Multi-scale physics during shear flow development in the TJ-II stellarator

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Abstract. The long distance coupling of plasma fluctuations and the non-linear properties of fluctuations have been investigated during transitions to improved confinement regimes in the TJ-II stellarator. Results show evidence of long distance correlation in plasma potential signals and much weaker in density fluctuations. Cross-correlation of fluctuations shows a maximum value when plasma density is close to the threshold for the development of spontaneous edge sheared flows and increase in plasma regimes with edge biasing induced enhanced confinement. Furthermore, experimental evidence of the dual role of electric fields as a stabilizing mechanism of plasma turbulence and as an agent affecting the momentum balance via turbulence (Reynolds stress) modification has been observed. These findings show the importance of multi-scale mechanisms in the transition to improved confinement regimes and the key role of electric fields to amplify them.

1. Introduction

At present most experimental evidence strongly support the paradigm of sheared electric field suppression of turbulence to explain the L-H transition, although the underlying mechanism that generate the electric fields is one of the fundamental open issues confronting the fusion community. Momentum transport and plasma rotation, less well understood than the other transport channels (ion, electron and particle channels), play a key role in stability and transport barrier development. Then, it is important to study the possible mechanisms that can drive plasma rotation like those related with plasma turbulence, fast particles and neoclassical mechanisms.

In the TJ-II stellarator sheared flows can be easily driven and damped at the plasma edge by changing the plasma density [1] or during biasing experiments [2], which makes TJ-II an ideal plasma physics laboratory to unravel the physics of shear flow development and momentum transport in fusion plasmas. The goal of this paper is to investigate the link between multi-scale mechanisms and the development of edge sheared flows. The main results reported in this paper are: 1) The discovery of long-range correlations in potential fluctuations that are amplified during the development of radial electric fields and transitions to improved confinement regimes. These experimental findings suggest the importance of long-range correlations during the development of edge shear flows [3]; 2) The experimental evidence of the dual role of electric fields as a stabilizing mechanism of plasma turbulence and as an agent affecting the momentum balance via turbulence (Reynolds stress) modification [4, 5].

The outline of the paper is as follows. First we describe the experimental set-up in the TJ-II stellarators and then we present the study of long range-range correlations and non-linear analysis (bicoherence) during TJ-II transitions and the interplay between parallel flows, turbulence and electric fields. Finally, we draw our conclusions.

2. 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, $\langle R \rangle = 1.5$ m, $\langle a \rangle \leq 0.22$ m, $\iota(\alpha)/2\pi \approx 1.5 - 1.9$). 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 using two similar multi-Langmuir probes installed on fast reciprocating drives and fast intensified visible cameras during spontaneous and biasing induced transitions to improved confinement regimes.

The arrangement of both probes in TJ-II is illustrated in figure 1. One of the probes (Probe 1) is located in a top window entering vertically through one of the "corners" of its beam-shaped plasma and at $\phi \approx 35^o$ (where ϕ is the toroidal angle in the TJ-II reference system). Probe 2 is installed in a bottom window at $\phi \approx 195^o$ and enters into the plasma through a region with a high density of flux surfaces (i.e. lower flux expansion) than Probe 1. It is important to note that the field line passing through one of the probes is approximately 120º poloidally apart when reaching the toroidal position of the other probe that is more than 5 m away.

A graphite electrode (12 mm high, 25 mm diameter) was used for biasing experiments on TJ-II and it has proved to be a valuable tool for controlling the edge plasma electric field and consequently to place the plasma in an enhanced confinement regime. The electrode is inserted typically 2 cm inside the last-closed flux surface (LCFS) ($\rho \approx 0.9$) and biased with respect to one of the poloidal limiters installed [2]. Edge radial profiles of different plasma parameters have been measured simultaneously at the two separated toroidal locations for the first time.

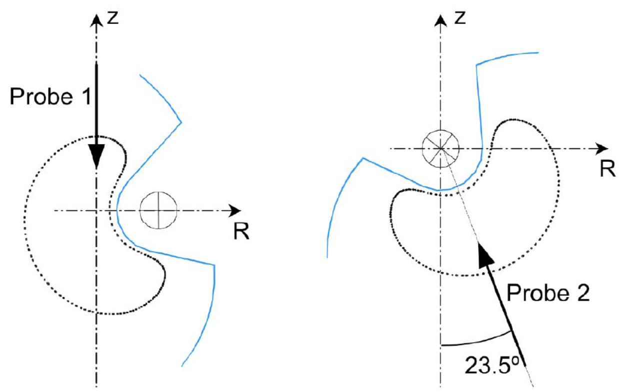

FIG 1. Schematic view of the location of the two probes (thick line arrows) and their positions relative to the TJ-II plasma.

Non-linear (bicoherence) analysis was computed using the standard calculation of the bicoherence [5].

3. Long-range correlations and transitions to improved confinement regimes

The evolution of edge fluctuations in the perpendicular electric field fluctuations (i.e. the turbulent radial velocity $\tilde{v}_r = \tilde{E}_\theta / B$) and the perpendicular phase velocity (measured with both Langmuir probe 1 and 2 systems) versus plasma density are shown in figure 2 which are located at approximately the same radial position (r=r/a≈0.9). The fluctuation levels and the turbulent transport increase as density increases up to the critical value for which sheared flows are developed. For densities above the threshold, fluctuations level and the turbulent transport slightly decreases and the edge gradients become steeper. Edge sheared flows are developed at the same threshold density in the two toroidal positions. It should be noted that

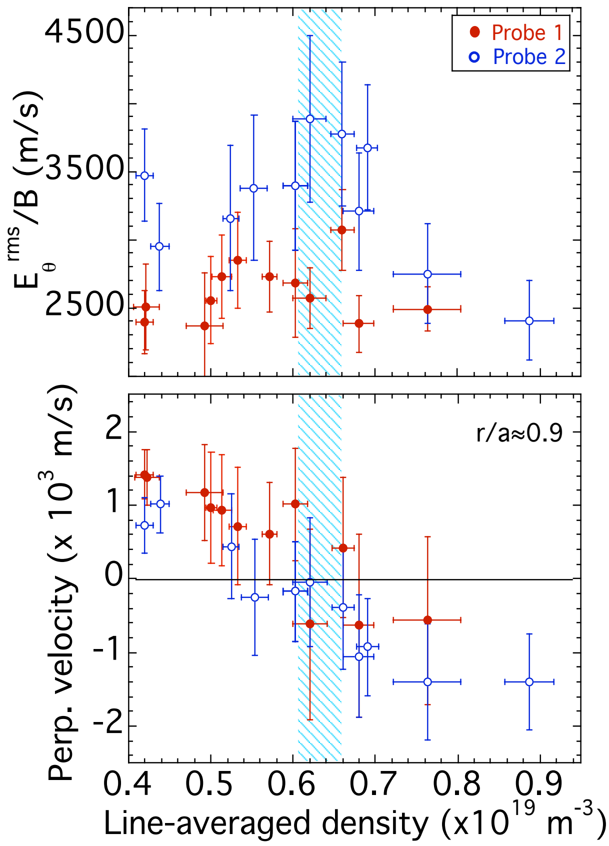

FIG 2. Averaged electric field fluctuations and perpendicular velocity measured at two toroidal locations and at approximately the same radial position (r/a≈0.9) as a function of plasma density.

the structure of fluctuations and perpendicular flows (investigated by means of fast visible cameras) has shown results fully consistent with those observed with Langmuir probes and that turbulent structures (blobs) are stretched and ordered above the threshold density [6].

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 electrode biasing depend on several parameters such as the biasing voltage, the electrode location and the plasma density. The response of the plasma to biasing is, therefore, different at densities below and above the threshold value needed to trigger the spontaneous development of ExB sheared flows [2] but it is similar at the two toroidal locations.

The toroidal cross-correlation of the floating potential and the ion saturation current signals measured at different radial positions of Probe 1 while Probe 2 is fixed at r= r/a ≈0.95 is shown in figure 3 for ECRH plasmas with and without electrode bias. The ion saturation current toroidal

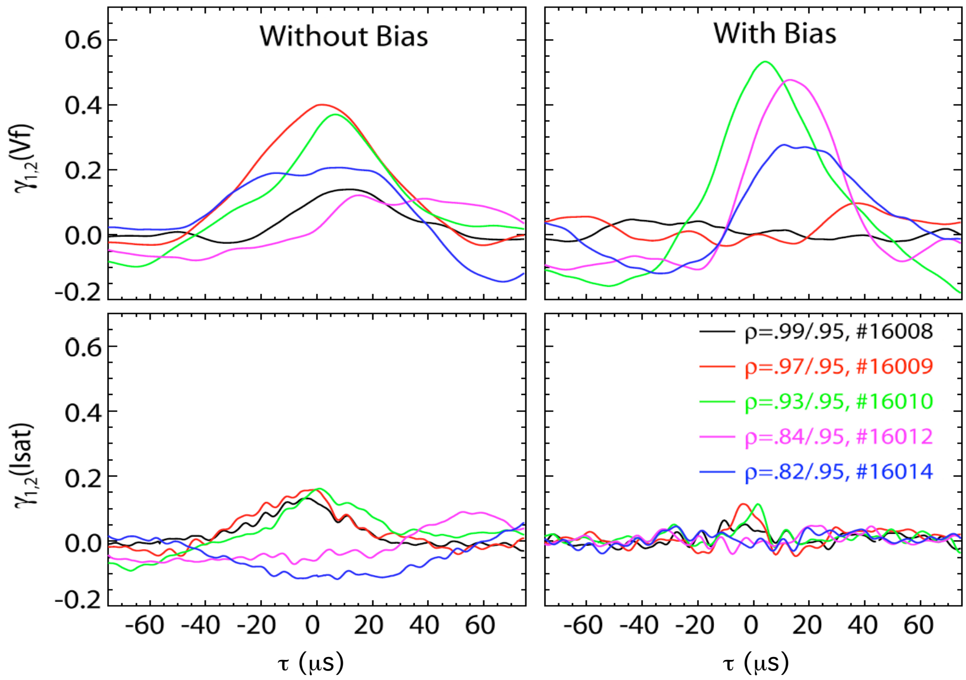

FIG 3. Cross-correlation function for floating potential and ion saturation current signals measured at different radial positions of probe 1 (while probe 2 is fixed) in ECRH plasmas with and without biasing.

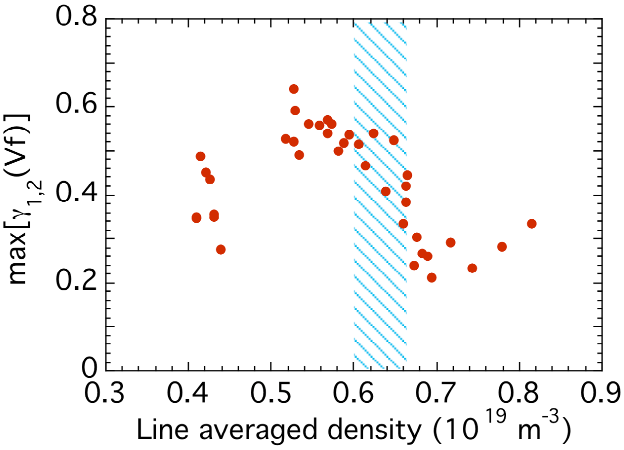

FIG 4. Maximum value of the cross-correlation function between floating potential signals measured at approximately the same radial positions of both probes (r/a≈0.9) as a function of plasma density.

correlation is very low in agreement with previous measurements of the parallel correlation in the SOL which have shown an increase of correlation only when probes were located at the same field line [7]. On the contrary the correlation between floating potential signals is significant, particularly during biasing where it increases while the ion saturation current correlation decreases. The maximum of the floating potential correlation is observed when probes are approximately at the same radial location. The toroidal correlation shows a maximum in the region just inside the LCFS, both with and without bias, being negligible in the proximity of the SOL.

Figure 4 illustrates the dependence of the toroidal floating potential correlation on the line-averaged density (for the same shots presented in figure 2). It is observed that the cross-correlation depends on the density, being larger in the proximity of n ≈ 0.6 x 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 the rise in the correlation at low frequencies (below 20 kHz). This means that the large amplitude floating (low frequency) potential fluctuations observed during the shear flow formation are toroidally symmetric.

Figure 5 shows the time evolution of plasma density and the cross-correlation between floating potential signals (for probes 1 and 2). It shows clearly the increase in the cross-correlation during the biasing phase with time delay for the maximum cross-correlation that results in the range 5 -10 μs in the different scenarios. It has to be

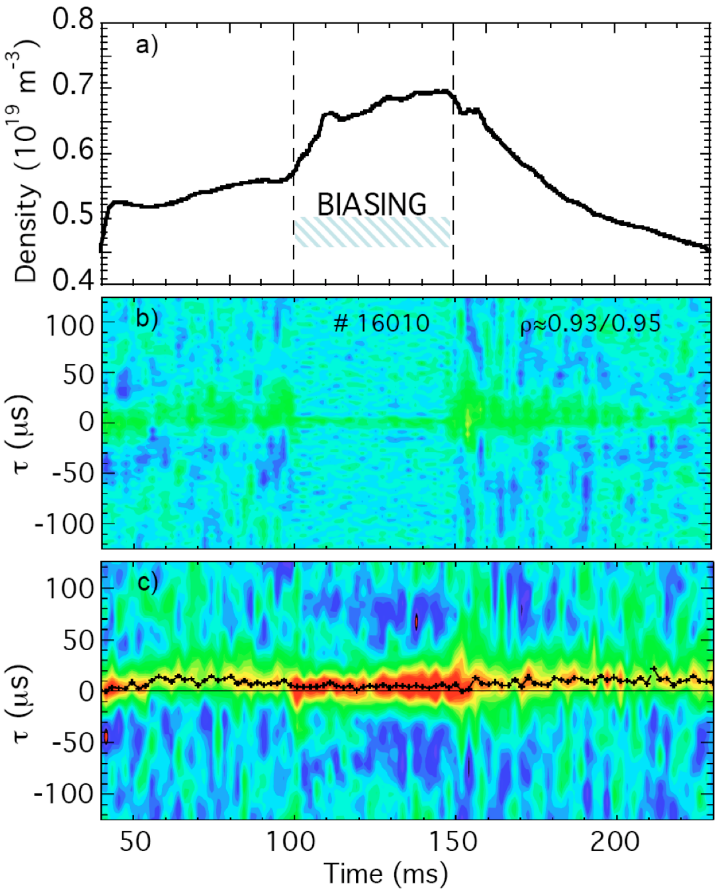

FIG 5. a) Time evolution of plasma density during biasing induced improve confinement regimes in TJ-II and cross-correlation function between b) ion saturation current and c) floating potential signals measured toroidally apart and at the plasma edge as a function of time for one shot during biasing experiments.

noted that in the biasing experiments reported in figure 5, the plasma density is below the critical value in the phase without biasing (t < 100 ms) reaching a value above the critical during the biasing phase (100 – 150 ms). 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 decreases in a much faster time scale. These results shows that the high degree of long-range correlation observed in floating potential signals in coupled to the value of radial electric fields and not to the plasma density.

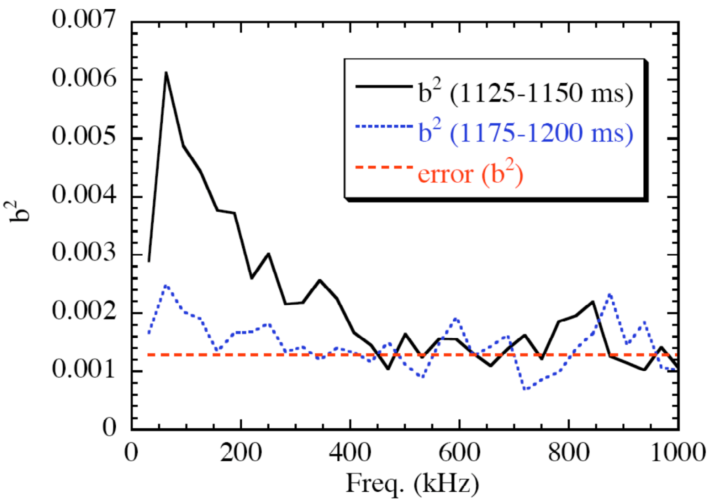

FIG 6. Summed bicoherence in a time window during biasing with high bicoherence (1125 < t < 1150 ms),, and a later time window (1175 < t < 1200 ms), i.e., a time window after biasing with low bicoherence, and the statistical error level (horizontal dashed line).

The behaviour of the bicoherence, computed for appropriate quantities (such as the fluctuating poloidal, i.e. perpendicular to the magnetic field in the poloidal direction, electric field, measured by Langmuir probes), shows an increase in non-linear coupling effects during forced confinement transitions (induced by biasing) [5] (Fig. 6); however, this increase in the auto-bicoherence was significant only in a narrow radial range in contrast to the fluctuation levels and the coupling between poloidal and radial fluctuating electric fields (see section IV) which were affected over a very broad radial extension.

It remains as an open question to clarify which mechanisms can provide such long range correlations in plasma potential but not in density fluctuations. Turbulence driven flows are expected to show such correlations in the order parameter related with the shearing rate (i.e. electric fields) and so an amplification of such correlation via electric fields would be also expected. Actually, the experimental results can be theorically understood by incorporating the dynamics of zonal flows to the second-order transition model for the emergence of the plasma edge shared flow layer [8]. Particle orbit losses might also trigger localized perturbation in the plasma potential which parallel propagation could also trigger 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.

Comparative studies with other devices are crucial to assess the importance of multi-scale physics in the development of sheared flows and transport and the role of magnetic configuration (e.g. influence of safety factor). In particular, recent experiments in the ISTTOK tokamak have shown an interplay between long-range correlations and local turbulent transport. It has been found that the floating potential fluctuations, dominated by low frequency oscillations, exhibit a significant toroidal correlation at long distance that can be attributed to the geodesic acoustic mode (GAM) [9]. Input from large-scale simulations would be particularly interesting to unravel the underlying physics of long-range correlations during development of sheared flows.

4. Flows, Reynolds stress and electric fields

The effect of the increased radial electric field shear on the radial profiles during an improved confinement regime due to external basing has been investigated [4, 5]. A reduction of the Reynolds stresses component as a result of the lower turbulence level was observed. However, the 'phase coherence' between the fluctuations (both radial-parallel and radial-poloidal Reynolds stress components as shown in Figure 7) was strongly enhanced inside the plasma.

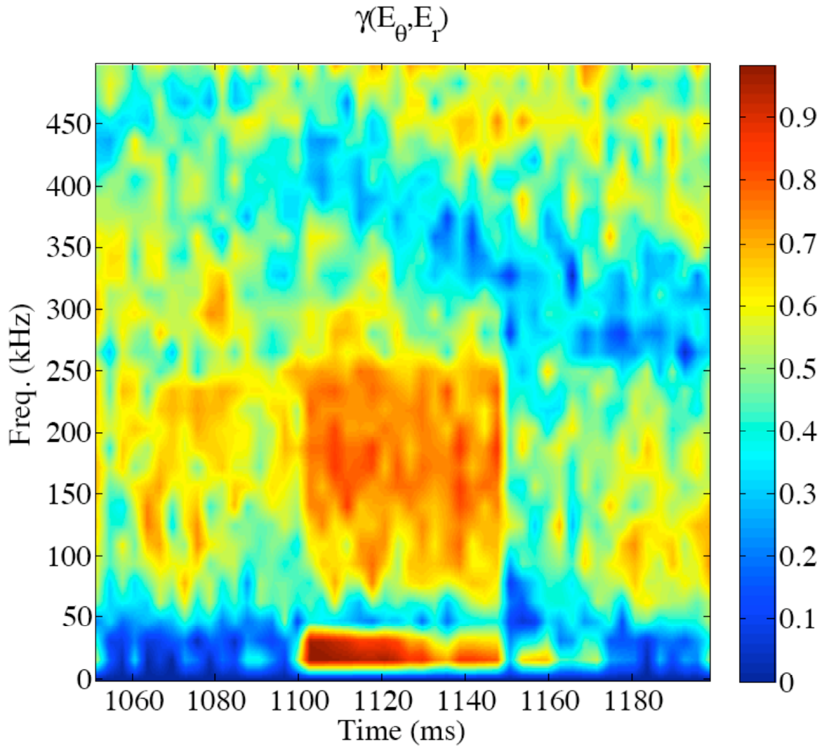

FIG 7. Coherence spectrum (E_θ, E_r) vs. time at r/a = 0.89 during biasing induced improved confinement regimes.

Concerning the evolution of the parallel dynamics during biasing, the resulting gradient in radial-parallel Reynolds stress component has a magnitude comparable to the observed change in the friction term. The order of magnitude comparison of local measurements suggests that the turbulence driven momentum flux should be taken into account when considering the parallel momentum balance equation, particularly in high electric field shear regimes [4]. The experimental findings show the dual role of sheared ExB flows as a fluctuation stabilizing term as well as an agent affecting the parallel momentum balance via turbulence modification.

5. Conclusions

Multi-scale physics during spontaneous and biasing induced transitions have been investigated in the TJ-II stellarator and the following conclusions have been found:

a) The observation of long-range correlations (in plasma potential signals) in the plasma edge, which are amplified during the spontaneous development of edge sheared flows and biasing induced transitions. This experimental finding suggests the possible role of long distance correlation during the development of edge sheared flows as a first step in the transition to improved confinement regimes (second order like phase transition [8]).

b) The dual role of radial electric fields as a fluctuation stabilizing mechanism and as an agent affecting the phase coherence of non-linear quadratic terms (both radial-poloidal and radial-parallel Reynolds stresses). This result suggests that Reynolds stresses and radial electric fields are linked in a feedback loop.

c) 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. Comparative studies stellarator-tokamak (during L-H transition) should be stimulated to provide a critical test for the L-H transition physics mechanisms.

Recent experiments in the TJ-II stellarator (operated under lithium coated walls [10] and with NBI heating conditions) have shown evidence of additional bifurcations characterized by a) edge Localized modes behaviour, b) increase in the perpendicular phase velocity of fluctuations (as compared with the one before the transition) and c) reduction in H_α signal in the level of broadband fluctuations. The characteristic of this additional TJ-II bifurcation would make TJ-II a unique experiment to study the two-step process (second and first order phase transitions [11 and references therein]) in the development of edge sheared flows in fusion plasmas [12].

Acknowledgments

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