Studies of cross phase in turbulent Reynolds stress and particle flux in the edge of tokamak plasma

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Turbulent transport events, including turbulent transport flux of momentum (i.e. turbulent momentum flux or Reynolds stress) and turbulent transport flux of particle (i.e. turbulent particle flux), have important effects on the confinement performance of magnetic confinement fusion devices [1,2]. Poloidal Reynolds stress is the ensemble average of the product of radial velocity fluctuations and poloidal velocity fluctuations, i.e. $\langle \tilde{v}_r \tilde{v}_\theta \rangle$. Turbulent particle flux is the ensemble average of the product of radial velocity fluctuations and density fluctuations, i.e. $\langle \tilde{n} \tilde{v}_r \rangle$. Changes in either amplitude of fluctuations or cross phase between fluctuations can cause changes in turbulent transport [3]. Study of cross phase in turbulent transport is significant for understanding plasma confinement. However, there are lack of simultaneous comparative experimental studies of cross phase in turbulent momentum and particle transport.

Cross phase dynamics in the Reynolds stress and turbulent particle flux at the tokamak edge are studied in this paper. Reynolds stress and turbulent particle flux are respectively written as the product of fluctuation amplitudes and an average cross phase factor [4], as given by equation (1) and equation (2). The mathematical expressions of the average cross phase factors X_{RS} and X_{PF} are derived respectively, as shown by expression (3) and expression (4). The average cross phase factors and the power spectra of cross phase are obtained by using experimental measurement data. We can see that the average cross phase factor is the auto-spectra product weighted average of $\gamma_{ab}(\omega)\cos\varphi_{ab}(\omega)$ in Fourier domain. Here, $x_{ab} = \gamma_{ab}(\omega)\cos\varphi_{ab}(\omega)$ is the product of coherence and cross phase of the cross spectrum, which is referred to as the spectral cross phase factor.

$$\langle \tilde{v}_r \tilde{v}_\theta \rangle = \sigma_{\tilde{v}_r} \cdot \sigma_{\tilde{v}_\theta} \cdot X_{RS} \quad (1)$$

$$\langle \tilde{n} \tilde{v}_r \rangle = \sigma_{\tilde{n}} \cdot \sigma_{\tilde{v}_r} \cdot X_{PF} \quad (2)$$

$$X_{RS} = \frac{\mathrm{Re}\left(\sum_\omega P_{\tilde{v}_r\tilde{v}_\theta}(\omega)\right)}{\left(\sum_\omega P_{\tilde{v}_r\tilde{v}_r}(\omega)\right)^{1/2}\left(\sum_\omega P_{\tilde{v}_\theta\tilde{v}_\theta}(\omega)\right)^{1/2}} = \frac{\sum_\omega P_{\tilde{v}_r\tilde{v}_r}(\omega)^{1/2} P_{\tilde{v}_\theta\tilde{v}_\theta}(\omega)^{1/2}\ \left[\gamma_{\tilde{v}_r\tilde{v}_\theta}(\omega)\cos\varphi_{\tilde{v}_r\tilde{v}_\theta}(\omega)\right]}{\left(\sum_\omega P_{\tilde{v}_r\tilde{v}_r}(\omega)\right)^{1/2}\left(\sum_\omega P_{\tilde{v}_\theta\tilde{v}_\theta}(\omega)\right)^{1/2}} \quad (3)$$

$$X_{PF} = \frac{\mathrm{Re}\left(\sum_\omega P_{\tilde{n}\tilde{v}_r}(\omega)\right)}{\left(\sum_\omega P_{\tilde{n}\tilde{n}}(\omega)\right)^{1/2}\left(\sum_\omega P_{\tilde{v}_r\tilde{v}_r}(\omega)\right)^{1/2}} = \frac{\sum_\omega P_{\tilde{n}\tilde{n}}(\omega)^{1/2} P_{\tilde{v}_r\tilde{v}_r}(\omega)^{1/2}\ \left[\gamma_{\tilde{n}\tilde{v}_r}(\omega)\cos\varphi_{\tilde{n}\tilde{v}_r}(\omega)\right]}{\left(\sum_\omega P_{\tilde{n}\tilde{n}}(\omega)\right)^{1/2}\left(\sum_\omega P_{\tilde{v}_r\tilde{v}_r}(\omega)\right)^{1/2}} \quad (4)$$

It is found that the cross phase dynamics in Reynolds stress and particle flux are very different [5-7]. Reynolds stress is found to be more sensitive to cross phase than particle flux is. In the strong $E \times B$ shear layer at $-0.6\ \mathrm{cm} < r - r_{LCFS} < 0\ \mathrm{cm}$, spatial slips of cross phase lead to the obvious radial gradient of Reynolds stress, as shown by Figure 1(a). In the no/weak $E \times B$ shear region $-1.8\ \mathrm{cm} < r - r_{LCFS} < -1.2\ \mathrm{cm}$, the cross phase in Reynolds stress tends to lock. Here, phase locking refers to that the power spectra of phase tend to distribute around a fixed phase which does not change with radial position, while phase slip means that the power spectra of cross phase tend to distribute around a phase that varies with radial position. Phase slip or locking mainly describes the central phase weighted by the power spectra, while the phase scattering mainly describes the dispersion of the power spectrum distribution of the phase. The increased scattering of cross phase, which indicates the power spectra distribution of the phase is more dispersed, contributes to the decreased Reynolds stress for higher collisionality (higher density), as shown by Figure 1(b)(d).

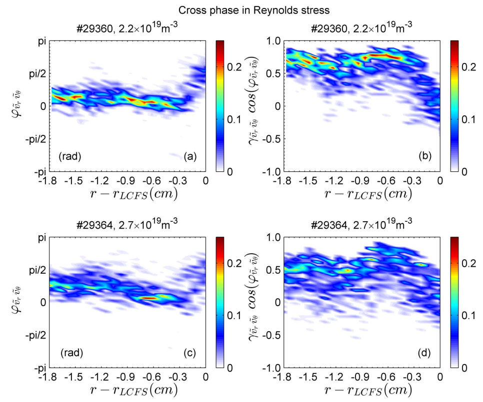

Figure 1. Cross phase dynamics in Reynold stress.

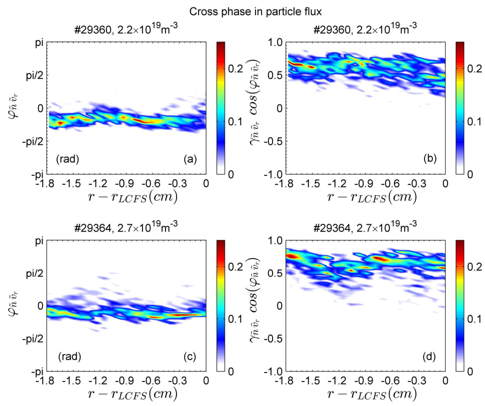

Figure 2. Cross phase dynamics in particle flux.

The cross phase in particle flux tends to lock in both strong and no/weak shear regions. The degree of scattering of cross phase in the particle flux doesn't change obviously as collisionality increases, as shown in Figure 2. For higher collisionality, it is the increased density fluctuation amplitude rather than cross phase dynamics that leads to the increased particle flux. The underlying physical mechanism that causes Reynolds stress and particle flux to exhibit different phase dynamics is discussed.

References

[1] Biglari H, et al. Physics of Fluids B, 1990, 2(1): 1-4.
[2] Guo Z B, et al. Physical Review Letters, 2015, 114(14): 145002.
[3] Boedo J A, et al. Physical Review Letters, 2000, 84(12): 2630-3
[4] Terry P W, et al. Physical Review Letters, 2001, 87(18): 185001.
[5] Long T, et al. Reviews of Modern Plasma Physics, 2025, 9(1): 7.
[6] Tian W J, et al. AAPPS-DPP 2023, Invited talk.
[7] Guo D, et al. Nuclear Fusion, 2018, 58(2): 026015