

Investigation of high-frequency plasma oscillations in Hall thrusters

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Numerous plasma instabilities with frequencies ranging from the kHz to the GHz are observed in Hall thrusters [1]. Besides the large amplitude low frequency (10-30kHz) oscillations (the so-called "breathing mode") high-frequency (> 1 MHz) bursty fluctuations are also frequently observed. These high frequency bursts are correlated to decay periods of breathing oscillation component of discharge current. Previous analyses of signals taken from azimuthally separated probes have shown clear evidences of an azimuthal propagation at a velocity of the order of the $E \times B$ drift [2]. The physical mechanism of these HF bursts is not yet clarified, but they could play an important role in the cross-field axial transport of electrons.

Experimental set-up

The experimental data were obtained with the PPS-X000 Hall thruster, which is a 5 kW-class laboratory model of the PPS-5000 Snecma's thruster, at the French national facility PIVOINE. Typical values of plasma parameters in 1.5 kW Hall thrusters are: an axial electric field $E_z \sim 10^4$ V/m, a radial magnetic field $B_r \sim 20$ mT, an electron temperature $T_e > 10$ eV, a charged particle density (under quasi-neutrality condition) $n_i \approx n_e \sim 10^{17}$ m⁻³, and a mass flow rate of gas $\dot{m}_a \sim 5$ mg/s.

HF fluctuations were recorded by using a three-probes arrangement with azimuthal and axial separation of shielded Langmuir probes installed around the accelerating channel external wall and outside the ionic plume. Their active part is made of 0.125 Ta wire and has a length of ~ 6 mm. To access the azimuthal propagation properties of the fluctuations two probes (P1 and P2) were aligned in the channel cut-off plane separated by a fixed distance of 1.1 cm between their tips, as sketched in Fig. 1a.

To access the axial propagation properties of the HF fluctuations two probes spaced at 1 cm (P3 and P4) were aligned along the thruster axis (Fig. 1b). In this second configuration the probe pair could be moved in axial and radial directions. The axial position L_h of the P3 tip relatively to the channel cut-off and the radial position L_r relatively to the channel external wall define the probe pair location (see Fig. 1b). The probe signals are recorded on a digital 4-channel Tektronix 5104B oscilloscope in AC 50 Ω mode. Typical recording length is 80 μ s at a sampling rate of 1.25×10^9 Samp/s. In a second campaign (Fig. 4b) a different probe arrangement consisting of three fixed axially aligned probes located very close to the exit plane was used.

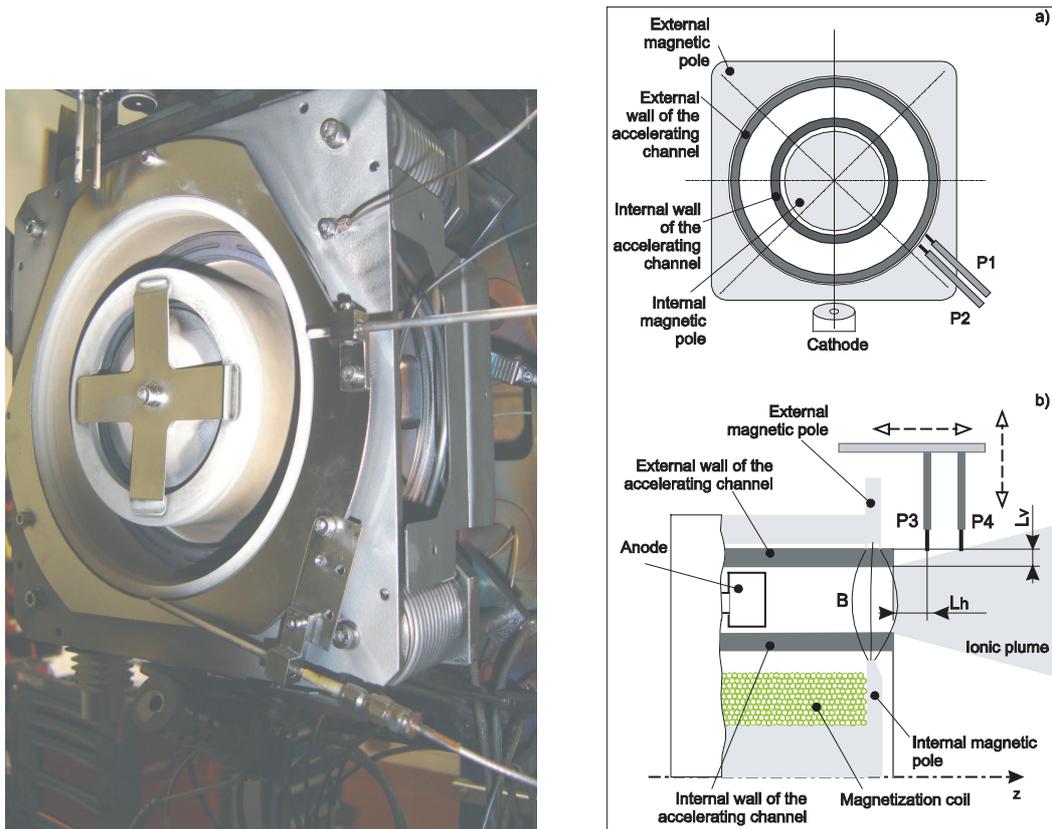


Figure 1: View of the PPS-X000 thruster and probe location. a) front view: for estimating azimuthal correlations, $L_{P1-P2} = 1.1$ cm; b) side view (transversal cut): for estimating axial correlations, $L_{P3-P4} = 1$ cm; the magnetic field geometry is shown schematically.

Results and discussion

Because of the strong intermittent and nonlinear character of the HF bursts (see Fig. 2) their propagation properties cannot be obtained by using simple Fourier methods and by calculating cross-correlation functions of times series taken at two azimuthally or axially separated probes.

Instead, the data are analyzed by using wavelet-based methods, such as the wavelet cross-coherence, which make it possible to extract information not only about the average correlation and phase shift between two time series but also on its time-frequency distribution. Dispersion relations can thus be obtained from two-point measurement [3] as depicted in Fig.3b. A second method, based on the so-called Empirical Mode Decomposition [2] was also implemented. It consists first to apply the EMD in order to get a set of Intrinsic Mode Functions (IMFs) for each times series and then to cross-correlate the corresponding IMF pairs. From the measured time delay in each frequency range we thus obtain an effective dispersion relation as depicted in Fig. 3a for the same time series. The points corresponding to the different IMF pairs fit very well a line crossing the origin, which slope is 3.15×10^6 m/s, of the order of the $E \times B$ drift

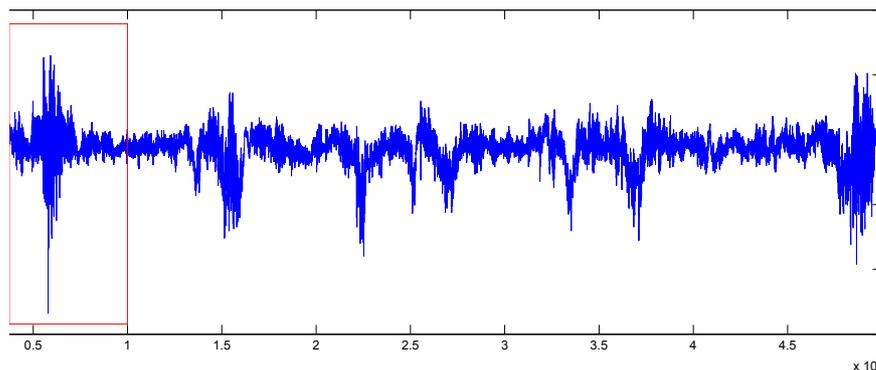


Figure 2: Time series of plasma fluctuations (mass flow rate $\dot{m}_a = 6$ mg/s, discharge voltage $U_d = 700$ V. The frame indicates the burst related to Fig. 4b.

velocity. This corresponds to a non dispersive behaviour of azimuthally propagating waves with mode number from $m = 1$, $f \sim 7$ MHz up to $m \sim 20$, $f \sim 120$ MHz.

The situation depicted in Fig. 4 is much more difficult to understand. It corresponds to two axially separated probes. We observe a change in the sign of the time shift in the cross-correlation functions with increasing frequencies. We still do not know if such time shifts correspond to a true axial propagation property of the HF fluctuations or if this is only a consequence of some special phase variation along the axial direction, i.e. the inhomogeneity direction. Anyway the results are reproducible and this experimental evidence of the combined axial and azimuthal phase shift distributions could bring new ideas on the excitation mechanism of the HF bursts and on their role regarding the cross-field transport.

Besides these correlation studies we started to use the wavelet bicoherence to study nonlinear coupling phenomena and energy transfers between fluctuations of low and high azimuthal mode numbers and preliminary results have been obtained.

Acknowledgments

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References

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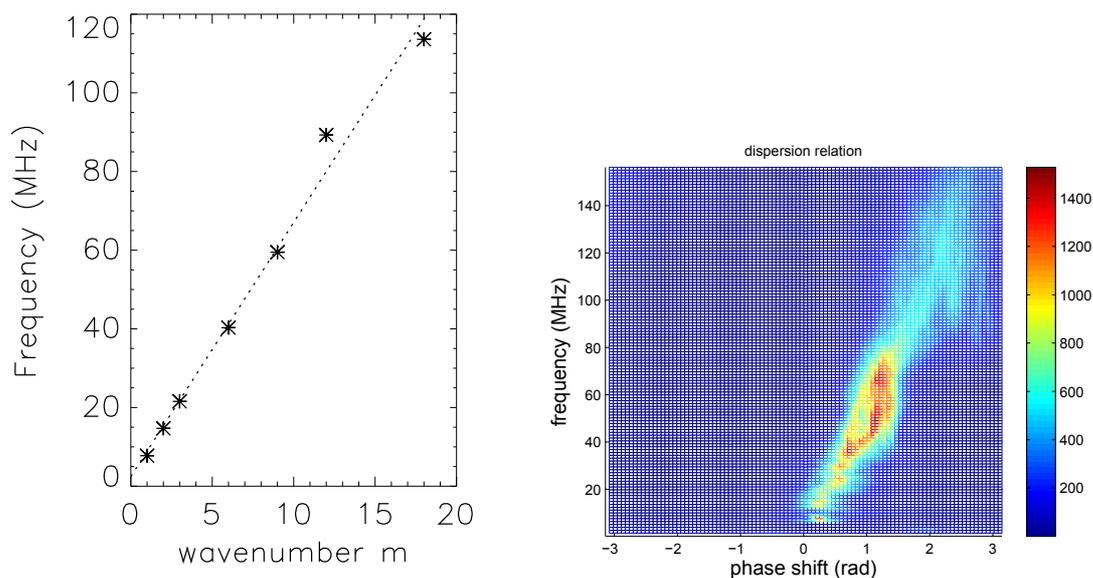


Figure 3: Azimuthal dispersion relation a) (left) from EMD and b) from wavelet cross-coherence. Mass flow rate $\dot{m}_a = 6$ mg/s, discharge voltage $U_d = 350$ V.

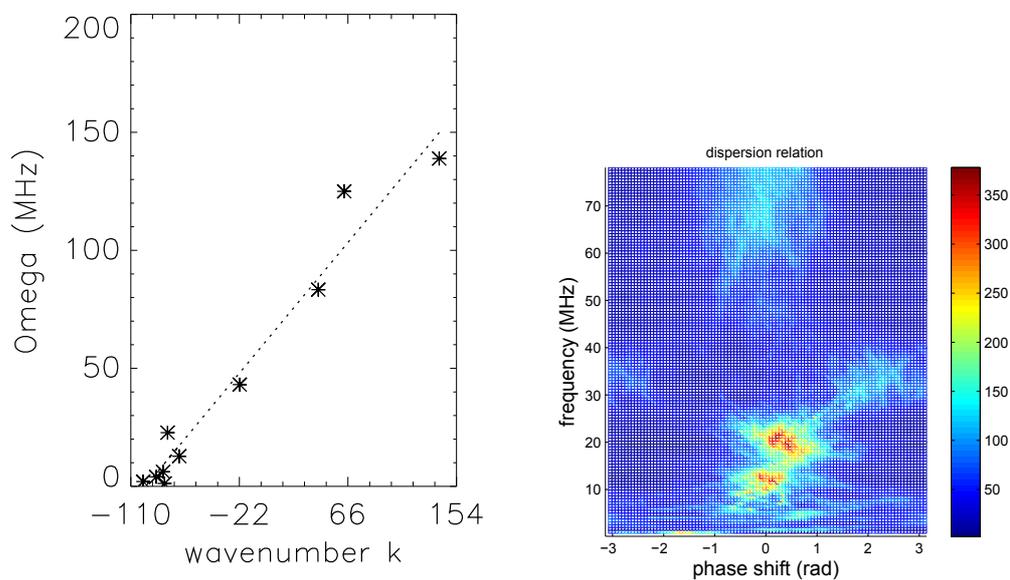


Figure 4: Axial phase shift vs. frequency a) (left) From EMD ($\dot{m}_a = 8.34$ mg/s, $U_d = 550$ V) and b) From wavelet cross-coherence ($\dot{m}_a = 6$ mg/s, $U_d = 700$ V). With the second probe arrangement with probes separation 3.8 mm.