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PERFORMANCE TESTS OF THE SUPERCONDUCTING 217 MHz CH CAVITY FOR THE CW DEMONSTRATOR

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Abstract

Regarding the future research program of super heavy element (SHE) synthesis at GSI, high intense heavy ion beams above the coulomb barrier and high average particle currents are highly demanded. The associated beam requirements exceed the capabilities of the existing Universal Linear Accelerator (UNILAC). Besides the existing GSI accelerator chain 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. As a consequence a new dedicated superconducting (sc) continuous wave (CW) linac is highly demanded to keep the SHE research program at GSI competitive on a high level. In this context the construction of the first linac section, which serves simultaneously as a prototype to demonstrate its reliable operability has been finished at the end of 2016. The so called demonstrator cryomodule comprises two sc 9.3 T solenoids and a sc 217 MHz Crossbar-H-mode (CH) cavity with 15 equidistant accelerating gaps. Furthermore, the performance of the cavity has been successfully tested at cryogenic temperatures.

INTRODUCTION

Regarding the future construction of a sc CW linac at GSI an R&D program has been initiated. It is intended to build and test the first linac section with beam at the GSI High Charge State injector (HLI) [1, 2]. Regarding this, a sc 217 MHz multigap CH cavity [3] with 15 accelerating cells was built (see Fig. 1 and Table 1). The beam dynamics concept of the cavity is based on the special EQUidistant mUlti-gap Structure (EQUUS) [4]. Three dynamic bellow tuners inside the cavity allow frequency adjustment during operation [5]. For future beam tests a 5 kW power coupler is available. After final surface preparation steps the new cavity has been extensively tested with low level RF power at 4.2 K.

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CAVITY RF TESTS

At the beginning of 2016 a first RF test of the sc 217 MHz CH cavity (without helium vessel) at the Institute of Applied Physics (IAP) of Goethe University Frankfurt has been performed [6]. The performance of the cavity was limited by field emission caused by insufficient surface preparation at that time. Nevertheless, a maximum accelerating gradient of $E_a = 6.9$ MV/m at $Q_0 = 2.19 \times 10^8$ has been reached (see Fig. 2).

Figure 1: Sectional view of the sc 217 MHz CH cavity [6].

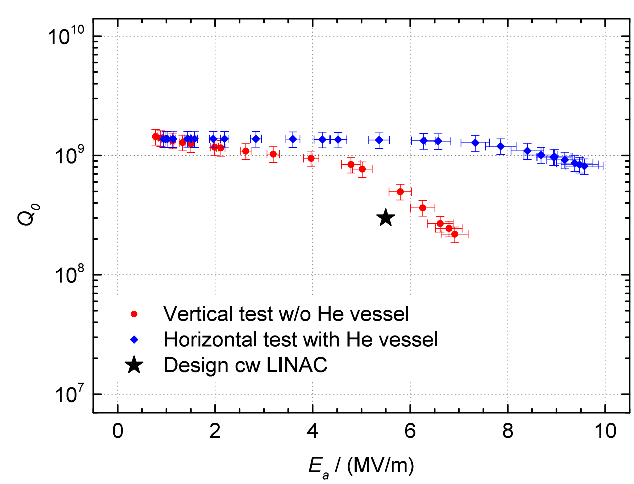

Figure 2: Measured Q_0 vs. E_a curves at 4.2 K for two different RF tests [7].

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Table 1: Main Parameters of the Cavity

β (v/c)		0.059
Frequency	MHz	216.816
Accelerating cells		15
Effective length ($\beta\lambda$)	mm	612
Diameter	mm	409
Tube aperture	mm	18 / 20
G	Ω	52
R_a/Q_0		3240
R_aR_S	kΩ^2	168
E_a (design)	MV/m	5.5
E_p/E_a		6.3
B_p/E_a	mT/(MV/m)	5.7

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 a horizontal cryostat. A 50 W broadband amplifier was used to deliver the required RF power. The cavity was operated as a generator driven resonator directed by an RF control system. Subsequently, after fast cool down (3 K/min in average) of the cavity to 4.2 K avoiding hydrogen related Q-disease, RF conditioning has been performed. All multipacting barriers up to 4 MV/m could permanently be surmounted. Afterwards, the RF performance of the cavity was reviewed. Figure 2 shows the related Q_0 vs. E_a curves measured in vertical position (without helium vessel, red curve) and in horizontal orientation (with helium vessel, blue curve), respectively. 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 4. Furthermore, a maximum accelerating gradient of $E_a = 9.6$ MV/m at $Q_0 = 8.14 \times 10^8$ was reached, which is a promising result considering the complex multigap structure of the cavity. The maximum gradient was limited by thermal cavity quenches. Table 2 summarizes the main measurement results of both RF tests.

Table 2: Results of the Vertical and Horizontal RF Test[7]

		Vertical test w/o He vessel	**Horizontal test with He vessel**
Q_0^{low}		1.44×10^9	1.37×10^9
R_S	nΩ	36	38
R_{BCS}	nΩ	15	15
R_{mag}	nΩ	9	12
R_0	nΩ	12	11
E_a	MV/m	6.9	9.6
Q_0		2.19×10^8	8.14×10^8
V_a	MV	4.2	5.9
E_p	MV/m	43	60
B_p	mT	39	55

COUPLER CONDITIONING

For the first beam operation of the demonstrator a 217 MHz, 5 kW power coupler with two Al_2O_3 RF windows (cold and warm part) has been developed [8]. Providing appropriate beam acceleration up to 1 mA beam current with $A/q = 6$ and a sufficient cavity bandwith of 300 Hz, the cavity should be strongly overcoupled. Therefore, the external Q value of the coupler was adjusted accordingly to $Q_e = 7.1 \times 10^5$. Furthermore, a new dedicated test bench [9] allowing RF conditioning in transmission (traveling wave, TW) and full reflection (standing wave, SW) mode of two power couplers at the same time has been built and set up at GSI. The setup consists of a quarter wave like cavity with an extended center tube which enables the connection of two power couplers with variable configurations of the inner conductor (see Fig. 3). This compact arrangement provides a broad pass band of ±10 MHz.

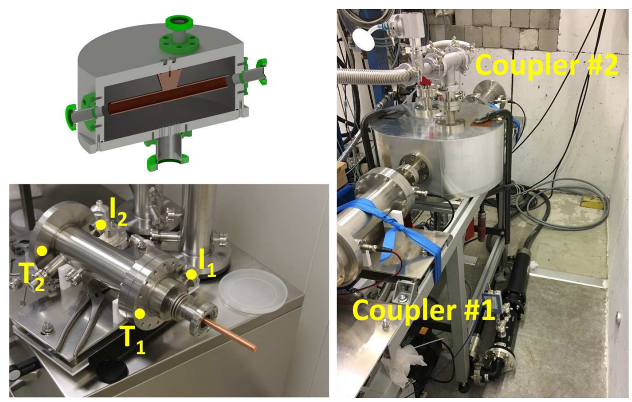

Figure 3: Configuration of the coupler test assembly.

A 5 kW solid state CW amplifier connected to a 1-5/8" coaxial transmission line was used to deliver the required RF power. Vacuum has been provided by a turbomolecular pump mounted at the bottom of the cavity. Each coupler was equipped with two Langmuir probes (I_1, I_2) biased with 50 V to measure the electron current of multipacting avalanches, two Pt-100 elements (T_1, T_2) for temperature observation and an ion gauge measuring the pressure between the RF windows. In addition to these values the forwarded (P_f), the reflected (P_r) and the transmitted (P_t) power has been recorded to detect multipacting events. The conditioning of the power couplers was started with different RF pulse lengths and repetition rates which have been gradually increased up to CW operation.

In the first stage of testing, the system was operated in TW mode while the output power was terminated into a matched load. After two days of smooth conditioning with different pulse settings the maximum power of 5 kW could be reached without major difficulties. Multipacting barriers at a forward power of 400 W, 1 kW, 2.1 kW, 3.5 kW and 4.7 kW could easily be surmounted. Furthermore, some small pressure variations have been seen without any rise in electron current. This is caused by degassing and RF cleaning of the coupler's surface.

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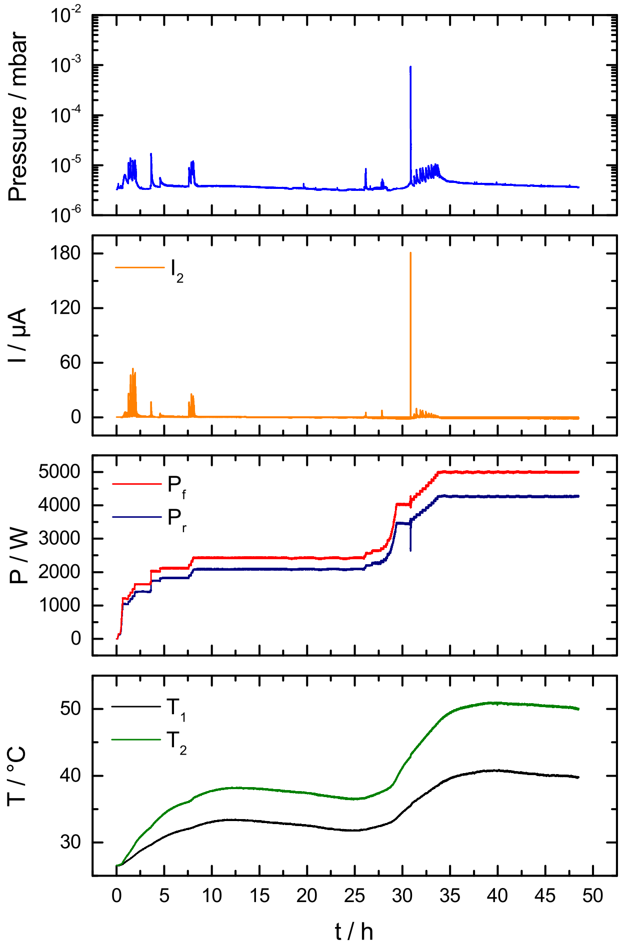

Figure 4: Measuring results of coupler #2 for 5 Hz, 15 ms RF pulses in SW mode up to 5 kW.

For the second stage of conditioning the matched load was replaced by a short and couplers have been tested in SW mode. Figure 4 shows the measuring results of coupler #2 for 5 Hz, 15 ms RF pulses in SW mode. The forward power was ramped up to 2.4 kW within 8 hours. In that range several multipactors occurred at the warm RF window leading to a distinct increase in vacuum and electron current (see Fig. 4). The strongest event at 1.5 kW produced an maximum electron current of $I_2 = 54\,\mu$A while the pressure decreased from 3.3×10^{-6} to 1.4×10^{-5} mbar. After 17 hours of stable operation at a constant level of 2.4 kW with no special incidents power has been further ramped up. At 4.3 kW a sparking effect appeared followed by a vacuum drop down to 8.8×10^{-4} mbar and a significant increase in electron current up to 180 μA. This was also clearly seen by the behavior of the reflected power. Finally, the system was operated at 5 kW for another 14 hours without any further events. Nevertheless, the temperatures at both RF windows increased significantly during the power ramping. In this configuration, the highest temperature was located at the warm window and has been measured as approximately $T_2 = 51\,°$C which is 24.5 °C higher than the initial value. Consequently, the maximum power level is limited by RF losses presumably caused by the TiN coating of the ceramic windows, especially regarding beam operation at cryogenic temperatures.

At 2.5 kW CW operation in TW mode a maximum temperature of $T_1 = 81\,°$C has been measured at the cold window which corresponds to a growth of even 54.5 °C. During first beam commissioning of the sc 217 MHz CH cavity the coupler was cooled by the LN_2 shield of the cryostat allowing stable operation up to 2.5 kW in CW mode. This was necessary to keep the heat load into the liquid helium bath as low as possible. For future 5 kW CW operation an improved coupler design is currently under development.

BEAM COMMISSIONING

After the sc 217 MHz CH cavity was successfully tested with low level RF power at 4.2 K in 2016, recently a full performance test with beam has been performed at GSI. Finally, after a short commissioning phase the cavity accelerated heavy ion beams with full transmission up to the design energy of 1.85 AMeV for the first time (28th of June 2017). During the whole beam test the cavity was operated in CW mode. Considering the forward and the reflected RF power by neglecting the losses inside the walls, the cavity was initially powered with 10 W providing an accelerating gradient of more than 2.3 MV/m (2.6 MV/m, $\beta\lambda$-definition). Meanwhile the design gradient could be verified by accelerating heavy ions with $A/q = 6.7$. The maximum achieved beam intensity of 1.5 pμA was limited by the pulse intensity of the HLI and its duty factor of 25%. Figure 5 show the measured

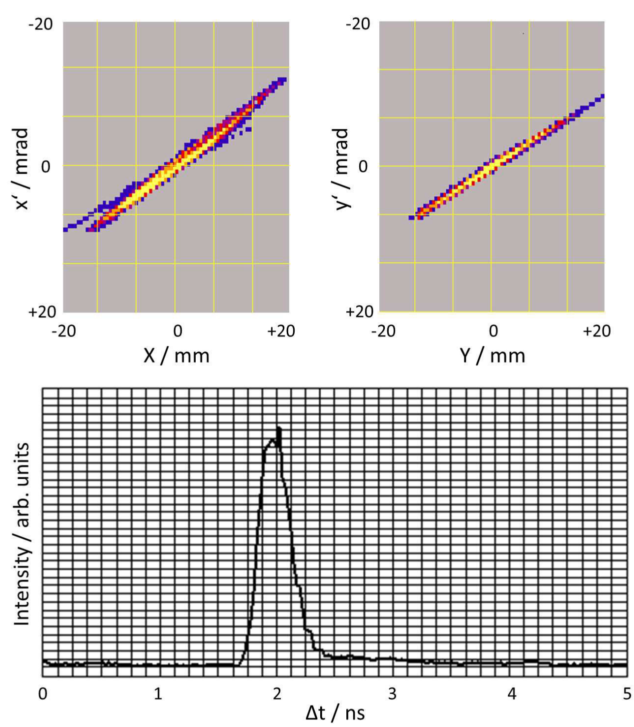

Figure 5: Measured beam emittance (top) and bunch shape (bottom) for accelerated heavy ion beam behind the demonstrator.

parameters of the heavy ion beam attending a nice beam quality. A minimum bunch length of 300 ps (FWHM) could be detected by means of the dedicated device [10] behind the demonstrator setup while the transversal beam emittance growth (90%, total) is less than 15%. Further tests as well as detailed evaluation of the collected data are envisaged.

SUMMARY & OUTLOOK

The sc 217 MHz CH cavity has been successfully 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. Prospectively, an optimized HPR device will be used allowing to rinse the cavity besides the beam axis additionally inside each quadrant. Other methods, like an argon plasma discharge or a 300°C bakeout, are also foreseen to improve the surface quality of the cavity.

A new power coupler test assembly for RF conditioning has been built and set up. Two couplers were successfully operated up to 5 kW with 5 Hz, 15 ms RF pulses and up to 2.5 kW in CW mode, respectively. For CW operation at 5 kW an improved coupler design is currently under development.

Recently a full performance test of the cavity with heavy ion beam was performed. The demonstrator cavity almost reached acceleration of heavy ions up to the design beam energy [11–13]. Furthermore, the design accelerating gradient was achieved even above the design mass to charge ratio at high beam intensites. At full beam transmission the beam quality was measured as excellent. Further studies as well as a detailed evaluation of the collected data are in preparation.

Additionally, two short sc 217 MHz CH cavities [14] with a simplified geometry for the advanced demonstrator [15,16] are currently under construction, at least reproducing or probably improving the excellent results made so far. First intermediate RF measurements on the first short CH cavity have been already performed [17].

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