Plasma Diagnostics in an Applied Field MPD Thruster*

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The paper describes the main results of an investigation of the spatial structure and the temporal behavior of electron temperature, density and floating potential in the plume of a gas-fed, applied field MPD thruster (called Hybrid Plasma Thruster, HPT). The HPT consists of a central hollow cathode 20 mm in diameter, and an anode, consisting of a cylinder 200 mm in inner diameter and of eight straps, which divide a central chamber from a peripheral chamber. The thruster is powered by a pulse forming network, capable of delivering up to 15 kA for 2.5 ms. Tests were performed using a mass flow rate of 660 mg/s of argon, both with and without a 40 mT external magnetic field generated on the thruster axis by a 70-turns coil surrounding the thruster. A system of 7 aligned electrodes was inserted into the thruster plume in order to simultaneously measure both average values and fluctuations of electron temperature, electron density and plasma potential using the balanced triple probe configuration. It is shown that the external magnetic field flattens the density profile and increases the fluctuation levels of electron temperature and density. Moreover, the power spectra of the measured plasma quantities, obtained with the wavelet technique, at various thruster operating conditions, exhibit a correlation with the plasma density.

Introduction

Magneto-plasma-dynamics (MPD) thrusters are currently under investigation as a possible high-power electric propulsion system for space missions. The addition of a magnetic field has proved to increase the performance. However, critical regimes, observed when the power is increased, limit at present the performance of these thrusters. In the critical regime, large fluctuations in cathode and anode voltage are measured. In order to understand the origin of these large fluctuations, and the role in the deterioration of the overall performance, an investigation of the mean and fluctuating plasma parameters such as electron density and temperature has been carried out by an array of electrical probes. In this paper the analysis has been focused on the effect of an externally applied magnetic field.

The Experimental Apparatus

The experimental apparatus, shown in Fig.1, is an axisymmetric MPD thruster with an applied magnetic field, called Hybrid Plasma Thruster (HPT) [1, 2, 3]. The HPT, developed by RIAME-MAI and Centrospazio, consists of a central hollow cathode (copper, 20 mm diameter, 50 mm length), through which 70-90% of a gaseous propellant is injected in the discharge chamber, and an anode, consisting of a cylinder (aluminum, 200 mm inner diameter, 180 mm length) and eight straps, made of copper, which divide a central chamber from a peripheral chamber. 10-30% of the propellant is injected through eight peripheral hollow electrodes (copper, 12 mm in diameter each). These electrodes can be used as auxiliary cathodes to pre-ionise the peripheral propellant by means of a secondary discharge between the cathodes and the anode. The peripheral electrodes were not activated during the tests described herein. A 70-turns coil surrounds the

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thruster and can be powered in order to generate a magnetic field up to 100 mT on the thruster axis.
The thruster is mounted on a thrust stand inside the Centrospazio IV3 vacuum chamber, capable of maintaining a back pressure during the pulse in the 10^{-4} mbar range. The electric power to the HPT is supplied by a Pulse Forming Network (PFN), configurated to supply quasi-steady current pulses 2.5 ms long. The propellant is injected by two gas feeding systems, one for the central cathode and the other for the peripheral cathodes, based on fast acting solenoid valves, which provide gas pulses with long plateau after few milliseconds from valve activation [3]. When a steady state mass flow is reached, the electric circuit is closed by switching an ignitron on and the discharge takes place. The solenoid is supplied by a DC generator, switched on few seconds before the discharge. Fig. 2 shows typical current and voltage signals.

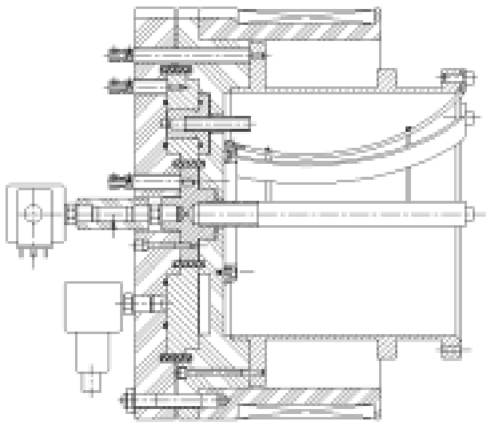

Fig. 1: Schematic drawing of the thruster assembly.

Diagnostics description

The probe system consists of 7 aligned graphite electrodes, 8-mm apart from each other, and housed in a boron-nitride case. The probes were used in a five-pins balanced triple probe configuration [4] to avoid phase shift problems and to obtain simultaneous measurements of electron density and temperature. The signal bandwidth was 500 kHz and the sampling frequency is 10 MHz in order to obtain measurements of both average value and fluctuations of electron temperature, electron density and plasma potential. The central electrode was placed at 80 mm from the thruster outlet, along the thruster axis; with respect to this position, other measurements were performed by moving the probe by 115 mm in the direction perpendicular to the axis of the thruster.

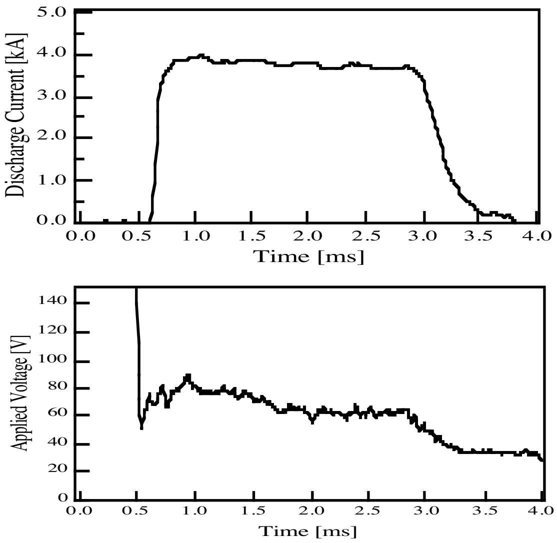

Fig. 2: Discharge current and arc voltage vs time.

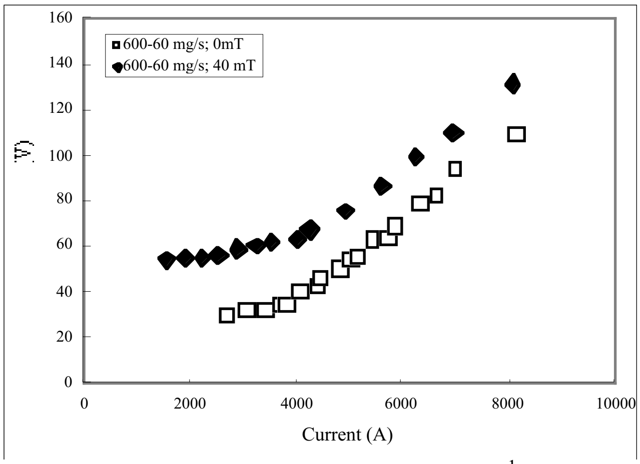

Fig. 3 Electrical characteristics (660mg s^{-1} of argon).

Thruster Performance

Tests were performed at a mass flow rate of 660 mg s^{-1} of argon (600 mg s^{-1} injected by the central cathode, 60 mg s^{-1} by the peripheral electrodes). The conditions with no applied magnetic field and with an applied field (maximum applied induction field of 40 mT on the axis) were investigated. Figs. 3 and 4 show the measured electrical characteristics and thrust. For each shot, current and voltage were measured by averaging on a window 100 microseconds long taken in the middle of the pulse. The thrust value was obtained by a ballistic method which measures the impulse of the thrust for each shot. The thrust is computed by dividing the measured impulse by the pulse duration, and thus the value represents an average thrust for each shot. Each data point in Fig. 3 and 4 was obtained as an average of the relevant values obtained from four-five shots at the same nominal condition (i.e. PFN charging voltage). Current and voltage measurements showed a good repeatability (the uncertainty is within the marker dimension). Error bars on thrust measurements include both the standard deviation and the measurement uncertainty (about 10% of the thrust value) [2, 3].

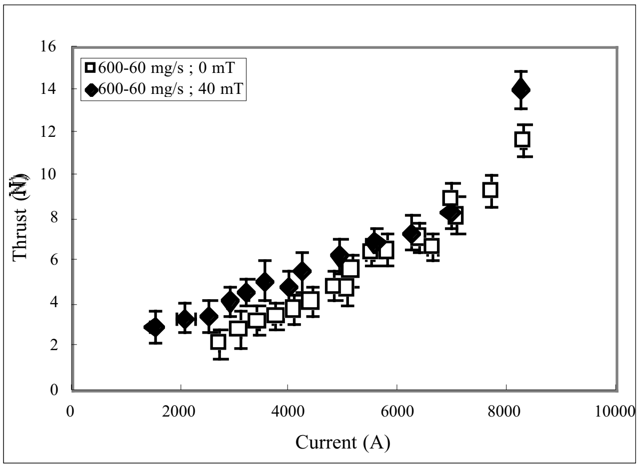

Fig. 4: Thrust vs current (660 mg s^{-1} of argon).

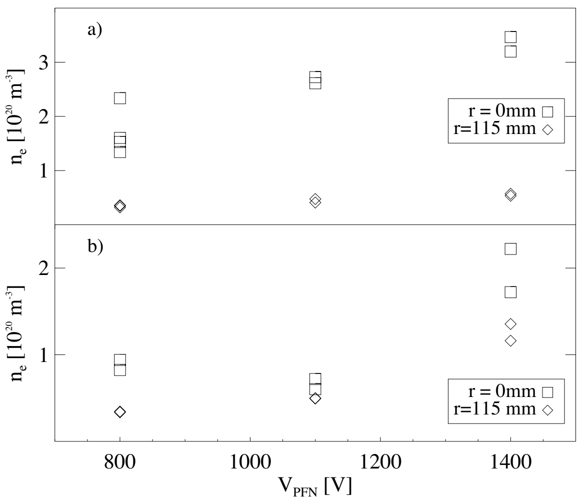

Fig.5: Density at different V_{PFN} for two different radial position without external magnetic field a) and with external magnetic field b).

Measurements of mean parameters

To relate the thrust to the plasma main parameters, the electron density and temperature, averaged in a time interval of 0.1 ms around t = 1 ms have been analysed by comparing different conditions of input power (i.e of V_{PFN}) and magnetic field. In figure 5 a) the density in two different positions (on axis r = 0 and off-axis r = 115 mm) is shown for different values of V_{PFN}. It appears that the density, which is typically of the order of some 10^{20} particle/m^{-3}, is peaked around the axis. On increasing the input power, the difference between the values on axis and off-axis slightly increases, indicating a tendency to peaking with V_{PFN}.

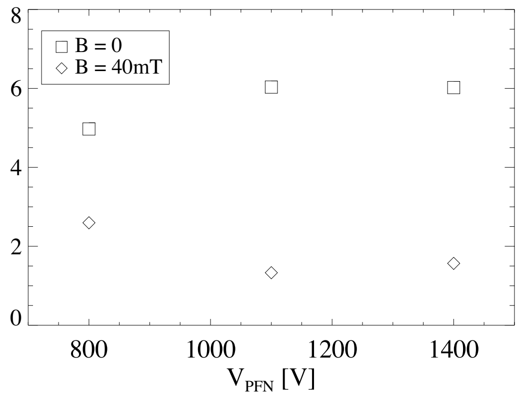

Fig. 6: Ratio of density value at r =0 and r = 115 mm as a function of applied voltage with and without external magnetic field.

The effect on the density of the external magnetic field B_{ext} is shown in figure 5 b). The application of B_{ext} reduces the electron density on axis and increases that at r = 115 mm, flattening the profile with a tendency to further flattening at higher V_{PFN}. To summarise the effect on the profiles, the ratio between the density value at r = 0 and r = 115 mm is shown in figure 6 as a function of V_{PFN}. The values range from 6 to 5 without B_{ext} and from 2.5 to 1.5 with B_{ext}.

The analysis of the electron temperature has revealed a different behaviour with B_{ext}. In figure 7 a) the values of T_e at two different radial positions for shots without B_{ext} are shown as a function of V_{PFN}. The typical values span from 3 to 5 eV with a tendency to a slight increase with V_{PFN}. An important observation is that temperature profiles are rather flat: there are little differences between values on axis and values off-axis.

The application of the external magnetic field causes an increase of the value of T_e as observed in figure 7 b) which assumes value from 6 to 9 eV. In figure 8 the ratio between T_e at r = 0 and r = 115 mm for shots with and without external field are shown.

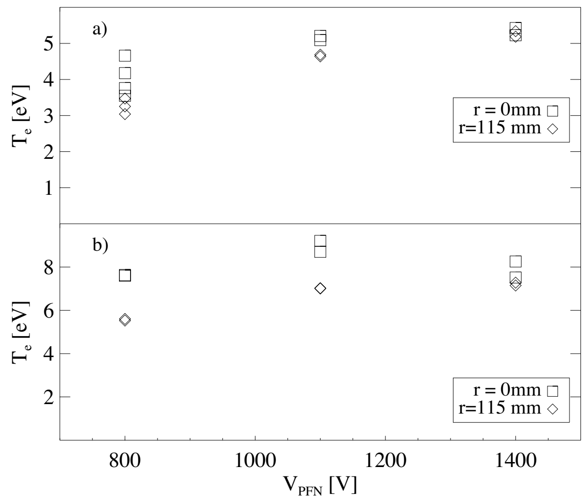

Fig.7: a) Electron temperature value at different V_{PFN} for two different radial positions without B_{ext} a) and with B_{ext} b).

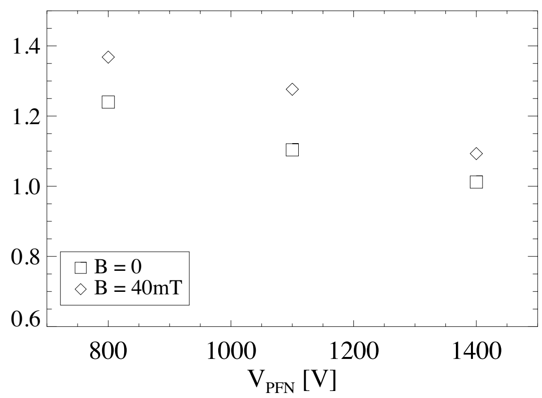

Fig. 8: Ratio of electron temperature value at $r = 0$ and $r = 115$ mm as a function of applied voltage with and without external magnetic field.

To summarise, it has been observed that without B_{ext} density profiles are peaked while temperature profiles are flat. The application of an external B_{ext} increases the temperature and reduces the density, flattening its profile. Since the thrust is strongly affected by the application of the external magnetic field, a close relationship between mean profiles of density and temperature and thruster performance is expected. In particular the different behaviour of density and temperature profiles could indicate different mechanisms underlying the transport processes responsible for their diffusion in the radial direction. It is known from plasma fusion experiments that plasma turbulence largely affects transport across magnetic field lines.

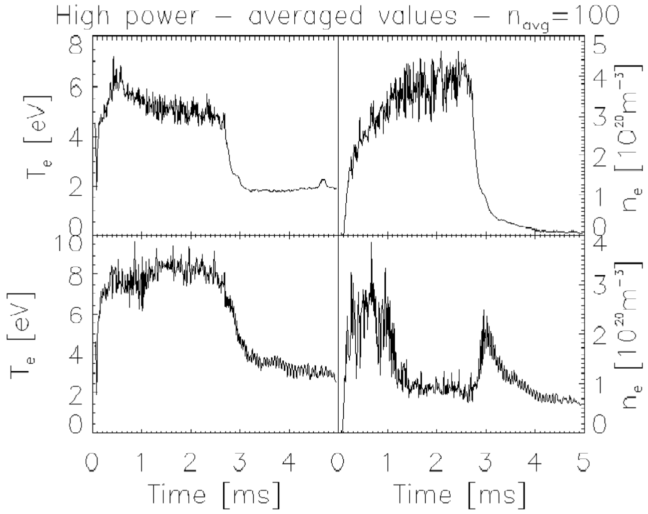

Fig.9: Temporal behaviour of T_e and n_e at high power pulses (V_{PFN} = 1400 V) vs time: upper figures without B_{ext}, lower ones with B_{ext} = 40mT.

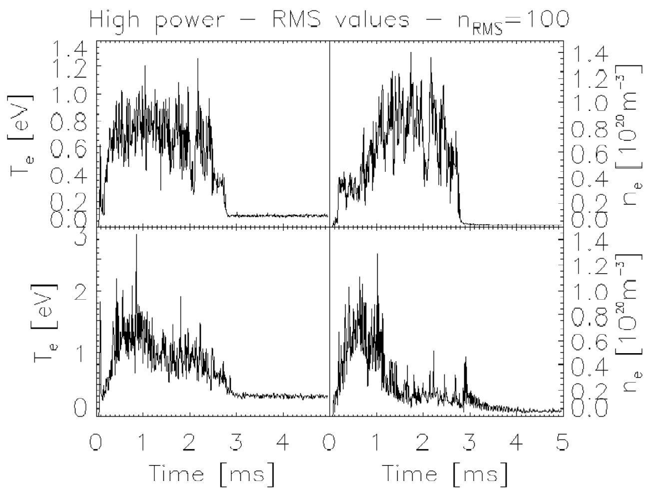

Fig.10: Temporal behaviour of RMS of T_e and n_e vs time at V_{PFN} = 1400 V: upper figures without B_{ext}, lower ones with B_{ext} = 40mT.

As in MPD thrusters magnetic fields self generated by the flowing current and by external field are present, the study of the electrostatic fluctuations has been addressed to characterise the regimes with and without external field and in particular the onset of the critical regimes at higher power. These regimes are characterised by a high level of fluctuations on cathode and anode voltage, and by a decrease of the density close to the cathode.

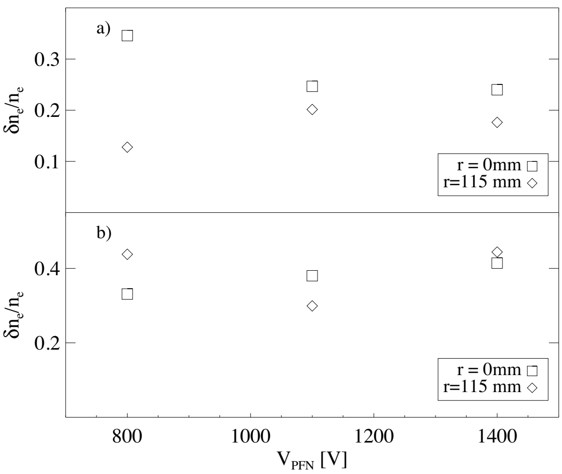

Fig.11: Average RMS value of n_e normalised to average value as a function of V_{PFN} for two different radial position without B_{ext} a) and with B_{ext} b).

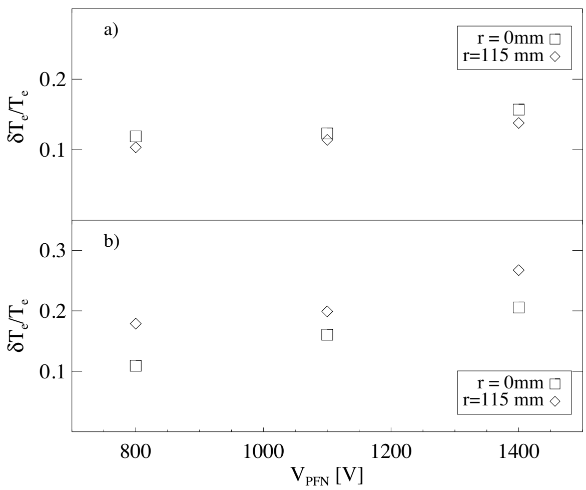

Fig.12: Average RMS value of T_e normalised to average value as a function of V_{PFN} for two different radial position without B_{ext} a) and with B_{ext} b).

Measurement of fluctuations

As an example, in figure 9 the time evolution of density and temperature in two different shots with and without external field are shown. The signals exhibit a high level of fluctuation throughout the discharge. The time evolution of the corresponding Root Mean Square (RMS) of the signals, obtained by averaging over 0.01 ms time intervals, is shown in figure 10. The application of an external magnetic field causes an increase of the absolute level of RMS for T_e and a reduction of the RMS of the density.

In figure 11 and 12, the mean value of the RMS normalised to the mean density and temperature are reported as a function of applied voltage. Each point is obtained averaging over an interval of 0.1 ms around t = 1 ms and over similar pulses.

Summarising the experimental finding, it is observed that the normalised RMS for density fluctuations is about twice that for temperature fluctuations, that the application of an external magnetic field tends to increase the normalised RMS and that higher power results in larger RMS of temperature fluctuations. It is also observed that, except for the density at low power, in general the normalised RMS values slightly depend on the radial location.

To obtain insights on the origin and time behaviour of these fluctuations, a spectral analysis of the fluctuating quantities has been performed. The wavelet technique [5] has been applied to study the temporal behaviour of the power spectra.

The power spectra reveal that most of the power is concentrated at frequencies below 300 kHz. In figure 13 a contour plot of the time evolution of the density and temperature fluctuation power spectrum (in logarithmic scale and normalised for each time value) is shown for the same discharges of figure 9. After the initial phase, the power spectrum of temperature (fig. 13 a)) exhibits a peak at 150 kHz which decreases to lower frequencies (~50 kHz at 2 ms) with time. A secondary peak appears at higher frequencies (~200 kHz) which is also shown by the density signal (fig. 13 b)). It was found that these peaks track the behaviour of the average density [6]. By applying the external field (fig. 13 c) and d)) the peaks disappear and a tendency towards a broadening of spectra is observed.

Conclusion

A preliminary study of the fluctuations of electron density and temperature in MPD thrusters with and without externally applied magnetic field has revealed the following properties:

Temperature and density profiles have different behaviour with power and externally applied magnetic field. In particular the application of an external magnetic field flattens the density profile. Fluctuation analysis reveals that normalised RMS of density are larger than those for temperature and that the application of an external magnetic field increases the fluctuation level. The power spectra analysis reveals that without magnetic field temperature fluctuations depend on the density

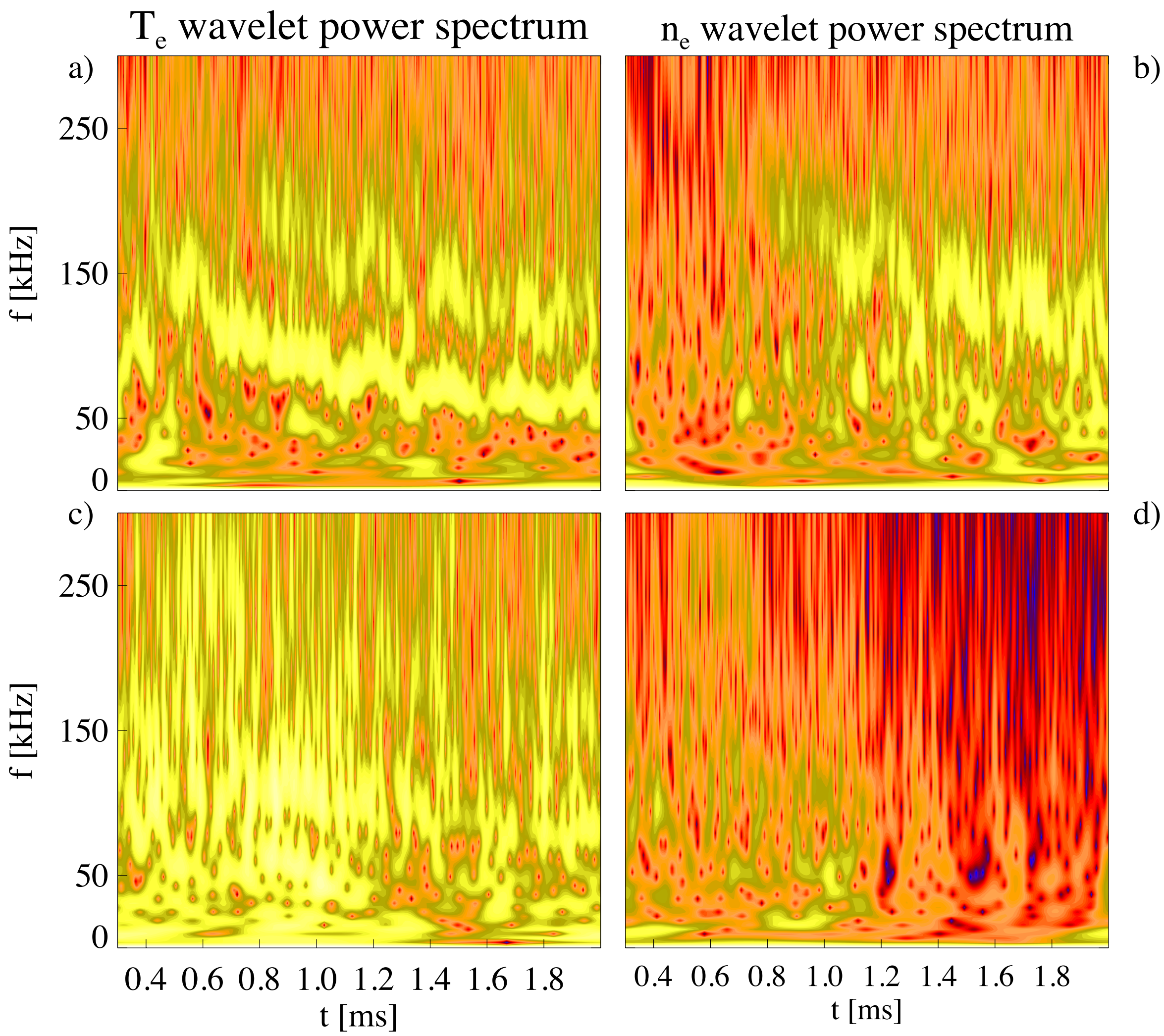

Fig. 13: Wavelet power spectrum of temperature and density signal at high V_{PFN} (1400 V): upper figures (a) and (b) without B_{ext}, lower ones (c) and (d) with B_{ext}.

value and that the application of an external magnetic field affects this dependence. All these findings suggest that the instabilities underlying the fluctuations are strongly affected by the application of an external field as well as the related profiles of the mean quantities. Further work on this field is in progress to identify the instabilities, to relate them to the mean profiles and to study the transport processes responsible for the profile modifications.

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