Development of 2D Laser-Induced Fluorescence (LIF) System in High-Density Helicon Plasma*)

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Lifetimes of most electric propulsion devices are limited owing to electrode erosion and contamination by plasmas. To overcome this problem, a Helicon Electrodeless Advanced Thruster (HEAT) was proposed by our research team. This scheme employs a high-density ($\sim 10^{13}\,\mathrm{cm}^{-3}$) helicon plasma accelerated by the Lorentz force, which is produced by various acceleration methods. For feasibility of this method, a Laser-Induced Fluorescence (LIF) system was developed. The LIF is a powerful tool for plasma diagnostics because it is a non-invasive method that allows high spatial resolution. Using the LIF, it is possible to deduce velocity distribution functions of different particles (ions, atoms, and molecules). In this paper, we report the details of our novel 2D LIF system as well as some preliminary experimental results. Argon ion velocity distributions at different axial and radial locations were obtained using the novel 2D system. Ion velocity was greatest (~ 2.8 km/s) at $z = -24$ cm among all the points measured along the z-axis. Velocity values were approximately 2.7 and 3.2 km/s for radial positions of $r = 0$ and 3 cm, respectively. Ion temperature values were approximately 0.56 and 0.61 eV at $r = 0$ and 3 cm, respectively.

Keywords: helicon plasma, electrodeless, high-density, laser induced fluorescence, two dimensional measurements

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1. Introduction

Plasma technology is used in diverse applications, including the manufacture of industrial materials, medicine, and space propulsion systems. Regarding space propulsion, electric propulsion systems (plasma thrusters) are suitable for prolonged space missions because of their high specific impulse (exhaust plasma velocity by gravity). For example, the asteroid explorer "Hayabusa," which used four ion engines, succeeded in a prolonged space mission. However, lifetimes of most contemporary systems are limited owing to electrode erosions and contamination by plasmas. To overcome these problems, we proposed a novel high-efficiency electrode-free electric propulsion system with a long lifetime, referred to as the Helicon Electrodeless Advanced Thruster (HEAT) [1]. This scheme employs a high-density ($\sim 10^{13}\,\mathrm{cm}^{-3}$) helicon plasma [2] accelerated by the Lorentz force, which is the product of the azimuthal current j_θ induced in the plasma and the radial magnetic field B_r.

To prove the feasibility of this device, it is important to measure the plasma parameters. Laser-Induced Fluorescence (LIF) is a powerful tool for plasma diagnostics because it is a non-invasive method with high spatial resolution. LIF was first introduced more than 35 years ago for measurement of the Ion Velocity Distribution Function (IVDF) in argon plasma [3]. Following this initial application, many studies have utilized the LIF technique. Boivin et al. measured Ar and He plasmas using a tunable diode laser [4], which has many advantages compared to a dye laser, such as good stability, lower cost, non-toxicity, easier maintenance, and considerably smaller size. Keesee et al. investigated density profiles of argon's neutral particles using the LIF method [5].

In this paper, we report IVDF (argon) of measurements at different axis and radial locations obtained using a recently developed 2D LIF system with a tunable diode laser in a Large Mirror Device (LMD) [6]. Using these measurements, we demonstrate the possibility of acceleration by the magnetic field gradient.

2. Theory

If laser wavelength has an absorption line in the plasma, particles (ions, atoms, and molecules) absorb photons. Then, these particles exhibit a downward transition and emit photons. Figure 1 shows a three-state LIF scheme for an argon ion and its corresponding neutral particle. In Ar II (argon ion), the $3\mathrm{d}^4\mathrm{F}_{7/2}$ metastable state is optically pumped using a 668.16 nm (in vacuum) laser light to the $4\mathrm{p}^4\mathrm{D}_{5/2}$ state, which decays to the $4\,\mathrm{s}^4\mathrm{P}_{3/2}$ state as a pho-

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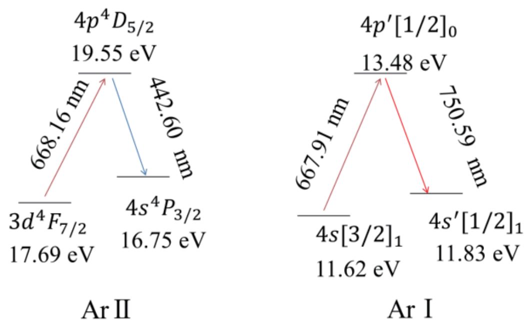

Fig. 1 LIF three-level scheme for Ar II (argon ion) and Ar I (argon neutral particle).

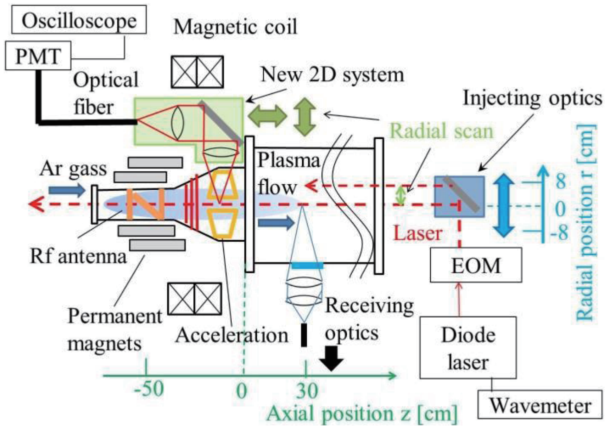

Fig. 2 LIF system on the LMD.

ton is emitted at 442.60 nm. In Ar I (argon neutral particle), the $4s[3/2]_1$ metastable state is optically pumped using a 667.91 nm laser light to the $4p'[1/2]_0$ state, which decays to the $4s'[1/2]_1$ state as a photon is emitted at 750.59 nm [5, 7].

Ion velocity and ion temperature are obtained from the Doppler shift and Full Width at Half Maximum (FWHM) of the IVDF, respectively, as shown in Eqs. (1) and (2):

$$c\Delta\nu/\nu_0 = v. \tag{1}$$

$$T_i = \left(\frac{\Delta\nu_{\mathrm{FWHM}}}{2\sqrt{ln4}\nu_0}\right)^2 \frac{m_i c^2}{k}. \tag{2}$$

Here, ν_0 is the resonant frequency, $\Delta\nu$ is the frequency shift due to the Doppler effect, v is the ion velocity, c is the speed of light, m_i is the ion's mass, k is the Boltzmann constant, and T_i is the ion's temperature. The velocity and temperature of the corresponding neutral particles can be obtained from these equations by replacing the relevant variable values with those of neutrals.

3. Experimental Setup

In this section, we demonstrate our LIF system by using the LMD, as shown in Fig. 2. A vacuum vessel in the LMD comprised a tapered quartz tube (inner diameter i.d. of 10 ~ 17 cm with an axial length L of 100 cm) in a discharge region and a main SUS chamber (i.d. of 44.5 cm and L of 170 cm) in a diffusion region. The LMD had two turbo-molecular pumps (1000 l/s and 2400 l/s) with a base pressure of a few 10^{-4} Pa. Argon gas was used as a propellant, and typical discharge pressure was approximately 0.2 Pa in the source region. A half-helical antenna for plasma generation was fed by a radio frequency (rf) power supply. The power and excitation frequency of the power supply were approximately 3 kW and 7 MHz, respectively. An external magnetic field was generated using electromagnets. Our proposed acceleration methods require a strong radial magnetic field B_r to achieve high plasma thrust due to the Lorentz force; thus, permanent magnets were also installed. Neodymium magnets (NeoMag Co. N35) were used as permanent magnets. The maximal magnetic field intensities generated by these permanent magnets were as follows: the axial magnetic field B_z was 909 G and B_r was 149 G [8]. Acceleration antennas were placed on a tapered quartz tube at a position where strong B_r was present.

The tunable diode laser used in these experiments was TA100 (TOPTICA Co.), and it had an oscillator and an amplifier. The laser frequency width and tuning range were 1 MHz and approximately 663.5 ~ 669.3 nm, respectively. The maximal output power was approximately 500 mW, and the laser was usually operated at approximately 300 mW. An injected real-time laser frequency was monitored using a Wavemeter WS7 (High Finesse / Angstrom Co.) whose wavelength accuracy was ± 0.1 GHz, corresponding to a velocity error of ± 66 m/s. In this experiment, the injected laser diameter was 2 mm, and the axial length of the observed area was 5 mm. Thus, the observed volume was approximately 16 mm^3. In order to separate LIF signals from background noise (electric noise and background light from plasma), laser light was electrically chopped using an Electro-Optic Modulator (EOM) (QIOPTIQ Co., LM2020P). Fluorescent emission was collected using a focus lens (SIGMA KOKI Co., Ltd. SLB-50-150P) that had focal length of approximately 150 mm and spot diameter of approximately 3 μm. Using optical fiber cables (Prolinx Co., custom-made article), the fluorescent signal was passed through a 4 nm bandwidth interference filter with wavelength centered at 443 nm (Asahi Spectra Co., Ltd., custom-made article) and ultimately to a high-gain photomultiplier tube (PMT) (HAMAMATSU PHOTONICS K.K., H7422-40). For measurement of neutral particles, a 1 nm bandwidth interference filter with wavelength centered at 750.5 nm was used. We employed the Fast Fourier Transform (FFT) method to obtain LIF signals modulated with laser-chopped frequency (< 500 kHz) by the EOM. LIF signals were monitored using an oscilloscope (LeCroy Co., 104MXs-A).

In order to extend the measurement area, we developed a novel 2D LIF system, as shown in Fig. 3. The sys-

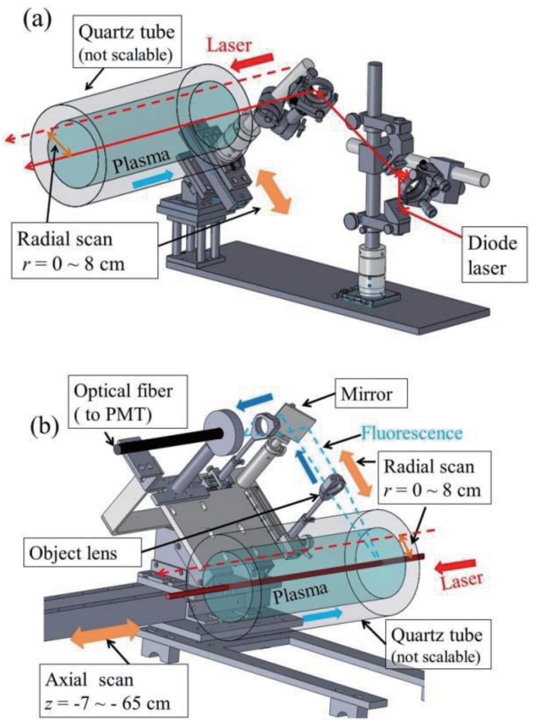

Fig. 3 (a) Laser injecting optics. A rack and pinion stage under the left side mirror moves for a radial scan r of approximately $0 \sim 8$ cm. The relative orientation of laser light and plasma is shown in the upper left side of this figure. (b) Fluorescence receiving optics. For a radial scan r of approximately $0 \sim 8$ cm, an object lens with small rack and pinion stage moves. The optical stage moves for axial z scans with z ranging from -7 cm to -65 cm.

tem consisted of laser injecting optics, shown in Fig. 3 (a), and fluorescence receiving optics, shown in Fig. 3 (b). In our previous LIF system, the measurement area was limited to $z = 30$ cm and $r = 0$ cm. Our novel 2D LIF system has an observation region given by $z \approx -7 \sim -65$ cm and $r \approx 0 \sim 8$ cm. The novel system is compact and has neither magnetized materials nor interference with other measurements.

4. Experimental Results

Figure 4 shows a typical example of the measured IVDF at $z = -62$ cm and $r = 0$ cm. Pulsed discharge plasma was operated at 3,000 W and 4.6 mTorr for rf power P_{rf}, and argon neutral pressure P_{Ar}, respectively. The maximal magnetic field generated by the permanent magnets along the z-axis was approximately 600 G near the rf antenna. The duration of each plasma pulse was 75 ms, and data was collected in the interval of $40 \sim 50$ ms owing to some instability during the initial discharge phase. Each measurement was averaged over 16 successive plasma pulses. The derived values of plasma velocity and plasma temperature [obtained using Eqs. (1) and (2)] were approximately -0.1 km/s and 0.07 eV, respectively.

Next, we demonstrate IVDF results for different radial positions, as shown in Fig. 5. At radial positions of $r = 0$ and 3 cm, ion velocity values were approximately 2.7 and 3.2 km/s, respectively, and its temperature values were approximately 0.56 and 0.61 eV, respectively. Ion velocity in the edge area seemed to be faster than that at the center of plasma; this should be verified as more data is collected.

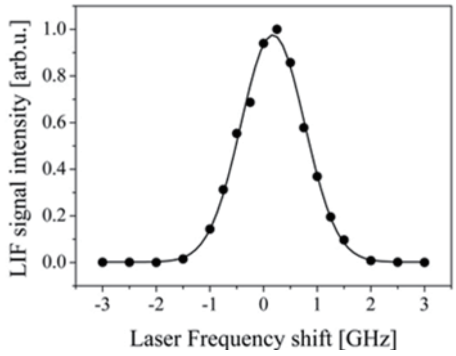

Fig. 4 A typical Ar II LIF signal plotted vs laser frequency shift. Closed circles denote measured values, and solid curve is a Gaussian distribution fit ($z = -62$ cm, $r = 0$ cm, P_{rf} = 3,000 W, P_{Ar} = 4.6 mTorr, and axial magnetic field B_z = -90 G).

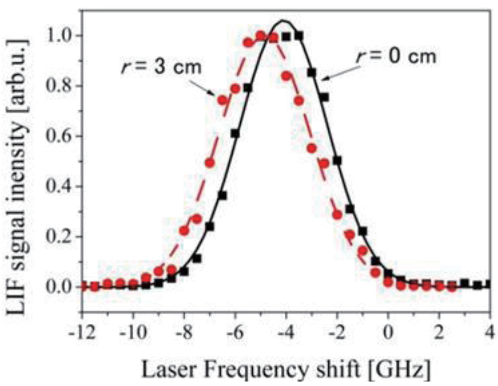

Fig. 5 Radial variation of IVDF. Closed squares and circles are measurements results at $r = 0$ cm and 3 cm, respectively ($z = -24$ cm, P_{rf} = 3,000 W, P_{Ar} = 4.6 mTorr, andB_z = 216 G).

Figure 6 shows the axial distribution of ion velocities, along with the magnetic field profile. Among the measured points along the z-axis, the ion velocity is greatest (~ 2.8 km/s) at $z = -24$ cm. This is attributed to the $-\mu\nabla B$ force generated by the permanent magnets' fields, where μ is the magnetic moment: an acceleration effect due to a strong negative magnetic field gradient can be observed for $z \sim -30$ cm. The same tendency was observed using the L-shaped Mach probe. There was a slight difference between velocity values shown in Fig. 5 ($r = 0$ cm) and those shown in Fig. 6, which may be attributed to the reproducibility of discharge plasmas.

Velocity and temperature measurements of argon's neutral particles are currently in progress.

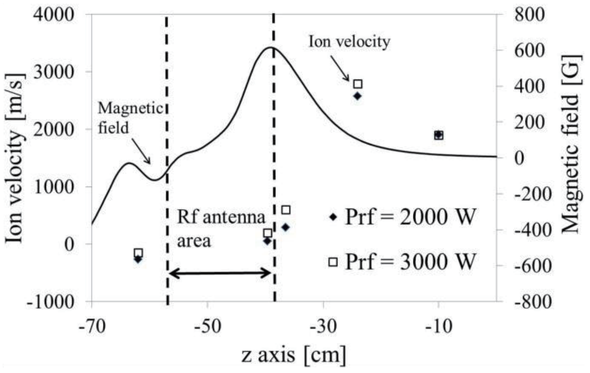

Fig. 6 Axial distribution of ion velocities with $P_{\mathrm{rf}} = 2000$ W and 3000 W, $P_{\mathrm{Ar}} = 4.6$ mTorr, and $r = 0$ cm. Solid line denotes the magnetic field, calculated in the presence of permanent magnets near the rf anntena area.

In these experiments, Ar gas was used as a propellant because it is easily-obtainable and can be easily ionized. However, results do not come close to our preset goal (∼ a few tens of km/s). To demonstrate high-density plasma production by acceleration methods, a different propellant may be required. In general, exhaust plasma velocity is inversely proportional to the square root of the particle's mass with other parameters fixed [9]. Gaseous helium is lighter than Ar by a factor of 10. Therefore, the velocities of He ions and neutral particles are expected to be faster than those of Ar ions and neutral particles. Velocity and temperature measurements for He ions are currently underway. To perform measurements for neutral He particles, the present laser must be tuned to 667.82 nm to pump from the 2^1P state to the 3^1D upper level. A fraction of the excited electrons then undergo collisional excitation transfer from the 3^1D to the 3^1P state. After that the 3^1P state must decay to 2^1S by photon emission at 501.57 nm [4].

5. Conclusions

In this study, we developed a 2D LIF system for plasma propulsion using helicon high-density plasma. LIF is suitable for plasma measurements because it is a non-invasive method with high spatial resolution for detecting a variety of particles (ions, atoms, and molecules). We obtained the IVDF for argon in different axial and radial locations using our novel 2D LIF system. At radial positions of $r = 0$ and 3 cm, velocity values were approximately 2.7 and 3.2 km/s, respectively, and temperature values were approximately 0.56 and 0.61 eV, respectively. The obtained velocity may be explained by the acceleration due to the action of $-\mu\nabla B$ force near $z = -24$ cm, which is consistent with the results obtained using an L-shaped Mach probe.

Ion and neutral particle velocity profile measurements are needed to further validate the applicability of our acceleration methods. In the future, we will attempt to obtain more detailed 2D profiles of Ar I, Ar II, and He I lines. The obtained results should be compared using electrostatic probes, non-invasive optical instruments (a high-speed camera and a high-resolution monochromator), and a thrust stand [10].

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