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Questioning the quasi-linear nature of turbulent flux by means of gyrokinetic flux-driven non-linear simulations

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Quasilinear (QL) theory is widely used to estimate heat and particle fluxes in tokamaks, based on experimental profiles and gradient-driven codes. Its validity relies on a number of assumptions, especially regarding the hierarchy of typical linear and nonlinear times. These are revisited by means of flux-driven simulations which reveal new features at intermediate scale, such as avalanches and turbulence self-organisation close to marginal stability[1]. Those events are responsible for so-called nonlocal transport, which echoes experimental observations[2]. Using the GYSELA code[3], we study the interplay between zonal flows, mesoscale structures and turbulent filaments, and their impact on heat flux and QL estimates. In particular, these results are shown to significantly depart from QL heat flux predictions obtained with QuaLiKiz[4]. Comparison to local non-linear GKW[5] simulations is in process, and will be presented.

Computed Kubo numbers, ratio of Lagrangian correlation times to the eddy turnover, are between unity (mixing length estimate) and a few units. This suggests marginal validity for the QL framework. Taking the time-averaged and radially coarse-grained GYSELA flux-driven profiles as equilibrium profiles, QuaLiKiz predicts heat fluxes from 0 to 20 times those of GYSELA. To identify the culprit, GYSELA's heat flux is decomposed into contributions of the fluctuations' amplitude and phase shift. QuaLiKiz and GYSELA agree on the amplitude ratio and phase shift between the pressure fluctuations with respect to density fluctuations, for wave numbers with significant turbulent intensity. This suggests linear features are somewhat preserved in the considered nonlinear regimes. Furthermore, fluctuations of the non-linear heat flux are dominated by turbulent intensity (instead of phase shift), emphasizing the importance of the QL saturation closure. This issue is out of the predictions of the QL theory, and requires an adequate closure.

The usual QL saturation closure in integrated modelling tools relies on prescribing the electric potential spectrum as a power-law adjusted on non-linear local simulations and validated against experimental observations. Self-organisation effects like the zonal flow staircase weaken the scale separation between turbulent dynamics and the profiles. Turbulent avalanches rapidly propagate across the radial domain. As a result, the turbulent spectrum may fluctuate away from this reference power law. To quantify their effect, the shape and motion of turbulent structures are computed from the 3D flux-driven electric field. The inferred motion is mostly toroidal: the ballooned character of the underlying instability compensates the poloidal advection, resulting in an overall toroidal motion of turbulent structures. The radial pattern of turbulent structures appears to be governed by the shear of the zonal mean flow profile, instead of being distorted by this shear.

Computed radial velocities also correlate well with stationary flow shear rates[6,7], and are related to the local ballooning angle. Depending on the zonal flow curvature, turbulent structures can converge towards a zonal flow layer and feature increased turbulent correlation time, or diverge from it and exhibit increased radial correlation length. This asymmetry is reminiscent of turbulent wave trapping[8], and challenges oft-used prescriptions of shear regulation which are independent of the zonal flow curvature. This asymmetry can be incorporated in a description of turbulent structures as pseudo-particles, such as wave-kinetic theory. Its consequence on the fluctuations of turbulent intensity and on the growth of geodesic acoustic modes will be discussed.

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