

RF COMMISSIONING OF THE SUPERCONDUCTING 217 MHz CH CAVITY FOR HEAVY IONS AND FIRST BEAM OPERATION

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Abstract

Future research programs at GSI in the field of super heavy element (SHE) synthesis require high intense heavy ion beams above the coulomb barrier and high average particle currents. The upcoming demands exceed the technical opportunities of the existing UNiversal Linear ACcelerator (UNILAC). Furthermore, the existing machine will be exclusively used as an injector for FAIR (Facility for Antiproton and Ion Research) providing high power heavy ion beams at a low repetition rate. Consequently, a new dedicated superconducting (sc) continuous wave (cw) linac is crucial to keep the SHE research program at GSI competitive on a high level. Recently the first linac section, serving as a prototype to demonstrate the reliable operability of 217 MHz multi gap crossbar-H-mode (CH) cavities under a realistic accelerator environment, has been extensively tested with heavy ion beams delivered from the GSI High Charge State Injector (HLI). Fulfilling its role as a key component of the whole demonstrator setup, the first sc 217 MHz CH cavity (CH-0) successfully accelerated heavy ions up to the design beam energy and even beyond at high beam intensities and full transmission. In this contribution the RF commissioning and the first beam operation of the cavity is presented.

INTRODUCTION

Regarding the future construction of a sc cw linac at GSI an R&D program has been initiated in collaboration with the Institute of Applied Physics (IAP) of Goethe University Frankfurt. In a first step realizing the proposed HELmholtz LInear ACcelerator (HELIAC) it was intended to build and test the first linac section with beam as a demonstrator at the GSI High Charge State injector (HLI) [1, 2]. The demonstrator setup is directly located behind the HLI as shown in Fig. 1. As a key component it contains a 850 mm long 15 gap sc CH cavity (CH-0) [3] operated at 217 MHz (see Fig. 2). Three dynamic bellow tuners inside the cavity allow slow and fast frequency adjustment during operation [4]. The beam dynamics concept of the cavity is based on the EQUidistant mUlti-gap Structure (EQUUS) layout [5, 6]. For beam tests with strong input coupling a 2 kW cw coax-

ial power coupler is available. Furthermore, the cavity is embedded by two sc 9.3 T solenoids providing the required transverse beam focusing. All components are mounted on a common support frame suspended inside a horizontal cryomodule. After final surface preparation steps and assembly of the helium jacket, the cavity has been extensively tested with low level RF power at 4.2 K followed by a successful full performance test with heavy ion beams.

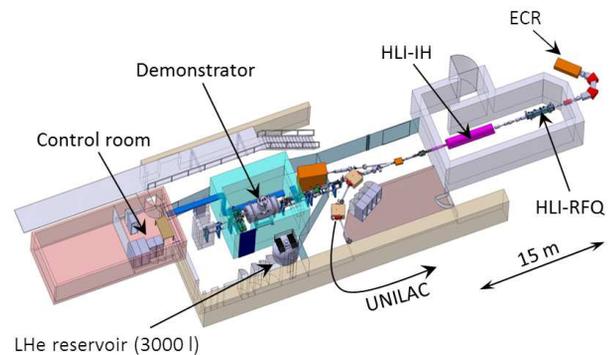


Figure 1: Demonstrator test environment at GSI.



Figure 2: 3D model of the sc 217 MHz CH cavity [7].

RF COMMISSIONING

A first cold test of the CH-0 cavity with low level RF power has been performed in a vertical bath cryostat without helium jacket at IAP beginning of 2016 [7]. During this test the cavity performance was strongly limited by field emission due to an insufficient surface preparation. Nevertheless,

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a maximum accelerating gradient of $E_a = 6.9$ MV/m at $Q_0 = 2.19 \times 10^8$ has been reached.

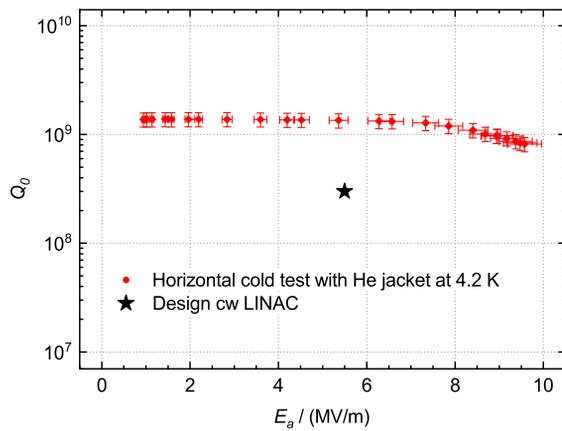


Figure 3: Measured Q_0 vs. E_a curve at 4.2 K [8].

After final assembly of the helium vessel and further High Pressure Rinsing (HPR) the cavity was delivered to GSI and prepared for a second RF test in the horizontal cryomodule. To determine Q_0 during the test and especially for RF conditioning, a slightly over coupled input probe was used. Therefore, a coupling strength of $\beta_e \approx 7$ leading to an external quality factor of $Q_e = 1.9 \times 10^8$ has been chosen. A 50 W broadband amplifier was used to deliver the required RF power. The cavity was operated within a phase locked loop (PLL). Subsequently, after cool down of the cavity to 4.2 K, RF conditioning has been performed. For conditioning with low field levels a network analyzer (VNA) was used sweeping over the resonance frequency of the cavity while varying the forward power. A strong multipacting band remaining for 6 hours occurred at accelerating gradients between 0.2–0.33 MV/m which corresponds to a transmitted power (P_t) in the range of 110–290 μ W. All multipacting barriers up to 3.6 MV/m (340 μ W) could permanently be surmounted within 24 hours. Afterwards, the RF performance of the cavity was reviewed. Figure 3 shows the related Q_0 vs. E_a curve measured in the horizontal cryomodule. The maximum Q -value at a low field level (Q_0^{low}) was measured for 1.37×10^9 . Recently, the cavity showed an improved performance due to an advanced HPR treatment. The initial design quality factor at 5.5 MV/m has been exceeded by a factor of four. Furthermore, a maximum E_a accelerating gradient of $E_a = 9.6$ MV/m at $Q_0 = 8.14 \times 10^8$ was reached, which is an excellent performance result considering the complex multigap structure of the cavity. The maximum gradient was limited by thermal cavity quenches.

SETUP OF THE RF SYSTEM

After the final RF test the whole demonstrator setup was modified and prepared for beam commissioning. In this context the cavity was demounted from the cryomodule and brought into the clean room at GSI for cold string assembly. Thereby, the input coupling probe has been replaced by a 2 kW high power coupler. Previously, coupler conditioning

up to 2.5 kW in cw and 5 kW in pulsed mode has been performed [9–11]. To optimize the power delivery to the beam as well as to provide stable frequency operation during the beam test, the cavity was strongly over coupled to reach a sufficient bandwidth of 300 Hz. Therefore, Q_e was adjusted accordingly to 7.1×10^5 . In a next step three tuning devices were mounted to the cavity for controlling the resonance frequency. Each tuning device consists of a stepper motor connected in series with a piezo actuator to drive one of the bellow tuners with a maximum force <800 N. This leads to a maximum mechanical displacement of ± 1 mm which corresponds to a total tuning range of ± 60 kHz per tuner. After reassembling the string to the cryomodule and cool down to 4.2 K a short RF conditioning phase has been performed. The high power coupler was cooled by the LN₂ shield of the cryostat. This was necessary to keep the heat load into the liquid helium bath as low as possible. In addition, the bellow tuning system has been tested for the first time. Tuner #3 did not respond during the test due to a short at the limit switch. Nevertheless, tuner #1 and #2 showed the desired behavior under cold conditions. Moving each stepper motor 1000 steps in forward (pushing) and backward (pulling) direction caused a bellow displacement of respectively ± 50 μ m. The related frequency shift per tuner was measured for ± 1.4 kHz.

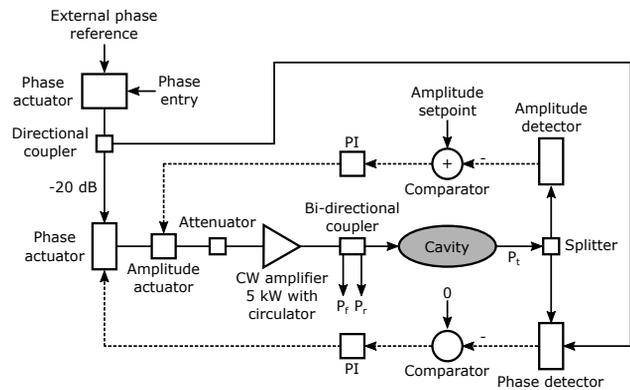


Figure 4: Schematic view of the RF feedback loop. The straight lines represent the RF path while the dashed lines indicate the low frequency part.

In beam acceleration mode the cavity was operated within an analog feedback loop (see Fig. 4). In this system the control units for RF phase and amplitude can be activated independently. The required RF power was provided by a 217 MHz, 5 kW solid state cw amplifier connected to a 1-5/8" coaxial transmission line. Resonance frequency tuning of the cavity during operation was accomplished within a separate feedback loop driving bellow tuner #1, while tuner #2 was kept in standby mode. The piezo actuators have not been used at this time. A maximum frequency shift of 700 Hz during the whole commissioning phase could be observed. This corresponds to a step width of 500 and a bellow displacement of 25 μ m, respectively. The average movement of the stepper motor over the complete test range was about 1 step/min due to helium level changes inside the

cryomodule. Within the chosen resonance bandwidth the bellow tuning system allowed stable frequency operation of the cavity during the complete test period. Due to a broken resistive heater it was not possible to determine Q_0 during this test in presence of the heavily coupled input antenna. In other words, the helium gas flow-meter could not be calibrated to measure the cryogenic losses and to deduce the related power losses. Recently, this was fixed and the measurement will be repeated during the next cold test at the end of this year. Nevertheless, a maximum accelerating gradient of 6.4 MV/m at a forward power of 1.5 kW could be reached.

BEAM COMMISSIONING

After the sc 217 MHz CH cavity was tested with low level RF power at 4.2 K, a full performance test with beam has been performed at GSI [12–14]. Therefore, argon and helium ion beams with different charge states ($^{40}\text{Ar}^{11+}$, $^{40}\text{Ar}^{9+}$, $^{40}\text{Ar}^{6+}$, $^4\text{He}^{2+}$) have been provided by the ECR source of the HLI. The maximum achieved average beam intensity of 1.5 μA was limited by the pulse intensity of the HLI and its duty factor of 25% (50 Hz, 5 ms). Initially, the cavity accelerated successfully $^{40}\text{Ar}^{11+}$ ions with 95% of beam transmission up to the design energy of 1.86 MeV/u, which corresponds to a total energy gain of 0.5 MeV/u. Considering the forward and the reflected RF power by neglecting the losses inside the cavity walls, the cavity was powered with 10 W (net RF power) providing an accelerating gradient of more than 2.6 MV/m ($\beta\lambda$ -definition). During the whole beam test the cavity was operated in cw mode. A minimum bunch length of 0.25 ns (FWHM) or 20° could be detected by means bunch shape monitor (BSM) [15] behind the demonstrator setup while, the beam emittance growth is less than 15% in transversal and 10% in longitudinal plane. For determining the beam emittance a slit grid scanner was used. Meanwhile the design gradient could be verified by accelerating heavy ions with $A/q = 6.7$. Figure 5 shows a full measured 3D-scan for $^{40}\text{Ar}^{9+}$ of beam energy and transmission depending on different accelerating fields and RF phases. By ramping up the accelerating gradient a linear increase of beam energy could be observed for different RF phases, while beam transmission was kept above 90%. These measurements confirm nicely the feature of energy variation between 1.2 – and 2.2 MeV/u by changing the RF phase and amplitude without particle losses and significant beam quality degradation referable to the EQUUS beam dynamics.

SUMMARY & OUTLOOK

The sc 217 MHz CH cavity has been tested at GSI with low level RF power at 4.2 K. A very promising gradient of 9.6 MV/m could be reached after an advanced surface preparation. Afterwards the cavity was prepared for beam operation. Therefore, the 2 kW high power coupler and the new RF control system in combination with slowly driven bellow tuners have been successfully commissioned for the

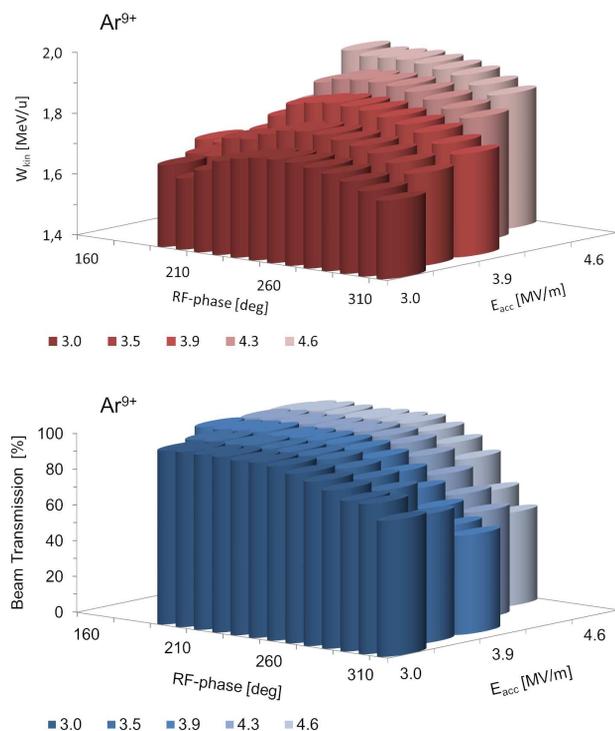


Figure 5: Measured 3D-scan of an $^{40}\text{Ar}^{9+}$ beam showing beam energy (top) and beam transmission (bottom) versus accelerating gradient and RF phase [12].

first time. Recently a full performance test of the cavity with heavy ion beam was accomplished. The demonstrator cavity reached acceleration of heavy ions up to the design beam energy. Furthermore, the design accelerating gradient was achieved even above the design mass to charge ratio ($A/q = 6.7$) at high beam intensities. At full beam transmission the beam quality was measured as excellent. The worldwide first successful beam test of the sc CH cavity was an important step on the way realizing the proposed cw HELIAC. Additionally, the first short sc 217 MHz CH cavity (CH-1) with a simplified geometry for the advanced demonstrator [16, 17] has been already successfully tested with low level RF power at 4.2 K in a vertical cryomodule [18, 19]. The cavity reached a very nice gradient of 9 MV/m at $Q_0 = 2.4 \times 10^8$ reproducing the excellent results made so far with the demonstrator cavity (CH-0). Furthermore, the fabrication of a second short sc 217 MHz CH cavity (CH-2) is almost finished. It is planned to test this cavity with low level RF power at the end of this year.

ACKNOWLEDGEMENT

The full performance test of the demonstrator especially successful beam commissioning could only be accomplished by the strong support of highly motivated people from different GSI departments. The first beam operation of a sc CH cavity is an important milestone of the R&D work of HIM and GSI in collaboration with IAP, Goethe University Frankfurt.

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