

Observation of ion beam properties in the Hall thruster plasma using an axial electron density fluctuation mode

IEPC-2011-225

*Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden, Germany
September 11–15, 2011*

Sedina Tsikata ^{*}, Cyrille Honoré[†] and Dominique Grésillon[‡]
Ecole Polytechnique, UMR 7648 CNRS, Palaiseau, France

Anne Héron[§]
Ecole Polytechnique, UMR 7644 CNRS, Palaiseau, France

Nicolas Lemoine[¶] and Jordan Cavalier^{||}
Université Henri-Poincaré, UMR 7198 CNRS, Nancy, France

Collective light scattering has been used to identify millimeter-scale instabilities in the Hall thruster, including an azimuthal mode implicated in anomalous electron transport. This paper describes the influence of the ion beam properties on the development of the azimuthal instability and the use of the same diagnostic for the measurement of the ion properties via an axially-propagating mode.

Nomenclature

$\vec{E}, E_0$	= electric field
$\vec{B}, B_0$	= magnetic field
$\vec{k}$	= observation wave vector
k_y	= wave vector component parallel to the $\vec{E} \times \vec{B}$ direction
k_x	= wave vector component parallel to $\vec{E}$
k_z	= wave vector component parallel to $\vec{B}$
v_i	= ion axial velocity
v_{thi}, v_{the}	= ion and electron thermal velocities
V_d	= azimuthal electron drift velocity
c_s	= acoustic ion velocity
α	= orientation angle of observation wave vector in the $(\vec{E}, \vec{E} \times \vec{B})$ plane
v_g, v_ϕ	= group and phase velocities
LIF	= laser-induced fluorescence

^{*}CNES postdoc, Laboratoire de Physique des Plasmas, sedina.tsikata@polytechnique.edu

[†]Research engineer, Laboratoire de Physique des Plasmas, cyrille.honore@polytechnique.edu

[‡]Professor emeritus, Laboratoire de Physique des Plasmas, dominique.gresillon@polytechnique.edu

[§]Researcher, Centre de Physique Théorique, anne.heron@polytechnique.edu

[¶]Assistant professor, Institut Jean Lamour, nicolas.lemoine@ijl.nancy-universite.fr

^{||}PhD student, Institut Jean Lamour, jordan.cavalier@ijl.nancy-universite.fr

I. Introduction

Instabilities in the Hall thruster plasma are believed to influence numerous aspects of thruster operation, including stability of the discharge, particle transport and wall erosion. Experimental and theoretical approaches to characterizing such instabilities may provide clues as to how to improve codes and ultimately thruster performance.

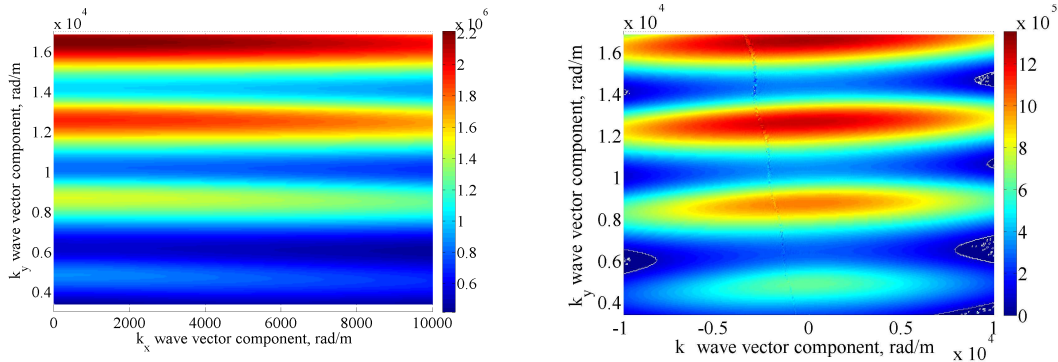
The role played by a cyclotron drift instability in electron transport was first described through self-consistent 2D PIC simulations by Adam, Héron and Laval¹. They showed that the presence of this instability, driven naturally by the high-velocity azimuthal electron drift, could cause axial electron transport. To study these predictions, a collective light scattering experiment was designed and implemented to identify the azimuthally-propagating wave^{2,3}. Apart from characterizing the transport mode, the experimental studies also provided evidence of other plasma fluctuations at the same length scales: a low-amplitude mode identified in the vicinity of the cathode, and a mode propagating axially.

II. The role played by ions in electron transport

The azimuthal cyclotron instability is strongly influenced by the ion beam properties: the ion velocity and temperature. The ion influence has been considered by Héron and colleagues in some detail and a few general features are discussed here. The three-dimensional dispersion relation⁴ is of the form

$$1 + \frac{1}{k^2 \lambda_D^2} \left[1 + \frac{\omega - k_y V_d}{k_z v_{the} \sqrt{2}} e^{-\gamma} \sum_{m=-\infty}^{+\infty} Z(\zeta_m) I_m(\gamma) \right] - \frac{1}{2k^2 \lambda_{Di}^2} Z' \left(\frac{\omega - k_x v_i}{k v_{thi} \sqrt{2}} \right) = 0 \quad (1)$$

where v_{thi} , v_i and λ_{Di}^2 are the ion thermal velocity, axial velocity and Debye length.



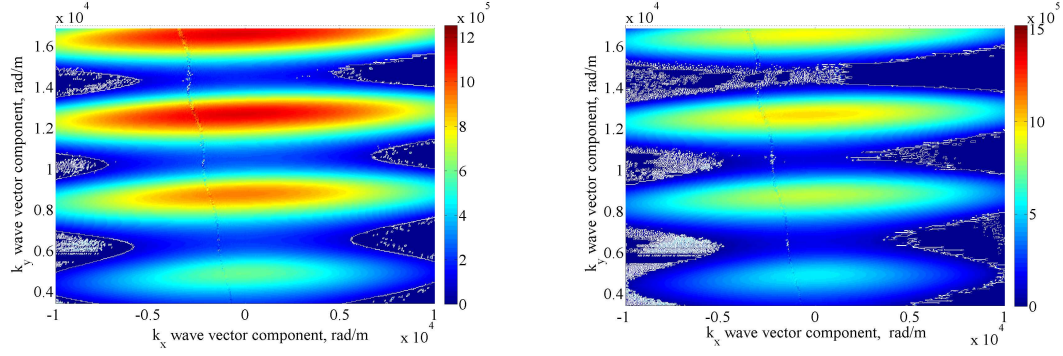
(a) Azimuthal mode growth rate in the absence of an axial ion velocity (b) Azimuthal mode growth rate in the presence of an axial ion velocity of 20 km/s

Figure 1. Influence of ion axial velocity on growth rate of the azimuthal mode

The presence of a large ion velocity tends to shift the position of the maximum growth rate to a non-zero axial (k_x) component (Fig. 1). Fig. 1 shows the growth rate solution with a radial k_z component of 470 rad/m and a temperature ratio of v_{thi}/v_{the} which is $7.5e-4$. Fig. 1(a) shows the growth rate in the absence of ion velocity; Fig. 1(b) shows the effect of an axial ion drift of 20 km/s. The unstable growth rate lobes are tilted such that the maximum growth rate is no longer obtained for $k_x = 0$. Experimental observations confirm this feature: the maximum amplitude mode is tilted on the order of ten degrees towards the thruster face³.

The effect of a small increase in the ion (transverse) thermal velocity is to damp the instability (Fig. 2). In the cases shown, v_i and k_z are the same as used in Fig. 1. The temperature ratios shown are $8e-4$ and $8.5e-4$, and the growth rate is uniformly reduced for the latter case (Fig.2(b)).

The influence of ions on the azimuthal instability, and ultimately, on electron transport, is clearly important. The axially-propagating instability which has been observed in the experiment displays features reflecting a strong coupling between the ions and electron density fluctuations. By orienting the observation



(a) Azimuthal mode growth rate for $v_{thi}/v_{the} = 8e-4$ (b) Azimuthal mode growth rate for $v_{thi}/v_{the} = 8.5e-4$

Figure 2. Influence of ion thermal velocity on growth rate of the azimuthal mode

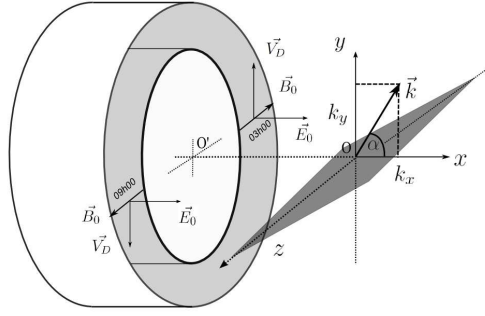


Figure 3. Thruster coordinate system used in the experiment

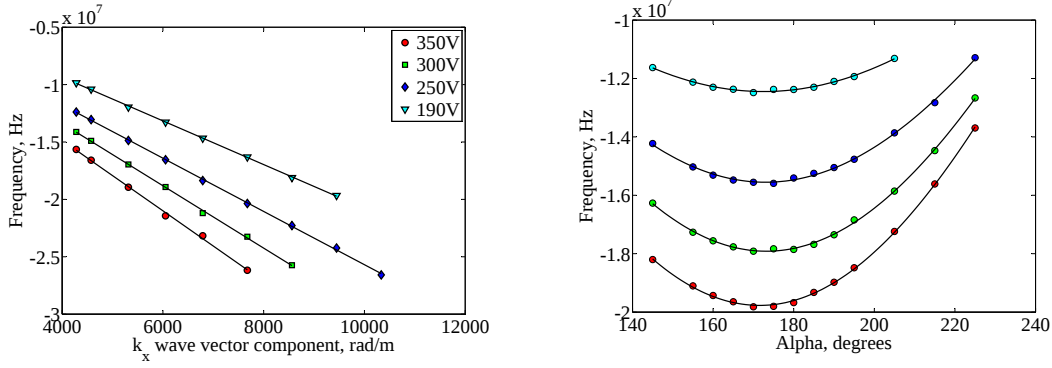
wave vector appropriately, we may exploit this feature to obtain information on the ion velocity, as will be shown below.

III. Collective scattering experiment

Experiments are carried out using a modified version of the experimental collective scattering bench PRAXIS⁴. A continuous power, 10.6 μm -wavelength, 40W CO₂ laser is used to create a primary and local oscillator beam. The primary beam (99% of the original laser power) is used both to furnish a high-amplitude scattered signal, and to define the scattering volume. The local oscillator provides an interference with the scattered signal, from which the appropriate phase and amplitude components are extracted. Experiments are carried out in the PIVOINE thruster facility in Orléans, using the 6kW PPS®-X000 thruster designed by Snecma. The beam diameter for this version of the optical bench is 3.4 mm. The accessible wavenumber range is 3100 to 10300 rad/m, or 2 to 0.6 mm. The thruster flow rate used in the experiments shown is 12 mg/s.

The thruster coordinate system used is shown in Fig. 3. The magnetic field is directed radially outwards (in contrast to previous studies). The resulting electron drift velocity V_d is anticlockwise when viewed from the front of the exit channel. The observation volume is shown as a dark grey lozenge formed by the intersection of the laser beams. The light grey volume shows the thruster channel plasma. In the experiments discussed here, the observation volume is situated a distance of 11 mm from the exit plane and 12.5 mm above the thruster axis. The angle α can be varied over 360 degrees in the $(\vec{E}, \vec{E} \times \vec{B})$ plane.

In order to observe the axial fluctuation mode, the wave vector must be positioned by changing α , to measure fluctuations propagating along or near Ox , the thruster axis. An exploration with $\vec{k}$ oriented along or



(a) Dispersion relations for the axial mode for different discharge voltages (b) Variation of mode frequency with wave vector orientation angle

Figure 4. Frequency characteristics of the axial mode at different acceleration voltages

near $\alpha = 0^\circ$ means that $\vec{k}$ has the same sign as the outward-directed ion velocity v_i . The resulting frequencies measured are positive. On the other hand, an exploration along or near $\alpha = 180^\circ$ gives negatively-signed frequencies. In the examples considered here, explorations are performed in this latter direction. Velocities discussed will be absolute values.

To describe features of the unstable modes, two aspects will be considered: the measured frequency and amplitude. The measured mode frequency is obtained via a Gaussian fit to the normalized signal spectral density. The mode amplitude, the form factor, is obtained through an integral of the normalized signal over an appropriate frequency range, and corresponds to the intensity of the electron density fluctuations at the particular wavenumber and frequency considered.

IV. Determining an ion velocity from axial electron density fluctuations

In order to change the ion velocity, the discharge voltage is varied. The variation of frequency with wavenumber for a number of discharge voltages is considered at a fixed $\alpha = 175^\circ$. The voltage range for this experiment has been limited by restrictions of the available cathode. The dispersion relations are shown in Fig. 4(a), plotted against the k_x wave vector component, $k \cos(\alpha)$.

In Fig. 4(a), at a fixed discharge voltage, the frequency increases linearly with wavenumber, and the group velocities, v_g , are obtained from the slopes at each voltage value. The group velocity is seen to increase with discharge voltage. The frequencies corresponding to the mode are on the same order as the ion plasma frequency (tens of megahertz) and it is expected that some signature of the ions is present. It is possible that these group velocities are composed of an ion velocity and acoustic ion velocity component, but these cannot be directly extracted from the group velocity. On the other hand, the evolution of the mode phase velocity is instructive.

The observation wave number is fixed at an arbitrary value (5483 rad/m) - and the variation of mode frequency with α is followed at different values of the discharge voltage. The variations over a range of angles with the wave vector pointed near the $-Ox$ direction (resulting in negatively-signed frequencies) are shown in Fig. 4(b).

The data follows a general trend: at the same value of α , the mode frequency increases with the discharge voltage. From the variations shown in Fig. 4(b), it is possible to determine an ion velocity which is consistent with measurements obtained via other well-established tools such as LIF. In this analysis of the mode phase velocity, the hypothesis made is that the axial mode phase velocity may be expressed as a Doppler-shifted ion acoustic velocity,

$$v_\phi = v_i \cos(\alpha - \alpha_0) + \text{sgn}(\cos(\alpha - \alpha_0)) \cdot c_s \quad (2)$$

In such a case, the frequency data may be fitted to the form $f = \frac{1}{2\pi} \{kv_i \cos(\alpha - \alpha_0) + \text{sgn}(\cos(\alpha - \alpha_0)) \cdot kc_s\}$.

where α_0 is an off-axis angular shift and c_s the ion acoustic velocity. The parameters v_i , α_0 and c_s are optimized at all voltages, and the resulting fits show a very good match to the experimental data (Fig. 4(b)).

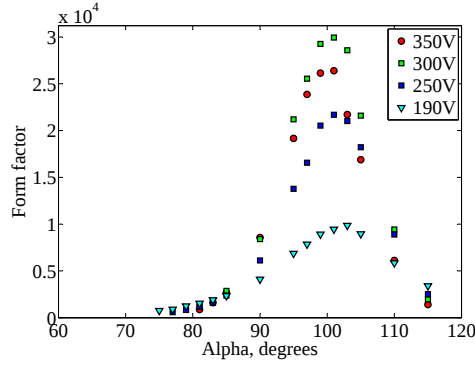


Figure 5. Azimuthal mode amplitude angular variation with discharge voltage

The group and phase velocities are summarized in Table 1 (absolute values).

V	v_g (km/s)	v_i (km/s)	c_s (km/s)
350	19.3	17.3	5.36
300	17.1	15.7	4.82
250	14.6	12.6	5.25
190	12.0	8.22	6.05

Table 1. Mode group velocities and deduced ion velocities and acoustic ion velocities

The values of v_i from Table 1 may be compared with the velocities measured during previous LIF experiments. At these low-voltage conditions, few equivalent measurements of the ion velocity are presently available for this thruster. Under similar conditions and at 300V, the corresponding measured LIF mean ion velocity is 15 km/s⁵, a value very close to that shown in Table 1.

V. Implications for the azimuthal mode directivity

It has been reported that the azimuthal mode does not propagate purely along the $\vec{E} \times \vec{B}$ direction. It possesses a component aligned with the thruster axis ($-Ox$) as well as a non-zero component along the magnetic field.

Data obtained from studying the axial mode, and therefore, the ion beam properties, might be used to account for the angular deviation of the azimuthal mode. Is the directivity of the azimuthal mode in the $(\vec{E}, \vec{E} \times \vec{B})$ plane dictated only by convection effects? This is difficult to conclude based on the angular variation of the form factor of the azimuthal mode (Fig. 5).

Fig. 5 shows a maximum in the azimuthal mode amplitude at 300V which is located at 101°, consistent with previous observations at this voltage. What is interesting is that the directivity does not vary at all significantly with the discharge voltage. This is because the changes made to the ion velocity when the voltage is changed cannot be decoupled from changes to other parameters, such as the electron temperature and electric field axial profile, which also affect the azimuthal mode properties. Another experiment, involving translating the observation axially but maintaining the same discharge voltage, provides a clearer idea of the effect of ion acceleration on the directivity of the azimuthal mode and is described in another paper⁶.

VI. Conclusion

A better understanding of the electron cyclotron instability involved in transport requires accounting for the influence of ions. The collective scattering diagnostic may be used for the measurement of ion properties, via an axial density fluctuation mode. This mode is susceptible to changes in thruster parameters which change the ion features, and may be described as an ion acoustic mode convected at the ion velocity.

Acknowledgments

S.T thanks CNES for financial support. This work was performed with support from the Joint Research Program GDR No. 3161 CNRS/CNES/SNECMA/Universités *Propulsion par plasma dans l'espace*.

References

- ¹Adam, J.C, Héron, A., and Laval, G., “Study of stationary plasma thrusters using two-dimensional fully kinetic simulations,” *Phys. Plasmas*, Vol. 11, No. 1, 2004, pp. 295-305.
- ²Tsikata, S., Lemoine, N., Pisarev, V., and Grésillon, D., “Dispersion relations of electron density fluctuations in a Hall thruster plasma, observed by collective light scattering,” *Phys. Plasmas*, Vol. 16, 2009, pp. 033506-033506(10).
- ³Tsikata, S., Honoré, C., Lemoine, N. and Grésillon, D., “Three-dimensional structure of electron density fluctuations in the Hall thruster plasma: ExB mode,” *Phys. Plasmas*, Vol. 17, 2010, 112110
- ⁴Tsikata, S., PhD thesis, “Small-scale electron density fluctuations in the Hall thruster, observed via collective light scattering,” *Ecole Polytechnique*, 2009
- ⁵Gawron, D., PhD thesis, “Phénomènes de transport ionique dans le plasma d’un propulseur à effet Hall à forte puissance: étude par spectroscopie laser,” *Université d’Orléans*, 2007
- ⁶Honoré, C., Tsikata, S., Grésillon, D., Héron, A., Lemoine, N., Cavalier, J. “Hall Thruster small-scale plasma fluctuations : qualifying 2D PIC simulations against collective scattering data,” *International Conference on Electric Propulsion, Wiesbaden, Germany*, IEPC-208-2011