

Number Density Measurement of Xe I in the ECR Ion Thruster $\mu 10$ Using Optical Fiber Probe

IEPC-2011-318

*Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011*

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Abstract: The microwave discharge ion thruster $\mu 10$ was firstly demonstrated in space for 40,000 hours through a Japanese asteroid sample returner HAYABUSA. Based on the success of the mission, $\mu 10$ will be installed in the successor HAYABUSA-2 and commercial spacecrafts. In order to expand the possibility of $\mu 10$ without any major change of designs for preserving its flight heritage, it needs to improve its thrust force although it already saturated with an input microwave power. In this paper, two internal spectroscopic measurements are conducted to reveal a mechanism of the saturation of $\mu 10$. At first, a luminescence distribution was measured using a multi mode optical fiber probe. Then the experiment set up was developed for a laser absorption spectroscopy for metastable neutral Xenon particles at the wavelength of 823 nm using a single mode optical fiber. A result of the luminescence measurement indicates that plasma emission increases with propellant mass flow rates, and that the highest intensity was recorded not in the discharge chamber but in the waveguide. In the laser absorption spectroscopy, the highest number density of Xe I at 823 nm was also recorded in the waveguide, which was $1.57 \pm 0.09 \times 10^{18} \text{ m}^{-3}$. Based on those results, this paper will predict that the plasma in the waveguide attenuates the microwave propagation to the discharge chamber. In addition, this paper will also claim that the change of propellant distribution suppresses plasma in the waveguide, which results in the improvement of the thrust force.

Nomenclature

A	= Einstein A coefficient
B	= Einstein B coefficient
c	= velocity of light
d_0	= length of laser path
ΔE	= energy gap
g	= statistical weight
h	= Planck's constant
I	= intensity of laser
K	= integral absorption coefficient

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k	= Boltzmann's coefficient
T_{ex}	= excitation temperature
n	= numerical density
ν	= frequency
λ	= wave length

I. Introduction

The Japanese asteroid explorer Hayabusa was launched on May 9, 2003, and it returned to Earth on June 13, 2010, powered by four microwave discharge ion thrusters “ $\mu 10$ ”. By the end of the mission, the total operation time of the four $\mu 10$ s amounted to 40,000 hours. $\mu 10$ is the first successful ion thruster produced in Japan, and it is scheduled to be commercialized in the next three years. To expand the possibilities of $\mu 10$ for future missions, such as in Hayabusa-2 and 1-ton class commercial geosynchronous satellites, it needed an improved thrust force preserving the flight heritage. However, it had seemed that the ion beam current was already at maximum with respect to the microwave input power until the new propellant inlets were opened in the discharge chamber^{1, 2)}. In addition, as figure 1 shows, the beam current gradually increases with respect to propellant mas flow rates, then it suddenly jumps up to over 120 mA at 1.90 sccm. The difference between the two modes can be also observed by photographs of $\mu 10$. The pictures in figure 1 are the front faces of $\mu 10$. The emission of high beam current mode is higher than that of a low beam current mode around the center. However, we had no options to measure inside the microwave discharge ion source without any destructive method in ion beam acceleration.

To discover reasons for the saturation of the thrust force, in this study we have applied optical fibers to $\mu 10$ and carried out internal spectroscopic investigations. At first, a multi mode optical fiber probe is simply inserted via the center aperture of the grids system and it measures the inside of local plasma luminescence distributions. Then the experimental setup was developed for laser absorption spectroscopy. In order to demonstrate this measurement, the wavelength of the target was chosen as Xe I 823 nm for its high detectability and a heritage³⁾. This paper will report results of measurements, and it will be the first paper to reveal the internal state of the microwave discharge ion source in ion beam acceleration.

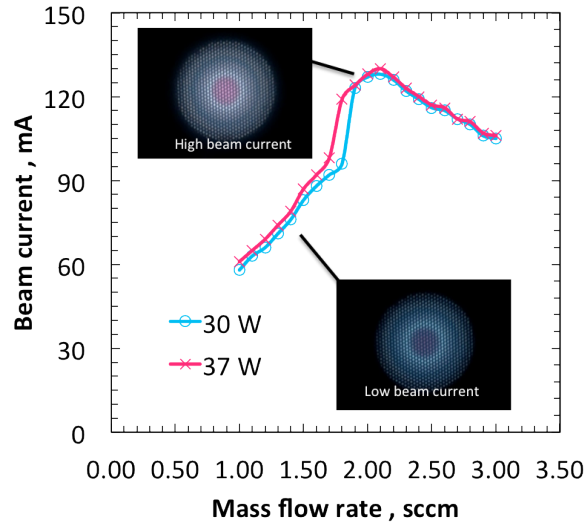


Fig. 1 Profiles of the ion beam current with respect to mass flow rates. Left picture shows a front face of a low beam current mode, Right picture is that of a high beam current mode.

II. Laser Absorption Spectroscopy

An absorption spectrum is obtained by sweep wavelengths of a laser, which has a sharp line width. The intensity of a laser, which goes through target particles of the measurement, is expressed in Eq. (1). This is called the law of Beer-Lambert.

$$I = I_0 \exp(-kd_0) \quad (1)$$

Here, absorption coefficient k is a function of a frequency ν shown in Eq. (2).

$$k(\nu)d\nu = \frac{h\nu}{c} (B_{ij}dn_i - B_{ji}dn_j) \quad (2)$$

The Einstein B coefficient is written as Eq. (3)

$$\begin{aligned} A_{ji} &= \frac{8\pi h\nu^3}{c^3} \frac{g_i}{g_j} B_{ij} \\ &= \frac{8\pi h\nu^3}{c^3} B_{ji} \end{aligned} \quad (3)$$

Substituting Eq. (3), integrated absorption coefficient K is expressed as Eq. (4).

$$\begin{aligned} K &\equiv \int_{-\infty}^{+\infty} k_\nu d\nu \\ &= \frac{c^3}{8\pi h\nu^3} \frac{g_j}{g_i} A_{ji} n_i \left(1 - \frac{g_i}{g_j} \frac{n_j}{n_i} \right) \end{aligned} \quad (4)$$

Assuming the Boltzman equilibrium between upper density n_i and lower density n_j , then n_j is written as follows.

$$n_j = \frac{g_j}{g_i} n_i \exp\left(-\frac{\Delta E_{ij}}{kT_{ex}}\right) \quad (5)$$

From Eq. (4) and (5), the relationship integrated absorption coefficient and number density is expressed as follows.

$$K = \frac{\lambda^2}{8\pi} \frac{g_j}{g_i} A_{ji} n_i \exp\left(-\frac{\Delta E_{ij}}{kT_{ex}}\right) \quad (6)$$

In this measurement, the integrated absorption coefficient is experimentally obtained using an optical fiber probe. Then, by inserting an optical fiber probe, the length of the laser path is variable, the distribution of number densities are obtained. In this measurement, an excitation temperature is assumed constant with respect to laser path.

III. Experimental Facilities

A. Thruster

A schematic of the microwave discharge ion thruster $\mu 10$ is shown in figure 2. The microwave discharge ion thruster $\mu 10$ consists of a waveguide, a discharge chamber, a three-grid system and a neutralizer. Additionally, there is a microwave antenna and a propellant inlet at one end of the waveguide. The other end of the waveguide is connected to the discharge chamber. As an improved model, new propellant inlets are opened written as “Port B” in fig. 2. (In this measurement, Port B were not used.)

A microwave with a frequency of 4.25 GHz is transmitted through the waveguide to the discharge chamber. In the discharge chamber there are two rings of samarium-cobalt magnets. A propellant, Xenon, is injected via the inlet and flows into the discharge chamber. In the discharge chamber, electrons are continuously accelerated by a mirror magnetic field and Electron Cyclotron Resonance (ECR). By subsequent electron-neutral and electron-ion collisions, ECR plasma is formed. The plasma is biased at 1,500 V, and Xenon ions are electrostatically accelerated by an accelerator grid and a decelerator grid, which voltages are -350 V and grounded respectively. In order to keep the spacecraft’s potential, the microwave discharge cathode emits the same current of electrons. $\mu 10$ generates 135 mA of ion beam current, which is equivalent to 8.0 mN of thrust force at 34 W of microwave input power as table 1 shows.

B. Space Chamber

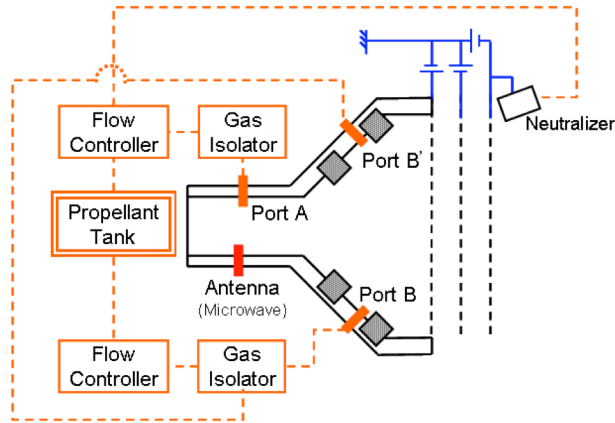


Fig. 2 A schematic of the microwave discharge ion thruster $\mu 10$. In the flight model of $\mu 10$, there is only one propellant “Port A.” Port B are new inlets. (In this experiment, port A was used.)

Table 1 Nominal operation conditions of the microwave discharge ion thruster $\mu 10$ (flight model).

Beam diameter (mm)	105
Microwave frequency (GHz)	4.25
Screen voltage (V)	1500
Accelerator voltage (V)	-330
Decelerator and neutralizer voltage (V)	~ -30
Thrust force (mN)	8.0
Beam current (mA)	135
Specific impulse (sec)	3200
Mass utilization efficiency (%)	85
Ion production cost (eV)	230
Nominal Xenon flow rate (sccm)	2.20
Microwave power (W)	34

The diameter of the vacuum chamber used in the experiment is 2.0 m and the length is 5.0 m. This chamber is equipped with four cryogenic pumps which exhaust velocity is respectively 11,200 l/s (nitrogen). The chamber has two sub-chambers sub-A and sub-B, separated from the main chamber by gate valves. Each sub-chamber has a turbo booster pump, and they are connected to a common rotary pump. The measurements were conducted in Sub-B chamber. The background pressure is 4.0×10^{-4} Pa at 2.00 sccm.

C. Optical Fiver Probe

In this study, two different types of optical fibers are used. One is a multi mode optical fiber for measuring plasma luminescence. A diameter of the multi mode optical fiber probe is 1.80 mm. This is the same as the aperture diameter of the accelerator grid. The diameter of the core is 1.50 mm so as to collect local luminescence as much as possible. Another probe is a single mode optical fiber for the laser absorption spectroscopy. As figure 3 shows, the diameter of the clad is also 1.80 mm, and its mode field diameter is $5.7 \mu\text{m}$ to realize collimated laser emission from the probe. At one edge of the fiber, a collimation lens is attached by heat-sealing, whose focal length is long enough to be detected at the waveguide. The other end of the probe gradually decreases its diameter, and it becomes a flexible optical fiber connected to a feed-through of the vacuum chamber.

Since the probes are made of glass, its advantages against microwave discharge ion sources are shown as following;

1. It creates little disturbance in the microwave electromagnetic field.
2. It has high accessibility to high-voltage plasma.
3. It can endure high temperatures.
4. It enables nondestructive monitoring of spectroscopic measurements inside ion sources through a grid aperture in ion accelerating state.

D. Laser and Photo Detector

In the measurement of laser absorption spectroscopy, Littrow type external cavity diode laser was used (Toptica, DL100). Compared with Littman type, this laser features a higher intensity laser emission: lower cost and a simpler configuration. By controlling a grating mirror, this laser is able to sweep 20 GHz band of wavelength. The laser line width is 100 KHz to 1 MHz.

The photo detectors used for both measurements are “DET10A” made by Thorlabs. The detectors have a high sensitivity ranging from 400 to 1100 nm.

IV. Experimental Setups

A. Luminescence Measurement

An experimental set up of the luminescence measurement is shown in figure 4. A multi mode optical fiber is driven by a stepping motor, and it collects the local luminescence inside of $\mu 10$. A photo detector records the intensity of the luminescence, which is differentiated with respect to the displacement of the probe. Then the distribution of the luminous bodies is obtained.

B. Laser Absorption Spectroscopy

An experimental set up of laser absorption spectroscopy is shown in figure 5. The probe is set using high accurate linear stage, which is automatically inserted from the center aperture of the grid system by a stepping motor. At the edge of the waveguide, a collimation lens is attached, which is connected to a photo detector via a multi mode optical fiber inside a vacuum chamber. A data logger records the signal from the photo detectors and etalon. Conditions of the experiment are shown in table 2.

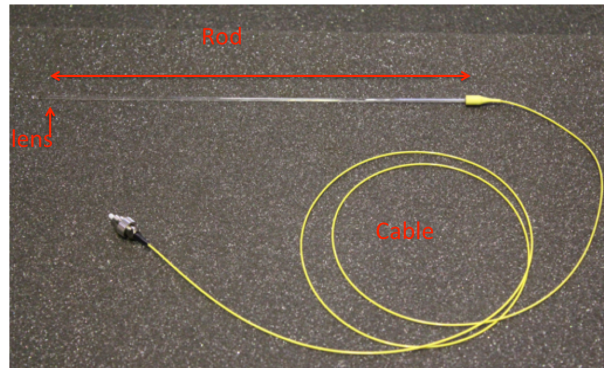


Fig. 3 A picture of a single mode optical fiber probe. A collimation lens is attached at the tip by heat sealing.

Table 2 Experimental conditions in the laser absorption spectroscopy.

Mass flow rates (sccm)	1.00	2.00	3.00
Beam current (mA)	77 – 80	114 - 131	83 - 99
Accelerator current (mA)	0.4 – 0.5	0.5 – 0.6	0.7 – 1.0
Input microwave power (W)		34	
Reflected microwave power (W)	9	6 - 11	11 – 12
Background luminescence intensity (mV)	19.7	30.2	33.2
Measurement point from grid (cm)		0 – 15	
Sampling rate (μ sec)		500	
Frequency of laser (Hz)		1.1	

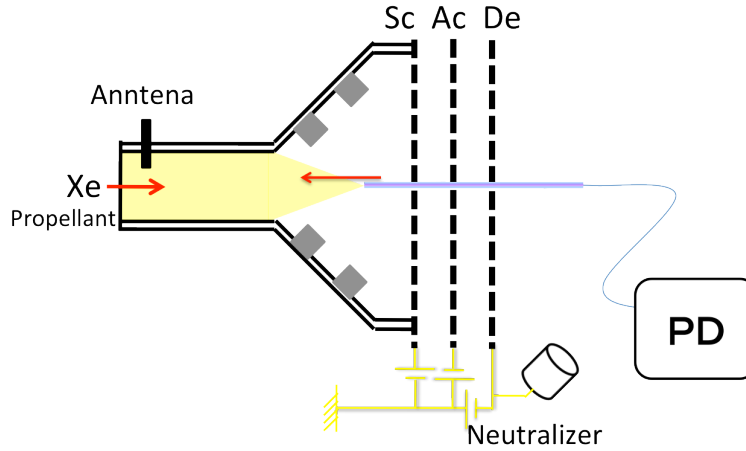


Fig. 4 The experimental set up of the luminescence measurement.

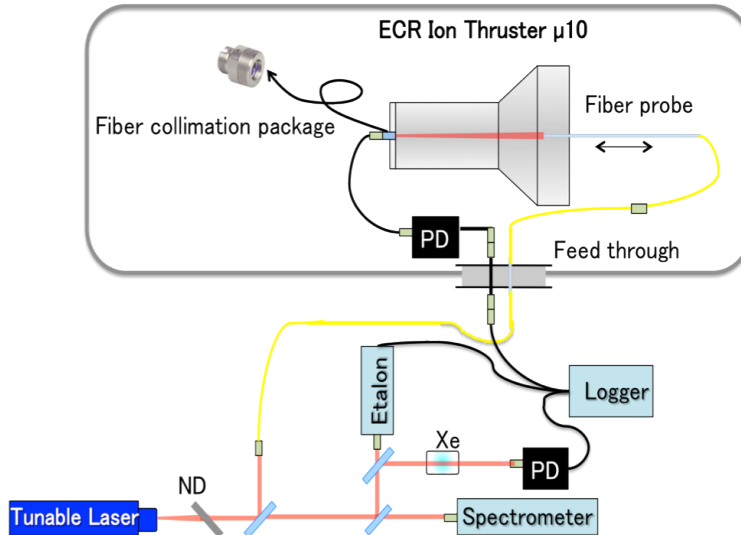


Fig. 5 The experimental set up of the laser absorption spectroscopy.

V. Results and Discussion

A. Luminescence Measurement

Figure 6 shows the luminescence distribution inside the $\mu 10$. As the output voltage of the luminescence represents accumulated light emission, it is differentiated with respect to the displacement of the probe. The relative position is indicated in the background of the graph. In figure 6, the luminescence does not increase monotonically with the beam current, but monotonically with mass flow rates. Starting at 1.00 sccm, there is minimum luminescence. Increasing mass flow rates to 1.50 sccm, the luminescence starts to oscillate. This oscillation ceases if the mass flow rate is increased over 1.75 sccm. From this mass flow rate onward, no oscillation can be detected and the luminescence in the waveguide monotonically increases with respect to mass flow rates.

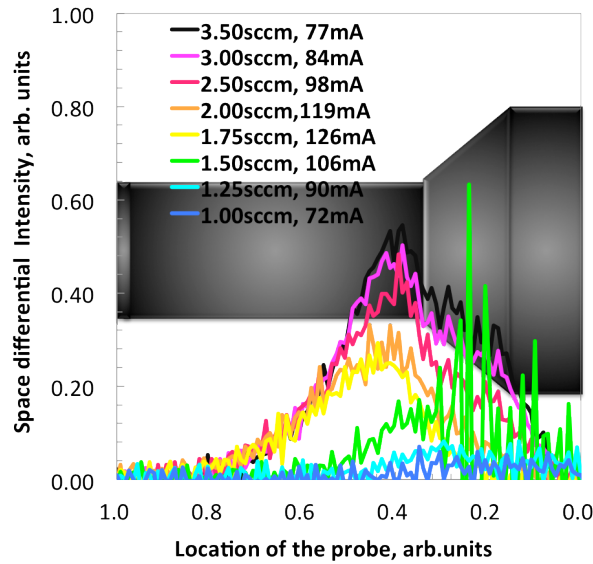


Fig. 6 Luminescence intensity distribution in $\mu 10$. The output of a photo detector is differentiated with respect to the displacement of the probe.

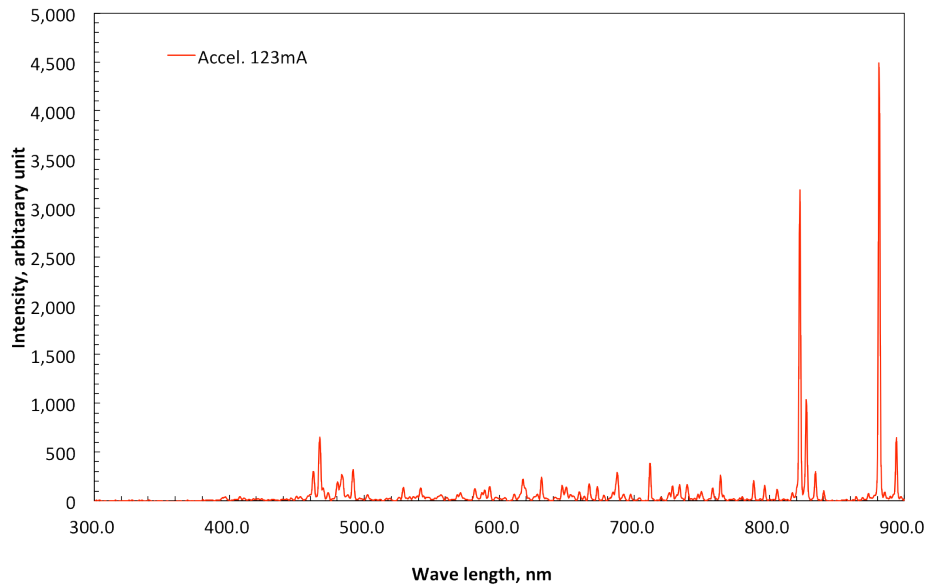


Fig. 7 The spectrum diagram in $\mu 10$ at the mass flow rate of 2.00 sccm and the ion beam current of 123 mA.

Figure 7 shows the spectrum diagram of the luminescence when the edge of the probe was set at the grid. It indicates that there are two major peaks at 823.16 nm and 881.94 nm. These lines derive from excited particles of Xe I. As for Xe II, though the lines are detected, it was less than 10% of the emissions of neutral particles.

B. Laser Absorption Spectroscopy

By figure 7, it is predicted that the number density of the upper state of Xe I at 823.16 nm and 881.94 nm are fairly higher than other lines. Assuming the Boltzmann equilibrium between a lower state and upper state, these two lines are expected a high detectability in the measurement of laser absorption spectroscopy. In this experiment a metastable line 823.16 nm is chosen as a target. At this line, plasma parameters were already experimentally obtained for getting number density⁴⁾. The optical fiber probe is inserted from the screen grid, and there are fifteen

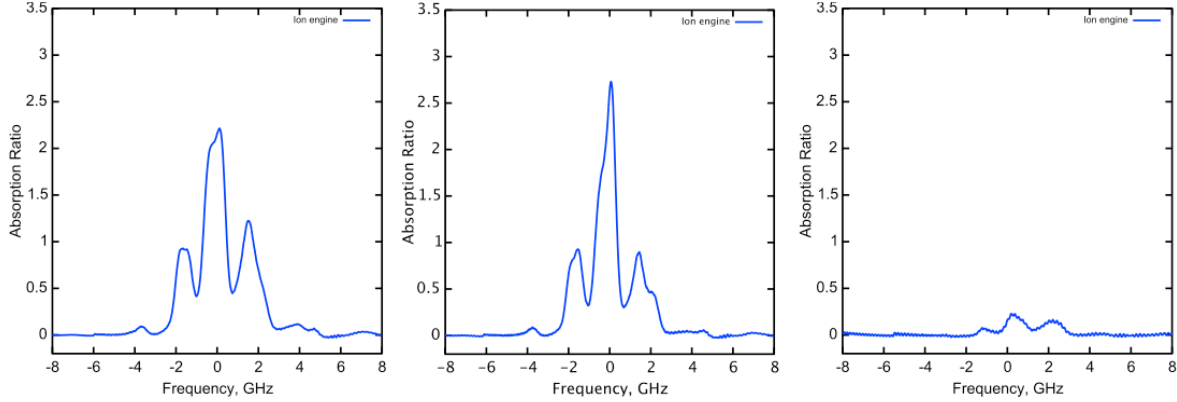


Fig. 8 Absorption spectrum of Xe I $5p^5(2P_{3/2}^0)6s^2[3/2]^0$ in $\mu 10$. Left picture is the spectrum when the laser path is the longest. (The probe is set at the grids.) Middle picture is when the probe is set at the boundary of the discharge chamber and the waveguide. Right picture is just before disappearing of absorption.

measurement points from the grid to the waveguide. Some of the obtained absorption spectra are shown in figure 8. The absorptions are split up for the hyperfine structure of Xenon. As the probe is driven into the ion thruster, an area of the absorption gradually decreased. Number densities of Xe I $5p^5(2P_{3/2}^0)6s^2[3/2]^0$ were obtained by evaluating differences of absorption areas. Distributions of the densities are shown in figure 9. In estimating the densities, electronic excitation temperature was uniformly assumed $3.0 \text{ eV}^{(5)}$.

At 1.00 sccm , 10^{17} m^{-3} order of Xe I was measured in the discharge chamber. At 2.00 sccm , the density increased to $1.20 \times 10^{18} \text{ m}^{-3}$ at maximum, and it distributed from the waveguide to the discharge chamber. The densities at 3.00 sccm are higher than those of at 2.00 sccm . The highest density is also recorded in the waveguide, which was $1.57 \times 10^{18} \text{ m}^{-3}$.

Considering that the lifetime of the particle of upper state of 823 nm is nanoseconds^(6,7), figure 6 shows the birthplace. On the other hands, it is reported that the lifetime of Xe I $5p^5(2P_{3/2}^0)6s^2[3/2]^0$ is 43 to 150 seconds^(8,9). The mean free path is estimated from 10 cm to several meters assuming that the total density is 10^{19} m^{-3} at highest. Therefore at 2.00 or 3.00 sccm , xenon is injected from the waveguide, and quickly become excited neutral particles in the waveguide, which finally collides with a wall.

An error of the densities is estimated $\pm 9 \times 10^{16} \text{ m}^{-3}$, which comes from an accuracy of zero line. Therefore it is difficult to estimate the density from the result at 1.00 sccm . Less than 10^{17} m^{-3} on, though tiny absorptions are recorded, the integrated area was neglected for its noise. In order to make the measurement more accurate for ion measurement, the chopper and rock-in-amplifier are schedule to be installed.

By the measurements, the number density increases with respect to propellant mass flow rates of Xenon, and the highest density was at the waveguide. Both measurements indicate that the plasma forms not only in a discharge chamber, but also in the waveguide. And the plasma in the waveguide possibly interferes the propagation of microwave to the discharge chamber, which results in the saturation of the beam current.

In addition, the microwaves cannot sufficiently propagate into the discharge chamber, which results in a decrease in the ion beam current from a mass flow rate of 2.00 sccm onward. As a consequence, the plasma in the waveguide causes saturation

VI. Conclusions

In this study, two kinds of spectroscopic measurements are operated. In the luminescence measurement, it turns out that the presence of plasma luminescence in the waveguide makes the difference between the low beam current mode and high beam current mode. Based on its spectrum diagram, the wavelength of 823.16 nm is selected for laser absorption spectroscopy for its high detectability. From the measurement, following knowledge is obtained;

1. The number density of Xe I $5p^5(2P_{3/2}^0)6s^2[3/2]^0$ increases with respect to mass flow rates.
2. At 1.00 sccm , Xe I uniformly distributes in $\mu 10$. At 2.00 sccm and 3.00 sccm , the highest density was detected in the waveguide, which were $1.20 \times 10^{18} \text{ m}^{-3}$, $1.57 \times 10^{18} \text{ m}^{-3}$ respectively.

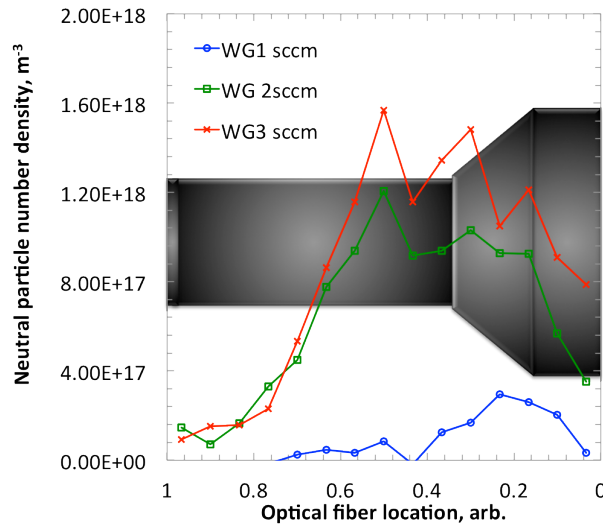


Fig. 9 The distribution of number density of Xe I.

3. The error of the measurement is $\pm 9 \times 10^{16} \text{ m}^{-3}$. This value does not include the effect of electronic excitation temperature.

In the microwave discharge ion thruster, once the plasma in the waveguide reaches to the cut off density, the input microwave power to the discharge chamber starts decreasing. Plasma in the waveguide is supposed to be suppressed for further improving of the thruster.

Acknowledgments

This work is financially supported by grant-in-aid 22•5571 for JSPS fellows.

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