Self-calibration Laser Induced Fluorescence technic in Electric Propulsion plasma diagnosing

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Abstract: The double-layer acceleration mechanism of divergent magnetic field provides a new idea for small and medium power electric propulsion. In order to evaluate the acceleration performance of ions in helical wave plasma, this paper attempts to measure the ion velocity distribution function near the outlet of helical wave plasma source by laser-induced fluorescence technique, which provides a feasibility test for the concept of compact helical wave plasma thruster. In the process of LIF measurement, a new self-calibration technique is adopted to calibrate the absolute velocity reference point, which reduces the complexity of the measurement system and improves the accuracy of measurement. The results show that the ion velocity in the compact helical wave plasma thruster without additional acceleration device is lower than that of the double layer acceleration target.

Nomenclature

n	=	ion number density
υ_z	=	axial ion motion velocity
k_b	=	Boltzmann coefficient
m	=	particle mass
v_0	=	peak absorption frequency when the motion speed is 0
c	=	velocity of light
$h(v)$	=	hyperfine structure broadening
$l(v)$	=	natural broadening
$s_a(v)$	=	saturation effect broadening
$L(v)$	=	collision broadening
$s_t(v)$	=	Stark effect broadening
$z(v)$	=	inverse Zeeman effect broadening
$u(v)$	=	instrumental broadening

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I.Introduction

The double-layer acceleration mechanism of divergent magnetic field or current-free double-layer acceleration provides a way to apply helical wave discharge plasma to small and medium power electric propulsion[1-3]. The plasma potential suddenly decreases in the magnetic field of the expanding configuration. The intense local electric field can accelerate the ion greatly, thus realizing the compact design of plasma ionization-acceleration in spiral wave discharge. Since the discovery of double-layer phenomenon, compact helical wave plasma thruster has rapidly become a research hotspot in the field of electric propulsion because of its high ionization-acceleration efficiency, electrodeless corrosion and the minimal structure concept of "plasma source is thruster".

Laser-induced fluorescence (LIF), as a non-invasive, highly sensitive and highly selective diagnostic measurement method, has been widely studied and applied. In 2000, Williams[4] systematically measured the radial and axial velocities of the plume and the ion temperature of the thruster using a two-beam injection laser incidence scheme. Smith applied Fourier deconvolution technology in 2003 to develop a more adaptable LIF velocity measurement method without presupposition of particle velocity distribution. It is believed that the actual measurement of LIF optical spectrum signal is a comprehensive result of element hyperfine structure, natural broadening, Doppler effect and energy saturation effect lines convolution plus noise. The filtering algorithm separates the Doppler effect in LIF spectrum, and then obtains the velocity of the target particle.

In the process of LIF measurement, the reference point of absolute velocity needs to be carefully calibrated. Usually this process is realized by a perspective hollow cathode lamp. Because the static plasma source is stable and repeatable, it can be considered that the average velocity of a large number of particles is zero, which constitutes the basis of traditional calibration methods. However, the calibration method of perspective hollow cathode lamp has many shortcomings. Firstly, besides the complex LIF measurement system, a special calibration equipment is needed, which will reduce the reliability of the system; secondly, it is difficult to achieve complete consistency between the calibration source and the object under test. There are always errors and the accuracy is not high. Usually, when the pressure or density of plasma is not the same, the wavelength offset of the specific spectral line caused by Stark effect will be different, which will directly cause the error of velocity measurement, and this error can not be ignored when the gap between the measured source and the calibration source is large. In order to solve the drawbacks, a new self-calibration LIF measurement technology is adopted to realize online calibration.

II.Self-calibration Laser Induced Fluorescence

According to the basic principle of LIF for particle velocity measurement, an experimental scheme of self-calibration laser-induced fluorescence measurement is presented. The ion acceleration effect of compact helical wave discharge plasma thruster is measured and analyzed.

A. Basic Principles of LIF Diagnosis

the stimulated radiation process of laser interaction with moving particles is shown in Fig. 1. A particle system in thermodynamic equilibrium has a large number of particles in collision equilibrium. The number of particles in unit volume （υ_z，$\upsilon_z+d\upsilon_z$）conforms to Maxwell distribution.

$$n(\upsilon_z)d\upsilon_z = n\left(\frac{m}{2\pi k_b T}\right)^{1/2} \exp\left(\frac{-m\upsilon_z^2}{2k_b T}\right)d\upsilon_z \tag{1}$$

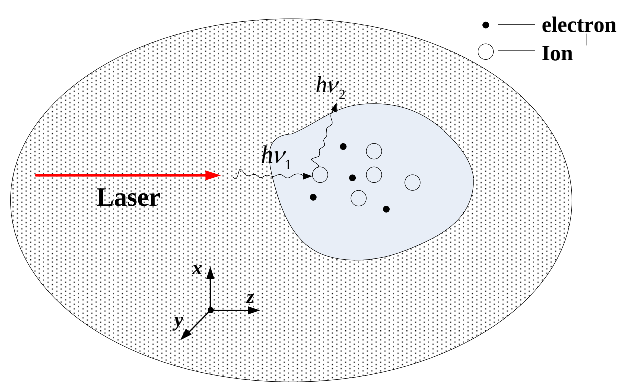

Figure 1. Schematic Chart of Stimulated Radiation of Laser Interaction with Moving Particles.

The center frequency of ion absorption laser is ν_0，and the velocity in zdirection is υ_z。Laser with frequency ν propagates along z direction and interacts with particles. When the particle is stationary（υ_z=0），the laser frequency it feels is ν，and it reaches resonance absorption when $\nu = \nu_0$, which also achieves the maximum stimulated transition probability. When the particle moves along the direction with υ_z，the laser frequency it feels is ν'

$$\nu' = \nu\sqrt{\frac{1-\upsilon_z/c}{1+\upsilon_z/c}} \tag{2}$$

In the condition of $\upsilon_z/c \ll 1$, the upper formula (2) could be expressed in Taylor's first order approximation.：

$$\nu' = \nu(1 - \upsilon_z / c) \tag{3}$$

When ν'=equals ν_0, which indicating the resonance absorption is achieved，the distribution of particles in the frequency domain can be expressed as

$$n(\nu)d\nu = n g_D(\nu_0, \nu)d\nu \tag{4}$$

and

$$g_D(\nu_0, \nu) = \frac{c}{\nu_0}\left(\frac{m}{2\pi k_b T}\right)^{1/2} \exp\left[-\frac{mc^2}{2k_b T}\left(\frac{\nu - \nu_0}{\nu_0}\right)^2\right] \tag{5}$$

In addition to the Doppler effect of the absorption spectra mentioned above, the spectral signal $i(v)$ measured by the actual instrument also contains the superposition effect of many other effects, including element hyperfine structure $h(v)$, natural broadening $l(v)$, saturation effect $s_a(v)$, collision broadening $L(v)$、Stark effect $s_t(v)$、Inverse Zeeman effect $z(v)$, instrumental broadening $u(v)$, etc. Assuming that the spectral measurement system of the above effects is linear and time-invariant, the measurement spectrum formed by the superposition of various mechanisms can be expressed by convolution as following.

$$i(v) = h(v) \otimes l(v) \otimes s_a(v) \otimes d(v) \otimes L(v) \otimes s_t(v) \otimes z(v) \otimes u(v) \tag{6}$$

Although the broadening mechanism of laser-induced fluorescence spectrum is very complex, the influence of various factors on the final spectrum is not the same in the scope of this study, so we can eliminate some of the less important mechanisms by contrast. Taking the following typical Ar plasma parameters as an example: n_e=10^{19}m^{-3}, p=10mTorr, T_i=0.1eV, B=500G, λ_0=610nm ， The typical spectral broadening of each mechanism is summarized in Table 1.。

Table 1. Broadening mechanisms and spectral line broadening.

Broadening mechanisms	Linewidth value (nm)
Doppler effect $\Delta\lambda_n$	2.4×10^{-3}
Collision broadening $\Delta\lambda_L$	9.7×10^{-8}
Stark effect $\Delta\lambda_{st}$	$\sim1.2\times10^{-6}$
Inverse Zeeman effect$\Delta\lambda_z$	2.1×10^{-3}
Hyperfine structure $\Delta\lambda_h$	3.4×10^{-3}
Natural broadening $\Delta\lambda_n$	2.4×10^{-5}
Saturation effect $\Delta\lambda_{sa}$	$[(1+S)^{0.5}-1]\Delta\lambda_n$
Instrumental broadening $\Delta\lambda_u$	1.3×10^{-6}

Collision broadening, Stark effect and instrument broadening effect are obviously lower than other mechanisms, which can be neglected in analysis. Natural broadening is relatively small, combining it with saturation effect . When laser saturation is high,the saturation effect broadening may be the main influence factor, thus it is retained in the spectral model. Based on the above considerations, formula (6) can be simplified to：

$$i(v) = h(v) \otimes l\_s(v) \otimes d(v) \otimes z(v) \tag{7}$$

$l\_s(v)$ represents the comprehensive effect of saturation effect and natural broadening. $l\_s(v)$, $z(v)$ and $h(v)$ are obtained by theoretical calculation. By combining the measured absorption spectrum $i(v)$，the Doppler absorption spectrum $d(v)$ can be obtained by the deconvolution filtering algorithm. The ion velocity distribution function can be obtained by considering the frequency shift with the static plasma Doppler spectrum.

B. Layout of experiments

The Layout of the experimental system is shown in Fig. 2. The tunable laser is pumped by Nd:YAG laser (532 nm) pump source. the linewidth of the tunable laser is less than 250 kHz (611.662 nm) and the power is about 550 mW. The energy reflected by the beam splitter is about 10% into the wavelength meter to monitor the laser frequency. The rest of the energy is modulated by the chopper and transmitted into the vacuum chamber by a group of mirrors. It is focused on the excitation point and reacts with the particles, so that the stimulated particles emit fluorescence (461.086 nm). The fluorescent signal is transmitted to the monochromator through the optical fiber coupling mirror group. After the grating splitting, the fluorescent signal is emitted in a slit of a certain width and enters the input of the photomultiplier tube(Hamamatsu, R928). After amplification, the amplifier detects the frequency signal of the chopper in a phase-sensitive manner (Stanford Research, SR830). The weak fluorescence signal was separated and recorded by the computer.

In order to diagnose the absolute value of velocity information, it is necessary to calibrate the frequency starting point of velocity. Traditional calibration using perspective hollow cathode lamp as reference plasma source reduces the reliability and accuracy of the system. A self-calibration LIF measurement technology is adopted in our work, as shown in Figure 3. After the excitation laser passes through the plasma area to be measured, it is reflected by a mirror and travels through the plasma area in the opposite direction along the original transmission path. Then the plasma at the excitation point is stimulated by the positive and negative two-way laser. The measured Doppler absorption spectrum shows a double peak phenomenon, as shown in Figure 4.

The analysis shows that the relative motion relationship between plasma and forward and backward bidirectional excitation laser transmission shows the characteristics of equal velocity and opposite direction. Therefore, compared with the static plasma spectrum, the frequency shift of the two peaks is equal in forward and backward direction. By calculating the arithmetic average of the frequency shift, the reference point with absolute velocity of 0 can be obtained. Thereafter, the single peak absorption spectrum distribution can be obtained by removing the reflector. According to the method of Part A, the IVDF can be obtained.

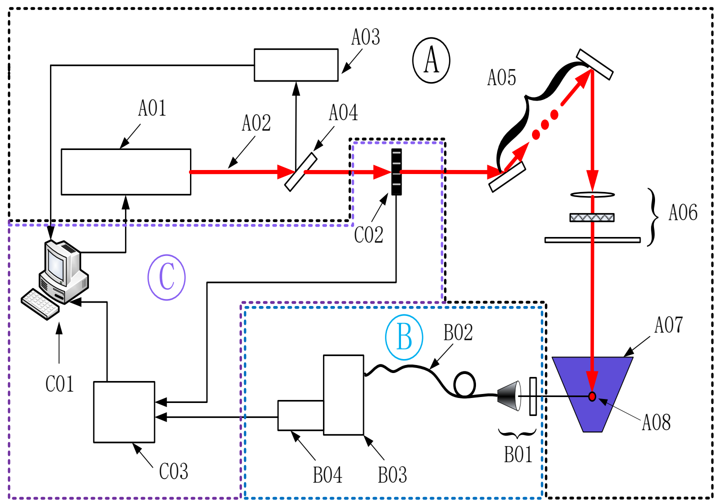

Figure 2. Layout of LIF measurement system for helical wave discharge plasma.

Part A: A01 tunable laser, A02 Laser Optical Path, A03 wavelength meter, A04 splitter, A05 group of mirrors, A06 Laser Injection Regulating Mirror Group (including Focusing lens, 1/4wave plate and Protection window), A07 plasma, A08 Measuring point;
Part B: B01 Fiber Coupled Mirror Group, B02 Multimode Optical Fiber, B03 monochromator, B04 photomultiplier tube;
Part C: C01computer, C02 chopper, C03 lock-in amplifier

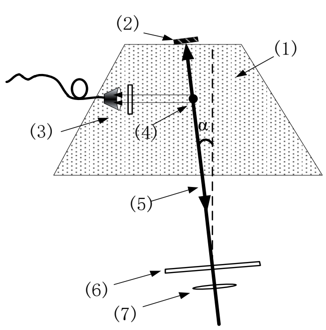

Figure 3. Self-calibration scheme of speed reference.

(1)plasma (2) two-dimensional regulating mirror (3) Fluorescence acquisition mirror group (4) Measuring point (5) Laser Optical Path (6) Protection window (7) Long focal lens

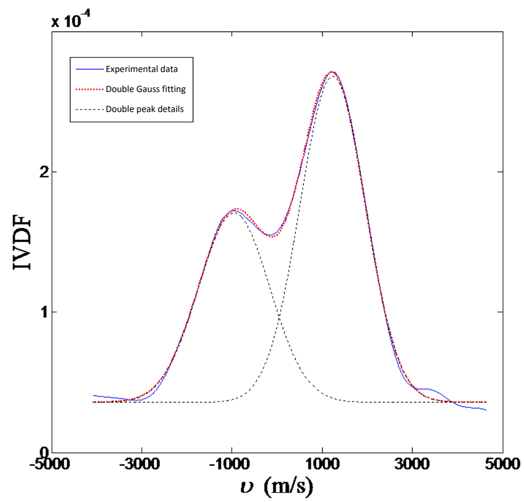

Figure 4. Self-calibration measurement results.

C. Analysis

LIF signals at different positions on the axis are measured. Fig. 5 shows IVDF under different magnetic field conditions at Z_s=-20mm and Z_s=80mm, respectively. It can be seen that the ionic distribution line becomes wider with the increase of magnetic field, and the overall distribution is more inclined to the high-speed region. When the measuring point is located in the near-field region near the discharge center (Z_s=-20, -5, 5, 40mm), The IVDF is symmetrically distributed along the central velocity; when the measuring point is located in the near-far field region far from the discharge center (Z_s=80, 100mm), the asymmetry begins to appear on both sides of IVDF, in which the low-speed part rises steeply, while the high-speed part falls slowly, and the IVDF moves toward the discharge center, sloping in low speed zone.

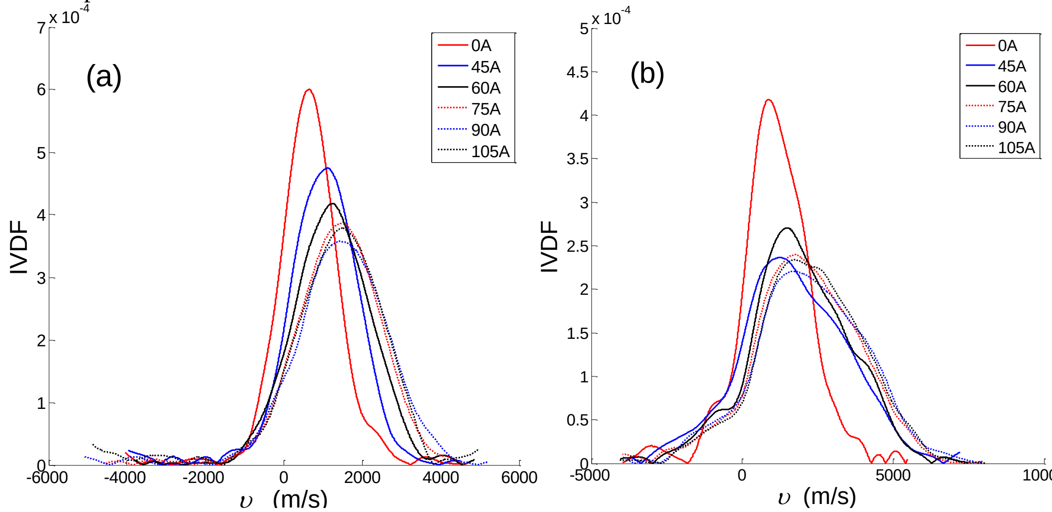

Figure 5. IVDF Self-calibration measurements under different magnetic fields (a) (Zs=-20mm)；(b) (Zs=80mm)

The average velocity of an ion is defined as：

$$\upsilon_a = \int_{\upsilon_1}^{\upsilon_2} f(\upsilon) \cdot \upsilon d\upsilon \tag{8}$$

Ions eject from the discharge chamber at a certain speed to form a reverse thrust. If the flux of working medium is constant, the velocity is proportional to the thrust, so the average velocity can be used to measure the relative thrust. Fig. 6 shows the relationship between the average ion velocity at different positions and the current of the electromagnetic coil, in which the gas flow rate is 25 SCCM. It can be seen that the average ion velocity increases with the increase of the magnetic field, but the increasing speed begins to slow down when the magnetic field is higher.

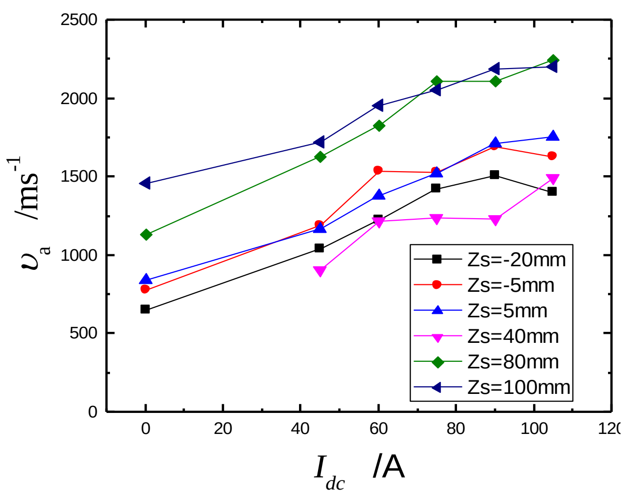

Figure 6. The relation of average ion velocity with Current.

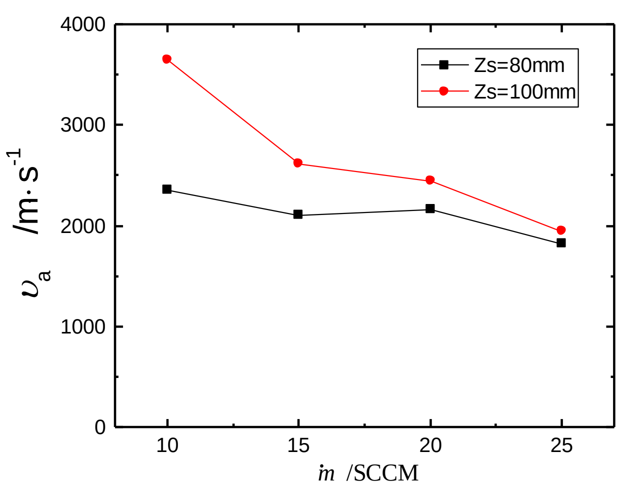

Figure 7. The relationship of average ion velocity with gas flow rate.

On the other hand, it can also be seen from Fig. 6 that the average ion velocity increases as the measuring point moves downstream of the discharge chamber, but the increment is only about 1000m/s. According to the experimental results in reference 2, Charles measured a sudden drop of plasma potential of about 25V in the range of mm downstream from the helical wave discharge plasma source. The electric field should accelerate Ar+ to over 1000m/s. The experimental results show that although the ion velocity increases downstream of the discharge chamber, its amplitude is much smaller than the expected acceleration value of the current-free double layer, so it may be only caused by the distributed electric field formed by the bipolar diffusion.

Current-free bilayers may form at lower gas pressures, usually around 0.04-2 mTorr. In order to study the effect of low pressure, IVDF with different gas flow rates at Z_s=80mm and 100mm was measured. When the gas flow rate is less than 10 SCCM, the discharge can not be maintained under too low gas pressure, so it is taken as the minimum gas flow rate in the measurement. Figure 7 shows the relationship between average ion velocity and gas flow rate. With the decrease of gas flow rate, the average ion velocity increases obviously, but it is still far below the expected acceleration value of current-free double layer. The relationship between average ion velocity and gas flow rate can also be explained from the viewpoint of bipolar diffusion acceleration: when the gas pressure drops, the probability of collision between electrons and neutral particles is smaller in the discharge equilibrium state, so the energy lost by collision decreases, and the final electron temperature T_e is at a higher level; if discharge is defined If the wall potential is 0, the central potential of Ar plasma is about 5.2Te under sheath regulation. That is to say, the plasma potential is higher under lower gas pressure, and it will form a larger potential gradient through bipolar diffusion, which will eventually make the ions reach a higher acceleration value.

III.Conclusion

In this paper, the LIF measurements of plume ion axial velocity of a helical wave discharge plasma source thruster show that IVDF located in the near field has good symmetry and its distribution is highly consistent with the Gauss distribution, while the IVDF located in the far field inclines to the low speed region. The average ion velocity increases with the increase of magnetic field, decreases with the increase of pressure, and generally increases with the measurement point moving downstream of the discharge chamber. However, the maximum average ion velocity measured is about 3700m/s, and the increment of velocity is much smaller than the expected acceleration value of the current-free double layer. The analysis shows that the acceleration of ions in helical wave discharge plasma is only caused by the electric field bipolar electric field formed by the bipolar diffusion under magnetic constraints.

Acknowledgments

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Periodicals

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