Experimental evidence of coupling between sheared-flow development and an increase in the level of turbulence in the TJ-II stellarator

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The link between the development of sheared flows and the structure of turbulence has been investigated in the plasma boundary region of the TJ-II stellarator. The development of the naturally occurring velocity shear layer 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. The resulting shearing rate in the phase velocity of fluctuations is comparable to the one required to trigger a transition to improved confinement regimes with reduction of edge turbulence, suggesting that spontaneous sheared flows and fluctuations keep themselves near marginal stability. These findings provide the experimental evidence of coupling between sheared flows development and increasing in the level of edge turbulence. The experimental results are consistent with the expectations of second-order transition models of turbulence-driven sheared flows.

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One of the important achievements of the fusion community has been the development of techniques to control plasma fluctuations based on the shear stabilizing mechanism [1]. When the shearing rate approaches the characteristic frequency of the turbulence, a reduction in the turbulence amplitude is predicted [2]. The earliest theory of shear suppression is valid when the time variation of the radial electric field is much slower than the correlation time of the ambient turbulence. More recently, the theory of $E\times B$ shear suppression of turbulence has been extended to include time-dependent $E\times B$ flows [3]. The best performance of existing fusion plasma devices has been obtained in plasma conditions where $E\times B$ shear stabilization mechanisms are likely to play a key role: both edge and core transport barriers are related to a large increase in the $E\times B$ sheared flows [1]. These results emphasize the importance of clarifying the driving mechanisms of sheared flows in fusion plasmas.

A reversal in the poloidal phase velocity of fluctuations (v_θ) has been observed in the proximity of the last closed flux surface (LCFS) in all magnetic fusion devices. Experiments show that the resulting radial gradient dv_θ/dr is comparable to the inverse of the correlation time of fluctuations, suggesting that the naturally occurring shear layer and fluctuations organize themselves to be close to marginal stability [4]. The overall similarity in the structure of naturally occurring velocity shear layer in different devices has led to the conclusion of the possible role of turbulence-driven mechanisms as a universal ingredient to explain the underlying driving mechanisms of sheared flows in the plasma boundary region [5].

First- and second-order critical transition models, in which the suppression of turbulence via $E\times B$ sheared flows is a key ingredient, have been invoked to explain the transition to enhanced confinement regimes [6,1]. In the framework of deterministic theories of first-order phase transitions large hysteresis is expected in contrast to the expectations of recent statistical model for the bifurcation [7]. A second-order transition is also possible when turbulence-driven flows play a dominant role in the momentum balance. In this case the order parameter (the sheared poloidal flow) is expected to increase when the turbulent energy is large enough to overcome the flow damping.

This Brief Report shows that the generation of spontaneous sheared flows is coupled with an increase in the level of edge turbulence. Experimental findings are consistent with the expectations of second-order transition models of turbulence-driven sheared flows.

Experiments were carried out in electron-cyclotron-heated plasmas [$P_{\mathrm{ECRH}}=200$ kW, $B_T=1$ T, $R=1.5$ m, $\langle a\rangle \approx 0.22$ m, $\iota(a)\approx 1.7-1.8$] created in the TJ-II stellarator. In the present experiments plasma density was systematically modified (on a shot-to-shot basis) in the range $(0.35-0.80)\times 10^{19}$ m^{-3}. Shearing rates of spontaneous sheared flows have been compared with those needed to reduce turbulent transport in biasing-induced-improved confinement regimes [8]. For the latter, two mobile limiters were used. The inner limiter was radially localized up to 2 cm inside the LCFS ($\rho=r/a=1$) and was biased ($\Delta V_{\mathrm{limiter}}=160-250$, $I_{\mathrm{limiter}}\approx 30-50$ A) with respect to the second mobile outer limiter located in the scrape-off layer region (0.5 cm beyond the LCFS).

Edge profiles and fluctuations were simultaneously measured at the plasma edge region using a multiarray of Langmuir probes [9]. Probes were inserted into the plasma edge region from the top of TJ-II at a velocity of about 1 m/s. With this probe array, it is possible to measure edge plasma profiles in a single shot. The probe signals were digitized at a sampling rate of 500 kHz.

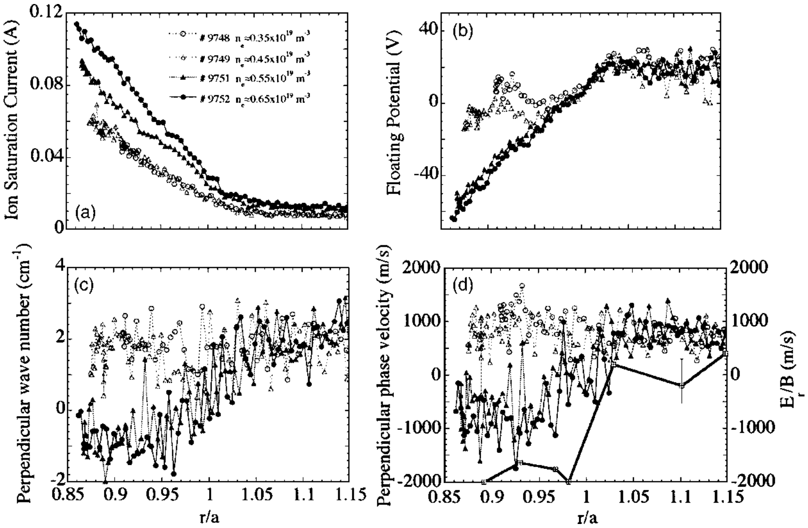

FIG. 1. (Color online) Profiles of (a) ion saturation current ($I_s \approx nT_e^{-1/2}$, n and T_e being the plasma density and electron temperature, respectively), (b) floating potential, (c) poloidal wave number and (d) phase velocity measured at different plasma densities (No. 9748, $0.35\times10^{19}\ \mathrm{m}^{-3}$, No. 9749, $0.45\times10^{19}\ \mathrm{m}^{-3}$, No. 9751, $0.55\times10^{19}\ \mathrm{m}^{-3}$, No. 9752, $0.65\times10^{19}\ \mathrm{m}^{-3}$) in a TJ-II plasma configuration with $\iota(a)\approx1.7$. (d) also shows (thick line) the E_r/B velocity estimated from floating potential profiles (b).

The influence of the plasma density on the ion saturation current, floating potential, poloidal wave number, and phase velocity of fluctuations has been investigated near the LCFS ($\rho\approx0.85-1.15$). Results are shown in Fig. 1 in plasma configurations with $\iota(a)\approx1.7$. The poloidal phase velocity of fluctuations (perpendicular to the magnetic field and to the radial direction) has been computed using the two-point correlation technique [10] from two floating potential signals poloidally separated about 0.3 cm.

As the plasma density increases, the edge ion saturation current (I_s) and its radial gradient increase and the floating potential becomes more negative in the plasma edge. Because the edge temperature profile (in the range of 20–30 eV) is rather flat in the TJ-II plasma periphery [11], the radial variation in the floating potential signals directly reflects changes in the radial electric fields (E_r), which turn out to be radially inwards in the plasma edge as density increases above $0.5\times10^{19}\ \mathrm{m}^{-3}$. In consistency with this result, the poloidal wave number and poloidal phase velocity reverse sign in the plasma edge ($\rho\approx1$) from positive to negative values as the density increases. As shown in Fig. 1, the resulting radial profiles of k_θ and v_θ are radially flat for plasma density below $0.5\times10^{19}\ \mathrm{m}^{-3}$, whereas above this critical density the poloidal phase velocity reverses and the naturally occurring velocity shear layer appears in the proximity of the last closed flux surface.

This phase velocity reversal can be explained, or at least is consistent, in terms of $E_r\times B$ drifts [Fig. 1(d)] in agreement with previous results in other devices [12,13]. The link between the development of sheared flows and plasma density in TJ-II has also been observed in other plasma configurations. In particular, Fig. 2 shows the results measured in configurations with slightly higher edge rotational transform values [$\iota(a)\approx1.8$]; above a critical density, sheared flows (in both phase velocity of fluctuations and E_r/B) are clearly developed.

Electrostatic fluctuations produce a fluctuating radial velocity given by $\tilde{v}_r=\tilde{E}_\theta/B$, $\tilde{E}_\theta$ being the fluctuating poloidal electric field and B the toroidal magnetic field. The electrostatic-fluctuation-driven radial particle flux is given by $\Gamma_{E\times B}=\langle\tilde{n}(t)\tilde{E}_\theta(t)\rangle/B$. The local $E\times B$ turbulent transport has been measured neglecting the influence of electron temperature fluctuations. Radial profiles of turbulent ($E\times B$)-induced transport ($\Gamma_{E\times B}$) and root-mean-squared values of radial velocity fluctuations (i.e., $E_\theta^{\mathrm{rms}}/B$) are shown in Fig. 3. The level of local turbulent transport remains radially rather constant and small in the low-density regimes. During the development of the shear layer (i.e., above the critical plasma density), $E\times B$ transport increases about a factor of 10 in the plasma edge ($\rho\approx0.9-0.95$); in the scrape-off-layer side of the velocity shear, $\Gamma_{E\times B}$ decreases when moving radially out-

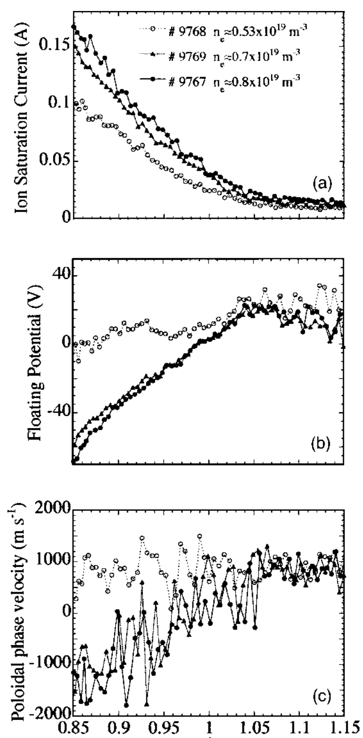

FIG. 2. (Color online) Profiles of (a) ion saturation current, (b) floating potential, and (c) phase velocity measured at different plasma densities (No. 9768, $0.5\times10^{19}\ \mathrm{m}^{-3}$, No. 9769, $0.7\times10^{19}\ \mathrm{m}^{-3}$, No. 9767, $0.8\times10^{19}\ \mathrm{m}^{-3}$) in a TJ-II plasma configuration with $\iota(a)\approx1.8$.

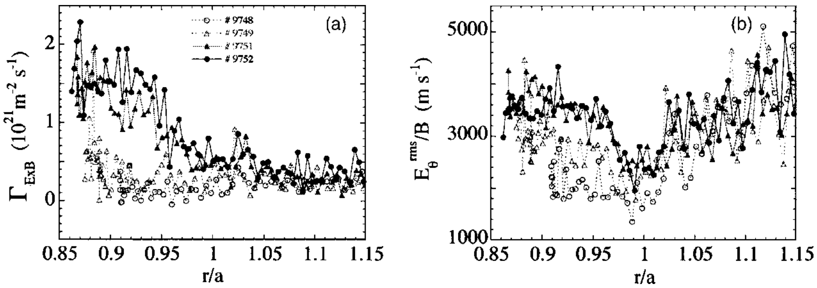

FIG. 3. (Color online) Profiles of (a) turbulent transport and (b) radial velocity fluctuations at different plasma densities (No. 9748, 0.35×10^{19} m^{-3}, No. 9749, 0.4×10^{19} m^{-3}, No. 9751, 0.55×10^{19} m^{-3}, No. 9752, 0.65×10^{19} m^{-3}). TJ-II plasma configuration with $\iota(a) \approx 1.7$ (see Fig. 1).

wards [Fig. 3(a)]. Turbulent radial velocity fluctuations ($E_\theta^{\mathrm{rms}}/B$) increase in the plasma edge as plasma density increases [Fig. 3(b)].

Although experimentally our external control knob is the plasma density, it is more appropriate to characterize experimental results in terms of gradients in plasma density (e.g., I_s gradients). Figure 4 shows gradients in the phase velocity, radial velocity fluctuations, and $E \times B$ turbulent transport versus gradients in the ion saturation current computed in the plasma edge ($\rho \approx 0.95-1.0$) for plasma configurations with $\iota \approx 1.7$ and 1.8 (see Figs. 1 and 2). Within experimental error bars, there is a smooth (continuous) evolution of shearing rates (i.e., radial gradients in the poloidal velocity) and fluctuation levels as gradients in the ion saturation increase. Experimental results suggest that a minimum level of turbulence (plasma density gradient) is needed in the plasma edge to trigger the spontaneous formation of sheared flows.

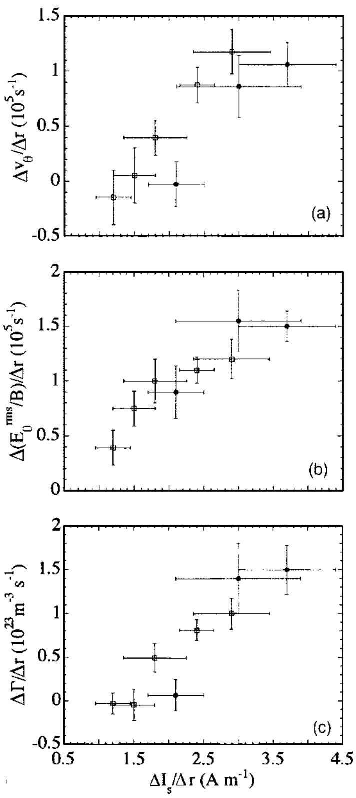

FIG. 4. (Color online) Gradients in phase velocity, radial velocity fluctuations, and $E \times B$ turbulent transport versus gradients in the ion saturation current (computed in the proximity of $\rho \approx 0.95-1$) for plasma configurations with $\iota(a) \approx 1.7$ (open symbols), 1.8 (solid symbols).

The increase in the radial gradient of velocity fluctuations during sheared-flow development points out the possible role of Reynolds stress as a momentum driving mechanism [1]. Strong gradients in the level of fluctuations can provide a modification in the degree of anisotropy in the radial-poloidal structure of fluctuations (i.e., radially varying Reynolds stress), allowing the turbulence to rearrange the profile of the poloidal momentum, generating sheared poloidal flows. It must be noted that the level of radial velocity fluctuations at the shear layer location shows a clear dip (near $\rho \approx 1$) once the velocity shear layer is formed (Fig. 3). Thus the radial gradient in the turbulent velocity significantly increases during the development of sheared flows. The dip of the turbulence velocity fluctuations (about 1500 m/s) near $\rho \approx 1$ is consistent with the modification in the dc velocity (about 2000 m/s) [Fig. 1(d)]. This result suggests a significant energy transfer between turbulence and dc flows at the shear layer location.

Finally, it is important to compare the magnitude of the spontaneous developed sheared flows with those measured during biasing induced improved confinement regimes in

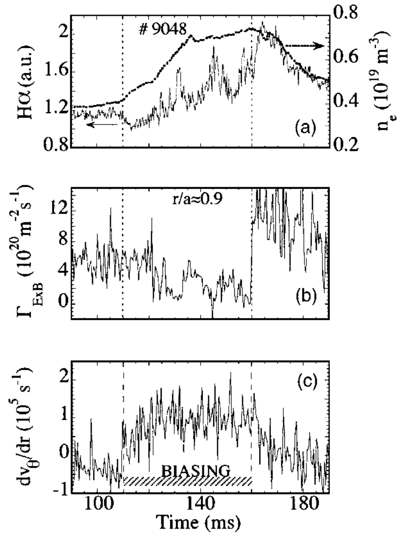

FIG. 5. (Color online) Time evolution of the plasma density, H_α (a), turbulent transport (b), and radial gradient in the poloidal phase velocity of fluctuations (c) during limiter biasing experiments. The time evolution of dv_θ/dr was computed from simultaneous measurements of the poloidal phase velocity at two different radial locations ($\Delta r \approx 0.5$ cm). Biasing is turned on at 1150 ms; however, turbulent transport reduction takes place 10 ms latter when gradients in the phase velocity of fluctuations are close to 10^5 s^{-1}. When biasing is turned off, dv_θ/dr decreases with a concomitant drastic increase in the turbulent transport.

TJ-II. Biasing-induced-improved confinement transitions, with some characteristics that resemble those of previously reported H-mode regimes in other stellarator devices, has been observed in the TJ-II stellarator [8]. During the transition to improved confinement regimes induced by limiter biasing, a clear reduction in the $E\times B$ turbulent flux has been observed. Figure 5 shows the time evolution of plasma density, edge turbulent transport, and shearing rate (i.e., dv_θ/dr). Experimental results (Figs. 4 and 5) show that both the spontaneous and biasing regime shearing rates are comparable. Thus it appears that fluctuations and spontaneous sheared flows organize themselves so as to be close to marginal stability. This finding is also consistent with previous results which have shown that dv_θ/dr (in the range of $10^5\ \mathrm{s}^{-1}$) is also comparable to the inverse of the correlation time of fluctuations (in the range of 10 μ s) [5].

It is interesting to compare present findings with the properties of a model of second-order phase transitions in resistive pressure-gradient-driven turbulence [14,15]. These simulations have shown that no poloidal flow is generated for a flow damping above a critical value and a minimum value of the pressure gradient is needed for a sheared flow to be generated. In these models, the effect of the shear flow on the turbulence saturation level is weak [15]. Consequently, as the pressure gradient increases and the modes are destabilized, the fluctuation level increases and so does the shear flow above the minimum gradient. The consistency between experimental findings and transition models based on turbulence driven sheared flows is remarkable.

In conclusion, the investigation of the coupling between the generation of sheared flows and turbulence in the plasma boundary region of the TJ-II stellarator has shown the following.

(a) The development of the naturally occurring velocity shear layer requires a minimum plasma density (in the range of $0.5\times 10^{19}\ \mathrm{m}^{-3}$). Near the critical density, where the sheared flow is developed, the level of edge turbulent transport and the turbulent kinetic energy significantly increases.

(b) The characterization of experimental results in terms of plasma density gradients shows that, within experimental error bars, there is a continuous evolution of shearing rates (i.e., radial gradients in the poloidal velocity) and fluctuation levels as gradients in the ion saturation current increase. Experimental results show a connection between increasing in the level of edge turbulence and the development of the spontaneous sheared flows.

(c) The resulting shearing rate in the phase velocity of fluctuations is comparable to the one required to trigger a transition to improved confinement regimes with reduction of edge turbulence, suggesting that spontaneous sheared flows and fluctuations keep themselves near marginal stability.

(d) These findings are consistent with the expectations of second-order transition models of turbulence-driven sheared flows.

The present results have a direct impact in our understanding of the physical mechanisms underlying the generation of critical sheared flows, pointing out the important role of turbulent-driven flows. Future experiments will be focused on the quantification of the energy transfer between flows and turbulence and results will be reported in ongoing publications.

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