CURRENT STATUS AND PROGRESS OF DESIGN AND COMMISSIONING OF HELIAC CAVITIES

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Abstract

The GSI Helmholtzzentrum für Schwerionenforschung is developing various particle accelerators, with the superconducting Helmholtz Linear Accelerator (HELIAC) as a key project, complementing the existing UNILAC. The project of HELIAC targets beam energies exceeding 7 MeV per nucleon via a four-cryomodule structure, optimised for heavy-ion acceleration at around 217 MHz resonant frequency. The first cryomodule, incorporating Crossbar-H (CH) cavities, has been successfully constructed and is currently undergoing vacuum, cryogenic, and RF tests, validating the design for subsequent modules.

This contribution overviews HELIAC's general aspects, focusing on CH resonators. It details the current project status, including design, fabrication, and testing of SRF components, optimised via simulations to target resonance frequency, with tolerances managed through assembly adjustments, buffered chemical polishing (BCP), and tuning. Plans and expected performance are discussed.

INTRODUCTION

The GSI Helmholtzzentrum für Schwerionenforschung has operated the Universal Linear Accelerator (UNILAC) for five decades as its primary heavy-ion driver. While UNILAC remains an excellent pulsed machine delivering high beam energies (up to ~11.4 MeV/u) with excellent beam quality, its pulsed nature (duty factor typically below a few percent) and normal-conducting technology limit the average beam intensity and continuous operation required by many modern experiments.

To overcome these limitations and to complement the upgraded UNILAC within the FAIR facility, the superconducting HElmholtz LInear ACcelerator (HELIAC) was proposed about ten years ago. In contrast to UNILAC, which is pulsed based accelerator, HELIAC is designed as a fully superconducting continuous-wave (CW) LINAC operating at 217 MHz. This fundamental difference enables high duty factor, significantly higher average beam currents (up to 1 mA), lower operating costs, and excellent energy stability — features that are essential for superheavy element (SHE) discovery, nuclear structure studies, material science under extreme conditions, and high-precision atomic physics.

HELIAC DESIGN

The HELIAC is a project of a superconducting continuous-wave heavy-ion linear accelerator dedicated to complement the existing UNILAC, providing high-duty-factor beams for experiments. The normal-conducting pre-accelerator section, driven by a 108 MHz RF source, delivers ions with a mass-to-charge ratio of up to 6 at an injection energy of 1.4 MeV/u to the superconducting section. The primary design plan (see Fig. 1) implies that the superconducting part must consist of four sequentially connected cryomodules, accelerating the beam to a final energy of up to 7.3 MeV/u, with a maximum beam current up to 1 mA.

Each cryomodule contains three Crossbar-H (CH) cavities, two superconducting solenoids for transverse focusing, and a dedicated rebuncher. It receives ions with $A/q \leq 6$ at 1.4 MeV/u from the High Charge State Injector (HLI) and accelerates them to a final energy of 7.3 MeV/u with beam currents up to 1 mA in CW mode with acceleration of ions up to ^{238}U and similar species.

The cryomodule CM1 (see Cryomodule 1 on Fig. 1) [1], which is currently in operation, comprises cavity CH0, which primarily handles initial acceleration of the incoming ion beam after pre-acceleration section, which is then focused by the first solenoid S1 before entering a dedicated buncher B1 section—a single-gap or low-cell cavity optimized for longitudinal beam compression to ensure synchronous operation with the subsequent accelerating cavities CH1 and CH2. The beam then undergoes further acceleration in the remaining two CH cavities before passing through the final solenoid S2 for transverse beam focusing. Each subsequent cryomodule will work according to the afore-described algorithm, ensuring continuous ion-beam acceleration up to the projected output energy.

CAVITY DESIGN

The most important component of the cryomodule is the SRF cavity. Its design, fabrication, and commissioning represent one of the most complex parts of HELIAC design [2].

The Crossbar H-mode (CH) cavity is a specialised superconducting radio-frequency (SRF) resonator optimised for the acceleration of low- to medium-energy heavy ions ($\beta = v/c \approx 0.05$–0.08) in continuous-wave (CW) linear accelerators. Unlike conventional TM-mode structures (e.g.,

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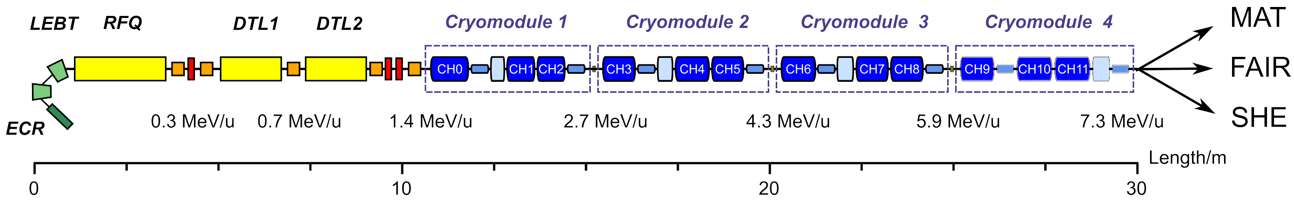

Figure 1: The diagram of the designed HELIAC.

elliptical cavities), the CH design operates in the H_{211} mode. In this mode, the electromagnetic field configuration features a strong longitudinal electric field E_z on the beam axis within the drift-tube gaps for efficient acceleration. As for the magnetic field, locally, there are components, such as an azimuthal magnetic field H_ϕ formed around the stems. However, the addition of the B-field from several stems leads to mainly a longitudinal magnetic field B_z in the four quadrants of the cavity.

The CH cavities offer advantages: optimized geometry G-factor; a compact multi-cell layout, which enables a short overall length ($\sim$ 0.5–1 m) while providing high voltage gain; mechanical robustness, as the crossbar geometry distributes mechanical stresses evenly, thereby minimizing Lorentz-force detuning and microphonics; efficient surface cooling thanks to a large surface-to-volume ratio and direct liquid-helium contact, allowing stable CW operation at accelerating gradients $E_{\text{acc}} > 5\,\text{MV/m}$; and advanced tunability ensured by integrated static and dynamic tuners for precise frequency control.

The 3D model (see Fig. 2), initially created in the CST Studio as a perfectly conducting entity with the vacuum volume, was thoroughly simulated and converted to the technological model for further production.

RESONANCE FREQUENCY ADJUSTMENTS

After cavity fabrication, installation and for further operation, the resonance frequency must be tuned to the target 216.816 MHz, accounting for all systematic effects [3], [4].

The nature of the SRF cavity's high performance is a tremendous sensitivity to adherence to the precise value of the target resonance frequency. The primary design, a purely metal structure, is the main, but not the only, factor determining the resonance frequency of the cavity. For precise and efficient operation of the cavity, the range of other factors (see Table 1) must be considered. The first factor influencing on to cavity resonance frequency, after the metal manufacturing, is buffered chemical polishing (BCP).

Table 1: Factors influence on designed resonance frequency of the cavity

Parameter	Unit	Value
Thermal shrink	kHz	+300...+400
Pressure sensitivity	Hz/mbar	-100..-150
ϵ_r – effect	kHz	+50...+100
BCP-etching	kHz/µm	<+3.0...+5.0>

Figure 2: CST model of CH3 cavity (upper picture). Manufactured parts of cavity CH3. Left lower: Welded two-arched main cylindrical body immediately after welding (welding seam visible between arches). Right lower: One of the CH cavity spokes.

This is a post-production surface chemical treatment for niobium SRF cavities with etching up to ~200 µm of material using a HF-HNO_3-H_3PO_4 solution to remove damaged layers, surface contamination of niobium, reduce roughness, and minimise field emission. The BCP primarily affects frequency via a slight volume increase (inner surface recession), but also indirectly via surface quality. In the table, the average evaluation of BCP is based on the simulation results and experimental data obtained during the manufacturing of cavities CH0-CH2. For different cavities, BCP etching can take different values, as confirmed by simulations and experimental data. Moreover, the discrepancy between simulated BCP-induced frequency shifts and experimental results can be significant. This is compensated by selecting appropriate BCP etching steps, typically between 50 µm and 100 µm. After each step the resonance frequency is measured by vector analyser to control a proper approximation of the target frequency after accounting for manufacturing tolerances.

The BCP influence on to resonance frequency might be explained in frame of Slater's perturbation theory. According to this theory, small geometric variations shift the resonance frequency according to the local balance of electric and magnetic stored energy. The surface formulation commonly used for wall perturbations in SRF cavities is written as:

$$\frac{\Delta f}{f} = -\frac{1}{2U}\int_S \left(\epsilon_0|E_{\perp 0}|^2 - \mu_0|H_{\parallel 0}|^2\right)\delta n\, dS, \qquad (1)$$

where U is the unperturbed stored energy and $\delta n > 0$ denotes inward normal displacement of the wall (material removal).

The sign and magnitude of the frequency shift are governed by the local difference between magnetic and electric field energy densities. In magnetic-field dominated regions ($\mu_0|H|^2 > \epsilon_0|E|^2$), material removal ($\delta n > 0$) produces a positive Δf. In electric-field-dominated regions, the same perturbation produces a negative Δf.

For BCP the influence of alteration of geometric volume or a material removal in terms of electric and magnetic fields can act differently depending on the geometric areas of the cavity. In the CH cavity, the field distribution is strongly non-uniform, which determines the sign of the main effects. Axial zone (beam axis and drift-tube gaps) has stronger longitudinal electric field E_z and lower magnetic field on the surface, so is E-dominated. Material removal here decreases the frequency. Meanwhile, cylindrical zone (internal cylinder radius, crossbar stems, and cavity walls) has stronger azimuthal magnetic field H_ϕ, almost zero electric field on the surface, so strongly H-dominated. Material removal here increases the frequency. For BCP, the resonance frequency shift is positive because in the cavity, the walls, and stems are predominantly magnetic-field dominated.

After manufacturing and BCP, the cavities and rebunchers are installed in the cryomodule following final tests and adjustments. Before the first RF tests of the complete cryomodule, the operational volume is evacuated to high vacuum. This evacuation shifts the dielectric permittivity inside the cavity from air ($\epsilon_r \approx 1.0059$) to vacuum ($\epsilon_r = 1.0$), causing a positive resonance frequency shift due to reduced effective capacitance.

After evacuation, the cavity undergoes cool-down to cryogenic temperature ≤ 4 K. This introduces two further factors influencing the resonance frequency. The first is thermal contraction at ≤ 4 K, which isotropically reduces the cavity volume and produces a positive frequency shift. The second is pressure sensitivity: variations in helium bath pressure deform the cavity walls, leading to a negative shift.

After all the aforementioned operations, all cavities in cryomodules undergo thorough final RF tests at a temperature of 4 K. Here, to compensate for any other possible frequency shifts and detuning effects and to ensure proper operation of the cavity at a specific resonance frequency of 216.816 MHz, the cavity is equipped with four frequency tuners during manufacturing. Two of them are static tuners, which are hollow niobium plungers for coarse, permanent frequency adjustment during manufacturing and final assembly. The other two are dynamic tuners, which are flexible niobium bellows actuated by a stepper motor (via axial compression) for compensating any unaccounted-for effects and manufacturing tolerances that might influence the resonance frequency, within the range of the tuner's adjustment capability ($\Delta f < 100\,\mathrm{kHz}$). Additionally, the dynamic tuners are equipped with piezoelectric actuators for fast compensation of Lorentz-force detuning and microphonics ($\Delta f \sim \pm 100\,\mathrm{Hz}$). The design, structure and all the aforementioned effects were successfully considered in simulations.

CONCLUSION AND OUTLOOK

The HELIAC represents a significant advancement in superconducting CW heavy-ion acceleration technology. The SRF section is under active development and construction, comprising four cryomodules in series to achieve a final energy of 7.3 MeV/u at the resonant frequency.

To date, the first cryomodule CM1, featuring CH cavities CH0, CH1, and CH2, two superconducting solenoids, and an integrated buncher, has been fully manufactured and assembled. Extensive vacuum, cryogenic, RF, and ongoing beam tests, are being implemented. The results of these tests will confirm stable CW operation, with accelerating gradients of > 5 MV/m and unloaded quality factors $Q_0 \geq 10^9$ at 4 K, aligning with design parameters. Observed destabilising phenomena, such as microphonics-induced detuning and multipacting barriers, will be effectively mitigated through enhanced helium cooling, active tuner feedback, and optimised manufacturing. The subsequent cryomodules CM2 and CM3 are slated for assembly and initial commissioning in late 2027-2029.

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