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How the narrow Edge—Scrape-Off Layer Interface Self-Organises Turbulence Globally

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For over three decades, the observation of rapid core confinement improvement upon favourable modifications of edge operating conditions has been a nagging source of puzzlement for experimentalists investigating conditions for a lasting source of fusion energy in tokamaks. The transport properties of drift-wave turbulence and the interaction of the confined plasma with its material boundaries have long been recognised as essential to the resolution of this conundrum. Key aspects of the turbulent dynamics in the plasma edge are poorly quantified, owing to the disparity of temporal and spatial scales and the inadequacy of performing scale separations. Here we show, relaxing oft-made scale separation assumptions that a narrow region at the interface between open and closed magnetic field lines is central to explaining the transport properties of turbulence, globally. The proposed presentation, based on actual experimental parameters, discusses three main results. We unambiguously show (1) that turbulence is not only locally driven by local gradients but nonlocally controlled by fluxes of turbulence activity, primarily though not exclusively borne at the edge. This 'nonlocal' influence is mediated through vortex-flow localised interactions near the material boundaries and has two major consequences: (2) the nonlinear destabilisation of the linearly stable edge, providing a possible resolution for the so-called 'shortfall'conundrum and (3) the spontaneous emergence of a stable and localised transport barrier at the closed/open field line transition, possible prelude to the formation of a pedestal.

Low-frequency microturbulence in fusion plasmas is appropriately described by gyrokinetics. GYSELA[1] models ions and trapped electrons gyro-kinetically in the core and edge regions as well as the closed/open field line transition and the Scrape-Off Layer (SOL) through introduction of a simplified penalised limiter[2] mimicking the role of a heat and momentum sink, Fig.1-a. Importantly core, edge and SOL are treated on an equal footing. Specifically, GYSELA is built such that: (i) no scale separation is assumed as this simplification tends to break down towards the edge; (ii) the system is flux-driven implying that both fluxes and gradients are dynamic. Both properties are instrumental to the results here and have stringent implications for modelling as all spatial scales from the short ion-scale Larmor radius (ρ_i˜1mm) to the global machine scale (L˜1m) and intermediate gradient mesoscales typically˜$\sqrt{\rho_i L}$, where turbulence self-organises, are self-consistently treated. Similarly, the fast turbulent motion (˜10^{-5}s) and long collisional transport and energy confinement (˜1s) scales are treated on an equal footing.

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(1) Limiter-borne localised sources of nonlocal spreading. Spatial asymmetries spontaneously develop from the presence of the limiter. Starting from a poloidally-symmetric state, the combined action of magnetic drift and parallel losses leads to a poloidally-asymmetric kinetic equilibrium. Parallel gradients of density and temperature develop which lead to local accumulation (resp. depletion) of density (resp. temperature) in the vicinity of the limiter, though the pressure remains quasi-constant along the field lines. This asymmetry spans the SOL and extends in the confined edge plasma, typically within 10% of the last closed flux surface (LCFS). It leads to a poloidally-localised enhanced linear drive for ion-scale drift-wave instabilities, as confirmed through linear gyrokinetic analysis of the GYSELA profiles using the gyrokinetic code GKW[3] in the local approximation limit. Kelvin-Helmholtz like instabilities are weakly driven or stable. This instability source of is generic to the presence of the limiter and absent without, despite all other parameters being equal, as illustrated in Fig.1.

(2) Nonlocal SOL—edge—core interplay. In L-mode, key to apprehend the transition to H-mode, the situation of the edge is clouded. The universal observation in experiments that the relative level of fluctuations ⊠n/n monotonically increases from core to edge, n being the plasma density is often strongly under-predicted when pushing gyrokinetic approaches towards the edge region, bearing witness to the difficult understanding of its dynamics. This underprediction is commonly referred to as the "transport shortfall". Recently, further works have tested aspects of this shortfall; the issue, however, remains largely open and we will discuss it. Our work suggests a paradigm shift in how we model turbulence, suggesting that it is clearly not only locally driven. We find that an incoming front provokes ambient fluctuations to produce a controlled outward heat flux, first fuelling the otherwise linearly-stable edge turbulence then percolating through the transport barrier into the

open field-line region and depositing its energy onto the boundaries. In our approach, these dynamics solves the shortfall conundrum.

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(3) A spontaneous edge barrier. Only with the limiter and with an interface to the SOL, does a spontaneous radially-localised shear layer nucleate at the transition from closed to open field lines. Orbit loss through the LCFS results in a net radial current which equilibration is modified by the position of the limiter. Nonlinearly, the Er well is also sustained via vortex-flow positive feedback. This is shown in Fig.3, displaying the ExB flux of vorticity, proxy for the time increment in poloidal momentum deposition in the vicinity of the LCFS. Vortices of a definite vorticity are radially advected in a systematic direction. The resulting force acts such that each individual vortex in the vicinity of the shear layers either deposits its momentum into the flow or extracts the negative of its momentum from the flow, in both cases reinforcing it. A detailed discussion of the statistics of orbit loss and vortex-flow interaction is proposed. These nonlinear processes are important dynamical players for the organisation of turbulence in the edge region. Similarly to other non-equilibrium systems in nature, the tokamak plasma self-organises into a globally critical state, allowing a narrow 'tail' region at the edge—SOL interface to 'wag' the bulk core and edge plasma in a turbulence propagation time far faster than the plasma transport time[2].

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