A Study on Microwave Discharge Ion Thruster

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A10-cm-diam. ECR (Electron Cyclotron Resonance) microwave discharge ion thruster has been fabricated. This thruster produces plasma by means of ECR heating. The ions in the plasma are extracted and accelerated by electrostatic grids. Performance tests of the thruster were carried out for several kinds of magnetic field configurations inside its discharge chamber and at different distances between Sm-Co magnets and the electrostatic grids. Preliminary estimations of ion production cost, propellant utilization efficiency, and beam divergence of the thruster are reported. In addition, plasma characteristics inside the discharge chamber are examined by using Langmuir probe. Furthermore a computer code to analyze ECR plasma behavior in the thruster is described. The test results and the computer code will be used to develop a larger system (with larger than 20-cm-diam.).

1. Introduction

An ECR microwave discharge ion thruster (ECR ion thruster) generates thrust by emitting ions in ECR plasma with electrostatic grids. The ECR plasma is produced by ionizing propellant with high-energy electrons accelerated by microwave in a magnetic field that is created by samarium-cobalt (Sm-Co) permanent magnets. Thus the thruster utilizes no cathodes for plasma production, so the thruster is relieved from the cathode heater failure that results from the degradation of the cathodes. In addition, the thruster unit consists of only one microwave power source, with which quick ignition without any preheating sequence is possible. These features as well as very simplified power supply units will assure longer lifetime and higher reliability as compared to conventional DC discharge thrusters with cathodes such as hollow ones [1].

The Institute of Space and Astronautical Science (ISAS) is planning to launch a space probe in 2002 for a near-earth asteroid exploration mission as MUESE-C (Mu Space Engineering Satellite), which tries to touchdown to the asteroid and brings back the sample. The probe will employ four 10-cm-diam. ECR ion thruster heads, each of which will produce thrust of 8mN.

The purpose of our study is to develop a thruster which could meet future missions and then is larger (20-cm-diam.) than the system which is going to be used for MUSES-C. As the first step, we constructed a 10-cm-diam. thruster to accumulate the basic data for the large system design and here we will report on the status of the ECR thruster study.

2. Experiments

2.1 Experimental apparatus

Figure 1 shows an experimental setup adopted here. The experimental apparatus consists of a cylindrical vacuum chamber (inner diameter of 40cm and axial length of 100cm), 2.45GHz microwave power source (the maximum power
is 800W), ECR ion thruster, and vacuum pumps. The apparatus is run with Ar gas as propellant. Microwave power is supplied from the power source in a continuous wave mode through a wave-guide and a quartz window to the thruster. The ECR ion thruster is shown in Fig. 2. A resonance field of 0.0875T (ECR layer) is generated in the discharge chamber by using Sm-Co permanent magnets [2]. ECR plasma is generated and confined in cusp magnetic field produced by the magnets. Ions in the plasma are extracted and accelerated by electrostatically biased grids made of Carbon-Carbon(C/C) composite material. The screen grid is biased to 1kV towards the ground; the acceleration grid to -150V and the deceleration grid is grounded [3]. Vacuum chamber is evacuated below 6.4x10^-2Pa by an oil diffusion pump (1500l/s) for the operation of the discharge chamber.

2.2 Experimental condition

2.2.1 Ion extraction

Ion production cost, propellant utilization efficiency, and beam divergence were estimated to know performances of the thruster by measuring ion currents through the grids with Faraday cup.

The performance tests were carried out for three kinds of magnetic field configurations in the discharge chamber. Two kinds of permanent magnets (surface magnetic flux density of 0.22T and 0.37T) were used. The 0.37T magnets were arranged to generate two types of magnetic field configurations. Figure 3 shows these three types of magnetic field configurations that are called here 0.22T, 0.37T type I, and 0.37T type II respectively. The setup of the Faraday cup measurement is illustrated in Fig. 4. The Faraday cup was set 12.5cm far from the deceleration grid. Radial distributions of ion currents were measured by moving it in radial direction. The above performance tests were done at a distance of d=15mm, where d is the distance between the permanent magnets and the screen grid (Fig.2). For 0.37 type II, ion currents were also measured at d=50mm.

The experimental conditions described above, input microwave power, and Ar gas flow rate are summarized in Table1. Ion production cost, propellant utilization efficiency, and beam divergence were defined here as follows [4].

Ion production cost:
\[ C_1 = \frac{P_f}{I_b} \]

Propellant utilization efficiency:
\[ \eta_u = \frac{I_b}{m_f} \]

Beam divergence: a half apex angle of conical area that contains 95% of the ion current.

Here \( P_f \) is input microwave power ranging from 30 to 80W, \( I_b \) ion current, and \( m_f \) propellant flow rate with 0.8 to 1.0sccm.

These parameters are determined by the radial distributions of the ion currents measured by the Faraday cup.

2.2.2 Probe measurements

For a two-dimensional probing inside the discharge chamber, the ions were not accelerated because inserting probe through the grids biased as much as 1 kV is very difficult. In place of the grid system, a punching metal is used only to keep the pressure inside the discharge chamber to a certain value. However, the punching metal has a larger opening ratio compared to the grid system, and the pressure inside the discharge chamber with or without ion acceleration is quite different even for the same mass flow rate. To simulate the pressure state for an accelerating thruster, the mass flow rate was selected as follows.

For an accelerated ion engine, the mass flow rate is a sum of ion current and neutral particles as
\[ m_{f1} = m_{f1} \eta_u + C_1 P_1 \]

Here \( P_1 \) the pressure inside the engine, and \( C_1 \) conductance of the grid. On the other hand, for a non–accelerated plasma with a pressure \( P_2 \) and a punching metal of conductance \( C_2 \),
\[ m_{f2} = C_2 P_2 \]

This is because the beam current can be ignored. Equating both \( P_1 \) and \( P_2 \), one can write,
\[ m_{f2} = m_{f1}(1 - \eta_u)C_2/C_1 \]

Here \( C_2/C_1 \) is determined from the open ratio and the area of both the grid and the punching metal. That is, accelerated state at efficiency and a mass flow rate correspond to the discharge for smaller mass flow rate, both of which are in the same pressure.

For plasma density \( n_p \) and electron temperature \( T_e \) measurements, cylindrical Langmuir probe was used. The probe was inserted from the slit of the punching metal, and scanned every 10mm to obtain the two-dimensional distribution inside the engine [5]. In this probe measurement, magnets were configured as shown in Fig. 5.

3. Experimental Results and Discussions

The radial distributions of the extracted beam current are shown in Fig. 6. These curves peak at the center of the grids and are similar to each
other. However, the measured values of the beam current for the 0.37T types are more than 10 times larger than that for 0.22T. Ion production cost, propellant utilization efficiency, and beam divergence are calculated from these beam currents. The results are shown in Table 1. In Fig. 3, ECR layers (0.0875T area) are drawn. The ECR layer of the 0.37T type II (Fig.3(c)) is larger than the others and the extracted current from it is also larger.

Radial distributions of the extracted beam current for the 0.37T type II with d=50mm are shown in Fig. 7 for several microwave input powers. The values of the measured beam current are smaller than that for the 0.37T type II with d=15mm. However, discharge and plasma generation were stable for d=50mm case, as compared with d=15mm case.

The test results described above imply the following: extracted ion beam current increases as ECR layer becomes broader. The magnetic field configuration must be designed to minimize loss of plasma to the chamber wall. The ECR ion thruster works stable when the bias voltage of the electrostatic grids does not affect plasma generation in the chamber by accumulating an enough quantity of plasma between the ECR layer and the screen grid.

Figure 8 shows the plasma density and electron temperature distributions in the discharge chamber measured by Langmuire probe. In the case of P=3.2x10^-2Pa (η_u = 70%), very high plasma density was found near the ECR point. Also electron temperature was very high near the ECR point and gradually decreases towards centerline of discharge chamber. On the other hand, in the case of P=6.4x10^-2Pa (η_u =50%), plasma density and electron temperature were relatively uniform. These results are qualitatively consistent with the ISAS’s ones [5]. In other words, when propellant utilization efficiency is large, plasma density is especially high only near the ECR point, and high electron temperature gradually extends from ECR point to centerline of discharge chamber. When propellant utilization efficiency is low, plasma density is uniform on the whole. Electron temperature is high only near the ECR point.

From the measurement, plasma characteristics were strongly related to the pressure inside the discharge chamber. In the case of large propellant utilization efficiency (low pressure), microwave is effectively absorbed in plasma (ECR mode), but in the case of low propellant utilization efficiency (large pressure), microwave is reflected from uniform density plasma (Upper Hybrid Resonance mode)[5].

Because of lower cut-off density of 7.5x10^{16} m^-3 for 2.45 GHz microwave, and relative high ionization potential and low cross section for ionization of propellant (Ar), the plasma density obtained was low. From the above reason, performance (ion production cost and propellant utilization efficiency) of the 10-cm-diam. engine was low. Ion production cost was 10 times higher, while propellant utilization efficiency was 40% smaller than the results from the ISAS engine. These results are not surprising due to the difference of microwave frequency and propellant used (ISAS engine; microwave frequency-4.2GHz, propellant-Xe).

4. Simulation Code Development

To numerically investigate the plasma behaviors in the discharge chamber, a simulation code is being developed [6].

The static magnetic field \( H_0 \) generated by Sm-Co magnets is found by solving a finite difference equation for the scalar magnetic potential in cylindrical coordinates.

\[
\nabla^2 \phi_M = \nabla \cdot M \quad (1)
\]

Here, \( \phi_M \) is the scalar magnetic potential that gives \( H_0 = \nabla \phi_M \) and \( M \) is the magnetization. Figure 3 shows the results obtained by this code.

The electric fields \( E \) and time-varying magnetic fields \( H \) are solved by using the Maxwell equations

\[
\nabla \times E = -\mu \frac{\partial H}{\partial t} \quad (2)
\]

and

\[
\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + J \quad (3)
\]

These equations are solved by using the finite-difference time domain (FDTD) method. The current densities \( J \) in eq. (3) are calculated from the particle motions by the particle-in-cell (PIC) method.

The electron and ion particle motions are determined by a time integration of the Lorentz force equation

\[
\frac{d\mathbf{v}}{dt} = \frac{q}{m} [\mathbf{E} + \mathbf{v} \times (\mathbf{B}_0 + \mathbf{B})] \quad (4)
\]

and
Here v is the particle velocity, r the particle position, q the particle charge, and m the mass. These equations are solved by using a time-centered, leapfrog, and finite difference method for each particle.

Figure 9 shows test results by the simulation code. The calculation area is shown in Fig. 9(a) and the surface magnetic density of the permanent magnet adopted in the figure is 0.37T. The following assumptions are used in this simulation, 1) B induced by a microwave is much weaker than that by the magnet and is negligible, 2) E induced by a microwave lies in the R-θ plane, 3) a wavelength is long enough that E is uniform in the calculation area, and 4) a microwave is not attenuated by ECR. Therefore, the electromagnetic field induced by the microwave is described by the following equations.

\[
\begin{align*}
E_r &= E_0 \cos(2\pi ft - \theta + \phi), \\
E_\theta &= E_0 \sin(2\pi ft - \theta + \phi), \\
B_r &= B_z = B_\theta = 0
\end{align*}
\]

f and \( \phi \) are the frequency and the phase of the microwave.

A trajectory of an electron in the discharge chamber is shown in Fig. 9(b). The electron moves along the line of the magnetic force. The energy of the electron and the magnetic density at the electron position are shown in Fig. 9(c). The energy of the electron increases or decreases when it goes across the resonance layer of 0.0875T. Crosses in Fig. 9(d) indicate the Ar ions produced by collisions with energetic electrons. In this simulation, the discharge chamber is assumed to be 0.1Pa with Ar gas and electrons of \( 10^5 \) move around in the chamber. Several electrons are energized above the threshold energy for Ar ionization of 15.8eV by ECR heating. When the collision between the electron and Ar occurs in the calculation area, the position is marked with a cross. Ar ions are generated along the lines of magnetic force.

5. Conclusion

A 10-cm-diam. ECR ion thruster was fabricated and tested, and the results obtained are as follows.

1) Radial distributions of the extracted beam current for three kinds of magnetic field configuration are measured. These curves peak at the grid center. The measured values of the beam current for the 0.37T case are more than 10 times larger than that for 0.22T.
2) The ECR layer of the 0.37T type II is larger than the others and the extracted current from it is also larger. Extracted ion beam current increases as ECR layer becomes broader.
3) Although the extracted beam current becomes small, the plasma in the discharge chamber is stable when the distance d between the magnets and grids becomes larger (d=15 vs. d=50mm case for 0.37 type II).
4) The ECR ion thruster works stably when the bias voltage of the electrostatic grids does not affect plasma generation in the chamber. The distance between the ECR layer (and then the magnets) and the screen grid must be optimized to emit ions stably.
5) Probe diagnosis of a microwave ion engine were conducted to obtain two dimensional plasma distributions inside the discharge chamber. The maximum plasma density inside the chamber was about \( 6 \times 10^{16} \text{m}^{-3} \), which is close to the cut-off density \( 7.5 \times 10^{16} \text{m}^{-3} \) of 2.45GHz microwave for plasma generation.
6) A simulation code is being developed to analyze the experimental results.

6. Future plan

An ISAS type engine has been already fabricated as shown in Fig. 10. First ignition test will be conducted soon. We will also fabricate new engines based on the different idea such as multi-slot antenna.

References

Fig. 1 Schematic illustration of the experimental setup

Fig. 2 The ECR ion thruster

Fig. 3 Magnetic field configurations
(a) 0.22T, (b) 0.37T type I, (c) 0.37T type II

Fig. 4 Ion current measurement with a Faraday cup
Table 1 Performance test results of the ECR ion thruster

<table>
<thead>
<tr>
<th>Surface magnetic flux density of Sm-Co (T)</th>
<th>0.22T</th>
<th>0.37 (I)</th>
<th>0.37 (II)</th>
<th>0.37(II) d=50mm</th>
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</thead>
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<tr>
<td>Microwave power (W)</td>
<td>30</td>
<td>80</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Ar gas flow rate (sccm)</td>
<td>0.8</td>
<td>0.8</td>
<td>1.0</td>
<td>1.0</td>
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<td>Total ion beam current (mA)</td>
<td>-</td>
<td>26.1</td>
<td>35.3</td>
<td>19.1</td>
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<tr>
<td>Ion production cost (eV)</td>
<td>-</td>
<td>3.0x10^3</td>
<td>2.3x10^3</td>
<td>2.1x10^3</td>
</tr>
<tr>
<td>Propellant utilization efficiency (%)</td>
<td>-</td>
<td>46</td>
<td>50</td>
<td>26.6</td>
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<td>Beam divergence (degrees)</td>
<td>-</td>
<td>29</td>
<td>31</td>
<td>26</td>
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</table>

![Fig. 5 Probe measurement](image1)

![Fig. 6 Radial distributions of the extracted ion beam current.](image2)

![Fig. 7 Radial distributions of the extracted ion beam current for the 0.37 type II](image3)

![Fig. 8 Distributions of plasma density and electron temperature (microwave power, 30W) with P=3.2x10^{-2}(Pa) and P=6.4x10^{-2}(Pa)](image4)
Fig. 9 (a) Calculation area, (b) Trajectory of an electron in the magnetic field, (c) Time variation of kinetic energy of the electron, (d) Production of Ar ions by collisions with energetic electrons

Fig. 10 20-cm-diam. engine (ISAS type)