Broad beam gas ion source with hollow cathode discharge and four-grid accelerator system

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Abstract

A broad beam gas ion source based on low-pressure hollow cathode glow discharge is described. An axial magnetic field produced by AlNiCo permanent magnets enhances the glow discharge in the ion source as a result of the magnetizing electrons between the hollow cathode and rod anode. The gas plasma is produced by magnetron hollow cathode glow discharge in the hollow cathode and a collimated broad ion beam is extracted by a four-grid accelerator system. A weak magnetic field of several millitesla is enough to ignite the magnetron glow discharge at pressure lower than 0.1 Pa, thereby enabling stable and continuous high-current discharge to form the homogeneous plasma. A four-grid accelerator, which separates the extraction and acceleration of the ion beam, is used in this design to generate the high-energy ion beam from 10 keV to 60 keV at a working pressure of 10^-4 Torr. Although a higher gas pressure is necessary to maintain the low-pressure glow discharge when compared to hot filament discharge, the hollow cathode ion source is operational with reactive gases such as oxygen in the high-voltage continuous mode. A laterally uniform ion beam can be achieved by using the four-grid accelerator system. The effects of the rod anode length on the characteristics of the plasma discharge as well as ion beam extraction from the ion source are discussed.

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1. Introduction

Ion sources with wide energy and current ranges are used extensively in industrial applications such as ion implantation, etching, and deposition. Broad beam ion sources with uniform current distributions are needed for many industrial applications and development of commercial ion beam technologies for surface modification of materials is impossible without highly efficient, simple, and dependable ion sources. These and other needs have spurred the development of high efficiency ion sources that can produce ion beams with high energy and current and require low or no maintenance [1–5].

Different methods have been used to produce gas plasmas. The traditional method is to use thermionic cathodes to emit electrons and ignite plasma discharge in multi-cusp magnetic field [6]. This type of ion sources that are commonly used industrially is commonly called a Kaufman source [7,8]. The glow discharge constitutes an attractive source for plasma-charged particle systems due to its stability and simplicity. The hollow cathode glow discharge with [3] and without [9,10] the applied magnetic field can be used for plasma production and plasma electron emitters. Therefore, for long time operation and when reactive gases are used, the hot filaments are usually replaced with hollow cathode electron sources. Compared to hot cathode sources, they are also called cold cathode sources with different hollow cathode configuration [3,9–12].
The ion beam can be extracted from the plasma utilizing a single or dual stage electrostatic acceleration system [13–15]. In generally, the two- or three-grid accelerators systems are used to extract and accelerate ion beams. The acceleration voltage can vary from several ten of volts to tens of kilovolts. High energy (>40 keV) acceleration is usually achieved by means of four-grid or two-stage acceleration [13]. Recently, the four-grid ion acceleration system has been proposed to generate highly collimated low energy ion beams [16] and the multi-aperture grids are employed in broad beam ion sources.

The glow discharge can be operated at low-pressure in the high-current, low-voltage mode. The minimum discharge pressure needed for the high-current, low-voltage mode is about $10^{-2}$ Torr. However, the pressure at the extraction gap required for ion beam generation and transport should be less than $10^{-4}$ Torr [17,18]. With regard to a broad beam ion source, the pressure differential between the plasma region and ion beam region cannot be achieved by the pressure drop across the multi-aperture grids. However, the plasma discharge can be sustained in low-pressure employing the applied magnetic fields.

In this paper, a broad gas ion source based on low-pressure hollow cathode glow discharge is described. The four-grid multi-aperture accelerator system is used to generate the collimated broad ion beam. The characteristics of the plasma discharge and ion beams are experimental investigated and discussed.

2. Experimental setup

The schematic diagram of the hollow cathode broad beam ion source is depicted in Fig. 1. The ion source consists of the plasma production and ion beam extraction systems. The plasma is produced by hollow cathode glow discharge using the applied axial magnetic field. The hollow cathode is composed of the upper and lower magnetic poles and stainless steel shield. AlNiCo permanent magnets in lieu of magnetic coils are mounted outside the discharge chamber to form an axial magnetic field in the discharge region via magnetic shunts. Therefore, no water cooling is needed for normal operation. The cylindrical cathode made of stainless steel and iron forms a hollow chamber with a diameter of 150 mm and length of 100 mm. The dual helical tungsten mounted centrally through the insulating feedthrough serves as the anode. The axial magnetic field strength is only several tens of Gauss in the central location when four magnets are placed. The working gas is fed via a stainless steel pipe into the discharge chamber.

The four-grid multi-aperture acceleration system is used in this ion source to separate ion extraction from ion acceleration. Therefore, ion beams with wide energy ranges can be produced. The four grids which are the screening grid, extraction grid, acceleration grid, and ground grid, respectively are made of stainless steel 4 mm thick. The diameter of the aperture is 6 mm and the transparency of the grid is about 50%. The four grids are mounted and separated by ceramic insulators. The gaps in the extraction, acceleration, and deceleration regions are 6, 15 and 4 mm, respectively. The ratio of the aperture diameter to the gap in the extraction region is about $S = 0.5$, which bodes well for small beam divergence.

Because the magnetic field is generated by permanent magnets, the glow discharge can be triggered at low-pressure. One 0.8 kV DC power supply is used in our experiments to initiate and sustain a stable glow discharge. A resistor in series is used to limit the discharge current and to prevent arc discharge. The broad ion beams are extracted using a 5 kV DC applied between the screening and extraction grids. Then ion beams are accelerated by 60 kV DC applied to the acceleration grids during extraction. A deceleration power supply provides a negative electric field to suppress the secondary electrons flowing back to the extraction and acceleration regions. The total ion beam current is measured by a large Faraday cup with a diameter of 200 mm at the exit of the ion source. The ion beam current distribution is measured by several small Faraday cups with a diameter of 5 mm.

3. Results and discussion

The glow discharge can be easily ignited when the work gas N$_2$ is fed into discharge region. One way to initiate the glow discharge is to use a triggering power supply with high-voltage (3 kV) and low short circuit current (0.01 A). The glow discharge is maintained by superposition of the main DC glow discharge power supply. Meanwhile, the glow discharge can also be initiated directly by the main DC power supply at a high working pressure ($10^{-2}$ Torr) and then sustained at low-pressure ($10^{-4}$ Torr) by slowly reducing the gas flow. The glow discharge current diminishes with smaller gas flow or pressure as demonstrated in Fig. 2. In our experiments, the glow discharge voltage is 800 V. The potential drop between the anode and cathode is less than the output voltage of the power.
supply due to the 500 Ω resistor in series. Fig. 2 shows that the discharge current is about several hundred mA in the pressure of high-voltage ion beam acceleration. Therefore, the high-current, low-voltage mode is achieved in the reverse magnetron glow discharge and produces the plasma at low-pressure [3].

The plasma discharge parameters are influenced not only by the magnetic field and work gas pressure but also the anode length and diameter. The hollow cathode glow discharge at low-pressure can be attributed to oscillations of the discharge plasma electrons under the magnetic field. The electron oscillation reduces the pressure required for sustained ionization due to an increase in the ionizing electron trajectory length. The mean trajectory length of electrons oscillating inside the cathode is given by [10]:

\[ L = \frac{4V}{S_a} \]  

(1)

where \( V \) is the volume of the cathode cavity and \( S_a \) is the anode surface area. Accordingly, a smaller anode surface favors enhanced ionization by the oscillating electrons. In our experiments, the dual helical tungsten anode with a diameter of 11 mm is used to reduce the anode surface. The influence of the anode length on the discharge current is experimentally investigated at a low-pressure of \( 1.5 \times 10^{-4} \) Torr and the results are in Fig. 3. The discharge current is observed to decrease with a longer helical anode and it is consistent with other reports [3,10]. However, our results indicate that the reduction of anode area should not fall below an optimal value because a small anode area will limit the current transfer to the anode. In our experiments, the glow discharge becomes unstable and extinguishes frequently when the length of the anode is less than 30 mm. Because the tungsten anode is not subjected to direct heating, the lifetime of the tungsten anode is much longer. Therefore, the lifetime of the ion source is not limited by the tungsten anode and can be very long.

In our setup, a two-stage four-grid acceleration system is used to collimate the ion beam. The total ion current is used to control the ion beam. The total ion current is affected mainly by the plasma discharge parameters and extraction voltage. The total ion current varies with the extraction voltage as shown in Fig. 4 and it can be inferred that the ion current increases with the extraction voltage. The acceleration voltage is 30 kV. When the ion beam is extracted from the plasma region and enters the acceleration region, a high energy ion beam can be obtained downstream. In our four-grid accelerator system, the total ion current varies slightly with the acceleration voltage. Therefore, the ion energy can be varied independently. A wide range of ion energies can also be achieved in a single system. Generally, the ion beam energy spread has a fixed value for a set of extraction and acceleration voltages used in the four-grid accelerator ion source. The ion beam current distributions at different acceleration voltages are measured at a distance of 300 mm from source exit, and the results are displayed in Fig. 5. The non-uniformity of the

![Fig. 2. Discharge current changes with working gas pressure.](image1)

![Fig. 3. Discharge current variation with anode length at low-pressure.](image2)

![Fig. 4. Total ion current versus extraction voltage at 30 kV acceleration voltage.](image3)
broad ion beam current density in the range of 150 mm is about ± 5%. The non-uniformity of the current density is not affected significantly by the acceleration voltage. However, it is found that the radial profile of the ion current density is not influenced very much by the extraction voltage. The high extraction voltage helps to focus the ion beam and the non-uniformity of the radial profile increases.

4. Conclusion

A broad beam gas ion source based on low-pressure hollow cathode glow discharge is described. An axial magnetic field increases the oscillating electron trajectories and enhances the glow discharge at low-pressure. This special hollow cold cathode configuration works well for reactive gases and requires low maintenance. A stable glow discharge can be achieved at low-pressure with the simple helical anode and low axial magnetic field. The four-grid extraction-accel-decel system is used to form the collimated broad ion beam with a wide range of ion energies. Uniform broad ion beams can be formed with wide ion energy ranges from 10 keV to 60 keV at a working pressure of $10^{-4}$ Torr.

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References


Fig. 5. Ion current density distribution versus acceleration voltage at 0.5 kV extraction voltage.