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On the Momentum Re-distribution Via Turbulence in Fusion Plasmas: Experiments in JET and TJ-II

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Abstract. The mechanisms underlying the generation of plasma flows play a crucial role to understand transport in magnetically confined plasmas. The amplitude of measured parallel flow is significantly larger than those resulting from simulations. Recent experiments have pointed out the possible influence of turbulence to explain flows in the plasma boundary region. This paper reports the first experimental evidence of significant radial gradients in the cross-correlation between parallel and radial fluctuating velocities near the LCFS in JET tokamak and TJ-II stellarator. These gradients are mainly due to the radial variations in the level of poloidal electric field fluctuations and in the cross-phase coherence. These findings might provide the underlying physics of spontaneous toroidal rotation and large parallel flows in plasma boundary reported in fusion plasmas.

1. Introduction

The mechanisms underlying the generation of plasma flows play a crucial role in understanding transport in magnetically confined plasmas. The amplitude of parallel flow measured in the scrape-off layer (SOL) including the effects of diamagnetic, $E \times B$ and $B \times \nabla B$ drifts is significantly larger than those resulting from simulations [1]. Recent experiments have pointed out the possible influence of turbulence in perhaps explaining a component of the anomalous flows observed in the plasma boundary region [2]. In the plasma core region, evidence of anomalous toroidal momentum transport has been reported in different tokamak devices [3]. Different mechanisms have been proposed to explain these results, including neoclassical effects [4], turbulence driven models [5, 6] and, in the case of ICRF heating, fast particle effects. Spontaneous toroidal flow not driven by neutral beams has also been observed in stellarator devices [7]. The flow reversal observed in the CHS stellarator can be explained by the spontaneous flow driven by large radial electric fields.

It is well known that in a turbulent flow energy can be interchanged between the mean flows (large scales) and the turbulence (small scales). Several theoretical works pointed out the importance of Reynolds stress as a way to interchange energy between the different scales presented in the plasmas [8, 9]. These works have suggested not only the possibility of a energy (or momentum) transference from the macroscopic flows to the turbulent scales, but also the possibility of an energy flux going from the small scales to the macroscopic flows driving rotation. More recent works have been focused on the study of the formation of the so-called zonal flows in plasmas [10]. From the experimental point of view, pioneer works were focused in a direct measure of the radial-poloidal component of the Reynolds stress in the plasma boundary region of fusion plasmas [11, 12, 13, 14]. Several other works focused in a frequency domain analysis have studied the formation or evolution of zonal flows in fusion plasmas and the spectral energy transfer [10, 15, 16]. In these works, energy transfer between different scales has been identified but the amount of energy transferred has not been estimated. Experimental results on the energy transfer between perpendicular flows and turbulence in JET, showing the dual role of turbulence as damping and driving of flows in fusion plasmas, were recently presented [17].

The aim of this paper is to study the possible role of turbulence on the momentum re-distribution mechanisms in the plasma plasma boundary region of tokamak and stellarator plasmas. The paper is organized as follows. In section 2 the experimental set-up is described. Section 3 shows the influence of plasma density in the structure of turbulence and parallel flows in the TJ-II stellarator. Evidence of significant radial gradients in the cross-correlation between parallel and radial fluctuating velocities near the Last Closed Flux Surface (LCFS) in JET tokamak and in the TJ-II stellarator is reported in section 4. The energy transfer term between turbulence and parallel flows, computed following classical woks [18,19], is discussed in section 5. The dynamical relation between instabilities and parallel flows in JET and TJ-II is discussed in section 6. Section 7 gives the conclusions.

2. Experimental set-up

Plasma profiles and turbulence have been investigated in the JET tokamak and TJ-II stellarator plasma boundary region Plasma profiles and turbulence have been investigated using a fast reciprocating Langmuir probe system that consists of arrays of Langmuir probes allowing the simultaneous investigation of the radial structure of fluctuations and parallel Mach numbers. Plasma fluctuations are investigated using 500 kHz digitisers. The Mach number has been computed as $M=0.4\ ln(I^{ct}/I^{co})$ where I^{co} and I^{ct} represent the ion saturation current measured at each side of the Mach probe (i.e. co and counter direction magnetic field) [20]. Plasmas studied in this paper were produced in X-point plasma (forward and reversed toroidal field) in ohmic and neutral beam heated L-mode regimes with toroidal magnetic fields B = 2 T and plasma current Ip = 2 MA in JET and with ECR heating plasma (P_{ECRH} = 200-400 kW) in TJ-II.

3. Influence of plasma density on flows and fluctuations in TJ-II

Recent experiments in the TJ-II stellarator have shown that the generation of spontaneous poloidal sheared flows requires a minimum plasma density. Near this critical density, the level of edge turbulent transport and the turbulent kinetic energy significantly increases in the plasma edge [21,22].

Figure 1 shows the evolution of parallel Mach number and the level of edge fluctuations (quantified as the rms value of poloidal electric field fluctuations) during a density scan in the range (0.3–1 x 10^{19} m^{-3}) for measurements taken at $\rho \approx 0.85$. As the density increases the level of plasma turbulence increases until a

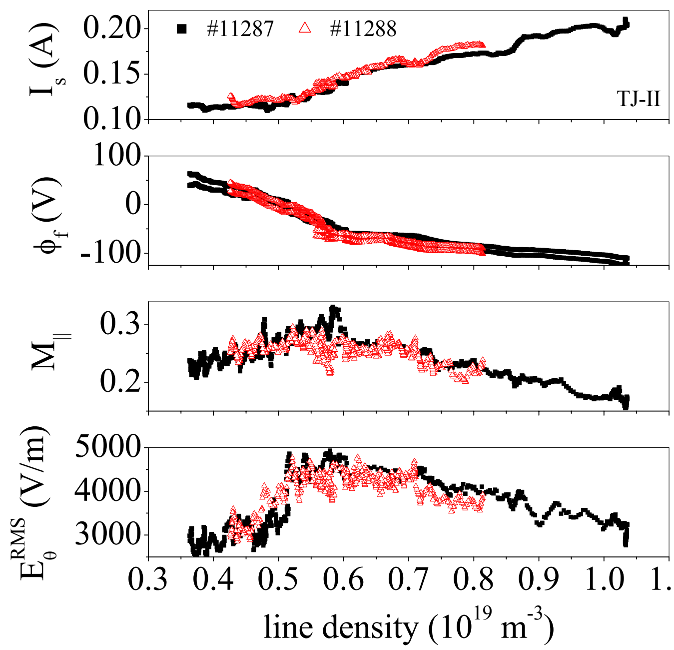


Fig. 1. Ion saturation current, floating potential, parallel flows and level of edge fluctuations versus plasma density in the plasma boundary of the TJ-II stellarator. Measurements were taken near $\rho \approx 0.85$.

critical edge gradient is reached (where sheared perpendicular flows are developed). Above this value the level of turbulence decreases with a concomitant development of ExB sheared flows which can be observed in the sharp change of the floating potential. Those results point out that the evolution of parallel flows is coupled both with the level of poloidal electric fields fluctuations and the generation of ExB sheared flows.

The influence of plasma density on ion saturation current, floating potential, parallel Mach number and level of fluctuations profiles has been investigated near the LCFS (ρ ≈ 0.85–1.05) (Fig. 2). Above a threshold plasma density the floating potential profile becomes negative and exhibits a strong gradient compatible with the generation of shear flows. Whereas the level of fluctuations increases in the plasma edge as density increases, it must be noted that at the shear layer location the level of turbulent velocities show a clear dip once the velocity shear layer is formed. This result suggests an energy transfer between turbulence and DC flows at the shear layer location.

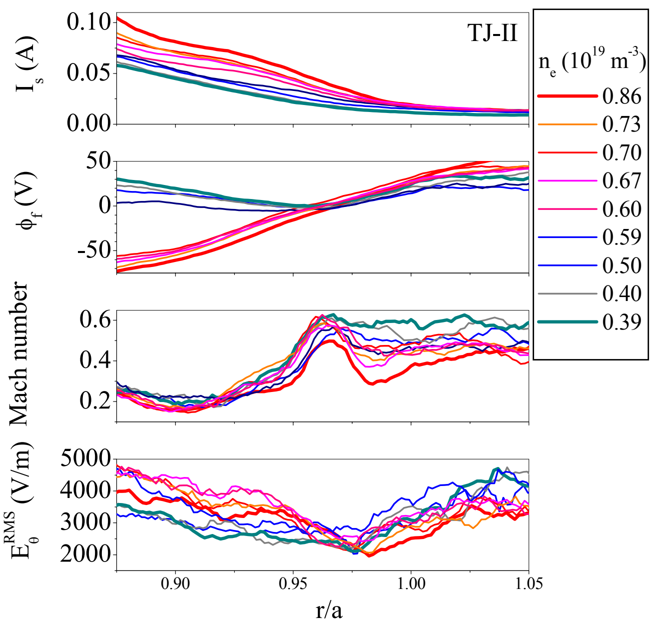


Fig. 2. Profiles of ion saturation current, floating potential, parallel flows and level of fluctuations. The experiments were performed in the same configuration and the plasma density was increased in a shot-by-shot basis. The plasma density was increased from 0.3-0.8x10^{19} m^{-3}

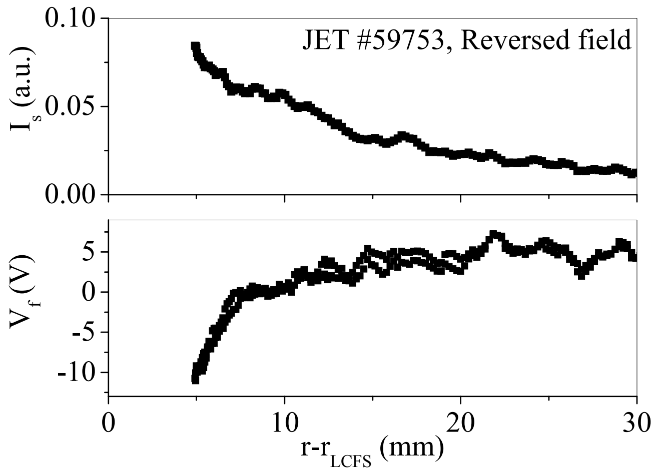


Fig. 3. Ion saturation current and floating potential profiles in a reversed field discharge near the LCFS. The probe position is mapped to the outside mid-plane. Measurements were taken in reversed magnetic field configuration at the JET top region.

The Mach number measurements show the existence of a naturally arising shear in the parallel flow even at low density regimes (where sheared poloidal flows are not yet developed). As density increases, the radial structure of parallel flows is significantly modified with the appearance of additional gradients in the proximity of the LCFS. This result is consistent with previous finding showing a modification in the radial structure of the average parallel Mach number as TJ-II magnetic well is varied (i.e. as the level of edge fluctuations is modified) [23].

It should be noted that the absolute value of the Mach number can be affected by differences in the probes area (if any) as an offset, as well as changes in the probe orientation with the respect to the magnetic field in the boundary region. However, the observed modification of parallel flows as density and the level of turbulence increases are not affected by such uncertainties.

4. On the cross-correlation between parallel and radial fluctuating velocities

The contribution of the Reynolds stress term, $d < \tilde{v}_r \tilde{M}_{\|} > / dr$, $\tilde{v}_r$ and $\tilde{M}_{\|}$ being the fluctuating (ExB) radial velocity and the fluctuating parallel Mach number respectively, provides the mechanism to convert the turbulent scales (high frequency fluctuations) into a mean parallel flow. The radial structure of the cross-correlation between parallel and radial fluctuating velocities have been investigated in the proximity of the LCFS in TJ-II stellarator and JET tokamak (forward and reversed toroidal fields).

4.1. JET results

Figure 3 shows the ion saturation current and floating potential profiles in an ohmic plasma with reversed field. The probe position is mapped to the outside mid-plane. In these experiments there was an uncertainty of about 2 cm in the EFIT which prevents correct identification of the position of the LCFS. Following previous works [24] an approximate correction of 22 mm was used at the outside mid-plane radial position. Also, the presence of a strong gradient of the floating potential (linked with a reversal in the poloidal phase velocity) provides a good indicator for the location of the last closed flux surface in magnetic fusion devices [25] and is consistent with the applied correction. A comparison between the parallel flow profiles between forward and reversed field discharges is presented in figure 4. In the forward field direction, (ion $B \times \vec{\nabla} B$ drift direction downwards towards the divertor), a strong parallel flow is measured at the top of the machine in the direction from the outer to the inner divertor. For reversed field, the measured flow is smaller but approximately symmetric with respect to a symmetry axis given by a positive offset. These profiles are

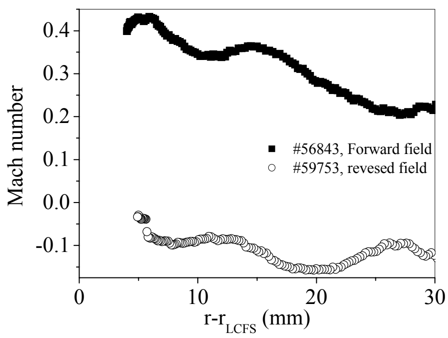


Fig. 4. Comparison of Mach number profiles between a forward and reversed toroidal field discharges in JET.

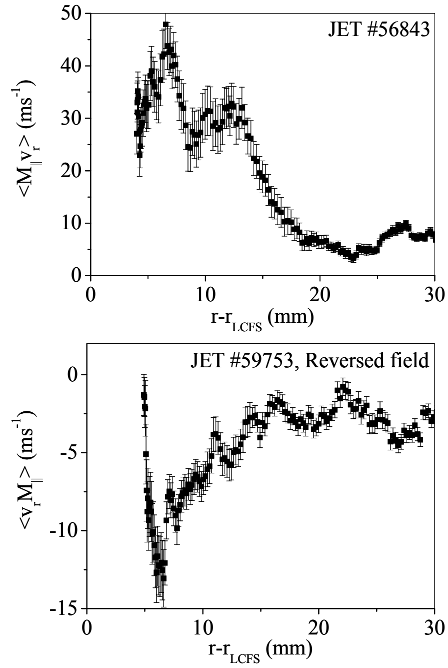


Fig. 5. Radial profiles of the cross-correlation between parallel and radial fluctuating velocities in JET L-mode plasmas near the LCFS in forward and reverse field discharges

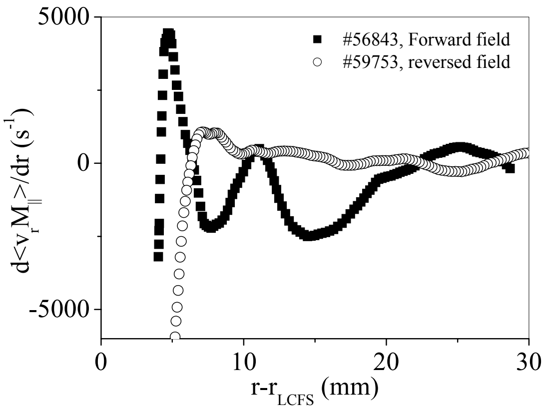


Fig. 6. Gradients in the cross-correlation between parallel and radial fluctuating velocities in JET in forward and reversed toroidal field discharges.

comparable to the profiles obtained also in JET using the retarding field analyser [24]. Figure 5 shows radial profiles of $< \tilde{v}_r \tilde{M}_{\|} >$ obtained in forward and reversed field in the proximity of the LCFS in the JET tokamak. The errors in the velocity component cross-correlation were estimated following [26] and are given by $\varepsilon(< \tilde{v}_r \tilde{M}_{\|} >) = \sigma(v_r)\sigma(M_{\|}) / \sqrt{N}$ where N is the number of samples used to calculate the cross correlation and $\sigma(v_r)$, $\sigma(M_{\|})$ are the standard deviations of radial velocity and Mach number fluctuations. In the plasma region where the floating potential becomes more negative (which turns out to be very close to the region where the perpendicular velocity shear is developed) there is evidence of significant radial gradients (in the order of $10^3 - 10^4$ s^{-1}) in the cross-correlation between parallel and radial fluctuating velocities (Fig. 6). It should be noted that the quadratic term of fluctuating velocities changes sign when the magnetic field is reversed.

4.2. TJ-II results

Experiments in the TJ-II stellarator have also shown radial variations in the cross correlation between parallel and radial velocity fluctuations (comparable to JET) near the LCFS (Fig. 7). These gradients are due to the radial variations in the level of poloidal electric field fluctuations and in the cross-phase coherence. The radial structure of $d < \tilde{v}_r \tilde{M}_{\|} > / dr$ changes with increasing plasma density; in particular, strong gradients in $d < \tilde{v}_r \tilde{M}_{\|} > / dr$ are developed at the radial location where perpendicular sheared flows and double gradient in the Mach number are developed above a critical density.

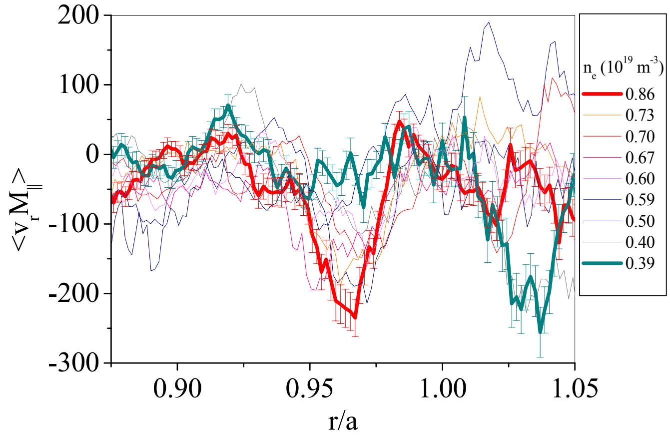


Fig. 7. Radial profiles of the cross-correlation between parallel and radial fluctuating velocities in TJ-II plasmas near the LCFS at different plasma densities.

4.3. Momentum balance equation

An estimate of the importance of turbulence in the evolution equation of the parallel flow requires a comparison of $d < \tilde{v}_r \tilde{M}_{\|} > / dr$ with the magnitude of the parallel flows damped / driven by different mechanisms. The radial derivative of $< \tilde{v}_r \tilde{M}_{\|} >$ was computed from the obtained experimental profiles using a Savitzky-Golay smoothing filter to reduce corruption of the derivative computation due to noise. Near the shear layer this value can be in excess of 5×10^3 s^{-1} both in forward and reversed field in JET tokamak. This result implies that, in the framework of our limited data base, the transport related momentum source ($n_e m_i \, d < \tilde{v}_r \tilde{v}_{\|} > / dr$) will be in the range of 1 – 5 N/m^3 in the JET tokamak boundary region. It is interesting to compare this estimation with previous analysis of force balance concluding that Mach number measurements in JET would require a momentum source at the level of 10 N/m^3 [27]. Therefore, in the plasma edge, the Reynolds stress seems capable of sustaining a non- negligible parallel velocity.

5. Energy transfer between parallel flows and turbulence

From the gradient of the radial profile of the mean parallel flow and the radial-parallel component of Reynolds stress, the turbulence production (P) is computed as [18,19],

$$P = < \tilde{v}_r \tilde{M}_{||} > \frac{\partial M_{||}}{\partial r}$$

This term combines the velocities cross-correlations $< \tilde{v}_r \tilde{M}_{||} >$ (momentum flux) with the mean velocity gradient ($\partial M_{||} / \partial r$) and gives a measure of the amount of energy per unit mass and unit time that is transferred between mean flow and fluctuations. As can be shown in the figure two different signs are found in P, thus implying that the turbulence can act as an energy sink for the mean flow (viscosity) or energy source (pumping) near the shear layer. As before the derivative was performed using a Savitzky-Golay smoothing filter. From the figures 9 it is clear that the production term can be of the order of 500 s^{-1} in forward toroidal field. Experiments in TJ-II show production terms with the same order of magnitude as JET for high density plasmas (Fig. 8-9). In low density plasmas the production term is reduced or inexistent.

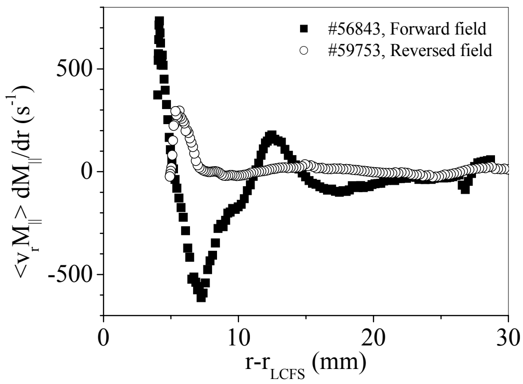


Fig. 8. Radial profile of production term in JET

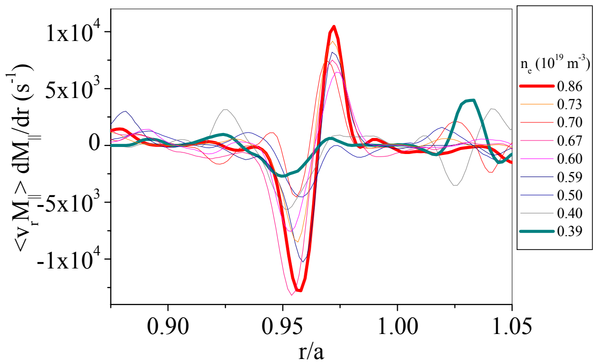


Fig. 9. Radial profile of production term in TJ-II

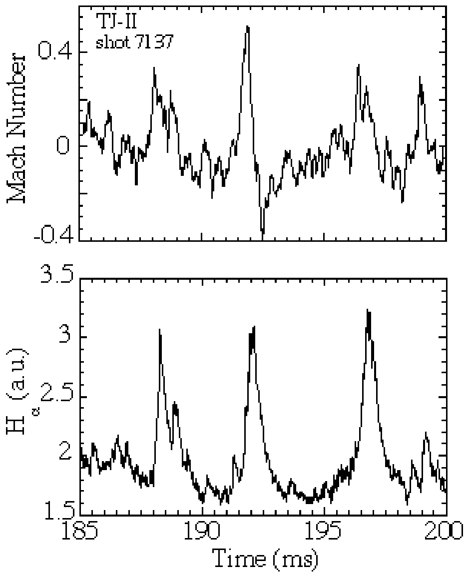
The power per unit mass necessary to pump the flow up to the velocity value experimentally measured in a turbulence characteristic time (τ_c) is given by

$$W = \frac{E}{\tau_c} = \frac{\frac{1}{2} M_{||}^2}{\tau_c}$$

Assuming τ_c in the range of a few turbulence correlation times it follows that W is of the order of 10^3 s^{-1}, which turns out to be comparable to the production term (fig. 6 and 9)in this region. This result suggests the mean flow generated by turbulent mechanisms is relevant.

6. On the dynamical relation between parallel flows and instabilities in JET and TJ-II

The influence of low frequency instabilities (ELM-like) on the transient behaviour of parallel flows has been recently investigated in the JET tokamak [28] and TJ-II stellarator [23]. Due to the flexibility of the TJ-II configuration, both the magnetic well depth and its radial variation may be modified over a broad range of values. It has been shown that the level of edge fluctuations and the degree of intermittency show a significant increase when magnetic well is reduced in the TJ-II stellarator. The time evolution of parallel flows and edge instabilities (indicated by the H_α variation) is shown in figure 10 for configurations with reduced well in the edge. With the appearance of edge instabilities parallel flows are significantly modified, showing a coupling between edge transport and parallel flows [23]. This result is consistent with recent experiments carried in the plasma boundary of JET tokamak, which has shown that during the appearance of ELMs, perturbations in the ion saturation current are larger in the Mach probe facing the outer divertor (e.g. region of bad curvature) than in the Mach probe facing the inner divertor (e.g. region of good curvature) showing a modification on the parallel flow during ELM events (fig. 11). An increase in the parallel flows with a delay of the order of ms is observed to follow an ELM event. These observations both in TJ-II and JET might reflect the strong ballooning character of ELMs but it also shows the parallel momentum redistribution during the generation of ELM events [28].



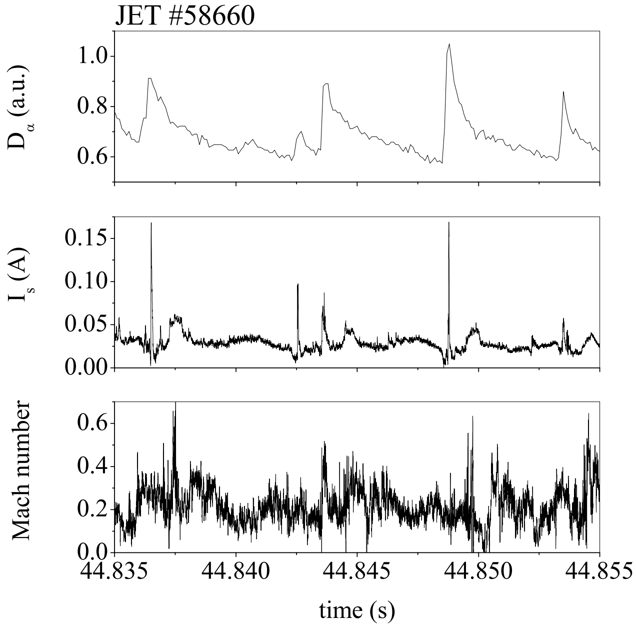


Fig. 10. Time evolution of parallel flows and edge instabilities in TJ-II

Fig. 11. Time evolution in JET

7. Conclusions

The investigation of the interaction between flows and fluctuations becomes one of the important open issues in the plasma edge dynamics and an active research programme in progress in tokamaks and stellarators. Experiments carried out in the plasma boundary of JET tokamak and TJ-II stellarator have shown the existence of significant gradients in the cross-correlation between parallel and perpendicular flows as well as a dynamical coupling between edge (ELM-like) instabilities and parallel flows.

Therefore, the Reynolds stress seems capable of sustaining a non-negligible parallel flow in the plasma edge region. This mechanisms might be an ingredient to explain recent observations in Alcator C-mod [3,29] showing that the toroidal momentum propagates in from the plasma edge, without any external source involvement. This mechanism can be particularly relevant during the L-H transition where the level of turbulence is mainly reduced near the edge. Then, radial gradients in the level of turbulence will be developed, allowing a momentum redistribution (driven by internal-turbulent forces). In order to quantify the importance of this mechanism, simultaneous measurements of parallel flows are needed in both SOL/edge as well as non-linear (quadratic) fluctuating velocities during the H-mode development.

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