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BEAM COMMISSIONING OF THE FIRST HELIAC CRYOMODULE

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Abstract

The superconducting heavy ion HELmholtz LInear ACcelerator (HELIAC) is designed to meet the needs of the Super Heavy Element (SHE) research and material science user programs at GSI in Darmstadt. The beam energy can be varied smoothly between 3.5 and 7.3 MeV/u, with an average current of up to 1 mA and a duty cycle of 100 %. Recently the first cryomodule CM1 was fully commissioned and tested. CM1 comprises three Crossbar H-mode (CH)-type accelerating cavities, a CH-rebuncher, and two superconducting solenoid lenses. Following the commissioning of the cryogenic supply- and RF-systems, a successful beam test was conducted at the end of 2023. A Helium ion beam was successfully accelerated to the design energy of 2.7 MeV/u. The beam energy could be varied continuously between 1.3 MeV/u and 3.1 MeV/u without any significant particle losses inside the cryomodule. In June 2024 a Argon ion beam was accelerated to the design energy of 2.7 MeV/u. This contribution covers the construction and commissioning of the first HELIAC cryomodule and the results of the beam test campaign.

INTRODUCTION

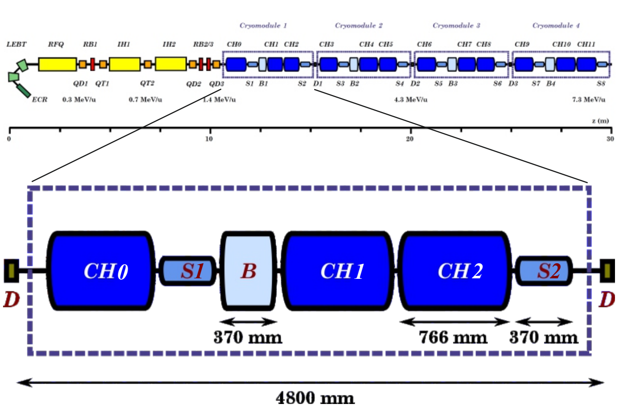

Figure 1: Sketch of the HELIAC (top) and the first cryomodule (CM1), referred to as the Advanced Demonstrator (bottom).

To sustain and enhance the research programs in superheavy ions, material sciences, and biophysics at GSI Helmholtz Centre for Heavy Ion Research (GSI), the superconducting (SC) heavy ion Helmholtz Linear Accelerator (HELIAC) [1–4] is foreseen to be constructed on the GSI campus. It will provide for continuous wave (CW) heavy ion beams of smoothly variable energies between 3.5 and 7.3 MeV/u with a mass to charge ration A/Z between 1 and 6. HELIAC comprises a normal conducting injector and the SC main accelerator [2]. The injector consists of an Electron Cyclotron Resonance Ion Source (ECR), a radio frequency quadrupole (RFQ), and two alternating phase focusing (APF) interdigital H-mode (IH) cavities [5, 6] for acceleration up to 1.4 MeV/u. The SC part comprises four separate cryomodules, each consisting of three SC crossbar H-mode (CH) cavities [7–9] for beam acceleration, a SC rebuncher and two SC solenoid lenses with integrated steering coils, as well as two cold beam position monitors (BPMs).

Highlighted in Fig. 1 the first of the series HELIAC cryomodule CM1, (called Advanced Demonstrator) was assembled in the clean room of Helmholtz Institute Mainz (HIM), transported to GSI and tested with a $^{4}He^{2+}$ and $^{40}Ar^{8+}$ beam provided by the GSI High Charge State Injector (HLI) [10].

CRYOMODULE ASSEMBLY AND INSTALLATION

Figure 2: Fully assembled cold string on rail system.

After the previous test of the first of series cavity CH0 in 2018 with beam [11], the cavity was transported back to HIM to be assembled together with the remaining components of the coldstring of CM1 in the HIM clean room [12].

The assembly procedure of the cold-string components in the clean room consists of an initial cleaning of all components in an ultrasonic bath, followed by a conductivity rinse. The cavities are subjected to a high pressure rinse (HPR) treatment at the manufacturer. Solenoids and bellows are cleaned with HPR in the clean room. After drying, the components are mounted on a trolley that runs on a rail system (Fig. 2). The cold part of the power couplers [13] are first as-

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sembled and then connected to the cavities. The cavities are successively attached to the cold string and evacuated for a leak test. Afterward, the evacuated cold string is transported via the rail system outside the clean room and installed in the cryostat (for further information see [14]). Thanks to the four sufficiently large service doors of the cryostat, the warm part of the power coupler and other additional equipment can be installed outside of the clean room and can even be maintained and modified in the accelerator tunnel.

Finally the fully equipped cryomodule was transported to GSI for cryogenic and radio frequency (RF) commissioning, as well as for full test campaigns with beam in 2023 and 2024.

RADIO FREQUENCY AND CRYOGENIC OPERATION

The test site of the Advanced Demonstrator is located in a 40 m^2 long radiation cave. Beam is provided by the HLI. The testing area features a Helium supply from the cryo plant of the Serial Test Facility (STF) [15], which includes a 50 K Helium circuit with a capacity of 2 kW at 10 bar and a 4 K Helium circuit with a capacity of 700 W at 3 bar. After initial RF conditioning, all cavities exceeded their respective design gradients (necessary to accelerate ions with $A/Z = 6$) in phase locked loop (PLL) mode (see Table 1). The maximum field gradient, except for CH0, was limited by vacuum interlocks. For CH0, the limitation was presumably caused by the so far missing magnetic shielding. Measuring the quality factors Q_0 was not possible due to strong coupling ($\beta > 100$) and the unavailability of a calibrated flowmeter. Instead, the quotient of transmitted and forward power was used as a measure of non-ohmic losses, as shown in Fig. 3.

Table 1: Design and Maximum Achieved Field Gradients for the CM1 Cavities

	Design gradient	Max. gradient	Limitation
CH0	5.8 MV/m	6.8 MV/m	Mag. shielding
CH1	6 MV/m	8.1 MV/m	Coupler vac.
CH2	6.5 MV/m	12.4 MV/m	Beam vac.
B1	5.7 MV/m	10.1 MV/m	Coupler vac.

The resonance frequency control loop consists of an analog phase discriminator, a stepper motor controller, and a proportional-integral-derivative (PID) controller supplying the piezo actuator [16], which provides fast frequency tuning. Despite reaching the gradients in PLL mode as shown in Table 1, instabilities in the resonance frequency control loop occurred in generator-driven mode, which is required for beam operation. Mechanical resonances of the cavities were excited at 180 Hz (CH0) and 320 Hz (CH1 and CH2). In generator-driven mode, initially about 40 % of the design gradient could be reached, which was sufficient for the acceleration of a He^{2+} beam ($A/Z = 2$) in December 2023.

By increasing the coupling strength and improving the resonance controller, the cavities were operated stably at field

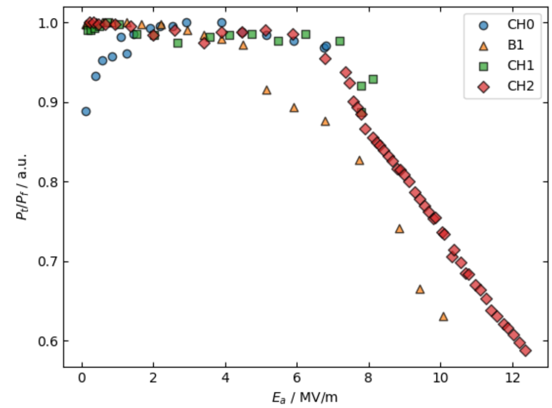

Figure 3: Quotient of transmitted and forward power as measure of non ohmic losses vs. the applied gradient for all CM1 cavities in PLL mode.

gradients of up to 83 % of the design gradient, sufficient for the acceleration of a Ar^{8+} -beam ($A/Z = 5$) during a second beam test conducted in June 2024.

CRYOMODULE COMMISSIONING WITH BEAM

The ECR ion source provides various ion species accelerated in the HLI to an energy of 1.4 MeV/u. The matching beam line from HLI to CM1 consists of two buncher cavities for longitudinal matching, two quadrupole doublets and a triplet for transverse matching, as well as two phase probes, sufficient for beam energy measurements by time of flight (ToF), several secondary electron emission (SEM) grids for beam profile measurement, beam current transformers for transmission measurement, a Feschenko type bunch shape monitor (BSM) [17, 18], and a slit-grid emittance meter [19], enabling the 6D characterization of the beam using reconstruction methods [20].

With this the beam was successfully matched to the acceptance of CM1. The following optimization approach was applied to set up the cavities of the Advanced Demonstrator:

- Applying probe beam set by collimation system [21] in front of CM1.
- Switch on the cavity at half of the design gradient and perform an E_{kin} vs. RF-phase scan (see also [11]) and stick to the RF-phase at max. beam energy.
- Increase the voltage until the design $E_{kin, target}$ is reached.
- Adjust the solenoids for optimal transmission.

Using this procedure, the cavities CH0, CH1, and CH2 were consecutively put into operation.

Finally, in Q4 2023 He^{2+} beam was accelerated up to a beam energy of 3.1 MeV/u, 0.4 MeV/u above the design requirement. The beam transmission through the cryomodule was up to 95 %. In June 2024 an Ar^{8+} beam was accelerated to various beam energies of up to 2.7 MeV/u. Like for

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He^{2+} the beam energy could be varied smoothly, as shown in Fig. 4.

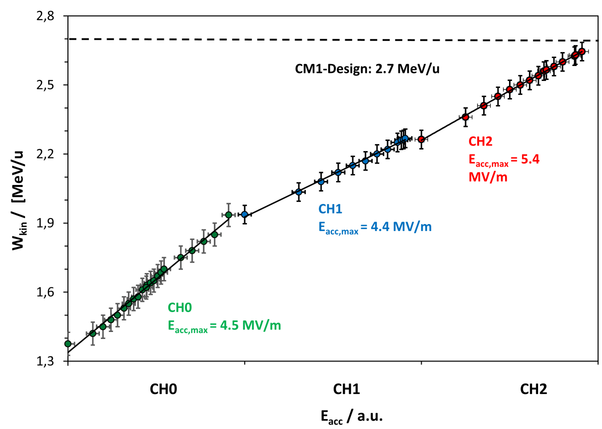

Figure 4: 2024 Ar^{8+} test of the Advanced Demonstrator, providing for a smoothly variable beam energy.

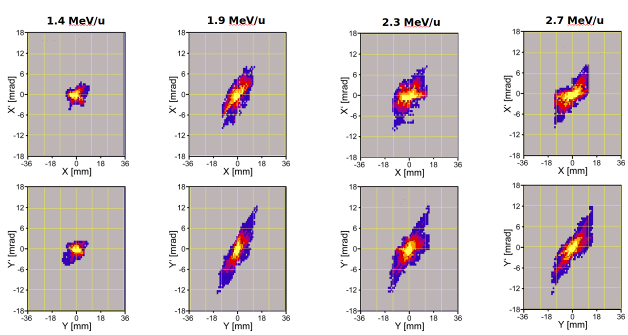

Figure 5: Ar^{8+} beam emittance measurement for different beam energies.

In addition to beam energy measurements, extensive emittance and beam profile measurements in front and behind CM1 were conducted. Figure 5 displays the measured transversal emittance of the argon beam at different beam energies. The emittance increases with rising beam energy by almost a factor of two. Figure 6 shows the beam transmission for the same energies. Both can be attributed to a reduced performance of the injector compared to 2023. Figure 7 depicts the bunch profile of the injector, recorded with the BSM during both machine test campaigns. In 2024 a secondary peak is observed in the bunch profile, leading to poor matching to the Advanced Demonstrator. This resulted in lower beam transmission and higher emittance.

CONCLUSION

The recent commissioning and testing of the Advanced Demonstrator has been successfully completed. The first of four HELIAC cryo modules, containing four accelerator cavities and two superconducting solenoids, was put into operation. Since December 2023, two beam times have been conducted, demonstrating the capabilities of the HELIAC.

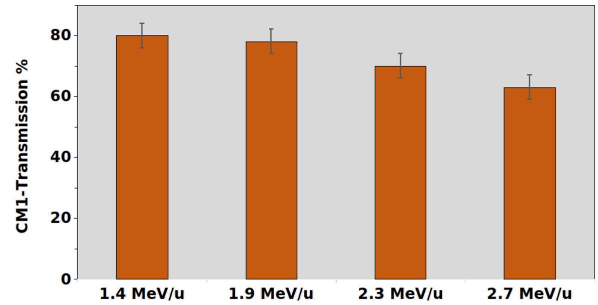

Figure 6: Beam transmission of argon beam at different energies.

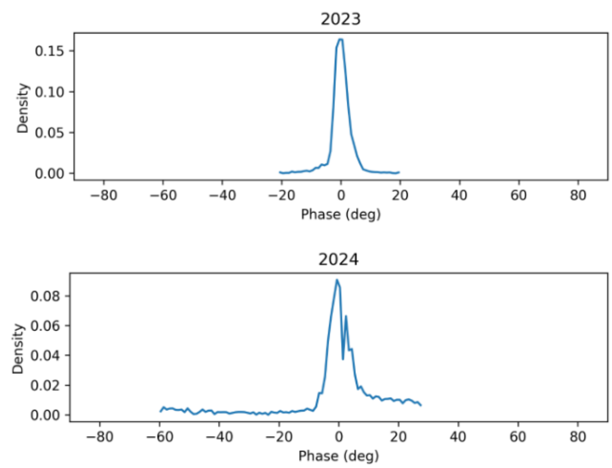

Figure 7: Bunch profile of injector recorded with the BSM during the 2023 and 2024.

An acceleration of an ions beam with a mass-to-charge-ratio of up to 5 could be achieved, with the beam energy smoothly varied between 1.4 MeV/u and the design output energy of 2.7 MeV/u. For a He^{2+} beam with mass to charge ratio of 2 a maximum beam energy of 3.1 MeV/u was accomplished. For stable operation with ions with $A/Z = 6$ and above, further improvements in the low-level RF control are necessary. Additionally, further tuning of the HLI is planned to minimize longitudinal and transverse emittance, ensuring high beam quality. Future beam campaigns with the HELIAC Advanced Demonstrator are planned to address these challenges.

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