New insights into electron transport in Hall plasma thrusters: the collective Thomson scattering diagnostic

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1 Introduction

Electric propulsion has extended our capabilities of space flight, and such technologies are expected to continue to do so over the next decades. These technologies are based on the acceleration of charged particles to produce thrust and/or electrical heating of a propellant. The key attraction of these technologies is the propellant economy made possible because of the very high propellant ejection velocities (tens of km/s). Such mass savings render electric propulsion key for long-distance, long-duration space travel.

The Hall thruster is an electric propulsion device distinguished by a long flight history since its invention by A. I. Morozov in the 1960s. Hundreds of Hall thrusters have flown or are in operation for geosynchronous satellite station-keeping. As the primary propulsion drive, a Hall thruster (a 1.5 kW PPS-1350 model designed by SNECMA) was first used in 2003 aboard ESA's SMART-1 Earth-Moon mission. More ambitious and demanding applications are envisaged for the future: on heavy satellite platforms, for orbit tranfer, cargo transfer, and other space missions.

To achieve such goals, predictive simulation codes for thruster scaling and for forecasting operation are needed. Such codes do not yet exist, because many phenomena occurring in the thruster (including, but not limited to, secondary electron emission from the thruster walls, and anomalous electron transport) are difficult to model. A major research effort worldwide over the last couple of decades has been therefore been devoted to achieving a better understanding of Hall thruster physics. This effort has taken the form of theoretical analyses, numerical simulations, and experiments. In France, this effort has united partners in academia and industry. The work discussed in this paper concerns research within the framework of the collaborative five-year ANR research project TELIOPEH (*Transport ELectronique et IOnique dans les Propulseurs à Effet Hall*) initiated in 2006.

2 Ideas on thruster anomalous transport

The Hall thruster is a device in which crossed electric and magnetic fields to confine electrons, accelerate ions and produce thrust. The discharge is produced in an annular ceramic chamber, from a flow of a neutral propellant at the anode, ionized by electrons produced from an external cathode.

One of the long-standing goals of the community is to understand anomalous electron transport in the thruster. This transport refers to the abnormally high axial electron flux across magnetic field lines, which results in an overall reduction in thruster efficiency and may even contribute to thruster erosion. Within the thruster, the cumulative effect of different collisions gives a mobility close to the expected classical value. However, outside the thruster channel, despite the scarcity of such collisions, the observed mobility exceeds that predicted by classical models by two or three orders of magnitude. Plasma turbulence has been suggested as the culprit.

Studies of the plasma have revealed the presence of a diverse range of instabilities, of frequencies from the kHz to the GHz range [1]. The first numerical and theoretical study to reveal the presence of a particular instability linked to electron transport was made in 2004 by J-C. Adam, A. Héron and G. Laval (Centre de Physique Théorique, Ecole Polytechnique). Particle-in-cell simulations in an axial-azimuthal geometry showed the presence of an azimuthally-propagating mode with frequencies in the MHz range and wavelengths on the order of the electron Larmor radius. The presence of this instability gave rise to particle heating and an electron drift towards the anode. Linear kinetic theory analysis showed excitation of the mode in the vicinity of electron cyclotron resonances, $k_y V_d \approx n\omega_{ce}$, where k_y represents the mode azimuthal wavenumber, V_d the electron azimuthal drift velocity, n a whole number, and ω_{ce} the electron cyclotron frequency.

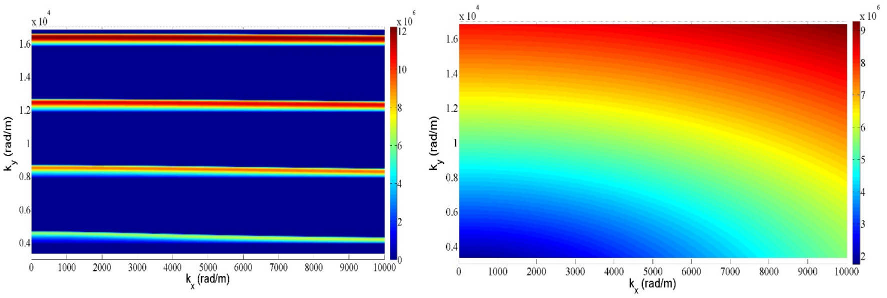

Figure 1: Linear kinetic theory dispersion relation solutions from Adam et al., as a function of azimuthal and axial wave vector components. A discrete dispersion relation (left) is expected from initial theoretical models, but experiments have provided additional information to obtain a realistic solution (right)

Confirmation of the presence of this instability is beyond the capacity of conventional thruster diagnostics (probes or antennae), due to the high electron temperatures (several tens of eV) and magnetic field in the plasma regions concerned, and the short length scales of the instability (mm and sub-mm) involved. For this reason, it was suggested by A. Bouchoule that a collective scattering diagnostic be built for detection of the instability.

This effort posed major challenges because of the low plasma density (three orders of magnitude lower than that found in tokamak experiments). An evaluation performed by N. Lemoine and D. Grésillon revealed the possible presence of a scattered signal situated at a level 1000 times below that of the noise. It was therefore necessary to consider the design a new high-performance diagnostic capable of maximizing the signal to noise ratio.

3 The PRAXIS diagnostic

In the thruster, the diagnostic is used to measure electron density fluctuations to detect the instability predicted by Adam et. al. Observation length scales are set to those of the instability, and a summation of correlated field phases produces a large scattered wave signal. The PRAXIS (PRopulsion Analysis eXperiments via Infrared Scattering) diagnostic uses a 40W CO_2 continuous laser, of wavelength 10.6μm. The incident beam is split into a primary (99% of laser power) beam and a frequency-shifted, low-power local oscillator beam. A system of mirrors and lenses is used to tailor both beams to the desired waists at different locations on the bench, while a translator-rotator element is used to vary the observation wave vector magnitude and orientation. The local oscillator and primary beams intersect in the plasma in front of the thruster exit plane, defining the observation region by their common volume, as well as the observation wave vector properties. Heterodyne detection is used to detect the scattered signal: the interference between the plasma-scattered radiation and the frequency-shifted local oscillator beam produces a term from which the amplitude and phase of the plasma-scattered signal alone may be extracted, after appropriate filtering, amplification, and post-processing. Signal detection requires both a high resolution and a very large sample depth for post-acquisition signal treatment. The bench uses a 14-bit digitizer card, with acquisitions of two channels of typically 6.5 million samples at a rate of 50 MHz.

Experiments are performed at the national thruster facility PIVOINE, on the 5 kW PPSX000-ML thruster (SNECMA), which is operated using xenon propellant.
The optical bench is shown in Fig. 2.

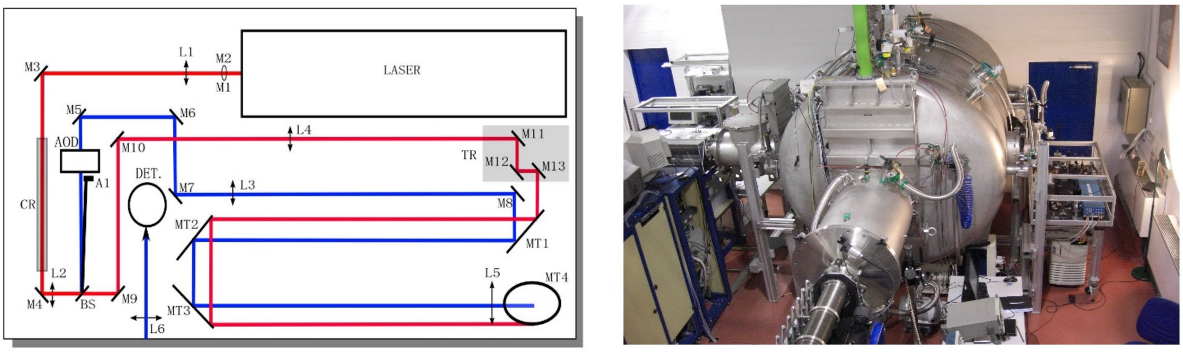

Figure 2: The PRAXIS diagnostic: (left) a schematic of the optical trajectories showing the primary (red) and blue (local oscillator) beams. The diagnostic is installed at the PIVOINE thruster facility (right) during experiments. A structure of external mirrors is mounted on support beams around the vessel, in order to guide and recover the plasma-scattered wave

4 Experimental results

The predicted mode was successfully identified in the experiment [3]. A sample spectrum is shown in Fig.3, following averaging of Fourier transform segments of the signal time series. The plasma signal (blue) shows signal peaks around ± 5 MHz, with the positively-signed peak corresponding to observations from one channel (where the wave vector is pointing in the same direction as the wave propagation), and the negatively-signed peak to observations from the opposite channel. For the case shown, the observation length scale is 0.7 mm. A plot of the frequency-wavenumber variation, together with the fluctuation amplitude levels, shows a linear variation, with a group velocity corresponding to 3.5 km/s.

Apart from identifying the predicted instability, the collective scattering experiments revealed other interesting properties of the mode. Contrary to initial theoretical ideas, which considered a purely azimuthal, or azimuthal-axial propagation of the instability, experiments showed the necessity of a full three-dimensional description of the mode,

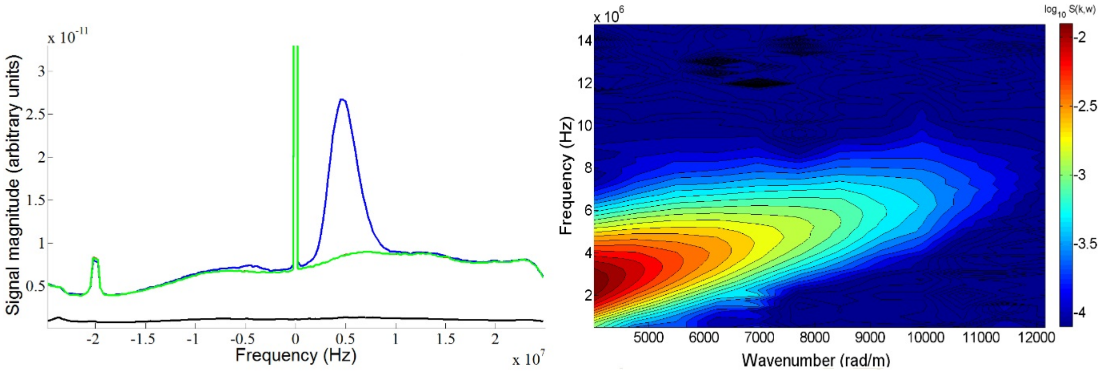

Figure 3: Typical spectra obtained from the experiment, after signal averaging (left). The plasma-scattered signal is in blue, and the laser noise is in red. The experimental dispersion relation of the instability is shown (right), showing the variation in peak frequency as a function of the observation length scale (right)

accounting for the radial component (the wave vector component parallel to the magnetic field). This idea, together with the ion contributions, was used to refine the dispersion relation to the full form shown in Eq. 1[4].

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

In Eq.1, v_{the}, v_{thi} represent the electron and ion thermal velocities, v_i the ion axial velocity, and λ_D, λ_{Di} the electron and ion Larmor radii, and $\zeta_m = \frac{\omega-k_yV_d-m\omega_{ce}}{k_z v_{the}\sqrt{2}}$ and $\gamma = \left(\frac{k_\perp v_{the}}{\omega_{ce}}\right)^2$.

From a close examination of the mode amplitude variation as a function of the orientation of the observation wave vector in two planes (the $(\vec{E},\vec{E}\times\vec{B})$ and $(\vec{B},\vec{E}\times\vec{B})$ planes) it was possible to obtain a characterization of both the mode directivity.[5] The mode was observed to propagate with a 10 degree inclination toward the thruster face in the $(\vec{E},\vec{E}\times\vec{B})$ plane, and an inclination in the $(\vec{B},\vec{E}\times\vec{B})$ of about 5 degrees. These results are summarized by the projection in Fig. 4, where α represents the angle measured from the axial direction in the $(\vec{E},\vec{E}\times\vec{B})$ plane, and β the angle measured from the radial direction in the $(\vec{B},\vec{E}\times\vec{B})$ plane.

The experiment revealed an exponential scaling law for the mode fluctuation amplitude over the length scales studied (0.4 to 1.8 mm). The fluctuation amplitude drops off as a function of wavenumber with an e-decrement on the order of the electron Larmor radius. An integration of the fluctuation intensity over the wave vector space was performed using the knowledge of this scaling law, and the angular distribution of the mode amplitude in the $(\vec{E},\vec{E}\times\vec{B})$ and $(\vec{B},\vec{E}\times\vec{B})$ planes. This provided an estimate of the absolute density fluctuation level, which is only 3 % for a mean density of 10^{18} per m^3. This provides an illustration of the very high level of sensitivity of the diagnostic.

5 Conclusions

The development of the PRAXIS diagnostic has provided a new tool for studying thruster plasmas. With support for theoretical models, and detailed information on instabilities,

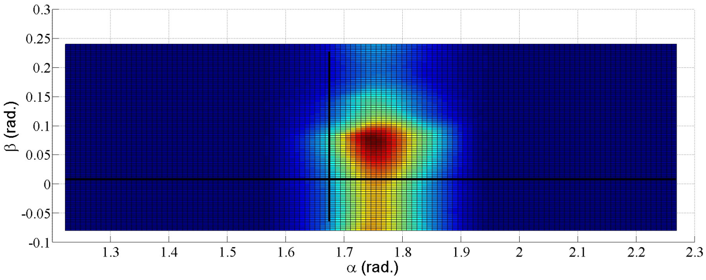

Figure 4: Angular directivity of the instability, a projection shown using the two planes of observation. The thick black horizontal and vertical lines show angles corresponding to the origins of the radial and azimuthal directions respectively

clearer ideas on the origins of anomalous electron transport are now available. Challenges remain in the understanding of thruster physics, however. The non-linear coupling of a number of phenomena in the thruster means that in addition to new diagnostics, sophisticated theoretical models must continue to be developed.

6 Acknowledgments

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