Azimuthal Velocity Measurement of μ10 Microwave Ion Thruster by Laser Induced Fluorescence Spectroscopy

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This paper reports the first ground study to measure the azimuthal velocities of an ion thruster that produces roll torque. Through the operation of ion thrusters in space, it has been confirmed that thrusters cause an unexpected roll torque about the ion beam axis. To reveal the physical mechanism that produces this torque, laser-induced fluorescence spectroscopy was applied to a microwave ion thruster that has been installed in Japanese asteroid probes. This technique can be used to measure the azimuthal velocity by estimating the Doppler shift of the velocity functions of Xe II $5p^4(^3P_2)6p\ ^2[3]^0\ 5/2$. To simplify this problem, the measurement was conducted without a neutralizer cathode to avoid the possibility of the cathode affecting the trajectory of the ion beam. The azimuthal velocities were successfully measured and were found to range from -700 to 600 m/s. The based on the results, the roll torque was estimated as 0.5 μN·m about the thrust axis. Also the azimuthal velocity profile was modeled based on the rotational misalignments of the grids and the magnetic field from the discharged chamber, which will be reported in oral presentation.

I. Introduction

Through various space missions, it has been confirmed that gridded ion and Hall thrusters generate not only a thrust force along the ion beam axis but also a roll torque about the thrust axis.[1,2] The authors have also confirmed the generation of a roll torque through the operation of the μ10 microwave ion thruster, which was developed for Japanese asteroid sample return missions in the Hayabusa series.[3] Throughout

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these missions, an undesigned torque about the axis of the ion beams was detected, as shown in Table 1. Though it is too weak to directly measure the torque, it is important to measure it to precisely control the attitude of spacecraft. In this study, laser-induced fluorescence (LIF) spectroscopy has been used to measure the azimuthal velocities of xenon ions. In previous studies, the torque was measured for Hall thrusters, which have an azimuthal current derived from the Hall effect.[4–8] However, no previous studies have focused on ion thrusters. The following possible mechanisms of roll torque production have been proposed:[1,3]

1. Rotational misalignment of the accelerator grid with respect to the screen grid,
2. Magnetic field effect from the discharge chamber,
3. Electrostatic force produced by the potential of the neutralizer cathode and its electron beam,
4. Lorentz force produced by the magnetic field of the microwave neutralizer cathode,
5. Electrostatic force produced by the potential of solar panels biased at a positive potential.

Mechanisms (3) and (4) arise from the use of neutralizer cathodes that emit an electron current equal to the ion beam current to maintain the potential of the spacecraft. These cathodes are located close to the ion sources of the ion thruster, as shown in Fig. 1. Mechanism (4) only arises in the μ10 microwave ion thruster because other ion thrusters generally use non-magnetized hollow cathodes. Mechanism (5) is dependent on the design of the spacecraft. To generalize this study, LIF spectroscopy was applied to the ion beam of the μ10 microwave ion thruster without its microwave cathode.

This study will report the azimuthal velocities of xenon ions in plume and roll torque will be estimated. In addition, the modeling of the roll torque will be discussed based on the above mechanisms (1) and (2) in oral presentation.

Table 1. Roll torque about the beam axis of the μ10 microwave ion thruster.

Thruster	Roll torque [μN·m]
Ion Thruster A	–
Ion Thruster B	−3.3
Ion Thruster C	1.1
Ion Thruster D	2.0

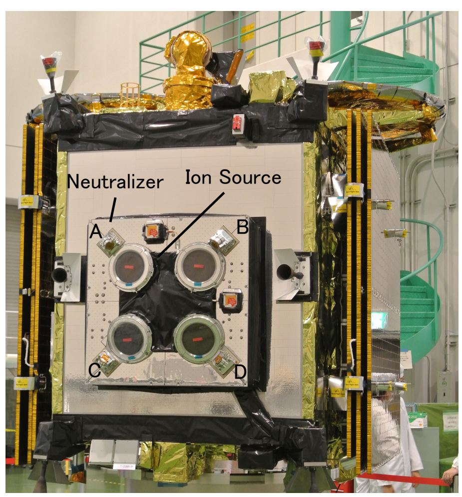

Figure 1. μ10 microwave ion thrusters mounted on the gimbal system of the Japanese asteroid sample return spacecraft Hayabusa 2.

II. Experiment

A. μ10 microwave ion thruster

A schematic of the μ10 microwave ion thruster is shown in Fig. 2. The thruster consists of a waveguide, a discharge chamber, three carbon-carbon composite grids,[9] and a neutralizer. Additionally, a microwave antenna and a propellant inlet are located at one end of the waveguide. The other end of the waveguide is connected to the discharge chamber. Microwaves with a frequency of 4.25 GHz are transmitted through the waveguide into the discharge chamber. Two rings of samarium–cobalt magnets in the plasma source serve to generate plasma through electron cyclotron resonance (ECR) heating.

A propellant, xenon, is injected into the inlet and flows into the discharge chamber, where electrons are continuously accelerated by a mirror magnetic field and microwave electric oscillation by means of ECR. As a result of subsequent electron–neutral collisions, ECR plasma is formed. The plasma is biased at 1500 V, and xenon ions are electrostatically accelerated by a screen grid, an accelerator grid, and a decelerator grid. The screen grid has the same potential as the discharge chamber and the waveguide, the accelerator grid is biased at −350 V, and the decelerator grid is grounded. To maintain the potential of the spacecraft, the microwave discharge cathode emits an electron current equal to the ion beam current.

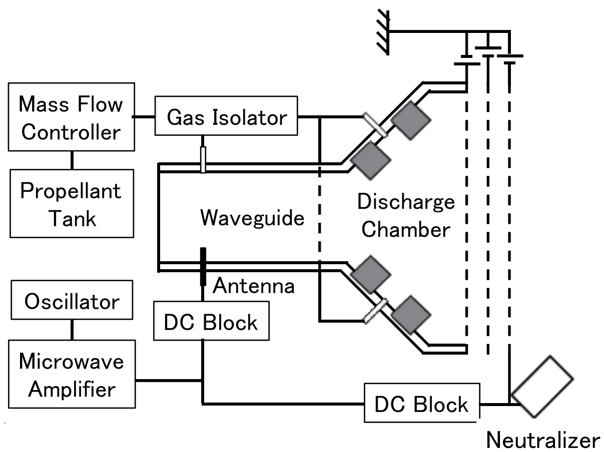

Figure 2. Schematic of the μ10 microwave ion thruster.

The performance of the μ10 microwave ion thruster is presented in Table 2. Since the first launch of Hayabusa in 2003, it has been continuously improved. The thrust force, which was originally 8.0 mN in 2003 at a total efficiency of 36%, was improved to 10.0 mN at 38% for Hayabusa2 in 2014, and it can currently achieve 11.2 mN at 40%.[10–12]

Though the improved μ10 ion thruster is capable of emitting an ion beam current of 192 mA, in this study, the operation conditions were set to Hayabusa mode to compare the simulation results with the flight data. The specifications of Hayabusa and Hayabusa2 are given in parentheses in Table 2.

B. Laser-induced fluorescence spectroscopy

Fig. 3 and Fig. 4 show the experimental setup for the azimuthal velocity measurement of the microwave ion thruster by LIF spectroscopy. In this measurement setup, a diode laser (DL100, Toptica Photonics AG), which emits 50-mW laser light with a diameter of 2 mm, is used. The controller of the laser sweeps wavelengths (vacuum) ranging from 834.930 to 834.985 nm. The polarization of the emitted laser beam is changed using a half-wave plate, and the beam is then injected into an amplifier (BoosTA, Toptica Photonics AG). The amplifier boosts the power of the seed laser beam from 50 to 500 mW. Then, the laser beam is split into a wavemeter, a reference cell (Xe tube), and an optical fiber. Using an optical fiber feedthrough, the laser beam is injected to the 135-mA ion beam in the vacuum chamber. The laser beams sent to the reference cell and the optical fiber are modulated at 5.6 kHz by a chopper to improve the signal-to-noise ratio using a lock-in-amplifier (7270DSP, Signal Recovery, Inc.).

Two photomultiplier detectors (H11462-031MOD, Hamamatsu Photonics K.K.) are used to detect the

Table 2. Specifications of the μ10 microwave ion thruster. The most recent performance is given, followed by the specifications for Hayabusa/Hayabusa2 in parentheses.

Parameters	Values
Beam diameter [mm]	105
Electric power [W]	440 (340/410)
Microwave power [W]	34
Thrust [mN]	11.2 (8.0/10.0)
Beam current [mA]	192 (135/170)
Specific impulse [s]	3150 (3200/3050)
Total propulsion efficiency [%]	40 (36/38)
Screen voltage [V]	1500
Acceleration voltage [V]	−350
Decelerator voltage [V]	grounded
Lifetime [h]	30,000 (15,000)

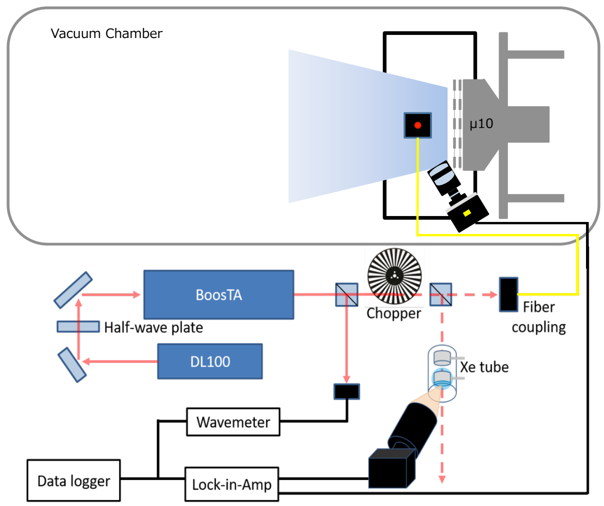

Figure 3. Experimental setup for the azimuthal velocity measurements of the μ10 microwave ion thruster.

output laser beams. One is located on the optical bench for the reference cell, and the other is located on a linear stage inside the vacuum chamber. In front of the photomultipliers, 542-nm bandpass filters are included to improve the signal-to-noise ratio, and two convex lenses are used to collect the fluorescence signals. The probe laser and the detector are mounted on an automated linear stage, which can be moved ±48 mm from the reference position along the Y-axis. The system is located 110 mm downstream from the ion thruster. The fluorescence signals were recorded three times at each location. The averages of these three measurements were used in the analysis of the Doppler shift. To measure the azimuthal velocities, the laser was set at an angle of 90°.

Fig. 5 shows the part of the Xe II Grotrian diagram relevant to the present measurements. The probe laser excites the Xe II $5p^4(^3P_2)5d\ ^2[4]\ 7/2$ band at a wavelength of 834.956 nm. Then, the excited Xe II $5p^4(^3P_2)6P\ ^2[3]^0\ 5/2$ band emits a fluorescence signal at approximately 542.065 nm. The ion velocity distribution functions have a symmetric Gaussian distribution, which is a convolution of hyperfine structures. It is well known that each spectrum is affected by different types of broadening, such as natural broadening, Doppler broadening, Zeeman broadening due to the magnetic field, and saturation broadening. In this study, it was estimated that saturation occurs at a laser power of approximately 0.1 mW/mm^2, which results in the highest degree of broadening among the types of broadening listed above.[13]

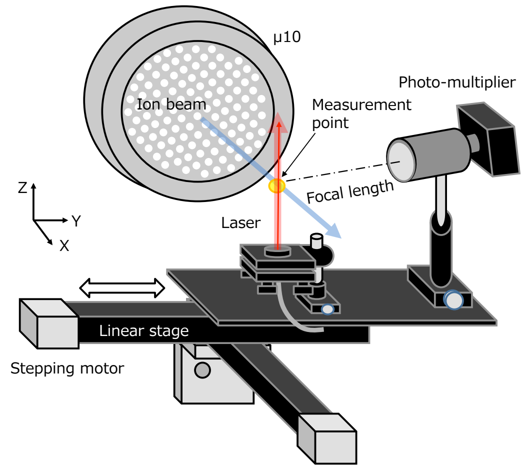

Figure 4. Schematic of the measurement system mounted on a Y-axis linear stage located 110 mm downstream from the thruster.

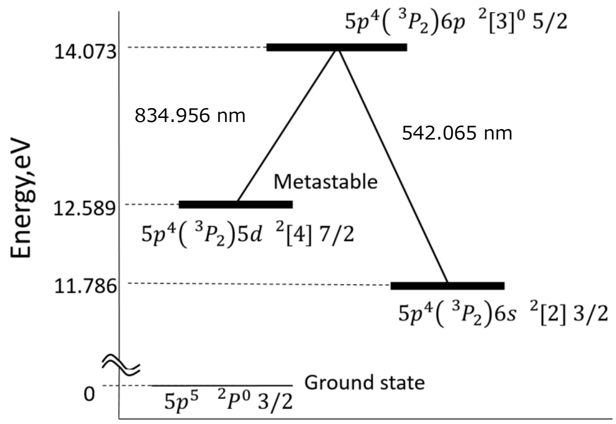

Figure 5. Xe II Grotrian diagram showing the energy levels relevant to this study.

III. Results and Discussion

A. Azimuthal velocities of xenon ions

The measured velocities are summarized in Fig. 6. From Y=−48 to −18 mm, the velocity increased from 550 to 600 m/s. Additionally, from Y= −18 to 18 mm, the velocity drastically decreased from 600 to −600 m/s. When the radial position exceeded Y=18 mm, the velocity was approximately −550 to −700 m/s. A positive velocity is defined as clockwise when viewed from downstream to upstream along the ion beam. Though the absolute values of the velocities at equal distances from the center of the thruster were not equal, the profile of the velocities was roughly symmetric.

B. Projected roll torque

To compare the flight data of the roll torque observed in Hayabusa, measurements were conducted at 135 mA. Fig. 7 shows the beam profile at 135 mA.

The roll torque can be expressed as

$$\mathrm{d}T = y\,\mathrm{d}F = yv(y)\frac{\mathrm{d}m_i}{\mathrm{d}t}, \tag{1}$$

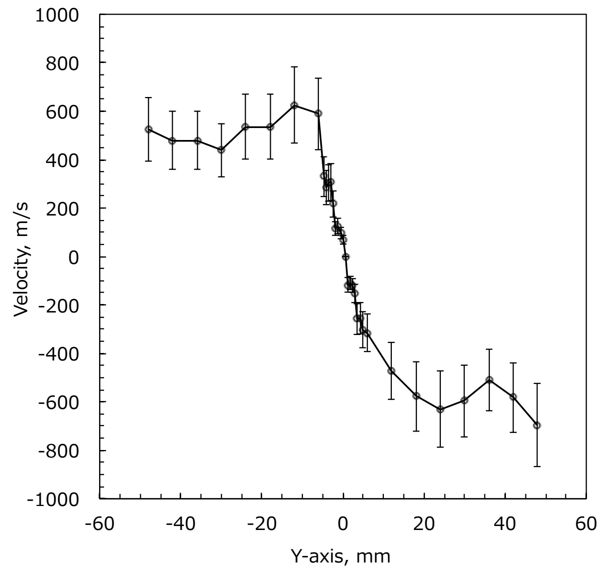

Figure 6. Relative azimuthal velocity distribution in the ion beam 110 mm downstream from the thruster. Positive velocities correspond to the +Z direction, as defined in Fig. 4. "B field" indicates the simulated velocities based on the effect of the magnetic field of the discharge chamber, and "Misalignment" indicates that of the electrostatic effect of the misalignment of the accelerator grid.

where $\mathrm{d}F$ is an infinitesimal force, $\mathrm{d}m_i/\mathrm{d}t$ is the mass flow rate of xenon ions, and vy is the azimuthal velocity. Additionally, the mass flow rate is defined as

$$\frac{\mathrm{d}m_i}{\mathrm{d}t} = i(y)\frac{m_{Xe}}{e}2\pi y\,\mathrm{d}y, \tag{2}$$

where $i(y)$ is an infinitesimal ion beam current and m_{Xe} is the mass of one xenon atom. The infinitesimal ion beam current $i(y)$ can be obtained from the ion beam profile shown in Fig. 7.

Using Eqs. (1) and (2), the roll torque produced by the azimuthal ion velocity is expressed as

$$T = \int v(y)i(y)\frac{m_{Xe}}{e}2\pi y^2\,\mathrm{d}y. \tag{3}$$

From Eq. (3), the calculated roll torque is 0.5 μN·m. The order of magnitude of the calculated torque is within the observed values in space given in Table 1. There are several hypotheses to explain the difference between the calculated roll torque and the observed torque. One is that the neutralizer cathode and its electron beams electrostatically bend the beam trajectories, which may result in a higher roll torque. Alternatively, the microwave cathode also requires a strong magnetic field to produce ECR plasma. Leaked magnetic field can apply a force to the ion beam. Finally, in actual space missions, spacecraft contain solar panels biased to a potential higher than the ground potential, which may interfere with the ion beam. For these reasons, although there remain some differences between the torque simulated using the proposed the model and the observed torque, the results of this study confirm that the azimuthal velocity is caused by the rotational misalignment of the grid and the magnetic field of the discharge chamber.

IV. Conclusions

To reveal the physical mechanisms producing the roll torque, LIF spectroscopy was successfully applied to the ion beam of the μ10 microwave ion thruster without a neutralizer. The fluorescence of Xe II $5p^4(^3P_2)6p\ ^2[3]^0\ 5/2$ was measured 110 mm downstream from the ion thruster, and the measured spectra were considered to consist of the charge exchange xenon ions and the xenon ions accelerated by a potential of 1500 V. After deconvolving the measured spectra, the following conclusions were obtained.

- The azimuthal velocities were measured. The direction of the velocities was found to be clockwise when looking upstream along the ion beam. The velocities ranged from −700 m/s to 600 m/s.

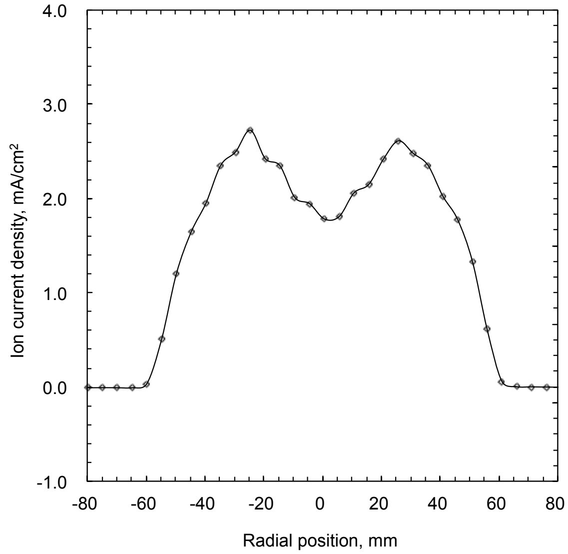

Figure 7. Ion beam profile of the μ10 microwave ion thruster at a beam current of 135 mA (Hayabusa mode).

- The calculated torque was 0.5 μN·m. The order of magnitude of this estimation is within the range of the torques observed during the Hayabusa mission.
- The measured velocities agreed well with those simulated using the proposed model, which included the effects of the misalignment of the accelerator grid with respect to the screen grid and the magnetic force from the discharge chamber. (in oral presentation.)

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