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 \( \mu \)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 \( 6.2 \pm 0.4 \times 10^{17} \) m\(^{-3} \) and electron temperature 2.2±0.4 eV at a xenon mass flow rate of 20 \( \mu \)g/s and incident microwave power of 6 W.

Nomenclature

\[
\begin{align*}
A_{ki} & = \text{Einstein coefficient} \\
E_i & = \text{threshold probe laser energy for photo-ionization.} \\
E_l & = \text{energy level} \ l \text{ of lower state} \\
E_k & = \text{energy level} \ k \text{ of upper state} \\
E_L & = \text{incident laser energy} \\
f & = \text{focal length} \\
g_i & = \text{statistical weight} \ l \text{ of lower state} \\
g_k & = \text{statistical weight} \ k \text{ of upper state} \\
K & = \text{integrated absorption coefficient} \\
l_{ab} & = \text{absorber length} \\
m & = \text{mass flow rate} \\
N_e & = \text{electron number density} \\
N_m & = \text{number density of metastable atoms} \\
P & = \text{incident microwave power to miniature microwave discharge ion thruster} \\
T_e & = \text{electron temperature} \\
T_z & = \text{thruster axis} \\
\phi & = \text{diameter} \\
\lambda & = \text{wave length}
\end{align*}
\]

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. There have been many studies to measure plasma property inside the discharge chamber 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) 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 $N_e > 10^{19}$ m$^{-3}$, $^2$ 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. 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. A previous study, however, showed that the laser induced some perturbation on the xenon plasma; 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 ($6s[3/2]_J$) 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 $\dot{m} = 0.018$ 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 x 50 mm x 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. $^{15}$ 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.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Screen</th>
<th>Accel.</th>
<th>Decel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole diameter, mm</td>
<td>3.0</td>
<td>1.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Potential, V</td>
<td>1200</td>
<td>-200</td>
<td>0</td>
</tr>
<tr>
<td>Thickness, mm</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hole pitch, mm</td>
<td>3.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Pyrolytic carbon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid gap, mm</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of holes</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Grid parameters.
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.\textsuperscript{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 $5.0 \times 10^{-2}$ 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 \(\mu\)m and 165 \(\mu\)m 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 \(\mu\)m. The scattering volume is $0.165 \times 0.165 \times 2$ 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.\textsuperscript{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.](image)
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(3P°)3s(3S°)) × 7/2(7/2). The transition data for this measurement are shown in Table 2 (from NIST database\(^5\) and Ref.\(^{10}\)). The modehop 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.

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.

<table>
<thead>
<tr>
<th>(\lambda), nm (Air)</th>
<th>(E_i), eV</th>
<th>(E_f), eV</th>
<th>(A_{ki}), s(^{-1})</th>
<th>(g_i)</th>
<th>(g_k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>467.12</td>
<td>8.315</td>
<td>10.969</td>
<td>1.0 \times 10^6</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>711.96</td>
<td>9.721</td>
<td>11.462</td>
<td>6.6 \times 10^6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>796.73</td>
<td>9.447</td>
<td>11.003</td>
<td>3.0 \times 10^3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>823.16</td>
<td>8.315</td>
<td>9.821</td>
<td>2.5 \times 10^7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>840.92</td>
<td>8.315</td>
<td>9.789</td>
<td>1.0 \times 10^6</td>
<td>5</td>
<td>3</td>
</tr>
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</table>

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), \(6s[3/2]P_{\perp}\) excited xenon atom (the energy level is 8.32 eV) absorb two photons for photo-ionization. So, the signal count number by photo-ionization from metastable atoms is proportional to the \(E_i^3\), on the contrary, Thomson scattering signal is proportional to \(E_i\).

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 \(E_i\) at \(E_i < 50\) mJ and then it is proportional to \(E_i^3\). Therefore \(E_i < 50\) 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 \(\mu\)m, it is two times larger than that using f-theta lens. Figure 4b) shows the relation between the signal count number and \(E_i\) using plano-convex lens. The threshold laser energy increase to 150 mJ; at \(E_i < 150\) 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, \(m=20\) \(\mu\)g/s.

proportional to \(E_L\) and then, it is proportional to \(E_L^3\). The threshold intensity using plano-convex lens is \(1.2\times10^{15}\) W/m\(^2\), which is good agreement as that using f-theta lens, considering the uncertainty of the spot size of 10 \(\mu\)m.

In the case of the \(f=200\) mm f-theta lens, signal count number increase with \(E_L^{1.5}\) at 90 mJ < \(E_L\) < 180 mJ. This would be due to the saturation; almost the all meta-stable xenon atoms are ionized by the probe laser. At \(E_L > 180\) 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 \(\mu\)g/s, 10 \(\mu\)g/s, 20 \(\mu\)g/s, 30 \(\mu\)g/s and 40 \(\mu\)g/s. The thresholds of the photo-ionization are almost the same when mass flow rate is changed; the threshold for \(m=5\) \(\mu\)g/s, 10 \(\mu\)g/s, 20 \(\mu\)g/s, 30 \(\mu\)g/s and 40 \(\mu\)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 \(P_i = 6\) W and \(m = 20\) \(\mu\)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) model\(^18\) 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 \(6.2\pm0.4\times10^{17}\) m\(^{-3}\) and \(2.2\pm0.4\) 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. \(P_i = 6\) W, \(m = 20\) \(\mu\)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 $P_i = 6 W$, $\dot{m} = 6.2 \mu g/s$. 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]$^1_2$ 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]$^1_2$ 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]$^3_2$) 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 $N_i/N_m$ is almost the same, therefore, the threshold is constant.

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

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.

The 32nd International Electric Propulsion Conference, Wiesbaden, Germany
September 11 – 15, 2011
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