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Unexpected transverse velocity component of Xe$^+$ ions near the exit plane of a Hall thruster

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The velocity component of singly charged xenon ions in a plane perpendicular to the thrust axis of the 1 kW-class PPS100-ML Hall effect thruster is deduced from laser induced fluorescence measurements on the 5d $^2F_{7/2} \rightarrow$ 6p $^2D^0_{5/2}$ electronic transition at 834.72 nm. Measurements are carried out at several locations in the near field of the channel exhaust. Thruster operating parameters, such as magnetic field strength, discharge voltage, and xenon mass flow rate, are varied over a wide range. The initial aim of this work was to measure the azimuthal velocity of the ions due to their weak magnetic deflection. Surprisingly, experimental results cannot be explained by the one and only Lorentz force acting on Xe$^+$ ions. A realistic picture of the ion trajectory in the $\mathbf{E} \times \mathbf{B}$ drift plane is obtained when adding a velocity component directed toward the external cathode. © *2010 American Institute of Physics*. [doi:10.1063/1.3507308]

I. INTRODUCTION

Electric propulsion is more and more often used for satellite orbit correction, station keeping, and space probes owing to its high efficiency and large propellant mass saving. Several techniques have been investigated in order to reach a high ionization efficiency, a large specific impulse, and a great thrust.[1] Among all the different devices, the Hall effect thruster (HET) is valuable for its capabilities in terms of thrust-to-power ratio, efficiency, and lifetime.[2]

The Hall effect thruster is a gridless ion accelerator in crossed electric and magnetic field configuration.[3,4] The propellant gas is usually xenon, chosen for its high atomic mass and low ionization potential. Electrons are injected into a ring shaped dielectric channel by a hollow cathode placed outside the channel. The anode, which also acts as gas injector, is located at the upstream end of the thruster channel. The magnetic barrier, which is generated by a combination of coils and a ferromagnetic circuit, traps the electrons, hence leading to an enhanced ionization rate close to the channel end. Besides, a strong electric field is induced by the reduced electron mobility within the high magnetic field region. The electric field accelerates ions to high speed, which produces the thrust.

In the crossed-field discharge of the HET, xenon ions are commonly assumed to be unmagnetized, contrary to the electrons that are highly confined. The Larmor radius of Xe$^+$ ions reaches about 0.5 m, whereas it is ~ 1 mm for electrons with a 200 G magnetic field magnitude. Here, ion and electron temperatures are fixed at 50 and 20 eV, respectively.[5,6] These quantities must then be compared to the typical channel dimensions, which never exceed a few centimeters. Therefore, electrons undergo a fast $\mathbf{E} \times \mathbf{B}$ drift in the azimuthal direction, which forms the so-called Hall current. By contrast, ions never achieve a complete rotation along the channel circumference. However, under the influence of Lorentz force, which reads as $\mathbf{v}_{\text{axial}} \times \mathbf{B}$, ions can be slightly azimuthally deflected from a purely axial trajectory. This is a crucial point for the thruster operation since it can affect the thrust vector direction and apply a torque to the satellite, thus inducing its rotation.

The first attempt to measure the azimuthal velocity of Xe$^+$ ions was made by Manzella in 1994 with a 1.5 kW-class SPT-100 thruster.[7] The measurements of ion azimuthal velocity were realized for the normal operating point (300 V and 5 mg/s) by applying the Doppler-shifted laser induced fluorescence technique. The goal was to evaluate the intensity of the torque created by the thruster. The velocity was only examined at one position: at the center of the channel in the exit plane. The azimuthal velocity was found to be around 250 m/s and the torque was 5×10^{-3} N cm. Swirling ions then create a force that corresponds to 2% of the axial thrust. Recently, Hargus and Charles[8] used the same laser induced fluorescence (LIF) technique to study the evolution of the ion rotation velocity in a 600 W-class Hall thruster operating at 300 V. Measurements were performed at several locations along the channel axis on either side of the thruster channel. An azimuthal velocity around 500 m/s was measured at the channel outlet. The velocity increases slightly when moving downstream. Scaling laws were used to explain the larger value of the velocity measured in that work compared to the value reported by Manzella.[7] Moreover, Hargus and Charles[8] found a small gap in the ion azimuthal velocities between the two opposite sides of the channel. However, the origin of the asymmetry was not discussed in their paper. The torque was estimated to be 3×10^{-3} N cm, which is close to the value obtained by Manzella.

In this work, the azimuthal velocity component of Xe$^+$ ions was determined by means of Doppler-shifted LIF spectroscopy in the near infrared with the 1 kW-class PPS100-ML Hall thruster. Experiments were carried out at various locations both at the thruster exhaust and in the plume near field. The objective of the study was twofold: to

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compare our velocity magnitudes and torque estimation with the previously reported values and to investigate the evolution of the azimuthal velocity with the thruster firing parameters, especially the magnetic field strength.

II. EXPERIMENTAL SETUP

A. Optical train

Doppler-shifted LIF spectroscopy has been widely used during the past decades to measure the axial and radial velocities of singly charged xenon ions in Hall thrusters.[5,9] Based on the Doppler shift of the absorption frequency of Xe$^+$ ions, this nonintrusive diagnostic tool enables to determine the velocity distribution function (VDF) of the ions along the laser beam direction. The LIF scheme is based on the excitation of Xe$^+$(5d $^2F_{7/2}$) metastable ions with a laser tuned on the 5d $^2F_{7/2} \rightarrow 6p$ $^2D^0_{5/2}$ transition at $\lambda_{air} = 834.7233$ nm. The fluorescence light is collected at 541.915 nm. The long-lived Xe$^+$(5d $^2F_{7/2}$) state is populated here by either electron impact on the ground-state Xe atoms or electron impact on the ground-state Xe$^+$ ions. The velocity distribution function of these metastable ions is thus similar to the VDF of the ground-state Xe$^+$ ions. The laser bench used in this study has been extensively described in preceding papers.[5,10] The laser diode is a continuous tunable MOPA system that delivers up to 750 mW light power in the 810–840 nm spectral domain. It remains mode hop-free over 10 GHz. A wavemeter provides the laser frequency with an absolute precision of 80 MHz ($\sim$60 m/s). The laser beam is coupled into a single-mode optical fiber and carried into the vacuum chamber of the PIVOINE-2g ground-test facility. Before being injected into the fiber, the laser beam is modulated at 1.5 kHz by a mechanical chopper to allow phase-sensitive detection of the fluorescence signal. At the exit of the optical fiber, collimation optics form a 1 mm in diameter beam of which the power was maintained at 5 mW/mm^2, as a trade-off between a strong saturation of the transition and a high enough fluorescence signal. Proper functioning of the diode is real-time checked with a 1 GHz free spectral range confocal Fabry–Pérot interferometer. The fluorescence detection branch is made of a 40 mm focal length lens that focuses the LIF light onto a multimode fiber. Collection optics is mounted at 90° with respect to the direction of the laser beam and thruster axis.

B. Measurement points and rule

Figure 1 sketches the thruster channel and the orientation of the monitoring laser beams. The azimuthal velocity profiles were examined at five locations. The exact positions of the measurement points are given in Table I. Three of them are situated in the same (y,z) plane close to the channel exit plane, which corresponds to the extremity of the channel wall. They are all on the channel midpoint at various angles (see Fig. 1). The other two are situated downstream on the same channel side along a horizontal line that crosses the thruster axis, as shown in Fig. 1. The accuracy in the coordinates is 0.2 mm. For all measurement points, the laser beam wave vector is such that only the azimuthal component of the velocity can be detected.

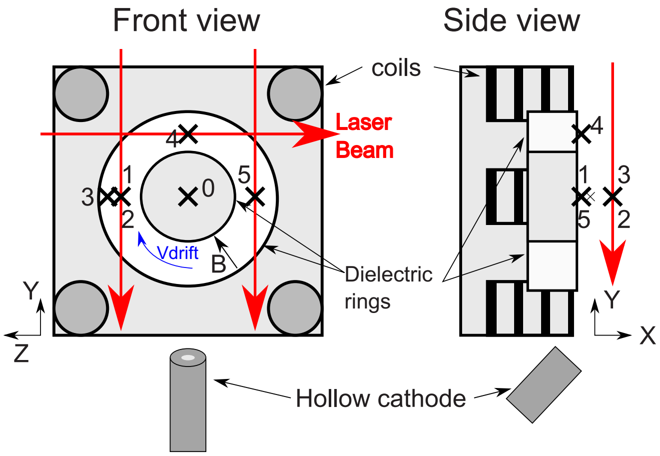

FIG. 1. (Color online) Front and side view diagrams of the Hall thruster and laser beams. Point 1–5 coordinates are detailed in Table I. Also shown is the drift direction ($I_c > 0$). The coil current is positive, so plasma drift is clockwise when facing thruster exhaust plane.

In LIF technique, the acquired quantity is the velocity component along the propagation direction of the laser beam. Hence, the Doppler shift can be either positive or negative. To get a clear idea of the direction of the Xe$^+$ azimuthal velocity, a rule that depends neither on the laser beam direction nor on the magnetic field direction is preferred. The sign of the azimuthal velocity is then chosen with respect to the direction of rotation of ions due to the Lorentz force $\mathbf{v}_{\text{axial}} \times \mathbf{B}$. Note that the Lorentz force direction is similar to the electron $\mathbf{E} \times \mathbf{B}$ drift direction. If ion azimuthal velocity is only driven by the magnetic deflection, its sign according to our convention is always positive, i.e., in the direction of the Lorentz force. Then, any change in velocity sign indicates that another mechanism is acting on the ion trajectory. In the remainder of this paper, an azimuthal velocity along the Lorentz force is said to be positive and referred to as “along the drift.” On the contrary, a velocity in the opposite direction is counted negative and referred to as “against the drift.”

C. Hall effect thruster

The studied Hall thruster, so-called PPS100-ML, is a laboratory model of the Snecma-built PPS100 thruster of which design and dimensions are close to those of the Russian SPT100 thruster. During the experiments campaign,

TABLE I. Coordinates of the examined positions in millimeters. The (0,0,0) origin refers to the thruster centerline in the channel exit plane.

Position No.	X coord.	Y coord.	Z coord.	Location
1	2	0	42.5	Left
2	12	0	42.5	Left
3	12	0	47	Left
4	2	42.5	0	Top
5	2	0	−42.5	Right

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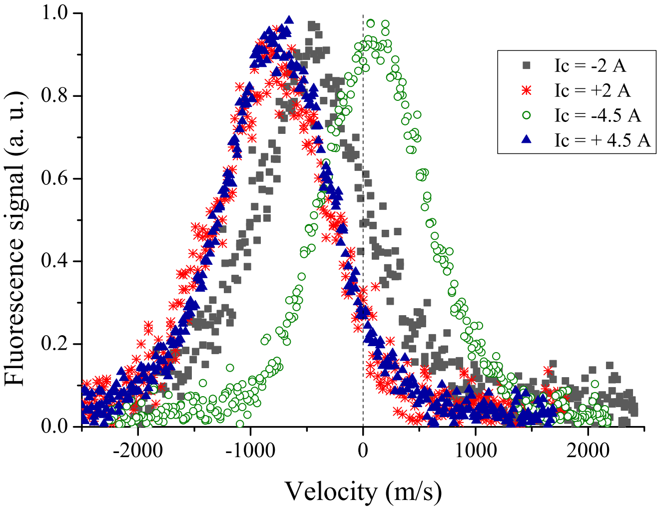

FIG. 2. (Color online) Raw fluorescence profiles measured at point 2. U_d is set at 200 V and Φ_a at 3 mg/s. Positive velocity refers to ion rotation in the drift direction.

the thruster was equipped with BN–SiO_2 dielectric channel walls. The xenon mass flow rate injected in the cathode Φ_c was kept fixed at 0.4 mg/s. The applied voltage U_d was varied from 100 up to 350 V. The anode mass flow rate Φ_a was changed from 2 to 5 mg/s. The background pressure inside the vacuum chamber was $\sim 2\times 10^{-5}$ Pa Xe for all conditions. The coil current I_c was varied from 2 to 6 A, i.e., the magnetic field strength was varied from 80 to 240 G. The sign of the current flowing through the coils was also reversed. Here, the **B** field points inward (from the outer to the inner channel wall) when the coil current is positive. It is directed outward when the coil current is negative. Current reversal does not modify thruster characteristics and performances. The accelerating electric field remains in the same direction. Although the magnetic field and the Hall current $\mathbf{I}_{\mathrm{Hall}}$ change direction when reversing I_c, the Laplace force $\mathbf{I}_{\mathrm{Hall}}\times\mathbf{B}$ at the origin of the thrust remains unchanged.

D. Raw spectra

Several raw spectra recorded at point labeled 2 are shown in Fig. 2. The existence of seven xenon isotopes with abundance above 1%, two of them with a nonzero nuclear spin, leads to a complex isotopic and hyperfine structure for each optical transition. The 834.72 nm line exhibits, in fact, 19 components. Besides, in the discharge of a Hall thruster, the magnetic field is at the origin of the Zeeman splitting of the levels. The measured spectra are therefore relatively broad, as can be seen in Fig. 2. To extract the true ion VDF from the experimental spectra is quite cumbersome all the more, so saturation due to the laser power must be accounted for.[11] For the sake of simplicity, here we solely considered the most probable ion velocity that corresponds to the peak of the profile. Uncertainty in velocity determination is given by the wavemeter precision as the center of the lineshape is dominated by even isotope ^{132}Xe. The systematic error bar on measurements is then ±60 m/s.

Figure 2 clearly indicates that the ion azimuthal velocity v_θ depends strongly on the strength and the direction of the magnetic field. According to the convention for the sign of the velocity (see Sec. II B), v_θ is expected to be positive, i.e., in the direction of the Lorentz force, whatever the coil current value. It is obviously not the case. The azimuthal velocity is appropriately aligned only when $I_c=-4.5$ A. Analysis of raw spectra therefore shows that the azimuthal velocity of Xe^+ ions is not entirely governed by the Lorentz force. Another mechanism must then be put forward to explain the origin of the ion transverse velocity.

III. ION AZIMUTHAL VELOCITY

A. Influence of the magnetic field

Although Xe^+ ions are weakly magnetized in the discharge of a Hall thruster, they experienced an azimuthal drift with a large curvature radius due to the Lorentz force. The value of the associated velocity v_θ can be estimated under the following assumptions: the electric field **E** is purely axial; the magnetic field **B** points in the radial direction and its magnitude solely depends on the x coordinate. Then, the Lorentz force in the azimuthal direction reads as

$$\frac{dv_\theta}{dt}=\frac{e}{m}v_xB_r-\frac{v_rv_\theta}{r}\approx\frac{e}{m}v_xB_r, \tag{1}$$

where e is the elementary charge, m is the ion mass, and v_x and v_r are the ion axial and radial velocities, respectively. Assuming ions follow straight trajectories, the time derivative changes into a derivative along the x direction. Equation (1) becomes

$$v_\theta=\frac{e}{m}\int B_rdx. \tag{2}$$

The velocity v_θ can then be numerically computed from Eq. (2) knowing the magnetic field distribution. The calculation was performed with $I_c=4.5$ A for points 1 and 2 (see Table I), which are positioned on the channel axis at $x=2$ and 12 mm, respectively. When ions are solely created ahead of the magnetic barrier, one finds $v_\theta=178$ m/s at point 1 and 288 m/s at point 2. A more rigorous calculation that accounts for the overlapping between the ionization and the acceleration zones[5,10] gives $v_\theta=113$ m/s at point 1 and 223 m/s at point 2.

The evolution of the Xe^+ ion azimuthal velocity with the magnetic field intensity and orientation was investigated, while keeping the discharge voltage and the mass flow rate constant: $U_d=200$ V and $\Phi_a=3$ mg/s. The graph in Fig. 3 displays v_θ against the coil current I_c for three locations on the left side of the PPS100-ML Hall thruster. Surprisingly, all velocities are negative, i.e., opposite to the drift direction. This suggests that a force is acting on ions to direct their velocity from the top to the bottom of the thruster. When excluding data points acquired below $I_c=3$ A, which do not correspond to normal operation conditions of the HET, one observes that the velocity magnitude grows slowly when increasing the magnetic field strength and it levels off above $I_c=5$ A. This effect cannot be related to magnetic circuit

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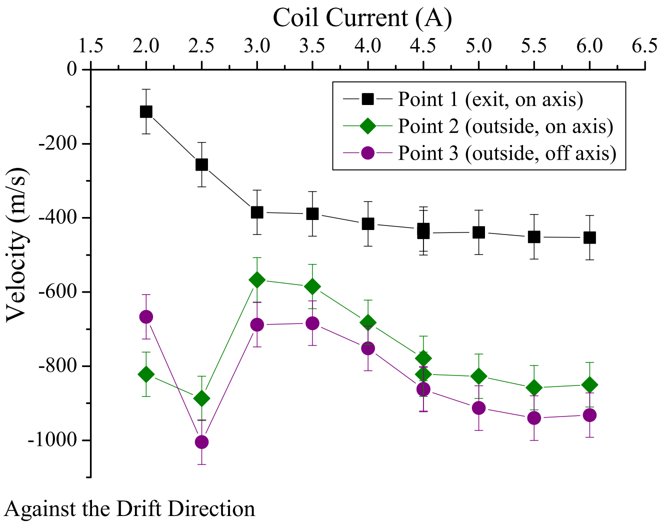

FIG. 3. (Color online) Ion azimuthal velocity against coil's current for three locations on the thruster left side (U_d=200 V and Φ_a=3 mg/s). Positive velocity refers to ion rotation in the drift direction.

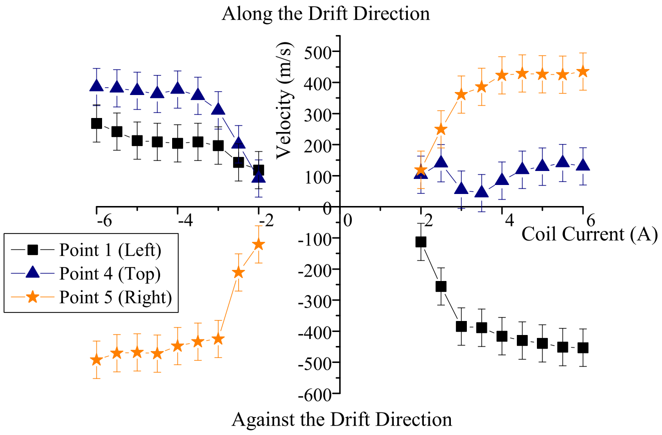

FIG. 5. (Color online) The evolution of the ion azimuthal velocity with the coil current for the three points at x=2 mm (U_d=200 V and Φ_a=3 mg/s).

saturation since the response of the circuit remains linear even above I_c=6 A. Azimuthal velocities measured at points 2 and 3, both at 12 mm from the exit plane, are almost comparable and approximately twice the velocities at point 1. The velocity must indeed be larger at x=12 mm as ions have traveled a longer distance within the magnetic barrier. However, in all cases, the velocity magnitude is much larger than the value calculated from the magnetic deflection. Note that the change of velocity between points 2 and 3 is in agreement with a solid-like rotation of the plasma.

To get more insight into the origin of the Xe^+ azimuthal path, the magnetic field direction was changed by inverting the coil current. So, only the direction of the Lorentz force is modified with this operation. If the ion azimuthal velocity is driven by the magnetic field, the velocity would keep the same magnitude. As can be seen in Fig. 4, the sign of the **B** field does not influence significantly the thruster discharge properties. The discharge current waveform is independent of the coil current direction.[12] In a similar manner, it was checked that the thrust is not affected by the magnetic field orientation. The azimuthal velocity is plotted in Fig. 5 as a function of the coil current, with both positive and negative values, for observation points 1, 4, and 5. The three points are placed at x=2 mm at angles of 0°, 90°, and 180°, respectively (see Table I and Fig. 1). As shown in Fig. 5, for two of the six measurement series, the velocity is in the direction opposite to the plasma drift. For these two cases—point 1 with $I_c>0$ and point 5 with $I_c<0$—the Lorentz force is oriented in an upward direction. We should point out that except for point 4 with $I_c>0$, the modulus of the azimuthal velocity is much larger than the calculated values. Figure 6 helps the reader visualize the direction and relative magnitude of v_θ for points 1, 4, and 5 according to the sign of I_c.

It finally comes out that for the side observation points 1–3 and 5, whatever the magnetic field direction, the main transverse force acting on ions is from the top to the bottom of the thruster. Consequently, the force applied on ions can be attributed to the asymmetry of the plasma due to the position of the cathode. The latter is located below the thruster

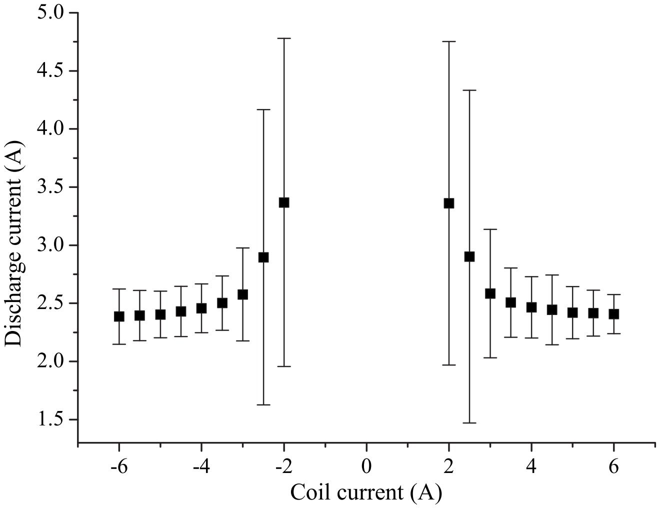

FIG. 4. Discharge current as a function of the coil current (U_d=200 V and Φ_a=3 mg/s). Bars give the standard deviation at the breathing mode frequency of ~20 kHz (Ref. 12).

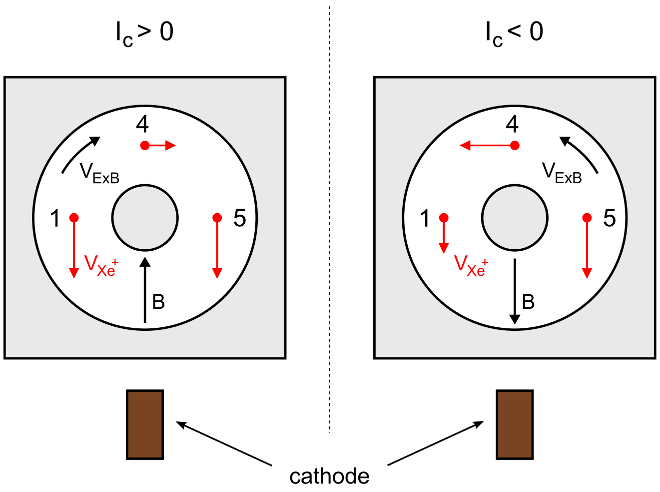

FIG. 6. (Color online) Visualization of direction and magnitude of Xe^+ ion azimuthal velocity for points 1, 4, and 5 for $I_c>0$ and $I_c<0$ (see Fig. 5).

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body, just beyond the channel exit plane (see Fig. 1). The potential of the cathode lies around -20 V with respect to the vacuum chamber electrical ground for the PPS100-ML Hall thruster. Ions leaving the channel can then be attracted toward the cathode and gain velocity in the direction orthogonal to the main acceleration direction. In fact, a potential difference of only 0.03 V in the y direction induces a Xe^+ ions transverse velocity of about 200 m/s. This transverse velocity would exceed 500 m/s for a potential drop of 0.2 V.

However, a weak transverse electric field purely aligned in the y direction of which the magnitude would be independent of the discharge parameters cannot fully explain experimental facts. First, such an electric field would have no impact at point 4 located at the top as the velocity is measured here along the z axis. Second, if the cathode attraction force was insensitive to the direction of the magnetic field, the measured velocity would always be directed downward, except for very strong magnetic field. Therefore, the magnitude and sign of the weak electric field component directed toward the external cathode must depend on the magnetic field strength and polarity.

Previous azimuthal velocity measurements by Manzella[7] and Hargus and Charles[8] can naturally be revisited in light of our analysis. Manzella recorded the circumferential velocity profiles of Xe^+ ions in the plasma of an SPT100 Hall thruster. At a position comparable to point 5, he measured an azimuthal velocity of 250 m/s in normal conditions (300 V and 5 mg/s) with two counterpropagating laser beams. The relatively large magnitude of v_θ can be explained by an ion drift toward the cathode. Hargus and Charles measured the Xe^+ azimuthal velocity in a 600 W HET operating at 300 V. The velocity increases with the axial distance in compliance with the outcomes of this work. More interestingly, they observed a discrepancy between measurements realized at two opposite positions with respect to the thruster axis, which correspond to points 1 and 5 in Fig. 3. The gap in velocity amplitude reaches 200 m/s at $x=5$ mm. Such a result clearly supports the idea of an additional phenomenon superimposed to the magnetic deflection.

B. Impact of discharge voltage and mass flow rate

The influence of the discharge voltage on the Xe^+ azimuthal velocity was extensively studied. The anode mass flow rate was set to 3 mg/s. The coil current was fixed at ± 4.5 A. Figures 7(a)–7(c) show the azimuthal velocity as a function of the applied voltage for all observation points. The voltage has a strong impact upon the magnitude of v_θ whatever the measurement position. The magnitude of the ion velocity increases when the voltage is ramped up for $I_c > 0$ as well as $I_c < 0$. If we assume that the Lorentz force governs the ion azimuthal trajectory, the results shown in Fig. 7 would indicate that the ionization region moves upstream when the voltage augments as ions would have to spend more time in the magnetic barrier. However, two facts contradict this viewpoint. First, curves would be identical for points 1, 4, and 5. Second, the polarity of the **B** field would have no effect. This is obviously not the case. Moreover, v_θ exceeds by far the theoretical value. Experimental outcomes summarized in Fig. 7 are compatible with the existence of an electric field component directed toward the external cathode. If the electric field would have only one constant component along the y axis, the velocity at point 4 would be constant for all U_d at a given value of I_c. Moreover, at point 5 where the Lorentz force induces a clockwise azimuthal deflection for $I_c \geq 0$, the measured velocity magnitude would be greater when I_c is positive and invariant with respect to U_d.

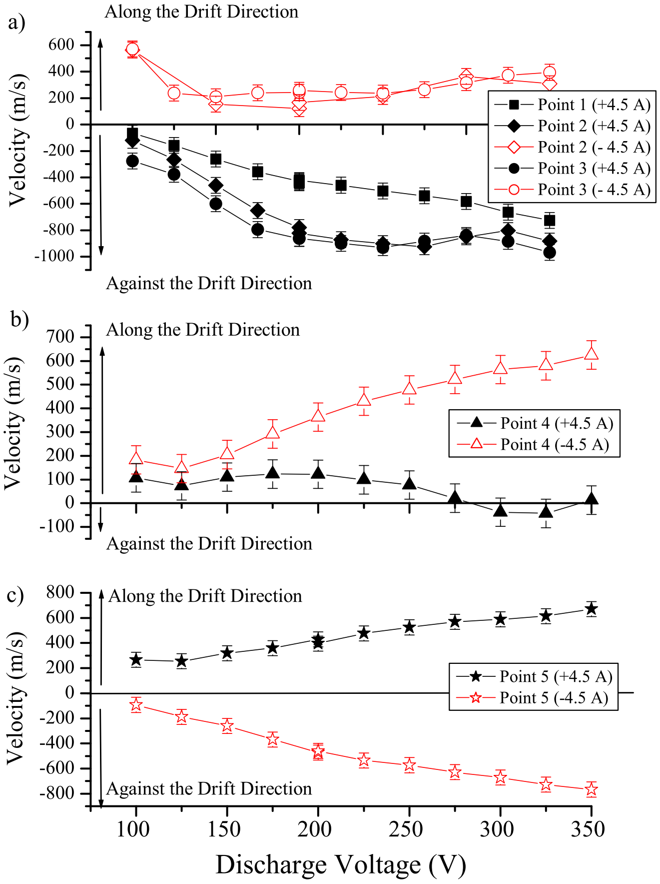

FIG. 7. (Color online) Xe^+ ion azimuthal velocity against discharge voltage for the five measurement locations ($I_c = \pm 4.5$ A and $\Phi_a = 3$ mg/s).

A systematic study of the impact of the xenon mass flow was not carried out; only point 1 was examined at $U_d = 200$ V and $I_c = +4.5$ A. The velocity v_θ increases linearly with the anode mass flow rate, from 380 m/s at $\Phi_a = 2$ mg/s to 550 m/s at $\Phi_a = 5$ mg/s. The azimuthal velocity is not expected to depend on the mass flow rate. As in the preceding cases, the ionization zone could be displaced toward the anode when increasing Φ_a, thus increasing the ion path length in the magnetized region. Alternatively, the transverse electric field component produced by the external cathode could change direction and strength with Φ_a.

IV. CONCLUSION

Examination of the Xe^+ ion azimuthal velocity component by means of LIF spectroscopy in the plasma of the Hall effect thruster reveals a rather complex picture. The most important result of this work is the likely presence of a weak transverse electric field directed toward the external cathode.

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This field greatly influences the transverse trajectory of Xe^+ ions, of which the azimuthal velocity is no longer driven by the only magnetic deflection. The cathode attraction force is particularly dominant when the measurement location is at a right angle with respect to the cathode axis, as it is the case for points 1 and 5 (see Fig. 3). It is worth highlighting once more that a potential difference along the y axis of only 0.03 V induces a drift velocity along this axis of about 200 m/s, i.e., identical to or even larger than the velocity driven by **B** field. To eliminate any contribution due to misalignment of the anode, it was of course verified that Xe atoms do not rotate in the discharge of the HET. The $6s[3/2]_2^0$ metastable state of Xe atom was probed by way of Doppler-shifted LIF spectroscopy at 823.16 nm.[13] Measurements were performed for point 5 only for I_c tuned between -6 and $+6$ A. As expected, the atom mean azimuthal velocity was found to be zero within our accuracy limit.

This study shows that the external cathode has a strong impact on the symmetry of the plasma. In fact, it breaks the cylindrical symmetry by slightly tilting the thrust vector. Our measurements naturally confirm the existence of a small torque in the Hall thruster. Magnetic deflection is not large in our case; however, its effect on the spacecraft stability may be non-negligible for high power thrusters operating with a large propellant mass flow rate. An internally mounted cathode placed on the thruster centerline would render the system more symmetrical. A small gain in thrust efficiency may be expected due to a reduced plume divergence. The main drawback could be the cathode erosion and the subsequent lifetime reduction. Moreover, the critical issue linked to the torque would not be avoided. Two sets of experiments appear of particular interest to complete these works, namely, acquiring v_θ at one fixed location while changing the cathode position and carrying out measurements with thrusters of different sizes, structures, and normal power. Moreover, the influence of discharge voltage and anode mass flow rate on v_θ must be investigated deeper to better understand the involved mechanisms and consequences. Finally, comparisons with numerical simulations would also be a rich source of information; however, investigation of the ion azimuthal trajectory in a Hall thruster would necessitate the utilization of a full three-dimensional model.

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