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Simulation of ion beam extraction and focusing system

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Abstract: The characteristics of ion beam extraction and focused to a volume as small as possible were investigated with the aid of computer code SIMION 3D version 7. This has been used to evaluate the extraction characteristics (accel-decel system) to generate an ion beam with low beam emittance and high brightness. The simulation process can provide a good study for optimizing the extraction and focusing system of the ion beam without any losses and transported to the required target. Also, a study of a simulation model for the extraction system of the ion source was used to describe the possible plasma boundary curvatures during the ion extraction that may be affected by the change in an extraction potential with a constant plasma density meniscus.

Key words: ion beam emittance, plasma meniscus, space charge, argon ion trajectories

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1 Introduction

Computer simulation has become an important tool in understanding the optics of charged particles [1]. The extraction of ions from plasma sources can be investigated by computer simulation. Two dimensional (2D) and three dimensional (3D) computer programs are now available for the optimization of ion extraction systems [2]. SIMION 3D 7.0 is a full windows program [3], featuring 3D electrostatic/magnetic arrays, data recording, charge repulsion, solid geometry definition files and a user program interface. The original version of the SIMION program for an electrostatic lens was developed by D. C. McGilvery at Latrobe University in Australia (1977) [4]. SIMION provides direct and highly interactive methods for simulating a wide variety of general ion optics problems, such as designing and analyzing charged particle (ions and electrons) lenses, ion transport systems, various types of mass spectrometers, detector optics, time of flight instruments, ion traps, quadrupoles and magnetic sectors. In order to extract ion beams from the appropriate ion source, a carefully designed arrangement must be used. This electrode must create the proper configuration of the electric field at the surface of the ion source and along the acceleration of the ion beam region [5]. The surface which forms the source of ions can either be of fixed geometry (surface ionization and field ion sources) or be the boundary of the plasma (plasma ion sources), in which the shape of the surface is fluid depending on the current density, ion supply rate and the electric field applied. The design of an extraction system must take into account the nature of this system and initiate the ion beam as free from aberrations as possible. Ion beam extraction from different types of ion sources is influenced by many parameters [6], such as geometry, applied extraction voltage, magnetic flux density, space charge of the extracted beam and finally the shape of the plasma boundary. In this work, the ion beam trajectories for different shapes of plasma meniscus were simulated and optimized. Indeed, a study of the simulation of ion beam extraction and focusing to a small volume was carried out.

2 Simulation of ion beam trajectories for different shapes of plasma meniscus

In general, the fundamental steps to simulate a model extraction system are to define the physical and electrical boundaries of the electrodes. SIMION

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defines the ions that are making the beam, selects what output data to record and also simulates ions through the extraction system. Each electrode of the triode extraction system was separately designed using a potential array. Such a potential array is a two or three dimensional array of points, consisting of a collection of equally spaced points forming a rectangular grid. Points in the potential array will be bound within a certain shape creating an electrode or non-electrode. Using a finite difference method, SIMION uses the potentials of electrode points to calculate the potential of non-electrode points. Once all three electrodes are designed and defined within a potential array, SIMION solves the Laplace equation,

$$\nabla^2 V = 0. \tag{1}$$

A simulation model for the extraction system of the ion source was used to describe the possible plasma boundary curvatures during the ion extraction that may be affected by the change in an extraction potential with a constant plasma density meniscus. The plasma-electrode was considered as the plasma emission surface, where the ions started to fly away. The voltage applied to the plasma-electrode was +5 kV and the decel-electrode on ground potential. The voltage applied to the accel-electrode was varied and optimized to accomplish the suitable shapes of the plasma boundary curvatures. At the extraction end of the plasma, a sheath will be formed between the plasma surface and the accel-electrode. The ions penetrating the sheath will experience an electric field due to the negative potential on the accel-electrode and will be accelerated. At low extraction voltage, a convex shape is formed and the ions will be strongly divergent (Fig. 1(a)). In this case, the plasma boundary is nearly spherical with its centre of curvature outside the plasma surface. As the extraction potential is gradually increased, more positive ions are extracted and the plasma boundary recedes until it becomes flat (Fig. 1(b)) and finally becomes concave at appropriately high values of the extraction potential (Fig. 1(c)). For the concave meniscus, it acts as a converging lens due to the electric field strength; therefore, a parallel beam is produced.

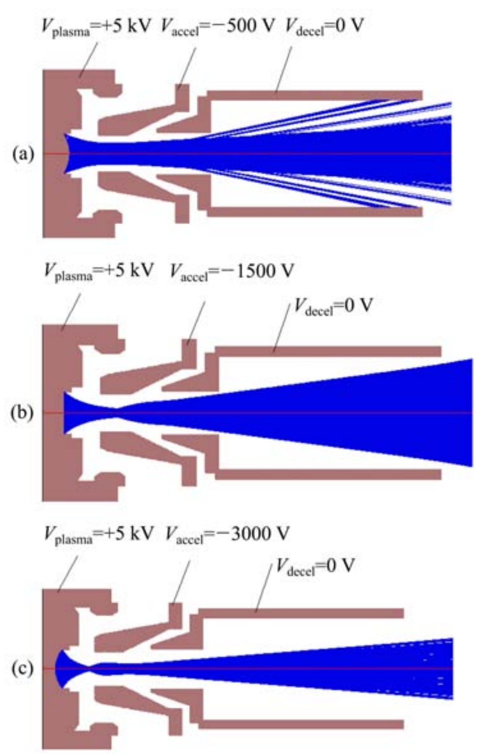

Fig. 1. Plasma boundary and beam envelope for the simulation of singly charged ions through the triode extraction system.

2.1 Simulation process for ion beam extraction system

Ion beam extraction from ion sources is influenced by many parameters, such as electrode geometry, applied extraction voltage, space charge in the extracted beam and finally the shape of the plasma boundary. The construction of the extraction system (triode extraction system) used in this work consists of an acceleration/deceleration electrode arrangement with a 4 mm diameter plasma aperture electrode, as shown in Fig. 2. The triode extraction system provides a negative potential with respect to the plasma on axis of the extraction system. A negative potential between the acceleration and the deceleration electrodes creates a barrier for electrons in the extracted beam region to keep them inside the ion beam. These electrons are necessary for space charge compensation. The plasma electrode terminates the plasma surface at the boundary of the discharge. The downstream side of this electrode must be designed to work as a focusing electrode to provide the proper electric field configuration for optimal ion trajectories.

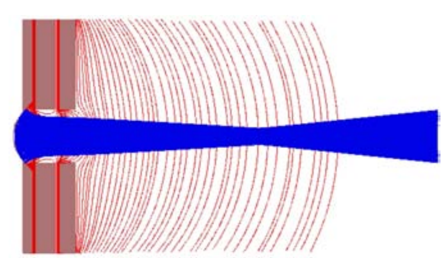

Fig. 2. Three-electrode extraction system.

Simulation of the singly charged ion trajectories for a plasma concave of curvature 3.5 mm was studied with and without the space charge effect using a triode extraction system with the aid of the SIMION computer program. The plasma-electrode was considered as the plasma emission surface, where the ions started to fly away. Ions would fly individually and the number of flying ions was 500. The simulation process was carried out at an assumption of a constant plasma density. The voltage applied to the plasma electrode was +5 kV. The voltage applied to the acceleration electrode was varied and optimized to accomplish suitable ion trajectories without hitting the extraction electrode (Fig. 3). The influence of the plasma voltage on both the beam emittance and the beam diameter was studied. It was found that an increase in the voltage applied to the plasma electrode was accompanied by a decrease in both the beam emittance and the beam diameter. In this work, the beam simulation is carried out to reveal the influence of the acceleration voltage on the beam emittance and beam radius.

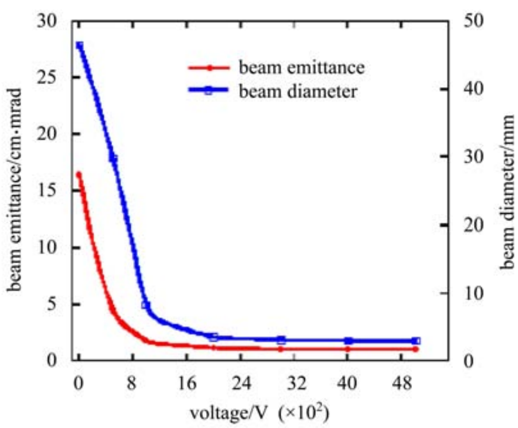

Fig. 3. Influence of the plasma voltage on both the beam emittance and the beam diameter.

The influence of the applied negative voltage to the acceleration electrode on both the beam emittance and the beam diameter has been studied (Fig. 4). It is clear that the minimum ion beam emittance has been obtained for a negative voltage of 2500, 3000 V, respectively, for both the beam emittance and the beam diameter.

The increase in the extraction voltage affects the decrease in the beam emittance (Fig. 4), and this can be explained by the decrease in the angle of the beam divergence, which is found to be [7]

$$\theta=\sqrt{\frac{KT_{\mathrm{i}}}{eV}}, \tag{2}$$

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

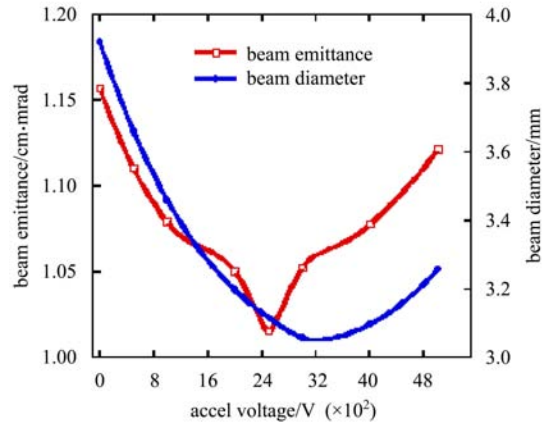

Fig. 4. Influence of the acceleration voltage on both the beam emittance and the beam diameter.

The influence of the distance between the plasma-electrode and the acceleration electrode (extraction gap width) on the ion beam envelope was investigated for a concave meniscus with 3.5 mm curvature radius (Fig. 5). In these calculations, the voltage applied to the plasma electrode V_{plasma}=+5 kV. The voltage applied to the acceleration electrode was fixed to V_{extr}=−2500 V, which showed that the ion beam envelope fully passed through the extraction region. The simulation of singly charged ions at different geometrical distances was achieved. It was found that the optimum extraction gap width was 5 mm for the triode extraction system. At this distance, the ion beam envelope fully passed through the extraction region.

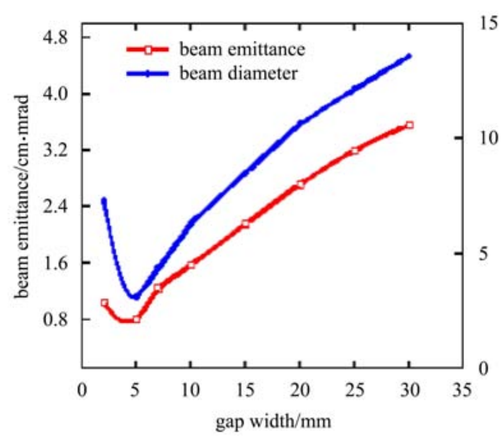

Fig. 5. Influence of the gap width on both the beam emittance and the beam diameter.

The beam emittance and beam diameter as a function of the focusing points at different distances for singly charged ion trajectories of the triode extraction system have been investigated (Fig. 6). Minimum beam emittance was found downstream by 40 mm for the triode extraction system while minimum beam diameter was found downstream by 50 mm.

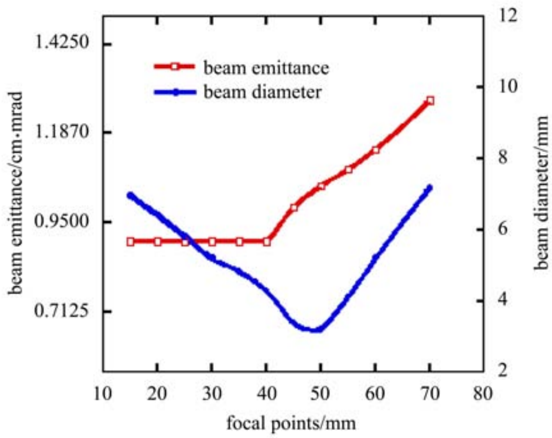

Fig. 6. Focal points as a function of both the beam emittance and the beam diameter.

Ion beams which propagate through a given beam line are subject to blowing up because of the tendency of like charged (positive) ions within the ion beam to mutually repel each other (space charge effect). The influence of ion space charge is disadvantageous for both the quality and the intensity of extracted ion beams. In order to reduce this problem, space charge neutralization (compensation) has to be used.

In the presence of space charge, the electric field acting on an ion beam is [8, 9]

$$E_r = \frac{q}{2\pi\varepsilon_0 r} = \frac{I_0}{2\pi\varepsilon_0 \nu_0 r}, \quad (3)$$

where q is the charge of the beam per unit length within radius r and $q=\frac{I_0}{\nu_0}$, I_0 is the total beam current, ν_0 is the axial ion velocity and ε_0 is the permittivity of free space.

The SIMION program supports three estimates of charge repulsion: beam, columbic and factor repulsion. In this work, simulation of the singly charged argon ion trajectories for a variable meniscus shape of the plasma is studied with the space charge effect

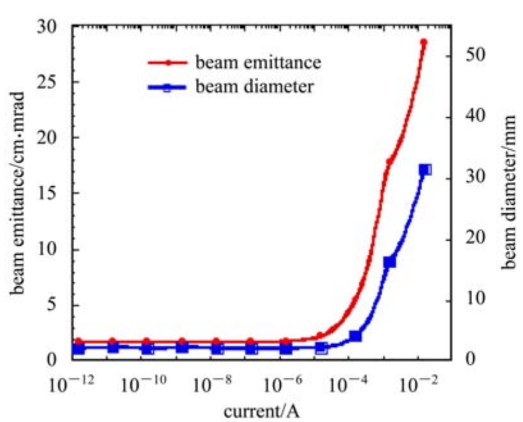

Fig. 7. Influence of ion beam current on the beam emittance and the beam diameter.

by using columbic repulsion. The influence of space charge on the extracted ion beam emittance for a curvature of concave plasma meniscus of 3.5 mm at acceleration voltage V_{acc}=−2500 V applied to the acceleration electrode of the triode extraction system has been studied, as shown in Fig. 7. It is found that the space charge has a large effect on the extracted ion beam emittance at currents higher than 10^{-4} A.

2.2 Ion beam simulation for the focusing system

Design of the focusing lens system has been done by using the SIMION computer program, which is used to trace and simulate the ion beam during its transport. In order to design the system, we studied it with different parameters in the absence of space charge. This study includes the design and optimization of the operating parameters for the two-and-three cylinder lens systems. In a two-cylinder lens system, the first electrode was set at 0 V and the voltage applied to the second electrode was varied from 0 to −5 kV. The influence of the negative voltage applied at the second electrode for the two-lens system on both the beam emittance and the beam diameter has been investigated for singly charged argon ion trajectories. Also, the beam emittance and the beam diameter for a singly charged argon ion as a function of the focusing points at different distances measured directly from the end of the two-lens system have been investigated.

The influence of the focusing voltage on both the beam emittance and the beam diameter for the two-cylinder lens system has been studied (Figs. 8 and 9). The minimum beam emittance and minimum beam diameter were found at the focusing voltages applied to the second electrode of the two-lens system of −1000 and −2000 V, respectively.

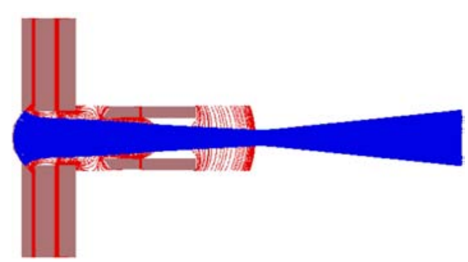

Fig. 8. The three-electrode extraction system with a focusing system.

The beam emittance and the beam diameter as a function of the focusing points at different distances for singly charged ion trajectories of the two lens systems have been investigated (Fig. 10). The minimum beam emittance was found downstream by 45 mm for the two-cylinder lens system while the minimum beam diameter was increased at different distances after the exit of ion trajectories from the lens system.

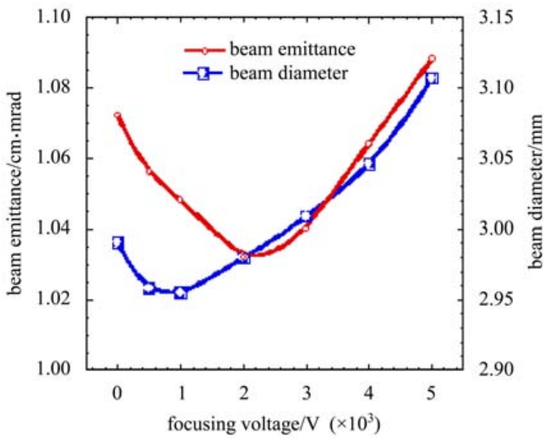

Fig. 9. Influence of the focusing voltage on both the beam emittance and the beam diameter.

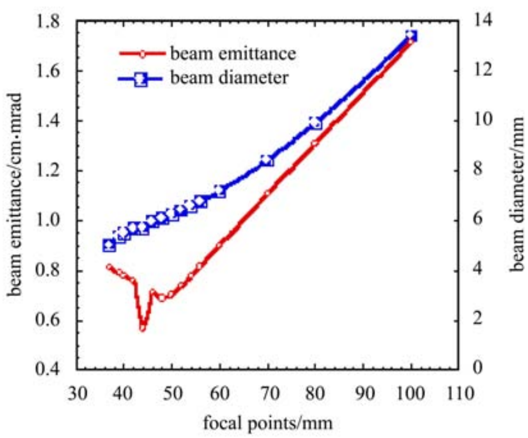

Fig. 10. Focal points as a function of both the beam emittance and the beam diameter.

3 Conclusion

In this paper, the ion beam trajectories for different shapes of the plasma meniscus were simulated and optimized. The variation in the plasma sheath with respect to the change in extraction potential at constant plasma density is illustrated in Fig. 1. With a low negative voltage applied to the extractor electrode, the plasma boundary will retreat toward the discharge chamber. In this case, the extracted ions will strongly diverge because of the convex shape of the plasma boundary (Fig. 1). By applying appropriately higher values of the extraction potential to the extractor, the plasma boundary will move further back into the discharge chamber according to the applied voltage, which just defines the space charge limited ion flow from the plasma boundary according to that which the plasma can furnish (Fig. 1). The influence of the acceleration voltage applied to the acceleration electrode of the triode extraction system on the extracted ion beam emittance has been investigated. It can be concluded that the minimum beam emittance was found at the acceleration voltage=-2500 V. Also, the influence of the extraction gap width on the ion beam emittance without space charge at acceleration voltage=-2500 V has been determined. It is found that the minimum beam emittance is obtained at the extraction gap width of 5 mm. Also, the effect of space charge on the extracted ion beam emittance at the acceleration voltage=-2500 V has been studied. It is found that the space charge has a large effect on the extracted ion beam emittance at currents higher than 10^{-4} A. Finally, a study of the ion beam focusing system has been optimized and investigated. It is found that the minimum beam emittance and minimum beam diameter were found at the focusing voltages applied to the second electrode of the two-lens system of -1000 and -2000 V, respectively. The minimum beam emittance was found downstream by 45 mm for the two-cylinder lens system while the minimum beam diameter was increased at different distances after the exit of ion trajectories from the lens system.

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