

Development and high-current cw operation of 166.6 MHz high-power, higher-order-modes-damped $\beta = 1$ quarter-wave SRF modules at the High Energy Photon Source

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The High Energy Photon Source (HEPS) is a recently commissioned 6 GeV fourth-generation synchrotron light source that utilizes a novel low-frequency superconducting radio-frequency (SRF) system. This system was designed to handle high beam power and achieve heavy damping of higher-order modes (HOMs) within strict spatial constraints. To meet these stringent requirements, we in-house developed and subsequently installed five $\beta = 1$ quarter-wave SRF cavities operating at 166.6 MHz and 4.2 K with a compact envelope. The design incorporates an enlarged beam pipe (505 mm in diameter) with a beamline absorber for effective HOM damping and adopts a single coaxial power coupler with on-cell coupling to handle a high continuous-wave power of 200 kW. Following rigorous cleaning and assembly protocols, the cryomodules demonstrated a peak electric field of 42 MV/m with negligible radiation and maintained a low dynamic heat load of 5 to 7 W at the operating voltage of 1.2 MV, results that significantly surpassed the design goals. Installed in Summer 2025, the cavities were instrumental in the successful acceleration of a 100 mA electron beam at HEPS in September 2025. This work represents the first successful implementation of superconducting quarter-wave cavities as the main accelerating system for a high-current storage ring, thereby extending the application limits of quarter-wave cavities from their conventional use in low- β accelerators to high-current electron storage rings and establishing a proven technology for future high-performance light sources.

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I. INTRODUCTION

The High Energy Photon Source (HEPS), located in Beijing, is a fourth-generation synchrotron light source featuring a beam energy of 6 GeV and a kilometer-scale storage ring. Designed by the Institute of High Energy Physics, the construction of HEPS began in June 2019 and successfully passed its key performance tests in October 2025. A hybrid seven-bend achromat (7BA) lattice was developed to achieve a natural beam emittance of 34 pmrad while maintaining a high-brilliance hard x-ray synchrotron radiation [1–3]. The electron beam is first

accelerated to 500 MeV by the linear accelerator, then injected into the 454 m booster ring to further ramp its energy to 6 GeV, and finally injected into the 1360.4 m storage ring, where a beam current of 200 mA can be stored. The main parameters of HEPS are listed in Table I.

A double-frequency radio-frequency (rf) system was employed for the storage ring to realize bunch lengthening and to facilitate the novel on-axis accumulation beam injection scheme, which alleviates the stringent requirements on the dynamic aperture [4]. The fundamental rf frequency was chosen as 166.6 MHz to ensure adequate separation between adjacent rf buckets, as necessitated by state-of-the-art kicker technology [5], while also maintaining a relatively high rf frequency to prevent excessive cavity envelope. Consequently, the third-harmonic rf frequency was determined to be 499.8 MHz, leveraging mature technologies for both cavities and power transmitters. However, after a set of thorough evaluations and assessments, the injection scheme was revised to the on-axis swap-out technique, which is less demanding for both the kicker and the rf system [6]. Although no longer mandatory, the low fundamental rf frequency was nonetheless retained to preserve future

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TABLE I. Main parameters of HEPS. ID, insertion device.

Parameter	Value	Unit
Circumference	1360.4	m
Beam energy	6	GeV
Beam current	200	mA
Energy loss per turn (w/14 IDs)	4.14	MeV
Total beam power	850	kW
Fundamental rf frequency	166.6	MHz
Total main rf voltage	5.16	MV
Third-harmonic rf frequency	499.8	MHz

possibilities for on-axis accumulation, utilizing either the current double-frequency rf system or a triple-frequency system by adding a second-harmonic rf [7]. Furthermore, the low fundamental rf frequency yields a longer bunch, potentially lowering the bunch current density, thus reducing intrabeam scattering, raising the impedance threshold for coupled-bunch instabilities, and eventually improving beam lifetime. Superconducting rf (SRF) technology has been adopted for both cavities, based on careful evaluations of current machine parameters and future HEPS upgrade involving additional insertion devices. The rf system therefore comprises five 166.6 MHz SRF cavities serving as the main accelerating cavities and two 499.8 MHz SRF cavities as the third harmonic for bunch lengthening in the HEPS storage ring [8]. The configuration of the rf system is illustrated in Fig. 1.

For the 166.6 MHz cavity, a superconducting quarter-wave resonator (QWR) geometry was adopted to achieve both the low resonant frequency and the $\beta (= v/c) = 1$ requirement. Furthermore, the heavy damping of higher-order modes (HOMs) in the cavities is essential to achieve high beam current. Given the limited space in the straight sections and the requirement for a realistic cryomodule

footprint, a compact cavity design was necessary in both the longitudinal and transverse directions. The high input power of 200 kW required a reliable fundamental power coupler (FPC) design featuring strong on-cell coupling and low cryogenic heat load. Finally, a significant margin in rf parameters was desired to guarantee stable user operation and possible cavity performance degradation over many years of beam operation.

The 166.6 MHz SRF modules were subsequently developed, encompassing several crucial design considerations to ensure optimal performance and long-term reliability. First, robust HOM damping was realized through an enlarged beam pipe with a diameter of 505 mm, which was subsequently coupled to a beamline absorber of the same aperture. This design was the result of an exhaustive campaign to achieve effective HOM damping while reconciling it with structural complexity [9]. The large beam aperture, however, posed significant difficulties in maintaining the cleanliness of the SRF cavity during postprocessing and string assembly. To preserve the excellent performance achieved during vertical tests of the bare and jacketed cavities, a set of comprehensive procedures was carefully developed and implemented for the cavity string assembly and cryomodule integration. Second, the largely asymmetrical beam pipes, resulting from the requirements of HOM damping and the pursuit of compactness, created considerable complexity in simultaneously complying with mechanical codes and ensuring adequate frequency tunability. An integrated stiffening and support strategy was therefore developed for the dressed cavities. This strategy was designed to achieve the required large tuning force and stress safety across all working conditions, particularly when balancing the significant pressure loads on the cavity surface following evacuation. Finally, the inherently limited tuning range of the QWRs mandated precise frequency control and monitoring throughout the entire process, including fabrication, postprocessing, assembly, testing, and installation. A deliberate frequency control and tuning scheme was developed to guarantee the attainment of the target frequency of 166.6 MHz at 4.2 K.

Five 166.6 MHz SRF modules were successfully developed and installed in the HEPS tunnel during the summer of 2025. This installation was followed by a smooth cooldown and rf conditioning of the cavities. Stable beam operation at 100 mA was achieved in September 2025, with all five cavities operating simultaneously. This marks the successful commissioning and operation of the 166.6 MHz SRF modules. These constitute the development and continuous-wave (cw) operation of the first high-power, HOM-damped quarter-wave $\beta = 1$ SRF modules in a storage ring.

This paper is organized as follows: Sec. II details the design of the 166.6 MHz SRF module, including the cavity, power coupler, higher-order modes, cryostat, and frequency control. Section III focuses on the cavity string assembly

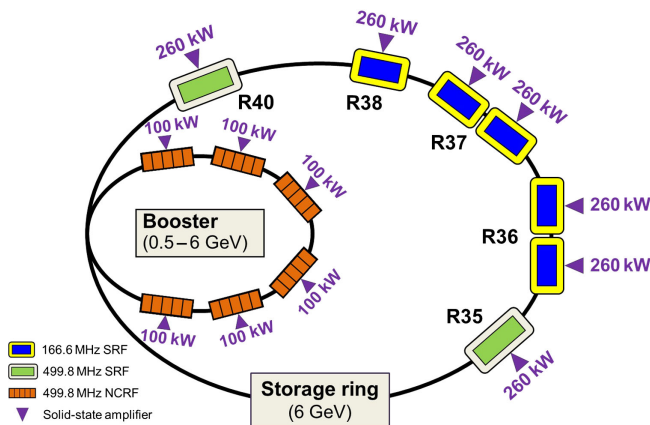


FIG. 1. Layout of the HEPS rf system. R35 to R40 represent the straight sections 35 to 40 in the storage ring, where the cavities are installed. The purple triangles represent the solid-state amplifiers, with their corresponding nominal rf powers indicated alongside. NCRF, normal-conducting rf.

and module integration to form a complete cryomodule. Section IV presents the subsequent high-power testing of the complete cryomodule at the horizontal test stand. Section V elaborates on the transportation, tunnel installation, commissioning, and operation of these modules at HEPS. Section VI concludes with a summary.

II. SRF MODULE DESIGN

The 166.6 MHz SRF module was required to be compact to fit within the restricted straight section of the HEPS storage ring. Under this constraint, the design was focused on achieving low-frequency, $\beta = 1$ operation, high cw power capability, and robust HOM damping. Furthermore, frequency control and tuning were also vital for this cavity. Within a total length of 2792 mm, a complete SRF module was successfully designed, featuring a comfortable rf margin, heavy HOM damping, and reasonable cryogenic heat loads.

A. SRF cavity and string

Superconducting quarter-wave resonators (QWRs) have been widely employed in accelerating low-velocity particles [10,11], while their application in high- β accelerators is less common [12]. The most notable existing examples include their use in rf guns [13,14] and crab cavities [15]. A recent instance is the 56 MHz bunch shaping cavities developed by the Brookhaven National Laboratory for RHIC [16,17]. The development and successful implementation of the 166.6 MHz cavities for HEPS further extends the usage of QWRs as the main accelerating structures for relativistic electrons.

The QWR geometry was selected to simultaneously meet the requirements for low frequency and $\beta = 1$ operation in a SRF cavity. Unlike conventional low- β applications, the electron beam is accelerated through the “open” end, necessitating a horizontal orientation of the cavity rather than the typical vertical arrangement. Beyond the standard goal of minimizing peak electric and magnetic fields, the design addressed unique challenges posed by the horizontal inner conductor. Mechanical stability (stress, deformation, and microphonics) for this 400 mm long cantilever structure was achieved by adding a bowl-shaped stiffener and local reinforcement on the cavity’s “short” end [18,19]. Tapering the inner conductor was also crucial for liquid helium (LHe) flow to benefit cooling, though this presented a design trade-off that compromised HOM damping and the fundamental mode’s R/Q value. Multipacting, inherent to coaxial structures, was thoroughly analyzed to ensure all related bands are “soft” and easily processed by rf conditioning [20,21].

Concerning the mechanical design, the primary focus was on compliance with mechanical codes across all working conditions throughout the entire life cycle of the cavity. The cavity features a large aperture of

505 mm to facilitate HOM damping, while the inner conductor side utilizes a small beam pipe of 80 mm. Due to these excessively asymmetrical cross-sectional areas, the equivalent force corresponding to the atmospheric pressure reaches 20 kN. This is too large for either the cavity or the bellows to withstand without further stiffening. Improved mechanical stiffness benefits pressure safety, pressure sensitivity, microphonics, and Lorentz-force detuning. However, stiffness must be balanced with frequency tunability, particularly for a QWR, where the tuning range is inherently small. A comprehensive stiffening scheme was therefore developed, incorporating localized wall thickness increase, strategic reinforcement, and hybrid stiffeners [19].

Despite being a large structure, the cavity was designed to be easily fabricated, accessible for surface treatment, compatible with cleanroom assembly, and have an overall envelope that is suitable for the cryogenic testing infrastructure. Measures taken to address these aspects included: optimized high-pressure rinsing (HPR) ports on the cavity [20], a simplified helium jacket design achieved by relocating the pickup antenna [22], and a detachable hash-shaped stiffener outside the LHe jacket [19].

Drawing on previous experience developing the proof-of-principle (PoP) cavity [18,20,23], the 166.6 MHz HOM-damped cavity was designed as shown in Fig. 2. Table II summarizes its rf and mechanical performance. The cavity features a length of 880 mm, an aperture of 505 mm, and an iris of 240 mm.

To deliver a minimum of 170 kW of rf power to the beam from each cavity, a 250 kW fundamental power coupler (FPC) was designed. The required power significantly exceeds the current level for TEM-type SRF cavities [24–29]. The FPC was chosen to be mounted on the cavity’s main body to realize the required strong coupling of $Q_{\text{ext}} = 5 \times 10^4$. The combination of high cw power, on-cell coupling, and the required clean assembly with the cavity presented significant challenges for the FPC and the cavity-coupler interface design. The 166.6 MHz FPC features a TRISTAN-type rf window [30] adopting a coaxial disk ceramic made of 97.6% alumina. The coupling is electric, and the interface with the transmission line is 9-3/16 in coaxial. The FPC incorporates a water-cooled inner conductor and a gas-helium-cooled outer conductor on its vacuum side, while air cooling was adopted for the inner conductor and T-box on the air side. The FPC model is shown in Fig. 3.

The FPC port location was carefully optimized to balance the increased heat load in the vicinity of the cavity’s “magnetic end” and the increased risk of field-emission electron bombardment on the ceramic window caused by the transverse electric field close to the cavity’s “electric end” [31]. The cavity-coupler interface area received particular focus [32]. An elongated niobium extension tube at the coupler port and enhanced cooling

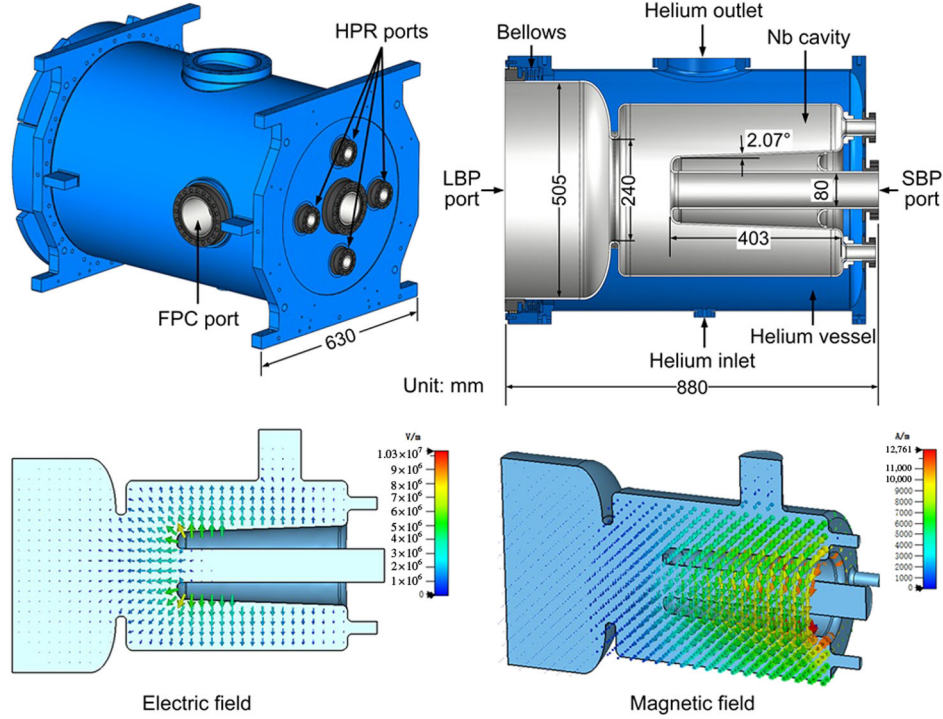


FIG. 2. The 166.6 MHz jacketed cavity and its electromagnetic field distributions. The electric and magnetic field values are normalized to a cavity stored energy of 1 J.

of the FPC's outer conductor and cold flange were implemented [33]. Overheating observed in the PoP cavity was effectively mitigated, resulting in a largely reduced dynamic heat load and a much lower flange temperature. To enable assembly of the FPC with the cavity in the cleanroom, both the coaxial section and the rf window were designed to be sufficiently compact to fit within the cryostat's cylindrical envelope.

TABLE II. rf and mechanical parameters of the 166.6 MHz HOM-damped cavity. VTS, vertical test stand; HTS, horizontal test stand; and LFD, Lorentz force detuning.

Parameter	Value	Unit
Frequency	166.6	MHz
Operating voltage V_{op}	1.2	MV
Operating gradient E_{acc}	10	MV
E_p/E_{acc}	3.18	
B_p/E_{acc}	4.97	mT/(MV/m)
Q_0 at VTS ($V_c = 1.5$ MV)	$\geq 1 \times 10^9$	
Q_0 at HTS ($V_c = 1.2$ MV)	$\geq 5 \times 10^8$	
R/Q ($= V ^2/\omega U$)	139	Ω
Geometry factor G ($= R_s \times Q_0$)	56	Ω
External Q	5×10^4	
Nominal input cw rf power	170	kW
Frequency tuning range (4.2 K)	76.6	kHz
Pressure sensitivity (df/dp)	20.3	Hz/mbar
LFD coefficient	-0.9	Hz/(MV/m) ²
Lowest mechanical mode	108	Hz

The compactness requirement for the 166.6 MHz SRF cavity string necessitated balancing several critical factors, including heat load management, mechanical safety, wake-field loss factor, HOM damping, synchrotron light collimation, and accessibility for installation and maintenance [34]. The cavity string components, designed under these constraints, comprise a jacketed cavity, a 250 kW FPC, two thermal break beam tubes (TBTs), an HOM absorber, a collimating taper transition, and gate valves on both ends, as shown in Fig. 4. Each 6 m straight section contains two identical and interchangeable cryomodules. The electron beam enters the module from the side with the smaller beam pipe. The water-cooled collimator on the taper effectively shields synchrotron light and absorbs the heat load. Despite its large diameter, the TBT design effectively minimizes the overall static heat load within the extremely limited longitudinal space. The calculated static heat load at 4.2 K is 8.76 and 1.37 W for the large and small TBTs, respectively [35]. Furthermore, the HOM absorber design successfully reduces the impedance below the threshold required to prevent coupled-bunch instabilities. Detailed information on HOM damping is provided in the subsequent section.

B. Higher-order modes

The 200 mA beam current at HEPS requires heavy damping of HOMs in the 166.6 MHz cavities to avoid coupled multibunch instabilities. The frequency of the first longitudinal HOM is 464 MHz, while the first transverse mode is 424 MHz. The primary challenges involved the

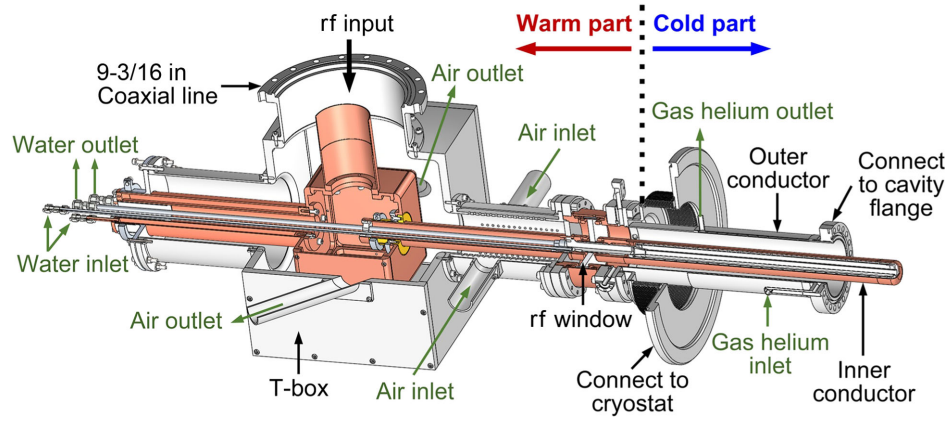


FIG. 3. The 166.6 MHz 250 kW fundamental power coupler (sectional view). The cold part is placed inside the cryostat.

heavy damping of these low-frequency HOMs with large R/Q values and the handling of the high HOM power, all while maintaining a compact geometry. Various design options were explored and compared, and the baseline finally adopted an enlarged beam tube with a room-temperature HOM absorber [9].

The impedance threshold and the HOM damping requirements were established based on two scenarios: the first considering only the fundamental rf at 166.6 MHz, while the second including the third-harmonic rf. In the first scenario, damping of the longitudinal HOM is dominated by the synchrotron radiation, allowing the classic analytic formulas to be used for calculating the impedance threshold that causes coupled-bunch instabilities [9],

$$Z_{L,\text{total}}^{\text{th}} = \frac{1}{f_{\text{HOM}}} \frac{2E_0 Q_s}{I_b \alpha \tau_z}, \quad (1)$$

$$Z_{x/y,\text{total}}^{\text{th}} = \frac{2E_0}{f_{\text{rev}} I_b \beta_{x/y} \tau_{x/y}}, \quad (2)$$

where $Z_{L,\text{total}}^{\text{th}}$ and $Z_{x/y,\text{total}}^{\text{th}}$ are the total longitudinal and transverse impedance threshold, f_{HOM} is the HOM modal frequency, E_0 and I_b are beam energy and beam current, Q_s

is the synchrotron tune, α is the momentum compaction factor, f_{rev} is the bunch revolution frequency, $\beta_{x/y}$ are the maximum β functions at the rf cavity locations, and $\tau_{x/y/z}$ are radiation damping time in three directions. In the most pessimistic situation, where all five 166.6 MHz cavities share identical HOM frequencies, they must equally share the total impedance budget, yielding the most stringent damping requirements. The impedance thresholds are shown in Fig. 5(a) as the dashed curve. Coupled-bunch instabilities are predicted not to emerge if HOMs are damped such that their impedance values lie below the corresponding threshold curves.

Once third-harmonic cavities are installed, the bunches in the storage ring are lengthened, which changes the synchrotron tune (Q_s) and consequently alters the longitudinal impedance threshold for coupled-bunch instabilities. To evaluate instabilities with harmonic cavities, the algorithm described in the literature [36] was adopted. The resulting impedance threshold is shown in Fig. 5(a) as the solid curve. An even lower threshold occurs for HOMs with frequencies below 2 GHz, dictating more rigorous HOM damping. The transverse impedance thresholds are independent of whether harmonic cavities are added, thus only one set of thresholds is provided, as shown in Fig. 5(b).

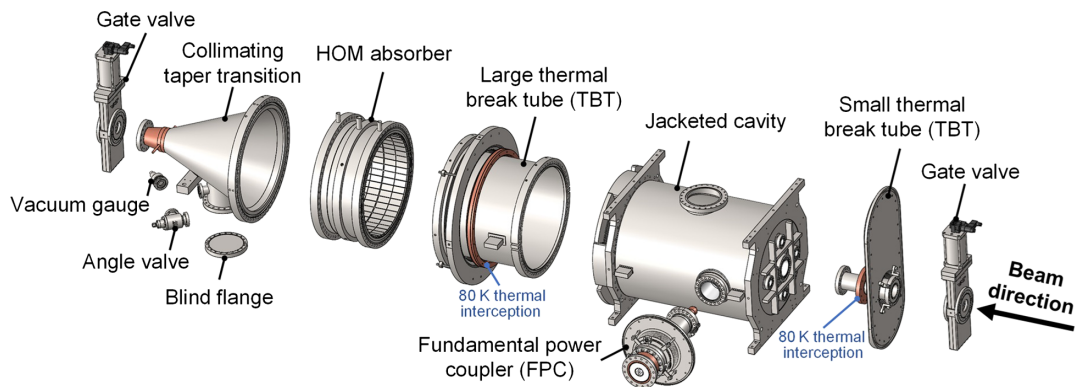


FIG. 4. The 166.6 MHz cavity string (before assembly with the ion pumps, exploded view).

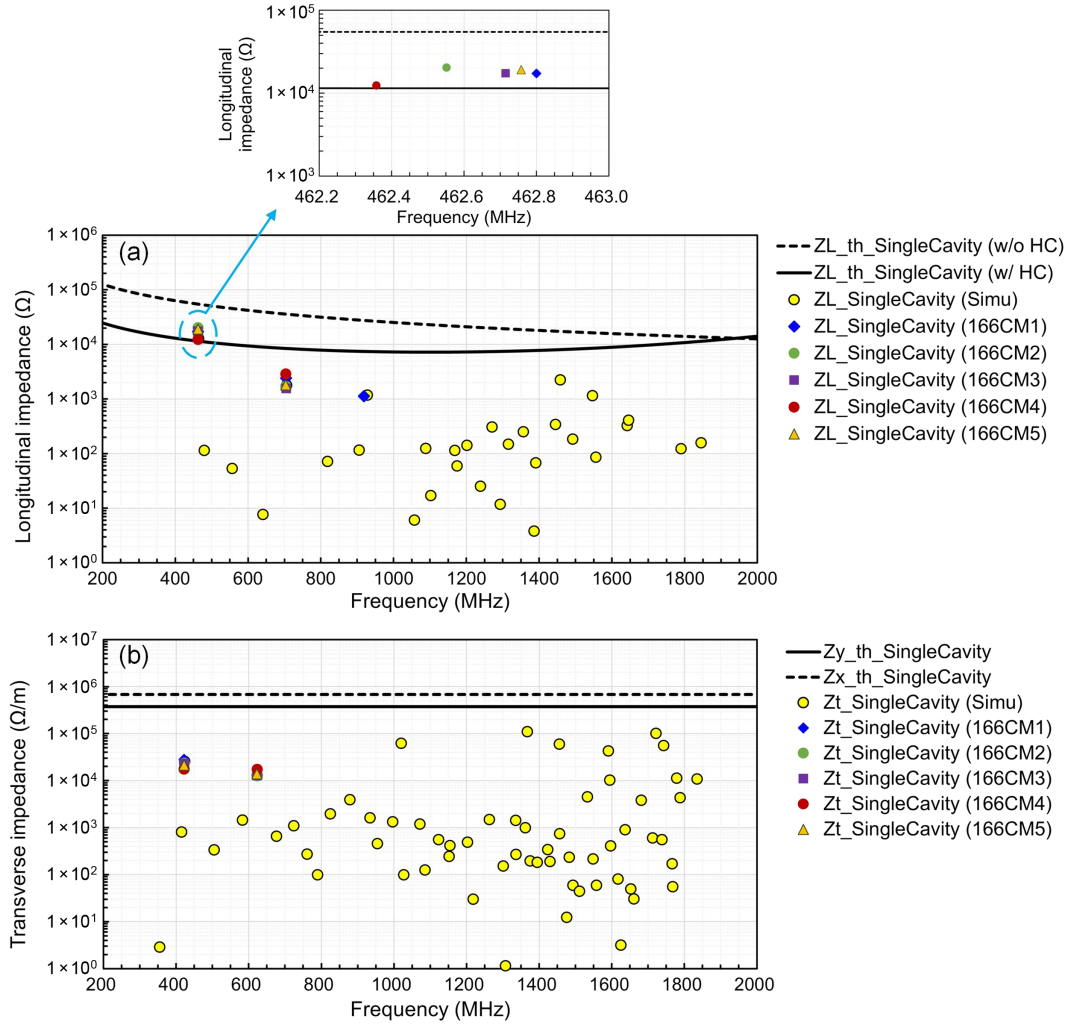


FIG. 5. HOM measurement results compared with simulation and impedance threshold: (a) monopole modes, (b) dipole modes. The frequency spread of M2 among five cavities is higher than 0.4 MHz. HC, harmonic cavities, which are the 499.8 MHz SRF cavities for HEPS. “Z_L” and “Z_t” are longitudinal and transverse impedances, respectively, th, threshold.

The wakefield in the cavity string was calculated using the ABCI code [37]. For the bunch length of 5.06 mm, which corresponds to the operation case without harmonic cavities, the loss factor (k) of each 166.6 MHz SRF module was calculated to be 2.6 V/pC, and five cavities will contribute approximately 19% of the total longitudinal loss factor. The loss factor is significantly reduced to 0.8 V/pC per module once the bunch is lengthened to its design value of 29.8 mm under ideal harmonic cavity settings [2]. The average HOM power (P_{HOM}) was calculated as a single-pass excitation using the formula $P_{\text{HOM}} = kqI$ (k : loss factor, q : bunch charge, I : beam current) [38]. The average HOM power per cavity was calculated to be 676 W for nominal operation (high-brightness mode, 680 bunches, 1.33 nC per bunch), and 7.32 kW for the high-bunch-charge mode (63 bunches, 14.4 nC per bunch). The filling pattern for HEPS was designed to be mostly uniform and evaluated to have a minimum impact on HOM power [9].

The ferrite absorber was chosen due to its optimal damping performance below 1 GHz, the frequency where the dominant HOMs of the 166.6 MHz cavities are located. Since ferrite is a porous material that is not fully compatible with modern SRF cleanliness standards, it was placed at a distance from the cavity to mitigate contamination. This choice, however, consumed longitudinal space, resulting in limited room for the taper transition and potentially elevating the impedance at the high-frequency end. A necessary compromise was made regarding the final location of the absorber.

The HOM absorber consists of 200 ferrite tiles (each 60×29 mm with a 4 mm thickness) arranged to form a 50-sided polygon, as shown in Fig. 6(a). Each ferrite tile was brazed to a copper-alloy substrate to ensure good thermal contact. Water cooling channels were machined in the copper base to provide the cooling capability required for absorbing the designed HOM power of 10 kW. Under these conditions, the ferrite tiles were calculated to reach a

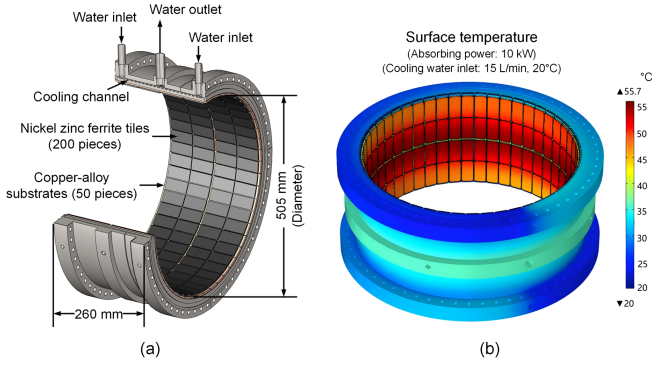


FIG. 6. (a) Geometry of the HOM absorber (sectional view). (b) Temperature distribution of the HOM absorber under 10 kW power dissipation in ferrite tiles with water cooling.

temperature of 55.7 °C (a rise of 35.7 °C), as shown in Fig. 6(b), which is acceptable for operation. Later high-power tests of the HOM absorber, with 10 kW rf power dissipated in the ferrites, confirmed the design specification [8].

The simulated damping results are shown in Fig. 5, and the magnetic field distributions are shown in Fig. 7. The first monopole HOM at 464 MHz marginally fulfills the impedance requirement, while all other modes are comfortably below their respective impedance thresholds. A majority of this mode's energy is efficiently transferred from the cavity along the beam tube to the beamline HOM absorber, as shown in Fig. 7(b). Calculations indicate that the impedance threshold will be increased by a factor of 1.7 when the HOM frequency spread is 0.2 MHz, thus satisfying the damping results. The unwanted damping of the fundamental mode (166.6 MHz) was minimized to a

quality factor of 1.3×10^{10} , which is one order of magnitude higher than the designed cavity Q_0 specification.

The HOM frequencies and quality factors were measured for each module after the final assembly. The first several modes can be coupled through the FPC without the T-box, whose results are in close agreement with the simulations, as shown in Fig. 5. The measured frequency spread among modules was 0.4 MHz. According to measurements performed during the absorber bakeout, the quality factor of the first monopole HOM can be further reduced when the ferrites are heated up to 60 °C, corresponding to a power absorption of 10 kW. Under these conditions, all measured modes fully met the stringent impedance requirements.

C. Cryostat design

The cryomodule contains a single 166.6 MHz SRF cavity immersed in LHe, operating at 4.2 K, as shown in Fig. 8. The vacuum vessel of the cryostat is made of stainless steel 316 L with an inner diameter of 1500 mm and a length of 1540 mm. The jacketed cavity has an envelope diameter of 630 mm, while the fully dressed cavity, including the vacuum part of the FPC, has a diameter of 1208 mm. The LHe volume within the helium jacket is 89 L due to its compact nature. To ensure stable operation, this volume is supplemented by a two-phase pipe of 273 mm in diameter and 1237 mm in length, which is placed on top of the cavity, increasing the total LHe capacity to 157 L. The LHe supply connects at both the top and bottom of the cavity jacket to stabilize helium pressure during cooldown. The outer conductor of the FPC is cooled by helium gas evaporating from the LHe vessel, with a regulated flow rate.

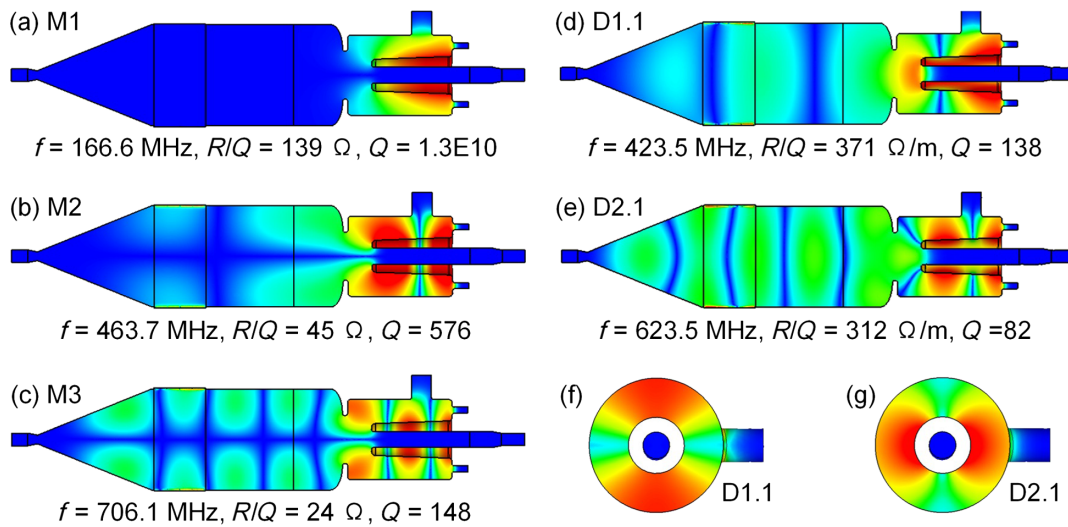


FIG. 7. Magnetic field distribution of the fundamental mode and the dominant HOMs. M, monopole; D, dipole; D1.1 and D2.1, the first polarization of D1 and D2, respectively. The magnetic field distribution of the second polarization is orthogonal to that of the first. The frequency, R/Q , and the loaded quality factor are marked for each mode.

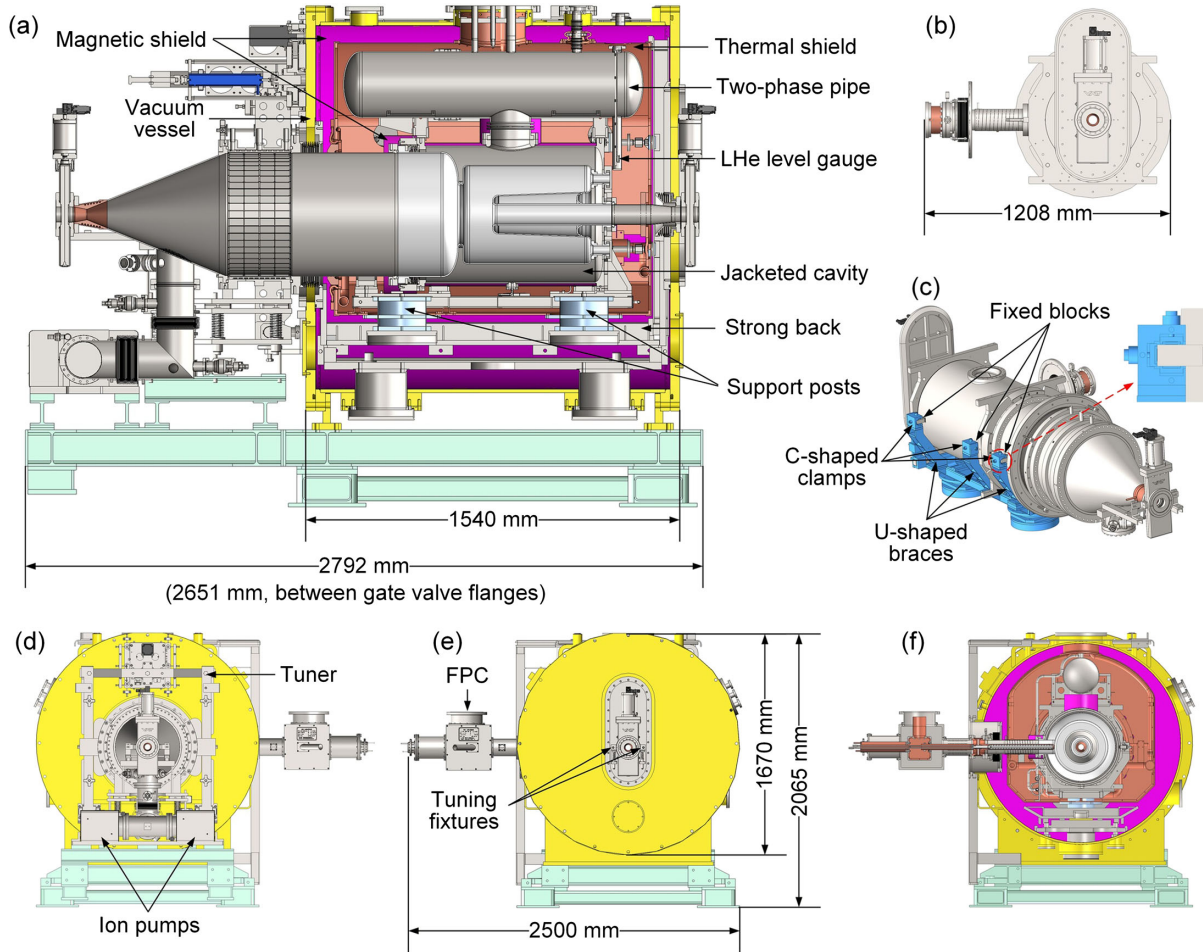


FIG. 8. The 166.6 MHz cryomodule. (a) Sectional view of the complete module. (b) Side view of the cavity string with an envelope of 1208 mm. (c) Cavity string placed on the support posts with a detailed view of the C-shaped clamps holding the fixed supports. (d) Side view from the large beam pipe. (e) Side view from the small beam pipe. (f) Sectional view of the CM cutting through the FPC.

The 80 K thermal shield is made of aluminum alloy and cooled by liquid nitrogen. The two TBTs provide the transition between the 4.2 K cavity and the room-temperature environment. Due to the cavity string's compact longitudinal footprint, these tubes contribute substantially to the total static heat load. Thermal interceptions at 80 K are therefore added to both tubes at optimized locations [34]. This balances a minimized heat load transferred to 4.2 K against maintaining the temperature of the external flange outside the cryostat to prevent condensation. The jacketed cavity, the FPC's outer conductor, the two TBTs, the two-phase pipe, the 80 K thermal shield, and the connecting cryogenic pipes are all wrapped with multilayer insulation to minimize radiation heat load. Thermal analysis of the 166.6 MHz cryostat is detailed in a previous publication [35].

Temperature sensors are strategically installed on the surface of the jacketed cavity, FPC, and the two TBTs to monitor the temperatures during cooldown and operation. A maximum difference of 10 K over the cavity surface and a maximum rate of 5 K/h were enforced during cooldown

and warm-up. These limits are necessary to thermalize the large cold mass, thus preventing excessive thermal stress on the large cavity flange that could cause vacuum leaks. Heaters are installed on the inner surface of the two-phase pipe for calibration in subsequent tests and to regulate heat loads during operation.

To ease the shielding of the Earth's magnetic field, the cavities' beam axis is placed in the east-west direction. The magnetic shielding of the 166.6 MHz cavity consists of two layers, one outside of the jacketed cavity at 4.2 K to prevent intervention with LHe flow, and the other inside the cryostat at room temperature to enhance the shielding performance [39]. Both shielding layers are 1.5 mm thick and are made of Mu-metal permalloy: Ni79Mo4 (1J79) alloy for cavity shield at 4.2 K, Ni80Mo5 (1J85) alloy for cryostat at room temperature. The maximum residual magnetic field measured inside the inner shield was 30 mG, successfully meeting the specified 40 mG and consistent with simulation predictions, as shown in Fig. 9.

The cavity and the large TBT are supported by three U-shaped braces connected to the support posts. C-shaped

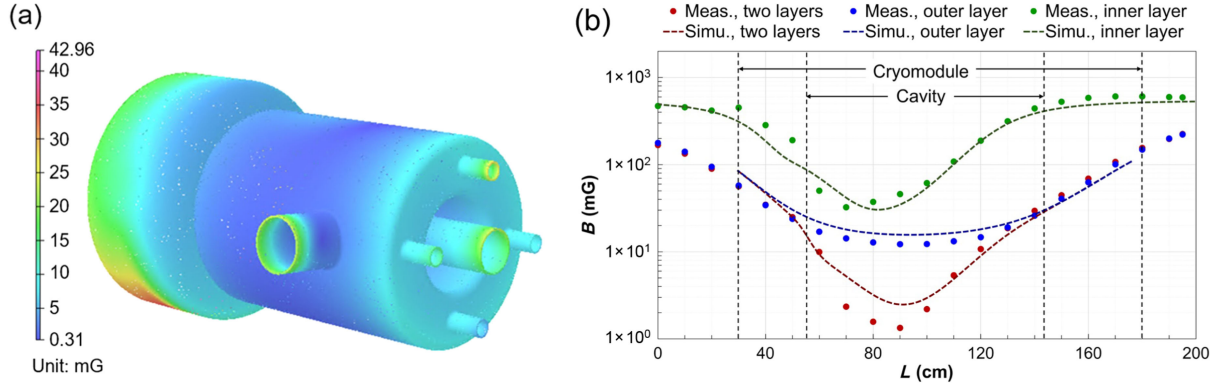


FIG. 9. (a) Simulated residual magnetic field on the cavity with two layers of magnetic shielding, (b) measurements of the magnetic field inside the cryostat with different shielding setup compared with simulations.

clamps connect the U-shaped braces to fixed blocks on both sides of the cavity and the large TBT, ensuring alignment through adjustable bolts and spring washers, as shown in Fig. 8(c). The end plate of the cavity is fixed by a stainless-steel triangular plate on the support posts. Additional reinforcement connecting the cavity to the cryostat and the support posts is implemented to enhance the cavity's stability, particularly during vacuum evacuation and frequency tuning. This measure was adopted following unsatisfactory performance observed during the initial test of the first module (CM1). Because the thermal transition distance of this scheme is relatively short, G10 plates are incorporated into the connection, which successfully reduced the static heat load penalty at 4.2 K to 4.8 W. Ultimately, the design ensures that 60% of the tuning displacement measured on the large beam pipe (LBP) can be utilized for the necessary cavity deformation.

D. Frequency control and frequency tuning

The 166.6 MHz cavity requires precise frequency control throughout the entire production, treatment, assembly, and operation process. This requirement stems from two inherent design challenges: the relatively low tuning sensitivity due to the large beam aperture on the capacitive plate at the cavity's open end, and a high tuning stiffness compared to other SRF cavities. Consequently, the coarse tuning range is intrinsically limited. The frequency shift for each processing step was previously determined and carefully monitored for each cavity, as shown in Fig. 10.

The common free parameter for pretuning during QWR fabrication is the capacitive gap between the inner conductor head and the end plate [40]. However, this region constitutes the accelerating gap for the 166.6 MHz cavity due to its horizontal orientation. If the gap was modified via cavity trimming, the overall cavity length would be varied,

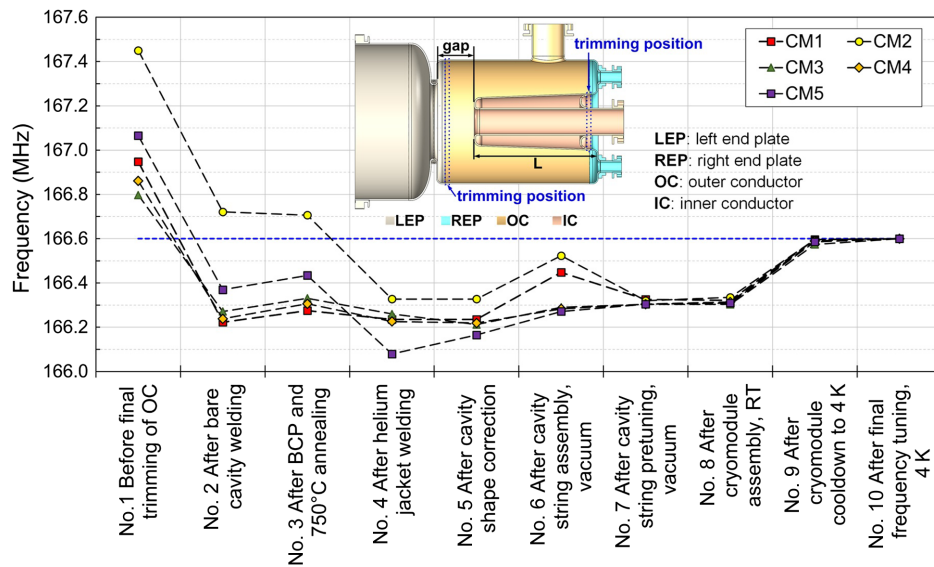


FIG. 10. Frequency evolution of all five cavities from manufacturing to operation at 4.2 K.

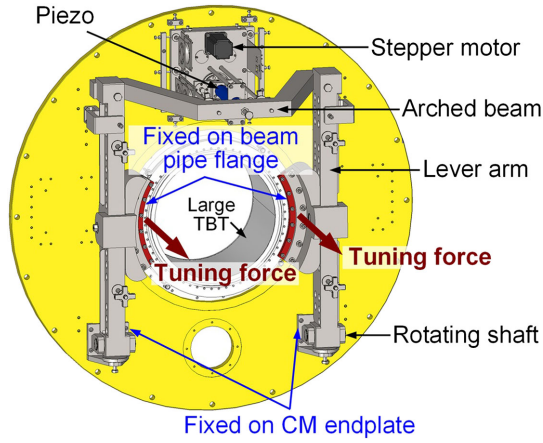


FIG. 11. Tuner system mounted on the cryomodule's endplate and connected to the large TBT. Other module components are hidden in this view.

potentially consuming most of the available range of the bellows located on the large TBT and the bellows outside the gate valve. Since these bellows must also compensate for thermal contraction during cooldown, installation errors, and alignment issues, a new pretuning scheme was developed [41]. This scheme involves coordinating the trimming of both the inner and outer conductors to maintain a constant overall cavity length, as shown in Fig. 10. Furthermore, the higher frequency sensitivity associated with the inner conductor length allows for a smaller trimming quantity.

Once the cavity string is assembled and baked, the frequency can still be adjusted using the installed hash-shaped stiffener if required. Finally, a specialized fixture was designed to be mounted on the small beam pipe (SBP) side outside the cryostat. This fixture allows the frequency to be adjusted even at 4.2 K should unexpected frequency variations occur during cooldown. These measures constitute a comprehensive frequency control scheme to mitigate the inherent small tuning range of $\beta = 1$ QWRs.

A dynamic (fast and slow) tuner system was developed for the 166.6 MHz cavity. The tuner is mounted on the endplate outside the cryostat, shown in Figs. 8 and 11, ensuring that all tuning components operate at room temperature to maximize reliability and simplify maintenance. The mechanism utilizes a reduction gearbox (including a motor and a piezo actuator), which, through a system of lever arms connected to the warm flange of the large TBT, applies an axial force to induce the required longitudinal deformation of the cavity, as shown in Fig. 11. The system, estimated to have a mechanical stiffness of 32 kN/mm, provides two operational regimes: a slow (coarse) tuning range of over 50 kHz driven by the motor, and a fast tuning regime provided by the piezo actuator, offering a fine range of over 1 kHz with a resolution of approximately 1 Hz.

III. CAVITY STRING AND CRYOMODULE INTEGRATION

The cryomodule integration process involves four sequential steps: first, assembly of the cavity string within the cleanroom; second, integration of the cavity string and the cryostat to form an intermediate assembly; third, mounting of the ion-pump group with the intermediate assembly in the cleanroom, thereby finalizing the core module structure; and fourth, installation of the tuner and FPC's T-box onto the resultant structure. Following these steps, a full cryomodule is constructed. This process requires only one vacuum break, with the sealing port located far from the cavity and oriented downward to minimize potential contamination during installation.

In the first step, the entire cavity string, excluding the ion-pump group, is assembled in a class 10 cleanroom. The components involved are one jacketed cavity, two TBTs, one HOM absorber, one collimating taper transition, two gate valves, and one FPC. The overall length of the cavity string is 2651 mm, and it weighs 612 kg (excluding the ion-pump group). Due to the large component diameters, the complex structure, and the significant weight, the clean assembly of the cavity string posed unprecedented challenges regarding vacuum sealing, cleanliness, and precision. A comprehensive clean assembly procedure, shown in Fig. 12(a), was developed to address these challenges.

Prior to clean assembly, the cavity, the two TBTs, and the taper were high-pressure rinsed with ultrapure water with a resistivity of 18 M Ω cm [20]. After the high-power tests previously completed on the test stand, the vacuum section of the FPC was stored under vacuum in the cleanroom. This FPC assembly was subsequently backfilled and purged with dust-free nitrogen gas. Similarly, the HOM absorber was rinsed with ethanol and dried via nitrogen purging, while the gate valves were also purged with dust-free nitrogen.

To facilitate the sealing of large flanges with an inner diameter of 505 mm, all components featuring large apertures were assembled vertically. Precise alignment was critical: the supporting blocks on the cavity and the large TBT required a rotational tolerance of 1°, while the angular orientation of the ion-pump port on the taper required a tolerance of 2°. Following cleaning of the cavity, the large TBT, the collimating taper, and the HOM absorber, these four components were first joined vertically with a gate valve, an angle valve, and a vacuum gauge, as shown in Fig. 13(a). Rotatable flanges were incorporated to accommodate screw hole tolerances. Dedicated tooling was utilized to ensure the proper positioning of these heavy parts during this vertical assembly. Subsequently, this joined subassembly was rotated to the horizontal position and placed on a platform cart. After the preassembly of the small TBT and the second gate valve (also performed vertically), these components were then integrated horizontally with the cavity. Finally, the FPC was assembled with the cavity, also in the horizontal orientation. The ion-pump port

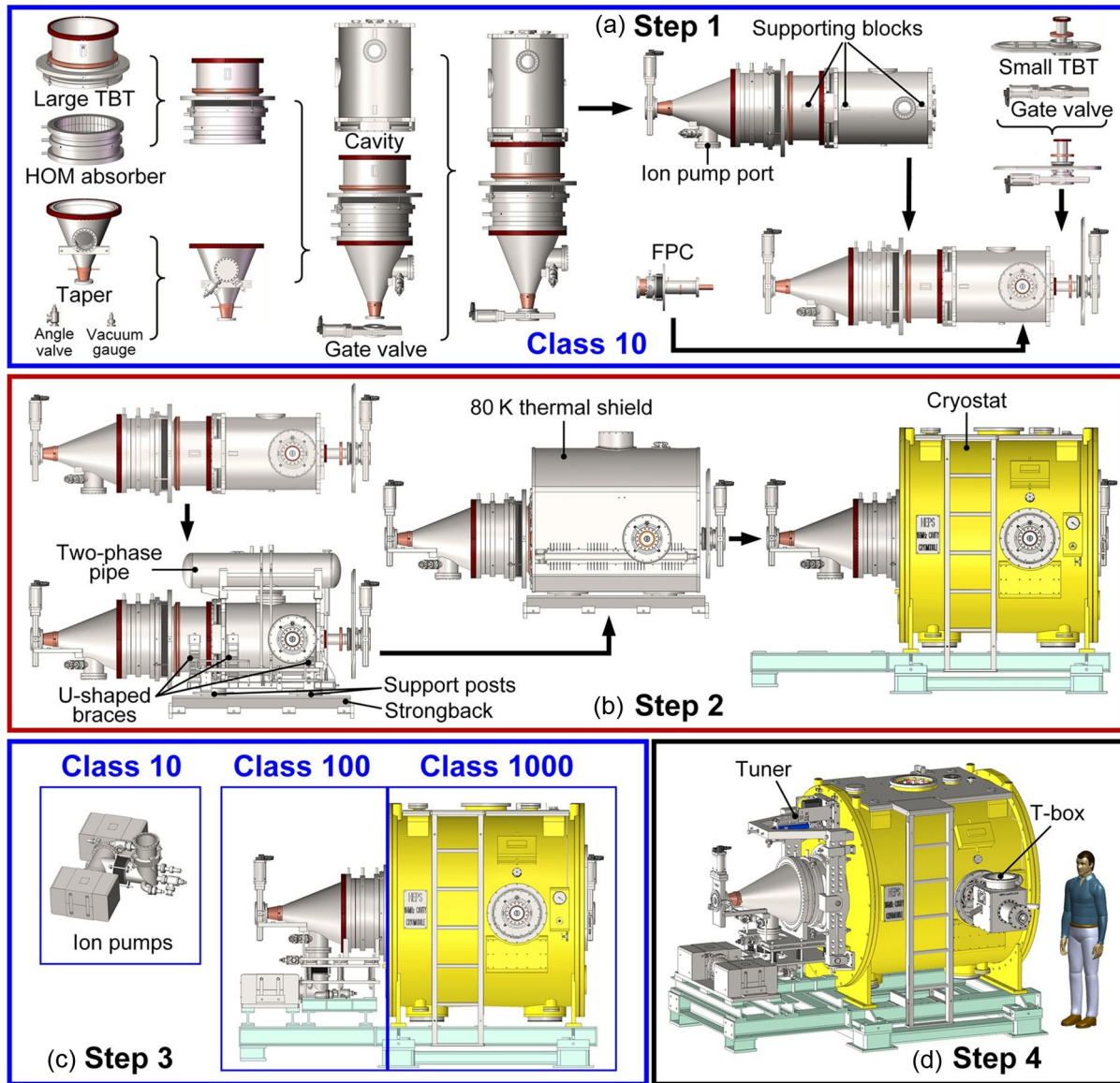


FIG. 12. Cryomodule integration in four sequential steps. The first and the third steps are conducted in the cleanroom.

on the taper was sealed using a blind flange. This completed the first step of the integration process, forming a cavity string, as shown in Fig. 13(b).

Following a slow pumping procedure and a leak check, the cavity string was transferred outside the cleanroom for baking. Due to its porous composition, the HOM absorber required an initial bakeout above 120 °C for a minimum of 48 h before the baking of the other components began. The niobium cavity bakeout was specified at 120 °C for 48 h. During this period, other components, including the HOM absorber, were maintained at temperatures below 110 °C. The typical temperatures and vacuum pressure measured throughout the baking process are shown in Fig. 14. After the bakeout, the frequencies and the Q values of the fundamental and the higher-order modes were measured.

The second step of the integration process started with a fiducialization of the cavity string. The string was then transferred to the strongback, and a subsequent alignment was performed between the cavity string and the cryostat's vacuum vessel to meet the specified tolerance of ± 1.5 mm in transverse direction, ± 1.0 mm in beam axis, and ≤ 1 mm offset for the FPC flange. Various sensors, cryogenic pipelines, magnetic shields, and thermal shields were installed, as shown in Fig. 13(c). Subsequently, the cold mass was moved into the vacuum vessel, and the end plates were mounted. A leak check of the vessel and the cryogenic pipeline then followed. This process completed the intermediate assembly of the cryomodule, as illustrated in Fig. 12(b). It is notable that the cavity string was maintained under vacuum throughout this step.

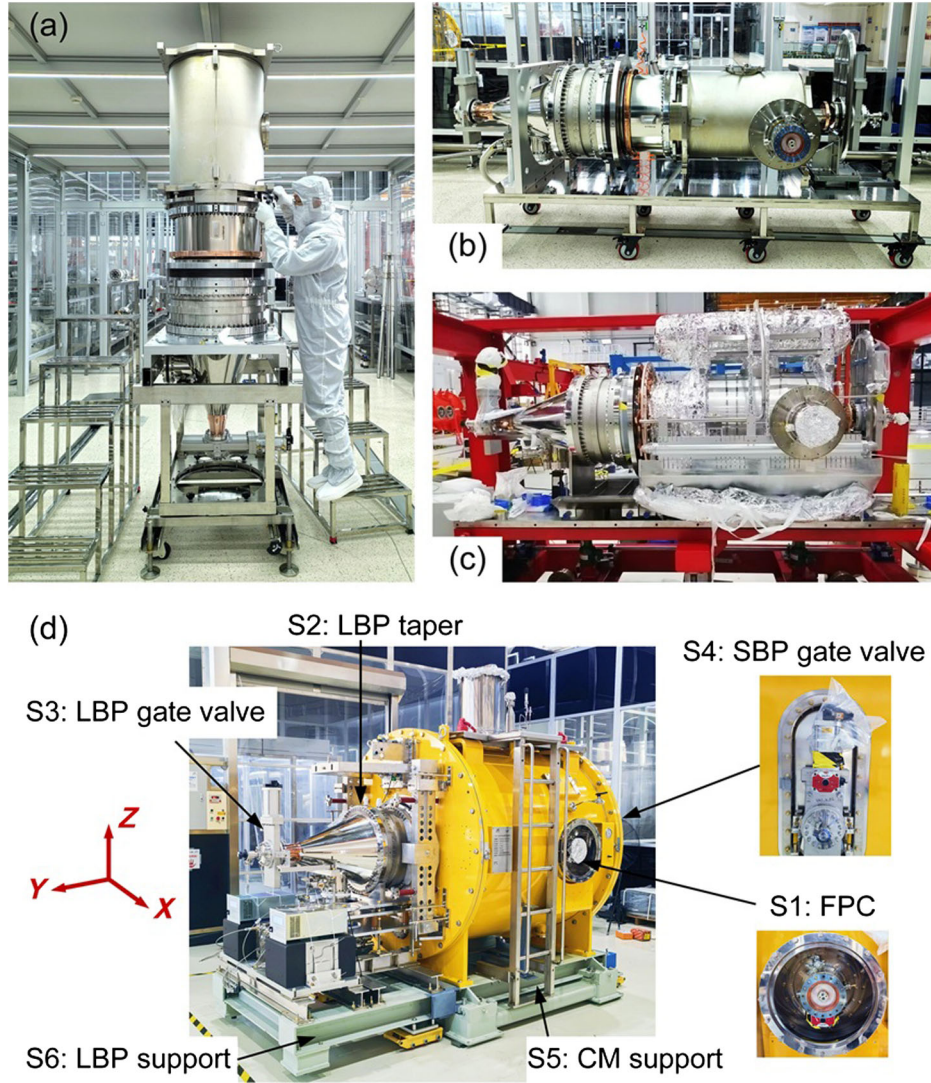


FIG. 13. Cavity string and cryomodule assembly: (a) cavity string assembly in class 10 cleanroom, (b) complete cavity string, (c) cavity string on the strongback with two-phase pipe and cavity magnetic shielding installed, (d) complete cryomodule. S1 to S6 are accelerometers installed at various locations during transportation. “*x* direction” is the horizontal axis, “*y* direction” is the beam axis, and “*z* direction” is the vertical axis.

Concurrently, the ion-pump group was also assembled in a class 10 cleanroom, with all components thoroughly cleaned beforehand. A bakeout and a leak check were performed to ensure the readiness of this subassembly. The intermediate assembly of the cryomodule was then transported to an adjacent cleanroom and integrated with the ion-pump group, as shown in Fig. 12(c). A final leak check was subsequently performed on the cavity string.

A variety of gasket types were employed for vacuum sealing of the cavity and the cryostat. Aluminum alloy 6082-T6 gaskets, developed in-house, were used throughout the beamline assembly [34]. Their reliability has been extensively validated in dedicated experiments and cavity vertical tests. Exceptions were the knife-edge flanges on gate valves, vacuum gauges, angle valves, and ion pumps,

where copper gaskets were employed. For the helium system, the inlet and outlet lines were connected to the cavity’s helium jacket using indium gaskets. Finally, the cryomodule’s vacuum vessel was sealed with ethylene-propylene-diene monomer (EPDM) gaskets, except at the knife-edge flanges housing multipin feedthroughs, which utilized copper gaskets. The performance of both indium and EPDM gaskets has been successfully demonstrated in various IHEP projects [42].

Finally, the module was moved out of the cleanroom, where the tuner and the FPC’s T-box were installed, as shown in Figs. 12(d) and 13(d). A room-temperature tuner test was conducted to examine the tuning function of the module. After all these procedures, the cryomodule integration was completed.

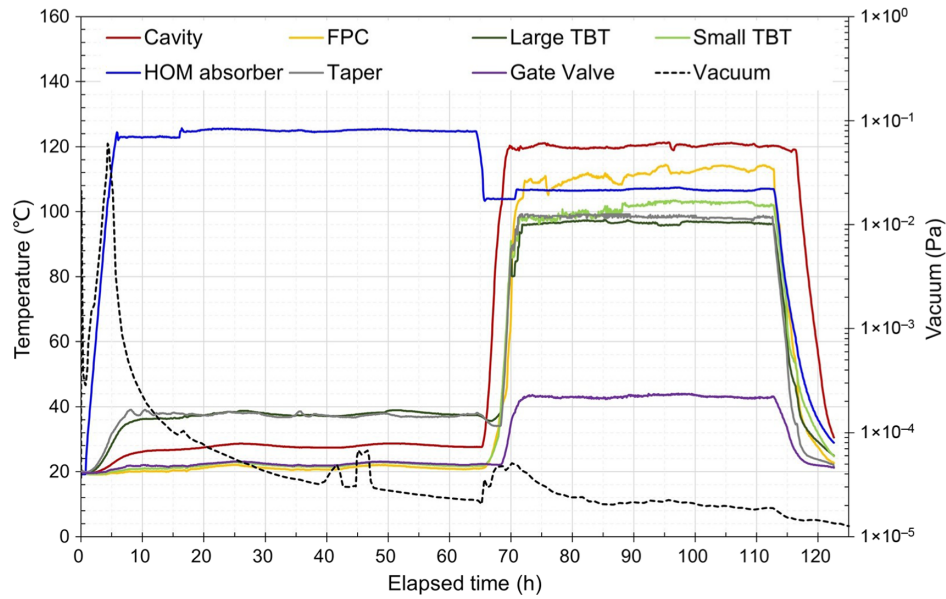


FIG. 14. Temperature readings and vacuum pressure of the cavity string in the baking process. The HOM absorber was baked first.

IV. CRYOMODULE HORIZONTAL TEST

Following assembly, each cryomodule was transferred to the horizontal test stand (HTS) at the Platform of Advanced Photon Source Technology R&D (PAPS). The module was then connected to a high-power transmitter via an rf transmission line and to the cryogenic system. A subsequent horizontal test was performed at 4.2 K to assess the rf and mechanical performance of the modules. The in-house developed automatic conditioning system [43] was implemented for all modules, improving conditioning efficiency both during horizontal tests and in the HEPS tunnel.

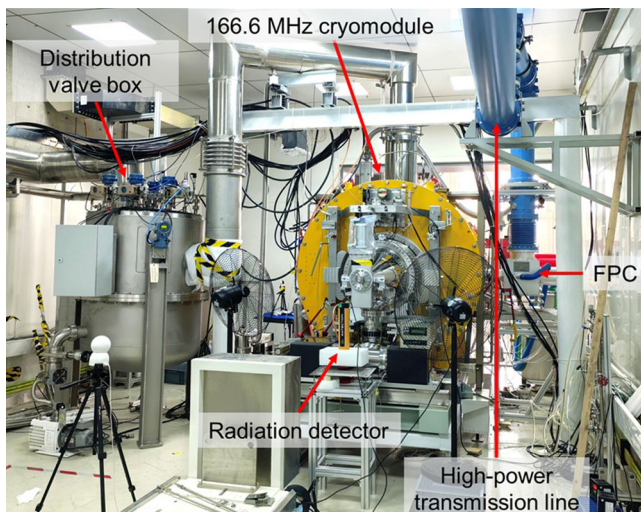


FIG. 15. Horizontal test stand for 166.6 MHz cryomodules within a bunker.

A. Preparation, cooldown, and conditioning

The HTS at PAPS was constructed to facilitate high-power testing of the 166.6 MHz cryomodules at 4.2 K, as shown in Fig. 15. It is equipped with a 166.6 MHz 260 kW solid-state amplifier, a 166.6 MHz 300 kW circulator, and a low-level rf control system. Initially, the module underwent room-temperature conditioning up to 110 kW with the frequency detuned by 400 kHz from the cavity's resonant frequency. This was done to process the rf surface of the FPC. This standing-wave power level is sufficient to establish an accelerating field of 1.6 MV in the cavity at 4.2 K. To aid the processing by intentionally exciting multipacting electrons, a dc bias was applied across the FPC's inner and outer conductors, sweeping from -800 V to $+800$ V. High-power conditioning began in a pulsed mode, with the pulse width gradually increased until cw operation was reached. Vacuum bursts and electron activity, consistent with multipacting, were observed, as shown in Fig. 16. The outgassing band due to multipacting, ranging from 1 to 5 kW, is consistent with simulation predictions [31]. Throughout the process, the interlock system protected the FPC and the cavity from deteriorated vacuum pressures, arc discharging, and overheating. Completing the initial room-temperature rf conditioning typically required 14 to 28 h, as summarized in Fig. 17.

Due to the relatively large size of these cavities compared to their high-frequency counterparts, stringent thermal specifications were enforced during the cooling process: a maximum cooldown speed of 5 K/h and a maximum allowable temperature difference of 10 K across the cavity surface. These limits were specified to prevent vacuum leaks induced by excessive thermal stress. Throughout this

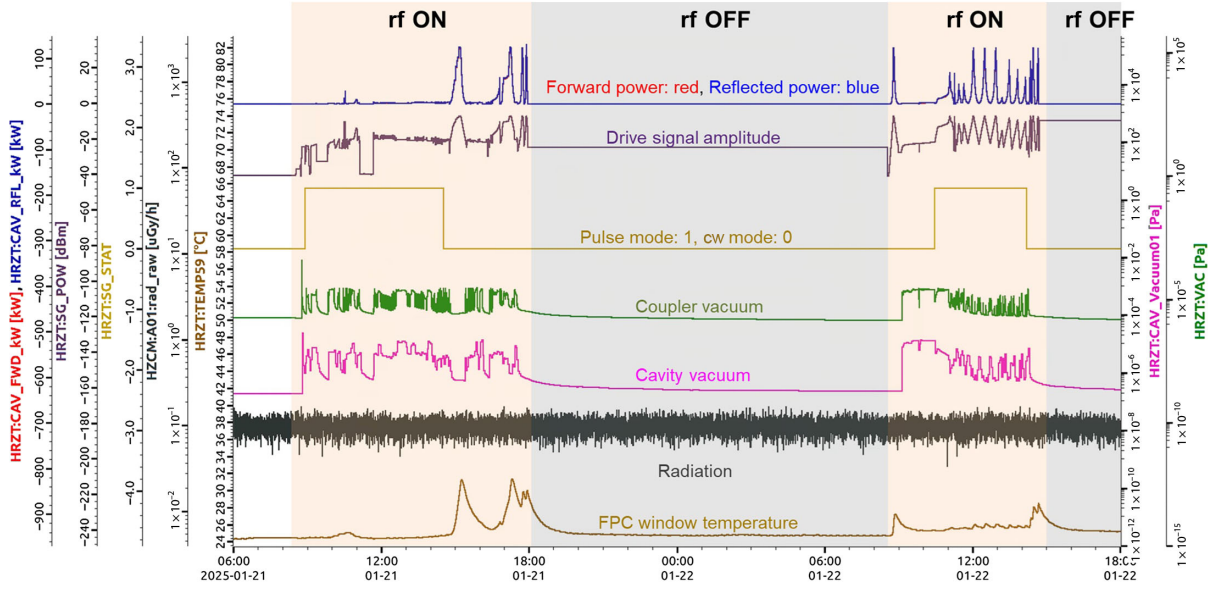


FIG. 16. rf conditioning process of 166CM2 at room temperature at HTS.

process, the average temperature, the maximum temperature difference among all sensors on the jacketed cavity, and the cavity vacuum pressures were carefully monitored. The entire cooldown process lasted for 7 to 11 days, maintaining an average cooldown rate of 1.1 to 1.7 K/h, as shown in Fig. 17. Even with this slow cooling rate through the critical temperature range (150 to 60 K), the cavities did not exhibit Q-disease during horizontal tests, attributable to the low residual hydrogen achieved through well-controlled acid temperatures during the buffered chemical polishing (BCP) treatment, as well as the 3-h heat treatment at 750 °C performed after the bulk BCP to degas the absorbed hydrogen [19].

Once the cooldown process was completed, the cavity was tuned to its target resonant frequency of 166.6 MHz. A subsequent rf conditioning of both the cavity and the FPC was then performed at 4.2 K. Multipacting bands of the cavity were encountered, and these were found to be consistent with simulation predictions [21]. The bands were easily cleaned using rf power. Following 10 to 26 h

of rf conditioning at 4.2 K, the cavities successfully exceeded their design voltage, reaching 1.6 MV. The conditioning process is illustrated in Fig. 18, and the duration consumed for the conditioning of all cavities is presented in Fig. 17.

The displacements of the beam pipes and the FPCs during both cooldown and warm-up processes were measured using digital indicators mounted on these components for all five cryomodules. Figure 19 presents the recorded displacements. The vertical displacement measurements indicated that the cavity string slightly tilted during cooldown, with the SBP side translating downward while the LBP side lifted upward; the original position was recovered after the warm-up process. The horizontal displacement indicated a slight shift of the cavity string toward the SBP side during cooldown, which was recovered during frequency tuning, where over 500 kgf of tuning force was applied on the LBP side. Shielded bellows installed on each side of the cavity string are used to compensate for these displacements. Notably, the horizontal displacement of the FPC could not be accurately measured due to interference of the indicator with the supporting frame at HTS. These displacement values will be subsequently used for module alignment inside the HEPS tunnel.

B. rf measurements

The static and dynamic heat losses were measured at 4.2 K for all five cryomodules. Initially, the heater located inside the two-phase pipe, which connects to the cavity helium jacket, was used to calibrate the relationship between the cryogenic heat load and the helium boil-off rate (in percentage per second), as demonstrated for 166CM5 in Fig. 20. During this measurement, the LHe

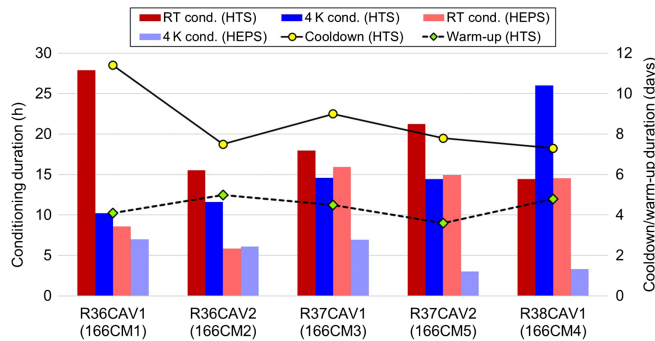


FIG. 17. Time consumption for rf conditioning at HTS and in the HEPS tunnel. RT, room temperature; cond. conditioning.

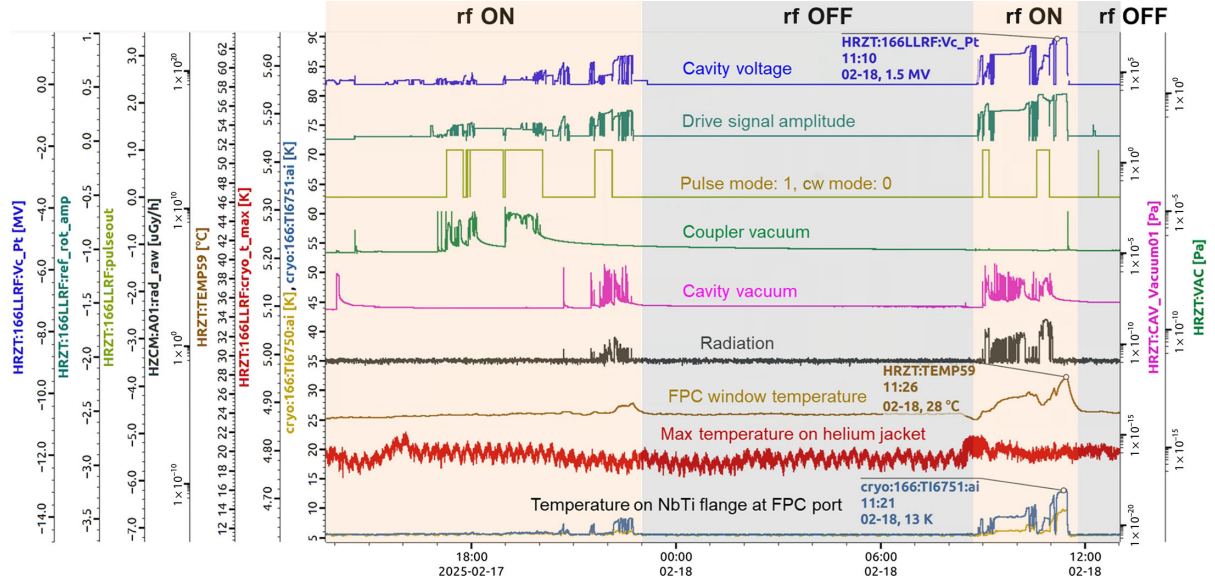


FIG. 18. rf conditioning process of 166CM2 at 4.2 K at HTS.

inlet valve was closed to isolate the cryomodule under test from the valve box, while the LHe level and He gas pressure were continuously monitored. The cavity remained submerged in the LHe throughout the entire measurement period.

The accelerating voltage, V_c , was determined by measuring the transmitted power, P_t , through the cavity pickup antenna, using the following equation [38]:

$$V_c = \sqrt{(R/Q)Q_{\text{ext}}^{\text{pu}} P_t}, \quad (3)$$

where $Q_{\text{ext}}^{\text{pu}}$ is the external quality factor of the cavity pickup, measured before and after cooldown. The unloaded quality factor of the cavity system, Q_0 , can be calculated by

$$Q_0 = \frac{V_c^2}{(R/Q)P_c}, \quad (4)$$

where P_c represents the dissipated power of the module, which includes the cavity and its ancillaries but excludes the static heat load. P_c was obtained by subtracting the previously measured static heat load from the total heat load measured at different cavity voltages. Additionally, a detector was installed on the LBP side to monitor the radiation levels during the tests. Take the R37CAV2 cavity as an example, the heater calibration was first conducted to obtain the coefficient between the helium boil-off rate and the applied heater power, as described in Fig. 20. Then the static heat load (with rf off) of the module was measured to

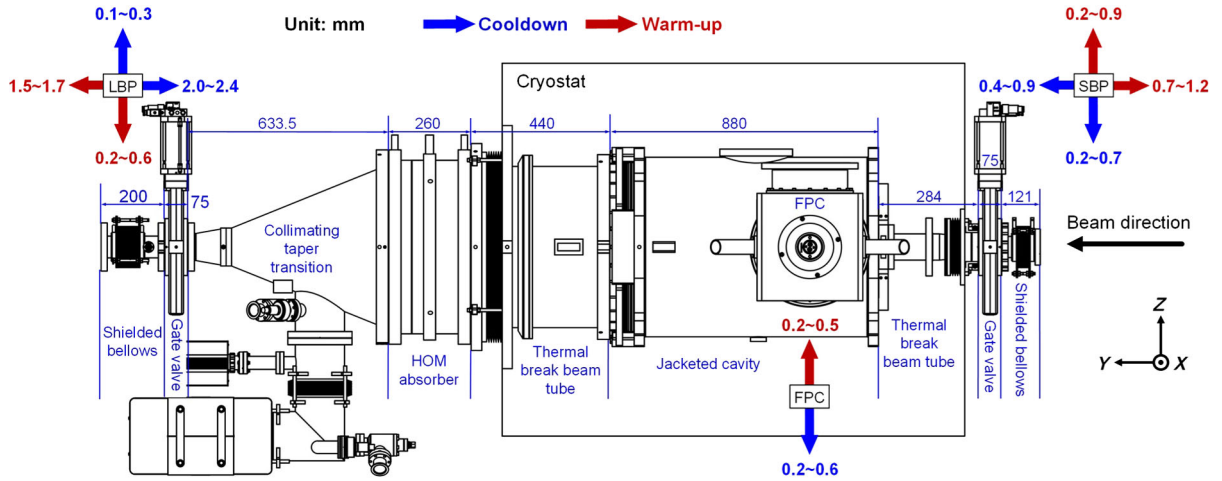


FIG. 19. Displacements of the LBP, SBP, and FPC for all five modules after the cooldown and warm-up processes. The direction of the displacement is indicated by the direction of the blue and red arrows, while the magnitude of the displacement in mm is written alongside each arrow.

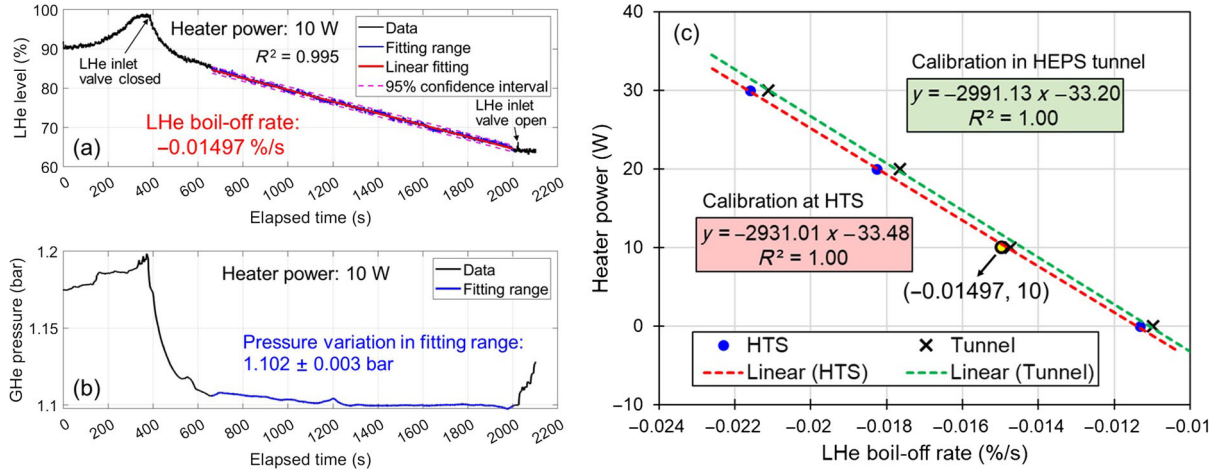


FIG. 20. Heat load measurement of R37CAV2 (166CM5). GHe, gas helium. (a) Variation of the LHe level over time under a heater power of 10 W. (b) Measured GHe pressure of the module. The helium boil-off rate is the fitted slope of the consumption curve in (a) where the helium pressure is stable. (c) LHe boil-off rate as a function of applied heater power. The slope obtained represents the relationship between helium consumption and heat load. The dashed lines represent the calibration conducted at HTS (red) and in HEPS tunnel (green).

be 33.4 W. Subsequently, an rf voltage was built up in the cavity, 1.2 MV as an example. With the rf on, the total module heat load increased to 38.5 W. Hence, the dynamic heat load P_c is derived as 5.1 W, corresponding to an unloaded quality factor Q_0 of 2.1×10^9 . The radiation dose rate during testing was recorded at 1.1×10^{-4} mSv/h.

The unloaded quality factor (Q_0) and the radiation level of all five cryomodules were measured at the HTS across various accelerating voltages, with the results presented in Fig. 21. The results demonstrate that the Q_0 values of all five modules at 1.2 MV were above 1×10^9 , substantially exceeding the design specification of 5×10^8 at the same voltage. The radiation level remained below 10 μ Sv/h for four modules, indicating no field emission occurrences up to 1.6 MV, which corresponds to a peak electric field of

42 MV/m and a peak magnetic field of 66 mT. These results are equivalent to the levels observed during vertical tests of the bare cavities, demonstrating the success of the cryomodule assembly process. However, the radiation level for 166CM3 was raised to a few tens of μ Sv/h across all measured voltages. This anomaly stemmed from nonconforming knife-edge flanges on the taper (hardness degradation and physical damage to the knife edge) that were identified during initial cavity assembly. These issues caused vacuum leaks and necessitated multiple assembly attempts with several replacement tapers. Although the flanges eventually met the qualification standards, the repeated disassembly and reassembly processes likely introduced contaminants into the cavity string. Fortunately, this mild radiation could be effectively mitigated by rf processing, as later measurements in the HEPS tunnel confirmed. Specifically, the radiation level was recorded to be 12 μ Sv/h after the rf conditioning subsequent to the first in-tunnel cooldown.

The heat load results are summarized in Table III. The contribution of various components to the static heat load is detailed in a previous publication [35]. The dynamic heat load at 1.2 MV is broken down into four parts: 2.3 to 3.7 W from the cavity itself, based on its VTS measurements, which accounts for approximately 53% of the total loss; 0.16 W from the additional surface resistance induced on the cavity by residual ambient magnetic field [39], 1.3 W from the FPC with nominal He gas cooling, and 1.25 W from rf dissipation on the inner surface of the large TBT [34]. The heat load values for the latter three parts are derived from simulations. The relatively large heat load on the large TBT is attributed to the strict longitudinal space restriction of the cavity string. This constraint necessitated a limited niobium tube length, which represented a

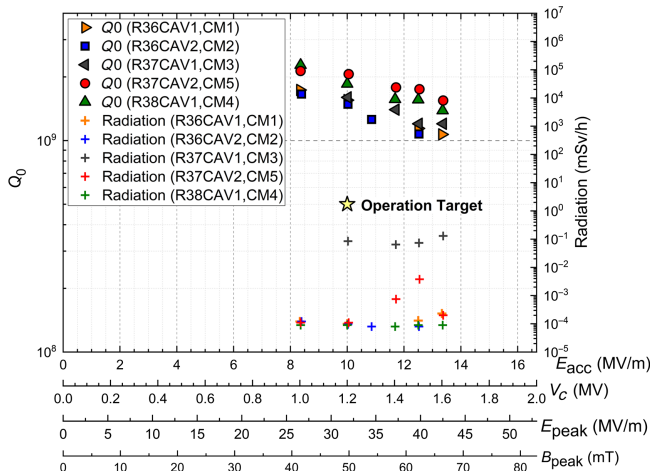


FIG. 21. Quality factor and radiation level of the modules measured at HTS.

TABLE III. Performance summary of all five 166.6 MHz SRF modules measured at operation voltage of 1.2 MV. SL, static heat load and DL, dynamic heat load with a 1.2 MV rf voltage inside the cavity.

Cryomodule	HTS			HEPS tunnel	
	SL (W)	DL (W)	Q_0	DL (W)	Q_0
R36CAV1 (CM1)	35.9	6.7	1.6×10^9	5.3	2.0×10^9
R36CAV2 (CM2)	32.7	7.0	1.5×10^9	7.3	1.4×10^9
R37CAV1 (CM3)	35.3	6.3	1.6×10^9	5.8	1.8×10^9
R37CAV2 (CM5)	33.4	5.1	2.1×10^9	5.5	1.9×10^9
R38CAV1 (CM4)	32.7	5.6	1.9×10^9	6.2	1.7×10^9

TABLE IV. Mechanical properties measured at HTS compared with simulation results and design specifications.

Parameter	HTS	Simulation	Specification	Unit
df/dp	11.4–19.1	20.3	≤ 27.5	Hz/mbar
Tuning sensitivity	34.6–36.9	43.1	Not applicable	kHz/mm
Tuning stiffness	11.4–13.4	10.9	≤ 10.0	kN/mm

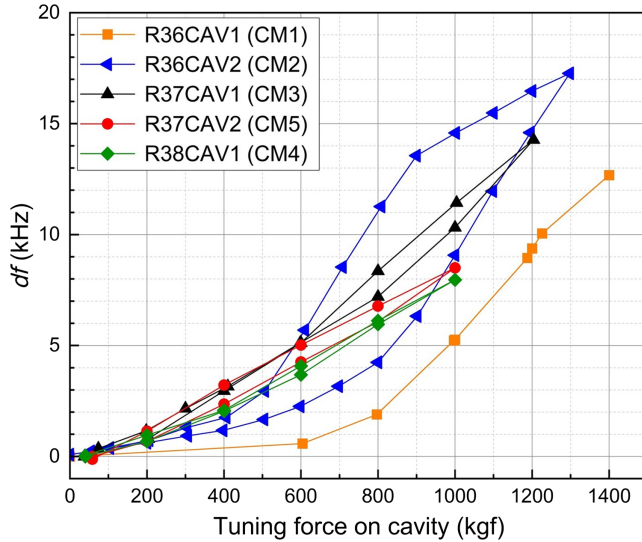


FIG. 22. Dependence of frequency variation on the tuning force applied to cavities. The measurements were conducted during the horizontal tests. The tuning force was applied in a stepwise manner, increasing to a predetermined maximum value and then decreasing back to the initial value (typically a few tens of kgf). During the process, the tuning force was recorded by the force sensor installed on the tuner. Meanwhile, the displacements of both the large and the small TBTs were monitored using installed digital indicators. The cavity frequency was measured from the FPC using a network analyzer. CM3 through CM5 were tested with tuning fixtures installed on the small beam pipe side. In contrast, CM1 and CM2 were tested without these fixtures due to their unavailability at the time. A larger tuning force was applied for CM1 to CM3, pushing their frequencies beyond 166.6 MHz. For CM4 and CM5, the tuning procedure was stopped once the frequency reached 166.6 MHz as a precautionary measure. Measurement data for CM1 were not recorded during the tuning force reduction phase.

trade-off between the overall loss factor (affected by the taper slope) and the static heat load of the TBT [34].

The resonant frequencies of all five cavities were successfully adjusted to 166.6 MHz at 4.2 K using the mechanical tuners. The tuning sensitivity and stiffness for each module were subsequently measured, and the results are summarized in Table IV. Both parameters show reasonable agreement with simulation predictions. However, the installation tolerance between the fixed blocks and the C-shaped clamps on the large TBT may introduce additional friction, which may explain the observed increase in tuning stiffness. The frequency response of the cavities to tuning force was also measured, and the results are shown in Fig. 22. All five cavities exhibit comparable tuning behavior, while the differences can be largely explained by the presence of the tuning fixtures on the small beam pipe side, which were implemented for CM3, CM4, and CM5 in the horizontal tests. The fine tuning range achieved with the piezo actuator was measured to be 1.4 kHz with a resolution of 1.5 Hz/V. The cavities required less than the maximum allowed tuning force of 2000 kgf to reach the target frequency. Thus, the ultimate coarse tuning range was estimated to be 18 to 36 kHz by extrapolating the measurements presented in Fig. 22. The discrepancy between these measured ranges and simulation predictions can be mostly attributed to the tuning displacement loss originally reserved for cavity deformation, as detailed in Sec. II C. Furthermore, the pressure sensitivity, df/dp , was measured to be below 20 Hz/mbar, which is also consistent with simulation results. By installing tuning fixtures on the small beam pipe side for all modules in the tunnel, the degraded tuning performance was

improved, with no additional constraints introduced for beam operation.

V. TUNNEL INSTALLATION, COMMISSIONING, AND BEAM OPERATION

Following successful qualification testing at HTS, all cryomodules were transported to the HEPS tunnel and installed in their designated straight sections. Subsequent alignment and integration with the beamline vacuum chambers were performed inside a temporary clean booth. This was followed by the installation of cables, rf transmission lines, and cryogenic piping. Commissioning then proceeded with rf conditioning and cooldown of the modules, followed by a final measurement of the static and dynamic heat loads for each cavity. Initial beam operation was successfully demonstrated, with the beam current gradually increased to above 100 mA. The ramping of the beam current was ultimately limited by the administrative threshold set for the vacuum pressure.

A. Transportation and tunnel installation

The cryomodule transportation route covered an approximate distance of 1.5 km between HTS at PAPS and the HEPS site. The route presented several logistical challenges, including multiple 90° turns, two signalized intersections (crossroads), an overpass, and a 100-m underpass with a 5% slope connecting the interior and exterior of the storage ring complex. Drawing from our previous experience in transporting the 499.8 MHz cryomodules for HEPS and BEPCII [42], modal and stress analyses were conducted for sensitive cryomodule components under various acceleration scenarios. The primary goal of the transportation was to ensure that the cavity and insulating vacuums remained uncompromised, physical deformation of components was minimized, and the cryomodule's performance was not degraded. To monitor these conditions, multiple accelerometers were installed at strategic locations to record shock events during transportation.

Based on the analysis, the FPC was identified as the most delicate component with respect to shock loads, thus establishing the transportation requirements. Finite element analysis simulations were performed to model the mechanical response of the FPC under various shock loads (accelerations). The simulation results indicated that the ceramic window assembly is the critical region, specifically the joint between the annealed copper transition and the ceramic disk. The maximum allowable load for the FPC was determined to be 0.4 g in the transverse direction with respect to the FPC [*Y* in Fig. 13(d)] and 0.4 g (excluding the gravitational acceleration, *g*, in the same direction) in the vertical direction [*Z* in Fig. 13(d)], with a safety margin of 2 reserved for both directions. The limiting factor is the maximum peak stress on the annealed copper welded to the ceramic window, which was determined to be 33.3 MPa.

The cryomodule was loaded onto an air-ride flatbed truck. Six accelerometers (ShockLog® 298 Impact Recorder) were strategically mounted on various module components, as illustrated in Fig. 13(d). Peak accelerations in all three spatial directions were recorded every 10 s. The entire transportation process took approximately 4 h for each module and was broken down as follows: module loading and securing onto the trailer took 30 min; transit from PAPS to HEPS took 1 h; unloading and final positioning in the tunnel took an additional 2.5 h. During transportation, the accelerations experienced by all monitored module components (excluding supports) remained below 0.5 g in all directions, as shown in Fig. 23. The maximum acceleration recorded on the FPC was 0.06 g (*X*), 0.21 g (*Y*), and 0.33 g (*Z*), resulting in a maximum peak stress of 22.8 MPa in the copper-ceramic welding according to simulations, fulfilling the specification previously established. The higher acceleration recorded on the support structure for R37CAV2 was attributed to improper handling of the tooling during module unloading. Fortunately, only a slightly elevated acceleration (0.45 g) was registered on the LBP gate valve, while all other sensors showed normal readings. Based on these observations, we conclude that the high acceleration on the CM support did not propagate to the cryomodule components, thus is considered acceptable.

The cavity vacuum pressure was measured to be between 1.6×10^{-7} Pa and 6.0×10^{-7} Pa at PAPS prior to transport, and between 1.8×10^{-7} Pa and 7.4×10^{-7} Pa following module placement in the tunnel. The insulation vacuum space inside the cryomodule was backfilled with dry nitrogen during the transport and was subsequently evacuated and leak-checked after tunnel installation. Neither the cavity vacuum nor the insulating vacuum was compromised during the process. All five modules were successfully transported and installed. The vertical displacement (*Z* direction) of the cavity string due to cooldown was reserved in the module alignment according to measurements at HTS, as listed in Fig. 19. Following final alignment, the modules were connected to the beamline vacuum chambers inside a temporary clean booth of class 1000 to minimize the risk of contamination. The final steps included the installation of cabling and rf transmission lines, as well as the connection to the cryogenic system (in particular, LHe and liquid nitrogen lines of the module were welded to the corresponding distribution lines). Figure 24 shows all five cryomodules installed in the HEPS storage ring tunnel.

B. First cooldown and conditioning

All five cavities were cooled down simultaneously in the tunnel. The same cooldown requirements were applied: a maximum temperature difference of 10 K and a

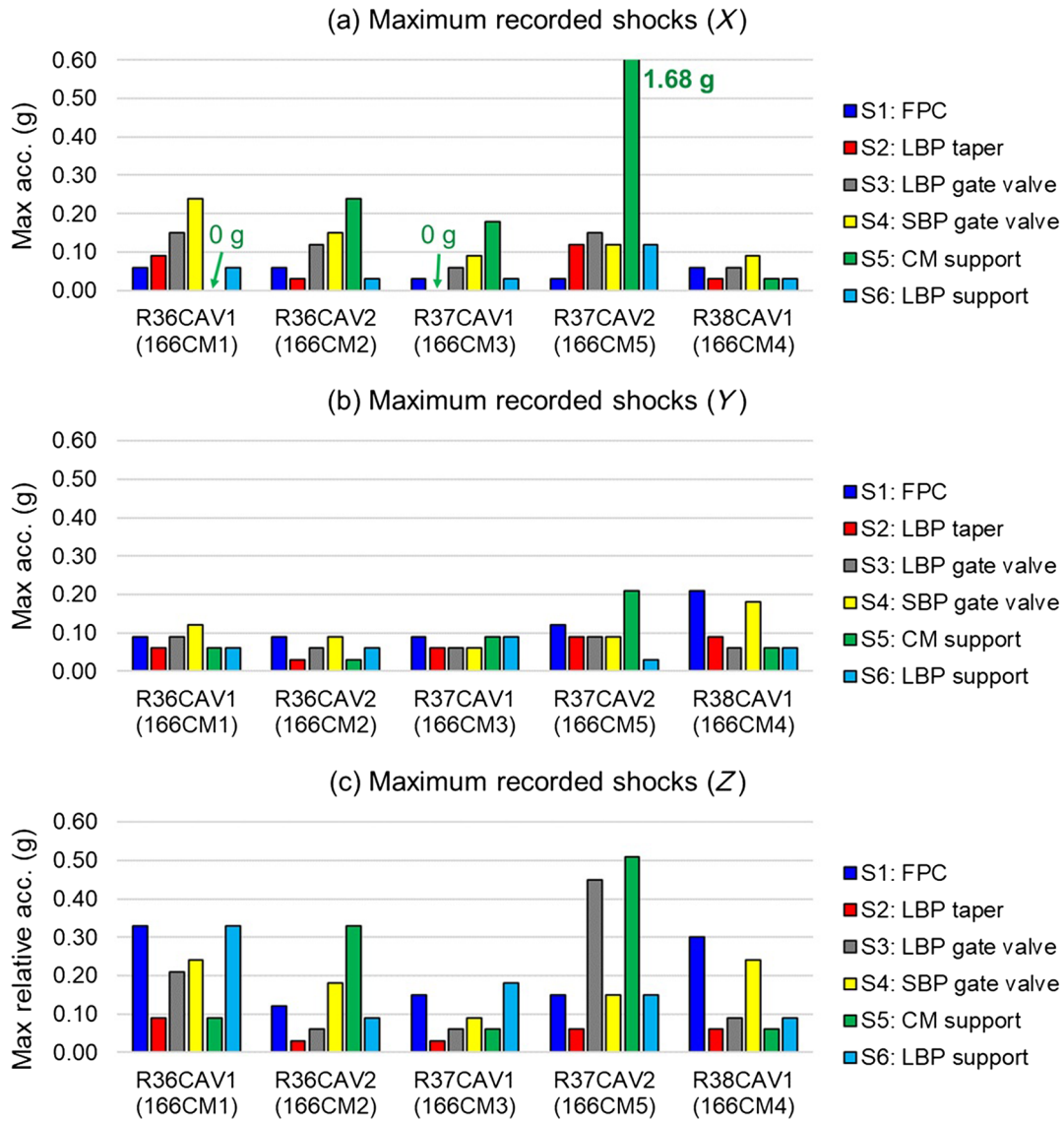


FIG. 23. Maximum acceleration (absolute values) in X (a), Y (b), and Z (c) directions recorded during module transportation from PAPS to the HEPS tunnel.

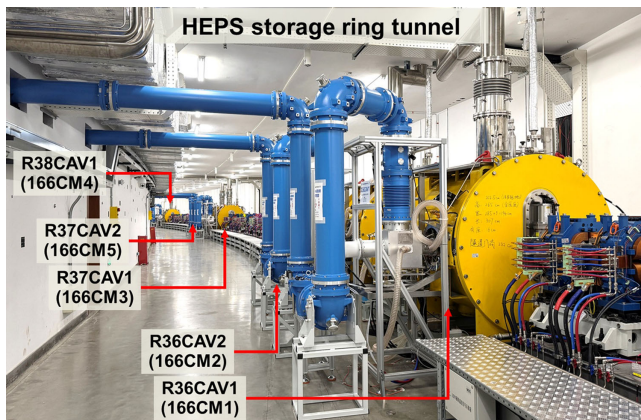


FIG. 24. 166.6 MHz SRF modules installed in the HEPS storage ring tunnel.

maximum rate of 5 K/h. The temperature and corresponding cavity vacuum pressure for all five cavities are presented in Fig. 25. The temperature difference exceeded the 10 K limit when the cavities were cooled below 40 K. However, the thermal contraction of niobium is largely completed at this temperature (Fermilab specification document: 5500.000-ES-371110), which minimizes the risk of a vacuum leak by thermal stress. The entire cooldown from room temperature to 4.2 K, including reaching the required LHe level, took 12 days. Following the cooldown, the final vacuum pressures of all five cavities were measured to be in the range of 7.0×10^{-9} Pa to 1.4×10^{-8} Pa.

Conditioning of all five cavities was again performed both at room temperature and at 4.2 K, following the same procedure utilized at the HTS. Following a duration of

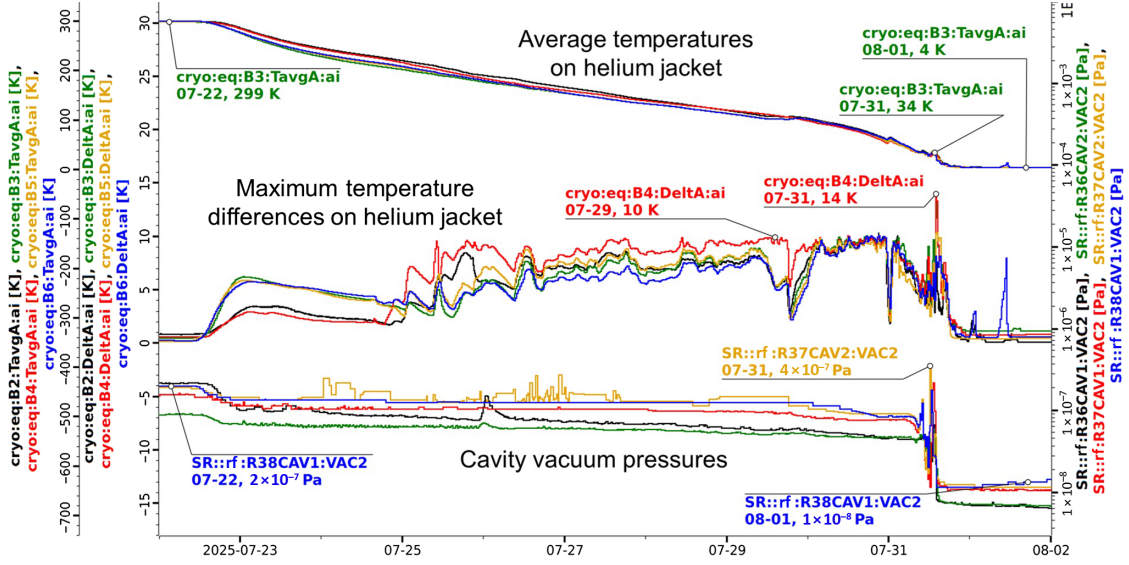


FIG. 25. Temperatures and vacuum pressures during the first cooldown of all five 166.6 MHz cavities in the HEPS tunnel.

3 to 7 h of rf conditioning at 4.2 K, all cavities successfully reached their design voltage of 1.5 MV. The time consumed for rf conditioning at various stages across all cavities is detailed in Fig. 17.

Following conditioning, a re-calibration of the helium boil-off rate versus the applied heater power in the helium vessel was conducted for all cavities, the average difference between these two calibrations is 5.3%. The final heat load measurements were subsequently performed. Evaluation of the cavity performance revealed an unloaded quality factor range of 1.4×10^9 to 2.0×10^9 at an accelerating voltage of

1.2 MV. This corresponds to a dynamic heat load of 5.3 to 7.3 W. These results show no degradation when compared to the values obtained previously at the HTS, as summarized in Table III. Furthermore, no increase in field emission was observed, further confirming that the module's excellent performance was preserved throughout the transportation, installation, and final commissioning process. The estimated measurement errors are 1.8% for the accelerating voltage V_c and 6.4% for the unloaded quality factor Q_0 . The V_c error stems from a 3% error in $Q_{\text{ext}}^{\text{pu}}$ measurement and a 2% uncertainty in the transmitted

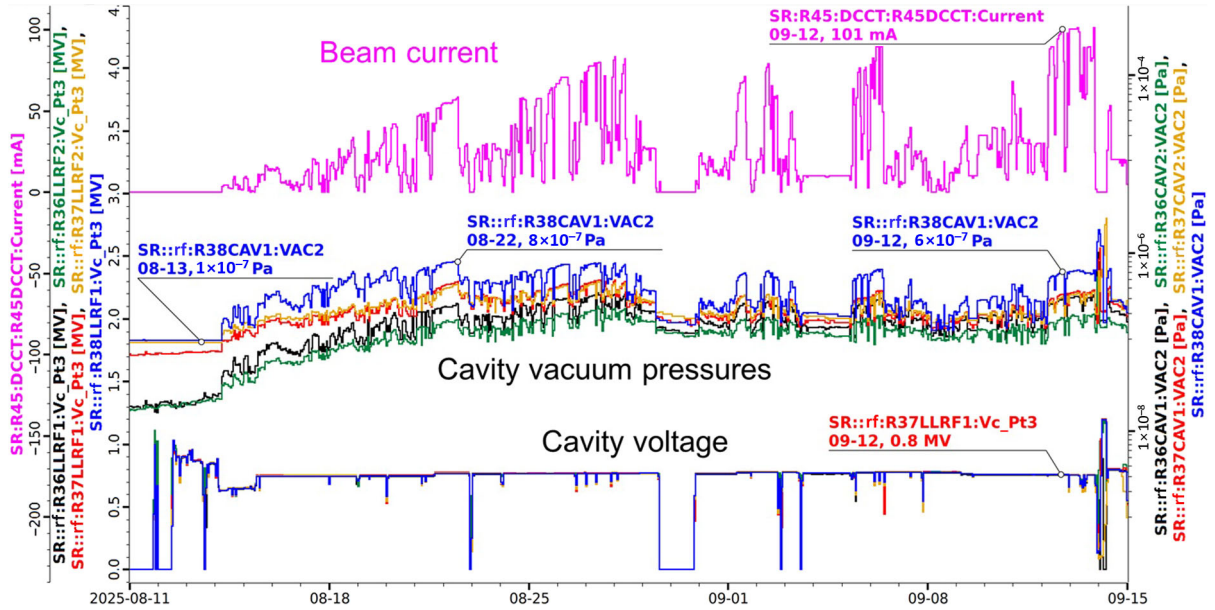


FIG. 26. Beam current, cavity vacuum pressure, and cavity voltage monitored during the first month of beam commissioning with the 166.6 MHz SRF cavities.

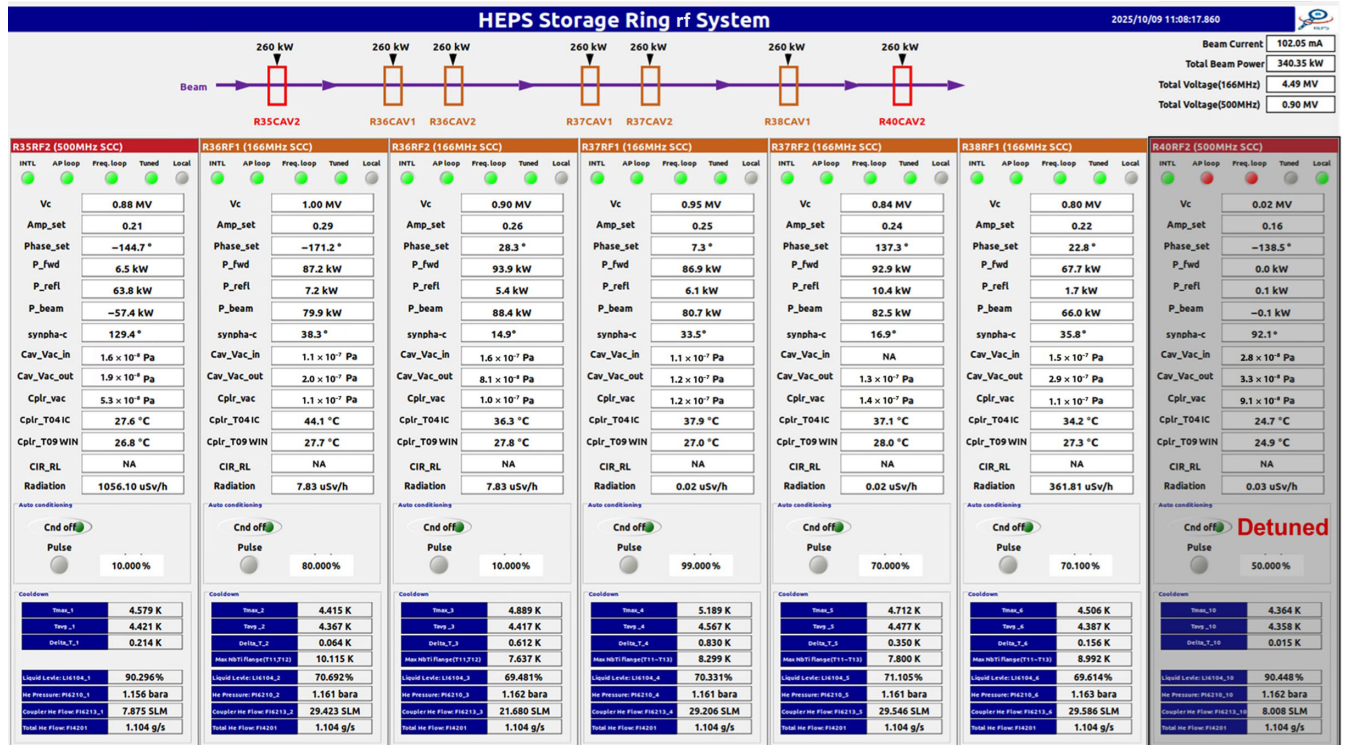


FIG. 27. Cavity parameters at 100 mA of beam current.

power P_t measurement. The larger Q_0 error is a composite of the V_c error term (1.8%) and a 5.3% uncertainty in the heat load measurement, dominated by the calibration differences.

C. Beam operation

Beam commissioning of HEPS utilizing the nominal SRF cavity setup commenced on August 12, 2025. The beam current was gradually increased, surpassing 100 mA on September 12, 2025. This beam current ramp was administered with the vacuum pressure restricted to 1×10^{-6} Pa across all SRF cavities to prevent excessive outgassing from adjacent vacuum chambers. The variation in cavity vacuum pressure throughout this period is detailed in Fig. 26. During the operation, all five 166.6 MHz SRF cavities were employed to accelerate the 6 GeV electron beam. One 499.8 MHz SRF cavity was dedicated to bunch lengthening (the other one was detuned sufficiently as a standby cavity at 4.2 K). Subsequently, the insertion device gaps were closed in sequence to commission the beamlines and end-stations. This increased the beam energy loss, while the beam power was therefore increased, necessitating a corresponding increase in cavity voltage and rf power.

The specific operational status of the cavities at the 100 mA beam current is presented in Fig. 27 from the recent commissioning. The five 166.6 MHz SRF cavities collectively provided 4.49 MV of accelerating voltage and delivered 397.5 kW of rf power to the beam. Meanwhile,

57.4 kW of power was absorbed from the beam by the 499.8 MHz harmonic cavity to realize bunch lengthening. The average temperature on the cavity helium jacket (T_{avg}) was maintained at approximately 4.5 K. Applying He gas cooling to the FPC's outer conductor limited the highest temperature reading on the NbTi flange at the FPC port (Max NbTi flanges) to 10 K for the first module (R36CAV1). A reduction in flange temperature was evident in subsequent modules due to modified cooling channel designs, which improved operational reliability. The temperature of the FPC ceramic window (Cplr_T09 WIN) remained below 28 °C, confirming sufficient cooling. The cavity vacuum pressure across all five cavities was maintained better than 3.0×10^{-7} Pa. High radiation readings were observed, attributable to beam loss, and were found to be sensitive to both beam orbit and current.

All five 166.6 MHz SRF cavities have demonstrated stable operation on the first day of beam commissioning with nominal rf setup since August 12, 2025, conclusively marking the successful development and deployment of the world's first HOM-damped active quarter-wave SRF cavities in a storage ring.

VI. CONCLUSIONS

The in-house developed 166.6 MHz $\beta = 1$ quarter-wave SRF modules provided a successful technological solution for the demanding requirements of HEPS, specifically integrating a high-power capability of 200 kW, and heavy

HOM damping within strict spatial constraints. Module tests demonstrated a peak electric field of 42 MV/m with negligible radiation and maintained a low dynamic heat load of 5 to 7 W, underscoring the efficacy of both the comprehensive cleaning and assembly procedures and the robust mechanical design. The commissioning and subsequent acceleration of a 100 mA electron beam with the five installed cryomodules is a major milestone, representing the first successful deployment of a superconducting quarter-wave structure as the main accelerating system in a high-current storage ring. This work significantly extends the operational limits and proven usage of low-frequency nonelliptical SRF cavities, offering a validated and high-performance alternative for the next generation of high-current light sources.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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