Interplay between turbulence & large scale flows in the presence of two competing instabilities at the edge of tokamak plasmas

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In magnetized plasmas, small scale turbulence is often predicted – and sometimes experimentally reported – to self-organize as a result of its interaction with large scale sheared flows. In controlled fusion plasmas, such flows originate from several physical mechanisms, one of them being turbulence itself via nonlinear couplings. From the viewpoint of the energy confinement, these so-called zonal flows are beneficial since they pump out energy from turbulence – hence contributing efficiently to its saturation – without leading to any deleterious transport across magnetic flux surfaces [1]. It has been found recently – in first principles numerical simulations [2] and later in experiments [3] – that these zonal flows can structure into localized sheared layers separating regions dominated by avalanche-like transport events. The result is a staircase-like structure of the pressure profile, analogous to what is observed in the salinity and temperature vertical profiles in the ocean [4]. The mechanisms of the generation of these structures, their impact on turbulent transport and their robustness with respect to the various types of turbulence remain active research topics.

In the present work, we report on the competition between two instability mechanisms that are suspected to be dominant at the edge of tokamak plasmas. They feature drift waves (akin to Rossby waves in atmospheric turbulence) and turbulent eddies driven unstable either by the finite phase shift between electrostatic wave and particle fluctuations or by the inhomogeneity of the magnetic field that introduces an effective gravity (leading to a Rayleigh-Bénard type instability) [5]. The reduced 1-dimensional model derives from the constitutive fluid equations under the isothermal assumption. It retains the self-consistent interplay between mean gradients and fluctuations in a regime driven by a prescribed flux. As such, it allows one to study the generation and structuration of large scale flows as well as their impact on turbulent transport.

Whatever the scanned regime of plasma parameters, zonal flows are always active. They are found to be driven by both components of the Reynolds stress, electric and diamagnetic [6], the contribution of the former being dominant when interchange dominates. Two regimes are observed, where zonal flows are either structured in staircases or not. Staircases are found to emerge as a result of an anti-diffusive process while density fluctuations peak at the points of convergence of the group velocity of the drift-waves. Not so much the shear of the zonal flows v'_{ZF} but more critically their curvature v''_{ZF} – the sign matters – proves to be an essential characteristics to control the turbulent transport, mainly by mitigating the cross phase between density and electric potential fluctuations.

These results help to characterize the large scale flow dynamics and their efficiency in regulating turbulent transport, and to discriminate plasma regimes where staircases are likely to be observed experimentally.

Références

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