MICROWAVE ION THRUSTER WITH ELECTRON CYCLOTRON RESONANCE DISCHARGE

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Abstract

The electron cyclotron resonance discharge ion thruster YOSHINO-II was designed and tested. It produces the plasma using 5.9 GHz microwave power and permanent magnets. The beam extraction with the ion production cost 700 eV/ion at the propellant utilization efficiency 90% was demonstrated.

Nomenclature

\[ A_s = \text{area of screen grid, m}^2 \]
\[ B = \text{magnetic induction, G} \]
\[ C_i = \text{ion production cost, eV/ion} \]
\[ e = \text{electronic charge, 1.6x10^{-19} C} \]
\[ E = \text{electric field, V/m} \]
\[ E_i = \text{ionization potential, eV} \]
\[ k = \text{wave number, m}^{-1} \]
\[ l = \text{mean free path, m} \]
\[ m = \text{mass of electron, 9.1x10^{-31} kg} \]
\[ M = \text{mass of propellant gas, kg} \]
\[ \dot{m} = \text{mass flow rate} \]
\[ n_e = \text{plasma density, m}^{-3} \]
\[ T_e = \text{electron temperature, eV} \]
\[ \nu_{es} = \text{velocity of resonance particle, m/sec} \]
\[ \Lambda = \text{characteristic diffusion length, m} \]
\[ \nu_c = \text{collision frequency, sec}^{-1} \]
\[ \omega = \text{microwave frequency, sec}^{-1} \]
\[ \omega_{ce} = \text{electron cyclotron frequency, sec}^{-1} \]
\[ \omega_{pe} = \text{electron plasma frequency, sec}^{-1} \]
\[ \eta_u = \text{propellant utilization efficiency} \]
\[ \zeta_l = \text{open area fraction of screen grid} \]

Introduction

The electron bombardment ion thruster, which is the most popular ion thruster, is advanced in development. The critical parts in life-time of the electron bombardment ion thruster are the main cathode and the acceleration grid system. The thruster performance is degraded due to erosion and sputtering of the electrodes in the discharge chamber. The electron bombardment ion thruster requires at least seven power supplies for: acceleration, deceleration, discharge, main-cathode heater, main-are the ordinary (O) wave and the extraordinary (X) wave. The O wave are possible to propagate in cold magnetized plasmas. They electron bombardment ion thruster requires at least seven power supplies for, according to Verniel. The performance is degraded due to erosion and sputtering of the main cathode and the acceleration grid system. The thruster waves.

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According to Stix, two modes of the electromagnetic wave are possible to propagate in cold magnetized plasmas. They are the ordinary (O) wave and the extraordinary (X) wave. The O wave is not affected by the magnetic field because it has no components of the electric field perpendicular to the magnetic field. Whereas the X wave is interacts with the magnetic field. The plasma waves lose their energy mainly at the ECR layer, which is satisfied with the following condition:

\[ \omega = \omega_{ce} \]

(1)

The microwave discharge is seriously dependent on whether the microwave energy reaches the ECR layer. This problem is taken into account as the "accessibility" using the CMA diagram. Under a constant microwave frequency the abscissa and the ordinate in the CMA diagram correspond to the plasma density and the magnetic field strength, respectively. If a microwave is launched into a plasma from the side with low density plasma and low magnetic field, the X wave can not reach the ECR layer due to the cut-off as seen in Fig. 1. On the other hand, it is easy for the O wave to approach the ECR layer. The microwave frequency must be chosen to be satisfied that the optimum density of the ion thruster is less than the cut-off density.

Principle of Operation

The ECR discharge is divided into three processes: propagation of waves, absorption of waves and relaxation of waves.

1) to demonstrate the operation of the ECR type microwave ion thruster,
2) to get the thrust performance, and
3) to acquire guidelines to improve the performance of the ECR microwave ion thruster.

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The energy of the O wave in the ECR layer is effectively transformed into the kinetic energy of electrons due to the collisionless damping process via either the finite Larmor radius effect in the low density plasma or the O-X-B transformation effect in the over dense plasma, which exceeds the cut-off condition in the plasma density. The microwave energy is absorbed by the 'resonance particles', which are satisfied with

\[ \nu_{ce} = \frac{\omega - \omega_{ce}}{\nu} \]

(2)

The high energy electrons which are generated through the above-mentioned processes collide and ionize neutral particles. MacDonald\(^4\) indicates the following equation as the breakdown condition in the microwave discharge.

\[ \frac{eE^2}{m} \frac{v_I^2}{2} = 2I^2 \]

(3)

Equation (3) says that the microwave discharge requires \((\omega - \omega_{ce})\) times as large as the electric field of the direct current discharge. The off-resonance microwave ion thruster realizes this strong electric field by the resonance cavity. But in case of the ECR discharge, the \(\omega\) is replaced by \(\omega - \omega_{ce}\) in Eq. (3):

\[ \frac{eE^2}{m} \frac{v_I^2}{2} = 2I^2 \]

\[ \frac{\omega - \omega_{ce}}{\nu} E \]

(4)

According to Eq. (4), the ECR discharge requires almost the same electric field of the direct current discharge.

**Experimental Apparatus**

Figure 2 shows the cross sectional view of the ion thruster, Y-II. The discharge chamber was a cylinder 120 mm in diameter made of the mild steel to form the magnetic circuit with permanent magnets in the discharge chamber. Samarium-cobalt magnets, 4000 gauss, and ferrite magnets, 1500 gauss at their surface, were arranged to form the ring cusp shape. The discharge chamber was water-cooled to maintain the magnet temperature less than 200°C. The microwave power was introduced in the discharge chamber through the waveguide arranged on the side wall in alignment of the H surface of waveguide with the center line of the chamber.

Figure 3 shows the thruster system diagram. Propellant gas was provided through the isolator from the side wall. The argon or xenon gas was controlled by the thermal mass flow controller.

The conventional two grids system was adopted. The major characteristics of the two grid system are summarized in Table 1. The extracted ion beam were neutralized by electrons from a thermionic cathode.

<table>
<thead>
<tr>
<th>grid set</th>
<th>open area fraction of screen grid</th>
<th>open area fraction of accel. grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>51%</td>
<td>24%</td>
</tr>
<tr>
<td>B</td>
<td>65%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Figure 4 shows the microwave transmission circuits. The 5.9 GHz microwave power was amplified by TWTA and transmitted to the discharge chamber through rectangular waveguides in TE01 mode. The circuit was matched by an EH tuner. Input and reflected power were monitored by directional coupler. The DC break was inserted in the circuit in order to isolate the discharge chamber electrically. The vacuum window was also inserted into the circuit to seal.

All experiments were carried out in a space chamber which is 2800 mm in length and 1500 mm in diameter. The space chamber made of stainless steel and electrically grounded was evacuated by an oil diffusion pump of pumping speed 3000 l/sec. The diffusion pump was backed by an oil rotary pump of pumping speed 4500 l/sec. The pressure in the space chamber was around 8x10⁻⁶ torr before the working gas was supplied. The back pressure in the space chamber during an experiment was around 0.4 - 1.0x10⁻⁴ torr Experimental results were corrected for back currents of the working gas in Dushman's manner\(^5\).

The thruster was operated in the electrical configuration seen in Fig.3. The currents \(I_S\), \(I_A\), \(I_G\) and \(I_e\) through the screen grid, the acceleration grid, the neutralizer and the grounded point are measured depending on experimental parameters. Total beam current \(I_b\) was calculated by the following equations:
Fig. 4 Microwave transmission circuit

\[ I_0 = |I_0| - |I_0| \]
\[ I_s = |I_s| \pm |I_s| \]

(5)

And the characteristic of the ion source was estimated using the ion production cost \( C_i \) and the propellant utilization efficiency \( \eta_p \), which are defined as:

\[ C_i = \frac{\text{input microwave power}}{\text{beam current}} \]
\[ \eta_p = \frac{\text{beam current}}{\text{propellant flow rate}} \]

The plasma parameters were measured by the Langmuir probe. The probe was positioned one centimeter apart from the screen grid on the center line of the discharge chamber to avoid the influence of the magnetic field as little as possible. The probing was performed on the conditions of the grounded screen grid without the beam extraction. In the probe data analysis, the plasma density was estimated by the ion saturation current at the vicinity of the floating potential.

The experiment was conducted about three parameters: the magnetic field configuration in the discharge chamber, the input microwave power, and the mass flow rate of the propellant.

Results and Discussion

The photograph of the Y-II in discharge is represented in Fig. 5. The discharge was self-ignited at power level above 60 W in the argon mass flow rate above a few sccm so that a start-up electron source was unnecessary. The high energy electrons which were accelerated in the ECR layer caused drift along the azimuth direction because of the spatial inhomogeneous magnetic field. According to the Y-II, they go around in 10^-5 of the permanent magnets near the accelerator grids makes the ionization collision of electron. The electrons drift a few revolutions in the discharge chamber till they collide with and ionize the neutral particles. The discharge was not stabilized if the magenet field lines was cut by removing several pieces of magnets arranged on the side wall (showing in Fig. 6). The experimental observation is consistent with the understanding on the behavior at the primary electrons. The plasma was confined and stabilized by the ring cusp magnetic field so that the Y-II was removed the quartz glass, which wall-stabilizes the generated plasma and limits the life of the operation of the Y-I. The shadow on the Y-II in Fig. 5 and Fig. 6 is the thermionic cathode to neutralize the ion beam.

Figure 7 shows the typical ion source characteristics of the Y-II. The experimental data points on the same mass flow rate are linked by a unique curve. The measured points were shifted the upper right side in the diagram, namely the high \( \eta_p \) and high \( C_i \) side in the progression of the microwave power. As the mass flow rates were increased, the measured points were shifted the lower left side in the diagram. In this experiment, the ion beam were not extracted enough to estimate the ultimate performance of the ion source in the high mass flow rate case due to the high background pressure in operating. The double "knee point" in Fig. 7 was the remarkable characteristic of the ECR ion source. The drastic change of the coupling with the microwave and the plasma was not observed when the end plate was slid. It is concluded that the standing waves as the off-resonance ion source did not exist in the discharge chamber.

The magnetic field in the discharge chamber influences upon the ECR plasma production in the following three points:
1) to form the ECR layer which generates the high energy electrons to ionize neutral particles,
2) to confine and stabilize the generated plasma, and
3) to disturb the motion of ions to be extracted as the ion beam.

Figure 8 shows the effect of the number of permanent magnets in the discharge chamber. As the number of the permanent magnets were increased, the area of the ECR layer were enlarged, so that the performance of the ion source was improved. Arrangement of the permanent magnets near the accelerator grids makes the performance of the ion source degrade because ions could not be extracted effectively due to the ion's Larmor motion. It is suggested that there is the optimum arrangement and number of the permanent magnets in the discharge chamber.

Figure 9 shows the effect of the species of the permanent magnet in the discharge chamber. The ion source with the ferrite magnets is inferior to that with the samarium-cobalt magnets. The ferrite permanent magnet are a dielectric and are reduced.
seriously their intensity of magnetization in the progression of temperature. It is thought that the microwave absorption by the ferrite magnets and the degraded magnetic field decrease the performance of the ion source.

Figure 10 shows the $C_I - \eta_u$ diagram and the magnet arrangement in the discharge chamber when recorded the most high performance in the series of the experiment. The argon propellant utilization efficiency of 75% was achieved at the ion production cost of 750 eV/ion and xenon performance of 90% propellant utilization efficiency at 700 eV/ ion. Figure 11 shows the comparison of the ion source performances between Y-I and Y-II. The modification of the discharge from the off-resonance type to the ECR type leads obviously improvement of the performance of the microwave ion source: the propellant utilization efficiency increases by 3.5 times and the ion production cost decreases by a tenth.

The ion saturation current to the Langmuir probe as a function of the input microwave power is represented in Fig.12 when Y-II was operated using the argon gas in the magnetic field configuration showed in Fig.10(a). Figures 13 and 14 show the electron temperature and the plasma density, respectively, which were achieved by analyzing Fig.12. The electron temperature was increased smoothly as a function of the discharge power. The plasma density had a discontinuous change around $3 \times 10^{11} \text{ cm}^3$ at every mass flow rate. The cut-off density for the 5.9 GHz microwave is $4.3 \times 10^{11} \text{ cm}^3$. It was found that the electron temperature was higher than that of the electron bombardment ion source. It seems that the input microwave power not only generate plasmas but also heat plasmas by means of the electron cyclotron heating (ECH).

It is the remarkable characteristic of the ion source that $C_I - \eta_u$ diagram had the discontinuity. Masek6 points out that the ion sheath is formed in front of the screen grid and the extracted beam current is described by means of the Bohm’s stable sheath condition:

$$I_B = \exp\left(-\frac{1}{2}\frac{e}{m_e}V_{M}^2 \frac{s}{\sqrt{2}} \frac{A_r \zeta}{M}ight) \quad (6)$$

Figure 15 shows the measured beam current and calculated beam current estimated from the measured electron temperature and plasma density using Eq. (6). The two lines coincide with each
other qualitatively, so that it is concluded that the discontinuous change of the plasma density in Fig.14 causes the discontinuity in the $C_{1-\Pi}$ diagram. Because the beam extraction makes selective drain of ions from the discharge chamber, the neutral particle density is different from the non-extracting condition. The estimated data points equivalent in the neutral density to the beam extraction condition are also represented in Fig.15. They coincide with each other quantitatively.

The double knee points in Fig.7 are associated with the discontinuity of the plasma density in Fig.14. Two modes to produce plasma are thought to exist. One is the low density mode associated with the lower knee. The other is the high density mode with upper knee point. The microwave is possible to propagate to the ECR layer in the plasma less than the cut-off density. The microwave produces plasma in the ECR layer at the low density mode. If the discharge chamber is filled with the over dense plasma, the plasma is produced via the O-X-B transformation between the upper hybrid resonance layer and the ECR layer. It seems that the ECR ion thruster is preferable to operate in the low density mode from the viewpoint of optimum density in the ion thruster.

Figure 13 tells that the electron temperature of Y-II is higher than that of the electron bombardment ion thrusters. It seems that the input microwave power not only generate plasmas but also heat plasmas (ECH). The high electron temperature increases the plasma potential, and accelerate ions toward walls. These high energy ions sputter walls and the surface breakdown is caused by particles of wall material contaminating on the insulator. The low electron temperature is preferable from the viewpoint of the thrust performance and the life-time of the microwave ion thruster.

It seems that the input microwave power localizes, so that the plasma production depends on the direction and the mode to launch the microwave power into the discharge chamber. The magnetic field configuration in the discharge chamber affects the accessibility of the microwave and the plasma confinement. In order to improve the thruster performance, the significant items are the following: the magnetic field configuration, the direction and the mode of the microwave.

**Fig.10** $C_{1-\Pi}$ diagram on the magnetic configuration marking the best performance

**Fig.11** Comparison of the ion source characteristics between Y-I and Y-II

**Fig.12** Dependence of the ion saturation current on the discharge power

**Fig.13** Dependence of the electron temperature on the discharge power
Concluding Remarks

The experiment of the microwave ion thruster Y-II, which produced the plasma by means of the ECR discharge was conducted. The xenon beam extraction test demonstrated the ion production cost 700 eV/ion when the propellant utilization efficiency is 90%. The ECR microwave ion thruster Y-II was highly efficient in comparison with the microwave ion thruster Y-I with the off-resonance discharge, where the ion production cost was 7000 eV/ion at the propellant utilization efficiency 25%. The magnetic stabilization of plasma removes the quartz glass from the discharge chamber so that the limitation of thruster lifetime is resolved completely. The double knees in the C-D diagram of the Y-II were found experimentally. This phenomena is thought to be associated with two modes to produce plasma by the ECR microwave discharge.

In addition, the following guidelines to improve the performance of the ECR ion thruster were found:
1) to keep the ECR layer as large area as possible,
2) to avoid the arrangement of the permanent magnets near the accelerator grids, and
3) to inhibit usage of the dielectric magnets in the discharge chamber.

References