Beam Extraction from a Hall-type Ion Accelerator

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Beam extraction from a Hall-type ion accelerator[a)]

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Fundamental characteristics of beam extraction from a Hall-type accelerator working with permanent magnets were investigated. Ions were extracted by an axial electric field E_z in a small annular plasma channel with a radial magnetic field B_r. Effects of discharge current and voltage, length of discharge channel, and gas flow rate were examined. It can deliver a large beam current density of more than 100 $\mathrm{mA/cm^2}$ with low beam energy of 50 eV. By biasing an additional plasma chamber attached at the extraction area, the beam energy was controlled independently of the beam current. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2801645]

I. INTRODUCTION

A particle beam is utilized in many researches such as semiconductor processes, nuclear fusion, and electric propulsion. Recently, demands for the development of high particle flux sources with low energy below 0.1 keV have increased in surface treatment and nanobioapplications. It is difficult for a conventional ion beam source using electrostatic grids to extract a high particle beam flux with a low acceleration voltage, since ion beam current is limited by space-charge effect according to the Child-Langmuir law.

A Hall-type accelerator can deliver a high flux of low energy particles, since it is operated without the space-charge limitation because quasineutrality is maintained even in the beam acceleration region. It has been developed as one of the promising electric propulsion devices used for near-earth missions such as satellite station keeping and orbit transfer.[1–3]

The Hall-type accelerator for electric propulsion, named as a Hall thruster, has achieved high performance of thrust efficiency of 40%–50% at specific impulse of 1000 s. Here, the thrust efficiency is defined as a ratio of the kinetic energy flux exhausted from the thruster exit to the input electric power. A small satellite, SMART-1, utilized a Hall thruster as a main rocket engine in the mission to the moon.[4]

In a Hall-type accelerator, ions are accelerated in a small annular discharge channel where an axial electric E_z and a radial magnetic field B_r are applied. The radial magnetic field strength is large enough for electrons to drift azimuthally in the annular channel by $E_z \times B_r$ drift, but small enough for ions to leave from the source by E_z acceleration. An azimuthal Hall current is formed and efficient ionization of working gas takes place in the discharge channel. Because of the existence of B_r, an axial electric field E_z can be formed in a plasma in spite of the quasi-charge-neutrality condition and ions are accelerated along the electric field direction without the limitation of space charge. Though the operational principle is simple and a high performance of beam extraction is expected, the structure of annular channel and electric and magnetic fields significantly affect the total performance of the source.[5–7]

The purpose of this research is to investigate characteristics of beam extraction from a Hall-type accelerator working with permanent magnets in order to apply it as a low energy particle source. Dependences on discharge current and voltage, length of discharge channel, and gas flow rate were obtained. In order to control the extraction energy of particles, an additional plasma chamber was attached at the extraction area. The effects of biasing to the second chamber were also investigated.

II. EXPERIMENTAL SETUP

A. Hall-type accelerators and measurement devices

Figure 1 shows a schematic view of the experimental setup for the Hall-type ion accelerator. A source was installed in a large vacuum chamber (1.0 m in diameter, 2.1 m in length), which was evacuated by 2000 l/s turbomolecular pump. The source was mounted on the pendulum set in the vacuum chamber. Electric cables and water-cooling lines were transferred into the chamber through a small port above the pendulum pivot. The extracted beam flux was evaluated from the thrust generated by ion beam extraction. The pendulum slightly swifts due to the reaction force by the beam extraction. The position shift was detected by a noncontacting gap-type displacement sensor. The thrust stand was calibrated by using a weight that pulls the pendulum with a known force. Plasma parameters in the source were measured by a movable Langmuir probe. A small calorimeter and an electrostatic energy analyzer (EEA) were attached on another movable stand in the chamber to measure an extracted beam profiles and beam energy, respectively. Argon gas was used as a working gas in the experiments.

Figure 2 shows cross-sectional views of the Hall-type ion accelerators used in the experiments. It has an annular acceleration channel of 70 mm in outer diameter and 50.8 mm in inner diameter. The radial magnetic field B_r is formed by permanent magnets and magnetic circuit formed

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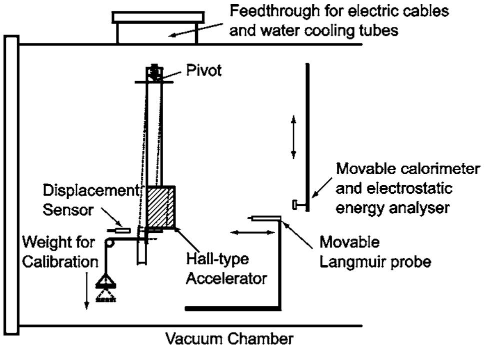

FIG. 1. Schematic view of the experimental setup.

by soft iron. The radial magnetic field strength becomes the maximum near the exit of discharge chamber. The maximum magnetic field strength can be varied from 0.5 to 1.3 kG with the number of magnets. The discharge voltage V_d was applied between the anode and a filament cathode. Working gas is ionized in the annular channel and produced ions are accelerated by the electric field. The length of discharge channel, L, was varied as 4, 10, and 20 mm in the experiments.

In order to control beam energy, we added isolated metal wall to form a second plasma region (second chamber), which was biased to the discharge region (first chamber). The effect of bias voltage V_{bias} to beam energy was examined.

B. Beam current estimation from the generated thrust

In the Hall-type accelerator, ions are accelerated without an electrostatic grid system. Although the discharge voltage V_d corresponds to an acceleration voltage, a drain current of a power supply, I_d, does not equal to the beam current I_b. In order to estimate a beam current extracted from the source, we measured the thrust due to the reaction force by the extracted beam momentum using a pendulum.

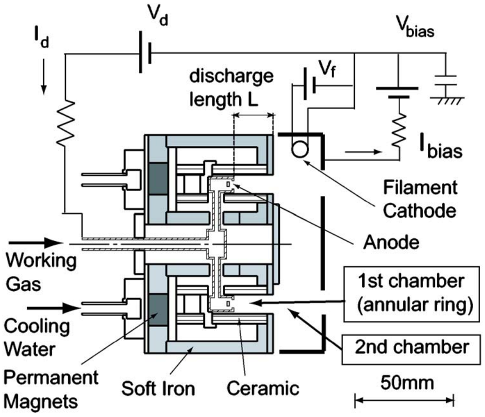

FIG. 2. (Color online) Schematic view and electric circuit of the Hall-type accelerators with the isolating metal wall to form the second chamber.

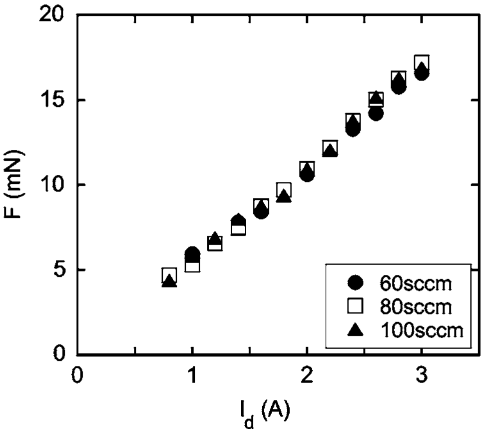

FIG. 3. Dependence of thrust F on I_d for various Ar gas flow rate. V_d=160 V and B_r=0.13 T.

When ions with the mass of m_i are accelerated to energy E_b, an extraction velocity of ions becomes $v_i=\sqrt{2eE_b/m_i}$. The thrust F is related to the sum of extracted particles' momentum,

$$F\Delta t = N m_i v_i. \tag{1}$$

Here, N is the number of ions extracted during the period of Δt. We assume that single ions are extracted from the source. The ion beam current I_b can be evaluated from the thrust as the following equation:

$$I_b = \frac{Q}{\Delta t} = \frac{Ne}{\Delta t} = e\frac{F}{m_i v_i} = F\sqrt{\frac{e}{2m_i E_b}}. \tag{2}$$

Here, e is a charge of electron. The current density j_b is calculated as $j_b=I_b/S$, where S is a cross section of beam extraction area (18.2 cm^2 in the experiments).

III. EXPERIMENTAL RESULTS

A. Thrust measurement and effects of various parameters

Figure 3 shows the dependence of measured thrust F on I_d for various Ar gas flow rates. The thrust increased almost linearly with I_d, but was independent of gas flow rate. The thrust slightly increased with B_r and decreased when B_r was more than 0.13 T. Then, B_r and gas flow rate were fixed at 0.13 T and 60 SCCM (SCCM denotes cubic centimeter per minute at STP) in the experiments, respectively.

We have measured the dependence for various discharge channel length L (4, 10, and 20 mm). Effect of the channel length on the thrust was examined and results are shown in Fig. 4. The thrust slightly increased with the channel length of 10 mm compared with that of 20 mm. In case of L=4 mm, the thrust resulted in worse performance and an unstable discharge occurred. Energy of the beam extracted from the source was measured by EEA and obtained 53 eV at V_d=160 V and I_d=2 A. Using the measured thrust and the beam energy, we have estimated beam currents I_b and current density j_b according to Eq. (2) and obtained I_b=1.6 A (j_b=88 mA/cm^2) at I_d=2 A. The ratio of I_b to I_d attained to nearly 80% and the maximum current density reached more than 100 mA/cm^2 with the beam energy of 50 eV when I_d was more than 2.5 A. This high particle beam flux with low energy is useful in many industrial applications.

Although the extracted current ratio was high, the thrust was almost constant when V_d changes from 100 to 300 V

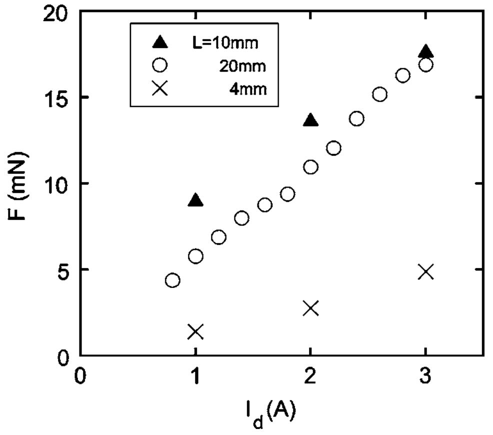

FIG. 4. Dependence of thrust F on I_d with different channel length L. V_d=160 V, B_r=0.13 T, and gas flow rate is 60 SCCM.

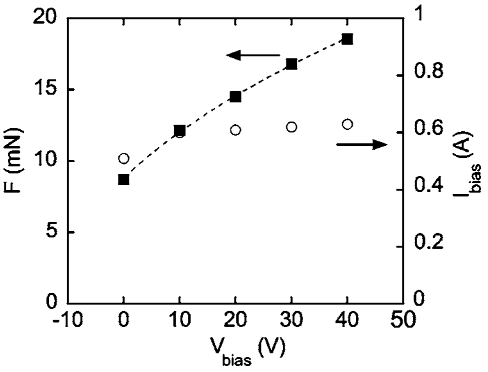

FIG. 5. Dependence of thrust F (closed rectangular) and drain current I_{bias} (open circles) on V_{bias}. Dotted curve is a fitted one according to Eq. (3). V_d=130 V and B_r=0.13 T. I_d is slightly changed around 1 A. Gas flow rate is 50 SCCM.

with keeping I_d constant. The beam energy was measured by the EEA and did not change with V_d. This was confirmed by a spatial profile measurement of a plasma potential. When V_d increased, only the space potential near the filament cathode changed and no effect appeared in the discharge region, where ions were accelerated along the electric field.

B. Effects of the second chamber

In order to control the extracted beam energy, we added an isolated metal plate to form a plasma region (called as second chamber) and to apply a bias voltage, as shown in Fig. 2. Because of the existence of B_r, an axial electric field can be formed near the exit of the annular discharge region (called as first chamber).

Figure 5 shows dependences of thrust and drain current I_{bais} of the power supply on the applied bias voltage V_{bias}. The thrust gradually increased with the increase of V_{bias}, whereas I_{bias} is almost constant. This result indicates that the increase of the thrust was due to the increase not of particle flux but of particle energy.

According to Eq. (2), the thrust is related to beam current I_b and energy E_b as

$$F = \sqrt{\frac{2m_i}{e}} I_b \sqrt{E_b}. \tag{3}$$

We fitted the measured thrust in Fig. 5 as $F=\alpha\sqrt{V_{\mathrm{bias}}+\beta}$ and obtained α=2.6 and β=11.4, which is shown as the dotted line in Fig. 5. The constant α corresponds to I_b=2.8 A in Eq. (3). Although this value is several times larger than I_d and I_{bias}, the measured thrust is well fitted with a constant value of beam current. The discrepancy is probably caused by the existence of charge-exchanged neutral particle flux. The constant β corresponds to initial beam energy when V_{bias}=0. We measured the beam energy by the EEA and confirmed the increase of beam energy by the biasing. Further experiments should be necessary to evaluate total ion beam flux extracted from the double chamber Hall accelerator.

In summary, we have investigated beam extraction from a Hall-type accelerator working with permanent magnets. Ion beam current was evaluated by thrust measurements. A large beam current density more than 100 mA/cm^2 with low beam energy of 50 eV was extracted from the Hall accelerator. In order to control the beam energy, it was effective to apply a bias voltage to an additional plasma chamber attached at the extraction area.

[1] J. Ashkenazy, Y. Raitses, and G. Appelbaum, Phys. Plasmas **5**, 2055 (1998).
[2] A. Morozov, Plasma Phys. Rep. **23**, 587 (1997).
[3] V. Kim, J. Propul. Power **14**, 736 (1998).
[4] B. H. Foing, G. D. Racca, A. Marini, E. Evrard, L. Stagnaro, M. Almeida, D. Koschny, D. Frew, J. Zender, J. Heather, M. Grande, J. Huovelin, H. U. Keller, A. Nathues, J. L. Josset, A. Malkki, W. Schmidt, G. Noci, R. Birkl, L. Iess, Z. Sodnik, and P. McManamon, Adv. Space Res. **37**, 6 (2006).
[5] J. A. Linnell and A. D. Gallimore, Phys. Plasmas **13**, 103504 (2006).
[6] A. Shirasaki, H. Tahara, J. Appl. Phys. **101**, 073307 (2007).
[7] A. Smirnov, Y. Raitses, and N. J. Fisch, Phys. Plasmas **14**, 057106 (2007).