Spatio-temporal fluctuation spectra in the Hall thruster plasma : electron density and the induced electron transport

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Hall thruster performance improvement requires a good understanding of electron transport through the ion acceleration zone. In this zone, electrons are confined thanks to a permanent radial magnetic field. The electron mobility in the axial direction is higher than predicted by collisional models and more localized at the thruster exit than predicted by Bohm models. PIC simulations show small scale instabilities could be a good candidate for explaining this anomalous transport.

Collective scattering measurements performed in front of a Hall thruster [3] showed the presence of small scale (mm) fluctuation modes in the azimuthal ExB drift direction as foreseen by linear models and PIC simulation [1, 2]. These observations were compared with 2D axial-azimuthal PIC simulations [5, 7]. From PIC simulation result analysis, we emphasize the spatio-temporal behavior of this mode. Thruster front plasma observations with Langmuir probes show a fast large scale azimuthal mode is also present in front of the thruster [8]. The intensity of this mode also present in PIC simulations is compared to the intensity of the small scale one.

A model to link small scale azimuthal instabilities to the electron axial mobility is presented [6].

Axial and azimuthal 2D PIC simulation : small scale azimuthal mode spatial correlation

Using the electron density or the azimuthal electric field time snapshot 2D spatial map, we observe the electron density small scale azimuthal fluctuation cross-correlation between 2 axial positions x_0 and x_1. The axial cross-correlation extreme absolute value decreases with the axial distance $|x_1 - x_0|$ showing the azimuthal fluctuations are correlated over a few millimeter width. This correlation width is plot as a function of x_0 initial position. Figure 1 shows the density azimuthal axial correlation is short (2 mm) inside the

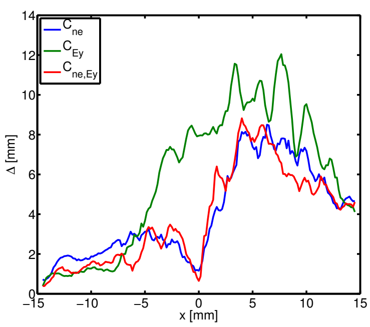

Fig. 1: Correlation width

ionization zone ($-15 \leq x_0 \leq -8mm$), and is rather long (7 mm) in the acceleration zone ($-8 \leq x_0 \leq 8mm$). As we apply the same treatment to the electric field azimuthal component, or to the density and electric field cross-correlation, we observe the correlation width is at least as large in the acceleration zone.

The small scale mode propagates with α angle from the pure azimuthal direction. This angle can be observed through the azimuthal variation of the correlation extreme position with the correlation distance $x_1 - x_0$ for each axial position. Figure 2 shows the variation of this mode angle with the axial position has the same behavior for the electron density or the azimuthal electric field (negative values correspond to the direction toward the thruster). This angle varies from -45^o to 0 along the axis. If ion convection plays a role in the mode propagation, this could explain part of the α angle reduction along the axis.

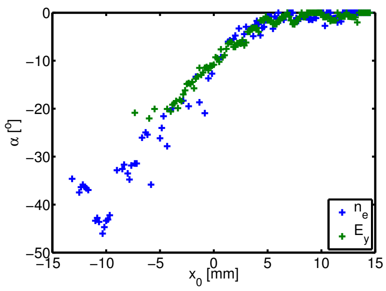

Fig. 2: Mode angle

The small scale slow azimuthal mode and the large scale fast one

Figure 3 shows the time evolution of the potential azimuthal fluctuations at the thruster exit position for the PIC simulation. It shows two different modes : a small scale (millimeter) mode with a velocity (given by the wave front slope and estimated as 2.3 km s^{-1}) close to the ion acoustic velocity, and a large scale with a much larger velocity (450 km s^{-1}) of the order of ExB drift velocity at the thruster exit.

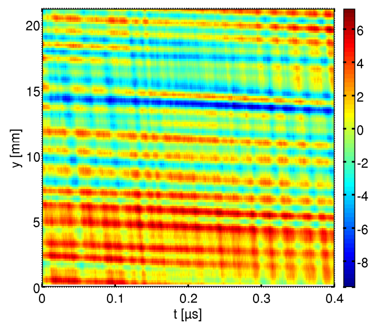

Fig. 3: Potential mode evolution

The azimuthal and temporal Fourier transform allows to separate these slow and fast modes (figure 4) : for $k \leq 1500$ m^{-1} discrete high frequency modes ($F \geq 20$ MHz) appear. For $k \geq 1500$ m^{-1}, only low frequency ($F \leq 5$ MHz) modes appear. The wavenumber range distinction allows to separate these low and high velocity modes.

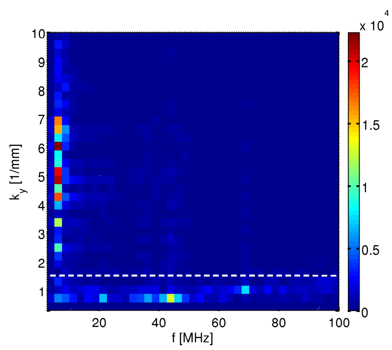

Fig. 4: Potential spectrum

Using the azimuthal Fourier transform it is possible to estimate the low to fast velocity mode intensity ratio along the axial direction. Figure 5 shows this ratio for the plasma potential, the azimuthal electric field component and the electron density. We observe that especially for E_y the azimuthal electric field and for the density, the low velocity mode dominates.

From small scale azimuthal fluctuation spectrum to the electron mobility model

Following former results [6], we propose here a mechanism which generates electron axial mobility from an azimuthal propagating electric field component with a wide wavenumber spectrum. For this model, the azimuthal electric field spectrum $S_E(k,\omega)$ is considered as a small perturbation for a single electron movement in an axial E_0 electric field and a given B_0 radial magnetic field. The electron Larmor radius is ρ_c and its drift velocity is v_d (and $\rho_d = |v_d/\omega_c|$).

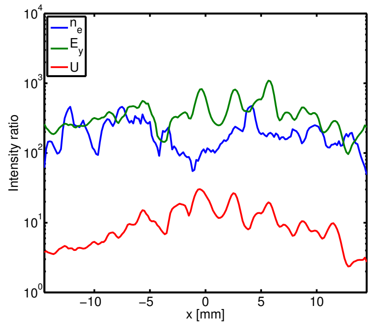

Fig. 5: Low to fast velocity mode intensity ratio

According to the perturbation development second order, the electron velocity u_{x2} in the axial direction is non zero when the azimuthal electric field frequency is close to a harmonic of the electron cyclotron frequency in the electron drift moving frame. If we take into account the Maxwellian distribution of the perpendicular velocity for the electrons with v_{th} as the mean velocity (ρ_{cth} is the corresponding Larmor radius), we obtain the mean mobility $\mu_G = \frac{\langle u_{x2}\rangle}{E_0}$ deduced from the mean axial electron velocity $\langle u_{x2}\rangle$ for this thermal velocity :

$$\mu_G = \frac{\pi}{4B^2E_o}\int dkk\Sigma_N\{S_E(k,\omega = kv_d + N\omega_c)e^{-k^2\rho_{cth}^2}\Sigma_n I_n(k^2\rho_{cth}^2)(1-2\frac{n-N}{z})\frac{d}{dz}J_{n-N}^2(z)|_{z=k\rho_d}\}$$

Inside μ_G expression integral, the azimuthal electric field is weighted for each N by the function $f_{N,G}$:

$$f_{N,G}(k,v) = ke^{-k^2\rho_{cth}^2}\Sigma_n I_n(k^2\rho_{cth}^2)(1-2\frac{n-N}{z})\frac{d}{dz}J_{n-N}^2(z)|_{z=k\rho_d}\}$$

Because the drift velocity v_d is much larger than the electric field spectrum mode velocity v_φ, and because the electric field wavenumber spectrum decreases exponentially, the main term is for $N=-1$. Figure 6 shows this weighting $f_{-1,G}(k,v)$ function behavior. Wavenumber axis is normalized by ρ_d^{-1}. velocity axis is normalized by v_d. $S_E(k, kv_d - \omega_c)$ is large for $k \sim \rho_d^{-1}$ and $v \ll v_d$: around these values $f_{-1,G} \sim -0.286$ is negative : the electron velocity is oriented in opposition to the ion velocity, as expected.

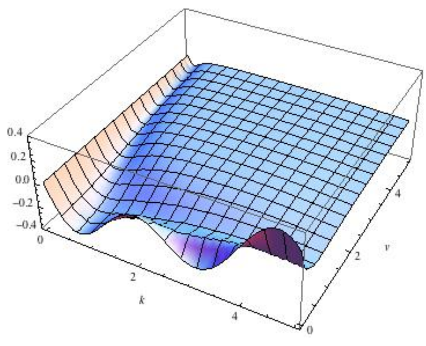

Fig. 6: $f_{-1,G}$ weighting function

In order to estimate $S_E(k,\omega)$ from collective scattering measurements that give the electron density spectrum $S_{ne}(k,\omega)$, we have to link the azimuthal electric field fluctuations $\tilde{E}_y$ with the electron density fluctuation $\tilde{n}_e$. The simplest relation is given by the no magnetic field fluid approximation : $\tilde{E}_y = k_0 \frac{k_B T_e}{q_e} \frac{\tilde{n}_e}{n_{e0}}$ (where k_0 is the main mode wavenumber). Figure 7 shows the observed value of both members of this relation along the thruster axis according to the PIC simulation. It shows both terms are of the same order but the trends are not the same.

Conclusion

The small scale mode axial correlations show this mode is persistent over quite long distances, even if the main plasma parameters (the magnetic field and the axial electric field) vary consequently along this axis. Even if this mode is persistent the relation between the electron density fluctuations and the azimuthal electric field fluctuation is not direct.

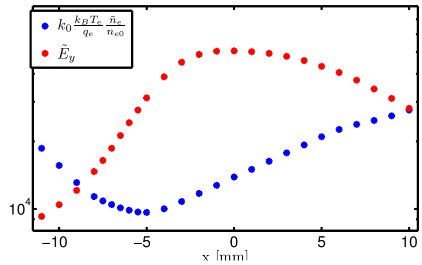

Fig. 7: $\tilde{n}_e$ and $\tilde{E}_y$ comparison

Acknowledgement : this work was performed in the framework of the collaborative-research program GdR 3161 CNRS-CNES-Snecma-Universities “Propulsion par Plasma dans l’Espace“

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