Simulation of high-intense beam transport in electrostatic accelerating column (Postprint)

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Abstract

An electrostatic accelerating column was designed and fabricated by Lanzhou University for an intense D-T/D-D neutron generator. In order to achieve a neutron yield of 5.01012 n/s, a deuteron beam of 30 mA, accelerated to 400 kV, and transported in the electrostatic accelerating column smoothly are required. One particle-in-cell code BEAMPATH was used to simulate the beam transport, and the IONB1.0 code was used to simulate the intense beam envelopes. Emittance growths due to space charge effect and spherical aberration were analyzed. The simulation results show that the accelerating column can transport deuteron beam of 30 mA smoothly and the requirement for the neutron generator is satisfied.

Full Text

Simulation of High-Intensity Beam Transport in an Electrostatic Accelerating Column

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Abstract: An electrostatic accelerating column was designed and fabricated by Lanzhou University for an intense D-T/D-D neutron generator. To achieve a neutron yield of 5.0 × 10^{12} n/s, the system requires a 30 mA deuteron beam accelerated to 400 kV and transported smoothly through the electrostatic accelerating column. The particle-in-cell code BEAMPATH was employed to simulate beam transport, while the IONB1.0 code was used to simulate intense beam envelopes. Emittance growth due to space charge effects and spherical aberrations was analyzed. Simulation results demonstrate that the accelerating column can transport a 30 mA deuteron beam smoothly, satisfying the neutron generator requirements.

Keywords: Electrostatic accelerating column, Intense beam, Simulation, Space charge
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Introduction

In recent years, high-current ion accelerators have attracted considerable interest for various applications including accelerator-driven systems (ADS) [?], accelerator-based neutron sources [?], next-generation radioactive ion beam facilities [?], and ion cancer therapy facilities [?, ?]. Lanzhou University is developing a D-T/D-D neutron generator that serves as a monoenergetic neutron source driven by an electrostatic accelerator. An electrostatic accelerating column has been designed and installed on the neutron generator to accelerate and transport high-intensity beams. To achieve a neutron yield of 5.0 × 10^{12} n/s, the system requires a 30 mA deuteron beam accelerated to 400 kV and transported smoothly through the electrostatic accelerating column [?, ?].

This paper analyzes and simulates the transport of high-intensity deuteron beams in the electrostatic accelerating column for the D-T/D-D neutron generator. BEAMPATH [?], a well-validated code using the particle-in-cell (PIC) method, is employed to conduct beam transport simulations and investigate emittance growth due to space charge effects [?] and spherical aberrations [?] in the electrostatic accelerating column. Additionally, a computer code named IONB1.0 for simulating intense beam envelopes based on the K-V equation has been developed and applied.

II. Analysis of Beam Emittance Growth

A. The Accelerating Column

The accelerating column measures 1370 mm in length (Fig. 1 [Figure 1: see original paper]) and consists of two accelerating zones, A1 and A2, each with dimensions of Φ90 mm × 110 mm. These zones function as two electrostatic lenses. Two negatively biased electrodes are installed at the accelerating column exit to repel secondary electrons back into the column and prevent them from reaching the ion source. A permanent magnet lens at ground potential is positioned between these two electrodes. The magnet lens and electrodes form a space charge lens [?] that prevents excessive beam divergence and adjusts the beam envelope size at the accelerating column exit.

B. Effects of Spherical Aberrations

Transport of space charge-dominated beams is typically analyzed using linear approximation methods. In the presence of a linear focusing field, beam emittance remains constant. However, realistic focusing elements possess strong aberrations that distort the phase space area occupied by the beam. Among these, spherical aberration cannot be eliminated and therefore has the most significant effect on particle dynamics. The spherical aberration coefficient C_s is defined as [?, ?]:

$$C_s = \left(\frac{f}{r}\right)^3 \Delta r$$

where f is the focal length, r is the radial distance of an incident ray parallel to the axis, and Δr is the radial distance at the paraxial-image plane.

The change in slope of a particle trajectory can be expressed in terms of focal length f and aberration coefficient C_s [?, ?]:

$$\Delta\left(\frac{dx}{dy}\right) = -\left(\frac{x}{f}\right)\left[1 + C_s\left(\frac{r}{f}\right)^2 / f\right]$$

Assuming the initial beam distribution is described by the ellipse:

$$\frac{x^2}{R^2} + \frac{(x')^2}{(R'/\epsilon)^2} = 1$$

where R is the beam envelope size and ϵ is the beam emittance.

The transformation from initial particle variables before the lens (x_0, x_0') to those after the lens (x, x') is given by:

$$x = x_0, \quad x' = x_0' - \frac{x_0}{f}\left[1 + C_s\left(\frac{r}{f}\right)^2\right]$$

Changing variables (x, x') to action-angle variables (J, Ψ):

$$x = \sqrt{2J}\cos\Psi, \quad x' = -\sqrt{\frac{2J}{\epsilon}}\sin\Psi$$

The beam ellipse distortion becomes:

$$T + T_{22}\upsilon \sin\Psi \cos^3\Psi + T_3\upsilon^2 \cos^6\Psi = 1$$

where $T = 2J/\epsilon$ and $\upsilon = C_{sR}^4/(\epsilon f^4)$. Without nonlinear perturbation ($\upsilon = 0$), the beam emittance shape is round. While the phase space areas occupied by the beam before and after the lens remain the same, the effective area occupied by the beam increases. The beam emittance can be estimated as the total area of elements $dxdx'$ occupied by the beam. Although the actual areas are identical in both cases, the number of elements covered by the beam in phase space differs. The increase in effective beam emittance is proportional to the square root of the product of minimum and maximum values of T:

$$\epsilon_{\text{eff}}/\epsilon = (T_{\max}T_{\min})^{1/2}$$

where $T_{\max}$ and $T_{\min}$ are determined numerically. The dependence of emittance growth on parameter υ can be approximated by:

$$\epsilon_{\text{eff}}/\epsilon = \left(1 + K\upsilon^2\right)^{1/2}$$

where $K \approx 0.4$. Finally, the effective beam emittance growth due to spherical aberrations can be approximated by:

$$\epsilon_{\text{eff}}/\epsilon = \left[1 + K\left(\frac{C_{sR}^4}{f^4}\right)^2\right]^{1/2}$$

C. Aberrations of Space Charge Effect

The space charge density and space charge field of a beam with Gaussian distribution in free space are given by [**?**, **?**]:

$$\rho(r_0) = \frac{I}{2\pi\epsilon_0\beta c r_0}\left[1 - \exp\left(-\frac{r_0^2}{2\sigma^2}\right)\right]$$

$$E_r(r_0) = \frac{I}{2\pi\epsilon_0\beta c r_0}\left[1 - \exp\left(-\frac{r_0^2}{2\sigma^2}\right)\right]$$

where ϵ_0 is the permittivity of vacuum, I is the beam current, and $\beta = v/c$ where v is the particle velocity and c is the speed of light in vacuum.

The nonlinear function in the space charge field can be expanded:

$$f(r_0) = 1 - \exp\left(-\frac{r_0^2}{2\sigma^2}\right) \approx \frac{r_0^2}{2\sigma^2} - \frac{r_0^4}{8\sigma^4} + \cdots$$

At the initial stage of beam emittance growth, we can assume that the particle radius does not change while the trajectory slope changes. This yields the following nonlinear transformation:

$$r = r_0, \quad r' = r_0' - \frac{2zP}{R^2} r_0 + \frac{2zP}{R^4} r_0^3$$

where $P = 2I/(I_c \beta^3 \gamma^3)$ is the generalized perveance, γ is the relativistic factor, and $I_c = 4\pi\epsilon_{0mc}^3/q$ is the characteristic beam current.

Using the same approach as above, the effect of spherical aberration on beam emittance can be determined as:

$$\epsilon_{\text{eff}}/\epsilon = \left[1 + \kappa \left(\frac{I}{I_c \beta^3 \gamma^3}\right)^2 \left(\frac{z}{\epsilon}\right)^2\right]^{1/2}$$

where z is the drift length and $\kappa = 0.6$ is a factor accounting for beam uniformity for Gaussian beams.

III. Envelope Simulation Based on K-V Equation

A. High-Current Ion Beam Envelope Equation

For designing the intense neutron generator, a computer code called IONB1.0 was developed. Assuming a continuous, elliptically symmetric particle beam, its dynamics can be modeled by the K-V (Kapchinsky-Vladimirsky) coupled envelope equations [**?**, **?**, **?**]. Let the z coordinate represent the position along the design trajectory, and the x-y plane represent the transverse plane for the particle beam. The high-current beam envelope equation is given by [**?**]:

$$X'' + \frac{\phi'}{\phi} X' + \frac{\phi''}{2\phi} X + K_{xX} - \frac{2\Pi}{X + Y} = 0$$

$$Y'' + \frac{\phi'}{\phi} Y' + \frac{\phi''}{2\phi} Y + K_{yY} - \frac{2\Pi}{X + Y} = 0$$

where $X(z)$ and $Y(z)$ are the dimensions of the semi-axes of the beam envelope in the x and y planes, respectively. The prime indicates differentiation with respect to z. ϕ, ϕ', and ϕ'' are the generalized potential, the electric field strength, and the derivative of electric field strength on the beam axis, respectively. K_x and K_y

refer to the focusing functions of transport elements in the x and y directions, respectively. ϕ_0 is the normalized potential, ϵ_{x0} and ϵ_{y0} are the normalized emittances of the beam on the (x, x') and (y, y') phase planes, respectively. 2Π is the generalized perveance, which reflects the space charge effect of the high-intensity beam and can be calculated by:

$$\Pi = \frac{I(1-F)}{2\epsilon_0\sqrt{2\eta\phi_0^3}}$$

where I is the beam current, F is the space charge compensation factor, η is the charge-to-mass ratio of the charged particle, and ϵ_0 is the permittivity of vacuum.

B. Numerical Simulation Method

For calculating X, the K-V equation can be expressed as:

$$X'' = -\frac{\phi'}{\phi}X' - \frac{\phi''}{2\phi}X - K_{xX} + \frac{2\Pi}{X+Y}$$

As shown in Fig. 2 [Figure 2: see original paper], the z axis is divided into a series of micro-units Δz. When Δz is sufficiently small, we can approximate that X'' is a constant A in each micro-unit.

After the beam passes through a Δz, its envelope and divergence can be approximately calculated by:

$$X' = A\Delta z + B$$

$$X = \frac{1}{2}A\Delta z^2 + B\Delta z + C$$

where A, B, and C can be determined from the initial conditions of the beam envelope. As shown in Fig. 2, if the initial conditions at point P are (X_P, X'_P), then $B = X'_P$ and $C = X_P$. A can be calculated using the equation above. The beam parameters at the next interval point $Q(X_Q, X'_Q)$ are determined by these equations. Then, treating Q as the start point, we can calculate the beam parameters at the next point $R(X_R, X'_R)$. As long as Δz is sufficiently small, accurate beam parameters can be obtained at each interval point. The same method is used to calculate Y.

IV. Beam Simulation

A. Optimization of Accelerating Column Fields

The electric field distribution must not only meet the requirements for increasing beam energy and inhibiting excessive beam divergence but also ensure reasonable allocation of the 400 kV voltage to avoid local field strengths becoming too large and causing discharge. Using the POISSON/SUPERFISH code [**?**, **?**], the equipotential surface distribution was simulated as shown in Fig. 3 [Figure 3: see original paper]. The electric field strengths in all regions are less than half of the maximum breakdown electric field strength, with electric field directions marked by arrows. Figure 4 [Figure 4: see original paper] shows the maps of radial fields $E_r(z, r)$ and $E_z(z, r)$ at radii of 0–4 cm.

B. Initial Parameters

Numerous PIC codes have been developed for simulating space charge-dominated beam dynamics [**?**, **?**]. Among them, BEAMPATH can simulate unbunched continuous beam dynamics using the PIC method. Our simulation began at point S (Fig. 1). A Gaussian distribution was assumed for a 20 keV axially symmetric deuteron beam. Based on experimental data from the duoplasmatron ion source [**?**], the initial parameters at point S were chosen as follows: beam envelope radius $X = Y = 10$ mm; divergence angle $X' = Y' = 50$ mrad; natural emittance $\epsilon = 150$ mm · mrad; and normalized beam emittance 0.7 mm · mrad. The $E(z, r)$ field map of the accelerating column was calculated using POISSON/SUPERFISH and input into BEAMPATH and IONB1.0, respectively. When using BEAMPATH, the beam intensity was set to 30 mA and 0 mA to consider and ignore space charge effects, respectively. For IONB1.0, space charge compensation had a significant impact on simulation results. In our previous study, a fully unneutralized beam was assumed in the accelerating zones with a space charge compensation factor of 0.8 in the non-accelerating zones [**?**], but comparing IONB1.0 results with BEAMPATH results indicated that it should be 0.65 in the non-accelerating zones and 0 in the accelerating zones.

C. Simulation Results

Charged particle motion in the electrostatic accelerating column depends on both the external electrostatic field and the space charge self-field, with the space charge force causing beam divergence and emittance growth. Simulation results indicate that a 30 mA deuteron beam can successfully pass through the accelerating column.

The simulation results with space charge effects are shown in Fig. 5 Figure 5: see original paper. The maximum beam envelope radius at the accelerating column exit is about 2.5 cm using IONB1.0, and the beam envelope radii of the vast majority of deuterons at the exit are 2–3 cm using BEAMPATH. In contrast, without space charge effects (Fig. 5(b)), the maximum beam envelope radius at the exit is about 1.2 cm, and the beam envelope radii of the vast majority of deuterons are approximately 1.2 cm. The beam divergence and maximum beam envelope radius are significantly smaller than those in Fig. 5(a).

Figure 6 Figure 6: see original paper illustrates the oscillation of emittance along the accelerating column for both 0 mA and 30 mA deuteron beams. Significant beam emittance growth is observed in the BEAMPATH simulation. The beam emittance for 0 mA differs from that for 30 mA in the accelerating zones, and they vary differently in different accelerating zones. The beam emittance at the accelerating column exit is 0.3 cm • mrad, which is 4.3 times greater than the original emittance. As shown in Fig. 6(b), the space charge effect plays a significant role in beam emittance growth in the accelerating zones. The maximum value of ϵ_{30}/ϵ_0, which is the ratio of beam emittance at 30 mA to that at 0 mA, is 1.24 in the accelerating zones, but it is nearly 1 in the non-accelerating zones. This demonstrates that beam emittance increased rapidly before entering A1, was inhibited in A1, and decreased in A2.

Figure 7 [Figure 7: see original paper] shows the final deuteron distributions in phase space and real space, with and without space charge effects. With space charge effects, beam divergence increases (Figs. 7(a) and 7(b)) and a hollow beam is formed (Figs. 7(c) and 7(d)). An annular distribution is formed by a large number of deuterons, with inner radii of about 2 cm and outer radii of about 3 cm at the accelerating column exit (Fig. 7(d)), indicating that the electrostatic accelerating column can transport a space charge-dominated beam of 30 mA as required by the design.

V. Conclusion

The transport of high-intensity beams in the electrostatic accelerating column with two gaps was simulated using BEAMPATH and IONB1.0. The results demonstrate that the strong focusing performance of the accelerating column and high-gradient electric field can effectively counteract ion beam divergence caused by space charge effects, and the accelerating column can satisfy the requirements for the intense D-T/D-D neutron generator.

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Note: Figure translations are in progress. See original paper for figures.