SIMULATION OF HIGH-CURRENT ION BEAM ENVELOPE AND DESIGN OF BEAM TRANSPORT LINE FOR AN INTENSE NEUTRON GENERATOR*

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Abstract

Based on the ion beam envelope equation (K-V eq.), a numerical simulation method of the high-current ion beam envelope and a computer code (IONB1.0) were developed. The envelopes of 40 mA D^+ ion beam in 400 kV intense neutron generator were simulated using IONB1.0 code. A design proposal of D^+ ion beam transport line was presented for 400 kV intense neutron generator.

INTRODUCTION

In 1988, a 3.3 $\times 10^{12}$ n/s neutron generator (ZF-300) with a rotating target, based on T(d, n)^{4}He reaction (d-T), had been built at Lanzhou University[1]. It had been applied in the research fields of nuclear data measurements, radiation hardening and radioactive breeding[2]. Recently, a higher intensity d-T neutron generator with 400 keV D beam energy is being developed at our laboratory. In order to complete the beam transport line design of the neutron generator, a numerical simulation method and a computer code named IONB1.0 on the high-current ion beam envelope based on the beam envelope equation (K-V eq.) are developed. A design proposal of D^+ ion beam transport line for 400 kV intense neutron generator is also presented in this paper.

LAYOUT OF NEUTRON GENERATOR

The D^+ ion beam transport line of neutron generator is shown in figure 1. A Cockcroft-Walton accelerator will be used to accelerate and transport D beam. D beam of 20 keV extracted from the duoplasmatron ion source is sent to the accelerating column, and accelerated to 400 keV. A space charge lens and a magnetic quadrupole triplet lens are used to focus the beam. To increase target lifetime, a 45^o double focusing analytical magnet is used for D^+ separation from molecular ions. Then, another magnetic quadrupole triplet lens is installed. A high-speed rotating target system cooled with water will be used to limit the peak temperature of the target. The rotating vacuum seal will be accomplished by using a magnetic liquid sealing axis. The target diameter is 20.2 cm. The spot size of beam requires less than 2 cm. The design parameters of neutron yield are 5×10^{12} n/s^{-1} for D-T reaction and 5×10^{10} n/s^{-1} for D-D reaction.

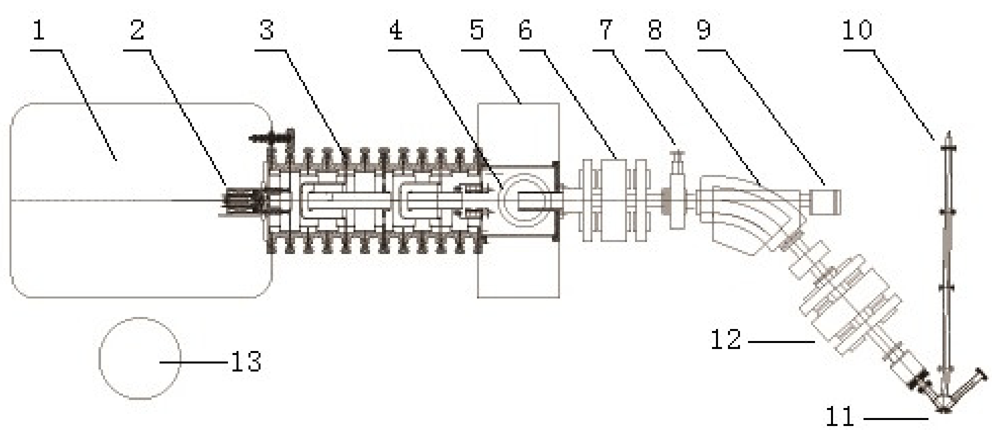

Figure 1: Schematic diagram of D-T/D-D intense neutron generator.

1-HV electrode; 2-Duoplasmatron; 3-Accelerating column; 4-Vacuum channel; 5-Ground electrode; 6,12-Quadrupole triplets lens; 7-Gate; 8-Analytical magnet; 9,10-Observation window; 11-Target; 13-HV supply.

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SIMULATION METHOD

High Current Ion Beam Envelope Equation

The beam envelope equation was first proposed by Kapchinsky and Vladimirsky (K-V equation) in 1959[3], and was developed for high-current beam by the later researchers[4,5,6]. The high-current beam envelope equation is as follows[5]

$$\begin{cases} X'' + \dfrac{\varphi'}{2\varphi}X' + \dfrac{\varphi''}{4\varphi}X + K_x X - \dfrac{2\Pi}{X+Y} - \dfrac{\varepsilon_{x0}^2\varphi_0}{X^3\varphi} = 0 \\ Y'' + \dfrac{\varphi'}{2\varphi}Y' + \dfrac{\varphi''}{4\varphi}Y + K_y Y - \dfrac{2\Pi}{X+Y} - \dfrac{\varepsilon_{y0}^2\varphi_0}{Y^3\varphi} = 0 \end{cases} \quad (1)$$

Where, X and Y are respectively the semi-axes of the beam envelope in the horizontal direction and the vertical direction, φ, φ' and φ'' are respectively the generalized potential, the electric field strength and the derivative of electric field strength at Z-axis (Beam axis). 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 respectively the normalized emittance of ion beam on the (x, x') and (y, y') phase plane. 2Π is the generalized perveance, it reflects space-charge effect of the intensity beam, and can be calculated by following formulas

$$2\Pi = \frac{I(1-F)}{2\pi\varepsilon_0}(2\eta)^{-\frac{1}{2}}\varphi^{-\frac{3}{2}} \quad (2)$$

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

Numerical Simulation Method

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

$$X'' = -\frac{\varphi'}{2\varphi}X' - \frac{\varphi''}{4\varphi}X - K_x X + \frac{2\Pi}{X+Y} + \frac{\varepsilon_{x0}^2\varphi_0}{X^3\varphi} \quad (3)$$

As in Figure 2, the Z-axis may be divided into a lot of micro-units, Δz. When Δz is enough tiny, we may approximately hold that X'' is a constant A in each micro-unit.

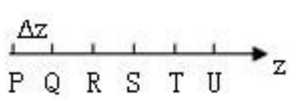

Figure 2: Divided diagram for the beam axis.

After the beam pass through a Δz, its' envelope and divergence may be approximately calculated by following formulas

$$\begin{cases} X' = A\Delta Z + B \\ X = \dfrac{1}{2}A\Delta Z^2 + B\Delta Z + C \end{cases} \quad (4)$$

Where, A, B and C can be fixed by the initial conditions of beam envelope. As in Figure 2, if the initial conditions at P point are (X_P, X'_P), in that case, $B = X'_P$ and $C = X_P$. Constant A can be calculated through equation (3). The beam parameters at next interval point $Q(X_Q, X'_Q)$ are determined by formulas (4). Then, Q is regarded as the start point, we can calculate the beam parameters at next point $R(X_R, X'_R)$ by the same ways as above. So long as Δz is enough tiny, the better consults of beam parameters may be got at each interval point. The same method is used to compute the Y.

SIMULATION RESULTS AND DISCUSSION

According to experimental data of the duoplasmatron ion source[7], the initial parameters of D beam is chosen as: the beam envelope radius $X = Y =$ 10 mm, the divergence angle $X' = Y' =$ 50 mrad, the emittance $\varepsilon = 150$ mm.mrad with the energy of 20 keV, and the beam current $I =$ 40 mA. The $E(z,r)$ field map of accelerating column was calculated with the POISSON/SUPERFISH program and input into the IONB1.0. The beam has been assumed to be fully unneutralized in the accelerating region, while the factors of space charge compensation has been held to 0.8 in the rest region. Figure 3 shows the beam envelopes from the ion source to the target in the x and y directions respectively.

The results show that the strong focus performance from the accelerating column with two gap high gradient electric field can effectively offset ion beam divergence caused by the space charge effect. The radius of envelope is about 3cm at accelerating column exit. The beam transport system composed of a space charge lens, a double focusing analytical magnet and two triple quadrupole magnetic lens can focused 40 mA / D+ beam on the target at 150 cm distance, and the beam spot diameter is less than 2 cm.

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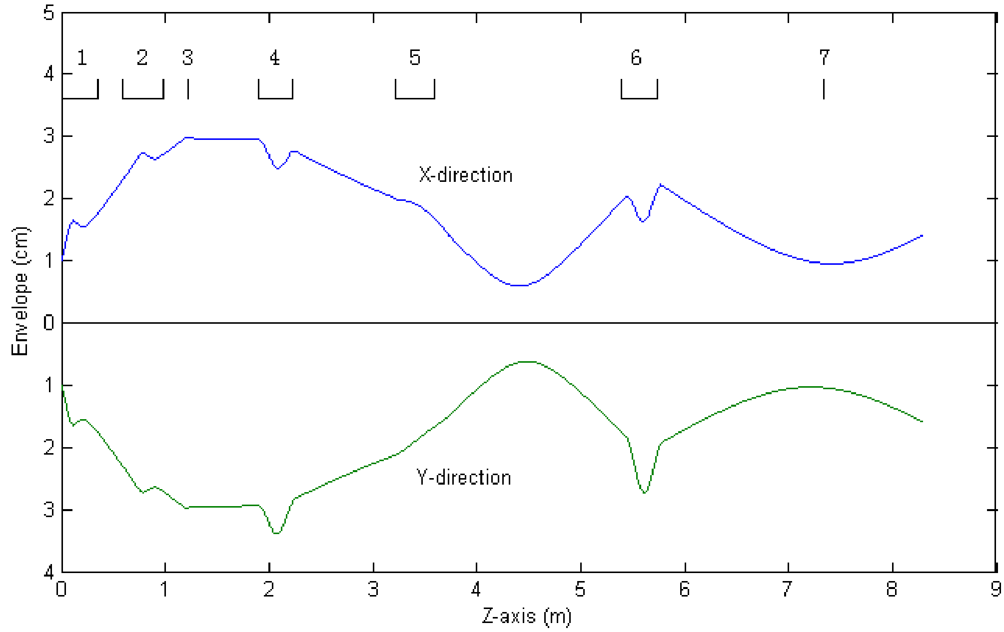

Figure 3: D beam envelope of the transport lines of neutron generator.

1-accelerating region ⅰ; 2- accelerating region ⅱ; 3- space charge lens; 4,6 - quadrupole triplet lens; 5- analytical magnet; 7- target.

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