EXPERIMENTAL STUDIES ON THE EFFECT OF TURBULENCE-DRIVEN EDGE POLOIDAL SHEAR FLOW ON TOKAMAK PLASMA CONFINEMENT

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High confinement operations are expected on ITER, to achieve high fusion power and fusion gain. Plasma poloidal shear flow is of great interest to fusion community, for its critical interactions with turbulence, and thus important roles in plasma transport and confinement on tokamaks. In this paper, we report our recent experimental studies on the effects of turbulence-driven poloidal flow in plasma confinement under different conditions, including conditions for increased heating power (related to L-H transition), increased density (related to density limit) and enhanced impurity radiation (related to divertor detachment). The experiments were carried out on HL-2A and J-TEXT tokamak, which are both medium-size tokamaks. It is found that: (1) With heating power injection, turbulence taps the free energy sources and a finite turbulent residual stress develops due to spectral symmetry breaking in drift wave turbulence, which leads to the turbulent generation of poloidal shear flow and significant deviation from the neoclassical prediction; (2) As density limit is approached, instead of driving the turbulent stress and poloidal flow, turbulence power is channeled to outward turbulence spreading, which becomes prominent and leads to edge cooling when the poloidal flow shearing rate is weaker than the turbulence scattering rate; (3) During divertor detachment, edge poloidal shear flow driven by turbulent Reynolds stress decreases and results in enhanced turbulence level, which contributes to the moderate degradation of global confinement. These results elucidate the fundamental physical processes in the interactions between poloidal shear flow and turbulence, which is beneficial to the comprehensive understanding of the evolution of plasma confinement.

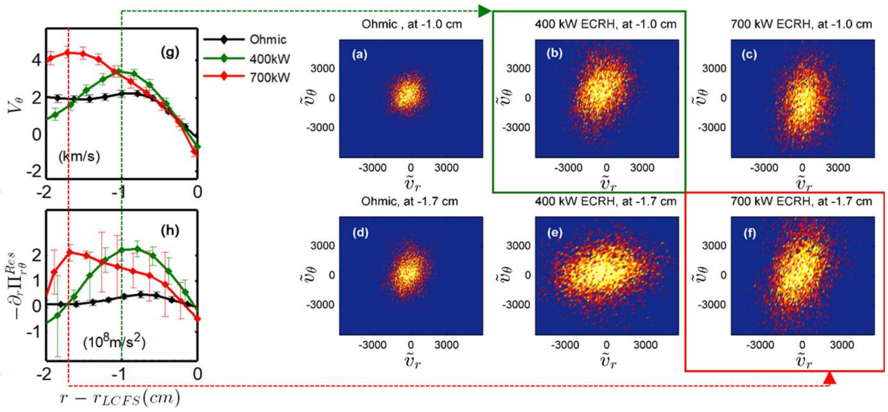

Figure 1. *(a)(b)(c) Joint PDF of radial and poloidal velocity fluctuations at 1.0 cm inside LCFS; (d)(e)(f) joint PDF of radial and poloidal velocity fluctuations at 1.7 cm inside LCFS; (g) $E \times B$ poloidal flow; (h) intrinsic poloidal torque, in Ohmic and 400/700 kW ECRH heated discharges.*

Figure 1 shows the measured $E \times B$ poloidal flow, the intrinsic poloidal torque characterized by the divergence of the non-diffusive turbulent residual stress $-\partial_r(\Pi_{r\theta}^{Res})$ and the joint PDF (probability distribution function) of radial and poloidal velocity fluctuations (i.e. $\tilde{v}_r$ and $\tilde{v}_\theta$) in Ohmic and 400/700 kW ECRH heated discharges, at the edge of HL-2A tokamak. Note that, at the position -1.0 cm (i.e. 1.0 cm inside LCFS), the joint PDF for 400 kW ECRH tilts more to the first and third quadrants than the other two cases, as shown in Figure 1(a)(b)(c). At this position, the $E \times B$ poloidal flow and intrinsic poloidal torque for 400kW ECRH in Figure 1(g)(h) peaks. Besides, at the position -1.7 cm where the $E \times B$ poloidal flow and intrinsic poloidal torque for 700 kW ECRH peaks, the joint PDF tilt is larger, as shown in Figure 1(f). The physical process of the turbulent generation of edge poloidal flows can be deduced experimentally: With injection of heating power, the turbulent stress more efficiently taps the free energy source, and a finite residual stress develops from the spectral symmetry breaking in drift wave turbulence [1]. These ultimately lead to the generation of poloidal flow.

Scans of line-averaged density $\bar{n}$ and plasma current I_p are carried out to approach the Greenwald density limit ($n_G = I_p/\pi a^2$) on the J-TEXT tokamak. Figure 2(a) shows that when the Greenwald fraction $f_G = \bar{n}/n_G$

increases, the edge normalized $E \times B$ shearing rate $\omega_N = \omega_s/\omega_t$ (i.e. relative strength of flow shearing rate and turbulence scattering rate) decreases. A reduction in the ratio of Reynolds power density to fluctuation power production is observed as $\bar{n} \rightarrow n_G$. It indicates that the collapse of the edge poloidal flow shear layer as $\bar{n} \rightarrow n_G$ is a consequence of reduced efficiency of zonal flow drive. Figure 2(b) shows that the normalized turbulence spreading power $\mathcal{P}_N = \mathcal{P}_S/\mathcal{P}_I$ increases as the normalized $E \times B$ shearing rate $\omega_N = \omega_s/\omega_t$ decreases. The measurements suggest that the Reynolds power ultimately is channeled to turbulence spreading as $\bar{n} \rightarrow n_G$ [2]. Figure 2(c) shows that edge electron temperature T_e decreases as the normalized turbulence spreading power $\mathcal{P}_N = \mathcal{P}_S/\mathcal{P}_I$ increases. Combined with the results, as the Greenwald fraction increases, the edge $E \times B$ shear flow drops and turbulence self-regulation breaks down, which results in the cooling of edge plasma approaching density limit [3,4], as shown by Figure 2(d).

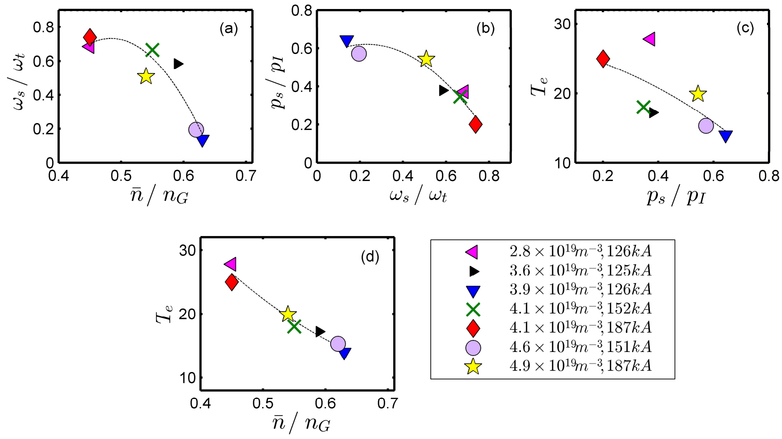

Figure 2. *(a) The normalized $E \times B$ shearing rate $\omega_N = \omega_s/\omega_t$ VS the Greenwald fraction $f_G = \bar{n}/n_G$; (b) the normalized turbulence spreading power $\mathcal{P}_N = \mathcal{P}_S/\mathcal{P}_I$ VS the normalized $E \times B$ shearing rate $\omega_N = \omega_s/\omega_t$; (c) the edge electron temperature VS the normalized turbulence spreading power $\mathcal{P}_N = \mathcal{P}_S/\mathcal{P}_I$; (d) the edge electron temperature VS the Greenwald fraction $f_G = \bar{n}/n_G$*

Edge plasma poloidal flow and turbulence momentum transport are also studied experimentally during the divertor detachment on HL-2A tokamak. The detachment is achieved by injecting a mixture of gas (60% nitrogen+40% deuterium) into the divertor. In the process of attached to pre-detached, the $E \times B$ poloidal flow velocity in the near scrape-off layer (SOL) changes from ion-magnetic to electron-magnetic drift direction. The negative radial gradient of Reynolds stress, exhibits the same trend. In the detached phase, both the $E \times B$ flow and the Reynolds force become extremely small. Therefore, the dynamics of $E \times B$ poloidal flow velocity is consistent with the turbulent momentum transport [5]. Compared with the attached state, when the divertor is detached, the edge poloidal flow shearing rate decreases significantly, leading to the obviously enhanced turbulence level. Under the influence of both enhanced turbulent transport and radiation, the global confinement degrades moderately. The energy confinement time decreases about 15% and the confinement factor H_{89-P} decreases about 10%. These results indicate that edge turbulent transport and plasma rotation dynamics play a role in the core-edge coupling process in which the divertor detachment affects the global confinement.

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