Research paper

Determination of the optimum design and extraction optics for a glow discharge Ion source

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Abstract

This study of the extraction system of a glow discharge ion source, with a view to optimizing its geometrical and physical parameters, followed by comparison with experimental data taken at the optimal conditions. Simulation of the nitrogen ion trajectories with the SIMION 3D, version 7.0, package was done to optimize the extraction system of a glow discharge ion source and compared the results with experimental data obtained under the same operational conditions. The simulation investigated the influence of space charge effect and the extraction gap width that maximize the ion beam current for singly charged nitrogen ions. The experiment measured the input electrical discharge and output ion beam characteristics of the source at different nitrogen pressures. The extractor electrode voltage and the extraction gap width were determined at 1×10^{-3} Torr nitrogen gas. The results of the simulation process agreed well with the experimental data.

Keywords: SIMION computer program, nitrogen ion trajectories and beam emittance, extraction system and glow discharge ion source.

Introduction

The performance of an ion-beam source depends critically on the design of its electrodes **[1-2],** which determines the electric-field configuration at the surface of the source and along the acceleration path **[3-7].** To simulate the ion beam extraction system, we used version 7.0 of the commercial ion/electron optic-simulation program SIMION 3D **[8-10].** This enables the tracking of electrons or ions through static and magnetic fields defined by a three-dimensional geometric electrode model. 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 **[11-16].** 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 value of the extracted ion current should be large, its divergence low and the ion losses to the extractor must be small. The ideal ion source featured by the following characteristics:

(1)The discharge should be of width comparable with the diameter of the extraction orifice

(2) The efficiency of ionization must be as maximum as possible to prevent escape of neutral atoms through the extraction orifice

(3) To avoid the presence of aberrations, the plasma boundary should be plane or slightly spherical in shape with constant current density everywhere.

When potential difference is sufficiently applied across two electrodes in a chamber containing a gas at low pressure, a glow discharge is initiated and can be maintained. It is, therefore, a stage characterized after a gas experiences an electrical breakdown when its neutral atoms are ionized leading to the formation of glow discharge plasma **[17-19].** Over a number of decades, glow discharges have been the subject of considerable researches and a wide area of applications in science, technology, and industry **[20].**

Experimental outline

Figure 1 schematically shows a glow discharge ion source with its electrical circuit comprising a plane copper cathode with different hole diameters at the top and a hollow st. steel anode connected with a plane of diameter 2 mm at the bottom. The anode has an internal diameter equal to 20 mm and its length is equal to 20 mm. The copper cathode has different holes to permit the gas flow through the anode cylinder. Both the anode cylinder and the plane cathode are immersed in an insulator of Perspex material. The collector (Faraday cup) is situated at a distance of 5 cm from the ion exit aperture of the plane anode and used to measure the output ion beam. The working gas is admitted to the ion source through a hose fixed in a Perspex flange at the upper side of the cathode. A 10 KV power supply is used for initiating the discharge (glow discharge) between the anode and the cathode. The ion source was cleaned before introducing inside the vacuum system. It was polished, and washed by acetone. The polishing of the electrode parts should remove the irregular parts from their surfaces and the contamination due to the erode materials of the discharge. The assembled ion source was placed inside the vacuum chamber. The ion source terminals (the anode terminals, the cathode terminal, the extractor terminal and the Faraday cup terminal) are connected by wires to the end connection fixed into the Perspex flange.

A complete vacuum system is used to evacuate the ion source chamber. It consists of stainless steel mercury diffusion pump of speed 270 L / S provided with electrical heater and backed by 450 L / min. rotary fore vacuum pump. The rotary pump is used to evacuate the system with ultimate pressure of 10^{-2} to 10^{-3} mbar, while the mercury diffusion pump is used to yield low pressure in the ion source vacuum chamber of the order of 10^{-5} mbar. The mercury diffusion pump is surrounded by water tubes for cooling during the operation. A liquid nitrogen trap is fixed between the ion source chamber and the mercury oil diffusion pump in order to prevent the mercury vapour from entering the ion source chamber. The working gas is transmitted to the ion source from a gas cylinder through a needle valve to regulate the rate of gas flow.

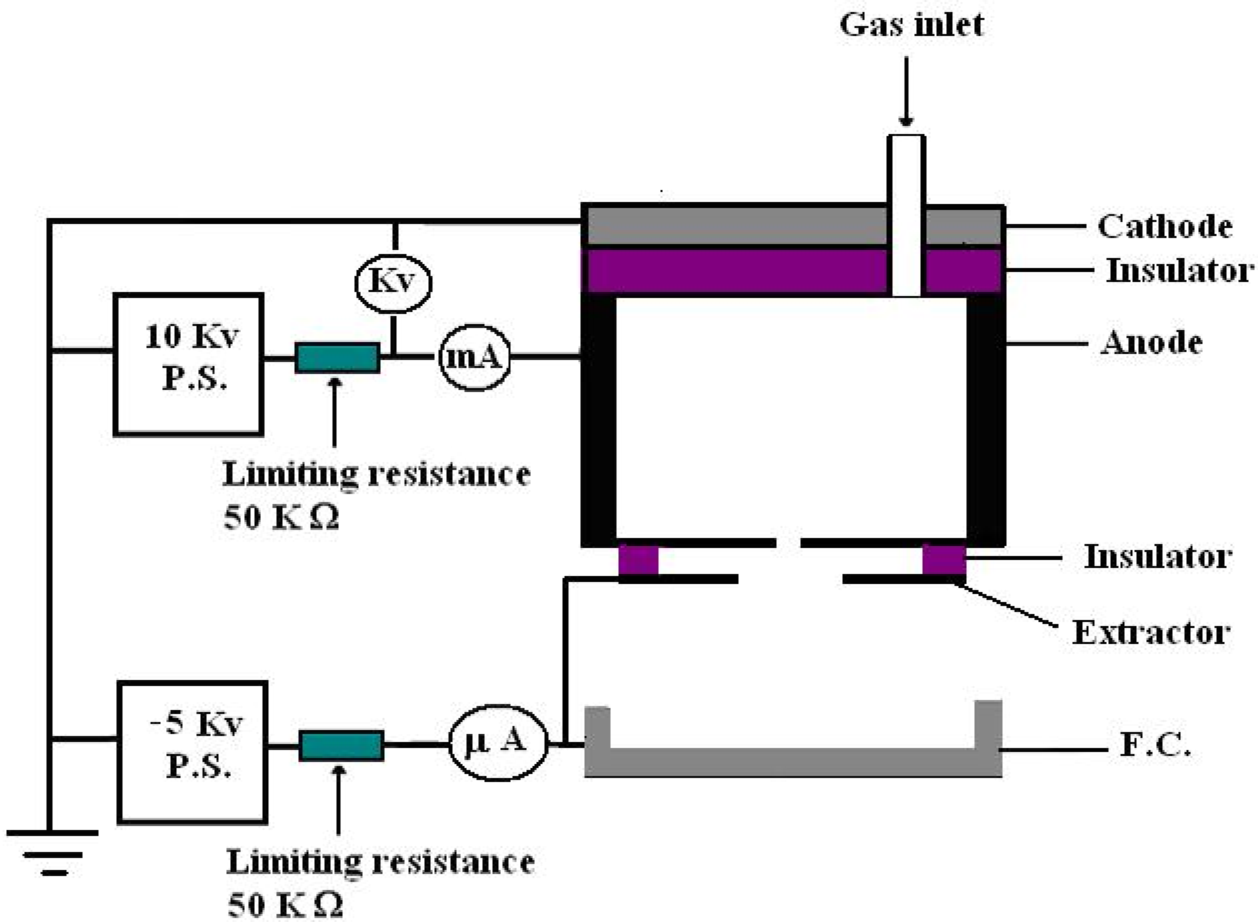


Fig. 1: schematic view of a glow discharge ion source with its electrical circuit.

Results and Discussion

Figure 2 shows the discharge characteristics using nitrogen gas, i.e., the relation between the discharge voltage V_d and the discharge current I_d at different operating gas pressures for the gap distance between the anode and the cathode of 3 mm and with a distance between the anode and the extractor = 6 mm. From this figure, it was found that an increase of the discharge voltage was accompanied by an increase of the discharge current, where the characteristics of such discharge is known as abnormal glow **[21].**

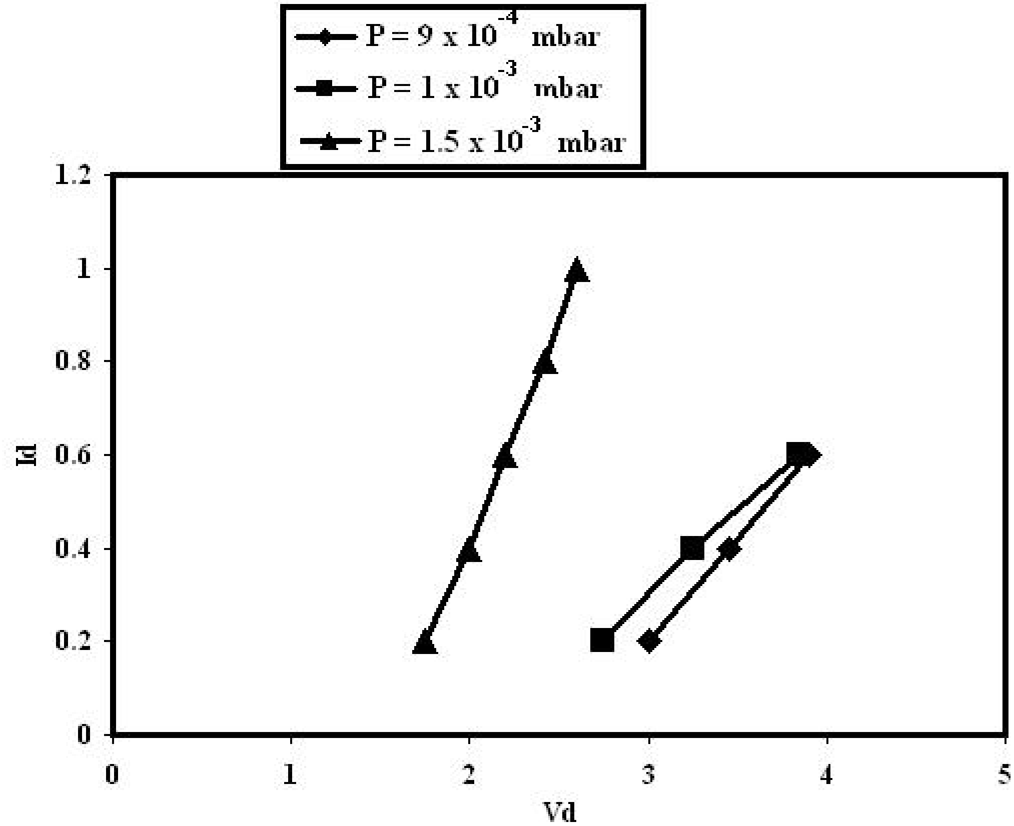


Fig.2: Relation between discharge voltage and discharge current at different nitrogen gas pressure with a distance between the anode and the extractor = 6 mm.

Figure 3 shows the ion beam efficiency, i.e, the relation between the discharge current and the output current at different operating gas pressures for the gap distance between the anode and the cathode of 3 mm and with a distance between the anode and the extractor = 6 mm. From this figure, it is clear that, when the discharge current increases, the output beam current increases and reaches a value of 50 µA.

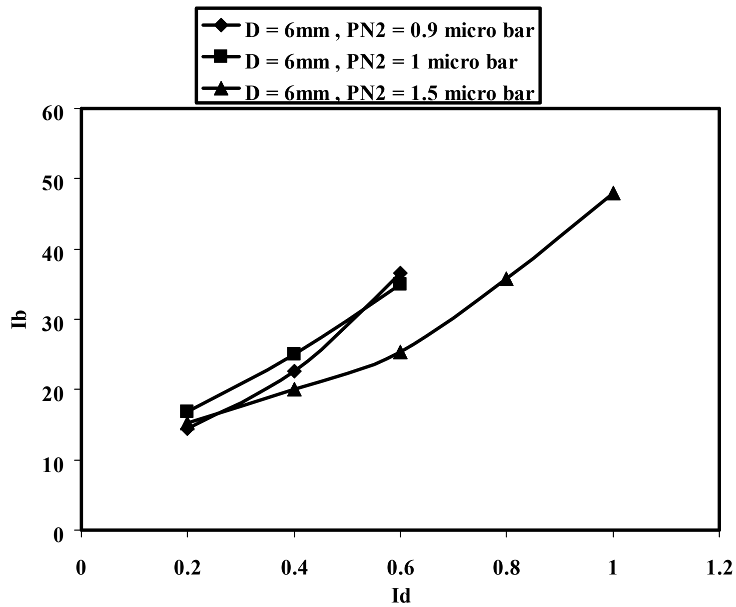


Fig.3: Relation between discharge current and output current at different nitrogen gas pressure with a distance between the anode and the extractor = 6 mm.

Figure 4 shows the influence of the extraction voltage applied to the extraction electrode on the ion beam current at a pressure of $1x10^{-3}$ mbar, the distance between the anode and the extractor = 6 mm, and with different discharge currents for extraction hole diameter of 7 mm. It is seen from this figure that a maximum ion beam current can be obtained at an extraction hole diameter of 7 mm, where the ion beam current reaches 80 µA at extraction voltage - 3 kV.

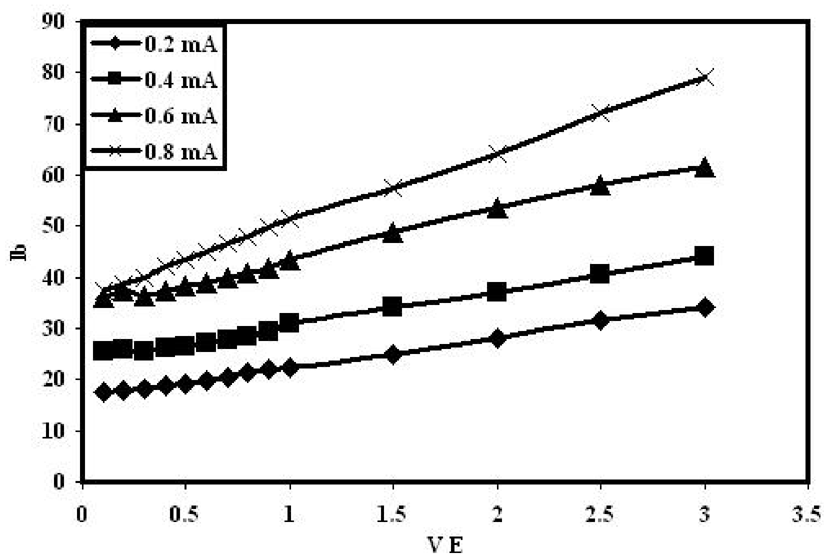


Fig. 4: Relation between extraction voltage and extracted ion beam at pressure 1×10^{-3} mbar, different discharge currents and a distance between the anode and extraction electrode = 6 mm.

Figure 5 shows the relation between extraction voltage and extracted ion beam at pressure 1 x 10^{-3} mbar, 0.4 mA discharge current and different distances between the anode and extraction electrode. It is seen from this figure, the maximum output beam current could be obtained at distance of 6 mm.

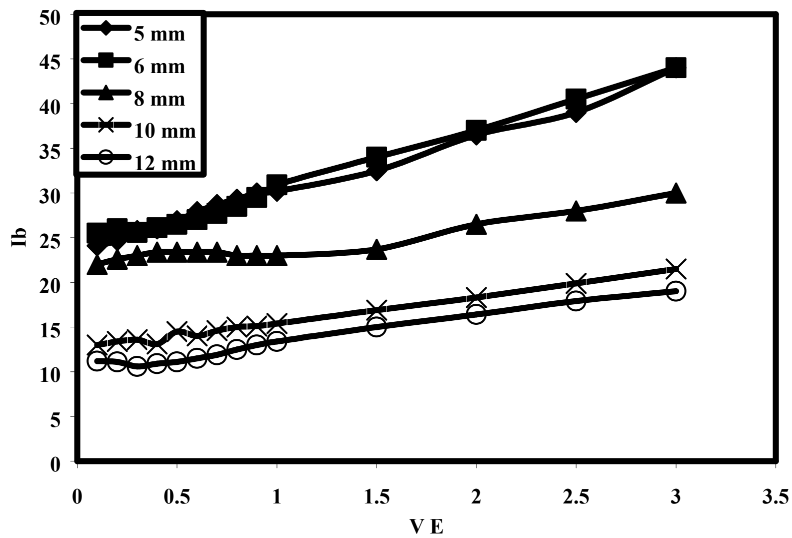


Fig. 5: Relation between extraction voltage and extracted ion beam at pressure 1 x 10^{-3} mbar, 0.4 mA discharge current and different distances between the anode and extraction electrode.

Fig.6 shows the relation between the separated distances of anode and extraction electrode and extracted ion beam at pressure 1 x 10^{-3} mbar, 0.4 mA discharge current and -1.5 Kv extraction voltage. It is clear from this figure that the maximum and minimum output beam current could be obtained at a distance of 6, 12 mm, respectively.

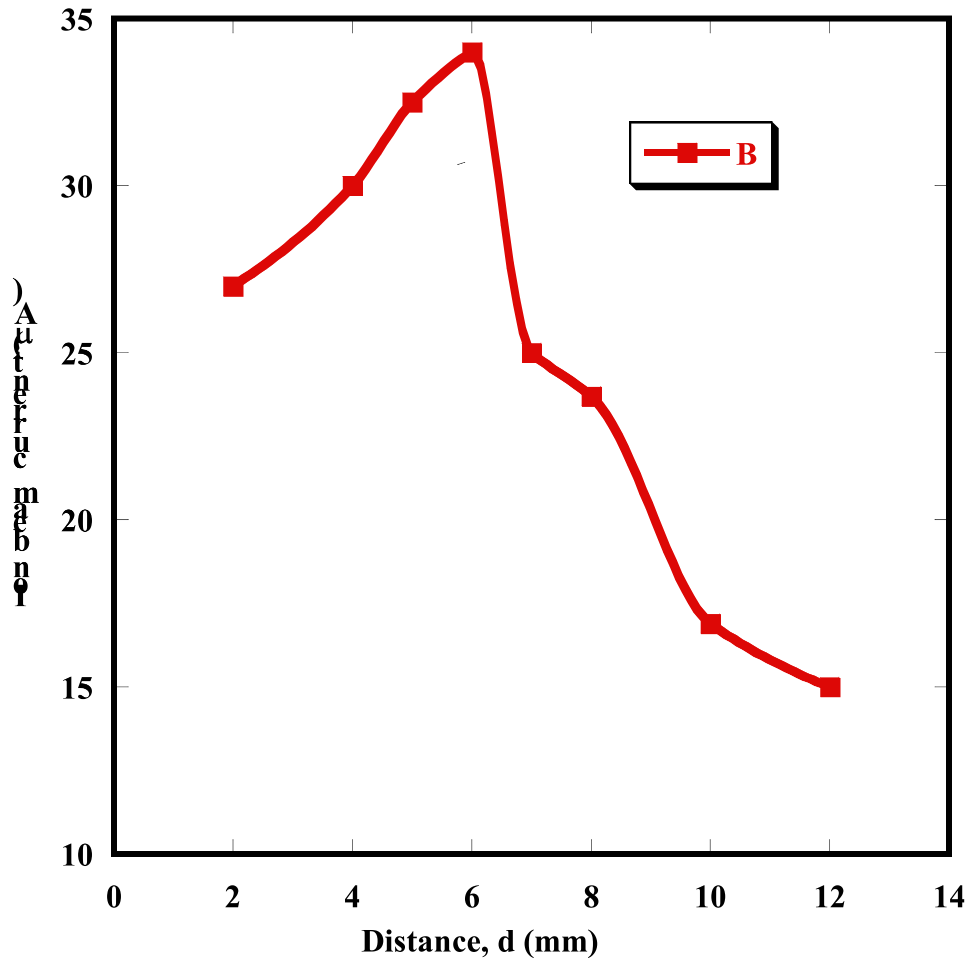


Fig. 6: Relation between the separated distances of anode and extraction electrode and extracted ion beam at pressure 1 x 10^{-3} mbar, 0.4 mA discharge current and -1.5 Kv extraction voltage.

Theoretical aspects for ion beam simulation in the extraction region

Ion beam extraction from ion sources is influenced by many parameters such as electrodes geometry, applied extraction voltage, space charge in the extracted beam and finally the shape of the plasma boundary. In general, the first 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 are making the beam, selects output data to be recorded and simulates ion trajectories through the extraction system. Each electrode of the diode 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 the electrode points to calculate the potential at the non-electrode points. Once all three electrodes are designed and defined within a potential array, SIMION solves the Laplace's equation:

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

In order to simulate the charged particles using SIMION program, a basic equations concerning the motion of charged particles in vacuum are:

$$\frac{d}{dt}(mv) = q.(E + v \times B) \tag{2}$$

where E the electric field, B the magnetic flux density, m , q and ν are the mass, charge and velocity of charged particle, respectively and in our case, no magnetic field exists, so, B= 0. If work is done on a charge it gains energy as:

$$\frac{1}{2} m v_d^2 = eV \tag{3}$$

where v_d is a drift velocity. The energy eV can be gained by moving a given distance, x_1, in the direction of an electric field **[22]:**

$$eV = \int_0^{x_1} eE dx . \tag{4}$$

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. The field strength in the extraction area determines the reduction of the plasma density of the plasma-sheath and how far the extraction potential reaches into the plasma.

In any case, the Child-Langmuir law must apply for the space charge dominated region:

$$J = \frac{4}{9}\varepsilon_0 \sqrt{\frac{23q}{m_i}} \frac{U^{\frac{3}{2}}}{d^2} \rightarrow I = \frac{4\pi}{9}\varepsilon_0 \sqrt{\frac{2eq}{m_i}} U^{3/2} S^2 . \tag{5}$$

where $S = \frac{r}{d}$ is the spect ratio of the distance between the Plasma electrode and the extraction electrode and the orifice radius of the plasma electrode r.

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

$$I = \frac{4\pi}{9}\varepsilon_0\sqrt{\frac{2eq}{m_i}}\sqrt{S}.r^{3/2}.E^{3/2} = 1.7\times10^{-7}\sqrt{\frac{q}{A}}\sqrt{S}.r^{3/2}.E^{3/2} \tag{6}$$

Fig.7 shows the relation between the distance and the electric field with different applied voltages on the ion source. It is shown from this figure, at distances from 1 to 5 cm, an increase of the distance was accompanied by a decrease of the electric field while at distances from 5 to 9 cm, a slightly decrease was obtained for an eelctric field.

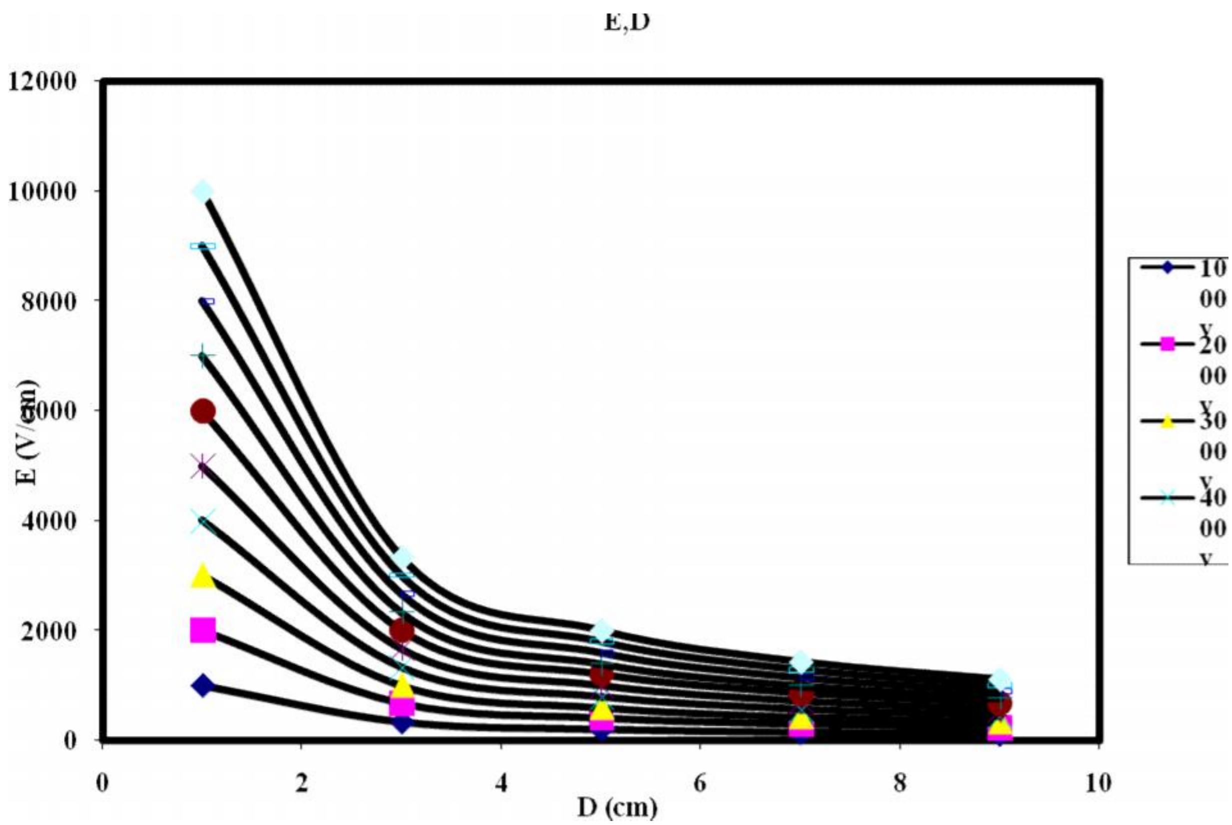


Fig.7: Relation between the distance and the electric field with different applied voltages on the ion source.

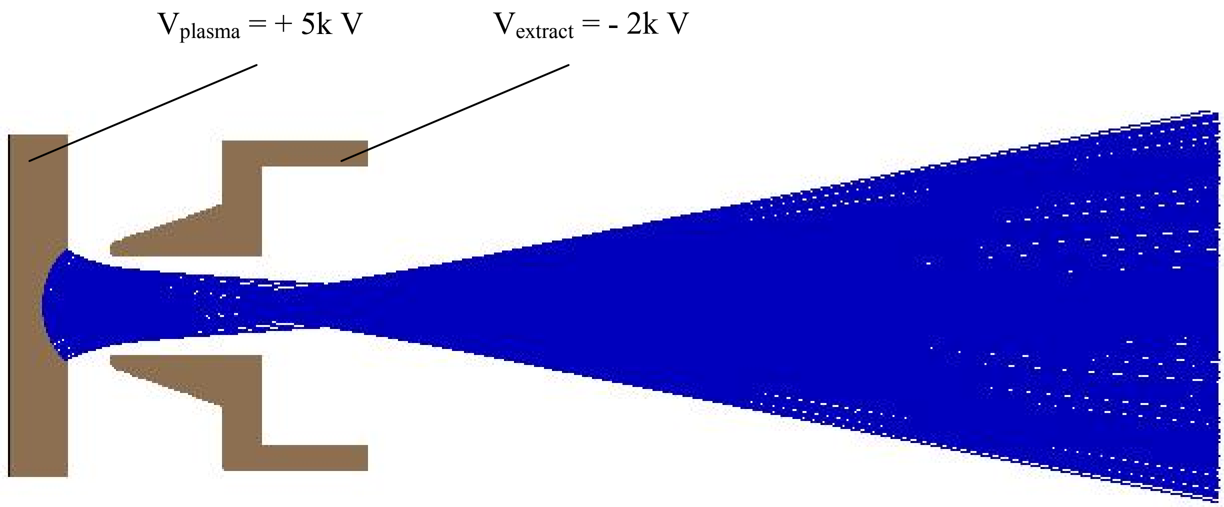
The influence of the space charge on the ion beam envelope

In order to extract ion beams from the appropriate ion source, an arrangement of carefully designed 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. The surface which forms the source of ions can be either of fixed geometry (surface ionization and field ion sources) or it can 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 must initiate the ion beam as free of aberrations as possible. Pierce solved the problem of extracting an absolute parallel beam analytically for electrons. The law found by Pierce was not suited for the extraction of ions from plasma, especially of high current ion sources for the following reasons:

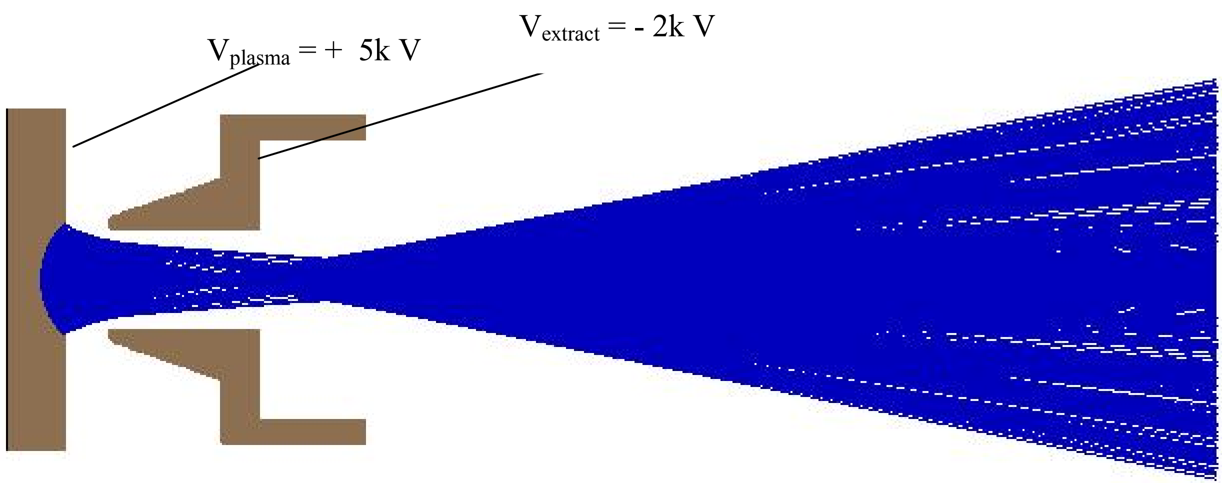
1- Mechanical and power load, where the outlet electrode is not infinitely thin
2- The plasma potential is not exactly the same as the potential of the electrode
3- The plasma cannot deliver the same current density all over the aperture of the electrode because the plasma density decreases near the electrode
4- The equipotential surface near the second electrode is not planar, but curved outward.

In high current ion sources and in transport systems for protons or heavier ions the repulsive force due to the space charge carried out by the beam itself plays an important role for the design of the focusing system and for conservation of beam emittance. The space charge is only considered in the gap between the plasma boundary and the extraction electrode, where the axial potential changes rapidly. In this region, the electrons formed by ion impact on residual gas atoms will always be pulled out of the ion beam. Therefore, in this region space charge repulsion between the ions is important as soon as the ion current density becomes sufficiently large. On the other hand, in a freely drifting ion beam (no acceleration potential applied) space charge compensation will automatically work and therefore space charge repulsion is not considered there. The influence of space charge on the ion beam envelope through the extraction region of ion source was investigated. Space charge was compensated in the extraction region for ion currents between micro amps and milliamps. The same curvature radius for the concave plasma meniscus with 4 mm was assumed. The voltage applied to the plasma-electrode V_{plasma} = +5 kV, the extraction electrode V_{ext} = −2 k V. It was found that space charge has no influence on the ion beam envelope at currents of micro amps. The space charge started to have a clear influence on the ion beam envelope at currents of 10^{-4} A (Fig. 8a, b, c, d). Space charge depends on the geometry of the electrodes, applied potentials and ion current. Therefore, the change of the ion current has a clear influence where other parameters were fixed. The space charge force acts as a diverging force because particles of the same charge repel each other.



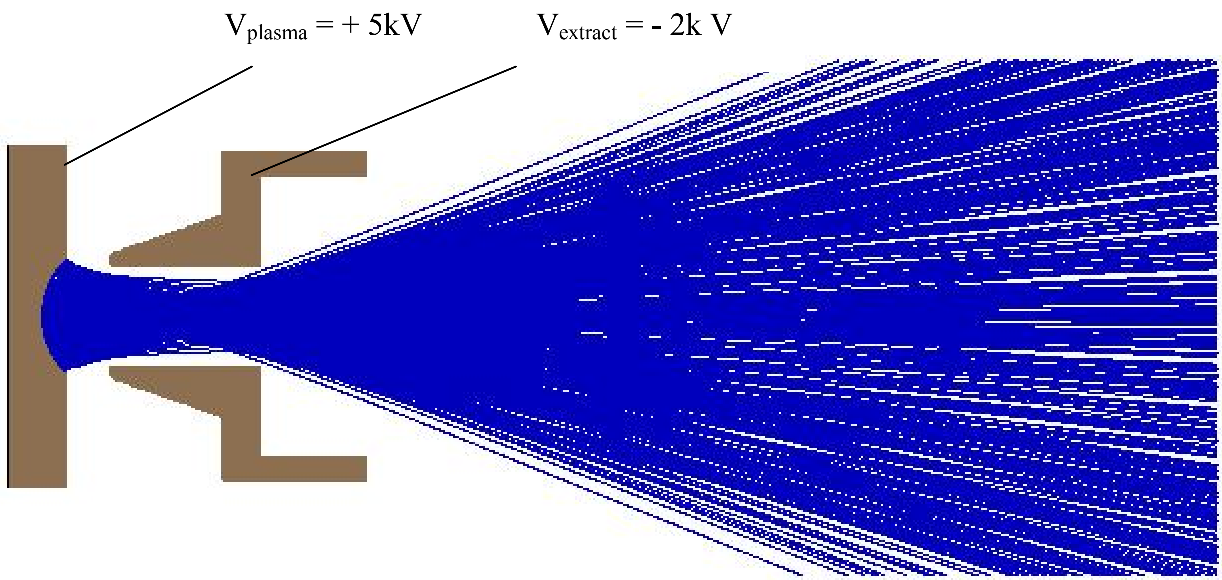
Without space charge

(a)



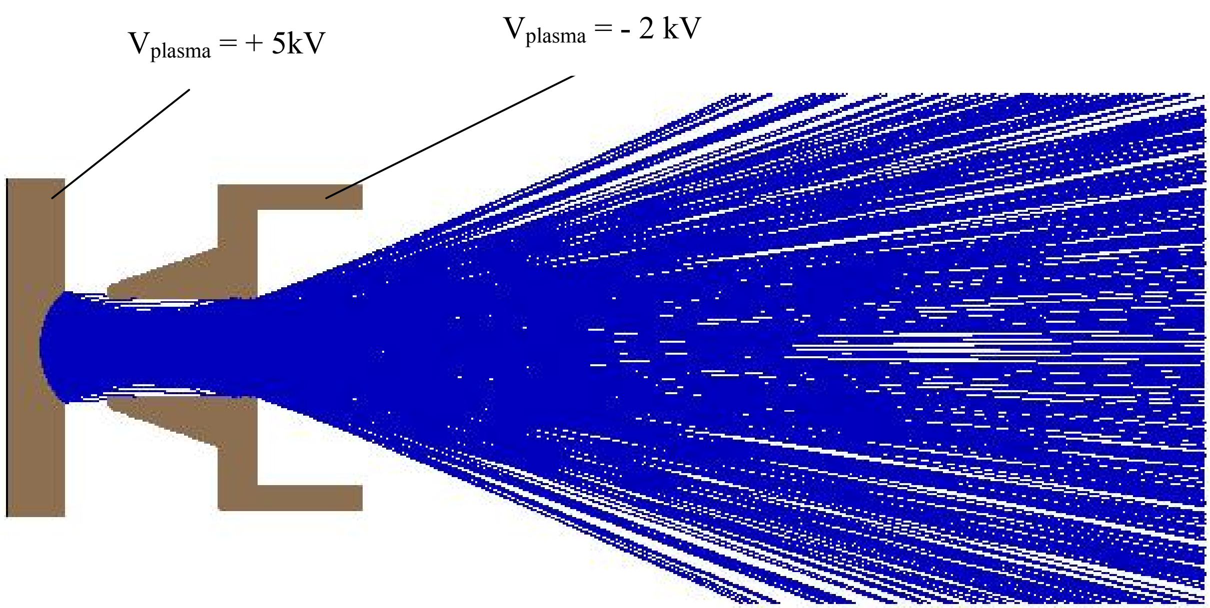
With space charge of 1 microampere

(b)



With space charge of 1 millamp

(c)



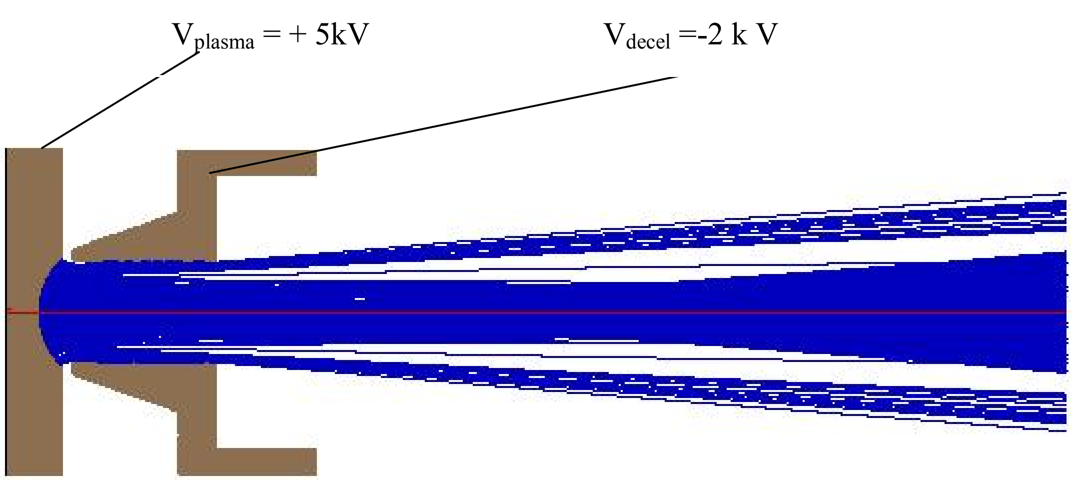
With space charge of 100 millamp

(d)

Fig. 8: The influence of the voltage applied to the extractor electrode on the ion beam envelope for singly charged ions.

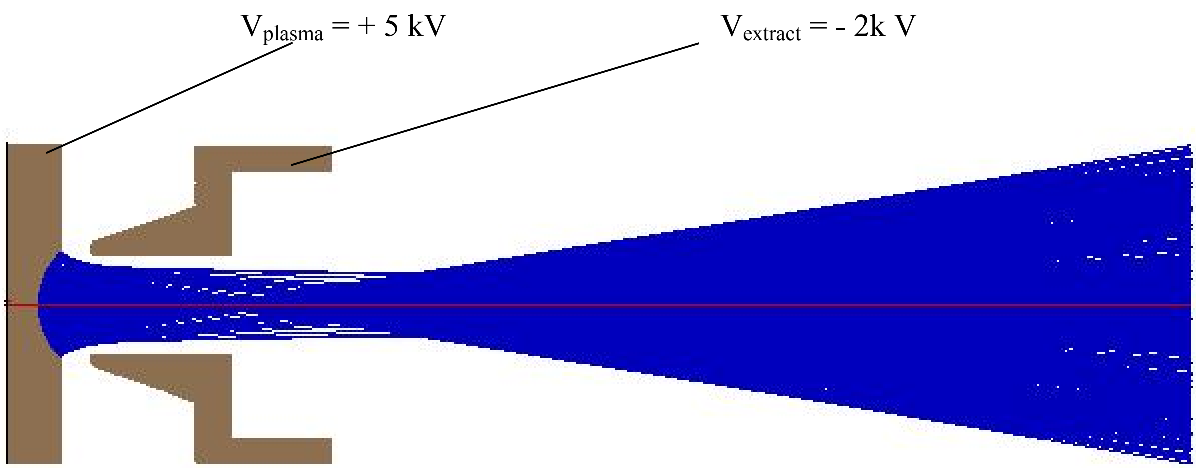
The influence of the extraction gap width on the ion beam envelope

The influence of the distance between the plasma electrode and the extractor 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} = + 5 kV. The voltage applied to the extractor electrode was fixed to $V_{extractor}$= – 2 k V, permitting the ion beam envelope to remain narrow in the extraction region. 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. 9 a, b, c). It was found that the optimum extraction gap width is 3 mm. At this distance, the ion beam envelope was best passed through the extraction region (Fig. 9b). The ion beam waist was downstream approximately 30 mm from the plasma emission surface. As the extraction gap width increased, (d = 20 mm) (Fig. 9c), the ion trajectories made a cross over downstream of the extraction region. At this distance, the ion beam waist was downstream nearly of 22 mm 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 20 mm from the plasma electrode, therefore a cross over is made and were hitting the extraction electrode (Fig. 9 a).



Gap width of 1 mm

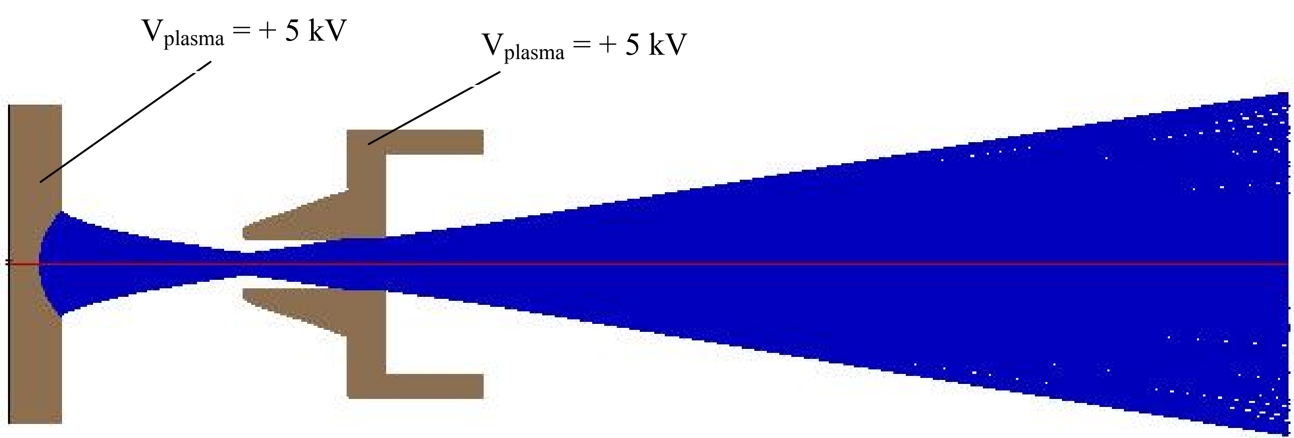
(a)



Gap width of 3 mm

(b)

(c)



Gap width of 20 mm

(c)

Fig. 9: The influence of the extraction gap width on the ion beam envelope for singly charged ions.

Conclusion

This paper reports the optimization of the extraction system for glow discharge ion source. The dependence of the ion beam envelope on the negative voltage applied to the extractor electrode and on the extraction gap width was numerically computed with help of the SIMION 3D, version 7.0, simulation package. Singly charged nitrogen ions trajectories from a concave plasma shape were calculated. Minimal ion-beam trajectories were obtained at an extraction voltage, V_{ext}=−2,000 V with an extraction gap width of 5 mm. Under such optimal conditions, ion beam trajectories pass fully through the extractor electrode aperture without hitting it. Good agreement was found when the simulation was compared with experimental results under the same operational conditions.

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