



Design and commissioning of a multiharmonic bunching system for the high-intensity heavy-ion accelerator facility

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Abstract

The high-intensity heavy ion accelerator facility (HIAF) is currently under construction in China for multidiscipline research. The front-end section has been completed and is currently undergoing commissioning. To optimize beam quality, an external multiharmonic buncher (MHB) that reduces longitudinal emittance has been installed before the radio frequency quadrupole. The MHB system includes both cavity and low-level radio frequency (LLRF) system designs. The cavity consists of a quarter-wave resonator and a half-wave resonator, with a single grid-less gap, capable of providing the required voltage of 1.5 kV. With the newly developed multiharmonic LLRF control system, precise individual control of the four-harmonic components can be achieved, enabling flexible synthesis of various waveform configurations. The buncher can generate a 1st + 2nd + 3rd + 4th harmonic bunching electric field with a fundamental frequency of 40.625 MHz, or a 1st + 2nd harmonic bunching electric field with a fundamental frequency of 81.25 MHz. In addition, the first O⁶⁺ beam commissioning results of front-end accelerator are presented herein, providing insights into the contribution of the MHB.

Keywords Heavy-ion · Buncher · Linear accelerator · Multiharmonic signal

1 Introduction

The HIAF project at the Institute of Modern Physics, Chinese Academy of Sciences, is a large-scale heavy-ion research facility, distinguished by its exceptional heavy-ion beam intensities (e.g., 1.0×10^{11} ppp for $^{238}\text{U}^{35+}$ in the booster ring) [1, 2]. As illustrated in Fig. 1, the facility comprises a superconducting electron cyclotron resonance ion source (SECR) [3], a superconducting ion linear accelerator (iLINAC), a booster ring (BRing) [4], a high-energy fragment separator (HFRS), an experimental spectrometer ring

(SRing) [5, 6], and experimental setups [7]. The design incorporates a superconducting linear accelerator coupled with a high-energy synchrotron to generate stable beams with ion energies ranging from MeV/u to GeV/u. The iLINAC accelerates highly charged beams with a mass-to-charge ratio (A/q) of 7 to a maximum energy of 17 MeV/u. Subsequently, the ion beams are injected into the BRing. For example, using $^{238}\text{U}^{35+}$, approximately 1.0×10^{11} particles, with a maximum energy of 835 MeV/u, can be stored in the booster. Finally, the beams are either extracted to external targets or transferred to the SRing for various experiments. In addition, a low-energy experiment station will be constructed at the end of the iLINAC in the near future.

The iLINAC, spanning 180 m in length, incorporates an 81.25-MHz room-temperature radio frequency quadrupole (RFQ), 30 quarter-wave resonator (QWR) superconducting cavities operating at 81.25 MHz, and 66 half-wave resonator (HWR) superconducting cavities operating at 162.5 MHz. The RFQ is required to meet the goal of providing a beam, exhibiting a longitudinal emittance of $0.1\pi \text{ mm} \cdot \text{mrad}$, with a transmission efficiency of 98%. To achieve a small longitudinal beam emittance and minimize beam loss in such

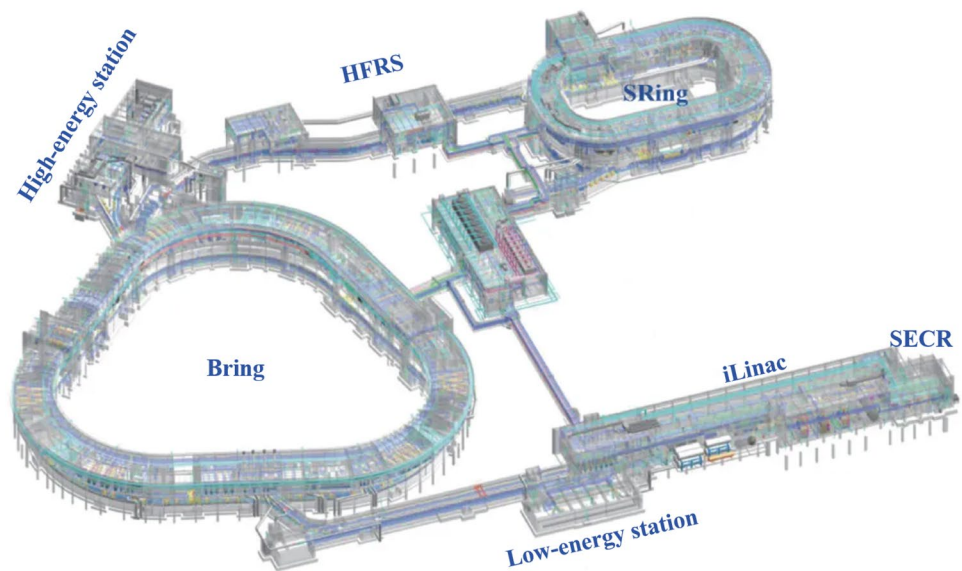
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Fig. 1 (Color online) Layout of the HIAF project



a superconducting LINAC, the ion beams must be prebunched using an MHB prior to injecting them into the first accelerator [8].

Several existing prebunching schemes employ the traditional resonant circuit approach [9] to generate the bunching voltage in the gap, including the dual-gap prebuncher at the Heavy Ion Research Facility in Lanzhou (HIRFL) [10] and the four-harmonic single-gap prebuncher at the Argonne Tandem Linac Accelerator System (ATLAS) [11]. However, this approach cannot be employed when the frequency exceeds 30 MHz under high-voltage conditions. Coaxial resonator prebuncher schemes have been widely adopted across research facilities, such as the Positive Ion Accelerator at Ultra Low Energy (PIAVE) LINAC [12], National Superconducting Cyclotron Laboratory (NSCL) [13], Facility for Rare Isotope Beams (FRIB) [14], and the latest planned upgrades at ATLAS [15].

Drawing from these precedents, the designed MHB implements a coaxial resonator structure that integrates both QWRs and HWRs. The novel design facilitates the generation of a bunching field with 1st + 2nd + 3rd + 4th harmonics at a fundamental frequency of 40.625 MHz or 1st + 2nd harmonics at a fundamental frequency of 81.25 MHz. In addition, the introduction of the MHB reduces the RFQ length from 11 m to 8.5 m [16]. This paper presents the physical engineering design and details on the

commissioning of the bunching system. Section 2 describes the principle and program selection of the MHB as well as the radio frequency (RF) design and multiphysics analysis. Section 3 presents the low-level radio frequency (LLRF) system design and RF testing. Section 4 provides details of the first beam commissioning in the HIAF with the MHB and RFQ. Finally, Sect. 5 summarizes the study.

2 Principle of velocity modulation

As shown in Fig. 2, a buncher employs a high-frequency electric field to modulate the longitudinal velocities of particles within its gap, thus maintaining a constant velocity for the reference particle. Particles ahead of the reference particle experience deceleration, whereas those behind undergo acceleration. Following an appropriate drift distance, the particles within a defined phase width converge into a concentrated phase space around the reference particle, forming a pulsed beam.

A sawtooth waveform, representing an idealized bunching voltage, exhibits a perfectly linear ramp and subsequently instantaneously returns to the starting voltage at the end of each period. This waveform is the primary choice for bunching in low-energy beam-transport systems [17]. In practical engineering applications, a sawtooth wave is typically

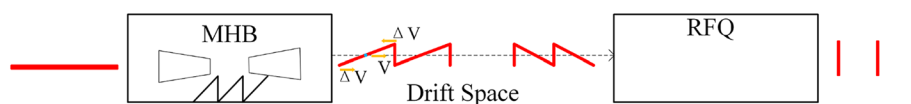


Fig. 2 (Color online) Principle of the MHB operation. v represents the beam velocity, Δv is the velocity change of particles under bunching voltage, and drift space is the distance between MHB and RFQ

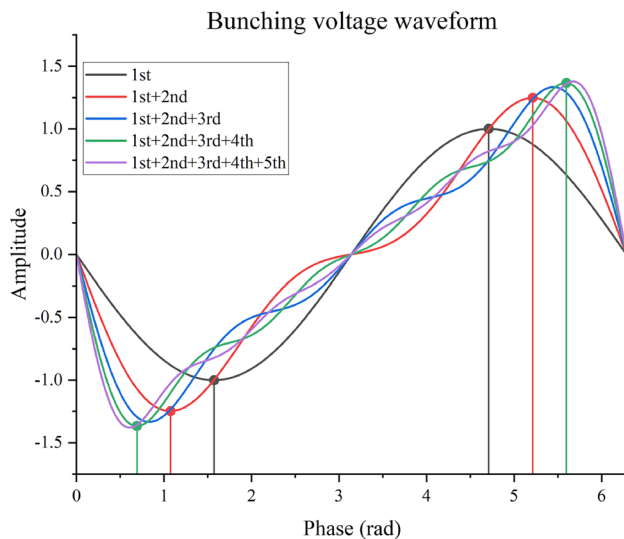


Fig. 3 (Color online) Comparison of bunching efficiency for different harmonics. Vertical lines represent the effective bunching phase

approximated by superimposing multiple sinusoidal waves. The sawtooth wave voltage form can be expressed using the time-dependent Fourier expansion formula [18, 19]:

$$V_{(t)} = U_1 \sin(\omega t) - U_2 \sin(2\omega t) + U_3 \sin(3\omega t) - U_4 \sin(4\omega t) + \dots + (-1)^{n+1} U_n \sin(n\omega t). \quad (1)$$

Figure 3 compares different harmonics fitted to a sawtooth wave. The bunching efficiency is defined as the ratio of the rising edge portion to the entire cycle. As the number of harmonics increases, the accuracy of the sawtooth wave approximation improves, resulting in enhanced bunching efficiency [20].

Table 1 compares various harmonic superpositions. The contribution of harmonics beyond the fourth order to the

beam electric field becomes negligible, whereas additional harmonics increase the complexity of cavity tuning. Based on these considerations, the four-harmonic synthesis scheme emerges as the optimal configuration.

The designated ion beam, $^{238}\text{U}^{34+}$, is injected into the RFQ with an energy of 14 keV/u and a beam energy spread of 0.05%. A beam current of approximately 100 eμA is maintained throughout the study.

Figure 4 depicts the transverse envelope of the beam. The MHB is positioned 1.1 m upstream of the RFQ. A solenoid, installed after the MHB, facilitates transverse matching with the RFQ.

In the calculation of the beam-transport characteristics using the TRACK code [21], the prebuncher model was simplified to consider only the central field in the gap between the electrodes. Comprehensive simulations were conducted using various harmonic combinations (1st, 1st + 2nd, 1st + 2nd + 3rd, and 1st + 2nd + 3rd + 4th). For the U^{34+} beam, the characteristic bunching voltages (considering the transit time factor (TTF)) were 1400 V, 560 V, 250 V, and 84 V for the harmonics at 40.625, 81.25, 121.875, and 162.5 MHz, respectively. These voltage values were adjusted according to the A/q ratio of the accelerated beam.

3 Mechanical design and RF analysis

The modified MHB comprises a fourth harmonic cavity, incorporating both a QWR and an HWR. The system generates harmonics at four distinct frequencies of 40.625, 81.25, 121.875, and 162.5 MHz, which are synthesized within the bunching gap. The electric and magnetic field distributions of the four harmonics, simulated using Computer Simulation Technology (CST) Microwave Studio [22], are shown in Fig. 5.

Table 1 Simulation results of different schemes (the values of $U_1 \sim U_5$ show the amplitudes of different harmonics, and η denotes the bunching efficiency of the synthesized sawtooth wave)

Harmonics	U_1	U_2	U_3	U_4	U_5	η
1	1	/	/	/	/	50.0%
1 + 2	1	0.303	/	/	/	65.8%
1 + 2 + 3	1	0.351	0.115	/	/	73.5%
1 + 2 + 3 + 4	1	0.4	0.18	0.06	/	78.2%
1 + 2 + 3 + 4 + 5	1	0.41	0.20	0.1	0.03	80.8%

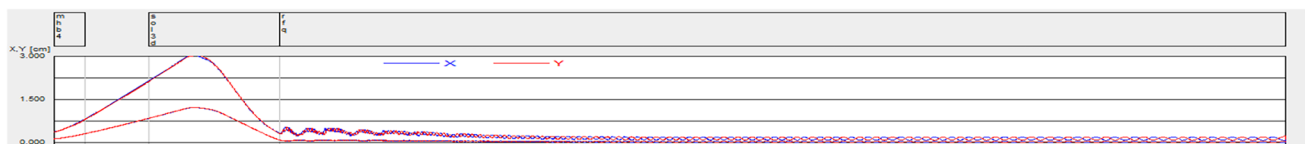


Fig. 4 (Color online) Transverse beam transmission along the beamline

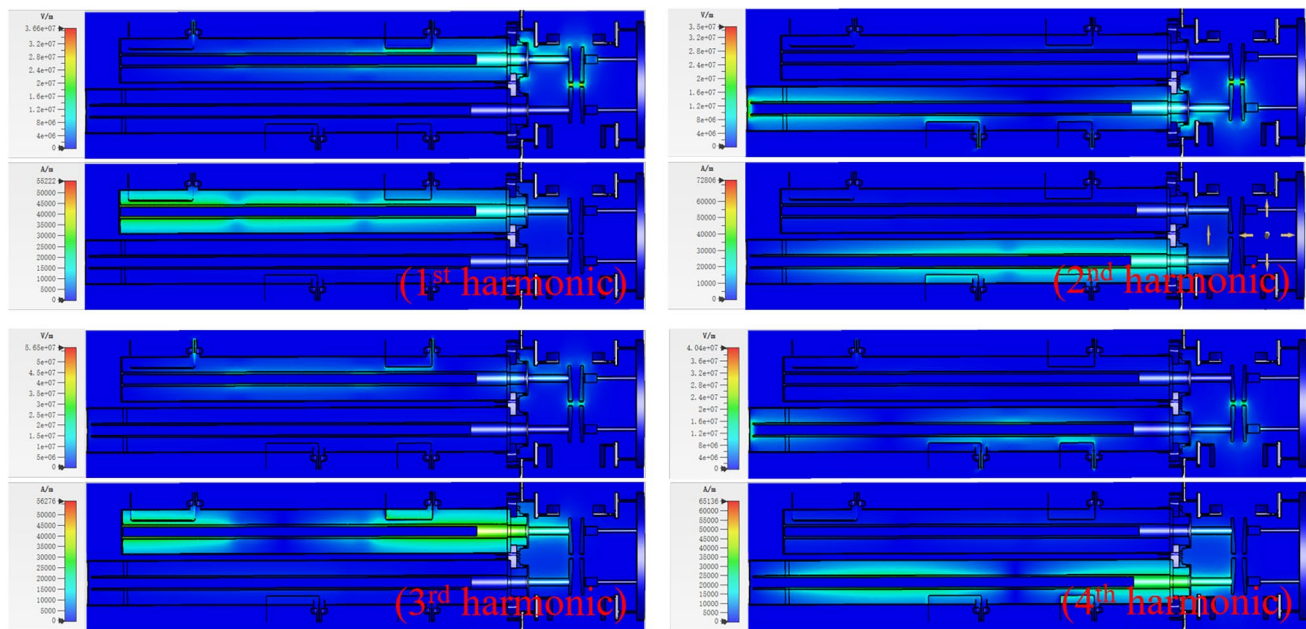


Fig. 5 (Color online) Electric and magnetic fields of four harmonics profile along the resonator axes

The mechanical structure, shown in Fig. 6, comprises two primary components: the vacuum chamber and resonators. The design of the vacuum chamber is based on the architecture of the Low Energy Accelerator Facility (LEAF) MHB. Beamline constraints prevent longitudinal space expansion for improvements. Therefore, to maintain compatibility with the restricted space of the HIAF beamline while optimizing the cost efficiency, the resonators have been fabricated using standard EIA 4-1/2" transmission lines. The QWR features a short-circuit at one end and remains open at the other, showing a length of approximately 1.3 m. The HWR maintains open ends on both sides with an approximate length of 1.4 m. Table 2 presents the mechanical parameters of the MHB.

A pair of bunching electrodes is directly connected to the inner conductor of the resonator, creating a bunching gap enclosed within the vacuum chamber. Considering that gridded electrodes would result in a 20% loss of beam current, we have used modified grid-less electrodes, following the previous design [23, 24]. Compared to the previous LEAF MHB, the spacing between the bunching electrodes has been reduced to 4 mm to maintain a large transit time factor. Additionally, the electrode aperture has been reduced to 16 mm. The longitudinal electric field along the beam axis for the old and new electrodes is analyzed, and the corresponding results are presented in Fig. 7.

In addition to the bunching field within the electrode gap, leakage fields are present beyond the electrodes along the beam passage [25]. To assess the influence of the bunching field of the improvement, the relevant TTF is calculated using the following equation:

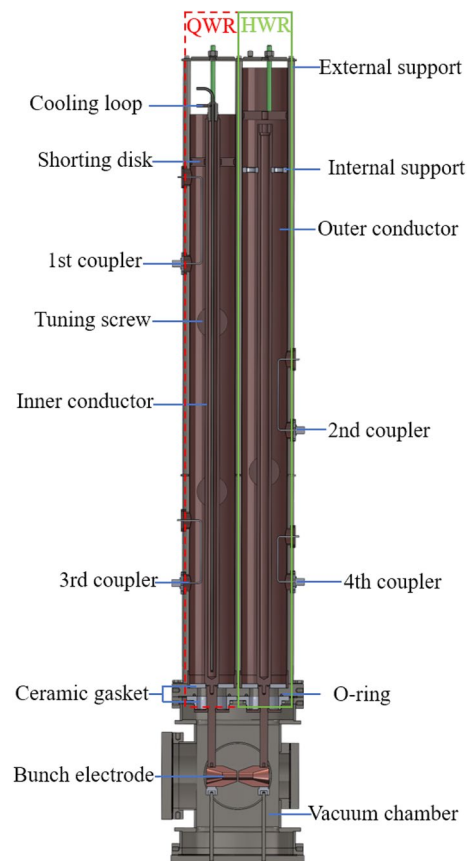


Fig. 6 (Color online) Design model of the MHB

Table 2 Mechanical design parameters of the MHB

Parameter	Value
Frequency of the 1st harmonic (MHz)	40.625
Number of harmonics	4
Maximum m/Q	7
Maximum effective voltage (V)	1400
Diameter of the inner conductor (mm)	33.4
Diameter of the outer conductor (mm)	106
Length of QWR (mm)	1315
Length of HWR (mm)	1423

$$T = \frac{\int E(0, z) \cos \frac{2\pi z}{\beta \lambda} dz}{\int E(0, z) dz}, \quad (2)$$

where $E(0, z)$ is the electric field along the axis, β is 0.0055 with a beam energy of 14 keV/u, and λ denotes the wavelength.

Following the electrode improvements, the TTF increases from 0.63 to 0.83 at 40.625 MHz. At 81.25 MHz, the TTF remains relatively constant owing to the low β (0.0055). Additionally, λ decreases with increasing frequency. The modifications effectively suppress the leakage electric field, reducing its TTF value at 40.625 MHz from 0.11 to 0.02. Table 3 presents the principal design parameters of the MHB.

Ceramic insulators are positioned on both the upper and lower portions of the vacuum chamber, as illustrated in Fig. 8. The upper ceramic component provides structural support, whereas the lower ceramic, welded to the inner conductor and combined with an O-ring, maintains and seals vacuum.

The upper parts of both the resonators have copper shorting disks. In the upper parts, silver-plated garter springs mounted in the recess ensure reliable electrical contact. One shorting disk connects to the inner conductor to establish the QWR, whereas the other remains separated from the inner conductor to form the HWR. Three long screws secure each disk to the external bracket, maintaining their positions. The positions of the disks can be adjusted by sliding them along the screws, facilitating coarse tuning of the resonators.

The coarse tuner influences both frequencies in each cavity. To optimize frequency control, three fine-tuning screws (each with a diameter of 70 mm) are implemented. The RF response of each tuner is evaluated through simulations at various positions relative to a predetermined depth of 30 mm to assess the tuning capabilities at each location. Figure 9 illustrates the frequency response of the tuner at different positions in the HWR. To minimize interference with the 2nd frequency while adjusting the 4th frequency, the tuner is positioned at a distance of

890 mm within the cavity, as indicated by the blue point in Fig. 9. A similar tuning approach is applied to the QWR design. Based on the frequency response curve, the tuner is mounted at 440 and 830 mm within the QWR. The tuner positioned at 440 mm will aid in the implementation of the 5th harmonic in the future.

The coupler design depends on the electromagnetic field distribution across various frequencies, with the magnetic field concentrated in the upper section of the cavity and the electric field concentrated in the vacuum chamber. For the input couplers, magnetic coupling rings are selected. The minimum coupling loop area required for critical coupling ($\beta = 1$) can be calculated using the following equation [26]:

$$A_s = \frac{\sqrt{100P}}{\omega \mu_0 H_0 \cos \alpha}, \quad (3)$$

where P is the dissipated power when the energy is 1 J, $\omega = 2\pi f$, and H_0 is the peak of the cavity magnetic field at the location of the loop. The coupling ring remains perpendicular to the magnetic field with $\cos \alpha = 1$.

The calculations show that the designed couplers meet the dimensional requirements between the inner and outer conductors. The coupler assembly comprises a copper structure with an N-type connector. The upper section of the coupler loop connects to the outer conductor, ensuring effective grounding. The pickup port extracts the bunching electric field from the gap, and thus, the pickup end is placed within the vacuum chamber. Given the electromagnetic field distribution, an electrically coupled probe is implemented to sample the bunching field effectively.

To mitigate the thermal management challenges encountered in comparable projects [27, 28], in this study, we implement a water-cooled structure for the QWR. To improve structural integrity, the inner conductor is replaced by solid copper rods, which provide enhanced durability. A 22-mm-diameter hole is drilled deep into the rod to accommodate the water-cooling pipe. The water circulation system is illustrated in Fig. 10. The system maintains consistent water supply at 25 °C with a flow rate of 1 L/min.

Based on the pipe dimensions, the cross-sectional area is calculated as $A = 3.8 \times 10^{-4} \text{ m}^2$, and the flow velocity is $v = 4.4 \times 10^{-2} \text{ m/s}$. The Reynolds number Re can be calculated as follows

$$Re = \frac{\rho \cdot v \cdot D_h}{\mu} \approx 97.2 \quad (4)$$

where D_h is the pipe diameter, ρ is density, and μ is the dynamic viscosity ($0.001 \text{ Pa} \cdot \text{s}$).

Given that $Re < 2300$, the flow is characterized as laminar, indicating that the Nusselt number Nu is 3.66. The thermal conductivity (k) of water at 25 °C is approximately

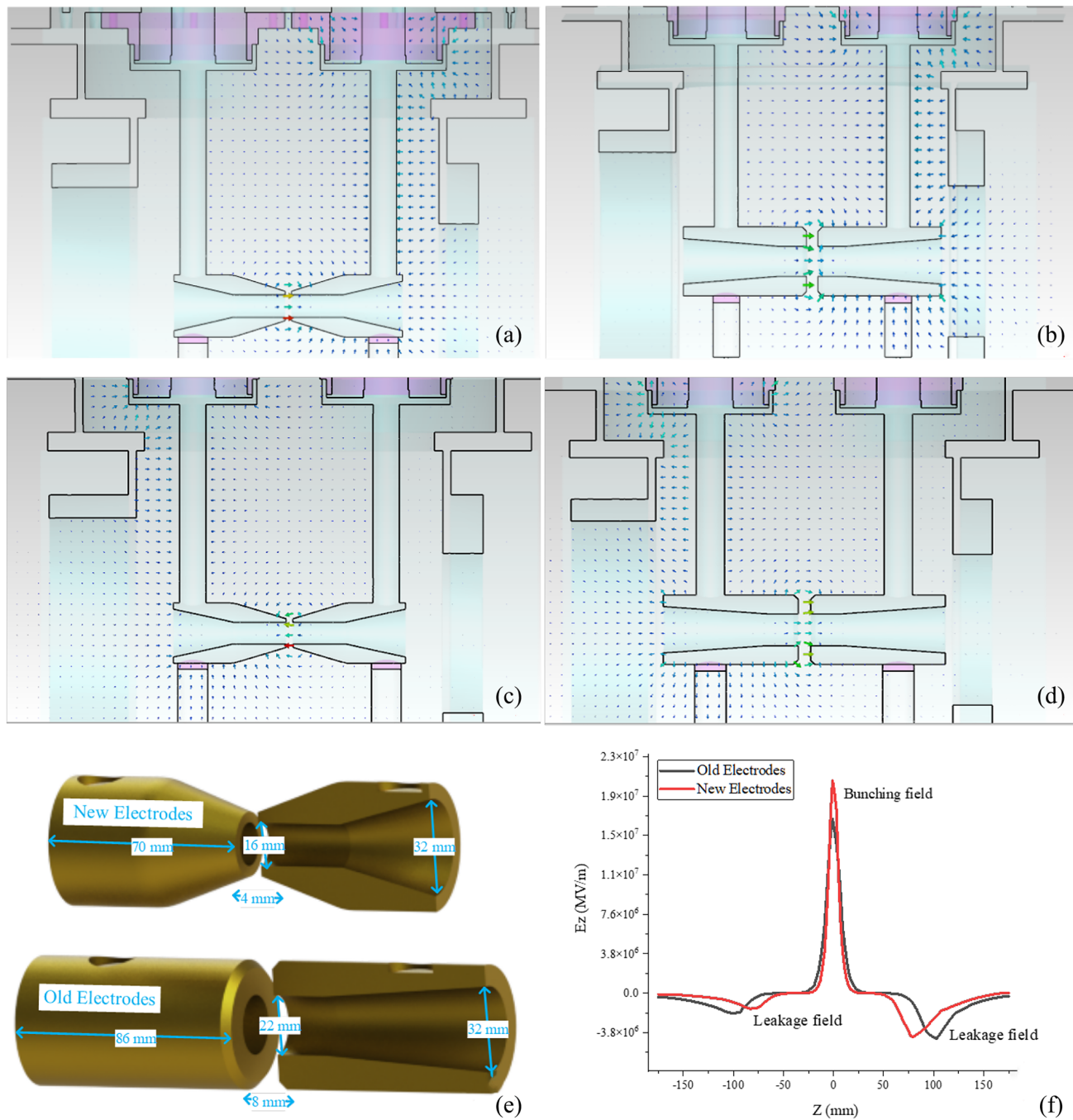


Fig. 7 (Color online) **a** Electric field distribution of the 1st harmonic within the chamber of the new electrodes. **b** Electric field distribution of the 1st harmonic of the previous electrodes. **c** Electric field distribution of the 2nd harmonic within the chamber of the new electrodes. **d** Electric field distribution of the 2nd harmonic of the previous electrodes. **e** Structural comparison of the previous and new electrodes. **f** Comparison of the distribution of the E_z component along the cavity axis between the previous and new electrodes under 1st + 2nd + 3rd + 4th harmonic synthesis

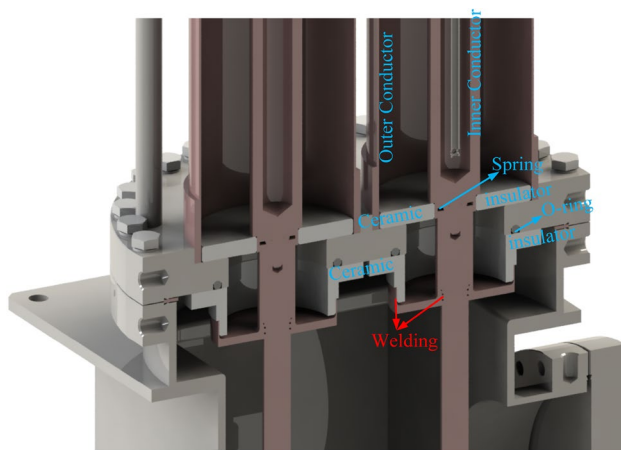
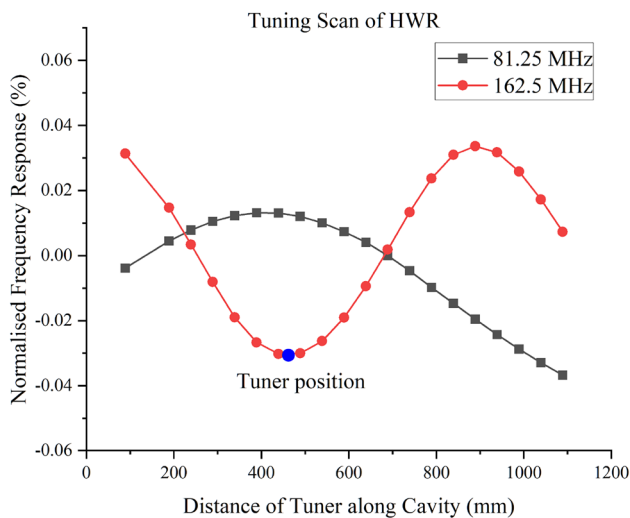
0.606 W/(m · K). The heat transfer coefficient (h) can be determined using the following equation:

$$h = \frac{Nu \cdot k}{D_h} \approx 104 \text{ W/(m}^2 \cdot \text{K)} \quad (5)$$

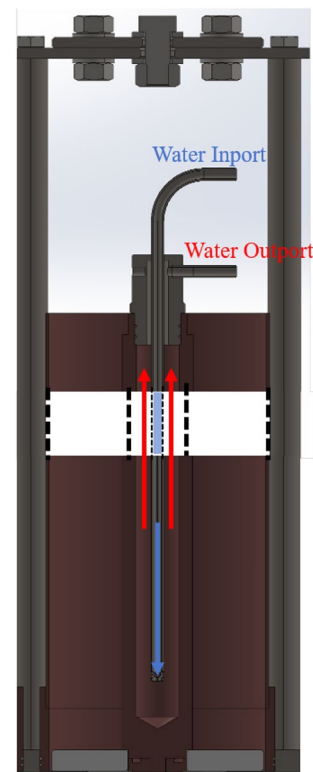
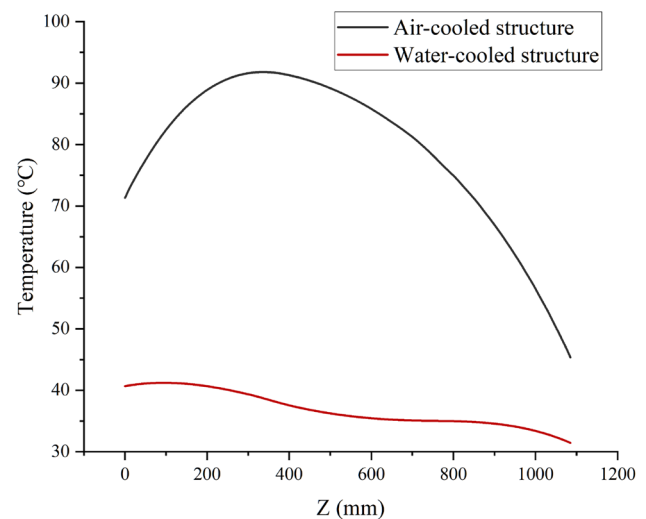
Due to the complexity associated with tuning multiple harmonics, fine tuners cannot facilitate automatic tuning. To

Table 3 RF design parameters of the MHB at the four harmonic frequencies

Harmonic (MHz)	40.625	81.25	121.875	162.5
Mode quality factor	1873	2727	3426	4501
Transit time factor	0.86	0.51	0.25	0.11
Effective bunching voltage (V)	1400	560	252	84
Voltage on the electrode (V)	1505	1098	969	763
Coupling factor	1	1	1	1
S_{11} (dB)	-30	-25	-25	-30
RF power (W)	38	30	31	20

**Fig. 8** (Color online) Diagram of the vacuum chamber seal structure**Fig. 9** (Color online) Response sensitivity as a function of tuning screw position along the HWR

mitigate thermal deformation-induced frequency shifts, the cavity is operated at a temperature close to the cold measurement temperature. The thermal distribution of the inner

**Fig. 10** (Color online) Schematic of the water-cooling structure of the QWR**Fig. 11** (Color online) Thermal distribution comparison of the QWR inner conductor with various cooling methodologies at an input RF power of 100 W

conductor, with water cooling, is compared to that obtained in the previous generation design under the same identical power input conditions (Fig. 11). The enhanced design reduces the inner conductor temperature from 90 °C to

40 °C, resulting in a more uniform temperature distribution. The integration of the water-cooling system substantially improves thermal control management throughout the QWR.

The other cavity, i.e., the HWR, possesses structural constraints that prevent the implementation of a water-cooling system. Therefore, the design incorporates the air cooling approach applied to the previous generation. The heat dissipation mechanism is improved through forced convection; this cooling method is effective when the HWR operates at a moderate input power. As shown in Fig. 12, when the total input RF power reaches 150 W, the peak temperature increases to 46 °C.

Following assembly, cold measurements of the MHB were performed using a vector network analyzer. The four operational frequencies were established by adjusting the coarse and fine tuners. At 40.625 MHz, the RF reflection coefficient S_{11} was measured at -25.85 dB, and the unloaded quality factor reached 790, representing 84% of the intended design value. Table 4 presents the comprehensive test results across all frequencies, showing that losses increase proportionally with frequency. Notably, at the 4th harmonic, the unloaded quality factor drops to 70% of its design specification, necessitating increased input power to maintain operational performance. To compensate for these losses, an additional input power of 10 W per harmonic is required.

4 Design of a low-level control system

At the HIAF, LLRF data acquisition systems will measure the amplitude, phase, and frequency. In addition, various signal processing methods will be implemented to monitor and control the RF field [29, 30]. All the LLRF systems will maintain the architecture established in previous projects, with modifications to accommodate specific application requirements. Among all the cavities, the MHB uniquely requires operation at multiple frequencies.

As the crucial initial component of the RF system, the MHB must maintain precise synchronization with the

Table 4 Test results for each mode of the HIAF MHB

Design frequency (MHz)	Test frequency (MHz)	S_{11} (dB)	Q_0
40.625	40.626	-25.85	790
81.25	81.248	-21.21	1042
121.875	121.877	-21.15	1283
162.5	162.502	-24.31	1560

accelerator's RF control. The signal generator supplies a reference synchronization signal at 81.25 MHz, which is distributed to the LLRF of each cavity through a power divider to achieve signal locking.

Figure 13 illustrates the RF link of the MHB. The violet block represents the digital LLRF system. The bunching electric field signal from the cavity pickup port undergoes filtering and down-conversion (DC) to distinct 40.625 MHz intermediate frequency (IF) signals. Analog-to-digital converters sample the IF signals at 100 MHz and transmit them to a Zynq FPGA board. Within the FPGA, the discrete IF signal undergoes demodulation into in-phase and quadrature (I/Q) signals. Through the Coordinate Rotation Digital Computer (CORDIC) algorithm, the I/Q signals are transformed into amplitude and phase (A/P) signals. These A/P signals from the cavity pickup are compared with a reference signal and then calibrated to the error signal. Subsequently, the PI controller processes the error signals. The controlled amplitude and phase signals are fed into another CORDIC model to reconstruct the 40.625-MHz digital IF signal. Then, the IF signal is fed into an analog up-conversion (UC) channel via a 16-bit digital-to-analog converter to reconstruct the corresponding RF signal. An ARM chip is integrated into the FPGA. An Experimental Physics and Industrial Control System (EPICS) operates on the ARM chip as an embedded Linux system for data acquisition.

The gray block in Fig. 13 represents the RF front-end, which comprises analog circuitry. It contains the UC, DC, and local oscillator (LO) boards. The pickup signal from the cavity is expressed as

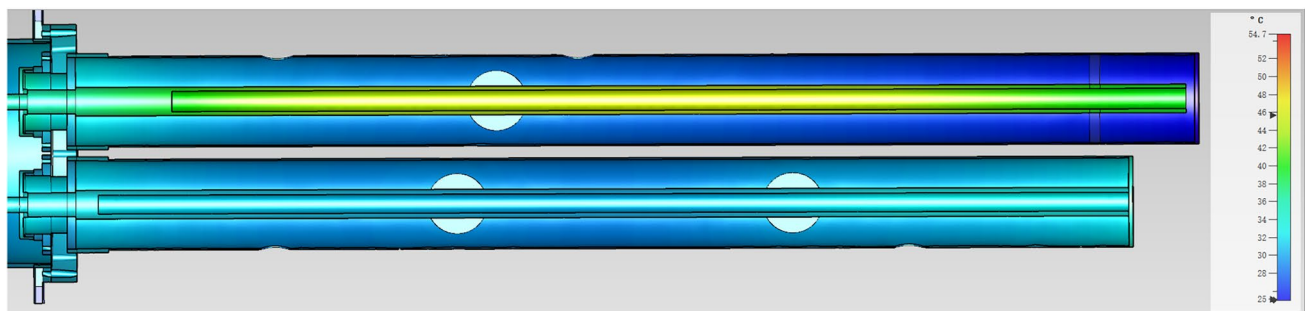
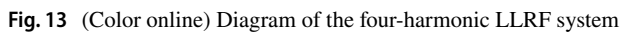


Fig. 12 (Color online) Temperature distribution of the MHB for a total input RF power of 150 W



where $A_0(t)$ is the amplitude, $\omega_0(t)$ is the frequency, and $\phi_0(t)$ is the phase of the fundamental frequency. $A_{1-3}(t)$, $\omega_{1-3}(t)$, and $\phi_{1-3}(t)$ are the parameters of the corresponding harmonics.

The demodulated IF signal from the LLRF system mixes with the frequency ω_3 during the UC process of the 3rd channel. Following passage through the bandpass filter, the 3rd channel produces an output frequency of ω_2 , indicating successful signal reconstruction [31, 32]. Subsequently, this reconstructed signal drives the power amplifier, which then feeds the signal into the cavity.

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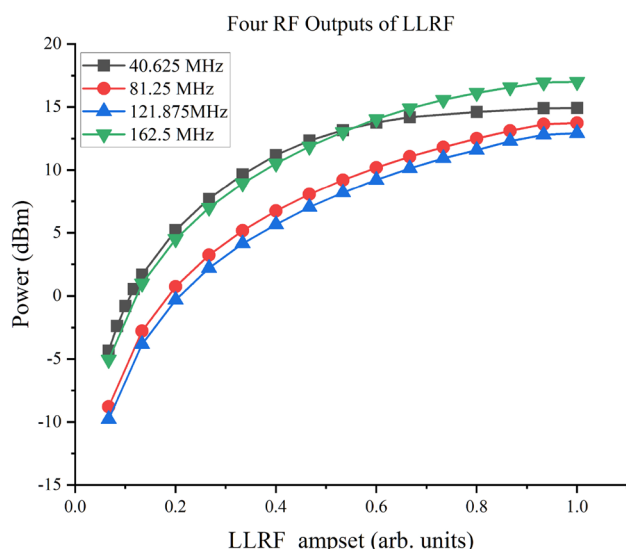


Fig. 14 (Color online) Test of the four-harmonic LLRF system

5 Beam commissioning

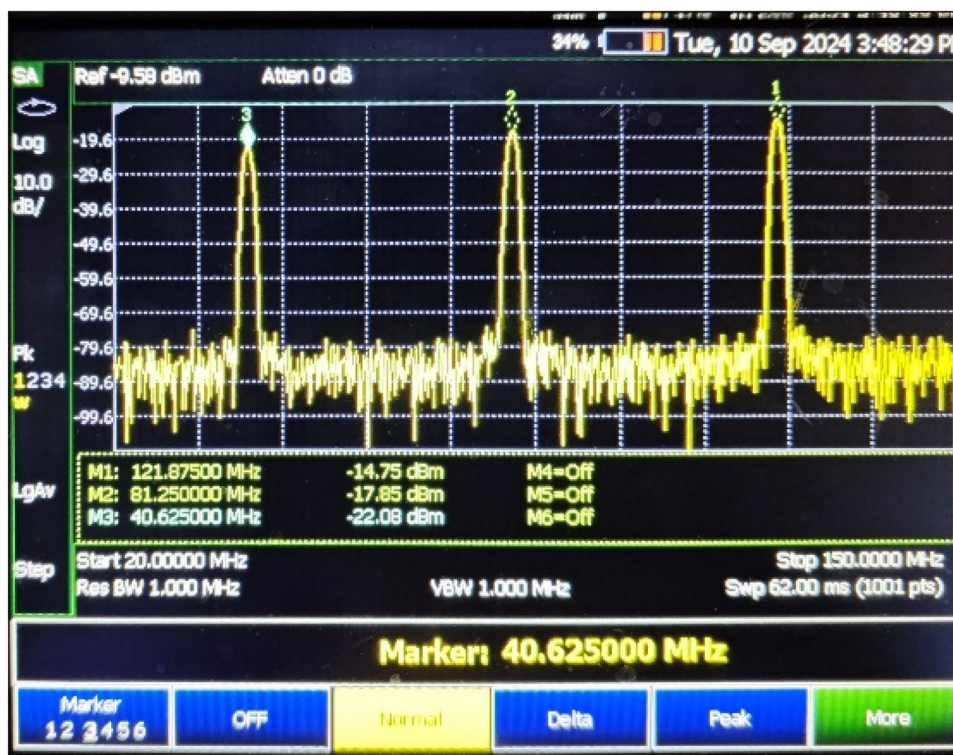
Figure 16 depicts the installed devices. Following completion of device-level commissioning, an initial beam test was performed using O^{6+} beams, with a beam current of 100 μA , to evaluate the performance of the accelerator system. Through precise optimization, we observed that

the RFQ transmission efficiency exceeded 98% (calculated as the ratio of beam currents measured by two AC current transformers (ACCTs) located on either side of the RFQ). The acceleration efficiency of the RFQ exceeded 88% with appropriate phase and amplitude settings of the MHB. This acceleration efficiency is determined as the ratio of beam currents at the Faraday cup positioned downstream of the medium-energy beam-transport quadrupole triplet and ACCT-1 (located at the RFQ entrance).

During the commissioning process, the host computer initialized the fundamental frequency at a reduced output power. A phase scan with 5° spans was conducted simultaneously to identify the optimal phase for RFQ matching. Then, the output power of the fundamental frequency was increased in steps to achieve the optimal output amplitude. Notably, excessive output power can lead to over-bunching and thus reduce the acceleration efficiency. Using the optimal phase and amplitude of the fundamental frequency as a reference point, the 2nd and 3rd harmonics were sequentially introduced. The acceleration efficiency was optimized by carefully adjusting the phase and amplitude of these harmonics. While introducing additional harmonics, a constant fundamental frequency phase was maintained; however, its amplitude needed to be increased.

Table 5 compares the measured transmission and acceleration efficiencies under various operating conditions (without MHB, with the 1st frequency, the 1st + 2nd harmonics, and the 1st + 2nd + 3rd harmonics). Because the entire

Fig. 15 (Color online) Pickup signal with 1st + 2nd + 3rd harmonic loading



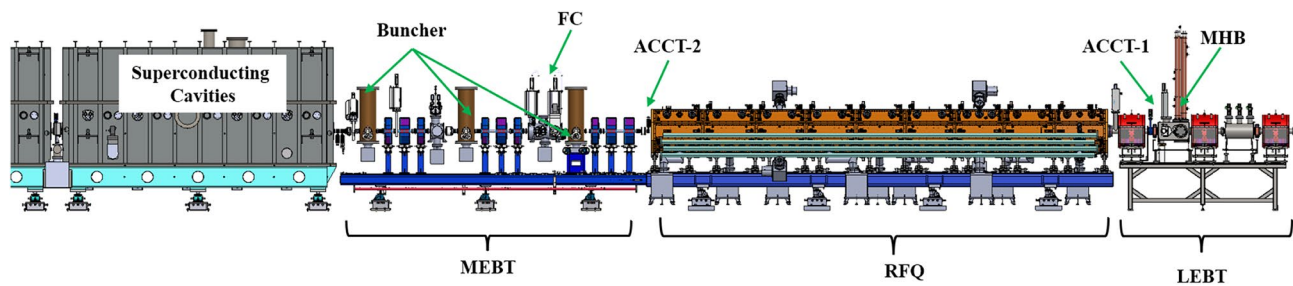


Fig. 16 (Color online) Layout of the front-end accelerator of the HIAF

Table 5 Beam commissioning results for each mode of the HIAF MHB

Bunching mode	Trans-eff (%)	Acc-eff (%)	Simulated acc-eff (%)
Without MHB	92.27	50.75	48.9
1	97.09	75.50	74.6
1 + 2	97.45	86.25	84.5
1 + 2 + 3	99.18	88.81	86.8

system is still in the debugging process, fluctuations in the test values are expected. The observed test values are higher than the simulation values owing to the accuracy limitations of the measurement equipment.

Without the MHB, the acceleration efficiency for the O^{6+} beam is 50.75%. Following the integration of the MHB, the acceleration efficiency increases to 88.8% with the 1st + 2nd + 3rd harmonic. The measured acceleration efficiencies well align with the simulation results. Furthermore, the MHB increases the transmission efficiency by 5%. Figure 17 illustrates the test results obtained under the condition of 1st + 2nd + 3rd harmonics.

The temporal structure of the beam was measured by beam position monitors (BPM) installed after the RFQ. The signals were captured using an oscilloscope with a 6-GHz bandwidth and 20-GSa/s sampling rate (Fig. 17). At a fundamental frequency of 40.625 MHz, the two main bunches maintained an interval of approximately 28.6 ns, and the trace revealed one satellite bunch between the adjacent main bunches. Based on the positions of the two BPMs, the calculated beam energy was 0.8 MeV/u. These measurements demonstrate that the MHB effectively establishes the desired beam time structure and fulfills the design specifications.

Due to the space charge effect, the longitudinal phase space of intense beams result in severe distortions with non-linear effects, which prevent the realization of the sawtooth

waveform of energy spread [34]. For the HIAF, using 81.25 MHz as the fundamental frequency has been proposed for a dual-harmonic bunching scheme. This scheme improves the acceleration efficiency, which consequently becomes 2% higher than that achieved using the three-harmonic bunching beam scheme [35]. The three-harmonic scheme employs a fundamental frequency set at half the RFQ operating frequency, leading to 50% underutilization of the RF bucket. For the next commissioning phase, the implementation of a dual-frequency bunching system, combining 81.25 and 162.5 MHz, is planned to optimize the beam dynamics.

6 Summary

The MHB has been upgraded for the HIAF project to reduce the longitudinal emittance of the beam injected into the RFQ, improve beam quality, and optimize the RFQ length. The prebuncher system incorporates a QWR and an HWR, both constructed using the standard EIA 4–1/2" coaxial transmission line. The deployment of the multiharmonic LLRF system (developed for the MHB), which enables independent control of the four-harmonic signals, has been successfully completed. The upgraded MHB enables the simultaneous operation of 1st + 2nd + 3rd + 4th harmonic operation at a fundamental frequency of 40.625 MHz, or 1st + 2nd harmonic at 81.25 MHz. A water-cooling system has been implemented for the QWR to substantially improve its operational stability; this stability improvement was confirmed by thermal analysis results. During beam commissioning at the fundamental frequency of 40.625 MHz, the O^{6+} beam achieved an acceleration efficiency of 88% with the 1st + 2nd + 3rd harmonic configuration. Future tests will be focused on evaluating the performance at the fundamental frequency of 81.25 MHz.

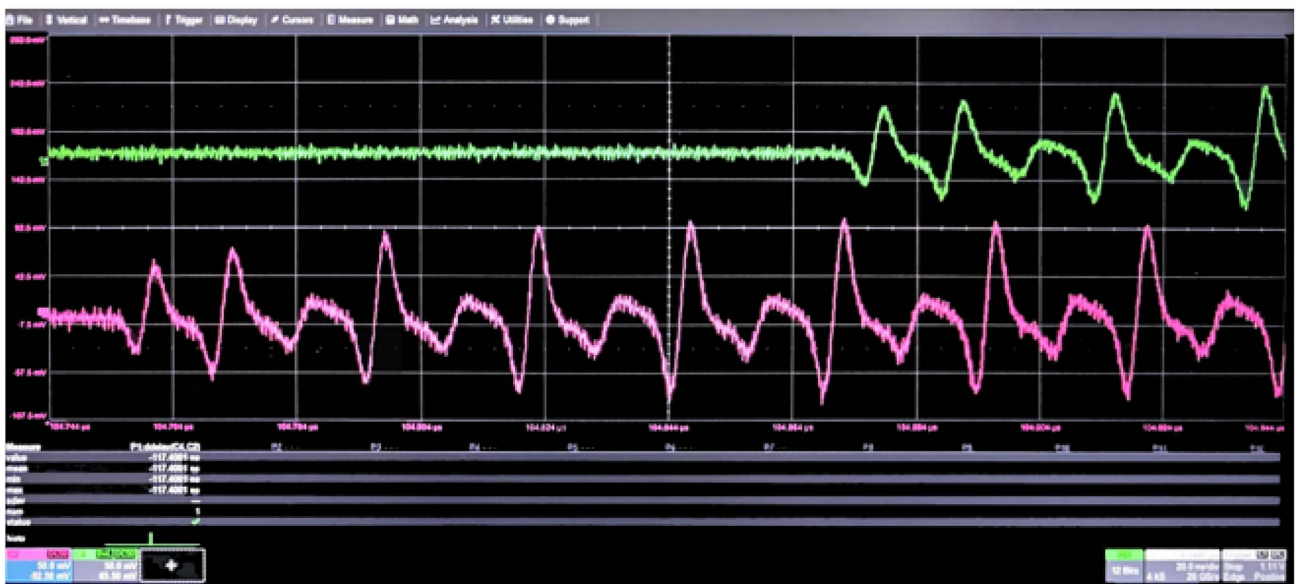
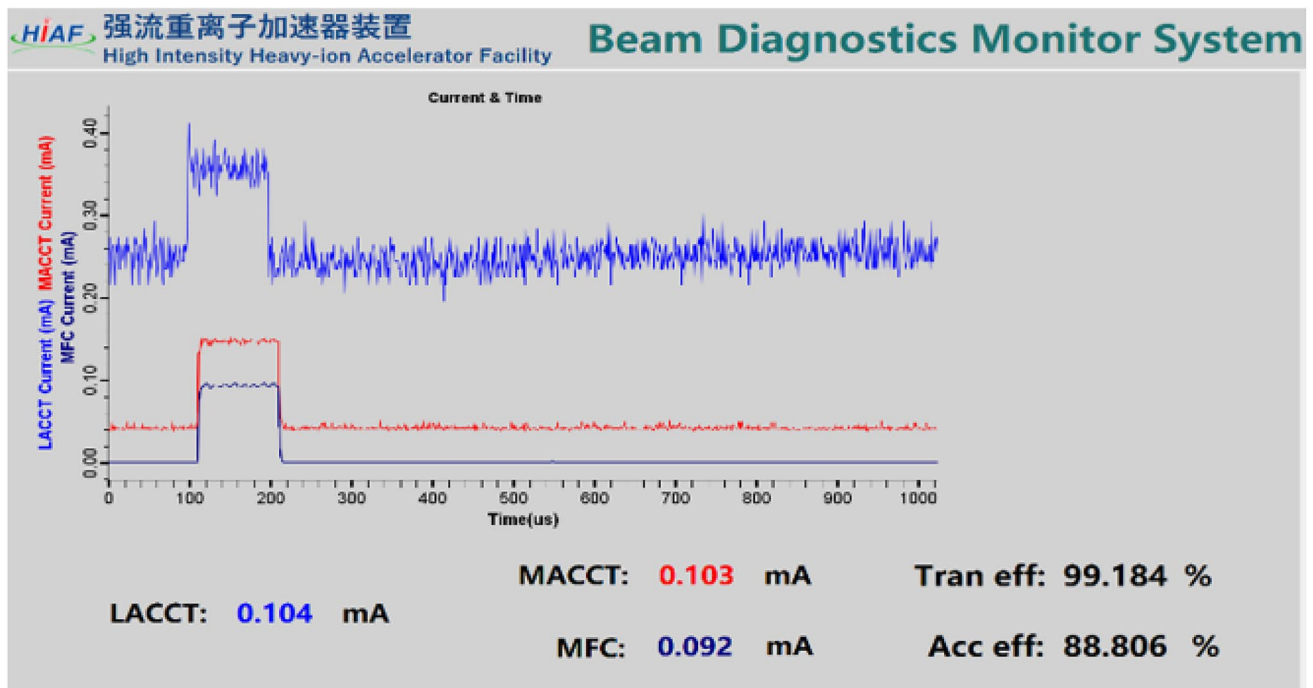


Fig. 17 (Color online) Interface of the beam diagnostics (up). Measured beam longitudinal time structure (down)

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Data Availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11.scienceadb.j00186.00764> and <https://doi.org/10.57760/sciencedb.j00186.00764>.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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