

FURTHER RF MEASUREMENTS ON THE SUPERCONDUCTING 217 MHz CH DEMONSTRATOR CAVITY FOR A CW LINAC AT GSI

F. Dziuba^{1,2,4,*}, K. Aulenbacher^{1,2,4}, W. Barth^{1,2}, M. Basten³, C. Burandt^{1,2}, M. Busch³, T. Conrad³, V. Gettmann^{1,2}, M. Heilmann², T. Kürzeder^{1,2}, S. Lauber^{1,2,4}, J. List^{1,2,4}, M. Miski-Oglu^{1,2}, H. Podlech³, J. Salvatore², A. Schnase², M. Schwarz³, S. Yaramyshev²

¹HIM Helmholtz Institute Mainz, 55099 Mainz, Germany

²GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

³IAP Goethe University Frankfurt, 60438 Frankfurt am Main, Germany

⁴KPH Johannes Gutenberg University Mainz, 55128 Mainz, Germany

Abstract

Recently, the first section of a superconducting (SC) continuous wave (CW) linac has been extensively tested with heavy ion beam from the GSI High Charge State Injector (HLI). During this testing phase, the reliable operability of 217 MHz multi-gap crossbar-H-mode (CH) cavities has been successfully demonstrated. The SC 217 MHz CH cavity (CH-0) of the demonstrator setup accelerated heavy ions up to the design beam energy and even beyond at high beam intensities and full transmission. This worldwide first beam test with a SC CH cavity is a major milestone on the way realizing the entire SC CW linac project. In this contribution further RF measurements on the cavity are presented providing full characterization of the RF structure CH-0.

INTRODUCTION

Within the scope of building a new SC CW linac at GSI an R&D program has been initiated in collaboration with the Helmholtz Institute Mainz (HIM) and the Institute of Applied Physics (IAP) of Goethe University Frankfurt in 2010. On the way 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 test setup is shown in Fig. 1. In this context, a 850 mm long 217 MHz SC CH cavity (CH-0) [3] with 15 equidistant gaps based on the EQUUS (EQUidistant mUlti-gap Structure) beam dynamics layout [4–6] serves as a key component (see Fig. 2). Three dynamic bellow tuners inside the cavity allow slow and fast frequency adjustment during operation [7]. To achieve strong input coupling a 2 kW CW coaxial power coupler was available. Furthermore, two SC 9.3 T solenoids surrounding the cavity have been used to provide the required transverse beam focusing. Nevertheless, all components were mounted on a common support frame suspended inside a horizontal cryomodule. Finally, the cavity has been extensively tested with low level RF power at 4.2 K and was successfully commissioned with beam for the first time [8–10].

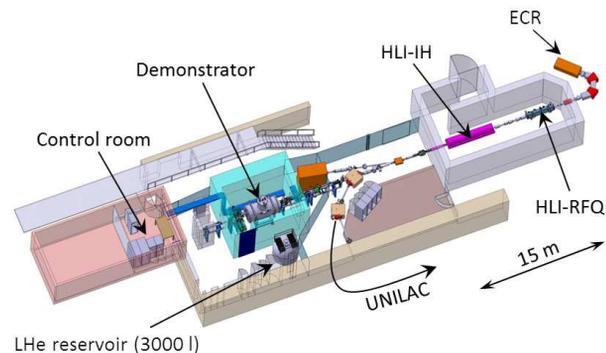


Figure 1: Demonstrator test environment at GSI.



Figure 2: 3D model of the SC 217 MHz CH-0 cavity.

LOW LEVEL RF COMMISSIONING

After assembly of the helium jacket and final surface preparation steps the cavity was delivered to GSI and prepared for a low level RF test in a horizontal cryomodule [11, 12]. 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 $\beta_e \approx 7$ was chosen, resulting in an external quality factor of $Q_e = 1.9 \times 10^8$. The required RF power has been delivered by a 50 W broadband amplifier while the cavity was operated within a phase locked loop (PLL). Subsequently, after cool down to 4.2 K, the cavity has been RF conditioned with low field level power. For this purpose, a network analyser (VNA) was used sweeping over the resonance frequency of the cavity while varying the forward power (P_f). All multipacting

* f.dziuba@gsi.de

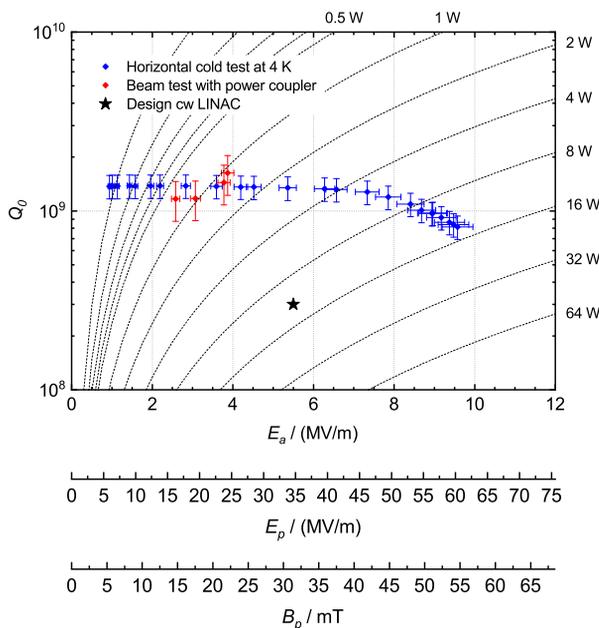


Figure 3: Q_0 vs. E_a curve at 4.2 K with related peak fields for the low level RF test (blue marks) and during beam commissioning with a 2 kW power coupler (red marks).

barriers could permanently be surmounted within 24 hours. In a next step, the RF performance of the cavity has been determined. Figure 3 shows the corresponding Q_0 vs. E_a curve with related peak fields measured in the horizontal cryomodule at 4.2 K. At a low field level the maximum Q -value (Q_0^{low}) was measured for 1.37×10^9 . The initial design quality factor at 5.5 MV/m could be exceeded by a factor of four. Furthermore, a maximum accelerating gradient of $E_a^{max} = 9.6$ MV/m at $Q_0(E_a^{max}) = 8.14 \times 10^8$ was reached, resulting in a maximum effective voltage of $V_a^{max} = 5.9$ MV [11]. This is an excellent performance result with respect to the complex multi-gap structure of the cavity. At maximum field level the electrical (E_p) and magnetic (B_p) peak fields reach moderate values of 60 MV/m and 55 mT, respectively.

TEST OF RF TUNING SYSTEM

In a next step the three tuning devices controlling the resonance frequency of the cavity have been tested under cold conditions for the first time. 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 of 800 N. This leads to a maximum mechanical displacement of ± 1 mm, which corresponds to a total tuning range of ± 60 kHz per tuner. Figure 4 shows the behaviour of tuner #1 at 4.2 K only driven by the stepper motor. Moving the motor 2000 steps in forward (pushing, red curve) and backward (pulling, blue curve) direction caused a bellow displacement Δx of $\pm 100 \mu\text{m}$. The related frequency shift per tuner was measured for $\Delta f = \pm 2$ kHz. As one can see from Fig. 4 (top) the tuner system shows a hysteresis due to a backlash at the change of rotational direction of the motor. This effect

has to be minimized by using a different spindle with an appropriate trapezoidal thread. The same behaviour has been observed when tuner #1 was driven by the piezo actuator only (see Fig. 4 bottom). With a maximum piezo voltage of $U = \pm 100$ V, a frequency shift of ± 230 Hz could be measured. Nevertheless, the hysteresis effect had no impact during the beam tests at all since the bandwidth of the cavity was quite high (see below).

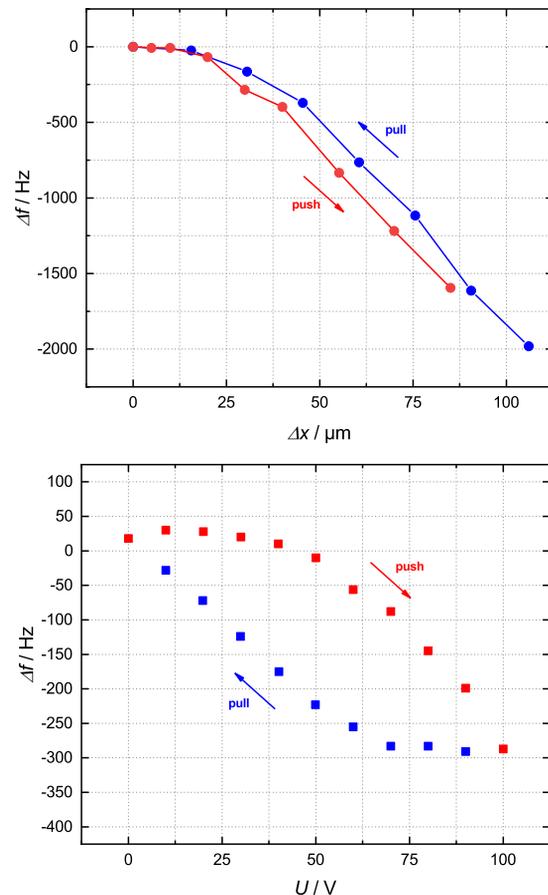


Figure 4: Measured frequency shift Δf of tuner #1 at 4.2 K as function of the tuner displacement Δx by driving a stepper motor (top) and as function of the piezo voltage U (bottom).

RF MEASUREMENTS WITH 2 KW POWER COUPLER

After the final RF test with low level power the whole demonstrator setup was modified and prepared for beam commissioning. In this context, the cavity was dismantled from the cryomodule and replacement of the input coupling probe by a 2 kW power coupler has been accomplished inside the clean room at GSI. Previously, coupler conditioning up to 2.5 kW in CW and 5 kW in pulsed mode has been performed [12–14]. After reassembling the cavity to the cryomodule and cool down to 4.2 K a short RF conditioning phase took place. In order to keep the heat load into the liquid helium bath as low as possible the cold RF window of the power coupler was connected by the LN₂ shield of

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the cryostat. Two full performance cavity tests with beam have been accomplished, first in June 2017 and second in December 2018. Both times the cavity was strongly over coupled to reach a sufficient bandwidth of up to 500 Hz to provide stable frequency operation. Accordingly, Q_e was adjusted to 4.1×10^5 resulting in a coupling strength of $\beta_e \approx 2900$. For beam commissioning, 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 pμA was limited by the pulse intensity of the HLI and its duty factor of 25% (50 Hz, 5 ms). Initially, at an accelerating gradient of 2.6 MV/m 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. During the whole beam test the cavity was operated in CW mode.

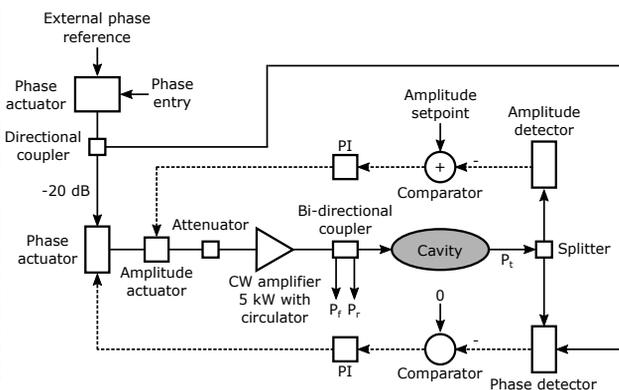


Figure 5: Schematic view of the RF feedback loop. The straight lines represent the RF path, while the dashed lines indicate the low frequency part.

Figure 5 shows the diagram of the analogue feedback loop used to operate the cavity in beam acceleration mode. In this system the control units for RF phase and amplitude can be activated independently. The required RF power is generated by an 217 MHz, 5 kW solid state CW amplifier connected to a 1 5/8" coaxial transmission line. Cavity tuning during RF-operation was accomplished within a separate feedback loop driving tuner #1, while tuner #2 was kept in standby mode. Due to strong input coupling the piezo actuators were not needed. A maximum frequency shift of 700 Hz during the whole commissioning phase could be observed. This corresponds to a bellow displacement of 25 μm. The total movement of the stepper motor during the test was about 500 steps with an average rate of 1 step/min in consequence of helium level changes inside the cryomodule. Within the chosen resonance bandwidth the bellow tuning system allowed stable frequency operation of the cavity during both test periods. In presence of the heavily coupled input antenna Q_0 could not be determined during the first beam test due to a defective resistive heater. Nevertheless, a maximum accelerating gradient of 6.4 MV/m at a forward power of 1.5 kW could be reached. During the second beam test the defective heater was replaced and Q_0 could be measured successfully.

For this purpose the calorimetric measuring method was used to determine the cryogenic losses and to deduce the related cavity losses P_c . The results are represented by the red marks in Fig. 3. At $P_f = 445$ W and a transmitted power of $P_t = 23$ mW, for instance, the stored energy in the cavity was $W = 0.54$ J while 0.64 W was measured for P_c . This results in an accelerating gradient of 2.6 MV/m at a quality factor of $Q_0 = 1.16 \times 10^9$. In this context, dynamic losses of 1 W in the power coupler have been determined by detuning the cavity off-resonance. No drop in Q -value could be detected after installation of the power coupler, confirming the excellent cavity performance during the beam tests.

SUMMARY & OUTLOOK

In future the existing UNILAC (UNIversal Linear ACcelerator) [15–18] at GSI will be exclusively used as an injector for FAIR (Facility for Antiproton and Ion Research) providing short pulse high intensity heavy ion beams at low repetition rates [19–21]. The new SC CW linac HELIAC should provide heavy ion beams above the coulomb barrier to keep the SHE (Super Heavy Element) program at GSI world wide competitive. In this context, the SC 217 MHz CH-0 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. Afterwards the cavity was prepared for beam operation. Therefore, the 2 kW power coupler and the new RF control system in combination with fast and slowly driven bellow tuners have been successfully commissioned for the first time. Recently, two full performance tests of the cavity with heavy ion beams have been accomplished. The demonstrator cavity reached acceleration of heavy ions up to the design beam energy with very well performance. 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 operation of the SC CH-0 cavity was an important step on the way realizing the proposed HELIAC. Additionally, the second SC 217 MHz CH cavity (CH-1) for the advanced demonstrator [22] has been already successfully tested with low level RF power at 4.2 K in a vertical cryomodule [23, 24]. The cavity reached a very nice gradient of 9 MV/m at $Q_0 = 2.4 \times 10^8$ reproducing the excellent results received so far with the demonstrator cavity (CH-0). Furthermore, the fabrication of the third SC 217 MHz CH cavity (CH-2) is almost finished. Vertical RF cold tests of the cavity without helium jacket are currently in progress.

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