On the zonal flows identification in the plasma edge of the TJ-II stellarator

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TJ-II has revealed to be an ideal laboratory to study the development of edge sheared flows that can be easily driven and damped at the plasma edge changing the plasma density or during biasing experiments. Cross-correlation between edge magnitudes (density and potential) simultaneously measured with Langmuir probes located at two different positions approximately 180º toroidally apart, has been obtained in TJ-II. Results show a long distance correlation between floating potential signals that increases when probes are approximately at the same radial location, whereas there is no correlation between ion saturation current signals. Cross-correlation shows a maximum value when plasma density is close to the threshold for the development of spontaneous edge sheared flows with cross-phase close to zero. Furthermore, correlation between potential signals increases in the presence of externally applied electric fields. These findings show for the first time that the development of fluctuating perpendicular flows (with zonal flow-like structure) is the first step in the transition to improved confinement regimes.

Keywords: Turbulence, zonal flows, plasma edge, correlation, electric fields, stellarators.

1. Introduction

It is well known and widely accepted the importance of turbulent transport effects on plasma confinement in fusion devices. In particular it is very important to develop techniques to improve plasma confinement. Recently, fusion community has focused its attention on turbulent toroidally and azimuthally symmetric sheared flows (zonal flows) and the role that they can play in the turbulence regulation. It has been theoretically assessed that zonal flows play a role in the dynamics of turbulence and its self-regulation [1, and references therein]. Experimental works in different magnetically confined plasmas have been carried out to prove the existence of these zonal flows and some fingerprints of their presence have been found in different fusion devices [2, 3, 4, 5, 6, 7]. Zonal flows have also been suggested as an important ingredient to explain the Low to High transition (L-H) in magnetic confinement devices [8].

Due to the recent development of two sets of Langmuir probes located at two different toroidal positions, TJ-II can be considered a good laboratory to study the presence of zonal flows in the plasma edge region. Moreover, it has been reported that sheared flows can be easily driven and damped at the plasma edge by changing the plasma density [9, 10] or during biasing experiments [11]. Toroidal cross-correlations between plasma edge magnitudes have been studied in TJ-II in extremely different plasma conditions and different magnetic configurations providing valuable experimental data.

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2. Experimental set-up

Experiments were carried out in the TJ-II stellarator in Electron Cyclotron Resonance Heated plasmas (P_{ECRH}≤400 kW, B_T = 1 T, <R> = 1.5 m, <a> ≤ 0.22 m, $\iota(a)/2\pi \approx 1.5 - 1.9$). Different edge plasma parameters were simultaneously characterized in two different toroidal positions approximately 180º apart using two similar multi-Langmuir probes, installed on fast reciprocating drives (approximately 1 m/s) [12]. One of the probes is in the low field side (LFS) and the other in the high field side (HFS) of the TJ-II as is schematically shown in figure 1.

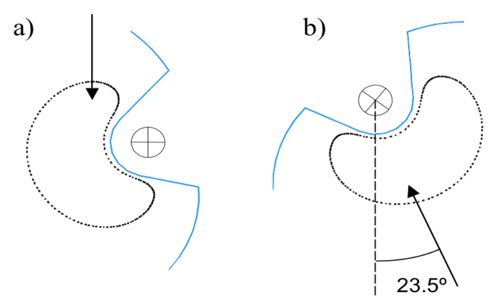

Fig 1 Schematic view of the location of the probes (arrows) at the high (a) and low (b) field sides in TJ-II.

3. Plasma edge measurements comparisons

Radial profiles of different plasma parameters have been measured at two far away toroidal locations simultaneously for the first time. Profiles were obtained both shot to shot and in a single shot with both probes and in different plasma configurations.

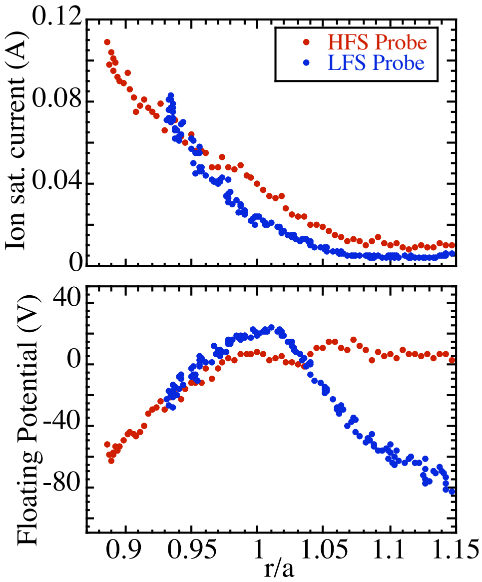

Fig. 2 Radial profiles of ion saturation current and floating potential measured simultaneously at two toroidal locations for plasma density above the threshold.

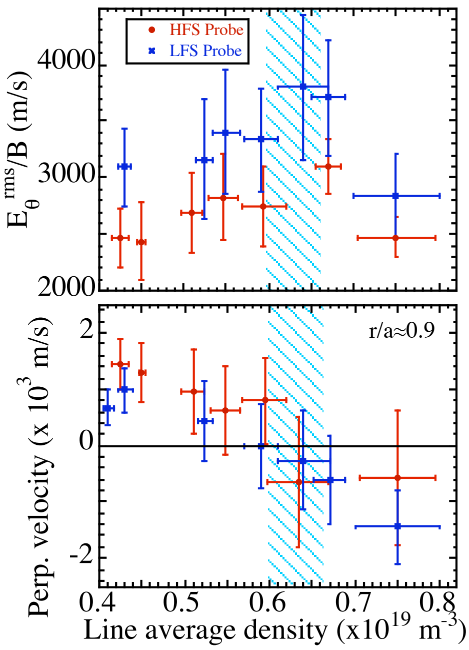

Fig. 3 Electric field fluctuations and perpendicular velocity measured at HFS and LFS positions as a function of plasma density at r/a≈0.9.

Figure 2 shows profiles of the ion saturation current and the floating potential measured simultaneously in the two mentioned toroidal positions in one shot. Profiles of the ion saturation current are slightly different in both probes: gradient is steeper at the LFS for all the plasma configurations studied up to now. Floating potential profiles are similar in both probes inside the last closed flux surface (LCFS) but they differ in the scrape-off layer (SOL) region probably due to the different particles losses rate at both positions.

The perpendicular electric field fluctuations and the phase velocity measured with both probes simultaneously and located both at r/a≈0.9 in different shots as a function of density are shown in figure 3. The behaviour of the velocity and fluctuations measured at the LFS is similar to the one reported at the HFS and the effect of the threshold density can be as well clearly seen [10, 13]. These results have been explained in TJ-II using a simple second order phase transition model [14].

4. Toroidal cross-correlations

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. Figure 4 shows the raw data of the floating potential and ion saturation current signals measured in both probes simultaneously at approximately the same radial position. 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 [13]. This means that the large amplitude floating potential fluctuations observed during the shear flow formation are toroidally symmetric.

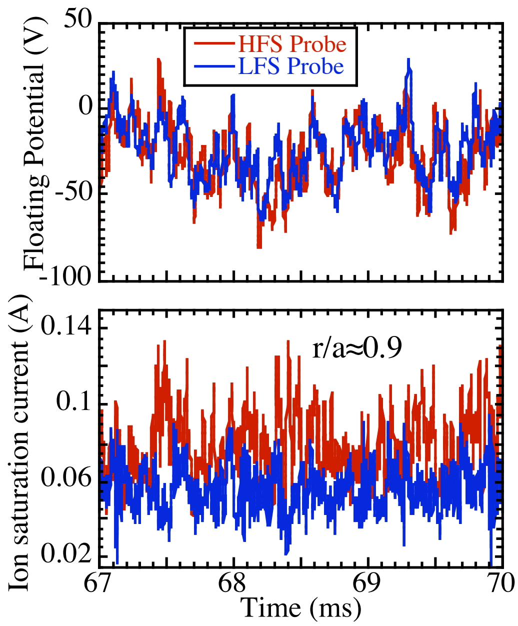

Fig. 4 Raw data of the floating potential and ion saturation current signals measured in both probes simultaneously.

To quantify the similarity between signals the toroidal cross-correlation has been computed in TJ-II in particular. The cross-correlation functions is defined as

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

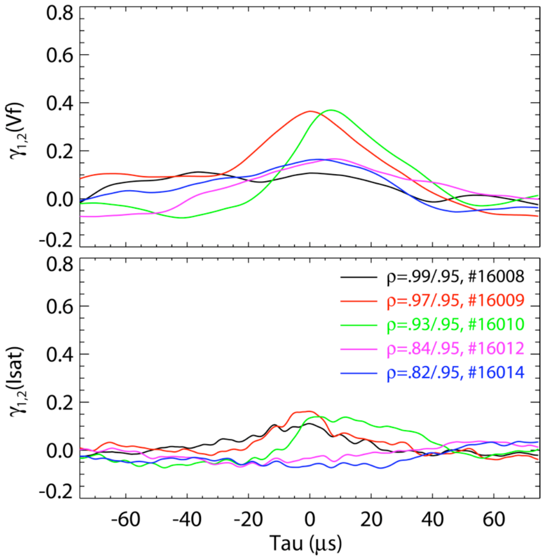

Fig. 5 Cross-correlation function for floating potential and ion saturation current signals measured at different radial positions of probe at the HFS and in ECRH plasmas without bias.

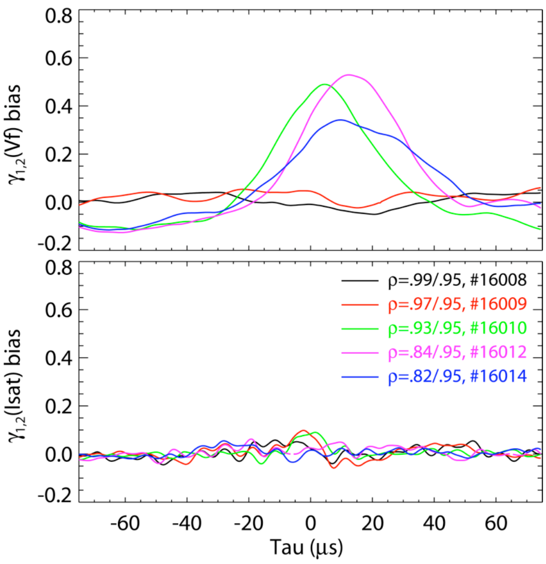

Fig. 6 Cross-correlation function for floating potential and ion saturation current signals measured at different radial positions of probe at the HFS and in ECRH plasmas with bias.

Cross-correlation of plasma edge magnitudes have been obtained from probe measurements, during experiments in TJ-II with and without electrode bias and for different plasma density values. As illustrated in figures 5 and 6, the ion saturation current signals correlation is significantly smaller than that of floating potential signals particularly during bias where the ion saturation current correlation is decreased and the floating potential correlation increased Bias makes also the cross-correlation more concentrated around τ=0. The maximum of the floating potential correlation (see figure 7) is observed when probes are approximately at the same radial location. The toroidal correlation shows a maximum in the region just inside the LCFS, being negligible in the SOL.

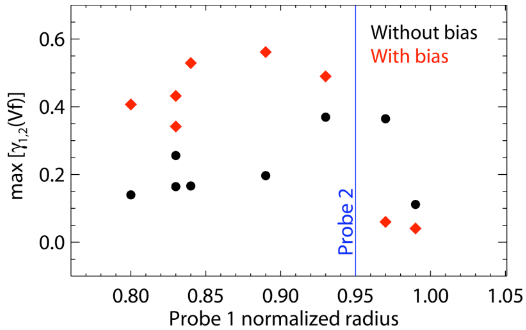

Fig. 7 Cross-correlation of floating potential signals measured as a function of the radial position of probe at the HFS in plasmas without and with bias. Vertical line indicates the position of the LFS probe.

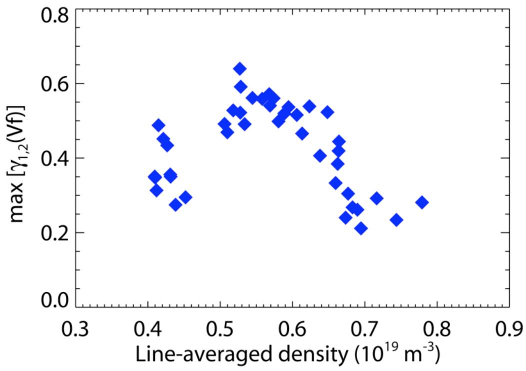

Fig. 8 Cross-correlation function of floating potential signals measured at approximately the same radial positions of both probes as a function of plasma density.

Figure 8 illustrates the dependence of the toroidal floating potential correlation on the line-averaged density (for the same pulses presented in figure 3). It is observed that correlation depends on the density, being larger for n ≈ (0. 5- 0.6)x10^{19} m^{-3}, which corresponds to the threshold density for shear flow development. Note that this correlation increase with density results mainly from the rise in the correlation at low frequencies (below 20 kHz).

Figure 9 shows the cross-power spectrum and the phase between the floating potential signals of the two probes. It is clear that the toroidal correlation is dominated by low frequencies (below 20 kHz) and that the phase between the two signals is close to zero for the whole frequency range. Electrode bias reduces the edge fluctuations and therefore the cross-power spectrum ($\langle |S_{xy}(f)| \rangle$) is also reduced. Note however that the coherence $\left\langle \frac{|S_{xy}(f)|}{\sqrt{|S_x(f)||S_y(f)|}} \right\rangle$ increases during bias in agreement with the results presented in figures 5-7.

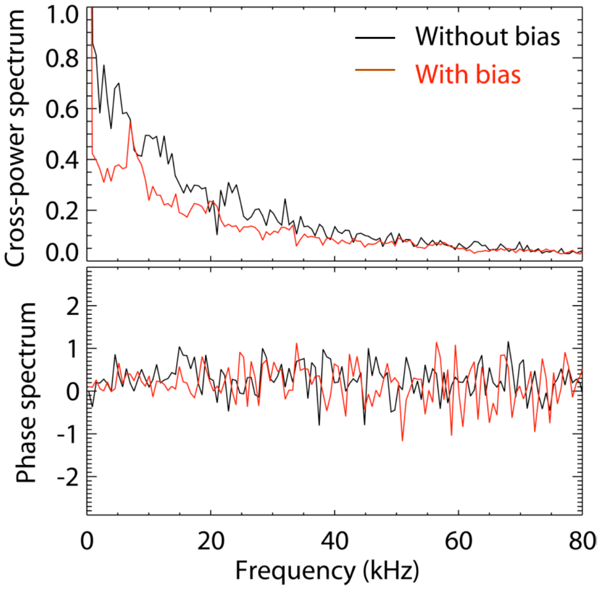

Fig. 9 Cross-correlation spectrum and cross-correlation phase spectrum between two floating potential signals toroidally apart.

Previous measurements of the parallel correlation in the SOL have shown an increase of correlation only when probes were located at the same field line [15, 16]. Other measurements have been performed more recently with the aim of identifying zonal flows [3, 4, 5, 6, 7], Measurements in TJ-II allows to compute the cross-correlation both in the SOL and in the edge plasma regions with the probes not located in the same field line being results compatible with those previously obtained [15, 16].

Experiments with fast visible cameras have investigated with 2-D resolution the development of edge sheared flows, showing a dithering phase at the threshold density with fluctuating perpendicular flows consistent poloidal symmetric structure.

5. Interpretation of the experimental results

The toroidal coupling of density and potential fluctuations has been investigated, for the first time, during the transition to improved confinement regimes in the TJ-II stellarator. It has been observed high cross-correlation at the plasma edge between floating potential signals measured approximately at the same radial location but toroidally apart. As the probes are not in the same filed line, this effect is compatible with the presence of zonal flows at the plasma edge. Moreover the phase between both signals is around zero indicating a toroidally symmetric structure, as is characteristic of the zonal flows. This fact is also demonstrated observing the similar waveforms of the raw data when probes are located radially closed. Besides that, the spectra are dominated by low frequency fluctuations as expected for zonal flows.

The observation of a maximum in the cross-correlation for a plasma density around the threshold value for shear flow development suggests a relationship between the generation of zonal flows and the improvement of confinement, being possible to consider the zonal flows generation as a trigger for plasma confinement improvement.

TJ-II experimental results are consistent with model for L-H transition based on the generation of zonal flows.

New experiments are going to be done in TJ-II looking for the presence of zonal flows and their relationship with confinement.

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