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GENERAL AND APPLIED PHYSICS

Optimization of Extraction System for Cold Cathode Ion Source

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Abstract We have simulated ion trajectories with the SIMION 3D, version 7.0, package to optimize the extraction system of a cold-cathode ion source and compared the results with experimental data collected under the same operational conditions. The simulation determined the negative voltage applied to the extractor electrode and the extraction gap widths that maximize the ion-beam current for singly charged nitrogen ions with low emittance and small diameter. 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 8×10^{-4} Torr nitrogen. The results of the simulation agreed well with the experimental data.

Keywords Cold cathode ion source · Ion beam emittance · Extraction system

1 Introduction

The performance of an ion-beam source depends critically on the design of its electrodes [1], which determines the electric-field configuration at the surface of the source and along the acceleration path [2]. The surface can either be of fixed geometry (surface ionization and field ion sources) or form the boundary of the plasma (plasma ion sources) [3]. In the latter case, the shape of the surface depends on the current density, ion supply rate, and applied electric field. In other words, it is fluid.

After a suitable high-density plasma is produced, the plasma must be converted into an ion beam with the desired kinetic energy. An electrode biased at a negative voltage with respect to the plasma boundary is then needed [4, 5], and the designer is faced with the problem of optimizing the electrode geometry. Various factors, such as the applied extraction voltage and the shape of the emitting plasma surface, contribute to the beam quality. The ion density, the extraction voltage, and the geometry of the extraction system define the shape and position of the ion-emitting surface, i.e., of the plasma boundary. Variations in the potential difference between the plasma and electrode affects the sheath thickness. The plasma boundary retreats under increasing potential differences until it becomes flat and eventually concave at sufficiently high extraction potentials. The extracted ion beam must be intense and minimally divergent, with as little aberration as possible [6–8].

A number of two-dimensional (2D) and three-dimensional (3D) numerical simulation softwares can be found to optimize the extraction of ions from plasma sources. To that end, the SIMION 3D version 7.0 code [9] is particularly convenient. This program allows one to design and analyze charged-particle (ion and electron) lenses, ion transport systems, various types of mass spectrometers, detector optics, time-of-flight instruments, ion traps, magnetic sectors, among other components. It offers direct and interactive methods to simulate a wide variety of ion-optics conditions [10].

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2 Description of the Ion Source

Figure 1 schematically shows a cold-cathode ion source comprising two copper plane anode discs A, of 30 mm diameter and 4 mm thickness. The outer diameter and thickness of the copper plane cathode are 14 and 2 mm, respectively, with 2-mm center aperture. In order to confine the discharge in ion exit aperture area, 8 mm diameter area of the cathode disc is insulated with perspex. The two anode discs are symmetrically positioned with respect to the cathode disc. The cathode and two anode discs are immersed in an insulating cylinder of pure perspex. The extractor electrode E, 30 mm in diameter with a center aperture of 4 mm diameter, is placed 3 mm beyond the exit aperture of the cathode disc. A copper collector plate, C.P., 5 cm away from the ion-exit aperture of the cathode disc, collects the output ion beam. A hole of 1 mm diameter in the outer surface of the perspex insulating cylinder lets the working gas in.

Figure 2 shows the electrical circuit of the ion source. The extractor electrode is connected to the 5-kV negative power supply (−P.S.), while the two anode discs are connected to 10 kV positive power supply (P.S.), which initiates the glow discharge between the two anode discs and the plane cathode. A milliampere meter monitors the electrical discharge current between the two anodes and the cathode, while the kilovolt meter measures the electrical discharge voltage between them. The cathode is grounded, while the ion-collector plate is grounded through the microampere meter, which measures the output-ion beam current through the central aperture of the cathode.

The vacuum system comprises a stainless-steel mercury diffusion pump of 270 l/s speed equipped with an electrical heater, backed by a 450 l/min rotary pump evacuates the ion-source chamber. The rotary pump brings the pressure down from 10^{-2} to 10^{-3} Torr, while the diffusion pump reduces the pressure to 10^{-4} to 10^{-6} Torr in the ion-source chamber. An Edwards digital meter with two gauge heads monitors the vacuum inside the connecting tubes and ion-source vacuum chamber. A pirani vacuum gauge head measures the fore vacuum inside the connecting tubes and ion-source vacuum chamber, while an ionization-lamp vacuum gauge head measures the vacuum inside the ion-source vacuum chamber. The working gas from a gas cylinder is admitted into the ion source through a finely controlled needle valve.

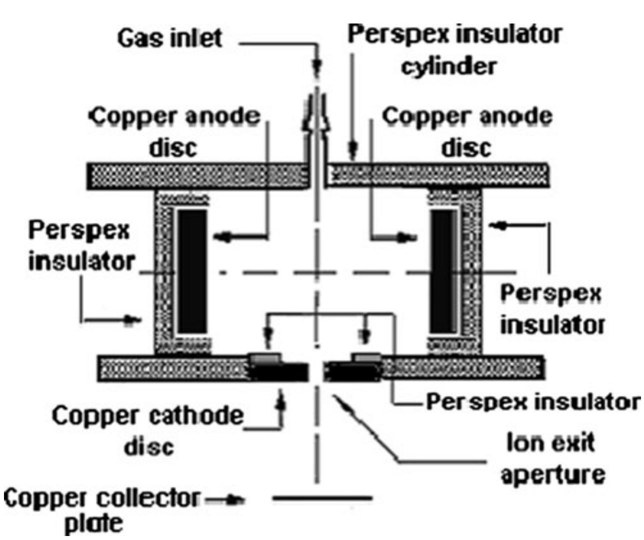

Fig. 1 Schematic drawing of the cold-cathode ion source

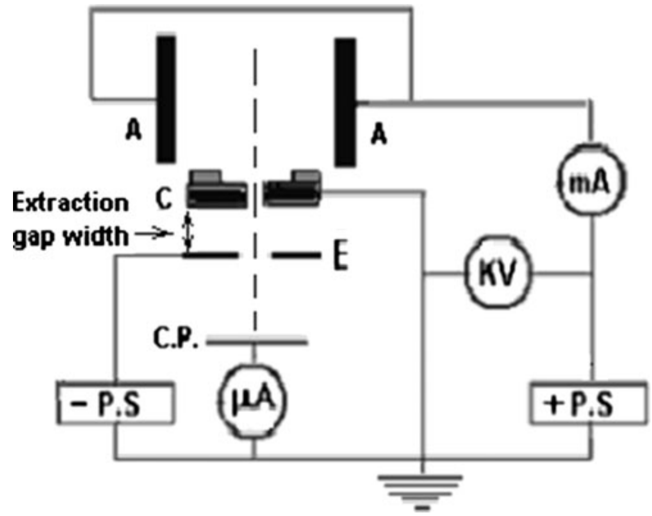

Fig. 2 Electrical circuit of the ion source, showing the connection of the extractor electrode to the negative power supply

3 Simulation

Version 7.0 of the commercial code SIMION 3D [11] was used to track the trajectories of singly charged nitrogen ions. The dependence of the ion-beam diameter and emittance on the negative voltage applied to the extractor electrode was examined, along with the response of the ion-beam envelope to different extraction gap widths. The optimum extraction voltage V_{ext} was found to be −2,000 V, the ion beam then crossing the aperture without hitting the extraction electrode. Figure 3 shows a simulation of ion-beam extraction from a concave plasma shape due to a negative extraction voltage applied to the extractor electrode [12].

3.1 Negative Voltage Applied to the Extractor Electrode

The study the influence of the negative extraction voltage V_{ext} applied to the extractor electrode on the ion-beam

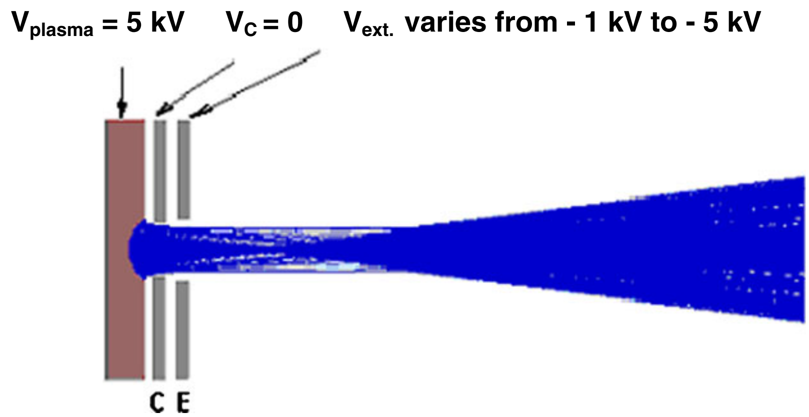

Fig. 3 Simulation of ion-beam extraction from a concave plasma. *C* cathode, *E* extractor electrode. The extractor gap width is the separation between E and C

envelope, we assumed the plasma voltage V_{plasma} to be almost equal to the electrical discharge voltage, equal to 5 kV, and fixed the extraction gap width at 3 mm to adequately reduce the width of the ion-beam envelope in the extraction region.

Figure 4 shows the resulting ion-beam emittance as a function of the extraction voltage V_{ext}. The plot shows a minimum ion-beam emittance of 1.75 cm mrad for V_{ext}=−2,000 V, at which voltage the ion-beam emittance passes fully through the extraction region.

Figure 5 shows the ion-beam diameter as a function of extraction voltage V_{ext} applied to the extractor electrode for a extraction gap width of 3 mm. For V_{ext}=−2,000 V the ion-beam diameter is minimized, at 2.5 mm.

3.2 Extraction Gap Width

The dependence of the ion-beam envelope on the extraction gap width was also studied, for a concave meniscus plasma as shown in Fig. 3. In these calculations, the plasma and extractor electrode voltages were fixed at V_{plasma}=5 kV and V_{ext}=−2,000 V, respectively. Figure 6 shows the resulting ion-beam emittance as a function of extraction gap width. A minimum ion-beam emittance of 1.75 cm mrad is obtained, at the extraction gap width of 3 mm.

In Fig. 7, ion beam diameter versus extraction gap width at extraction voltage applied to the extractor electrode equals −2,000 V. It was found that a minimum ion beam diameter equal to 2.5 mm can be obtained at extraction gap width equals 3 mm, while before and after this distance the ion beam diameter increases.

4 Experimental Results

The experimental data were collected under the conditions described by Abdel Salam et al. [13], which

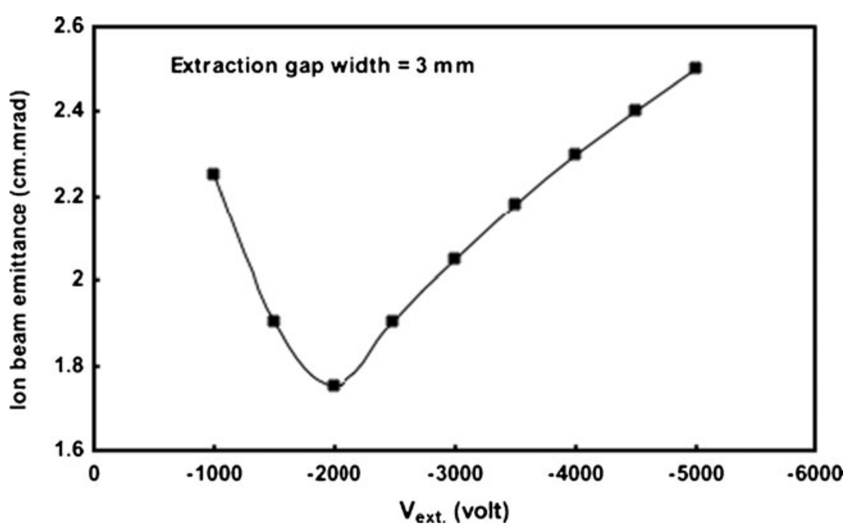

Fig. 4 Ion-beam emittance as a function of extraction voltage for the indicated extraction gap width

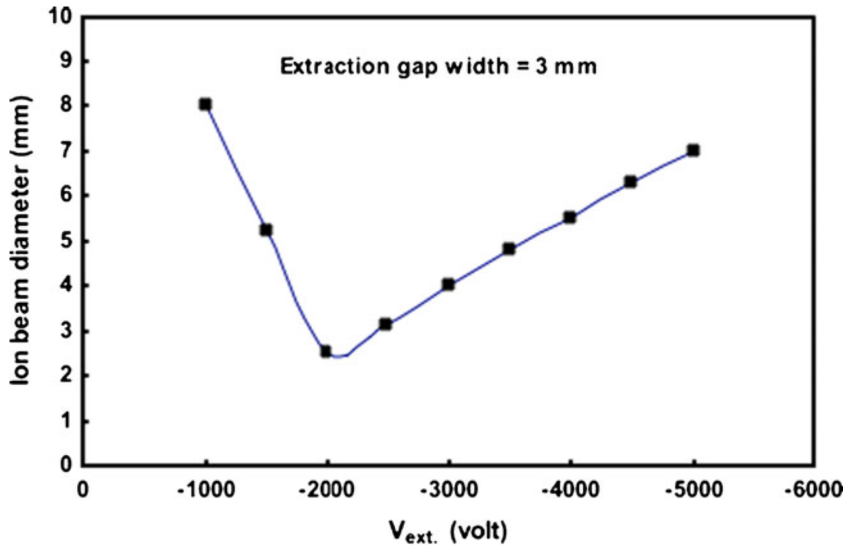

Fig. 5 Ion beam diameter as a function of extraction voltage for the indicated gap width

optimize the stability of the electrical discharge current and maximize the output ion-beam current. The electrical discharge and the output ion-beam characteristics of the ion source were studied under different experimental conditions. The dependence of the ion-beam current on the (negative) extractor voltage and on the extraction gap width was investigated.

4.1 Ion Source Characteristics

Figure 8 shows the output ion-beam current I_b as a function of the discharge voltage V_d under different pressures. Clearly, the output ion-beam current rises with the discharge voltage. The discharge voltage starts at higher values as the pressure is increased from $P=1.3\times10^{-3}$ Torr to $P=8\times10^{-4}$ Torr.

Figure 9 shows the output ion-beam current I_b as a function of the discharge current I_d at different pressures. The output ion-beam current increases with the discharge current. At $I_d=1$ mA and $P=8\times10^{-4}$ Torr, a maximum output ion beam current of 315 μA can be obtained.

4.2 Ion-Beam Current Dependence on the Extractor-Electrode Voltage

Next, to improve the performance of the cold-cathode ion source at optimum extraction gap, various negative voltages were applied to the extractor electrode, and the resulting ion-beam currents were measured. Figure 10 shows the output ion beam current I_b as a function of the (negative) extraction voltage V_{ext} at $P=8\times10^{-4}$ Torr and

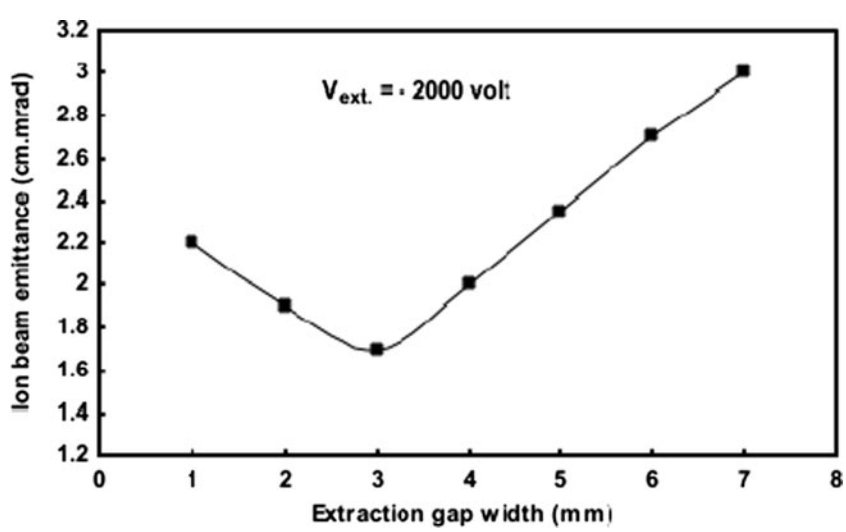

Fig. 6 Ion-beam emittance as a function of extraction gap width at −2,000 V extraction voltage

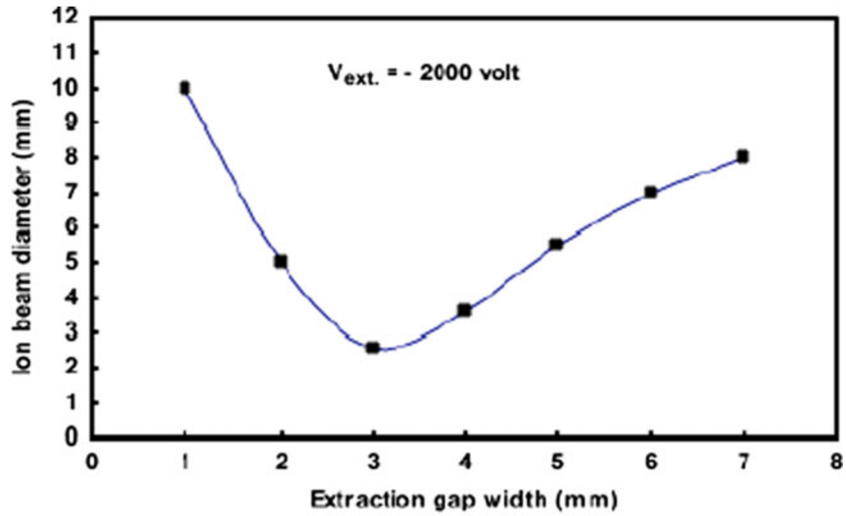

Fig. 7 Ion-beam diameter as a function of extraction gap width at the indicated extraction voltage

3 mm extraction gap width. A maximum output ion-beam current of 360 μA resulted, at V_{ext}=−2,000 V.

4.3 Influence of Extraction Gap Width on the Output Ion-Beam Current

The extraction gap width must be adjusted to optimize the performance and efficiency of the ion source. Maximum output ion-beam current and small divergence angle are desirable. In this experiment, the plasma voltage V_{plasma} was fixed at 5 kV and the extraction voltage V_{ext} applied to the extractor electrode, at −2,000 V. The extractor electrode was placed at different distances—1, 2, 3, 4, 5, and 6 mm—from the cathode ion exit aperture and for each distance the output ion-beam current was measured at the collector plate.

Figure 11 shows the output ion-beam current as a function of the extraction gap width at $P=8\times10^{-4}$ Torr and $V_{ext.}$=−2,000 V. The output ion-beam current reaches a maximum, I_b=360 μA, at the extraction gap width of 3 mm.

5 Conclusion

This paper reports the optimization of the extraction system for a cold-cathode 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 emittance and diameter were obtained at V_{ext}=−2,000 V with an extraction gap width of 3 mm. Under such optimal conditions, both the ion beam emittance and ion beam diameter pass fully through the

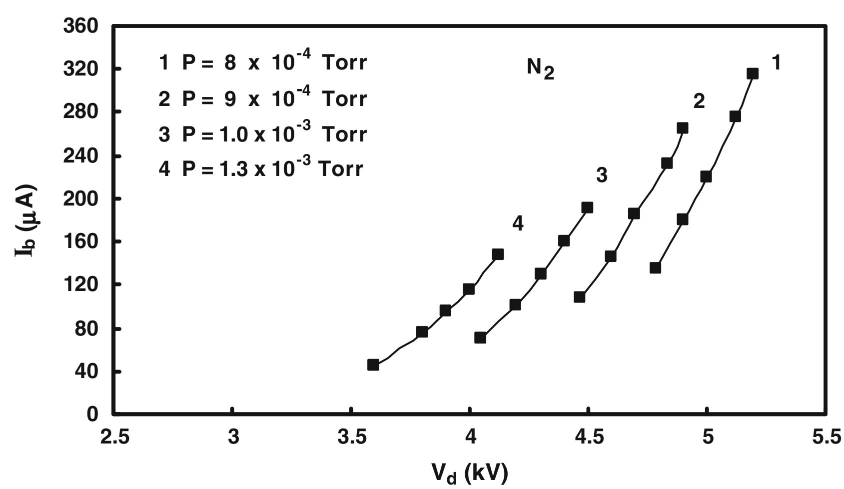

Fig. 8 Output ion beam current as a function of discharge voltage under different nitrogen pressures

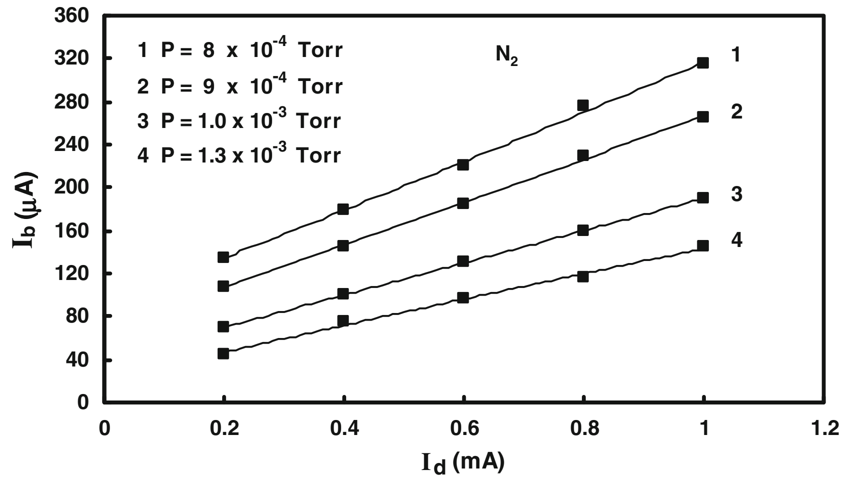

Fig. 9 Output ion-beam current as a function of discharge current under different nitrogen pressures

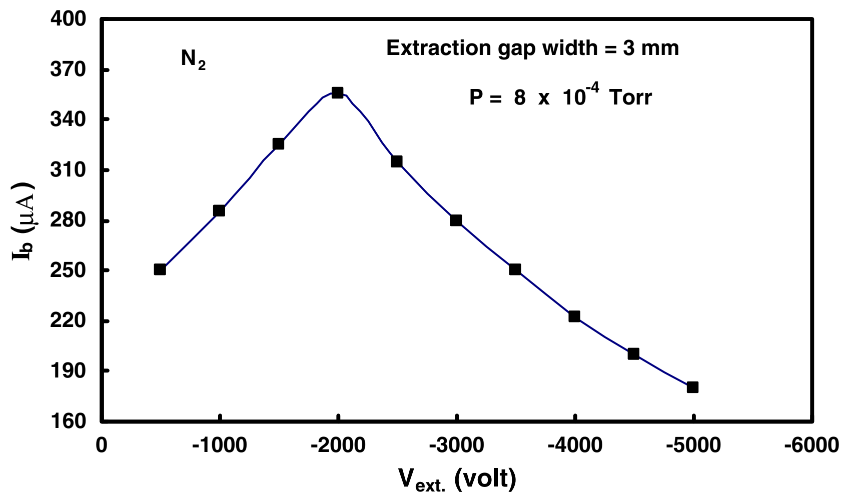

Fig. 10 Output ion-beam current as a function of the voltage applied to the extractor electrode under fixed nitrogen pressure

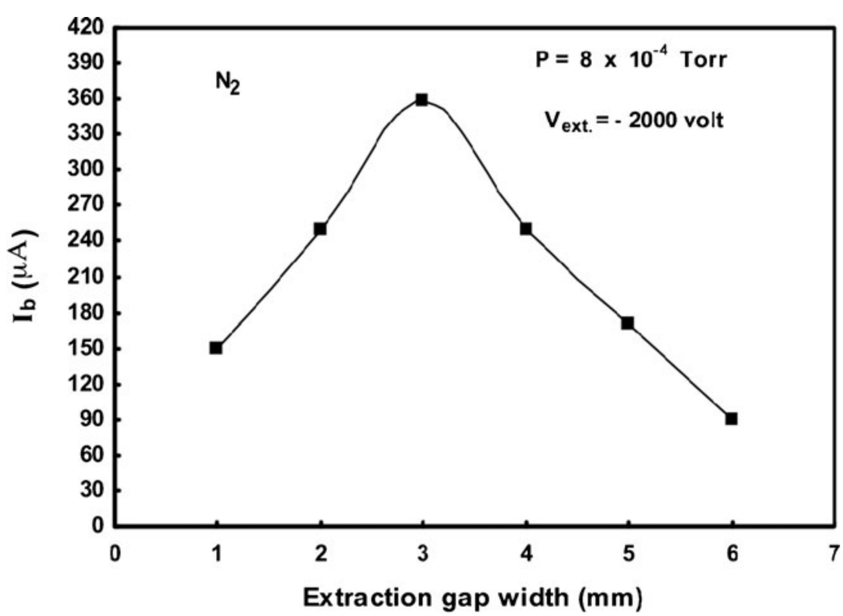

Fig. 11 Output ion-beam current versus extraction gap width at $P = 8 \times 10^{-4}$ Torr

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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