SUPERCONDUCTING CAVITIES AND CRYOMODULES FOR PROTON AND DEUTERON LINACS

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Abstract

We review the recent advances in the design plans and test results of the superconducting structures for proton (ESS) and deuteron linacs (SPIRAL2, IFMIF). A variety of RF resonators is used for these purposes, from multicell elliptical cavities for the acceleration of pulsed proton beams to half and quarter wave resonators for CW deuteron beams. The increase in beam power with respect to previous generations of linacs brings new challenges to cavities and RF couplers. Test results of the available SRF prototypes and cryomodules of the aforementioned projects will be presented.

EUROPEAN SPALLATION SOURCE

The European Spallation Source ESS will be built in Lund, Sweden. It is based on a 2 GeV, 62.5 mA superconducting (SC) pulsed proton linac [1]. It is composed of a spoke resonator section running at 352.21 MHz which brings the proton beam energy up to 220 MeV, followed by two 704.42 MHz elliptical cavity sections. The first one, based on 6-cell β=0.67 cavities accelerates the beam to 570 MeV. The higher energy section is using 5-cell β=0.86 cavities to increase the proton energy to 2 GeV. Each SC cavity is fed by an independent RF power source. Nominal RF parameters for the ESS cavities are summarized in table 1.

Table 1: RF Operation parameters of ESS cavities

	Spoke	Medium β	High β
Frequency (MHz)	352.21	704.42	704.42
Nominal E_{acc} (MV/m)	9	16.7	19.9
Qo at Nom. E_{acc}	1.5 10^9	>5.10^9	>5.10^9
βg	0.50	0.67	0.86
RF peak power (kW)	335	1100	1100
FPC Q_{ext} (x10^5)	2.85	7.5	7.6

Helium for cavity cooling is supplied at 4.5K by the common cryogenic transfer line (CTL). Each cryomodule (CM) is fed through a valve box and jumper connection. He-II is produced at the CM level using a heat exchanger and JT valve, vapour being pumped out. The operation temperature of SRF cavities is 2 K. All CM types use a 40 K shield and MLI for thermal radiation insulation. A common characteristic of all types of CMs is the use of single, room temperature window power couplers (FPC), connected to the cavities using rigid double-wall outer conductors which ensure thermal insulation using He counter flow. Cold tuning systems combining slow and fast tuning capability are used on all cavities to cope with pulsed operation. The cold magnetic shielding surrounds the He jacket of cavities. The current phase of the CM and cavity development consists in designing and building technical demonstrators of each type of CM. A collaboration between ESS, CEA-Irfu and IN2P3-IPNO is performing this tasks. Important decisions concerned the maximum allowable pressure (PS) of CMs: it was chosen sufficiently low for minimizing licensing constraints of He vessels, while conserving operation margins.

Spoke Cavities and Cryomodules

Two β=0.5 double spoke resonators are housed in each of the 13 CMs (fig. 1) designed by IPNO [2]. Besides achieving low peak surface field and tunability, the cavity design [3] must conserve a sufficient mechanical resistance of the end caps and spoke bars for sustaining pressure and leak tests at room temperature. The Ti He jacket is free of any bellow and contributes to the stiffening of the resonator. In the framework of the European pressure vessel directive PED PS was chosen at 0.8 barg for the CM. The He vessel of the spokes can thus be classified as "§ 3.3" i.e. required to be designed using sound engineering practice only.

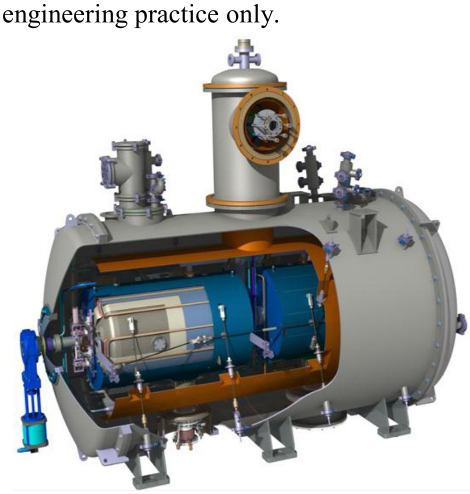

Figure 1: Double spoke ESS cryomodule.

They are supported by antagonists tie rods directly from the vacuum vessel, four radial and one axial pairs. The alignment mechanism allows adjusting the resonator position even in the operating conditions. Currently, the manufacturing of three prototypes is close to completion.

Elliptical Cavity Cryomodules

The cryomodule design is performed by IPNO in collaboration with CEA-Irfu. Medium and high β CMs have the same design and physical length. The design of the vessel, thermal shield and cavity support is described in [4] and a cut view is shown on fig. 2. A stiff, room temperature tubular structure supports the cavity string and the 40 K thermal shield which is sled into the vacuum vessel after cavity alignment has been carried out.

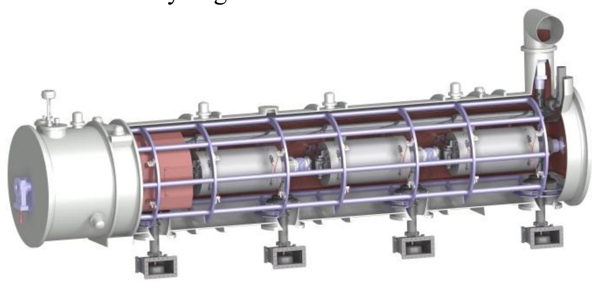

Figure 2: ESS elliptical cavities cryomodules layout.

The arrangement of the cavity supporting system is visible on fig. 3: four pairs of TA6V tie rods maintain the individual cavity position independently of temperature.

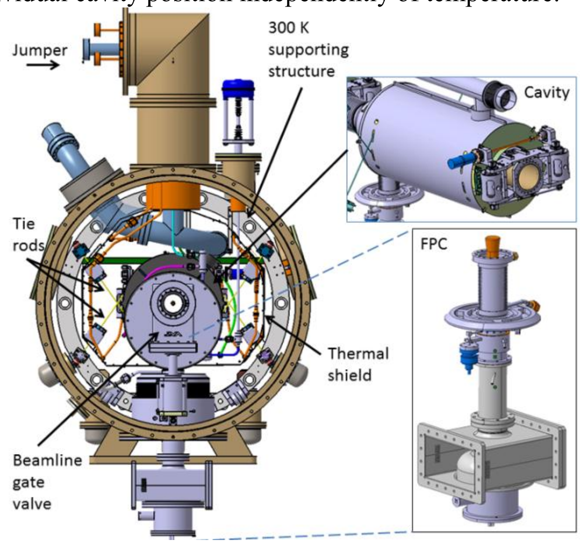

Figure3: Cross section of a ESS elliptical cryomodules.

The cavity package comprising the cavity, FPC, tuning system and magnetic shield is described in detail in [5]. The 1.2 MW FPCs are attached vertically below the cavities. Their interface to VV prevents them to move horizontally. Since FPCs are rigid, the FPC port on cavities is not affected by thermally induced movements. The vertical motion is enabled to accommodate the shrinkage of FPC's cold part. A spring-based atmospheric pressure compensation in implemented in the FPC to vacuum vessel interface. The PS of the elliptical CM was fixed to 0.9 barg given the mechanical properties of the elliptical cavities.

High Beta Prototype Cavity First Test Results

Two prototypes of the β=0.86 cavities have been build, using high purity Nb sheets (RRR> 300). Their main purpose is to demonstrate the performance in terms of accelerating gradient and Qo, but also to test all auxiliary components, flanges and gaskets in particular. Most material choices are derived from the Tesla technology. Beam and power coupler port flanges are built from NbTi. The helium vessel employs Ti as a base material, and includes a Ti bellow on the tuner side.

The un-jacketed cavities (fig. 4) have been delivered through two different manufacturers. The follow-up of dumbbell frequencies during manufacturing was targeting the operation frequency and field flatness. The field flatness of the prototypes was improved after delivery at Saclay using a dedicated tuning machine, reaching 92% and 90% starting from 86% and 39% respectively.

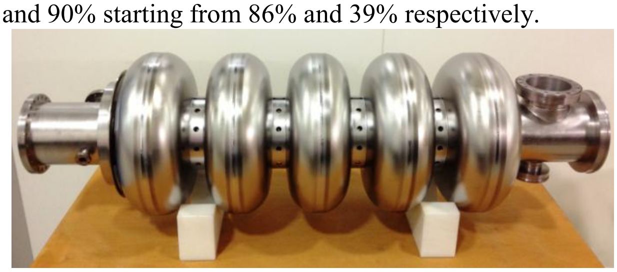

Figure 4: First β =0.86 prototype.

The chemical processing of the first cavity was done with the standard FNP 1-1-2.4 mixture. A minimal material removal goal of 150 μm (average 200 μm) was obtained in three processing steps on the vertical EP-BCP cabinet. For the third pass, the cavity was flipped over to minimize the effects of etching asymmetry between upward and downward facing cavity walls which showed up after the second pass was completed. Due to the size limitation of the current HPR setup in the Class 100 clean room, flipping the cavity over midway was required to ensure the complete rinsing of the cavity surface. The cavity was equipped with 100 mm long stainless steel end-caps simulating the presence of inter-cavity bellows.

The first cryogenic series test was performed without any preceding baking in order to assess the base performance of the cavity [6]. A fast cooldown was performed to prevent Q-disease at this early stage. The performance was ultimately limited by the cooling capability of the test cryostat. No quench was observed at high field. Field emission (FE) was observed during the first ramp up of the field but processed within minutes. All subsequent measurements were free of FE.

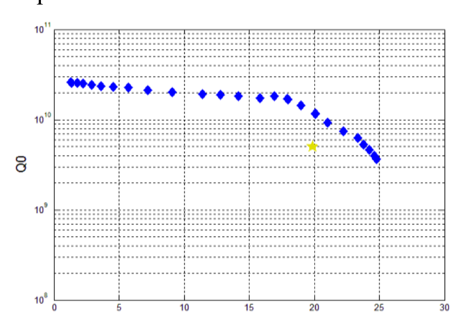

Figure 5: First ESS β=0.86 2K VT test result.

The Q=f(E) curve of the cavity is shown on figure 5 for the last test of this campaign at the nominal temperature of 2 K. Up to now, the prototypes have been processed with BCP in order to prepare for cryogenic vertical test (VT). The second prototype VT is scheduled in the coming weeks. Next steps will include a de-hydrogenation heat treatment at 650°C, followed by optional field flatness correction, final BCP and baking.

The validation of the large Al Hex gaskets (for the 140 mm diameter beam pipe) in an asymmetrical flange material configuration – one side is NbTi, the other side is stainless steel was also obtained through the test in He-II. Previous test involving repeated thermal shocks at 77 K on this sub-assembly had been performed beforehand to determine the bolting procedure and torque calibration.

Cryomodule Test Plans

A technology demonstrator of the 4-cavity medium β cryomodule will be build first in order to test all components in final configuration. Since most components are common with the high beta CM, it will be subsequently disassembled and rebuild around a high beta cavity string. Beforehand, the procurement of 6 power couplers and 6 medium beta cavities has been launched. The processing and test infrastructures linked to ESS CMs at CEA-Saclay are evolving: the new clean room is complete, the test area preparation work progresses with the installation of the cryogenic transfer line which will supply He to the CM test bunker. The Saclay 704 MHz pulsed RF power source was capable of delivering 2 ms pulses of 1.1 MW at 50 Hz. It is now refurbished in order to achieve the pulse length of 3.1 ms which will be required to test ESS FPC and cryomodules with the nominal RF pulse flat top of 2.86 ms.

IFMIF-EVEDA LIPAC

In the framework of the International Fusion Materials Irradiation Facility (IFMIF), which consists of two high power accelerator drivers, each delivering a 125 mA deuteron beams at 40 MeV in CW, a Linear IFMIF Prototype Accelerator (LIPAc), is presently under construction for the first phase of the project [7,8]. The main purpose of the LIPAc is to validate the technical options and prepare for the future IFMIF accelerator. LIPAc consists in the front end of a 125 mA IFMIF linac, stopping at the energy of 9 MeV, after the first cryomodule. A specific HEBT and test cell follows downstream. The EU contributions to this accelerator (CEA-Saclay, CIEMAT and INFN Legnaro) are coordinated by the Fusion for Energy organization. The D+ injector and LEBT are being installed on the Rokkasho site (JAEA) in Japan. The CM accelerates the beam from 5 to 9 MeV transferring a power of 500 kW to the beam through eight 175 MHz Half-Wave Resonators (HWR) operating at a temperature of 4.45 K.

Update of Cryomodule Design

The eight HWRs and solenoids [9] are contained in a single, 6 m long CM, and supported by a common frame. Figure 6 shows the cross section of the CM. The vacuum vessel is a rectangular section tube. It contains, in that order, the room temperature magnetic shield, MLI, thermal shield, cold-mass wrapped in MLI. One original feature of the design is the horizontal orientation of the HWRs. The power couplers are connected to each HWR in their mid-plane (electric region of the resonators).

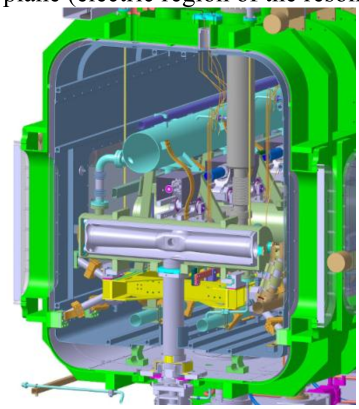

Figure 6: IFMIF LIPAc CM cut view.

Due to their size, they are supported in vertical position below the cavities. The cavity support frame is hanging from the top of the vacuum vessel thanks to ten TA6V rods. A more detailed description of internal positioning systems is available in [10]. Now, considering an earthquake scenario and the potential swinging of the whole cold mass and resulting damage to internal vacuum piping, bellows and lateral tie-rods for horizontal positioning of the support frame, an additional mechanical structure has been designed to reduce the excursion of the frame along the beam axis. It consists in two tripods which are fixed on each side of the vacuum vessel, near its centre lengthwise (fig. 7). The apex of the tripod is equipped with thermally insulated adjustable jaws fitted with a residual play around a pad extension of the support frame. The movement of the frame in the horizontal plane is kept minimal while it is left possible in vertical direction to accommodate the shrinkage of the vertical tie rods during cooldown. The thermal load due to the new structure has been minimized through thermal anchor points to the thermal shield. The tripods are designed to sustain a 1.2 g acceleration of the 2.5 ton cold-mass without damage.

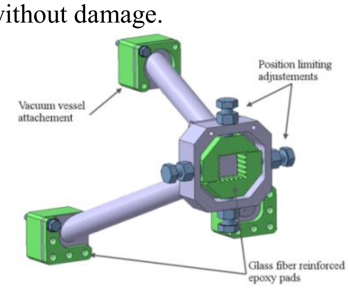

Figure 7: Frame excursion limiting tripod.

The frame has been optimized in order to reduce the thermal mass and ease its manufacturing. The material was switched to Ti alloy in an effort to cancel the risk of magnetization due to the solenoids and steerers operation.

The internal cryogenics have been revised after recent changes in the cryoplant and CTL configuration. In contrast with the former setup, the only supplied cryo-fluid is 5 K He. In the CM, a single phase separator

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supplies He for the HWRs and gas for the TS, which is now enabled to operate between 5 and 50 K. Other recent optimizations of the internal cryogenic circuit have been driven by the need to lower the pressure in the accidental scenarii and progress towards having a design compliant with the Japanese High Pressure Gas Safety Law. This was mainly obtained by specifying safety devices (burst disk on beam vacuum and safety valve on vacuum vesse) and lowering of the pressure drop in the exhaust circuits.

The initial HWR design [11] was updated by switching to a compression mechanical tuner which includes a disengagement system [12]. The resonator is housed in a Ti helium jacket which is equipped with 4 fiducials serving the purpose of aligning and monitoring the cavity position (fig. 8).

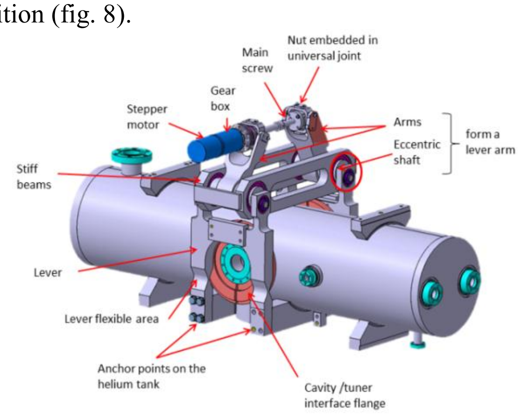

Figure 8: HWR tuner and He jacket layout.

Prototypes

Two HWRs had previously been built in order to validate the original design, without success. One was then modified and stripped from its He jacket in order to assess the performance of the bare HWR with its basic electromagnetic design features, i.e. without perturbation of the former SC plunger tuner extension. The VT results were satisfactory with performance above project specifications of 4.5 MV/m and Qo of 5.10^8 (fig. 9).

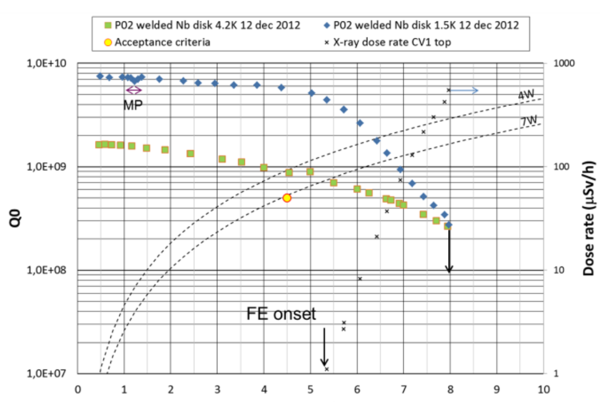

Figure 9: VT results of the modified HWR prototype.

The process of obtaining the approval of the HWR design by Japanese authority is on-going. Then the manufacturing series HWR will be launched, starting with a pre-production resonator which will be used firstly for the optimization of the tuning procedure, and validate the overall manufacturing and processing sequence.

The power couplers have been designed with the 200 kW CW power capability of the IFMIF accelerator [13]. These single disk window FPCs are connected to the HWR through a He-cooled double wall, rigid outer conductor. During the LIPAc operation, the forward RF power will be limited to 70 kW. A pair of FPCs prototypes has been manufactured and recently processed on a test bench [14] at room temperature. An intermediate objective of 100 kW CW forward power in travelling wave mode has been chosen as a trigger for launching the manufacturing of LIPAc FPCs. This goal was reached after an integrated RF-on time of 125 hrs (fig.10).

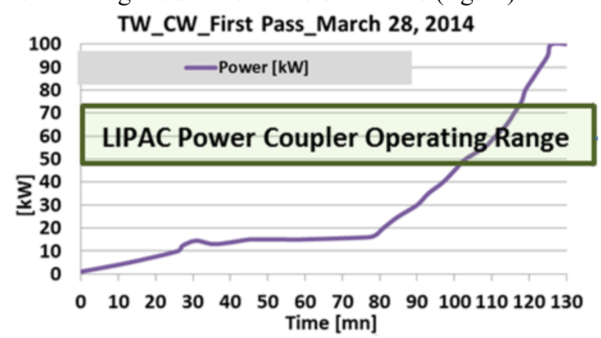

Figure 10: Coupler processing power ramp.

Subsequently the test in standing wave mode has been conducted up to 100 kW CW forward power using a variable short circuit, focussing on the most stressing high electric field position on the alumina disks and air parts.

New Test Cryostat

A integrated test of a HWR, FPC and tuner assembly has been included in the development plan. A dedicated test cryostat Sathori is being designed to house this setup. Conceptually, it is a box-shaped top-loading satellite CM of the existing Cryholab horizontal test cryostat at Saclay is shown on fig. 11. Its role is to support and shield the HWR from radiation and magnetic field, while the main module (Cryholab) provides the cryogenic fluids.

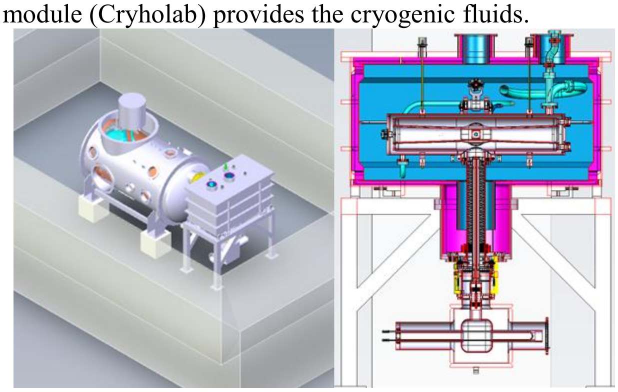

Figure 11: Sathori HWR test satellite of Cryholab.

This setup will enable to test the FPC behaviour in presence of the HWR and cryogenic cooling and perform a complete test of tuner and HWR performance before installation in the LIPAc CM. The first test will be carried out using the pre-production HWR and one of the FPC prototypes. Test in such configuration will be repeated with selected cavities from the series production.

SPIRAL-2

The 5 mA CW deuteron SPIRAL2 superconducting linac is composed of 88 MHz quarter wave resonator (QWR) low (0.07) and high β (0.12) cryomodules build by CEA-Irfu and IPNO respectively [15,16]. The operation temperature is 4.5 K. Transverse focussing elements are room temperature quadrupoles, so CM have been designed to be as short as possible to fit requirements of beam dynamics. In contrast to most of the former QWR based heavy ion linacs, the high intensity of the beam and the step in nominal gradient (6.5MV/m) led to opt for separated vacuum for beam. The 40 kW capable CW power couplers [17] and the required frequency adjustment range of typically 15 kHz depart from usual requirements for QWRs at that time. The single QWR low β and dual QWR high β CMs share a few design features, mainly the supporting of the cavities from the vacuum vessel using tie rods, the use of a part of the vacuum vessel during the assembly of the beam vacuum parts (bellows, gate valves, FPCs and cavities) in the clean room.

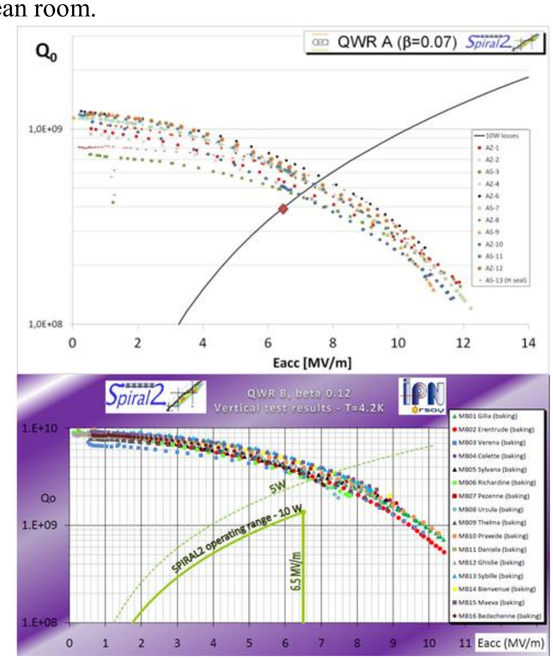

Figure 12 : VT results of QWRs (top : low β, bottom: high β)

In view of the linac installation at GANIL, both low and high β cryomodules testing at Orsay and Saclay are approaching completion. As of today, all individual components have been tested. The VT test results at 4.2K are shown on fig. 12. The validation tests of 8 of the 12 low β CMs and 5 out of 7 high β CMs have been completed. A detailed analysis of cavity performance from VT to CM test is presented in [18]. Updates of the test areas had to be carried out during the CM test period at both sites (example of additional shielding surrounding the low β CM, fig. 13).

Figure 13: Low beta CM in test area at Saclay.

A validation of the handling and transportation tooling and procedures was carried out by a road test transport from Saclay to GANIL (approx. 250 km) and return. The recorded acceleration values were below the FPC damage level. After this round trip, no performance degradation was observed during the full RF test of the cryomodules.

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