Role of Turbulence on Edge Momentum Redistribution in the TJ-II Stellarator

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Radial profiles of the parallel-radial Reynolds stress component, proportional to the cross correlation between parallel and radial fluctuating velocities, have been measured in the plasma boundary region of the TJ-II stellarator. Experimental results show the existence of significant parallel turbulent forces at plasma densities above the threshold value to trigger perpendicular $E \times B$ sheared flows. This finding provides the first experimental evidence of the role of parallel turbulence forces on edge momentum redistribution in fusion devices.

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Plasma flows play a crucial role on transport in magnetically confined plasmas. It is well known the importance of flow shear in driving plasma rotation and its influence in the development of transport barriers [1]. Toroidal rotation can be driven by external forces such as momentum from neutral beam injection (NBI) but, in large scale devices like ITER, the NBI driven rotation will be limited. It is therefore important to identify other mechanisms which can drive plasma rotation but, when compared to energy and particle transport, there has been much less effort dedicated to study momentum transport in fusion plasmas.

Recent experiments have shown the possible influence of turbulence as a component of the anomalous flows observed in the plasma boundary region [2,3]. In the plasma core region, evidence of anomalous toroidal momentum transport has been reported in different tokamak devices [4–7]. Poloidal rotation measurements an order of magnitude higher than the neoclassical predictions for thermal particles across internal transport barriers has been reported in the JET tokamak [8].

The dominant role of external momentum (e.g., NBI) is being questioned due to experimental evidence of significant toroidal rotation with no-momentum input. Experiments in the Alcator *C*-Mod tokamak show that toroidal rotation propagates radially inwards from the plasma edge after the transition from low to high improved confinement regimes (*L*-*H* transition) and the resulting core rotation was found to depend strongly on edge magnetic configuration [9]. Different mechanisms have been proposed to explain these results, including neoclassical effects [10], turbulence driven models [11,12], and fast particle effects [13]. Spontaneous toroidal flow not driven by neutral beams has also been observed in stellarators [14]. The flow reversal observed in the CHS stellarator can be explained by the flow driven by large radial electric fields.

In a turbulent flow, energy can be interchanged between the mean flows (large scales) and the turbulence (small scales) [15,16]. Recent works have been focused on the study of the formation of the so-called zonal flows in plasmas [17]. It has been argued that zonal flows can be driven by radial-perpendicular turbulent stress component but saturation is obtained by the damping of the parallel flow component by parallel turbulent forces [18,19]. Experimentally, pioneer works were focused in a direct measure of the radial-perpendicular component of the Reynolds stress in the boundary region of fusion plasmas [20–26]. Other works, focused on frequency domain analysis, have studied the formation or evolution of zonal flows and the spectral energy transfer [17,27,28]. Driven flows, via strong turbulent ballooning transport poloidal asymmetry, have also been considered [3,29].

The aim of this Letter is to study the role turbulent forces momentum redistribution in the plasma boundary region of the TJ-II stellarator. To our knowledge it shows the first experimental evidence of the role of parallel turbulence forces on edge momentum redistribution in fusion devices.

Experiments were carried out in the TJ-II stellarator ($R = 1.5$ m, $a \leq 0.22$ m, $B \leq 1.2$ T) [30]. Present studies were done in a magnetic configuration with iota (a) ≈ 1.6. Plasma profiles and turbulence have been investigated using a fast reciprocating probe, located on the top region of the device, consisting of arrays of Langmuir probes (with 500 kHz digitizers) allowing the simultaneous investigation of the radial structure of fluctuations and parallel Mach numbers in the plasma boundary region. Fluctuating $E \times B$ radial velocities ($\tilde{v}_r$) have been estimated from floating potential probes aligned perpendicular to the magnetic field and separated (Δd_{perp}) poloidally, $\tilde{v}_r = \Delta\tilde{\Phi}_f / B \Delta d_{\mathrm{perp}}$. The Mach number has been computed as $M = 0.4 \ln(I^{\mathrm{ct}}/I^{\mathrm{co}})$, where I^{co} and I^{ct} represent the ion saturation current measured at each side of the Mach probe (i.e., codirection and counterdirection magnetic field) [31]. Plasmas studied in this Letter were produced with electron cyclotron resonance heating (ECRH) ($P_{\mathrm{ECRH}} = 200$ kW).

In spite of the differences between tokamaks and stellarators, previous works have shown that edge turbulence properties are remarkably similar in different magnetic confinement devices [32]. A naturally occurring shear layer near the last closed flux surface (LCFS) was observed in both devices and an empirical similarity in the probability density function of turbulent transport in the edge plasma region was found [33].

Recent experiments in TJ-II have shown that the generation of spontaneous perpendicular sheared flows (i.e., naturally occurring shear layer) 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 [34,35]. Above this threshold, the level of turbulence decreases with a concomitant development of $E \times B$ sheared flows which can be observed in the sharp change of the floating potential [35]. Figure 1 shows ion saturation current, floating potential, parallel Mach number, and level (rms) of poloidal electric field and parallel Mach number fluctuations profiles during a density scan in the range (0.3–1 $\times$ 10^{19} m^{-3}) in the proximity of the LCFS ($\rho \approx 0.85$–1.05). Above a threshold plasma density ($n \approx 0.6 \times 10^{19}$ m^{-3}) the floating potential profile becomes negative and exhibits a strong gradient. Because electron temperature profiles are rather flat in the TJ-II edge region, this result reflects the generation of a negative radial electric field (and $E \times B$ sheared flows [34,35]). On the contrary, at densities below the threshold value, the floating potential is rather flat.

The Mach number measurements show the existence of a naturally arising shear in the parallel flow even at low density regimes (where gradients in floating potential and $E \times B$ sheared 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. rms values of fluctuations in the parallel Mach number are in the range $(0.1$–$0.3)M_{\parallel}$. 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 plasma density increases is not affected by such experimental uncertainties. The contribution of the Reynolds stress term, $\langle \tilde{v}_r \tilde{M}_{\parallel} \rangle$, $\tilde{v}_r$ and $\tilde{M}_{\parallel}$ being the fluctuating ($E \times B$) radial velocity and the fluctuating parallel Mach number, respectively, provides the mechanism to transfer momentum or energy between turbulent scales and mean parallel flow. In high beta plasmas the cancellation between Reynolds stress and the Maxwell stress terms is expected in ideal MHD systems [36–38]. The influence of the Maxwell stress in the parallel momentum generation is, to our knowledge, still to be studied from the theoretical point of view.

Similar measurements to the above described have been performed by means of density scans in a single shot. Figure 2 shows the time evolution of floating potential, ion saturation current, Mach number, level of fluctuations ($E_{\theta}^{\rm rms}$), and the quadratic term in fluctuating velocities for measurements taken at a fixed radial location in the plasma edge ($\rho \approx 0.85$) and during plasma density scan (in the range $0.8 - 0.4 \times 10^{13}$ cm^{-3}). As density decreases, the ion saturation current decreases and floating potential becomes less negative. As density approaches the threshold value (time $\approx$ 1120 ms), the floating potential becomes close to zero (shadow region in the figure) and the level

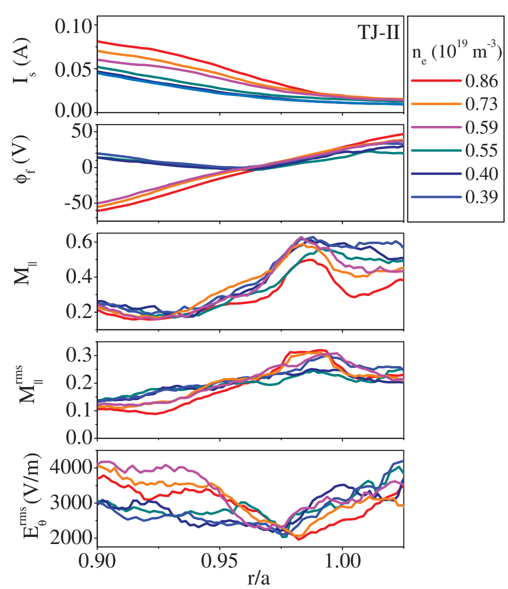

FIG. 1 (color). Radial profiles of ion saturation current, floating potential, parallel flows, and the level of edge fluctuations versus plasma density in the plasma boundary of the TJ-II stellarator. As density increases above a threshold value ($\approx$0.55 m^{-3}), the edge floating potential becomes negative.

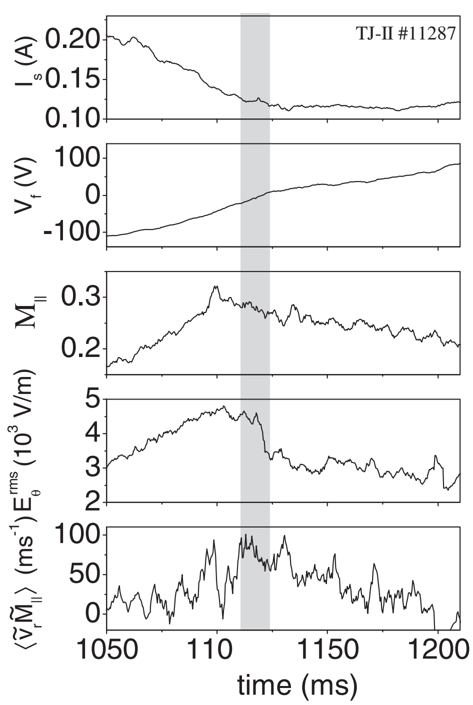

FIG. 2. Time evolution of ion saturation current, floating potential, Mach number, the rms of the poloidal electric field, and the quadratic term $\langle \tilde{v}_r \tilde{M}_{\parallel} \rangle$ at a fixed position ($\rho \sim 0.85$) during a density scan.

poloidal electric field fluctuations and $\langle \tilde{v}_r \tilde{M}_\parallel \rangle$ is maximum. The level of turbulence (quantified as $E_\theta^{\rm rms}$) significantly decreases above the threshold density in agreement with previous experiments [35]. In this regime $\langle \tilde{v}_r \tilde{M}_\parallel \rangle$ also decreases.

Figure 3 shows the radial structure of the cross correlation between parallel and radial fluctuating velocities in the proximity of the LCFS in the TJ-II stellarator. The radial structure of $d\langle \tilde{v}_r \tilde{M}_\parallel \rangle/dr$ changes with increasing plasma density; the level of cross correlation increases for plasma densities above the threshold value to generate $E \times B$ sheared flows (Fig. 3). The appearance of gradients on this quantity is due to both radial variations in the level of fluctuations and in the cross-phase coherence between fluctuating radial and parallel velocities. Gradients in $d\langle \tilde{v}_r \tilde{M}_\parallel \rangle/dr$ mainly appear at the radial location where perpendicular and parallel sheared flows are developed. The radial derivative of $\langle \tilde{v}_r \tilde{M}_\parallel \rangle$ was computed from the obtained experimental profiles using a Savitzky-Golay smoothing filter to reduce corruption of the derivative computation due to noise. This value can be both positive and negative and is of the order of $10^4\ \mathrm{s}^{-1}$.

The energy transfer term between turbulence and parallel flows was computed following classical works [39,40]. From the radial derivative of the mean parallel velocity and the radial-parallel component of Reynolds stress, the radial-parallel contribution to the production of turbulent kinetic energy (P) is computed as [39],

$$P = -\langle \tilde{v}_r \tilde{M}_\parallel \rangle \frac{\partial M_\parallel}{\partial r}.$$

This quantification of the energy transfer between flows and turbulence by means of the production term (P) is different from the approach used in previous works ([20] and references therein). In those works the flux surface average of the momentum balance equation relates the radial gradient in Reynolds stress and the perpendicular plasma rotation. In the energy approach used in this Letter, the production term combines the velocities cross correlations $\langle \tilde{v}_r \tilde{M}_\parallel \rangle$ (momentum flux) with the mean velocity gradient ($\partial M_\parallel/\partial r$) and gives a measure of the amount of energy per unit mass and unit time that is transferred locally between mean flow and fluctuations. Because of diagnostic limitations, present measurements only allow a local estimation of the production term and care should be taken in extrapolating from these local measurements the influence in the whole plasma.

In low density plasmas, the production term (P) as well as gradients in $d\langle \tilde{v}_r \tilde{M}_\parallel \rangle/dr$ are small and, in some cases, within experimental error bars (see. Figure 4). That means that, at low density, there is not any significant energy transfer between flows and turbulence. As the density approaches the threshold value to trigger $E \times B$ perpendicular flows the results show a different behavior. The production term clearly increases in the region where sheared flows are developed, reaching values up to $10^4\ \mathrm{s}^{-1}$ [41]. Furthermore, two different signs are found in P and $d\langle \tilde{v}_r \tilde{M}_\parallel \rangle/dr$, thus implying that the turbulence can act as an energy sink ($P > 0$) for the mean flow or energy source ($P < 0$) near the shear layer [20].

Slow density ramp experiments have revealed the presence of two different time scales in the time evolution of edge plasma parameters during edge shear flow development. A slow time scale (in the order of tens of ms) determined by the density evolution scan time scale is observed (see Fig. 2). The investigation of short time scales has also shown the existence of fast transients in the local plasma parameters (e.g., floating potential) in the proximity of the threshold density (Fig. 5). These fast jumps can take place in a time scale of the order of tens of microseconds (a few turbulence correlation times).

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

$$W = \frac{E}{\tau_c} = \frac{M_\parallel^2}{2\tau_c}.$$

Assuming τ_c in the range of a few turbulence correlation times ($\approx$10–100 μs) gives $W \approx 10^3$–$10^4\ \mathrm{s}^{-1}$, which turns out to be of the same order of magnitude of the production term (P) (see Fig. 4). Furthermore, assuming τ_c in the order of the slow time scale ($\approx$10 ms) gives $W \approx 10\ \mathrm{s}^{-1}$, which is even smaller than the measured local production

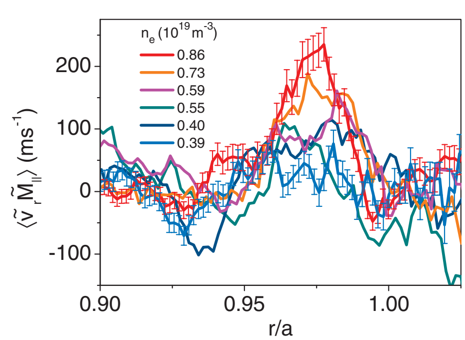

FIG. 3 (color). Radial profiles of the cross correlation between parallel and radial fluctuating velocities in TJ-II plasmas near the LCFS at different plasma densities (for the time series shown in Fig. 1).

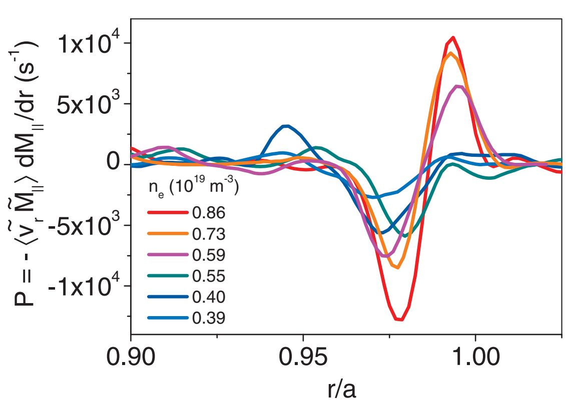

FIG. 4 (color). Radial profile of production term (P) at different plasma densities in TJ-II (for the time series shown in Fig. 1).

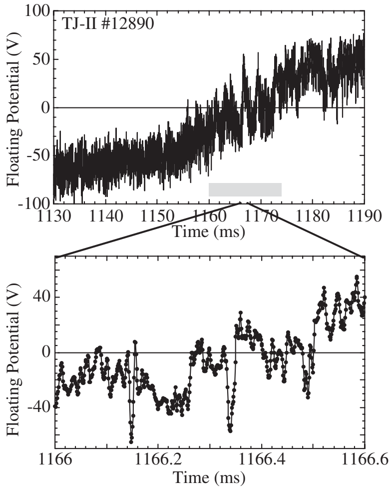

FIG. 5. (a) Density ramp experiments show transients in floating potential in the proximity of the TJ-II threshold density (shadow region in the figure) to trigger edge sheared flows. (b) Time evolution of floating potential at a fixed position ($\rho \sim 0.9$) during a density scan. Fast transients are observed in the proximity of the threshold density to trigger edge sheared flows.

term (P). This result suggests that parallel turbulent forces are relevant in momentum dynamics during the development of sheared flows in the proximity of the LCFS.

In conclusion, experiments carried out in the plasma boundary of the TJ-II stellarator have shown the existence of significant parallel turbulent forces at plasma densities above the threshold value to trigger perpendicular $E \times B$ sheared flows. These turbulent parallel forces are mainly localized at the radial location where sheared flows are developed. The results suggest that parallel turbulent force is an important ingredient to explain flow momentum redistribution in the boundary of fusion plasmas (i.e., shear flow physics requires a 3D description). These findings are consistent with numerical simulations pointing out the role of turbulent forces on both perpendicular and parallel flow components during the development of zonal flows [18].

Because of the 3D nature of the shear flow physics in fusion plasmas and the experimental evidences shown, several components of the production term, including radial-parallel ($\langle \tilde{v}_{\parallel} \tilde{v}_r \rangle$) and radial-perpendicular ($\langle \tilde{v}_{\perp} \tilde{v}_r \rangle$) components of Reynolds stress, should be considered. It remains as a challenge for experimentalists to measure simultaneously the evolution of the whole production term during the development of sheared flows.

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