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DESIGN OF BEAM DYNAMICS FOR A HIGH-POWER DC PROTON ACCELERATOR AT THE MeV LEVEL*

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Abstract

This paper aims to design the beam dynamics of a MeV-level high-power DC proton accelerator for use in high-voltage accelerators. The high-power proton accelerator has essential applications such as ion implantation equipment, neutron therapy equipment, and accelerator-based neutron source equipment. With the increasing use of high-voltage generators due to their stable and reliable operation, these accelerators have gained significant popularity in the field. The paper discusses the design considerations of the accelerator equipment, including the functions and requirements of the acceleration tube, electric field distribution, and voltage holding issues. Additionally, the paper focuses on the design aspects of beam optics, encompassing topics such as electric field distribution, beam focusing, beam transmission, divergence, and the impact of space charge effects on beam quality. Calculations and optimizations are performed based on the parameters and requirements specific to high-voltage accelerators. Finally, the paper presents and analyzes the results of the accelerator tube and beam optics design.

INTRODUCTION

MeV-level proton accelerators, as powerful and versatile particle acceleration devices, play a significant role in various industries, scientific research, and medical applications. In the industrial sector, MeV-level proton accelerators are widely utilized in material processing and surface treatment techniques, enabling high-energy material modification and ion implantation processes. In the field of scientific research, MeV-level proton accelerators provide robust tools for nuclear physics and particle physics investigations. In the medical domain, MeV-level high-power DC proton accelerators generate high-power proton beams that produce neutrons through target interactions. These neutrons are utilized in Boron Neutron Capture Therapy (BNCT) for targeted tumor radiation treatment. For MeV-level high-power DC proton accelerators operating with a single-ended electrostatic acceleration scheme, beam optics design becomes particularly crucial.

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DESIGN ISSUES OF ACCELERATOR TUBES

Beam Parameters of the Incident Ion Beam in the Accelerator Tube

Based on the output characteristics of the high-current DC microwave ion source [1-3], the beam parameters of the incident ion beam in the accelerator tube can be set as shown in the Table 1.

Table 1: Parameters of the Incident Beam at the Entrance of the Accelerator Tube

Parameters	Value
Emittance ε	0.5 π mm mrad
α	0.2
β	0.4 mm/mrad
Spot diameter	4 mm

The Space Charge Effect of the Ion Beam

As the current passing through the accelerator tube increases, the effect of space charge becomes more significant, leading to an increase in the radius of the ion beam and a deterioration in the focusing properties of the accelerator tube system. Consequently, more current is lost on the electrodes, resulting in a sharp increase in the load on the accelerator tube due to secondary electrons. The simulation results for proton beams with beam currents of 0.1 mA, 1 mA, and 15 mA, initial energy of 40 keV, and a 1 cm beam spot radius drifting in an infinite space are shown in Figure 1.

The radial potential distribution of the ion beam is a crucial aspect of the accelerator's beam dynamics, as shown in Figure 2. It describes the variation of electric potential across the radial dimension of the ion beam.

Considering the ion beam to be infinitely long and axially symmetric, the potential distribution function generated by space charge is determined by the following equation.

$$U(r)=\begin{cases}\dfrac{\rho r_b^2}{4\varepsilon_0}\left[1+2\ln\left(\dfrac{R}{r_b}\right)-\left(\dfrac{r}{r_b}\right)^2\right], 0\le r\le r_b\\[2ex] \dfrac{\rho r_b^2}{4\varepsilon_0}\ln\left(\dfrac{R}{r_b}\right), r_b\le r\le R\end{cases} \quad (1)$$

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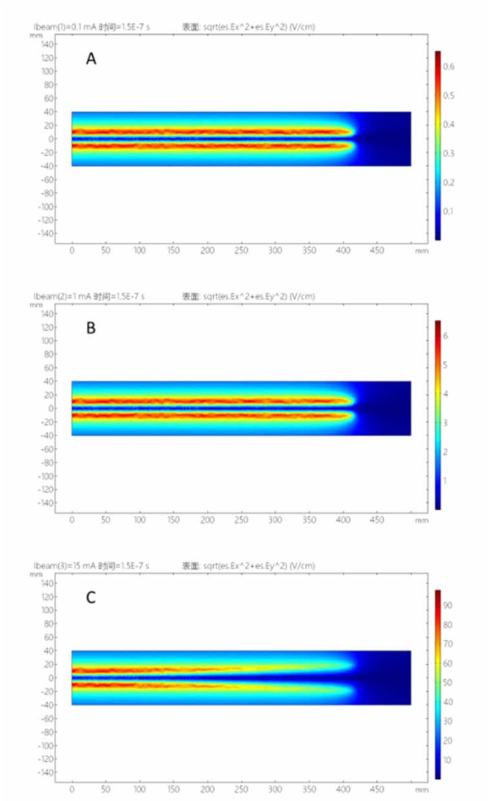

Figure 1: The radial electric field distribution.

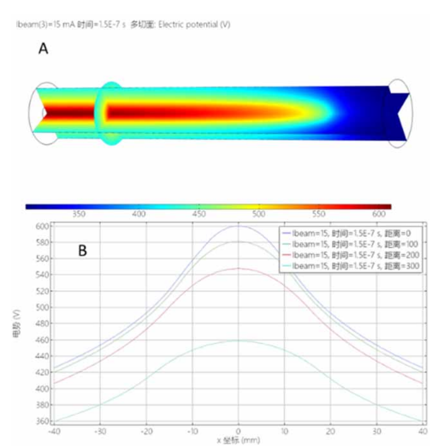

Figure 2: Radial Potential Distribution of the Ion Beam.

The r_b represents the beam radius, ρ is the spatial charge density distribution, and $\rho = I/\pi r_b^2 v$, where v is the velocity of particles in the beam.

In practical calculations, the beam divergence needs to be taken into account, and r_b will gradually increase along the direction of beam propagation. In the simulation process, the beam divergence has already been considered. The electric field generated by the space charge on the beam axis is E(0) = 0. The radial electric field distribution caused by the space charge is shown in Figure 1.

The charged beam simultaneously generates a spatial distribution of the magnetic field. The magnetic force acting on particles due to this magnetic field is relatively small compared to the electric force. Therefore, it can be neglected in subsequent calculations.

Beam Divergence Caused by Space Charge

As mentioned earlier, higher beam currents generate significant electric and magnetic fields. The electric field force due to space charge always leads to beam divergence, while the magnetic field force from space charge has a certain axial converging component. For slow-moving particles at the head of the accelerator, the magnetic field force is relatively weak compared to the dominant electric field force. Consequently, the beam at the head of the accelerator exhibits a stronger tendency to diverge. For smaller parallel beams, such as a 0.1 mA proton beam, the particles only deviate by 0.06 mm from their initial positions after a free-space drift of 400 mm. However, as the current increases to 15 mA, the deviation of particles from their initial positions at the end of the drift will reach 8 mm. Therefore, in the design of the head section of the accelerator, a strong focusing force is required to mitigate the spatial divergence effect for high-current low-energy beams.

ACCELERATOR TUBE AND BEAM OPTICS DESIGN

High-current Accelerator Tube System

As the effect of space charge increases, the radius of the ion beam also increases, deteriorating the system's focusing properties. Consequently, the beam collision on the electrodes increases, and the load on the accelerator tube sharply rises due to the secondary electrons generated. The vacuum conditions of the accelerator tube also deteriorate due to the increased flow of neutral gas generated by the ion source. To maintain a stable voltage on the tube section despite the increased leakage current, the current passing through the voltage-divider resistors should be increased. Among the lens electrodes in the uppermost part of the accelerator tube, the double-cylinder lens has the highest voltage ratio, which also has the most significant impact on the overall focusing characteristics.

The Particle's Motion Equation and Focusing System

In the high-voltage accelerator tube's electric field, the radial motion equation of particles is as follows, where r represents the radial coordinate of the particle, z is the axial coordinate, and ρ is the spatial charge density. In different regions of the accelerator tube, the variation of electric field gradients is not uniform, and the entire optical electric field gradients have different Q-value regions along the axial direction. When Q > 0, the focusing effect of the externally applied electric field is greater than the divergent effect of the space charge. When Q < 0, the divergent effect of the space charge field predominantly affects the beam. When Q ≈ 0, the focusing effect of the external electric field is essentially balanced with the divergent effect of the space charge field, and the radial size of the beam remains unchanged.

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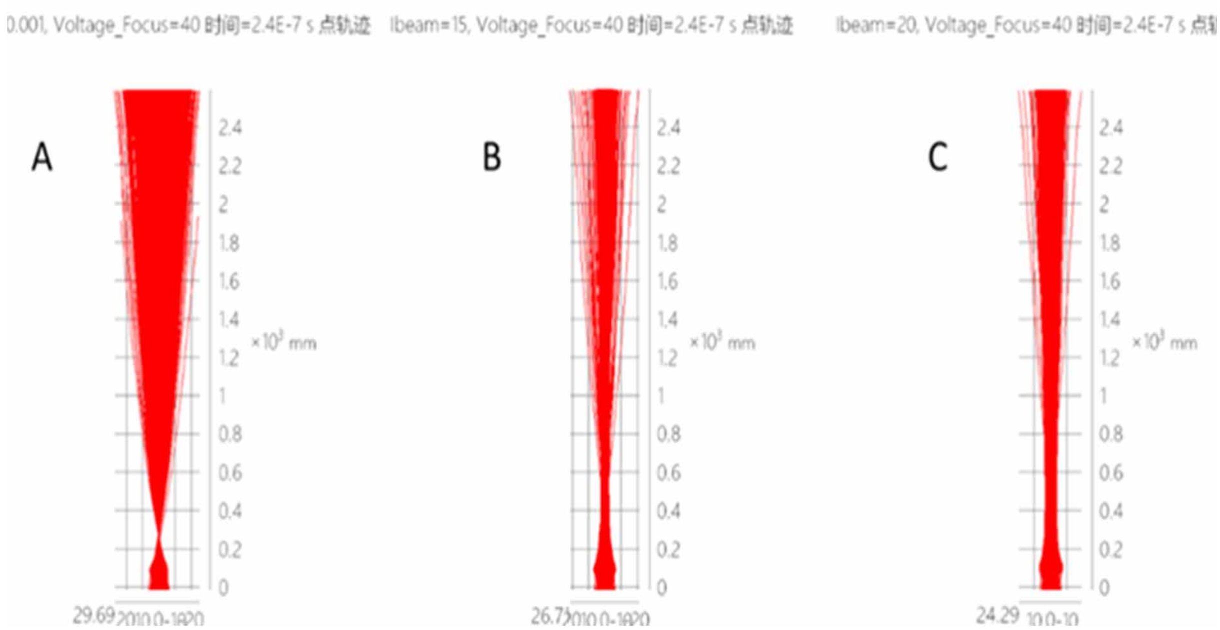

Figure 3: 2.5 MeV Proton Beam, A–0.001mA, B–15mA, C–20mA.

$$r'' + \frac{U'}{2U}r' + \frac{1}{4U}\left(U'' + \frac{\rho}{\varepsilon_0}\right)r = r'' + \frac{U'}{2U}r' + \frac{Q}{4U}r = 0 \qquad (2)$$

By placing optical elements at different positions in the accelerator tube, it is possible to create an axial electric field gradient distribution that satisfies the beam's passage. This gradient distribution can be obtained by establishing a full-size simulation model. In general, in the forward direction of the beam, in addition to the initial focusing system, compensation for the accelerator system's aberration should also be designed.

The design approach of the initial focusing system is to adjust its parameters, such as the focusing voltage VF, when the space charge effect caused by the ion beam's current affects the characteristics of the initial focusing system. By doing so, the image point can be brought back to the desired position, and the focusing system can be in a matched state. This kind of system typically employs a single lens, where the focusing characteristics of the initial focusing system can be adjusted by changing the potential of the middle electrode without affecting the characteristics of other lenses adjacent to it in the front and rear.

The focusing compensation of the acceleration system can be achieved using either magnetic lenses or electrostatic lenses. If electrostatic lenses are used, the potential distribution inside the acceleration tube can be utilized to set potentials on the internal electrodes of the tube, allowing the addition of several individual lenses within the acceleration tube. These individual lenses can provide focusing compensation for the ion beam inside the acceleration tube [4, 5].

RESULT

The envelope calculations of the beam for different current intensities are shown in the Figure 3. Since the focusing system of the accelerator's electrode is optimized for high beam currents, the focusing effect of the beam is not very good for low beam currents. Therefore, during the accelerator tuning process, it is necessary to quickly raise the beam to the optimized design point.

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