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Long-distance correlations of fluctuations and sheared flows during transitions to improved confinement regimes in the TJ-II stellarator

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I.- Introduction

The importance of the *ExB* sheared flows as a stabilizing mechanism to control plasma fluctuations in magnetically confined plasmas has been widely established. First and second-order phase transition models have been invoked to explain the transition to improved confinement regimes [1 and references therein]. In the framework of the physics of second-order phase transition the correlation length and relaxation time are expected to diverge at the critical point.

Edge sheared flows can be easily driven and damped at the plasma edge of TJ-II by changing the plasma density [2, 3] or during biasing experiments [4]. A second-order phase transition model has been used to explain the experimental results obtained in TJ-II near the transition to improved confinement regimes [5]. Measurements of the relaxation time of externally induced electric fields show an increase above the threshold gradient to trigger the development of sheared flows in agreement with the model [6]. Long-range correlations between plasma edge magnitudes have been recently investigated during the TJ-II edge sheared flows development showing the important role of electric fields to amplify them [7].

II.- Experimental set-up

Experiments were carried out in the TJ-II stellarator in Electron Cyclotron Resonance Heated plasmas ($P_{ECRH} \leq 400$ kW, $B_T = 1$ T, <R> = 1.5 m, <a> ≤ 0.22 m, $\iota(a)/2\pi \approx 1.5 - 1.9$). The plasma density was modified in the range (0.35 – 1) x 10^{19} m^{-3}. Different edge plasma parameters were simultaneously characterized in two different toroidal positions approximately 160º apart using two similar multi-Langmuir probes systems [8]. It is important to note that the field line passing through one of the probes is approximately 150º poloidally apart when reaching the toroidal position of the other probe that is more than 5 m away. A graphite electrode was used for biasing experiments; it is inserted typically 2 cm inside the last-closed flux surface (LCFS) ($\rho = r/a \approx 0.9$) [4].

III.- Plasma edge measurements at the two long-distance apart positions

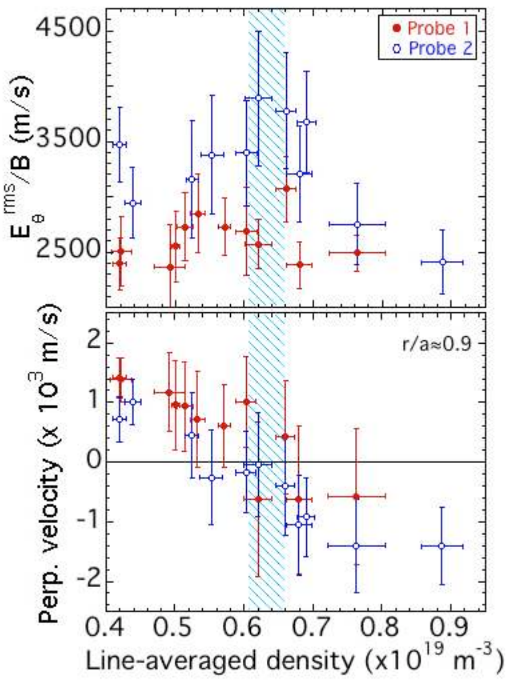

Fig. 1 Electric field fluctuations and perpendicular velocity measured at two long-distance apart positions as a function of plasma density at r/a≈0.9.

Edge radial profiles of different plasma parameters have been measured simultaneously in both shot to shot and single shot scenarios with the two probes and in different plasma conditions. As plasma density increases the gradient of the ion saturation current (i.e. local density) increases; the floating potential becomes more negative [2, 3] and above a threshold density the perpendicular phase velocity reverses sign at the plasma edge from positive to negative values due to the development of the natural shear layer.

Figure 1 shows the measurements of the perpendicular electric field fluctuations (i.e. the turbulent radial velocity) and the perpendicular phase velocity at the plasma edge as a function of plasma density, obtained simultaneously with both probe systems, located at approximately the same radial position (r/a≈0.9), while changing density from shot to shot. The fluctuation levels and the turbulent transport increase as density increases up to the threshold value for which sheared flows are developed, and once sheared flows are fully developed, fluctuations level and the turbulent transport slightly decrease and the edge gradients become steeper.

Edge sheared flows development has also been induced in TJ-II using an electrode that externally imposes a radial electric field at the plasma edge. The modifications in the plasma properties induced by the electrode biasing depend on several parameters such as the biasing voltage, the electrode location and the plasma density. The plasma response to biasing is different at densities below and above the threshold value needed to trigger the spontaneous development of *ExB* sheared flows [4] but it is similar at the two toroidal locations.

IV.- Long- distance correlation measurements

Floating potential signals measured at both toroidal locations show a clear similarity mainly for low frequencies components, contrary to that observed with ion saturation current signals. The similarity in the floating potential signals is also observed in shorter time scales (lower than 1 ms), particularly in the fast events related to the shear flow development. To quantify the similarity between probe signals the cross-correlation defined as

$$\gamma_{xy}(\tau) = \frac{E\{[x(t+\tau)-\bar{x}][y(t)-\bar{y}]\}}{\sqrt{E\{[x(t)-\bar{x}]^2\}.E\{[y(t)-\bar{y}]^2\}}}$$

has been computed for a wide range of TJ-II plasma conditions, including a line-averaged density scan as well as with and without electrode bias in plasmas without MHD activity.

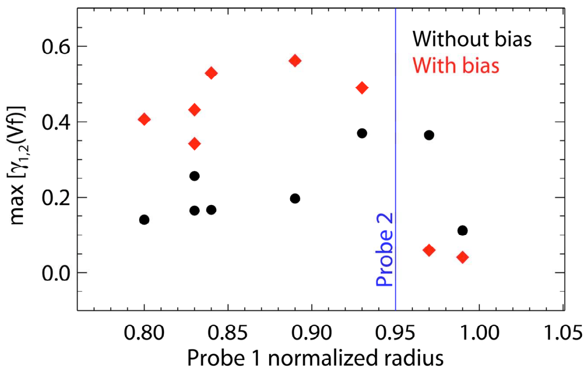

Fig. 2 Cross-correlation of floating potential signals measured as a function of the radial position of Probe 1 in plasmas without and with bias. Vertical line indicates the position of the Probe 2.

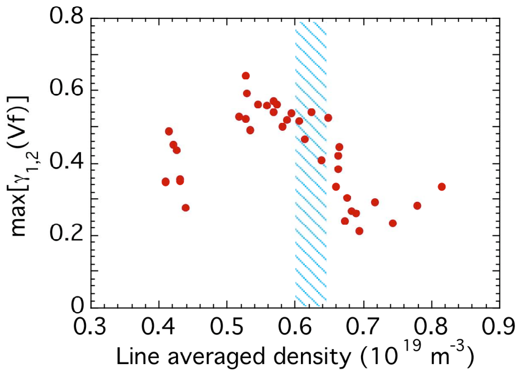

Fig. 3 Cross-correlation function of floating potential signals measured at approximately the same radial positions of both probes as a function of plasma density.

Figure 2 shows the cross-correlation of the floating potential signals measured at different radial positions of Probe 1, while Probe 2 is fixed at ρ= r/a ≈0.95, for ECRH plasmas, with and without biasing, and with similar line averaged density ($n_e \approx 0.6 \times 10^{19}$ m^{-3}), close to the critical value. The correlation shows a maximum in the region just inside the LCFS, both with and without bias, being negligible in the proximity of the scrape of layer.

The cross-correlation, computed at different plasma density values, is shown in figure 3 (for the same shots presented in figure 1). The cross-correlation depends on the plasma density, being larger as density increases up to $n_e \approx 0.6 \times 10^{19}$ m^{-3}, which corresponds to the threshold density for shear flow development for the selected plasma configuration. The increase of correlation with density results mainly from low frequencies rise (below 20 kHz).

Figure 4 shows the time evolution of plasma density and the cross-correlation between ion saturation current and floating potential signals (measured by Probes 1 and 2) before / after biasing induced improved transition regimes. It shows clearly the increase in the floating potential cross-correlation during the biasing phase. On the contrary, the degree of long-range correlation is negligible in density fluctuations. Once the biasing is turned off, the density decreases in the time scale of the particle confinement time (in the range of 10 ms) whereas both the electric field and the degree of long-range correlation decrease in a much

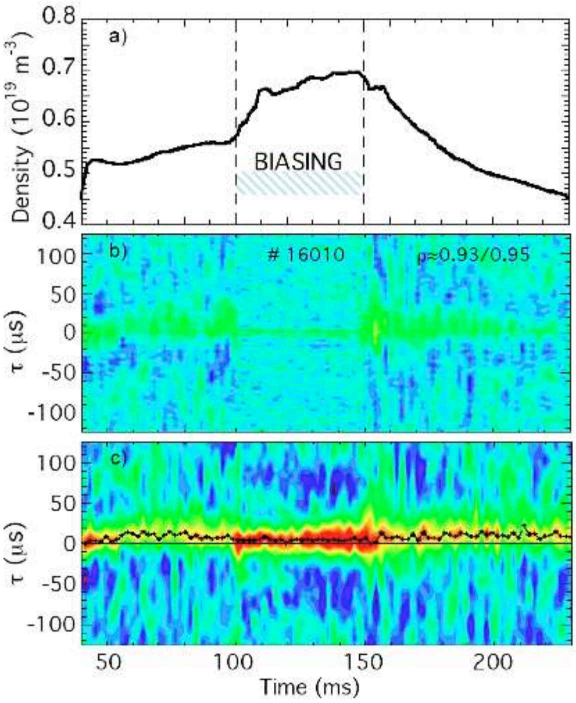

Fig. 4 Delay of cross-correlation function between b) ion saturation current and c) floating potential signals measured toroidally apart and at the plasma edge as a function of time for one shot during biasing experiments. The over-plotted solid line in c) represents the evolution of the time delay where the correlation is maxima. Line averaged density for the same shot is also shown a).

faster time scale. These results show that the high degree of long-range correlation observed in floating potential signals is coupled to the value of radial electric fields and not to the plasma density.

V.- Discussion and conclusions

It remains as an open question to clarify which mechanisms can provide such long-range correlations in plasma potential but not in density fluctuations. In the framework of the second-order phase transition, fluctuations are expected to show such correlations in the order parameter related with the electric fields (i.e. shearing rate) and so an amplification of such correlation via electric fields would be also expected. Particle orbit losses might also trigger localized perturbation in the plasma potential which parallel propagation could also give rise to long range correlations in potential fluctuations; however, in this case, it remains to be clarified why such particle orbit losses induced long-range correlations should be amplified by electric fields.

TJ-II results show the important role of long distance correlation as a first step in the transition to improved confinement regimes and the key role of electric fields to amplify them. Present findings point out the important role of edge diagnostic development to characterize simultaneously at different plasma locations the structure of sheared flows and fluctuations to unravel of physics of sheared flows.

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