Beam Dynamics Design of a 50 mA D^+ RFQ *

Fang-Jian Jia(贾方健)[1], Kun Zhu(朱昆)[1**], Yuan-Rong Lu(陆元荣)[1**], Zhi Wang(王智)[1], Zhi-Yu Guo(郭之虞)[1], Qi Fu(傅琪)[1], Yuan He(何源)[2]

[1]*State Key Lab of Nuclear Physics and Technology, Peking University, Beijing 100871*
[2]*Institute of Modern Physics, China Academy of Sciences, Lanzhou 730000*

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A new 973 project was proposed by Peking University and Institute of Modern Physics of Chinese Academy of Sciences recently. The project requires a 50 mA, 162.5 MHz, cw mode radio frequency quadrupole (RFQ) to accelerate the D^+ to 1 MeV. In a high-current linear accelerator, the strong space charge effect causes the growth of envelope and emittance along with heavy beam losses. In the beam dynamics design of this RFQ, beam envelope mismatching is discussed and a matching dynamics method is proposed to minimize the envelope and emittance growth. The influence of limiting current on the beam transmission is discussed and used in the optimization of transverse and longitudinal parameters. After the optimization, the beam transmission efficiency reaches higher than 98%.

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Radio frequency quadrupole (RFQ) accelerators have been applied as injectors in high-current linear accelerators due to their remarkable capability of simultaneously transverse focusing, longitudinal bunching and accelerating. However, in high-current linacs, due to the influence of strong space charge effect, the beam properties and transmission efficiency become worse, which challenges the beam dynamics design and operations of high-current RFQ accelerators. Therefore, this project aims to investigate the envelope and emittance growth by the dynamics design of this 50 mA cw mode D^+ RFQ. The beam dynamics design method used in this project is based on traditional four-section procedure, and variable transverse focusing strength is applied to realize envelope matching and to reduce the emittance growth. The influence of limiting current on the beam transmission efficiency is also discussed in detail during the beam dynamics design.

The dynamics simulation of this RFQ was carried out by the code of PARMTEQM,[1] which was developed at Los Alamos National Laboratory and widely applied to designs of many RFQs. According to the code, the whole RFQ is divided into four sections: radial matching (RM), shaper (SH), gentle buncher (GB) and acceleration section (ACC).[2] Since the beam current of this cw RFQ is quite high, the input energy of ions should not be set too low. If not, the strong space charge effect would reduce the beam transmission efficiency. Conversely, too high input energy would lead to a gentle buncher section that is too long. Finally, the input energy of the beam was set as 50 keV according to the experience of IFMIF,[3] SARAF,[4] PKUNIFTY[5] and other projects. To reduce sparking risks, the inter-vane voltage was chosen as 60 kV. Beam dynamics parameters in the traditional four-section procedure are shown in Fig. 1, where B is the radial focusing strength, $a_{\rm p}$ is the minimum radial aperture, $\varphi_{\rm s}$ is the synchronous phase, m is the vane modulation factor, and W is the kinetic energy of the synchronous particle. From Fig. 1, it can be seen that in the traditional design method the parameters change sharply from one section to the next. In high-current linacs the dynamics parameters should be kept as smooth as possible to avoid beam loss and emittance growth. Therefore, the parameters need to be optimized in the beam dynamics design.

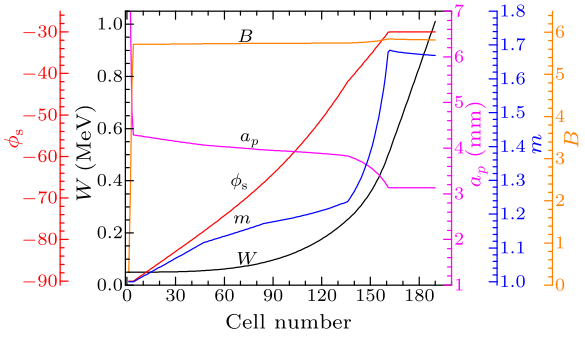

Fig. 1. Beam dynamics parameters in the original design.

For a matched input dc beam, according to the smooth approximation, the transverse radius of the matched beam meets the envelope equations[6]

$$\sigma_{\rm t}^2 = \sigma_{0\rm t}^2 + \Delta_{\rm sc} = \left(\frac{B^2}{8\pi^2} + \Delta_{\rm rf}\right) + \Delta_{\rm sc},$$
$$\varepsilon_{\rm tn} = \frac{a^2\sigma_{\rm t}\gamma}{\lambda}, \quad (1)$$

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**Corresponding author. Email: zhukun@pku.edu.cn; yrlu@pku.edu.cn
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where σ_t and σ_{0t} represent the transverse phase advance with and without beam current, respectively, B is the radial focusing strength, Δ_{rf} and Δ_{sc} are defocusing parameters of rf and space charge (sc) respectively, ε_{tn} is the transverse normalized rms emittance, a is the transverse beam radius, γ is the relativistic mass factor, and λ is the rf wavelength. In an RFQ accelerator, the rf defocusing parameter Δ_{rf} is described as $\Delta_{rf} = \pi^2 qeAV_0 \sin\varphi_s/(2\gamma m_0 c^2 \beta^2)$, where q is the charge state of ion, A is the accelerating factor, V_0 is the inter-vane voltage, φ_s is the synchronous phase, m_0 is the particle mass, γ is the relativistic mass factor, e is the charge of an electron, and β is the ratio of particle velocity to the speed of light. From the formula of Δ_{rf}, it can be obtained that with the increase of the accelerating factor A, the value of $|\Delta_{rf}|$ increases. As $\varphi_s < 0$ and B is kept as a constant, from RM to ACC in the RFQ we can obtain from Eq. (1) that σ_t becomes weaker with the increase of A. This means that the external force is not strong enough to focus the beam in the transverse plane, which leads to beam envelope growth and emittance growth.[7] Figure 2 shows the beam envelope and emittance growth in the original design. It is obvious that the envelope has a large oscillation in the original design and the beam radius range from 0.9 to 1.3 mm. Especially from cell 50 to cell 120, the envelope grows most and the emittance has a large growth in this region simultaneously.

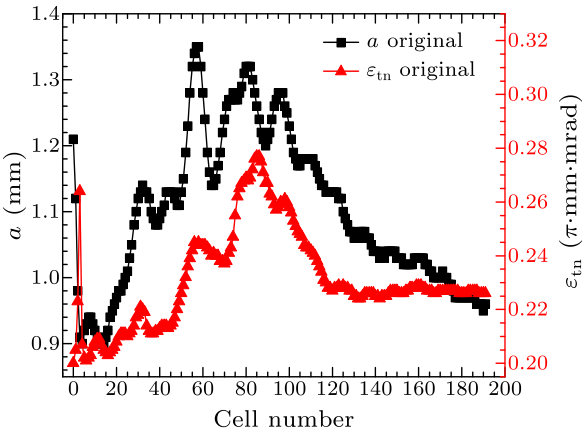

Fig. 2. Beam envelope a and emittance ε_{tn} growth in the original design.

To mitigate the oscillation of the envelope, the mid-cell radial aperture r_0 is changed along the z-direction in the optimized design (as shown in Fig. 3). Compared with the original design, the focusing parameter B is increased when the envelope is rising, which happens in the region when particles are transferred from SH to GB. The increased B helps to strengthen the external focusing force to reduce the envelope growth. On the contrary, from GB to ACC, B is minimized where the envelope falls and the longitudinal accelerating efficiency would be increased correspondingly. The beam envelope is kept around 0.95 mm in the optimized design and the emittance growth is also significantly reduced compared with the original design (Fig. 4).

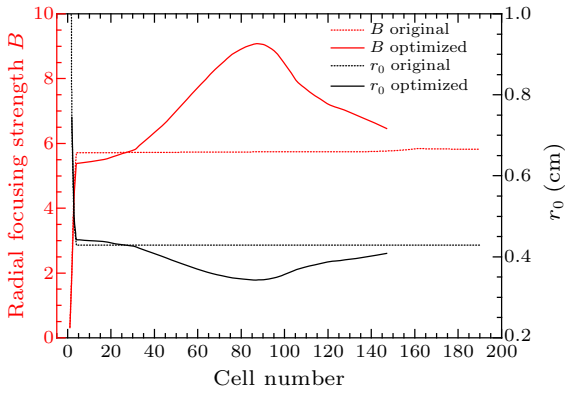

Fig. 3. Transverse focusing strength B and mid-cell radial aperture r_0 in the original and optimized design.

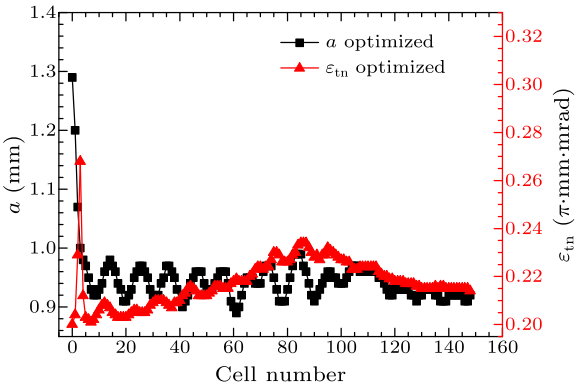

Fig. 4. Beam envelope a and emittance ε_{tn} growth in the optimized design.

For a given synchronous phase and accelerating field, the transverse and longitudinal limiting current can be written as[8]

$$I_{lim,t} = \frac{a^2(\gamma b)\gamma^2\sigma_{0t}^2}{\lambda^3 k(1-F)},$$
$$I_{lim,l} = \frac{a^2(\gamma b)\gamma^2\sigma_{0l}^2}{2\lambda^3 kF}, \quad (2)$$

where a and b are the transverse and longitudinal rms beam radii, respectively, $F \approx a/3\gamma b$ is the ellipsoid form factor, and $k = (3\times10^{-6}/8\pi)(Z_0 q/mc^2)$ with $Z_0 = 1/\varepsilon_0 c = 376.73\,\Omega$ being the free-space impedance. The limiting current, which is chosen to be larger than the design current including a safety margin for errors,[9] can be used as a basis for the optimized RFQ-linac design. Equation (2) shows that there is a positive correlation between zero current phase advance σ_0 and the limiting current. Therefore, the limiting current can be improved by increasing the value of phase advance, which is applied in

the optimized design of this project. In the RFQ, the transverse focusing force is always larger than the longitudinal bunching force, which leads to a result that $I_{\mathrm{lim,t}}$ is larger than $I_{\mathrm{lim,l}}$. Thus the improvement of the longitudinal limiting current should be paid more attention in the beam dynamics design. In the optimized design, the longitudinal modulation factor m and the synchronous phase φ_{s} are improved. Figure 5 shows the comparison of parameters m and φ_{s} in the original and optimized designs. After they are optimized, both m and φ_{s} grow slower than the original design in the entrance from cell 1 to cell 60. This helps the beam focus well in the transverse direction and guarantees a wide stable region for the phase motion which contributes lower longitudinal beam loss. Starting from cell 60, where particles have reached the GB section, both m and φ_{s} grow more quickly than the previous period to improve the longitudinal bunching force. From Fig. 6 we can see that after optimizing, the longitudinal limiting current in the GB and ACC sections is much improved and the intensities of $I_{\mathrm{lim,t}}$ and $I_{\mathrm{lim,l}}$ are larger than the design current of 50 mA in this part, which guarantees good beam transmission and lower beam loss.

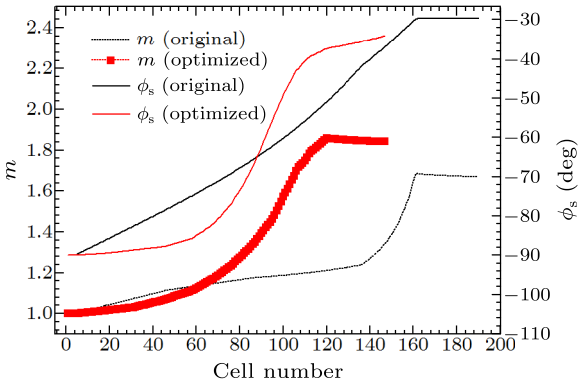

Fig. 5. Comparison of the modulation factor m and synchronous phase φ_{s} in the original and optimized designs.

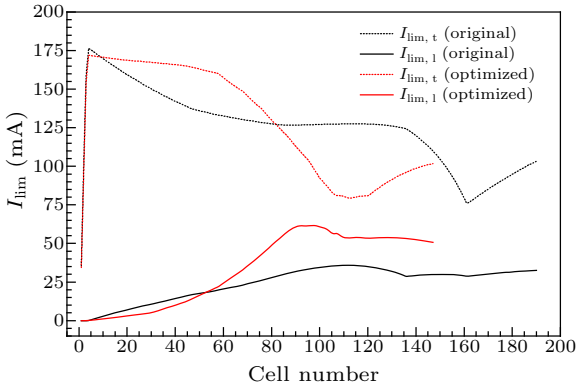

Fig. 6. Comparison of the transverse and longitudinal limiting current in the original and optimized designs.

Based on the above optimized design method, the beam transmission efficiency is improved to 98.2%. The maximum peak surface electric field is 22.74 MV/m, which equals to $1.67E_k$, and meets the criterion of Kilpatrick that the maximum peak surface electric field should not be larger than $1.8E_k$.[10,11] Table 1 shows the optimized beam dynamics parameters.

Table 1. Design parameters of this RFQ.

Parameters	Value
Particle	D^+
Frequency (MHz)	162.5
Beam current (mA)	50
Beam duty factor (%)	100
Inter-vane voltage (kV)	60
Input energy (MeV)	0.05
Output energy (MeV)	1.01
Minimum aperture radius (mm)	2.63
Vane length (m)	1.79
Synchronous phase (deg)	−90−−34
Modulation factor	1–1.86
Transverse input emittance (πmm·mrad)	0.20
Transverse output emittance (πmm·mrad)	0.22
Longitudinal output emittance (MeV·deg)	0.12
Maximum peak surface electric field (MV/m)	22.74
Kilpatrick coefficient	1.67
PARMTEQM Transmission efficiency (%)	98.2

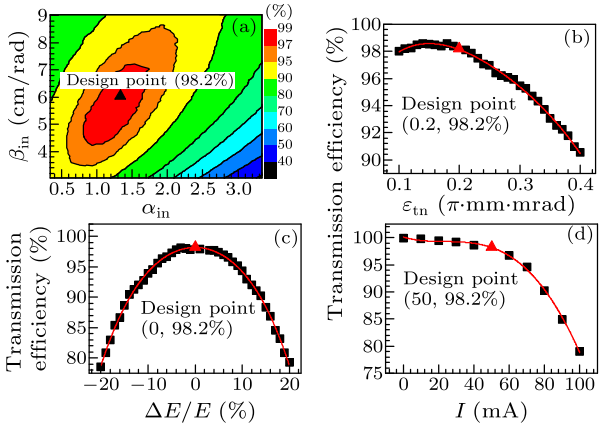

Fig. 7. Transmission efficiency versus input (a) the Twiss parameters, (b) emittance, (c) energy spread and (d) beam current.

In practice, due to the unavoidable errors in fabrication, assembling precision and operating environment, tolerance analyses should be studied to verify the reliability of the design results. A number of error types are considered and studied in this optimized design, including the input Twiss parameters, emittance, energy spread and beam current. The transverse beam quality at the entrance of the RFQ has a significant influence on the beam transmission efficiency,[12] which is plotted as a function of the Twiss parameters α and β in Fig. 7(a). For different input emittances, too high input emittance would lead to the large emittance growth which causes lower transmission efficiency. On the contrary, if the input emittance is too low, the strong space charge effect between particles would also cause beam loss and influence beam transmission. In

the optimized design, the normalized rms transverse input emittance is set as $0.2\,\pi$mm·mrad (as shown in Fig. 7(b)). For different input energy spreads and beam currents, there is also a wide redundancy for beam transmission in this design as shown in Figs. 7(c) and 7(d).

In summary, beam dynamics design of this 162.5 MHz, 50 mA RFQ provides a feasible method to optimize the beam transmission in the high-current RFQ. Based on the traditional four-section procedure, the radial focusing strength B is not kept as a constant but varies with the variable space charge forces along the RFQ to keep the beam stay in the state of matching in the optimized design. Furthermore, the longitudinal limiting current is optimized through the improvement of modulation factor and synchronous phase. The transmission efficiency is increased to 98.2% and the length of the RFQ is shortened from 2.44 m to 1.79 m. A number of error types are considered, which can verify that the design parameters are reliable. The rf structure has been designed based on this beam dynamics design and we will start the fabrication of the RFQ cavity soon.

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