JOURNAL OF PROPULSION AND POWER
Vol. 26, No. 2, March–April 2010

# Technical Notes

## Thomson-Scattering Diagnostics of Plasmas Produced in a Miniature Microwave Discharge Ion Engine

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DOI: 10.2514/1.39145

### Nomenclature

| | | |
|---|---|---|
| $e$ | = | electron charge |
| $f$ | = | focal length |
| $I_b$ | = | ion beam current |
| $k$ | = | Boltzmann constant |
| $m_i$ | = | ion mass |
| $n_e$ | = | electron density |
| $P_i$ | = | incident microwave power |
| $S$ | = | total ion beam extraction area |
| $T_e$ | = | electron temperature |
| $V_B$ | = | Bohm velocity |
| $\Delta\lambda$ | = | wavelength difference from laser wavelength |
| $\lambda$ | = | wavelength |

### Introduction

THE adoption of small satellites, with their flexibility, short development time, and low cost, has been a breakthrough in space applications [1,2]. Until recently, however, size restrictions have limited the capacity of the available propulsion systems. Hence, the demand for millinewton-class miniature propulsion systems is expected to grow in the future with miniature microwave discharge ion engines as ideal candidates for use on these satellites [3–5]. Conventional ion engines produce high thrust efficiency (60–70%) with specific impulses above 3000 s [6–8].

A 30 W miniature ion engine has been developed for deorbiting 100-kg-class satellites [5]. To miniaturize the engine while maintaining its superiority in performance, a microwave discharge ion source was used. The results demonstrate good performance of the 16-mm-diam version of the source, including a thrust efficiency of 0.51. This is competitive with the miniature ion engine developed at NASA, for which the thrust efficiency is 0.56 [9], and has been the best performance at its size [9]. The thrust density of our engine was $5.6\ \mathrm{N/m^2}$, which is several times higher than that of conventional ion engines ($1.1$–$1.6\ \mathrm{N/m^2}$) [1–3]. This higher thrust density is a significant advantage for small satellites, since it means the volume of the engine can be dramatically reduced. Understanding the reason for this superiority is essential in developing this engine. It has not yet, however, been thoroughly investigated, since it is difficult to measure the plasma properties without disturbing the plasma as a result of intrusive diagnostic methods, such as an electrostatic probe.

The aim of this study is to measure plasma properties by laser Thomson scattering (LTS) to understand the physics inside this engine. LTS is nonintrusive, in that no physical object need be placed in the plasma [10–12].

Application of this method to the plasma produced in the miniature microwave ion engine faces the following difficulties. First, the $n_e$ is estimated to be less than $10^{18}\ \mathrm{m^{-3}}$. This results in a weak Thomson-scattering signal. Second, the effect of stray laser light becomes very strong. To overcome these difficulties, we used the photon-counting method with a double monochromator. These efforts made it possible to detect LTS signals.

### Experiment

Figure 1 shows a cross section of the miniature microwave discharge ion engine. The inner diameter is 18 mm. The ion source includes a magnetic circuit, which has four samarium cobalt (Sm–Co) permanent magnets and iron yokes. Microwave power at 2.45 GHz was fed through a coaxial line and into an antenna in the engine. The screen grid and the ion source body were biased at $+1500$ V relative to ground and the acceleration grid was biased at $-300$ V. The primary electrons are confined in the mirrorlike magnetic field formed between the central and front yokes, gaining energy from microwave emission by electron cyclotron resonance heating. Energetic electrons then collide with and ionize neutral atoms. Detailed explanations about the ion engine and the electric circuit are described in [13,14].

Figure 2 shows the relation between $P_i$ and $I_b$. The extracted $I_b$ was estimated by subtracting the current through the accelerator power supply from the current through the screen power supply [13]. In this experiment, pure Kr gas was used as the propellant. The pressure inside the discharge chamber was taken to be $5.5\times 10^{-2}$ torr. This value can be estimated given the conductance of the discharge chamber ($5.7\times 10^{-4}\ \mathrm{m^3/s}$), the mass flow rate ($0.16$ mg/s), and the background pressure ($5.0\times 10^{-5}$ torr). As can be seen from Fig. 3, the ion beam current increases with the incident microwave power. For example, when $P_i = 24$ W, the ion beam current density is $240\ \mathrm{A/m^2}$, approximately nine times larger than that of the ion engine adopted in the Deep Space 1 mission [2]. This elevated current density is due to the substantially higher plasma density in the discharge chamber.

Figure 3 shows an experimental setup of LTS measurements on the miniature microwave discharge ion engine. A 0.3-m-diam by 0.4-m-long vacuum chamber was used in the experiments. The background pressure of Kr is $1.5\times 10^{-4}$ torr, though the pressure inside the chamber is almost the same as the above experiments. For our LTS measurements, the plasma was generated with a microwave power of 8 W. To measure the plasma inside the discharge chamber, two small holes ($d = 2$ mm) to inject the laser and another hole ($d = 5$ mm) to collect scattering light were made. A $d = 5$ mm hole was made at an angle of 90° from the laser path.

Our light source was the second harmonic of a Nd:YAG laser having $l = 532$ nm with an energy of 150 mJ, a pulse rate of 10 Hz, and a pulse width of 6 ns. The laser beam was focused to a distance of 2 mm from the tip of the microwave discharge antenna through a focusing lens ($f = 300$ mm). Scattered light from the plasma was

Received 24 June 2008; accepted for publication 27 October 2009. 

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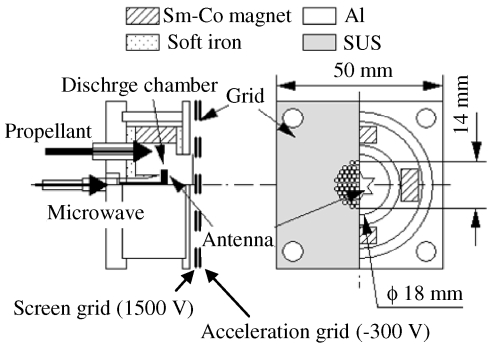


**Fig. 1 Cross section of miniature ion engine developed at Kyushu University.**

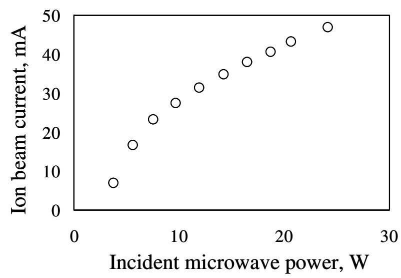


**Fig. 2 Miniature microwave discharge ion engine performance.**

focused onto the entrance slit of the double monochromator with two achromatic lenses of $f = 350$ and 250 mm. The scattering volume was $0.08 \times 0.1 \times 1$ mm$^3$, determined by the laser beam size, the slit width, and the slit height, respectively.

The scattered light was dispersed by passing through the double monochromator and was detected by a photomultiplier tube (Hamamatsu, R943-02, quantum efficiency $\sim$10%). The instrumental function of the detection system had a full-width at half-maximum of 0.4 nm. In this situation, if $n_e$ of the plasma is $10^{18}$ m$^{-3}$, the Thomson-scattered photon number detected for one laser shot is expected to be about 0.02. This estimated Thomson-scattered photon number is so small that a photon-counting method was used. The detected Thomson-scattered signals were analyzed by a Stanford Research Systems, Inc., SR430 photon counter after accumulating over 5000 laser shots.

Since the probing laser was focused to 2 mm above the tip of the antenna and the discharge chamber was small, strong surface-reflected light (stray light) rose on the components in the chamber, initially overwhelming the LTS signals. To reduce reflections, a double monochromator ($f = 575$ mm) was added. The double monochromator used in this experiment could reduce stray light by a factor of $10^{-7}$ at a wavelength of 2 nm from the laser wavelength. With this addition, we eliminated the majority of the strong stray light, enabling us to successfully detect LTS signals.

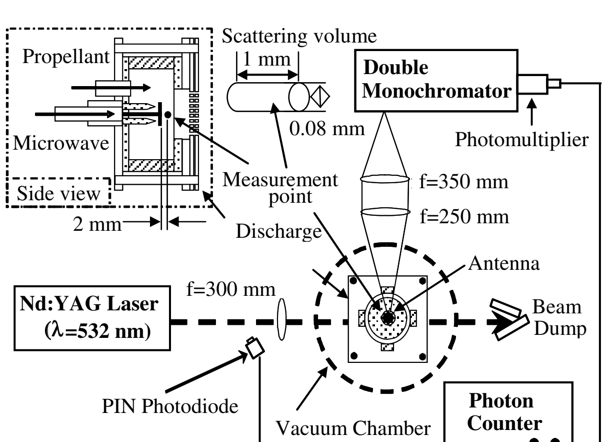


**Fig. 3 Schematic of a laser Thomson-scattering system for the miniature ion engine.**

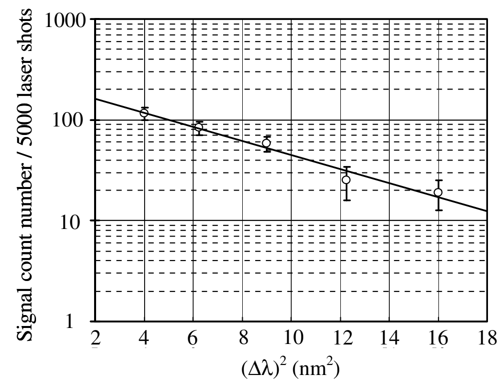


**Fig. 4 Thomson-scattering spectrum measured at 2 mm above the antenna.**

## Results and Discussion

In Fig. 4, Thomson-scattering intensities are plotted in a logarithmic scale in the ordinate against $(\Delta\lambda)^2$, where $(\Delta\lambda)^2$ is proportional to the electron energy. The parameter $\Delta\lambda$ was controlled by scanning the double-monochromator passband center relative to the laser wavelength. From the linearity of the Thomson spectrum, we conclude that the electron energy distribution function was Maxwellian. From this spectrum and the Rayleigh scattering calibration using nitrogen gas, $n_e$ and $T_e$ were calculated to be $(1.1 \pm 0.2) \times 10^{18}$ m$^{-3}$ and $2.9 \pm 0.5$ eV, respectively. The experimental uncertainty for each point was determined primarily by the statistical fluctuation in the number of detected photons [12].

Next, we discuss the results of our measurements. According to the Bohm sheath criterion, the velocity of an ion from the plasma into the ion sheath on a grid is assumed to be $V_B$, expressed as follows [15]:

$$V_B = \sqrt{\frac{kT_e}{m_i}} \tag{1}$$

Given that $n_e$ in the bulk plasma decreases by a factor of $\exp(-1/2)$ at the point where the ion velocity reaches $V_B$, the ion beam current is evaluated as shown below:

$$I_b = en_e \exp\left(-\frac{1}{2}\right) S \sqrt{\frac{kT_e}{m_i}} \tag{2}$$

Under the conditions in the LTS measurement, $m_i = 1.4 \times 10^{-25}$ kg, $T_e = 2.9$ eV, $n_e = 1.1 \times 10^{18}$ m$^{-3}$, and $S = 1.0 \times 10^{-4}$ m$^2$. Substituting these values into Eq. (2), we obtain $I_b = 20$ mA. From Fig. 2, the ion beam current measurement taken under the same conditions as the LTS measurement was found to be 25 mA when $P_i = 8$ W, which is within the measurement uncertainty. From the results of this LTS measurement, it was confirmed that $n_e$ in this engine was several times higher than those of conventional ion engines [16]. This high $n_e$ leads to the high ion beam current density of this engine.

## Conclusions

The plasma parameters in the miniature microwave discharge ion thruster were successfully measured without perturbation by nonintrusive optical methods of LTS for the first time. At an incident microwave power of 8 W and a krypton mass flow rate of 0.16 mg/s, $n_e$ and $T_e$ were calculated to be $(1.1 \pm 0.2) \times 10^{18}$ m$^{-3}$ and $2.9 \pm 0.5$ eV, respectively. We confirmed that the measured $n_e$ and $T_e$ were consistent with the high ion current achieved by this thruster.

The adoption of these methods could reveal the plasma production-loss mechanism in the microwave discharge ion thruster as well as physical mechanisms inside other electric propulsion devices.

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