On the Validity of the Local Diffusive Paradigm in Turbulent Plasma Transport

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Transport and turbulence in tokamaks have traditionally been treated as local processes, in which localised instabilities drive local mixing and diffusive transport, so that well separated regions of the plasma interact with one another only by diffusive pulse propagation. And this, despite frequent experimental observations such as either hot/cold pulse experiments, Bohm-like scaling for the energy confinement time or *e.g.* off-axis heating experiments showing inconsistencies with *local* and *diffusive* models. While studying as simple a case as the heat conduction generated by the ITG instability, we show that the 'standard' model described above is surely incomplete, in that turbulence and transport dynamics are intrinsically nonlocal. We also report on the first observation of a novel self-organised flow structure which we call the '$\mathbf{E}\times\mathbf{B}$ *staircase*'.

The process of thermal avalanching, observed in both digital and physical experiments, suggests a nonlocal description of the heat flux of the generic form: $Q(r) = -\int \mathcal{K}(r,r')\nabla T(r')\mathrm{d}r'$. We present a systematic and constructive analysis of the structure of the nonlocal thermal conducting kernel $\mathcal{K}(r,r')$, allowing one to rigourously quantify local, diffusive transport *v.s.* nonlocal, non-diffusive action at a distance in plasma turbulence [1]. This analysis is based on a large database of fully self-consistent results, in realistic geometry, spanning widely different representative plasma parameters and obtained using the *full–f*, flux-driven gyrokinetic GYSELA [2] and XGC1 [3] codes, thus with *no pre-conceived hypotheses regarding the nature of the thermal transport.*

Our findings indicate that the kernel $\mathcal{K}(r,r')$ has the structure of a universal Lévy distribution with divergent second moment, characterised by a radial *influence length* Δ (quantifying how transport events happening at location r could drive a flux at a distance Δ from this event) which fills in the mesoscale range –*i.e.* $\ell_c \ll \Delta \ll L_{T_i}$, where ℓ_c is the turbulence autocorrelation length and L_{T_i} is the profile scale. This influence length Δ is systematically 4–5 times larger than ℓ_c, strongly alerting to the dubiety of local and diffusive approaches for an accurate description of nonlinear transport. Physically, Δ also corresponds to the typical avalanche size in the system, connecting this physics to the oft-invoked paradigm of self-organised near-critical transport. At scales smaller than Δ, transport is scale-invariant, avalanche-mediated, nonlocal and non-diffusive. Remarkably, Δ saturates at mesoscales: this influence length also characterises the spacing of a quasi-regular pattern of $\mathbf{E}\times\mathbf{B}$ shear layers, which structure has not been previously observed in studies of drift-wave turbulence. We call it the '$\mathbf{E}\times\mathbf{B}$ *staircase*' and emphasise that the location of the 'steps' in the staircase are *not* correlated with low q resonances. This $\mathbf{E}\times\mathbf{B}$ *staircase* represents the footprint of the radial influence length on the flow structure, and reflects the surprising tendency of the stochastic avalanche ensemble to self-organise at scales larger than Δ in a jet-like pattern: few avalanches indeed exist beyond this influence length Δ.

Ongoing work is concerned with exploring the dependencies of Δ and elucidating the mechanisms whereby the staircase emerges as well as identifying, beyond the aforementioned 'universal' characteristics, potential discrepancies: origin locus of avalanches (core/edge) and the role of flow shear in the direction of propagation.

References:

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