

Measurement of Plasma Property in an Ion Thruster using Laser Thomson Scattering Technique

IEPC-2011-200

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

Naoji Yamamoto,¹ Kensaku Sugita,² Tomoaki Kurita,³ Kentaro Tomita,⁴ Kiichiro Uchino⁵ and Hideki Nakashima⁶
Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

Abstract: We report the development of a plasma property measurement system using Thomson scattering technique for the validity of the lifetime validation numerical simulation code of the ion thrusters and the improvement of the thrust efficiency of them. For the application to the xenon plasma, we investigate the thresholds of the photo-ionization and number density of meta-stable atoms using laser absorption spectroscopy for several conditions. The measured threshold energy of probe laser using $f = 200$ mm plano-convex lens is 150 mJ for a xenon mass flow rate of 20 $\mu\text{g/s}$ and incident microwave power of 6 W. Therefore, we set the probe laser energy as 80 mJ, and we succeeded to measure the plasma properties; electron number density is $6.2 \pm 0.4 \times 10^{17} \text{ m}^{-3}$ and electron temperature $2.2 \pm 0.4 \text{ eV}$ at a xenon mass flow rate of 20 $\mu\text{g/s}$ and incident microwave power of 6 W.

Nomenclature

A_{ki}	= Einstein coefficient
E_i	= threshold probe laser energy for photo-ionization.
E_i	= energy level o of lower state
E_k	= energy level o of upper state
E_L	= incident laser energy
f	= focal length
g_i	= statistical weight of lower state
g_k	= statistical weight of upper state
K	= integrated absorption coefficient
l_{abs}	= absorber length
$\dot{m}$	= mass flow rate
N_e	= electron number density
N_m	= number density of metastable atoms
P	= incident microwave power to miniature microwave discharge ion thruster
T_e	= electron temperature
T_e	= electron excitation temperature
z	= thruster axis
ϕ	= diameter
λ	= wave length

¹ Assistant professor, Department of Advanced Energy Engineering Science and yamamoto@aees.kyushu-u.ac.jp.

² Graduate student, Department of Advanced Energy Engineering Science and sugita@aees.kyushu-u.ac.jp.

³ Master of engineering, Mitsubishi Heavy Industry.

⁴ Assistant professor, Department of Applied Science for Electronics and Materials and tomita@ence.kyushu-u.ac.jp.

⁵ Professor, Department of Applied Science for Electronics and Materials and uchino@ence.kyushu-u.ac.jp.

⁶ Professor, Department of Advanced Energy Engineering Science and nakasima@aees.kyushu-u.ac.jp.

I. Introduction

Measurement of plasma property in the vicinity of the screen grid is essential for the development of an ion thruster. Since plasma properties, electron number density and electron energy distribution function (EEDF) are useful for designing a grid system. Furthermore, this information will play an important role in the validation of numerical models for lifetime estimation.¹ There have been many studies to measure plasma property inside the discharge chamber² and these results contributed to the development of ion thrusters. However, it has been difficult to measure the plasma properties in the vicinity of the screen grid without disturbance by means of intrusive method, such as electrostatic probes. So, non-intrusive method is needed for the measurement of the plasma property in this region: that is a Laser Thomson scattering (LTS)³ technique. LTS is a laser based optical method for a measurement of plasma properties, such as electron number density /electron temperature. In the incoherent regime, the scattered spectrum reflects the Doppler motion of individual electrons, and the scattered intensity is proportional to N_e . This method was developed to measure plasma properties in high temperature plasma having $N_e > 10^{19} \text{ m}^{-3}$.⁴ During the last decade, its applicability has been extended to lower density plasma, with densities of less than 10^{16} m^{-3} , by a signal accumulation technique.⁵ This technique allows us to apply LTS to the plasma in the vicinity of the screen grid and we showed that LTS technique was useful and validate tool for the measurement of plasma property and contributed to improve the accuracy of erosion evaluation code.⁶ A previous study, however, showed that the laser induced some perturbation on the xenon plasma.⁷ This is due to photo-ionization of excited xenon atoms; metastable xenon atoms are ionized by the laser (wavelength 532 nm and photon energy 2.3 eV).

The aim of this study is to measure the electron temperature/number density of the xenon plasma in the ion thruster. In order to prevent from photo-ionization, we investigate the threshold energy of photo-ionization effect. Then, we measure the plasma properties by LTS technique below this threshold. We also measure the population of the metastable xenon atoms ($6s[3/2]_2^0$) by laser absorption spectroscopy (LAS).⁸⁻¹⁰

II. Experimental equipment

A. Miniature Ion Thruster

The cross section of a 30 W class miniature microwave discharge ion thruster is shown in Fig. 1. The thrust performance of our ion thruster, that is, thrust and thrust efficiency, are 0.79 mN and 0.57, respectively at xenon $\dot{m} = 0.018 \text{ mg/s}$ and input power of 28 W (incident microwave power, P_i , of 8 W).^{11,12} This performance is competitive with that of the thruster developed by Wirz, which has hitherto shown the best performance in this class of miniature thruster.¹³ The inner diameter of the discharge chamber is 21 mm and the length is 12 mm. The overall size of the thruster is 50 mm×50 mm×30 mm. The ion source consists of an antenna and a magnetic circuit, which is made up of several samarium cobalt (Sm-Co) permanent magnets and iron yokes. The magnetic field strength inside the discharge chamber can be changed by changing the number of the permanent magnets. In this study, the number of the magnets is twelve due to easy ignition and good performance. The magnetic mirrors are located at the tip of a front yoke and the tip of a central yoke. Microwave power at 2.45 GHz is fed through a coaxial line and into the antenna. A DC block with a loss of 0.43 dB at 2.45 GHz was inserted to protect the microwave amplifier. A star antenna is used, since it showed good performance in previous studies.¹² The antenna is inscribed in a 9 mm diameter circle and is made of molybdenum. The thickness of the antenna is 1 mm. Flat square grids were used to

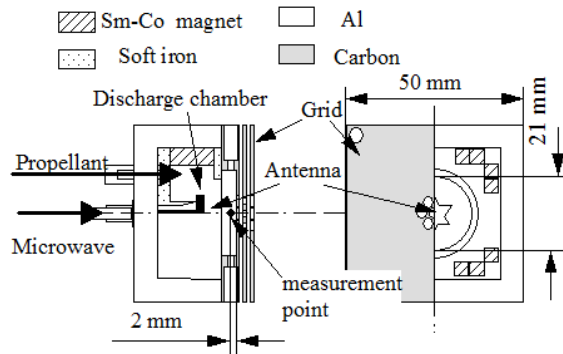


Figure 1. Cross section of a 30 W class miniature microwave discharge ion thruster.

Table 1. Grid parameters.

Parameter	Screen	Accel.	Decel.
Hole diameter, mm	3.0	1.8	3.0
Potential, V	1200	-200	0
Thickness, mm		1.0	
Hole pitch, mm		3.50	
Material	Pyrolytic carbon		
Grid gap, mm		0.5	
Number of holes		7	

extract the ion beam. The geometric parameters are shown in Table 1. This geometry was designed using a numerical analysis code developed by Arakawa et al.¹⁴ The grid is made of pyrolytic carbon and ceramic insulators are used as an isolator between the three grids. The gap between the grids is 0.5 mm and the ion beam diameter is 12 mm. In this experiment, we have not extracted ion beam, so we don't use a neutralizer.

High-purity (99.9995%) xenon gas was used as the propellant. A thermal mass flow controller was used. The flow rate error is less than 5% for most of the conditions. A 0.3 m diameter by 0.4 m long vacuum chamber was used in the experiments. The pumping system comprised a turbo molecular pump with overall pumping speed of 150 l/s for air. The background pressure was maintained below 5.0×10^{-2} Pa for most of the operating conditions.

B. Laser Thomson Scattering Measurement System

Figure 2 shows the experimental setup for LTS measurements on the miniature microwave discharge ion thruster. The scattering light inside the discharge chamber is collected through a hole ($\phi=3$ mm) and the laser beam go pass through two small holes ($\phi=2$ mm). The $\phi=3$ mm hole is positioned at an angle of 90 degree to the laser pass.

The light source is the second harmonic beam of an Nd:YAG laser having a wavelength of 532 nm with a maximum energy of 200 mJ, a repetition rate of 10 Hz, a pulse width of 6 ns and a beam divergence of 0.6 mrad. The measurement point is 2 mm upstream of the screen grid on the thruster axis (z axis). The laser beam is focused through a focusing lens ($f=200$ mm). We use a f-theta lens and a plano-convex lens; The size of the focal spot with the f-theta lens and with the plano-convex lens was estimated as 80 μm and 165 μm in diameter, respectively, by observing the spatial profile of Rayleigh scattering from 40 kPa air gas. Scattered light from the plasma is focused onto the entrance slit of the triple grating spectrometer (TGS) with two achromatic lenses of $f=350$ mm and $f=250$ mm. The slit width is 200 μm . The scattering volume is $0.165 \times 0.165 \times 2 \text{ mm}^3$, as determined by the laser beam size, the slit width and the slit height, respectively. The solid angle of observation is about 0.025 sr. Strong stray light is generated from the surface of the components, due to the small size of discharge chamber, and the LTS signals are overwhelmed by it. In order to reduce stray light, the discharge chamber wall was made of carbon and TGS was used. The scattered light is dispersed by passing through the TGS, and is detected by photo-multiply tube (PMT). The TGS used in this experiment could reduce stray light around 10^{-8} at the wavelength of 2 nm from the probing laser, where the LTS signal is observed.

The estimated Thomson scattered photon number is so small that we used a photon counting method. The detected Thomson scattered signals were analyzed by a photon counting mode after more than 10,000 laser shots had been accumulated. The data accumulation process technique, taking advantage of the DC or repetitive operation of some discharges, was first suggested for lowering the limiting electron densities by Sakoda et al.¹⁵ We count photons for two conditions at each condition, condition 1; with plasma and laser and condition 2; plasma without laser. We also count photons for the condition 3; laser without plasma. We evaluate actual LTS signal by subtracting the number of photons obtained for condition 2 and 3 from the number of photons obtained for condition 1.

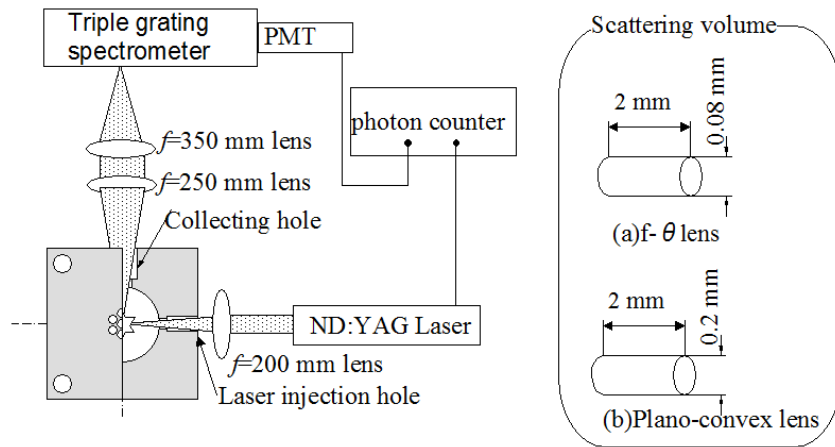


Figure 2. Experimental setup for LTS measurements.

C. Laser Absorption spectroscopy

Figure 3 shows a diagram of the experimental setup emphasizing the LAS. We use a laser diode to measure the transition line of xenon at 823.16 nm ($5p^5(^2P^{\circ}_{3/2})6s^2(^3S_1) - 5p^5(^2P^{\circ}_{3/2})6p^2(^3P_2)$). The transition data for this measurement are shown in Table 2 (from NIST database¹⁵ and Ref.10). The mode-hop free tuning range of the laser is about 30 GHz. The laser output power is ~ 30 mW with a power of ~ 0.1 mW injected into the ion thruster through neutral density filter (Optical Density: 3.0) in order to prevent saturation. The diode laser is set for a 25 GHz mode-hop-free sawtooth frequency scan every 5 seconds (up- and down- scan in 10 s). An optical isolator is used to prevent back reflections into the laser. Light is detected by a photo diode (PD) outside the vacuum chamber. A dielectric interference filter (10 nm band-pass, center wavelength of 820 nm) and an iris are used to suppress background light and emission from the plasma.

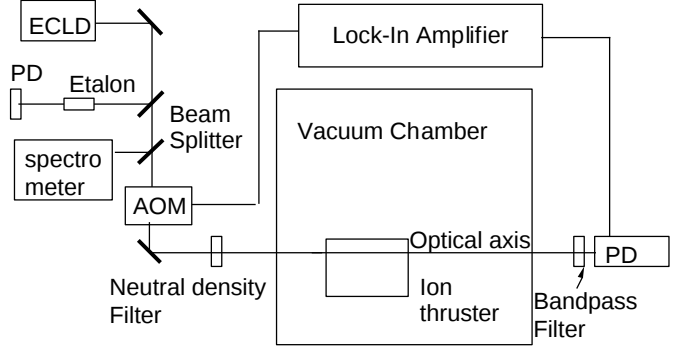


Figure 3. Experimental setup for LAS measurements.

To improve the Signal-to-noise ratio(SNR). We use an acousto-optic modulator (AOM) and lock-in amplifier. Laser was chopped at 1 kHz by AOM and modulated signal was detected by lock-in amplifier. A solid etalon (free spectral range = 1.15 GHz) is used as a frequency reference and a spectrometer is used for coarse frequency measurement. All signals were recorded using a PC based data acquisition system and a 100 KHz 16-bit A/D module.

A spectrometer is used for the measurement of an electron excitation temperature. However, the uncertainty of Einstein coefficient is too large to estimate the accurate temperature.

Table 1. Transition data for target xenon line.

λ , nm (Air)	E_i , eV	E_k , eV	A_{ki} , s^{-1}	g_i	g_k
467.12	8.315	10.969	1.0×10^6	5	7
711.96	9.721	11.462	6.6×10^6	7	9
796.73	9.447	11.003	3.0×10^5	1	3
823.16	8.315	9.821	2.5×10^7	5	5
840.92	8.315	9.789	1.0×10^6	5	3

III. Results and Discussion

A. Effect of laser intensity on Thomson scattering signal

We investigate the thresholds of the laser intensity on these conditions, since the laser induced some perturbation on the xenon plasma due to photo-ionization of the excited xenon atoms. We focus on the metastable xenon atoms. Meta-stable xenon atoms are ionized by the incident laser; if the wavelength of the laser is 532 nm (photon energy is 2.3 eV), $6s[3/2]^0_2$ excited xenon atoms(the energy level is 8.32 eV) absorb two photon for photo-ionization. So, the signal count number by photo-ionization from metastable atoms is proportional to the E_L^3 , on the contrary, Thomson scattering signal is proportional to E_L .

Figure 4a) shows the relation between the signal count number and the incident laser energy at xenon mass flow rate of 0.02 mg/s and incident microwave power of 6 W. The signal count number is proportional to E_L at $E_L < 50$ mJ and then it is proportional to E_L^3 . Therefore $E_L < 50$ mJ, photo-ionization effect can be negligible. However, 50 mJ is not enough energy in order to observe plasma properties in this plasma. This photo-ionization is nonlinear effect, so if we decrease the laser intensity at the observed volume, the possibility of photo-ionization will be decreased. So we use plano-convex lens instead of f-theta lens. The spot size of the plano-convex lens is about 165 μm , it is two times larger than that using f-theta lens. Figure 4b) shows the relation between the signal count number and E_L using plano-convex lens. The threshold laser energy increase to 150 mJ; at $E_L < 150$ mJ, The signal count number is

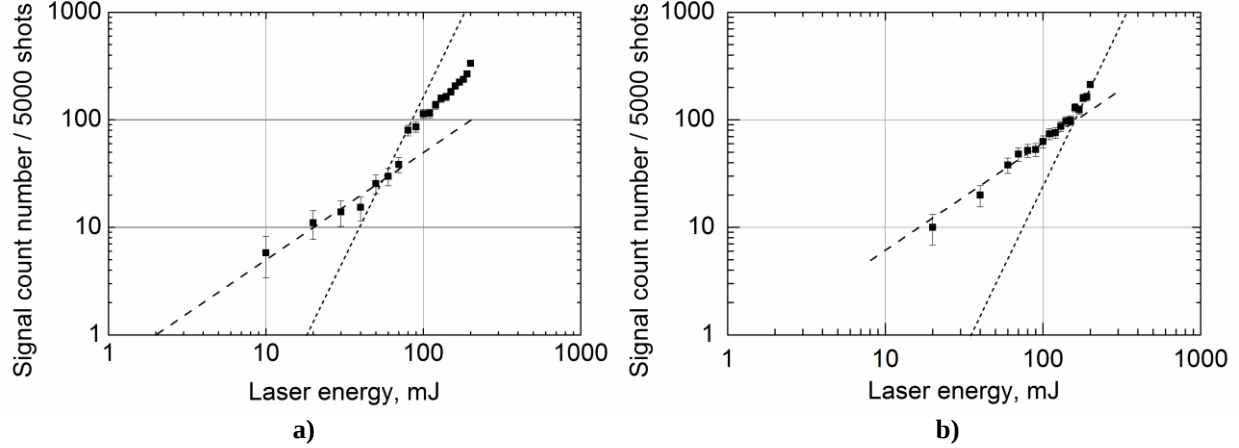


Figure 4. signal count number vs. laser energy. a) using $f=200$ mm f-theta lens b) using using $f=200$ mm plano-convex lens. $P_i=6$ W, $\dot{m}=20$ $\mu\text{g/s}$.

proportional to E_L and then, it is proportional to E_L^3 . The threshold intensity using plano-convex lens is 1.2×10^{15} W/m^2 , which is good agreement as that using f-theta lens, considering the uncertainty of the spot size of $10 \mu\text{m}$.

In the case of the $f = 200$ mm f-theta lens, signal count number increase with $E_L^{1.5}$ at $90 \text{ mJ} < E_L < 180 \text{ mJ}$. This would be due to the saturation; almost the all meta-stable xenon atoms are ionized by the probe laser. At $E_L > 180 \text{ mJ}$, signal count number is proportional to E_L^7 , this would be due to the photo-ionization from the ground state xenon atoms. Since ionization energy of xenon is 12.13 eV and photon energy of 532 nm light is 2.3 eV , six photons is necessary to photo-ionization.

We investigate the thresholds for five mass flow rates; $5 \mu\text{g/s}$, $10 \mu\text{g/s}$, $20 \mu\text{g/s}$, $30 \mu\text{g/s}$ and $40 \mu\text{g/s}$. The thresholds of the photo-ionization are almost the same when mass flow rate is changed; the threshold for $\dot{m} = 5 \mu\text{g/s}$, $10 \mu\text{g/s}$, $20 \mu\text{g/s}$, $30 \mu\text{g/s}$ and $40 \mu\text{g/s}$ are 180 mJ , 140 mJ , 150 mJ , 170 mJ and 140 mJ , respectively at incident microwave power of 6 W and using $f=200$ mm plano-convex lens.

B. Number density and electron temperature measurement by LTS

The thresholds of the photo-ionization using $f=200$ mm plano-convex lens are 140 mJ to 180 mJ , so the incident probe laser energy is set as 80 mJ . Figure 5 shows the measured Thomson scattering spectrum at $P_i = 6 \text{ W}$ and $\dot{m} = 20 \mu\text{g/s}$. From the shape of the Thomson spectrum, we conclude that the electron energy distribution function (EEDF) is Maxwellian, as krypton propellant.^{6,16} We measure Thomson scattering spectra for various mass flow rates, and all of the spectrum can be fit by Gaussian. These results show flux tube model can be used to simulate ion beam trajectory for the ion engine grid erosion evaluation code; calculation cost is much lower than that by Full Particle in Cell (PIC) model. Because Miyasaka et al.¹⁷ shows there is no difference between the numerical results using full-Particle In Cell (PIC) model¹⁸ and that using flux tube model,^{19,20} if EEDF in the vicinity of the screen grid is Maxwellian. From this spectrum and the Rayleigh scattering calibration using nitrogen gas, N_e and T_e were calculated to be $6.2 \pm 0.4 \times 10^{17} \text{ m}^{-3}$ and $2.2 \pm 0.4 \text{ eV}$, respectively. The experimental uncertainty for each point was determined primarily by the statistical fluctuation in the number of detected photons.²¹

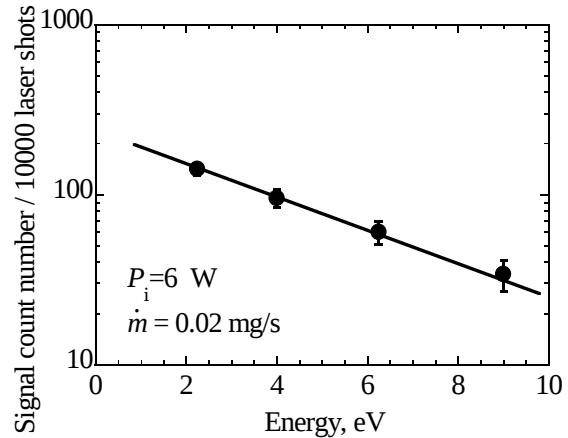


Figure 5. Spectrum of Thomson scattering. $P_i = 6 \text{ W}$, $\dot{m} = 20 \mu\text{g/s}$, using $f=200$ mm plano-convex lens, incident probe laser energy of 80 mJ .

C. Number density of meta-stable xenon atoms by LAS

Figure 6 shows the measured absorption spectrum of metastable xenon atoms at $P_i = 6\text{W}$, $\dot{m} = 6.2\text{ }\mu\text{g/s}$. The Spectrum was numerically integrated for estimation of the metastable xenon atoms population, though we can see hyperfine structure (Isotope shift, nuclear spin splitting and anomalous Zeeman shifts). The electron excite temperature is assumed as electron temperature deduced from LTS, the linear density of $6s[3/2]_2^0$ metastable atoms is estimated as $3.4 \pm 0.2 \times 10^{15}\text{ m}^{-2}$. If we assume the absorber is uniformly present over a length l_{abs} , and l_{abs} is assumed as 0.021 m, which is inner diameter of the discharge chamber, the population of $6s[3/2]_2^0$ metastable atoms is estimated as $1.7 \pm 0.1 \times 10^{17}\text{ m}^{-3}$.

If we assumed electron excite temperature as electron excite temperature deduced from emission spectroscopy, electron excitation temperature is estimated as 0.42 eV, the meta-stable xenon atoms ($6s[3/2]_2^0$) is estimated as $8.3 \times 10^{16}\text{ m}^{-3}$.

Table 3 shows the threshold of the photo-ionization from the metastable atoms and plasma properties for four mass flow rates. As I mentioned above, the threshold is almost constant; this is because both number density of metastable atoms and electron number density increases with increase in mass flow rate. Considering the uncertainty of the number density, the ratio of N_e/N_m is almost the same, therefore, the threshold is constant.

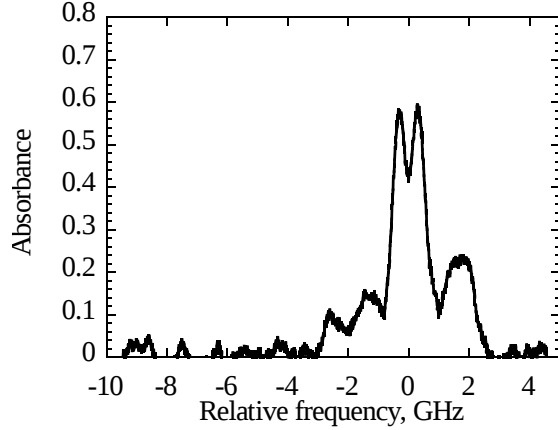


Figure 6. Absorption profile of metastable xenon atom. $P_i = 6\text{ W}$, $\dot{m} = 20\text{ }\mu\text{g/s}$.

Table 3. Thresholds of the photo-ionization at several conditions . * :using T_{ex} by emission spectroscopy

$\dot{m}$, $\mu\text{g/s}$	P , W	E_{critical} , mJ	N_e , m^{-3}	T_e , eV	N_m , m^{-3}	N_e/N_m	T_{ex}^* , eV	N_m^* , m^{-3}
10	6	140	5.2×10^{17}	2.1	1.3×10^{17}	4	0.44	6.4×10^{16}
20	6	150	6.2×10^{17}	2.2	1.7×10^{17}	3.6	0.42	8.3×10^{16}
30	6	170	5.9×10^{17}	1.4	1.5×10^{17}	3.8	0.41	9.7×10^{16}
40	6	140	8.6×10^{17}	1.6	1.8×10^{17}	4.8	0.40	1.1×10^{17}

IV. Conclusion

We succeed in measurement of xenon plasma property using laser Thomson scattering technique (LTS) in a miniature ion thruster. The threshold of the probe laser intensity against photo-ionization in a miniature xenon ion thruster is $1.2 \times 10^{15}\text{ W/m}^2$. This value is almost constant for various mass flow rates, since there is a correlation between population of the meta-stable atoms and electron number density. For the understanding the photo-ionization, we should measure more various conditions; it will contribute the estimation of the threshold intensity in various xenon plasma. On the other hand, even in the absence of more detailed modeling, we demonstrate the ability of the LTS technique for the measurement of xenon plasma under the condition of probe laser intensity < threshold. The non-intrusive nature of the LTS can be of great utility in understanding the physics inside the electric propulsion, as well as ion thrusters.

Acknowledgments

This work was supported by Kyushu University Interdisciplinary Programs in Education and Projects in Research Development, the Engineering Digital Innovation Center and the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency and the Japan Society for the Promotion of Science, Japan for their financial support through a Grant-in-Aid for Young Scientists (A), No. 23686123 and Grant-in-Aid for Grant-in-Aid for challenging Exploratory Research, No. 23656540.

References

- ¹Nakano, M. "Grid Erosion Analysis and Lifetime Evaluation of Ion Engines," *Frontier of Applied Plasma Technology*, 2 (2009) pp.21-24.
- ²Herman, D. A. and Gallimore, A. D.: An ion thruster internal discharge chamber electrostatic probe diagnostic technique using a high-speed probe positioning system, *Rev. Sci. Instrument*, 79, (2008) 013302.
- ³Sheffield, J., *Plasma Scattering of Electromagnetic Radiation*, Academic press, New York, 1975, Chap. 9.
- ⁴Evans, D. E., and Katzenstein, J.: *Laser Light Scattering in Laboratory Plasmas*, Report on Progress in Physics, 32,(1969) pp. 207-271.
- ⁵Muraoka, K., Uchino, K., and Bowden, M. D.: Diagnostics of Low-density Glow Discharge Plasmas Using Thomson Scattering, *Plasma Physics and Controlled Fusion*, 40, (1998) pp.1221-1239.
- ⁶Yamamoto, N., Hiraoka, Y., Sugita, K., Kurita, T., Tomita, K., Uchino K. and Nakashima, H, "Thomson Scattering Diagnostics in the Plasma of an Ion Thruster," *Proceedings of the 28th International Symposium on Space Technology and Science*, ISTS paper 2011-b37, Okinawa, (2011).
- ⁷Kim, Y. K., Tomita, K., Hassaballa, S., Uchino, K., Muraoka, K., Hatanaka, H., Kim, Y. M., Lee, S. E., Son, S. H. and Jang, S. H.: Development of an Infrared Laser Thomson Scattering System for Measurements of Electron Density and Electron Temperature of a PDP Micro-discharge Plasma, *SID International Symposium Digest of Technical Papers*, 35 (2004) pp. 550-553.
- ⁸Walsh, A. L., *Spectrochim. Acta* 7,108,1955
- ⁹Matsui, M., Komurasaki, K., Herdrich, G., and Auweter-Kurtz, M., "Enthalpy Measurement in Inductively Heated Plasma Generator Flow by Laser Absorption Spectroscopy," *AIAA Journal* Vol.43, (2005) pp.2060-2064.
- ¹⁰Matsui, M., Yokota, S., Takayanagi, H., Koizumi, H., Komurasaki, K., Arakawa, Y., "Plume Characterization of Plasma Thrusters Using Diode-Laser Absorption Spectroscopy," 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, AIAA paper 2006-0767.
- ¹¹Yamamoto, N., Kondo, S., Chikaoka, T., Masui H. and Nakashima, H.: Effects of Magnetic Field Configuration on Thrust Performance in A Miniature Microwave Discharge Ion Thruster, *Journal of Applied Physics*, 102 (2007), 123304.
- ¹²Yamamoto, N., Masui, H., Kataharada, H., Nakashima, H., and Takao, Y.: Antenna Configuration Effects on Thrust Performance of Miniature Microwave Discharge Ion Engine, *Journal of Propulsion and Power* Technical Note, 22,(2006) pp. 925-928.
- ¹³Wirz, R. E., "Discharge Plasma Processes of Ring-Cusp Ion thrusters," Ph D. Diss., California Institute of Technology, April , 2005.
- ¹⁴Nakano, M. , Tachibana, T., and Arakawa, Y. : A Scaling Law of the Life Estimation of the Three-Grid Optics for an Ion Engin, *Transactions of the Japan Society for Aeronautical and Space Sciences*, 45, (2002), pp.154-161.
- ¹⁵Sakoda, T., Momii, S. Uchino K., Muraoka, K., Bowden, M., Maeda, M., Manabe, Y., Kitagawa, M., and Kimura, T.: Thomson Scattering diagnostics of an ECR Processing Plasma, *Jpn. J. Appl. Phys.*, 30, (1991), pp.L1425–L1427.
- ¹⁶Yamamoto, N., Tomita, K., Yamasaki, N., Tsuru, T., Ezaki, T., Kotani, Y., Uchino K. and Nakashima, H.: Measurements of Electron Density and Temperature in a Miniature Microwave Discharge Ion Thruster Using Laser Thomson Scattering Technique , *Plasma Sources Science and Technology*, 19 (2010), 045009.
- ¹⁷Miyasaka, T., Kobayashi, T., Asato, K.: Numerical Prediction of Grid Erosion of Ion Engine, *Transactions of the Japanese Society for Artificial Intelligence, Aerospace Technology Japan*, 8 (2011), pp. Pb_61-Pb_66.
- ¹⁸Vahedi, V. and Surendra, M.: A Monte Carlo Collision Model for the Particle-in-cell Method: Applications to Argon and Oxygen Discharges, *Computer Physics Communications*, 87 (1995), pp179-198.
- ¹⁹Nakayama Y. and Wilbur, P. J.: Numerical Simulation of Ion Beam Optics for Multiple-Grid Systems, *Journal of Propulsion and Power*, 19 (2003), pp.607-613.
- ²⁰Arakawa, Y. and Ishihara, K.: A Numerical Code for Cusped Ion Thruster, *Proceedings of 22nd International Electric Propulsion Conference, IEPC-91-118*, 1991.
- ²¹Kunze, H. J., *The laser as a tool for plasma diagnostic*, Plasma diagnostics, ed. Lochte-Holtgreven W, Noth-Holland Publishing Company, Amsterdam (1968), 550.