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A SUPERCONDUCTING 217 MHz SINGLE SPOKE CAVITY FOR THE HELMHOLTZ LINEAR ACCELERATOR AT GSI *

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Abstract

A new superconducting (SC) continuous wave (CW) linac, providing high efficient heavy ion acceleration above the coulomb barrier, is going to be built at GSI to fulfill the upcoming demands in the research field of super heavy element (SHE) synthesis. The so-called HELIAC (HElmholtz LInear ACcelerator) delivers ion beams in the energy range of 3.5 MeV/u and 7.3 MeV/u with a mass to charge ratio (A/z) of up to 6. Superconducting multi-gap crossbar-H-mode (CH) cavities with a resonance frequency of 217 MHz are used for beam acceleration. In addition, SC single spoke buncher cavities should ensure longitudinal beam matching to the following CH sections. Therefore, the first 217 MHz single spoke cavity with $\beta = 0.07$ has been developed at HIM/GSI. In this paper the design of the cavity and first RF measurements during manufacturing are presented.

INTRODUCTION

After the reliable operability of SC CH cavities [1, 2] with beam at 4 K was successfully shown within the demonstrator project [3–7], the next step on the way realizing the proposed HELIAC [8–10] is the construction, commissioning and operation of the so called 'Advanced Demonstrator' CM1 cryomodule [11]. In future, the Advanced Demonstrator is foreseen to be used as the first of a series of up to four cryomodules (CM1–CM4) of the entire HELIAC accelerator. The new CM1 will be fully equipped with three SC CH cavities, a SC single spoke resonator (SSR) and two SC solenoids (see Fig. 1). In 2021, cryomodule CM1 has been successfully tested within SAT at HIM/GSI under 4 K conditions. Meanwhile, all mentioned components have been built and delivered to GSI. Currently, cold string assembly of CM1 is taking place in the ISO4 cleanroom at HIM [12].

BUNCHER CAVITY LAYOUT

The first layout of a SC 217 MHz SSR with a particle velocity of $\beta = 0.07$ for CM1 has been presented in [13, 14]. Based on this early design, the cavity has been optimized regarding compactness, electrical and magnetic peak fields, the appearance of multipacting and its pressure sensitivity.

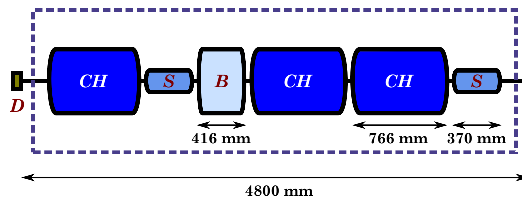

Figure 1: Layout of cryomodule CM1 containing three CH cavities, a single spoke buncher (B) and two solenoids (S).

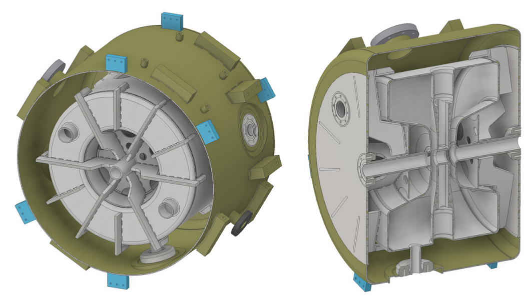
Figure 2: 3D-model of the SC 217 MHz SSR.

The optimized cavity (see Fig. 2) is 416 mm long and has an equidistant gap length of 13 mm. A dynamic bellow tuner inside the cavity allows slow and fast frequency adjustment during operation at 4 K. Furthermore, a helium jacket made from titanium provides a closed helium circulation around the cavity. Two additional flanges at each end cap of the cavity allow adequate surface processing. The main parameters of the cavity are summarized in Table 1. Due to its compact geometry within the mentioned velocity and frequency domain the resonance frequency of the cavity is extremely sensitive to external influences. This makes the design, the construction and operation of such a type of cavity to be extremely challenging tasks. Nevertheless, as described in [15] stable cavity beam operation is quite possible.

RF MEASUREMENTS

The manufacturing of the SSR started in 2020. Several RF measurements during the production process have been performed in order to achieve the target frequency. All important steps were carried out on the basis of detailed RF and structural-mechanical simulations. Initially, the resonance frequency was designed to be higher than the target fre-

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Table 1: Main Parameters of the SC 217 MHz SSR

β (v/c)		0.07
Frequency	MHz	216.816
Effective length ($\beta\lambda$)	mm	97
Gap length	mm	13
Total length	mm	416
Total diameter	mm	565
Tube aperture	mm	30
R_a/Q_0		140
E_a (design)	MV/m	5.5
E_p/E_a		6.1
B_p/E_a	mT/(MV/m)	8.9

quency and lowered successively during production. Other frequency-influencing effects caused by evacuation, cool down and surface processing for instance have been determined and considered as well. The following measurements were performed after the spoke had been finally welded into the cylindrical cavity tank.

Sequential Assembly of Bare Cavity

At the beginning of the measuring campaign both end caps were oversized by 19 mm and were temporarily attached to the bare cavity tank (see Fig. 3). As previous simulations show, reducing the oversize of a single cap should lower the frequency by 1.5 MHz/mm. Both caps were trimmed by 9 mm in order to validate this value. In this condition the frequency was measured as 247.641 MHz, which is 613 kHz (0.25 %) higher than expected confirming the simulations very well. In a next step, the oversize of cap 1 had been completely removed while 2 mm were left at cap 2. Thereupon the tuner was welded into the tank. Subsequently, cap 1 was welded to the cavity, which caused a frequency mismatch of +2.1 MHz. The reason for this large frequency deviation was an insufficiently calculated welding shrinkage, which has been carefully corrected for the following welding procedures. Compensating this mismatch, two virtual welds were placed outside the cavity on cap 1, which corrected the frequency to within 0.04 %. According to the recalculated shrinkage, cap 2 was trimmed and welded as well completing the bare cavity. In Fig. 4 the electric field distribution along the beam axis of the cavity is shown. The expected behaviour of the field corresponds to the measurements perfectly. With the dynamic bellow tuner a design tuning range of ±60 kHz at a maximum displacement of $\Delta x = \pm 1$ mm could be performed. Figure 5 shows the measured frequency shift Δf of the tuner at room temperature for a displacement of ±0.5 mm, the simulation is depicted as a blue line. A displacement of more than ±0.6 mm is not possible without damaging the bellow due to the yield stress of niobium at room temperature. As one can see, the frequency shift is roughly 25 kHz (67 %) higher than simulated, which also shows the high frequency sensitivity of the cavity. A total tuning range of ±110 kHz/mm is expected during cavity operation under cold conditions.

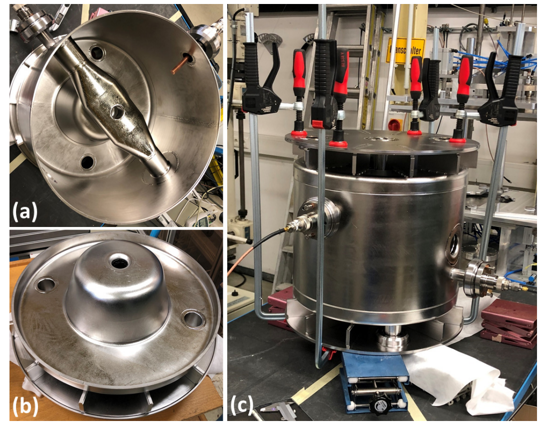

Figure 3: Open SSR (a) before attachment of trimmed end cap (b). Temporarily assembled cavity for RF tuning (c).

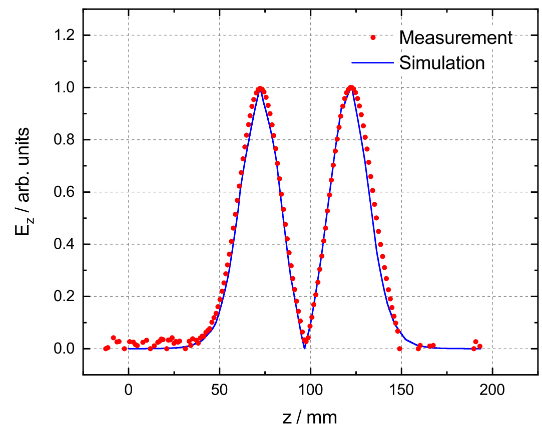

Figure 4: Measured electric field distribution along the beam axis after finalization of bare cavtiy.

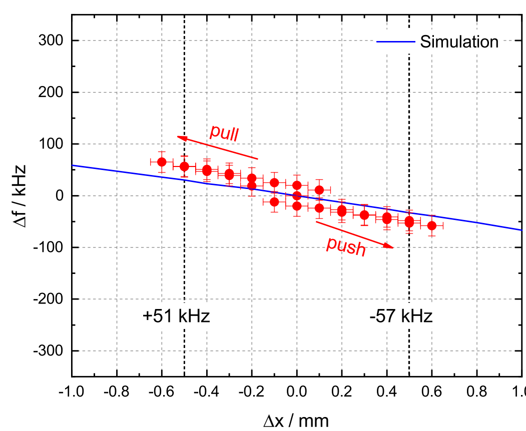

Figure 5: Measured frequency shift of the dynamic tuner.

Evacuation & Cool Down of Bare Cavity

In order to study the frequency change of the bare cavity caused by evacuation, coupled structural - radio frequency electromagnetic simulations have been performed. For the analysis model the inner drift surface of the spoke and the tuner were chosen as a fixed support while a pressure of 1 bar on the surface of the cavity walls was adopted as ap-

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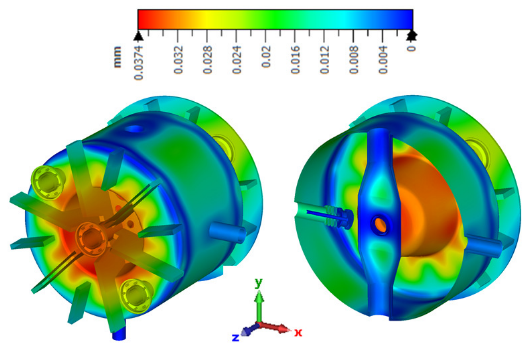

Figure 6: Deformation of the cavity due to the evacuation.

plied load. To minimize the frequency sensitivity, the cavity is equipped with ten stiffener ribs on each end cap. While the spoke and the cylindrical tank have a wall thickness of 4 mm, the end caps are implemented in a thickness of up to 5 mm. In addition, the outer disc of the helium jacket has a thickness of 6 mm. The resulting maximum deformations of 0.37 µm appears mainly at the end caps of the cavity (see Fig. 6). This leads to an decrease of the resonance frequency and yields to a pressure sensitivity of −112 Hz/mbar. Additionally, the relative permittivity ϵ_r is decreasing during the evacuation process which in turn will lead to an increase of the frequency by +64 kHz. The related frequency shift was measured under evacuation at room temperature in order to verify the simulation results. The pressure sensitivity of −155 Hz/mbar is measured 38 % higher than expected. A total shift of −91 kHz has been compensated during end cap tuning and surface processing with Buffered Chemical Polishing (BCP). By cooling down to 4 K the cavity shrinks asymmetrically. While the cavity remains almost unchanged along the spoke in y-plane, it shrinks transversely and longitudinally in x,z-plane (see Fig. 6 for axes orientation). The thermal shrinkage and the related frequency shift has been determined by the total linear contraction. Based on this the cavity shrinkage after cooling down to 4 K is about 0.6 mm in longitudinal and transverse direction (x,z-plane) which increases the resonance frequency by 42 kHz. Validating this assumption the cavity has been cooled down with LN_2 while the frequency change was observed. A total shift of 38 kHz has been measured and compensated by BCP whereas the corresponding estimated value is 27 kHz.

Surface Preparation & Cavity Finalization

In December 2021, the bare cavity was ready for surface preparation, which included seven BCP treatments with a total removal of 230 µm, a 650 °C baking for 24 hours, and High Pressure Rinsing (HPR) with ultrapure water. Any BCP leads to a significant increase in resonance frequency of 12 kHz/µm. This effect has been used for final cavity tuning as well. The first six treatments were performed successively up to a removal of 210 µm. After main etching was done, the cavity has been baked for 24 h at 650 °C avoiding *Q*-disease and hydrogen contamination. Subsequently, the

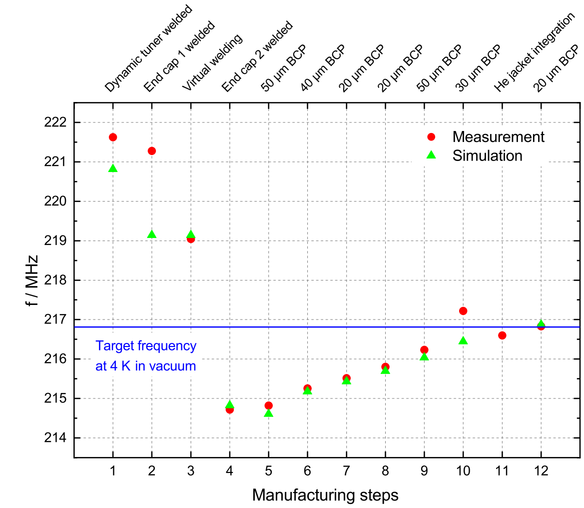

Figure 7: Measured resonance frequency of the cavity during different steps of manufacturing.

cavity was integrated to the helium jacket followed by a last smooth BCP of 20 µm. Finally, the cavity has been high pressure rinsed from both sides along the beam axis as well as off-axis through the preparation ports for almost 15 h. Afterwards, the cavity has been assembled, leak checked and evacuated for shipment. Finally, in April 2022, the buncher cavity arrived at HIM. The frequency (in vacuum) at room temperature was measured to be 216.715 MHz, which is 59 kHz below the target frequency under this condition, but within the dynamic tuner range. Thus, one of the most important milestones in the manufacturing process, namely achieving the resonance frequency of the cavity within the area of the tuner, has been confirmed. Figure 7 shows the frequency development of the cavity during the production process for selected milestones.

SUMMARY & OUTLOOK

The production of the SC 217 MHz SSR started in 2020. All frequency-influencing effects during the manufacturing process, have been successfully verified with corresponding simulations and measurements. After final surface preparation the target frequency has been successfully reached within the dynamic tuner range. In April 2022, the cavity was delivered to HIM. A full performance test of the cavity with low-level RF power at 4 K is planned for the 4th quarter of 2022.

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