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SIMION Simulation Studies for Pentode Extraction System

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ABSTRACT

A five-electrode system (pentode extraction system) for optimally extracting, singly-charged ion beams has been computationally designed. The presented paper exploits the capabilities of commercial software (SIMION 3D v.7) in tuning up some of the main parameters (current density, extraction voltage and extraction gap width) and conditions needed for the optimal design of the optical system associated with a specified ion source before its fabrication. The space-charge effects expressing the mutual repulsion of charged ions within the ion beam are also considered during the simulation. The studied subject is of great importance especially for nuclear applications etc…. This work addresses the parameteric study and conditions on the performance of an ion-beam extraction system, the trajectories of the particles in the beam being simulated by SIMION. Space-charge effects are accounted for and criteria allowing optimization of the system are proposed. Ion beam trajectories with and without space charge have been determined and, from the results, optimum extraction conditions have been deduced. Simulation of singly charged ion trajectories for a concave meniscus with 4 mm curvature radius was studied with and without space charge has been done using a singly charge argon ion trajectories. Firstly, for a concave meniscus with 4 mm curvature radius, the influence of the current density on the ion beam shape was investigated. Furthermore, influence of the acceleration voltage applied to the second electrode on the ion beam envelope was studied. Finally, the influence of the extraction gap width on the ion beam envelope was also studied.

KEYWORDS

Ion Beam Emittance, Pentode Extraction System, First and Second Extraction Gap Widths.

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INTRODUCTION

Today, every ion source is studied by computer simulation before any part of its optical system is fabricated [1]. Sophisticated techniques for simulating the actions of electric fields on the motion of charged particle beams under their influence have greatly facilitated the design of beam transport components (extraction systems, lenses, magnets, steerers, deceleration/acceleration electrode systems, etc.) with low-aberration effects. Extraction and focusing are strongly influenced by the kind and geometry of the electrode system, the plasma parameters inside the ion source chamber as well as by the ion beam spatial charge.

Optimization of the beam optics should result in a significant improvement in the emittance of the source [2-3]. The extracted current is limited by the emission capability from ion sources with fixed emitting surface or by space charge forces resulting from plasma sources. For sources with a solid emitting surface (field and surface ionization sources) the area of the plasma is given by the geometry of the emitting surface.

Ion beam properties are determined by the emitting area, the shape and the temperature of the emitted particles. In the case of the plasma sources, the shape of the plasma surface is not fixed by any mechanical operation but is determined by the rate of the influx of the ions from the plasma surface and the rate of withdrawal by the potential on the extractor.

The extraction of an ion beam from the plasma boundary in the plasma ion sources is an important mechanism. The second important step for plasma ion sources after the production of suitable plasma is to extract the plasma ions in the form of an ion beam with given energy. This can be done by using an electrode system that is biased at a negative voltage with respect to the plasma.

The extraction systems for the different types of the ion sources consisting the plasma electrode and grounded puller are used. During the last several years many designers have tried to find the different shapes of electrodes, more complicated, but with better parameters of the extracted ion beams [4].

The ion beam extraction from an ion sources is affected by many parameters as geometry, kinds of electrodes and applied potentials, space charge of the extracted beam and the shape of the plasma boundary. This plasma boundary itself is dependent on the plasma density, the extraction field strength and the electron distribution of the slow electrons [5-7].

This work studies the influence of various parameters and conditions on the performance of an ion-beam extraction system, the trajectories of the particles in the beam being simulated by SIMION 3D,v.7. Space-charge effects are accounted for and criteria allowing optimization of the system are proposed. Ion beam trajectories with and without space charge have been determined and, from the results, optimum extraction conditions have been deduced.

Theoretical Treatment of extraction system

The extraction system is a series of electrodes with the purpose of accelerating and guiding the ions that come out of the source to the beam line. The minimum number of electrodes is two (diode system). This includes the plasma electrode, which is in contact with the ion source plasma and has a hole, the extraction aperture, through which the beam can exit the source. The plasma electrode is at the same potential as the source itself. The distance between plasma electrode and the next electrode is usually called extraction gap. Often a puller electrode is added, which is biased negatively with respect to ground potential to keep electrons created further along the beam line from back-streaming into the source. This improves source stability. The simplest system including such a puller electrode consists of three electrodes (plasma-, negative-, ground potential) and is called accel-decel triode system [8]. More sophistiecated designs exist with even more electrodes on individually adjusted potentials (four electrodes - tetrode system, etc.) [9].

The theoretical description of the extraction of ions from the plasma is not as simple as the electron beam formation. The difference is related to the shape of the plasma edge that changes with the extraction potential and the gas pressure. The working principle of a plasma ion source is divided into two functional parts. A plasma generator is needed for the ion production and an extraction system is required for the beam formation. In any case, the Child-Langmuir law must apply for the space charge dominated region [10]:

$$J = \frac{4}{9}\varepsilon_0 \sqrt{2q/m_i}\,\frac{U^{3/2}}{d^2} \rightarrow I = \frac{4\pi}{9}\varepsilon_0 \sqrt{2q/m_i}\,U^{3/2}S^2 \qquad (1)$$

with $S = \frac{r}{d}$, the aspect ratio of the distance between the plasma electrode and the orifice radius of the plasma electrode r.

With the electric field strength, the law can be re-written as:

$$J = \frac{4\pi}{9}\varepsilon_0 \sqrt{2q/m_i}\,\sqrt{S}\cdot r^{3/2}E^{3/2} = 1.7 * 10^{-7}\sqrt{q/A}\,\sqrt{S}\cdot r^{3/2}E^{3/2} \qquad (2)$$

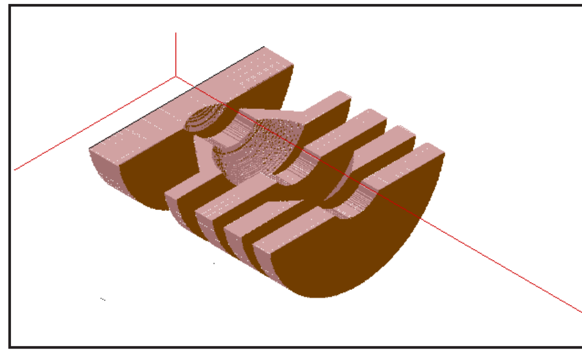
With the design of the extraction system, certain parameters have to be optimized, depending on the application. Nevertheless, following relations are experimentally confirmed.

$I_{tr}\,\alpha\sqrt{q/A}$ and $I_{tr}\,\alpha U^{3/2}$ where I_{tr} is the transported current through the system. A modified Child-Langmuir-law has been determined experimentally:

$I_r = P^* \cdot U^{3/2}\left(\frac{S^2}{1+aS^2}\right)$, where a is the aberration factor = 3 and P^*, Perveance factor, which can be calculated for ideal systems from the perveance of planar systems:

$$P^* = \frac{4\pi}{9}\varepsilon_0 \sqrt{2q/m} \qquad (3)$$

Pentode extraction system (Two-gap-extraction system), in this case, a puller-electrode (PE) supports the beam formation by tuning the Pierce-edge (like in the case of a Wehnelt-electrode). The shielding-electrode (SE) is surrounded by two grounded-electrodes for a more stable operation.



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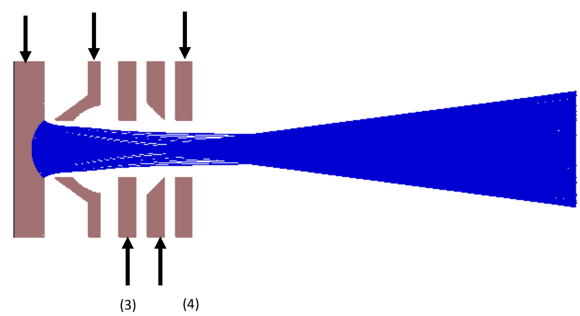


(b)

Fig. (1): Pentode extraction system.
(a) Pentode extraction system geometry with 3D assumed for the SIMION calculations.
(b) Pentode extraction system designed: (1) Plasma electrode, (2) puller electrode (3) ground electrode and (4) shielding electrode, (5) ground electrode.

RESULTS AND DISCUSSIONS

Simulation strategy

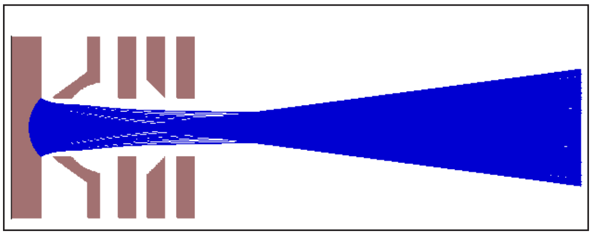
SIMION 3 D Version 7.0 is a software package[11, 12] primarily used to calculate electric fields and the trajectories of charged particles in those fields when given a configuration of electrodes with voltages and particle initial conditions, including optional RF (quasistatic), magnetic field, and collisional effects. This program provides extensive supporting functionality in geometry definition, user programming, data recording, and visualization.. In general, the fundamental steps for simulating the properties of a model extraction system are to define the physical and electrical boundaries of the electrodes. SIMION defines the ions that make up the beam, selects output data to be recorded and simulates ion accelerated trajectories through the extraction system. Each electrode of this extraction system is 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 takes the potentials of the electrode points to calculate the potential at the non-electrode points. Once all electrodes are designed and defined within a potential array, SIMION solves Laplace's equation:

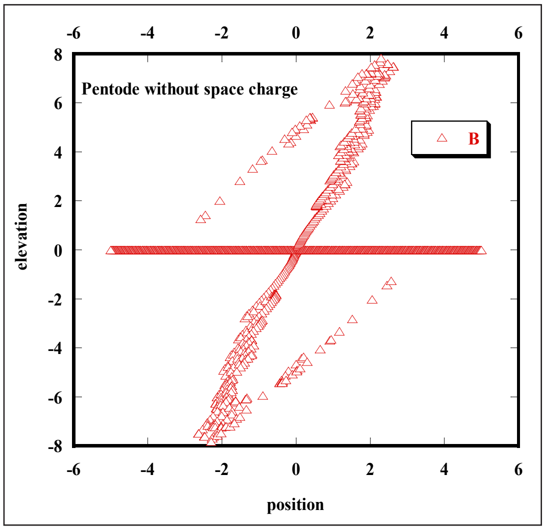
$$\nabla^2 V = 0 \tag{4}$$

SIMION uses a highly modified 4^{th} order Runge-kutta technique for modelling the ion trajectories. Ion trajectories are a result of electrostatic and space charge repulsion forces on the basis of the current position and velocity of the ions. These forces are then used to compute the current ion acceleration and used by numerical integration techniques to predict the position and velocity of the ion at the next time step. Electrostatic forces are initially computed in terms of volts per grid unit. As the ion progresses through the potential array it moves from one square of grid points into another. SIMION automatically generates a small 16 point array that represents the current for four grid points and the 12 grid points around it. The values of these grid points are determined by symmetry assumptions and grid point location. The potential at each point is normally calculated via linear interpolation using four grid points bounding the grid square it falls in. When an ion is outside electrostatic instances, SIMION looks both directions along its current trajectory path for the closest electrostatic instance of intersection in both directions. If the present ion trajectory intersects electrostatic instances in both directions, SIMION will determine the potentials at the points of intersection and estimate the resulting electrostatic acceleration assuming a linear gradient.

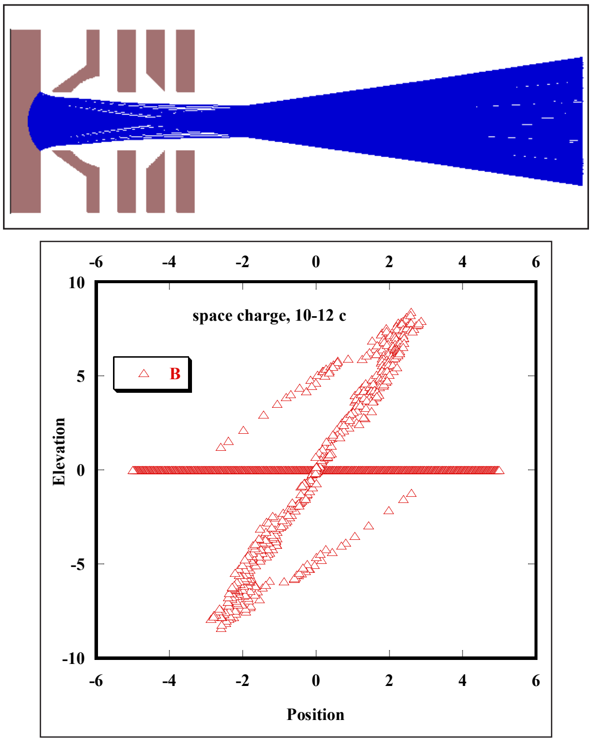
The influence of the current density

Simulation for singly charged ion trajectories in the extraction region was studied without and with space charge at different current densities (between microamps and milliamps) (Fig2.a, b, c and d). The voltage applied to the plasma electrode V_{plasma} = + 50 kV, to the extraction electrode $V_{extract}$ = - 5 k V and to the second acceleration voltage, V_{acc} = + 30 kV. It was found that space charge nearly had no influence on the ion beam envelope for currents of microamps. The space charge started to show a clear influence on the ion beam envelope at currents of 0.1 mA (Fig. 2c). Space charge compensation is expected downstream of the potential minimum located approximately 420 mm from the plasma electrode. The residual gas particles in the beam line will be ionized by ion beam impact and thus a sufficient number of compensating electrons is generated which must be kept from being accelerated back into the source by the extraction field.

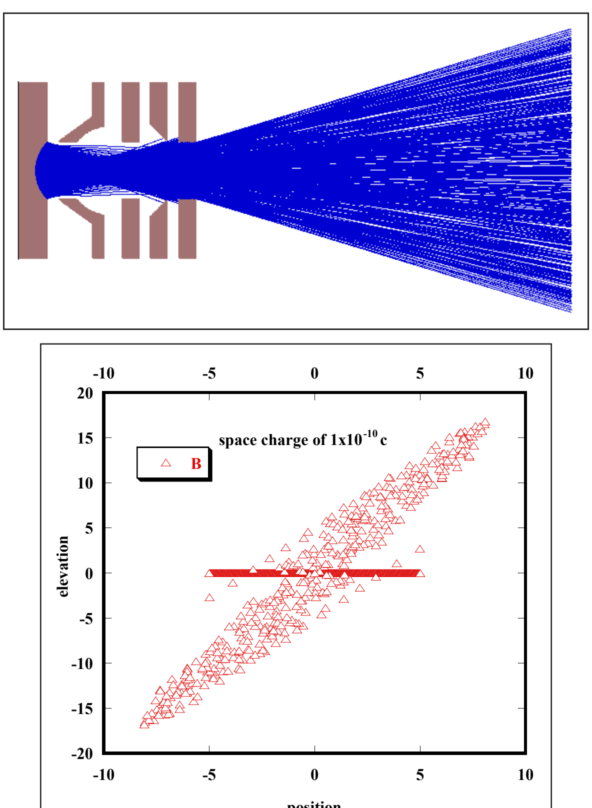




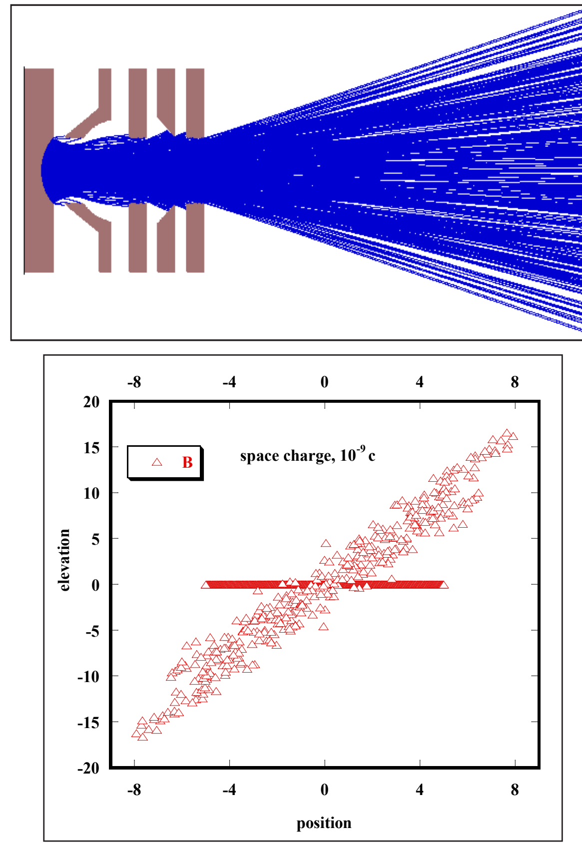
(a) Without space charg



(b) Current density of 1 mA.



(c) Current density of 10 mA.



(d) Current density of 50 mA.

Fig. (2): The influence of the current density on the ion beam envelope for singly charged ions with 4 mm curvature radius of a concave plasma meniscus.

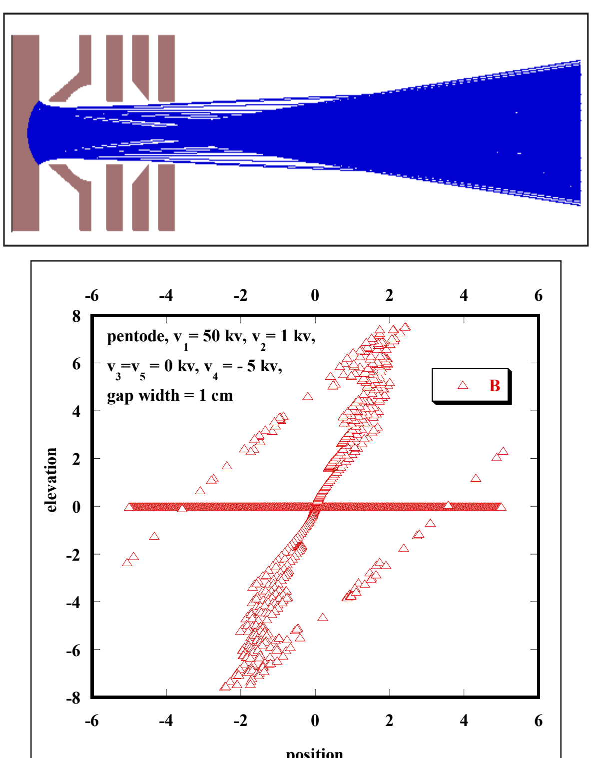
Fig. 2d is expected to 10 mm. The space charge action depends on the geometry of the electrodes, the applied potentials and the ion current. Therefore, a change of the ion current has now a clear influence if all other parameters remain fixed. The space charge force acts as a diverging force because particles of the same charge repel each other. The effect of space charge on ion trajectories is shown in Fig.2a, b, c and d for four values of space charge parameter. As is well known, there is a matching value for space charge which corresponds to minimum beam divergence. This matching value is shown in Fig. 2 c.

The influence of the acceleration voltage on the ion beam envelope

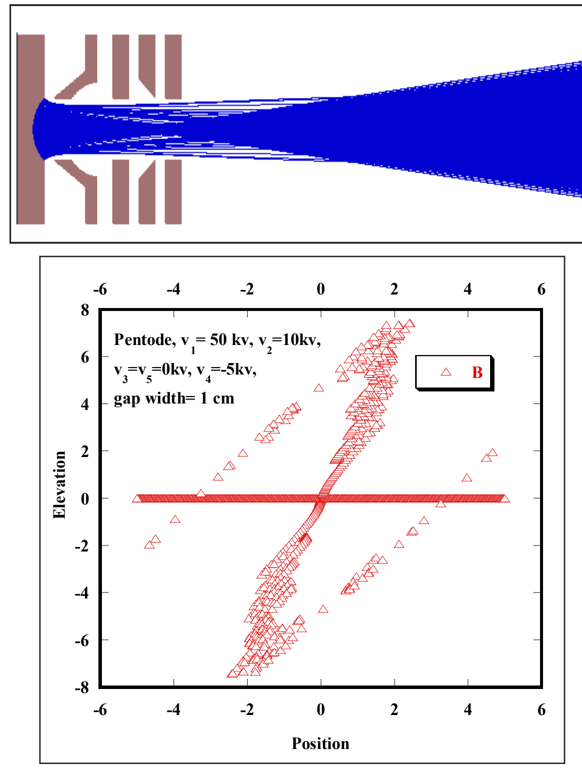
In order to examine the ion acceleration characteristics of the pentode extraction system for a concave meniscus with 4 mm curvature radius, a variable voltage was applied to the acceleration electrode (Fig 3a, b, c). The plasma boundary was assumed approximately spherical with its centre of curvature outside the plasma. The plasma electrode was set at a voltage V_{plasma} = + 50 kV.

Simulations were done for singly charged ions and different voltages applied to the acceleration electrode. The optimum voltage applied to the acceleration electrode was found at voltage $V_{extract}$ = + 30 kV, where the ion beam envelope passed fully into the extraction region without hitting the electrodes of the pentode extraction system (Fig. 3a).

At a larger voltage, the ion trajectories were compressed due to the action of the electric field (Fig. 3b). With further increasing the voltage applied to the extraction electrode, the position of the ion beam waist changed, and therefore the ion trajectories made a second cross over downstream into the extraction region (Fig. 3c).



(a)



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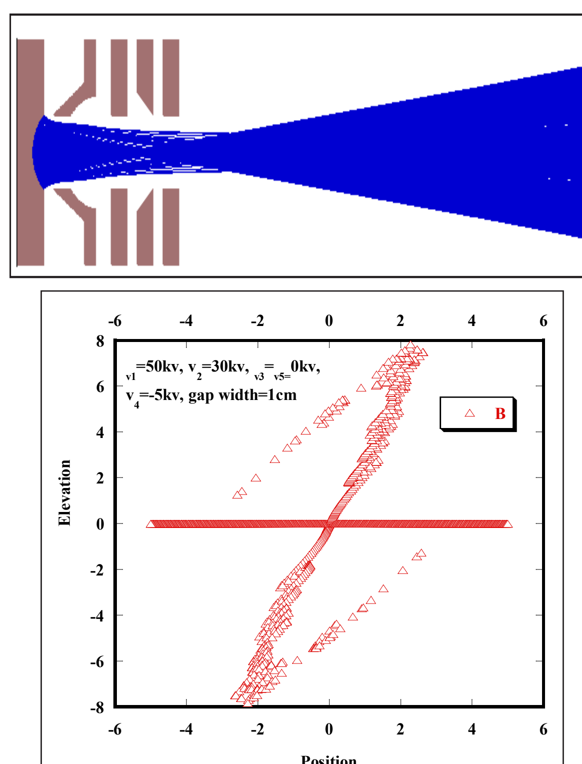

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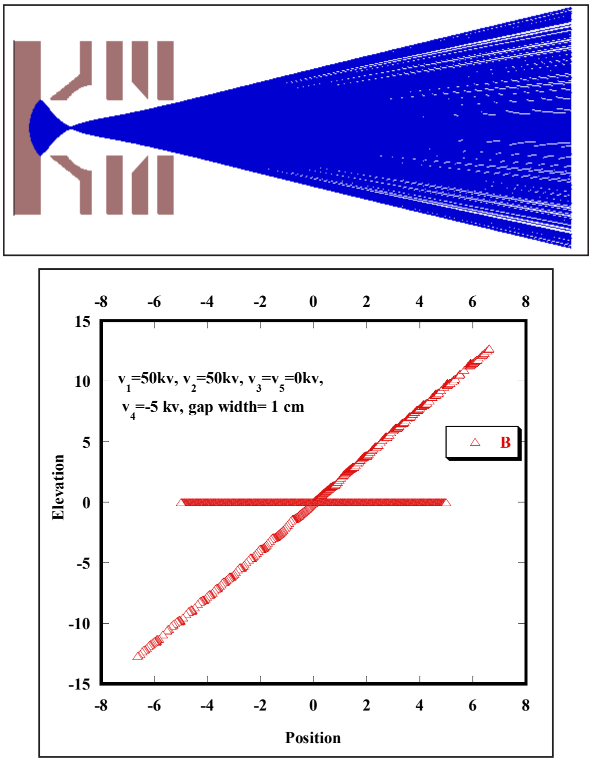
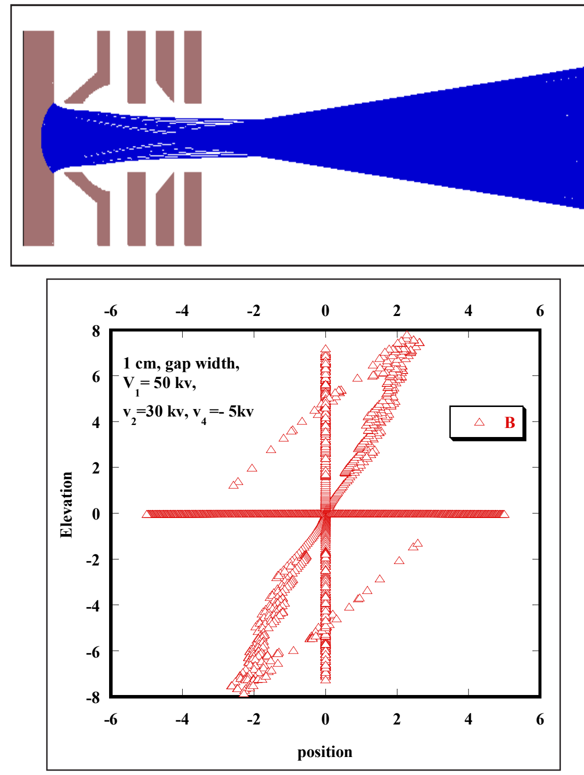


(d)

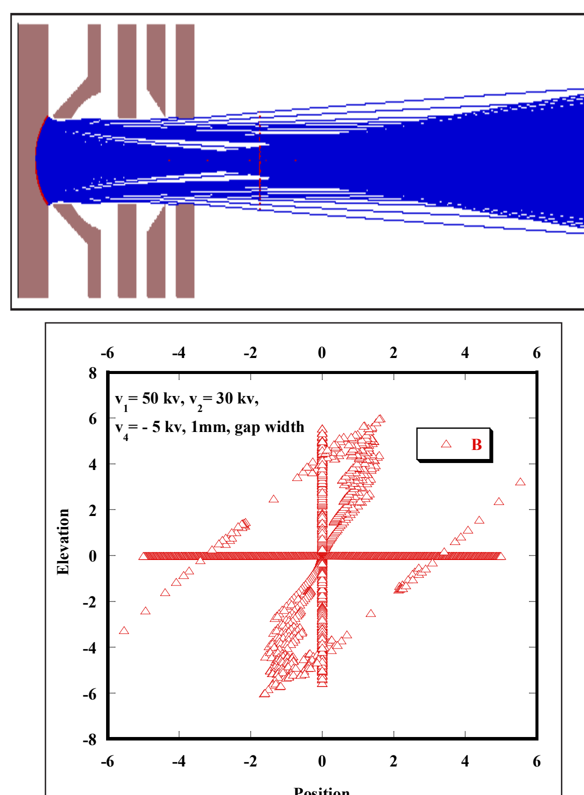
Fig. (3): The influence of the voltage applied to the acceleration electrode on the ion beam envelope for singly charged ions with 4 mm curvature radius of a concave plasma meniscus.

The influence of the extraction gap width on the ion beam envelope

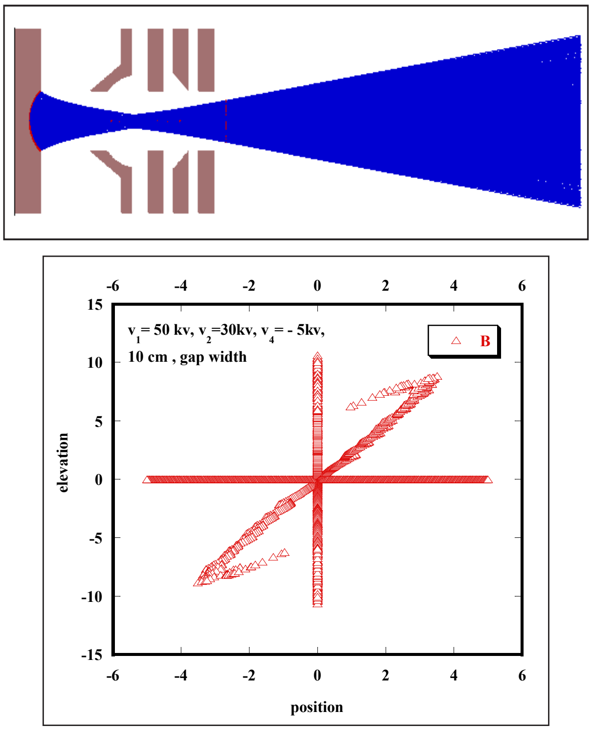
The influence of the distance between the plasma electrode and the extraction electrode (extraction gap width) on the ion beam envelope was investigated for a concave meniscus with 4 mm curvature radius. In these calculations, the voltage applied to the plasma electrode was V_{plasma} = + 50 kV. The voltage applied to the extraction electrode was fixed to $V_{extract}$ = – 5 kV, permitting the ion beam envelope to remain narrow in the extraction region and the voltage applied to the acceleration electrode, V_{acc}= 30 kV. Simulation for singly charged ion trajectories at different geometrical distances was done. The variation of the extraction gap width results in the variation of the shape of the ion beam envelope and the position of the ion beam waist (Fig. 4a, b, c). It was found that the optimum extraction gap width is 1 cm. At this distance, the ion beam envelope was



(a) Gap widt,1 cm.



(b) Gap width, 1 mm.



(c) Gap width, 10 cm.

Fig. (4): The influence of the extraction gap width on the ion beam envelope for singly charged ions with 4 mm curvature radius of a concave plasma meniscus.

best passed through the extraction region (Fig. 4b). The ion beam waist was downstream approximately 18 mm from the plasma emission surface. As the extraction gap width increased, (d = 10 cm) (Fig. 4c), the ion trajectories made a cross over downstream of the extraction region and the ground electrode of the triode extraction system. At this distance, the ion beam waist was downstream nearly of 25 cm from the plasma emission surface. When the extraction gap width is decreased, (d = 1 mm), the size of the ion beam waist was compressed and moves downstream to 10 mm from the plasma electrode, therefore a cross over is made and were hitting all the electrodes.

CONCLUSION

This paper studies the influence of various parameters and conditions on the performance of an ion-beam extraction system, the trajectories of the particles in the beam being simulated by commercial software (SIMION 3D v7). Space-charge effects are accounted for and criteria allowing optimization of the system are proposed. Simulation process for the extraction region of the diode extraction systems for a singly charged argon ion trajectories has been done. Optimum extraction conditions for the high current ion sources have been determined and deduced. The optimum voltage applied to the extraction electrode was found at voltage $V_{extract}$ = – 5 k V and to the acceleration voltage, V_{acc} = + 30 kV, where the ion beam envelope passed fully into the extraction region without hitting the electrodes of the diode extraction system.). It was concluded that the optimum extraction gap width is 1 cm. At this distance, the ion beam envelope was best passed through the extraction region. Finally, space charge compensation is expected downstream of the potential minimum located approximately 420 mm from the plasma electrode.

REFERENCES

1. R. Becker, Rev of Scientific Instrum 77 (2006).
2. M. Turek et al, Vacuum **78**, 649 - 654 (2005).
3. J.W.G Thomason et al, Proceedings of EPAC 2004, Lucerne, Switzerland.
4. A. Zelenak and S. L. Bogomolov, Rev. Sci. Instrum., **75**, 1672 (2004).
5. J. H. Whealton and J. C. Whitson, Particle Accelerators, Vol. 10, (1980).
6. A. Septier, Focusing of Charged Particles, Vol. II, Academic press, New York (1967).
7. HP. Winter, Production of Multiply Charged Heavy Ions, in Lecture notes in Physics, Vol. 83, ed. K. Bethge, Springer, Berlin 1978, 2 – 80.
8. M.M. Abdelrahman, Arab Journal of Nuclear Sciences and Applications, 45(2)254-262(2012).
9. R. Keller, Workshop on "High-Current, High-Brightness, and High-Duty Factor Injectors" San Diego, California, USA (May 21-23, 1985).
10. R. Hollinger, in The Physics and Technology of Ion Sources, I.G. Brown (Ed.), John Wiley, New York (2004).

11. P.R. Hobson et al, Nucl. Instrum and Meth in Phys Res A, 567, 225 (2006).

12. D. A. Dahl, SIMION 3 D Version 7.0 User's Manual INEEL – 95 / 0403, Idaho National Engineering and Environmental Laboratory, I D 83415 (2000).