Effects of magnetic field gradient on ion beam current in cylindrical Hall ion source

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(Received 25 September 2007; accepted 24 October 2007; published online 20 December 2007)

The effects of the magnetic gradient on the ion beam current in an end Hall-type ion source with a magnetic mirror field are investigated. In a cylindrical Hall ion source in which a cylindrical magnetic ring other than a regular magnetic pole is shortened and centrally inserted, a mirror magnetic field profile can be formed around the annular anode. A positive-negative variable magnetic gradient is shown experimentally to enhance ionization; the ionization efficiency is substantially affected by the different magnetic gradient. The high ionization results in 60% efficiency in the conversion of discharge current to ion beam current. The experimental results and interpretation of the effects are presented in this paper. © 2007 American Institute of Physics. [DOI: 10.1063/1.2825625]

I. INTRODUCTION

A Hall ion source is a crossed electric and magnetic field device that emits ions that are accelerated in a quasineutral plasma. Different from electrostatic acceleration in a grid ion source, an electromagnetic acceleration method is used to offset the current density limitations of a grid ion source. Typically, a strong electric field is established in the discharge region with a strong magnetic field. The magnetic field is large enough to magnetize electrons but not ions. The electrons experience an $E \times B$ flow in the azimuthal direction when electrons move across the magnetic field. Therefore, a Hall current is formed due to the closed drifting of the electrons in the $E \times B$ fields. Due to recent advances in magneto-hydrodynamic methods for plasma acceleration, accelerators employing closed drifting electrons in a plasma discharge in crossed fields are promising for practical applications.\textsuperscript{1,2} A Hall ion source with a conical hollow anode and a circular open end was introduced by Kaufman in 1987.\textsuperscript{3} It is also called an end Hall ion source or gridless ion source, which can generate intense fluxes of charged particles much higher than those offered by the conventional Kaufman-type grid ion source. It is because of the presence of electrons avoiding the disruptive mutual repulsion of positive ions in the crossed $E \times B$ fields. In a conventional end Hall ion source, the magnetic field in the circular discharge region has a mainly axial profile and decreases significantly from the main area of about 1 kilo gauss to the discharge exit with only about several tens of gauss. Therefore, the end Hall ion source has a negative magnetic gradient in the discharge channel, thereby making a large number of axial electrons flow upstream to the gas distributor but resulting in a low ionization efficiency of atomic particles in the discharge region.

In addition to the electric field acceleration of ions in the Hall ion source, there is another major mechanism by which a potential difference accelerates the ions generated in the magnetic field. Because the electrons are magnetized in the crossed fields, the plasma conductivity across the magnetic field is substantially reduced. The big difference between the plasma conductivity parallel and normal to the magnetic field gives rise to different potential distributions. That is, the potential difference parallel to the magnetic field is expected to be small compared to that of the normal direction. Therefore, the magnetic field distribution is extremely important in a Hall ion source since the potential is governed by the magnetic field so that equipotential contours tend to line up with the magnetic field lines. A cylindrical Hall thruster with a cusp magnetic field for enhanced ionization, especially a low-power Hall thruster, has been investigated by Smirnov et al.\textsuperscript{4} The major difference from a conventional end Hall ion source / thruster is the cylindrical configuration with an enhanced radial component of a cusp-type magnetic field. A
efficiency Hall ion source with improved magnetic field has been reported.\(^9\) Here, magnetic screens are introduced to the end Hall-type ion source to produce a positive magnetic gradient in the axial discharge channel. Recently, the use of a concave magnetic field has shown some advantages in thruster operation.\(^6\) Both high-efficiency and high-voltage performance have been achieved by using trim coils in the Hall thruster, and the enhancement can be ascribed to the magnetic mirror effect.\(^7\)

II. EXPERIMENTAL

A Hall ion source with a magnetron hollow cathode discharge has been investigated in our laboratory.\(^8\) In the work reported here, the effects of the variable magnetic gradient and mirror magnetic field profile are studied. The ion source, which is schematically depicted in Fig. 1, consists of an annular anode and a cylindrical hollow cathode enclosed by magnetic poles and an inner shield. The magnetic field is produced by permanent, back shunt, inner and outer magnetic poles. A cylindrical magnetic ring is shortened and centrally inserted as an inner magnetic pole. The cylindrical, high magnetic permeability tube, in lieu of the rod magnet found in a conventional end Hall ion source, enhances the magnetic field close to the annular anode in the discharge channel. A mirror magnetic field profile in the discharge channel is formed and the radial component at the open end exit is enhanced. The variable magnetic gradient is produced in the axial discharge channel as shown in Fig. 2. The positive magnetic gradient results in an upstream discharge channel and a negative magnetic gradient forms the downstream one. Because the permanent magnet is outside the stainless-steel inner shield, the magnetic field gradient in the discharge channel can be easily changed by adjusting the number of the permanent magnets. The maximum axial magnetic field appears below the annular anode, which is different from that in a conventional end Hall ion source.

III. RESULTS AND DISCUSSION

For a variable magnetic field gradient in the discharge channel, the time-averaged force of a nonuniform magnetic field on electrons moving in a circular orbit can be calculated from the electron momentum equation.\(^10\)

\[
0 = e n \nabla \phi - nkT_e B \frac{1}{B} \nabla B - \nabla (nkT_e),
\]

where \(e\) is the electronic charge, \(n\) is the electron density, \(k\) is the Boltzmann constant, \(\phi\) is the potential, \(B\) is the magnetic field, and \(T_e\) is the electron temperature. For a uniform plasma density, the potential difference in the plasma required to balance the magnetic field force on the electrons can be deduced from Eq. (1).

\[
\Delta V_p = \frac{kT_e}{e} \ln \frac{B}{B_0},
\]

where \(B\) and \(B_0\) are the magnetic field strengths at the two locations and \(V_p\) is the plasma potential in the discharge channel. According to Eq. (2), it can be concluded that the plasma potential is more positive in the high magnetic field region.
cylindrical Hall ion source which produces an electron trap in the axial direction. The axial electrons are reflected between the inner and outer pole cathodes along the axial magnetic field lines, similar to a cold cathode Penning discharge.\textsuperscript{12} Therefore, the axial electron loss is reduced and more efficient ionization can be established by multiple collisions among the oscillating electrons.

In our experiments, the effects of the magnetic field profile on the performance of the cylindrical Hall ion source are investigated. A high anode voltage can be achieved by increasing the discharge current as shown in Fig. 3. The discharge voltage is substantially higher than that of a conventional end Hall ion source. The experimental results also indicate that the discharge voltage can be increased by decreasing the gas flux. It means that the voltage can be adjusted by varying the working pressure in the Hall ion source. The ion beam current can be measured downstream from the open exit by an electrostatic planar probe. The saturation ion beam current is measured by a −50 V negatively biased circular planar probe 50 mm downstream from the open exit. It is found that the ion beam current is influenced substantially by the magnetic field strength and magnetic gradient. The ion beam current versus discharge current increases with the permanent magnets as illustrated in Fig. 4. When four magnets are used in the Hall ion source, the ratio of the ion beam current to discharge current increases slightly from 0.3 to 0.35 with increasing discharge current. However, 12 magnets change the ratio significantly between 0.38 and 0.6 in the cylindrical Hall ion source when the discharge currents are changed from 0.5 to 4 A. The experimental results indicate that the conversion ratio of the low discharge current varies slightly when changing the magnets, that is, the magnetic field strength and gradient. However, the conversion ratio increases substantially when the Hall ion source is operated in the high-current mode. It is concluded that the ion beam current increases with higher magnetic field strength and gradient, especially for the high discharge current. This is partly contributed by the saddle field profile in the discharge channel induced by the positive-negative variable magnetic gradient. This magnetron glow discharge constitutes a hybrid ion source having the properties of both an end Hall ion source and saddle ion source.\textsuperscript{13} The saddle field can reflect axial electrons and effectively enhance the ionization efficiency with a higher azimuthal Hall current.

IV. CONCLUSION

The magnetic field effects on the conversion ratio of the ion beam current to discharge current in a cylindrical Hall ion source are investigated. The positive-negative magnetic gradient provides a saddle field profile in the plasma discharge channel. The cylindrical Hall ion source can be operated at high voltages over 300 V, which is the upper limit of conventional end Hall ion source. The ion beam current increases with the magnetic field and a conversion ratio of up to 60% can be achieved 50 mm downstream from the source exit. The strong magnetic field and variable gradient enhance the efficiency of the ion source.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grant No. 10675040 and City University of Hong Kong Direct Allocation Grant No. 9360110.


\textsuperscript{7}R. Hofer and A. D. Gallimore, AIAA Paper-2002-4111.


