Plasma Properties in a Miniature Microwave Discharge Ion Thruster

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In order to improve the thrust performance of a 1-mN-class miniature microwave discharge ion thruster, we investigate the dependence of inner plasma properties inside the thruster on operational conditions, krypton mass flow rate, incident microwave power and magnet field strength by laser Thomson scattering (LTS) technique. With an increase in mass flow rate, the electron temperature decreases and the electron number density increases at an incident microwave power of 16 W and the number of magnets of twelve. These results indicate that there is an optimum mass flow rate, which is 0.6 sccm in this condition. The electron number density and temperature increase with incident microwave power and is saturated at 8 W for a mass flow rate of 0.4 sccm and the number of magnets of twelve. With an increase in magnetic field strength, the electron temperature and the electron density suddenly jump from $9.8 \times 10^{17} \text{ m}^{-3}$ and 5.2 eV to $1.7 \times 10^{18} \text{ m}^{-3}$ and 7.3 eV at the number of magnets of thirteen at a mass flow rate of 0.4 sccm and incident microwave power of 16 W.

Key Words: Ion Thruster, Laser Thomson Scattering, Plasma Property, Miniature Propulsion

Nomenclature

- $e$: elementary electric charge
- $F$: thrust
- $I_b$: ion beam current
- $k$: Boltzmann constant
- $\dot{m}$: mass flow rate
- $m_i$: ion mass
- $N_e$: electron number density
- $N_{mag}$: number of magnets
- $P_i$: incident microwave power
- $S$: beam extraction area
- $T_e$: electron temperature
- $V_b$: beam voltage
- $\gamma_t$: thrust coefficient
- $\varepsilon$: quantum efficiency
- $\lambda$: incident laser wavelength
- $\Delta \lambda$: wavelength difference from incident laser wavelength

1. Introduction

The demand for mN class miniature propulsion systems is expected to grow in the future for small satellites, since the adoption of small satellites, with their flexibility, short development time and low cost, has been a breakthrough in space applications. Until recently, however, size restrictions have limited the capacity of the available propulsion systems.

Since an ion thruster produces high thrust efficiency with a specific impulse of 3,000-8,000 sec, the adoption of ion thruster into small satellites will expand their ability, that is, missions such as Mars exploration and self-disposal of satellites would become possible. The miniature ion thrusters can also be used for precise high-stability attitude and position control in large spacecrafts, as well as for primary propulsion of small space explorers.

Several studies have been conducted on the miniature ion thrusters. Wirz et al. showed good performance of a 30 mm Miniature Xenon Ion (MiXI) thruster, that is, the propellant utilization and the ion beam production cost were 0.8 and 500 W/A, for 0.2 sccm of mass flow rate1). An electron bombardment-type ion source was used for ion production, so that operation time was limited by the thermionic cathode lifetime. A microwave discharge ion source would offer a potentially longer thruster lifetime than the electron bombardment-type, since it would be free from contamination and degradation of electron emission capacity2-7).

We have been developing a miniature microwave discharge ion thruster. However, the thrust performance of our ion thrusters has thus far been inferior to conventional ion thrusters, because of the high cost of ion production due to poor microwave-plasma coupling as well as high losses from ion and electron collisions with the walls. This type of ion source has magnetic mirrors formed by a magnetic circuit and it also has an antenna to emit microwaves. The region between magnetic mirrors works as a virtual cathode, since trapped electrons gain energy from the microwaves by electron cyclotron resonance (ECR) heating and they ionize neutral atoms8). For effective microwave-to-plasma energy transfer, the antenna will contact with the ECR layer, since a high electric field appears in the vicinity of the antenna. On the other hand, a magnetic confinement will affect the performance of the ion source. These assumptions have not been proofed due to the difficulty of measuring the inner plasma properties.
The aim of this study is to measure the internal plasma property of this thruster and to understand the mechanism of the plasma production and loss inside the discharge chamber. This leads to improve the thrust performance.

However, it is difficult to measure inner properties of the plasma, since the ion thruster is so small that we cannot insert measurement equipments without perturbations. Therefore, plasma property in the discharge chamber were measured by laser Thomson scattering (LTS)\textsuperscript{8-10}. The LTS is a nonintrusive method for the measurement of plasma properties. In the incoherent regime, the scattered spectrum reflects the Doppler motion of individual electrons, and the scattered intensity is proportional to the electron density.

For the application of the method to the plasma produced in the miniature microwave ion thruster, the following difficulties exist. First, the size of the plasma is around 10 mm and the electron density is estimated to be less than $10^{18}$ m\(^{-3}\). This results in a very small Thomson scattering signal. Secondary, the stray laser light becomes very strong because the wall of the discharge chamber and the surface of the microwave discharge antenna are close to the scattering volume. In order to overcome these difficulties, we used the photon counting method, and a triple grating spectrometer which had a stray light rejection factor of $10^5$. These made us possible to detect LTS signals from the plasma in the miniature microwave discharge ion thruster.

2. Experimental Setup

2.1. Miniature microwave discharge ion thruster

The schematic of a miniature microwave discharge ion thruster used in the experiment is shown in Fig. 1. This thruster consists of soft iron yokes, samarium-cobalt (Sm-Co) magnets, a carbon discharge chamber, and a molybdenum antenna. The size of this thruster is $50\times50\times30$ mm\(^3\). The magnetic circuit consists of some Sm-Co permanent magnets and iron yokes. The magnetic field strength is varied by changing the number of magnets.

The discharge chamber is made of carbon because light reflectance and thermal expansion rate of carbon are small. There are two holes ($\varphi = 2$ mm) on side of the discharge chamber for laser injection and a hole ($\varphi = 5$ mm) on upside for collection of Thomson scattering light. A measurement point of LTS is shown in Fig. 2. It is at 4 mm downstream on the antenna in the axial direction and 6 mm far from the axis in the radial direction.

The ion beam was not extracted in this experiment due to limitations of our facility. An 8 mm diameter orifice was used in order to keep almost the same pressure as in the case of ion beam extraction from the plasma, assuming propellant utilization of 0.7 and a ratio of the doubly charged ion current to the singly charged ion current of 0.15; the conductance of the orifice is about three times larger than that of the grids. In order to keep a constant temperature, a cooling system was used.

Krypton gas (99.999 % pure) is used as a propellant. A thermal mass flow controller (Brooks Instrument, 5850S, full scale = 3 sccm) is used. The error of this is 0.009 sccm at $\dot{m} = 0.4$ sccm.

Microwave power at 2.45 GHz is fed through a coaxial line followed by an antenna. The star-shape antenna is used since it showed good performance in our previous study\textsuperscript{2).}

A 267 mm diameter by 400 mm long vacuum chamber was used in the experiments. The pumping system comprised a rotary pump and a turbo molecular pump. The background pressure was maintained below $1.2\times10^{-2}$ Pa for most of the operating conditions.

2.2. LTS measurement apparatus

Figure 3 shows a schematic diagram of the optical system. The light source is the second harmonic beam of an Nd:YAG laser having a wavelength of 532 nm with an energy of 180 mJ, a repetition rate of 10 Hz, a pulse width of 6 ns and a beam divergence of 0.6 mrad. A scattering angle is 90 degree. To eliminate stray light, a triple grating spectrometer was used. Thomson scattering light generated by 5,000 incident laser shots and passed through the triple grating spectrometer was detected by a photomultiplier tube (Hamamatsu Photonics K.K., R943-02, quantum efficiency: $\varepsilon = 0.1$ at $\lambda = 532$ nm). Detected Thomson scattering light was converted into an electrical signal and was detected by a photon counter (Stanford Research Systems Inc., SR-430). The photon counter starts to detect photon when a PIN photodiode detects laser light.
3. Results and Discussion

A relation between the ion beam current and the plasma properties is represented as the following equation.

$$I_b = eN_e \exp \left( \frac{1}{2} \sqrt{\frac{kT_e}{m_i}} \right).$$  (1)

The thrust of the ion thrusters is estimated as,

$$F = \gamma_e I_b \sqrt{\frac{2mV_b}{e}}.$$  (2)

According to Eqs. (1) and (2), the thrust is proportional to $N_e$ and the square root of $T_e$. Therefore, the thrust is increased if $N_e$ and $T_e$ increase.

Thomson scattering intensities are plotted in a logarithmic scale in the ordinate against $(\lambda \Delta \lambda)^2$, as shown in Fig. 4. $(\lambda \Delta \lambda)^2$ is proportional to the electron energy. The solid line represents Maxwellian distributions at $T_e$ of 4.7 eV. From the straight line of the Thomson spectrum, we conclude that the electron energy distribution function is Maxwellian. From this spectrum and the Rayleigh scattering calibration using air gas, $N_e$ and $T_e$ are evaluated to be $(1.2\pm0.2) \times 10^{18}$ m$^{-3}$ and $4.7\pm0.7$ eV, respectively (where the error is due to the shot noise)$^8$.

3.1. Dependence on mass flow rate

Figure 5 shows the dependence of $T_e$ on $\dot{m}$ at $P_i$ of 16 W and $N_{mag}$ of twelve. $T_e$ decreases with an increase in $\dot{m}$, that is, $T_e$ is 8.6 eV and 4.6 eV, respectively at $\dot{m}$ of 0.2 sccm and 0.8 sccm. This is because trapped electrons gain less energy from the microwaves with the increase in $\dot{m}$, since mean free path of electrons decreases with the increase in neutral atom number density, that is, the pressure inside the discharge chamber, and electrons has less chance going through the ECR layer, where electrons effectively gain energy from the microwaves.

Figure 6 shows the dependence of $N_e$ on $\dot{m}$ at $P_i$ of 16 W and $N_{mag}$ of twelve. $N_e$ increases with $\dot{m}$. $N_e$ is $8.2\times10^{14}$ m$^{-3}$ and $1.3\times10^{15}$ m$^{-3}$, respectively at $\dot{m}$ of 0.2 sccm and 0.6 sccm.

This is because the chance of ionization collision between electrons and neutral atoms increases with the increase in $\dot{m}$. Too high pressure, however, decreases $T_e$ as shown in Fig. 5, and this leads to decrease $N_e$. Therefore, there is an optimum $\dot{m}$ and it is 0.6 sccm at this condition.

3.2. Dependence on incident microwave power

Figure 7 shows the dependence of $N_e$ on $\dot{m}$ of 0.4 sccm and $N_{mag}$ of twelve. $N_e$ increases at $P_i < 8$ W, and then is saturated.

Fig. 3. The schematic diagram of the optical system.

Fig. 4. Thomson scattering spectrum measured at $\dot{m}$ of 0.4 sccm, and incident microwave power of 16 W.

Fig. 5. The dependence of $T_e$ on $\dot{m}$ when $P_i$ was 16 W and $N_{mag}$ was twelve.

Fig. 6. The dependence of $N_e$ on $\dot{m}$ when $P_i$ was 16 W and $N_{mag}$ was twelve.
at $P_i > 8$ W. This is because $T_e$ is saturated $P_i > 8$ W, as shown in Fig. 8. The saturation of $T_e$ beyond $P_i$ of 8 W would be due to the increase in loss on the wall, since diffusion coefficient is proportional to $T_e$. Too much incident microwave power doesn’t contribute to the improvement of the thrust performance, therefore, there is an optimum $P_i$, which is 8 W at this condition.

3.3. Dependence on magnetic field strength

Figure 9 shows the dependence of $T_e$ on the magnetic field strength inside the discharge chamber at $\dot{m}$ of 0.4 sccm and $P_i$ of 16 W. $T_e$ increases with the increase in magnetic field strength and suddenly jumps from 5.2 eV to 7.3 eV at $N_{mag}$ of thirteen. Figure 10 shows the dependence of $N_e$ on the magnetic field strength at $\dot{m}$ of 0.4 sccm and $P_i$ of 16 W. $N_e$ increases with the increase in the magnetic field strength and suddenly jumps from $8.0\times10^{17}$ m$^{-3}$ to $1.2\times10^{18}$ m$^{-3}$ at $N_{mag}$ of thirteen.

Figure 11 shows the result of magnetic field analysis (calculated by QuickField 3.4, Tera Analysis Co.). This result shows that the ECR layer overlapped the antenna when $N_{mag}$ is less than thirteen. This means that highly energetic electrons collide frequently with the antenna and lost this energy on the antenna surface at $N_{mag} < 13$. Therefore, $T_e$ suddenly jumps up at $N_{mag}$ of thirteen. However, we could not ignite the plasma when $N_{mag}$ was fourteen. This is because the distance between the ECR layer and the antenna is too far and the ECR heating doesn’t work effectively.
4. Conclusions

The plasma properties in a 1-mN-class miniature ion thruster were measured by laser Thomson scattering technique for the improvement of the thrust performance. The results are as follows.

1) The dependence of the electron temperature/number density on the mass flow rates was investigated. With the increase in the mass flow rate, the electron temperature decreases while the electron number density increases. With the increase in mass flow rate from 0.2 sccm to 0.6 sccm, the electron temperature decreased from 5.9 eV to 2.1 eV and the electron density increased from $1.3 \times 10^{18}$ m$^{-3}$ to $1.7 \times 10^{19}$ m$^{-3}$ at incident microwave power of 16 W and the number of magnets of twelve. These results indicate that there is an optimum mass flow rate. The optimum mass flow rate is 0.6 sccm at incident microwave power of 16 W and the number of magnets of twelve.

2) The dependence of the electron temperature/number density on the incident microwave power was investigated. The electron temperature and the electron number density are saturated at a critical incident microwave power. This indicates there is an optimum net incident microwave power for the thrust performance. The optimum net incident microwave power is 8 W at mass flow rate of 0.4 sccm and the number of magnets of twelve. Then the electron temperature and the electron number density are 5.0 eV and $1.3 \times 10^{19}$ m$^{-3}$, respectively.

3) The dependence of the electron temperature/number density on the magnetic field strength was investigated. The electron temperature and the electron number density jump up from 5.2 eV and $9.8 \times 10^{15}$ m$^{-3}$ to 7.3 eV and $1.7 \times 10^{19}$ m$^{-3}$ when the number of magnets is changed from twelve to thirteen. However, we cannot ignite the plasma with fourteen magnets. Therefore, there is an optimum magnetic field strength. The optimum number of magnets in this condition is thirteen.

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References