Plasma Diagnostics in a Miniature Microwave Discharge Ion Thruster

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Abstract: The ion thruster µ1 was developed by ISAS/JAXA in Japan and is intended to be installed on 50 kg small spacecraft. The thruster µ1 can operate at low microwave power (1W) and has been developed including neutralizer. In order to develop more sophisticated model, internal plasma diagnostic is indispensable. In an experimental plasma measurement, non-intrusive methods are required because microwave pattern is easily disturbed by the insertion of any electrode. In this study, laser absorption spectroscopy was applied to obtain plasma profiles inside the ion thruster µ1. Laser absorption spectroscopy is a useful technique for the sensitive and quantitative measurement of plasma parameters. We developed experimental setups of laser absorption spectroscopy for µ1 visualized model. As a result, number density distributions of Xe I 823.16 nm and Xe I 828.01 nm were obtained.

Nomenclature

I_0 = laser intensity of incident beam
I_t = laser intensity of transmitted beam
l = absorption length

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k = absorption coefficient
ν = frequency of laser beam
λ = wavelength of laser beam
n = number of density
A = Einstein coefficient
g' = degeneracy factor of higher level
g = degeneracy factor of lower level

I. Introduction

RECENTLY, the larger scale electric propulsion systems are required for the space exploration and the quasi-zenith satellites. On the other hand, the needs of small ones are gradually increasing. A series of small scale satellites is expected to use instead of traditional large scale satellites for reducing launch cost and risk of a mission with a single spacecraft.

The ion thruster μ1 was developed by JAXA/ISAS Japan. This thruster is feasible for the installation on 50 kg size small spacecraft. The thruster μ1 can operate at low microwave power (1W) and has been developed as full set including neutralizer. The developed ion thruster system was named as μ1 ("mu-1"), due to the 1cm class-beam and 1-W-class microwave power. The schematic diagram and photograph image of this thruster is shown in Figure1[1-3]. Since 2011, by using an ion beam source and a neutralizer, development of a miniature ion propulsion system: MIPS has started using the ion thruster mu-1 at the University of Tokyo, collaborating with the Next Generation Space Technology Research Association (NESTRA) in Japan. The MIPS is intended for the installation on a 50 kg-class spacecraft, HODOYOSHI-4[4].

On the other hand, there would be a space for its further optimization. In order to increase thruster performance, it is necessary to clarify the physical phenomenon of plasma producing process and develop the sophisticated modeling for the small scale ECR plasma. Our final target is to obtain plasma profile inside the ion thruster and refurbish our plasma modeling to increase its thruster performance.

In this study, we conducted plasma diagnostics of μ1 visualized model. The experiment using visualized model is useful to clarify the physical phenomena of plasma producing process. And this experiment also has significance of validation of numerical simulations. Numerical simulations represent a powerful tool to obtain plasma profile and the study of numerical simulations for a miniature microwave discharge ion thruster μ1 is conducted to clarify the mechanism of ECR discharges confined in a small space[5]. The results obtained by the computations should be carefully compared with the experimental results to validate that numerical simulation code. Then, the major purpose of this study is to provide experimentally-obtained plasma profiles for that validation. For this purpose, there are several requirements for the measurement. Firstly, the measurement must be non-intrusive because microwave pattern is easily disturbed by the insertion of any electrode. Secondly, quantitative measurement is necessary for the plasma modelling. Especially, absolute number density of plasma is the most important. Finally, the miniature thruster requires a highly resolved measurement. We developed a basic setup of laser absorption spectroscopy and high-resolved 2D scanning system to fulfil these requirements[6]. Laser absorption spectroscopy is a useful technique for the non-intrusive, sensitive and quantitative measurement of plasma parameters. As a first step to obtain number density of plasma, we measured neutral particle

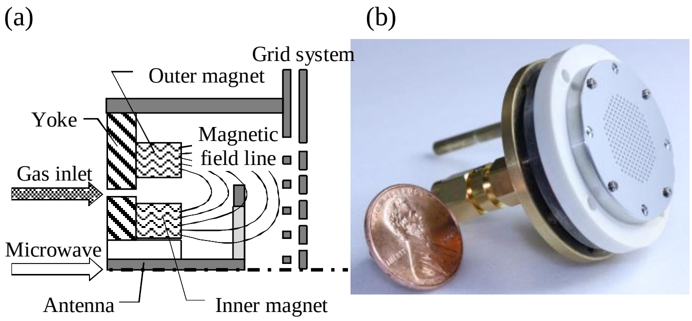

Figure 1. (a) Schematic and (b) photograph image of miniature ion thruster μ1.

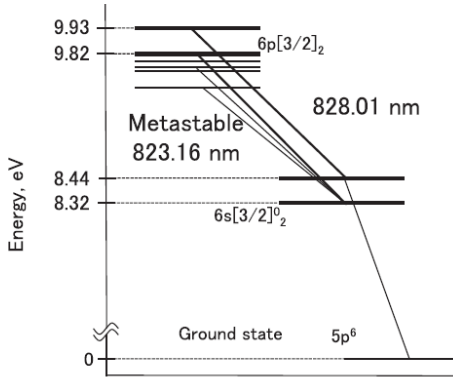

Figure 2. Grotrian diagram of Xe I

in the μ1 visualized model. The targets of the measurement are metastable Xe I 823.16 nm and non-metastable Xe I 828.01 nm. A Grotrian diagram of Xe I is shown in Figure 2. Neutral xenon particle of metastable state 823.16 nm was the most suitable for a demonstration of absorption spectroscopy. The lifetime of metastable excited Xe I $5p^5(^2p^0{}_{3/2})6s[3/2]^0{}_2$ is experimentally reported to be from 43 to 150 s. Though the metastable has a high absorption ratio for its long life time, it is difficult to know the locality of electrons. The lifetime of non-metastable Xe I 828.01 nm (Xe I $5p^5(^2p^0{}_{3/2})6s[3/2]^0{}_2$) is 1-10 μs. Therefore, density distribution of non-metastable Xe I 828.01 nm could contain of the distribution of energetic electrons[7].

II. Laser Absorption Spectroscopy

Laser absorption spectroscopy (LAS) is a useful technique for the sensitive and quantitative measurement of plasma particles. LAS is the method for measuring number density and translational temperature. Laser beam which is adjusted the wavelength of energy level of measurement target particle and swept around the wavelength and irradiates plasma source. Then, target particle transits from one excited state to a higher excited one. And, laser absorption is occurred as a function of number density of target particle. When laser beam pass through a medium, the relationship between intensity of incident beam and transmitted one is shown by Beer-Lambert law:

$$I_t = I_0 \exp(-kl) \tag{1}$$

where l is absorption length (plasma length) and k is absorption coefficient. From the equation (1), absorption coefficient is shown by

$$k = -\left(\frac{1}{l}\right)\ln\left(\frac{I_t}{I_0}\right) \tag{2}$$

Absorption coefficient is a function of frequency, and the relationship between absorption and number density is shown by

$$\int k(\nu)d\nu = \frac{\lambda^2 g' An}{8\pi g} \tag{3}$$

That is, number density is obtained by integration of absorption profile over frequency[8-9].

III. Experimental setups

A. μ1 visualized model

The ion thruster μ1 can be modified to a device dedicated for the inside visualization, which we refer to as μ1 visualized model. Its picture and illustration is shown in Figure 3. This model is designed to numerical model[5]. The four modifications exist between ion thruster μ1 and μ1 visualized model. First modification is the replacement of the side wall by a glass wall. It makes possible to pass through laser beam. Second is the modification of discharge chamber shape. The shape of discharge chamber for μ1 visualized model is cuboid although ion thruster μ1 is cylindrical shape. Third is acceleration mechanism. μ1 visualized model has not grid system for ion acceleration mechanism. A grid system is replaced by an orifice plate. Last modification is the shape of antenna. The shape of antenna has quarter-symmetry to adapt numerical model. This model is a validation model for the basic measuring system. Therefore, in this study, the change in plasma profiles caused by modifications of the discharge chamber is not considered.

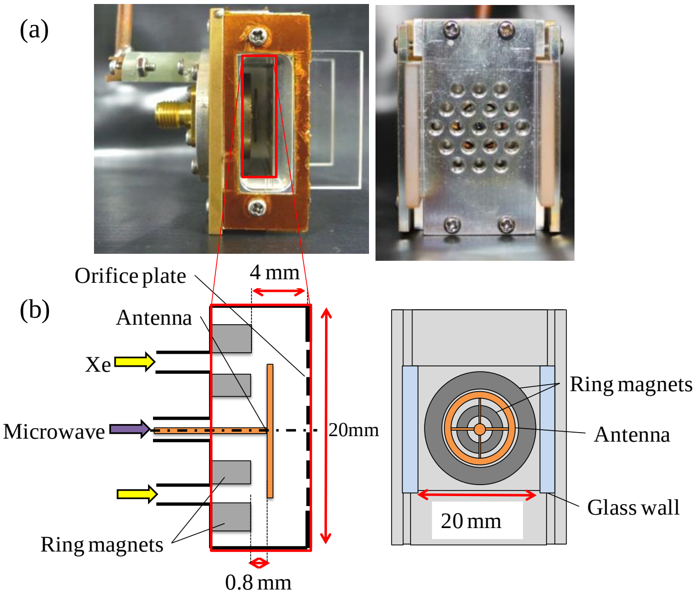

Figure 3. (a) Photograph image and (b) inner schematic of μ1 visualized model.

B. Setup for Laser Absorption Spectroscopy

A schematic of the setup for LAS experiment is shown in Figure 4. The infrared, single longitudinal mode diode laser (OPNEXT 8325G) has a nominal wavelength of 830 nm at 25°C and a typical output power of 40mW. The laser diode is placed in a thermoelectrically cooled mount (Thorlabs TCLDM9) and its current and temperature are controlled by a precision diode laser driver (Thorlabs LDC202 and TED200C). Wavelength adjustment toward the target 823.16 nm was conducted by temperature tuning. Around this wavelength, fine wavelength scanning was conducted by the current tuning using triangle waveforms generated by a function generator. One part of emitted laser beam was transmitted into a wavemeter to check the wavelength, and was transmitted into a confocal Fabry-Perot etalon (free spectral range: FSR is 0.375 GHz) for frequency calibration of the absorption spectrum. The other part of emitted laser beam was transmitted reached to a photo-detector (Thorlabs PDA8GS) via a xenon discharge tube to refer to absorption profile. The rest part of the beam goes into the µ1 visualized model in a vacuum chamber using a single mode fiber (Thorlabs SM800-5.6-125). Beam through µ1 visualized model is reached to a photo-detector.

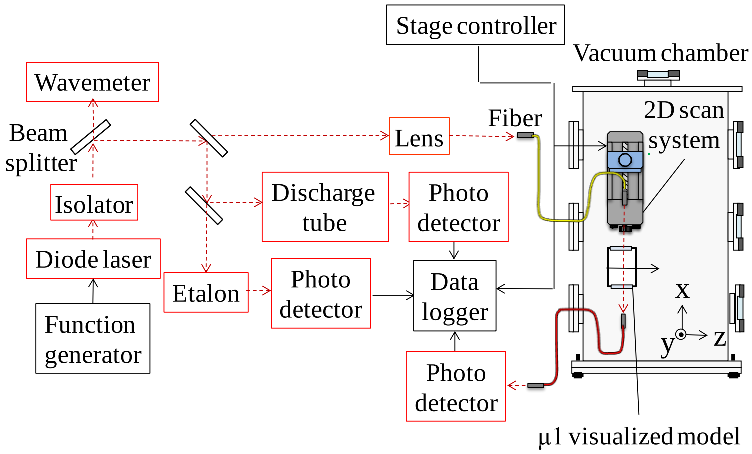

Figure 4. Experimental setups for number density measurement in µ1 visualized model by laser absorption spectroscopy.

C. Laser probe pass

The illustration of laser probe pass of µ1 visualized model in vacuum chamber is shown in Figure 5. This single mode fiber has a mode field diameter of 5.6 µm and NA value of 0.12. Another end of this single mode fiber is installed inside the vacuum chamber. Beam emitted from this vacuum-side-end is collimated by a molded glass aspheric lens (Thorlabs C150TME-B). The lens has the focal length of 2.0 mm and the expected diameter of the collimated beam is 0.48 mm. the collimated beam goes into the µ1 visualized model, and the beam passing through it goes toward another multimode fiber (Thorlabs GIF50). This multimode fiber has the core diameter of 50 µm and receives the beam directly on its end surface. Hence, only the beam which arrives just on the core of the multimode fiber end can enter into it. Thus the minimum resolution of this laser probe system is the detecting diameter of 50 µm. The emitting port of the single mode fiber, its beam collimation lens, and the detecting port of the multimode fiber are all fixed on a rigid aluminum stage. This aluminum stage is installed on a two axes liner stage system driven by stepping motors.

D. 2D Distribution Measurement System

Figure 6 shows Experimental setups for 2D distribution measurement system visualized model. As mentioned earlier, laser probe system is fixed on a rigid aluminum stage installed on a two axes stage driven by stepping motor. µ1 visualized model is fixed on a vacuum chamber wall. By moving two axes stage relative to fixed visualized model, density distribution of y-z plane is obtained. Stepping motor used to drive two axes stage is controlled by a controller device. Using this device, stage is moved according to a sequence control program. Hence, by scanning wavelength with moving stage continuously, distribution measurement is conducted automatically. Then, the signal of stage controller is recorded together with other experimental data. Based on the signal of stage controller device, analysis of density distribution data is conducted effectively. We developed an analytical program to analyze experimental data automatically.

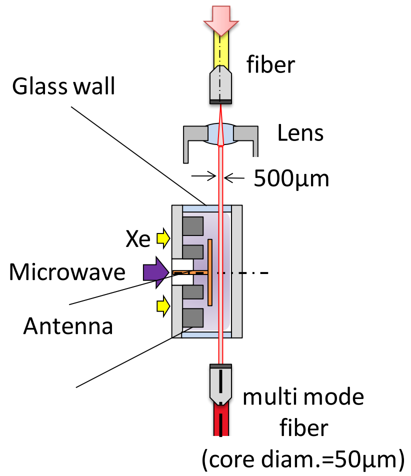

Figure 5. μ1 visualized model and laser probe pass.

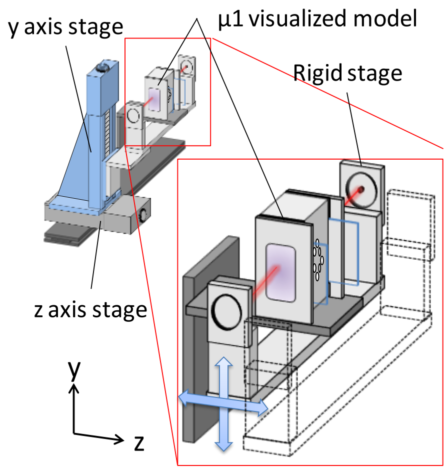

Figure 6. Experimental setups for 2D distribution measurement system visualized model.

IV. Results and Discussion

A. Number density distribution of Xe I 823.16 nm

Experimental condition is shown in table 1. Typical obtained absorption spectrums are shown in Figure 7. Figure 8 shows number density distribution of Xe I 823.16 nm. Measurement space is a square area measuring 4-10 mm. Measurement interval is 0.1 mm and measurements points are 4558 points. In Figure 8, Red square is measurement space shown in red space includes base of the antenna and wall of downstream. The black area shown in the right figure is the area that analysis is impossible because laser beam does not pass thorough discharge chamber to collide with the antenna or wall. Hence, the black area is shown the shape of the antenna or wall. Near the antenna, the number density is about 6-9 × 10^{17} m^{-3} and this value is reasonable compared with previous studies of ECR plasma source[10]. And this figure shows that high density of Xe I 823.l6 nm is gathered in the center. That is, metastable particles exist in large numbers in the center.

Table 1. Experimental condition

Xenon mass flow rate (sccm)	0.15
Microwave power (W)	1.0
Measurement interval (mm)	0.1
Measurements points	4558
Frequency of laser sweep (Hz)	10
Sampling number	6

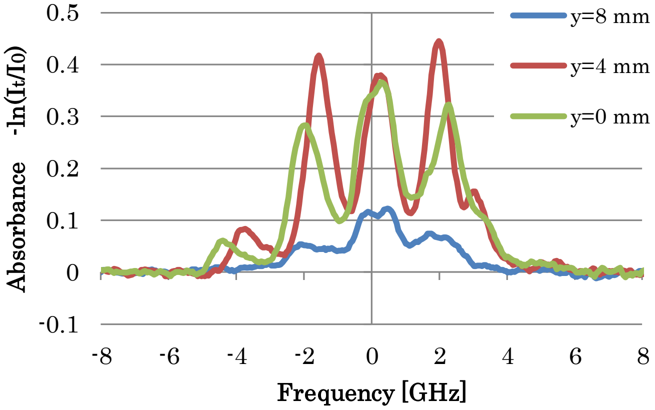

Figure 7. Typical absorption profile Xe I 823.16 nm in μ1 visualized model (z=3 mm).

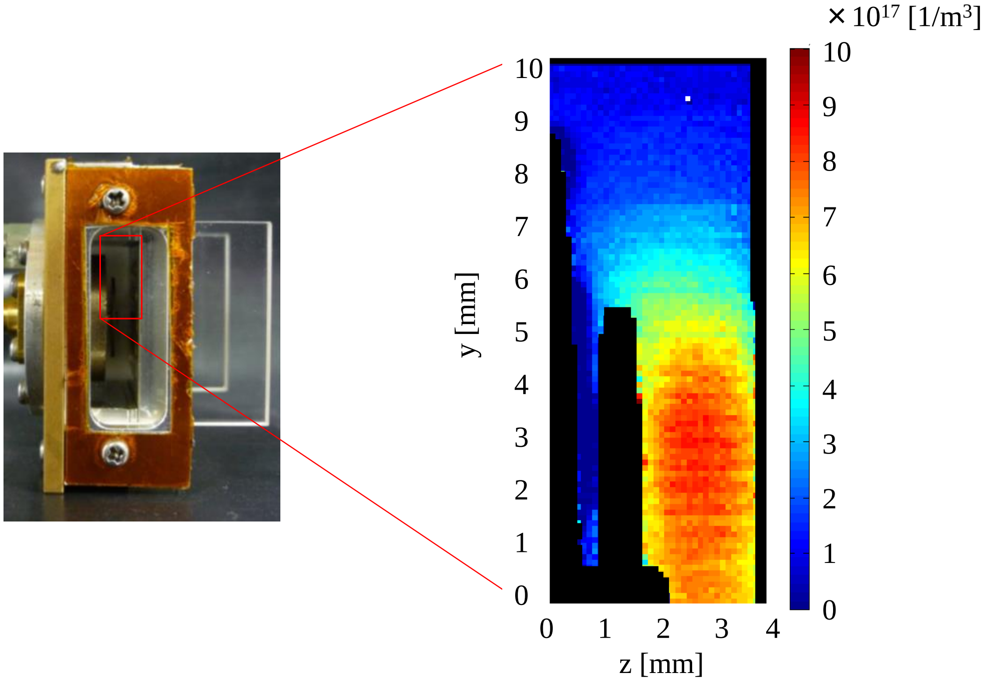

Figure 8. Measurement space and density distribution of Xe I 823.16 nm.

B. Number density distribution of Xe I 828.01 nm

The experimental condition is shown in table 2. The condition is changed from measurement of Xe I 823.16 nm because it was difficult to observe absorption spectra of Xe I 828.01 nm under the condition shown in table 1. Typical obtained absorption spectrums are shown in Figure 9. Figure 10 shows number density distribution of Xe I 828.01 nm. Measurement space and distribution plot method is same as Figure 8. The shape of distribution of Xe I 828.01 nm is similar distribution of Xe I 823.16 nm although density value is about four times smaller than Xe I 823.16 nm. However, because experimental condition was changed to observe absorption, it is not proper to compare the results of two. The main problem is that standard laser absorption spectroscopy has low sensitiveness for the measurement of short lifetime particle in the μ1 visualized model. As a future works, we try to apply high sensitivity method, such as frequency modulation laser absorption spectroscopy, to μ1 visualized model.

Table 2. Experimental condition

Xenon mass flow rate (sccm)	0.50
Microwave power (W)	2.0
Measurement interval (mm)	0.2
Measurements points	1144
Frequency of laser sweep (Hz)	10
Sampling number	6

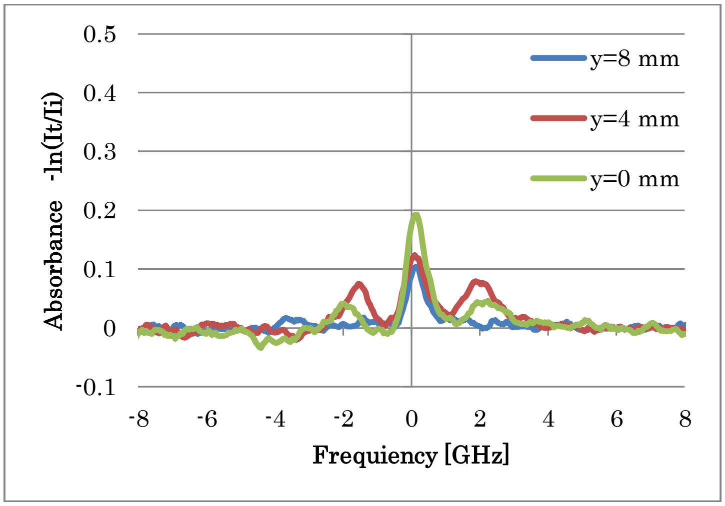

Figure 9. Typical absorption profile Xe I 828.01 nm in μ1 visualized model (z=3.2 mm).

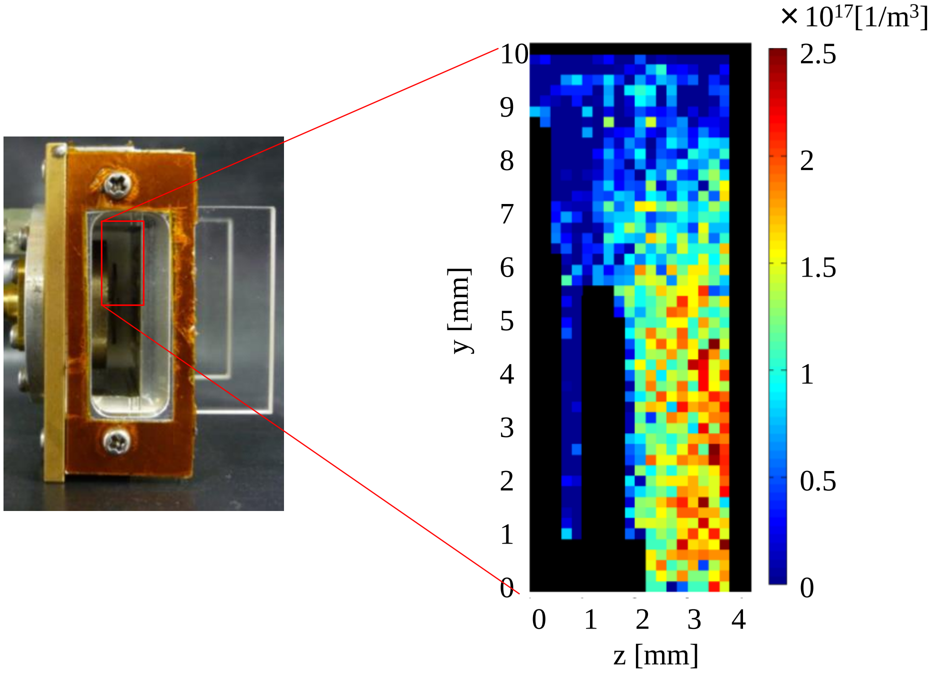

Figure 10. Measurement space and density distribution of Xe I 828.01 nm.

V. Conclusion

In this study, we developed µ1 visualized model adapted numerical model. And laser absorption spectroscopy was applied to µ1 visualized model. As a result, the number density distribution of neutral particle of metastable Xe I 823.16 nm and non-metastable Xe I 828.01 nm was obtained by measuring less than 0.2 mm spatial resolution. In the measurement of Xe I 823.16 nm, the number density is about 10^{17} m^{-3} and high density of Xe I 823.l6 nm is gathered in the center. In the measurement of Xe I 828.01 nm, the shape of density distribution is similar distribution of Xe I 823.16 nm although density value is about four times smaller than Xe I 823.16 nm.

Acknowledgments

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References

[1] Kuninaka, H., and Satori, S., "Development and Demonstration of a Cathodeless Electron Cyclotron Resonance Ion Thruster," *Journal of Propulsion and Power*, Vol.14, No.6, 1998, pp.1022-1026.

[2] Nakayama, Y., Funaki, I., and Kuninaka, H., "Sub-Milli-Newton Class Miniature Microwave Ion Thruster," *Journal of Propulsion and Power*, Vol.**23**, No.2, March-April,2007, pp.495-499.

[3] Koizumi, H., and Kuninaka, H., "Performance of the Miniature and Low Power Microwave Discharge Ion Engine," *Proceeding of Joint Propulsion Conference*, AIAA-2010-6617.

[4] Koizumi, H., Komurasaki, K., and Arakawa, Y., "Development of the Miniature Ion Propulsion System for 50 kg Small Spacecraft," *Proceedings of the 48th AIAA/ASME/SAE/ASEE Joint propulsion Conference &Exhibit*, Atlanta, Georgia, USA, 2012, AIAA-2012-3949.

[5] Takao, Y., Eriguchi, K. , Ono, K., Sugita, Y., Koizumi, H., and Komurasaki, K., "Three-Dimensional Particle-in-Cell Simulation of a Miniature Microwave Discharge Ion Thruster µ1," *Proceedings of the 33rd International Electric Propulsion Conference*, Washington, D.C., USA, 2013, IEPC-2013-186.

[6] Koizumi, H., Nishiyama, K., and Kuninaka, H., "Study of Frequency Modulation Laser Absorption Spectroscopy for the Plasma Measurement of a Miniature Microwave Discharge Ion Thruster," *28th International Symposium on Space Technology and Science*

[7] Tsukizaki, R., “Plasma Diagnostics of the Microwave Ion Thruster Utilizing Optical Fiber Probes,” Ph.D. Dissertation, Aeronautics and Astronautics, The University of Tokyo, Japan, 2013

[8] Matsui, M., Komurasaki, K., Arakawa, Y., “Laser Absorption Diagnostics of High Temperature Plasma Flow,” *Institute of Applied Plasma Science*, Vol.9, 2001, pp. 17-22.

[9] Aymar, M., and Coulombe, M., “Theoretical Transition Probabilities and Life Times in Kr I and Xe I Spectra,” *Atomic Data and Nuclear Data Tables*, Vol.21, No.6, pp.537-566, 1978.

[10] Tsukizaki, R., Koizumi, H., Hosoda, S., Nishiyama, K., and Kuninaka, H., “Numerical Density Measurement of Neutral Particles in Microwave Discharge Ion Engine mu10,” *Proceedings of Space Transportation Symposium: FY2010*