Radial electric fields and improved confinement regimes in the TJ-II stellarator

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Abstract. The influence of plasma density and edge gradients in the development of perpendicular sheared flows and radial electric fields, has been investigated in the plasma edge region of the TJ-II stellarator. Experimental results show that the development of the "naturally occurring" velocity shear layer requires a minimum plasma density (or gradient). Near this critical density, the level of edge turbulent transport and the turbulent kinetic energy significantly increase in the plasma edge; once sheared flows are fully developed the level of fluctuations and turbulent transport slightly decreases whereas edge gradients and plasma density increase. Furthermore, the resulting shearing rate of the spontaneous sheared flows turns out to be close to the one needed to trigger a transition to an improved confinement regimen (H-mode like regimes), suggesting that spontaneous sheared flows and fluctuations keep themselves near marginal stability. These findings provide the first experimental evidence of coupling between the development of sheared flows and increasing in level of edge turbulence. Experimental results are consistent with the expectations of second-order transition models of turbulence driven sheared flows.

1. Introduction

Controlling plasma fluctuations by means of the shear stabilization mechanism [1] has become a new and important technique in plasma confinement studies. The best performance of existing fusion plasma devices has been obtained in plasma conditions where ExB shear stabilization mechanisms are likely playing a key role; both edge and core transport barriers are related to a large increase in the ExB sheared flows. When the shearing rate approaches the characteristic frequency of the turbulence, a reduction in the turbulence amplitude is predicted. The similarity in the structure of the naturally occurring velocity shear layer in different devices points to the possible role of turbulence driven mechanisms as a universal ingredient to explain the driving mechanisms of sheared flows in the plasma boundary region [2]. These results emphasize the importance of clarifying the driving mechanisms of sheared flows in fusion plasmas.

Spontaneous and biasing-induced improved confinement transitions have been observed in the TJ-II stellarator [3, 4, 5]. Experiments have shown that the development of the naturally occurring edge velocity shear layer requires a minimum plasma density (or/and minimum level of plasma turbulence). Although experimentally the external control is the plasma density, it would be more appropriate to characterize experimental results in terms of edge plasma gradient (e.g. I_s gradients) [6]. These findings open a unique possibility to characterize the dynamics of sheared flow development in fusion plasmas.

This paper reports the evolution and dynamics of plasma turbulence and plasma profiles during the onset of the naturally occurring velocity shear layer in the edge region of the TJ-II stellarator. Recent experiments focused in the study of the influence of plasma density, heating power and magnetic configuration on the structure of radial electric fields are reported. Also comparison to biasing-induced improved confinement regimes is shown.

2. Experimental set-up

Experiments were carried out in Electron Cyclotron Resonance Heated plasmas (P_{ECRH}= 200 - 400 kW, B_T = 1 T, R = 1.5 m, $\langle a \rangle \leq 0.22$ m, $\iota(a)/2\pi \approx 1.7 - 2.1$) created in the TJ-II stellarator. Plasma line density was systematically modified in the range (0.35–1) x 10^{19} m^{-3}. Radial profiles and fluctuations were simultaneously measured at the plasma edge region using Langmuir / Mach probes [7]. The design of the probe allows us to measure radial profiles of different plasma magnitudes at the plasma edge (up to 3 cm inside the last closed flux surface (LCFS) r/a=1) and to deduce the perpendicular and parallel flows as well as the radial turbulent particle flux. The probe signals were digitized at a sampling rate of 500 kHz.

For biasing-induced improved confinement regimes [5] two mobile limiters have been used for biasing experiments; one of them was radially localized up to 2 cm inside the LCFS and was biased ($\Delta V_{limiter}$ =160 – 250 V, $I_{limiter} \approx 30 - 50$ A) with respect to the second outer limiter located in the scrape-off layer region (0.5 cm beyond the LCFS).

Radial profiles of the electron temperature and the electron density have been measured by the Thomson Scattering system [8]. The radial profiles of electron density at the plasma edge (up to 5 cm inside the LCFS) have been also obtained by reflectometer signals [9].

3. Spontaneously developed sheared flows and edge turbulence

The influence of plasma density on ion saturation current, floating potential, poloidal wave number and phase velocity of fluctuations has been investigated in the plasma edge region (r/a ≈ 0.8 – 1.15) by means of different approaches: changing density from shot to shot and by density ramp experiments. Experimental results show that the development of the naturally occurring edge velocity shear layer requires a minimum plasma density (or gradient) in the TJ-II stellarator.

Radial profiles of the different magnitudes measured at the plasma edge have been obtained when modifying density from shot to shot in a wide range and with $\iota(a)/2\pi \approx 1.7$ (figure 1). As the plasma density increases, above a critical value of density, 0.5 x10^{19} m^{-3} approximately, edge ion saturation current and its radial gradient increase and the floating potential becomes more negative in the plasma edge. Because the edge temperature profile (in the range of 20 – 40 eV) is rather flat in the TJ-II plasma periphery [10], the radial variation in the floating potential signals directly reflects changes in the radial electric field (E_r), which turns out to be radially inwards in the plasma edge as density increases above the critical value (≈0.5 x 10^{19} m^{-3}).

The electrostatic fluctuation driven radial particle flux, $\Gamma_{ExB} = \langle \tilde{n}(t)\, \tilde{E}_\theta(t) \rangle / B$, has been obtained neglecting the influence of electron temperature fluctuations. The level of local turbulent transport (figure 1.c) remains radially rather constant and small in regimes with

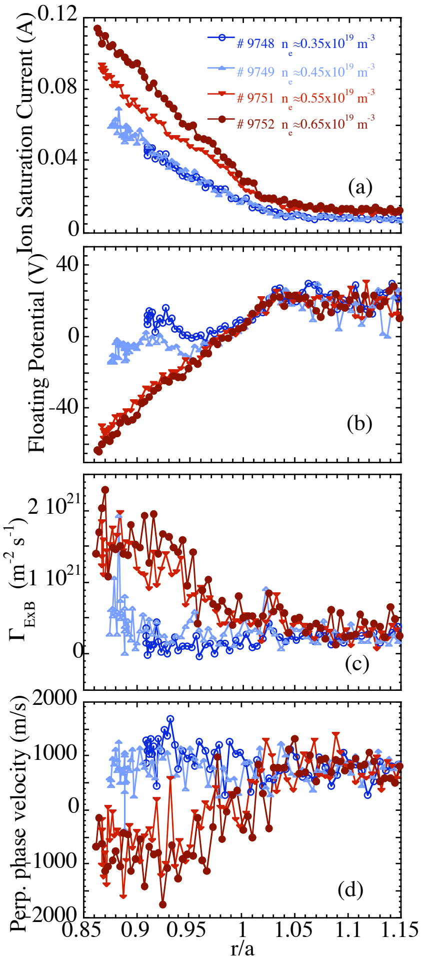

Figure 1.- Radial profiles of (a) the ion saturation current, (b) the floating potential, (c) the local turbulent transport and (d) the deduced perpendicular velocity obtained for different values of the line averaged density in a plasma configuration with $\iota(a)/2\pi \approx 1.7$.

low density. During the development of the shear layer (i.e. above the critical plasma density) Γ_{ExB} increases about a factor of ten in the plasma edge (r/a ≈ 0.9 – 0.95) whereas Γ_{ExB} decreases when moving radially outwards.

The resulting radial profile of the perpendicular phase velocity of fluctuations, v_θ, (perpendicular to the magnetic field and to radial direction) [11] (figure 1.d) is radially flat for a mean plasma density below 0.5 x 10^{19} m^{-3}, above this critical density the naturally occurring velocity shear layer appears in the proximity of the LCFS. This phase velocity reversal can be explained, or at least is consistent, in terms of E_rxB drifts in agreement with previous results obtained in other devices [12,13]. It can be deduced that the shearing rate obtained in spontaneous sheared flows regime is in the order 10^5 s^{-1}.

Plasma density and electron temperature profiles, measured by Thomson scattering have been obtained for shots with different values of line-averaged density. Figure 2 shows the profiles of the electron temperature and the electron density obtained in plasmas with different line averaged density (see figure 1): below the critical value (0.35x10^{19} m^{-3}), near the critical value (0.55 x 10^{19} m^{-3}), and above the critical value (0.75 x 10^{19} m^{-3}). Results show an increase in the whole density profile and in its gradient at the plasma edge without relevant changes in the temperature profile; that means that pressure profile increases as the mean density increases. Abrupt changes in density gradients with plasma density have been also observed by means of reflectometry. This shows the strong impact of plasma density in the global confinement scaling in the TJ-II stellarator.

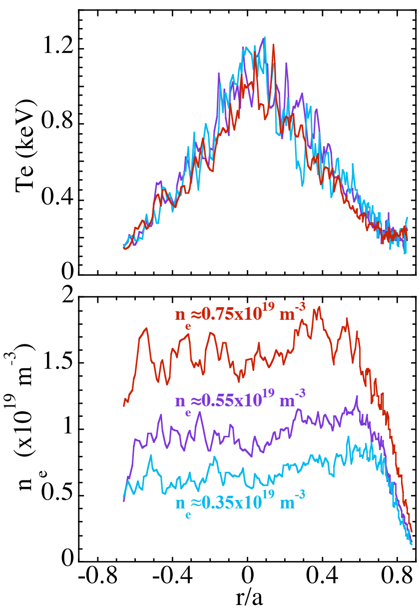

Figure 2.- Electron temperature and plasma density profiles measured by Thomson Scattering in three shots with different line averaged density value.

The behaviour of plasma edge magnitudes has been investigated at a fixed position as density was changed in the range (0.35 – 1) x 10^{19} m^{-3}, both shot to shot and during a single shot. Results obtained at r/a≈0.8 are shown in figure 3 for magnetic configuration with $\iota(a)/2\pi \approx$ 1.7. The reproducibility obtained in the experimental findings changing density shot to shot and with density ramp is remarkable. A sharp change can be observed in the different magnitudes around the critical density (≈ (0.5 - 0.6) x 10^{19} m^{-3}) at which sheared flows are developed. The local turbulent particle flux and the

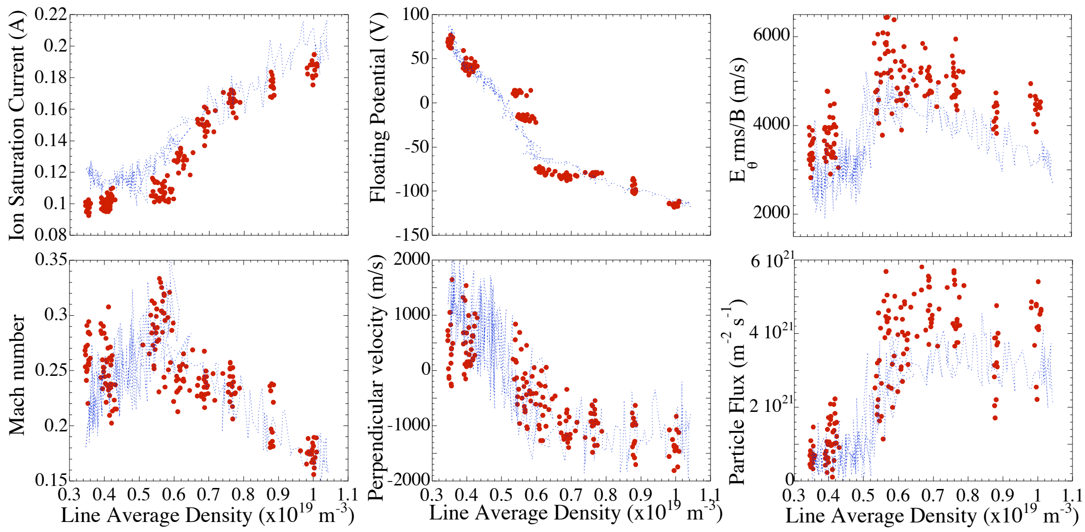

Figure 3.- Behaviour of the edge plasma parameters (r/a≈0.8) as a function of the line averaged density for shot too shot (red dots) and density ramp (blue line) experiments. Each dot means the average of the corresponding signal over half a millisecond. The dispersion of the measurements can be an indication of the corresponding error value.

parallel flow increase with density until the critical value is reached. Beyond this point, fluctuations, parallel flow and turbulent transport slightly decrease although edge gradients become steeper (see figure 1). The perpendicular velocity changes sign above the critical density value due to the development of the natural shear layer (and so does the radial electric field). Below the critical density the shear layer does not exists at least up to 3 cm inside the LCFS (r/a≈0.8). These results indicate that the evolution of parallel flows, the level of poloidal electric field fluctuations and the generation of ExB sheared flows are coupled [14]. The correlation between the increase in the edge-shearing rate with an increase in the turbulent velocity fluctuations (E_θ/B) [6] suggest that a minimum level of turbulent kinetic energy is needed in the plasma edge to trigger the spontaneous formation of the sheared flows.

In order to unravel the underlying physics of the development of sheared flows it is important to clarify the existence of hysteresis. With this purpose in mind, density ramp up and down (near the critical value) experiments have been compared. Results are presented in figure 4 for measurements taken at three different radial locations (r/a ≈ 0.8, 0.9, 1). No evidence of hysteresis has been found within the experimental uncertainties.

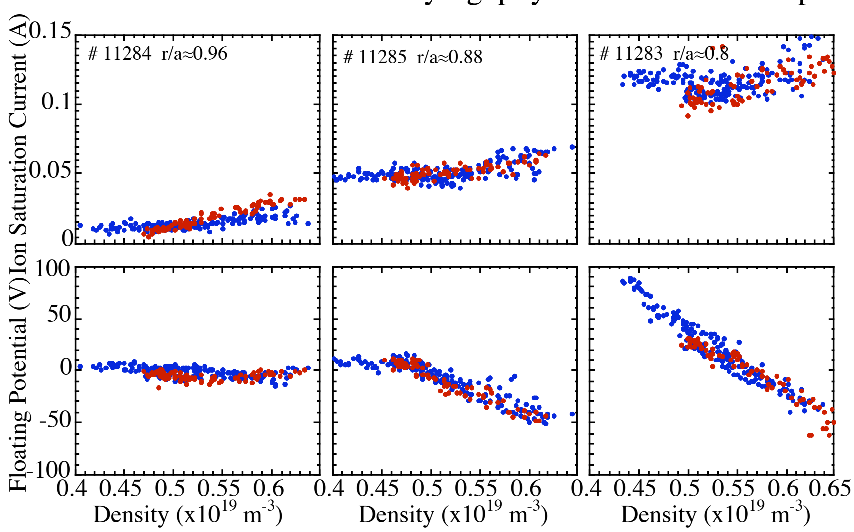

Figure 4.- Behaviour of the ion saturation current and the floating potential as a function of the line averaged density during density ramp up (red) and down (blue) experiments at three different radial positions.

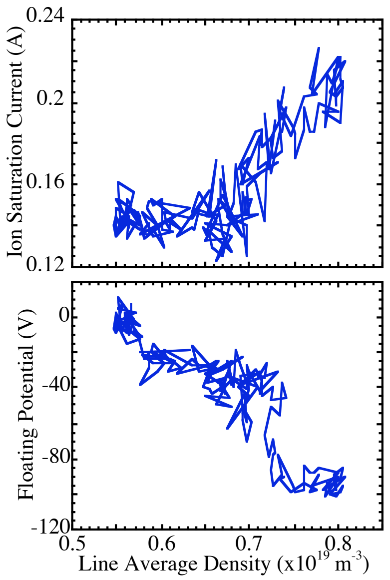

Figure 5.- Behaviour of the edge plasma parameters as a function of the line averaged density. Measurements were taken at r/a≈0.85 and for ι(a)/2π ≈ 2.1.

4. Magnetic configuration effect on the sheared flows

The operational flexibility and the control of the magnetic topology in TJ-II make it a useful laboratory to investigate the role of magnetic configuration and iota on the spontaneously developed sheared flows. The influence of the iota value on the level of fluctuations and on the parallel and perpendicular flows has been recently reported [14].

The effect of the magnetic configuration on the critical density to establish the edge radial electric field is under study. Preliminary results show that the value of the critical density increases as the iota increases. Figure 5 shows the results of ramp density experiments for magnetic configuration with $\iota(a)/2\pi \approx 2.1$. As can be deduced from the comparison of the results shown in figures 3 and 5, the critical density value increases as iota increases.

The link between the development of sheared flows and plasma density in TJ-II has been observed in different plasma magnetic configurations. Experiments with lower iota values are in progress to assert this result.

5. Heating power effect on the sheared flows

The effect of power input has been also studied both heating shot to shot with one or two gyrotrons with the same average plasma density and varying the density by means of one gyrotron power modulation

First results show that the critical density to trigger the development of edge sheared flows increases with heating power. Figure 6 shows the perpendicular velocity, measured in shots with $n_e \approx 0.55 \times 10^{19}$ m^{-3} and $P_{ECRH} \approx 200$ and 400 kW. It can be observed that velocity shear layer is developed for lower power heating, which means that for lower power the critical density is probably lower. This result is consistent whit that obtained by modulating ECRH power. Two gyrotrons (on axis-heating) were used for this experiment: one of them was modulated (between 0 and 200 kW) whereas the other one was at a fixed heating power (200 kW), providing a power modulation between 200 and 400 kW. As power increases (400 kW) plasma density decreases and when only one gyrotron is working (200 kW) density increases. Such behaviour is typical in TJ-II and it is interpreted as a manifestation of an outward particle flux induced by ECRH (density pump-out) [15]. In the present experiments the initial plasma density was set near the critical value to trigger the onset of sheared flows. As density increases above the critical value, the edge perpendicular velocity changes sign, reflecting the development of the velocity shear layer; consequently the floating potential becomes more negative in the plasma edge (r/a≈0.9) (Fig. 7). The behaviour of the edge parameters is strongly

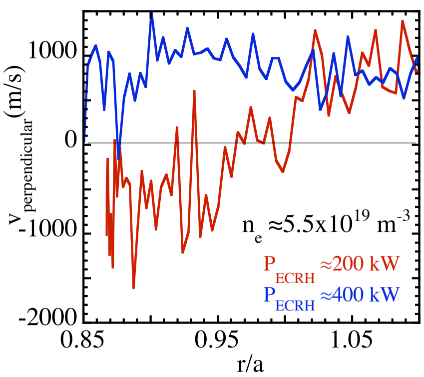

Figure 6.- Radial profile of the perpendicular velocity and line average density as a function of time for shots with different power heating.

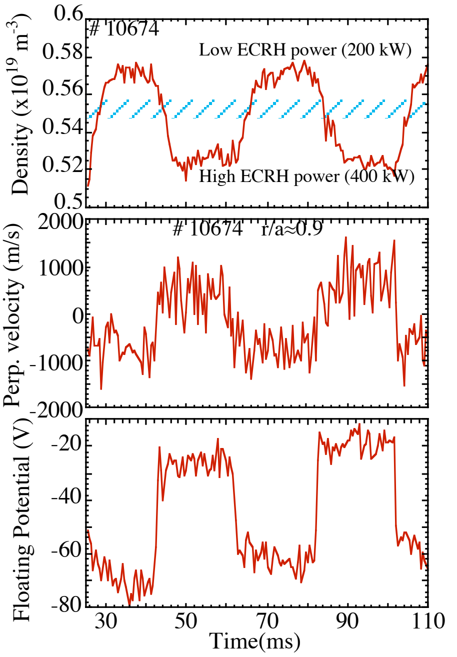

Figure 7.- Line averaged density modulation around the critical value (shadowed area), and the response of the perpendicular velocity and floating potential during ECRH power modulation experiments.

dependent on the probe position (see figure 1), so the position close to the LCFS (r/a≈0.9) is the most suitable to observe the appearance and disappearance of the velocity shear layer. The decay time of floating potential and radial electric fields are in the order of 50 – 100 microseconds, in agreement with results obtained by limiter biasing [5] shown in the next section.

6. Comparison with limiter biasing experiment results

During the transition to improved confinement regimes induced by limiter biasing [5] a clear reduction in the ExB turbulent flux has been observed in the TJ-II stellarator. Time evolution of plasma density, H_α, turbulent transport and the radial gradient in the poloidal phase velocity of fluctuations during limiter biasing experiments are shown in figure 8. Biasing is turned on at 110 ms, however turbulent transport reduction takes place 10 ms later when the gradient in the phase velocity of fluctuations is close to 10^5 s^{-1}. When biasing is turned off dv_θ/dr decreases with a concomitant drastic increase in the turbulent transport.

The evolution with plasma density of shearing rates and turbulent radial velocities measured at the plasma edge (r/a≈0.9) in plasma regimes without (figures 9 a and c) and with biasing (figures 9 b and d) has been compared, at the same probe position and in the same magnetic configuration. As has been deduced by experimental results shown in the previous sections, shearing rate increases as density increases above the critical value (during sheared flows development) and remains constant for higher densities (perpendicular velocity remains constant once the sheared flows are developed). It is remarkable that the observed shearing rates during improved confinement regimes are (at most) a factor of two larger than those observed associated to the naturally occurring shear layer. Fluctuations increase during the sheared flow development and then remain constant as density increases above the critical and when the density is high enough they tend to slightly decrease (see figure 1). For biasing experiments a strong decrease of fluctuations is observed. Thus, it appears that fluctuations and spontaneous sheared flows organize themselves to be close to marginal stability. This result is a key to provide an interpretation of results presented in figure 3.

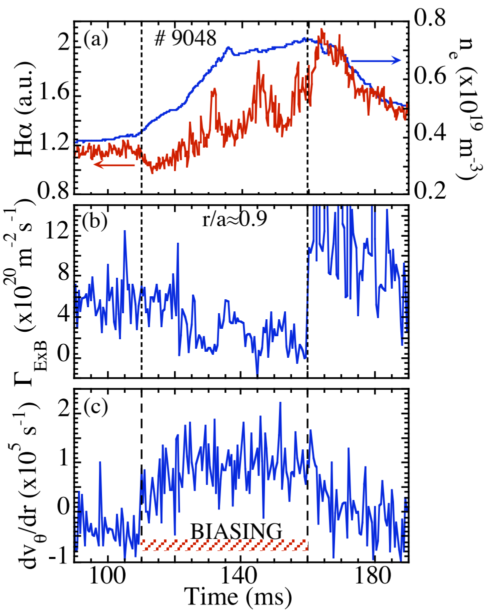

Figure 8.- Hα radiation and line averaged density (a), particle flux (b) and shearing rate (c) during biasing experiments. The vertical dashed lines enclose the biasing limiter time interval.

Electron density and temperature profiles before and during the negative biasing phase show a

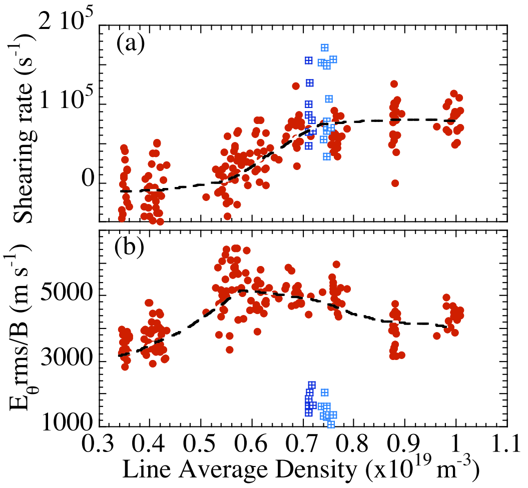

Figure 9.- Shearing rates (a), and radial velocity fluctuations (b) obtained in the shot to shot experiment (red) compared to values measured in biasing-induced improved confinement regimes (blue) as a function of the plasma density at r/a≈0.85. Dot lines are guides for the eye.

broadening in the density profile during biasing while the temperature profile remains similar in both cases. In these regimes radial electric fields are mainly modified in the proximity of the LCFS whereas core plasma potential, as measured by the HIBP system, becomes more negative as plasma density increases.

The decay times of flows, plasma potential and radial electric fields have been measured to investigate the role of magnetic topology on perpendicular / parallel viscosity. Experimental evidence of two different time scales has been found. The fast time scale (50 - 100 μs) is a factor of 5 – 10 larger than the typical correlation times of plasma turbulence whereas the slow one (1 – 10 ms) is linked to plasma density evolution. The phenomenology of TJ-II improved confinement regimes looks similar to the H-mode regimes previously reported in stellarators. This similarity calls into question the leading role of neoclassical viscosity to access improved confinement regimes in stellarator devices [5].

7. Discussion and conclusions

The evolution and dynamics of plasma turbulence and plasma profiles during the onset of the naturally occurring velocity shear layer in the edge region of the TJ-II stellarator has been studied. It has been experimentally observed that the existence of sheared flows in TJ-II requires a minimum plasma density that depends on the magnetic configuration and to the heating power. The phase velocity reversal can be explained, or at least is consistent, in terms of E_rxB drifts in agreement with previous results obtained in other devices. The shearing rate of the spontaneous sheared flows is found to be close to the one needed to reduce turbulence in biasing-induced improved confinement regimes. These findings provide the first direct experimental evidence of coupling between sheared flows development and increasing in the level of edge turbulence and can provide the underlying physics of the spontaneous improved transitions observed in TJ-II [3, 4, 5].

The reported maximum level of fluctuations at the onset of shear flows development, the concomitant decreasing in turbulent transport and fluctuations beyond the critical point (figures 3) as well as the absence of hysteresis during the spontaneous shear development (figure 4) are consistent with the expectations of second-order transition models of turbulence driven sheared flows. First and second order critical transition models, in which the suppression of turbulence via ExB sheared flows is a key ingredient, have been invoked to explain the transition to enhanced confinement regimes. Simulations have shown that no poloidal flow is generated for a flow damping above a critical value and a minimum value of pressure gradient is needed for a sheared flow to be generated in remarkable agreement with the presented experimental results [16, 17].

Present results have a direct impact in the understanding of the physics mechanisms underlying the generation of critical sheared flows, pointing out to the important role of turbulent driven flows.

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