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The influence of cross-phase on turbulent transport of toroidal momentum

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Previous works indicate that intrinsic rotation is of significant importance for the next generation devices like ITER, where external momentum input is not sufficient to drive large enough toroidal rotation to stabilize MHD instabilities such as the resistive wall mode [1]. Plasma intrinsic rotation is believed to be the synthesized result of multiple effects, such as effects of MHD, neoclassical and turbulent fluctuation and so on. Results in DIII-D ohmic L mode and ECH H-mode plasma show a clear disagreement in neoclassical prediction and measured velocities [2]. In this case, influence of turbulence must be taken into account.

The key physics quantity related to intrinsic rotation is turbulent momentum flux, which can be showed as equation (1)[3]:

$$\Gamma_{\phi}^{tur} = \langle n \rangle \langle \tilde{V}_r \cdot \tilde{V}_{\phi} \rangle + \langle V_{\phi} \rangle \langle \tilde{n} \cdot \tilde{V}_r \rangle + \langle \tilde{n} \cdot \tilde{V}_r \cdot \tilde{V}_{\phi} \rangle \quad (1)$$

The three terms on the right-hand side are Reynolds stress term, convective term and triplet term, respectively. The Reynolds stress could be decomposed as follows,

$$< \tilde{V}_r \tilde{V}_{\phi} > = \sum_{w} \left| P_{\tilde{V}_r \tilde{V}_{\phi}}(w) \right| \cos\varphi(w) \quad (2)$$

$$\varphi(w) = \arctan\left(\frac{\mathrm{Im}(P_{\tilde{V}_r \tilde{V}_{\phi}}(w))}{\mathrm{Re}(P_{\tilde{V}_r \tilde{V}_{\phi}}(w))} \right) \quad (3)$$

The Reynolds stress relies on fluctuation intensity as well as the cross phase between V_r and V_{ϕ}.

A shot-by-shot density ramp-up experiment is operated in J-TEXT tokamak. The plasma is ohmicly heated, with no external toroidal momentum source. Tens of discharges are operated with line averaged density among 0.32-0.55 n_G, the Greenwald density limit. A set of reciprocating Langmuir probe array which is capable of measuring all terms in equation (1), provides significant parameters for the experiment.

The edge toroidal rotation V_{ϕ} is in co-Ip direction in low density and reverses to counter-Ip direction in high density. The predicted neoclassical V_{ϕ} is in counter-Ip direction. The deviation from neoclassical prediction is analyzed by direct measurement of the turbulent momentum flux and its three components. The former two terms both contribute to momentum transport. Reynolds stress term provides a strong co-Ip torque in low density, which becomes weak in high density in which case the convective term kicks in with a minor counter-Ip torque. Cross-phase dynamics for Reynolds stress and particle flux are analyzed. The varied contribution of Reynolds stress term in varied densities is from the change of cross-phase behavior. In low density, the cross-phase shows a phase slip characteristic and provides a large radial gradient to the Reynolds stress and thus a strong torque. While in high density, the cross-phase concentrates around π in the whole profile, giving rise to a flat profile. These trends can be clearly seen in figure 1. As a comparison, the cross-phase in particle flux has a flat profile around 0 rad. The counter-Ip torque from convective term in high density is the result of synthetic effects of V_{ϕ} gradient and increased density fluctuation gradient.

References
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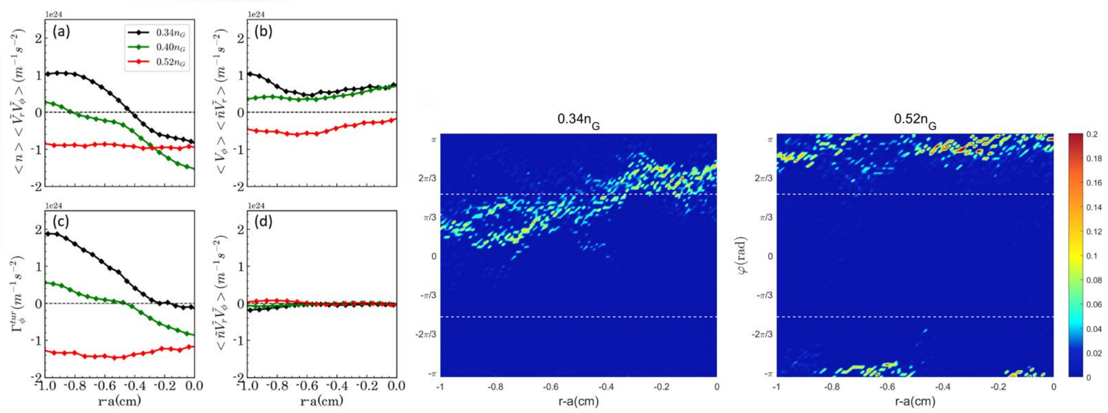

Figure 1. Left: profiles of the components in equation (1) in three different densities. Right: the cross phase of Reynolds stress in 0.34 n_G and 0.52 n_G.