How Zonal Flow Affects Trapped-Electron-Driven Turbulence in Tokamak Plasmas

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In tokamak plasmas, the drift wave-zonal flow (ZF) paradigm, as one of major achievements of modern plasma turbulence theory, has been established after intensive studies of ion temperature gradient (ITG) turbulence. At present it has been widely accepted that ZF-induced energy transfer from the unstable mode to stable modes provides the primary saturation mechanism for ITG turbulence. However, noting that fusion power increases as the square of density and fusion produced alpha particles mainly heat electrons, the collisionless trapped-electron-mode (CTEM) turbulence may show more pronounced effects in future burning plasmas such as ITER.

Although it has long been recognized that the CTEM turbulence is of theoretical and practical interests, the significance of ZF in regulating the CTEM turbulence, nevertheless, is still being actively debated. Numerical studies have shown that the role of ZF in CTEM turbulence is parameter sensitive, with different controlling parameters identified from different simulations. Specifically, the ZF excitation is empirically found to be sensitive either to the ratio between electron and ion temperatures, magnetic shear, and electron temperature gradient scale length [1-4]; or to η_e (the ratio between gradients of the density and electron temperature) only [5]. It is conjectured that the importance of ZF may be connected with the linear stability of CTEM [5], but the underlying physics mechanism is as yet unknown. The need for a clear physical picture of CTEM ZF interplay is thus the main motivation for this work.

By employing the nonlinear gyrokinetic theory, here we show [6], for the first time, that the zonal flow excitation in the CTEM turbulence is formally isomorphic to that in the ion temperature gradient turbulence. Interestingly, although the turbulence is driven by trapped electrons, the nonlinear CTEM-ZF interplay is governed by ions and circulating electrons. Trapped electrons contribute implicitly only via linear physics. Therefore, linear CTEM properties play a unique role in determining the importance of ZF. Theoretical analyses further suggest that while ZF scattering can be important in saturating long wavelength CTEMs, for short wavelength CTEMs, the zonal flow excitation is weak and, more importantly, not an effective saturation mechanism. Linear short wavelength CTEMs are thus revisited analytically. It is found that the short wavelength CTEM instability without ZF scattering channel is essentially of two types. One is kinetically excited via toroidal precessional resonance. In this case, the instability threshold depends on the aspect ratio between major and minor radii, the temperature ratio, magnetic shear, and electron temperature gradient; consistent with previous numerical simulation observations in Refs. [1–4]. The other case is a fluid-like interchange-driven instability set by η_e in the steep density gradient regime, explaining thereby the simulation results in Ref. [5].

These findings not only offer a plausible explanation for previous seemingly contradictory simulation results, but can also facilitate controlling the CTEM instability and transport with experimentally accessible parameters.

References
[1] T. Dannert, et al, Phys. Plasmas 12, 072309 (2005)
[2] R. Waltz, et al, Phys. Plasmas 15, 122503 (2008)
[3] J. Lang, et al, Phys. Plasmas 14, 082315 (2007)
[4] J. Lang, et al, Phys. Plasmas 15, 055907 (2008)
[5] D. R. Ernst, et al, Phys. Plasmas 16, 055906 (2009)
[6] H. T. Chen, et al, Phys. Rev. Lett. 128, 025003 (2022)