Zonally dominated dynamics and the break-up of the Dimits state in ion-scale plasma turbulence

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We present analytical and numerical results on the nonlinear saturation of ion-scale electrostatic turbulence driven by ion-temperature-gradient (ITG) instabilities in slab geometry with constant magnetic curvature (a Z-pinch). Our work is based on a three-dimensional extension of our two-dimensional, long-wavelength, cold-ion fluid model [3]. We identify two qualitatively distinct routes to saturation: a Dimits state [2] dominated by strong, coherent zonal flows (ZFs), and a strongly turbulent state whose saturation is aided by small-scale ITG modes.

The Dimits state is governed by the same underlying mechanisms as the two-dimensional model [3]. 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 [1]. 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 distinctive feature of three-dimensional cold-ion ITG turbulence, as opposed to its two-dimensional counterpart, is the existence of a small-scale instability that is driven by the gradients of large-scale perturbations. The modes produced by this instability give rise to an effective large-scale thermal diffusion. The combination of this additional diffusion and the favourable turbulent momentum flux of the small-scale modes extends the Dimits regime to temperature gradients far higher than those allowed in two dimensions. Beyond the Dimits regime, the small-scale instability aids saturation by breaking up large-scale structures.

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