Spatial Profile of Ion Velocity Distribution Function in Helicon High-Density Plasma by Laser Induced Fluorescence Method

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Abstract: **A completely electrodeless electric thruster, which is expected to have a high efficiency and a long lifetime, is effective for a deep space exploration. In order to demonstrate and optimize this thruster system, it is important to have detailed distributions of plasma flow. Laser induced fluorescence (LIF) diagnostics has advantages from a view point of, e.g., high resolution in time and space, and it can determine an absolute particle velocity and its temperature in addition to its relative density. Here, we have been developing a LIF measurement system using Multi-Pixel Photon Counter (MPPC) for a multi-channel system. Ion velocity depending on the magnetic field gradient in a downstream region is measured by this LIF measurement system.**

Nomenclature

c	=	speed of light
$f(r, v)$	=	ion particle distribution function
F_i	=	thrust by ion
FR	=	flow rate
k	=	Boltzmann constant
N	=	the number of electrode magnets
n_e	=	electron density
n_i	=	ion density
m_i	=	ion mass
P_RF	=	RF input power
T_i	=	ion temperature
v	=	particle velocity
μ	=	magnetic moment
ν_0	=	resonant frequency
$\Delta\nu$	=	frequency shift by Doppler effect
$\Delta\nu_\mathrm{FWHM}$	=	full width at half maximum of ion velocity distribution function

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I. Introduction

ELECTRIC propulsion is effective for a deep space exploration. Most of plasma thrusters, for example, ion engine, Hall thruster, and MPD, have a limited lifetime because of electrodes' erosion and contamination. To explore the space much more, our group has been studying a new electrodeless electric propulsion system with a high efficiency and a long lifetime under the Helicon Electrodeless Advanced Thruster (HEAT) project[1].

Our propulsion system adopts a high-density helicon plasma[2] generated by a helicon wave. As the radio frequency (RF) wave is applied from outside of a discharge cylinder, a discharge antenna does not contact with plasma directly. For the higher thrust, the dense plasma is accelerated[1] by Lorentz force, which is produced by the induced azimuthal current j_θ with an electrodeless condition and the static radial magnetic field B_r.

To demonstrate and optimize this system, it is also important to measure various plasma parameters. Laser Induced Fluorescence (LIF) method[3] can estimate velocity distribution function of ions, atoms and molecules non-invasively with a high spatial resolution. It can also derive their temperatures, flow velocities and relative densities from the distribution functions[3]. In a previous research, we developed 2D LIF system to measure the plasma flow distributions[4]. This system had movable laser injection and fluorescence receiving optics for radial and axial scans.

To get spatial distributions of plasma flow conveniently, we have been developing a multi-channel LIF measurement device. This includes a fluorescence receiving array along the laser axis. With this aim, we have also adopted a Multi-Pixel Photon Counter (MPPC) instead of a photo multiplier tube (PMT), because the former is simple, easy, and inexpensive, and it is also as sensitive as the latter[5].

In this research, we will show a development of LIF measurement system using a MPPC as the initial stage for a multi-channel system. Additionally, argon ion velocity and the plasma thrust force in blue mode plasmas will be shown, depending on the magnetic field gradient in a downstream region by this LIF system. In addition, we have derived a thrust force from these results.

II. Principle of LIF measurement

A. LIF scheme

Our LIF system adopted a three-level scheme of ion particle[3], which is shown in Fig. 1. Ar II (argon ion) is optically pumped by 668.43 nm (668.63 nm in vacuum) Laser light from $3d^4F_{7/2}$ metastable state to $4p^4D_{5/2}$ excited state. Then the ion in excited state decays to the $4s^4P_{3/2}$ state by emitting photons at 442.60 (442.73 nm in vacuum).

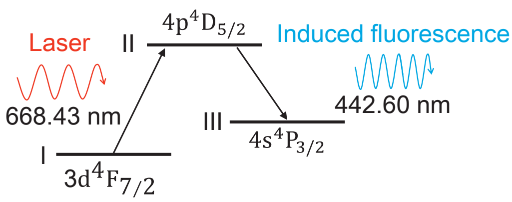

Figure 1. LIF scheme of Ar II.

When a target particle have a velocity along a pumping laser axis, the excitation wave length is changed by a Doppler shift. Here, flow velocity and ion temperature of the target particles can be calculated in the following Eqs. (1) and (2). Additionally, relative density can be obtained from the area of IVDF.

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

$$T_i = \left(\frac{\Delta\nu_{FWHM}}{2\sqrt{\ln 4}\nu_0}\right)^2 \frac{m_i c^2}{k}. \tag{2}$$

III. Experimental Devices

A. Large Mirror Device (LMD)

Table 1 shows specifications and operating conditions of Large Mirror Device (LMD)[6], and Fig. 2 shows the LIF measurement system on this device. LMD has a tapered quartz tube connected to a main chamber. This tube has a discharge part, and its length L is 100 cm with its inner diameter i.d. of 10-17 cm. The main SUS chamber (L = 170 cm and i.d.

Table 1. Specifications and operating conditions of LMD.

Axial length	1700 mm
Inner diameter of chamber	445 mm
Background pressure	~ 10^{-4} Pa
Propellant	Ar gas
Discharge pressure	~ 0.1Pa
RF input power	2.5~ 3.5kW
RF excitation frequency	7 MHz

is 44.5cm) is in a diffusion region, and the left edge of this chamber is defined as the axial position of $z = 0$ cm. Here, the chamber has three square optical windows, and their center positions are $z = 30$, 60 and 90 cm. LMD has two turbo-molecular pumps, and their pumping speeds are 1,000 and 2,400 *l/s*, leading to a base presence of ~ 10^{-4} Pa.

A half-helical antenna is used to generate the plasma with radio frequency (RF) input power R_{RF} of 2.5 ~ 3.5 kW. Two kinds of magnets are used for generating the various magnetic field configurations on LMD. The electromagnets (EMs) can produce external magnetic field B of 0-600 G flexibly and easily. Additionally, the permanent magnets (PMs) are also installed around the tapered quartz tube position where the strong B_r is obtained[7].

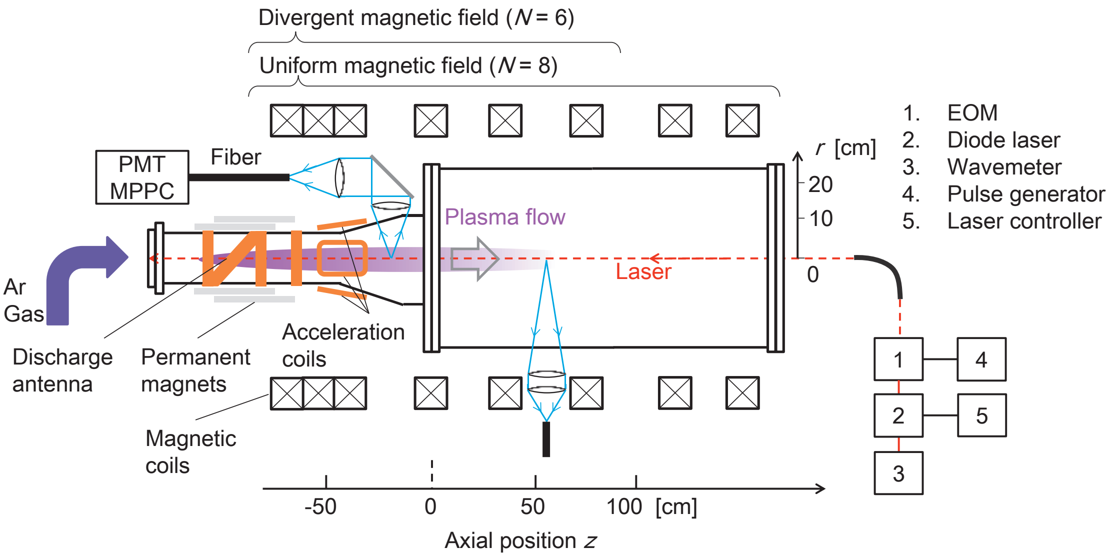

Figure 2. LMD and LIF measurement system.

In order to see the acceleration effect in a downstream region by a grad B force, as shown in Eq. (3), LIF measurement has been carried out with a uniform field and a divergent magnetic field configurations.

$$F_z = -\mu \frac{\partial B_z}{\partial z}. \tag{3}$$

Figure 3. shows an axial profile of magnetic field strength, calculated by a FEMM[8] code. In the positive z region, the uniform magnetic field is generated by 8 magnets and the divergent one by 6 magnets. The blue mode plasma can be obtained by each magnetic field. Here, all the coil current of these experiments was 350A, with the coil voltage of 69 (53) V for $N = 8$ (6).

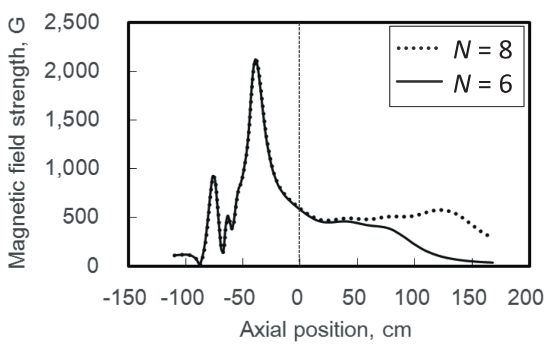

Figure 3. Magnetic field strength for $N = 8$ and 6.

B. **LIF measurement system**

In a typical LIF measurement, a laser with a narrow bandwidth of frequency is necessary. The LIF system on LMD is shown in Fig. 2. The tunable diode laser used in these experiments is TA100 (TOPTICA Co.), which includes an oscillator and an amplifier. The laser wavelength width and its tuning range are 1 MHz and 663.5 ~ 669.3 nm, respectively. The maximum output power is ~ 500 mW, and usually, it is operated at ~ 300 mW level. An injected real time laser frequency was monitored by the wavemeter WS7 (High Finesse / Angstrom Co.), whose wavelength accuracy is ± 0.1 GHz, corresponding to the velocity error of ± 66 m/s. In this experiment, an injected laser diameter via single-mode fiber is 5 mm. Signal receiving lenses of diameters are 100 mm with the focal lengths of 150 and 300 mm, and the diameter of an image at focal point with these lens is 3 mm. In order to separate a LIF signal from background noises including electric noise and background light of plasma, the laser light is electrically chopped by an Electro-Optic Modulator (EOM) LM0202 (LINOS PHOTONICS). The fluorescent emission is collected by a focus lens and optical fiber cables, and then it passes through a 4 nm bandwidth interference filter with a central wavelength at 443 nm to reach a high-gain sensitive optical device MPPC instead of PMT. The voltage signal passes through a high gain and highly sensitive detector circuit, and then goes to an oscilloscope. The Fast Fourier Transform (FFT) method is used to obtain the LIF signals modulated with a laser chopped frequency (455 kHz) by the EOM.

In order to investigate plasma behavior in detail at the same time, a plan of multi-channel measurement system, as shown in Fig. 4, is under development. In a laser injection system, a single-mode optical fiber is adopted because flexible laser injection can measure a radial velocity distribution easily. In a signal receiving system, MPPC is adopted as a photodetector because MPPC is easy to use, inexpensive and as supersensitive as PMT. On the occasion of this modification, above mentioned detector circuit (including effective lock-in amplifier circuit) amplifies the signal to derive Ion Velocity Distribution Functions (IVDF) with multi-channelization.

For realizing this concept, a single channel LIF signal receiving device with MPPC and this laser measurement system using a single-mode optical fiber has been developed. The measuring region of a channel 2D LIF system is z = -7 ~ -65 cm and r = 0 ~ 8 cm in a plasma source. In the SUS chamber, positions of z = 30, 60 and 90 cm can be used for measurements. As shown in a graph inserted in Fig. 4, the measuremental results using the previous system with PMT and the new system with MPPC show a good agreement. This was done under the condition that z = -20 cm, r = 0 cm, P_{RF} = 2.5 kW, and gas flow rate FR = 50 sccm.

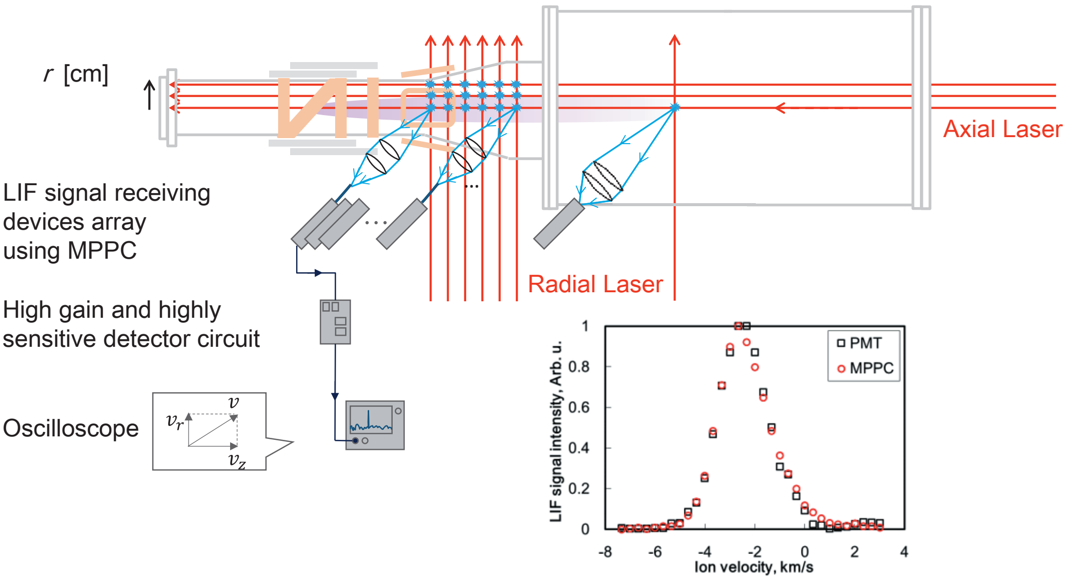

Figure 4. A proposed plan of LIF multi-channel system.

IV. Experimental results

C. Ion Velocity Distribution Function (IVDF)

Figures 5 and 6 show the measured IVDF at z = 30 and 60 cm with Gaussian distribution fitting curves, respectively. A pulsed discharge plasma was operated with two kinds of magnetic field configurations, mentioned before. In this analysis, the signal intensity is normalized that the maximum value becomes one. In a pulsed plasma of 75 ms, we took the data in a period of 40 – 50 ms due to some instabilities in the initial phase. Each measurement was averaged over successive 4 plasma pulses, and from Eqs. (1) and (2), these plasma velocities and their temperatures were derived.

Here, argon ion velocity v_i was 0.17 km/s at z = 30 cm, 0.067 km/s at z = 60 cm under the uniform magnetic field, which showed no acceleration effect. Under the divergent magnetic field, v_i was 0.095 km/s at z = 30 cm, 0.46

km/s at z = 60 cm, 0.67 km/s at z = 90 cm. From this, acceleration effects of $-\mu\nabla B$ could be confirmed. Note that not only the effect of $-\mu\nabla B$ but also that of ∇p must be considered. Here, argon ion temperature T_i was 0.16 eV at z = 30 cm and 60 cm under the uniform magnet field, while it was 0.15 eV at z = 30 cm, 0.11 eV at z = 60 cm and 0.072 eV at z = 90 cm under the divergent magnetic field. From this, T_i was not changed under the uniform magnetic field and it decreased under z in the divergent magnetic field.

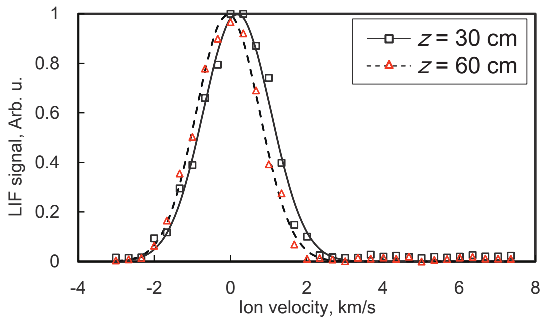

Figure 5. Ion velocity distribution functions at z = 30 and 60 cm with N = 8. *[P_{RF}: 3.0 kW, Gas flow rate: 90 sccm]*

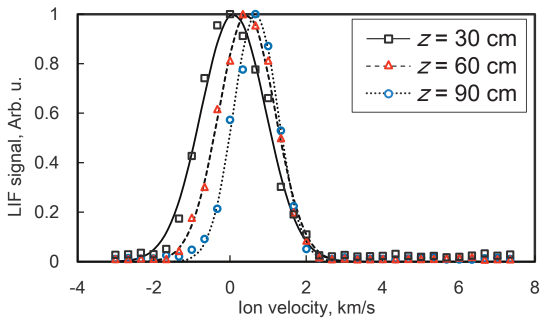

Figure 6. IVDF at z = 30, 60 and 90 cm with N = 6. *[P_{RF}: 3.0 kW, Gas flow rate: 90 sccm].*

D. Calculation of thrust

In order to calculate the thrust, we also need the radial electron density distribution, as shown in Fig. 6. Here, this distribution was obtained by an electrostatic probe. Because the blue mode plasmas were not obtained at P_{RF} 3.0 kW, RF power was increased to 3.5 kW.

The plasma thrust is derived as follows with this particle density.

$$F_{\mathrm{i}} = \int m_{\mathrm{i}} f(r,v) v_i^2 \, dvdr. \qquad (5)$$

$$\int f(r,v)\, dv = n_{\mathrm{e}}(r)$$

Here, $f(r,v)$ is an ion particle distribution function in (r,v) space, where under the divergent magnetic field, F_i is 3.3 mN at z = 30 cm, 4.3 mN at z = 60 cm, and 3.1 mN at z = 90 cm. Here, a constant value of v_{i} was assumed in the same z position, and n_{e} was from this probe measurement.

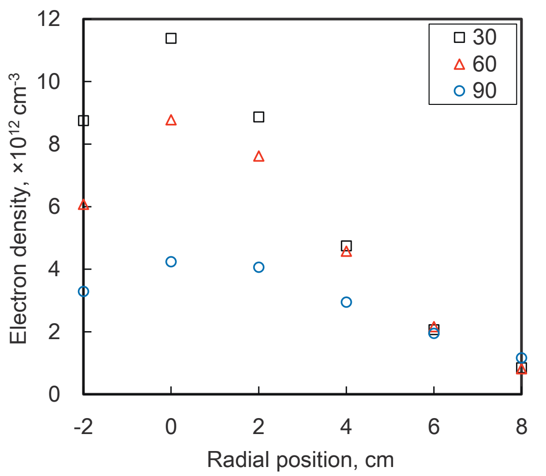

Figure 6. Measured electron density by an electrostatic probe in blue mode plasma. *[P_{RF}: 3.0kW at z=60, and 90, 3.5 kW at z=30, Gas flow rate : 90 sccm]*

These values are not contradictory to the previous results[8]. However, we need to consider the followings: 1) the effect of the thrust stand on the plasma performance, 2) the effect of neutral flow, and 3) the measurements from the center to the edge of plasma. We have plan to measure the various parameters in the presence of the thrust stand.

V. Conclusion

In order to estimate the electromagnetic acceleration method in an electrodeless propulsion system, we have been developing the multi-channel LIF system. A single channel LIF measurement system has been established which includes a flexible laser injection system by optical fibers and a highly sensitive signal receiving device with MPPC. We have carried out ion flow measurement by the LIF system using two magnetic field configurations, and an acceleration by $-\mu\nabla B$ term was confirmed in the downstream region under the divergent field: ion flow velocity (ion temperature) was increased (decreased) with z. The plasma thrust was also estimated by the LIF system and the Langmuir probe which was consistent with the direct thrust measurement. We are going to estimate various parameters using the multi-channel system developed with additional diagnostics of Langmuir probe, spectroscopy and a high-speed camera.

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