Significant acceleration of Xe II ions outside discharge channel in cylindrical Hall thruster plasmas

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Abstract: Velocity distributions of Xe II in cylindrical Hall thruster plasmas were measured and analyzed using laser-induced fluorescence diagnostics. The anode voltage and Xe flow rate were varied in the ranges of 200–400 V and 4–10 sccm, respectively, and significant ion acceleration was exhibited outside the discharge channel (up to 60 mm or further) regardless of the discharge condition. In addition, the velocity distribution is close to Gaussian near the thruster exit plane; however, the distribution shows a larger population of ions faster than the peak velocity with increasing distance from the exit plane.

Nomenclature

e	=	magnitude of the electron charge
f	=	focal length of the optical lens
r	=	radial distance from the thruster axis
V_a	=	anode voltage
W_{peak}	=	peak kinetic energy in the velocity (or energy) distribution
z	=	axial distance from the exit plane in the downstream direction of the thruster

I. Introduction

Cylindrial-type Hall thrusters (CHTs) have a retracted central part compared with the conventional annular-type Hall thrusters (AHTs), to obtain a large plasma volume-to-surface ratio, which can be advantageous, particularly for low power operation. A fundamental difference between CHTs and AHTs is their magnetic field structures. In an AHT, the magnetic field is arranged in such a way that the radial component is dominant; however, CHTs have both prominent radial and axial magnetic field components. Previous studies on CHTs have revealed many interesting physics-related phenomena that rarely occur in AHTs, including the presence of multiply-charged ions, ions having a higher kinetic energy than the anode voltage, and high-frequency oscillations.[1-8] It is well known that ion acceleration occurs predominantly near the end of the discharge channel or thruster exit in an AHT,[9] and information on the ion acceleration profile in a CHT will also be valuable for understanding the ion acceleration mechanism. In this study, the ion acceleration profile was measured and analyzed using our newly developed laser-induced fluorescence (LIF)

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diagnostics. Spatial profiles of both axial and radial velocity distributions of the $5d^2F_{7/2}$ state of Xe II were examined under various discharge conditions.

II. Experimental setup

A. Cylindrical Hall thruster

The outer channel diameter of the CHT used for study is 50 mm, and the other details can be found in Ref. 7. In this work, the anode voltage and anode flow rate were varied in the ranges of 200–400 V and 4–10 sccm, respectively. Experiments were conducted in a 3-m-long, 1.5-m-diameter vacuum chamber, and the operating pressure was 12 μTorr at a total Xe flow rate of 11 sccm.

B. Laser-induced fluorescence diagnostics

LIF is a diagnostic method that can non-intrusively measure the velocity distribution of a target atomic state, and it has been used to investigate Hall thruster plasmas.[4,9-15] In this study, the target transition of Xe II is from $5d^2F_{7/2}$ state to $6p^2D^0_{5/2}$ state (834.72 nm), and the resulting fluorescence is the transition to $6s^2P_{3/2}$ (541.9 nm). The overall LIF setup is illustrated in Fig. 1, where some optical components (a Faraday isolator right after the tunable laser, R:T = 5:5 beam splitter, the radial beam path, and a single-mode fiber connected to the wavelength-meter) are omitted from the diagram for the sake of simplicity. A tunable diode laser (Newport TLB 7115-01) is used as the excitation source for $5d^2F_{7/2}$ to $6p^2D^0_{7/2}$ Xe transition, and its wavelength is monitored using a wavelength-meter (Newport WM1210). Axially and radially injected laser beams are transformed to 500 Hz and 350 Hz trapezoidal beams, respectively, and are subsequently focused by *f* = 4 m plano-convex lenses where *f* is the focal length, so the average power density of the laser beam is 5 mW/mm^2. Two of the three corners of the probing volume of the beam are restricted by slits: 0.5 mm axially and 2.0 mm vertically (radial). The other lengths of the corner of the axial and radial beam are measured using a knife-edge method, and are determined to be 2.38 mm and 2.80 mm, respectively.[16] A pair of plano-convex lenses (*f* = 250 mm inside and *f* = 500 mm outside the vacuum chamber) collect and focus the induced fluorescence on the entrance slit of the monochromator (Chromex-500sm). A photomultiplier tube (Hamamatsu R7518P) is mounted next to the exit slit of the monochromator. The output signal is sent to the lock-in amplifier (Stanford Research Systems SR830), which has a 1-s time constant, 24-dB/oct roll-off, and a low noise reserve. Finally, the output signal of the lock-in amplifier is collected by a personal computer.

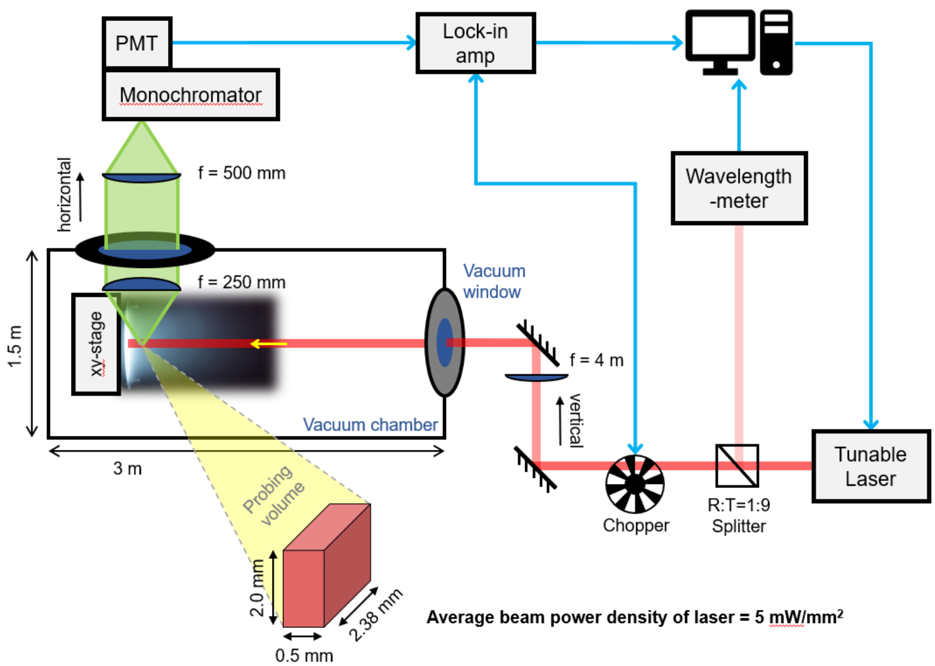

Figure 1. A schematic diagram of the laser-induced fluorescence diagnostic setup.

The excitation wavelength of an axially stationary Xe II ion at the $5d^2F_{7/2}$ state is estimated by the laser reflection method, and this is repeated 18 times. The obtained excitation wavelength is 834.7234 ± 0.00014 nm, where the error indicates a 99% confidence interval and corresponds to ±49 m/s. The detection range is z = 0–100 mm, where z is the coordinate along the thruster axis.

III. Results and Discussion

Figure 2 shows both the axial and radial velocity distributions at different locations along the thruster axis at an anode voltage of 300 V and flow rate of 7 sccm. As shown in Fig. 2(a), the peak axial ion velocities are 9.2, 12.2, 15.5, 17.3 km/s at z = 0, 10, 30, 60 mm, respectively. On the other hand, the radial velocity is significantly lower than the axial velocity, as depicted in Fig. 2(b), which indicates that the ions moving along the thruster axis have mostly axial velocity component. This is because the measurement locations are along the thruster axis and the probing volume is 2.0 mm (radial) × 2.38 mm × 0.5 mm as described in the previous section. The full two-dimensional velocity map will be reported elsewhere. The increase in the peak axial velocity shown in Fig. 2(a) clearly demonstrates that significant acceleration of ions occurs outside the discharge channel in CHT plasmas, which is different from the AHT plasmas where ion acceleration occurs only up to a several mm from the exit plane.[9,11,12] Another important observation shown in Fig. 2(a) is the change in the shape of the velocity distributions. The velocity distribution is close to Gaussian at z = 0 mm; however, at larger z, the distribution clearly indicates the existence of a large population of ions faster than the peak velocity.

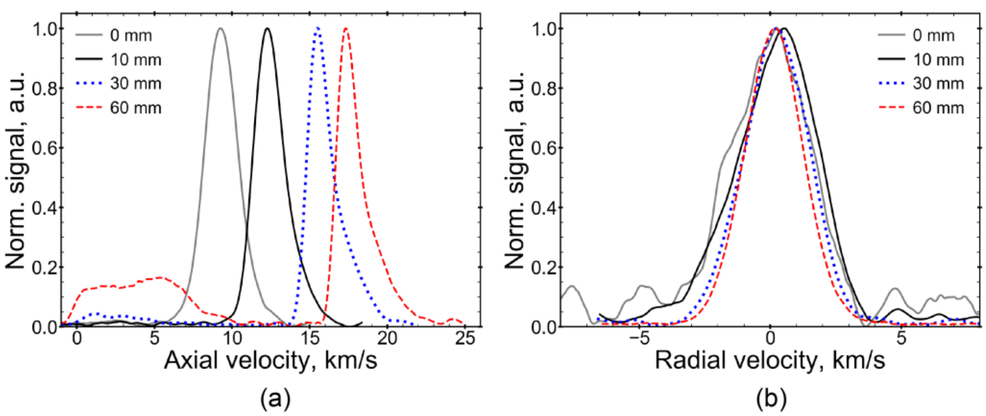

Figure 2. (a) The axial, and (b) radial velocity distributions along the thruster axis at 300 V and 7 sccm measured by the LIF diagnostics. The legend indicates the distance from the thruster exit plane, and each velocity distribution is normalized by its maximum value.

To examine the axial energy change, the peak velocity of the velocity distribution was chosen as a representative value. Figures 3 depicts the axial energy change of Xe II ions along the thruster axis. Significant ion acceleration is shown outside the discharge channel, and ions are accelerated up to 60 mm or further from the thruster exit plane, regardless of the discharge conditions. The ratio between the peak ion energy and eV_a (i.e. W_{peak}/eV_a), where V_a is the anode voltage, inside the discharge channel is increased with increasing anode voltage. This is possibly due to the increased electron temperature because the electron temperature generally increases with the anode voltage.[16] In contrast, there is an insignificant change in the W_{peak}/eV_a ratio inside the discharge channel, with increasing anode flow rate. At the end of the measurable region of LIF, or at z = 100 mm, W_{peak}/eV_a increases with anode voltage, but there is only a small change with anode flow rate; this can also be identified in Fig. 4, although the measurement locations are different.

Figures 4(a) and 4(b) depict the ion energy per charge at the anode flow rate of 7 sccm and anode voltage of 300 V, respectively, measured by a retarding potential analyzer (RPA) placed 480 mm away from the exit plane. The figure shows that the W_{peak}/eV_a ratio is increased with V_a but is not significantly affected by the flow rate. Figure 4 also reveals that the population of ions exceeding the anode voltage increases with the anode voltage and flow rate. Our previous work in CHT plasmas reported that this is related to the transit time instability.[8,18] It is clear that the energy spectra obtained by RPA is consistent with the observations made by the LIF measurement.

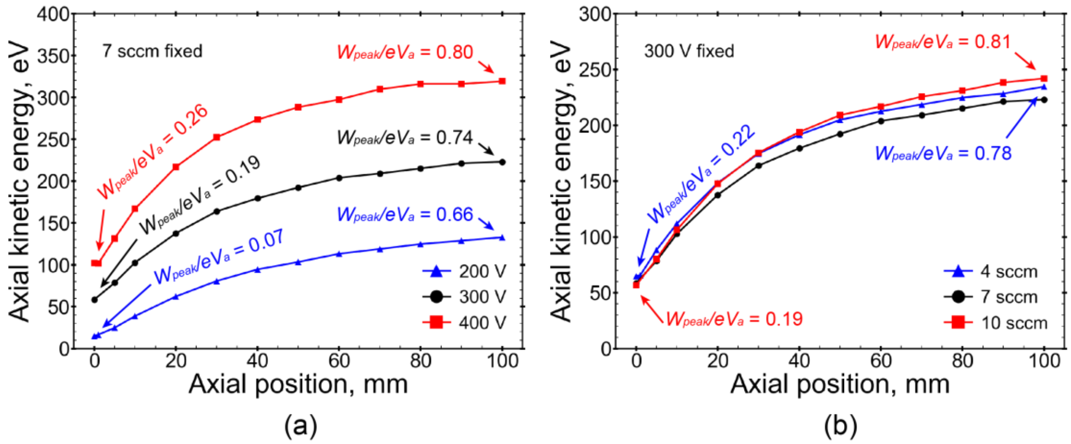

Figure 3. The axial energy of Xe II ions along the thruster axis, measured by LIF, at (a) the anode flow rate fixed at 7 sccm and at (b) the anode voltage fixed at 300 V. Each W_{peak}/eV_a value at z = 0, 100 mm is designated by an arrow.

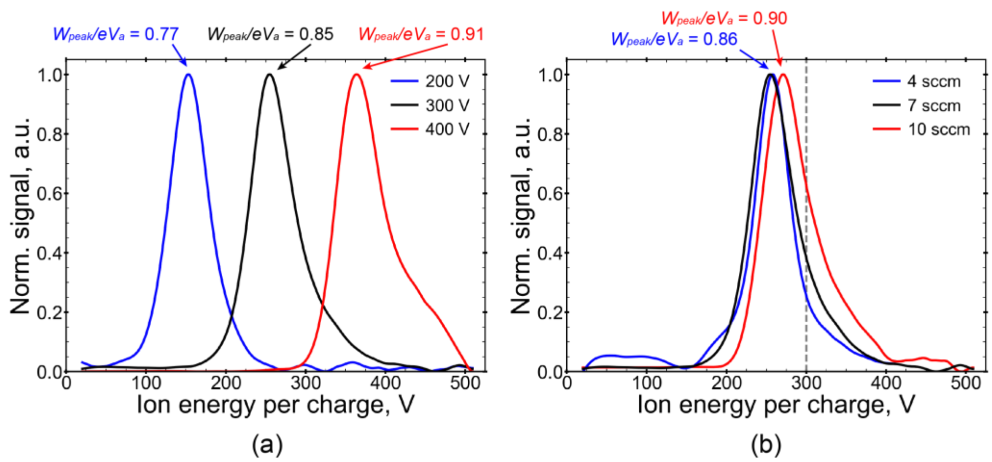

Figure 4. Ion energy per charge at (a) the anode flow rate fixed at 7 sccm and at (b) the anode voltage fixed at 300 V, measured by a RPA

IV. Summary

The spatial profiles of the velocity distributions of Xe II ions in CHT plasmas were measured and analyzed along the thruster axis in the plume region by using LIF diagnostics. It is noteworthy that significant ion acceleration occurs outside the discharge channel up to approximately 60 mm or further away from the thruster exit plane. Studies continue to focus on the cause of these differences compared with the case of the conventional AHTs.

Acknowledgments

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