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On the physics of shear flows in 3D geometry

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Recent experiments have shown the importance of multi-scale (long-range) mechanisms in the transition to improved confinement regimes and the key role of electric fields to amplify them. Flows driven by turbulence might explain such experimental observation, which would imply to consider the importance of 3-D effects on the energy transfer between flows and turbulence. Comparative studies in different magnetic configurations (tokamaks vs stellarators), diagnostic development and large-scale simulation are needed to assess the importance of multi-scale physics in the development of sheared flows.

Keywords: Transport, Flows, Turbulence, Transport Barriers.

1. Introduction

The discovery of the transition to edge improved confinement regimes at the beginning of the 1980's brought on a new era in magnetic confinement fusion. After more than 25 years of active research, most experimental evidences support the paradigm of sheared electric field suppression of turbulence to explain transport barrier physics, although the underlying mechanisms that generate the electric fields still remain as the fundamental open issue confronting the fusion community.

As pedestal plasma parameters have a strong impact on global confinement, prediction of the ITER pedestal parameters and the H-mode transport barrier width remain a key and fully open research area. Indeed, large uncertainties are still present in the empirical description of the L-H transition power threshold, with significant implications for the overall structure of the ITER research plan.

Critical tests of models for transport barriers based on second order (turbulent driven flow) and first order (pressure gradient driven flows) phase transition as well as role of equilibrium flows and edge localized neutral particle sources are needed for the development of a comprehensive theory of the L-H transition and transport barriers. In the case of edge transport barriers, the influence of plasma boundary conditions on empirical power threshold should be also addressed. Due to the times/spatial scales involved this research area is a real challenge for both theorists and experimentalists.

Recent experiments have shown the importance of multi-scale (long-range) mechanisms in the transition to improved confinement regimes and the key role of electric fields to amplify them [1]. The detection of lon-range correlations in stellarators [2, 1] and tokamaks [3] is consistent with the theoretically predicted (low frequency) zonal flows.

The possible interplay between turbulent and neoclassical transport mechanisms has been recently reported; Ion temperature gradient driven turbulent simulations have shown an enhancement of zonal flows in stellarator configurations optimized for reducing neoclassical transport [4].

2. Long-range correlations and transition to improved confinement regimes

In the TJ-II stellarator sheared flows can be easily driven and damped at the plasma edge by changing the plasma density or during biasing experiments [5, 6]. The experimental results on the emergence of the shear flow layer in TJ-II have some of the characteristics of a transition and are consistent with the expectations of second-order transition models of turbulence driven sheared flows [7].

In addition, the TJ-II is equipped with a unique system for multi-scale physics studies: two Langmuir probe arrays (measuring ion saturation current, floating potential and poloidal electric fields) located in two different toroidal positions installed on fast reciprocating drives. One of the probes (P 1) is located in a top port 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). The other probe (P

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2) is installed in a bottom port at $\phi \approx 195^{\circ}$ and enters into the plasma through a region with a higher density of flux surfaces (i.e. lower flux expansion) than P 1 (Fig. 1).

This unique experimental set-up (with probe toroidally separated in the order of 5 m) allows the simultaneous investigation of short (in the range of few millimeters) and long-range (in the order of ten meters) fluctuation scales in the plasma edge .

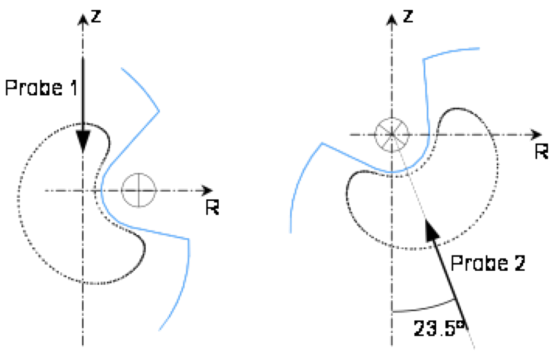

Fig.1 Schematic view of the location of the two probes (thick line arrows) and their positions relative to the TJ-II plasma.

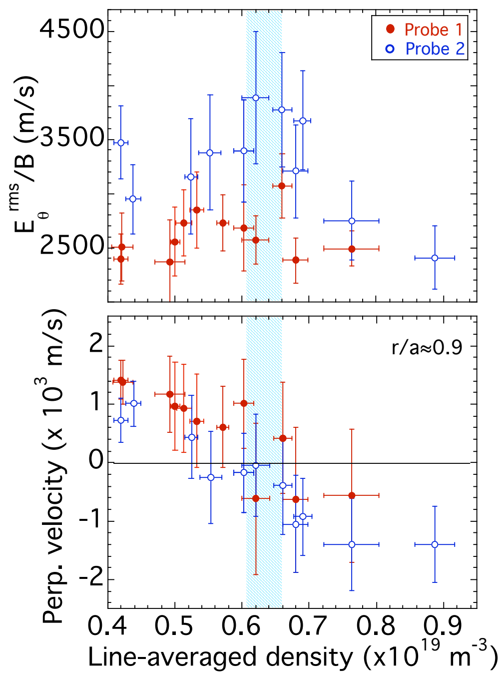

Fig.2 Averaged electric field fluctuations and perpendicular velocity measured at two toroidal locations and at approximately the same radial position (r/a≈0.9) as a function of plasma density.

It has been previously 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 [5, 6]. For densities above the threshold, and once sheared flows are fully developed, 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 (probes P1 and P2) (Fig. 2). 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 it is more clear during fluctuation events with time scales in the range of (0.1 – 1) ms related to the shear flow development. To quantify the similarity between probe signals the toroidal cross-correlation defined as

$$\gamma_{xy}(\tau) = \frac{E\{[x(t+\tau)-\bar{x}][y(t)-\bar{y}]\}}{\sqrt{E\{[x(t)-\bar{x}]^2\}.E\{[y(t)-\bar{y}]^2\}}}$$

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 in plasmas without MHD activity as showed the pick-up coils installed in TJ-II.

Figure 3 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 as density increases up to n ≈ 0.6 x 10^{19} m^{-3}, which corresponds to the threshold density for shear flow development

Figure 4 shows the time evolution of plasma density and the cross-correlation between floating potential and ion saturation signals during biasing induced improved transitions (for probes 1 and 2). It shows clearly in the increase in the cross-correlation during the biasing phase. 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

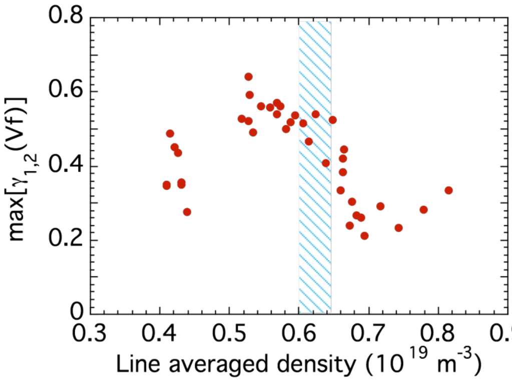

Fig.3 Maximum value of the cross-correlation between floating potential signals measured at r/a = 0.9 as a function of the plasma density. The shadow area indicates the threshold density for the development of edge sheared flows.

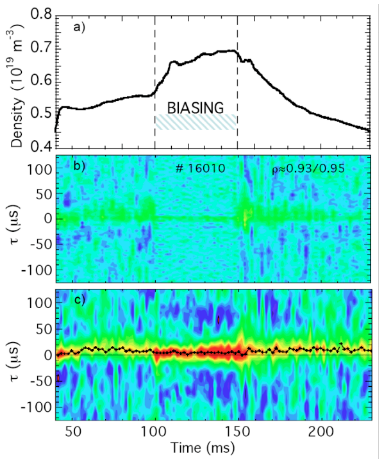

Fig.4 Time evolution of plasma density during biasing induced improve confinement regimes in TJ-II and cross-correlation function between b) ion saturation current and c) floating potential signals measured toroidally apart and at the plasma edge as a function of time for one shot during biasing experiments.

not to the plasma density.

Recent experiments with Li-coating and NBI heating have shown evidence of spontaneous bifurcations characterized by the increase of plasma density and stored energy with a concomitant reduction in the H_a emission (showing a decrease of the outward particle flux) together with the reduction of the level of broadband fluctuations and a steeper density gradients. All these phenomena are characteristic of plasma bifurcations to improved confinement regimes (H-mode) [8 9]. Experimental evidence of long (spatial) range correlations has been recently observed during the L-H transition in the TJ-II stellarator.

3. Driving and damping mechanisms of multi scale mechanisms

TJ-II results, showing the amplification of multi-scale physics features during spontaneous transport bifurcations and more recently during the development of spontaneous L-H transition, can help to provide a critical test for L-H transition models.

The resistance of fluids to shearing motion is a well known observation. The tendency of sheared motion to be reduced with the passage of time, if no other forces are at work to maintain it, leads to the concept of (positive) coefficient of viscosity, the constant of proportionality relating the stress to the shear. In a turbulent flow, when the momentum flux perpendicular to the mean flow direction is directed from regions of larger values toward regions of smaller values of mean flow, it is said that a turbulent (eddy) viscosity is present.

The concept of a reverse effect (e.g. negative viscosity) is something which appears to be again common sense [10]. However, for certain kind of flows (e.g. planet´s atmosphere and plasmas [11]) evidence of negative viscosity effects have been reported. In this case the mean flow can gain kinetic energy from the turbulence with direct impact in the development of sheared flows. Some conditions must be fulfilled in the system to show negative viscosity behaviour in steady state plasmas (Fig. 5). First eddies which transport the momentum contrary to the gradient of mean flow must have a supply of turbulent kinetic energy (otherwise they will die out). Second, the mean flow should experience some form of braking (i.e. positive viscosity) so that its value does not increase without limit. However, this braking should be low enough to allow the generation of differential rotation. Third, some kind of turbulent irregularity must be present. In steady state the turbulent drive is equal to the damping, i.e. for the poloidal dynamics

$$d\langle \tilde{v}_r \tilde{v}_\theta \rangle / dr = \mu V_\theta$$

In the framework of bifurcation transition models based on second order phase transitions triggered by zonal flows (i.e. via negative viscosity mechanisms), fluctuations are expected to show long range correlations in the order parameter related with the electric fields. Then, TJ-II findings reported in section 2 are consistent with this theoretical framework.

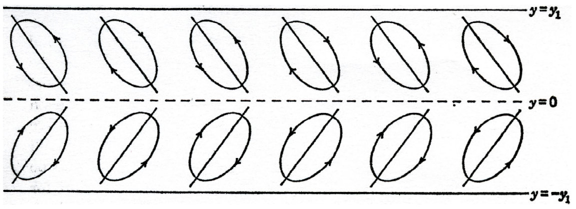

Fig.5 Some kind of turbulent irregularity must be present to get flow driven by instabilities in plamas. This ingredient is illustrated in the figure, showing a flow with some hypothetical pattern producing a convergence of momentum into the mid-channel [10].

The poloidal rotation is damped by the magnetic pumping (i.e. the plasma rotation in the presence of inhomogeneous magnetic field heats up the plasma and leads to an irreversible transformation of the kinetic energy of rotation into thermal energy which damps the rotation) [12]. Also, a neoclassical theory of plasma rotation is available and the main result is that the poloidal rotation is proportional to the gradient of the ion temperature [13]. It should be noted that multi-scale physics might be also expected in the framework of other L-H transition models like those based on particle orbit losses or Stringer spin-up [14]. However because radial electric fields are expected to reduce both edge particle losses and the degree of poloidal asymmetries during transition to improved confinement regimes [15], it remains to be clarified why multi-scale physics mechanisms should be amplified at the H mode regime if those mechanisms are playing a leading role during the development of transport bifurcations.

3. The 3-D energy transfer between edge flows and turbulence

Experiments in tokamaks and stellarators have shown that the edge velocity shear layer appears to organize itself to reach a condition in which the radial gradient in the poloidal phase velocity of fluctuations is comparable to the inverse of the correlation time of fluctuations (1/t). This result suggests that ExB sheared flows organized themselves to be close to marginal stability (i.e. $\omega_{ExB} \approx 1/\tau$). Considering that this property has been observed in different devices with tremendous differences in the magnetic topology (e.g JET tokamak and the TJ-II stellarator), we conclude that this result should be considered as a fundamental property of spontaneous edge shear flow in fusion devices (and so an important ingredient in the modelling of the L-H transition).

From this perspective, an important question is to identify which mechanism allows fluctuations and sheared flows to organize themselves to be close to marginal stability. It is easy to understand why turbulent driven flows (e.g. via Reynolds stress) allow sheared flows and fluctuations to reach marginal stability condition $\omega_{ExB} \approx 1/\tau$. The Reynolds stress tensor (whose components can be quantified as the quadratic cross-correlation of fluctuating velocity components) allows the interchange of energy (and momentum) between mean flows and fluctuations. Once the Reynolds stress driven sheared flows reach the critical value to modify fluctuations a negative feedback mechanism will be established which will keep the plasma near the condition ω_{ExB} critical.

Experiments in the TJ-II stellarator [16] have investigated the evolution of turbulence during edge shear development by quantifying the quadratic term of fluctuating radial and parallel velocities. Radial variations in the radial-parallel Reynolds stress components are developed in the proximity of the threshold density to trigger the development of edge sheared flows. In addition, experiments using fast cameras and probes suggest that also the quadratic term (radial-perpendicular Reynolds stress component) is modified during edge shear flow development in the TJ-II stellarator [17] and the JET tokamak [18]. The fact that different quadratic terms in fluctuating velocities (radial-parallel and radial-perpendicular) changes during edge sheared flow development has an important consequence: shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics are involved.

3. Conclusions

Recent experiments have shown the importance of multi-scale (long-range) mechanisms in the transition to improved confinement regimes and the key role of electric fields to amplify them. Flows driven by turbulence might explain such experimental observation, which would imply to consider the importance of 3-D effects on the energy transfer between flows and turbulence. Comparative studies in different magnetic configurations (e.g. tokamak, stellarators and RFPs), diagnostic development and large-scale simulation are needed to assess the importance of multi-scale physics in the development of sheared flows.

References

[1] M. A. Pedrosa et al., Phys Rev. Lett. **100**, 215003 (2008)

[2] A. Fujisawa et al., Phys. Rev. Lett. **93**, 165002 (2004)

[3] D. K. Gupta et al., Phys. Rev. Lett. **97** 125002 (2006).

[4] T. Watanabe et al., LHD reference Phys Rev. Lett. **100**, 195002 (2008).

[5] C. Hidalgo et al., Phys. Rev. E **70**, 067402 (2004).

[6] M.A. Pedrosa et al., Plasma Phys. Control. Fusion **47**, 777 (2005).

[7] B. A. Carreras et al., Phys. Plasmas **13**, 122509 (2006).

[8] F. L. tabarés et al., Plasma Phys Control Fusion (2008).

[9] J. Sánchez et al., Nuclear Fusion (2008).

[10] V. P. Starr, "Physics of Negative Viscosity Phenomena" (1968) McGraw-Hill.

[11] P. Diamond et al., Plasma Physics and Controlled Fusion **47**, R35 (2005).

[12] A. B. Hassam and R. Kulsrud Phys. Fluids **21**, 2271 (1978).

[13 J. H. F. Severo et al., Nuclear Fusion **43**, 1047 (2003).

[14] J W Connor and H R Wilson Plasma Phys Control Fusion **42**, R1 (2000).

[15] G. Tynan et al., Phys. Rev. Lett. **68**, 3032 (1992).

[16] B. Gonçalves et al., **96**, 145001 (2006).

[17] J. A. Alonso et al., Plasma Phys. Control. Fusion **48**, B465 (2006).

[18] E. Sánchez et al., J. of Nuclear Materials **337**, 296 (2005).