On the link between edge momentum redistribution and turbulence in the TJ-II stellarator

C. Hidalgo 1), J.A. Alonso 1), P. Carvalho 2), A.A. Chmyga 4), J.L. de Pablos 1),
L. Eliseev 5), T. Estrada 1), B. Gonçalves 2), S.M. Khrebtov 4), A.D. Komarov 4),
A.S. Kozachok 4), L. Krupnik 4), A.V. Melnikov 5), R. Orozco 1), M.A. Pedrosa 1),
S.V. Perfilov 5), E. Sánchez 1), C. Silva 2), M. Spolaore 6) S. Zweben 3), and TJ-II team

1) Laboratorio Nacional de Fusión, Euratom-Ciemat, Madrid, Spain
2) Associaçao EUTATOM/IST, Centro de Fusao Nuclear, 1049-001 Lisboa, Portugal
3) Princeton Plasma Physics Laboratory, Princeton, NJ USA
4) Institute of Plasma Physics, NSC "KIPT", 310108 Kharkov, Ukraine
5) Institute of Nuclear Fusion, RNC "Kurchatov Institute", Moscow, Russia
6) Consorzio RFX, Associazione EURATOM-ENEA, Padova, Italy

e-mail contact of main author: Carlos.Hidalgo@ciemat.es

Abstract. The link between edge sheared flows and turbulence is investigated in the plasma edge region of the TJ-II stellarator. In the TJ-II stellarator there is a threshold density to trigger the development of edge shear flows. During sheared flow development the degree of turbulence anisotropy is modified. The fact that different quadratic terms in fluctuating velocities (radial-parallel/radial-poloidal) change during edge sheared flow generation means that shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics are involved. A new strategy has been recently applied to plasma physics to quantify the local energy transfer between flows and turbulence by computing the production term. Experimental results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer. Measurements of the turbulence production show the importance of 3-D effects on the energy transfer between flows and turbulence.

1. Introduction

Plasma flows play a crucial role on transport in magnetically confined plasmas [i]. It is well known the importance of flow shear in the development of transport barriers; both edge and core transport barriers are related to a large increase in the ExB sheared flow [ii]. Thus momentum is expected to play a key role to control both energy and particle confinement. However, compared to energy and particle transport, there has been much less effort to study momentum transport in fusion plasmas. Plasma rotation can be driven by external forces such as momentum from Neutral Beam Injection (NBI). However, the dominant role of external momentum to explain plasma rotation in fusion plasmas is called into question by experiments showing evidence of significant toroidal rotation with no-momentum input [iii]. Recently, poloidal rotation measurements, an order of magnitude higher than the neoclassical predictions, for thermal particles across internal transport barriers have been reported in the JET tokamak [iv]. In addition, poloidal rotation measurements have been recently compared with neoclassical theory predictions in the DIII-D tokamak showing a significant discrepancy [v]. Different mechanisms have been proposed to explain these results, including neoclassical effects [vi], turbulence driven models [vii,viii] and fast particle effects [ix].

Recent experiments carried out in the TJ-II stellarator have shown that the generation of spontaneous edge perpendicular sheared flow can be externally controlled by means of plasma density (as an experimental control knob) with good reproducibility and reliability [x, xi]. Because this spontaneous sheared flow is developed in the proximity of the Last Closed Flux Surface (LCFS) where many plasma diagnostics with time and spatial resolution are available, this opens great possibilities to improve our understanding of the mechanisms underlying the generation of sheared flows in fusion plasmas.

This paper deals with the physics of generation of edge sheared flows their self-consistency with plasma turbulence and describing a strategy recently applied to plasma physics to quantify the energy transfer between flows and turbulence.

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, <a> = 0.22 m, $i(a)/2p \approx 1.7-1.8$) created in the TJ-II stellarator. Plasma 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 multi-arrays of Langmuir and Mach probes. Recently, the physics of ExB sheared flow has been investigated by means of multiple diagnostics in the TJ-II stellarator, including Langmuir probes [xi], Ultra High Speed cameras [xii], Heavy Ion Beam (HIBP) diagnostic [xiii] and reflectometry [xiv]. The link between the development of sheared flows and plasma density in TJ-II has been observed in different plasma magnetic configurations and plasma regimes. Those results have a direct impact in the understanding of the mechanisms underlying the generation of sheared flows in fusion plasmas. In addition experiments in the TJ-II stellarator are compared with experiments carried out in the edge of the JET tokamak [xv,xvi].

3. Properties of spontaneous sheared flows in TJ-II

The existence of edge sheared flow in TJ-II requires a minimum plasma density. Near (below) this threshold density, the level of edge turbulent transport and the turbulent kinetic energy significantly increases in the plasma edge [x, xi]. Above this threshold value, once sheared flow is completely developed, fluctuations and turbulent transport slightly decreases although edge gradients become steeper. The influence of magnetic configuration in the development of edge sheared flows is under investigation. The origin of the threshold density is possibly related with a threshold gradient which is a driving mechanism for turbulent transport.

Slow density ramp experiments (up and down) in the proximity of the threshold density have been performed to clarify the existence of hysteresis during edge sheared flow development. So far, within the experimental uncertainties, no evidence of hysteresis has been found [xi]. However, this slow density ramp experiments has revealed the existence of fast transients in the floating potential profiles in the proximity of the threshold density. These fast jumps take place in a time scale of the order of tens of microseconds which can be interpreted as the characteristic time scale for the development of the edge sheared flow.

The reversal in the ExB rotation at a threshold density, first reported by means of Langmuir probes measurements, has been recently 2-D visualized by means of Ultra Fast Speed cameras. The view plane is in a near-poloidal cross-section with optimized B-field perpendicularity. Neutral recycling at the poloidal limiter is used to light up the outer plasma region ($r/a \approx 0.7-1$). Spatially coherent turbulent fluctuations are frequently seen as 'blobs' with a spatial extent of few centimetres. Those structure show predominant poloidal movements with typical speed in the range of 10^3 - 10^4 m s^{-1} in agreement with the expected ExB drift rotation direction. Heavy Ion Beam Probe (HIBP) measurements in ECR heating plasmas show that the plasma potential increases up to 1 kV in the plasma core (i.e. radial electric fields are radially outwards) [xiii]. In addition, the plasma potential shows a strong dependence on the plasma density. At plasma densities near the threshold value evidence of radially inwards radial electric fields has been observed at the plasma edge, whereas in the plasma core radial electric field (as measured by the HIBP system) remains positive. This result implies the simultaneous development of two sheared flows at the threshold density: one located in the proximity of the LCFS (r/a ~ 1) (the one investigated by means of probe measurements) and the other one near $r/a \approx 0.7$. Reflectometry measurements have permitted the characterization of the velocity shear layer that develops spontaneously in the edge of TJ-II plasmas above a certain critical density; experimental findings show that the inner shear layer moves inwards as density increases above the threshold.

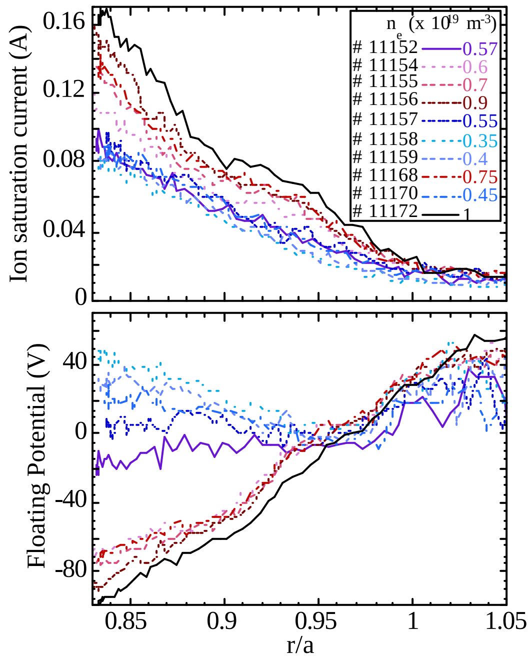

FIG. 1 Edge profiles of ion saturation current and floating potential measured at different plasma densities with $\iota(a)/2\pi \approx 1.7$. When plasma density reaches a threshold value (0.55 x 10^{19} m^{-3}) the edge ion saturation current gradient increases and the floating potential becomes more 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, the radial variation in the floating potential signals directly reflects changes in the radial electric field [xi].

Fast imaging of the H_α fluctuations in the plasma edge allowed to study the effect of the sheared flow on turbulent structures. A wavelet-based method was used to characterize turbulent structures' geometry (orientation angle and aspect ration) in different poloidal velocity shear regimes [xii]. The analysis is carried out for wave vectors in the range $k \approx 0.5-2.5\,\text{cm}^{-1}$. As sheared flows are developed turbulence structures tend to be more stretched (see Figure 2). This observation, together with the observed reduction in the angular dispersion of the turbulent structures can be interpreted as a modification in the degree of perpendicular turbulence anisotropy. This result is qualitatively consistent with a basic prediction of the shear decorrelation model (put forward more than 15 years ago). Turbulence suppression during biasing-induced improved confinement regime is clearly reflected on the number of turbulent structures in the observable range of scales. The scale and polarity selectiveness of this suppression is under investigation.

4. Flows near marginal stability and energy transfer between flows and turbulence.

Previous experiments have shown that the magnitude of the spontaneous developed sheared flow (quantified as the radial derivate of the perpendicular phase velocity) is comparable to that measured during biasing-induced improved confinement regimes in the TJ-II stellarator.

This result suggests that in TJ-II stellarator the spontaneous ExB flows and fluctuations organized themselves close to marginal stability (i.e. the shearing rate is close to the critical value to modify plasma turbulence).

It should be noted that TJ-II results are consistent with previous observations in tokamaks, stellarators and reversed field pinches. In particular, the structure of the naturally occurring velocity shear layer has been investigated in the JET plasma boundary region [xvi].

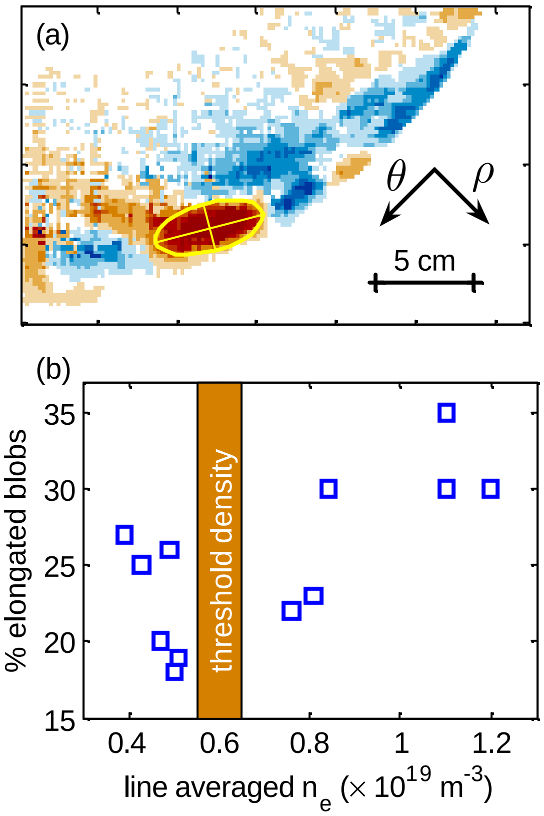

FIG. 2 (a) Sample background-subtracted image of the plasma edge of TJ-II. The image plane is very approximately perpendicular to the magnetic field-lines. The yellow ellipse marks a detected positive turbulent structure, its orientation and aspect ratio. (b) Percentage of elongated blobs dependence on line averaged electron density. The percentage of elongated blobs is a measure of the shift of the aspect ratio histogram towards higher values (stronger stretching or higher anisotropy). Line averaged electron density is a robust knob parameter to trigger sheared poloidal flows. The threshold density is marked with an orange strip.

The 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. $v_{ExB} \approx 1/t$) in agreement with TJ-II findings. In spite of the tremendous differences between the magnetic topology of JET tokamak and the TJ-II stellarator the edge shear properties are remarkably similar. Thus 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. Whereas this property is consistent with turbulent driven fluctuating radial electric field, it is difficult to understand in which way other mechanisms, like those based on ion orbit losses mechanisms and neoclassical mechanisms, can allow sheared flows and fluctuations to reach marginal stability. It is easy to understand why turbulent driven flows (e.g. via Reynolds stress) allow sheared flows and fluctuations to reach the condition $v_{ExB} \approx 1/t$. The Reynolds stress tensor (whose components can be quantified as the cross-correlation of fluctuating velocity components $\langle \tilde{v}_i \tilde{v}_j \rangle$) allow 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.

Following this argument the degree of anisotropy of fluctuations should be modified during the development of spontaneous sheared flows in the TJ-II stellarator. Recent experiments in the TJ-II stellarator have investigated the evolution of turbulence during edge shear development by quantifying the quadratic term of fluctuating radial and parallel velocities. Radial variations in $\langle \tilde{v}_{\parallel} \tilde{v}_r \rangle$ are clearly developed in the proximity of the threshold density ($n \approx 0.6 \times 10^{19}$ m^{-3}) [xvii]. In addition, experiments using fast cameras suggest that also the quadratic term $\langle \tilde{v}_{\perp} \tilde{v}_r \rangle$ is modified during edge shear flow development in TJ-II. Interesting gradients in $\langle \tilde{v}_{\perp} \tilde{v}_r \rangle$ have been reported near the edge shear region in other devices like JET.

The fact that different quadratic terms in fluctuating velocities ($\langle \tilde{v}_{\parallel} \tilde{v}_r \rangle$ and $\langle \tilde{v}_{\perp} \tilde{v}_r \rangle$) 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. This conclusion is consistent with previous experiments showing that sheared perpendicular and parallel flows are linked.

Those results support the view that turbulence plays a key role to explain the physics of edge shear flows near marginal stability with fluctuations. In the framework of this interpretation, a key issue is to quantify the coupling between flows and turbulence. The measure of the energy transfer between turbulence and flows is an appropriate strategy to quantify this coupling. The energy transfer can be computed by means of the turbulence production term following classical works to derive equations for the mean flow ($E = \frac{1}{2} V^2$) and turbulence ($k = \frac{1}{2} \langle \tilde{v}^2 \rangle$) kinetic energy evolution. The equations for E and k can be written as

$$\frac{dk}{dt} + \nabla \cdot T = P - e$$

$$\frac{dE}{dt} + \nabla \cdot \overline{T} = -P - \overline{e}$$

$$P \equiv -\langle \tilde{v}_i \tilde{v}_j \rangle \frac{\partial V_i}{\partial x_j}$$

where the quantity P is called the production of turbulent kinetic energy [xviii].

There are four terms in the k equation: the mean flow convection (dk/dt), the turbulent transport and diffusion, included in the divergence term ($\nabla \cdot T$), the viscous dissipation (e) and the production (P). It should be noted that the production term (P) appears with different sign both in the mean-kinetic-energy equation and turbulent-kinetic-energy equation. It combines fluctuating velocity cross-correlations with mean velocity gradients and gives a measure of the amount of energy per unit mass and unit time that is transferred locally between mean flow and fluctuations.

Due to the 3-D nature of the shear flow physics in fusion plasmas and the experimental evidences previously mentioned, several components of the production term should at least be considered

$$P \approx -\langle \tilde{v}_{\perp} \tilde{v}_r \rangle \frac{\partial V_{\perp}}{\partial r} - \langle \tilde{v}_{\parallel} \tilde{v}_r \rangle \frac{\partial V_{\parallel}}{\partial r}$$

The strategy of quantifying the energy transfer between flows and turbulence by means of the production term (P) is a different point of view with respect to previous works [xv and references therein]. In those works a flux surface averaging was implicit in the momentum balance equation relating radial gradient in Reynolds stress and perpendicular plasma rotation, while in the energy approach discussed in this paper all averaged quantities are time-averaged and flux surface-averaging is not supposed. Thus, the quantity P should be considered as a local estimate of the turbulent kinetic energy production. Considering that with the present state of art in plasma diagnostics local (instead of flux averaged) measurements of fluctuating velocities are available, this local character in P strongly simplifies the interpretation of measurements. On the contrary, care should be taken in trying to extrapolate from these local measurements the influence in the whole plasma.

The radial –perpendicular component of the production term has been investigated in the LCFS vicinity in the JET tokamak. It has been found that the energy transfer from DC flows to turbulence, directly related with the momentum flux (e.g. $\langle \tilde{v}_\perp \tilde{v}_r \rangle$) and the radial gradient in the perpendicular flow, can be both positive and negative in the proximity of sheared flows. Furthermore, the energy transfer rate is comparable with the mean flow kinetic energy normalized to the correlation time of turbulence, implying that this energy transfer is significant. These results show, for the first time, that turbulence can act as an energy sink and energy source for the mean flow near the shear layer, emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

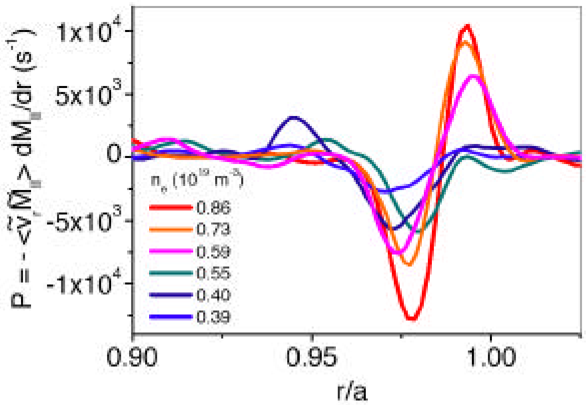

FIG. 3 Parallel-radial component of the turbulence production term during edge sheared flor development in the TJ-II stellarator [4]. Evidence of significant energy transfer between turbulence and parallel flows at the on-set of sheared flows has been found.

Experiments in TJ-II stellarator have investigated the radial-parallel component of the production term $\left(-\langle \tilde{v}_\parallel \tilde{v}_r \rangle \frac{\partial v_\parallel}{\partial r}\right)$ showing the existence of significant parallel turbulent forces at plasma densities above the threshold value to trigger edge sheared flows. This finding provides the first experimental evidence of the role of parallel turbulence forces on edge momentum redistribution in fusion devices.

The dynamical coupling between radial and perpendicular dynamics in the TJ-II stellarator is made evident in figure 4, which shows the expectation value of the parallel Mach number conditioned to the value of the turbulent ExB flux in the radial direction. This figure shows that large outward-directed turbulent transport events are coupled with large bursts in parallel momentum. Similar behaviour has been reported in the scrape-off layer of JET tokamak device [xix].

Recently, it has been shown that the experimental results for the emergence of the plasma edge shear flow layer in TJ-II can be explained using a simple model for a second order transition based on the sheared flow amplification by Reynolds stress and turbulence suppression by shearing. In the dynamics of the model, the resistive interchange instability was used. This model gives power dependence on density gradients before and after the transition consistent with experiment [xx].

Finally, combined ECRH and NBI experiments reveal that, once ECRH heating power is turned-off, a confinement regime characterized by a strong reduction in ExB turbulent transport and fluctuations and significant increase in the perpendicular velocity and plasma density is achieved. Whether this transition can be related to a full developed H mode transition, in which perpendicular flows are dominated by pressure gradient term, still remain as an open question.

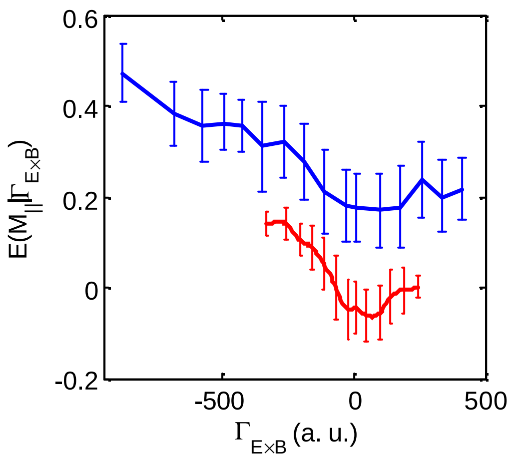

FIG. 4 Expectation value of the parallel Mach number conditioned to the turbulent ExB flux value for a standard TJ-II shot (blue curve) and for a shot with external biasing (red curve). The external biasing reduces the fluctuation level and the radial flux decreases. Parallel momentum is damped by the external biasing. In both cases a positive coupling between radial turbulent fluxes (negative flux means outward-directed particle transport) and parallel momentum can be noticed.

4. Conclusions

In spite of the differences between tokamak and stellarator the properties of turbulence and sheared flows are remarkably similar in the plasma boundary region. In the TJ-II stellarator there is a threshold density to trigger the development of edge sheared flows. 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.

During sheared flow development the degree of turbulence anisotropy is modified: changes in the $\langle \tilde{v}_\perp \tilde{v}_r \rangle$ quadratic term of fluctuations near the shear flows have been reported in many confinement devices. In addition TJ-II shows changes in the $\langle \tilde{v}_{||} \tilde{v}_r \rangle$ quadratic term. The fact that different quadratic terms in fluctuating velocities ($\langle \tilde{v}_{||} \tilde{v}_r \rangle$ and $\langle \tilde{v}_\perp \tilde{v}_r \rangle$) changes during edge sheared flow generation means that shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics play a role. 3-D effect should be taken into account in the strategy recently applied to plasma physics to quantify the local energy transfer between flows and turbulence by computing the production term. Experimental results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer. Looking into the future it remains as a challenge for experimentalist to measure simultaneously the evolution of the whole production term during the development of sheared flows.

Acknowledgements

This research was sponsored in part by Ministerio de Educación y Ciencia of Spain under Project No. FTN2003-08337-C04-02.

[i] DIAMOND, P.H. et al., "Zonal flows in plasma—a review" Plasma Phys. Control. Fusion 47 (2005) R35.

[ii] TERRY, P. "Suppression of turbulence and transport by sheared flow" Reviews of Modern Physics, **72** (2000) 109.

[iii] RICE, J E et al., Observations of anomalous momentum transport in Alcator C-Mod plasmas with no momentum input Nucl. Fusion 44 (2004) 379.

[iv] CROMBÉ, K. et al., "Poloidal rotation dynamics, radial electric field, and neoclassical theory in he Jet internal-transport-barrier region" Phys. Rev. Lett. **95** (2005) 155003.

[v] SOLOMON, W.M. et al., "Experimental test of the neoclassical theory of impurity poloidal rotation in tokamaks" Phys. Plasmas **13** (2006) 056116.

[vi] ROGISTER, A. L. "Theoretical interpretation of the toroidal rotation velocity observed in Alcator C-Mod Ohmic H-mode discharges" Nuclear Fusion 44 (2002) 339.

[vii] COPPI, B. "Accretion theory of `spontaneous' rotation in toroidal plasmas" Nuclear Fusion 42 (2002) 1.

[viii] GARBET, X. et al., "Turbulence simulations of transport barriers with toroidal velocity" Phys. Plasmas 9 (2002) 3893

[ix] KOIDE, Y et al.,in Plasma Physics and Controll. Nuclear Fusion Research 1992 (Proc. 14th Int. Conf. Wurzburg 1992) vol 1, IAEA, Vienna (1993) 777.

[x] HIDALGO, C. et al., "Experimental evidence of coupling between sheared flows development and an increasing in the level of turbulence in the TJ-II stellarator" Phys. Rev. E, **70** (2004) 067402.

[xi] PEDROSA, M.A. et al., et al., "Threshold for sheared flow and turbulence development in the TJ-II stellarator" Plasma Phys. Control. Fusion, **47** (2005) 777.

[xii] ALONSO, J A et al., "Impact of different confinement regimes on the two dimensional structure of edge turbulence" Plasma Physiscs and Control Fusion (2006)

[xiii] MELNIKOV, A V et al., "Plasma potential measurements by the heavy ion beam diagnostic in fusion plasmas : biasing experiments in the TJ-II stellarator and T-10 tokamak" Fusion Science and Technology 46 (2004) 299.

[xiv] ESTRADA, T et al., Proc. 32th EPS-2005

[xv] SANCHEZ, E et al., "On the energy transfer between flows and turbulence in the plasma boundary of fusion devices" J. of Nuclear Materials 337 (2005) 296.

[xvi] HIDALGO, C et al., "Experimental evidence of fluctuations and flows near marginal stability and dynamical interplay between gradients and transport in the JET plasma boundary region" J. Nuclear Materials 313 (2003) 863.

[xvii] GONÇALVES, B et al., "Role of Turbulence on Edge Momentum Redistribution in the TJ-II Stellarator" Phys. Rev. Lett 96 (2006) 145001

[xviii] POPE, S. B. "Turbulent Flows" Cambridge University Press. Cambridge 2001.

[xix] HIDALGO, C. "Experimental Investigation of Dynamical Coupling between Turbulent Transport and Parallel Flows in the JET Plasma-Boundary Region " Phys. Rev. Lett. 91 (2003) 065001.

[xx] CARRERAS, B A et al., "Critical transition for the edge shear layer formation: comparison of model and experiment" Plasma Physics (2006) submitted