

Field tuning and rf measurement of the four-vane radio frequency quadrupole with piecewise linear intervane voltage

C. B. Yue, H. Zhou, X. Y. Zhou, P. F. Ma[✉], C. T. Du[✉],
Q. Z. Xing[✉],* S. X. Zheng[✉], and X. W. Wang

Key Laboratory of Particle and Radiation Imaging (Tsinghua University), Ministry of Education,
Beijing 100084, China;
Laboratory for Advanced Radiation Sources and Application, Tsinghua University,
Beijing 100084, China;
and Department of Engineering Physics, Tsinghua University, Beijing 100084, China

W. L. Liu, B. C. Wang, and Z. M. Wang[†]

National Key Laboratory of Intense Pulsed Radiation Simulation and Effect, Xi'an 710024, China



(Received 2 August 2025; accepted 3 March 2026; published 18 March 2026)

This paper presents the results of the beam dynamics design, radio frequency (rf) structure design, and rf field tuning of a 108 MHz four-vane radio frequency quadrupole (RFQ) with a piecewise linear intervane voltage. Typically, a constant or a linearly ramped intervane voltage is employed in the beam dynamics design of RFQ accelerators. However, to enhance the acceleration gradient of the RFQ, we apply a linearly increasing intervane voltage configuration in the initial part of the RFQ. Furthermore, we adopt a constant intervane voltage design in the subsequent part of the RFQ to lower the peak surface electric field. A transition section between the constant and linearly increasing voltage regions is specially designed to ensure a smooth second derivative of the voltage. The beam dynamics design indicates that the RFQ cavity measures 3.27 m in length and is capable of accelerating Bi^{32+} ions with a peak current of 50 μA from 4 keV/u to 0.4 MeV/u, achieving a transmission efficiency of 95.9%. During the rf structure design, the vane base width is tailored as a function of longitudinal position to maintain the desired local frequency. It is revealed that measuring the magnetic field near the cavity wall makes it challenging to guarantee the intervane voltage distribution of the RFQ. This difficulty arises from a localized dip in the magnetic field within the transition section because of the localized dip of the vane base width, together with the additional disturbance effect of the nearby tuners on the field. As a result, establishing a voltage baseline in the transition section is not feasible. Instead, the electric field near the vane tip was measured and the field was tuned by adjusting the insertion depths of 48 tuners after the RFQ cavity was machined and assembled. After tuning, the relative error between the measured field distribution and the designed curve for the operating quadrupole mode is within $\pm 1\%$, and the dipole components are within $\pm 2\%$ of the quadrupole mode. The unloaded quality factor of the RFQ cavity was measured to be 13,179, which is 83% of the value predicted by the CST software.

DOI: [10.1103/n28r-cdrw](https://doi.org/10.1103/n28r-cdrw)

I. INTRODUCTION

A 0.4 MeV/u radio frequency quadrupole (RFQ) has been designed, manufactured, and tuned for the heavy-ion injection line [1] of the Xi'an 200 MeV Proton Application Facility (XiPAF) upgrading project. XiPAF consists of a

7 MeV H^- linac injector followed by a compact synchrotron, which has delivered proton beams to users, with energies ranging from 10 to 200 MeV, and proton numbers exceeding 5×10^{10} in each cycle at various energy levels [2]. To enable heavy-ion experiments, the XiPAF upgrading project has been launched. This project includes the addition of a heavy-ion injection line, the conversion of the current H^- injection line to a proton line, and enhancements to the ring. The existing magnets and rf cavity in the ring will be retained to minimize costs. Consequently, ion beams such as He^+ , C^{4+} , Si^{8+} , Ar^{11+} , Kr^{18+} , and Bi^{32+} , with an energy of 4–9 MeV/u, will be available [3,4].

The heavy-ion injection line consists of an electron cyclotron resonance (ECR) ion source (IS) system, a

*Contact author: xqz@tsinghua.edu.cn

†Contact author: wangzhongming@nint.ac.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

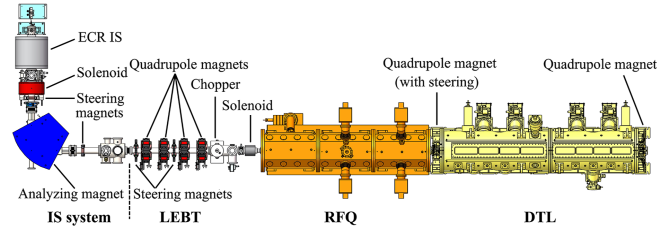


FIG. 1. Layout of the ECR IS system, LEBT, RFQ, and DTL of the heavy-ion injection line for the XiPAF upgrading project.

low-energy beam transport line (LEBT), an RFQ accelerator, an interdigital H-mode drift tube linac (IH-DTL), and a linac-to-ring beam transport line. Figure 1 shows the layout from the ECR IS to the IH-DTL of the heavy-ion injection line. The room-temperature ECR IS generates ion beams with an energy of 4 keV/u at a repetition rate of 0.1 to 0.5 Hz. Four quadrupole magnets and one solenoid are adopted to match the asymmetric beam at the outlet of the analyzing magnet to the entrance of the RFQ. The desired beam pulse width of 60 to 100 μ s is obtained through a chopper positioned between the last quadrupole and the solenoid. The four-vane RFQ accelerates the beam to 0.4 MeV/u. The IH-DTL with an electromagnetic quadrupole structure accelerates the beam from 0.4 to 2 MeV/u while maintaining a low growth of transverse emittance [5]. A single quadrupole magnet with bidirectional steering magnets between the RFQ and IH-DTL is used to match the beam to the IH-DTL.

The process for beam dynamics design of the RFQ is a multiparameter optimization problem with multiple objectives. An RFQ can contain several hundreds of acceleration cells, with each cell defined by the space between an adjacent peak and valley on the vane tip. Each cell has four independently variable parameters: the intervane voltage, the minimum or average bore radius, the modulation factor, and the synchronous phase. The common objective for all the RFQs is stable operation, with the corresponding design strategy of sufficiently low surface peak field. The other optional objectives include short RFQ length, low consumed rf power, high beam transmission, and low beam emittance growth. For the heavy-ion RFQ of the XiPAF upgrading project, because of the limited space and the need for the beam's transverse emittance at the injection point of the ring, a short length and a low beam emittance growth of the RFQ are required for its beam-dynamics design. To achieve various combinations of objectives, different sets of design criteria need to be applied.

Among the independent parameters of the RFQ, the intervane voltage V is the only one that can be adjusted through field tuning after the RFQ is manufactured. And a smooth second derivative curve of V is necessary to avoid the additional tuning difficulty. Therefore, many RFQs are designed with a predefined intervane voltage. There are currently three types of V profiles for designing the variable

parameters of RFQ cells: (i) constant voltage, such as the traditional four-section designed RFQ [6], J-PARC RFQ III [7], LEAF RFQ [8], ATLAS RFQ [9], and SESRI RFQ [10]; (ii) linearly ramped voltage, such as CPHS RFQ [11], X-BNCT RFQ [12], RISP RFQ [13], and FRIB RFQ [14], which increase the acceleration gradient at the cost of a higher consumed rf power; and (iii) constant voltage at first, and then ramped, such as IFMIF-EVEDA RFQ [15], BISOL RFQ [16], and SPIRAL2 RFQ [17], aimed at increasing the acceleration gradient while reducing the power consumption and sparking risk by limiting the maximum voltage; LEDA RFQ [18], which enhances the acceleration gradient and beam transmission; and epRFQ [19], designed with the equipartitioning condition to achieve low emittance growth.

In this paper, we propose a specific intervane voltage characterized by a curve that increases linearly in the shaper and bunching section of the RFQ to improve the acceleration gradient and remains constant in the rest part to reduce the peak surface electric field. Additionally, adiabatic shaping [10,20] is adopted to guarantee a high beam transmission. Because of the low beam current for the heavy-ion RFQ, we abandon the adiabatic bunching approach used in the conventional gentle buncher (GB) and instead maintain a constant normalized longitudinal acceptance, following the method suggested in [10].

In practical experiments, the second derivative of the intervane voltage curve should be smooth, which necessitates the inclusion of a transition section between the two areas of constant voltage and linearly increasing voltage. Furthermore, the vane base width needs to be tailored as a function of longitudinal position to keep the desired local frequency during the rf structure design. It is revealed that measuring the magnetic field near the cavity wall makes it challenging to guarantee the intervane voltage distribution of the RFQ. This difficulty arises from a localized dip in the magnetic field within the transition section because of the localized dip of the vane base width, together with the additional disturbance effect of the nearby tuners on the field. As a result, establishing a voltage baseline in the transition section is not feasible. Instead, the electric field near the vane tip was measured and the field was tuned after the RFQ cavity was machined and assembled.

The remainder of this paper is organized as follows. Section II presents the dynamics design and rf structure design of the XiPAF heavy-ion RFQ. Section III describes the result of mechanical measurement, the experimental setup, and the tuning process and final result. Finally, the conclusions are summarized in Sec. IV.

II. PHYSICAL DESIGN

A. Beam dynamics design

The heavy-ion RFQ for the XiPAF upgrading project is designed to accelerate 4 keV/u $^4\text{He}^+$ $\sim$ $^{209}\text{Bi}^{32+}$ beams to

TABLE I. Main design parameters of XiPAF heavy-ion RFQ.

Parameter	Value	Unit
Particle species	Bi^{32+}	
Input energy	4	keV/u
Output energy	0.4	MeV/u
Frequency	108	MHz
Input peak current	50	μA
Repetition rate	0.1–0.5	Hz
Beam pulse length	10–40	μs

0.4 MeV/u and deliver them to the downstream IH-DTL. The synchrotron has a repetition cycle of 3 s for heavy-ion beams. The minimum peak currents required at the injection point are 0.32 μA for He^+ , C^{4+} , and Si^{8+} , and 0.54 pA for Ar^{11+} , Kr^{18+} , and Bi^{32+} , that is, 0.32 – 17.12 μA for ${}^4\text{He}^+ \sim {}^{209}\text{Bi}^{32+}$ beams. The RFQ was designed based on the Bi^{32+} ion with the smallest charge to mass ratio. The main design parameters of the RFQ are listed in Table I. Because of the limited space, a short length of the RFQ is of primary importance. The need for minimal beam emittance growth within the RFQ can be easily met because of the low peak current of the beam.

The objective of the beam dynamics design for the RFQ is to determine the independently variable parameters of each acceleration cell. These parameters include the inter-vane voltage V (the potential difference between adjacent vanes), minimum bore radius a (or mean bore radius r_0), modulation factor m (the ratio between the maximum and minimum bore radii within a single cell), and synchronous phase ϕ_s (the phase of the sine wave at the moment when the synchronous particle is at the start of the cell). These parameters are derived from the two-term potential function near the RFQ axis:

$$U(r, \theta, z, t) = \frac{V}{2} \left[X \left(\frac{r}{a} \right)^2 \cos 2\theta + \frac{1}{AI_0(kr)} \cos kz \right] \sin(\omega t + \phi), \quad (1)$$

with boundary conditions:

$$\begin{aligned} U(a, 0, 0, t) &= \frac{V}{2} \sin(\omega t + \phi) \\ U\left(ma, \frac{\pi}{2}, 0, t\right) &= -\frac{V}{2} \sin(\omega t + \phi) \end{aligned} \quad (2)$$

From this, we can obtain the accelerating efficiency:

$$A = \frac{m^2 - 1}{m^2 I_0(ka) + I_0(kma)}, \quad (3)$$

as well as the focusing efficiency $X = 1 - AI_0(ka)$, and $r_0 = a/\sqrt{X}$, where I_0 is the zero-order modified Bessel

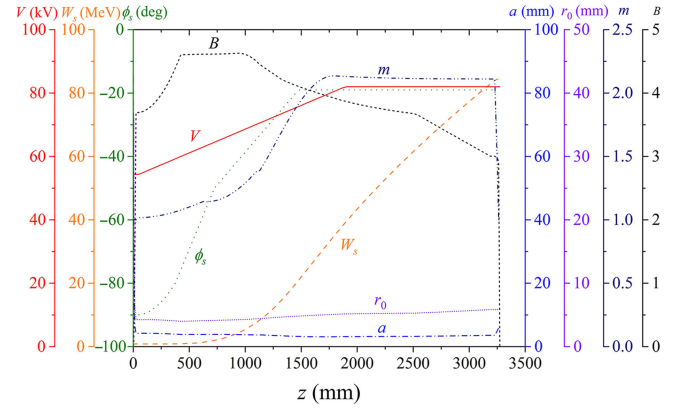


FIG. 2. Main physical parameters of the heavy-ion RFQ versus longitudinal position: V is the inter-vane voltage, W_s is the synchronous energy, ϕ_s is the synchronous phase, a is the minimum bore radius, r_0 is the average bore radius, m is the modulation factor, and B is the focusing strength.

function of the first kind, $k = 2\pi/(\beta\lambda)$, β is the relativistic velocity of the synchronous particle, λ is the wavelength in free space, and VA denotes the potential difference along the axis from the start to the end of the cell.

The beam dynamics of the 108 MHz heavy-ion four-vane RFQ was designed by the RFQGen code [21]. The main physical parameters of the heavy-ion RFQ are plotted in Fig. 2, in which W_s is the energy of the synchronous particle, $B = q\lambda^2 V / (m_0 c^2 r_0^2)$ is the focusing strength, q is the particle charge, m_0 is the rest mass of the particle, and c is the light speed in vacuum. The ratio of ρ to r_0 , with ρ representing the transverse curvature of the vane tip, is kept constant at 0.75 throughout the structure, balancing multipole effects and the peak surface field. A piecewise linear inter-vane voltage V is designed to increase linearly in the shaper and bunching section of the RFQ and remain constant in the rest parts. The vane of the RFQ has a length of 3.259 m and contains 288 cells.

In the radial matching section (RMS), weak focusing facilitates the matching of the beam into the RFQ. As a result, a lower voltage can be utilized in this region, thereby conserving rf power.

In the shaper, adiabatic shaping is adopted to lower the longitudinal emittance of the beam and hence improve the longitudinal capture efficiency. This indicates that the relative change rate in bucket area is much slower than the longitudinal oscillation frequency in the shaper. Compared with the traditional design of the shaper by RFQGen, the growth rates of the synchronous phase ϕ_s and modulation factor m are slower. Figure 3 compares the synchronous phase and modulation factor between the traditional design and the adiabatic shaping design of the shaper section. The simulated buckets at the end of the two shapers are shown in Fig. 4. The longitudinal emittance of the beam at the end of the shaper is reduced from 0.017π mm mrad with the traditional method to 0.013π mm mrad with adiabatic

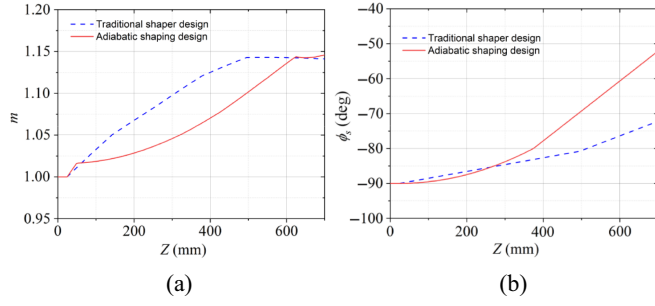


FIG. 3. Comparison of the synchronous phase (a) and modulation factor (b) between the traditional design and the adiabatic shaping design of the shaper section.

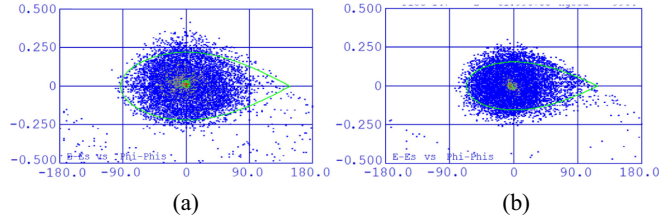


FIG. 4. Simulated longitudinal distribution of the beams and buckets (green lines) at the end of the two shapers designed by the (a) traditional method and (b) adiabatic shaping.

shaping, at a cost of an additional increase in the shaper length by 10 cm. The beam energies at the ends of both shapers are the same as 0.62 MeV/u.

In the traditional design of a gentle buncher, adiabatic bunching is beneficial for the beams with high peak current, with the longitudinal small oscillation angular frequency at zero current and the spatial length of the separatrix held constant [6]. However, in the case of the XiPAF heavy-ion RFQ, the peak current of the beam is low. Therefore, adiabatic bunching is not necessary, as it would result in a longer GB section. Instead, we opt to keep a constant longitudinal normalized acceptance in the bunching section by increasing ϕ_s and the accelerating efficiency A . The longitudinal normalized acceptance can be written as [22]

$$A_B = 16 \sqrt{\frac{m_0 c^2 \beta^2 \gamma^3 q V A}{2 \pi \omega^2}} \alpha_b(\phi_s), \quad (4)$$

where γ is the relativistic factor of the particle, ω is the angular frequency, and

$$\alpha_b(\phi_s) \approx \frac{1 - \cos \phi_s}{1 + \cos \phi_s}. \quad (5)$$

The intervane voltage V increases linearly from 54 to 82 kV to enhance the acceleration gradient in the shaper and bunching section. Then it remains constant until the end of the RFQ which helps keep the Kilpatrick factor

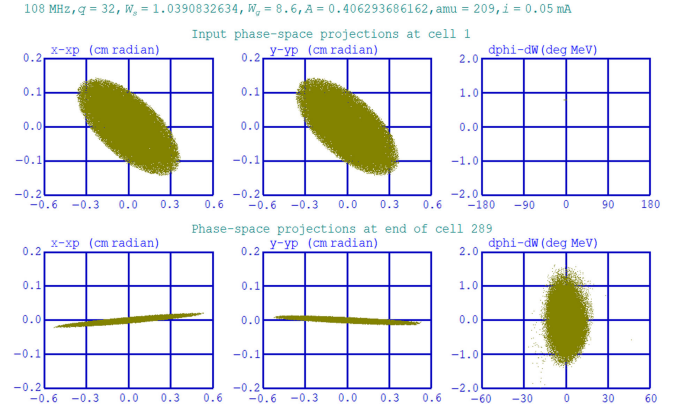


FIG. 5. Phase spaces of the beam at the entrance (top) and exit (bottom) of the RFQ simulated by the RFQGen code.

below 1.8. The Kilpatrick factor is defined as the ratio of the actual peak surface field to the Kilpatrick field [23]. If the voltage keeps rising, the aperture must be enlarged to prevent the maximum surface electric field from becoming excessively high. However, this enlargement will reduce the focusing strength, making it difficult to effectively match to the IH-DTL following the RFQ. At the RFQ exit, the zero-current transverse phase advance is set to $150^\circ/\text{m}$ by adjusting B to 3.0, while the zero-current longitudinal phase advance is set to $130^\circ/\text{m}$ by tuning m to match with the IH-DTL.

The dynamics simulation for the RFQ was performed using the RFQGen code. An initial beam with a four-dimensional water-bag distribution containing 1×10^5 macroparticles was adopted. The input beam has a peak current of 50 μA , Twiss parameters of $\alpha = 0.84$, $\beta = 3.36$ cm/rad, and a normalized RMS emittance of 0.2π mm mrad. Phase spaces of the beam at the entrance and exit of the RFQ are shown in Fig. 5. The beam distribution evolution of the transverse position, and the

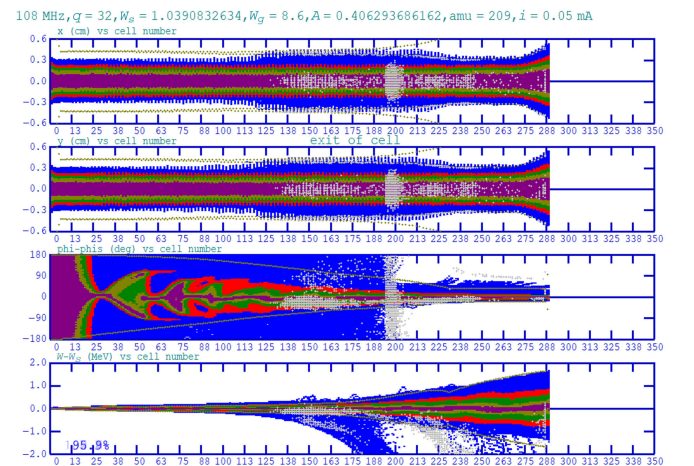


FIG. 6. Beam dynamics simulation result of the RFQ using RFQGen, with an input peak current of 50 μA .

TABLE II. Dynamics design result of the XiPAF heavy-ion RFQ by RFQGen (Bi^{32+}).

Parameter	Value	Unit
Input energy	4	keV/u
Input peak current	50	μA
Input Twiss parameter	$\alpha = 0.84$ $\beta = 3.36$	cm/rad
Input transverse emittance (normalized RMS)	0.2	π mm mrad
Output energy	0.4	MeV/u
Output transverse normalized RMS emittance	0.205	π mm mrad
Beam transmission	95.9%	
Peak surface field	21.0 (1.8 Kilp)	MV/m
Cavity length	3.27	m

relative phase and energy with RFQ longitudinal position are presented in Fig. 6. The simulated transmission efficiency is 95.9%, and the growth of the beam transverse normalized RMS emittance is 2.5%. Table II lists the dynamics results of the XiPAF heavy-ion RFQ.

For comparison, we have designed an RFQ with a linearly ramped intervane voltage, but with the traditional four-section design procedure of the RFQGen code. Under the condition that the maximum surface electric field and transmission are basically the same, the RFQ length is 3.38 m, which is slightly longer than the design result presented in Table II. While adiabatic shaping lengthens the shaper, the overall length of the RFQ can still be shortened benefiting from the nonadiabatic bunching. Nevertheless, nonadiabatic bunching is more suitable for beams with low peak current.

B. rf structure design

The XiPAF heavy-ion RFQ is mechanically separated into three segments to facilitate machining and brazing. Each segment measures approximately 1.1 m in length. Additionally, there will be no coupling plate between the adjacent segments. Figure 7 illustrates the structural drawing of the XiPAF heavy-ion RFQ.

As the vane-tip geometry varies along the longitudinal position, the half-width of the vane base W_b is tailored by the Superfish code [24] to keep the desired local frequency. Figure 8 illustrates the view from the low-energy end of the RFQ, with the labeled $2W_b$ representing the vane base

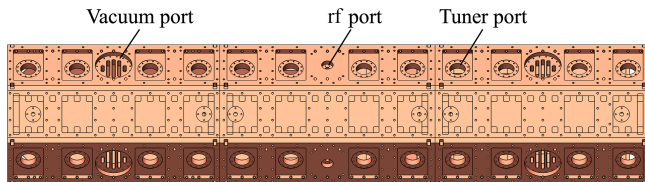


FIG. 7. Structural drawing of the XiPAF heavy-ion RFQ.

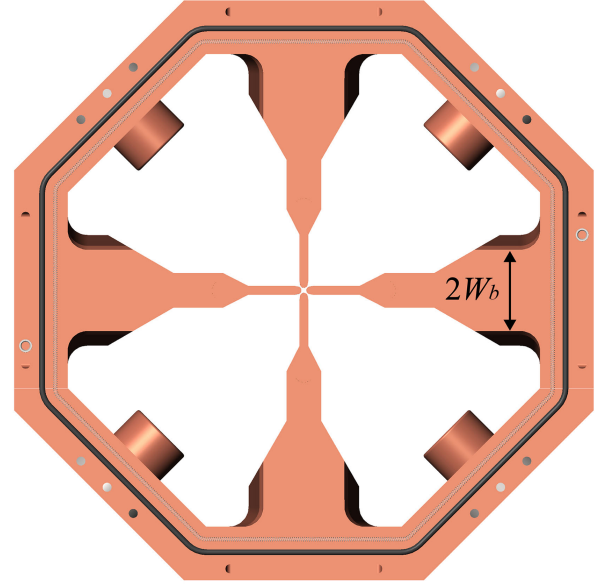


FIG. 8. Cross-sectional diagram of the XiPAF heavy-ion RFQ.

width at the RFQ entrance. A total of 48 tuners with the same diameter of 80 mm are distributed in the four quadrants of the RFQ cavity. The resonant frequency of the operating quadrupole mode TE_{210} is designed to be 107.5 MHz with all the tuners flush with the interior wall of the RFQ.

The shape and dimensions of the undercuts will affect the local frequency, thereby altering the local slope of the intervane voltage. The undercuts at both ends of the RFQ are designed to achieve a field distribution close to the desired one, facilitating the future field tuning after the assembly of the RFQ cavity. Figure 9 shows the undercuts at the two ends of the RFQ cavity. However, because of the discontinuity of the slope of the piecewise linear intervane voltage V , there is a large deviation between the desired V curve in Fig. 2 and the calculated V curve by the CST software [25], which is based on the vane base half-width

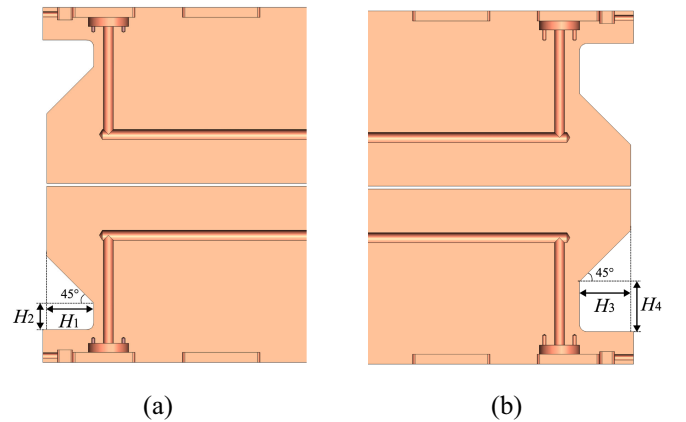


FIG. 9. Undercuts at the two ends of the XiPAF heavy-ion RFQ. (a) Low-energy end. (b) High-energy end.

W_b predicted by Superfish. The reason is that the local TE₂₁ cutoff frequency $f_0(z)$ inside the RFQ cavity is related to the second derivative of the V curve as [23]

$$\frac{\partial^2 V}{\partial z^2} = \frac{4\pi^2}{c^2} (f_0^2 - f^2)V, \quad (6)$$

where f is the resonant frequency of the operating quadrupole mode TE₂₁₀ inside the RFQ cavity. At the intersection point, the second derivative of the V curve approaches infinity, and it is not possible to match the local cutoff frequency f_0 to infinity by varying the vane base half-width. Therefore, a transition section is needed between the linearly increasing voltage and the constant voltage.

The voltage curve in the transition section, which has a length of δz , approximated using a fourth-order polynomial, as expressed in Eq. (7):

$$V(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4, \quad (7)$$

where z is the longitudinal position. The five coefficients a_0 - a_4 and δz can be determined by the conditions of smoothing up to second order, and we can obtain

$$V(z) = V_1 + kz - \frac{k^3 z^3}{4(V_2 - V_1)^2} + \frac{k^4 z^4}{16(V_2 - V_1)^3}, \quad (8)$$

where k is the voltage gradient at the linearly increasing section, V_1 is the voltage at the end of this section, and V_2 is the voltage at the constant voltage section.

Figure 10(a) presents the calculated intervane voltage V of the XiPAF heavy-ion RFQ using CST before and after smoothing. For both cases, the dimensions of the undercuts at each end of the RFQ cavity have been optimized [26] to minimize the discrepancy of the calculated intervane voltage from the designed curve shown in Fig. 2. As illustrated in Fig. 10(b), the relative error of V between the smoothed value and the designed curve remains within $\pm 1\%$. In contrast, the value of V before smoothing shows a large deviation from the smoothed value, as indicated in Fig. 10(a).

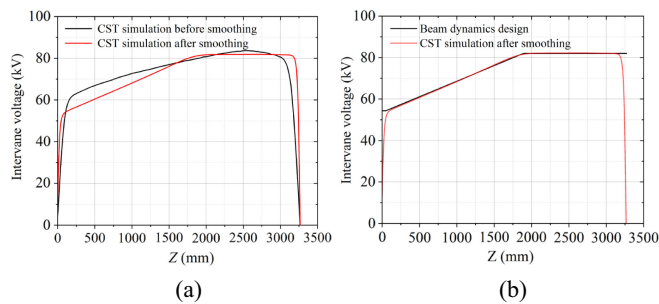


FIG. 10. Intervane voltage of the XiPAF heavy-ion RFQ. (a) CST simulation before and after smoothing. (b) CST simulation after smoothing and the designed curve.

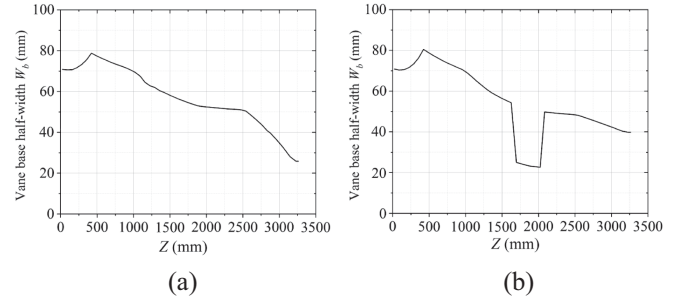


FIG. 11. Vane base half-width calculated by Superfish before (a) and after smoothing (b) of the intervane voltage curve.

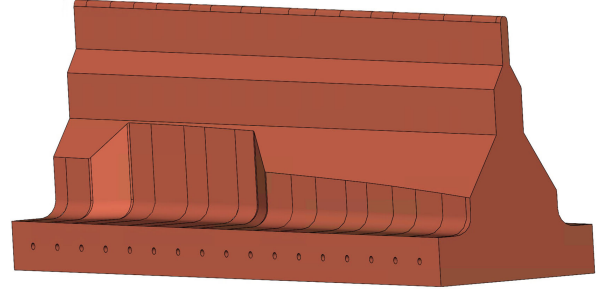


FIG. 12. Three-dimensional model of the second segment of the RFQ featuring a localized dip in the width of the vane base (low-energy end is on the right).

Figure 11 presented the vane base half-width W_b calculated by Superfish before and after the intervane voltage curve is smoothed. At the transition section, there is a localized dip of the vane base width curve after smoothing, in the second segment of the RFQ. The three-dimensional model of the second segment is shown in Fig. 12.

The dimensions of the undercuts are as follows: $H_1 = 125$ mm, $H_2 = 105$ mm, $H_3 = 85$ mm, and $H_4 = 145$ mm. Four dipole-mode stabilizer rods are mounted on each of the two end flanges. To minimize the effect on the TE₂₁₀ mode, the rods should be positioned where the electric field's energy density matches that of the magnetic field. Because of the symmetry of the cavity, the rods should be located along the angular bisector between adjacent vanes. The Superfish code is utilized to find the proper radial positions of $r = 84.8$ mm for the low-energy end and 120 mm for the high-energy end. The frequency interval between TE₂₁₀ and its nearest neighboring dipole mode is enough large as 1.45 MHz, when the lengths of all the rods are zero. Nevertheless, to be conservative, the final rod lengths will be determined during field tuning.

The peak rf power dissipated on the cavity wall is calculated to be 67.3 kW with an unloaded quality factor of 15,900. Because of the low duty factor of the rf power, there is only one separate cooling passage in each vane of each segment of the RFQ, as shown in Fig. 9.

III. FIELD TUNING AND RF MEASUREMENT

A. Mechanical measurement

During the processes of machining, assembling, and brazing the RFQ vanes and walls, discrepancies between the actual vane profiles and the designed ones are unavoidable. Significant deviations can cause the real rf electric field distribution to differ from the intended design, thereby deteriorating the performance of the accelerator. To ensure accuracy of the rf electric field distribution, it is essential to verify that the final position of the vanes matches the theoretical position after the RFQ vanes and walls have been brazed together, forming the cavity.

After the assembly of the three segments of the XiPAF heavy-ion RFQ, the vane-tip gap distances between adjacent vanes at the position of the tuners and vacuum ports are measured by pin gauges. Figure 13 shows the gap distance errors between the measured and designed values across the four quadrants. Most of the points are within $\pm 100 \mu\text{m}$ of the designed values, with the exception of the region at the end of the first segment.

To estimate the acceptable range of vane-tip gap tolerance, error analysis with the TraceWin code [27] is performed incorporating the errors in beam injection, the RFQ field, and the longitudinal profile of RFQ vanes. The input beam errors are set with the position of $\pm 0.2 \text{ mm}$, divergence of $\pm 0.5 \text{ mrad}$, mismatch factor of $\pm 20\%$, energy of $\pm 0.1 \text{ keV/u}$, and current of $\pm 1\%$. The rf field error inside the RFQ cavity are set with the amplitude of $\pm 2\%$ and phase of $\pm 2^\circ$. Five sets of error limits for longitudinal profile of RFQ vanes have been selected: ± 0.05 , ± 0.1 , ± 0.15 , 0.2 , and $\pm 0.25 \text{ mm}$. Twenty cases are simulated for each set, with 10^5 macroparticles for each case. For all errors, randomly choose either the maximum or minimum value within the error range.

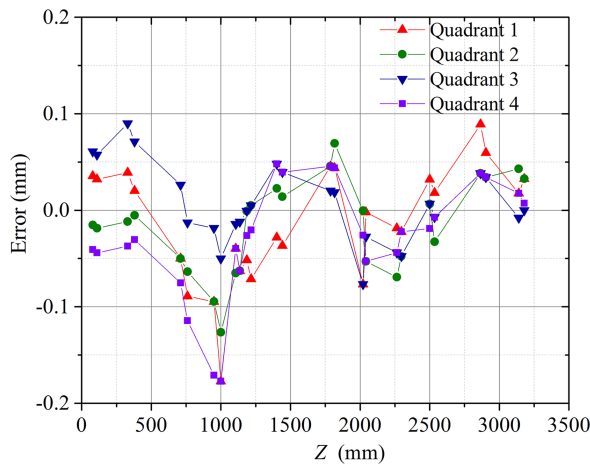


FIG. 13. Errors in the gap distance between adjacent vane tips, comparing the measured values to the designed values across the four quadrants of the RFQ.

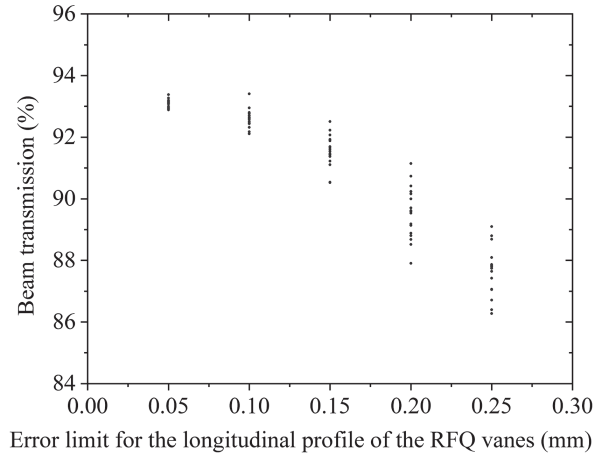


FIG. 14. Beam transmission with different error limit for the longitudinal profile of the RFQ vanes calculated by the TraceWin code.

Figure 14 presents the beam transmission with different error limit for the longitudinal profile of the RFQ vanes calculated by the TraceWin code. As the error limit for the longitudinal profile of the RFQ vanes increases, the RFQ transmission decreases. If the beam transmission is required to be higher than 90%, a maximum error for the longitudinal profile of $\pm 0.15 \text{ mm}$ can be accepted, corresponding to a vane-tip gap error of $\pm 0.21 \text{ mm}$.

B. Experimental setup

The three segments of the RFQ are aligned longitudinally for the field tuning, as shown in Fig. 15. The objectives of the tuning are as follows: (i) to acquire the required frequency; (ii) to ensure the measured quadrupole field is within $\pm 2\%$ of the designed values; (iii) to minimize the components of dipole modes; and (iv) to maximize the frequency interval between the quadrupole mode and its nearest neighboring mode.

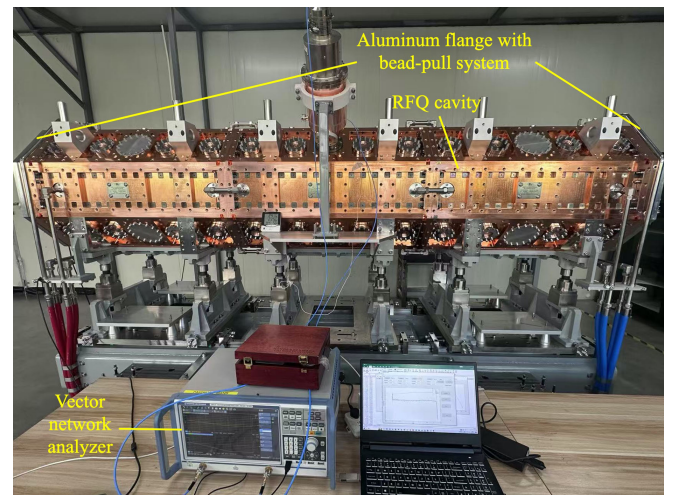


FIG. 15. Experimental setup for field tuning of the RFQ.

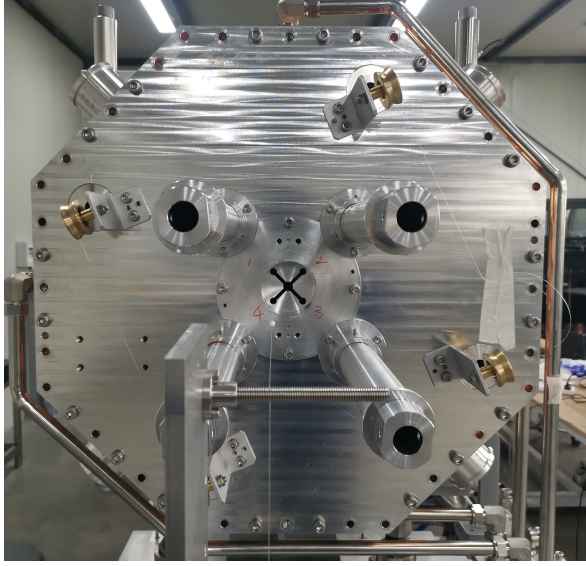


FIG. 16. Bead-pull system on an aluminum flange at one end of the RFQ.

Figure 16 shows the bead-pull system located at one end of the RFQ for field tuning. The fields of the quadrupole and dipole modes can be obtained both by measuring the electric field distribution near the axis with a spherical ceramic bead (shown in Fig. 16), as well as the magnetic field distribution near the outer wall with a hollow metal bead. One port of the vector network analyzer (VNA) is connected to the power coupler, and the other port is connected to a field probe. As the bead moves inside the RFQ cavity, a phase shift of the transmission coefficient S_{12} of the VNA will be induced, which is proportional to the square of the field magnitude at the position of the bead. The field distribution is then obtained by measuring the phase shift with the requirement that the phase of S_{12} shall be linear with the frequency near the resonant frequency.

C. Tuning and rf measurement

The localized dip of the vane base width, together with the adjacent tuners, have a combined disturbance effect on the measured magnetic field. Figure 17 shows the simulated and measured magnetic fields close to the outer wall of the RFQ. There are not enough valuable data points left after the disturbed data are removed. As a result, we need to measure the electric field distribution near the axis to acquire the fields of the quadrupole and dipole modes.

Field tuning is carried out through the iteration process described in [28], beginning with the end plates of all the aluminum tuners flush with the interior wall of the RFQ. Initially, the insertion depths of the dipole-mode stabilizer rods are determined. When the insertion depths of all the dipole-mode stabilizer rods are adjusted from 0 to a maximum of 254 mm, the frequency interval between the quadrupole mode and its nearest neighboring mode

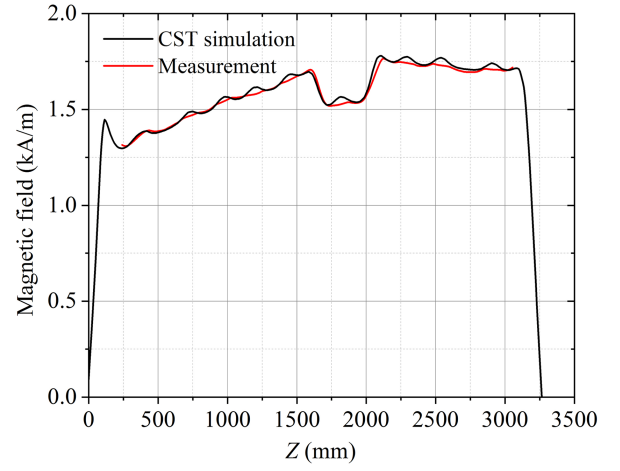


FIG. 17. Simulated and measured magnetic fields near the inner surface of the outer wall of the RFQ.

shifts from 1.42 to 1.92 MHz, while the frequency of the operating quadrupole mode changes by less than 0.01 MHz. Ultimately, an insertion depth of 200 mm is chosen for all the rods, resulting in a frequency interval of 1.76 MHz.

The electric field distribution near the axis is measured to determine the field distribution of the quadrupole and dipole modes. Once the field distribution is obtained, the tuning program THURT [29], later renamed RFQACCTUNE, is utilized to compute the new insertion depths for the aluminum tuners. Though the RFQ tuning code RFQACCTUNE is developed for an RFQ with either constant or linearly ramped intervane voltage, it still works for an RFQ with piecewise linear intervane voltage. Both the theoretical and measured field distributions can be expressed as the superposition of the first few bases [29]:

$$V(z) = \sum_{n=0}^N [a(n)Q(z, n) + b(n)D_1(z, n) + c(n)D_2(z, n)], \quad (9)$$

where $Q(z, n)$ represents the field distribution of the n th quadrupole mode, $D_1(z, n)$ and $D_2(z, n)$ represent the field distributions of the two n th dipole modes. Although N is theoretically infinite, but the sum can be truncated to a finite value, such as $N = 12$ in our case. For an RFQ with a piecewise linear intervane voltage profile, RFQACCTUNE still functions correctly, provided that we set the field of the zero-order quadrupole mode $Q(z, 0)$ as the desired piecewise linear voltage.

The difference between the measured and theoretical coefficients $a(n)$, $b(n)$, and $c(n)$ can be attributed to the local frequency perturbations induced by the tuners. This relationship can be accurately measured in the experiment, as the depths of the tuners directly determine the local frequency perturbation. Consequently, the insertion depths

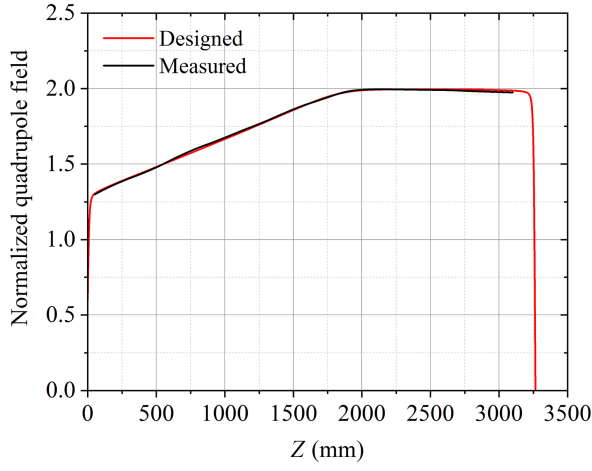


FIG. 18. Normalized measured and designed quadrupole fields of the RFQ after tuning.

of all the tuners can be derived to counteract the local frequency perturbations.

The above process is repeated multiple times until the desired frequency, the relative quadrupole field error, and the dipole component are achieved. Subsequently, 12 copper tuners are cut to the appropriate lengths and installed. The iterative process is then repeated to determine the lengths of the remaining 16, 8, and 12 copper tuners.

Figure 18 presents the measured and designed quadrupole field of the RFQ after tuning. Figure 19 shows the corresponding relative error of the quadrupole field and the dipole components. The relative error in the field distribution of the operating quadrupole mode is within $\pm 1\%$, and the two dipole mode components are within $\pm 2\%$ of the quadrupole mode. Subsequently, we conducted a second repeated experiment with all the tuners remaining stationary. The relative error in the electric field distribution across the four quadrants between the two sets of

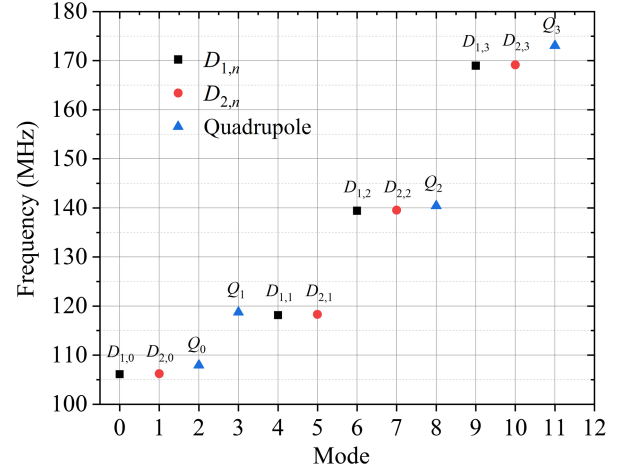


FIG. 20. Frequency spectrum of the RFQ after tuning (23.5 °C, 45% humidity, and 1 atm).

measurements was within $\pm 2.5\%$. The results from the second measurement indicate that the relative error for the field distribution of the operating quadrupole mode and the two dipole mode components stayed within the same range as observed in the first measurement.

Figure 20 shows the frequency spectrum of the heavy-ion RFQ cavity after tuning. The frequency interval between TE_{210} and its nearest neighboring dipole mode is 1.764 MHz. Table III summarizes the cavity parameters of the RFQ after field tuning. The target frequency of the operating mode is based on a room temperature of 23.5 °C, relative humidity of 45%, and ambient pressure of 1 atm during the field tuning. The unloaded quality factor is $Q_0 = (1 + \beta_1 + \beta_2)Q_L$, where Q_L is the loaded quality factor, and β_1 and β_2 are coupling coefficients for the coupler and field pickup, respectively. The value of Q_0 is measured at 13,179, which is 83% of the value predicted by the CST software.

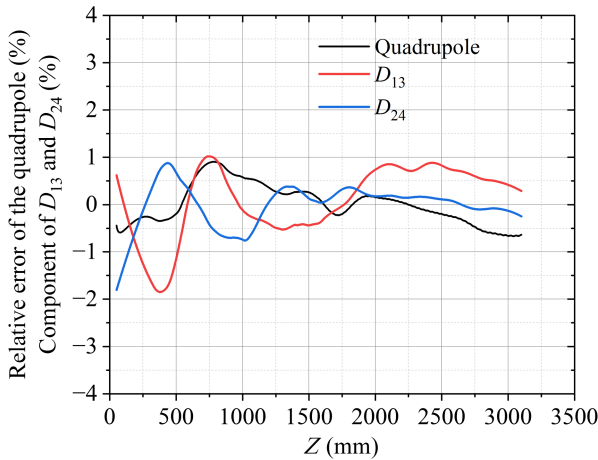


FIG. 19. Relative error between the measured and designed quadrupole fields, and dipole component of the quadrupole mode after tuning.

TABLE III. Cavity parameters of the RFQ after field tuning.

Parameter	Measured value	Designed value	Unit
Frequency of the operating mode	107.974	107.969	MHz
Frequency interval between the operating mode and its nearest mode	1.764	≥ 1.45	MHz
Loaded quality factor, Q_L	6324		
Coupling coefficient β_1 of the coupler	1.064	1.002	
Coupling coefficient β_2 of the field pickup	0.02		
Unloaded quality factor, Q_0	13,179	15,900	
Relative error of the operating quadrupole mode	$-0.6\% - 1\%$	$\leq \pm 2\%$	
Dipole component	$< \pm 2\%$	Minimization	

IV. CONCLUSIONS

A 108 MHz four-vane RFQ accelerator with a piecewise linear intervane voltage has been constructed for the heavy-ion injection line of the XiPAF upgrading project. This 3.27-m-long RFQ can accelerate the Bi^{32+} beam from 4 keV/u to 0.4 MeV/u with a peak current of 50 μA , a pulse width of 40–100 μs , and a maximum repetition rate of 0.5 Hz. The machining, assembly, and rf tuning of the RFQ cavity have been successfully completed.

The intervane voltage is designed to increase linearly in the shaper and bunching section of the RFQ to enhance the acceleration gradient and to remain constant in the remaining parts to control the peak surface electric field. With adiabatic shaping and a constant normalized longitudinal acceptance in the bunching section, the RFQ is designed to have a beam transmission of 95.9% and a maximum Kilpatrick factor of 1.8. Simulation indicates that the transverse normalized RMS emittance of the beam only increases by 2.5% from the entrance to the exit of the RFQ.

The smoothed piecewise linear intervane voltage can be achieved through a localized dip of the vane base width. During field tuning, the electric field near the axis is measured to obtain the field distribution of the operating quadrupole mode and the dipole modes. After tuning, the relative error in the field distribution of the operating quadrupole mode is within $\pm 1\%$, confirming that the smoothed piecewise linear intervane voltage can be successfully realized in the experiment.

ACKNOWLEDGMENTS

The authors would like to thank Shanghai Kelin Technology Development CO. LTD for the machining during field tuning. This work was supported by the National Natural Science Foundation of China (Grant No. 12475154).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

-
- [1] C. B. Yue, P. F. Ma, B. C. Wang, W. L. Liu, Q. Z. Xing, X. D. Yu, S. Wang, X. Y. Liu, S. X. Zheng, C. T. Du, M. T. Zhao, M. W. Wang, Y. H. Yan, W. Lv, Z. M. Wang, X. L. Guan, and X. W. Wang, Beam dynamics design of a proton/heavy-ion injector for the synchrotron of the XiPAF upgrading project, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1076**, 170537 (2025).
 - [2] Z. M. Wang *et al.*, Construction and beam commissioning of a compact proton synchrotron for space radiation

- environment simulation, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1027**, 166283 (2022).
- [3] X. Y. Liu, H. J. Yao, Y. Li, Z. J. Wang, Y. Xiong, S. X. Zheng, and X. W. Wang, Multiturn injection design and optimization for XiPAF-upgrading synchrotron, *J. Phys. Conf. Ser.* **2687**, 052034 (2024).
- [4] Z. M. Wang *et al.*, Current status and upgrade plan of Xi'an 200 MeV proton application facility, *Mod. Appl. Phys.* **15**, 040402 (2024).
- [5] P. F. Ma *et al.*, Beam-dynamics design of a 2 MeV/u heavy-ion IH-DTL with electromagnetic quadrupole structure, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1027**, 166298 (2022).
- [6] K. R. Crandall, R. H. Stokes, and T. P. Wangler, RF quadrupole beam dynamics design studies, in *Proceedings of the 1979 Linear Accelerator Conference, LINAC79, Montauk, New York, USA* (JACoW, Geneva, Switzerland, 1979), p. 205.
- [7] Y. Kondo, K. Hasegawa, T. Morishita, and R. A. Jameson, Beam dynamics design of a new radio frequency quadrupole for beam-current upgrade of the Japan Proton Accelerator Research Complex linac, *Phys. Rev. ST Accel. Beams* **15**, 080101 (2012).
- [8] W. Ma, L. Lu, X. B. Xu, L. P. Sun, Z. L. Zhang, W. P. Dou, C. X. Li, L. B. Shi, Y. He, and H. W. Zhao, Design of an 81.25 MHz continuous-wave radio-frequency quadrupole accelerator for Low Energy Accelerator Facility, *Nucl. Instrum. Methods Phys. Res., Sect. A* **847**, 130 (2017).
- [9] P. N. Ostroumov, B. Mustapha, A. Barcikowski, C. Dickerson, A. A. Kolomiets, S. A. Kondrashev, Y. Luo, D. Paskvan, A. Perry, D. Schrage, S. I. Sharamentov, R. Sommer, W. Toter, and G. Zinkann, Development and beam test of a continuous wave radio frequency quadrupole accelerator, *Phys. Rev. ST Accel. Beams* **15**, 110101 (2012).
- [10] Z. S. Li, Theoretical design and experimental studies of heavy ion radiofrequency quadrupole linacs, Ph.D. thesis, University of Chinese Academy of Sciences, 2017.
- [11] Q. Z. Xing, Y. J. Bai, J. Billen, J. C. Cai, C. Cheng, L. Du, Q. Du, T. B. Du, W. Q. Guan, X. L. Guan, Y. He, J. Li, J. Stovall, X. W. Wang, J. Wei, Z. F. Xiong, L. Young, H. Y. Zhang, and S. X. Zheng, A 3-MeV RFQ accelerator for the compact pulsed hadron source at Tsinghua University, *Phys. Procedia* **26**, 36 (2012).
- [12] H. P. Li, Y. Q. Chen, H. Q. Su, G. Q. Kong, J. L. Li, W. T. Deng, and S. Wang, Field tuning study and rf electromagnetic design of a continuous-wave RFQ with ramped intervane voltage for AB-BNCT, *J. Instrum.* **19**, P05007 (2024).
- [13] B. S. Park, I. S. Hong, and J. H. Jang, Installation of a four-vane radio-frequency quadrupole accelerator for the Rare Isotope Science Project, *J. Korean Phys. Soc.* **73**, 1111 (2018).
- [14] E. Pozdeyev, N. Bultman, G. Machicoane, G. Morgan, X. Rao, Q. Zhao, L. M. Young, J. Stovall, V. Smirnov, S. Vorozhtsov, and L. Sun, FRIB front end design status, in *Proceedings of Linear International Accelerator Conference, LINAC2012, Tel-Aviv, Israel* (JACoW, Geneva, Switzerland, 2012), p. 1047.
- [15] M. Comunian, A. Pisent, E. Fagotti, and P. A. Posocco, Beam dynamics of the IFMIF-EVEDA RFQ, in *Proceedings of European Particle Accelerator Conference*,

- EPAC08, Genoa, Italy* (JACoW, Geneva, Switzerland, 2008), p. 3536.
- [16] H. P. Li, Z. Wang, Y. R. Lu, K. Zhu, Q. Y. Tan, S. Liu, and M. Y. Han, Design and study of a continuous wave RFQ for the BISOL high intensity deuteron driver linac, *J. Instrum.* **15**, T05003 (2020).
- [17] R. Ferdinand, G. Congretel, A. Curtioni, O. Delferriere, A. France, D. Leboeuf, J. Thinel, J. C. Toussaint, and M. D. Giacomo, SPIRAL 2 RFQ design, in *Proceedings of European Particle Accelerator Conference, EPAC 2004, Lucerne, Switzerland* (JACoW, Geneva, Switzerland, 2004), p 2026.
- [18] L. M. Young, Simulations of the LEDA RFQ. 6.7-MeV accelerator, in *Proceedings of the Particle Accelerator Conference, PAC97, Vancouver, BC, Canada* (JACoW, Geneva, Switzerland, 1997), p 2752.
- [19] Y. Kondo, T. Morishita, and R. A. Jameson, Development of a radio frequency quadrupole linac implemented with the equipartitioning beam dynamics scheme, *Phys. Rev. ST Accel. Beams* **22**, 120101 (2019).
- [20] X. J. Kang, The cooler injector synchrotron at IUCF, Ph.D. thesis, Indiana University, 1998.
- [21] L. Young, RFQGen user guide, Technical report version 5.13, 2021.
- [22] S. Y. Lee, *Accelerator Physics*, 4th ed. (World Scientific Publishing Company, Singapore, 2018).
- [23] T. P. Wangler, *RF Linear Accelerators*, 2nd ed. (Wiley-VCH, Weinheim, 2008).
- [24] J. Billen and L. Young, Poisson Superfish, Technical Report No. LA-UR-96-1834, LANL, 2005.
- [25] CST Microwave Studio: Workflow & solver overview, Technical report, CST-GmbH, 2016.
- [26] J. C. Cai, Q. Z. Xing, X. L. Guan, and L. Du, Design of undercuts and dipole stabilizer rods for the CPHS RFQ accelerator, *Chin. Phys. C* **36**, 464 (2012).
- [27] D. Uriot and N. Pichoff, TraceWin documentation, Technical Report, CEA Saclay, 2022.
- [28] Q. Z. Xing, X. D. Yu, Q. K. Guo, P. F. Ma, Y. Lei, S. X. Zheng, Y. Li, S. Wang, K. Liu, X. L. Guan, X. W. Wang, B. C. Wang, C. Zhao, and Z. M. Wang, Field tuning and rf measurements of the four-vane radio frequency quadrupole with ramped inter-vane voltage, *Phys. Rev. ST Accel. Beams* **22**, 020102 (2019).
- [29] L. Du, Q. Z. Xing, S. X. Zheng, X. L. Guan, and C. X. Tang, A fast tuning method for a RFQ accelerator with ramped inter-vane voltage, *Nucl. Instrum. Methods Phys. Res., Sect. A* **726**, 91 (2013).