Experimental studies and modelling of edge shear flow development in the TJ-II stellarator

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The universality of the characteristics of sheared flows points to a general ingredient to explain the damping/driving mechanisms responsible for the development of these flows in the plasma boundary region of fusion devices. Experiments in the TJ-II stellarator showing that the generation of spontaneous sheared flows at the plasma edge requires a minimum plasma density or density gradient, open a unique possibility to characterize the dynamics of sheared flow development in fusion plasmas.

The effective viscosity at the plasma edge can be deduced by the decay rate of the perpendicular flow measurement once the driving force is removed. In TJ-II changes in the plasma rotation and turbulence have been studied when an electric field is externally applied. Measurements of the decay time suggest an increase in decay times above the threshold gradient value to trigger the emergence of shear flow (i.e. once edge perpendicular sheared flows are fully developed).

The emergence of the plasma edge sheared flow as a function of plasma density can be explained using a simple second order phase transition model. This simple model reproduces many of the features of the TJ-II experimental data and captures the qualitative features of the transition near the critical point.

Keywords: Turbulence, sheared flows, plasma edge, biasing, stellarators.

1. Introduction

The importance of the ExB shear in flows as a stabilizing mechanism to control plasma fluctuations in magnetically confined plasmas has been widely established. In fact, both H-mode and core transport barriers are related to a large increase in the ExB sheared flow [1, 2, 3]. Clarifying the driving/damping mechanisms of sheared flow remains a key issue for the development of fusion. Both neoclassical (e.g. ion orbit losses [4]) and anomalous mechanisms (i.e. anomalous stringer spin-up [5] and Reynolds stress [6, 7]) have been considered as candidates to explain the generation of sheared flows. Atomic physics via charge-exchange momentum losses [8, 9], parallel viscosity (magnetic pumping) [10] and turbulent viscosity are considered as candidates to explain perpendicular flow damping physics.

The role of neoclassical mechanisms to explain poloidal flows is an open issue in the fusion community. The result of the experiments carried out in TJ-II stellarator can help to understand and quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and flows in fusion plasmas.

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2. Experimental set-up

Experiments were carried out in Electron Cyclotron Resonance Heated plasmas ($P_{ECRH} \leq 400$ kW, $B_T = 1$ T, R = 1.5 m, $\langle a \rangle \leq 0.22$ m, $\iota(a)/2\pi \approx 1.5 - 1.9$) obtained in the TJ-II stellarator. The plasma density was modified in the range (0.35 – 1) x 10^{19} m^{-3}. Different edge plasma parameters were characterized using two multi-Langmuir probe systems, installed on similar fast reciprocating drives (approximately 1 m/s) [11], that allows obtaining radial profiles simultaneously in a single shot, in two toroidal locations approximately 180º apart in high (HFS) and low (LFS) field sides of TJ-II.

A Carbon composite mushroom-shaped electrode (12 mm high with a diameter of 25 mm) was installed on another fast reciprocating drive similar to the one used with probes. The electrode was inserted typically 2 cm inside the last-closed flux surface (LCFS) and biased positively (200-300 V) with respect to one of the two poloidal limiters located in the scrape-off layer region

(SOL) (about 0.5 cm beyond the LCFS). Measured electrode currents were in the range of 30-50 A [12].

3. Development of sheared flows

It has been previously shown that the development of the sheared flows at the plasma edge of the TJ-II requires a critical value of the plasma density or density gradient [13, 14] that depends on the plasma magnetic configuration [15].

Radial profiles of plasma edge are strongly modified as plasma density increases: Gradient of the ion saturation current (i.e. local density) increases and floating potential becomes more negative at the plasma edge [13, 14]. Consistent with the changes in the floating potential, 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 about 10^5 s^{-1} of the order of the inverse of the correlation time of fluctuations ($dv_\theta/dr \approx 1/\tau \approx 10^5$ s^{-1}) [16]. Figure 1 shows the perpendicular flows and the fluctuations of the perpendicular electric field (i.e. the turbulent radial velocity) deduced from measurements at the plasma edge of the TJ-II (r/a≈0.9, where a is the averaged minor radius of the plasma). Measurements have been obtained simultaneously in two toroidal locations and changing density from shot to shot. The levels of turbulent transport and fluctuations increase as density increases up to the critical value for which sheared flow is developed. For densities above the threshold fluctuations and turbulent transport slightly

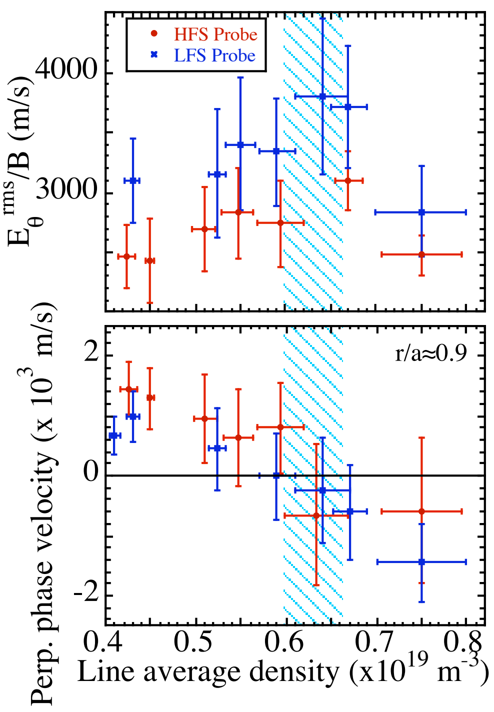

Fig. 1 Perpendicular flows and fluctuations of the perpendicular electric field measured for different plasma densities at the TJ-II plasma edge (r/a≈0.9).

decrease although edge gradients become steeper. Edge sheared flows are developed at the same threshold density in the two toroidal positions [17].

Sheared flows have been also developed in TJ-II using an electrode that externally imposed 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 on TJ-II as the edge parameters and global plasma confinement depend strongly on it. The response of the plasma to bias is, therefore, different at densities below and above the threshold value to trigger the spontaneous development of ExB sheared flows [12].

The results of the TJ-II biasing experiments presented in this paper correspond to positive applied bias in the plasma edge of TJ-II. The changes observed in the edge profiles, edge electric fields and fluctuation levels show evidence of biasing induced improved confinement as was observed in previous limiter biasing experiments in TJ-II [18]. The floating potential profile is strongly modified by the electrode bias in the region *r/a* < 0.9, leading to the formation of a strong positive radial electric field (up to 10 kV/m) and as a consequence the perpendicular phase velocity is also modified.

As in the spontaneous development of the shear [19], two different time scales arise in the relaxation of externally induced electric fields in TJ-II: a slow time scale, in the range of the particle confinement time (tens of milliseconds) that evolves with plasma density, and a fast time scale in the range of few turbulence correlation times (10 – 100 μs). The fast time evolution of floating potential signals (V_{fl}), when biasing is switched off, can be fitted to an exponential function using the expression

$$V_{fl}(t) = V_{max}\exp(-t/\tau) + V_{min} \qquad (1)$$

from which the exponential relaxation time τ is deduced. This fitting procedure has been done for floating potential signals measured at different densities and at different radial and toroidal locations. Experimental results show that the characteristic time decay obtained for the fast decay is in the range of 10 - 100 μs for different values of mean plasma density (in the range 0.4 – 1 x 10^{19} m^{-3}). Figure 2a shows the two time evolution scales of the floating potential signal measured inside the LCFS (r/a ≈ 0.77) in TJ-II together with the evolution of plasma density with biasing and in Fig 2b the fast decay scale is shown together with the fitting.

Figure 3 shows the behaviour of the fitting of the fast relaxation time at the TJ-II plasma edge (0.75<r/a<0.92) after switch-off the biasing as a function of the average ion saturation current, measured when switching off the biasing and normalized to its value at the critical point (i.e. when shear flow develops). Results suggest an increase in decay times above the critical value of the control parameter (i.e. once edge perpendicular sheared flows are fully developed).

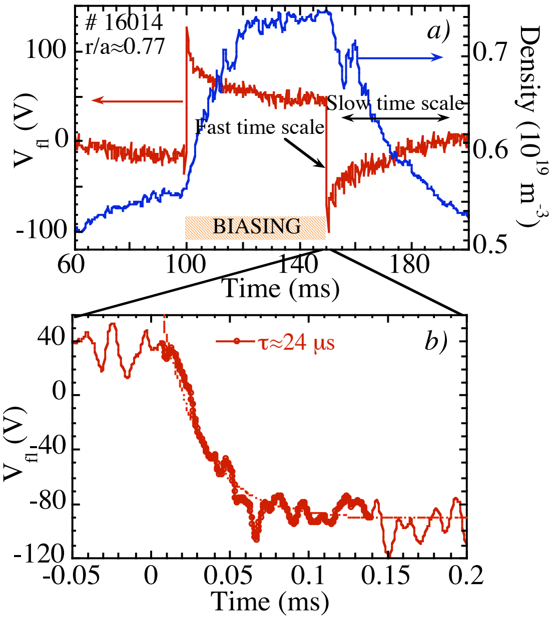

Fig 2 a) Time scales of the floating potential measured at r/a≈0.8 and plasma density evolution with biasing. b) Fast decay of the floating potential at the bias switch off (time =0).

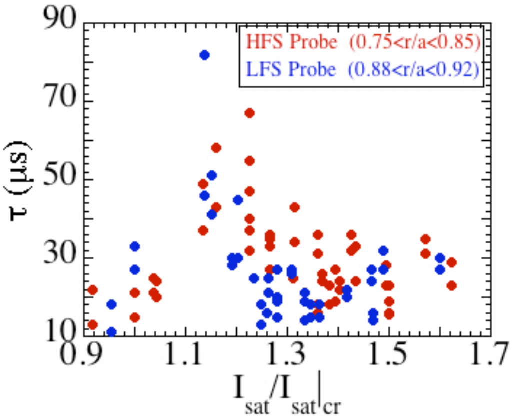

Fig. 3 Relaxation time measured at the TJ-II plasma edge in both probes, as a function of normalized ion saturation current measured after switch off the biasing.

These time decays have been compared with the ones obtained in similar experiments in other devices with different characteristics [19] being the values in the same range (tens of μs) in all of them. As a consequence and in spite of another mechanisms (i.e. magnetic pumping, charge exchange) turbulence can be considered as an important element in the physics of flows and electric fields. Turbulent damping mechanisms are likely to apply for short time scales, in the order of few turbulence correlation times (typically $\tau_c \approx 10$ μs), this being consistent with experimental time decay findings.

4. Model coupling shear flow and turbulence

A simple model to explain the generation of the sheared electric field has been used [20, 21]. This model, as the pressure increases, predicts two successive transitions. The first one is a second-order transition controlled by the poloidal shear flow that leads to a reduction of the turbulence level. The second, that describes the H-mode, is a first-order transition controlled by the pressure gradient that leads to the suppression of turbulence. The first transition model (the second-order one), that has the characteristic properties of the emergence of the sheared flow layer, has been used to compare the theoretical predictions with the experimental results of the formation of the sheared flow layer in TJ-II. In order to do that, we normalize all the physical magnitudes to their values at the critical point so we can write the solutions of the model in terms of measurable quantities [22].

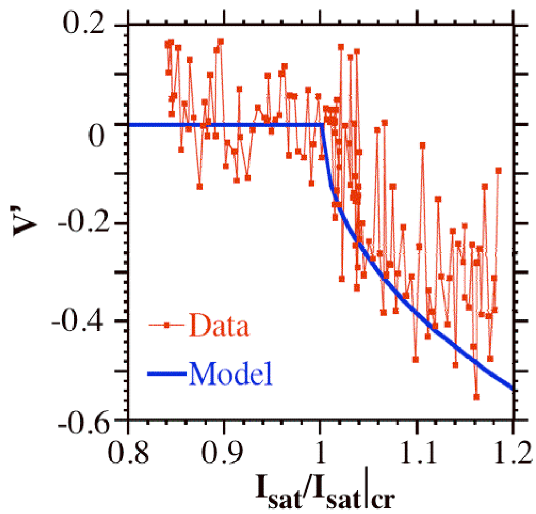

Fig. 4 Comparison between the velocity shear obtained by the model and from the experimental data.

Comparisons between the model and experimental data show that in spite of the simplicity of the model, it captures the qualitative features of the transition near the critical point as can be seen in Fig 4, that shows a comparison between the velocity shear obtained by the model and the deduced from the experimental data as a function of the control parameter defined in the previous section. Note that the model has no free parameters once the position of the critical point is determined. Results from plasmas with more complicated density evolutions than a simple ramp are also in good agreement with experiments [22].

Apart from the problem of interpreting the decay rate in terms of viscosity, an effective viscosity at the plasma edge can be determined by measuring the decay rate of the perpendicular flow once the driving force has been removed. The properties of the damping rate of the flow in TJ-II have been investigated in the framework of a model based in the previously described with an external drive added: the applied bias. Fig 5 shows the short time scale decay after switching off the bias potential deduced by the model showing an increase of the decay time close to the critical point as has been observed experimentally (Fig 3). The exponential decay of the flow is also reproduced, giving the model a qualitative description of the behaviour of the decay time obtained experimentally.

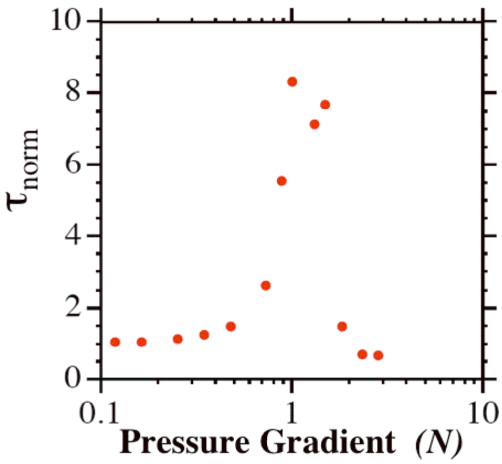

Fig. 5 Decay time obtained by the model as a function of the local average ion saturation current normalized at the corresponding critical point (development of shear flow).

5. Summary and conclusions

The generation of the shear layer depends in TJ-II on the plasma density gradient, being necessary a threshold value for its development. These sheared flows appear to be organized near marginal stability with fluctuations in TJ-II. The universality of this property is easily understood assuming that edge sheared flows are controlled by turbulence. These results can shed light in the understanding of the physics responsible for the generation of critical sheared flows, pointing to the important role of turbulence as a driving mechanism.

Two time scales have been found for edge plasma potential decay measured in the TJ-II edge plasma region when electrode applied potential is turned off. The fast scale decay times are in the range of few turbulence correlation times, suggesting the important effect of anomalous (turbulent) mechanisms in the damping rate of sheared flows in the plasma boundary of fusion devices. In the slow time scale (comparable to the particle confinement time) plasma potential modifications are linked to the evolution of the plasma density.

Measurements of the fast decay time suggest an increase in decay times above the threshold gradient value to trigger the emergence of shear flow (i.e. once edge perpendicular sheared flows are fully developed).

The emergence of the plasma edge shear flow as a function of the plasma density can be explained using a second-order phase transition model that reproduces many of the features of the TJ-II experimental data and of the transition near the critical point. The properties of the damping rate of the flow in TJ-II have also been described by means of the model adding a driving force.

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