8th Asia-Pacific Conference on Plasma Physics, 3-8 Nov, 2024 at Malacca

Unified picture of nonlinear generation of zonal flows in toroidal geometry

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Mesoscale structures, commonly referred to as Zonal Flows (ZFs) [1], are ubiquitous in various natural environments and geometries. In magnetic confinement fusion plasmas, ZFs under toroidal geometry have been extensively observed, and are believed to be a crucial role in suppressing turbulence and improving confinement in tokamaks, e.g., the transition from Low- to High-confinement (L-H transition) and the formation of internal transport barriers. The study of ZFs dynamics not only enhances our comprehension of fusion plasma confinement, but also provides an excellent framework for exploring highly complex nonlinear systems across multi-scale.

From the microscopic view, linearly stable ZFs can be spontaneously driven by the modulational instability [2]. Recent studies in the nonlinear gyrokinetic theory and simulations have further shown that ZFs can also be nonlinearly driven by the eigenmode self-interaction [3]. Unlike the feature that the growth rate of the modulation instability is dependent on the amplitude of pump waves, that of the eigenmode self-interaction is exactly twice as large as that of the eigenmode instability in collisionless plasma. It has been shown that the self-interaction dominates the nonlinear driving of ZFs during the quasilinear stage of Ion-Temperature-Gradient (ITG) mode, while the modulational instability is important during the nonlinear saturation of ITG turbulence.

From the mesoscopic view, ZFs are nonlinearly driven by the transport fluxes such as turbulent energy flows (TEF) [4], toroidal Reynolds stress (TRS), and poloidal Reynolds stress (PRS) [5]. Different from the cylindrical geometry, the gyrokinetic theory shows that in a collisionless toroidal plasma, the poloidal flow driven by ITG turbulence is shielded by the neoclassical polarization effects. Recent experimental observations on the Limit-Cycle-Oscillations in tokamak raise contentious issues, in which measurements of the PRS were found to be insufficient to reinforce ZFs. On the other hand, the ion pressure gradient is identified as significantly changing during the LCO phase in almost all tokamak devices.

In this report, by using the nonlinear gyrokinetic simulation, we find that the low-frequency ZFs in the toroidal geometry are driven by the TEF, the turbulent TRS and the turbulent PRS. The nonlinear driving effects of the turbulent TRS and the TEF are not shielded by the toroidal effects, but the effects of the turbulent PRS in the toroidal geometry is timescale dependent. On the time scale shorter than the ion bounce time, the turbulent PRS is not shielded by the neoclassical polarization factor, which is similar to the cylindrical geometry case [6]; while on the time scale longer than the ion bounce time, the turbulent PRS is shielded.

References

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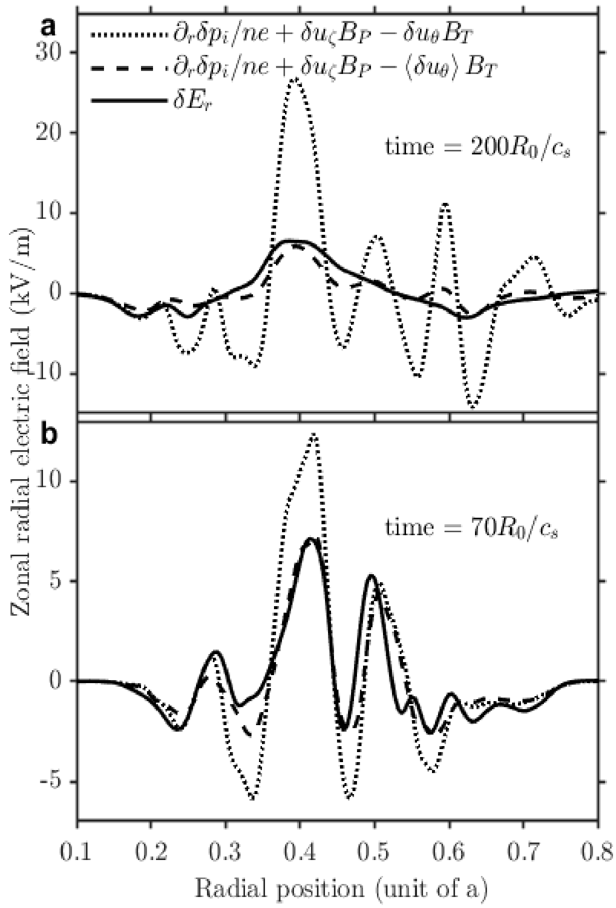

Figure 1. Radial structures of the zonal radial electric field and its nonlinear driving sources when the turbulence is quenched (a) and when the turbulence in the quasi-steady state (b).