A Particle-in-cell scheme of the RFQ in the SSC-Linac*

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Abstract A 52 MHz Radio Frequency Quadrupole (RFQ) linear accelerator (linac) is designed to serve as an initial structure for the SSC-Linac system (injector into Separated Sector Cyclotron). The designed injection and output energy are 3.5 keV/u and 143 keV/u, respectively. The beam dynamics in this RFQ have been studied using a three-dimensional Particle-In-Cell (PIC) code BEAMPATH. Simulation results show that this RFQ structure is characterized by stable values of beam transmission efficiency (at least 95%) for both zero-current mode and the space charge dominated regime. The beam accelerated in the RFQ has good quality in both transverse and longitudinal directions, and could easily be accepted by Drift Tube Linac (DTL). The effect of the vane error and that of the space charge on the beam parameters have been studied as well to define the engineering tolerance for RFQ vane machining and alignment.

Key words RFQ, PIC mode, parameters sweep analysis, manufacturing error, space charge effect

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1 Introduction

The present injector of the Heavy Ion Research Facility of Lanzhou (HIRFL) contains the Sector Focusing Cyclotron (SFC) together with the Separated Sector Cyclotron (SSC) to accelerate the heavy ions before injection into the Cooler Storage Ring (CSR) [1]. This arrangement is no longer able to meet the growing experimental requirements.

If a linear accelerator is added to the HIRFL-CSR system to serve as the injector for the SSC, the actual beam time available for experiments will grow substantially during the HIRFL-CSR's operation. The SSC-Linac system could supply Ca, Zn, and Fe ion beams with energies from 5 MeV/u to 6 MeV/u for Super Heavy Element experiments. The beam intensity is expected to be around 1 pμA. Additionally, it is suggested to inject all kinds of heavy ion beams with energy of 10 MeV/u into the CSR. In this mode of operation, the beam intensity is expected to be around 1 eμA (for uranium). As a part of SSC-Linac, Fig. 1 is the concept design of SSC-Linac, the 52 MHz RFQ has been designed and extensively simulated by the PARMTEQ-M code [2], and crosschecked by the BEAMPAH code [3], which has been developed based on the PIC method.

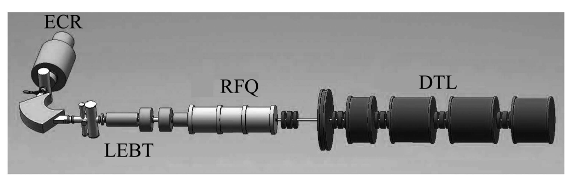

Fig. 1. The conceptual design of SSC-Linac.

2 RFQ beam dynamics

2.1 The specifications and choice of parameters

The RFQ structure is supposed to be used for the acceleration ion beam from 3.5 keV/u to 143 keV/u. It has been specified to have a length shorter than

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3 m and to be placed downstream of the Low Energy Beam Transport (LEBT). The designed frequency is chosen to be 52 MHz.

Since the injection energy is relatively low (3.5 keV/u), the short electrodes are chosen to bunch the beam. This option will increase the beam energy spread in the accelerator section. The bunching process results in an increase in beam density, which, in turn, increases the space charge force, and might result in the blow-up of the beam transverse emittance. In order to overcome the space charge effect, the gradient of acceleration has to be enhanced rapidly. The main parameters of the RFQ are listed in Table 1, and their evolutions along the structure are shown in Fig. 2.

Table 1. Parameters of the RFQ for U^{34+}.

parameters	value
input energy	3.5 keV/u
output energy	143 keV/u
RF frequency	52 MHz
Max. current	0.5 mA
Max. surface field	13.40 MV/m
RFQ length	251.01 cm
inter-vane voltage	68 KV
Max. modulation	1.966
final synchronous phase	−27°

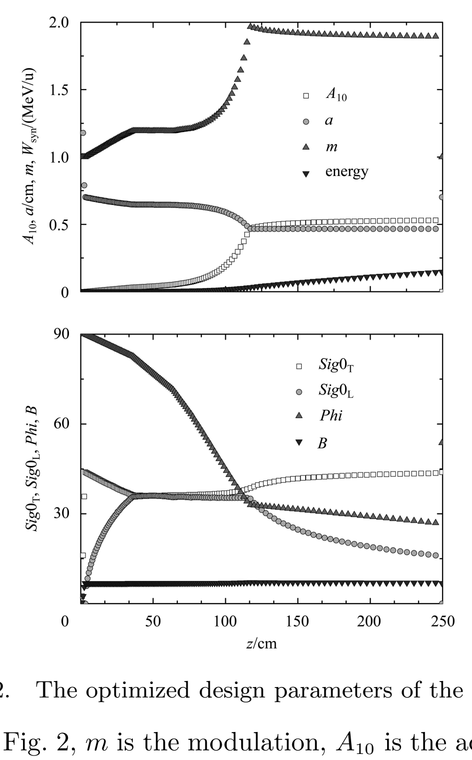

Fig. 2. The optimized design parameters of the RFQ.

In Fig. 2, m is the modulation, A_{10} is the accelerating term, a is the minimum radial aperture, $W_{\rm syn}$ is the energy, Phi is the synchronous phase, $Sig0_{\rm T}$ is the transversal phase advance, $Sig0_{\rm L}$ is the longitudinal phase advance and B is the focusing parameter.

2.2 PIC mode simulation

The initial design of the RFQ linac is made with the standard approach using the PARMTEQ-M code. The beam dynamics simulation was performed using BEAMPATH code with a beam represented as a collection of 20000 macro-particles.

The RFQ is designed to capture, bunch, and accelerate a continuous unbunched beam. However, to increase the longitudinal capture efficiency of the RFQ before injection into the cyclotron, a pre-bunching of the continuous beam in the Low Energy Beam Transport (LEBT) is required. The LEBT beam dynamics simulation indicates that the pre-bunching of the continuous beam reduces the total phase width of the beam at the entrance of the RFQ from 360° to 90°. The value of the momentum spread of the beam in this case will be increased from 0.01% to 1%. Parameters of the initial beam are listed in Table 2. Two different versions of the beam injector are compared.

Table 2. Initial beam parameters.

parameters	value
input energy	3.5 keV/u
emittance	0.1 πcm·mrad
distribution	water-bag
α_x and α_y	1.02
β_x and β_y	4.24 cm/rad
momentum spread	0.01% or 1%
phase width	360° or 90°

Figure 3(a) illustrates the continuous beam injection into the RFQ with the beam momentum spread of 0.01%. Fig. 3(b) demonstrates the particle distribution with 90° phase width and 1% momentum spread in the bunched beam injection mode. Fig. 3(c) shows the final particle distribution under continuous beam injection. The transmission efficiency of 93.6% is achieved in this operation mode. In this case the beam losses are mostly concentrated on the gentle buncher section of the RFQ. Fig. 3(d) illustrates the particle distribution at the exit of the RFQ in the bunched beam injection mode. In the latest case, the beam transmission efficiency is close to 100%, the phase width of the extracted beam from the RFQ is 7.5°, and the final momentum spread is about 0.7%. The quality of the beam in the longitudinal phase space in this case is substantially better than that under the continuous beam injection.

Additional beam dynamics simulation was done using BEAMPATH code to optimize the RFQ with respect to the transmission, beam quality and emittance growth. Fig. 4 illustrates the variation in optimized beam parameters along the RFQ.

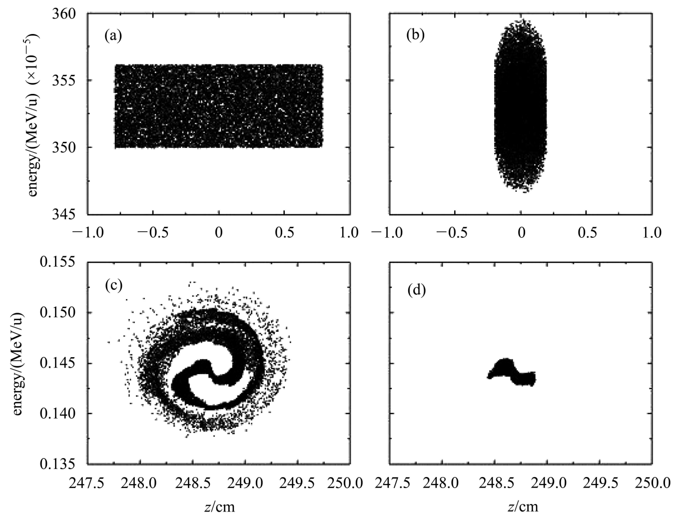

Fig. 3. (a) is the particle distribution in z-energy space at the entrance of the RFQ for the continuous beam; (b) is the particle distribution in z-energy space at the entrance of the RFQ for the bunched beam; (c) is the particle distribution in z-energy space at the exit of the RFQ for the continuous beam; and (d) is the particle distribution in z-energy space at the exit of the RFQ for the bunched beam.

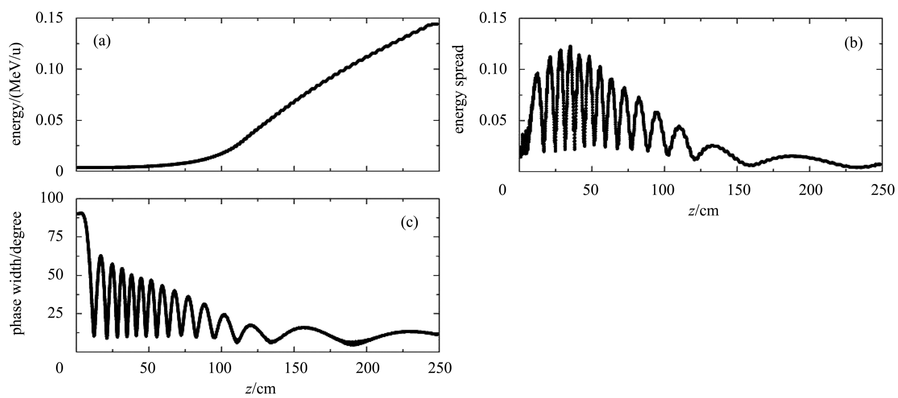

Fig. 4. (a) is the energy increase along the RFQ; (b) is the variation in energy spread along the RFQ; and (c) is the variation in phase width along the RFQ.

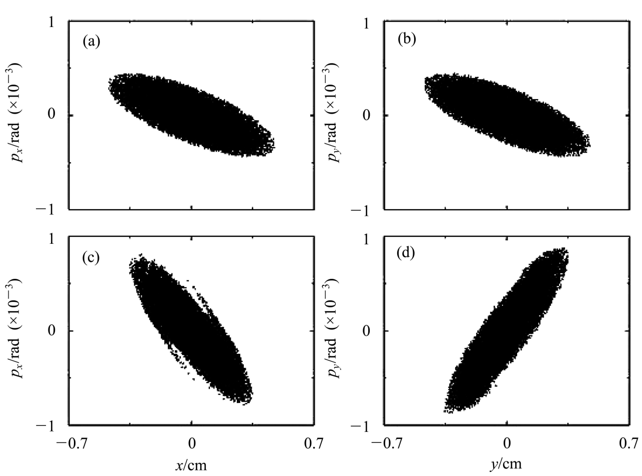

Fig. 5. The initial phase space plot in the horizontal direction (a) and in the vertical direction (b), and the final phase space plot in the horizontal direction (c) and in the vertical direction (d).

Figure 5 demonstrates initial and final transverse particle distributions in the RFQ. Let us note that the value of the initial beam emittance of 0.1 πcm·mrad was taken larger than that of the ECR ion source (0.06 πcm·mrad). This gives us a safety margin to cope with the misalignments and the mismatches of the ECR ion source.

3 Effects of beam mismatch on transmission efficiency and emittance growth in the RFQ

Unmatched conditions for the injected beam result in additional oscillations of the beam in the focusing structure [4]. The mismatch error is the reason for the decrease in beam transmission efficiency and the beam emittance growth. In the process of the transverse parameter sweep, the phase width of 90 degrees and momentum spread of 1% were fixed. The beam envelope $R_x=\sqrt{\beta_x\epsilon_x}$ and the tilt of the envelope

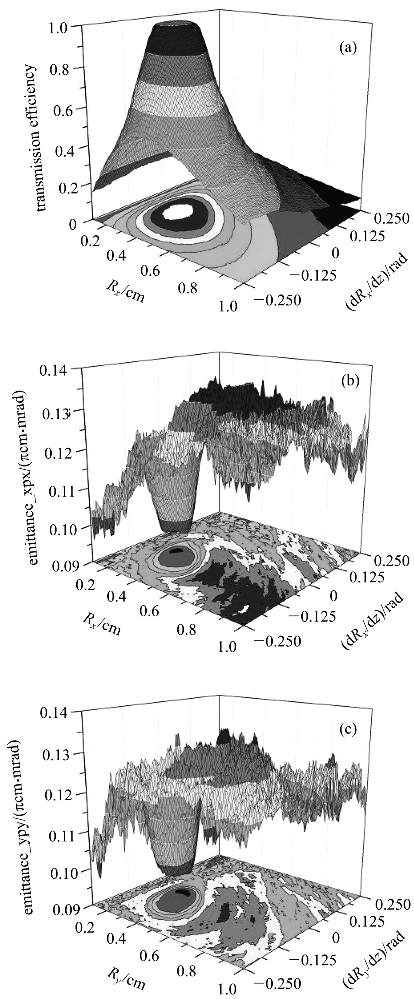

Fig. 6. The variation in the transmission efficiency and beam emittance growth due to mismatch of the injecting beam with the RFQ.

$dR_x/dz=-\alpha_x\sqrt{\epsilon_x/\beta_x}$ varied in the vicinity of the matching points. The same produce was done in the vertical direction. The transmission efficiency and the beam emittance were calculated as a function of initial beam conditions in order to test the tolerance of the mismatch error.

Figure 6(a) shows the dependence of the transmission efficiency on the variation of the initial beam parameters. The transmission efficiency reaches the value of 95% and more, while R_x changes from 0.25 cm to 0.55 cm and dR_x/dz varies from 0 rad to −0.185 rad. Fig. 6(b) and Fig. 6(c) illustrate the final RFQ beam emittance due to the variations in initial beam parameters. The study indicates that if the initial values of R_x and dR_x/dz vary in the area with high transmission efficiency, no significant beam emittance growth is observed. When the initial values of $R_x$and dR_x/dz are outside this region, serious emittance growth takes place.

4 Decrease in transmission efficiency due to vane manufacturing error and beam space charge effect

Random error in the manufacturing of RFQ vane tips result in the amplitude growth of the transverse and the longitudinal oscillations [5]. Analytical treatments show monotonous enlargement of the transverse oscillation amplitude $r_{\max}$ and vertical size of the separatrix $\langle\Delta g\rangle=\langle\Delta P\rangle/v_{\rm s}$ after passing through the RFQ section with N cells,

$$\langle\delta r_{\max}\rangle^2 = 2N\left[\langle\delta r_0\rangle^2+r_{\max}^2\left(\left\langle\frac{\delta U}{U}\right\rangle^2+4\left\langle\frac{\delta R_0}{R_0}\right\rangle^2\right)\right], \quad (1)$$

$$\langle\Delta g\rangle^2 = \pi^2\left(\frac{\Omega_{\rm f}}{\omega}\right)^2\left(\frac{E_0}{\Delta E}+N\right)\left\{\left(\frac{\Omega_{\rm f}}{\omega}\right)^2{\rm ctg}^2\phi_n\times\left(1-\sqrt{\frac{E_0}{E_{\rm f}}}\right)\left(\frac{\langle\delta A\rangle^2}{A^2}+\frac{\langle\delta U\rangle^2}{U^2}\right)+\frac{1}{3}\left[1-\left(\frac{E_0}{E_k}\right)^{\frac{3}{2}}\right]\frac{\langle\delta L\rangle^2}{L^2}\right\}, \quad (2)$$

where δr_0 is the axis displacement, δR_0 is the error in the average radius of the structure $R_0=a/\sqrt{x}$, δL is the error in cell length, δU is the inter-vane voltage instability, $\Omega_{\rm f}$ is the longitudinal oscillation frequency, ω is the RF frequency, E_0 and $E_{\rm f}$ are initial and final particle energy, A is the acceleration efficiency and ϕ is the synchronous phase. To study this effect via BEAMPATH simulation, the following parameters were randomly distributed at every cell within the max error $\pm\delta$: cell length L_i, aperture a_i, max distance from axis to electrodes ma_i and axis displacement $\delta r_{0,i}$.

According to the simulation (see Table 3), the error of 50 μm does not create any serious degradation of the beam parameters while the error of 100 μm could cause a notable decrease in the beam transmission efficiency. During the manufacturing process, the engineering tolerance of 50 μm is thus adopted for vane tip fabrication.

The particle trajectories were calculated using 100 steps per cell in the field, which is the combination of the RFQ, potential and self field of the train of bunches. The space charge field was found at each time step from the three-dimensional Poisson's equation on the mesh with the Dirichlet boundary conditions for the potential on the surface of the square and the periodic conditions in the longitudinal direction. Fig. 7 shows particle trajectories with a manufacturing error of (a) 0 μm, (b) 50 μm and (c) 100 μm at a current of 0 mA.

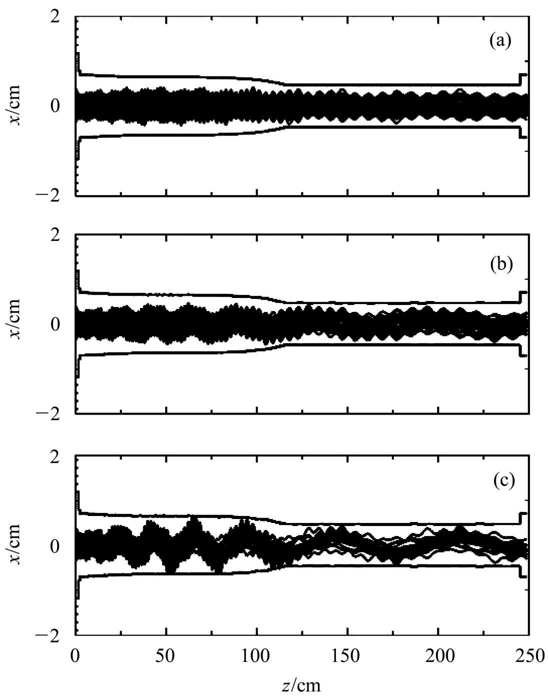

Fig. 7. The particle trajectories with manufacturing error of (a) 0 μm, (b) 50 μm and (c) 100 μm at a current of 0 mA.

Operation of the RIKEN RFQ linac under similar conditions indicates that 90% of the transmission efficiency is obtained steadily following this simulation [6].

Table 3. Transmission efficiency in the RFQ with a manufacturing error of 0 μm, 50 μm, and 100 μm at a beam current of 0 mA, 1 mA and 2 mA, respectively.

δ/μm	Transmission efficiency		
	I=0 mA	I=1 mA	I=2 mA
0	1.0000	0.9995	0.9760
50	0.9810	0.9975	0.9520
100	0.6035	0.6700	0.6920

5 Conclusion

Simulation of the RFQ dynamics via BEAMPATH code is similar to the results of the PARMTEQ-M code, and the beam from the RFQ could be accepted smoothly by the DTL linac. The parameter sweep analysis has been done to test the RFQ acceptances in both the transversal and the longitudinal directions. The influence of the transmission efficiency, which is caused by the vanes manufacturing error and the space charge effect, has been studied to confirm the engineering tolerance. The beam transmission efficiency and the emittance growth are not sensitive to the beam current when the current is lower than 2 mA and the beam dynamics are not strongly influenced by the space charge effect.

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