Zonally dominated saturation and Dimits threshold in curvature-driven ITG turbulence

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The saturated state of turbulence driven by the ion-temperature-gradient (ITG) instability is investigated using a two-dimensional long-wavelength fluid model that describes the perturbed electrostatic potential and perturbed ion temperature in a magnetic field with constant curvature (a Z-pinch). The model is derived in a long-wavelength asymptotic limit of the ion gyrokinetic (GK) equation (Frieman & Chen 1982). Numerical simulations reveal a well-defined transition between a finite-amplitude saturated state dominated by strong zonal-flow and zonal-temperature perturbations, and a blow-up state that fails to saturate on a box-independent scale. We argue that this transition is equivalent to the Dimits transition from a low-transport, zonal-flow-dominated state to a high-transport state seen in gyrokinetic numerical simulations (Dimits 2000).

In the near-marginal Dimits state, turbulence is suppressed by a quasi-static "zonal staircase" arrangement of the zonal flows and zonal temperature. This structure is reminiscent of the "$\boldsymbol{E} \times \boldsymbol{B}$ staircase" observed in global GK simulations (Dif-Pradalier 2010). The zonal staircase consists of interleaved regions of strong zonal shear that suppresses the ITG turbulence in those regions, and localised turbulent patches at the turning points of the ZF velocity.

The break up of the zonal staircase, and, thus, of the low-transport Dimits regime, is linked to a competition between the two different sources of poloidal momentum — the Reynolds stress of the $\boldsymbol{E} \times \boldsymbol{B}$ flow and the diamagnetic advection of the poloidal $\boldsymbol{E} \times \boldsymbol{B}$ flow. We find that the former drives the staircase ZFs, while the latter opposes them. By analysing the linear ITG modes, we obtain a semi-analytic model for the Dimits threshold at large collisionality.

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