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A collective scattering device for observation of a Hall thruster plasma

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Numerical models and simulations of ExB plasma discharges predict micro fluctuations at low frequencies and at the scale of electron cyclotron radius [1]. This paper describes the first experimental observation of volume fluctuation in these ranges.

Optical bench and principle

Volume plasma density fluctuations are diagnosed by the collective scattering of a CO_2 laser beam. The optical bench PRAXIS (PRopulsion Analysis eXperiments via Infrared Scattering) uses an RF-driven laser source with a beam power of 42 Watts DC, TEM00 with M^2=1.2. PRAXIS is shown in Figure 1, and a schematic of the observed region is shown in Figure 2.

Figure 1

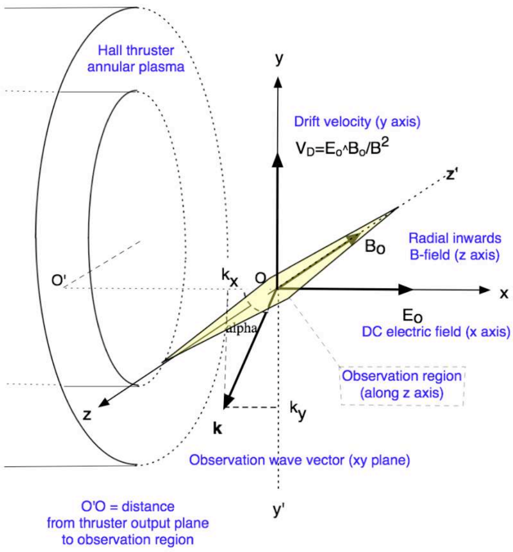

Figure 2

The thruster output jet is situated on axis of the vacuum test facility chamber PIVOINE [2]. The beam is sent to the plasma from a lateral window at a distance of 1.2 m from axis. It is focused in this central region with a waist of 2.5 mm. Scattered light is collected from a symmetrical window situated on the other side of PIVOINE at scattering angles θ from 6 to 20 mrad. A high sensitivity photodiode collects the scattered light together with a reference beam. The heterodyne detection scheme provides a complex signal that is proportional to the spatial Fourier transform of the electron volume distribution n(**r**, t) [3][4] at a wave vector **k** equal to the difference between the scattered $\mathbf{k}_s$ and incident $\mathbf{k}_i$ wave vectors , $\mathbf{k}=\mathbf{k}_s-\mathbf{k}_i$.

A mobile scattering plane allows for the scattering wave vector **k** to be axial (k_x) or transverse (k_y) to the thruster axis. The observation zone is centered on one side of the annular thruster plasma.

The frequency spectrum is calibrated as the "dynamic form factor" *S(k, ω)*[3][4] in units of sec^{-1} . This is done using the ratio of the scattered signal spectral density *I(k,ω)* to the photonic noise spectral density $I_{ph}(k,\omega)$,

$$S(\omega,k)=\frac{h\nu}{\eta P_0}\frac{\pi w^2}{\lambda^2 r_0^2}\frac{1}{n_0 L}\frac{I(k,\omega)}{I_{ph}(k,\omega)} \qquad (1)$$

Signal processing and spectra

The photocurrent which issues from the detector is amplified in a low noise pre-amplifier and demodulated into its real and imaginary parts by the second, analogous stage of the heterodyne detection. These two parts are simultaneously recorded at a rate of 50 MHz into two memory buffers each of $6.5\text{x}10^6$ samples. The samples are transferred to a computer, and a complex Fourier spectral analysis is performed.

As a background to the signal spectral density, the photo detection method provides a uniform photon noise density. In order to extract a weak scattered signal spectral density from this intrinsic base noise, the same spectral analysis is repeated a large number of times: the temporal Fourier analysis is typically performed 32500 (N) times over sequences of 200 consecutive samples, and spectra are cumulated to obtain a mean Fourier spectrum with a variance reduced by $\sqrt{N}$ i.e., about 180.

Each observation is made as a series of three different records of the detector preamplifier output: the amplifier's circuit noise (with the photo detector window closed); the "photon plus amplifier" noise (open detector window, no plasma); and the total signal (open window, laser beams and thruster on).

The plasma fluctuation spectrum is obtained by subtracting the spectra of the third record from that of the second. The relative value of this difference is weak, but is however significant as soon as it is larger than 10^{-2}. The dynamical form factor (Eq. 1) in absolute units is obtained by taking the ratio of this plasma spectrum *I(k, ω)* to the spectrum of photonic noise $I_{ph}(k,\ \omega)$. The latter is obtained as the second minus the first spectrum. A plasma density

$n_0=10^{18}$ m^{-3} and an observed length L=5cm are assumed throughout the normalization procedure.

The Hall thruster plasma is run at a bias of 300V, 17A current, inwards radial magnetic field and 20mg/s Xenon flux.

Frequency spectrum

Two different frequency spectra of the plasma signal are shown in Figure 3. The observed volume center is at a distance of 19 mm from the thruster output plane, and in the outer part of the plasma annular chamber (on the side of the laser source, see Fig. 2).

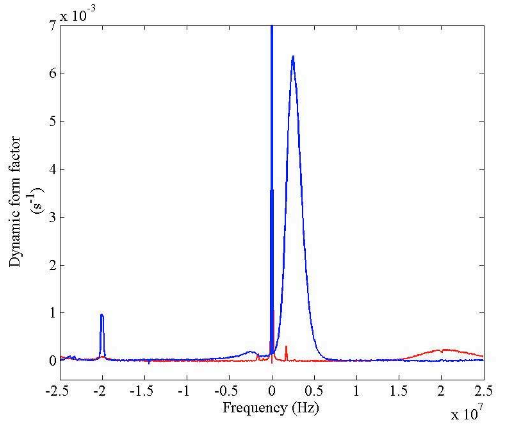

Figure 3

The wave number is 6200 rad/m, and each of the two spectra corresponds to a different direction. The blue spectrum is obtained when **k** is along the ExB (azimuth) axis. It shows a distinct peak at a positive frequency of 2.5 MHz, i.e. propagating along ExB, and a symmetric, less intense line at -2.5 MHz. For the red spectrum, k is aligned along the thruster jet axis: The line frequency is +20 MHz, propagating along the jet; its amplitude is smaller than for the previous case.

Dispersion relation

Fluctuations propagating in the axial or in the azimuth direction correspond to two different wave classes. Their line frequencies are plotted in Figure 4 as a function of the wave number when k is along the axis (red triangles) or along ExB drift (blue dots).

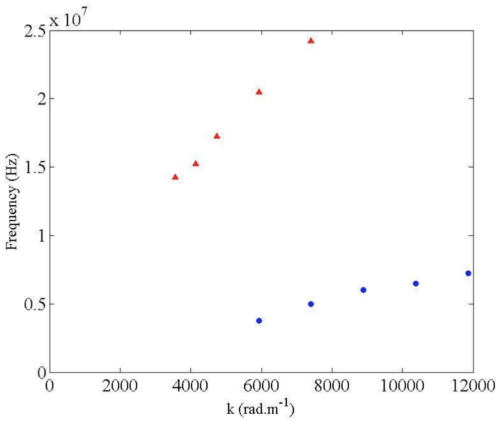

Figure 4

An almost linear variation is observed; the slope corresponds to a group velocity of 16 Km/s (axially propagating fluctuations) and 4.3 Km/s (ExB drift aligned fluctuations). The former is within 1% of the ion beam velocity (as measured by LIF in similar conditions [5]). The latter is much smaller than the ExB drift, but could correspond to the velocity of an ion acoustic wave in a xenon plasma of electron temperature 25 eV.

Form factor and spatial distribution

The frequency integrated spectrum provides the form factor S(k). This is plotted in Figure 5 in semi-log scales as a function of the axial distance as the thruster is moved backwards from the observation region. k (6200 rad/m) is oriented along the axis (red triangles) or along the ExB direction (blue dots).

When **k** is in the ExB direction the form factor is large, reaching a maximum at a distance of 14 mm and decaying almost exponentially until 100 mm. This is the region of significant ExB drift. For axial **k**'s, the form factor is initially smaller but it extends down to the thrusters far wake.

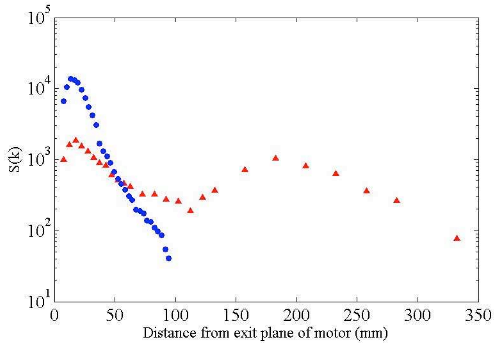

Figure 5

Collective scattering characterizes electron plasma density fluctuations in a Hall thruster by their dispersion relation, form factor and spatial distribution. Detailed comparisons with theory, PIC codes and anomalous transport fluid models can now be conducted for validations.

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