Application of Two-photon Laser-induced Fluorescence Spectroscopy to Microwave Cathode

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To investigate the neutral xenon density distribution of electric thrusters such as ion and Hall thrusters, two-photon absorption laser-induced fluorescence (TALIF) spectroscopy was applied to a microwave cathode. First, the background pressure of the vacuum chamber was measured by TALIF. In the present measurements, the ground state was excited by a 224.29 nm laser, and 834.68 nm fluorescence was detected. The first measurement confirmed that the fluorescence intensity linearly increases with respect to the ground state number density. Based on this result, the density of neutral ground-state xenon was measured at the exit of the nozzle of the microwave cathode. The variation in the density with the microwave power was successfully measured at xenon flow rates of 0.029 and 0.098 mg/s. The measured densities varied from $2.3 \times 10^{19}$ to $8.4 \times 10^{19}$ m$^{-3}$ with a maximum error of $\pm 20\%$ due to the plasma fluorescence.

Key Words: Microwave, Ion Thruster, Two-photon Absorbed Laser-induce Fluorescence Spectroscopy, Cathode

1. Introduction

To improve the thrust performance and lifetime of ion and Hall thrusters, it is highly important for the neutral propellant particle distribution to be optimized during thruster design. The Japanese microwave ion thruster $\mu$10 achieved a 30% improvement to the thrust by changing the propellant inlets from waveguides to discharge chambers.1–3 Additionally, the lifetime of its microwave cathode was improved by increasing the flow rate.4 It is also important for Hall thrusters to suppress discharge oscillations.5

To understand the neutral particle distribution of electric thrusters, direct simulation Monte Carlo (DSMC) simulations have been performed; however, the DSMC method requires certain assumptions, such as reflection at the boundary and a neutral temperature.6–8 In addition, ionization collisions and neutralization on the wall are considered to affect the neutral particle density distribution. Therefore, experimental validation of the density of neutral particles is necessary in order to provide useful information for numerical simulations.

In a previous study, Nakayama measured the neutral particle density inside a gridded ion thruster using a pressure gauge.9 Although the neutral particles were successfully measured, this technique cannot be applied to microwave ion thrusters because of the mutual disturbance of the microwaves and the metallic probe. We previously measured the excited neutral particle density inside a microwave ion thruster by coupling an optical fiber with laser absorption spectroscopy; however, the relationship between the excited and ground states was not investigated.10 Because most of the neutral particles are in the ground state, the use of two-photon absorbed laser-induced fluorescence (TALIF) spectroscopy is proposed in this study.11–13

Our group has successfully detected xenon fluorescence with a reference cell at various laser powers.14 Building on this previous work, in the present study, TALIF was applied to a microwave cathode. As a first measurement in this study, the background pressure in a vacuum chamber was measured as the amount of neutral xenon was increased. Then, to convert the detected signal intensity to the neutral ground-state xenon density, the empirical intensity–density relationship was referenced for the second measurement, in which the density at the exit of the nozzle of the microwave cathode was measured without electron extraction.

2. Experiment

Figure 1 shows the experimental setup for the TALIF measurements. The ND:YAG laser is a pumping laser for the dye laser, which emits a 10 ns pulsed laser at 300 mJ. The dye laser converts the wavelength of the input laser light from 532 nm to 224.29 nm at 3 mJ to excite the ground state of the neutral xenon $5p^61S_0$ to $6p[3/2]_2$. The power of the dye laser decreases to 1.2 mJ in the vacuum chamber because of the transmittance of the window. Inside of the vacuum chamber, the laser is focused at the exit of the cathode orifice using the 50-mm focal length lens. The focused laser beam has the 2-mm diameter. The collection optics have the same lenses. It is estimated that the measured volume is approximately the cross section of the 2-mm laser beam and the same diameter of the collection optics. In order to minimize the random noises, such as vibration of pumps, laser perturbation, and plasma luminescence, 100 data sets are averaged.

As shown in Fig. 2, the excited neutrals fluoresce at 834.68 nm. In this system, two photomultipliers (PMTs) are used. PMT1 is a detector to measure the ground state density of neutral xenon in the vacuum chamber. The collection
optics for PMT1 focus the center point of the orifice exit of the microwave cathode. The operation conditions of the cathode are shown in Table 1. In the measurement, electrons were not extracted. PMT2 is used to synchronize the pulsed laser with the oscilloscope as a function of a trigger.

In non-saturated TALIF, the intensity of the fluorescence $S_F$ is proportional to the number density $n_0$ of neutral ground-state xenon if the laser power $I$ is constant and the quenching is negligible, as described by

$$S_F = \frac{B_{20} I^2 A_{21}}{(B_{20} + B_{02})^2 + A_{21}^2} n_0$$

(1)

where $B_{20}$, $B_{02}$, and $A_{21}$ are the Einstein coefficients defined in Fig. 2. To confirm the above assumption and to demonstrate the measurement, $S_F$ was first measured without the microwave cathode using the same measurement system as shown in Fig. 1. $S_F$ was obtained by measuring the signal intensity while changing the background pressure of the vacuum chamber using xenon. The background pressure is equal to $n_0$, and the experiment reveals the relationship between $S_F$ and $n_0$. This empirical relationship was then used in the subsequent measurement of the microwave cathode to convert the measured signal intensity to the neutral ground-state xenon density.

3. Results

Figure 3 shows the intensity of the PMT1 signal plotted with respect to xenon pressure and density in the vacuum chamber. The signal intensity was found to linearly increase with respect to the background pressure of the neutral xenon. The error was small, which could be written within each marker. This relationship was used in the following measurement to convert the measured signal intensity to the neutral ground-state xenon density.

In the measurement, the relationship of signal intensity with respect to the wavelength was also measured shown in Fig. 4. The fluorescence signal with respect to the wavelength was fitted using Voight functions. The laser was scanned the wavelength ±8 pm. FWHM is approximately 5 pm. Since Doppler shift was not measured, the wavelength

![Fig. 1. Experimental setup for TALIF using microwave cathode.](image1)

![Fig. 2. Grotrian diagram for Xe I.](image2)

![Fig. 3. PMT1 signal strength plotted with respect to xenon pressure and density in calibration for TALIF measurement using vacuum chamber. The temperature is assumed at 300 K.](image3)

![Fig. 4. The intensity of a fluorescence signal with respect to the wavelength.](image4)

![Fig. 5. Neutral ground-state xenon density at exit of nozzle of microwave cathode without electron extraction under different microwave powers at mass flow rates of 0.029 and 0.098 mg/s. There is no plasma at 0 W.](image5)
of the laser is set at peak of the signal written as 0 pm for the following measurement of the neutralizer in the same way of other studies.12-14

Figure 5 shows the measurement results for the neutral ground-state xenon density at mass flow rates of 0.029 and 0.098 mg/s at input microwave powers ranging from 0 to 16 W. The lower flow rate of 0.029 mg/s was the minimum flow rate at which the microwave plasma could be maintained in the cathode, and this flow rate was used as a basis of comparison for the higher flow rate of 0.098 mg/s. Each point represents an average over three measurements, and the error bars show the deviation of the data, which ranged from approximately ±4% to ±20%. The error was presumed to have been caused by fluorescence from the microwave plasma in the cathode. A bandpass filter was set in front of PMT1 but could not completely eliminate the plasma luminescence. When there was no plasma (at a microwave power of 0 W), the deviation was too small to be depicted in Fig. 5. Compared with this error, the difference of the wall temperatures between the vacuum chamber in Fig. 3 and the cathode chamber in Fig. 5 could be negligible. The temperature of the vacuum chamber was about 300 K whereas that of the cathode was 400 K, which resulted in the 2.5% difference of the Doppler broadenings.

At both flow rates, the neutral ground-state xenon density decreased with increasing microwave power. The recorded densities were highest at 0 W and 0.098 mg/s, with an average density of $8.4 \times 10^{19}$ m$^{-3}$ over the three trials. As the power was increased to 8, 12, and 16 W, the density decreased to $7.5 \times 10^{19}$, $6.5 \times 10^{19}$, and $6.3 \times 10^{19}$ m$^{-3}$, respectively, as the ionization rate increased with increasing input microwave power. At 0.029 mg/s, the density was $2.5 \times 10^{19}$ m$^{-3}$ at 0 and 8 W, and it decreased slightly to $2.3 \times 10^{19}$ m$^{-3}$ at 12 and 16 W. The experimental results at 0 W have an agreement with the DSMC analysis.15

The ratio of the neutral ground-state xenon density at 0 W to that at 16 W was higher at 0.098 mg/s than at 0.029 mg/s. Because 0.029 mg/s was the minimum flow rate required to maintain the plasma, ionization changed very little as the microwave power was varied. At 0.098 mg/s, there was a greater number of neutrals in the cathode, and the ionization rate thus increased with increasing microwave power. In addition to the ionization, it is speculated that the higher net input microwave power increased the thermal velocities of neutrals and excitation temperature, which also could result in the decrease of the number densities of the ground state.

4. Conclusion

In this study, TALIF spectroscopy was applied to the nozzle of a microwave cathode. The following conclusions were reached in this work.

1. The relationship between the fluorescence intensity and the neutral ground-state xenon density was experimentally investigated. The intensity increased linearly with respect to the number density.

2. In the measurement of the microwave cathode, densities on the order of $10^{19}$ m$^{-3}$ were successfully measured at mass flow rates of 0.029 and 0.098 mg/s.

3. The measurement error ranged from ±4% to ±20%; this error is due to noise associated with plasma fluorescence.

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