Experimental Evidence of Significant Temperature Fluctuations in the Plasma Edge Region of the TJ-I Tokamak

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Density and temperature fluctuations have been measured in the plasma bulk side of the velocity-shear location of the TJ-I tokamak using a fast swept Langmuir probe technique. Evidence has been found that substantial temperature fluctuations have a phase difference of close to π with respect to the corresponding density fluctuations. This result suggests the possible role of radiation in determining edge fluctuation levels and calls into question the determination of the density and potential fluctuations from the Langmuir current probe and floating potential fluctuations.

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Much effort is being made to determine the underlying mechanisms responsible for the anomalous transport observed in tokamaks and stellarators. Langmuir probes have been extensively used to characterize the structure of edge fluctuations. Measurements of the edge particle transport induced by fluctuations have been made by studying the correlation between density and plasma potential fluctuations, assuming negligible temperature fluctuations ([1] and references therein). Under this approximation edge electrostatic fluctuations can account for most of the edge particle transport. Although no satisfactory theoretical model has been developed to explain all the edge turbulence features, turbulence driven by radiative instabilities has been considered as a possible candidate to partially account for the observed edge fluctuation levels [2-7]. Two simultaneous mechanisms contribute to the radiative instabilities. In the plasma region where dI_z/dT_e is negative, I_z and T_e being the cooling rates and the electron temperature, respectively, a decrease in the electron temperature causes an increase in the radiative loss rate, resulting in a further decrease of the electron temperature (thermal instability). Furthermore, providing that there is a coupling mechanism between density and temperature fluctuations (i.e., pressure balance), a decrease in the electron temperature implies an increase in the electron density, with a subsequent increase in the radiative loss rate (condensation instability). The experimental signature of radiative instabilities is the presence of substantial temperature fluctuation. In the case of the condensation drive, a significant coupling between density and temperature fluctuations is expected; in particular, if the pressure balance condition is fulfilled [5], the phase between density and temperature fluctuations should be in phase close to opposition, that is the phase difference is close to π. Thus, the comparison between the level of temperature and density fluctuations and their relative phase can provide key information to understand the basic mechanisms driving edge turbulence.

In this Letter we present experimental evidence of significant edge temperature fluctuations which are in phase close to opposition with the corresponding density fluctuations.

Density and temperature fluctuations have been measured in the plasma edge region of the TJ-I Tokamak ($R=30$ cm, $a=10$ cm) using a fast swept Langmuir probe technique [8]. Measurements were done in Ohmically heated discharges with $B=1$ T, $\bar{n}_e \approx (1\text{-}2)\times 10^{13}$ cm^{-3}, and $I_p \approx 30$ kA. The vacuum chamber acts as a belt limiter. Impurity radiation in the edge is dominated by oxygen and carbon impurities. Typically Z_{eff} is of the order of 3 [9]. The probe system consists of a square array of four Langmuir probes (2 mm × 2 mm); pins are 2 mm long and 0.4 mm in diameter. A broadband (1 MHz), 75 W amplifier was used to supply a swept voltage (≈ 150 V) to a single probe at 300 kHz. Measurements were digitized at 5 MHz, using a 12-bit CAMAC digitizer. Two tips, aligned perpendicular to the local magnetic field, are used to measure the poloidal phase velocity of the fluctuations, deduced from the floating potential fluctuations; this measurement provides the position where the poloidal phase velocity of the fluctuations reverses propagation (shear layer) from the ion to the electron drift direction when moving radially inwards. The position of the shear layer ($a_{\text{shear}} \approx a$) has been taken as the point of reference for the measurements. The importance of the shear layer location on edge turbulence has been reported in experiments done in ATF which have shown that the structure of the turbulence appears to be different in the plasma bulk side of the shear layer ($r/a_{\text{shear}} < 1$) and in the scrape-off layer region ($r/a_{\text{shear}} > 1$) [10].

Current probe ($\tilde{I}_s/I_s$), temperature ($\tilde{T}_e/T_e$), and density ($\tilde{n}/n$) fluctuations have been determined by sweeping the applied voltage (V) to a single Langmuir probe at a frequency of 300 kHz (Fig. 1). The current-voltage characteristic has been fitted by the expression [11]

$$I = I_s\{1-\exp[e(V-V_f)/kT_e]\},$$

where I_s is the ion saturation current and V_f is the floating potential. The ion saturation current is linearly proportional to the local plasma density (n) and to the velocity (v) of the ions entering the probe sheath [11]. The velocity is taken as $v \propto (T_e/m_i)^{1/2}$, although the ratio T_e/T_i is not known in the present experiment. Using a

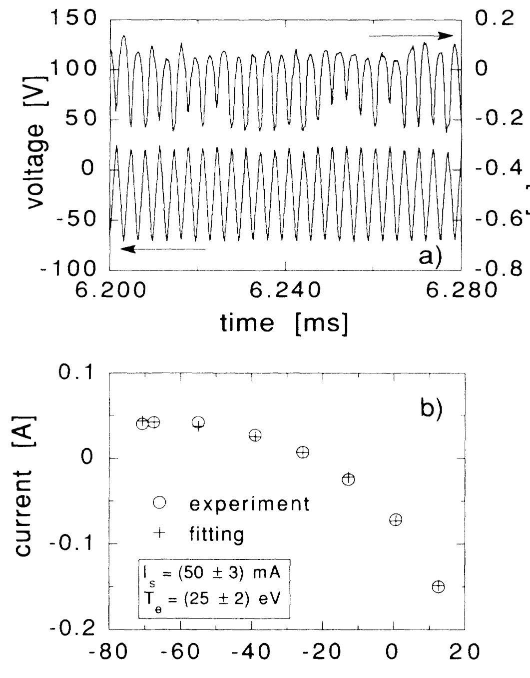

FIG. 1. (a) Langmuir probe (I-V) characteristics measured in the proximity of the velocity-shear layer in the TJ-I tokamak and (b) I-V characteristic with the deduced values for the electron temperature and ion saturation current.

nonlinear least-squares fitting routine, we have determined the electron temperature (T_e), the ion saturation current (I_s), and deduced the local plasma density ($n \propto I_s T_e^{-1/2}$) on a time scale ($\approx 2\ \mu$s) smaller than the relevant times of the turbulence ($\approx 10\ \mu$s). Capacitance to ground has been minimized to reduce parasitic capacitive currents to less than 3 mA (rms). Edge density and electron temperature are in the range $n_e \approx (1\text{-}3)\times 10^{13}$ cm^{-3} and $T_e \approx 10\text{-}30$ eV.

An important point is to determine which part of the I-V characteristic should be used to get the electron temperature [12-14]. The effect of varying the cutoff voltage V_c (i.e., fitting of the I-V characteristic for $V < V_c$) in determining the electron temperature and its fluctuations has been studied in the range $(V_c - V_f)/kT_e \approx 0\text{-}1$. In this range the determined parameters T_e and $\tilde{T}_e/T_e$ are not very sensitive to V_c [8]. In the present experiments we have used the cutoff voltage given by $(V_c - V_f)/kT_e \approx 0.5$. It has to be noted that this result is not in contradiction to previous experiments in JET [13], which show that a true departure from the exponential behavior occurs for $V_c > V_f$. It is expected that the larger the probe size (as is the case of the JET probes) the clearer the departure expected from the exponential behavior for $V_c > V_f$ [14]. As a consequence, small probes as those used in the present experiment allow one to sample a significant fraction of the electron distribution. The drawback of using small probes is that the effective probe area is not well defined [15] and thus only relative variation in the local electron density can be monitored.

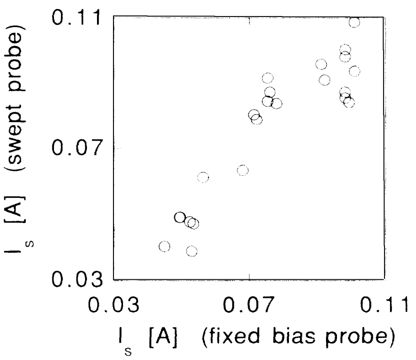

FIG. 2. Ion saturation current deduced from the fast swept Langmuir probe (300 kHz) and with the probe bias in the ion saturation regime.

The measured ion saturation currents by the fast swept probe method were in good agreement with those computed when the probe was at a fixed bias in the ion saturation regime (Fig. 2). This agreement shows the reliability of the fast swept probe technique.

Figure 3 shows the probe-current, density, and temperature (rms) fluctuation levels in the plasma bulk side of the velocity shear location ($r/a_{\text{shear}} < 1$). Measurements are plotted versus the local electron density deduced from the ion saturation current and the electron temperature ($n \propto I_s T_e^{-1/2}$). The local density can be considered as a monitor of the probe radial position: The higher the local density the further inside the plasma the measurements are taken. Measurements were done in the radial range $r/a_{\text{shear}} \approx 0.9\text{-}1$.

The estimated temperature fluctuation levels are on the order of 40%, and are comparable to the corresponding density fluctuations. The measured temperature fluctua-

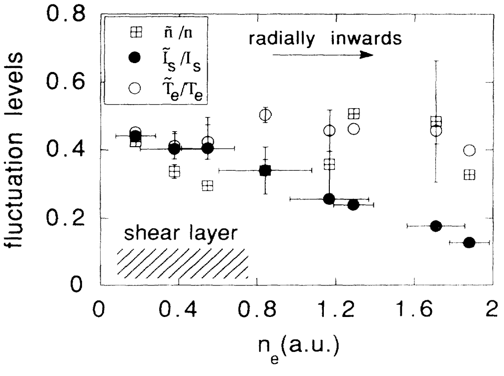

FIG. 3. Fluctuations in the ion saturation current ($\tilde{I}_s/I_s$), electron temperature ($\tilde{T}_e/T_e$), and density ($\tilde{n}/n$) vs the local plasma density ($n \propto I_s T_e^{-1/2}$). Measurements were done in the radial range $r/a_{\text{shear}} \approx 0.9\text{-}1$. The shaded area shows the location of the velocity-shear layer with respect to the density profile.

tion levels are higher than those previously reported in the Caltech tokamak [16]. However, it has to be noted that whereas in the present experiments the I-V characteristic has been fitted from the ion saturation regime up to about the floating potential, in the Caltech experiment the I-V characteristic was fitted from the floating potential up to the plasma potential. Fitting the I-V characteristics up to the plasma potential can possibly overestimate the electron temperature [13] and as a consequence could lead to an underestimate of the temperature fluctuations in the Caltech experiment [16].

Fluctuations in the ion saturation current decrease when the probe moves radially inwards. This result is common for all studied devices independent of their magnetic configuration (tokamaks, stellarators) and size [1,10]. However, whereas $\tilde{I}_s/I_s$, $\tilde{T}_e/T_e$, and $\tilde{n}/n$ are comparable near the shear location, $\tilde{I}_s/I_s$ is smaller than both $\tilde{n}/n$ and $\tilde{T}_e/T_e$ in the plasma edge region ($r/a_{\text{shear}} < 1$). Taking into account that the ion saturation current is proportional to the local electron density and to the square root of the electron temperature, the present results imply that density and temperature are fluctuating in phase close to opposition [Fig. 4(a)].

The current probe fluctuation levels ($\tilde{I}_s/I_s$) are given by

$$(\tilde{I}_s/I_s)^2 = (\tilde{n}/n)^2 + \tfrac{1}{4}(\tilde{T}_e/T_e)^2 + \langle \tilde{n}\tilde{T}_e \rangle / nT_e \,,$$

where $\langle \tilde{n}\tilde{T}_e \rangle$ is the correlation term between density and temperature fluctuations.

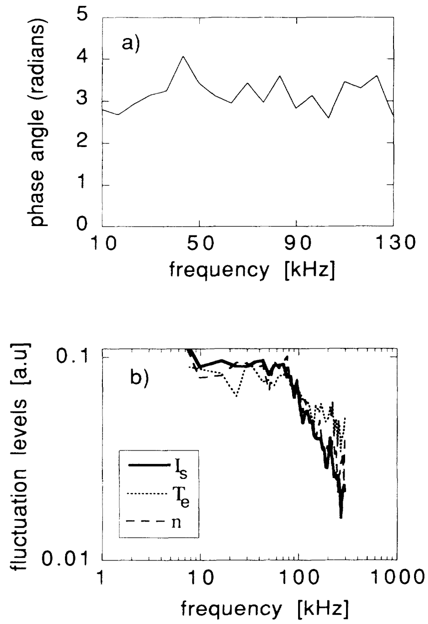

FIG. 4. (a) Phase between density and temperature fluctuations in the plasma edge region $r/a_{\text{shear}} \approx 0.9$ [n_e (a.u.) ≈ 1.6] and (b) frequency spectra for the ion saturation current, the electron temperature, and the density fluctuations deduced from the fast swept Langmuir probe technique.

It has to be noted that only when temperature fluctuations are negligible then the current-probe fluctuations are dominated by density fluctuations. However, when density and temperature fluctuations are strongly correlated with $\tilde{n}/n \approx \tilde{T}_e/T_e$ and $\alpha_{nT_e} \approx \pi$, it follows that $\tilde{I}_s/I_s \approx 0.5\tilde{T}_e/T_e$, in consistency with the results presented in Fig. 3.

Fourier analysis of the current probe, temperature, and density fluctuations deduced from the fast swept probe technique shows fluctuations that are dominated by frequencies below 100 kHz [Fig. 4(b)].

It has to be noted that whereas the thermal drive requires the restrictive condition $dI_z/dT_e < 0$, the relevant parameter for the impurity condensation drive is $n_z I_z$, n_z being the impurity concentration. Thus, the existence of radiation (present in all devices) and some kind of coupling mechanism between density and temperature fluctuations are the only required conditions for the condensation drive. The fulfillment of these general requirements in the present experiment make the condensation drive an attractive candidate to partially explain edge turbulence features. However, although the presence of significant temperature fluctuations can be an indicator of radiative drives, other models would also predict significant temperature fluctuations under realistic assumptions. A systematic study of the correlation between radiation levels and turbulence levels is needed to fully understand the role of radiative instabilities on edge turbulence.

Two different factors contribute to the total uncertainty associated with the electron temperature and current fluctuations deduced from the fast swept method. First, variations in the local plasma parameters (density, potential, and temperature) during the sweeping time of the probe are estimated to produce apparent temperature fluctuations of approximately 10% on the measured temperature fluctuations, using the analysis presented in Ref. [16]. However, the observed uncoupling between current probe and temperature fluctuations (that is to say, the fact that while current probe fluctuation levels decrease when moving radially inward, temperature fluctuation levels remain basically constant, see Fig. 3) strongly suggests that the inferred temperature fluctuations are not dominated by the contribution of plasma fluctuations occurring simultaneously. Second, additional errors on the measured level of temperature fluctuations are due to deviations from the electron Maxwellian distribution. The fitting errors of the I-V characteristics are in the range of (5–10)% for the ion saturation current and about (10–15)% for the electron temperature.

The accumulated errors imply that only fluctuation levels approximately above 10% and 20% for $\tilde{I}_s/I_s$ and $\tilde{T}_e/T_e$, respectively, can be resolved with the present experimental setup. However, as shown in Fig. 3 the measured fluctuation levels for current and temperature fluctuations are significantly above the maximum uncertainties.

In conclusion, the present experiments show that the fast swept Langmuir probe technique is a powerful method to determine the mechanisms underlying edge turbulence. Evidence of substantial temperature fluctuations has been found in the plasma edge region ($r/a_{\text{shear}} < 1$) with $\tilde{n}/n \approx \tilde{T}_e/T_e$. Furthermore, $\tilde{T}_e/T_e$ and $\tilde{n}/n$ are fluctuating in phase close to opposition. These results suggest that radiative instabilities, and in particular the condensation effects, could play a key role in driving plasma edge fluctuations. On the other hand, the presence of temperature fluctuations can significantly affect the interpretation of the Langmuir probe data (the approximation $\tilde{I}_s/I_s \approx \tilde{n}/n$ is called into question) and makes it necessary to reconsider the validity of the particle fluxes computed with the approximation $\tilde{T}_e/T_e \approx 0$. A systematic study of the correlation between edge radiation levels and the level of density and temperature fluctuations is needed.

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