Optimization and numerical simulation for the extraction system of the H^- multicusp ion source

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Abstract: A new ion source has been designed and manufactured for the CYCLONE30 accelerator, which has a much advanced performance compared with the original. It is expected that the newly designed ion source extraction system will transport a very large percentage of the beam without deteriorating the beam optics, which is designed to deliver an H^- beam at 30 keV. The accelerator assembly consists of three circular aperture electrodes made of copper. The simulation study was focused on finding parameter sets that raise the beam perveance as large as possible and which reduce the beam divergence as low as possible. Ion beams of the highest quality are extracted whenever the half-angular divergence is minimum, for which the perveance current intensity and the extraction gap have optimum values. The triode extraction system is designed and optimized by using CST software (for Particle Beam Simulations). The physical design of the extraction system is given in this paper. From the simulation results, it is concluded that it is possible to achieve this goal by decreasing the thickness of the plasma electrode, shortening the first gap, and adjusting the acceleration electrode voltage.

Key words: multicusp ion source, extraction, electron tracking, perveance, angular divergence

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1 Introduction

Plasma (ion) sources are widely employed in a number of technologically important applications, including particle sources [1, 2] , etching [3], implantation [4], deposition [5], fusion devices [6], production of precursors [7], etc. Multicusp ion sources have been used widely in fusion reactors and particle accelerators, mainly for radioisotope production.

The CYCLONE30 accelerator utilizes an ion source technology that is similar to a LBL style ion source, dating from the early 1980s [8]. The 30 keV H^- beam current produced by this ion source is typically about 2.5 mA, with an emittance of 400 mm mrad [9]. In the development of a negative ion source (e.g., for H^- ion cyclotron or negative-neutral beam injection into fusion plasma) extraction physics are one of the critical problems that researchers in this field must face. Thus, a new extraction system has been designed for CYCLONE30 in which the triode extraction system (also called the three-electrode extraction system or the accel-decel extraction system) is a key component.

In order to reduce angular divergence and increase the transported beam current from the CYCLONE30 multicusp-type H^- ion source, improvements to the extraction system are required. This paper describes the simulation studies to find the optimized design features of the new ion source and the possible electrode geometry modifications needed to extract the highest quality beam.

Due to the importance of the triode extraction system for a high current density plasma ion source, the operation principle of the ion source is carefully examined, and the triode extraction system is designed and optimized by using CST software (for Particle Beam Simulations) [10]. A detailed simulation process and the key parameters of the system are presented in this paper.

2 Description of plasma generator and present extraction system

The CYCLONE30 ion source is, mechanically and functionally, composed of two main parts: the plasma generator and the ion beam accelerator. The plasma generator is a 150 mm copper cylinder, which is 100 mm in diameter, around which ten columns of permanent magnets with magnetic field of 6.2 kg and a size of 20 mm×20 mm×30 mm are mounted [11, 12].

The plasma generator of the ion source is of an axially cusped bucket type, and the whole inner wall, except the

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cathode filaments and plasma electrode side, functions as an anode, as shown in Fig. 1.

The magnetic field created by permanent magnets is calculated by the 3D numerical solution based on the magnetic charge model by CST, as shown in Fig. 2. The line cusp field can be seen along the chamber wall.

Figure 3 shows the flux density profile on the line in the y direction from the wall to the center.

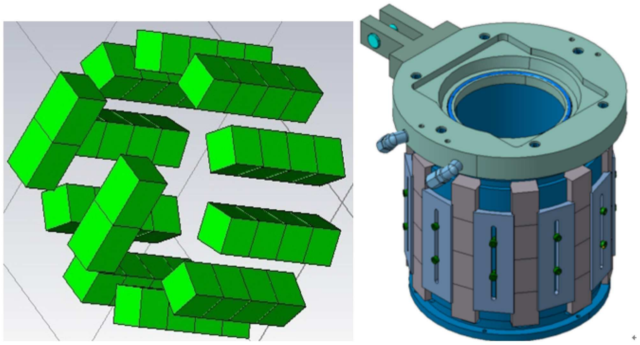

Fig. 1. Distribution of the magnets and the structure of the discharge chamber.

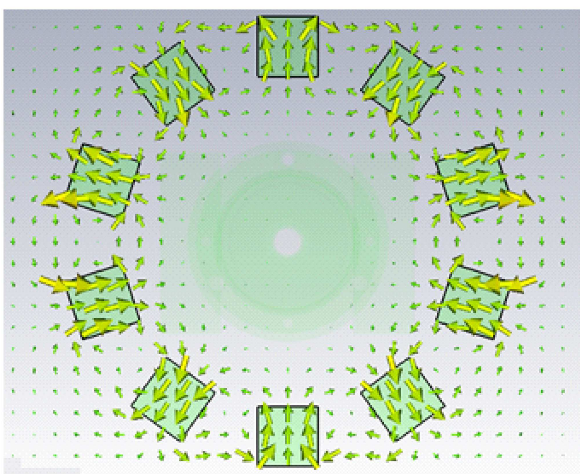

Fig. 2. (color online) The magnetic field distribution in the discharge chamber.

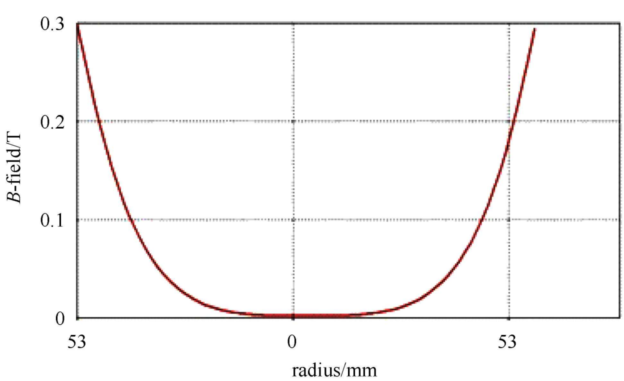

Fig. 3. (color online) Magnetic field density profile along the radius through the pole tips for N=10.

The ion beam acceleration system has a triode electrode column. The structure of the extraction system consists of a plasma electrode, an extraction electrode and a ground electrode [13, 14].

The dimensions of the present accelerating column are given in Fig. 4. The first electrode, or plasma electrode, defines the boundary of the source plasma, from which ions are extracted. The first gap extracts ions through the plasma electrode aperture and the second gap post accelerates the ion beam to a desired level. As is shown in Fig. 4, the plasma electrode thickness is 10 mm and the potential of the plasma electrode $V1$ and extraction electrode $V2$ are equal to -30 kV and -26 kV, respectively. The distance between the plasma and extraction electrode D12 is equal to 3.5 mm. The distance between the extraction and ground electrode D23 is equal to 29.1 mm. The plasma electrode inclination angle that affects beam divergence is 30°. Figure 5. illustrates the electrical potential lines of these three electrodes plotted by the CST PS program.

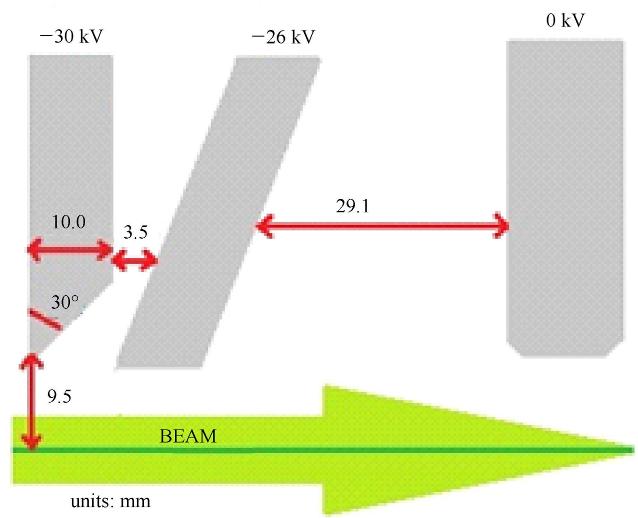

Fig. 4. (color online) Some parameters of the triode extraction system for the present accelerator structure and dimensions.

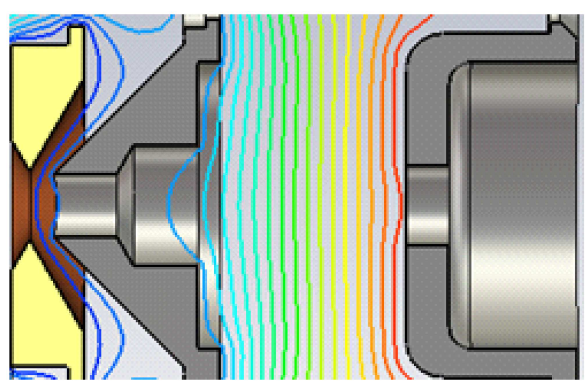

Fig. 5. (color online) The equipotential lines of CYCLONE30 extraction system.

3 Ion beam extraction

A thorough experimental analysis of extraction optics for a single circular aperture is given by Coupland [15]. For uniform emission from an infinite plane, the Child–Langmuir law [16] gives the current density, J, of singly ionized hydrogen as

$$J=\frac{1.74}{d^2}V^{3/2}\ \mathrm{mAmm}^{-2}, \tag{1}$$

where V is the applied extraction potential in kilovolts and d is the separation between the aperture and the extraction electrode in millimeters. For an emission from a concave surface with radius of curvature R_{M}, for small values of d/R_{M} it can be shown that Eq. (1) is multiplied by a factor

$$\left(1-1.6\frac{d}{R_{\mathrm{M}}}\right), \tag{2}$$

which is smaller than unity. The total beam current is found by multiplying the current density by the area of the emission aperture. For the cylindrical aperture of the ion source, the current is:

$$I=J\pi r^2=1.74\pi V^{3/2}S^2\left(1-1.6\frac{d}{R_{\mathrm{M}}}\right), \tag{3}$$

where $S=r/d$ is the aspect ratio, r is the radius of the hole in the plasma electrode, and $F=\pi r^2$ is the emitting area.

Space charge effect in beams is conveniently characterized by the perveance, taking into account the magnitudes of the beam current and the accelerating voltage. Beam perveance has been studied and calculated in order to define the beam trajectory and beam boundaries.

The perveance, P, of an ion beam is defined as

$$P=\frac{1}{V^{3/2}}=\left(1-1.6\frac{d}{R_{\mathrm{M}}}\right)P_0\ \mathrm{mAkV}^{-3/2}. \tag{4}$$

This is a function only of the geometry of the system.

The divergence angle ω at the exit of the extraction system is caused by: the shape of the plasma meniscus, the defocusing forces of the second aperture (as described above), the temperature of the ions (as we will see below), and by repulsive forces of the particles on themselves. The divergence angle has been calculated by Coupland [15],

$$\omega=0.29S(1-2.14P/P_0), \tag{5}$$

where $S=r/d$ as above, and P is the perveance in the extraction gap, $P=I/V^{3/2}$, and P_0 is the Child-Langmuir space-charge limited perveance for the one dimensional diode of length d with no electrons,

$$P_0=[(4/9)\pi](r^2/d^2)\varepsilon_0(2e/M)^{1/2}, \tag{6}$$

where ε_0 is the permittivity of the vacuum.

Equation (5) predicts that the divergence can be reduced to zero at a perveance equal to $0.47P_0$. In practice, the divergence does not decrease to zero and the perveance at the minimum divergence is less than $0.47P_0$.

4 Optimization of triode extraction system

This section will present a simulation of the extraction systems. Since there are many variables affecting the beam optics in a triode electrode accelerator, it is reasonable that the simulation study is concentrated on parameters related to the plasma electrode that most strongly affect the beam perveance and divergence. One of the easiest ways to augment the extracted beam current is to increase the transparency of the accelerator by enlarging the aperture diameters. However, with this solution, there is concern about deterioration in the beam optics. For this reason we have not considered this case. The ideas applied to the accelerator design are as follows: shaping the electrode angle, reducing the plasma electrode thickness, decreasing the first gap, and adjusting the extraction electrode voltage.

Using CST software, the influence of the key parameters of the system on the beam quality is evaluated by the root-mean-square angular divergence (rms divergence) of the extracted beam. When the optimal parameter is satisfied, the extraction beam has the lowest divergence and maximum perveance at the measure point.

In the above conditions, the influences of these parameters like thickness, D12, $V2$ and θ on the rms divergence are simulated and shown in Figs. 6–9.

4.1 Plasma electrode inclination angle

It has been accepted that shaping the plasma electrode, in general, is helpful to extract a beam at a low divergence angle. A well-known study by Pierce [17] found that a zero divergence electron beam can be extracted from either a slit or a cylindrically symmetric extractor if the plasma and extraction electrodes are shaped so as to match a Laplace solution outside to a Poisson solution inside the beam. The match requires the plasma electrode to have an inclination of 22.5°. However, H^- ion beams are produced and subsequently behave very differently from electron and even proton beams, so it is not so clear what the optimum plasma electrode angle is. Various angles, including 22.5°, 30°, and 45°, have been used here [18, 19]. In the configuration shown in Fig. 4, the angle of the plasma electrode was varied while keeping all of the other dimensions fixed. Table 1 summarizes the simulation results. The wider the electrode angle, the more H^- can be extracted. A wide electrode angle allows a higher field penetration into the ion source than a small angle; therefore, the plasma boundary surface is enlarged and more current is extracted. In addition, high field penetration into the ion source causes distortions of the plasma boundary, which leads to aberrations in the extraction system and divergence increase in the ion beam. The smallest divergence is achieved at small angle of 22.5°.

The perveance of the present geometry is 4.94E-10 A/$V^{3/2}$ and the beam divergence angle is about 3.14°, which is quite a large value. A beam divergence has the lowest value when the shaping angle of the backside edge of an aperture is about 67°.

Table 1. The extraction system simulation results with varying plasma electrode inclinations.

angle of inclination/(°)	beam divergence angle/(°)	perveance/ (A/$V^{3/2}$)
30	3.14	4.94E-10
22.5	2.2	5.11E-10
45	3.32	4.57E-10

4.2 Plasma electrode thickness

The simulation results for the effect of the plasma electrode thickness on the perveance and beam divergence are shown in Fig. 6, where the divergence angle is given in an rms value. The optimum perveance increases with a decrease of the plasma electrode thickness. From Fig. 6, one can see that a reduction of the thickness while the plasma electrode inclination angle is kept 22.5° also results in lowering the divergence angle. Thickness of 7 mm is the optimum point where the maximum perveance and minimum divergence are observed.

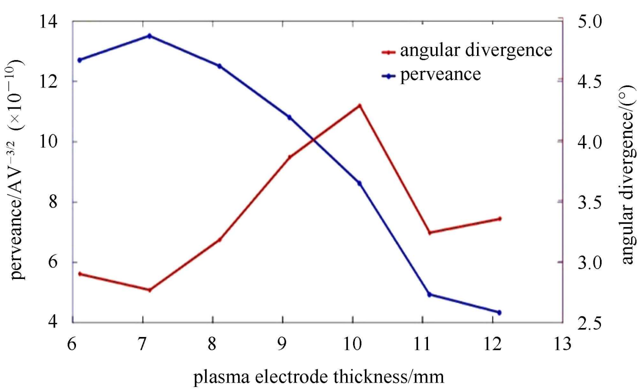

Fig. 6. (color online) Influence of the plasma electrode thickness on the beam perveance and rms angular divergence.

4.3 The first gap distance

We denote the first gap distance as D12. In Fig. 7, any reduction of the first gap while changing the plasma electrode inclination angle to 22.5° and its thickness to 7 mm raises the optimum perveance value and decreases the divergence angle of the beam. These tendencies can be explained reasonably in terms of familiar Child–Langmuir's law.

The beam current is inversely proportional to the electrode separation D12, which leads to higher beam perveance. But there is a limit to how small D12 can be due to breakdown by the potential $V1$. Here, a gap distance of 2.5 mm is adopted. Equation 5 shows that by increasing the beam perveance, the angular divergence decreases.

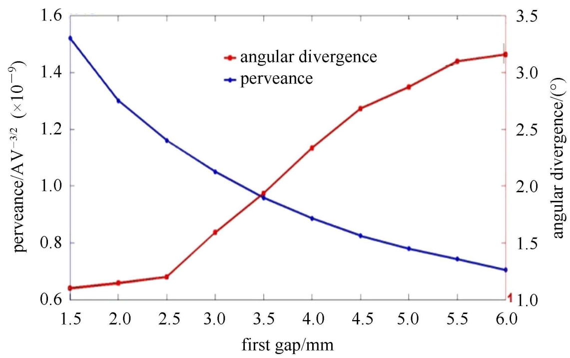

Fig. 7. (color online) Influence of the first gap width on the beam perveance and rms angular divergence.

4.4 Second electrode voltage

Figure 8 summarizes the simulation results for the effect of the variation in the voltage of the acceleration electrode, $V2$. An increase of the voltage results in higher perveance but deteriorating divergence, which means that there is an optimum point for the second electrode voltage compromising contradictory trends of two parameters. The potential of −24 kV is adopted for the second electrode to have a reasonable angular divergence and perveance; that is, a beam with high perveance and not too bad divergence.

According to the Child-Langmuir Law, the large acceleration voltage between the plasma electrode and the acceleration electrode can help to gain a high beam current [20].

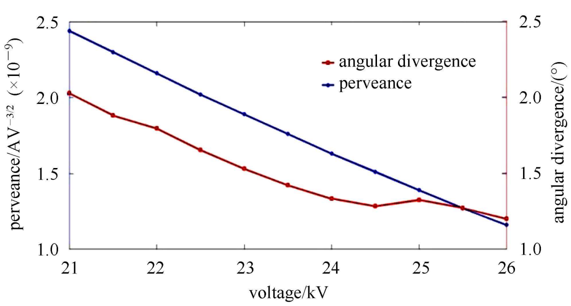

Fig. 8. (color online) Influence of the second electrode voltage on the beam perveance and rms angular divergence.

The increase in the extraction voltage affects the decrease in the beam emittance and this can be explained by the decrease in the angle of the beam divergence, which is found to be

$$\theta=\sqrt{\frac{KT_{\rm i}}{eV}}, \tag{7}$$

where θ is the angle of beam divergence, for small angle tan $\theta=\theta$, $KT_{\rm i}$ is the transverse kinetic energy (K is Planck's constant), $T_{\rm i}$ is the ion temperature, and eV is the axial accelerating energy.

5 Discussion

Fortunately, we could make a desirable accelerator design that satisfies the contradictory goals of high perveance and good optics. From the above simulations, an idea has been given in regard to reforming the accelerator configuration, which includes: first, shaping the plasma electrode angle; second, reducing the thickness of the plasma electrode is helpful for a high perveance beam extraction to maintain a low divergence; third, by decreasing the first gap both a high optimum perveance and improved beam optics can be attained; and, fourth, by adjusting the second electrode voltage, both an advantage of high optimum perveance and a disadvantage of bad optics is achieved.

Both sliming the plasma electrode to a 7 mm thickness and shortening the first gap to 2.5 mm are adopted for the new accelerator system. Fig. 9 is the calculated profile of the extracted ion beam in the upgrade accelerator structure, which shows acceptable beam optics properties of enlarged electrode holes. The perveance of the present geometry is 1.63E-009A/V$^{3/2}$ and its divergence angle is 1.3°, which has been improved considerably.

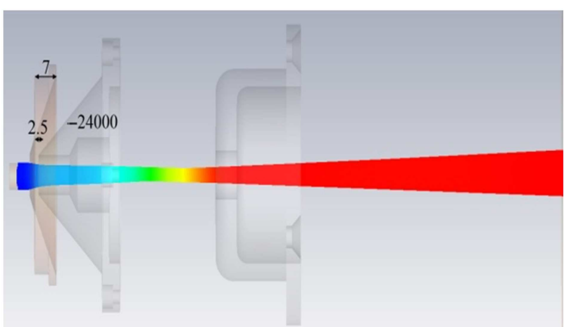

Fig. 9. (color online) Simulation runs for the upgrade accelerator structure.

6 Conclusion

This work is concerned with ion beam dynamics and optimizes the beam perveance and angular divergence of three-electrode extraction systems with the aid of CST software. The numerical results lead to the following qualitative conclusions:

1) A plasma electrode angle of 22.5° increases the extracted beam perveance, but the plasma electrode angle decreases.

2) The simulation results for the effect of the plasma electrode thickness on perveance show that the beam perveance increases with sliming plasma electrode, but the divergence angle decreases.

3) A high perveance ion beam requires reduction of first gap distance, at the same time this causes a decrease of the angular divergence of the beam due to the effect of the gap distance in the Child-Langmuir law.

4) Increasing the voltage results in a higher perveance but deteriorating the divergence, so a careful design is needed to choose the optimum value of $V2$ to prevent aberration in ion beams.

The simulation results will help to direct the experimental setup that is under development at Amirkabir University and the validity of the extraction system will be verified.

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