Long-range correlations during plasma transitions in the TJ-II stellarator

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Abstract

The mechanism underlying the development of edge transport barriers is still one of the fundamental issues confronting the magnetic fusion community. The results presented show the importance of long-range correlation as approaching plasma bifurcations in different plasma scenarios, including biasing induced and spontaneous edge transport bifurcations. These findings are consistent with the theory of zonal flows, pointing out the importance of both mean and fluctuating electric fields during the development of edge plasma bifurcations.

I. INTRODUCTION

The importance of turbulent transport effects on plasma confinement in fusion devices is well known and widely accepted. The transport bifurcation to an improved confinement regime is directly related to the formation of sheared flows that can stabilize the turbulence present in the plasma. Understanding the mechanisms governing the development of this bifurcation, which leads to the establishment of a transport barrier, are still one of the main scientific challenge for the magnetic fusion community after more than twenty years of intense research since the discovery of H-mode [1]. Thus, prediction of the ITER pedestal parameters and the H-mode transport barrier width remains as a key research area [2].

Zonal flows have been suggested to explain the Low to High transition (L-H) in magnetic confinement devices [3, 4 and references therein]. Indeed, the existence of zonal flows in toroidal plasmas has been experimentally confirmed [5 and references therein]. Recent experiments have shown that long-range correlations are present during the development of the edge shear flows and how these correlations are amplified by externally imposed radial electric fields [6, 7, 8]. As a consequence, multi-scale physics (i.e. coexistence of short and long-range spatial scales) can be considered a new fingerprint of plasma behaviour during edge transport bifurcations.

In the TJ-II stellarator sheared flows can be easily driven and damped at the plasma edge by changing the plasma density [9, 10]. Electrode biasing has been used in TJ-II to externally produce electric fields that modify the plasma confinement properties [11, 12]. New experiments using dynamic biasing to externally induce time depending electric fields are in progress. Dynamic biasing allows inducing reversible plasma transitions in different time scales depending on the applied frequency voltage. Recent TJ-II experiments with a Li-coated wall [13] and NBI heating have provided evidence of spontaneous bifurcations with the characteristics of transitions to improved confinement regimes [14]. The obtained results on the long-range correlations in NBI plasmas have revealed the importance of multi-scale physics as approaching the plasma conditions where edge transport bifurcations are developed [15] in consistency with the expectations of transition models of turbulence driven sheared flows including zonal flows effects [16].

II. EXPERIMENTAL SET-UP

Experiments were carried out in the TJ-II stellarator (B_T = 1 T, <R> = 1.5 m, <a> ≤ 0.22 m, $\iota(a)/2\pi \approx 1.5 - 1.9$), in Electron Cyclotron Resonance (ECR) heated plasmas ($P_{ECRH} \leq 400$ kW) and in Neutral Beam Injection (NBI) heated plasmas (P_{NBI} port through ≈ 450 kW, ECRH target plasmas) with Li-coated wall conditions [13]. A full set of plasma diagnostics has been used to characterize plasma parameters, in particular two sets of Langmuir probes installed on fast reciprocating drives working simultaneously (at approximately 1 m/s) [17].

Different edge plasma parameters were simultaneously characterized in two different toroidal positions approximately 160º apart using the above mentioned two multi-Langmuir probes systems. One of the probes (Probe 1) is located in a top window entering vertically 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 the plasma through a higher 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 150º poloidally apart when reaching the toroidal position of the other probe that is more than 5 m away. Measurements of the ion saturation current (i.e. the local plasma density), the plasma floating potential (i.e. the plasma potential) and electric fields as well as the fluctuations of these magnitudes are obtained by probes. A graphite electrode (12 mm high, 25 mm diameter) was developed 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 in TJ-II. A Photron SA1 fast camera has also been used to obtain 2-D resolved images simultaneous to probes measurements. This set-up allows the simultaneous investigation of short-range and long-range fluctuation scales (a few millimetres and about ten meters, respectively) in the plasma boundary region [6]. The comparison of results obtained with different diagnostics is also possible.

III. CONFINEMENT BIFURCATIONS IN TJ-II

Confinement transitions in ECRH plasmas. Transition to an improved confinement regime has been observed in TJ-II for some ECRH plasma conditions [18, 19]. In agreement with this result, it has been shown that the development of sheared flows at the plasma edge of the TJ-II requires a critical value of plasma density or density gradient that depends on global plasma parameters [9, 10, 20]. Radial profiles of measured plasma edge parameters are strongly modified as plasma density increases: the gradient of the ion saturation current increases and the floating potential becomes more negative at the plasma edge. Above a threshold density value the perpendicular phase velocity reverses sign at the plasma edge from positive to negative values due to the development of the natural shear layer, with a shearing rate of about 10^5 s^{-1} which is of the order of the inverse of the correlation time of fluctuations ($dv_\theta/dr \approx 1/\tau \approx 10^5$ s^{-1}) [21].

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, and once sheared flows are fully developed, the fluctuation level and the turbulent transport slightly decrease and the edge gradients become steeper. Edge sheared flows are developed at the same threshold density in the two toroidal positions. Fast imaging of the plasma edge in shots with different values of density has also revealed an effect of the shear layer on turbulent structures in good agreement with probes results [22].

Biasing induced transitions. 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 latter is very important in TJ-II as the edge parameters and global plasma confinement depend strongly on it as has been mentioned above. 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 but it is similar at the two toroidal locations. As has been shown in previous works [11, 12], depending on the plasma conditions the global as well as the edge parameters can be modified as the electric field is developed in the plasma edge by means of the applied bias: an increase in the plasma density simultaneous to a decrease in the H_α radiation as well as in the edge turbulence is observed.

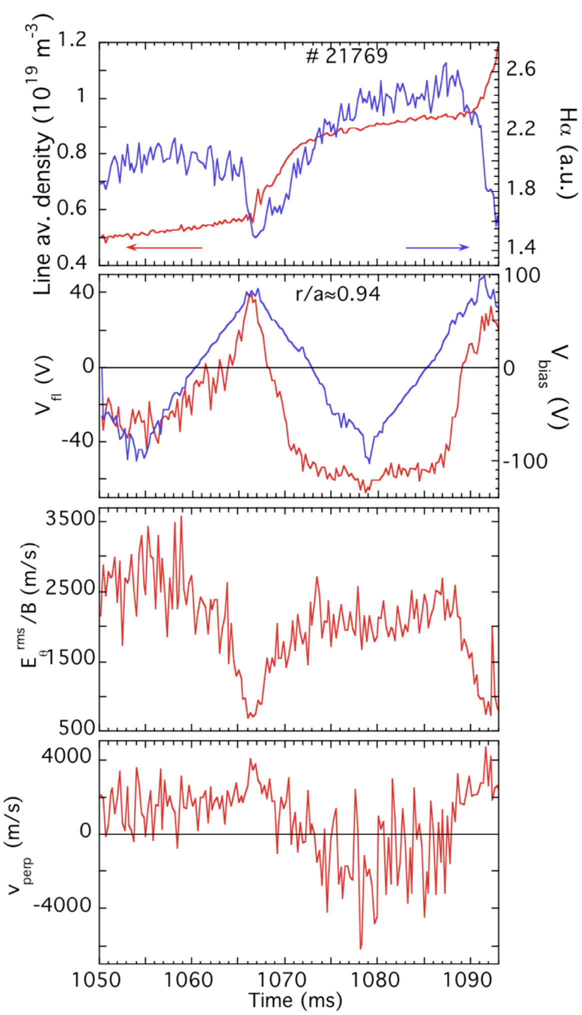

Fig. 1. Time evolution of global and edge plasma parameters during dynamic biasing (40 Hz) experiments.

New experiments using a modulated power supply for the electrode are in progress. The frequency of the applied voltage can be varied in a wide range. The response of the plasma to this modulated bias depends on the sweeping frequency and potential amplitude: for frequency below around 100 Hz plasma parameters evolve as the bias voltage. For frequency values above 100 Hz the global plasma parameters do not follow the evolution of biasing contrary to the edge parameters. Then dynamic edge biasing produces modulation in the edge electric field providing new strategy for studying edge momentum transport and transition physics. The electric field induced by bias competes with the effect on the electric field due to density increasing by biasing (Fig. 1).

Confinement transition in NBI plasmas. Recent experiments with Li-coating [13] and NBI heating have shown evidence for spontaneous bifurcations occurring at a threshold value of the plasma density ($2x10^{19}$ m^{-3}), leading to an increase of the density gradient and the stored plasma energy, and accompanied by a reduction in H_α emission (due to a decrease of the outward particle flux) and a reduction of the level of broadband fluctuations (typically by a factor of 2 – 3) on a short time scale (a few tens of microseconds) (Fig. 2). The observed phenomena are considered characteristic of a transition to an improved confinement regime triggered by an edge bifurcation [14]. The reduction in fluctuation level is evident from a drastic modification of the frequency spectra of density and potential fluctuations. However, whereas density fluctuations are reduced over a wide frequency range (1 – 200 kHz), low frequency fluctuations in the potential measurements (below 40 kHz) are not significantly reduced at the transition. This behaviour was observed with both probe systems, showing that this is a global phenomenon.

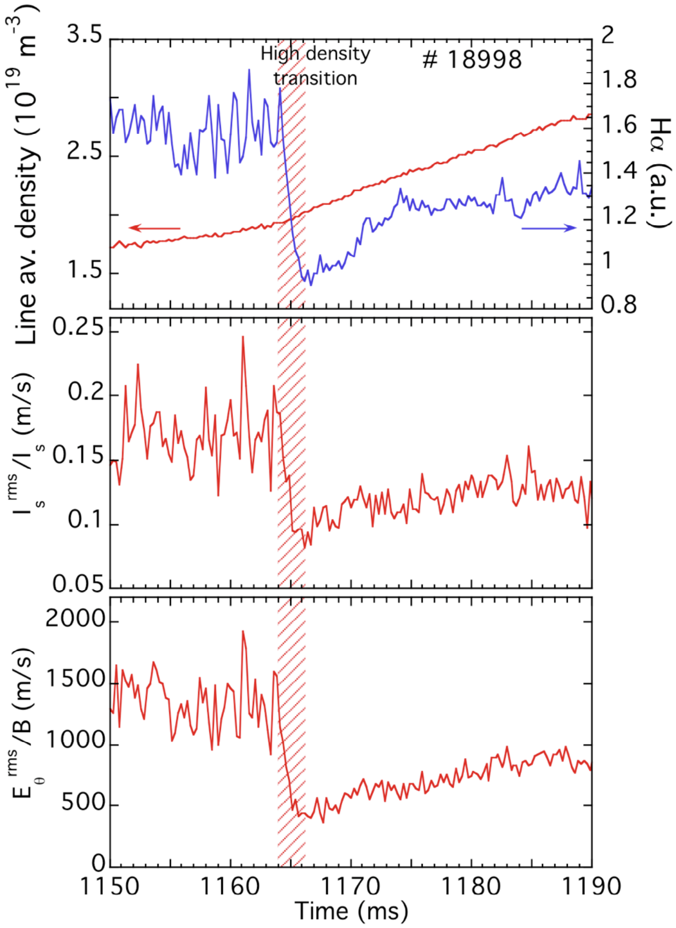

Fig. 2. Time evolution of global plasma parameters and edge fluctuations during NBI experiments.

IV. LONG-RANGE CORRELATIONS MEASUREMENTS

The long distance coupling between edge density and potential fluctuations has been investigated during transitions to improved confinement regimes in the TJ-II stellarator. To quantify the similarity between probe signals the toroidal cross-correlation 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 and in NBI plasmas.

Lon-range correlation in ECRH plasmas. Measurements have been obtained simultaneously with both Probe 1 and 2 systems, located at approximately the same radial position (ρ=r/a≈0.9), while changing density in ECRH plasmas. Floating potential signals measured at both toroidal locations show a striking similarity mainly for low frequency components, contrary to that observed in the ion saturation current signals. This similarity is observed at different time scales but is clearer during fluctuation events with frequency in the range of 1 – 2 kHz related to the shear flow development [9]. The cross-correlations for ion saturation (i.e. edge plasma density) and floating potential signals (i.e. plasma potential) have been computed at different plasma

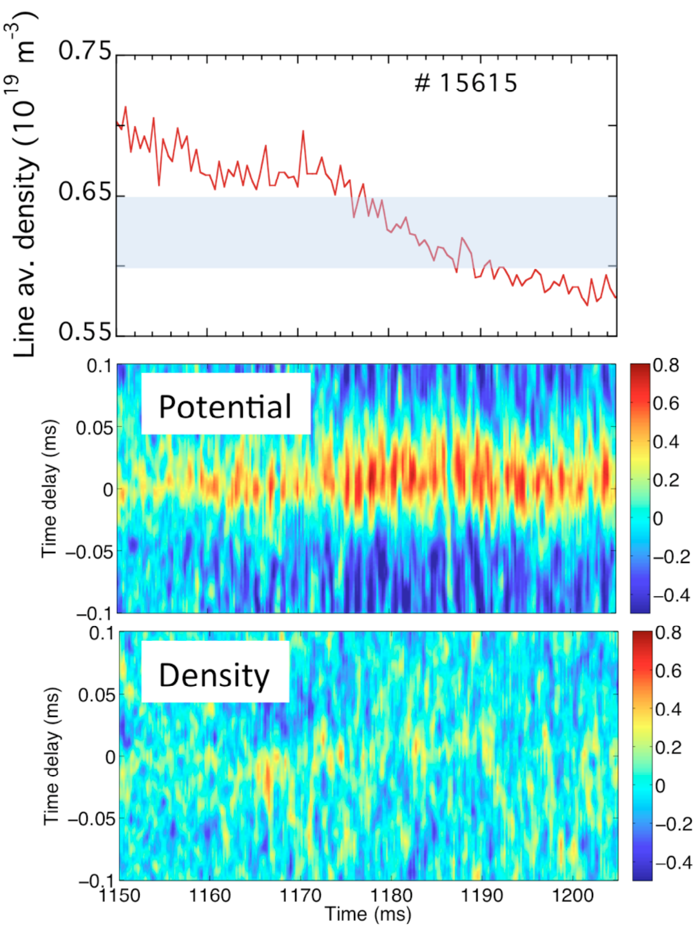

Fig. 3. Behaviour of floating potential and density long-range correlations as plasma density decreases. Shadowed area shows the density threshold for sheared flows development in the configuration under

density values. It is observed that the cross-correlation depends on the density, being larger as density reaches the value that corresponds to the threshold density for shear flow development for the selected plasma configuration (Fig. 3). The increase of correlation with density results mainly from the rise in the correlation at low frequencies (below 20 kHz) [6].

__Long-range correlations during biasing induced transitions.__ The toroidal cross-correlation of the floating potential and the ion saturation current signals measured at different radial positions were compared in experiments with and without applied biasing, in ECRH plasmas and with similar line averaged density. The ion saturation current toroidal correlation turns out to be very low. On the contrary the correlation between floating potential signals is significant, particularly during biasing where it increases while the ion saturation current correlation is in the noise level range. The maximum of the floating

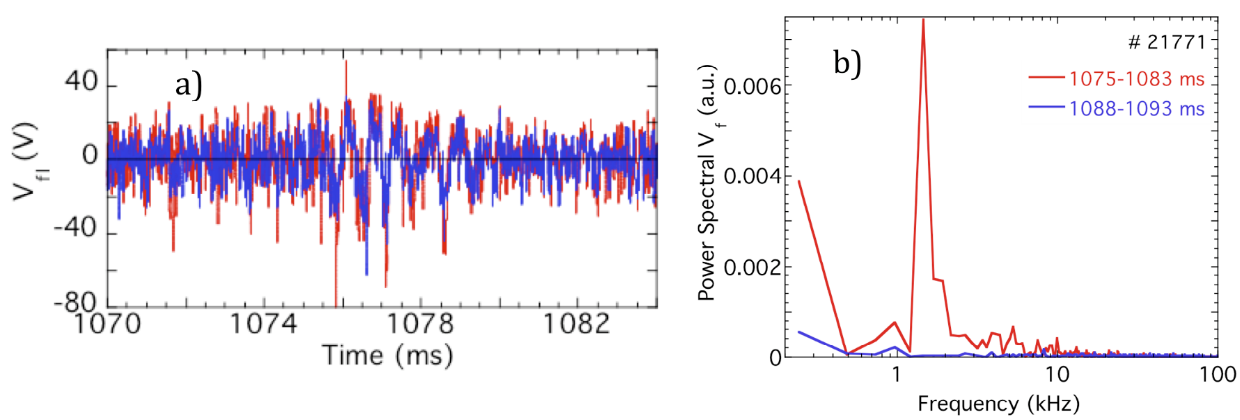

Fig. 4. a) Transient events observed in filtered floating potential signals (band-pass filter applied 1 to 40 kHz) during the dynamical biasing induced transition.
b) Floating potential power spectra obtained during (red) and after the transition (blue). (See also Fig. 5).

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 Scrape-Off Layer (SOL) [6]

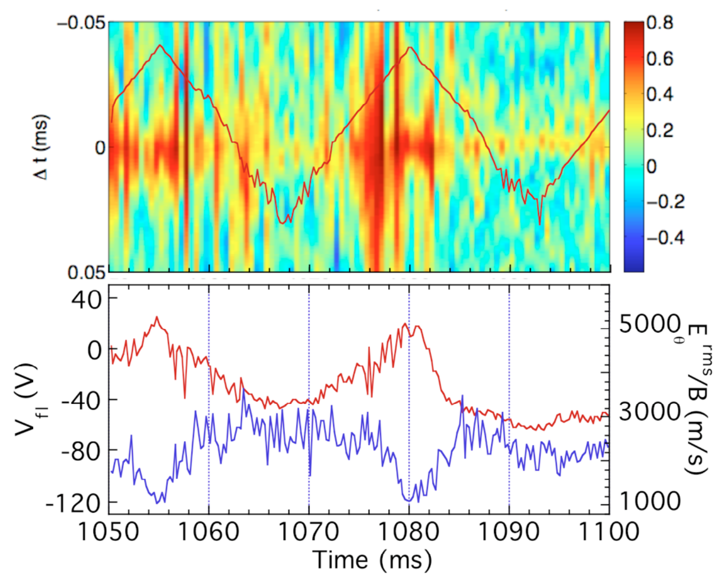

Fig. 5. Time evolution of long-range correlations between floating potential signals during dynamical biasing experiments. The evolution of floating potential and fluctuations is also shown.

Transient events have been observed during the transitions in the dynamical biasing experiments. Those events, with frequency of 1 – 2 kHz independent of the biasing applied frequency (Fig. 4 and Fig. 5), are strongly correlated in the two probe systems (Fig. 5).

Long-range correlation in NBI plasmas. The evolution of long-range correlation of potential fluctuations as a function of the line-averaged plasma density has been studied as plasma changes from ECRH to NBI phase. At the value of the plasma density at which the mean edge sheared flow develops in ECRH plasmas long-range correlation is detected with amplitude of about 0.5. As plasma density increases, ECR-heated plasmas ($n < 10^{19}$ m^{-3}) give way to pure NBI-heated plasmas ($n > 10^{19}$ m^{-3}), and the correlation increases up to about 0.6. Near the plasma conditions where the transport bifurcation occurs, characterised by a plasma density of $n \approx 2 \times 10^{19}$ m^{-3}, the correlation rises to 0.7 - 0.8. Once in the improvement regime, the long-range correlation decreases on the time scale of the energy confinement time (Fig. 6) [15].

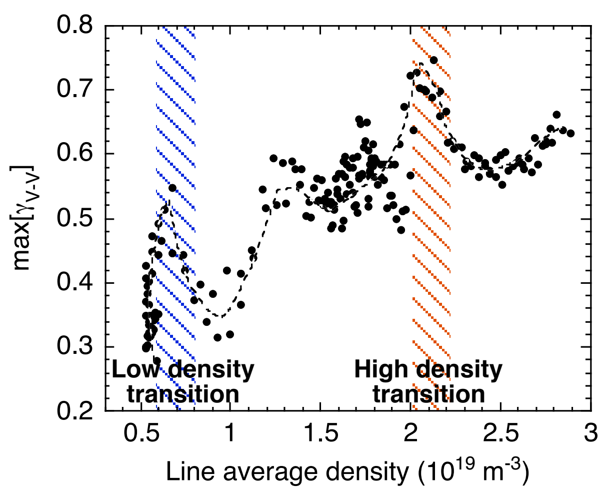

Fig. 6. Maximum value of the long-range correlation function for potential fluctuations as a function of the plasma density during ECRH and NBI phases.

Approaching the NBI transition, the long-range correlation of potential fluctuations is significant and matches the evolution of $1/H_\alpha$. During this phase (low confinement) the correlation shows transient events, with a frequency about 1 – 2 kHz, similar to the ones that have been observed in bifurcations obtained in other conditions.

The dynamical interplay between the different frequency ranges of the potential spectra has been investigated (Fig. 7). Experimental results show that the integrated power in the low (below 25 kHz) and high (above 60 kHz) frequency ranges are approximately anti-correlated; thus, as the low frequency fluctuation power increases the

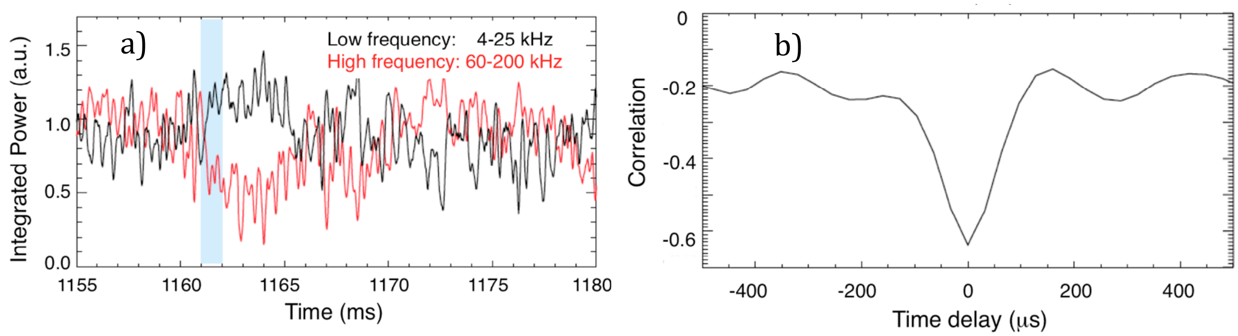

Fig. 7. a) Comparison between low and high frequency potential signals during NBI phase and b) correlation between them.

power in the high frequency range decreases. This result is consistent with the idea of an inversed energy transfer between broadband turbulence and low frequencies (i.e. between different plasma scales) [15].

V. COMPARISON WITH FAST CAMERA RESULS

Fast camera experiments have shown the capability to detect the 2-D structure of plasma fluctuations in different plasma conditions [22].

Comparative studies of the poloidal phase velocity of fluctuations measured by probes, using the two points correlation technique and 2-D evolution of blob velocity fields show good agreement. In addition, the evolution in the rms fluctuation levels (as measured with probes) is strongly correlated with the number of blobs (above a size threshold in the order of 1 cm) detected by fast camera measurements during the dynamical biasing (Fig. 8).

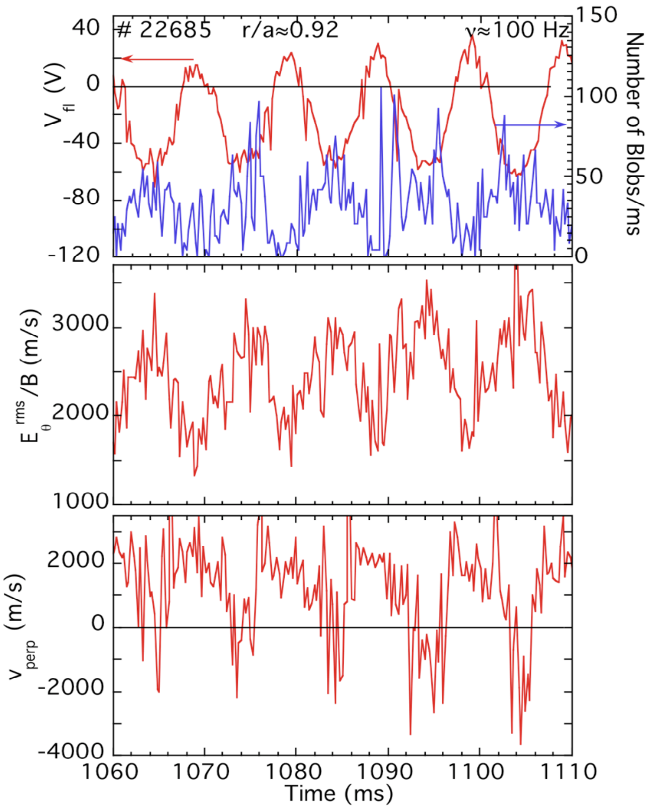

Fig. 8. Average number of blobs per ms compared with floating potential, fluctuations level and perpendicular velocity signals obtained with probes.

VI. COMPARISON WITH A THEORETICAL MODEL

The mean sheared flow development in TJ-II was described in terms of a simple transition model based on the paradigm of mean sheared flow amplification by the Reynolds stress and turbulence suppression by shearing [23]. This model has been recently extended [16] to give an interpretation of the results obtained during the ECRH density induced transitions. It has been proposed that the experimental findings can be understood in the framework of the above paradigm if one appropriately incorporates the contribution of zonal flows. Results show that the extended model is able to capture the essential features of the experimental observations. The numerical calculations detailed therein include a flux ramp traversing the critical point, going from a low to an improved confinement state. The good agreement between the model and the experimental results suggests that the phenomenon of the long-range correlations is a manifestation of the development of zonal flows during the transition.

VII. CONCLUSIONS

Experiments in the TJ-II stellarator have shown direct evidence of long-range spatial correlations that are amplified during the development of spontaneous edge transition and by biasing induced transition. This finding shows a direct interplay between mean radial electric field in the development of multi-scale mechanisms in fusion plasmas.

Modelling results suggest that the observed long distance correlations reflect the transitory development of zonal flows near the critical point.

These observations provide a guideline for further developments in plasma diagnostics and transport studies of plasma bifurcations. In particular experimental and simulation studies of multi-scale physics aspects and their interplay with electric fields and magnetic topology (e.g. magnetic stochasticity and rational surfaces) are needed to unravel the underlying physics of long-range correlations during the development of transport barriers. Studies of the impact of zonal flows on plasma transport in different plasma regimes (e.g. role of plasma density and heating power) are also needed. Further development of plasma diagnostic for studying the properties of mean and fluctuating electric fields during edge plasma bifurcations is necessary.

Acknowledgments

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