxygen recombination cross section, these industrial systems are not suitable for this application.

One of the early applications using a mixture of a noble gas and a small percentage of oxygen with positive results on was in 2012 at the Synchrotron Radiation Center located at University of Wisconsin, where the WiFEL SRF gun cathode surface fields were improved from 6 MV/m to 26 MV/m [3]. ORNL has an ongoing program of processing cryomodules in SNS using a neon/oxygen gas mixture. To date they have processed 36 cavities *in situ* with an average improvement of 2.5 MV/m [4, 5]. Staff at Fermilab started a program three years ago that is focused on processing LCLS II cavities via one of the HOM ports [6].

Current Jefferson Lab Program

A new plasma processing program was initiated at JLab in the spring of 2019, with initial plasma production in a C100 cavity in August 2019, a series of laboratory bench top measurements was initiated in the fall of 2019. A series of vertical test, plasma process, vertical test cycles started in the Fall of 2020 and a cryomodule, which was removed from the tunnel for rebuild, was processed in the cryomodule test facility in June 2021. The plan is to continue the vertical test series as well as the off-line development through FY22 and to start processing cryomodules in the tunnel as soon as it is practical.

METHODS

In this method a discharge is established, and electrons with an energy between 10 and a few hundred eV break the bond between oxygen atoms and free oxygen is produced. The free oxygen oxidizes the hydrocarbons on the surface

* Funding provided by SC Nuclear Physics Program through DOE SC Lab funding announcement Lab-20-2310 and U.S. DOE, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV005

PIP-II 650 MHz POWER COUPLER THERMAL STUDIES*

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Abstract

The Proton Improvement Plan - II (PIP-II) project is underway at Fermilab with an international collaboration involving CEA in the development and testing of 650 MHz cryomodules. One of the first main contributions of the CEA was the participation in the design efforts for the current 50 kW CW 650 MHz power couplers. This paper reports some of the results of thermal and parametric studies carried out by the CEA on these power couplers.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex [2]. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules [3, 4], equipped with 650 MHz Superconducting (SC) cavities are used. The same Power Coupler (PC) design, presented in Fig. 1, was adapted for both cryomodules. In total, sixteen unit of these PCs will be needed for the Linac.

The work presented in this paper was carried out in the frame of the French participation to the PIP-II project. PCs dedicated to the HB650 cryomodules will experience the most constraining operation conditions in terms RF power level. For that reason, this paper will only focus on studies using the maximum RF power level corresponding to this case.

The aim of the following calculations is to estimate the maximum heat loads transferred by the 650 MHz PC to cryogenic system through the cavity, the 5 K and 50 K intercepts. This corresponds to an input CW RF power of 50 kW with 20% reflection. The reflection phase that we have chosen for the main part of this study maximizes the 2K heat load. The calculation is based on 2D axisymmetric model taking into account the geometry and the material properties of all the coaxial coupler parts from the cavity interface to the waveguide transition. The results of heat loads calculations presented in this paper englobes both of static and RF losses.

The anomalous heat effect on copper plating was estimated in preliminary design calculation and found to be not very significant. We made the choice to not consider it for this study.

* Work supported, in part, by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under U.S. DOE Contract No. DE-AC02-07CH11359
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The Thermal Radiation Power (TRP) towards the SC parts is treated separately in the last part of this paper.

All the results presented here are obtained using the COMSOL Multiphysics software. Many of them were checked with HFSS-ANSYS software and good agreement between results was achieved.

POWER COUPLER DESIGN

Several design modification have been brought to the 650 MHz PCs during the last few years [5]. The current version (see Fig. 1) has a copper (Cu) plated stainless steel (SS) cold part instead of the electromagnetically shielded design [6]. The thickness of the outer conductor (OC) of the same part has been increased in order to enhance its mechanical strength. Moreover, a vacuum gauge port has been added. For some integration reasons, the corresponding cold cathode gauge will be used inside the cryomodule isolation vacuum witch is uncommon but already experimentally validated [7]. The window design has also been improved by modifying the vacuum RF volume geometry shape, increasing the ceramic thickness and replacing the aluminium sealing gaskets to CF. The warm coaxial part of the PC is now completely made of Cu plated SS. The 11.5"x 0.7" waveguide transition has been replaced by aluminium WR1150 waveguide type to overcome overheating issues encountered during RF power tests. Some improvements have also been carried out on the cooling air circulation inside the coupler for better efficiency and lower pressure drop. A simplified schematic representation of the cooling air circulation is shown in Fig. 2.

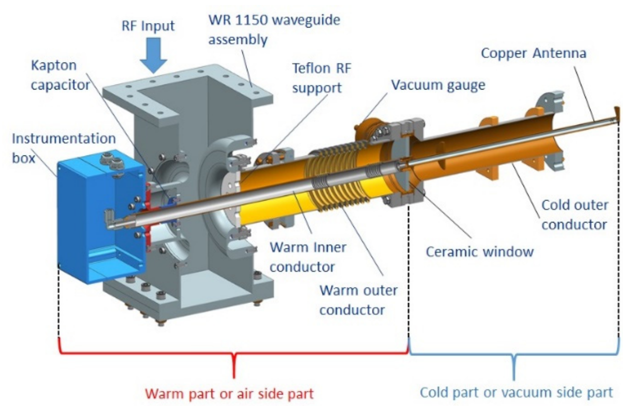

Figure 1: PIP-II 650 MHz Power Coupler.

CALCULATION MODEL AND ASSUMPTIONS

The use of the 2D axisymmetric model is motivated by the low contribution of the conductive heat transfer from waveguide transition to the cold part, through the warm coaxial part. This was corroborated by former calculation

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV006

DEVELOPMENT AND ADUSTMENT OF TOOLS FOR SUPERCONDUCTING RF GUN CAVITIES

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Abstract

For the superconducting radio frequency (SRF) 1.6-cell gun cavities (CV) developed at DESY, a similar fabrication and treatment process, as for the European XFEL 9-cell cavities [1] is foreseen. The different length and geometry of these cavities lead to a number of adjustments to existing and the development of new tools. This paper covers the new designs and adaptations of a tuning tool, chemistry flanges, a wall thickness measurement device, as well as a new high-pressure rinsing spray head and an optical inspection camera for the 1.6-cell 1.3 GHz DESY SRF gun cavities under the development for the European XFEL.

TUNING TOOL

In order to be able to modify the frequency changes after the production of the SRF 1.6-cell gun CVs and to adjust the cells to the respective conditions, a tuning device is designed and built up.

During the fabrication of SRF 1.6-cell gun CVs, it is necessary to adjust the resonance frequency, while ensuring the field flatness at DESY, straightness and length of the cavity. Therefore, a simple manually driven tuning tool prototype was constructed, which makes it possible to correct the length and frequency of the full cell. As part of a collaboration between DESY and KEK (High Energy Accelerator Research Organization), this tool was handed over to KEK, to check the field flatness during the horizontal electropolishing process of the gun CV 16G4.

For further improvement, adjustments on the cell design had to be made. In order to have a universal tuning device for all existing and maybe upcoming cell geometries a 2nd prototype was developed, built and tested (Fig. 1).

Changes in the cell geometry can now easily be adapted with new tuning inserts. It is possible to use the new gun tuning device in horizontal and vertical position. It allows to tune prototype gun CVs without cathode hole or with installed plug. For this purpose, a "bead-drop"-system was developed, that allows to perform the well-established RF measurements even on cavities with only one open end where standard bead-pull systems cannot be applied. The new device enables to change the frequency, while tuning the effected cells without disassembling the cavity during the process. This leads to significant time savings.

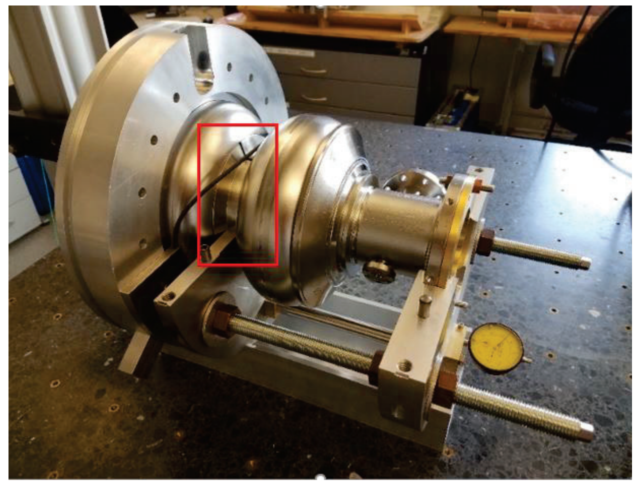

Figure 1: New tuning device with bead-pull system assembly and new tuning inserts.

CHEMISTRY FLANGE

At DESY the etching of multicell cavities is an established working process. Due to the gun CV design, several adaptations of this etching procedure as well as the tools are necessary.

During the usual etching procedure of XFEL CVs, the acid is filled through the bottom beam tube into the CV and is drained off the second upper tube as well, as over the other ports. In contrast, SRF gun CVs have only one beam tube to fill and drain the acid, (Fig. 2). The cavity is etched vertically, but must be turned several times 180°, back and forth for draining the acid after the chemistry and for refilling the water, during the rinsing procedure. During filling in the acid, no gas bubbles must remain in the gun CV. Gas bubbles can cause insufficient removal of material, as well as bubble traces can show up after etching. For this purpose, a "chemistry flange" with filling tube and nozzle head, which sits close to the cover plate, was designed.

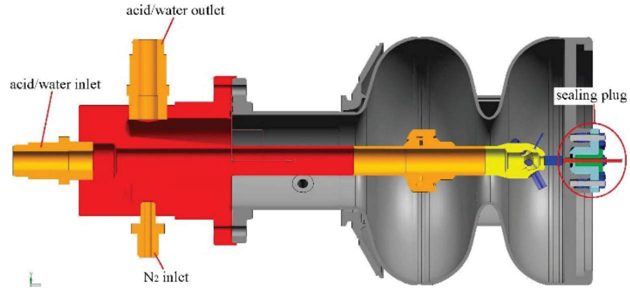

Figure 2: SRF 1.6-cell gun cavity with etching flange.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV009

SEAMLESS 1.3 GHz COPPER CAVITIES FOR Nb COATINGS: COLD TEST RESULTS OF TWO DIFFERENT APPROACHES*

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Abstract

A necessary condition for high SRF performances in thin film coated cavities is the absence of substrate defects. For instance, in the past, defects originated around electron beam welds in high magnetic field areas have been shown to be the cause of performance limitations in Nb/Cu cavities. Seamless cavities are therefore good candidates to allow an optimization of the coating parameters without the pitfalls of a changing substrate. In this work, we present the first results of two different methods to produce seamless cavities applied to 1.3 GHz copper single cells coated with thin Nb films by means of HIPIMS. A first method consists in electroplating the copper resonator on precisely machined aluminum mandrels, which are then dissolved chemically. As an alternative and a cross check, one cavity was machined directly from the bulk. Both cavities were coated with HIPIMS Nb films using the same coating parameters and the SRF performance was measured down to 1.8 K with a variable coupler to minimize the measurement uncertainty.

INTRODUCTION

The thin film technology has been historically used for superconducting radio frequency cavities at CERN, where various accelerators use SRF cavities made of Nb coatings on copper substrates. It was first implemented in the LEP [1], and later in the LHC and HIE-ISOLDE [2]. It is also expected to be one of the selected technologies for the future circular colliders (FCC) [3]. Coated cavities have several advantageous features. On one hand, raw material costs are lower. Also, cryogenics costs are reduced thanks to the higher thermal diffusivity of copper and optimized BCS surface resistance of sputtered Nb [4], allowing operation in liquid helium bath at 4.2 K instead of superfluid helium. Moreover, copper substrates provide sufficient thermal and mechanical stability so that thermal breakdowns do not occur and microphonics can be fully suppressed. Nb on copper cavities are also less sensitive to magnetic flux trapping, allowing savings on magnetic shielding of cryomodules [5].

However, degradation of the RF performance at high fields has been historically observed in these cavities [6]. The nature of this phenomeon, known as Q slope, has been the subject of research and is not yet fully explained. In any case, the presence of defects in the copper substrate is a known cause of performance degradation. The influence of the substrate on the growth process of thin films, and how it is affected by the microstructure of the copper is reported in [7]. To mitigate this, efforts have to be made on improving the quality of the thin film cavities at all levels:

- Interface between Nb film and substrate: a good adhesion is key to avoid the occurrence of peel-offs. A significant thermal resistance in the bad contact region can lead to a local increase of the temperature, and consequently of the BCS surface resistance, leading to the observed Q-drop [8].
- Quality of the film: an extensive R&D campaign has been carried out at CERN for finding and optimizing the best thin film deposition technique [9]. High Impulse Power Magnetron Sputtering (HIPIMS) has given promising results from the RF point of view, allowing for a dense, void-free layer at all the impinging angles of the niobium coating flux [10, 11]. In this work, the cavities under study have been coated with this optimized method.
- Quality of the substrate: defects in the substrate are propagated to the thin film deposited on top. This became evident after the experience with the HIE-ISOLDE quarter wave resonator (QWR), where a systematic loss of performance was observed in the series of cavities manufactured with electron beam welding. This was correlated with the presence of microscopic cracks in the welded region [12], and it served as motivation for producing a seamless substrate machined from a copper billet [13]. Dedicated experiments revealed that by controlling environmental variables (magnetic shielding and cool down dynamics [14]), Nb films deposited on these seamless substrates showed record-breaking RF performances for the Nb/Cu technology [15]. Following these studies, in this paper we investigate the performance of two 1.3 GHz Nb/Cu cavities produced with seamless copper substrates by two different methods.

PRODUCTION OF THE SUBSTRATES

In view of the importance of avoiding welds on high RF field regions, finding a technique for producing seamless substrates for mass production of SRF cavities becomes a keystone. Not only it has to be feasible in terms of costs and manufacturing time, but the quality has to be reproducible in a large scale production. Several methods have been already investigated, such as spinning [16] or hydroforming [17]. The disadvantage of those techniques is the varying wall thickness along the profile and extensive damage to the over strained material [18]. Regarding the hydroforming, a major issue was a higher intrinsic content in hydrogen resulting

* C. Pereira acknowledges the financial support provided by the Fundação para a Ciência e Tecnologia, project SFRH/BEST/150601/2020
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV010

CAMERA PLACEMENT IN A SHORT WORKING DISTANCE OPTICAL INSPECTION SYSTEM FOR RF CAVITIES

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Abstract

Inspection of the RF surface of cavities for the purpose of detecting surface anomalies has been well established, and is typically based on long working distance optical systems using on-axis camera and mirror systems to scan the cavity surface. In order to improve the systematic inspection of the full RF surface of large area cavities, a novel short working distance inspection system is being developed at CERN. This new system is based on a mechatronic robotic system to position that camera at normal incidence close to the cavity surface. To accommodate working distance fluctuations, and to provide increased depth of field resolution, the short working distance camera is coupled with a liquid lens focusing system, providing a programmable focusing function. Details of inspection bench design and first results are reported, as well as details on camera positioning optimisation and the proximity detection surveillance for collision-free scanning of the full-cavity surface.

INTRODUCTION

Inspection of the surface of RF cavities has been a well-established activity throughout SRF community with different laboratories adopting various technical solutions that matched individual needs and cavity geometries. These systems have had considerable success with spot inspection and classification of defects, as well as weld assessment and other such localised surface inspection. Typically, due to the difficulty in accessing the RF surface of a cavity, imaging solutions have opted for long focal length imaging systems. Cavity inspection systems on long working distance imaging with the camera positioned on the beam axis and the camera-to-surface optical path defined by a mirror system being well established, with the KEK-Kyoto system [1] an excellent example of this approach. More recent developments by KEK [2], and the DESY OBACHT - Optical Bench for Automated Cavity inspection with High resolution on short Timescales - system [3] show the ongoing development within the community, and the Jefferson Laboratory (JLab) very long distance microscope a mirror system, with the camera external to the cavity [4] is a balance of mechanical simplicity relative to optical complexity.

However, while such long working distance microscopes provide a simpler mechanical solution, there are issues with limited field of view at high resolution, full scanning coverage of the RF surface, image distortion due to non-normal incidence of the camera on the imaging surface, and lighting artifacts due to remote lighting sources. In order to address these concerns, an alternative approach is adopted, with a short working distance optical inspection system under development at CERN. This system uses a mechatronic robotic positioning of a camera at normal incidence, and at short working distance from the cavity surface. This system is designed for reproducible positional scanning of all the present set of axially symmetric cavities in the CERN inventory, ranging from large aperture 400 MHz LHC cavities, to 704 MHz 5-cells and small aperture 1.3GHz single cell elliptical cavities. Here, CERN has opted for a camera placement system that is producing images of uniform depth of field and image-wide field of view, in order to build a fully imaged mosaic of the entire cavity surface. To this end the top-level user requirements for this new inspection system [5] can be summarised as:

1. The entire cavity inner surface has to be scanned.
2. The system must be able to achieve reproducible camera positioning for imaging.
3. An image overlap between consecutive photos has to be ensured, with a target overlap of 30%.
4. The full scan for each cavity type has to be performed in less than 12 hours.
5. Imaging resolution of 10 µm is required.

In order to achieve this, a novel robotic arm based imaging system has been developed, and in what follows below, we detail the design and development of this mechatronic system.

CAMERA POSITIONING BY ROBOTIC ARM

In order to scan the RF surface with a short working distance camera, the camera positioning has to be carefully arranged for each imaging position, such that imaging requirements are met (i.e. achievable focus at normal incidence) and with no risk of the camera positioning system contacting the inner surface of the cavity at any point. To ensure this for a robotic arm system on an axially symmetric cavity, a 2D path of the camera arm has to be computed and evaluated in advance; for the dimension in the azimuth, axial symmetry along the beam axis implies that only a 2D path evaluation is necessary, as scanning is performed by cavity rotation around the beam axis.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV011

SRF ACCELERATING MODULES REPAIR AT DESY

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Abstract

Eight SRF cavities assembled in an accelerating module represent a building block of the particle linear accelerator based on TESLA SRF technology. DESY has two machines, European XFEL and FLASH. Both use almost same module and cavity types. During the module assembly many factors can deteriorate the cavity performance and cause a need for a repair action. Currently two European XFEL modules and two FLASH ones underwent reassembly procedures. The repair was not immediately successful on every of these modules and re-iterations did follow. The degradation causes were investigated. SRF modules were tested on both test-stands at DESY: AMTF and CMTB. The results of the described actions are presented and discussed.

INTRODUCTION

The European XFEL [1, 2] and FLASH [3] linacs are based on the TESLA SRF technology and are built with accelerating Cryo-Modules (CM) having 8 SRF cavities each. Currently 97 CM are installed in the XFEL and 7 CM in FLASH. Before the XFEL CM assembly SRF cavities were tested in the Vertical Cryostat Test (VT) in the Accelerating Module Test Facility (AMTF) at DESY [4]. After the assembly at CEA (Saclay, France) each CM was tested in AMTF [5, 6]. Two XFEL CMs XM50 and XM46 were re-assembled because of out of specs performances. During the FLASH upgrade in 2022 [7] two CMs presently under assembly and test will replace older CMs.

MODULES FOR EUROPEAN XFEL

CM XM50 was repaired [8] two years ago and re-assembled to XM50.1. The successful CM test in AMTF was reported during SRF2019 [9]. Subsequently CM was installed and tested on Cryo Module Test Bench (CMTB) with a CW test [10, 11] as a main goal. Cavities 1 and 2 did slightly degrade: cavity 1 with high Field Emission (FE) and cavity 2 with earlier breakdown – 20.5 MV/m in CMTB instead of 24.4 MV/m before in AMTF. Even with the first two cavities degraded CM XM50.1 was successfully tested in CW mode and is in specs for the SRF linac.

CM XM46 was delivered to DESY in Sep. 2015 after the assembly at CEA (Saclay). The first test of CM XM46 in Oct. 2015 showed a degradation of the cavity performance with high FE (Table 2 and Fig. 2). At that time the decision was taken not to install the CM in the XFEL linac and re-assemble it after cavities' re-treatment.

After disassembly all XM46 cavities underwent a re-treatment: High Pressure Rinsing (HPR) at DESY [8]. After a successful VT 7 out of 8 cavities were accepted for XM46.1 assembly. Cavities positions were changed and one cavity replaced (Table 1).

After reassembly CM XM46.1 (Fig.1) was tested on both module test-stands at DESY: AMTF (Sep. 2020, Table 3 and Fig. 3) and CMTB (May 2021), a successful CM repair is confirmed on both with a very close test results. Currently a CW CM test on CMTB is ongoing [10, 11].

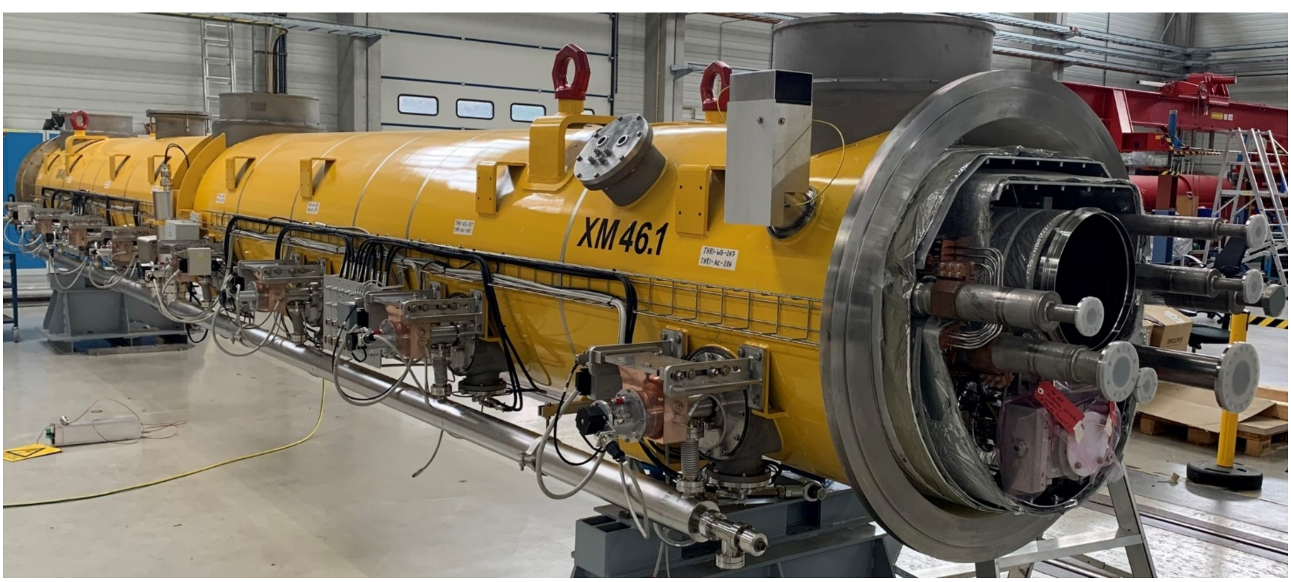

Figure 1: Module XM46.1 in AMTF.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV012

PROGRESS AND PRELIMINARY STATISTICS FOR THE ESS SERIES SPOKE CRYOMODULE TEST

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Abstract

The European spallation source (ESS), as a world-class high power proton accelerator facility, will be the first one to adopt 26 double spoke resonators (DSR) at its low energy section. As a new superconducting accelerating structure, these DSRs are therefore considered key technology and a challenge for the whole project. They will be the first DSRs in the world to be commissioned for a high power proton accelerator. Since 2019, FREIA Laboratory, Uppsala university, has successfully tested the first DSR prototype cryomodule and is now in charge of the acceptance tests of the ESS series cryomodules prior to installation in the tunnel. The cryomodule test, including cryogenic and RF testing, verifies operation of the cavities, couplers and cold tuning systems. This poster will present the test results for the ESS series spoke cryomodules, including preliminary statistics, experience in general.

INTRODUCTION

The European Spallation Source (ESS) is an accelerator-driven neutron spallation source built in Sweden whose layout is shown in Figure 1. Unique capabilities of high brightness and long pulses help to ESS forward as frontiers of the neutron science [1]. ESS is also facing challenges such as high efficiency and high availability demand in cavity control and operation, wide cavity and RF parameters spread in system operation, and enormous data collection from variety of test stands. Therefore, it requires strict quality control for each critical sub-system by an acceptance test before tunnel installation.

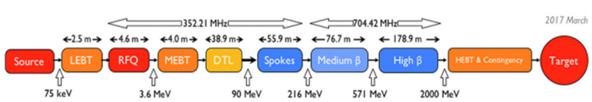

Figure 1: The layout of ESS accelerator.

The superconducting spoke section of the ESS linac accelerates the beam from the normal conducting section to the first family of the elliptical superconducting cavities. This spoke section includes a single family of β=0.5 bulk niobium double spoke resonator (DSR), as shown in Table 1, operating at a temperature of 2 K, and at a frequency of 352.21 MHz. A total of 26 spoke cavities are designed at IJCLab Orsay and will be grouped by 2 in 13 cryomodules [2]. From 2015, low power test of a dressed spoke cavity (Germain) had been done to verify the hardware and test procedure at Uppsala University, Sweden, where the Facility for Research Instrumentation and Accelerator development (FREIA) has been equipped with superconducting cavity test facility [3, 4]. Afterward the qualification of a cavity package, a DSR (Romea) with its fundamental power coupler (FPC) was tested with low level radio frequency (LLRF) system and radio frequency (RF) station, which represented an important verification before the module assembly [5]. As a milestone, the first DSR prototype cryomodule for ESS project has been successfully high power tested in 2019 and the series DSR CM acceptance has been official launched in 2020. In this qualification test of the cryomodule, including cryogenic and RF testing, fundamental power coupler (FPC), DSRs, cold tuning system (CTS) are verified.

Table 1: Main Parameters of Spoke Cavities

Parameter	ESS Spoke cavity
Frequency (MHz)	352.21
Temperature (K)	2
Pulse beam mode duty factor (%)	4
Repetition rate (Hz)	14
Nominal gradient (MV/m)	9
Beta (optimal)	0.5

FREIA TEST STAND

The FREIA laboratory at Uppsala University is established in order to support the development of instrumentation and accelerator technology [6, 7]. In a total 1000 m^2 area, FREIA developed a test stand infrastructure consists of a horizontal cryostat and a vertical cryostat, three concrete bunkers for radiation protection purposes, a helium liquefaction and recovery plant, RF station and affiliated equipment and, LLRF control system [8].

The high power test stand at FREIA for the ESS DSR prototype CM consists of two high power RF stations running with tetrode tubes, two high power circulator protection devices, a water cooling system, two loads, and two LLRF systems based on either self-excited loop (SEL), open loop or closed loop with proportional integrate (PI) feedback (FB) function. In order to maximize safety and to minimize interference, the FB mode based on the ESS LLRF system is the first choice for RF measurements and, the open loop using ESS LLRF system as a signal source is applied for FPC conditioning while the SEL will be used as a backup system for ESS series CM test. The interlock system integrates all interlock signals from the FPC/cavity/loop through NI compact RIO system and sends out an overall interlock control during RF on. A valve box was installed and connected to the FREIA cryo-plant where it is permanently located for all 13 series CMs acceptance testing [9]. This valve box is slightly modified from the final series to adapt it to the FREIA cryogenic infrastructure using a buffer helium tank and using liquid nitrogen for the thermal shield cooling.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV013

MANAGING SN-SUPPLY TO TUNE SURFACE CHARACTERISTICS OF VAPOR-DIFFUSION COATING OF NB_3SN*

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Abstract

Nb_3Sn promises better RF performance (Q and E_{acc}) than niobium at any given temperature because of superior superconducting properties. Nb_3Sn-coated SRF cavities are now produced routinely by growing a few microns thick Nb_3Sn films inside Nb cavities via the tin vapor diffusion technique. Sn evaporation and consumption during the growth process notably affect the quality of the coating. Aiming at favorable surface characteristics that could enhance the RF performance, many coatings were produced by varying Sn sources and temperature profiles. Coupon samples were examined using different material characterization techniques, and a selected few sets of coating parameters were used to coat 1.3 GHz single-cell cavities for RF testing. The Sn supply's careful tuning is essential to manage the microstructure, roughness, and overall surface characteristics of the coating. We summarize the material analysis of witness samples and discuss the performance of several Nb_3Sn-coated single-cell cavities linked to Sn-source characteristics and observed Sn consumption during the film growth process.

INTRODUCTION

Because of superior superconducting properties, Nb_3Sn (T_c ~ 18.3 K, H_{sh} ~ 425 mT, and Δ ~3.1 meV) promises better performance and a significant reduction in operational cost of SRF cavities compared to Nb (T_c ~ 9.2 K, H_{sh} ~ 210 mT, and Δ ~1.45 meV) [1]. Presently, it is the front running alternative material to replace niobium in SRF cavities. However, Nb_3Sn has a significantly lower thermal conductivity despite attractive superconducting properties than Nb at low temperatures. Further, it is very brittle and prone to develop cracks under stress, which primarily restricts the application of Nb_3Sn into a thin film form. Nb_3Sn thin films should be deposited or grown inside a built-in metallic (e.g., Nb, Cu) cavity structure. Since SRF cavities typically have complicated geometries and demand flawless uniform coating, suitable thin film deposition techniques are limited. Among several techniques attempted to deposit Nb_3Sn thin films, vapor diffusion coating is the most favorable and successful technique so far.

Vapor diffusion coating of Nb_3Sn on niobium cavities dates back to the 1970s [2-4]. This technique is adopted by most research institutions currently working to develop Nb_3Sn coated cavities around the world [5-8]. Recent performance results of such cavities are very promising, attaining high quality factors, > 10^{10} operating at 4.2 K at medium fields at ≥ 15 MV/m in several labs [5, 9-10]. A typical cavity coating process consists of two steps: nucleation and growth. First, tin chloride evaporates at about 500 ºC, depositing tin film and particles on the niobium surface to mitigate potential non-uniformity in the coating [11]. These tin deposits act as nucleation sites, which are assumed to grow with the influx of tin vapor during deposition at a higher temperature. The growth temperature should be above 930 °C to exclusively form the Nb_3Sn phase as dictated by the binary phase diagram of the Nb-Sn system [12]. A temperature of about 1100-1200 ºC is typical for Nb_3Sn growth at different labs.

The quality of coated Nb_3Sn layers is contingent on understanding coating layer formation and growth during the process. Several studies have investigated the effect of different coating parameters such as nucleation time, nucleation temperature, growth temperature, growth time, etc., to understand and control the Nb_3Sn growth kinetics [13-14]. Since the essence of the vapor diffusion technique is to create and transport tin gas to the substrate Nb in a suitable thermodynamic environment, the management of Sn during the process is of critical importance. Since many cavities coated recently at Jefferson Lab persistently showed Sn-residues on the coated surface, it further motivated us to correlate Sn effusion conditions, thin-film quality, and RF performance. In this contribution, we discuss several factors that could potentially influence Sn-supply and consumption during the Nb_3Sn film growth affecting the microstructure of the thin film and RF performance.

Nb_3Sn COATING

Each cavity or sample chamber was coated with 10 mm × 10 mm Nb coupon samples inside using a typical setup. The coating deposition system is described in [7]. Sn (99.999% purity from Sigma Aldrich) was loaded in a crucible, and $SnCl_2$ (99.99% purity from Sigma Aldrich) was packaged inside two pieces of Nb foil inside the cavity at the bottom flange. A Nb crucible was used for single-cell cavity coating each time. However, W crucibles of different cross-sectional areas were used for experiments using the sample chamber. Both sides of the cavity or sample chamber were closed with Nb covers by lightly tightening with molybdenum fasteners before installation into the furnace. A typical temperature profile included nucleation step at (540 ± 10) °C for 90 minutes and coating step at (1195± 10) °C for 75 minutes, as shown in Fig. 1. Following a series of experiments, the temperature and coating setup was later modified for single-cell cavity coating.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV016

UPGRADE OF THE RHIC 56 MHz SUPERCONDCUTING QUARTER-WAVE RESONATOR CRYOMODULE*

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Abstract

In preparation for the 2023 RHIC sPHENIX experimental program the superconducting 56 MHz quarter-wave resonator cryomodule, used operationally for longitudinal bunch compression with up to 1 MV RF voltage, is being refit to accommodate an expected beam current of 418 mA per ring, an increase of ~1.5 relative to previous operation. The upgrades to the system include an improved fundamental mode damper, and dual function fundamental power and higher-order mode damper couplers. This paper will describe the preliminary testing, select subsystem changes and plans for testing the cryomodule prior to installation in the RHIC beam line in 2022.

INTRODUCTION

Brookhaven National Laboratory (BNL) finished and used a 4.4 K 56 MHz superconducting Quarter-Wave Resonator (QWR) cryomodule in RHIC to reduce particle losses during transfer of the accelerated 28 MHz bunches to the 197 MHz storage system [1]. During several RHIC runs finishing in 2016 the 56 MHz QWR system was made operable with up to 1 MV RF voltage while avoiding several high-order mode driven beam instabilities, successfully demonstrating improved RHIC experimental luminosities [2]. During this effort several cryomodule subsystems were identified for upgrade to meet future sPHENIX experimental program requirements and ease manipulation of the cavity fields during operation.

Three areas dominate the improvements being made to the 56 MHz QWR's performance: RF voltage, higher power fundamental mode damping (FMD) and dual function power couplers capable of both fundamental power coupling and higher-order mode (HOM) damping. This paper briefly reviews the cryomodule geometry, the status of work in these areas and concludes with comments on our future work.

56 MHz QWR PERFORMANCE

The target RHIC operating voltage is 2-2.5 MV [3] and reaching this voltage is advantageous for sPHENIX, possibly increasing the total luminosity by >2 [4]. Previous experience with the 56 MHz QWR was limited to ~1 MV peak RF voltage at 4.4 K while operating in RHIC [2]. To measure the upper threshold of cavity operation and define the level all couplers need to operate the 56 MHz QWR was vertically tested at BNL in a 4.4 K bath dewar with

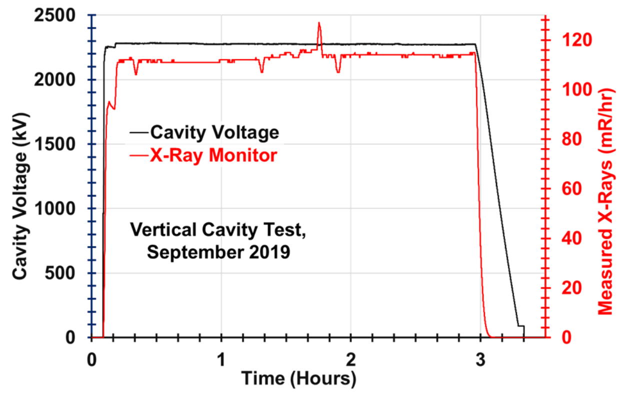

Figure 1: 56 MHz QWR operating at 4.4 K.

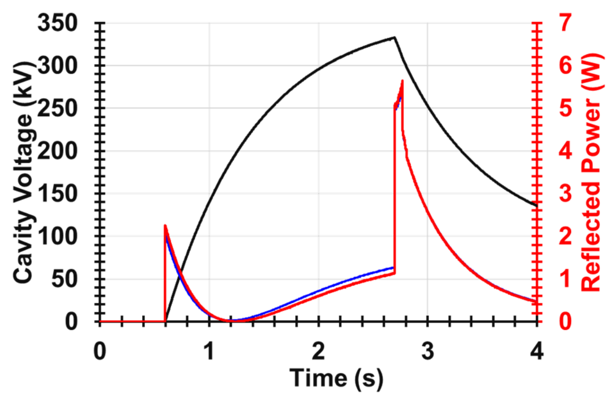

Figure 2: Pulsed 56 MHz QWR response showing uncertainty in coupling strength.

a beam-line mounted fixed power coupler and a pick-up probe located on the toroid end of the resonator, details of the BNL bath dewar and the 56 MHz QWR arrangement during testing are in [5].

The 56 MHz QWR attained an RF voltage of 2.3 MV at which point the cavity quenched. After quenching the cavity operated stably at 2.25 MV and 4.4 K, at this level Fig. 1 shows the 56 MHz QWR voltage and correlated x-rays during a run of several hours. The fixed power coupler was over-coupled to the resonator with β ~ 33 and Q_{ext} = 1.52x10^8 complicating cavity field and Q measurements. To calibrate the RF electronics and measure the cavity Q_0 a weakly coupled decay time was measured. A single pole double throw switch was installed in the RF transmission line at a location where it did not present a large impedance to the power coupler. The cavity was excited, and the switch was opened decoupling the RF drive amplifier and allowing the cavity fields to decay. The weakly coupled and coupling-strength corrected Q_0's were measured many

* Work supported by Brookhaven Science Associates, LLC under contract No. DE-SC0012704 with the U.S. Department of Energy.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV017

PROCESSING AND TEST RESULT OF 650 MHz 50kW CW PROTOTYPE COUPLERS FOR PIP-II PROJECT

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Abstract

For PIP-II project Fermilab is developing 650 MHz couplers to deliver up to 50kW CW RF power to the superconducting low-beta (LB650) and high-beta (HB650) cavities. To meet project requirements two different designs of the couplers were proposed, one is conventional design with copper plated stainless steel walls. In second design (EM-shielded) a copper screen is used to shield stainless steel wall from electromagnetic field. For prototyping we built two couplers of each type and tested them at 50kW with full reflection at different reflection phases. In each test the assembly of two couplers were processed with DC bias up to +5kV, starting with short pulses and ramping power up to 100kW. Final run for 2 hours in CW mode at 50kW to reach equilibrium temperature regime and qualify couplers. One pair of couplers was also processed without DC bias. Finally, all four couplers demonstrated full requirements and were qualified. Based on test results the conventional coupler with some modification was chosen as a baseline design. Modified version of coupler is now ordered for prototype of HB650 cryomodule. In paper we will discuss details of coupler processing and results.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules equipped with 650 MHz Superconducting (SC) cavities are used. The same 650 MHz Power Coupler (PC) design will be used for both low-beta (LB650) and high-beta (HB650) cavities. PIP-II requires that coupler should work in 50kW CW regime with 20% power reflection. Before installation to the cavity each coupler should be tested and conditioned at the room temperature test stand. Power requirements for the test stand more stringent: 50kW with full reflection at any reflection phase to have more margin during long time coupler operation in cryomodules.

COUPLER PROTOTYPING

During project R&D phase two design modifications of the coupler were developed, built and tested [2,3]. First design called conventional is shown in Fig. 1. In second design stainless steel outer conductor in vacuum part is shielded from electro-magnetic (EM) fields by copper screens, as shown in Fig. 2. It allows minimize cryogenic heat loads at 5K and 50K and eliminate copper plating on vacuum surfaces in vicinity of SC cavity (no flakes, no contaminations). All rf losses will be in copper. The only difference between two designs is a vacuum (cold) part with ceramic window and antenna.

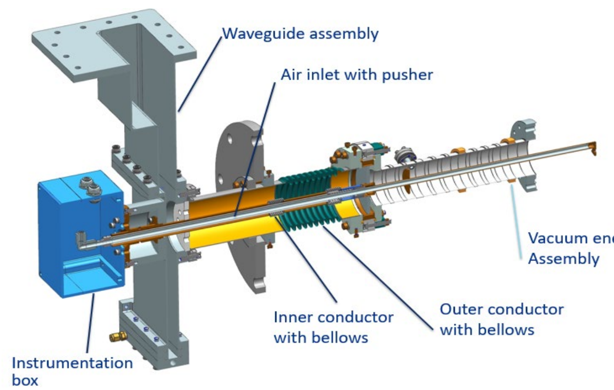

Figure 1: Cut view of the 650 MHz prototype coupler with convectional design.

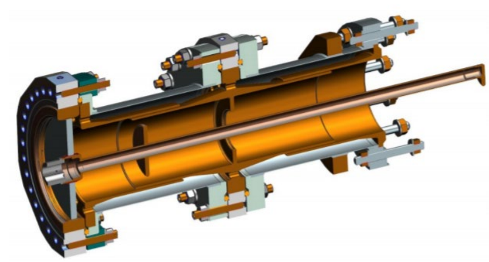

Figure 2: Cut-view of the vacuum part of the EM-shielded coupler. Middle copper shield is connected to 50K thermal strap.

Coupler consists of two parts: cold vacuum part with flat ceramic window brazed to antenna and air part with bellows in inner and outer conductors and transition to narrow WR1150 waveguide. All stainless steel tubes and bellows in air part are copper plated, antenna is made of solid copper, polished to reduce thermal radiation. In conventional design outer conductor of vacuum part also copper plated. Ceramic window is always kept at room temperature above freezing point even without heating from RF power, for that heater on the window flange are installed

Antenna and air part of the coupler are cooled by dry air with flow rate up to 5 g/s, propagation through coaxial tube in inner conductor. After returning back air will cool antenna and will go to the air part through the holes in inner conductor, cooling window and air part of coupler.

Kapton 5-layer foil isolates inner conductor and allows apply DC bias up to 5kV to damp multipactoring activity in the coupler vacuum part. Instrumentation box is used for air and high voltage connections.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV018

STATUS OF RF POWER COUPLER FOR HWR IN RISP*

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Abstract

A heavy-ion accelerator facility is under construction for Rare Isotope Science Project (RISP) in Korea. Four types of super conducting cavities, QWR, HWR, SSR1, and SSR2 are developed to accelerate the ion beams. The QWR cryomodule is already installed in the tunnel. The HWR cryomodule is transport to the tunnel. Here, the status of HWR RF power coupler is presented. After the fabrication, the coupler is test with high power RF. The some of the test results are described.

INTRODUCTION

Several prototype couplers are developed and tested for HWR cavities and cryomodules [1] [2]. With the bias tee, the mass production of HWR RF power coupler is proceeded. 104 couplers are fabricated, but 1 coupler could not accepted for assembly with the cryomodule. 4 couplers are re-fabricated due to the mechanical damage during the transportation from the vendor to IBS. Since 26th Jan 2021, 86 couplers are tested by applying high power RF up to 3.0 kW in standing wave mode. The number 86 means that the number of coupler to installation with HWR-type B cryomodule. Here, the requirements of HWR RF power coupler is summarized and the high power RF test results are introduced briefly.

Requirements

The requirements of RF power coupler for HWR cavity is presented in Table 1.

Table 1: Requirements for HWR RF Coupler

Parameters	Values
Frequency	162.5 MHz
RF power	0 ~ 4.0 W
External Q	$1.0 \sim 2.0 \times 10^6$
Coupling type	Capacitive
TiN Coating	Applied
Copper plating	Not-Applied
DC-bias tee	prepared

The HWR RF power coupler is assembled near the beam port of the HWR cavity, the RF coupling of coupler and cavity is by capacitive type. The external Q and required RF power is optimized as shown in Fig. 1 (a). There is a RF power limit by the HWR SSPA (4 kW). In Fig. 1 (b), the simulation and measurement of the external Q is presented. Measurement 1 and 2 are the measured external Q before the surface processing of the cavity. The trend of the simulation and the measurement of external Q could confirmed by the Measurement 1,2 in Fig. 1. Before the mass production of RF power coupler, two couplers are measured externral Q in room temperature and cyrogenic temperture. both of the external Q are matched with the predictions. The TiN coating on the surface of the ceramic window is applied. The coating is proceeded after the brazing of the ceramic window and outer conductor. The copper plating at the RF surface of outer conductor is not applied for this coupler. Also, the effect of the DC-bias tee could confirmed at the prototype cryomodule test [1].

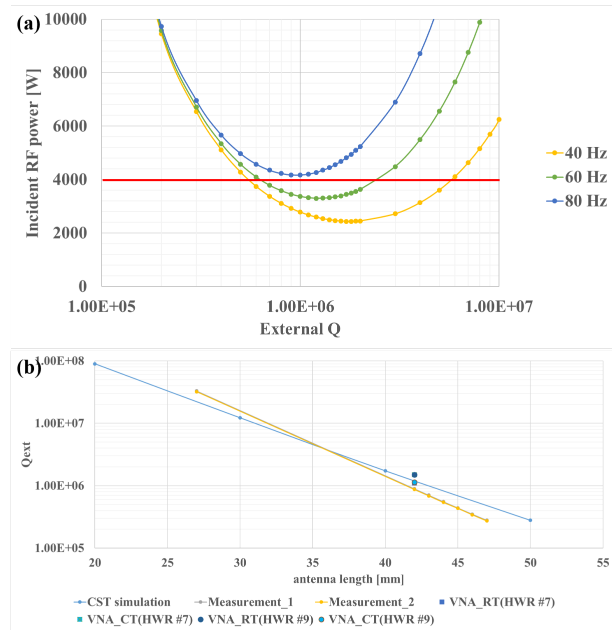

Figure 1: (a) Optimized RF power and external Q. (b) Measurement and simulation of external Q.

Figure 2: Installation of HWR cryomodule in the tunnel. DC-bias tee is assembled with the RF coupler in small picture.

* This work was supported by the Rare Isotope Science Project of Institute for Basic Science funded by Ministry of Science and ICT and NRF of Korea 2013M7A1A1075764.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFAV001

CRYOMODULE DEVELOPMENT FOR MATERIALS IRRADIATION FACILITIES: FROM IFMIF/EVEDA TO IFMIF-DONES

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Abstract

For several years, CEA has been involved in the development of superconducting linac for high flux neutrons sources aiming at testing and qualifying specific materials to be used in fusion power plants. In the framework of the ITER Broader Approch, a prototype cryomodule is under construction in Japan for the IFMIF/EVEDA phase (Engineering Validation and Engineering Design Activities) and the construction of the Accelerator Prototype (LIPAc) at Rokkasho, fully representative of the IFMIF low energy (9 MeV) accelerator (125 mA of D+ beam in continuous wave). Meanwhile, the design studies of a plant called DONES (Demo Oriented Neutron Source, derived from IFMIF) started. The superconducting linac is based on the same principles as the one developed for IFMIF/EVEDA, but taking into account the lessons learnt from the accelerator prototype. This paper presents the similarities but also the differences between the linacs and cryomodules for IFMIF/EVEDA and IFMIF-DONES.

INTRODUCTION

The mission of International Fusion Materials Irradiation Facility IFMIF is to provide an accelerator-based, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to about a full lifetime of anticipated use in fusion energy reactors.

Because of the challenging characteristics of the IFMIF accelerator – 125 mA CW D+ beam up to 40 MeV – is has been decided to have a staged approach, with a first step called Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA). This project is one of the three projects of the Broader Approach (BA) agreement between the Japanese government and EURATOM. The goal is to provide the detailed engineering design of the IFMIF and to validate the technological challenges on the major components with the construction of the Linear IFMIF Prototype Accelerator (LIPAc) at Rokkasho, in Japan. The LIPAc shall validate the low energy section of the IFMIF accelerator, including the first cryomodule housing accelerating superconducting cavities, by accelerating the 125 mA CW D+ beam up to 9 MeV.

The need of a neutron source for the qualification of materials to be used in future fusion power reactors have been recognized in the European (EU) fusion programme for many years. The construction and exploitation of this facility is presently considered to be in the critical path of DEMO. This issue prompted the EU to launch activities for the design and engineering of the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source) facility in parallel with the construction and operation of LIPAc.

IFMIF/LIPAC AND IFMIF-DONES SUPERCONDUCTING LINACS

In LIPAc [1], the deuteron beam delivered by the high-intensity injector is accelerated by the Radio Frequency Quadrupole (RFQ) and the superconducting linac (SRF Linac) to respectively 5 and 9 MeV. Beam lines inserted along the accelerator allow to transport, shape and match the beam to maximize the transmission through the successive components, with the ultimate goal to damp the 1.125 MW beam into the dedicated Beam Dump. The SRF Linac mostly consists of one cryomodule that houses eight superconducting cavities (β=0.091, called "low-beta cavities" hereafter) to accelerate the beam and eight superconducting solenoids to focus it.

The IFMIF-DONES accelerator consists of a section similar to LIPAc with the addition of four cryomodules in order to increase the energy from 9 to 40 MeV. To optimize the efficiency of the SRF Linac, two first cryomodules are equipped with low-beta cavities and the three others with high-beta cavities (β=0.18) [2]. A High Energy Beam Transport (HEBT) line transports and shapes the beam from the SRF linac towards a lithium target to produce the neutron beam. A second line to a beam dump is used during the commissioning phase of the accelerator (Figure 1). Details on each sub-system of the IFMIF-DONES accelerator could be found in [3].

THE IFMIF/EVEDA CRYOMODULE

The IFMIF/EVEDA cryomodule is designed to be as short as possible to meet the beam dynamics requirements. As shown in Figure 2, it is made of a rectangular section vacuum vessel, a warm magnetic shield, a thermal shield and a cold mass. The temperature of this one is 4.45 K (temperature of liquid helium at the pressure of 1.25 bar), while the thermal shield is cooled using cold helium gas from the phase separator (estimated shield temperature around 50 K).

The cold mass is made of the cavity string supported by a titanium frame and a cryogenic circuit to cool down the superconducting components to liquid helium temperature. There are two independent supply lines, one for the cavities and one for the solenoids. The gas boil-off is recovered inside a common upper main phase separator vessel collecting both the cavity and solenoid helium. The main part of the cold gas is then returned towards the cold box, and a small fraction is used to cool down the thermal shield.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFAV004

STATUS OF THE CRYOGENIC INFRASTRUCTURE FOR MESA*

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Abstract

The Institute of Nuclear Physics at the Johannes Gutenberg University Mainz, Germany is currently constructing the Mainz Energy-recovering Superconducting Accelerator (MESA). The centerpiece of the MESA consists of two superconducting cryomodules of the ELBE/Rossendorf type, which are operated at 1.8 K. Furthermore, accelerator elements for polarimetry, a 10 T solenoid, and the external SRF test facility of the Helmholtz Institute Mainz have to be supplied with 4 K helium. One challenge here is to supply the components located throughout the accelerator according to their requirements and to establish a 16 mbar system for 1.8 K operation. To ensure the required supply of helium at the different temperature levels, the existing helium liquefier has to be upgraded. The cryogenic infrastructure has to be adapted to the accelerator. The concept of the future cryogenic distribution network is presented in this paper and the design of the cryogenic facilities including the modifications is described in detail.

INTRODUCTION

In the moment, the energy recovery linac MESA (Mainz Energy Recovering Superconducting Accelerator) is under construction at the Institute of Nuclear Physics, Johannes Gutenberg-Univerität Mainz, Germany [1]. Its recirculating design, shown in Figure 1, has as its centerpiece two cryomodules designed for continuous wave operation at a temperature of 1.8 K [2]. Each cryomodule consists of two TESLA cavities, operating at 1.3 GHz and a field gradient of 12.5 MeV. To operate both cryomodules, they must be supplied with liquid helium, brought to 16 mbar, and liquid nitrogen to power the LN2 shields.

MESA will be used for nuclear and particle physics research and will supply three experiments in its first phase. The P2 experiment is designed as a fixed target experiment and is used for high-precision measurement of the electroweak mixing angle (Weinberg angle) [3]. It is supplied by MESA in external beam mode with 150 µA spin-polarized electrons with an energy of 155 MeV. The experiment will be realized as a liquid helium target inside a superconducting solenoid that must be integrated into the cryogenic supply. In addition, P2 requires an accurate measurement of the beam polarization before the experiment. This is measured in the beamline before the experiment with the so-called hydromøller [4]. This also requires connection to the cryogenic supply.

The so-called beam dump experiment ”Dark Mesa BDX” is operated in the same time as the P2 experiment and is looking for dark particles that can be created during the dumping of the electron beam in the P2 beam dump [5]. The experiment is located outside the accelerator halls to have a low background and does not need to be considered for cryogenic supply.

The third experiment is the MAGIX experiment that is supplied as an internal target in ERL mode with up to 105 MeV and a beam current of 1 mA. The MAGIX experiment is planned as a dual-arm multipurpose spectrometer and also does not need to be included in in the cryogenic supply [6]. As can be seen in Figure 1, the components to be supplied are distributed across the accelerator halls. The task of planning the cryogenic infrastructure is to design a distribution system that meets the different requirements of the components. Especially the requirements of the cryogenic modules demand an adaptation of the existing infrastructure. This paper is intended to give an overview of the components, as well as the current status of the planning and the required components.

HELIUM AND NITROGEN DEMANDS

The components have different liquid helium and nitrogen requirements, which are are shown in Table 1.

Table 1: Estimated demands of the MESA components to the cryogenic infrastructure. The existing valvebox for LHe-distribution needs additional 35 L h^{-1} LHe.

Component	LHe(4 K)	LN2 (77 K)
cryomodule system	187.1 L h^{-1}	12.5 L h^{-1}
hydromøller	9 L h^{-1}	TBD
P2-Solenoid	11 L h^{-1}	4.1 L h^{-1}
Total	207.1 L h^{-1}	16.6 L h^{-1}

The liquid helium demands of the cryomodules were measured during the horizontal tests [7]. While the hydromøller and P2-Solenoid will need 4 K for (pre-)cooling, the working temperature in the cryomodules is 1.8 K. A subatmospheric pumping stage (subatmospheric compressor) is needed to achieve this temperature by lowering the pressure of the return gas to 16 mbar. This has been taken into account in the Table 1. The existing LHe distribution valvebox needs additional 35 L h^{-1} LHe because of an inefficient design. The valvebox has to be changed before operation.

* This work is supported by the German Research Foundation (DFG) under the Cluster of Excellence ”PRISMA+” EXC 2118/2019
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFAV005

DESIGN OPTIMIZATION OF THE 166-MHz AND 500-MHz FUNDAMENTAL POWER COUPLERS FOR SUPERCONDUCTING RF CAVITIES AT HIGH ENERGY PHOTON SOURCE

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Abstract

Five 166-MHz quarter-wave β=1 cavities have been chosen for the fundamental srf system while two 500-MHz single-cell elliptical cavities for the third-harmonic system for High Energy Photon Source (HEPS). Each cavity will be equipped with one fundamental power coupler (FPC) capable of delivering 250-kW continuous-wave rf power. For the 166-MHz FPC, two prototypes were developed and excellent performances were demonstrated in the high-power operations. However, the inner air part was observed to be warmer than predictions. Therefore, an innovative cooling scheme was adopted. In addition, the Nb extension tube at the coupler port has been elongated to solve the overheating in the cavity–coupler interface region. Concerning the 500-MHz FPC, several improvements were proposed according to decades of operation experience of the BEPCII srf system. First, a doorknob adopting WR1800 instead of WR1500 waveguide was chosen to better match the operating frequency; Second, the window position was optimized to ensure multipacting-free on the window; Third, the cryogenic heat load was estimated carefully to obtain an optimum helium gas cooling. The main parameters and the design optimizations of the 166-MHz and 500-MHz FPCs are presented in this paper.

INTRODUCTION

High Energy Photon Source (HEPS) is a 6 GeV diffraction-limited synchrotron light source currently under construction in Beijing [1, 2]. In order to accommodate the on-axis accumulation injection scheme conceived for the future, a double-frequency rf system has been adopted with 166.6 MHz as the fundamental and 499.8 MHz as the active third harmonic [3]. Five 166-MHz quarter-wave β=1 superconducting cavities (SCC) have been chosen for the fundamental while two 500-MHz single-cell elliptical superconducting cavities for the third-harmonic system [4]. Each cavity is equipped with one fundamental power coupler (FPC) capable of delivering 250-kW continuous-wave rf power, as shown in Fig. 1. The main parameters of the cavities and their FPCs are listed in Table.1. The high-power grading, strong coupling, reasonable cryogenic heat loads and large design margins are the challenges of developing the two FPCs.

For the 166.6 MHz FPC, a compact geometric size to enable a clean assembly and protecting the ceramic window from bombardments by the cavity field emission induced electrons are two additional challenges. Two prototypes were developed and excellent performances were demonstrated in the high-power operations. However, the inner air part was observed to be warmer than predictions. Therefore, an innovative cooling scheme inspired by jet impingement was adopted in the formal coupler design. In addition, during the proof-of-principle (PoP) cavity horizontal test, an overheating in the cavity-coupler interface region was observed and analyzed. Then solution of elongating the niobium extension tube at the coupler port have been included in the formal coupler design.

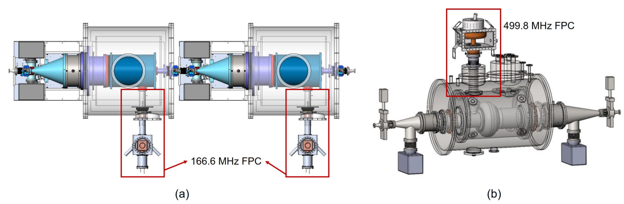

Figure 1: The general layout of the 166.6 MHz (a) and 499.8 MHz (b) cavity system for HEPS.

Concerning the 500-MHz FPC, several improvements were proposed according to decades of operation experience of the BEPCII srf system. First, a doorknob adopting WR1800 instead of WR1500 waveguide was chosen to better match the operating frequency; Second, the window position was optimized to ensure multipacting-free on the window; Third, the cryogenic heat load was estimated carefully to obtain an optimum helium gas cooling.

The details of the design optimizations of the two FPCs will be presented in the following sections.

166.6 MHz FPC

Air Cooling Improvement

Two 166.6 MHz prototype FPCs were fabricated and high power tested [5]. The rf conditioning was conducted initially on a room-temperature test bench shown in Fig. 2(a) in travelling-wave mode. The rf power were kept at 50 kW cw for more than 1 h, and both couplers showed excellent rf, vacuum, and thermal performances, as shown in Fig. 2 (b). However, a higher temperature rise was measured to be 1.5 °C for the inner conductor of the T-box for every 10 kW of power ramping, which almost doubled the simulated value of 0.8 °C/kW.

In order to reduce the temperature rise of the inner T-box, an innovative cooling scheme inspired by jet impingement

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFAV006

ILC ENERGY UPGRADE PATHS TO 3 TeV

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Abstract

We consider several ILC energy upgrade paths beyond 1 TeV depending on the needs of high energy physics. Parameters for four scenarios will be presented and challenges discussed.

1. **From 1 TeV to 2 TeV based on:**

A. Gradient advances of Nb cavities to 55 MV/m anticipated from on-going SRF R&D on Nb structures.

B. Radically new travelling wave (TW) superconducting structures optimized for effective gradients of 70+ MV/m, along with 100% increase in *R/Q* (discussed in more detail in paper [1] at this conference. The large gain in *R/Q* has a major beneficial impact on the refrigerator heat load, the RF power, and the AC operating power.

OR

2. **From 1 TeV to 3 TeV based on:**

A. Radically new travelling wave (TW) superconducting structures optimized for effective gradients of 70+ MV/m, along with 100% increase in *R/Q*. The large gain in *R/Q* has a major beneficial impact on heat load, RF power, and the AC operating power.

B. 80 MV/m gradient potential for Nb_3Sn with Q of 1×10^{10}, based on extrapolations from high power pulsed measurements on single cell Nb_3Sn cavities. Further, the operating temperature is 4.2 K instead of 2 K due to the high T_c of Nb_3Sn.

INTRODUCTION

Over the last few years, there has been general agreement [2] in the World High Energy Physics community that an electron-positron collider Higgs factory is one of the highest priorities for the field. In June 2020, the European Strategy for Particle Physics Report [3] offered strong support for ILC hosted by Japan, expressing their wish for European participation. Other paths to the Higgs Factory are the FC-Cee [4] or CLIC [5] in Europe, and CepC [6] in China, all in CDR stage with further development needed. With a TDR completed some years ago [7], the superconducting ILC remains the most technologically ready and mature of all possible Higgs factories options for an expeditious start. In the years after its TDR completion, ILC technology is being used on a large scale to establish a rich experience base with new accelerators such as European XFEL [8], LCLS-II [9] in the US and SHINE [10] in China, along with SRF infrastructure installed worldwide. The most significant development supporting the expeditious launch of ILC is that the cost of starting at 250 GeV as a Higgs Factory [11, 12] has dropped considerably (40%) from the original TDR estimate for the 500 GeV machine, with bottoms-up cost evaluations, substantiated by the experiences of EXFEL and LCLS-II. At 17.5 GeV, EXFEL is an SRF linac based on ILC technology that has been operating for several years. The average maximum cavity gradients for 400 cavities as received and prepared by the ILC recipe reached 33.3 ± 6.6 MV/m [13,14]. (The other 400 cavities which were treated with a different recipe reached 29.8 ± 6.6 MV/m.) Demonstration of gradients >30.5 MV/m in full scale cryomodules at KEK [15] and a CM gradient >32 MV/m has been achieved at Fermilab [16] with beam.

Demonstrations at ATF2 (KEK) in Japan have established confidence in ILC IP parameters [17, 18]. Demonstrations at CESR (Cornell) have established confidence in damping ring parameters [19].

A strong physics attraction of ILC is the energy upgradability to TeV and multi-TeV energies, offering clean e+e– physics to the next century. All energy upgrade paths will require intense SRF R&D to realize the very high gradient and high Q performances needed. But there are several decades of R&D ahead to accomplish those goals before the time for a 2 TeV or 3 TeV upgrade is indicated by physics. We are optimistic that the Snowmass [20] process in progress will stimulate funding for these avenues for high energies.

OPTION 1A: 2 TeV WITH 55 MV/m

We consider advances in SRF performance to gradients/Q of 55 MV/m/2×10^{10} based on the best new treatments [21, 22] applied to advanced shape structures such as the Reentrant [23], Low-Loss/ICHIRO [24, 25] or the Low-Surface-Field (LSF) candidates [26] for which gradients of 52–55 MV/m with Q >1×10^{10} have already been demonstrated with 1-cell cavities, using the standard ILC recipe [27]. The new shapes were developed to reduce H_{pk}/E_{acc} 15–20% below that of the TESLA shape. In addition, the *R/Q* for the advanced shapes is about 20% higher to help reduce the RF power, dynamic heat load and AC power.

Today the best result for a 1-cell cavity of standard TESLA shape given the best new treatment is 49 MV/m [21, 22], confirmed by retesting at many labs, and by about 50 tests on many 1-cell cavities [28]. Therefore, applying the best new treatments to the advanced shapes we can optimistically expect gradients 15% higher with successful R&D, so from 60–65 MV/m for single cells and 55 MV/m for 9-cells.

The strategy adopted for Option 1a is to replace the lowest gradient (31.5 MV/m) 0.5 TeV section of cavities/cryomodules, re-using the tunnel, RF and Refrigeration of this section, keep the 0.5 TeV section of the 1 TeV upgrade with 45 MV/m gradient (11,000 cavities), running with the slightly lower bunch charge, and add 1.5 TeV with 55 MV/m/Q=2×10^{10}. With this approach, it is possible to keep the total linac length to 52 km - well below the currently expected 65 km site limit [29,30]. Note: If we just add a full one TeV (24 km)

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV004

A NEW MODEL FOR Q-SLOPE IN SRF CAVITIES: RF HEATING AT MULTIPLE JOSEPHSON JUNCTIONS DUE TO WEAKLY-LINKED GRAIN BOUNDARIES OR DISLOCATIONS*

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Abstract

Several models have already been proposed for the medium field Q-slope (MFQS) and high field Q-slope (HFQS) in SRF cavities. However, the existing models do not explain both MFQS and HFQS in a unified way. A new model with multiple Josephson junctions at weakly-linked grain boundaries or dislocations is proposed for a unified explanation of both effects. The new model incorporates two kinds of junction: ceramic-like junctions for MFQS, and weak superconductor junctions for HFQS. In measurements of RF power dissipation (P_{loss}) versus RF field, an increase in P_{loss} proportional to the cube of the field is observed for MFQS. This is seen for cavities prepared with both buffered chemical polishing (BCP) and electropolishing (EP). An exponential increase in P_{loss} with field is often observed at high field for BCP'ed cavities (HFQS). If the number of Josephson junctions increases linearly with the RF field, as expected due to flux quantum penetration, these behaviors are easily explained. In addition, the new model can potentially explain the anti-Q slope behavior observed in nitrogen-doped or mid-temperature-baked cavities. In this paper, the new model will be described and compared with measurements.

MOTIVATION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) is a collaborative project with the US Department of Energy for research at the frontiers of nuclear science. A total of 324 superconducting resonators were fabricated, tested, and installed into the FRIB driver linac: 2 types of quarter-wave resonators (QWRs) at 80.5 MHz and 2 types of half-wave resonators (HWRs) at 322 MHz. First acceleration of ion beams through the full linac was achieved in May 2021 [1].

Analyses of Dewar certification testing results for FRIB cavities has been undertaken [2]. The cavities were prepared with buffered chemical polishing (BCP) but no low temperature bake (LTB).

Many of the FRIB cavities showed high field Q-slope (HFQS). An example is shown in Fig. 1: pure HFQS is seen with no field emission (FE) X-rays up to the maximum field. In the data analysis, a Fowler-Nordheim (FN) analysis was applied to the HFQS. FN analysis is usually applied to FE analysis [3], rather than HFQS. The FN model describes FE as an electron tunneling effect. The good FN fitting results for pure HFQS (Fig. 2) suggests that a quasi-electron tunneling mechanism can explain HFQS, which led us to consider the Josephson Effect [4].

Measurements of the accelerating gradient (E_{acc}) as a function of Q_0 (intrinsic quality factor) are often analyzed in terms of the RF surface resistance. For the FRIB cavities' MFQS, we took a different approach: we considered P_{loss} as the sum of contributions from various mechanisms. We observed an increase in RF power dissipation (P_{loss}) as the cube of the RF field for the FRIB cavities. An example is shown in Fig. 3: below the HFQS threshold, P_{loss} closely follows a cubic dependence on the peak surface electric field (E_p), as indicated by the black line.

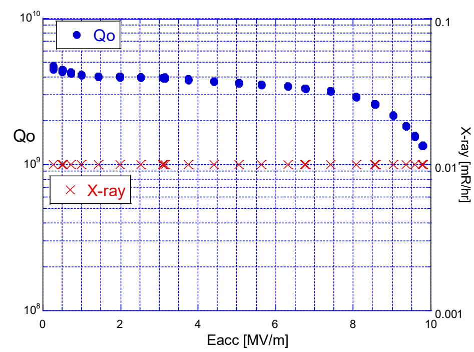

Figure 1: Quality factor as a function of accelerating gradient for a FRIB β = 0.29 HWR at 2 K.

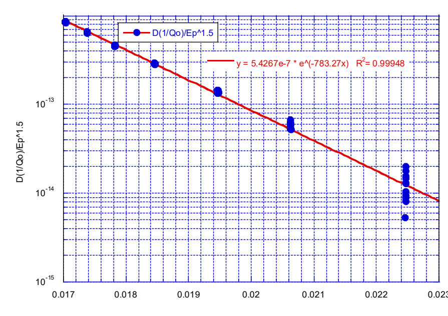

Figure 2: FN plot for the HFQS of Fig.1.

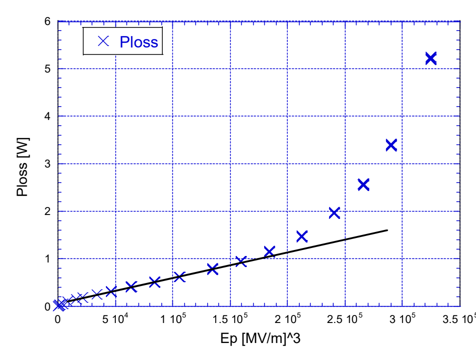

Figure 3: Power dissipation as a function of the cube of the peak surface electric field.

* Work supported by the U.S. Department of Energy Office of Science DE-S0000661 and the National Science Foundation under Cooperative Agreement PHY-1102511
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV005

TENSILE TESTS OF LARGE GRAIN INGOT NIOBIUM AT LIQUID HELIUM TEMPERATURE

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Abstract

Tensile tests at liquid helium temperature were performed using specimen taken from high purity large grain niobium ingot produced by CBMM. The measured RRR is 242. The ingot is 260 mm in diameter and sliced by a multi wire saw to 2.8 thickness. 5 specimens were cut off from one sliced disk. 3 disks were set in same phase to obtain same grain distribution. 3 specimens each of 5 grain patterns 5, 15 in total were used for the tensile test. The tensile test stand using a cryostat and liquid He was manufactured by ourselves. The measured tensile strength varied 379 to 808 MPa. The average value is 611 MPa. The tensile strength at room temperature is 84 MPa. The strength becomes high at low temperature like a fine grain niobium. The specimen includes a grain boundary, and causes the variation of strength. The different result was obtained in same grain patterns. The relationship between crystal orientation and strength is discussed.

INTORODUCTION

The start material of high-purity niobium used for the superconducting cavity is an ingot manufactured by electron beam melting. It is a polycrystal with a grain size of 10 to 200 mm. The center cell part of the 1.3 GHz superconducting cavity shown in Fig. 1 is fabricated by press-forming a niobium sheet with a thickness of about 3 mm. A niobium sheet is usually produced by forging an ingot and rolling. The crystals are fined and the grain size becomes about 0.01 to 0.1 mm. This is called a fine grain (FG). On the other hand, there is a method in which a cylindrical ingot is sliced into a cell disk and press-formed to produce a cavity. Since the sliced disk contains large crystal grains, it is called a large grain (LG). The LG cavity has features such as a higher maximum accelerating gradient and Q value than the FG cavity [1-3]. Moreover, the slicing process is simpler than the forging / rolling process, and it is effective to reduce the secondary process cost of the low material.

The superconducting cavity is housed in a helium tank and cooled with liquid helium. These are subject to the High-Pressure Gas Safety Act. The tensile strength of the niobium material at the liquid helium temperature is required for it [4]. Therefore, the authors are conducting the tensile testing in liquid helium using a commercially tensile testing machine, a jig, and a cryostat as shown in Fig. 1 [5].

Although the tensile strength of LG niobium at room temperature has been reported [6], there is no report of measurement at liquid helium temperature. Therefore, tensile testing in liquid helium was performed using the LG niobium specimen having the same shape as the measurement result of FG niobium. The new experimental procedure and results are reported.

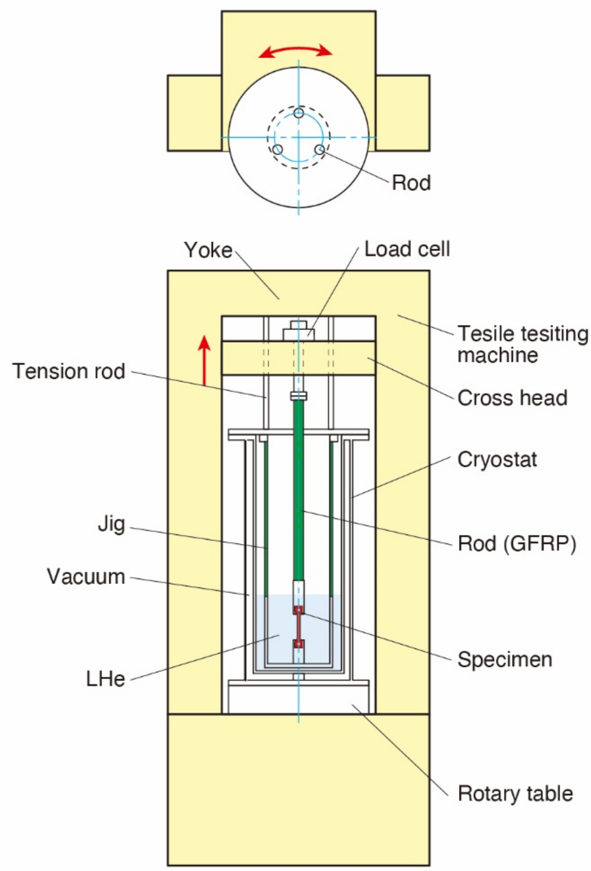

Figure 1: Schematic view of tensile testing machine with a cryostat (I.D. 317 mm) [5].

PREPARATION OF SPECIMEN

A niobium ingot with a diameter of 260 mm was sliced to a thickness of 2.8 mm using a multi-wire saw, and the JIS Z 2241 13B specimen shown in Fig. 2 was cut out by a wire EDM in the layout shown in Fig. 3. The specimens A to E were arranged so that the grain boundary was included in the center of each specimen. Using three disks with near slicing order, the grain pattern was set in the same order, and five specimens were prepared from each disk, for a total of 15 specimens. In addition, 14 13B specimens were cut out from one disk for the room temperature test. The shape of the grip part of the specimen for room temperature is different from that for the low-temperature test. The position of the grain boundary varies depending on each specimen. After cutting out, all the specimens were vacuum annealed at 800 ° C for 3 hours.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV006

ACTIVITIES AT NCBJ TOWARDS DEVELOPMENT OF THE FUTURE, FULLY-SUPERCONDUCTING, XFEL-TYPE, RF ELECTRON GUN

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Abstract

Our group at NCBJ is working on upgrade of 1.6-cell, SRF, XFEL-type injector in collaboration with DESY and other laboratories. The work is focused on preparation of lead-on-niobium photo-cathode, its positioning in the gun cavity and on the UV laser system for photocurrent excitation. RF focusing effect was used to minimize the predicted emittance and the transverse size of accelerated e^- beam. Following beam dynamics computation, it has been proposed that the photocathode be recessed 0.45 mm into the back wall of the gun cavity. It helps focusing e^- beam in its low-energy part. Preparation of superconducting (sc) photocathodes of Pb layer on Nb plugs is reported, aimed at reaching clean, planar and uniform Pb films. The laser system will consist of commercially available Pharos laser and a 4-th harmonic generator. A gaussian, 300 fs long, 257 nm in wavelength pulse will be transformed in time by pulse stretcher/stacker and in space by pi-shaper. The planned optical system will generate cylindrical photoelectron bunch 2 - 30 ps long and 0.2 - 3 mm wide.

BACKGROUND

R&D program on low and medium current, fully-superconducting, RF electron photo-injector is a part of the task of performance improvement of E-XFEL [1 - 3] and similar facilities. The injector is expected to produce electron beam bunches of normalized emittance below $1{\cdot}\pi$ µrad with charges up to hundreds of pC. Long pulse and continuous wave (CW) operation modes are also anticipated [1, 3]. At the present state-of-the art, reaching an average current of 25 µA from XFEL SRF gun at CW operation is expected in a few years [3]. The concept of a SRF, hybrid Nb-Pb electron injector for linear, sc accelerators was proposed and developed [1,4-8]. This solution assumes the use of a fully sc photocathode in the form of a Pb film applied to niobium surface. Both metals are superconductors with similar critical temperatures but lead exhibits much higher quantum efficiency (QE) of photoemission.

Long-time collaboration between TJNAF, DESY, HZB, BNL, HZDR,, Stony Brook University, NCBJ and SLAC resulted in a concept and design of a 1.6-cell TESLA-type SRF cavity with a replacable photocathode of niobium plug with applied lead film as a photoemitting element. The plug is mounted to the rear cavity wall. This solution, was first proposed at TJNAF [8]. Early tests on such guns with Nb-Pb photocathodes were performed at TJNAF, DESY and HZB [8 - 10]. To emit photoelectrons the lead photocathode is typically excited with an UV beam of photon energy above 4 eV, synchronized with the phase of RF field. The amplitude of the electric field on the cathode surface is 40-60 MV/m [8]. This solution allowed avoiding the cathode contact with mixtures of acids used for chemical treatment of cavities. Nevertheless, high pressure water rinsing of the injector with the photocathode is needed to obtain sufficiently high RF field intensity in the cavity. This preparatory step imposes demands on the lead layer adhesion to the plug.

The work of our team on the optimization of the electron gun for the use of Polish Free Electron Laser (PolFEL) is concentrated on three areas:

1. Improvement of e^- beam focusing and reduction of it transverse dimensions, based on beam dynamics computations.
2. Development of an optimal technique of applying a Pb layer on the photocathode plug.
3. Development and implementation of laser and optical systems for photocurrent excitation from the cathode surface.

The above issues are addressed in the following subsections of this paper.

IMPROVEMENT OF e^- BEAM FOCUSING INSIDE SRF ELECTRON GUN, BASED ON BEAM DYNAMICS COMPUTATION

The main challenge in designing superconducting RF guns is to counteract the space charge forces, particularly in the non-relativistic, low energy e^- beam region immediately downstream of the cathode. Beam focusing in this region by using axial magnetic field from external solenoid is not possible for superconducting structures. Therefore, it was decided to focus the near-cathode electrons by generating a radial component of electric RF field that comes from retraction of the photocathode tip (terminated with the emissive surface) back into the rear cavity wall.

The geometry of 1.6-cell gun cavity with electric field lines is shown in Fig. 1. The field distribution has been computed by using Poisson Superfish code [11]. The radial field component distribution 0.5 mm off the cavity axis is depicted in Fig. 2 for accelerating field amplitude E_{acc} on the axis equal 40 MV/m. A short focusing field spike is visible next to the cathode surface. The spike amplitude grows with the distance from the axis.

The discussed plug retraction reduces the field value on the cathode surface which typically elongates life-time of the cathode. On the one hand it reduces photocurrent emission at high space charge. The latter effect, however, may

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV007

MAIN HIGHLIGHTS OF ARIES WP15 COLLABORATION*

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Abstract

An international collaboration of research teams from CEA (France), CERN (Switzerland), INFN/LNL (Italy), HZB and USI (Germany), IEE (Slovakia), RTU (Latvia) and STFC/DL (UK), are working together on better understanding of how to improve the properties of superconducting thin films (ScTF) for RF cavities. The collaboration has been formed as WP15 in the H2020 ARIES project funded by EC. The systematic study of ScTF covers: Cu substrate polishing with different techniques (EP, SUBU, EP+ SUBU, tumbling, laser), Nb, NbN, Nb_3Sn and SIS film deposition and characterisation, Laser post deposition treatments, DC magnetisation characterisation, application of all obtained knowledge on polishing, deposition and characterisation, Laser post deposition treatments, DC magnetisation characterisation, application to the QPR samples for testing the films at RF conditions. The preparation, deposition and characterisation of each sample involves 3-5 partners enhancing the capability of each other and resulting in a more complete analysis of each film. The talk will give an overview of the collaborative research and will be an introduction to the detailed talks given by the team members.

INTRODUCTION

ARIES is a Horizon 2020 Integrating Activity, co-funded by the European Commission. An acronym of ARIES stands for Accelerator Research and Innovation for European Science and Society which started on 1st May 2017 for 4 years. ARIES includes three components: Networking, Transnational Access and Joint research activities divided in 18 WPs. Only four WPs were Joint research activities including WP15: Thin films for superconducting cavities.

The aim of this work package is to intensify systematic studies and development of the coating technology of superconducting materials to enable the superconducting thin film coated RF cavities, joining an effort of 9 partners from 7 countries brought together in this collaboration. It must be noted that 3 of them were new for accelerator related activities.

The main emphasis our team is on a systematic study of correlation between (1) substrate surface preparation, (2) deposition parameters, (3) film structure, morphology, chemistry and phase, (4) AC and DC superconductivity parameters and, finally, (5) the behaviour at RF conditions with the test cavities.

This paper reports the main results of the ARIES WP15 collaboration.

COPPER SUBSTRATE PREPARATION

For this project, small samples on copper substrate with a size of 53 mm × 53 mm were used as a standard. The objective was to investigate the effect of copper substrate polishing on Nb film. 50 planar copper samples were produced at CERN from the same copper sheet and polished with 4 different procedures: 25 samples were treated at CERN with chemical polishing (also known as SUBU5) solution and the other 25 samples were treated at INFN with SUBU5 solution, electropolishing (EP), SUBU+EP, and tumbling.

SUPERCONDUCTING THIN FILM DEVELOPMENT

Developing of Superconducting Thin Films (STF) is a core of the project. The substrates were prepared by INFN and CERN and were delivered to coating partners STFC, University of Siegen and INFN.

Nb Films

Subsequently, Nb thin films were deposited on copper samples from each procedure using direct current magnetron sputtering (DCMS). Although the deposition configuration is different from one centre to another, the deposition parameters were set to be comparable. The procedure and the applied deposition parameters in all three deposition facilities are reported in [1-3]. The results of sample evaluations with a full flux penetration field (B_{fp}) are shown in Fig. 1. Based on these results SUBU5 and EP were selected

* Work supported provided by European Union's ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV008

THERMAL CONDUCTIVITY OF ELECTROPLATED COPPER ONTO BULK NIOBIUM AT CRYOGENIC TEMPERATURES*

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Abstract

Superconducting radio-frequency (SRF) cavities made of high-purity bulk niobium are widely used in modern particle accelerators. The development of metallic outer coatings with high thermal conductivity would have a beneficial impact in terms of improved thermal stability, reduced material cost and for the development of conduction-cooled, cryogen-free SRF cavities. Several high-purity, fine-grain Nb samples have been coated with 2-4 mm thick copper by electroplating. Measurements of the thermal conductivity of the bimetallic Nb/Cu samples in the range 2 – 7 K showed values of the order of 1 kW/(m K) at 4.3 K. Very good adhesion between copper and niobium was achieved by depositing a thin Cu layer by cold spray on the niobium, prior to electroplating the bulk Cu layer.

INTRODUCTION

Modern particle accelerators rely more and more often to superconducting radio-frequency cavities (SRF) to accelerate the beam because of their higher efficiency, compared to normal-conducting ones. Research and development over the past 40 years has made bulk Nb the material of choice for this application and accelerating gradients close to the thermodynamic critical field of Nb have been achieved in state-of-the-art prototypes [1, 2]. One of the limitations towards reliably achieving accelerating gradients close to the theoretical limit is a thermal quench at lower field, initiated typically at defects introduced during the cavity manufacturing process [3].

The cost of high-purity Nb, having a residual resistivity ratio (RRR) greater than 300, is of the order of $1,000/kg, significantly higher than that of other metals used to produce accelerator cavities, and the requirement for the high RRR-value is dictated by the need for high thermal conductivity to push the quench field to higher values [3]. The availability of a method to provide a metallic coating with high thermal conductivity, κ, at liquid helium temperatures onto the outer surface of a Nb cavity would address both the thermal stability and the cost issues, as thinner Nb with lower RRR could be used to fabricate the cavities. The alternative approach of coating a high-κ substrate with a Nb thin film has yet to produce cavities which can achieve as high accelerating gradients with a high quality factor, as what can be routinely obtained with bulk Nb [4].

Alternative superconductors, other than bulk Nb, are being actively explored and significant progress has been made in recent years for Nb_3Sn films onto Nb substrate, with cavities achieving up to 17 MV/m with a quality factor of ~1×10^{10} at 4.3 K, much higher than what can be achieved in the same cavity with bulk Nb at the same temperature [5]. The capability of operating SRF cavities efficiently at 4.3 K, instead of 2 K, is a key to the development of SRF accelerators for industrial applications. In such applications, the cavities could be conductively cooled using cryocoolers if a high-κ coating is applied to the outer cavity surface [6-8].

In the past there were two most notable R&D efforts to produce bimetallic bulk Nb/Cu cavities: in one case, hydroforming was used to form the cavity from a Nb/Cu tube made by explosion bonding or hot-isostatic pressing [9-11], in the other plasma-spray techniques were used to add a copper coating on the outer surface of a standard bulk Nb cavity [12, 13]. It was shown that Nb/Cu cavities made by hydroforming achieve a performance similar to that of bulk Nb cavities [14], however this method is not applicable to the current method of Nb_3Sn thin film formation, which relies on thermal diffusion of tin into bulk Nb at temperatures above ~1000 °C. The plasma-spray methods investigated at IPN-Orsay were high-velocity oxy-fuel and inert plasma spraying, however the thermal conductivity at 4.3 K was not as high as that of high-RRR Nb [12, 13].

In this contribution we report on the deposition of 3 - 5 mm thick copper coatings by electroplating on high-purity bulk Nb samples and their thermal conductivity at cryogenic temperatures. Electroplating is a relatively inexpensive method which could be applied to fully finished cavities, whether bulk Nb ones or bulk Nb with a Nb_3Sn film on the inner surface.

SAMPLE PREPARATION

Samples Plated at AJ Tuck, Co.

For the plating done at A. J. Tuck Co., Brookfield, CT, USA, seven Nb samples, 3.175 × 3 mm² cross-section, 75 mm long and three Nb samples, 25 mm wide, 1 mm thick, 140 mm long were cut by wire electro-discharge machining (EDM) from a high-purity, fine-grain (ASTM > 5) Nb sheet used for srf cavity fabrication. The samples were chemically etched to remove ~100 µm from the surface by buffered chemical polishing (BCP), annealed in a vacuum furnace at 600 °C/10 h, followed by BCP removing

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177. I. P. and M. P. are supported by NSF Grant PHY 100614-010. The work at Nomura Plating was supported by the US-Japan Collaboration.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPFDV010

STRUCTURAL INVESTIGATION OF NITROGEN-DOPED NIOBIUM FOR SRF CAVITIES

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Abstract

Niobium is the standard material for superconducting RF (SRF) cavities for particle acceleration. Superconducting materials with higher critical temperature or higher critical magnetic field allow cavities to work at higher operating temperatures or higher accelerating fields, respectively. Enhancing the surface properties of the superconducting material in the range of the penetration depth is also beneficial. One direction of search for new materials with better properties is the modification of bulk niobium by nitrogen doping. In the Nb-N phase diagram, the cubic δ-phase of NbN has the highest critical temperature.

In this study niobium samples were annealed and N-doped in the high-temperature furnace at TU Darmstadt and investigated at its Materials Research Department with respect to structural modifications. Secondary ion mass spectrometry showed at which conditions N-diffusion takes place. X-ray diffraction (XRD) confirmed the appearance of γ-Nb_4N_3 and β-Nb_2N phases for the optimized doping process. XRD pole figures also showed grain growth during sample annealing. A single-cell cavity was nitrogen-doped using the parameters of the optimized recipe.

INTRODUCTION

After several decades of continuous research and technological innovation the performance of niobium cavities is very close to the theoretical limit. Today industrialised cavity production with fields up to 45 MV/m and a Q-factors exceeding 10^{10} at 2 K operation is possible [1, 2], in exceptional cases reaching beyond 50 MV/m [3, 4].

Surface modification of niobium, mostly nitrogen doping [5] can increase the Q-factor at 2K operation. Another approach is to use copper as bulk material, coated by Nb, as it is foreseen by the Conceptual Design Report of the Future Circular Collider. The application of both niobium coated copper and bulk niobium cavities is proposed for the accelerator structure of FCC-ee [6]. It builds on the long tradition of coated copper superconducting cavities at CERN. The high heat conductivity of copper would permit 4.5 K operation.

The research on new materials (non-bulk Nb [7]) could lead to more compact and energy efficient accelerators. Nb has the highest critical temperature amongst the elements, but already niobium containing compounds, like NbN and Nb_3Sn [8, 9] have higher critical temperature.

In this contribution the results on NbN phase forming by annealing in nitrogen atmosphere are presented. Here we are not focusing on the α-Nb phase modified by nitrogen doping [10] or nitrogen infusion [11]. In contrast to the previously mentioned cases, where the nitride formation could be detrimental and the surface NbN layer should be removed [12], our goal was to form a thick enough superconducting δ-NbN phase [13] on bulk niobium. In accordance with previous results on Nb cavities with similar annealing procedures [14], we managed to reach a γ-Nb_4N_3 surface phase.

METHODS

High quality niobium sheets [2.8 mm thick with residual-resistivity ratio (RRR) of 300] were treated by buffered chemical polishing (BCP), then cut to 5x5 mm^2 and 10x10 mm^2 squares by high pressure water at Research Instruments (RI). The cut samples were baked out and nitrogen-doped in the high-temperature UHV furnace located at IKP, TU Darmstadt ("Wuppertal oven") [15, 16]. The virgin and treated samples were characterized by x-ray diffraction (XRD), electron microscopy and secondary ion mass spectrometry (SIMS) at the ATFT group of TU Darmstadt. Finally a single cell cavity, purchased from RI, was treated according the optimized recipe.

The XRD measurements were done on a θ-θ geometry Rigaku SmartLab diffractometer with rotating copper anode (λ=1.54 Å), line focus and parallel beam set-up. 2θ-ω scans and pole figures at different Bragg reflections (constant 2θ detector angle) were taken.

The SIMS measurements were done on a Cameca ims5f spectrometer with O^{2+} ions.

RESULTS

The process parameters were optimized on the Nb samples. On Fig. 1 the XRD patterns of a test series are shown. The annealing temperature, nitrogen partial pressure and annealing time was increased from 1450 °C, 50 mbar, 30 min in four steps to 1578 °C, 100 mbar and 60 min, respectively. For the first run (with the lowest temperature, partial pressure and annealing time) we got β-Nb_2N phase, after the final optimization step, phase pure γ-Nb_4N_3.With those optimized conditions a single cell cavity was treated with witness samples at different positions. On Fig. 2 the XRD pattern of witness samples, located at positions "top" and "bottom" are shown. From the fit it can be seen, that the two samples have different ratios of NbN phases, the film on the top sample was almost phase pure: 98% γ-Nb_4N_3, while the bottom one contained still 13% β-Nb_2N phase.

The Q-factor of the single cell cavity was investigated. First the virgin cavity was measured [15]. After the treatment the 2K temperature range could not be reached due to a cold leak [16]. The most probable cause of the cold leak is the hard NbN film grown on the flange (see Fig. 3).

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV001

STUDY OF THE NIOBIUM OXIDE STRUCTURE AND MICROSCOPIC EFFECT OF PLASMA PROCESSING ON THE NIOBIUM SURFACE

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Abstract

A study of the niobium oxide structure is presented here, with particular focus on the niobium suboxides. Multiple steps of argon sputtering and XPS measurements were carried out until the metal surface was exposed. The sample was then exposed to air and the oxide regrowth was studied. In addition, three Nb samples prepared with different surface treatments were studied before and after being subjected to plasma processing. The scope is investigating the microscopic effect that the reactive oxygen contained in the glow discharge may have on the niobium surface. This study suggests that the Nb_2O_5 thickness may increase, although no negative change in the cavity performance is measured since the pentoxide is a dielectric.

INTRODUCTION

The work conducted at FNAL for the Linac Coherent Light Source-II (LCLS-II) 9-cell cavities [1, 2] and at Oak Ridge National Laboratory by Doleans [3–6] for high beta cavities proved that plasma processing removes hydrocarbons from the cavity surface, increasing the niobium work function [7] and therefore mitigating field emission [8, 9]. The processing uses a small percentage of oxygen in the glow discharge [10] to react with the hydrocarbons. For this reason, it is important to investigate if the presence of reactive oxygen in the plasma may be impacting the oxides that form the outermost layers of the cavity surface.

Here a comparative study of high RRR niobium samples prepared with different surface treatments and subjected to plasma processing is presented. The samples were analyzed via X-ray photoelectron spectroscopy (XPS) before and after plasma cleaning. The samples were inserted into a 9-cell cavity, on the iris of one end cell, and plasma processed for six hours using Ne-O_2 plasma.

To understand how plasma processing may affect the niobium oxide structure, it was necessary to start by investigating the niobium main oxide, Nb_2O_5, and the other suboxides, through argon ions sputtering and oxide regrowth in air. Sample PH 36 was used for this scope. The combination of the two experiments allowed us to have a better understanding of the suboxides present on the niobium surface.

SPUTTERING EXPERIMENT ON Nb SAMPLE

Sample PH 36 is a high RRR niobium sample, prepared with bulk electropolish, followed by heat treatment at 800 °C

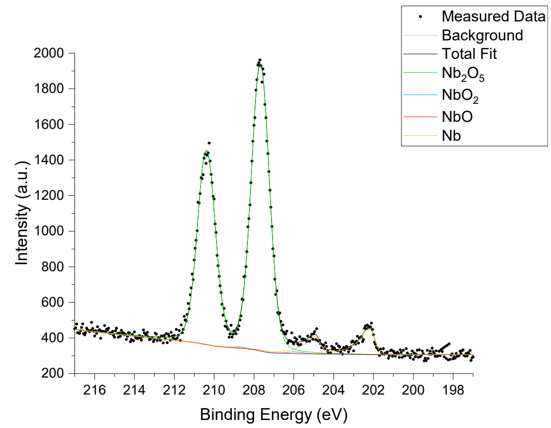

Figure 1: XPS Nb3d spectrum measured on sample PH 36 before starting the sputtering experiment. The sample's surface shows full, self-limited oxidization. As expected, the Nb_2O_5 doublet is the main feature present in the spectrum.

for 3 hours and further 20 µm of EP removal. This sample, along with PH 35 (used in the plasma processing experiment), received a 5-minute hydrofluoric acid (HF) rinse in order to remove a calcium carbonate contamination that was found on the samples surface. The HF rinse strips the oxide from the surface and allows to regrow a new oxide layer [11–14].

Sample PH 36 was analyzed with XPS one week after the HF rinse, allowing the sample surface to reach full self-limiting oxidization (as confirmed by the measurement shown in Fig. 1 carried out on the sample prior to starting the sputtering experiment). Cycles of sputtering and measuring were repeated at different time intervals, for a total of 600 s of sputtering time. In addition, the sample was sputtered for another 600 s the following morning to remove possible NbO that may have formed on the sample surface during the night, while the sample was kept in high vacuum with active pumping (baseline pressure: 3×10^{-9} Torr). This final measurement is indicated as '600 s + 600 s' in the plots. The results of the measurement carried out during the sputtering experiment are shown in Fig. 2. Panel (a) in Fig. 2 shows a progressive shift in the position of the main doublet toward lower binding energy (BE) values. The shift indicates a gradual removal of the pentoxide and the emerging of the suboxides, until the metal peak is the dominant feature in the spectrum. It is believed that NbO may be artificially created during the sputtering process, as the Ar ions knock off preferentially the lighter oxygen atoms rather than the niobium, gradually reducing the Nb_2O_5 to NbO. In addition, the oxygen molecules present in the HV atmosphere will

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV002

IMPROVEMENT OF CHEMICAL ETCHING CAPABILITIES (BCP) FOR SRF SPOKE RESONATORS AT IJCLAB

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Abstract

Buffered chemical polishing (BPC) is the reference surface polishing adopted for ESS and MYRRHA SRF spoke resonators at IJCLab. This chemical treatment, in addition to improving the RF performance, fits into the frequency adjustment strategy of the jacketed cavity during its preparation phase. In the framework of the collaboration with Fermilab for PIP-II project, IJCLab has developed a new setup to perform rotational BCP. The implementation of a rotation during chemical etching improves significantly the homogeneity and quality of surface polishing. In this paper, we present the numerical analysis based on a fluid dynamics model. The goal is to estimate the acid flow characteristics inside the cavity, determine the influence of several parameters as mass flow rate and rotation speed and propose the best configuration for the new experimental setup.

INTRODUCTION

Buffered chemical polishing is the chemical treatment performed at IJCLab on Spoke resonators equipped with their helium vessel (Fig. 1). A standard mixture of the three following acids is used: hydrofluoric HF, nitric HNO3 and ortho-phosphoric H3PO4, with 1:1:2 volume proportions. The heat generated during the chemical reaction is dissipated through both the acid maintained at 6°C and the cooling water inside the helium vessel.

Figure 1: Chemical treatment system equipped with a single Spoke resonator currently used at IJCLab.

The average material removal from the cavity surface by BCP is around 200µm in order to eliminate the damaged layer created during the manufacturing. Today, the cavity is static during the treatment. As a consequence, after half the time, the cavity is flipped in order to etch as homogeneously as possible the overall surface. The average removal rate measured on ESS and MYRRHA cavities by weighing is between 0.25 and 0.6 µm/min. The chemical treatments induce a frequency variation sufficiently well controlled, so that the RF frequency could be finely tuned. The BCP can be performed in vertical and horizontal positions for the ESS double Spoke cavities (Fig. 2) due to the presence of the high-pressure rinsing ports [1] (only in the horizontal direction for the MYRRHA single Spoke cavities [2]). These two BCP treatments do not etch the cavity walls in a same way and finally cause frequency changes which are different in magnitude and sign: around -0.6 KHz/µm in horizontal against +0.3 KHz/µm in vertical direction. Consequently, for each ESS cavity, a judicious combination of BCP operations is predefined to get the target frequency [3]. For MYRRHA cavity prototypes, the average frequency sensitivity is +1 KHz/µm.

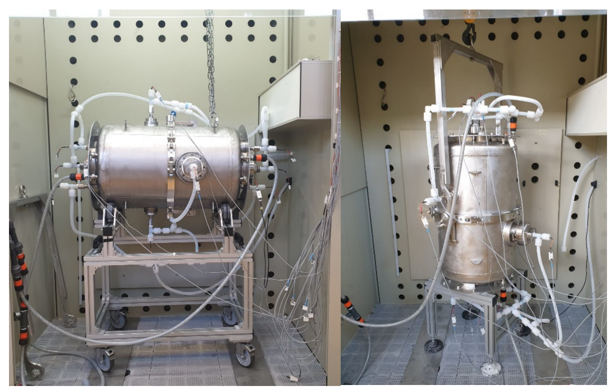

Figure 2: ESS cavity in horizontal and vertical position.

In the framework of the collaboration with Fermilab for PIP-II project, a new setup to perform rotational BCP was developed at IJCLab. Indeed, the implementation of a rotation during chemical etching improves significantly the homogeneity and quality of surface polishing. The idea is to integrate a rotation system along the axis of the beam tubes (called z axis) of the SSR2 cavity (Fig. 3) [4]. A gear mechanism makes the cavity rotate slowly back and forth with an amplitude of +/-180°. A continuous rotation is not possible so as to keep the ability to actively cool the helium vessel with chilled water. For this new experimental setup, a numerical simulation based on a fluid dynamics model was developed. The goal is to estimate the acid flow characteristics inside the cavity, determine the influence of several parameters as mass flow, rotation speed and filling factor to optimize the process in terms of temperature and material removal homogeneities.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV006

650 MHz ELLIPTICAL CAVITIES IN IMP FOR CiADS PROJECT*

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Abstract

650MHz multi-cell superconducting elliptical cavities with optimum beta equal to 0.62 and 0.82 were adopted in the driver linac of Chinese initiative Accelerator Driven Subcritical System (CiADS) to accelerate the 10 mA proton beam from 175 MeV up to 500 MeV, with the possibility to upgrade the energy to 1 GeV and higher. Mechanical design and optimization of the niobium cavity-titanium helium vessel assembly will be summarized in this paper. Vertical test results of three single cell prototype cavities will also be discussed, with comparisons with the simulation values.

INTRODUCTION

Chinese initiative Accelerator Driven Subcritical System (CiADS) is a Multi-MW proton source for energy generation and nuclear waste transmutation. The driver superconducting linac is composed of three categories of superconducting cavities, 162.5MHz half-wavelength resonators (HWR) with optimum beta equal to 0.10 and 0.19, 325 MHz double spoke resonators (DSR) with optimum beta equal to 0.42, and 650 MHz elliptical cavities with optimum beta equal to 0.62 (Ellip.062) and 0.82 (Ellip.082), as shown in Fig. 1 [1].

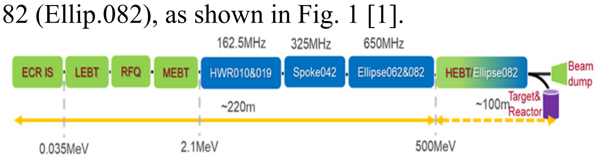

Figure 1: Layout of the CiADS injector linac.

Electromagnetic design and optimization of the six-cell Ellip.062 and five-cell Ellip.082 cavities, as well as the multipacting and high order mode analyses are summarized in [1]. Two different helium vessel options were studied, the titanium helium vessel with close linear expansion coefficient to niobium cavity, and the stainless steel helium vessel technologies with reduced material cost, potential reliability enhancement and well established fabrication and welding technology. Detail design of the stainless steel helium vessel option was summarized in [1], while the Titanium helium vessel option will be discussed in this paper.

CAVITY ASSEMBLY WITH TITANIUM HELIUM VESSEL

Similar mechanical structure of the cavity-helium vessel-tuner-coupler assembly were adopted for both the six-cell Ellip.062 and five-cell Ellip.082 cavities due to their same cavity length and closed equator radius, as shown in Fig. 2. Cavity will be made from 4 mm RRR300 Niobium sheets, while the stiffening ribs between cells and the end vessel plate connected to the beam pipe be made from 3 mm reactor grade niobium. Helium vessel is made from 4 mm Titanium with thicker end plate to get a better stiffness. NbTi55 was adopted to fabricate the flange, as well as the transit between niobium and titanium, as demonstrate in Fig. 3.

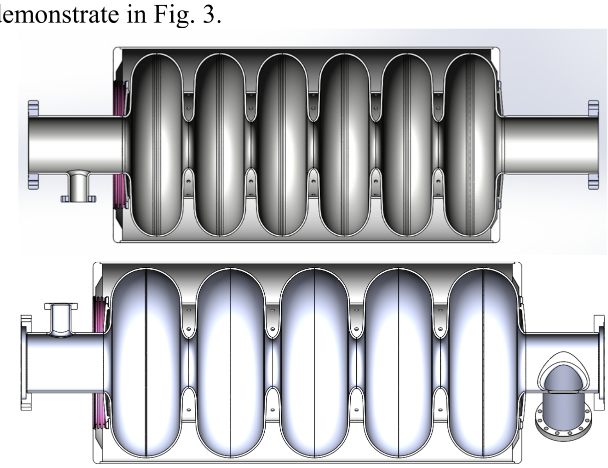

Figure 2: Mechanical structure of the CiADS 650 MHz elliptical cavity with Titanium Helium Vessel (Upper:Ellip.062; Lower:Ellip.082).

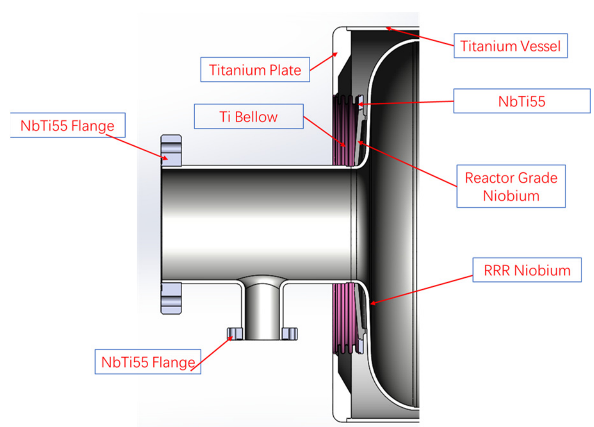

Figure 3: Material demonstration of the cavity-helium vessel assembly.

STIFFENING RIBS OPTIMIZATION

Position of the stiffening ribs between adjacent cells were optimized to minimize the Lorentz Force Detuning (LFD) and the frequency sensitivity to pressure fluctuation (df/dp). Figure 4 shows the dependence of cavity frequency to the helium pressure (df/dp) on different tuner stiffness for stiffening ring position of 105 mm and 110 mm for Ellip.062 cavity. The expected tuner stiffness is larger than

*Work supported by Large Research Infrastructures "China initiative Accelerator Driven System" (Grant No.2017-000052-75-01-000590) an National Natural Science Foundation of China (Grant NO. 11805249)
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV007

STATUS AND FIRST TESTS OF THE REDUCED-BETA CAPTURE CAVITY FOR THE S-DALINAC*

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Abstract

The superconducting part of the injector section of the superconducting Darmstadt electron linear accelerator (S-DALINAC) [1] consisted of one five-cell capture cavity and two 20-cell cavities at 3 GHz resonance frequency. All of them were geometrically adapted to electron velocities with a beta of 1, while the thermionic gun provides electrons with a beta of 0.74. This mismatch resulted in an insufficient capture process for optimum beam quality. For this reason, a new six-cell capture cavity with a beta of 0.86 has been designed and built. Field flatness tuning, a test in the vertical bath cryostat, and an UHV furnace treatment have been carried out in-house to finalize the cavity processing. The cryostat module was adapted to house the new cavity, which has been recently installed. Following the module assembly, a first RF test run was conducted at the S-DALINAC. We report on these latest advancements towards the implementation of the injector upgrade.

INTRODUCTION

The S-DALINAC [1] is a thrice-recirculating cw electron linac operated at 3 GHz. Mainly 20-cell elliptical niobium cavities at 2 K are used as acceleration structures. In addition to the conventional acceleration mode providing energies of up to 130 MeV at a design current of 20 µA for nuclear physics experiments, the machine is also capable of an operation as energy-recovery linac (ERL [2, 3]). The possible realization of an SRF multi-turn ERL has recently shifted into the R&D focus at the S-DALINAC. In this regard, improvements of the beam quality, especially concerning the injector, are necessary.

The accelerator layout with a detail view of the injector is illustrated in Fig. 1. A DC beam is produced in the thermionic 250 keV gun, while the spin-polarized electron gun [4] presently provides 100 keV electron bunches of several 10 ps length [5]. An upgrade of this source to 200 keV is foreseen [6]. The beam is then transformed into 3 GHz bunches within the chopper/prebuncher section. The bunches then enter the superconducting injector consisting of the capture cavity and two standard 20-cell-structures, providing a total output energy of 10 MeV. In the capture cavity, sufficient acceleration has to be provided to the beam in order to match the following structures while keeping the beam quality deterioration, which occurs due to phase slippage, as low as possible. For this reason, the formerly used five-cell, β=1 capture cavity was replaced

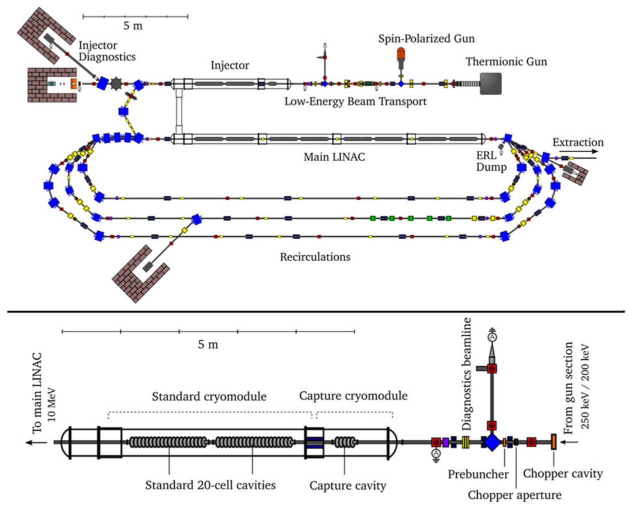

Figure 1: Schematic layout of the S-DALINAC accelerator (top) with detail view of the injector (bottom) housing the new beta-reduced capture cavity.

with a reduced-β structure [7-9] better adapted to the low source energies, especially in the case of beam generation in the spin-polarized gun (see Fig. 2). Key design features of the new cavity are a geometrical β of 0.86, a TESLA-shaped cell design and an increased mechanical stiffness in order to improve the stability during handling and installation. A moderate accelerating gradient of 5 MV/m is intended at a quality factor of $Q_0 > 1x10^9$. The following sections present the latest cavity processing steps, installation into the adapted cryomodule and first tests with RF power, thus summarizing the current status of the project.

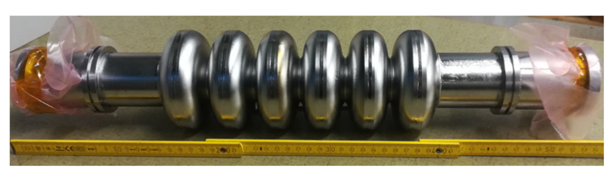

Figure 2: The six-cell reduced beta cavity after first delivery to TU Darmstadt.

IN-HOUSE CAVITY PROCESSING

The new six-cell niobium cavity has been produced by RI[1]. After delivery to TU Darmstadt, a first field-flatness tuning was applied to the cavity. During the manually applied deformation of individual cells, the target frequency of the cavity at this stage could be achieved at a length deviating only 1.3 mm from the design, while significantly improving the field-flatness at the same time (see Table 1).

* work supported by German research council (DFG) through GRK 2128 "AccelencE" and the state of Hesse through the LOEWE research project Nuclear Photonics and the Collaborative Research Cluster ELEMENTS
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV008

A FAST MECHANICAL TUNER FOR SRF CAVITIES

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Abstract

There is a particular need for fast tuners and phase shifters for advanced superconducting accelerator RF systems. The tuners based on ferrite, ferroelectric and piezo materials are commonly used. However, those methods suffer from one or another issue of high power loss, slow response, and narrow tuning range. We propose a robust, fast (up to ~5 MHz/sec), high efficient mechanical tuner for SRF cavities operating at the frequency 50 MHz. We develop an external mechanical tuner that is strongly coupled to the cavity. The tuner design represents a trade-off of high efficiency (low RF losses and low heat flux) and frequency tunability range. Our approach solves this trade-off issue. We propose RF design which exploits two coupled resonators so that a main high-field cavity is controlled with a small tunable resonator with a flexible metallic wall operating in a relatively low RF field. Simulations, carried out for a 7.5 MV/m 50 MHz SRF Quarter Wave Resonator (QWR), show that frequency tunability at level 10-3 is obtainable.

INTRODUCTION

High-energy cyclic accelerators of relativistic heavy ions, like PIP III, RHIC, and JLEIC, which have extensive roles in both fundamental and applied research, as well as in industrial applications, require fast tunable superconducting RF cavities providing high acceleration gradients. In PIP III new RF stations and new cavities will be required to accelerate a large amount of beam using a faster ramp [1]. The energy changes from 8 GeV to 120 GeV, and the RF frequency should change by 5×10^{-3}. This requires new tunable cavities with broad tuning range. The minimum acceleration voltage in this upgrade is planned to be 6.75 MV, and, assuming a maximum bucket area of 0.65 eV-sec after the transition, an RF voltage of 7.5 MV will be required [2]. The necessary RF voltage would require more normal conducting RF stations (between 31 and 33). The use of fast tunable superconducting cavities, operating at much higher gradients, can significantly reduce the impedance and decrease the number of the necessary cavities, and, therefore, can considerably reduce the overall power cost.

There are major efforts worldwide to develop high-gradient tunable SRF cavities. At the moment, the best devices provide ~2 MV acceleration per cavity and relatively small tuning range [3]. In particular, the RHIC 56 MHz cavity does not have a sufficient tuning range to follow a large change in frequency during the RHIC energy ramp. The RHIC cavity has a mechanical tuner located in a cryomodule. This represents a challenge for a tuner to provide fast tuning speed in large frequency range at cryogenic temperature. That is why, an external warm tuner strongly coupled with an accelerating SRF cavity seems appealing one.

There is also a particular need for fast tuners and phase shifters for advanced superconducting accelerator RF systems operating in the 0.05-1.3 GHz frequency range, and intended for ERL (Energy Recovery Linac) and ILC, etc. Specific features of ERL accelerator technology, and the challenges of ERL designs for X-ray light sources, are the high amplitude and phase stability requirements for their operation, in the range of 3×10^{-4} and 0.06 degree, respectively [4]. At the same time, mechanical vibrations (microphonics) contaminate the resonator frequency with characteristic frequencies in the range of ~100 Hz.

Fast tuners can be based on several concepts. In particular, ferrite tuners are widely used for boosters and proton cyclic accelerators, and provide acceptable tuning speeds [2], where the use of the orthogonally biased garnet tuner has been described. The major problem is to minimize the losses, which can limit the acceleration gradient. A simple estimate for a 50 MHz cavity that can provide energy gain of particles up to 8 MeV (R/Q~200 Ohm), with frequency tuning range 10^{-3}, shows that power loss can be as high as 15 kW (duty cycle is ~50%). Thus, the cooling of the tuner materials is still a severe issue. Note that ferrites have very low thermal conductivity, with a magnetic loss tangent of $\sim10^{-4}$.

Ferroelectrics can provide extremely high tuning speeds, as has been experimentally demonstrated [5]. More importantly, there are still many problems with the ferroelectric material quality and with metallization techniques, which results in high RF losses, which, again, may limit the gradient. In the example given in the last paragraph, if one substituted ferroelectric for ferrite, the power loss would still exceed 7.5 kW, taking into account the typical $\sim10^{-4}$ loss tangent for ferroelectrics. In addition, ferroelectrics have low thermal conductivity.

The use of piezoelectric deformation tuning is another approach for SRF cavity tuning [6]. However, there is only limited experience with the reliable long-term operation of piezoelectric actuators, especially in the CW regime. At DESY, piezoelectric actuators operate at a small duty factor (0.5%) without significant problems.

Up to the present date, a RF tuner with a rapid response, large tuning range, low RF loss, and high reliability is still lacking. That is why, we propose an approach to use a simple normal conducting metallic tuner, which incorporates an actuator with light flexible metallic wall that is electrically controlled by magnetic fields coils (similar to the function of piezo-elements), in order to produce a much lower RF power loss, which will increase the convenience of the cooling design. The main innovation of the proposed approach lies in the use of an external fast mechanical tuner

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV009

CONCEPTUAL DESIGN OF BALLOON DOUBLE SPOKE RESONATOR*

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Abstract

The balloon variant of the spoke resonator was proposed to eliminate the intensive multipacting (MP) barriers around the operating field level by modifying the local electro-magnetic (EM) fields. TRIUMF has previously reported the prototyping of a 325MHz beta=0.3 single spoke resonator (SSR) that demonstrated the principle of the balloon concept. To extend the benefits of the balloon variant to multi-spoke resonators, this paper will report a conceptual design of a 325MHz beta=0.5 balloon double spoke resonator (DSR). The consequences from the balloon SSR design, such as the relations between EM field distributions and the field levels of the MP barriers, were applied to the DSR design. Other particular geometry features were also added due to the characters of DSRs. The simulated MP barriers were significantly squeezed to the lower field level compared to a conventional DSR design. Simulation results and conceptual design will be reported.

INTRODUCTION

Spoke resonators have been widely proposed for proton accelerators, such as ESS [1], PIP-II [2], CADS [3], CSNS [4], heavy ion accelerators like RISP [5], and compact electron accelerators [6]. The modern designs have demonstrated the promising cavity performance around the world. But as a companion, the intensive and broader MP barriers, which could extend to the operating regime of the accelerating gradient, were brought to the community's attention. Some cavities requiring hours to days RF conditioning to overcome MP barriers have been reported for both SSR and multiple spoke resonators [7, 8].

The balloon variant of spoke resonator was proposed to eliminate MP barriers around the operating field by modifying the local EM fields [9]. TRIUMF has reported the prototyping of a 325MHz beta=0.3 SSR. It demonstrated that the balloon SSR constricts MP barriers well below the operating accelerating gradient and the required RF conditioning time can be reduced to minutes after in-situ low temperature baking [10]. The proven performance of the balloon concept encouraged the community to further investigate this new variant of SSR.

To augment the benefits of the balloon variant to multi-spoke resonators, this paper will report the conceptual design of the balloon DSR. The discussion starts with the conventional cavity geometry to analyze the characteristics of MP in DSR. Then the consequences from the balloon SSR are applied to the DSR design. As the geometry and the surface field distribution of DSR are more complicated, further geometry optimization is required to squeeze MP barriers to the lower gradient regime.

* Work supported by the National Research Council Canada.
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BASELINE

To study the balloon variant of DSR, a conventional DSR model is built as the baseline with the same resonant frequency and geometrical beta. The cavity geometry of the baseline model is optimized to obtain comparable RF parameters with existing designs. The MP barriers of DSR are characterized in the baseline. Both RF and MP are simulated with CST Studio Suite [11].

RF Optimization

To adapt the proposed proton or heavy ion accelerators, this study chooses the resonant frequency at 325 MHz and the geometrical beta of 0.5. The diameter of the beam tubes is 50 mm. The baseline model consists of a cylindrical cavity body and re-entrant end shells. The racetrack profile and transverse orientation are selected for both the spoke aperture region and spoke base to achieve lower peak surface fields and a higher shunt impendence [12]. The dimensions of the spokes and the end shells are optimized for RF parameters. The spoke positions along the beam axis are adjusted to maintain the geometrical beta. The resonant frequency is adjusted by the cavity diameter. Following the standard geometry optimization procedure, the baseline model is obtained as shown in Fig. 1 and the RF parameters are listed in Table 1 (1st column).

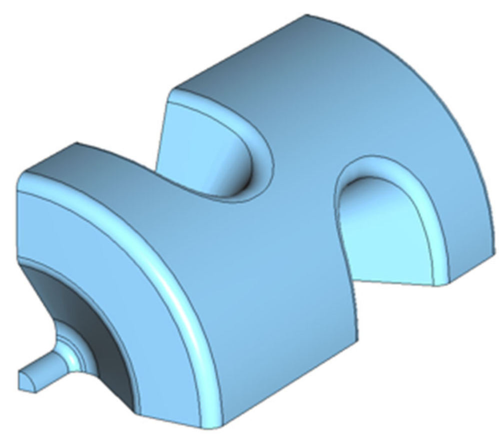

Figure 1: A quarter model of the baseline DSR model.

Multipacting

A niobium shell is added to the outer surface of the vacuum model. The shell material is defined as the 300 degC baked niobium, whose secondary electron yield (SEY) has the peak value of 1.49 at the impact energy of 300 eV. A uniform distributed particle source is defined in the simulation volume. The initial electrons are released equally every 30 degrees in the first RF period. The secondary electron counts and trajectories are recorded. The growth rate is defined as the power of the exponential increase of the secondary electrons. It represents a MP barrier when it is

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV010

COMPARISON OF ELECTROMAGNETIC PROPERTIES DURING FABRICATION OF COPPER AND NIOBIUM PROTOTYPES OF 325 MHz COAXIAL HALF-WAVE RESONATOR

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Abstract

The main fabrication stages of niobium and copper prototypes of coaxial half-wave resonators (HWR) operating at frequency 325 MHz for the Nuclotron-based Ion Collider fAcility (NICA) injector are presented and discussed. Results of intermediate measurements and electromagnetic properties control for niobium and copper cavities of equivalent geometrical characteristics are compared and analyzed. The comparison of electromagnetic properties of Cu- and Nb-prototypes allows estimating specific features and differences of intermediate "warm" measurements of niobium and copper cavities. The presented results will be used for further development and production of superconductive niobium cavities with a similar design for the NICA-project.

INTRODUCTION

The fabrication process of superconductive cavities for high energy particle acceleration consists of many intermediate stages including sheet niobium purity control, hydraulic stamping, rolling, electron beam welding, polishing, etc. The quarter- and half-wave resonators (HWR) with integrated helium vessel including a large number of components and their manufacturing process become even longer and complex. Usually, the cavity production process is started with the fabrication of a copper prototype with identical geometrical parameters. The detailed description of the HWR copper prototype operating at frequency 324 MHz was presented in our recent work [1]. The present communication is devoted to a comparison of electromagnetic characteristics during fabrication of Nb and Cu HWR of equivalent geometrical characteristics. The model of the HWR niobium prototype is presented in Fig. 1. This cavity is designed and developed for the Nuclotron-based Ion Collider fAcility (NICA) injector.

The cavity in Fig. 1 was designed in a classical coaxial half-wave configuration [2, 3]. The general difference from the copper prototype considered in [1] lies in the design of the cavity's flanges. In the copper prototype, stainless steel (AISI 316) CF40 flanges were electron beam welded to the cavity. For Nb-prototype, we used NbTi47-based [4] flanges and hexagonal AlMg alloy gaskets. This type of flanges allows performing electron beam welding with a cavity made of high purity niobium (RRR=300, produced by Ningxia) and with an integrated helium vessel made of titanium.

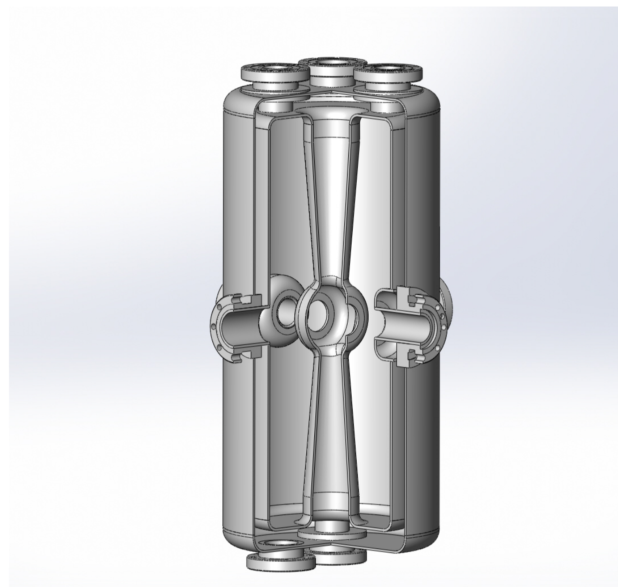

Figure 1: The sketch of the 324 MHz niobium HWR prototype model.

The most important geometrical parameters of considered cavities are inner height H and accelerating gap g. They may be varied during the fabrication process to achieve the goal resonant frequency f of the finally produced cavity. In the next sections, we will discuss the most important results related to frequency control during the fabrication of Cu and Nb HWR prototypes.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV011

PRESENT STATUS OF THE SPOKE CAVITY PROTOTYPING FOR THE JAEA-ADS LINAC

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Abstract

The Japan Atomic Energy Agency (JAEA) is proposing an accelerator-driven subcritical system (ADS) for efficient reduction of high-level radioactive waste generated in nuclear power plants. One of the challenging R&Ds for ADS is the reliability of the accelerator. In preparation for the full-scale design of the proton linac for the JAEA-ADS, we are now prototyping a single-spoke cavity for low-beta (around 0.2) beam acceleration. As there is no experience of manufacturing a superconducting spoke cavity in Japan, the cavity prototyping and performance testing are essential to ensure the feasibility of the JAEA-ADS linac. To proceed to an actual cavity fabrication, we have carefully reviewed the fabrication process. And then, we examined the electron-beam welding using niobium test pieces and investigated the welding condition for realizing the smooth underbead. We have finally started the press forming of niobium sheets and the machine work to shape the cavity parts. Now, we are parparing for the electron-beam welding of the shaped niobium parts.

INTRODUCTION

The Japan Atomic Energy Agency (JAEA) is proposing an accelerator-driven subcritical system (ADS) as a future project to transmute long-lived nuclides to short-lived or stable ones. In the JAEA-ADS, a high-power (30 MW) proton beam with a final beam energy of 1.5 GeV is required with high reliability. Furthermore, the accelerator needs to be operated in a continuous-wave (CW) mode in order to be compatible with the reactor operation. Since a normal conducting (NC) structure raises a difficulty in cavity cooling under the CW operation, a superconducting (SC) linac would be a suitable solution. Figure 1 shows the accelerating structure proposed for the JAEA-ADS linac. In the proposed linac, the high-intensity proton beam is accelerated by an NC radio-frequency quadruple (RFQ) and low-beta SC cavities such as half-wave resonators (HWRs) and single-spoke resonators (SSRs), and accelerated to the final beam energy of 1.5 GeV by elliptical cavities (ELLs). This accelerating structure is similar to that proposed in [1], and the latest design of the JAEA-ADS linac is reported in [2].

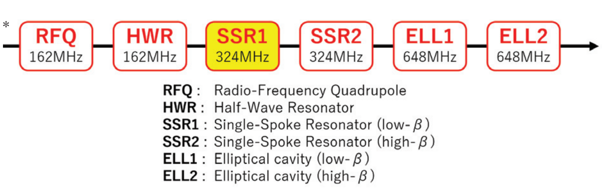

Figure 1: Accelerating structure proposed for the JAEA-ADS linac.

As the first step toward the full-scale design of the JAEA-ADS linac, we are planning to demonstrate a high-field cavity test by prototyping a low-beta single-spoke resonator (SSR1). A single-spoke cavity is one of the 2-cell $\lambda/2$-structure cavities. This prototyping will provide us various insights about developing SC $\lambda/2$ resonant cavities. Moreover, through the high-field cavity test, we will acquire valuable information such as how much accelerating gradient would be achievable with the required stability. In this paper, the present status of the spoke cavity prototyping is presented.

DESIGNED PROTOTYPE SPOKE CAVITY

We investigated the electromagnetic design of the prototype spoke cavity which operating frequency (f_0) is 324 MHz. The unit cell length defined as the distance between the two gap centers was fixed to $\beta_g\lambda/2 = 87.0$ mm, where β_g and λ represent the geometrical beta and the resonant wavelength, respectively. The dimensional parameters of the design model were optimized for higher cavity performance [3]. Figure 2 shows the electric (left) and magnetic (right) distributions of the designed cavity. The accelerating field distribution along the beam axis is shown in Fig. 3. The transit time factor as a function of beam velocity (β) obtained by

$$T(\beta) = \frac{\int E_z(z)\sin\left(\frac{2\pi}{\beta\lambda}z\right)dz}{\int |E_z(z)|dz} \tag{1}$$

is shown in Fig. 4. One can see that the transit time factor is maximized with the beam velocity of $\beta = 0.24$ (optimal beta : β_{opt}). Assuming that the beam velocity is at the optimal

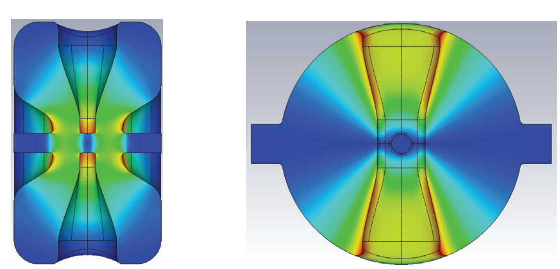

Figure 2: Electric field distribution on Y-Z plane (left) and magnetic field distribution on X-Y plane (right).

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV012

RESEARCH AND DEVELOPMENT OF 650 MHz CAVITIES FOR CEPC*

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Abstract

650 MHz 2-cell superconducting cavities are proposed for the main ring of the Circular Electron Positron Collider (CEPC) [1]. The design, fabrication, surface treatment (buffered chemical polishing) and vertical tests of the cavities with HOM couplers were conducted. The performance of the cavity at 2 K is not affected by the HOM coupler [2]. The maximum intrinsic quality factor (Q_0) of the cavity with the HOM coupler reached 3.1×10^{10} at 20 MV/m. The vertical test results showed that the fundamental mode external quality factor of all HOM couplers is an order of magnitude larger than quality factor of the cavity. Two 650 MHz 2-cell cavities jacketed have been integrated into a test cryomodule for CEPC. Another 650 MHz 2-cell cavity reached 6×10^{10} at 22 MV/m after nitrogen infusion [3]. In addition, two 650 MHz 1-cell cavities reached 2.7×10^{10} at 35 MV/m (fine grain) and 3.6×10^{10} at 32 MV/m (large grain) after electro-polishing, respectively. In future, electro-polishing will be applied to 650 MHz 2-cell cavity.

INTRODUCTION

Nowadays, cavities with frequency around 650 MHz are widely used by proton accelerators, such as PIP-II, CiADS and CSNS Upgrade. Baseline layout and parameters for CEPC Main Ring SRF system have been public [4]. There're two SRF sections in total, and each one has two SRF stations. There're ten cryomodules per station, which consist of six 650 MHz 2-cell cavities each. So there're two hundred and forty 650 MHz 2-cell cavities in total. These cavities are made of bulk niobium and operated at 2 K with Q_0 higher than 3×10^{10} at 22 MV/m for the vertical acceptance test and Q_0 higher than 2×10^{10} at 20 MV/m for the horizontal test. The accelerating gradient for Higgs is 19.7 MV/m with Q_0 higher than 1.5×10^{10} for long-term operation. This specification is critical for the SRF cavity of a circular collider, which usually have a more constrained environment than superconducting linac (such as LCLS-II and SHINE). So relevant research of 650 MHz cavities was carried out at IHEP, which have achieved some state-of-the-art results.

R&D OF 650 MHz 1-CELL CAVITY

Several 650 MHz 1-cell cavities have been fabricated for high Q & E_{acc}, which are made of fine-grain (650S4) and large-grain niobium (650S7, 650S8), respectively. Firstly, 650S4 and 650S8 received bulk BCP and light EP, while 650S7 received flexible polishing to repair surface defects. Then, all these cavities received annealing of 950°C and electro-polishing (EP). Finally, these cavities received high-pressure rinse (HPR), assembly in clean room and baking at 120°C for 48 h. The vertical test results are shown as Fig. 1. The vertical test results of 650 MHz 1-cell cavities are shown as Fig. 2. 650S4 quenched at 35 MV/m with Q_0 of 2.7×10^{10}. 650S8 quenched at 28 MV/m with Q_0 of 4.6×10^{10}, while 650S7 quenched at 32 MV/m with Q_0 of 3.6×10^{10}. The results above have reached the advanced level of large elliptical (<1 GHz) cavities.

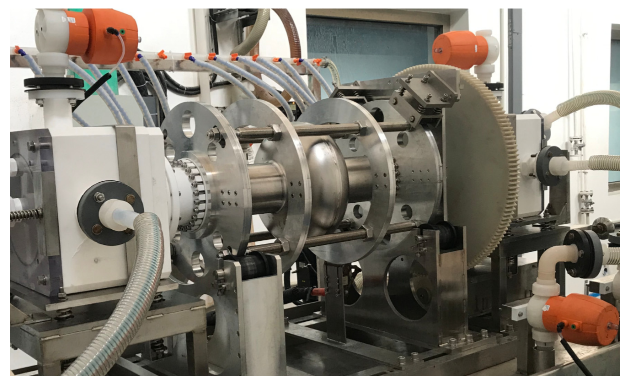

Figure 1: EP of 650 MHz 1-cell cavity

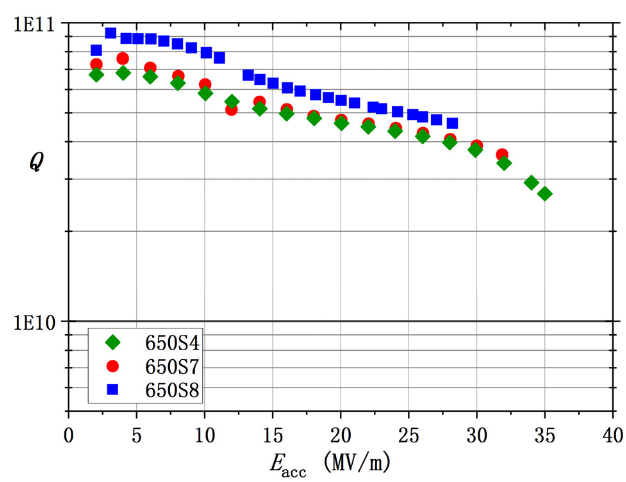

Figure 2: Vertical test results of 650 MHz 1-cell cavities

THE 650 MHz TEST CRYOMODULE

The 650 MHz TEST cryomodule consists of two 650 MHz 2-cell cavities, fundamental couplers, tuner, HOM couplers and other ancillaries, which is shown as Fig. 3. It will be connected with a DC photo-cathode gun at the Platform of Advanced Photon Source Technology (PAPS), which will produce 1~10 mA electron beam with 10~15 MeV.

*This study was supported by National Key Programme for S&T Research and Development (Grant NO.: 2016YFA0400400) and National Natural Science Foundation of China(Grant NO.:11505197).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV013

OCCURRING DEPENDENCY BETWEEN ADJUSTABLE COUPLING AND Q_0 - FINDING AND SOLVING A PROBLEM DURING VERTICAL CAVITY TESTING AT DESY

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Abstract

In the AMTF (Accelerator Module Test Facility) hall at DESY, various types of cavities have been tested for different accelerators and R&D projects during the last years. For R&D purposes, dedicated inserts with additional auxiliaries like a movable INPUT antenna can be used to perform accurate measurements at different temperatures between 1.4K and 4K. Since 2017 more than hundred vertical tests were conducted in these inserts without troubles besides rare expected occurrences of cold leaks or even rarer a loose antenna.

However, in the last months, an unexpected dependency between the measured quality factor and the coupling coefficient β has been observed. In order to understand the source of this measurement uncertainty, several different special checks have been performed. In a logical sequence of measurements with different cryostats, inserts and cavities the problem has been encircled and in the end was identified and solved. In this paper, the observed problem is described in detail as well as the entire path leading to its solution.

INTRODUCTION

Generally, it is considered that a movable antenna is much better to measure RF power precisely, especially for R&D projects. There are many different types of surface treatments, such as Nitrogen-infusion, Nitrogen-doping, medium temperature baking and so on, which are assumed to be strong candidates for the enhancement of SRF performance. Here at DESY in the AMTF, many R&D single cell cavities are used to verify the effectiveness of these surface treatments. Before implementing the vertical test, it was necessary to estimate the systematic error of both E_{acc} and Q_0. According to a early stage series of vertical tests, the systematic error of E_{acc} should be less than 10% while at the same time 20% for Q_0 were determined [1].

VERTICAL TEST SYSTEM WITH MOVABLE INPUT ANTENNAE

The topological diagram, shown in Fig. 1(b), describes the SRF cavity vertical test system. The generator feeds a small signal into the CW (continuous wave) amplifier. As the resonance width of SRF cavities is very sharp, a PLL (phase locked loop) is used to adjust the resonance frequency. Powermeters are responsible for showing the scopes of forward, reflected and transmitted signals. A cavity with movable INPUT antenna, which is used for the vertical test at AMTF, is shown in Fig. 1(a). A bellow is assembled between cavity beam tube and antenna, which makes the strength of the INPUT coupling adjustable.

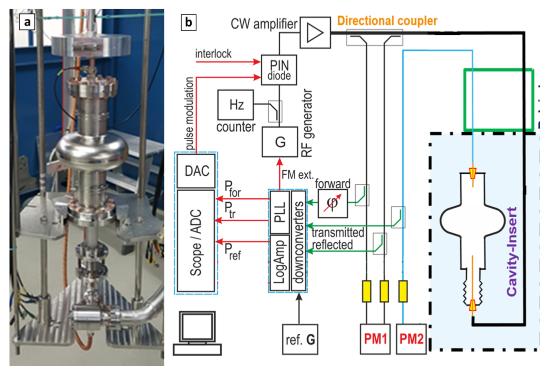

Figure 1: (a) Photograph of single cell cavity assembled on vertical test insert with movable antenna. (b) Topological diagram of SRF vertical test in AMTF.

For a vertical test, the maximum E_{acc} and its related quality factor are of importance. These values determine whether the cavity can be accepted, while it is impossible to measure them directly. These two values are determined by the measurable powers in the RF circuit and the decay time of the cavity RF amplitude. The coupling parameter β, which describes the matching of power coupler antenna and cavity, is important for obtaining the value of Q_0. During CW steady state, the β value can be calculated by the formula [2]:

$$\beta = \frac{1 \mp \sqrt{\frac{P_{for}}{P_{ref}}}}{1 \pm \sqrt{\frac{P_{for}}{P_{ref}}}} \tag{1}$$

In the AMTF, the steady state amplitude method is used, for this it is required to know beforehand whether the cavity is under- or overcoupled. For pulse mode, the β value can be easily judged by the power signals on the scope, which is usually used to make a rough estimate of the coupling coefficient while adjusting the antenna. These relationships are shown in Fig. 2. P_{for} indicates the power of the rectangular RF pulse applied on the cavity, which leads to two reflected peaks (switch on and off). The coupling state can be easily inferred by comparing the height of these two peaks. Switch on peak higher than, lower than, and equal to switch off peak corresponds to β >1, β <1 and β =1 respectively [3].

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV014

HOM DAMPER DESIGN FOR BNL EIC 197 MHz CRAB CAVITY*

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Abstract

The interaction region (IR) crab cavity system is a special RF system to compensate the loss of luminosity due to a 25 mrad crossing angle at the interaction point (IP) for Brookhaven National Lab electron ion collider (BNL EIC). There will be six crab cavities, with four 197 MHz crab cavities and two 394 MHz crab cavities, installed on each side of the IP in the proton/ion ring, and one 394 MHz crab cavity on each side of the IP in the electron ring. Both rings share identical 394 MHz crab cavity design to minimize the cost and risk in designing a new RF system, and it will be scaled from 197 MHz crab cavity. In this paper, the higher order mode (HOM) damper design for 197 MHz crab cavity is introduced.

INTRODUCTION

The EIC crab cavities are designed to provide local crabbing scheme (crab before entering IP and de-crab after leaving IP) in horizontal plane with 25mrad full crossing angle for both electrons and hadrons. Based on beam-beam simulations, there are three possible operation scenarios under consideration, hereafter summarized quoting the necessary total crabbing voltage per IP per side:

1, 24 MV deflecting voltage from 197 MHz crab cavity for HSR, and 2.9 MV deflecting voltage from 394 MHz crab cavity for ESR. This is the baseline.

2, 33.83 MV deflecting voltage from 197 MHz crab cavity, and -4.75 MV from 394 MHz crab cavity for HSR, and 2.9 MV deflecting voltage from 394 MHz crab cavity for ESR.

3, increase the voltages by a factor of 20%.

To meet the requirement, we consider putting two 197 MHz crab cavities in one 197 cryomodule and put one 394 MHz crab cavity in one 394 cryomodule. For HSR, two 197 cryomodules and two 394 cryomodules are used per IP per side; for ESR, one 394 cryomodule is used per IP per side, with ESR and HSR 394MHz cryomodules identical.

In the EIC hadron storage ring (HSR), for impedance budget consideration, 2 IPs are assumed, see Fig. 1, with four 197 MHz crab cavities per IP per side and total sixteen 197 MHz crab cavities in HSR. The longitudinal impedance budget per 197 MHz crab cavity is set at 10.0 kΩ, with circuit definition used in this paper unless otherwise noted, and the transverse impedance budget is 0.25 MΩ/m per cavity at crab cavity locations with 1300 m beta function. HOMs up to 2 GHz were evaluated. Comparing with the LHC impedance budget requirement, both longitudinal and transverse impedance budgets are tighter. The LHC double quarter wave (DQW) [1-3] or RF-dipole (RFD) [4, 5] HOM damper designs cannot be directly adopted to EIC crab cavities. New HOM damper designs for these two types of crab cavities are shown in this paper.

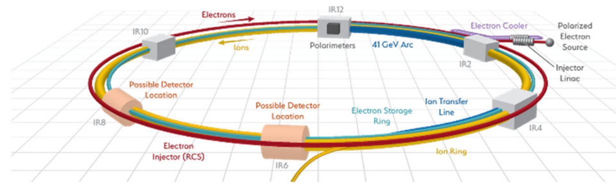

Figure 1: Possible locations of EIC crab cavities include IR6 and IR8.

Table 1: Key Parameters of 197 MHz Crab Cavities

Property	Specs	DQW	RFD
f_0 [MHz]	197.0	197.0	197.0
1st HOM [MHz]		304.2	345.9
Geometry factor [Ω]		68.2	99.0
R/Q [Ω, acc. def.]		1159.7	1148.0
V_t [MV]	11.5	11.5	11.5
E_{peak} [MV/m]	≤45	44.8	44.0
B_{peak} [mT]	≤80	69.5	78.0
Cavity length [mm]	≤1500	821.8	941.0
Cavity height [mm]	<900 ID	452.5	587.0
Cavity width [mm]		584.4	587.0
Tuning range [MHz]	≥0.8	≥0.8	±1.3
FPC Q_{ext}	3×10^6	3×10^6	3×10^6

DQW WITH HOM DAMPER

To minimize the peak magnetic field at certain deflecting voltage, the EIC DQW crab cavity is elongated along beampipe direction with an ovaloid profile while comparing with HL-LHC DQW. A small angle in the inner conductor wall allowed minimizing peak magnetic field further. A sufficiently large radius to blend the capacitive plate edges helped reaching smaller peak electric field. The corners of the cavity were also rounded to further reduce peak fields. The geometry of the EIC DQW cavity is shown in Fig. 2. Table 1 shows the key parameters of 197 MHz DQW.

To damp the first HOM at 304.2 MHz, a large (>500 mm rectangular width) HOM port is needed, we choose 530 mm × 75 mm rectangle. 75 mm is chosen to provide enough damping. To ease the fabrication, this HOM port is

* Work supported by Brookhaven Science Associates, LLC under U.S. DOE contract No. DE-AC02-98CH10886, and by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPCAV015

REFURBISHMENT AND TESTING OF THE WiFEL E-GUN AT ARGONNE*

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Abstract

We report on the refurbishment and testing of the Wisconsin Free Electron Laser (WiFEL) superconducting radiofrequency electron gun with application as an electron injector for DOE accelerators and as a possible future stand-alone tool for electron microscopy. Initial testing at ANL showed the cavity had a very low quality factor, ~107, later determined to be due to contamination sometime since the initial assembly. Following ultrasonic cleaning, high-pressure water rinsing, reassembly, and cold testing, the e-gun has largely recovered with Q~109 and surface electric fields ~15 MV/m. We intend that WiFEL be available as a testbed for future high brightness sources and, in particular, for testing an SRF gun photocathode loader design; an essential, and as yet, not sufficiently proven technology. We report here on many operationally important properties of a quarter-wave SRF cavity for application as an e-gun, including microphonics, pressure sensitivity, and mechanical tuning. New electromagnetic simulations show that the WiFEL cavity shape and design can be optimized in several respects.

INTRODUCTION

The Wisconsin Free Electron Laser superconducting RF electron gun was designed to meet the specifications for a high brightness, high repetition rate electron source [1]. This includes sources such as the LCLS-II-HE upgrade, which requires an emittance of < 0.1 µm @ 100 pC. The gun was designed at the University of Wisconsin (UW), and the cavity was fabricated by Niowave, Inc. The gun was initially tested at UW, and was later shipped to SLAC for continued study. In December 2019 the gun was shipped to Argonne, in large part, due to the availability of a liquid helium refrigerator which had not been available for WiFEL testing at the previous locations. After full disassembly, re-cleaning by HPR, and re-testing (as highlighted in Fig. 3) the cavity achieved useful, stable operating field with Epeak = 14.3 MV/m and Vacc = 1.07 MV as shown in Fig. 1.

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357, and the Office of High Energy Physics, under contract number DE-AC02-76CH03000. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility
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COLD RF TESTING

Q Curves and Conditioning

Following the cleaning of the cavity and re-assembly of the cryostat, the e-gun was cooled down to 4.5 K. The cavity initially hit a multipacting barrier that was conditioned (about V_{acc} = 8 kV to 30 kV) over multiple days before recording a full Q curve. The coupler was manually adjustable, and allowed a range of Q_{ext} from ~1 x 10^9 to 5 x 10^7. This adjustability was used to over-couple while conditioning.

The cavity then underwent multiple rounds of high power, pulsed RF conditioning, which allowed the cavity to be operated at higher field gradients. During pulsed conditioning, a maximum field level of ~24 MV/m was reached for short durations before breakdown. The results of multiple rounds of conditioning are shown below, in Fig. 1. A maximum CW peak electric field was found to be 14.3 MV/m.

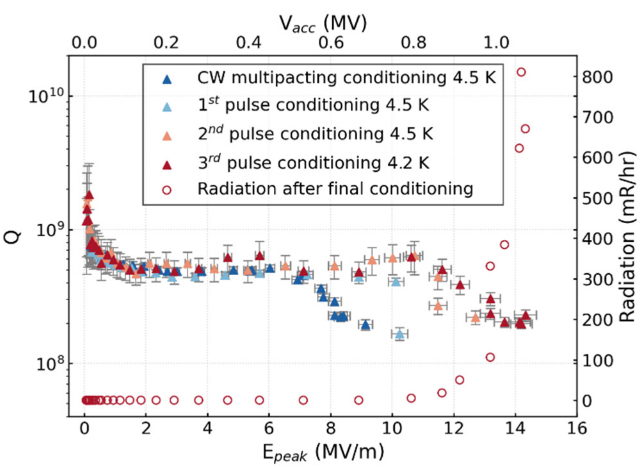

Figure 1: WiFEL cavity Q curves after multiple rounds of RF pulse conditioning.

The Q_0 measurement of the cavity at ANL, with low field Q ~10^9 and medium field Q ~5 x 10^8, are lower than made previously at Niowave and UW [1], however it should be noted these measurements were performed calorimetrically, a technique that is inherently more challenging than RF measurements at near critical coupling. Error bars in the ANL data are estimated systematic experimental errors associated with the measurement of RF decay time (ie. the Q), the forward and reflected power from the cavity, the field probe RF amplitude, and in the HP 437B power meter used as the absolute power reference.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV002

HIGH POWER COUPLER DEVELOPMENT FOR EIC*

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Abstract

The synchrotron radiation loss in EIC Electron Storage Ring is as high as up to 10 MW. This energy loss will be compensated by 17 2K 591 MHz single-cell SRF cavities with a combined total of 34 high power fundamental power couplers. Each power coupler will operate 92% of revolution time CW and ~8% of revolution time with 400 kW forward power due to the beam abort gap. To satisfy the EIC needs, we developed two 500 kW standing-wave FPC designs at BNL based on either a BeO and an Al_2O_3 RF window. This paper will briefly summarize test results of the BeO window FPC, and describe the design development of the Al_2O_3 window based FPC.

FPCS FOR EIC ESR SRF CAVITIES

The EIC operating scenarios has in a wide range of beam current and energy and scenarios [1], which demands a wide range of power and external Q variations. For each FPC, the power spans from 120 kW to 400 kW, and the variation of external Q is from 5.12E4 to 7.15E5. These FPCs are arguably one of the most critical and challenging components for the EIC RF/SRF systems. The concept design of EIC eSR SRF cavity cryomodule is shown in Fig. 1 with the dual waveguide-fed couplers protruding horizontally from the cryomodule.

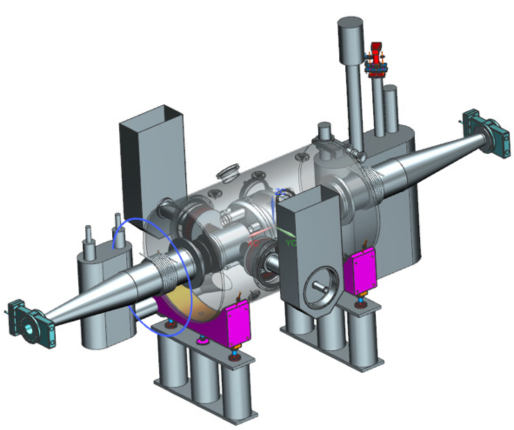

Figure 1: EIC eSR SRF cryomodule.

The design and testing of the EIC FPCs is based upon the couplers operating with a 1 MW travelling wave or 500 kW standing wave, all phases. In the following sections we review EIC developments for the design and testing of a BeO RF window and a new design for an EIC acceptable Al_2O_3 RF window. This paper concludes with a brief summary and comments on the future plans for this work.

* This work is supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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BEO WINDOW FPC TEST RESULTS

Refurbished FPC Conditioning Test Setup

The detailed design of the BeO window FPC tested here was described in [2]. These couplers have been used for operation in R&D ERL [3] and LeREC booster SRF cavity [4], although the power level was much lower than designed 1 MW. In 2018, we decided to test the BeO window FPCs but up to EIC operating power level, i.e, MW level. The primary test goal was to verify the power handling capability of these coupler. So, several improvements were done in 2019, prior to high power test.

- Upgraded the 704 MHz klystron to allow output power close to 1 MW.
- Reviewed and recalculated all the RF-thermal simulation of the FPCs and conditioning box.
- A pair of BeO window FPC were fabricated by CPI. We increased the size of water cooling channel in FPC airside outer conductor, and change braze-joint instrumentation port to tig-weld joint.
- Refurbished FPC conditioning setup, interlock, data logging.

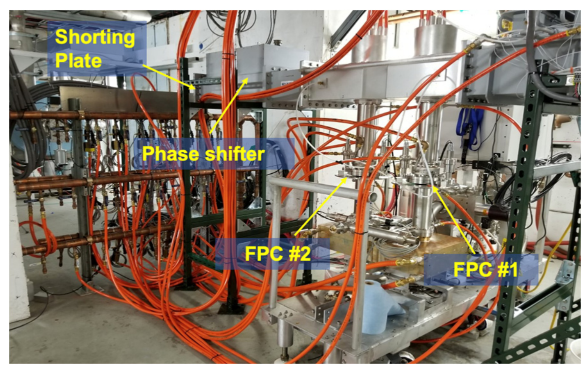

Figure 2: BeO window FPC test setup.

BeO FPC High Power Test Results

A pair of BeO RF window based FPCs were tested with a standing wave at 704 MHz in early 2020, the test setup is shown in Fig. 2. FPC conditioning proceeded in stages to accurately gauge coupler performance with forward power levels set at 100, 200, 300, 400, and 500 kW. At each power level the conditioning started with a low duty cycle, short pulse (1 μs) and ended up CW. Once CW operation at each level was achieved the reflected RF phase was varied in 10 degree increments over 80 degrees (limit of the high-power phase shifter) and the conditioning process was repeated before increasing the RF power to the next higher level. The highlights of test results are listed as followings.

- The BeO window FPCs were successfully conditioned to 400 kW, CW, standing wave, all phases, with no troubles detected with vacuum, arc, or thermal sensors.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV003

A SUPERCONDUCTING MAGNETIC SHIELD FOR SRF MODULES WITH STRONG MAGNETIC FIELD SOURCES

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Abstract

Frequently SRF modules require strong focusing magnets close to SRF cavities. The shielding of those magnetic fields to avoid flux trapping, for example during a quench, is a challenge. At HZB, the bERLinPro photo-injector module includes a 1.4 cell SRF cavity placed in close proximity to a superconducting (SC) focusing solenoid. At full solenoid operation, parts of the double mu-metal shield are expected to saturate. To prevent saturation, we developed a new superconducting Meissner-Shield. Several tests of different designs were performed both in the injector module and in the HoBiCaT [1] test facility. The measured results of the final design show a significant shielding that are in good agreement with calculations. Based on these results, a reduction of the magnetic flux density in the mu-metal shields of almost one order of magnitude is expected The design has now been incorporated in the injector module. In this paper we will present the design, the setup and results of the final testing of the superconducting shield.

INTRODUCTION

A superconducting photoelectron injector [2] is currently under construction at HZB as electron source for SeaLab/bERLinpro. The main parts for the electron beam are the 1.4 cell SRF gun (incl. LHe tank and double Mu shielding) and the superconducting (SC) solenoid for beam focusing. For best performance of space charge dominate electron beams the solenoid has to be positioned as close as possible to the SRF gun exit. Here the magnets fringe fields can interact with the outer Mu shield, consisting of Cryoperm [3]. In case of high flux densities, these high μ_r metal plates can be saturated, which yields to a permanent magnetization and therefore a degradation of the shielding efficiency. In [3] these effects were studied and a first concept of an SC shield was introduced. It blocks most of the magnetic flux of the solenoid and prevent the Mu shields for saturation. Magnetic calculations predicted a shielding efficiency for the Mu shields of at least a factor of five.

RESULTS OF THE FIRST DESIGN

The first SC shield design consists of a niobium plate, which should be installed as close as possible to the Mu Shield of the SRF gun. Furthermore the aperture for the beam tube should be as small as possible.

Figure 1 shows the setup of the ideal position between SRF gun flange and Mu shield. To meet these conditions the

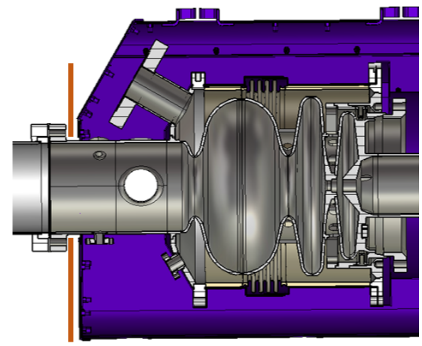

Figure 1: Drawing of the SC shield (brown) next to the Mu Shield (violet) of the SRF gun (grey).

shield has to be split into two identical pieces placed around the beam tube. The niobium plates are cooled down below the superconducting transition temperature $T_C = 9.2\,\mathrm{K}$ by two Cu plates, that are pressed together via an Aluminum frame work. The construction should passively cooled by connecting it with the gun flange ($\approx 5\,\mathrm{K}$). However this concept was not sufficient. Therefore, an additional direct LHe cooling tube was installed in the aluminum framework. In a second cryogenic test the shield was cooled down below T_C and the magnetic fields produced by an SC solenoid next the SC shield were measured. Due to a heater connected to the LHe tubes the shield temperature could be briefly increased above T_C. The differences in the magnetic field for $T_{\mathrm{shield}} > T_C$ and $T_{\mathrm{shield}} < T_C$ were used to calculate the efficiency of the shield resulting in a value of $\approx 1.3 \pm 0.3$, which is far below of the expected value of roughly 5 of the magnetic calculations. The reason for this is the split design itself. To shield the magnetic field of the solenoid an azimuthal eddy current around the beam tube is necessary. However the mechanical contact between both niobium plates is not sufficient for the super currents between both plates. Due to the broken symmetry, the shielding efficiency is extremely decreased. These effects were studied as part of an improved model for the SC shield that used an electromagnetic solver like the low frequency (LF) solver of CST [4] instead of pure magnetic solvers. It was also used for the interpretation of the magnetic test of the new shield design and for studies of the shielding efficiency for the SRF gun Mu-shield.

REDESIGN AND NEW INSTALLATION

To solve the issue of the broken azimuthal symmetry the shield needs a single niobium plate. One feature hereby is the

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV007

REVIEW OF THE APPLICATION PIEZOELECTRIC ACTUATORS FOR SRF CAVITY TUNERS*

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Abstract

Large SRF Linacs and HEP experiments require accurate frequency control, which is achieved using cavity tuners typically actuated by the piezoelectric ceramic stacks. The piezoelectric ceramic stacks become "standard" components of the SRF cavity tuner, and depending on the application, could be operated in different environments: in air, at cryogenic temperature, in vacuum, and submerged in liquid helium. Different applications place different requirements on the piezo actuators, but the important parameters common to all applications are the lifetime and reliability of the actuators. Several R&D programs targeting the development of reliable piezo actuators are reviewed in this contribution.

INTRODUCTION

For many years piezoelectric ceramics have been widely used in a variety of industrial applications and have proven to be highly reliable. There are many applications in space exploration research that have also demonstrated the capability of piezo actuators to tolerate up 109 cycles when operated in cold and vacuum environments [1]. The ability of the piezo actuator to generate large forces (3-4kkN for a stack with cross-section 10*10mm2) and withstand pressure up to 200MPa have made these actuators a good choice for deployment in SRF cavity tuners.

Recently, thousands of piezo actuators have been deployed as fast/fine tuning elements in several large SRF linac that are in or close to being in operation. In large machines (e.g., EuXFEL, LCLS II, ESS) piezo actuators are typically deployed close to the SRF cavity, inside insulated vacuum volume and at cryogenic working temperature. Operations of the piezo both cold and inside the vacuum has some advantages, especially for CW SRF linacs where the specifications for piezo are to deliver sub-micrometre stroke to compensate for microphonics. For pulsed SRF linacs, the piezo is utilized to compensate for the cavity's Lorenz Force Detuning (LFD). To compensate for LFD, the piezo must be driven with stimulus pulses with large voltage and frequencies of several 100' Hz. The piezo stack will experience significant acceleration forces that could quickly lead to cracks inside the piezo that result in failure. When operated in AC mode the piezo will heat up. Limited heat transfer from the piezo when inside a vacuum could generate additional challenges for reliable piezo operation.

The reliability of the piezo installed inside the SRF cryomodule became the most critical parameter, considering complexity and cost of replacement in cases of failure.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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There are examples of the utilization of piezo as part of SRF cavity tuners in an ambient environment. In these applications, there are another set of challenges that need to be considered to extend the lifetime of the piezo tuner: humidity, temperature, and the DC voltage applied to the piezo.

There are applications when the piezo must operate while submerged in liquid Helium (LHe). Several examples of projects when the piezo is operated inside LHe are presented at the end of this review.

MECHANICAL INTEGRATION OF THE PIEZO ACTUATORS INO FAST TUNERS

A fast tuner is installed between the slow tuner and cavity. When slow tuner bring cavity to operational frequency it delivered on the piezo actuator preload on the order of several kN. It is important that the design of the fast tuner and the mechanical integration of the piezoceramic stack as part of SRF cavity tuner are done according to piezo manufacturer recommendations.

There are many examples of when "in-house" integration of the piezo is done incorrectly, which leads to fast tuner failures. Several unsuccessful examples of piezo stack integration that the FNAL tuner team experienced are also presented.

One of the first single piezo actuators built and tested at FNAL's CC2 cavity [2] is presented in Fig. 1. It was modified copy of the first DESY fast tuner. There were efforts with design to mitigate and measure shearing forces experienced by piezo stack while the cavity was cooled down to T=2K and tuned to operational frequency. This example demonstrated: (a) efforts to minimize the shearing forces on the piezo stack with a stainless-steel bullet didn't work as expected; and (b) the piezo stack experienced significant shearing forces that considerably shorten it's longevity.

The second example shows assembly of the Slim Blade tuners on the two dressed cavities FNAL sent to KEK for the S1Global project. The picture of the piezo installed into tuner demonstrates that there is a significant angle between forces applied to the two ends of the piezo stack (Fig. 2). Significant shearing forces have been observed that led to development of cracks on the piezo ceramics, resulting in the piezo failing after just a couple days of operation (Fig. 3).

FNAL built CM2 [3] which was the FNAL SRF team's first experience in SRF cryomodule construction. Piezo's failure at S1Global cryomodule led to decision modified fast tuner design. Encapsulation was added onto the piezo stack (Fig. 4). Although encapsulation helps address some of the shearing force problems it does not entirely resolve all of the issues associated with piezo cracking.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV008

VSR DEMO COLD STRING: RECENT DEVELOPMENTS AND MANUFACTURING STATUS

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Abstract

Bunch length manipulation is mandatory in modern storage ring light sources and CW SRF provides the required high voltage in a compact system to reach this goal [1]. One possible technique as proposed in [1] is to combine higher harmonic SRF cavities (3 and 3.5 harm.) with the fundamental frequency of the BESSY II storage ring. VSR DEMO seeks to develop and demonstrate the required SRF technology to achieve this by means of "off-line" testing at Helholtz-Zentrum Berlin (HZB) SupraLab facilities of a setup comprising two 1.5 GHz SRF cavities.

Due to the high level of higher order mode (HOM) power expected, caused by the beam-cavity interaction, these SRF cavities will be equipped with waveguide-connected HOM loads. On the cavity a blade tuner and piezos will be installed for frequency control and microphonics detuning. To demonstrate the feasibility of this complex system the VSR DEMO cold string consists of two cavities, each featuring five waveguides and a fundamental power coupler (FPC), plus all elements connected to the beam vacuum.

For most of these components the fundamental development work is complete and has been reported in the past. This paper summarizes recent enhancements, component design detailing and the manufacturing status.

COLD STRING COMPONENTS

The goal of the VSR DEMO project is a technology and feasibility demonstrator of the SRF setup. If successful, the two-cavity module would be ready for commissioning in a storage ring such as BESSY II. This will represent the final step towards validating the proposed technology and a subsequent module with four cavities as presented in [2] offering beam flexible dynamics could be built.

The VSR DEMO cold string comprises all components in direct contact with the beam vacuum (Fig. 1), although only some are operated at cryo temperatures, while others stay warm. Assembly of the cold string and integration into the VSR module (see [3] for a design report) is planned for 2024, after all components have passed individual tests.

Warm Endgroup with Scraper

The Warm Endgroups (WEGs), located at both ends of the cold string, feature a taper from the BESSY II profile to the circular beam-pipe cross section of 110 mm diameter, a water cooled HOM absorber and a junction for attaching vacuum pumps. Upstream, a tuneable scraper protects the cavity from synchrotron light incidence (cf. Fig. 1).

The design of the WEGs, as reported in [4], was finalized. The vacuum chambers and the scraper are currently being manufactured by PINK GmbH Vakuumtechnik.

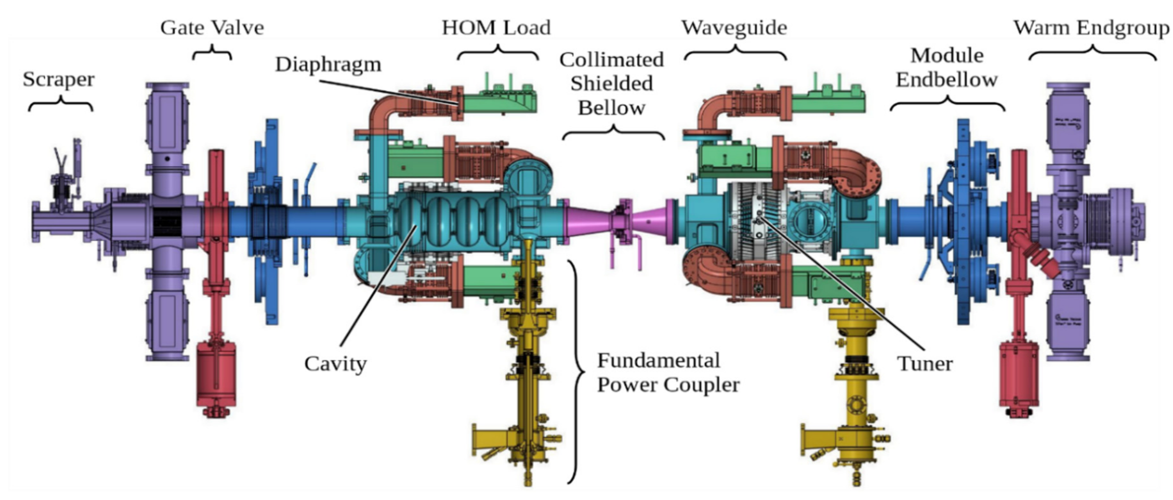

Figure 1: VSR DEMO cold string in top view.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV009

THE 1.5 GHz COUPLER FOR VSR DEMO: FINAL DESIGN STUDIES, FABRICATION STATUS AND INITIAL TESTING PLANS

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Abstract

The variable pulse length storage ring demo (VSR DEMO) is a research and development project at the Helmholtz Zentrum Berlin (HZB) to develop and validate a 1.5 GHz SRF system capable of accelerating high CW currents (up to 300 mA) at high accelerating fields (20 MV/m) for application in electron storage rings. Such a system can be employed to tailor the bunch length in synchrotron light source such as BESSY II. VSR DEMO requires a module equipped with two 1.5 GHz 4-cell SRF cavities and all ancillary components required for accelerator operations. This includes one 1.5 GHz fundamental power coupler (FPC) per cavity, designed to handle 16 kW peak and 1.5 kW average power. The final design studies, fabrication status and initial testing plans for these FPCs will be presented.

VSR DEMO

In order for VSR DEMO to reach its goal of validating SRF technology to achieve high current (300 mA) - high gradient (20 MV/m) – CW operation and enable future high current CW projects, a test module needs to be developed. This module comprises of two complex SRF cavities, two FPCs and ancillary components such as the collimated shielded bellows, the full module can be seen in Fig. 1. Full details of the current status of the cold string can be found in [1] and of the module in [2]. This module will be commissioned at peak power in the bERLinPro bunker at HZB, with a beam test in the bERLinPro accelerator considered as a final validation step.

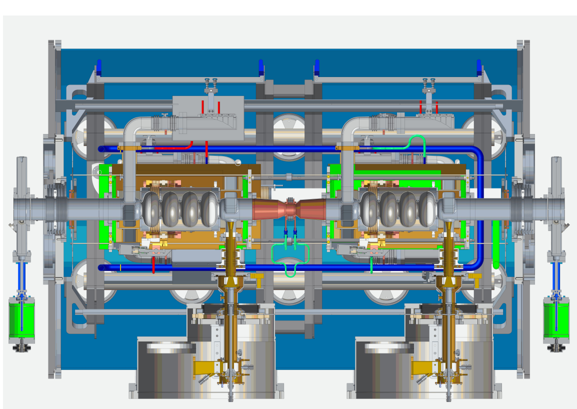

Figure 1: The VSR DEMO module showing the cold string components.

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COUPLER DESIGN AND RF RESPONSE

VSR demo requires couplers to provide 16 kW peak and 1.5 kW average power for CW operation at 1.5 GHz. The design has been extensively developed and the finalised RF design gives the results shown in Fig. 2. This S_{11} plot of the reflected power shows that the coupler gives a strong RF response within the VSR operating range. To ensure good performance VSR requires an RF response with S_{11} reaching at least -30 dB, equivalent to 0.1% reflected power. This design exceeds this requirement, reaching -50 dB at the central frequency and remaining well under -30 dB within the operating range.

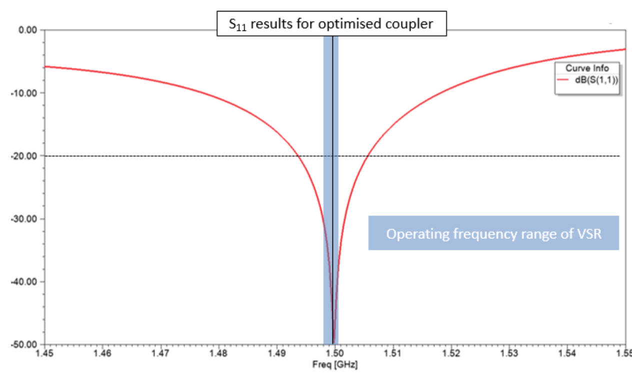

Figure 2: The S_{11} plot of the final coupler with the operational range for VSR superimposed over.

Figure 3 shows the final coupler design, which has undergone significant development to ensure the best possible performance, full details including the results of multipacting studies can be found in [3] and [4]. The design is based the Cornell coupler [5] and [6] scaled for the VSR DEMO frequency range. It is a coaxial style coupler with two cylindrical ceramic windows, one warm, one cold, and two sets of bellows for an adjustable coupling range. The main changes from this base design to meet the VSR DEMO requirements will be presented here.

The VSR DEMO cavity is highly complex due to the need to damp the higher order modes (HOMs) [7]. This is done using 5 waveguides which come off the cavity end groups and end in HOM loads. Since the FPC is also located on the cavity end group it is essential to stop or mitigate HOMs propagating up the coupler port. This could result in a standing wave in the coupler cold part, leading to damage of the cold window and performance degradation. By reducing the cold coaxial dimension, the HOMs are more likely to

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV011

DEVELOPMENT OF IN-SITU PLASMA CLEANING FOR THE FRIB SRF LINAC*

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Abstract

Development of techniques for in-situ plasma cleaning of quarter-wave and half-wave resonator cryomodules is underway at the Facility for Rare Isotope Beams (FRIB). If SRF cavity performance degradation is seen during future FRIB linac operation, in-situ plasma cleaning may help to restore performance without disassembly of the cavities from the cryomodules for off-line cleaning. Initial bench measurements have been performed on a FRIB half-wave resonator using noble gases (Ne, Ar), with and without added oxygen gas. The plasma ignition threshold was measured as a function of gas pressure and composition. Studies of plasma cleaning efficacy were undertaken. A first plasma cleaning attempt was done on a FRIB quarter-wave resonator.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) [1] is presently being commissioned at Michigan State University. The FRIB driver linac requires 46 cryomodules containing a total of 324 superconducting resonators. The cryomodules contain quarter-wave resonators (QWRs) and half-wave resonators (HWRs) optimized for a total of 4 different beam speeds. Long-term operation of FRIB as a user facility will require the cryomodules to run with high performance and high reliability.

As has been demonstrated at SNS, in-situ plasma cleaning is a promising method to restore the performance of a superconducting cavity without disassembly of the cryomodule for off-line cleaning [2, 3]. As such, plasma cleaning capability may be beneficial for long-term FRIB operations. A feasibility study for FRIB cryomodules indicates that plasma cleaning can be done on-line without modifications to the RF couplers or cryomodules.

This paper will cover the apparatus and methods developed for plasma cleaning bench tests; initial plasma cleaning development with a FRIB β = 0.53 HWR; a first plasma cleaning test on a FRIB β = 0.085 QWR, including before-and-after Dewar testing; and future plans.

APPARATUS AND METHODS

The gas delivery and pumping system for plasma cleaning is shown in Fig. 1. Gas from the cylinders is metered via mass flow controller valves and is then filtered upstream of the cavity. A mechanical pump is used to pump the gas out of the cavity. Some of the outgoing gas is sampled by a residual gas analyser, backed by a turbo-molecular pump. When using the RGA, the bypass valve is closed and the leak valve is adjusted to make the pressure low enough for RGA operation. Pressure gauges are included downstream of the cavity and upstream of the RGA.

We ignited the plasma with RF power applied via an input antenna designed for near-unity coupling at room temperature. We pulsed the RF power during plasma cleaning to reduce RF heating of the cavity walls and input antenna and mitigate surface oxidation. Moreover, past studies have shown that cleaning with pulsed RF is helpful for removal of hydrocarbons from both the top surface and the near surface, allowing extra time for diffusion of hydrocarbons to the surface [4].

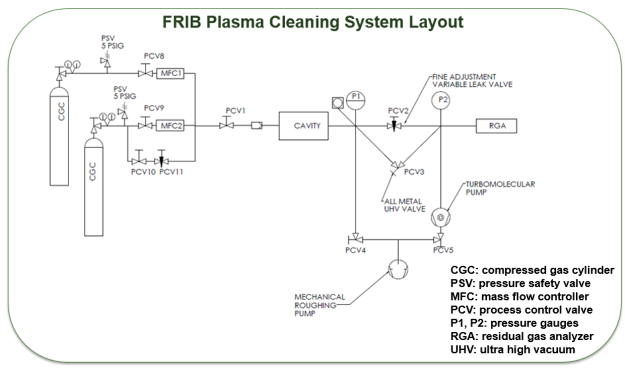

Figure 1: Schematic of gas supply and pumping system for bench plasma cleaning tests.

PLASMA CLEANING DEVELOPMENT

We did initial plasma cleaning bench tests with a β = 0.53 HWR, due to its multiple rinse ports which can be used for diagnostics (Fig. 2). HWR bench testing was done using a 100 W amplifier to excite the plasma, with an RF circuit and data acquisition system similar to that used for Dewar testing. We measured and recorded the RF power (forward, reverse, transmitted), pressures, light spectra, and RGA spectra.

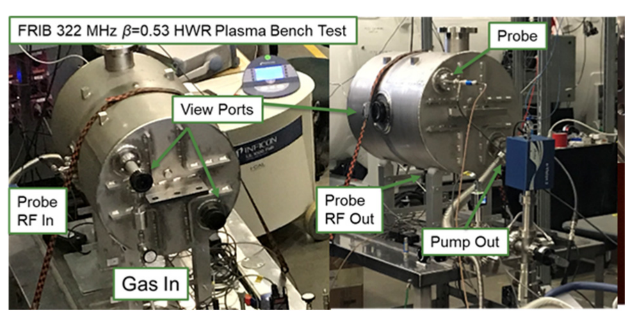

Figure 2: Bench plasma cleaning of a FRIB β = 0.53 HWR. Left: gas feed. Right: gas pumping.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV012

CHARACTERIZATION OF ATOMIC-LAYER-DEPOSITED NbTiN AND NbTiN/AlN FILMS FOR SIS MULTILAYER STRUCTURES*

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Abstract

SIS (superconductor-insulator-superconductor) multilayer structures are proposed designs to repel early flux penetration and ease the impact of defects in SRF cavities. The demonstration of such device physics is strongly affected by the film qualities – material structure and composition. Here, we characterized 100 nm NbTiN / 2 nm AlN / bulk Nb SIS structures and investigated the effect of the presence of the AlN layer on the NbTiN film properties. We find that the hcp-structured AlN layer results in a Nb composition gradient as a function of film depth, whereas the Nb concentration remains constant in the NbTiN/Nb samples, which suggests that interface mismatch could induce significant change in NbTiN composition. The surface composition variation further leads to different oxide structures, which might impact the superconducting performance. Our observations indicate that the choice of the insulating layer in SIS structures is critical, and that interface mismatch together with internal strain could deteriorate the superconducting film.

INTRODUCTION

SIS structures proposed by A. Gurevich [1] take advantage of an insulating (I) layer between a thin superconducting (S) film and the superconducting (S) Nb bulk. Through optimizing the topmost superconducting film thickness versus the London penetration depth [2,3], the SIS design could repel vortex penetration and support increased surface magnetic field. To experimentally validate the device physics, researchers have explored superconducting films such as NbN [3-5], NbTiN [5-7], and Nb_3Sn that have larger penetration depths (λ) and higher critical temperatures (T_c) than Nb.

However, the film quality is critical to effectively test the RF performance of SIS structures. Variation could be from two resources: material issues (stoichiometry, phase, and surface oxide) or multilayer design issues (choice of superconducting and insulating films, and their thickness), both of which should be prioritized to test a rational SIS design. Otherwise, for example, the material issue may become a dominant factor, when the field for vortex penetration does not achieve the theoretical predications [5,8,9].

Atomic layer deposition (ALD) for fabricating SIS structures recently attracts attention owing to the atomic-scale control of thickness and composition. Characterization of ALD-based SIS structures has not been extensively studied, while researchers have optimized sputter-based SIS structures [3,4,7-9]. Also, the role of the insulating layer as an intermediate layer during deposition is not clear yet. Interface characterization would facilitate future optimization of the deposition process.

In this work, ALD NbTiN/AlN films on the Nb substrate were characterized via elemental depth profiling and X-ray diffraction. Stoichiometry, phase structure, and surface oxides were determined. The influence of the AlN layer on the deposition was revealed by comparing results with NbTiN reference films directly grown on Nb surfaces.

EXPERIMENTAL PROCEDURES

The SIS films were prepared using a plasma-enhanced ALD system by Mark Sowa (Veeco-CNT). Two film structures (100 nm NbTiN / 2 nm AlN / bulk Nb vs. 100 nm NbTiN / bulk Nb) were fabricated as shown in Fig. 1.

A Zeiss Gemini 500 scanning electron microscope (SEM) was used to examine the surface morphology and grain size. Depth profiling via X-ray photoelectron spectroscopy (XPS) was performed to provide the stoichiometry as a function of the film depth. X-ray diffraction (Rigaku XRD) was used to probe the phase information.

RESULTS AND DISCUSSION

Surface Morphology and Grain Size

Figure 1 shows a comparison of surface morphology for NbTiN/AlN/Nb and NbTiN/Nb structures. Both films are smooth, while the grain size (~4 nm) is small. In literature, grain sizes ranging from 20 nm to 170 nm were reported for the sputtered NbTiN films [7,10]. Our results suggest post annealing is preferred to promote grain growth, leading to a lower density of grain boundaries.

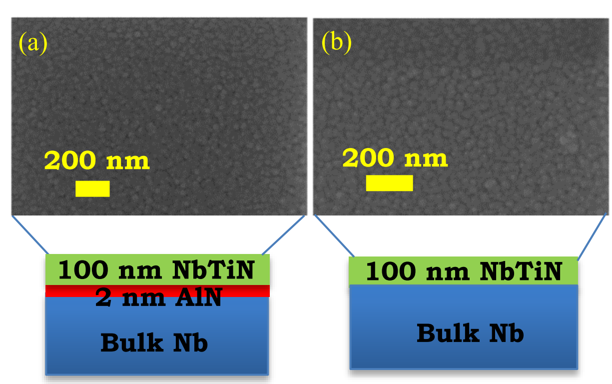

Figure 1: SEM surface morphology for (a) NbTiN/AlN/Nb structures and (b) NbTiN/Nb structures.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. Also, this work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875), and was performed in part at the Cornell NanoScale Facility, an NNCI member supported by NSF Grant NNCI-2025233.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV013

NEW FREQUENCY-TUNING SYSTEM AND DIGITAL LLRF FOR STABLE AND RELIABLE OPERATION OF SRILAC

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Abstract

The superconducting booster linac at RIKEN (SRILAC) has ten 73-MHz quarter-wavelength resonators (QWRs) that are contained in three cryomodules. The beam commissioning of SRILAC was successfully performed in January 2020. Frequency tuning during cold operation is performed by compressing the beam port of the cavity with stainless wires and decreasing the length of each beam gap, similar to the method adopted at ANL and FRIB. However, each tuner is driven by a motor connected to gears, instead of using gas pressure. Since the intervals of the QWRs are small due to the beam dynamics, a compact design for the tuner was adopted. Each cavity was tuned to the design frequency, which required frequency changes of 3 kHz to 7 kHz depending on the cavity. Although no piezoelectric actuator is mounted on the tuning system, phase noise caused by microphonics can be sufficiently reduced by a phase-locked loop using a newly developed digital LLRF. The details of the tuning system as well as the digital LLRF will be presented.

INTRODUCTION

The RIKEN heavy-ion linac (RILAC), consisted of normal conducting cavities [1–3], was used to accelerate intense ion beams to synthesize super-heavy elements Nh [4]. RILAC has been upgraded to allow further investigations of super-heavy elements and production of radioactive isotopes by introducing a new ECR ion source and a superconducting booster linac (SRILAC) [5]. The beam commissioning was performed successfully in January 2020. The SRILAC has ten quarter-wavelength resonators (QWRs) made of bulk niobium (Nb) contained in three cryomodules (Fig. 1). Quadrupole magnets are located in warm sections outside the cryomodules. In order to maintain a good beam quality and to limit the space taken up by cryomodules in the existing accelerator hall, the length of each cryomodule had to be minimized. The distance between the beam port flanges of the cavity in the cryomodules was set to as small as 110 mm. Since frequency tuning during cold operation is performed by compressing the beam ports [6], a compact mechanism for the frequency tuner was required.

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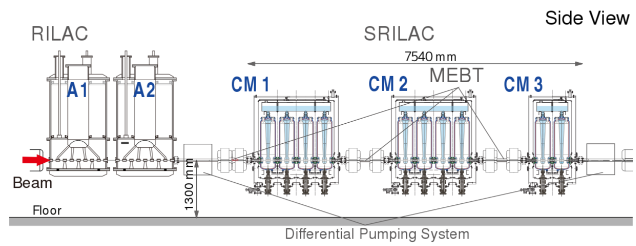

Figure 1: Schematic layout of the SRILAC and the last part of the RILAC. CM1–3: cryomodules, A1&A2: normal conducting cavities for RILAC. Quadrupole doublets are located in the Medium Energy Beam Transport line (MEBT).

FREQUENCY TUNING SYSTEM

Requirements of Tuner

Figure 2 shows a schematic view of a cavity with a titanium (Ti) jacket. Note that no stiffener was installed in the stem. The figure also shows a permalloy local magnetic shield with a thickness of 1.5 mm, which is put on a bare cavity before jacketing so that the magnetic shield is installed between the cavity and jacket. We chose a capacitive tuning method that decreases the frequency by compressing the beam ports, as mentioned above, and fabricated cavities so that the frequency is higher than the operating frequency by a few kHz when the tuner is free at cold temperatures. The tuner is used to decrease the frequency by a few kHz at the beginning of cavity excitation, as well as compensating the frequency shift by a few Hz caused by fluctuations of helium pressure. Based on the regulations regarding high-pressure gas safety in Japan, the cavities were designed to be rigid. We adopted a conical stem and fabricated the cavities from niobium sheet with a thickness of 3.5 or 4 mm. Although the stiffness helps to decrease the effects of microphonics, the required force of the tuner to change the frequency by -14 kHz is as high as 7.5 kN for each beam port, with a maximum displacement of 0.37 mm as determined from a simulation [6]. The simulation result of the displacement by a force applied perpendicular to the face of a beam port flange is shown in Fig. 3.

Tuner Mechanism

To fulfill the requirements mentioned above, the tuner mechanism was designed and fabricated by MHI-MS. Figure 4 shows the tuner mechanism assembled on a cryomodule. Each beam port of a cavity is pressed with a force less

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV015

DESIGN OF THE 650 MHz HIGH BETA PROTOTYPE CRYOMODULE FOR PIP-II AT FERMILAB*

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Abstract

The Proton Improvement Plan II (PIP-II) is the first U.S. accelerator project that will have significant contributions from international partners. The prototype High Beta 650 MHz cryomodule (pHB650 CM) is designed by an integrated design team, consisting of Fermilab (USA), CEA (France), STFC UKRI (UK), and RRCAT (India). The manufacturing & assembly of this prototype cryomodule will be done at Fermilab, whereas the production cryomodules will be manufactured and/or assembled by STFC UKRI, RRCAT, or Fermilab. Similar to the prototype Single Spoke Resonator 1 cryomodule (pSSR1 CM), this cryomodule is based on a strong-back at room temperature supporting the coldmass. The pSSR1 CM led to significant lessons being learnt on the design, procurement, and assembly processes. These lessons were incorporated into the design and processes for the pHB650 CM. Amongst many challenges faced, the main challenges of the pHB650 CM design were to make the cryomodule compatible to overseas transportation and to design components that can be procured in USA, Europe, and India.

INTRODUCTION

The design of the Single Spoke Resonator (SSR) and the 650 MHz PIP-II CMs share the same design concept: a room temperature strong-back and the cryogenic layout is identical (Figure 2) even if the cavities and solenoids configurations are different for each cryomodule type [1].

The design, assembly, and successful test of the pSSR1 CM [2] were a great source of lessons learned to design the pHB650 CM. Improvements have been made to increase the performance, ease the assembly process, and reduce the heat loads. Moreover, the experience from the transportation of the LCLS-II cryomodules from Fermilab to SLAC [3] had significant impact on the pHB650 CM design and led to transportation requirements for this new prototype. Thorough analysis on individual parts and on the full cryomodule assembly were performed to meet these requirements.

LESSONS LEARNED FROM SSR1 CM

Many lessons learned have been gathered during the design, assembly, and test of the pSSR1 CM. The main lessons learned applied to the design are listed below:

- The warm global magnetic shield of the pSSR1 CM was placed on the inner lower surface of the vacuum vessel without being connected to anything. Due to the weight of the shield it was difficult to maintain the shield in the proper position during the assembly.
- During the cold test, the temperature of the strong-back was lower than expected: 260 K instead of 280 K.
- The heat loads measurements were matching the calculations, but several optimisations could be done to lower the heat loads on the 2 K components.

All these lessons learned have been taken into consideration to design this new prototype cryomodule.

DESCRIPTION OF THE CRYOMODULE

The cryomodule is illustrated in Figure 1, which includes the following main components listed from bottom to top: the vacuum vessel, strong-back, G11 supporting post, thermal shield, cavity support, C-shape brackets, cavity, two phase pipe, heat exchanger, pressure transducer lines, and relief line.

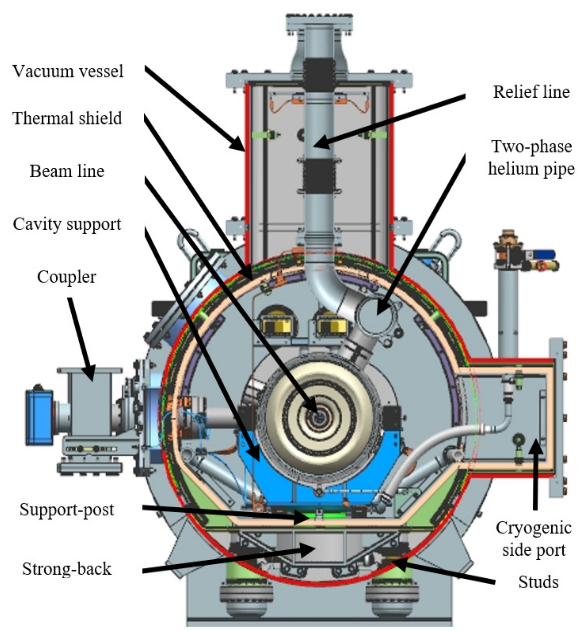

Figure 1: Cross-section of the pHB650 CM.

* Work supported by Fermi Research Alliance, LLC under Contract No. DE AC02 07 CH11359 with the United States Department of Energy
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV016

FIELD EMISSION STUDIES DURING ESS CRYOMODULE TESTS AT CEA SACLAY

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Abstract

For the development of efficient superconducting cavities, field emission is an important parasitic phenomena to monitor. A diagnostic system composed of Geiger-Mueller (G-M) probes, NaI(Tl) scintillators are placed in the cryomodule test stand. Collected data is analysed and confronted to particle tracking simulation and electro magnetic shower code. With such systematic analysis we aim to identify the most probable field emission location and hence help to improve clean procedures during assembly and operation.

INTRODUCTION

In addition to the production of the 30 medium and high beta cryomodules of the European Spallation Source (ESS) LINAC, CEA perform the test at high RF power of two prototype cryomodules and of the three first cryomodules of each type assembled at CEA Saclay. We present the results and analysis concerning the third cryomodule (i.e. CM03) for the medium beta section performance with a particular attention to its field emission behavior. The four cavities installed in the cryomodule were manufactured and prepared by Zanon Research&Innovation under the supervision of INFN LASA. The string assembly were done at CEA Saclay by a subcontractor, while the power test was performed by CEA personnel [1,2]

EXPERIMENTAL SET UP

CEA currently tested two cryomodule prototypes and three from the medium beta section series, which will be re-tested at ESS main site. In this paper we will mainly focus on the last cryomodule, namely CM03.

Cavities and Cryomodule

The cryomodule accommodate four medium beta cavity manufactured with fine grain high purity niobium [3]. In Table 1 are summarized the most significant cavity RF parameters.

Table 1: Design Parameters for Medium Beta Cavities [3]

Design parameters	Value
Geometrical beta - β_{geom}/β_{opt}	0.67/0.705
Nominal gradient E_{acc} [MV/m]	16.7
Q_0 at nominal gradient	$>5x10^9$
G [Ω]	198.8
R/Q [Ω]	374
E_{pk}/E_{acc}	2.55
B_{pk}/E_{acc} [mT/(MV/m)]	4.95
E_{pk}@nominal E_{acc} [MV/m]	42.6
B_{pk}@nominal E_{acc} [mT]	83

The two most relevant quantities concerning field emission are the ratio E_{pk}/E_{acc} and the accelerating field required during operation. This is due to the strong dependence of field emission current and surface electric field as demonstrated by Fowler and Nordheim [4] with equation (1).

$$J = \frac{A(\beta E_{surf})^2}{\varphi} e^{-\frac{B\varphi^{1.5}}{\beta E_{surf}}} \quad [\frac{A}{m^2}] \qquad (1)$$

where A and B are constant, φ is the material work function, E_{surf} is the electric field on the surface and β is the geometrical enhancing factor due to surface asperity.

In Fig. 1 is shown a section of the medium beta cryomodule highlighting the main components and a longitudinal cross section view.

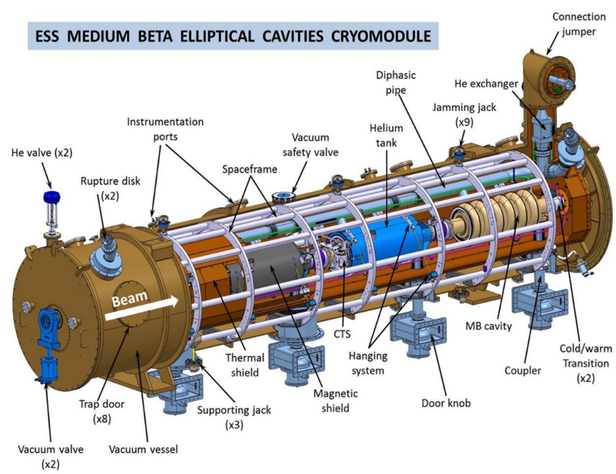

Figure 1: Medium beta cavity cryomodule main components highlight.

Details about cryomodule design parameters are given elsewhere [1,5], here it is worth to recall that the static heat load on the 2K bath is estimated to be around 17W, while the dynamic heat load due to cavity operation is about 20W. Each cavity at nominal field can dissipate about 5W corresponding to a quality factor bigger than $5x10^9$ (assuming a machine duty factor around 4%).

Gamma Ray Diagnostic System

A cryomodule test stand has been refurbished at Saclay in order to perform all the required high power test. As part of the new test, set up a gamma ray diagnostic system has been developed and upgrades are foreseen for future tests. A previous set up has been described in a previous publication [6], here will be discussed details concerning the latest cryomodule power test on CM03. In Fig. 2 is shown a medium beta cryomodule installed in the test stand with RF and cryogenic systems connected.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV017

TRANSPORTATION ANALYSIS OF THE FERMILAB HIGH-BETA 650 MHz CRYOMODULE *

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Abstract

The prototype High-Beta 650 MHz cryomodule for the PIP-II project will be the first of its kind to be transported internationally, and the round trip from FNAL to STFC UKRI will use a combination of road and air transit. Transportation of an assembled cryomodule poses a significant technical challenge, as excitation can generate high stresses and cyclic loading. To accurately assess the behavior of the cryomodule, Finite Element Analysis (FEA) was used to analyze all major components. First, all individual components were studied. For the critical/complex components, the analysis was in fine detail. Afterwards, all models were brought to a simplified state (necessary for computational expenses), verified to have the same behavior as their detailed counterparts, and combined to form larger sub-assemblies, with the ultimate analysis including the full cryomodule. We report the criteria for acceptance and methods of analysis, and results for selected components and sub-assemblies.

INTRODUCTION

pHB650 Design

As designed, the prototype High-Beta 650MHz Cryomodule (pHB650 CM) contains six jacketed cavities each with their own coupler, tuner, local magnetic shield, and connection to the two-phase pipe. Hydroformed bellows are used in the beamline and cryogenic piping to provide flexibility during assembly and reduce stresses during cool down. Each cavity has two supports that are mounted to the strongback, which in turn, is connected to the vacuum vessel, as shown in Fig. 1. A 50 K thermal shield protects the cold mass from radiation, and a global magnetic shield is mounted to the inner wall of the vacuum vessel. In total, the full CM assembly is approx. 12,500 kg, 10 m long, 2 m wide, and 2 m tall. Further design details can be found in [1].

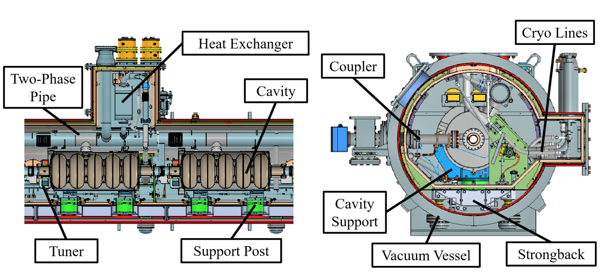

Figure 1: pHB650 CM components. Left: partial transverse section view. Right: partial axial section view.

* Work supported by Fermi Research Alliance, LLC under Contract No. DEAC02- 07CH11359 with the United States Department of Energy
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Transportation Scheme

The prototype HB650 CM will be built at FNAL, three production CMs will be an in-kind contribution from STFC UKRI of the U.K., and one CM kit will be provided by RRCAT of India. The trans-Atlantic transportation of the STFC UKRI CMs poses a significant risk, as previous CM transport failures have occurred which resulted in significant setbacks [2]. FNAL therefore set requirements for the transport frame and CM to mitigate these risks. The frame designed by STFC UKRI must not allow shocks greater than 3.5 G axial, 2.5 G vertical, or 1.5 G transverse on the CM, and 80% isolation must be achieved for shocks above 10 Hz. It is required that the CM components are designed to withstand 5 G axial, 3 G vertical, and 1.5 G transverse acceleration without yielding (some margin given over the frame requirements, but the transverse acceleration could not be increased due to design constraints), and critical components are to be designed to have frequencies above 20 Hz to mitigate fatigue failure.

To validate the CM design, cold RF and transportation testing will be performed separately onsite at FNAL, and afterwards, the prototype CM will be shipped to the U.K. and back via road/air transit. Prior to this shipment, a shipment of a dummy CM will take place to the U.K. to validate the transport configuration and logistics. The transport frame utilizes wire-rope isolators to mitigate shocks to the CM. The transport configuration with top port removed is shown in Fig. 2.

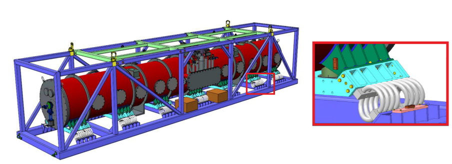

Figure 2: pHB650 CM in transport configuration within the transport frame.

ANALYSIS AND MODELING METHODS

Analysis Methods

ANSYS® Mechanical ™ R19 was used to perform the Finite Element Analysis (FEA). While in reality road excitation comes as momentary shocks, Static Structural linear-elastic analysis was used to study the cases of 5 G axial, 3 G vertical, and 1.5 G transverse since applying the maximum acceleration as a static load should yield conservative estimates of stress and deflection. Modal analysis was used to determine the resonant frequencies of each system. Dynamic structural and harmonic analyses were considered for structural

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEOCAV03

RF DIPOLE CRAB CAVITY TESTING FOR HL-LHC

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Abstract

RF Crab Cavities are an essential element of the High Luminosity LHC (HL-LHC) upgrade at CERN. Two RF dipole crab cavities used for the compensation of the horizontal crossing angle were recently manufactured and integrated into a titanium helium tank and equipped with RF ancillaries necessary for the beam operation. The two cavities will be integrated into a cryomodule in collaboration with UK-STFC and tested with proton beams in the SPS in 2023. This paper will highlight the RF measurements during the final manufacturing steps, surface preparation and cavity performance at 2 K.

INTRODUCTION

RF Crab Cavities are required for the HL-LHC upgrade [1] at CERN to transversely rotate the bunches and re-establish the head-on collisions at the interaction point (IP). This rotation compensates for the gemoetric factor and increases the peak luminosity by more than 65%. In the HL-LHC, the two IPs have alternating crossing angle, one horizontal (ATLAS) and one vertical (CMS). For the horizontal crossing, the RF dipole superconducting crab cavity will provide the crabbing manipulation to compensate for the horizontal crossing angle. A two cavity cryomodule is under construction towards a test with proton beams, hosting two RF dipole (RFD) crab cavities (see Fig. 1) [2]. The beam tests are planned for 2023 in the CERN-SPS machine. While the cryomodule integration will be done at the UK-STFC premises, the two bulk niobium, jacketed and dressed RFD cavities were fabricated and tested at CERN.

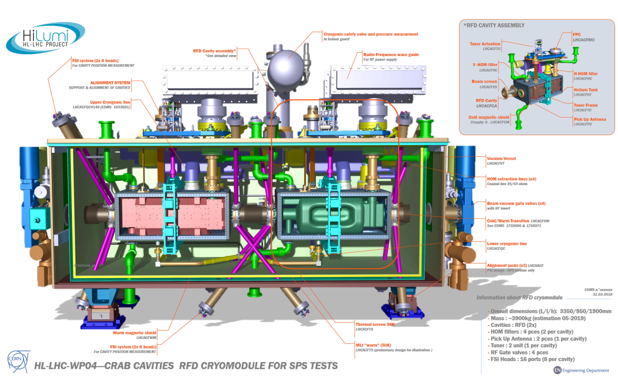

Figure 1: Cross section of the RFD cryomodule hosting two cavities (courtesy CERN EN-MME).

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Due to their exotic geometry, compact deflectors, such as the RFD cavities (see Fig. 2), follow a complex manufacturing procedure [3]. To ensure that the cavities are at the correct range of frequency during operation, careful calculations are performed to determine a “recipe” that lays out the frequency requirements for the different manufacturing and processing steps. To enforce this, rigorous RF controls are carried out during the identified key steps of the cavity life. The surface treatment and preparations for the cold test,

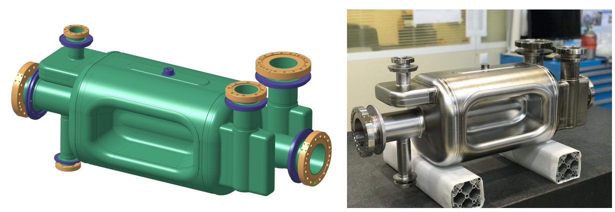

Figure 2: Left: The RFD cavity geometry. Right: RFD cavity manufactured from high RRR Niobium.

as well as results and performance will be presented in the following sections. This paper will also address some of the main challenges for preparing and processing RFD cavities in the final section and will close with some discussion and remarks.

FREQUENCY TUNING OF SUB-COMPONENTS

Table 1 lists the target frequency requirements for the crabbing mode at different steps of the production process of RFD cavities for the HL-LHC, including buffered chemical polishing (BCP), heat treatment (HT), vertical cold tests (VCT) for the bare cavity, as well as for the dressed cavity (DC), which is defined as the jacketed cavity with all the couplers and antennas installed. Further details on the manufacturing of the couplers can be found in Ref. [4].

All the values in Table 1 are expected to be measured within a ±0.05 MHz error threshold.

The first RF controls are visual inspections carried out throughout the deep drawing and welding of the individual sub assemblies, such as: ports, pipes, capacitive plates, etc. The first RF measurement at ambient temperature is possible upon the completion of the three main sub-assemblies (i.e.) the two end caps and the mid body (see Fig. 3).

The end caps were trimmed to their nominal length, and their edges machined to nominal thickness with calibration of the edge face to reach the specified planarity. During each fabrication step, metrology controls are performed to ensure

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEOCAV04

OPTIMIZATION OF A TRAVELING WAVE SRF CAVITY FOR UPGRADING THE INTERNATIONAL LINEAR COLLIDER*

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Abstract

The Standing Wave (SW) TESLA niobium-based superconducting radio frequency structure is limited to an accelerating gradient of about 50 MV/m by the critical RF magnetic field. To break through this barrier, we explore the option of niobium-based traveling wave (TW) structures. Optimization of TW structures was done considering experimentally known limiting electric and magnetic fields. It is shown that a TW structure can have an accelerating gradient above 70 MeV/m that is about 1.5 times higher than contemporary standing wave structures with the same critical magnetic field. The other benefit of TW structures shown is R/Q about 2 times higher than TESLA structure that reduces the dynamic heat load by a factor of 2. A method is proposed how to make TW structures multipactor-free. Some design proposals are offered to facilitate fabrication. Further increase of the real-estate gradient (equivalent to 80 MV/m active gradient) is also possible by increasing the length of the accelerating structure because of higher group velocity and cell-to-cell coupling. Realization of this work opens paths to ILC energy upgrades beyond 1 TeV to 3 TeV in competition with CLIC. The paper will discuss corresponding opportunities and challenges.

INTRODUCTION

A strong physics attraction for the ILC - besides the Higgs and Top Factories [1-2] - is the inherent energy upgradability. As described in the ILC TDR [3], ILC offers paths to energy upgrades of 0.5 TeV and 1 TeV for which higher gradients are critical for affordability, as cavities and cryomodules are dominant cost drivers. There has been steady progress in single and multicell cavity gradients [4] over the last 3+ decades along with SRF science and technology advances. Proof-of-principle is already in hand for cavity preparations that deliver single cell TESLA-shape cavities with gradients up to 49 MV/m [5-6], and for 9-cell cavities with gradients up to 45 MV/m [7]. These gradient advances come from high purity, high RRR Nb, electropolishing at low temperatures, and optimized 120°C baking in two steps, 800°C furnace treatment for hydrogen removal, and 100 atm high pressure water rinsing for removal of field emission particulates. The fundamental critical magnetic field of approximately 210 mT presents the ultimate hard limit to niobium cavity gradients. For the standing wave TESLA shape structure, with *peak surface magnetic field to accelerating field ratio* B_{pk}/E_{acc} = 4.26 mT/(MV/m), this limit translates to a maximum gradient of 50 MV/m. The peak electric field also presents a limit due to field emission, but this is a practical – not fundamental - limit which in principle can be overcome with technology advances in surface preparation (such as more effective final high-pressure rinsing). Further gradient advances from 50 – 59 MV/m have been demonstrated [8-10] with single cell cavities of advanced cavity geometries with 10 – 15% lower B_{pk}/E_{acc}, such as Re-entrant, Low Loss, Ichiro, and Low Surface Fields shapes.

Even higher gradients are needed for ILC energy upgrades beyond 1 TeV! This paper discusses optimized *traveling wave* (TW) superconducting niobium-based structures [12] with effective gradients up to 73 MV/m to open upgrade paths to 3 TeV, in competition with CLIC at 3 TeV. Another paper at this conference [11] shows the overall cost for 3 TeV ILC with 70 MV/m gradient is comparable to CLIC 3 TeV, and the AC power is 190 MW lower. TW structures offer two main advantages compared to standing wave (SW) structures: substantially lower peak magnetic and peak electric field ratios, and substantially higher *R/Q* (for lower cryogenic losses, and lower RF power demand). In addition, TW structure operates far off the passband boundaries, and therefore, has high stability of the field distribution along the structure with respect to geometrical perturbations [12]. This allows a much longer structure length and hence no gap between short (1 meter) cavities, thereby increasing the real-estate gradient, but this advantage substantially increases the engineering challenges. Besides, the TW structure requires a feedback waveguide for redirecting power from the end of the structure back to the front to avoid high peak surface fields in the accelerating cells. This requires careful tuning to compensate reflections along the TW ring to obtain a pure traveling wave regime at the desired frequency. Because the beam bunch charge for the 3 TeV upgrade is 3 times lower than the bunch charge for 0.5 TeV [11], (for lower IP backgrounds) it is further possible to lower the aperture (from 70 mm to 50 mm) to obtain an overall 50 % reduction in B_{pk}/E_{acc} and factor of 2 gain in *R/Q* over the TESLA standing wave structure. The lower bunch charge reduces the wakefields.

Previously, substantial progress was made at Fermilab and in Euclid Techlab on the way to realization of the TW structure in the regime of a resonant ring [12 - 15]. The present work makes use of that progress to advance the topic further.

The optimizations described below are enabled by accurate calculations of cavity parameters. 2D computer code SuperLANS [16] has the accuracy necessary for these optimizations.

GEOMETRY OF AN ELLIPTICAL CAVITY

Templates Contemporary superconducting RF cavities for high energy particle accelerators consist of a row of cells coupled together as shown in Fig. 1a. The contour of

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEOCAV06

SARAF-PHASE 2 LOW-BETA AND HIGH-BETA SUPERCONDUCTING CAVITIES QUALIFICATION

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Abstract

CEA is committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SARAF accelerator in order to accelerate 5 mA beam of either protons from 1.3 MeV to 35 MeV or deuterons from 2.6 MeV to 40 MeV. The SCL consists in four cryomodules. The first two identical cryomodules host 6 half-wave resonator (HWR) low beta cavities (beta= 0.09) at 176 MHz. The last two identical cryomodules will host 7 HWR high-beta cavities (beta = 0.18) at 176 MHz. The low-beta prototypes was qualified in 2019. Low-beta series manufacturing is on-going. The high-beta prototype was first tested in 2019 but failed. A new prototype was tested in the end of 2020. This contribution will present the results of the tests for low- and high-beta SARAF cavities, series and prototypes.

INTRODUCTION

In 2014, CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives, Saclay, France) was committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SNRC (Soreq Nuclear Research Center, Soreq, Israel), on the SARAF (Soreq Applied Research Accelerator Facility) site [1].

This new accelerator, called Saraf-Phase II, was designed to accelerate 5 mA beam of either protons from 1.3 MeV to 35 MeV or deuterons from 2.6 MeV to 40 MeV. CEA is currently driving the manufacturing of this new accelerator, called to be installed by SNRC and CEA at Soreq, Israel [2]. The commissioning of the MEBT began in 2021, and CEA planned the end of the commissioning of the last cryomodule for 2023.

In order to keep the existing RFQ of SARAF-Phase I, the frequency of the full accelerator was fixed to 176 MHz. During the pre-studies of this new accelerator, the beam dynamics fixed the optimal "geometric betas" to 0.09 and 0.18. The SARAF-Phase II accelerator contains 13 superconducting cavities with $\beta_{opt} = 0.09$, called low-beta (LB) cavities, and 14 superconducting cavities for $\beta = 0.18$, called high-beta (HB) cavities [3].

At this frequency, HWR (Half Wave Resonators) technologies seemed to be the most suitable [4]. Moreover, this technology showed good results for a previous CEA project: IFMIF [5]. It was also the technology chosen for the previous SARAF-Phase I prototype accelerator [6]. It is planned to use the superconducting cavities only at 4.45 K, at 1200 mbar. No operation is planned at lower temperature.

These two HWRs, LB and HB cavities, were designed in 2016 [7]. Research Instrument was chosen in 2017 to manufacture these cavities. CEA qualified the prototypes and the LB cavities series from 2018 to 2021 [8, 9]. The qualification of the HB cavities series is ongoing.

DESIGN

The design of both cavity kinds began in 2016 and was described in [7]. SNRC defined the frequency for the superconducting LINAC to 176 MHz, in order to keep the RFQ [6]. Thus, the superconducting cavities had to be tuned at 176 MHz. The expected maximal beam losses defined the aperture diameters of the beam ports: 36 mm and 40 mm for the LB and HB cavities respectively. The beam dynamics defined the required β_{opt} for both types of cavities: 0.09 and 0.18 [3]. The beam dynamics also fixed the accelerating voltage of the cavities to 6.5 and 7.5 MV/m for LB and HB cavities respectively. However, in order to keep some margin on the design, we designed them as if SNRC would have used them at 7.0 and 8.1 MV/m. It allows compensating potential lower performances of some cavities along time.

The beam dynamics defined the position of the cavities in the cryomodule. Considering the other components of the cryomodule (frequency tuner, couplers, thermal and magnetic shields, cold mass, etc. [10]), the cavity without helium tank had to be smaller in diameter than 200 mm and 320 mm for LB and HB cavities respectively (excluding the beam and coupler ports).

The peak magnetic and electric fields were optimized in accordance to these requirements. Based on the literature [11] and previous CEA projects [12, 5], it seemed possible to reach surface magnetic fields up to 140 mT and surface electric fields up to 70 MV/m, at the cost of a very high cryogenic power consumption. The test of PXIE HWR cavities demonstrated later that cavities could even reach surface electric fields up to 90 MV/m and 95 mT without quench or excessive field emission [13].

* Work supported by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, France) and by Soreq Nuclear Research Center (SNRC, Israel)
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEOTEV03

TOWARD STOICHIOMETRIC AND LOW-SURFACE-ROUGHNESS Nb_3Sn THIN FILMS VIA DIRECT ELECTROCHEMICAL DEPOSITION*

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Abstract

Reducing surface roughness and attaining stoichiometry of Nb_3Sn superconducting films are required to push their superheating field to the theoretical limit in SRF cavities. As such, we explore direct electrochemical processes that minimize involving foreign elements to deposit high-quality Sn, Nb, and Nb_xSn films on Nb and Cu surfaces. These films are then thermally annealed to Nb_3Sn. We find that smooth Sn pre-depositions via electroplating on Nb surfaces significantly reduce the average roughness of resultant Nb_3Sn to 65 nm. Structural and superconducting properties demonstrate a Nb_3Sn A15 phase with a stoichiometry of 25 at% Sn. This process has been scaled-up to a 3.9 GHz cavity. Moreover, preliminary results on electroplating on Cu surface show that Nb plating undergoes a slow growth rate while subsequent Sn plating on the plated Nb surface can be controlled with varied thickness. The Nb plating process is currently being optimized.

INTRODUCTION

Nb_3Sn superconducting films that are used on the inner surface of SRF cavities seek to advance the accelerating gradient up to 100 MV/m and allow operating at 4 K with a lowered cryogenic cost, enabled by a doubled superheating field (~400 mT) and a high critical temperature (18 K) of this material as compared to conventional niobium [1]. However, the RF performance of vapor-diffused Nb_3Sn cavities currently reaches accelerating gradients of up to 24 MV/m [2], significantly lower than the theoretical predicted limit of 100 MV/m. To overcome this big gap, researchers have identified two major issues in Sn vapor diffusion, the state-of-the-art method for making Nb_3Sn. One issue is the large surface roughness that is mainly induced by variation in grain size due to non-uniform nucleation events [3,4]. The peak regions result in field enhancement while the valley regions are enabling premature for vortex nucleation [5]. The second issue is Sn depletion regions that are frequently observed in the film [4,6] due to insufficient Sn supply during the vapour diffusion growth [7]. The off-stoichiometry degrades the critical temperature of Nb_3Sn, e.g., $T_c \approx 10$ K at 20 at% Sn [7]. Thus, it is desirable to develop a new deposition process that revolves these issues.

Our strategy is pre-deposition of a smooth Sn film on a Nb substrate and then thermal conversion to Nb_3Sn. Several advantages include promotion of uniform distribution of nucleation events to lower surface roughness and supplying sufficient Sn to satisfy the kinetic requirement for Nb_3Sn stoichiometry. To deposit the initial Sn film, an electroplating method is of interest due to the low cost and capability to scale up to cavities. Previous studies on Sn plating on Nb surfaces rely on a Cu seed layer [8] or bronze [9]. Here, we intend to avoid any Cu contamination and choose a different path via optimization of solution chemistry. Our earlier work [10-13] have demonstrated the success of stoichiometric Nb_3Sn deposition with extremely low surface roughness through Sn electroplating.

In this work, we continued the optimization and characterization of the electroplating-based Nb_3Sn, together with a comparison with vapor-diffused Nb_3Sn. We improved the understanding of the growth mechanism that is critical to future film design. Furthermore, we optimized the Sn plating process on a 3.9 GHz cavity, which is a main focus of this paper.

In addition, we are developing Sn and Nb electroplating processes on Cu substrates since Cu cavities are cost-effective and exhibit better thermal properties. Preliminary results are also discussed.

METHODS

A three-electrode electrochemical deposition system was installed at Cornell as shown in Fig. 1. The 3.9 GHz cavity was connected to the working electrode while a cylinder mesh Pt counter electrode and a saturated calomel reference electrode were inserted inside the cavity.

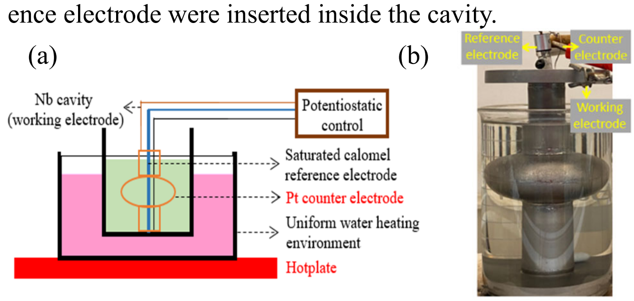

Figure 1: (a) Schematic and (b) picture showing the electrochemical deposition system at Cornell. Note that water heated bath and temperature feedback control are not shown in the picture.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. Also, this work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875), and was performed in part at the Cornell NanoScale Facility, an NNCI member supported by NSF Grant NNCI-2025233.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV02

STABLE BEAM OPERATION IN COMPACT ERL FOR MEDICAL AND INDUSTRIAL APPLICATION AT KEK

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Abstract

A superconducting Compact Energy Recovery Linac (cERL) was constructed in 2013 at KEK to demonstrate energy recovery concept with low emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL [1]. Recently, this cERL was operated to promote a variety of the industrial applications such as FEL, THz operation and Rare Isotope (RI) production for medical application. In this paper, we will present the status of the studies to realize the stable high-current, low-emittance CW beam and briefly report some industrial and medical applications with this beam in cERL.

INTRODUCTION FOR COMPACT ERL

Compact ERL Accelerator

Compact ERL (cERL) [1] is a test facility, which was constructed on the ERL Test Facility in KEK. Its aim was to demonstrate technologies needed for future multi-GeV class ERL light source [2]. In 2016 and 2018, we successfully operate the CW 1 mA beam in the energy recovery condition [3]. From 2017, KEK directorates kept the importance of the R&D for industrial application based on ERL technologies instead R&D of ERL light source.

cERL consists of a 500 kV DC photocathode gun [4], which made high charge and low emittance electron beam, the injector cavities [5], the main linac cavity [6], which made energy recovery, recirculation loop and the beam dump. Detailed design beam parameters are shown in Table 1. After cERL construction, we met severe field emission of main linac cavities of 8.6 MV. Therefore, we started beam operation with 20 MeV beam energy [7].

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Table 1 : Design Parameters of the cERL

Nominal beam energy	35 MeV
Nominal injection energy	5 MeV
Beam current	10 mA (initial goal) 100 mA (final goal)
Normalized emittance	0.1 – 1 mm-mrad
Bunch length (bunch compressed)	1-3 ps (usual) 100 fs (short bunch)

cERL consists of a 500 kV DC photocathode gun [4], which made high charge and low emittance electron beam, the injector cavities [5], the main linac cavity [6], which made energy recovery, recirculation loop and the beam dump. Detailed design beam parameters are shown in Table 1. After cERL construction, we met severe field emission of main linac cavities of 8.6 MV. Therefore, we started beam operation with 20 MeV beam energy [7].

cERL Beam Operation for the Applications

Superconducting accelerator with ERL scheme gives us high current linac-based beam with high quality of the electron beam such as small emittance and short bunch. The unique performance of cERL gives us several important industrial applications as follows:

1. RI manufacturing facility for nuclear medical examination
2. IR-FEL experiment with high current ERL beam
3. Intense THz light generation with ERL

In a few years from 2018, we performed these applications in cERL, Figure 1 shows the latest applications in cERL. First, the new beam line for ^{99}Mo RI production &

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV03

PROGRESS OF SUPERCONDUCTING RF ACTIVITIES IN INDIA*

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Abstract

This paper is a summary of the recent progress of SRF activities in India including the institutes viz., RRCAT, BARC, VECC and IUAC. The latest SRF activities for several national accelerator projects and international projects like PIP-II in FNAL are presented. RRCAT in Indore has been pursuing a complete chain of fabrication, RF tests and characterization at various stages including the SCRF infrastructure facilities, processing, HPR, Vertical Test Stand (VTS) and Horizontal Test Stand (HTS). Several cavities have been successfully tested in the vertical test stand, and the Horizontal Test Stand has been commissioned and ready to test the cavities. BARC in Mumbai has developed low beta single spoke cavities for PIP-II R&D in collaboration with IUAC. VECC is pursuing development of single cell and five cell low beta SCRF cavities for PIP-II R&D. IUAC in New Delhi developed SRF cavities using their infrastructure facilities and has supported institutes in India towards 1.3 GHz cavities, single cell LB and HB cavities and development of SSR1 cavities. Status of the SRF cavity development and the latest results of cavity performance qualification are presented in this talk.

INTRODUCTION

India is interested in High Intensity Superconducting Proton Accelerators (HISPA) for building a Facility for Spallation Research, Radio-isotope Production, Radio-active Ion Beam (RIB) facility etc. These demand high intensity proton beams; both pulsed and CW. Participation in International SCRF accelerator projects like PIP-II (Fig. 1) at Fermilab under Indian Institutions Fermilab Collaboration (IIFC), will enable to develop proven HISPA technology and develop essentially all individual components of a HISPA system. Institutes of Department of Atomic Energy are partners to PIP-II development for various subsystems like cryo-plant, Single Spoke Resonators, Low beta 650 MHz cavities and High Beta 650 MHz cavities [1]. RRCAT had developed infrastructure facilities for SCRF cavity development and tests starting from initial development of 1.3 GHz multi-cell SCRF cavities and later for high beta HB 650 MHz cavities under PIP-II R&D program (Fig. 2) [2–4]. BARC is setting up infrastructure facilities for developing Single Spoke Resonators (SSR) development. VECC is pursuing the development of low beta 650 MHz cavities and two single cell LB 650 cavities have been developed jointly with IUAC and tested at Fermilab. IUAC has developed 325 MHz SSR1 cavities. The jacketing of SSR1 cavities was done by BARC and the two cavities were supplied to Fermilab and successfully tested. IUAC has also developed quarter wave resonators for its 15UD Pelletron post SCRF accelerator and successfully accelerated variety of species for nuclear physics research. Apart from the SCRF cavity development, an intense effort has been made to develop 325 MHz, 7 kW solid state amplifiers by BARC as well 650 MHz, 40 kW class solid state amplifier prototypes by RRCAT. Nine 325 MHz, 7 kW amplifiers have been developed and shipped by BARC and installed in the PIP-II IT equipment hall at Fermilab and used for accelerating the beam [5]. One prototype of 40 kW SSPA has been developed and shipped by RRCAT to Fermilab which is made functional and will be coupled to the cavity test system at Fermilab. This paper will give an overview of various infrastructure facilities at the Indian Institutes and the latest results on the cavity and subsystem developments will be presented.

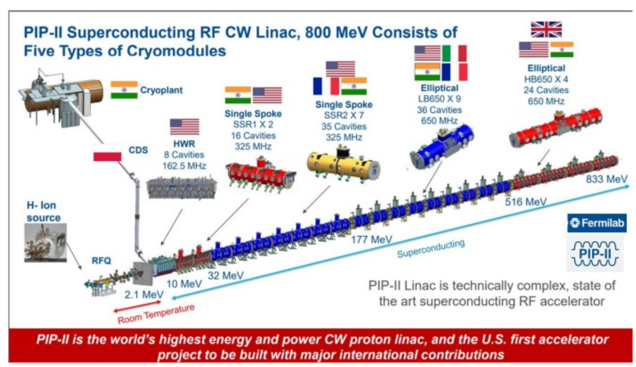

Figure 1: Schematic of PIP-II SCRF CW Linac showing various families of SCRF cavities and contributions from various international partners and India.

SCRF INFRASTRUCTURE AND HB 650 CAVITY DEVELOPMENT AT RRCAT

SCRF cavity development efforts to the R&D phase of PIP-II project under the Indian Institutions Fermilab Collaboration for the PIP-II project at RRCAT include following: (i) $\beta = 0.92$, 650 MHz (HB 650) five-cell bulk niobium SCRF cavities. (ii) Horizontal Test Stand (HTS) cryostats,(iii) 40 kW, 650 MHz solid state RF amplifiers, (iv) processing and HPR of HB 650 SCRF cavities. In addition participation in cryo-module development is also taken up.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV06

PLASMA ELECTROLYTIC POLISHING AS A PROMISING TREATMENT REPLACEMENT OF ELECTROPOLISHING IN THE COPPER AND NIOBIUM SUBSTRATE PREPARATION FOR SRF*

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Abstract

Superconducting radio frequency (SRF) cavities performances strongly depend on the substrate preparation. Currently, the conventional protocol of SRF surface preparation includes electropolishing (EP) as the main treatment achieving low roughness, clean and non-contaminated surfaces, both for bulk Nb and Cu substrates. Harsh and non-environmentally friendly solutions are typically used: HF and H_2SO_4 mixture for Nb, and H_3PO_4 with Butanol mixtures for EP of Cu. This research is focused on the application of a relatively new technique "Plasma Electrolytic Polishing" (PEP) for the SRF needs. PEP technology is an evolution of EP with a list of advantages that SRF community can benefit from. PEP requires diluted salt solutions moving to a greener approach in respect to EP. PEP can in principle substitute, or completely eliminate, intermediate steps, like mechanical and/or (electro) chemical polishing. Thanks to the superior removing rate in the field (up to 3.5 µm/min of Nb, and 10 µm/min of Cu) in one single treatment roughness below 100 nm Ra has been obtained both for Nb and Cu. In the present work a proof of concept is shown on Nb and Cu planar samples.

INTRODUCTION

The PEP technique was described for the first time in 1979 [1], but only in recent years it has really gained the interest of industries and research institutes. Dental implant, multi-metal, alloys, and semiconductor polishing are only some of the current fields of applications of PEP and different recipes were developed to apply PEP on stainless steels alloys, aluminium, titanium, and others [2-4]. Theoretically, the PEP technology can polish any metal structure and presents several advantages compared to other polishing methods. In particular, PEP uses low-concentration salts solution electrolyte, so no harmful gases are produced. Moreover, PEP is a very fast process capable to generate a good surface quality, with no mechanical stress and no thermal distortion or damage [5]. Despite these advantages, there are still very few works in literature and hardly any on the treatment of copper and niobium, the two materials of most interest in the SRF field.

From EP to PEP

The process setup of PEP is quite similar to the standard electropolishing: the metal part to be polished is immersed into the electrolyte and connected to the positive pole of the power supply (anode). A second electrode is connected to the positive pole and works as a cathode (see Fig. 1).

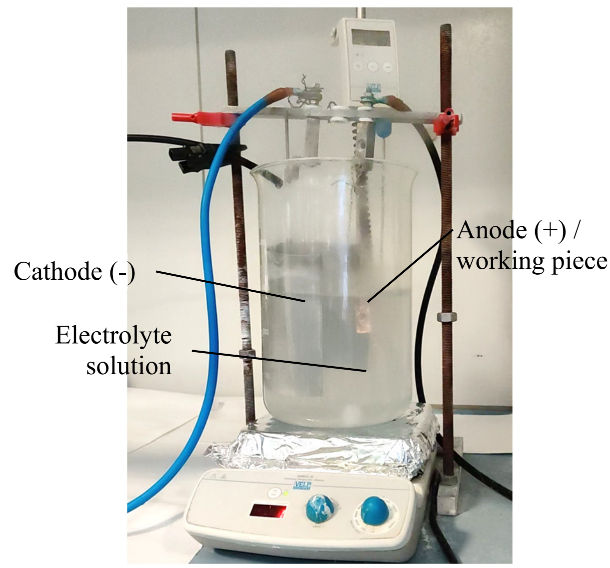

Figure 1: Chemical stand for the PEP study used at LNL.

The two principal differences between EP and PEP are a higher voltage regime and an electrolytic solution with a low conductivity. In particular, this last point is one of the advantages of PEP, especially in the case of Nb. The electrolytes are based on an environmentally friendly solution of various salts, normally in concentration range of 2-10 %. No HF and H_2SO_4 are necessary for the Nb polishing anymore. Moreover, the PEP solutions are less viscous than EP ones, thus simplifying the process plant requirements.

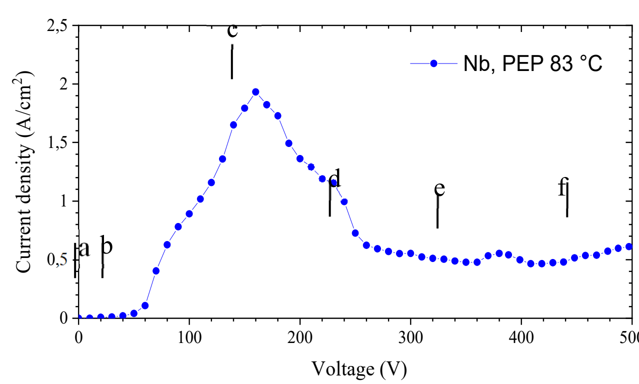

Figure 2: Current-voltage characteristics of Nb in PEP electrolyte developed at LNL (T=83 °C).

Figure 2 shows a typical current vs voltage curve obtained in this work for Nb. The general behaviour is quite

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV07

INDUSTRIAL X-RAY TOMOGRAPHY AS A TOOL FOR SHAPE AND INTEGRITY CONTROL OF SRF CAVITIES*

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Abstract

Industrial X-ray tomography offers the possibility to capture the entire inner and outer shape of a superconducting radio frequency (SRF) cavity, providing also insights in weld quality and material defects. As a non-contact method this is especially attractive to investigate shape properties of fully processed and closed cavities. A drawback is the inherently strong X-ray damping of niobium, which causes the demand for intense hard X-rays, typically beyond the capabilities of dc-X-ray-tubes. This also limits the accuracy of material borders found by the tomographic inversion. To illustrate both capabilities and limitations, results of X-ray tomography investigations using three different cavities are reported, also describing the fundamental parameters and the hard- and software demands of the technology. We also discuss the non-trivial transferring of tomography data into RF simulation tools.

INTRODUCTION

The extraordinary small line width of SRF cavity resonators makes it desirable to provide best geometrical control of such cavities whilst the entire sequence of production, preparation and installation. Furthermore such cavities are costly and delicate devices, which require best practiced quality control. Third they demand for highest cleanliness and should kept hermetically closed as far as possible. It is the aim of this paper to estimate the potential of industrial X-ray tomography (cf. Figs. 1 and 2) to serve as a tool for cavity shape and integrity control, since it matured in various fields – a very early reference is found in [1], a recent summary in [2] – as a non-destructive, non-tactile, highly permissive and accurate method. The term “industrial” shall be understood both as technical distinction from medical X-ray tomography, but also in the sense of a procurable service. In other words: Does it work and can we buy it?

The authors do not claim the priority being the first to apply X-ray tomography to a Niobium cavity, which to our best knowledge, was described in [3], there with a focus on surface defect analysis. Those experiments triggered our investigations applied to more and larger structures with higher wall thicknesses, also utilizing a significantly higher X-ray energy.

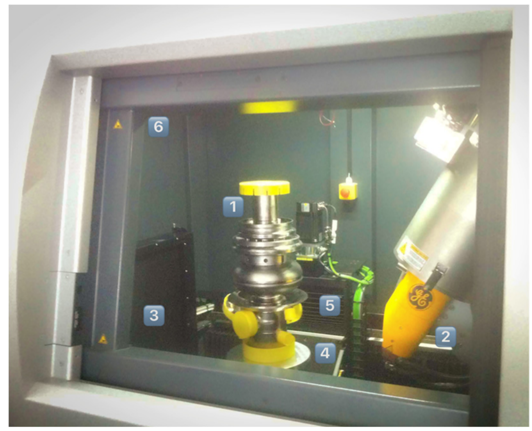

Figure 1: Gun1.1-cavity (1, [4]) placed in between a 300 keV X-ray tube (2) and a detector array (3) on a rotating (4) and lifting (5) table in a shielded cabinet with a lead glass window (6) at XRAY-LAB, Sachsenheim, Germany.

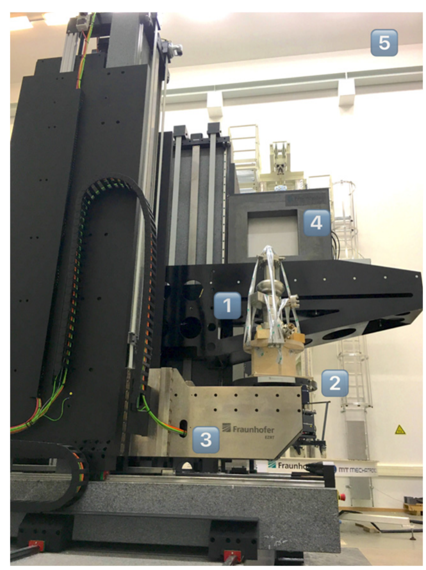

Figure 2: VSR-Single-Cell cavity (1, [5]) mounted on the rotating table (2) at the Fraunhofer-EZRT large scale X-ray tomography installation, Fürth, Germany [6]. The lifter (3) will move the cavity in the X-ray beam generated by a 9-MeV-accelerator-based source (not shown) in the height of the square X-ray array detector (4). For radiation protection the entire installation is housed in a bunker (5).

* Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin, and grants of the Helmholtz Association
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFAV002

FABRICATION AND INSTALLATION OF NEWLY DESIGNED CRYOSTATS AND TOP FLANGES FOR THE VERTICAL TEST OF RISP*

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Abstract

Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS), South Korea, is now operating SRF test facility in Sindong, Daejeon. Sindong SRF test facility has three vertical test pits and three horizontal test bunkers, 900W cryogenic system, RF power system, and radiation protection system. This paper explains about detail procedures of constructing cryostats and top flanges for the vertical test of RISP, Installed cryostats and top flanges have insulation vacuum layer, magnetic and thermal shield, 4K/2K reservoir, heat exchanger, cryogenic valves for supplying liquid helium, vacuum lines, and electrical instrumentations for the superconducting cavity tests.

INTRODUCTION

RISP is making and installing many devices such as ion source, superconducting (SC) linac, low and high energy experimental systems, cryogenic systems, RF powers and control system for RAON since 2012 [1]. And for the vertical test (VT) of SC cavity, RISP constructed and operated Munji SRF test facility from 2016 and larger SRF test facility at Sindong site from 2018. VT for SC cavity should be proceeded under same conditions as cryomodule such as 4K and 2K liquid helium (LHe) supply, thermal/magnetic shielding and ultra-high vacuum (UHV). This paper explains about whole process of constructing cryostat and top flange from design to installation.

CRYOSTAT AND TOP FLANGE DESIGN

Previous cryostat and top flange were conventional type, shown as figure 1 and 2, which had liquid nitrogen reservoir inside of cryostat walls for pre-cooling and thermal insulation and LHe reservoir at the cryostat inside. LHe reservoir was sealed with top flange so that UHV conditions was maintained, and LHe was filled within this reservoir so that SC cavity temperature was decreased to 4K/2K. Electrical instrumentation was connected through top flange feedthrough and magnetic shield was installed inside LHe reservoir. However, previous cryostat and top flange have a large heat load for cooling and warm-up because LHe reservoir was too large so that we should supply so much LHe for VT. Also, RISP should increase the VT capability for satisfying test and tunnel installation schedules. To increase the VT capability at Sindong SRF site, RISP decided to make a new

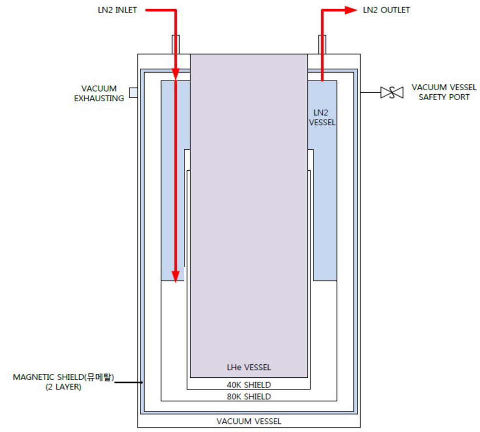

Figure 1: Conventional Cryostat PnID.

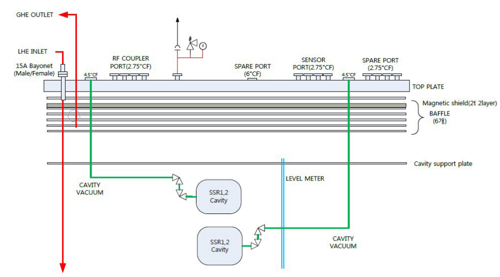

Figure 2: Conventional Top Flange PnID.

cryostats and top flanges which has similar cooling scheme with cryomodule and larger test capability, capable of 3 cavities simultaneously tested for QWR/HWR and 2 cavities for SSR1/2. Figures 3 and 4 shows the piping and instrumentation diagram (PnID) of newly designed cryostat and top flange for Sindong SRF site. Inner diameter of cryostat is increased up to 1200mm for installation three QWR/HWR cavities and two SSR1/2 cavities. And to decrease LHe supply, we decided to proceed VT with dressed cavity so that LHe is supplied only inside of LHe jacket. Following this decision, top flange design is changed almost same as cryomodule. LHe supply is controlled by cryogenic valves, supply and return lines are connected directly to LHe jacket so that the total LHe quantity is reduced. And likewise cryomodule, 4K/2K LHe reservoirs, heat exchanger and another cryogenic valve are installed inside of top flange for maintaining LHe level and stabilizing LHe pressure.

For increasing inner volume of cryostat and reducing heat load, liquid nitrogen (LN2) reservoir is substituted with thermal shield of cryostat. With this modifications, RISP con-

* Work supported by Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS) which is funded by the Ministry of Science and ICT, Republic of Korea
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFAV004

Solenoid Automatic Turn-On and Degaussing for FRIB Cryomodules*

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Abstract

The superconducting driver linac for the Facility for Rare Isotope Beams (FRIB) will accelerate heavy ions to 200 MeV per nucleon. The linac includes 46 SRF cryomodules, with a total of 69 solenoid packages for beam focusing and steering. For efficient beam commissioning and future operation, all of the solenoids must be turned on and reach a stable operating condition in a short time. Additionally, when a warm-up of the cryomodules is needed, degaussing of the solenoid packages is needed to minimize the residual magnetic field in the SRF cavities. An automatic turn-on and degaussing program had been implemented for FRIB cryomodules to meet these requirements. This paper will describe the design, development, and implementation of the automated solenoid control program.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac has 69 solenoid packages be installed. There are 6 length=250 mm solenoid packages are installed in three 0.041 cryomodules; 63 length=500 mm solenoid packages are installed in eleven 0.085 cryomodules, twelve 0.29 cryomodules and eighteen 0.53 cryomodules. Table 1 shows parameters of these solenoid packages [1].

Table 1: FRIB Cryomodule Solenoid Package Parameter

	Aperture	Solenoid integrated square strength	Length	Maximum magnetic field	Steering magnetic field	Steering integrated field strength	Solenoid Current	Steering Current
0.041 Cryomodule	40 mm	13.6 T^2m	250 mm	8 T	0.12 T	> 0.03 Tm	90 A	19 A
0.085, 0.29 and 0.53 Cryomodule	40 mm	28.2 T^2m	500 mm	8 T	0.12 T	> 0.06 Tm	90 A	19 A

When the solenoid package is turned-on and ramp-up to a high current level, the lead can temperature and lead voltages of the solenoid and steering dipoles will go up. The lead voltage has a high limit interlock set-point which can interlock the power supply. To keep the lead voltage not reached the limit, there is a flow cold helium gas out from the cryomodule 4 K header that can cool-down the lead and make the lead can temperature drop then the lead voltages will drop too. The cooling gas flow rate can be controlled by the lead flow valve opening degree. Once all lead voltages drop to a reasonable range, the lead flow valve control will keep the lead temperature not drop too much that can avoid the lead get frozen. Since all lead valve PID control parameters are already optimized during the solenoid commissioning, they don't need to be adjusted every time. Just if there is any instability happen, PID parameters will be adjusted again and some relevant changes will be investigated further. So to make sure the lead valve control is still good, the stability check in a short time for lead can temperature and lead voltages is important during the solenoid turn-on. For efficient beam commissioning and future operation, fast turn-on all 69 solenoids and automatic stability check is necessary.

Before the cryomodule warm-up, degaussing of the solenoid packages is needed to minimize the residual magnetic field in the SRF cavities [2]. The degaussing procedure requires the solenoid and steering dipoles ramp-up to maximum current first, then next each cycle ramp-down by 25% with opposite current polarity until the current go down to zero [2]. The solenoid maximum current is 90 A, with each degaussing cycle current decreased, there are at least 20 cycle times to ramp-done the current below 0.5 A. To implement the degaussing procedure, an automatic ramping check and setting is required.

To achieve these necessary requirements, an automatic program had been developed. Fast turn-on all solenoid packages and automated degaussing ramping control had been implemented on all solenoid packages of FRIB linac.

AUTOMATIC CONTROL STATE MACHINE

The solenoid package automatic control program is include two part: 1) auto turn-on, 2) degaussing. The structure for both parts are similar, main control logic is based on a state machine with 5 state: idle waiting, power supply turn-on, load set-point, ramp to set-point/status check and error. Figure 1 shows state-chart for these two parts logic.

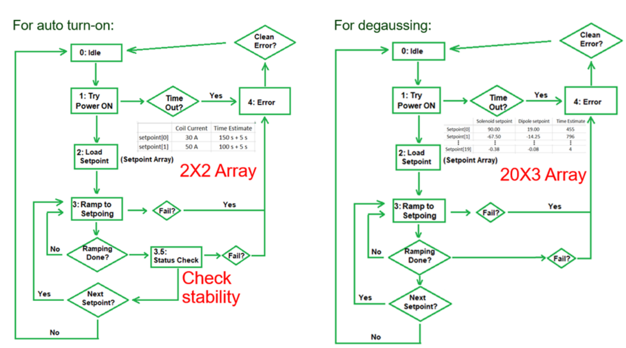

Figure 1: Solenoid auto turn-on and degaussing state-chart.

Left state-chart is auto turn-on procedure state machine. State "0" idle will do nothing but waiting for start. State change from "0" to "1" will try turn on the power supply of the solenoid package. Then go to state "2" that will load current set-point array. For auto turn-on, there are only two current set-points: 30 A and 50 A. State go "3" that will ramp solenoid current until it gets the set-point. State "3.5"

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFAV005

LCSL-II CRYOMODULE TESTING AT FERMILAB*

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Abstract

Cold powered testing of all LCLS-II production cryomodules at Fermilab is complete as of February 2021. A total of twenty-five tests on both 1.3 GHz and 3.9 GHz cryomodules were conducted over a nearly five-year time span beginning in the summer of 2016. During this campaign cutting-edge results for cavity Q0 and gradient in continuous wave operation were achieved. A summary of all test results will be presented, with a comparison to established acceptance criteria, as well as overall test stand statistics and lessons learned.

INTRODUCTION

LCLS-II is a next generation hard x-ray light source based on a superconducting RF electron linac operating in continuous wave regime. Its status is described elsewhere at this conference [1].

The LCLS-II cryomodule (CM) design is cutting edge in terms of continuous wave (CW) operating gradient and Q0. The design work and techniques to achieve such performance is described previously [2].

The scope of this paper focuses on test results only for Fermilab-built cryomodules and is an update to results shared at the most recent SRF conference [3].

TEST RESULTS

Every cryomodule tested was measured against a predetermined set of acceptance criteria adopted by the LCLS-II project and its partners [4,5]. With few exceptions these criteria were met and usually exceeded. Deviation were documented in testing travelers and communicated to the oversight team. Following the end of a CM's test results were shared, discussed, and room temperature warm-up and removal steps were not undertaken without this review and subsequent go-ahead. Only in rare circumstances were extended test runs undertaken.

1.3 GHz

Twenty-two cold tests of 1.3 GHz cryomodules for LCLS-II were conducted at CMTS1. Since the previous report in 2019, an additional four tests were conducted – two remaining production devices and re-test of two rebuilt ones. Figure 1 summarizes the gradient performance of all cryomodules while Fig. 2 shows the average Q0 for each 8-cavity cryomodule; Q0 was measured for each cavity singly. As these data indicate, performance in all respects exceeded specification.

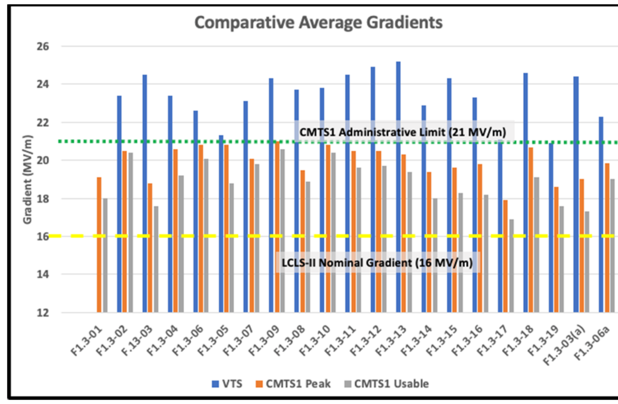

Figure 1: 1.3 GHz gradient summary.

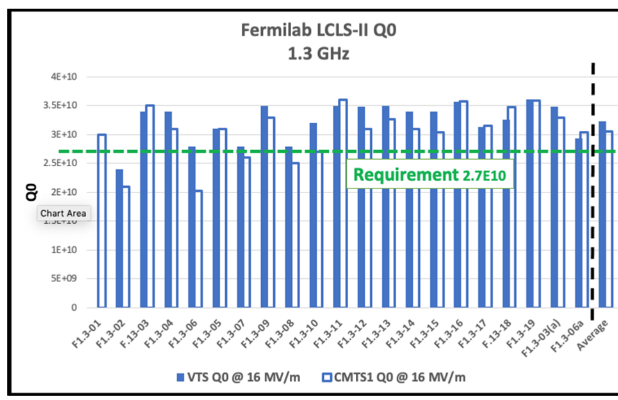

Figure 2: 1.3 GHz Q0 summary.

3.9 GHz

Three 'F3.9' series cryomodules were built for LCSL-II. Two are considered operational units and the third a spare. These proved to perform well above specification like the 1.3 GHz models as noted in Fig. 3 (gradient) and Fig. 4 (Q0).

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Work supported, in part, by the US DOE and the LCLS-II Project.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFAV006

DEGRADATION AND RECOVERY OF THE LHC RF CRYOMODULE PERFORMANCE USING THE HELIUM PROCESSING TECHNIQUE

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Abstract

The LHC RF cryomodule "Asia" suffered an accidental influx of about 0.5 l of tunnel air during the leak checks of the pumping manifolds. The resulting risk of particle contamination was difficult to assess, and could not be excluded with certainty. If one or more cavities were contaminated, a severe impact on beam operations in the LHC machine was to be expected. In order to minimize the risks, the Asia cryomodule has been replaced with a spare unit. Subsequently, the cryomodule was tested in the SM18 test facility without intermediate venting, and showed high levels of radiation due to field emission above 1.8 MV in one of the cavities. The other cavities were less strongly affected, but clear signs of contamination were observed. The helium processing technique was used to improve the performance of the SRF cavity with respect to field emission. This paper will discuss the results of the above-mentioned test.

INTRODUCTION

The RF section of the machine with a length of approximately 30 m consists of two cryomodules per beam, see Fig. 1.

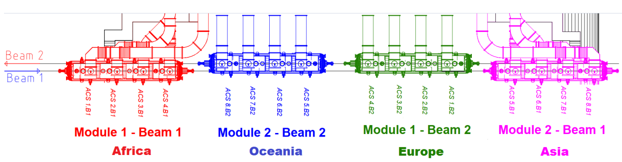

Figure 1: Layout and naming convention of the RF section in the LHC machine as at 31 August 2019.

Each cryomodule contains four single-cell niobium sputtered 400.8 MHz superconducting cavities working at 4.5 K and an average accelerating voltage of 2 MV per cavity. Each cavity is driven by a 300 kW klystron via a variable power coupler, according to the different requirements at injection and at top energy, together with a heavy beam loading. For damping of higher-order-modes (HOMs), four couplers of two different types are used. The narrow-band coupler covers the first two dipole modes at 500 and 536 MHz and the broad-band coupler covers the range from 700 MHz to 1300 MHz. The LHC niobium-coated cavities are almost insensitive to the Earth's magnetic field, therefore no magnetic shielding is installed inside the cryomodules. The cryomodule has three different and independent vacuum systems: for cavity, secondary beam and cryostat insulation. The cavity vacuum is pumped at room temperature by two 60 l/s ion pumps mounted at each extremity of the cryomodule. The cavity vacuum can be isolated by the gate valves at the ends of each module, to maintain a vacuum during transportation and installation. Due to the size of the beam separation, the second beam tube must pass through the insulation vacuum of the cryostat to allow the beam to pass in the opposite direction [1, 2].

The inner structure of the LHC RF cryomodule is shown in Fig. 2.

LONG SHUTDOWN 2

The currently ongoing long shutdown, LS2, is dedicated to preparations for Run III of the LHC machine, which will achieve an integrated luminosity equal to the two previous runs combined [3]. During this technical break, the LHC RF cryomodules also underwent consolidation works, one of which was to carry out leak checks of the pumping manifolds. These pumping manifolds had been designed for the Large Electron-Positron Collider (LEP) and they were recycled for the needs of the LHC. Since in previous years a corrosion process was observed on one of the pumping manifolds, which caused a vacuum leak, it was decided to visually inspect and leak check all pumping crosses in the LHC tunnel [4].

During the aforementioned leak checks in the LHC, the RF cryomodule M2B1 (Asia) suffered an accidental influx of about 0.5 l of tunnel air, giving a pressure spike of 0.65 mbar. The situation was carefully analysed and it was decided that, in order to minimise the risks, the cryomodule had to be replaced with the operational spare unit (America). It should be noted that the aforementioned accidental venting took place on the pumping cross near the cavity A [5].

Replacement of the Cryomodule

Removal of the possibly defective Asia cryomodule and installation of the spare America cryomodule was agreed and planned in accordance with the LS2 master plan. The operation started in October 2019 and it was completed 10 weeks later. The transportation is associated with a significant risk: any damage to the coupler ceramics can lead to a vacuum failure and, consequently, catastrophic dust contamination of the niobium surface of the cavities. This would require complete disassembly of the module in order to rinse and retest the cavities, and that could delay the restart of the LHC machine for several months [4]. Therefore, the America cromodule was safely transported to the LHC machine prior to start of Asia cryomodule removal. After disconnecting the

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV001

STATUS OF THE NEW QUADRUPOLE RESONATOR FOR SRF R&D

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Abstract

A basic understanding of the properties of SRF samples after being exposed to surface treatments will aid in the development of consistent theories. To study the RF properties of such samples under realistic superconducting-cavity-like conditions, a test device called Quadrupole Resonator (QPR) was fabricated. In this publication we report the status of the QPR as a joint project of Universität Hamburg and DESY. Our device is based on the QPRs operated at CERN [1] and at Helmholtz-Zentrum Berlin (HZB) [2]. Its design will allow for characterizing samples at temperatures between 2 K and 8 K, under magnetic fields up to 120 mT and with operating frequencies of 433 MHz, 866 MHz and 1300 MHz. Fabrication tolerance studies on the electromagnetic field distributions and simulations of the static detuning of the device, together with the commissioning report and the ongoing surface treatment, will be presented here.

INTRODUCTION

Niobium (Nb) is the material of choice for the construction of superconducting radio frequency (SRF) cavities in modern particle accelerators. Since the accelerating fields in these SRF cavities are reaching their theoretical limit, materials such as Nb_3Sn [3,4], multilayer structures (SIS) [5], and treatments like N-doping [6], N-infusion [7] and mid-T bake [8] of bulk Nb cavities have been shown to increase quality factors and the maximum fields they can achieve. However, further research is required before cavities made of these materials can be used to equip complete accelerators. An improved version of a sample characterization device called Quadrupole Resonator (QPR), originally developed and operated at CERN and HZB, has been further developed and built in a cooperation between Universität Hamburg and DESY. The measurement capabilities of the QPR will be discussed in the following sections.

THE QUADRUPOLE RESONATOR

The Quadrupole Resonator was developed at CERN in 1998 [9]. In the mid-2010s, the results of an optimized QPR were reported by Helmholtz-Zentrum Berlin [10]. A redesign of the CERN QPR was announced in 2017 [11] and new results were reported in 2019 [12]. In a collaboration between Universität Hamburg and DESY and Universität Rostock [13], an improved version of the resonator has been further developed and recently built. SRF sample properties will be measured with this device in the parameter space defined by the resonance frequency f, LHe bath temperature T, and applied magnetic field B. It will allow for systematic investigations of the sample's surface resistance R_s, critical magnetic field H_c, and superheating magnetic field H_{sh}. The previously mentioned data make it possible to determine the following material properties: London penetration depth λ_L, mean free path ℓ, critical temperature T_c, and the superconducting gap Δ.

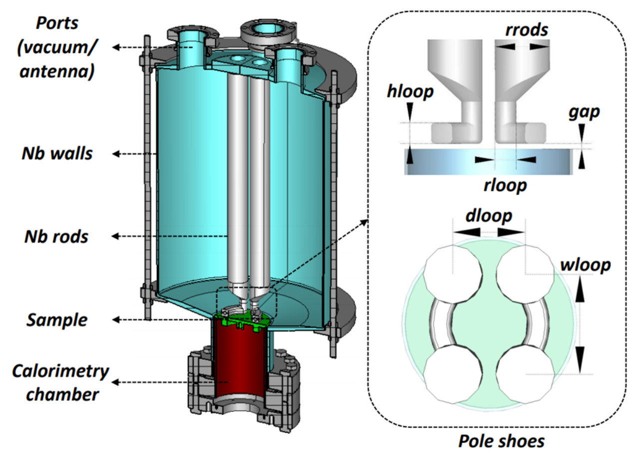

Figure 1: Cross-sectional view of a QPR (left) with the parametrized model of the pole shoes (right) [14].

The basic functionality of the QPR (Fig. 1) is as follows. RF fields enter the test cavity through the input antenna, which is situated in one of the ports on the top of the device. These fields resonate in the walls producing monopole-, dipole-, or quadrupole-like mode distributions of the electromagnetic field. The pole loops, formed by the rods and pole shoes, are employed to focus the magnetic field onto the sample surface, which reaches its maximum when only a quadrupole mode (operational mode) is excited. A probe antenna measures the energy of the RF field stored in the QPR, and this information is later used together with a calorimetric technique (Fig. 2) to determine the surface resistance of the sample [1,2].

The QPR has the following operational range specifications: temperatures between 1.5 K and 8 K, maximum applied field on sample $H_{sample,max}$ up to 120 mT, and the

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV002

THE INFLUENCE OF THE IRRADIATION ON THE CURRENT CARRYING PHENOMENA IN HTc MULTILAYERED SUPERCONDUCTORS

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Abstract

In the paper is theoretically investigated the influence of the irradiation arising during the work of SRF accelerators, on the current carrying phenomena appearing at HTc multilayered superconductors. The impact of the concentration and size of created then nano-defects, acting as pinning centers capturing the vortices is considered. The influence of the physical parameters such as magnetic field and temperature on the critical current is regarded too. The critical current analysis is applied then to investigations of the losses generated in the superconducting current leads to the accelerator's electromagnets.

INTRODUCTION

Proper work of the modern accelerators containing the superconducting elements as windings of coils or cover of the resonating cavities, as well as current leads to electromagnets is dependent on the superconducting materials parameters, especially their critical current [1]. These materials, such as multilayered HTc superconductors are however very delicate structures sensitive to mechanical defects introduced for instance by the bending strain [2] during the coil winding procedure. Defects are created too during the work of RF accelerators, as built in Poland PolFEL, which generate then irradiation, including fast neutrons arising as the result of fall RF-waves on the accelerator walls. To the analysis of the influence nano-defects on the current carrying phenomena is devoted just present paper. Research will be performed basing on elaborated model of the interaction pancake vortices specific for multilayered superconductors with pinning centers created just during irradiation process. The results of critical current analysis will be useful for determining then the electromagnetic losses generated in the superconducting current leads to electromagnets. Therefore considered here issue of the influence of irradiation on the properties of these fragile HTc superconducting materials is very important from pure scientific as well as technical point of view.

INFLUENCE OF IRRADIATION ON JC

The influence of the nano-sized defects created especially by the RF irradiation and in secondary way through fast neutrons striking the HTc superconductors was analysed basing on the general equation [2, 3]:

$$F(r_1,..,r_N) = \sum_{i=1}^{N} U(r_i) + \frac{1}{2}\sum_{i\neq j}^{N} F_{inter}(r_i - r_j) - J\emptyset_0 \sum_{i=1}^{N}(l_i - r_i) - \sum_{i=1}^{N} \frac{C(r_i-\xi)^2}{2} V_i \quad (1)$$

Equation (1) describes the energy of N magnetic pancake vortices, specific for layered superconductors, captured on the pinning centers at positions $r_1,..r_N$. U is pinning potential of the captured pancake vortices, while summation runs over N captured magnetic vortices, each of them is transporting quantized magnetic flux $\Phi_0 = 2.07\cdot10^{-15}$ Wb. Second expression in Eq. (1) describes the contribution to system energy connected with inter-vortex interaction, while third term is connected with Lorentz force. J is here electric current density, while last part in Eq. (1) describes the increase of the elasticity energy of the vortex lattice during the shift of the vortex from equilibrium position at the process of the magnetic flux capturing. V_i describes connected with this deformation volume, while C is spring constant of the vortices lattice. The geometry of the full capturing of the pancake vortex of the cross-section core area S, on cuboid pinning center of the width d is shown in Fig. 1. In the present paper it has been considered the individual vortex – pinning center interaction, it is neglecting the inter-vortex interaction term. Shift of this vortex from the equilibrium initial position shown in Fig. 1, is connected with Lorentz force induced by current flow, tearing off the vortices and leads to the enhancement of system energy. As the result of this movement the potential barrier arises, which maximal value ΔU appears for the shift of vortex onto distance x_m and is described then by the relation:

$$\Delta U(x_m) = \frac{\mu_0 H_c^2}{2} l\xi^2 \left(arcsin\frac{x_m}{\xi} - \frac{\pi}{2} + arcsin\left(\frac{d}{2\xi}\right) + \frac{x_m}{\xi}\sqrt{1-\left(\frac{x_m}{\xi}\right)^2} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} \right) - JB\pi\xi^2 l x_m \quad (2)$$

In Eq. (2) valid for the case of the half captured initially pancake type vortices H_c is thermodynamic critical magnetic field, μ_0 magnetic permeability of the vacuum, while l the thickness of the superconducting layer. x_m as it was mentioned before is value of the shift of the vortex against equilibrium position inside the defect onto the distance for which potential barrier reaches the maximum. It arises therefore the energy barrier, which should cross vortex during the flux creep process. In Fig. 1 is shown the geometry of the cross-section of the fully captured vortex inside the nano-sized defect. The radius of the vortex core shown in Fig. 1 is equal to the coherence length ξ. Enhancement of the current in static magnetic field B leads to the increase of the Lorentz force term in Eq. (1), tearing off the vortices from the initial equilibrium position and decreases in this way the potential barrier *ΔU*. This effect is well seen, if to

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV003

SIMS INVESTIGATION OF FURNACE-BAKED Nb

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Abstract

Impurity-alloying SRF cavities via thermal diffusion has yielded highly efficient Nb resonators. Recently, SRF cavities vacuum heat treated at 300 – 400 °C for a few hours have exhibited high quality factors and behavior typical of alloyed cavities. Using secondary ion mass spectrometry, we investigated the interstitial concentration of carbon, nitrogen, and oxygen in niobium prepared by this method. Our investigation shows that oxygen is likely the primary diffusant in such recipes and is well-described by Ciovati's model for native niobium oxide dissolution and oxygen diffusion.

INTRODUCTION

Recently, Ito [1] explored vacuum heat treating Nb SRF cavities between 200 °C and 800 °C. After vacuum heat treating the cavities for 3 hours in the temperature range of 300 °C to 400 °C, their RF tests showed a pronounced "anti-Q-slope" (decreasing surface resistance with increasing field), extremely high quality factors, and reduced quench fields, which are all typical qualities previously associated with nitrogen-alloyed Nb cavities. In Ito's work, oxygen diffusion from the native Nb oxide was assumed to be the alloying mechanism. Recent works performed at Fermi National Accelerator Laboratory (FNAL) are extremely similar to the vacuum heat treatments of Ito where cavities were first vacuum heat-treated, in some cases exposed to nitrogen, and RF tested without exposure to atmosphere [2, 3]. FNAL's time-of-flight secondary ion mass spectrometry (TOF-SIMS) measurements observed Nb_2O_5 dissolution and a qualitative increase in nitrogen concentration near the surface ~10 nm deep. From these observations it was assumed that nitrogen was the primary alloying diffusant. In both works, the cavities did not require the injection of gases or post heat treatment chemistry to yield the high quality factors.

Our recent SIMS investigation [4] found elevated oxygen content near the surface of samples prepared in the similar way as Ito [1]. RF measurements of a Nb SRF cavity prepared via vacuum heat treatment at 300 °C and subsequently electropolished 180 nm to exclude any ingress of C and N demonstrated that the enhancement in quality factor is mainly due to interstitial oxygen alloying via a thermal diffusion process. The measurements made in [4] found that the thermal diffusion process was consistent with Ciovati's model [5] of Nb_2O_5 dissolution and oxygen diffusion.

EXPERIMENTAL

Nb samples were prepared following a similar process to Ito [1]. Samples were cut from Tokyo Denkai ASTM 6 Nb stock procured using the XFEL/007 specification. First the stock was vacuum annealed at 900 °C to promote grain growth following the same procedure as the 1.3 GHz single-cell cavity, SC-11 used for RF validation. Samples were first nano-polished (NP) by a vendor to provide sufficiently flat samples for SIMS measurements. After the nano-polish, the samples underwent a 600°C/10hr heat-treatment to remove hydrogen introduced by the mechanical polishing. Subsequently samples underwent a 20 µm cold electropolish with the typical HF/H_2SO_4 solution [6]. During each heat treatment, samples were housed in a double-walled Nb foil container to minimize any furnace contamination [7]. To investigate the parameter space of the diffusion process, samples were baked for various times and temperatures.

A CAMECA 7f Geo magnetic sector SIMS instrument was used to acquire dynamic SIMS measurements. The primary ion beam is comprised of Cs^+ ions with an impact energy of 8 keV. The ion beam is rastered over a 150 ↘m × 150 ↘m area with a data collection area of 63 ↘m × 63 ↘m centered inside the larger raster. Quantitation of the SIMS depth profiles was performed using implant standards [8]. The implant standards used here were dosed with C, N and O at 2×10^{15} atoms/cm^2 at 135 keV, 160 keV and 180 keV, respectively by Leonard Kroko Inc.

Shallow depth profiles found expected background concentrations [9] of C and N, but a large enhancement in oxygen content as shown in Fig. 1. Any ingress of C or N was minor in samples vacuum heat treated at 350 °C for 2.7 hours. In a process of vacuum heat treating Nb without a gaseous oxygen source, the ingress of oxygen is due to oxygen dissolution from the 3-6 nm thick native pentoxide rather than from oxygen pickup from the furnace environment [10-12].An SRF cavity, SC-11, was subjected to a vacuum heat treatment at 320 °C for 1 hour using furnace caps [7] to confirm the effects of O alloying. Afterward, the heat treatment, the cavity underwent a high pressure rinsed before assembly for RF testing. RF measurements for SC-11 are shown in Fig. 2. Prior to O alloying, the cavity was high field Q slope limited. After the O alloying the cavity exhibited a pronounced "anti-Q-slope" with a maximum Q_0 of 4.6×10^{10} at 16 MV/m and

* Work supported by U.S. DOE Contract No. DE-AC05-06OR23177 and grant DE-SC0018918
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20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV005

SUPERCONDUCTING RF PERFORMANCE OF CORNELL 500MHz N-DOPED B-CELL SRF CAVITY*

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Abstract

The Cornell SRF group is working on rebuilding a 500MHz B-cell cryomodule (CRYO-2 BB1-5) as a spared cryomodule for operation of the CESR ring. To minimize BCS surface resistance, achieve a high quality-factor (Q_0), and increase maximum fields, we prepared the cavity's surface with electropolishing and performed a 2/6 N_2-doping. In this work, we report 4.2K and 2K cavity test results with detailed surface resistance analysis, showing improved performance, including significant higher fields.

INTRODUCTION

The CESR storage ring at Cornell University is now used as an X-ray source for a state-of-the-art X-ray facility, and includes four 500MHz B-cell cryomodules. During CESR operation, the cavity of the cryomodule CRYO-2 BB1-5 was damaged and the cavity cell had to be replaced. The cavity was originally built in 1999 [1]. The rebuild of this cavity and cryomodule now offered the opportunity to prepare the repaired cavity with cutting-edge SRF treatments to achieve higher RF performance. N_2-doping, which introduces a low level of impurity into the cavity surface to shorten the mean free path (MFP) and lower BCS resistance, had been shown in practice as an effective way to increase the quality-factor (Q_0) of a SRF cavity [2, 3]. Therefore, N_2-doping was selected for this project.

CAVITY TREATMENTS

The new cavity cell was fabricated by Research Instruments (RI) with the high-pure Nb (RRR=300) provided by Cornell University. After receiving the cavity back from RI, it was buffered chemical polished (BCP) for 32µm, followed by ~100µm electropolishing (EP) on both cavity body and waveguide. In total, the bulk surface removal was ~140µm, which is sufficient to remove surface contamination from the fabrication. Pictures from the BCP and EP of the cavity are shown in Fig. 1 and Fig. 2 respectively.

The cavity then received a 3 hour, 800ºC vacuum bake to degas H_2. Right after the vacuum bake, 2/6 N_2-doping [4] was performed in the furnace, in which the cavity was doped under ~30 mTorr N_2 atmosphere for 2 minutes, then annealed under vacuum for 6 minutes, and then cooldown to room temperature. When the N_2-doping was completed, 5µm surface removal by EP was carried out.

Figure 1: Photograph of Cornell B-cell BCP.

Figure 2: Photograph of the EP of the Cornell B-cell cavity.

The cavity then received a 3 hour, 800ºC vacuum bake to degas H_2. Right after the vacuum bake, 2/6 N_2-doping [4] was performed in the furnace, in which the cavity was doped under ~30 mTorr N_2 atmosphere for 2 minutes, then annealed under vacuum for 6 minutes, and then cooldown to room temperature. When the N_2-doping was completed, 5µm surface removal by EP was carried out. Figure 3 shows the Cornell vacuum furnace with the B-cell cavity placed inside.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV006

SEEBECK COEFFICIENT MEASUREMENT AT CRYOGENIC TEMPERATURES FOR THE LCLS-II HE PROJECT*

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Abstract

Reducing thermoelectric currents during cooldown is important to maintain high quality factors (Q_0) of the cavities in the LCLS-II HE cryomodules. The temperature-dependent Seebeck coefficients of the materials used in the cryomodules are needed for quantitative estimation of thermoelectric currents. In this work, we present a setup for cryogenic Seebeck coefficient measurements as well as the measured Seebeck coefficients of high-pure niobium at cryogenic temperatures between 4K and 200K.

INTRODUCTION

LCLS-II will be the first CW X-ray FEL based on 4 GeV CW superconducting linac. The energy upgrade program which is referred as the LCLS-II HE will increase the beam energy to 8 GeV. The empty space in the SLAC tunnel allows to install 20 additional cryomodules in which SRF cavities operate at an average quality factor $Q_0 \approx 2.7\times10^{10}$ and accelerating gradient $E_{acc} \approx 19.4$ MV/m without exceeding the cryoplant capacity [1]. To achieve such high-Q_0 at 2K, the SRF cavities were treated by a nitrogen-doping based recipe, which in turn causes a high sensitivity to additional RF dissipation from trapped magnetic vortices resulting from ambient magnetic fields in the cryomodules during cooldown. Therefore, reducing thermoelectric currents and resulting magnetic fields generated during cooldown is important to maintain high-Q_0 of the cavities in the LCLS-II HE cryomodules. The temperature-dependent Seebeck coefficient of the materials used in the cryomodules is the key parameter in thermoelectric current estimation.

EXPERIMENT SETUP

Seebeck Coefficient

The thermoelectric effect is a phenomenon in which a voltage V between two ends of an electrical conductor/semiconductor is created by a temperature different between them. It can be described by Eq. (1),

$$V = -\int_{T_2}^{T_1} S(T)\,dT. \tag{1}$$

where $S(T)$ is temperature-dependent Seebeck coefficient, T_1 and T_2 are the temperatures of two ends of a metal respectively. In a measurement, a dissimilar metal (metal B) is used as leads to connect the two ends of a sample (metal A) to extract voltage crossing the sample, as is shown in Fig. 1. In this scenario, the Seebeck effect of the two metals has to be considered, which is shown in Eq. (2),

$$\begin{aligned} V &= -\int_{T_0}^{T_1} S_b(T)\,dT - \int_{T_1}^{T_2} S_a(T)dT \\ &\qquad - \int_{T_2}^{T_0} S_b(T)dT \\ &= \int_{T_1}^{T_2} S_b(T) - \int_{T_1}^{T_2} S_a(T)dT \\ &= \int_{T_1}^{T_2} [S_b(T) - S_a(T)]dT, \end{aligned} \tag{2}$$

where S_a is the Seebeck coefficient of the sample to be measured and S_b is the Seebeck coefficient of the reference leads.

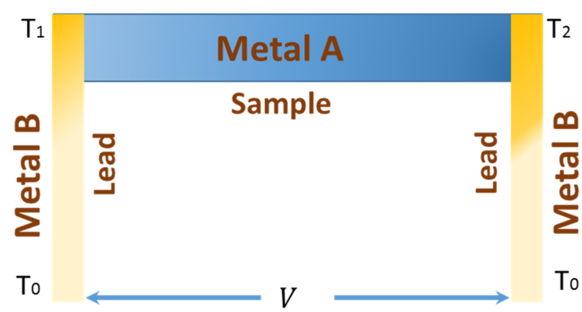

Figure 1: Sketch of the Seebeck effect of two dissimilar metals A and B at temperatures T_1 and T_2 at their contacts.

The differential method of approximating Eq. (2) is described in [2], from which the Seebeck coefficient of the sample can be written as Eq. 3,

$$S_a(T_{ave}) = -\frac{V}{\Delta T} + S_b(T_{ave}). \tag{3}$$

where $T_{ave} = \frac{1}{2}(T_1 + T_2)$, and $\Delta T = T_2 - T_1$. Since the temperature range of the measurements is 4K-200K, we choose lead (Pb) as the reference wire material (metal B). The Seebeck coefficient of high-pure lead (Pb) in the temperature range 4K-200K can be found in [3].

Experiment Setup

A 1.8W 2.8K Cryocooler (Model: CRYOMECH PT420) was employed for the setup, in which helium is circulated between the compressor and the cold head for cooldown. Figure 2 A) shows a 3D CAD model of the copper base of the experimental setup bolted to the cryocooler cold head that cools down the whole setup when the cryocooler is running. Figure 2 B) depicts the detailed view of the CAD model of the setup, which referenced the design from [4].

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPFDV008

RESEARCH ON CERAMIC FOR RF WINDOW

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Abstract

Kyocera and KEK have started joint research on the development of materials that satisfy the required characteristics as RF window material. In this report, the characteristics of the new material AO479U were evaluated by comparing it with other materials, including the presence or absence of Titanium-Nitride (TiN) coating. In order to clarify the influence of materials or its manufacturing processes on heat generation and multipactor discharge generated in RF windows, we measured important characteristics as RF window material (relative permittivity, dielectric loss tangent, surface resistivity, volume resistivity, secondary electron emission coefficient, and TiN thickness), and investigated their correlation.

INTRODUCTION

When accelerating charged particles in an accelerator, an alumina ceramic window is used as a partition of a waveguide to put microwaves generated in klystron into accelerating cavity. In previous studies, the alumina material AO479B had been developed for RF window material, and it has been applied to some products, however, AO479B has a size limitation. Recently, large RF windows is required from the market. Therefore, we have developed a new material AO479U which can be designed regardless of the product size. As required characteristics of the RF window, there are dielectric loss tangent (tan δ) and secondary electron emission coefficient (δ_{SEE}). Low tanδ is required to suppress heat generation in high power RF operation. Low δ_{SEE} is also required to suppress multipactor discharge on the ceramic surface. In addition, relative permittivity (ε), surface resistivity (ρ_s), and volume resistivity (ρ_v) were also measured.

RESEARCH ON SECONDARY ELECTRON EMISSION COEFFICIENT

The secondary electron emission coefficient on ceramic surface is the most important parameter to be evaluated by the effect of multipactor discharge in high power RF operation. A scanning electron microscope (SEM) with beam blanking system which can generate a pulse beam was installed at KEK for δ_{SEE} measurement in 2018. Since Alumina is an insulator material, it essentially uses a pulse beam to avoid charge-up on the ceramic surface. The specifications of this measurement system are described in these references [1, 2]. Table 1 shows four types of ceramic samples with different manufacturing processes. The coating was conducted by Company A (TiN A) and Company B (TiN B), respectively. The heat treatment (HT) was carried out under the same conditions as the brazing process for the accelerator manufacturing conducting at 1000 °C and 800 °C in the furnace of Canon Electron Tubes & Devices Co., Ltd. (CETD). Figure 1 shows the ceramic samples with diameter of 19 mm, without coating samples and with two different TiN coating samples. The samples for δ_{SEE} evaluation were prepared by a process equivalent to the accelerator cavity manufacturing process conditions, and the effects of δ_{SEE} were investigated under various additional process conditions. The charge of ceramic samples were measured using an electrometer, and all the samples were charged to several volts after measured the δ_{SEE}. Figure 2 shows summary of secondary electron emission coefficient for ceramic samples without TiN coatings, and Fig. 3 shows that with TiN coatings. Figures 2 and 3 show the following results:

- The TiN coating significantly reduced the δ_{SEE}.
- The measured values tended to be unstable without ethanol ultrasonic rinsing (USR).
- The δ_{SEE} tended to increase in the samples with and without TiN coating after heat treatment.
- There was a difference in the δ_{SEE} of the sample by the TiN coating company.
- There was no significant difference between ethanol ultrasonic rinsing and ozonized (O_3) water rinsing.
- The δ_{SEE} varied depending on the material, however, was almost same regardless of the TiN coated material.

Table 1: Ceramic Sample List for δSEE Measurement

Material	Coating	Heat treatment (°C)	Rinsing	#
AO479U	Free	No	No/USR	1/2
AO479U	Free	1000	USR	3
AO479U	Free	800	USR	3
AO479U	Free	1000→800	USR	3
AO479U	Free	1000→800	O_3	3
AO479U	TiN A	No	USR	3
AO479U	TiN A	1000	No/USR	1/2
AO479U	TiN A	1000→800	No/USR	1/1
AO479U	TiN A	1000→800	O_3	1
AO479U	TiN B	No	USR	3
AO479B	Free	No	No/USR	1/2
AO479B	TiN A	No	No/USR	1/2
AO473A	Free	No	No/USR	1/1
AO473A	TiN A	No	USR	3
HA95	Free	No	USR	1
HA95	TiN A	No	USR	2

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV001

MODAL ANALYSIS AND VIBRATION TEST OF SINGLE SPOKE RESONATOR TYPE-1 (SSR1) FOR RAON*

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Abstract

Rare Isotope Science Project (RISP) is developing the single spoke resonator type-1 (SSR1) and type-2 (SSR2) for making superconducting linear accelerator 2 (SCL2). For optimizing of SSR1 and SSR2, we should research every aspects of superconducting cavity including RF performances and mechanical properties. This paper explains about modal analysis of SSR1 using FEM (finite element method) applying material properties of RRR300 niobium for bare cavity and STS316L for liquid helium jacket. Also, this paper shows the vibration test results with modal analysis.

INTRODUCTION

RISP SCL is divided with two sections, SCL3 from ISOL/ECR to low-energy experimental area and SCL2 from the end of SCL3 to high-energy experimental area [1]. Through prototyping, RISP also investigated the resonant frequency characteristics of SSR1 SC cavity due to outer disturbance. This paper explains about modal and harmonic response simulation of SSR1 SC cavity using ANSYS ver.2018, and compares analysis result with the vibration test of dressed SSR1 cavity done by lateral vibration machine.

SSR1 MECHANICAL DESIGN AND MANUFACTURED SC CAVITY

RF Design of SSR1 SC cavity was proceeded based on the contract with TRIUMF. After contract, SSR1 engineering drawing was released by 2016 [2–5] and prototype test was finished by 2019 [6]. Figure 1 shows the first prototype of SSR1 SC cavity, and Table 1 shows the SSR1 cavity design parameters. Based on this design, RISP modified RF shape and fabrication process, and the modified SSR1 SC cavity was fabricated and tested at the RISP Sindong SRF. Currently four dressed cavity has been made, one of them has finished the cold test and satisfied target Eacc and Q factor, and three cavities is now preparing for the cold test.

Figure 1: SSR1 SC Cavity Design.

Table 1: SSR1 Cavity Design Parameters

Parameters	Values	Units
Operating Frequency	325	MHz
Beta	0.3	-
Operating Temperature	2	K
Epeak/Eacc	<4.5	-
Bpeak/Eacc	<7	mT/(MV/m)
Vacc	2.5	MV
df/dP	<10	Hz/mbar
Beam Aperture	50	mm
Pressure Envelop 300 K	>2	bar
Pressure Envelop 5 K	>5	bar

SSR1 MODAL ANALYSIS

For the operation of SC cavity, the natural/resonant frequency should be clearly defined for analyzing the sensitivity of microphonics and LFD according to its resonant frequency. Defining the resonant frequency, the modal and harmonic response analysis of SSR1 SC cavity was proceeded with commercial program ANSYS 18.0 [7]. Figure 2 shows the mesh shape of SSR1 SC cavity. Automated tetrahedral mesh, which is approximately 520,000 elements, was used for FEM analysis. Materials of bare cavity and liquid helium jacket were applied high purity niobium and stainless steel 316L [8], and ANSYS workbench solvers were connected with structural, modal, and harmonic response. Modal analysis checked resonant frequency modes up to 25, and harmonic response drew the bode plot up to 1000 Hz

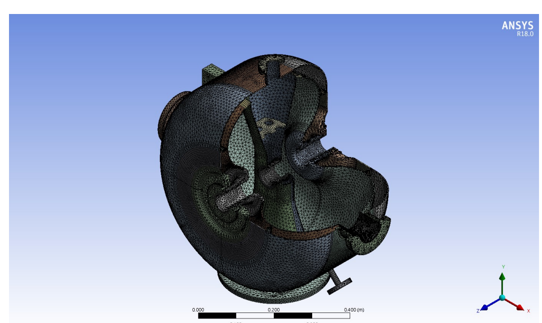

Figure 2: Mesh Shape of SSR1 Dressed Cavity.

* Work supported by Rare Isotope Science Project (RISP) in the Institute of Basic Science (IBS) which is funded by the Ministry of Science and ICT, Republic of Korea
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV002

LOW TEMPERATURE HEAT TREATMENT ON THE HWR CAVITY*

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Abstract

Institute for Basic Science have been constructing the superconducting LINAC, named RAON, composed of quarter-wave resonators (QWR) and half-wave resonators (HWR). All QWR cavities have been completely fabricated and successfully tested to be assembled in QWR cryomodules. For now, we have been testing HWR cavities over 50% of the total amount. For the testing period, a success rate experienced up and downs like we went through during the QWR tests. In many cases, we observed that some cavities did not reach requirement performance at 2K cryogenic temperature although they showed high performance at 4K. We increased the temperature of the heat treatment to cure the rapid Q drop at high gradient and observed most cavities passed the vertical tests after the heat treatment.

INTRODUCTION

Superconducting cavities have been tested to be installed in the low energy section of the linac, named RAON (it means 'delight' in Korean). This low energy section consists of two types of superconducting cavities, a quarter-wave resonator (QWR) and a half-wave resonator.

Total number of cryomodules needed for the low energy section are 22 of QWR cryomodules (1 QWR cavity per each cryomodule), 15 of type A HWR cryomodules (2 HWR cavities per each cryomodule), and 19 of type B HWR cryomodules (4 HWR cavities per each cryomodule). Thus, the total number of cavities to be installed for the low energy section are 22 QWRs and 106 HWRs, respectively.

All QWR cavities were fully tested and installed in the cryomodule last August, 2020. In the mean while, more than 50% of HWR cavities have been tested by the end of the 1st quarter of 2021 since the last August, 2020.

A domestic vendor (Vitzrotech Company) manufactured all HWR cavities and they performed a few critical surface treatment on the bare/jacketed cavities; chemical etching (BCP), high pressure rinsing, high temperature heat treatment [1] [2] [3] [4]. Typical conditions are summarized in Table 1. Surface-treated HWR cavities are delivered to IBS, and these cavities become ready to be tested by being carefully assembled through a vacuum system.

One of the important steps performed in IBS is "low temperature heat treatment on the cavity". It has been reported that the low temperature heat treatment not only saves the time needed for the RF cavity conditioning, but improves cavity performance at high electrical gradient by changing chemical compositions of the cavity surface. In this paper, vertical tests results of HWR cavities will be discussed, and furthermore, how cavity performance were cured by changing the heat treatment condition.

Table 1: Typical Surface Treatment for HWR Cavity

Surface Treatment	Values
BCP	$HF:HNO_3:H_3PO_4$=1:1:2
High Pressure Rinsing	Water pressure: 100 ~ 150 bar
High T. Heat treatment	650°C, 10 hrs
Low T. Heat treatment	Target temperature: 120°C

HEAT TREATMENT SETUP

A delivered cavity needs to be assembled/connected to vacuum system for the vertical test. Once the vacuum connection is over, cavities are heat-treated for 48 hrs in the test stand. Figure 1 shows the low temperature baking set up in the test stand.

During the baking, the cavity pressure remains under around 10^{-5} mbar, while the jacket is open at 1 atm. And because the cavity is connected to the jacket through only ports such as high pressure rinsing (HPR) ports and RF ports, the heat treatment is carried out mainly by a convection rather than conduction. Thus, the actual temperature of the cavities during the baking was not measured because it was difficult to directly measure the temperature of the outside/inside surface of the cavity.

The target temperature for low temperature baking in IBS was chosen 120°C because it has been reported that a cavity baked at this temperature shows good peformance. For this reason, the temperature of a heat controller is set 150°C by considering heat loss due to convection and surroundings for baking. The ramping speed of the controller is set 10°C/min. so that the cavity not to be contaminated by radical outgassing.

Q_0 with 150°C Setting

Vertical test results from two cavities are shown Fig. 2. Results were obtained from cavities of No.22 and No.38 out of 106 HWRs in total. In case of No. 22 HWR cavity, (a) of Fig. 2, it did not satisfy the requirement (2.3×10^9 at 6.6 MV/m of Eacc under 2K) at the 1st test. Similarly, No. 38 HWR cavity did not pass two times tests. Black and blue lines represent the results from the 1st test and 2nd test, respectively. For the 2nd test, another surface treatment

* This work was supported by the Rare Isotope Science Project of Institute for Basic Science funded by Ministry of Science and ICT and NRF of Korea 2013M7A1A1075764.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV003

IMPACT OF VERTICAL ELECTROPOLISHING WITH FLIPPING SYSTEM ON REMOVAL UNIFORMITY AND SURFACE STATE: STUDY WITH 9-CELL NIOBIUM COUPON CAVITY

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Abstract

We have been developing a vertical electropolishing (VEP) method for niobium superconducting RF cavities using a novel setup that allows periodic flipping of the cavity to put it upside down in the VEP process. The purpose of using the novel setup named as flipping system is to achieve uniform removal and smooth surface of the cavity. Previously, we have already introduced the VEP system and showed the preliminary results of VEP performed with the flipping system. In this article, we report VEP results obtained with a nine-cell coupon cavity. The results include detail on coupon currents with I-V curves for coupons, and impact of the cavity flipping on removal uniformity and surface morphology of the cavity.

INTRODUCTION

Marui Galvanizing Co., Ltd has been developing Niobium SRF cavity vertical electropolishing (VEP) technologies in collaboration with KEK. We developed new VEP methods of "2-flow VEP" and "cavity flipping VEP" with Ninja cathode so far. In case of 2-flow VEP, acceptable polished surface and accelerating gradient were achieved as the same level of horizontal electropolishing (HEP) [1]. In case of cavity flipping VEP, cavity removal uniformity was significantly improved, however IV curves and EP current of forward position and reverse position were different and polished surface was somewhat rough [2]. It is thought that the cause is the influence of EP temperature and inner hydrogen bubbles. To solve these problems, cavity flipping VEP experiment using 9cell coupon cavity with improved EP temperature and inner bubble status was performed and IV curves, EP condition, polished surface and removal uniformity were evaluated.

CAVITY FLIPPING VEP

Cavity flipping VEP was performed with dedicated cavity holder that can rotate around the central strut. Figure 1 shows a photo and a schematic of the cavity flipping VEP equipment, and Figure 2 shows a continuous photo of cavity flipping. It is defined that the case that a Ninja cathode rotation motor is at upper side is the forward position (F), at lower side is the reverse position (R). And it is defined that the cell close to the motor is the top (top cell (TC), top iris (TI) etc.), far from the motor is the bottom (bottom cell (BC), bottom iris (BI) etc.). Nb coupons were set at top iris position (TI), equator position (EQ) and bottom iris position (BI) of top cell (TC), center cell (CC) and bottom cell (BC), a total of 9 coupons were installed. Flipping was performed using semi-automatic motor drive. In this experiment, we modified the EP acid tank to improve the inner bubble status. This is to reduce the number of bubbles returning to the cavity during EP acid circulation by connecting a new tank to the conventional tank to increase the capacity and increasing the number of mesh filters. Figure 3 shows the modified EP acid tank.

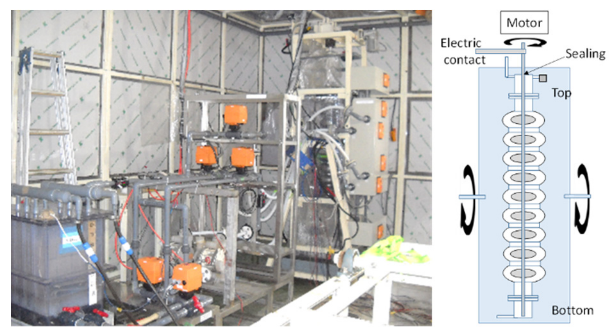

Figure 1: A photo and a schematic of the VEP equipment.

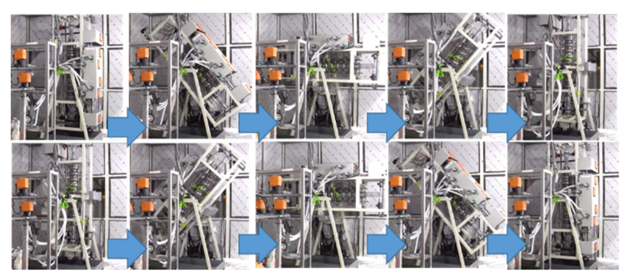

Figure 2: A continuous photo of the state of flipping (Upper: F to R, lower: R to F).

Figure 3: Improved EP acid tank.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV005

STATUS OF THE INFN-LASA CONTRIBUTION TO THE PIP-II LINAC

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Abstract

The international effort for the PIP-II project at Fermilab has been joined by INFN with its planned contribution to the PIP-II proton linac in the low-beta section. INFN-LASA is finalizing its commitment to deliver in kind the full set of the LB650 cavities, 36 plus spares resonators with 5-cell cavities at 650 MHz and geometrical beta 0.61. All cavities, designed by INFN-LASA, will be produced and surface treated in industry to reach the unprecedented performances required by PIP-II, qualified through vertical cold test at state-of-the art infrastructures and delivered as ready for the linac at the string assembly site. The status of INFN contribution to PIP-II, the development of infrastructures and prototypes as well as the ongoing activities toward the start of series production are summarized in this paper.

INFN-LASA CONTRIBUTION

The Fermilab Proton Improvement Plan II (PIP-II) Linac [1, 2] is designed to deliver a 1.2 MW H^- beam upgradable to multi-MW to enable LBNF and DUNE neutrino physics projects. The 800 MeV beam will be injected into the upgraded Booster Ring via a linac-to-booster transfer line and it will then proceed to the Main Injector Ring.

The PIP-II linac features a flexible time structure for its 0.55 ms beam pulse in order to satisfy different experimental needs, with RF repetition rate spanning from 20 Hz pulsed to continuous-wave (CW).

A key section of the linac is the 650 MHz superconducting part with geometric beta factor of 0.61 (LB650) that currently encloses 36 five-cell elliptical cavities in 9 cryomodules, accelerating beam from 177 MeV to 516 MeV. Target cavity accelerating gradient is set at 16.9 MV/m with a quality factor higher than 2 10^{10}, an unprecedented working point for this type of resonators.

INFN-LASA firstly provided a novel electromagnetic and mechanical design for the LB650 cavities [3], fully compatible to the performances and technical interfaces posed by the project as well with beam pipes and flanges, power coupler, helium tank, tuner.

On December 4th, 2018, the U.S. Department of Energy (DOE) and Italy's Ministry of Education, Universities and Research (MIUR) signed an agreement to collaborate on the development and production of technical components for PIP-II [4].

Following this milestone, INFN-LASA is finalizing the layout of its in-kind contribution aiming to cover the needs of the LB650 section of the linac, namely:

- Grand total of 40 SC cavities (36 plus 2 spares, and 2 initial prototypes) delivered as ready for string assembly, equipping a total of 9 cryomodules.
- Qualification via vertical cold-test provided by INFN either through the LASA test stand or through a qualified cold-testing partner infrastructure.
- Compliance to the PIP-II Technical Review Plan, the procedure issued by DOE and Fermilab in order to meet PIP-II technical, schedule and budget commitments.

PIP-II LB650 CHALLENGES

A successful cavity design is the result of an interplay of multiple state-of-the-art competences existing at INFN-LASA in electromagnetic, mechanical and technical domains [5].

PIP-II LB650 cavities are themselves among the key scientifical challenges of the whole project, requiring:

- An unprecedented quality factor for these resonators, e. g. more than four times higher than that of ESS cavities at a similar gradient. The proper surface treatment recipe must be developed and qualified addressing at first the challenges of Electro-Polishing (EP) etching on these low-beta resonators.
- Assessment of High-Order Modes (HOMs) risks so that neither instabilities nor additional cryogenic losses pose critical issues.
- Deep understanding of Lorentz Force detuning, pressure sensitivity and mechanical leading parameters as rigidities, yield limits, stresses [6]. PIP-II operational scenario is actually an uncharted territory in terms of cavity detuning control, especially in view of foreseen pulsed operation of these high loaded-Q cavities.
- Potential mutual compliancy required to both European (PED) and U.S. (ASME) pressure vessels codes.

R&D AND PROTOTYPE ACTIVITIES

In total, seven PIP-II LB650 prototype cavities have been produced counting both single and multi-cell, and three of them are shared with Fermilab since early 2020 for a joint development effort (Fig. 1).

Figure 1: INFN B61_EZ_001 LB650 cavity for PIP-II after final electron-beam welding.

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20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV006

RECENT ACTIVITIES REGARDING 9–CELL TESLA–TYPE CAVITIES AT KEK

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Abstract

In this contribution we report on two topics regarding recent activities on 9–cell TESLA–type cavities at the High Energy Accelerator Research Organization (KEK). First, we give an overview of the inner surface treatments and vertical test (VT) results of four fine grain 9–cell TESLA–type cavities over the last one and a half years. Secondly, we report on the upgrade of the VT DAQ system at the Superconducting RF Test Facility (STF) at KEK. In this upgrade, most components of the VT system were integrated in an EPICS control system. Based on Control System Studio (CSS) and Python a new user interface was created, improving the workflow during and after VTs at STF.

INTRODUCTION

In preparation of the possible realization of the International Linear Collider [1], the High Energy Accelerator Research Organization (KEK) is conducting R&D for the cost reduction of superconducting 9–cell TESLA–type 1.3 GHz cavities. To this end, new treatment methods are applied to four cavities. They are named MT–3, MT–4, MT–5, and MT–6 and are depicted in Fig. 1. All four cavities have a RRR > 300 and are manufactured from fine grain Niobium by Mitsubishi Heavy Industries Machinery Systems.

Figure 1: Top left: MT–3, top right: MT–4, bottom left: MT–5, bottom right: MT-6.

TESLA-TYPE CAVITY TESTING

R&D Cycle Overview

The cavity R&D cycle typically consists of a treatment and preparation phase, which is followed by a testing and evaluation phase. All procedures are performed at the Superconducting RF Test Facility (STF) [2] and the Center Of Innovation (COI) [3] on the KEK campus. At COI a furnace is located, which is used for the annealing process. At STF, electro-polishing (EP) procedures can be applied [4]. This is always followed by a high pressure rinsing (HPR) of the cavity. The next step is the assembly of the cavity, which can be done in a clean room at either facility. Baking is typically performed using a heater jacket inside the clean room. In a next step, the cavity performance is measured. This is done by a vertical test at cryogenic temperatures with radio frequency (RF) applied to the cavity. After the evaluation of the cavity performance and the limitations, actions for the following R&D cycle are decided. Table 1 gives an overview of the treatments applied as well as the VT results.

Table 1: Treatments and VT Results (Highest Recorded Gradient During the Final π–Mode Measurement) of MT-3 to MT-6 as of June 2021

MT-3	MT-4	MT-5	MT-6
100 µm EP1 900 °C 3 h 20 µm EP2 120 °C 48 h **VT1 16.3 MV/m**	100 µm EP1 900 °C 3 h 30 µm EP2 120 °C 48 h **VT1 cold leak**	100 µm EP1 900 °C 3 h 20 µm EP2 120 °C 48 h **VT1 35.1 MV/m**	100 µm EP1 900 °C 3 h 30 µm EP2 120 °C 48 h **VT1 28.7 MV/m**
HPR 120 °C 48 h **VT2 cold leak**	HPR **VT2 4.1 MV/m**	20 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT2 34.0 MV/m**	30 µm EP2 120 °C 48 h **VT2 26.0 MV/m**
HPR 120 °C 48 h **VT3 30.3 MV/m**	100 µm EP1 800 °C 3 h 30 µm EP2 120 °C 48 h **VT3 37.7 MV/m, cold leak**	5 µm cold EP2 N–dope (2/0) 5 µm cold EP2 **VT3 22.0 MV/m**	20 µm cold EP2 120 °C 48 h **VT3 23.4 MV/m**
20 µm EP2 120 °C 48 h **VT4 36.9 MV/m**	HPR **VT4 39.2 MV/m**	5 µm cold EP2 **VT4 26.3 MV/m**	30 µm EP2 120 °C 48 h **VT4 31.0 MV/m**
10 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT5 35.4 MV/m**	5 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT5 36.0 MV/m**	100 µm EP1 900 °C 3 h 10 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT5 30.9 MV/m**	Iris wiping 30 µm EP2 120 °C 48 h **VT5 42.8 MV/m**
	HPR **VT6 31.3 MV/m**	20 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT6 40.5 MV/m**	10 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT6 38.0 MV/m**
	Local grinding of iris 2-3 10 µm cold EP2 **VT7 31.7 MV/m**		
	9 µm cold EP2 & 10 µm cold EP2 75 °C 4 h & 120 °C 48 h **VT8 cold leak**		

Reference Measurements

The first goal while going through the cavity R&D cycles is to perform a reference measurement. To this all results yield with two–step baking or N–doping treatment methods are compared. To this end, 100 µm of the cavity surface is removed by EP-1, followed by annealing the cavity at e.g.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV007

THERMAL MAPPING STUDIES ON Nb/Cu SRF CAVITIES

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Abstract

A thermal mapping system is one of the most useful diagnostic tools to identify the mechanisms responsible of performance degradation in superconducting radio frequency (SRF) cavities. Unlike most of the thermal mapping systems currently in operation, we want to develop a system for mapping copper coated SRF cavities. This thermal mapping system, based on contact thermometry, will operate in both superfluid and normal liquid helium for the study of thin film cavities on copper built at CERN. This paper describes the R&D studies to design and develop the system. The characterisation of thermometers and the validation of their thermal contact are presented. Thanks to the use of some heaters with the aim of reproducing the presence of heat losses in a SRF cavity, temperature profiles on a copper surface will be shown at different conditions of the helium bath. In addition, preliminary results on magnetic field sensors, based on the anisotropic magnetoresistance effect, will be reported in view of their possible implementation in the thermal mapping system.

INTRODUCTION

Since the late '80s, CERN has pioneered development of thin film superconducting radio frequency (SRF) cavities for particle accelerators. Niobium (Nb) thin film cavities [1] on copper (Cu) have been successfully applied in LEP2 [2, 3], LHC [4] and HIE-Isolde linac [5]. However, thin film cavities historically featured a strong increase in surface resistance with accelerating field [6], resulting in a quality factor decrease (Q-slope). This is in part still unexplained and, together with the development of novel fabrication techniques and new thin film materials [7], is at the centre of an intense R&D program in the SRF community at CERN.

A thermal mapping system is one of the most useful diagnostic tools to investigate the mechanisms responsible of performance degradation in SRF cavities. This method, extensively applied in bulk Nb cavities, permits the localization of point-like and extended dissipation regions during cavity cold tests. We want to develop a thermal mapping system, based on contact thermometry, for the study of Cu coated SRF cavities in both superfluid and normal liquid helium (He). Since the thermal diffusivity of Cu at liquid He temperatures is higher than that of Nb, the detection of heat losses in thin film SRF cavities on Cu turns out to be more difficult, therefore preliminary R&D studies are needed in view of the design of the system. In addition, the implementation of a number of magnetic field sensors in the thermal mapping system is under investigation in order to monitor the magnetic field distribution around each SRF cavity under test.

The ongoing R&D studies for the design and development of the thermal mapping system are reported in this paper as follows. After the description of the experimental set-up, we present the characterisation of Allen-Bradley 100 Ω resistors, used as thermometers at low temperatures. Then, temperature measurements on Cu surfaces are examined at different heat flux values and He bath conditions. Finally, preliminary results on anisotropic magnetoresistance (AMR) sensors for magnetic field measurements are reported in this paper in view of their possible implementation in the thermal mapping system.

THE EXPERIMENTAL SET-UP

In order to characterise thermometers and their thermal contact, we used a 8 cm diameter tube in OFE Cu with a RRR of ~50 and a wall thickness of 2 mm. These features of the tube, shown in Fig. 1a, are similar to Cu substrates used for thin film SRF cavities. Two different heaters are glued in the internal surface of the tube with Stycast 2850FT epoxy, which is a high thermal conductive glue for cryogenics. One of the heaters is a thick film SMD resistor of 30 Ω at 300 K with a total area of ~1 cm^2, whereas the other one is a flexible heater in polyimide with a resistance value of 8 Ω at 300 K and a rectangular area of 9.1 x 3.8 cm^2. Thermometers are placed outside the tube and pushed towards the outer surface of the Cu tube thanks to a supporting system in Araldite MY750 and spring loaded pins (pogo-sticks) in BeCu, shown in Figs. 1a and 1b, respectively. Thermometers are embedded in an Araldite MY750 housing (see Fig. 1b) and sealed with Stycast epoxy, which is impervious to superfluid He [6]. Likewise thermometers, one Sensitec AFF755B sensor (see Fig. 1c) is placed on the outer surface of the Cu tube close to the SMD resistor. This type of sensor is based on the anisotropic magnetoresistance effect [8] and may represent a cheap solution for mapping the magnetic field around SRF cavities at cryogenic temperatures. Voltage signals of thermometers as well as the AMR sensor output are digitized by NI 9251 ADCs with a sampling rate of 1 KS/s, whereas the power supply is provided by two Keithley 2401 modules.

Different types of thermometers and various thermal contacts were tested with the Cu tube completely immersed in a liquid He bath while the internal pressure of the tube is kept at $\sim 1 \times 10^{-6}$ mbar. The Cu surface is vertically oriented during the tests. Thanks to the SMD resistor, we can reproduce point-like heat losses as those in SRF cavities. On the contrary, the rectangular heater is used to simulate extended dissipation regions, which may be present in SRF cavities, as well as evaluate different types of thermal contacts between the thermometer and the outer surface of the

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV008

RESULTS FROM THE PROTON POWER UPGRADE PROJECT CAVITY QUALITY ASSURANCE PLAN *

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Abstract

The Proton Power Upgrade (PPU) Project at Oak Ridge National Lab's Spallation Neutron Source (SNS) is currently under construction. The project will double the beam power from 1.4 to 2.8 MW. This is accomplished by increasing the beam current and adding seven new Superconducting Radio Frequency (SRF) cryomodules. Each new cryomodule will contain four six-cell, beta 0.81, PPU style cavities. A quality assurance plan was developed and implemented for the procurement of 32 PPU cavities. As part of this plan, reference cavities were qualified and sent to Research Instruments Co. for the development and verification of process steps. Here we present the results from this plan to date.

INTRODUCTION

A cavity quality assurance plan was developed early in the PPU project to address the risk for not achieving the designed energy gain in the seven new PPU cryomodules. It was clear from the beginning that the new cavities would be part of a early procurement plan due to the long lead times for the material procurement and fabrication. The accelerating gradient of 16 MV/m was chosen due to its demonstrated performance with beam from some cavities already installed in the SNS linac [1]. From operational experience, it was clear that the High Beta cavity design would be modified to improve its performance, first the end-groups would be fabricated from High-RRR niobium instead of reactor grade material to improve the end group thermal performance. Additionally, the resonant HOM couplers at each end of the cavity design would be removed to reduce the fabrication complexity and increase the effectiveness of the chemistry and cleaning of cavity surfaces. It has been known for some time that the HOM couplers were not needed for SNS operation and have cause additional issues in the past [2]. The concern for operations however, was how to address the risk from early onset of field emission which impacts not only the individual cavity but the entire cryomodule operation due to collective effects [3]. A decision to use electropolishing (EP) as the primary method of surface chemistry was made to increase the effectiveness of the standard cavity cleaning methods, in this case, ultrasonic cavity degreasing, High Pressure Rinsing (HPR) and ethanol rinsing. The original HB cavities surface processing was Buffered Chemical

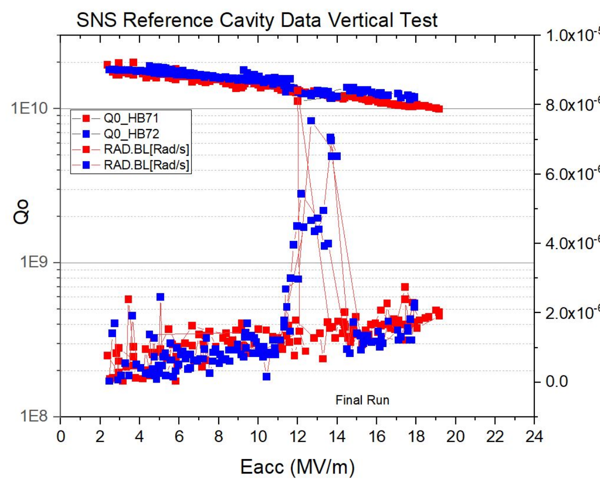

Figure 1: SNS VTA Data from the Reference Cavities.

Polish (BCP), the standard process at the time. Today, electropolishing (EP) of cavities is a well established method by the SRF community [4]. The problem with choosing EP for surface processing is it takes time for a vendor to adapt to the cavity design, resolve issues and gain experience before production. The PPU cavity has about a factor of 2 times the surface area of the 1.3 GHz 9-cell cavities and presents a challenge to maintain the quality of the electropolish electrolyte and cavity surface temperature. During the project planning stage,acceptance criteria were developed for the vendor delivered cavities and for vertical test for the project. The aim of the incoming acceptance was to verify that the cavity vendor followed their internal quality assurance plan as outlined in the contract and the vertical test acceptance was used as to set the pass/fail criteria for the vertical test results on the PPU cavities at JLab. The key criteria for the vertical test was, an administrative limit for the cavity gradient, set at 22 MV/m (not to exceed) to reduce the risk of an emitter degrading the performance at unreasonable gradients and secondly, a field emission limit set at <20 mRem/hr at 16 MV/m to achieve our gradient goal and determine the path for reprocessing of cavities.

THE CAVITY QA PLAN

A quality assurance plan was developed that would define the roles for the cavity vendor, Jefferson Lab who would be building the cryomodules and SNS staff. The focus of the plan was to give the responsibility of the niobium material

* Work supported by UT-Battelle, LLC, under contract DE-AC05-00OR22725
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV009

STATISTICAL MODELING OF PEAK ACCELERATING GRADIENTS IN LCLS-II AND LCLS-II-HE*

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Abstract

In this report, we study the vertical test gradient performance and the gradient degradation between vertical test and cryomodule test for the 1.3 GHz LCLS-II cavities. We develop a model of peak gradient statistics, and use our understanding of the LCLS-II results and the changes implemented for LCLS-II-HE to estimate the expected gradient statistics for the new machine. Finally, we lay out a plan to ensure that the LCLS-II-HE cryomodule gradient specifications are met while minimizing cavity disqualification by introducing a variable acceptance threshold for the accelerating gradient.

MODELING LCLS-II CAVITY GRADIENT PERFORMANCE

Our study begins with the vertical test results from the 1.3 GHz nine-cell SRF cavities built for the LCLS-II project. These cavities were prepared with the "2/6" nitrogen doping recipe (also called "2N6") described in previous work [1]. Figure 1 shows the distribution of peak accelerating gradients measured for the LCLS-II cavities in vertical test, measured after processing of any field emission or multipacting encountered. It should be noted that some LCLS-II cavity tests were performed while an administrative limit on gradient was in place; these artificially limited cavities have been omitted from this study. The results depicted here therefore represent the ultimate gradient limits of the LCLS-II cavities.

We can understand this distribution using a two-parameter thermal defect model, based on the thermal defect model developed at Saclay [2]. In this model, thermal defects are distributed across the surface of the cavity, and each cavity's ultimate gradient limitation is determined by the largest such defect. The cumulative probability distribution function of the size ϕ, with normalization constant ϕ_0, of the largest defect is given by the following:

$$P(\phi) = \exp\left(-s\left(\frac{\phi}{\phi_0}\right)^{-m}\right) \quad (1)$$

Fit parameter s relates to the total number of defects on the surface, with larger s corresponding to a higher overall number of defects; parameter m relates to the size distribution of defects, with larger m corresponding to more small defects and fewer large defects. We differentiate Eq. 1 to give the probability density function:

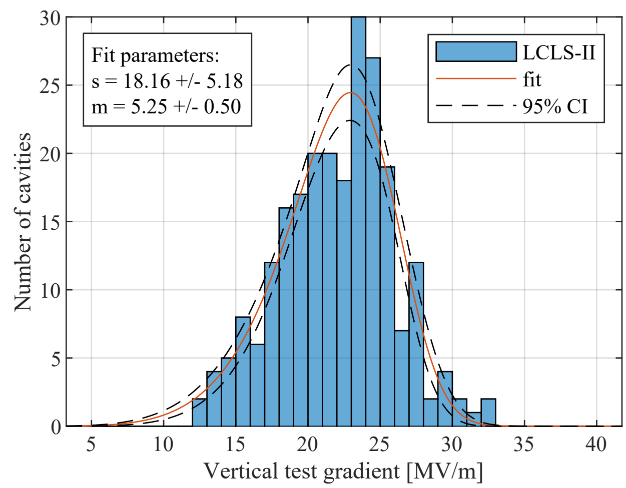

Figure 1: Distribution of peak gradients achieved by LCLS-II cavities in vertical test after administrative limit was removed. Also shown is the model with fitted parameters and 95% confidence interval.

$$p(\phi) = \exp\left(-s\left(\frac{\phi}{\phi_0}\right)^{-m}\right)\frac{s\,m}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^{-m-1} \quad (2)$$

As suggested by the fit to experimental data presented in the Saclay paper, we take the quench field B_q of a cavity with largest defect of size ϕ and a superheating critical field B_{sh} as follows:

$$b(\phi) = \frac{B_q}{B_{sh}} = \left(1+\left(\frac{\phi}{\phi_0}\right)^2\right)^{-1/2} \quad (3)$$

Then combining the above we can determine the the probability density function of b, which is defined over the interval $(0, 1)$:

$$p(b) = \exp\left(-s\left(b^{-2}-1\right)^{-m/2}\right)\frac{s\,m}{b^3}\left(b^{-2}-1\right)^{-m/2-1} \quad (4)$$

We note that the defect size and normalization parameter have dropped out, leaving us with the defect parameters s and m as well as the superheating field B_{sh} included in the definition of b.

* Work supported by the United States Department of Energy through the LCLS-II-HE project.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV011

OPERATIONAL EXPERIENCE WITH THE MECHANICAL TUNER SYSTEMS IN THE SUPERCONDUCTING LINAC AT IUAC

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Abstract

The phase locking of the QWRs by dynamic phase control method in the superconducting linac at IUAC is done in a fast time scale. The slow frequency drifts (few hundreds of ms) are corrected using a niobium bellows tuner attached at the open end of the cavity. Initially, the tuners in the cavities were operated using helium gas. This system had the limitation of non-linearity, hysteresis and slow response due to which the cavities could not be phase locked at higher fields. To address this, piezo based tuning system was implemented in the cavities of the 2nd and 3rd linac modules. But due to space constraints, the same could not be used in the 1st linac module and the buncher modules. For them, the helium gas based system was continued, albeit with suitable modifications. The old flow control valves which operated with DC voltages were replaced with valves operating in pulsed mode and controlled by varying the duty cycle of the input pulses. The above mentioned limitations were overcome by using this PWM based technique and this enabled phase locking at higher gradients. This paper presents our operational experience with all the different tuning systems and their comparison.

INTRODUCTION

The superconducting (SC) heavy ion linear accelerator (linac) [1-3] of Inter University Accelerator (IUAC) augments the energy of the heavy ion beams coming out of the Pelletron accelerator [4]. The linac consists of five cryostats housing 27 identical quarter wave resonators (QWR) [5] optimized for a normalized velocity (β=v/c) = 0.08, operating at 97MHz (Fig. 1). The superbuncher (SB) cryostat has a single QWR used to bunch the ion beams from ~ 1.5ns FWHM to 150ps FWHM beams. The next three cryostats, which are the accelerating modules, have twenty four QWRs for accelerating the ion beams. The last cryostat, namely rebuncher (RB), has two QWRs which are used to rebunch the accelerated ion beam either in time or in energy on to the experimental target.

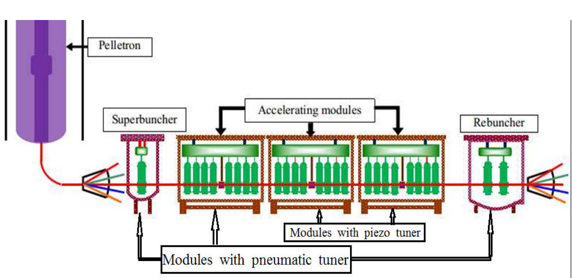

Figure 1: Schematic of Pelletron – Linac System.

In order to accelerate the heavy ion beams through the linac, the amplitudes and phases of the accelerating electric fields in the QWRs must be locked. The phase is locked using the dynamic phase control method [6, 7] and with the help of mechanical tuners operating parallelly. The IUAC-QWR and frequency tuner bellow is shown in Fig. 2. To maximize the phase locked fields in the cavities at a given input RF power, different techniques have been developed, e.g. modification of the power coupler design [5], damping of vibration of the central conductor of the QWR [3], improvements in the mechanical tuner design [8-12], surface treatment of the cavities [13], etc. This paper will focus only on the mechanical tuner systems used and modified from time to time till date.

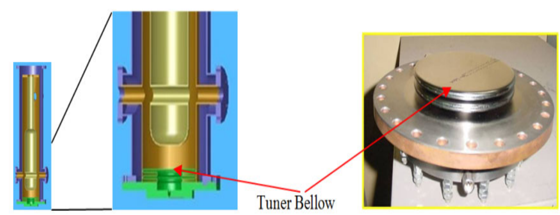

Figure 2: IUAC QWR (left) and frequency tuner bellows (right).

QUARTER WAVE RESONATOR

SC QWRs in the IUAC linac operate at 97MHz hence the operating temperature is 4.2K. The loaded quality factor (Q_L) [14] in the IUAC QWR is typically set around 10^6–10^7. Therefore the resulting narrow bandwidth makes these cavities quite sensitive to the surrounding mechanical microphonic vibrations. The QWRs are independently powered and phase locked [6, 7]. In the free running self-excited loop (SEL) [6, 7] (Fig. 3), the resonance frequency of the IUAC-QWR drifts in two time scales (Fig. 4). Therefore the phase locking scheme adopted, consists of two level of control. One acts in fast time scale (electronic) and

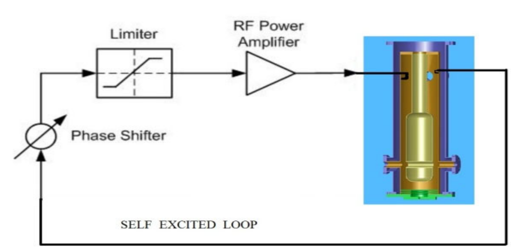

Figure 3: Cavity running in self excited loop.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV012

ESS MEDIUM BETA CAVITIES AT INFN LASA

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Abstract

INFN Milano - LASA contributes in-kind to the ESS ERIC Superconducting Linac supplying 36 cavities for the Medium Beta section of the proton accelerator. All the cavities have been mechanical fabricated, BCP treated and, for most of them, also qualified with vertical test at cold at DESY. We present the result of the cavities already qualified and delivered to CEA, discussing the lessons learnt so far. For remaining cavities, we discuss the actions taken and the plans foreseen to recover them to full specifications.

INTRODUCTION

The European Spallation Source (ESS) ERIC will be the most intense neutron source in the world [1]. ESS make use of a superconducting linac section (see Fig. 1) to accelerate a 62.5 mA proton beam to an energy of 2 GeV. This powerful beam will then be delivered to a target station for producing the neutron beams by the spallation process [2].

The 5 MW beam will be pulsed at 14 Hz with each pulse being 2.86 ms long. This long pulse operation is a real challenge and, to save in cost, superconducting cavities need to be operated at high gradient.

INFN Milano - LASA contributes, as part of the Italian In-Kind, to the Medium Beta Section of the ESS Superconducting Linac with thirty-six cavities that will boost the proton beam energy from 216 MeV up to 571 MeV [3, 4]. Table 1 reports the key parameters of the INFN MB cavities. Ref. [5] reports a detailed discussion on the choices made for the electromagnetic and mechanical design of the cavity.

In this paper, we briefly present the status of the mechanical production and then we will report on the results of the cavities tested so far. A dedicated section is reserved for discussing the not yet qualified cavities and our approach towards their recovery to specification.

CAVITY FABRICATION

The fabrication of the ESS cavities follows a quite traditional process based on Buffered Chemical Polishing (BCP) main treatment, assuring that the fabrication is done according to the Pressure Equipment Directive (PED) art. 4.3, i.e. pressure test and recording of "best engineering practice" and consequent certifications.

Fabrication Workflow

Sheets from OTIC were scanned at DESY with Eddy Current [6] before being deep drawn to form the half cell (HC) at Ettore Zanon (now Zanon Research & Innovation). We have three different types of HCs, namely End Cell, Pen Cell and Inner Cell. While the latest type is used for the middle dumb bells, the Pen Cell is used to match the Inner Cell to the End Cell having it a slightly larger diameter. The DumbBells and End Groups are then welded together to form the cavity.

The cavity is then BCP treated to remove about 180 µm into two steps, flipping the cavity at half of process to get more uniform final removal. A treatment at 600 °C for 10 h is done to remove hydrogen after the BCP process and to release the mechanical stress [7–9]. This low temperature treatment has been forced having the cavity already welded the Nb-Ti end plate necessary for integrating the He-Tank.

Afterwards, the cavity is tuned to goal frequency and field flatness before being integrated into the He-Tank. Finally, the cavity is prepared for Vertical Test (VT) with the "Final" BCP of 20 µm and long HPR. It is then shipped to DESY for qualification in AMTF or to INFN LASA for special cases [10].

Quality Control and Assurance

Based on the experience that our group developed during the European-XFEL cavities production, a specific Quality Control and Assurance (QC/QA) plan has been developed to follow all the fabrication phases from the reception of the sheets to the delivery of the cavity to CEA for integration into the module.

Table 1: ESS Medium Beta Cavities Main Parameters

Parameter	Value
R_{iris}	50 mm
Geometrical β	0.67
π-mode Frequency	704.42 MHz
Acc. length	0.855 m
Cell-to-cell coupling k	1.55 %
π-$5\pi/6$ mode sep.	0.70 MHz
Geometrical factor G	198.8 Ω
Optimum beta, β_{opt}	0.705
Max R/Q at β_{opt}	374 Ω
E_{acc} at β_{opt}	16.7 MV/m
E_{peak}/E_{acc}	2.55
E_{peak}	42.6 MV/m
B_{peak}/E_{acc}	4.95 $\frac{mT}{MV/m}$
Q_0 at nominal gradient	$>5 \times 10^9$
Q_{ext}	7.8×10^5

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPCAV014

DEVELOPMENT OF HIGH-Q TREATMENTS FOR PIP-II PROTOTYPE CAVITIES AT LASA-INFN

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Abstract

INFN-LASA is currently involved in the production of PIP-II low-beta cavity prototypes. The main challenge of this activity is to develop a state-of-the art surface treatment recipe on such cavity geometry, to achieve the high-Q target required for cavity operation in the linac. This paper reports the status of cavity treatments development and the first cold test results of a single-cell cavity. This cavity has undergone a baseline treatment based on Electropolishing as bulk removal step. Being this test successful, a strategy for pushing the cavities towards higher performances is here proposed.

INTRODUCTION

INFN-LASA joined the international effort for the PIP-II project in Fermilab and is appointed to build 40 650 MHz $\beta = 0.61$ superconducting cavities that will constitute the low-beta section of the Linac. Specifications for cavity operation in the machine are $E_{acc} = 16.9\,\mathrm{MV\,m^{-1}}$ with a $Q_0 \geq 2.4 \cdot 10^{10}$. Electropolishing (EP) was chosen for the upcoming production of PIP-II cavities, so to avoid the Q-slope behavior typical of BCP-treated cavites which would limit the cavity performance below the machine target. This is one of the key challenges of the PIP-II SRF cavity production, and in particular for the low-beta section, where the extremely compressed cavity geometry complicates further the surface processing steps.

To this aim, seven prototype cavities were produced, with both single and multi-cell geometry. Parts of them are shared with Fermilab in sake of a joint development effort on many technical issues. A single cell (B61S_EZ_002) and a multi-cell (B61_EZ_002) cavity are serving the main purpose of developing and optimizing the treatment recipe. This activity is currently carried out by the SRF group of INFN-LASA.

Cavity prototype production is currently ongoing at the company Zanon Research & Innovation Srl. This activity began with the refurbishment of the EP facility so to host the PIP-II cavities and with the optimization of the treatment parameters on the different cavity shape and geometry. This was done by means of several short EP treatments which were carried out on the single-cell prototype cavity B61S_EZ_002, until the outcome resulted satisfying in terms of surface smoothness, removal rate and iris/equator removal ratio [1]. Being this optimization phase successfully completed, the single cell cavity was ready to undergo the complete baseline treatment, employing a E-XFEL-like recipe [2]. Once the baseline treatment is validated by the results of cavity cold test, the same recipe is expected to be used on a multicell prototype cavity, but with the introduction of a high-Q surface treatment which will allow to reach the PIP-II target.

SINGLE CELL CAVITY SURFACE TREATMENT

The baseline surface treatment employed on the PIP-II single cell prototype cavity B61S_EZ_002 served the purpose of qualifying the surface processing facilities and is based on the same recipe used for the series production of EXFEL 1.3 GHz cavities, with the only variation of cold EP as final surface treatment. The goal of Cold EP is to obtain a smoother surface and a more uniform removal over the cavity [3]. A mirror-finish surface condition is essential for obtaining an high Q-value at the operating gradient, because a rough surface would introduce non-linear losses increasing cavity power dissipation at higher fields [4].

The main steps of the PIP-II baseline recipe are:

- 150 µm bulk EP, in two separate steps of 75 µm each.
- 800 °C heat treatment for 2 hours in ultra high vacuum (UHV) conditions.
- 25 µm final Cold EP.
- High pressure rinsing (HPR) for 12 hours with ultra pure water (UPW).
- 120 °C 48 h low temperature baking.

After each step, the cavity was HPR-rinsed for 2 hours, weighted and dried. A new design for the HPR nozzle head was developed by INFN-LASA so to improve the effectiveness of the rinsing operation on the PIP-II low-β cavity geometry. A RF check was done after every treatment step so to monitor the frequency response. Optical inspection is performed after the Electron Beam Welding and after the bulk EP treatment.

Bulk EP

The bulk EP overall target removal was 150 µm, to be performed in two separate steps of 75 µm each. The optimization campaign resulted in the following choices for the treatment parameters and of the plant layout:

- A 30 mm diameter Aluminum cathode was employed, with a cylindrical enlargement installed at the equator position. This allowed to remarkably increase the removal at the equator. Fresh acid flows in the cavity through a hole at equator position with a $1\,\mathrm{L\,min^{-1}}$

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV001

FPC FOR RIKEN QWR

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Abstract

In RIKEN Nishina Center, three cryomodules which contain ten SC-QWRs in total (4 + 4 + 2) were constructed, and beam supply has been started since last year. The FPCs for RIKEN QWR have a disk-type single vacuum window at room-temperature region. A vacuum leakage occurred at one FPC, after 4th cool-down test. In addition, second vacuum leakage occurred at another FPC, after starting beam supply. A dew condensation at air side of vacuum window may degrade the brazing of vacuum window. In order to prevent a dew condensation and to restore damaged FPCs, Additional outer vacuum windows using machinable ceramics were designed and attached to the damaged FPCs. In this contribution, a structure of the FPC, troubles, provision for those troubles, and plan for reconstruction are reported.

INTRODUCTION

The RIKEN Heavy-ion linac (RILAC) [1] is used to supply intense beams for the synthesis of super-heavy elements (SHEs) [2], as well as used as an injector for following RIBF accelerator complex comprises four ring cyclotrons [3].

For the synthesis of new SHEs with atomic number greater than 118 and the production of radioactive isotopes for medical use, the RILAC has been upgraded (Fig. 1(a)). For an enhancement of the beam intensity, a new 28-GHz superconducting ECRIS (R28G-K) [4] was installed at the uppermost-stream of RILAC. For an enhancement of the acceleration voltage, superconducting linac (SRILAC) [5-12] was installed at the downstream of RILAC. As shown in Fig. 1(b), the SRILAC comprises three cryomodules that mount ten superconducting quarter-wavelength resonators (SC-QWRs) in total.

A beam delivery to SHE research using R28G-K and SRILAC has started in June 2020.

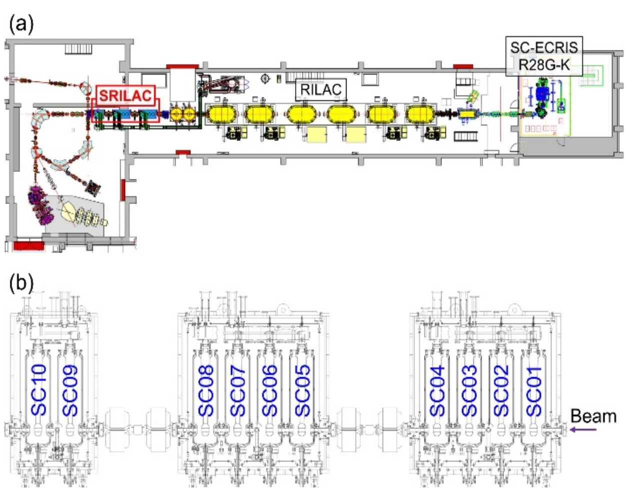

Figure 1: (a) An overview of RILAC upgrade. The R28G-K and SRILAC were installed at upmost-stream and downstream of RILAC, respectively. (b) A side view of SRILAC. Ten SC-QWRs are mounted in three cryomodules. Doublet quadrupole magnets are installed between each cryomodule.

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STRUCTURE OF FPC

Schematic view and photograph of a fundamental power coupler (FPC) for SRILAC are shown in Figs. 2(a) and 2(b). It is a coaxial type of 39D and has a disk-type single vacuum window made of alumina ceramics (KYOCERA A479B) with a TiN coating. An outer conductor is made of copper-plated stainless steel and has an 80-kelvin thermal anchor. A thickness of copper plating is 30 μm. Residual resistivity ratio (RRR) of the copper plating is evaluated to be ~5 [13]. An inner conductor is made of an oxygen-free copper pipe. An assumed maximum RF power is 5 kW (continuous wave). The FPC is mounted on SC-QWR via 34D port located at the bottom of cavity. An

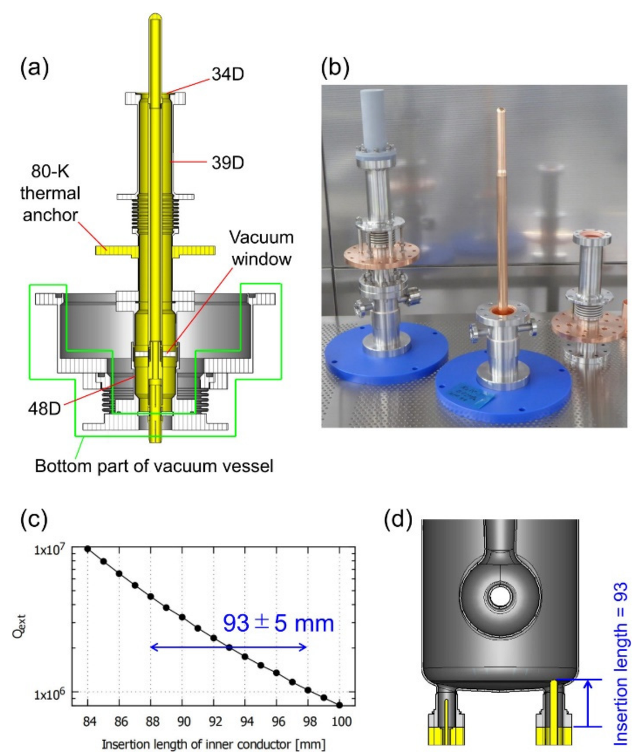

Figure 2: (a) Schematic view of FPC, including connecting portion with a vacuum vessel. (b) Photograph of FPCs. (c) Correlation between an insertion length of inner conductor and Q_{ext}, computed by CST MWS. (d) Schematic view with a standard insertion length of inner conductor.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV002

ENHANCED PNEUMATIC TUNER CONTROL FOR FRIB HALF-WAVE RESONATORS*

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Abstract

The superconducting driver linac for the Facility for Rare Isotope Beams (FRIB) includes a total of 46 cryomodules; 31 cryomodules contain half-wave resonators (HWRs) with pneumatic tuners. Pneumatic tuner control is via solenoid valves connecting the tuner to a helium gas supply manifold and a gas return line. For precise compensation of cavity detuning over a small range, the control voltage for the solenoid valves must be calibrated. Some valves have hysteresis in the gas flow rate as a function of control voltage, such that their response may be nonlinear and not repeatable—this makes the control algorithm challenging. To improve the system performance, a new pneumatic tuner control system was developed which regulates the position of one stepper motor instead of the two solenoid valves.

INTRODUCTION

The FRIB half wave resonators (HWRs) use a pneumatic tuner [1], which is linked to HWR beam port cups and actuated by a bellows. The bellows can be expanded or contracted by helium gas pressurization or discharge. The helium gas pressure can thereby shift the HWR frequency. The tuner parameters are shown in Table 1 [2].

Table 1: FRIB HWR Tuner Characteristics

Cavity Type	**HWR**
Deformation	Beam port cups
Actuation	Pneumatic
Force	1000+ lbs
Cavity β	0.29 / 0.53
Range (kHz)	62 / 39

PNEUMATIC TUNER CONTROL

Existing System

As shown in Fig.1, the pneumatic tuner is connected to the helium gas space. There are two solenoid valves, one connected to the gas supply pipe, the other connected to the gas return. The LLRF system controls these valves by roughly setting the voltages or precisely controlling them via a frequency feedback loop. For precise feedback control, the solenoid valves must to be calibrated: measuring the gas flow rate versus valve control voltage; the calibration provides the valve opening voltage and high limit flow rate voltage for each valve. However, for some valves, the opening voltage is not repeatable, the gas flow rate versus control voltage is nonlinear, or the valve has hysteresis (one voltage makes the valve open, but once open, a much lower voltage is required to close the valve again). These behaviours make it difficult to control the frequency. The calibration is repeated frequently to try to mitigate these effects.

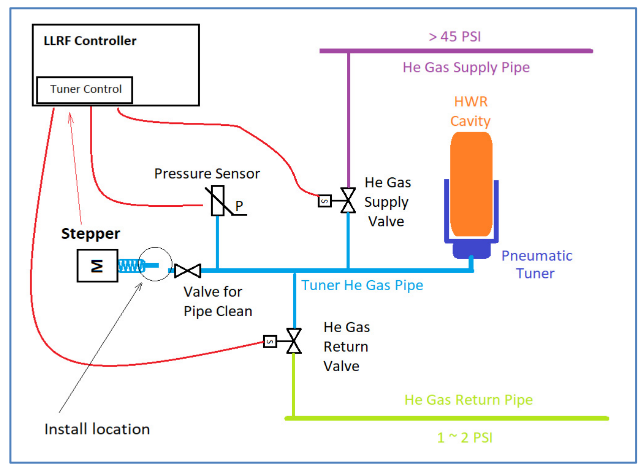

Figure 1: Schematic of pneumatic tuner system. The control valves for the existing control system and the stepper motor with bellows for the new system are shown.

New System

A new enhanced system was developed for improved control without excessive sensitivity to the solenoid valve calibrations. Once the tuner pressure is adjusted to the desired operating range, the supply and return solenoid valves are kept closed all the time during HWR cavity operation. The new method is to adjust the volume of the helium gas space for precise control of the tuner pressure and frequency. To implement this, a stepper motor with a bellows are added to a spare port (used for cleaning the system, as shown in Fig. 1; the location for installation of the new components is circled). Actuation of the stepper motor applies force to the bellows to change the volume of the gas space by a small amount, which produces a small change in the pressure, resulting in a small shift in frequency. Figure 2 provides more detailed information about the new components and the tuner.

The new tuner control system is an update of the existing system. The LLRF controller phase detector provides the cavity phase detune as the error signal for the phase control loop. In the existing tuner control algorithm, the tuner feedback loop shifts the frequency via the supply and return valves [3]. In the new method, the feedback loop controls the stepper motor position with both solenoid valves

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV003

LCLS-II CRYOMODULES PRODUCTION EXPERIENCE AND LESSONS LEARNED TOWARDS LCLS-II-HE PROJECT*

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Abstract

LCLS-II is an upgrade project for the linear coherent light source (LCLS) at SLAC. The LCLS-II Linac will consist of thirty-five 1.3 GHz and two 3.9 GHz superconducting RF (SRF) continuous wave (CW) cryomodules with high quality factor cavities. Cryomodules are produced at Fermilab and at Jefferson Lab (JLab) in collaboration with SLAC. Fermilab has successfully completed the assembly, testing and delivery of seventeen 1.3 GHz and three 3.9 GHz cryomodules. LCLS-II “High Energy” (LCLS-II-HE) is a planned upgrade project to the LCLS-II. The LCLS-II-HE linac will consists of twenty-three 1.3 GHz cryomodules with high gradient and high quality factor cavities. This paper presents LCLS-II-HE cryomodule production plans, emphasizing the improvements done based on the challenges, mitigations, and lessons learned from LCLS-II.

INTRODUCTION

Fermilab delivered the last LCLS-II cryomodule (CM) to SLAC in March 2021. LCLS-II-HE cryomodule production started at Fermilab with the assembly and testing of the verification cryomodule (vCM). With the goal of preserving the momentum for the experienced teams and for the proven functional facilities/infrastructure from LCLS-II, vCM assembly was done without a duration gap right after the last LCLS-II CM.

For LCLS-II-HE, as it was for LCLS-II, Fermilab is the engineer of record and is responsible for the cryomodule design. The vCM design is the same as the LCLS-II cryomodule except for two major differences: i) superconducting radio frequency (SRF) cavities are processed with a new processing protocol for the required performance specifications, ii) cavity end level tuner has an extended range which might be used for the dual frequency operations of the accelerator.

With the contributions from Fermilab, Jefferson Lab and SLAC, an R&D effort has been successfully completed to develop the new processing protocol and transfer the technology to industry. Ten fully dressed cavities were fabricated and processed with the newly developed treatment in industry, and successfully tested at Fermilab; performance exceeded the specification with average Q0=3.6e10 and Eacc=25.6 MV/m (specifications are Q0=2.7e10, Eacc=21MV/m) [1, 2]. The best 8 cavities were used for the string assembly of the vCM which is currently being cold tested at Fermilab with a 5-month test program. At Fermilab, production of series cryomodules will start in the Fall of 2021. Fermilab will assemble, test, and deliver 13 cryomodules to SLAC.

LESSONS LEARNED & CONTINUITY FROM LCLS-II

Cryomodule (CM) Design & Change/Configuration Control

LCLS-II CM design which started with the reference European XFEL pulsed CM design has evolved and significant changes were done first for the continuous wave design and then consecutively to mitigate the technical challenges throughout the lifecycle of CM production [3]. LCLS-II-HE CM design is practically identical to LCLS-II. There is an explicit effort and goal to not change the proven and working design of the cryomodule unless it is absolutely necessary for the performance requirements of the project. A specific lesson learned from LCLS-II is that substitution of parts thought to be equivalent must be reviewed and approved with the help of engineering reviews (peer and independent), small changes matter, and both can have ripple effects and make a big difference on the performance of the cryomodule [4]. Another important lesson learned from LCLS-II is that focusing CM design through a single individual is an organizational weakness since that places undue burden on that person. For the only major design change, which is the extended range tuner, LCLS-II-HE adopted a team approach with a lead design engineer supported by additional designers (as needed) and focused by an overall lead engineer/subject matter expert. Another improvement done for the LCLS-II-HE is to augment the change/configuration control. LCLS-II has a change control board (mostly to review/approve the scope and budget changes) and a records of decision process to document the significant changes. For LCLS-II-HE, a technical change control board and systems engineering structure are introduced early in the project. All proposed changes, even a simple redline drawing change from LCLS-II to LCLS-II-HE, are managed with this new scheme. Initially, this new scheme might seem to be additional and unnecessary paperwork/bureaucracy, but it will pay dividends on the long term.

Facilities/Infrastructure

Proven and successfully used Fermilab facilities/infrastructure for LCLS-II are fully functional and dedicated to LCLS-II-HE CM production. Throughout the LCLS-II CM production, based on audit/review recommendations,

* Work supported by supported by the United States Department of Energy, Offices of Basic Energy Sciences and High Energy Physics under Contracts No. DE-AC05-06OR23177 (Fermilab) and No. DE-AC02-76F00515 (SLAC)
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV004

SURFACE OXIDES ON Nb AND Nb_3Sn SURFACES: TOWARD A DEEPER UNDERSTANDING*

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Abstract

Surface oxides on Nb and Nb_3Sn SRF cavities, as a thin "dirty" layer, could be critical to their performance as suggested by recent theory. Although these oxides have been studied in the past, we intend here to provide a deeper understanding based on a systematic study on coupon samples that have been processed under the different conditions currently used in SRF cavity treatments. Our aim is to obtain a more complete picture of the oxide evolution. This then might help to explain the observed cavity performance variation, and might allow designing a process to achieve a designed, optimized surface with controlled oxides types and thickness. We find that the surface oxides are in amorphous phase that exhibits normal conducting behaviors, while the pentoxide further degrades with time. Also, we observed a thin hydroxide layer on the outermost surface and possibly $Nb(OH)_x$ motifs in the bulk. Moreover, distinctive oxide structures were found in Nb_3Sn samples from vapor diffusion, electroplating, and sputtering. The semiconducting SnO_x appeared through the oxide depth in vapor diffused Nb_3Sn, while a ~1 nm SnO_x layer merely exists at the outermost surface of electroplated Nb_3Sn.

INTRODUCTION

The role of oxygen in superconducting radio-frequency (SRF) cavities is not clear yet. We intend to investigate the surface oxides and the oxygen impurities after different acid and heat treatments. Surface oxides that are likely a normal conducting phase on the superconducting surface are theoretically critical to the RF performance due to the proximity effect [1]. Route toward a perfect surface is believed to be either a dielectric oxide or a normal conducting oxide of desired thickness (and electrical properties). However, it is challenging to achieve such perfect oxide surfaces.

Although numerous studies [2-7] have systematically characterized the surface oxides and investigated the oxidation process on Nb surfaces, applying the learnings from these materials investigations to fabricating a surface oxide layer under a controlled manner on a cavity scale is not straightforward. Eremeev [8] examined the RF response to removal and re-growth of surface oxides via baking and air exposure under modulated pressure and time, but the understanding of these results was not fully clear. The discrepancies he observed between repeated treatments and between their oxide characterization and the corresponding RF results, suggest one probable cause – the variation in treatment environment. This motivates us to gain a deeper understanding of the surface oxide structure on Nb after different processing conditions.

Also, new SRF materials such as Nb_3Sn push the need of surface oxide studies on these surfaces [9, 10]. For example, Porter [9] observed a two-gap behavior on the BCS resistance versus temperature curve for the Nb_3Sn cavities, which indicates a possible influence from the surface oxides.

Moreover, new processes such as low- and mid-temperature bakings together with nitrogen infusion and doping bring about our attention on the complexity of involvement of multiple impurities in the material system (at least oxygen and nitrogen). For example, the nitrogen infused niobium done by Koufalis [11] showed absolutely higher oxygen concentration than nitrogen concentration by several orders of magnitudes within several hundreds of nanometers in depth. Recently, Fermilab also confirmed this observation. It is necessary to understand the role of oxygen in the nitrogen-doped/infused and other baked niobium.

In this work, we present the oxide and oxygen results from Nb and Nb_3Sn coupon samples that were processed or made by multiple treatments.

EXPERIMENTAL

Nb samples were prepared using ozone, long time O_2/N_2 soaking, nitrogen doping, HF soaking, electropolish (EP), and buffered chemical polish (BCP). The sample information and treatment details are summarized in Table 1.

* This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams. Also, this work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875), and was performed in part at the Cornell NanoScale Facility, an NNCI member supported by NSF Grant NNCI-2025233. Utilization of the PHI Versaprobe III XPS within UVa's Nanoscale Materials Characterization Facility (NMCF) through NSF MRI award #1626201 is acknowledged.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV006

DESIGN OF THE PIP-II 650 MHz LOW BETA CRYOMODULE

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Abstract

The Proton Improvement Plan II (PIP-II) that will be installed at Fermilab is the first U.S. accelerator project that will have significant contributions from international partners. CEA joined the international collaboration in 2018, and is responsible for the 650 MHz low-beta section comprising 9 cryomodules, with the design of the cryostat (i.e. the cryomodule without the cavities, the power couplers and the frequency tuning systems) and the manufacturing of its components, the assembly and tests of the pre-production cryomodule and 9 production modules. This paper presents the design of the 650 MHz low-beta cryomodules.

INTRODUCTION

The PIP-project is an upgrade of the accelerator complex of Fermilab to enable the world's most intense neutrino beam for the Long Baseline Neutrino Facility (LBNF) and the Deep-Underground Neutrino Experiment (DUNE) located in South Dakota, 1200 km from the neutrino production in Illinois.

PIP-II will deliver 1.2 MW of proton beam power from the injector, upgradeable to multi-MW capability. The central element of PIP-II is an 800 MeV linear accelerator, which comprises a room temperature front end followed by a superconducting section. The superconducting section consists of five different types of cavities and cryomodules, including Half Wave Resonators (HWR), Single Spoke and elliptical resonators operating at state-of-the-art parameters [1].

The CEA contribution to the PIP-II project is mainly on the low beta elliptical cavity cryomodule – also called LB650 cryomodule (Figure 1).

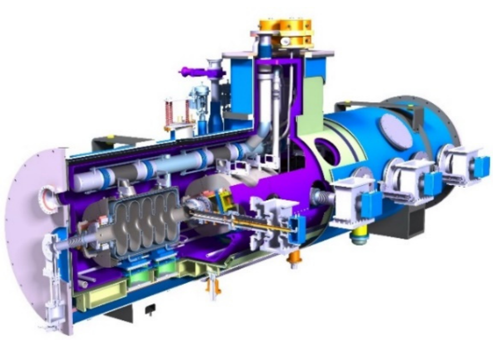

Figure 1: The LB650 cryomodule.

It includes the design of the LB650 cryomodule, the procurement of most of the components (except the cavities, tuning systems, power couplers, instrumentation and related feedthroughs, valves, heat exchanger, JT valve, and auxiliary cryogenic items supplied by Fermilab), the assembly and RF tests of all the cryomodules (one pre-production cryomodule and 9 series ones), and preparation to shipment between France and USA (including the design and manufacturing of the transport frame).

DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule benefits from the experience of the cryomodules previously developed for the PIP-II project (the first spoke cryomodule SSR1 [2]) or under development (the HB650 prototype cryomodule [3]). The concept of the supporting system for the cold mass is identical for the spoke and elliptical cryomodules: it is based on the strongback that stays at room temperature when the cryomodule is cold [4].

Each LB650 cryomodule houses four 5-cell β=0.61 cavities (developed by Fermilab, INFN, and VECC for the preproduction cryomodule [5] and series cryomodules [6]). The frequency tuning systems and the power couplers for the low beta and high beta cavities are identical. They are under the responsibility of Fermilab ([7] and [8]), with CEA contribution on the studies of the power couplers ([9] and [10]). The schematics of the cryogenic lines of the LB650 cryomodule is shown in Fig. 2, Fig. 3 presents the layout. It is similar in design to the HB650 cryomodule described in [11]. Each cavity is connected to the strongback using two support posts made of low thermal conductivity material to limit the thermal load between the room temperature strongback and the helium temperature devices. The posts have two thermal intercepts, one connected to the thermal shield (cooled around 40 K) and the 5 K line where liquid helium flows inside.

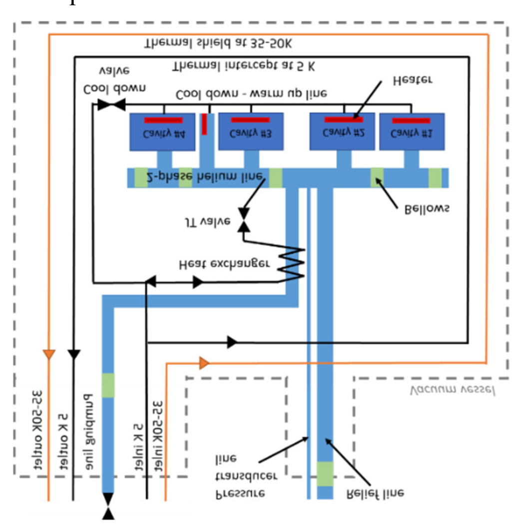

Figure 2: Schematics of the cryogenic lines of the LB650 cryomodule.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV008

DEVELOPMENT OF A DIGITAL LLRF SYSTEM FOR SRF CAVITIES IN RAON ACCELERATOR

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Abstract

An ion accelerator, RAON is planned and under construction in Daejeon, Korea by Rare Isotope Science Project (RISP) team in Institute of Basic Science (IBS). The purpose of this accelerator is the generation of rare isotope by ISOL (Isotope Separation On-Line) and IF (In-flight Fragmentation) method. To achieve this goal RAON adopted the superconducting cavities at three different frequency (81.25 MHz, 162.5 MHz and 325 MHz) and their RF field will be controlled independently for the acceleration of ions with various A/q. A solid state power amplifier and a low level RF (LLRF) controller pairs are under development to generate and to control the RF for the cavities. Recently the development and evaluation of the digital-based LLRF have been performed. For the operation and test of SRF cavities, self-excited loop (SEL) and generator-driven-resonator (GDR) algorithm is digitally implemented and its test was performed. In this paper the status and test result of RAON LLRF controller will be described.

INTRODUCTION

Rare Isotope Science Project (RISP) project is under way and the goal of this project is to build an ion accelerator, RAON since 2009. The acceleration of the high-energy stable ion beams and rare-isotopes are planned in RAON accelerator for the research of nuclear, material, medical science and many other areas [1]. The linear accelerator part of RAON adopted a superconducting two gap cavities and normal conducting quadrupole doublet structure instead of multi gap cavities such as a multi-cell elliptical cavity for the acceleration of various ion beams. Four kinds of superconducting cavities are planned and their operation frequencies are three. There are two linear accelerator sections are under construction. In the low energy superconducting linear accelerator, a quarter wave resonator (QWR) with 81.25 MHz and a half wave resonator (HWR) with 162.5 MHz are going to be installed and two single spoke resonators (SSR) with different beta are planned for high energy superconducting linear accelerator (SCL2). The operation frequency of SSRs is 325 MHz.

As described above, there are various RF cavities in RAON accelerator and the electromagnetic field and the synchronous phase of all cavities should be controlled individually for the acceleration of various ions. Also the RF control requirement of RAON RF system is decided by the beam dynamics simulation and error study and it is shown in Table 1. A low level radio frequency (LLRF) and a solid state power amplifier (SSPA) pairs are selected for the RF system of RAON accelerator. In Fig. 1, the layout of RAON RF system is shown. Recently the manufacturing and testing of superconducting cavities and cryomodules for the construction of SCL3 are ongoing at SRF test facility at Sindong site. As a prototype of the LLRF for RAON accelerator RF system, the development of a LLRF for RAON Superconducting Radio Frequency (SRF) test facility was performed and it is being tested during the test of the jacketed cavities and the cryomodules. In this paper, the status of the developed LLRF and its test results will be described.

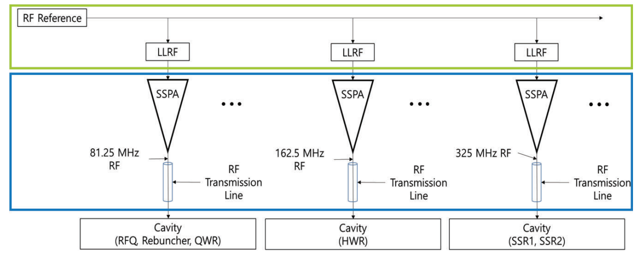

Figure 1: Schematic of RAON RF system.

Table 1: Specification of RAON RF Control System

RF Dynamic Phase Error Requirement	$\pm 1^o$ (p2p)
RF Dynamic Amplitude Error Requirement	$\pm 1\%$ (p2p)

DEVELOPMENT OF LLRF FOR THE RAON SRF TEST FACILITY

The LLRF for RAON SRF test facility should be able not only to control the RF inside the cavities but also to provide some functions which are necessary for the testing, such as the microphponics measurement, etc. Also it is preferred to be able to operate at all operating frequency for the ease of test setup. Some strategy to decide the specification of the LLRF were as following.

1. Phase locked loop (PLL) based RF clock generation
2. Non-IQ based RF direct sampling to reduce the temperature sensitive RF components
3. FPGA-based RF digital processing for the minimization of RF components at RF frontend

For the SRF test, the information of the RF signal from the cavity, the RF reference signal, and the forward and reflected RF signals from the high power amplifier is necessary. For this purpose the AD9656, 4-channel, 16 bit, 125 MSPS, serial interfaces ADC of Analog Devices was chosen. A variable amplifier was used at the RF input to enhance the

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV011

EXPERIMENTAL VALIDATION OF THE USE OF COLD CATHODE GAUGE INSIDE THE CRYOMODULE INSULATION VACUUM*

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Abstract

The Proton Improvement Plan - II (PIP-II) project is underway at Fermilab with an international collaboration involving CEA in the development and testing of 650 MHz cryomodules. The risk analysis related to cryomodule operation proposed to add a vacuum gauge on the power coupler to prevent the untimely rupture of its ceramic. Due to the advanced design of the cryomodules, the gauge needs to be integrated inside the insulation vacuum to reduce the impact of this new modification. The lack of experience feedback on a similar operating condition requires an experimental validation before the implementation. This article details the experimental tests carried out before the approval of this solution.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex [2]. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules [3, 4], equipped with 650 MHz Superconducting (SC) cavities are used. The same Power Coupler (PC) design was adapted for both cryomodules. In total, sixteen unit of them these PC will be need for the Linac. They each have a single ceramic window located inside the cryomodule vacuum tank, see Fig. 1.

The former design versions of the 650 MHz PC are not equipped with vacuum gauges (VG). However, recent risk analysis has raised the great impact of a PC ceramic failure, during operation, on the cryomodule and consequently on the Linac ability to produce the beam. Even if this problem is unlikely if all the precaution are taken, a high number of PCs and an operation during several years increase the probability to have this incident. Experience has shown that many of these incidents are reported [5-7] and are generally difficult to analyse without appropriate diagnostics. Ceramic degradation could be gradual due to some initially unseen weaknesses such as ceramic cracks and brazing problems, or due to many years of operation. But, it can also be instantaneous in case of a fail of the protection system, or of late detection of a strong event generating an important electron discharge.

In addition to insuring drastic quality control of the PC before its operation on the cryomodule, several strategies can be adopted from the design stage to reduce the risks of a PC window failure:

- Use double window design: it is expensive and complicates the design
- Use an existing well known design (even over designed): it is not always possible and may generate other design complications for the cryomodule.
- Use different types of diagnostics on PC: it may add integration complication and certainly increases the equipment's cost.

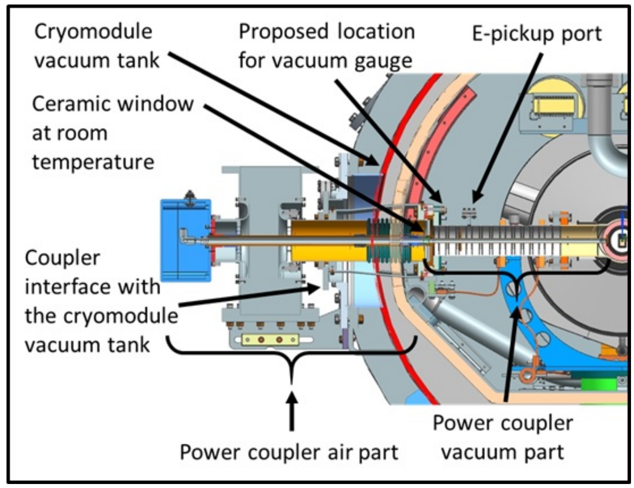

Figure 1: 650 MHz Power Coupler assembled on the HB650 cryomodule. This design version have not a vacuum gauge.

With the design of the 650 MHz PC almost complete, the natural strategy to adopt is to add a new diagnostic. In our case, the solution we propose was to add to the existing e-pickup a VG. This diagnostic, allows to trigger of a protection interlock in case of strong vacuum event in order to limit its impact. It is also the most efficient way to guarantee an early detection of window tightness issues. This allows to limit the degradation by adapting the operation conditions and to plan for a maintenance action. Without vacuum gauge on PC, it is difficult to detect the leak in operation because of the cryopumping induced by cavities. When the VG is not used on the PC, the beginning of the cavity performances degradation may be a sign of a tightness problem. This observation is not immediate, does not give the possibility to have a precise estimation of the magnitude of the leak and may not allow to designate the leaky coupler.

In the case of the 650 MHz PC, the implementation of the proposed solution (adding a VG) wasn't straightforward. This is because the advanced design of the HB650 cryomodule and the corresponding PC does not allow trivial use of the VG outside the vacuum tank (see Fig. 1). The use of the VG inside insulating vacuum seems to be the optimal option. Nevertheless, this configuration is not common for VGs generally used for these applications.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV012

SUBSTITUTION OF SPRING CLAMPS FOR BOLTS ON SRF FLANGES TO MINIMIZE PARTICLE GENERATION*

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Abstract

Hyperboloid LLC developed and successfully tested a System of High Force Spring Clamps to substitute, one for one, for bolts on the flanges of SRF Cavities. The Clamps are like exceptionally forceful binder clips. The System, that includes the Hydraulic Openers that apply the clamps, minimizes generation of particulates when sealing cavity flanges. Hyperboloid LLC used ANSYS to design the titanium clamps that generate the force to seal the hexagonal cross section, relatively hard aluminium gasket developed for TESLA and used at TJNAF and other accelerators. The System is developed to be suitable for use in SRF Clean Rooms. Results of particle counter readings during bolt and clamp installation and superfluid helium challenges to the sealed flanges are discussed. Results of a half-size clamp that could seal a soft aluminium gasket and the attempt to seal a gasket made of niobium are also discussed.

INTRODUCTION

Hyperboloid LLC designed, developed and tested the High Force Spring Clamp System characterized in Patent US 9756715 [1] that is a solution to this HBIR topic. The patent is held by Thomas Jefferson National Accelerator Facility (TJNAF).

This work validated a System that removes the greatest source of particle generation in the Superconducting Radio Frequency Cavity assembly clean room – the bolt and nut fasteners – and substitutes highly sprung "C" shaped spring clamps that may be thought of as robust Binder Clips. The clamps were installed inboard of the bolt holes of an existing flange of a Research SRF Cavity. The Cavity and parts, cleaning support, Flow Hood Facilities and Testing were supplied by TJNAF§. The Clamps were successful, established a vacuum tight seal challenged by superfluid helium, at 2 K, during two individual test cycles.

THE CLAMPS

The Prototype Clamp

The Prototype Camp was a proof of concept at the outset of the project. It formed a room temperature, helium gas leak tight seal on our assigned research cavity, RDT-05. As in all future tests, the opposite flange was sealed using standard bolts. This test proved the clamps produced the predicted high force necessary to crush a hexagonal section, high yield point, 5754 aluminium (In the US: 6060-T66) alloy gasket [2-3]. This gasket is used on cavities in US Accelerators and the International Linear Collider Project. See Fig. 1. The Prototype Test also validated the workings of the Hydraulic Clamp Openers described in the Patent.

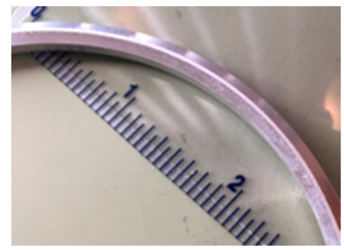

Figure 1: Hexagonal Cross Section, Aluminum Gasket.

Model 1 Clamp

Model 1 Clamps, shown in Fig. 2, with substituted hooks on the wings from the Prototype's eyelets, were installed on RDT-05 in a flow hood environment through two assembly/ test cycles. These cavity assemblies were internally clean enough to utilize the clean vacuum system of the JLab Vertical Test Area (VTA) and were pumped to a vacuum of 10^{-6} Torr. The cavities were mounted in one of the Area's Dewars and cooled by liquid helium, under reduced pressure, to 2 K in the Helium II or "Superfluid" state. This state is known for finding the smallest leaks. During both cycles, the readable vacuum within the cavities reduced to the 10^{-8} Torr range. The internal vacuum would not have remained in this range if there was the slightest leak. The Clamps (and their Hydraulic Openers) work as described in the Patent.

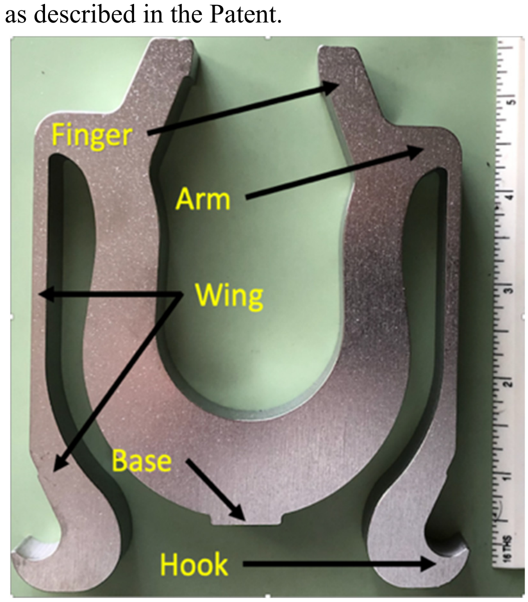

Figure 2: Model 1 Clamp.

*Work supported by DOE SBIR Grant # DE-SC0019579
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§ CRADA #JSA 2019S00

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV013

LCLS-II CRYOMODULE PRODUCTION AT JLab: SUMMARY AND LESSONS

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Abstract

Cryomodules (CMs) for the Linear Coherent Light Source II (LCLS-II) at SLAC National Accelerator Laboratory were jointly fabricated at Thomas Jefferson National Accelerator Facility (JLab) and Fermi National Accelerator Facility (FNAL). Procurements, cavity testing, cryomodule assembly, and cryomodule testing were carried out at the two labs. Twenty-one 1.3GHz cryomodules were fabricated at JLab. The LCLS-II cryomodules are based on the design used in the European X-Ray Free-Electron Laser (XFEL) but modified for continuous-wave operation. The higher performance requirements lead to challenges in cavity processing, microphonics, magnetic hygiene, and cryomodule transportation. This paper outlines the cryomodule production experience at JLab, as well as improvements to procedures and infrastructure to overcome the performance challenges of the LCLS-II design.

INTRODUCTION

The LCLS-II project involves the construction of a 4GeV continuous-wave superconducting linear acceleration at SLAC. The 35 new CMs were installed in a one-kilometer stretch of tunnel that formerly housed the normal-conducting LCLS. A total of 40 1.3GHz CMs were fabricated at JLab and FNAL.

The LCLS-II CM (Fig. 1) uses eight 9-cell TESLA-style cavities. The CMs are based on the design installed in the XFEL machine at DESY. The major difference between LCLS-II and XFEL is that the former is a CW machine and the latter is pulsed. Changes in design were implemented to allow for CW operation. Adapting the XFEL design was seen as a method for reducing risk. FNAL was chosen to be the design authority for the LCLS-II cryomodules due to their experience with TESLA-style CM design and assembly [1].

Cryomodule production for the LCLS-II project was carried out between 2015-2021. An extra five cryomodules were added to the initial count of 35, for redundancy. Twenty-one of these were fabricated at JLab and the remainder were fabricated at FNAL. Each lab built an initial prototype cryomodule (pCM) to test the new design and the two production lines. The pCMs were built using former ILC R&D cavities which were already fabricated. They also featured extra instrumentation to aid in qualification.

At the time of LCLS-II's conceptual start, JLab had completed four different cryomodule production runs in its history: the original CEBAF C20s, SNS high and medium beta CMs for ORNL, the JLab Free-Electron Laser (FEL), and the C100s for the recently completed CEBAF 12 GeV upgrade. Lessons and strategies from these projects were the basis for JLab's LCLS-II production strategies. The facilities and infrastructure used for producing these CMs would need to be modified for the very different ILC/XFEL-style CMs while remaining usable for future work on CEBAF-style CMs.

The evolution of the XFEL design to the CW LCLS-II cryomodules produced several unintended consequences during CM production. Work was stopped and restarted on several occasions to develop mitigations for these unforeseen issues.

Since the completion of the LCLS-II project, work has started on the LCLS-II High Energy Upgrade (LCLS-II-HE). JLab will assemble eleven HE cryomodules – which are the same as LCLS-II CMs apart from a different cavity processing recipe and tuner – utilizing the lessons learned from the original project.

Figure 1: An LCLS-II cryomodule being prepared for shipment to SLAC.

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV014

MANAGING PROCUREMENTS IN THE TIME OF COVID-19: SNS-PPU AS A CASE STUDY*

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Abstract

In early 2020, COVID-19 swept across the world. The accelerator industry, like many others, was impacted by disease, delays, shortages, and new working conditions. All Thomas Jefferson National Accelerator Facility (JLab) employees were sent home in mid-March 2020, with many still working remotely now. At the time, JLab was working on the Proton Power Upgrade (PPU) to the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL). Procurements had been placed and were being managed, parts were being received and inspected. This paper details the JLab procurement plan for the SNS PPU project, and the mitigations that were developed to continue to support this project smoothly under the limitations imposed by COVID-19.

BACKGROUND

The Proton Power Upgrade will increase the beam power of the SNS proton accelerator at Oak Ridge National Laboratory from 1.4 to 2.8 MW and increase beam energy by 30%. During the original design of SNS, space in the linac was reserved for additional cryomodules to be added at a future time. As part of the PPU upgrade, eight cryomodules, each containing four high-beta superconducting cavities, will be added to the existing linac [1, 2, 3]. (Seven of these cryomodules were part of the original project scope, with the last added in 2021.)

JLab began work on the Spallation Neutron Source Proton Power Upgrade SNS PPU for ORNL in fall of 2018, with a scope of designing, procuring, and constructing the cryomodules for the upgraded accelerator (Fig. 1). The cryomodule was based on the original JLab SNS design from the early 2000's, and incorporated modifications made by SNS over the ensuing years. JLab revisited the design of each component with an eye to updating the design to reflect the latest standards in accelerator technology. The first year or so of the project was spent in cryomodule design, and procurement activities began around a year later, in summer/fall 2019.

JLab is responsible for procuring all components to support construction of the cryomodules, except for the cavities and fundamental power couplers. These are provided by SNS but still received, inspected and installed at JLab. Major procurements managed by JLab include the vacuum vessels, space frames, magnetic shielding, beamline bellows, helium vessels, tuners, instrumentation, and end cans, for a total of over thirty separate components. The procurement activities for these major components, as well as for a number of smaller items and hardware, were well underway by early 2020, as was the spread of COVID-19.

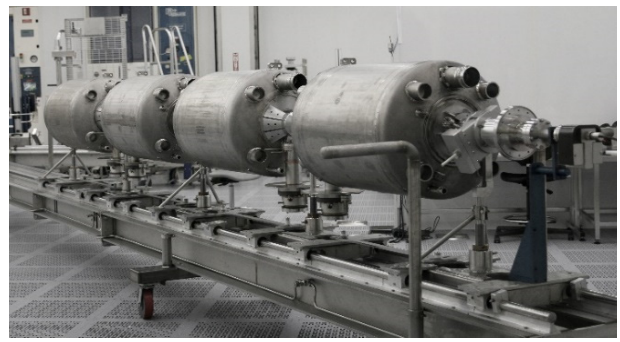

Figure 1: SNS PPU cavity string.

COVID-19 IMPACT

On March 17, 2020, JLab entered "MEDCON-6" status due to concerns about the increasing spread of COVID-19, and all but a few critical JLab employees were sent home. MEDCON-6 status requires that the lab close most facilities and limit staff on site to no more than 30 people in an attempt to interdict the spread of contagion. Employees who were able to work remotely, including scientists, engineers, and procurement staff, continued to do so. All inspection, testing and assembly activities ceased and were not able to resume, even partially, until mid-June, 2020, with JLab's reclassification to MEDCON-5 status (Fig. 2). This still restricted many operations but allowed a subset of staff to return to work on site to perform hands-on activities.

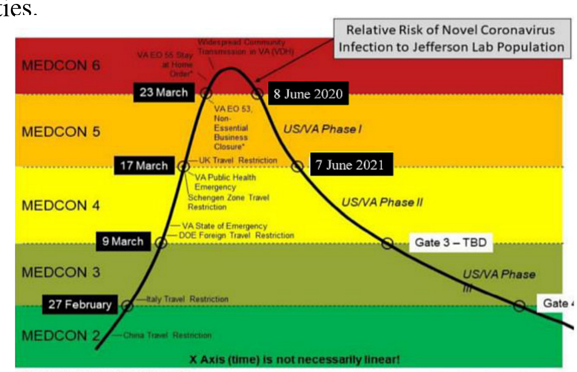

Figure 2: JLab's COVID-19 operations plan.

At the time of the JLab MEDCON-6 shutdown, about 85% of the approximately $9 million of procurements had been awarded, with over $1 million of that scheduled to be delivered to JLab within 3 months, and almost $3 million within 6 months.

* This work was supported by the Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177 (JSA); and by UT-B which manages and operates Oak Ridge National Laboratory under contract DE-AC05-00OR22725.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV015

CYLINDRICAL MAGNETRON DEVELOPMENT FOR Nb_3Sn DEPOSITION VIA MAGNETRON SPUTTERING*

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Abstract

Due to its better superconducting properties (critical temperature T_c 18.3 K, superheating field H_{sh} ~400 mT), Nb_3Sn is considered as a potential alternative to niobium (T_c 9.25 KTc, H_{sh} ~200 mT) for superconducting radiofrequency (SRF) cavities for particle acceleration. Magnetron sputtering is an effective method to produce superconducting Nb_3Sn films. We deposited superconducting Nb_3Sn films on samples with magnetron sputtering using co-sputtering, sequential sputtering, and sputtering from a stoichiometric target. Nb_3Sn films produced by magnetron sputtering in our previous experiments achieved DC superconducting critical temperature up to 17.93 K and RF superconducting transition at 17.2 K. A magnetron sputtering system with two identical cylindrical cathodes that can be used to sputter Nb_3Sn films on cavities has been designed and is under construction now. We report on the design and the current progress on the development of the system.

INTRODUCTION

Nb superconducting radiofrequency (SRF) cavities used in modern particle accelerators are reaching close to the theoretical limit for the quality factor and accelerating gradient due to the limited superconducting critical temperature Tc of 9.25 K and the superheating field Hsh of 200 mT [1, 2]. Nb_3Sn promises a better performance than niobium due to the high T_c 18.3 K) and H_{sh} (400 mT) [2]. Since Nb_3Sn is a brittle material, thin films of Nb_3Sn inside a Nb or Cu cavity are considered. The most widely used technique to coat Nb_3Sn inside the cavity is Sn vapor diffusion method [2–4]. Also, magnetron sputtering has been used to fabricate Nb_3Sn films on small substrates [5–12].

We have fabricated Nb_3Sn films on small Nb substrates by magnetron sputtering [7–12]. We are commissioning a cylindrical sputtering system to fabricate Nb_3Sn films inside a 2.6 GHz SRF cavity. Here, we report our initial progress on the cylindrical sputtering system fabrication.

Nb_3Sn GROWTH BY MAGNETRON SPUTTERING

We deposited superconducting Nb_3Sn films with magnetron sputtering in three ways: multilayer sputtering of Nb and Sn films followed by annealing, sputtering from a stoichiometric Nb_3Sn target, and co-sputtering of Nb and Sn followed by annealing. An AJA ATC Orion 5 Magnetron sputter coater was used for the fabrication. For the multilayered samples, we have deposited multiple layers of Nb and Sn films with a thickness of 20 and 10 nm respectively. The multilayers were annealed at 950 °C for 3 h. Figure 1 shows the transmission electron microscopic (TEM) images and EDS mapping of the cross-section of as-deposited multilayers and annealed Nb_3Sn film. The multilayers are easily distinguishable from the EDS mapping of the as-deposited films. The TEM-EDS mapping of the annealed film showed that Sn (green color in the mapping image) is uniformly diffused.

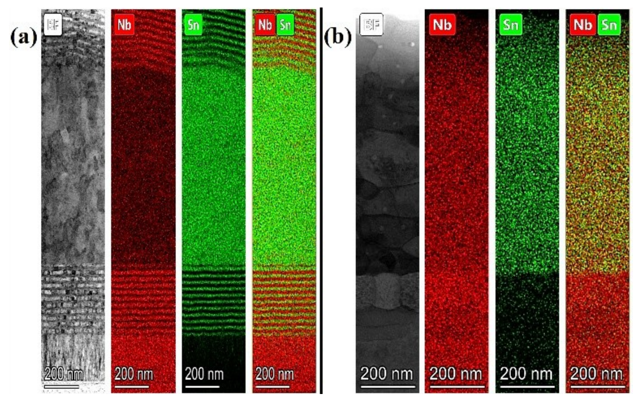

Figure 1: TEM image and EDS mapping of (a) as-deposited Nb-Sn multilayers, and (b) annealed Nb_3Sn film.

Table 1: The Superconducting Properties of Nb_3Sn Films Fabricated by Three Different Magnetron Sputtering Processes

Fabrication method	T_c	ΔT_c	RRR
Multilayer sputtering	17.93	0.02	5.1
Stoichiometric target	17.83	0.03	5.41
Co-sputtering	17.6	0.22	3.63

For the samples fabricated from a stoichiometric target, sputtering was performed at a 3 mTorr Ar pressure with a constant DC current of 150 mA on a substrate heated up to 800 °C. For co-sputtering, the powers of both targets were optimized to maintain the film stoichiometry and the co-sputtered samples were further annealed. The resistance vs temperature graph of the film co-sputtered at room tempera-

* Authored by Jefferson Science Associates, LLC under U.S. DOE. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics. Contract No. DE-AC05-06OR23177.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV016

THE ROLE OF OXYGEN CONCENTRATION IN ENABLING HIGH GRADIENTS IN NIOBIUM SRF CAVITIES

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Abstract

We studied the role of O concentration with depth in the performance of Nb SRF cavities. An ensemble of electropolished 1.3 GHz cavities, which initially showed high field Q-slope (HFQS), was subjected to sequential testing and treatment with *in-situ* low temperature baking at various temperatures. We find that increasing the bake duration causes (i) an increase in the onset of HFQS until it is absent up to quench (ii) a non-monotonic relationship with the quench field (iii) an evolution of the R_{BCS} toward a non-equilibrium behavior that drives anti-Q slope. Our data is qualitatively explained by assuming an O diffusion model and suggests that the mitigation of HFQS that arises from 120 C *in-situ* LTB is mediated by the diffusion of O from the native oxide which prevents the precipitation of proximity-coupled Nb nano-hydrides, in turn enabling higher quench fields. The decrease in quench field for cavities in which O has been diffused >90 nm from the RF surface may be due to a reduction of the field limit in the SS bilayer structure. We also suggest that the evolution of the R_{BCS} occurs due to the absence of proximity coupled inclusions, bringing about non-equilibrium effects.

INTRODUCTION

Recent work by Romanenko *et al.* on Nb SRF cavity cutouts has highlighted the involvement of oxygen diffusion in the 120 C bake effect [1,2], which describes the mitigation of high field Q-slope (HFQS) [3] by *in-situ* low temperature baking (LTB) fully assembled and evacuated SRF cavities at 120 C for a period of 48 hours [4]. The work shows that the 120 C LTB diffuses oxygen from the native niobium oxide according to Fick's law [5] and traps free hydrogen present within the niobium lattice [6], thereby inhibiting the precipitation of poorly superconducting niobium nano-hydrides upon cool down to cryogenic temperatures. This results in a lower volume fraction or elimination of nano-hydrides that in turn yields a larger proximity breakdown field, shifting up or eliminating the onset of HFQS. However, a systematic study that investigates the evolution of HFQS and cavity performance with increasing oxygen diffusion depths has not yet been reported.

Using the findings of Romanenko *et al.* as a driver, in this contribution, we report a systematic study on the effect of gradually increasing the depth to which oxygen diffuses on the RF performance of 1.3 GHz bulk niobium TESLA-shaped SRF cavities and show that oxygen plays a key role in enabling exceptional cavity performance. We find that the field of HFQS onset varies linearly with increasing oxygen diffusion depth, supporting the Romanenko model of HFQS and the 120 C baking effect. We also show that there exists a non-monotonic dependence of the quench field with O diffusion depth. Furthermore, we present a gradual evolution of the RF performance toward a doped-like anti-Q slope behavior that stems from a decrease in the BCS resistance with field after *in-situ* baking at 200 C for 6 hours, suggesting that O impurities may bring about these effects.

EXPERIMENTAL

We used an ensemble of TESLA-shaped 1.3 GHz Nb single cell SRF cavities that were initially treated with a bulk removal via electropolishing (EP) from the inner RF surface post initial fabrication and an 800 C degas step [4]. All cavities were then subjected to a 40 μm removal of the inner surface via standard EP. The cavities were then assembled for testing and evacuated. Most cavities were tested at this point to get a baseline, which will be referred to as "EP."

Cavities were subjected to sequential rounds of *in-situ* low temperature baking at various temperatures ranging from 90 C up to 200 C, diffusing oxygen from the native oxide toward the bulk according to Fick's law. After each step of treatment, cavities were RF tested at a temperature of 2 K. Most tests were repeated at <1.5 K to enable decomposition of the BCS and residual resistances [7]. To minimize the possibility of trapping of magnetic flux through superconducting transition, we used Helmholtz coils to provide a zero field environment and a fast cool down protocol to produce a sufficient thermal gradient along the length of the cavity [8].

Some cavities developed field emission after several rounds of treatment and testing. We found that high pressure rinsing effectively removed field emission without deleteriously affecting cavity performance. Only tests that showed minimal field emission are presented here.

While we extensively tested 7 cavities, we explicitly report the results of only three and present the rest in the form of statistics in the Discussion section.

Effect of Sequential 120 C Baking

Due to its wide use, we first studied the effect that sequential baking at 120 C has on cavity performance; the results are shown in Fig. 1. The baseline EP test, which was only performed at 2 K, showed the expected onset of HFQS at 25 MV/m. The test was power limited. After baking at 120 C for 30 minutes, the HFQS onset shifted up to 27 MV/m but we were still limited by available RF power. Following an additional 30 minute bake, for a net treatment of 120 C for 1 hour, HFQS onset shifted further up to 29 MV/m and quench occurred at 34.4 MV/m. Subsequent treatment and testing showed that both the field of HFQS onset and quench field increased with integrated bake duration.

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THPTEV017

STATUS OF THE LCLS-II-HE PROJECT AT JEFFERSON LAB*

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Abstract

The Linac Coherent Light Source II High Energy (LCLS-II-HE) upgrade at the SLAC National Accelerator Laboratory is being constructed in partnership with the Thomas Jefferson National Accelerator Facility (JLab) and the Fermi National Accelerator Laboratory (FNAL). The cryomodule production scope consists of the design, procurement, construction, and acceptance testing of 24 eight-cavity, 1.3 GHz cryomodules, as well as R&D activities necessary to develop the required technology. To achieve this, JLab and FNAL are also contributing to SLAC's effort to develop the cavity recipe and production processes necessary to meet the LCLS-II-HE goal of 20.8 MV/m and average Q_0 of 2.7×10^{10}. This paper details the JLab scope, focusing on the project initiation phase, in particular technology development and prototyping, project development and planning, and implementation of lessons learned from LCLS-II.

BACKGROUND

In the mid-2010s, SLAC began a major upgrade to its LCLS accelerator, called LCLS-II. Several Department of Energy national laboratories, including JLab, participated in this project. JLab, along with FNAL, was responsible for the construction of a total of 40 SRF cryomodules. SLAC is now beginning the upgrade to that project, LCLS-II-HE, which will increase the power of the linac from 4 GeV to 8 GeV. To achieve this, the requirements for cavity performance have increased to 20.8 MV/m and Q_0 of 2.7e10.

The LCLS-II cryomodule design was based on the XFEL design to reduce schedule risk and cost. Some modifications were added for LCLS-II to support the different requirements of the accelerator, particularly continuous wave operation. For LCLS-II-HE, the same design will be used except for a new cavity processing protocol and redesigned tuners. Otherwise, the hardware designs will, with some minor corrections, be identical to LCLS-II.

Jefferson Lab has many years of experience with design, construction and testing of SRF cryomodules, beginning with the design and construction of the CEBAF cryomodules in 1987. Since then, JLab has vertical tested more than 5500 cavities and built 42 cryomodules for CEBAF, 23 for SNS, 3 for JLab's FEL, 21 for LCLS-II, and is on track to build 8 for SNS PPU.

SCOPE OF WORK

The HE baseline project consisted of twenty 1.3 GHz cryomodules, each containing eight elliptical cavities. The project has since added four more cryomodules, three for the accelerator and one for the injector. JLab will be responsible for producing eleven of the cryomodules.

In the three-lab partnership for the cryogenics scope, SLAC is responsible for management of the overall project, FNAL is responsible for cryomodule design, all three labs will share the procurements, and JLab and FNAL will construct and test the cryomodules. As shown in Fig. 1, JLab and FNAL will follow generally parallel production paths.

This collaboration obviously requires significant interaction and communication between the partner laboratories to ensure smooth coordination of work. From the beginning, there have been frequent regular meetings and other paths of communication set up to insure the large and geographically distributed team works together cohesively.

PROJECT PLAN AT JLab

JLab developed a schedule which begins with pre-production activities such as developing procurement documents and evaluating lessons learned from LCLS-II. The schedule moves through all phases of production, from procurements to cavity testing to cryomodule assembly, testing, and shipping. There are separate activities for cavity research and development, which focus on developing the cavity treatment process necessary to produce the cutting-edge cavity performance required for this project (Fig. 2).

Schedule development was greatly facilitated by the recent work on LCLS-II, which was used as a basis of estimate to develop cost and labor estimates for HE [1]. A small learning curve at the beginning of HE production was planned, to allow for training of new staff or implementing process improvements.

The production rate is somewhat slower than on LCLS-II to allow other projects to be intermeshed with HE. While LCLS-II used two assembly rails in parallel, HE will use only one to allow other construction projects in the Test Lab to proceed simultaneously, including cryomodules for JLab's own CEBAF accelerator and SNS PPU.

The HE project is staffed by JLab employees drawn from several departments. Many of the HE team are veterans of LCLS-II, and therefore familiar with the work and lessons learned. The production staff from the SRF Institute, many of whom worked on LCLS-II, are supporting other projects in the interim between LCLS-II and HE, but will be available to transition to HE production as needed later this year. The project has worked with line managers to develop a staffing plan to integrate the needs of HE and other projects at JLab.

CAVITY R&D

The project focused initial efforts on research to develop the cavity recipe and production requirements necessary to reliably produce even higher performance cavities; JLab

* This work was supported by the U.S. Department of Energy Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177 (JSA); and for Basic Energy Science under contract DE-AC02-76SF00515 (SLAC).
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-FROFDV01

SYSTEMATIC INVESTIGATION OF MID-T FURNACE BAKING FOR HIGH-Q PERFORMANCE*

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Abstract

We report on an investigation of the effect of a new baking process called “furnace baking” on the quality factor. Furnace baking is performed as the final step of the cavity surface treatment; the cavities are heated in a vacuum furnace in a temperature range of 200 to 800°C for 3 h, followed by high-pressure rinsing and radio-frequency measurement. We find the anti-Q slope for cavities furnace-baked at a temperature range of 250 to 400°C and a reduction in the residual resistance for all cavities. In particular, an extremely high Q value of 5×10^{10} at 16 MV/m and 2.0 K is obtained for cavities furnace-baked at 300°C.

INTRODUCTION

Decades of continuous research for the improvement of the performance of superconducting radio-frequency (SRF) cavities [1, 2] have resulted in the establishment of various surface treatments; thus SRF cavities with superior performance in terms of the quality factor (Q_0) and accelerating gradient (E_{acc}) have been developed [3–5].

In this study, we investigated the increase of the Q_0 by a new heat-treatment method called “furnace baking” [6] which is a simpler method than the surface treatment methods such as nitrogen doping [7, 8], nitrogen infusion [8, 9], and two-step baking [10] that have been proposed and investigated in recent years.

EXPERIMENT

In the furnace baking process, a baking process in a vacuum furnace is performed following light electropolishing. After baking, high-pressure ultrapure water rinsing (HPR) is performed to remove any remaining impurities on the inner surface of the cavity and then assembled in a cleanroom. Finally, RF measurement is performed. In this study, these processes are repeated for 1.3 GHz single-cell cavities at different baking temperatures to investigate the relationship between baking temperature and Q-E behavior in furnace baking.

A large vacuum furnace is used for furnace baking [11]. The vacuum system consists entirely of oil-free pumps and can be depressurized to 1×10^{-6} Pa at room temperature using a cryopump. To prevent the inner surface of the cavity from being contaminated by the furnace, the cavities are placed in a large vacuum furnace with the flanges covered using niobium caps (see Fig. 1). The vacuum furnace is equipped with Quadrupole Mass Spectrometer (Q-mass) to monitor the partial pressure of each element during heat treatment. The main elements during heat treatment are mass 2, 18, 28, 44 which correspond to H_2, H_2O, N_2, CO_2 respectively, and the signals of the high mass molecules are small (see Fig. 2).

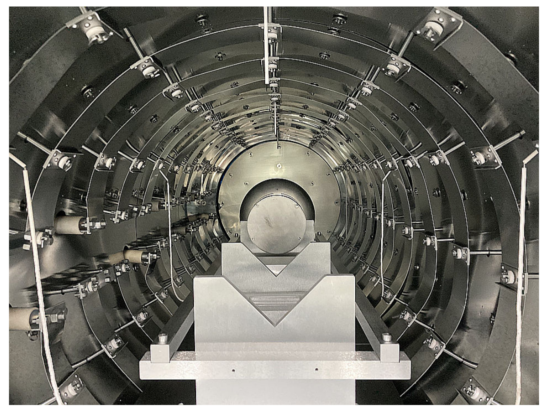

Figure 1: Photograph of inside of vacuum furnace and single-cell cavity with flange covered by niobium cap.

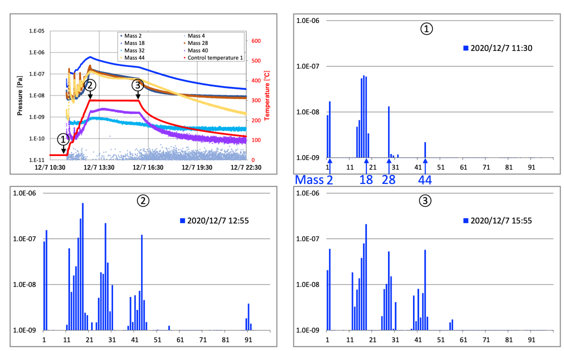

Figure 2: Temperature and Q-mass trends during 300°C 3 h furnace baking and Q-mass data at each moment. Red curve in upper left panel shows temperature trend of control temperature sensor, other curves show Q-mass trend of each element.

Figure 3 shows a photograph of the RF measurement setup including the heater, temperature sensors, and fluxgate sensors. Magnetic shielding inside the cryostat and a solenoid coil mounted at the outside of the cavity keep the magnetic field around the cavity below ~1 mG. In addition, flux expulsion is performed using a heater place at the top beam tube to minimize the flux trapping. The magnetic field around the cavity is monitored with fluxgate sensors. A temperature mapping system is equipped to detect the heating point.

* Work supported by JSPS Grant-in-Aid for Scientific Research(B) No. 19H04402.
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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-FROFDV03

INVESTIGATING THE ANOMALOUS FREQUENCY VARIATIONS NEAR T_C OF Nb SRF CAVITIES

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Abstract

We report recent studies on the anomalous frequency variations of 1.3 GHz Nb SRF cavities near the transition temperature T_c and use them to investigate the underlying physics of state-of-the-art surface treatments. One such feature, a dip in frequency, correlates directly with the quality factor at 16 MV/m and the anti-Q slope that arise in cavities with dilute concentrations of N interstitial in the RF layer achieved *via* N-doping and mid temperature baking. For N interstitial, we find that the dip magnitude and T_c follow exponential relationships with the electronic mean free path. We present the first observation of the frequency dip near T_c in a cavity baked at 200 °C *in-situ* for 11 hours, which is concurrent with the anti-Q slope, and may be driven by oxygen diffused from the native oxide, thus suggesting the possibility of "O-doping." We also investigate the conductivities of two cavities that display different resonant frequency behaviors near T_c and suggest that the anti-Q slope and frequency dip phenomena may occur in the presence of interstitial N or possibly O that inhibit the formation of proximity coupled Nb nano-hydrides.

INTRODUCTION

Most niobium superconducting radio-frequency (SRF) cavity research uses the quality factor Q_0 and thus the surface resistance R_s as a function of the accelerating gradient E_{acc} to gain insight on the microscopic mechanisms that enable the unprecedented performance of these resonators after undergoing various surface engineering treatments. However, there are far fewer studies on the resonant frequency f_0 behavior of cavities as a function of temperature, which yields valuable information on the surface reactance X_s and thus the superconducting carriers.

Recent work has shown that this frequency response holds a wealth of information. In particular, there exist features in the resonant frequency near the superconducting transition temperature T_c in bulk niobium SRF cavities that vary with surface processing and correlate well with cavity performance [1, 2]. This work shows that N-doped cavities, which exhibit high Q_0 and the anti-Q slope [3], a counterintuitive increase in Q_0 with E_{acc} that is suspected of having origins in non-equilibrium superconductivity [4] but has eluded full understanding, always produce a prominent dip in the resonant frequency just below the critical transition temperature. On the other hand, electropolished cavities [5], which are known to contain proximity coupled niobium nano-hydrides that drive high field Q-slope (HFQS) [6], often exhibit a sharp transition of the resonant frequency from the superconducting to the normal conducting regime, dubbed the standard feature. In addition, *in-situ* low temperature baked (LTB) cavities [5], which have historically achieved high quench fields, moderately high quality factors, and have been shown to mitigate HFQS by diffused oxygen preventing the precipitation of Nb nano-hydrides [7, 8], yield the foot feature in the frequency response near T_c, which describes a plateau of the resonant frequency just before going normal conducting. Such correlations between RF performance and frequency behavior stimulates continuing studies on the mechanisms at play as a full understanding would likely guide the development of new surface engineering protocols that further improve the performance of SRF cavities.

In this contribution, we investigate the frequency response near T_c of niobium SRF cavities subjected to state-of-the-art surface processing techniques (N-doping, mid-T baking, low temperature baking) and correlate with RF performance. We show that both nitrogen doped and mid-T baked cavities, which show high Q_0 and anti-Q slope, exhibit a prominent dip in the resonant frequency just before superconducting transition which is shown to scale with the measured quality factor at 16 MV/m. We find that the T_c and magnitude of the dip follow exponential relationships with the extracted electronic mean free path. Moreover, we show that *in-situ* low temperature baking brings about the anti-Q slope and dip phenomena *in the absence of nitrogen* and suggest that the behaviors may be driven by oxygen diffused from the native oxide, bringing about the concept of "oxygen doping." Lastly, to investigate possible differences in superconducting properties, we calculate and fit the complex AC superconducting conductivity of two cavities that exhibit different frequency features near T_c and find that the frequency dip and anti-Q slope occur when the average superconducting gap value is large and the inelastic scattering parameter is at a minimum, suggesting that these behaviors may be inherent to niobium that is void of proximity coupled inclusions.

EXPERIMENTAL

We performed our studies on TESLA-shaped 1.3 GHz bulk niobium single-cell SRF cavities that underwent a bulk removal from the inner RF surface *via* EP followed by an 800 °C degassing step and an additional 30 µm EP removal from the inner RF surface. Cavities were then treated with different state-of-the-art surface treatments, including nitrogen doping [3] and *in-situ* low temperature baking [5]. Note that nitrogen doping is usually referred to as "x/y + z µm

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ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-FROFDV06

SYNTHESIS OF Nb AND ALTERNATIVE SUPERCONDUCTING FILM TO Nb FOR SRF CAVITY AS SINGLE LAYER

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Abstract

The production of superconducting coatings for radio frequency (RF) cavities has been developed over several decades. It is widely accepted that for any further improvement in cavity RF performance, innovation is needed and one may have to turn to other forms of Nb and other superconducting materials. The potential benefits of using materials other than Nb would be a higher *T*c and a potentially higher critical field H_c. This could lead to potentially significant cryogenic cost reductions if the cavity operation temperature is 4.2 K or higher. We report on optimising deposition parameters and the effect of substrate treatment prior to deposition, on successful synthesis of Nb and A15 superconducting thin film. The materials characterization is determined using scanning electron microscopy SEM, energy dispersive spectroscopy EDS, glancing X-ray diffraction GXRD, atomic force microscopy AFM and Rutherford backscattering RBS. The DC superconducting properties have been tested using Vibrating Sample Magnetometer VSM and Magnetic Field Penetration MPF. This work involves a team of 8 research groups in 7 different countries and is part of the H2020 ARIES collaboration.

INTRODUCTION

Radio-frequency (RF) cavities are used to accelerate charged particles in particle accelerators which can be used for a wide range of applications in science, health, safety, industry, etc. RF cavities made of superconducting materials, such as niobium, are currently the preferred solution. Niobium has the highest critical temperature (T_c = 9.25 K) and the highest superheating magnetic field H_{sh} of all the pure metals, also, it can easily be formed into the required cavity shape. The RF performance of bulk Nb cavities has continuously improved over the years, it is now approaching the optimal performance achievable (H_{sh} ~ 210 mT) [1-4]. However, they are quite expensive and operate at the theoretical performance limits of the material at temperatures below 2 K. Although further improvement has been achieved with nitrogen surface doping [2–4], long term solutions for SRF surface efficiency enhancement need yet to be pursued.

Thin films are the most economical way to modify surface properties to achieve enhanced performance, whether it is via single or multilayer configuration. The ultimate performance and efficient implementation of the thin film coatings depends on deposition parameters, deposition process and, most importantly, the substrate surface that is going to be deposited.

There are several physical properties that can affect the film's superconducting performance such as surface roughness, microstructure in terms of grain size and boundary, localise defects, residual stress and interfacial voids. It is a non-trivial process to separate and control the individual contributions from each of these factors. In order to achieve optimal performance in SRF cavities, it is necessary to understand the relationship of different deposition parameters on the formation of these factors and, consequently, on the superconducting properties of thin films.

In general, and particularly SRF thin film synthesis, other factor which has strong effects on the optimum superconducting performance is substrate material, substrate surface morphology as well as surface chemistry [5]. Lattice parameters a_0 were measured for films deposited onto the native oxide of copper and oxide free copper, producing similar a_0 of 3.3240 and 3.3184 Å respectively [5]. Niobium films grown on the oxidised copper substrate form grains which measure approximately 100 nm across, whereas grainsize is the order of microns on the oxide free substrate, resulting in larger RRR [6, 7].

Hence, for SRF thin film, surface preparation which includes surface treatment (to change the properties of surface in a desirable way) as well as cleaning (reduction of surface contamination to an acceptable level) is a major step. Surface preparation is an essential prerequisite for thin film synthesis. Rough or chemically impure surfaces adversely affect the nature of the thin film. A substrate that is flat, has sufficient grain size, and is chemically pure is the ideal starting point for thin film deposition.

As part of Horizon 2020 Integrated Activity ARIES program, we studied the effect of different substrate prepara-

* Work supported provided by European Union's ARIES collaboration H2020 Research and Innovation Programme under Grant Agreement no. 730871.
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