

Zonally dominated dynamics and the transition to strong turbulence in ion-scale plasma turbulence

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Since the discovery of the Dimits shift (Dimits et al. 2000), the role of zonal flows (ZFs) for the turbulence in tokamak plasmas has been an area of intense research. We attempt to shed some light on this problem by studying the transition to turbulence in a cold-ion fluid model for ion-scale turbulence in magnetic geometry of constant curvature. Our equations are obtained in a collisional, cold-ion, asymptotic limit of the ion gyrokinetic equation and capture the two ion-temperature-gradient (ITG) instabilities driven by either magnetic curvature or parallel compression. We find that this model has a well-defined Dimits (low-transport, ZF-dominated) state characterised by a staircase-like arrangement of ZFs and zonal temperature that suppresses turbulence. Viscous decay of the ZFs leads to occasional turbulent bursts that reconstitute the staircase by providing a negative zonal turbulent viscosity. In 2D, at sufficiently large equilibrium temperature gradients, the zonal turbulent viscosity switches sign, hence the turbulent bursts no longer reinforce the zonal staircase and the Dimits state is destroyed. In 3D, the Dimits state is much more resilient and can always be sustained provided sufficient parallel extent of the system. This is because the large-scale curvature-driven perturbations go unstable to small-scale "parasitic" 3D slab-ITG modes that always give rise to a negative zonal turbulent viscosity. If we restrict the parallel extent of the system, the Dimits state is destroyed, and a strongly turbulent, high-transport state is established. In this state, energy is injected into large-scale perturbations by the curvature-ITG instability, then transferred into the parasitic small-scale modes, and finally dissipated by the finite collisionality. We find that sufficient parallel resolution is critical for the 3D Dimits state and failure to resolve the small parallel scales of the parasitic modes can result in a non-physical transition to strong turbulence.