Long-Range Correlations During Plasma Transitions in the TJ-II Stellarator

M. A. Pedrosa1, C. Hidalgo1, C. Silva2, B. A. Carreras3, D. Carralero1, I. Calvo1, and the TJ-II Team

1 Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, 28040 Madrid, Spain
2 Associação EURATOM-IST, Centro de Fusão Nuclear, Lisboa, Portugal
3 Departamento de Física, Universidad Carlos III, Madrid, Spain

Received 13 November 2009, revised 17 December 2009, accepted 4 January 2010
Published online 21 July 2010

Key words Plasmas, stellarators, turbulence, confinement

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 in ECRH and NBI plasmas. 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 transitions.

1 Introduction

The importance of turbulent transport effects on plasma confinement in fusion devices is well known and widely accepted. Transport bifurcation to improved confinement regime is directly related to the formation of sheared flows that can stabilize plasma turbulence. Understanding the mechanisms governing the development of this bifurcation, which leads to the establishment of a transport barrier, is still one of the main scientific challenges 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]. TJ-II experimental findings are in good agreement with the expectations of transition models of turbulence driven sheared flows including zonal flows effects [11]. Electrode biasing has been used in TJ-II to externally produce electric fields that modify the plasma confinement properties [12], [13]. 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 [14] and NBI heating have provided evidence of spontaneous bifurcations with the characteristics of transitions to improved confinement regimes [15]. The long-range correlations studies in NBI plasmas have revealed the importance of multi-scale physics as approaching the plasma conditions where edge transport bifurcations are developed [16].
2 Experimental Set-up

Experiments were carried out in the TJ-II stellarator \((B_T = 1 \, \text{T}, \langle R \rangle = 1.5 \, \text{m}, \langle a \rangle < 0.22 \, \text{m}, \epsilon(a)/2\pi \approx 1.5 – 1.9)\), in Electron Cyclotron Resonance (ECR) heated plasmas \((P_{\text{ECRH}} \leq 400 \, \text{kW})\) and in Neutral Beam Injection (NBI) heated plasmas \((P_{\text{NBI}} \text{ port through} \approx 450 \, \text{kW}, \text{ECRH target plasmas})\) with Li-coated wall conditions [14]. A full set of plasma diagnostics has been used to characterize plasma parameters, including 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 160\(^\circ\) 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 \(\phi \approx 35^\circ\) (where \(\phi\) is the toroidal angle in the TJ-II reference system). Probe 2 is installed in a bottom window at \(\phi \approx 195^\circ\) 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 150\(^\circ\) poloidally apart when reaching the toroidal position of the other probe that is more than 5 m away. Measurements of the for ion saturation current and floating potential (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.

3 Long-range correlation measurements during plasma transitions

The long distance coupling between edge density and potential fluctuations has been investigated during transitions to improved confinement regimes in TJ-II. To quantify the similarity observed between probe signals the toroidal cross-correlation [18] (that means between signals measured in the two toroidally apart probes) has been computed for a wide range of TJ-II plasma conditions. The long-range correlation has been measured during TJ-II transitions observed in density scan experiments as well as with electrode bias and in NBI plasmas.

3.1 Confinement transitions in TJ-II ECRH plasmas

Transition to an improved confinement regime has been observed in TJ-II for some ECRH plasma conditions [19], [20]. 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], [21], [22]. 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 \(10^5 \, \text{s}^{-1}\) which is of the order of the inverse of the correlation time of fluctuations \((dv_a/dr=1/\tau \approx 10^5 \, \text{s}^{-1})\) [23].

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 levels and the turbulent transport slightly decrease and the edge gradients become steeper [10]. Edge sheared flows are developed at the same threshold density in the two toroidal positions [6]. Fast imaging of the plasma edge in plasmas with different values of density has also revealed an effect of the shear layer on turbulent structures in good agreement with probes results [24].

Measurements have been obtained simultaneously with both Probe 1 and 2 systems, located at approximately the same radial position \((\rho_{max}/a=0.9)\), 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 the intermittent transient events with frequency in the range of \(1 – 2 \, \text{kHz}\) that appear related to the shear flow development [9]. The cross-correlations for ion saturation and floating potential signals have been computed at different plasma 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. Figure 1 shows the time evolution of the maximum long-range correlation between floating potential signals and between ion saturation current signals during a density ramp down experiment crossing the threshold density for sheared flows development. The increase of correlation in the proximity of the threshold density results mainly from the rise in the correlation at low frequencies (below 20 kHz) [6]. Simultaneously to the increase of the potential long-range correlation a decrease in the local (measured in one of the probes systems) density-potential correlation, directly related to the local radial particle flux, is observed. This result, shown in figure 2, has been also observed during biasing transitions and can suggest regulation of transport by means of long-range flows.

![Fig. 1](image1.png)  
**Fig. 1** Behaviour of maximum long-range correlations for floating potential and density signals as plasma density decreases. Shadowed area shows the density threshold for sheared flows development in the configuration under study.

![Fig. 2](image2.png)  
**Fig. 2** Long-range and local coherence spectra during ECRH density transition (1180-1190 ms, see figure 1).

The mean sheared flow development in TJ-II was described in terms of a simple transition model based on the paradigm of mean sheared flows amplification by the Reynolds stress and turbulence suppression by shearing [25]. This model has been recently extended [11] 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.
3.2 Biasing induced transitions in TJ-II

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 [12, 13], 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$_\alpha$ radiation as well as in the edge turbulence is observed.

![Figure 3](image1.png)  
**Fig. 3** Time evolution of global (density, H$_\alpha$ signal and applied bias) and edge plasma parameters (floating potential, fluctuations level and perpendicular velocity) during dynamic biasing (40 Hz) experiments.

![Figure 4](image2.png)  
**Fig. 4** Time evolution of floating potential raw signal measured in Probe 1 and maximum long-range correlations between floating potential signals during dynamical biasing (40 Hz) experiment.

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 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].

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. As in previous bias experiments [12], the response of the plasma to this modulated bias depends on the plasma density (or gradient), the sweeping frequency and the biasing / potential amplitude. Dynamic edge biasing produces modulation in the edge electric field providing a new strategy for studying edge momentum transport and transition physics. In figure 3, the evolution of the line averaged density and the Hα radiation as biasing (V_{bias}) is applied to the electrode are shown. Also the responses to the bias of the floating potential (Vf), the fluctuation level of the poloidal electric field (E_{pol}^{rms}, i.e. radial velocity) and the perpendicular velocity of fluctuations (v_{perp}) measured at the plasma edge are shown. It has been previously addressed that the development of sheared flows at the plasma edge of the TJ-II requires a minimum plasma density (or gradient) and that the onset of the sheared flows development is coupled with an increase in the level of fluctuations [10]. Depending on the plasma density value that evolves with the applied external electric field, the level of fluctuations changes along the time with the simultaneous sheared flows development. Plasma confinement improves for a given value of the density (or gradient) and of the external electric field applied, as is reflected by the increase in the plasma density and in the Hα decrease, with the concomitant sheared flow development and the additional reduction of fluctuations. Then, the effect of the electric field induced by bias superimposes to the effect of the electric field spontaneously developed at the plasma edge, which in its turn is a consequence of the improvement of confinement induced by bias, giving rise to the evolution of the global and edge parameters observed. The resulting electric field and the induced plasma changes depend on the applied bias (value and sign) together with the plasma conditions (mainly the density or density gradient) existing when the bias is applied.

Strongly long-range correlated transient events have been observed during the transitions to improved confinement regimes in the dynamical biasing experiments. Figure 4 shows the floating potential measured in probe 1 together with the time evolution of the maximum long-range correlation between the floating potential signals during a dynamic biasing (40 Hz) experiment similar to the one described in figure 3. Highly toroidal correlated transient events are observed, appearing at the time at which sheared flows develop (around 1058 ms and 1078 ms) with a simultaneous increase in the long-range correlation. These results can be interpreted as an indication of long-range correlated structures arising as sheared flows are developed. Figure 5a shows the similarity between floating potential signals measured in both probes and filtered in the frequency region of interest (1 - 40 kHz) during the above-described transient events. This similarity can be quantified by the increase of long-range correlation shown in figure 4. During these transients, the spectrum of fluctuations shows a peak at 1 – 2 kHz as can be seen in figure 5b, that shows the spectra obtained during transients and when long-range correlation decrease. This peak is independent of the biasing applied frequency and it possibly reflects the time scale of the intermittent long-range correlated transient event.

3.3 Confinement transition in NBI plasmas

Recent experiments with Li-coating [14] 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 Hα 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). The observed phenomena are considered characteristic of a transition to an improved confinement regime triggered by an edge bifurcation [15]. The reduction in fluctuation level is evident from a drastic modification of the frequency spectra of density and potential fluctuations [16]. 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 long-range phenomenon. Figure 6 shows the time evolution of the line averaged density, the Hα radiation, the fluctuations level and the maximum of the long-range correlation between potential signals measured at the plasma edge (r/a≈0.9) during the NBI transition.
The evolution of the 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 – 0.6 [6], [16]. As plasma density increases, ECR-heated plasmas \( n < 10^{19} \text{ m}^{-3} \) give way to pure NBI-heated plasmas \( n > 10^{19} \text{ m}^{-3} \), and the correlation increases up to about 0.6. Near the plasma conditions where the transport bifurcation occurs, characterised by a plasma density of \( n \approx 2 \times 10^{19} \text{ m}^{-3} \), the correlation rises to 0.7 - 0.8 as is shown in figure 6. Once in the improvement regime, the long-range correlation decreases on the time scale of the energy confinement time [16].

Approaching the NBI transition, the long-range correlation of potential fluctuations is significant and matches the evolution of \( 1/H_\alpha \) [16]. 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. 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 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 times scales) [16].

4 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 and the development of multi-scale mechanisms in fusion plasmas.

Modelling results suggest that the observed long distance correlations reflect the 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.

Acknowledgements The authors acknowledge the support from technicians, data acquisition group and the whole TJ-II team. One of us (BAC) thanks the financial support of Universidad Carlos III and Banco de Santander through a Cátedra de Excelencia. This research was sponsored in part by Ministerio de Educación y Ciencia of Spain under Project ENE2006-15244-C03-02.

References