Evidence for Global Edge–Core Interplay in Fusion Plasmas[*)]

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Large-scale reactor-relevant fusion plasmas are likely to operate near marginal stability. In this regime, we show clear evidence of interplay between core and edge regions of the plasma. This result illustrates aspects of the controversial ‘shortfall problem’ in the far-core, near-edge so-called ‘No Man’s Land’ region and a possible route to resolve this issue. More generally, it emphasises global-scale organisation of turbulence and relevance of edge dynamics to core confinement.

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Magnetically confined plasmas are often separated in spirit and in modeling into an inner core region of fusion performance and a somewhat outlying and disconnected edge and Scrape-Off-Layer (SOL) region, dedicated to interactions with the material structure of the confining device. The degree to which it is actually reasonable to disconnect core and edge is addressed in this paper. Conclusions are threefold: (*i*) core and edge can significantly interplay, hence global-scale description of turbulence self-organisation appears important, (*ii*) inward propagation of edge turbulence is a major contribution to core–edge interplay, (*iii*) this interplay is all the more important close to a critical point, marginal instability for instance.

The regime of near-marginality [1] for magnetised plasmas is not merely academically-appealing for its rich dynamics and manifestations of self-organisation [2–8]. It is as well a likely practical operating regime for current and future confinement devices for which the ratio of plasma volume over external heating is large, favouring proximity to marginality. Whilst a submarginal state may exist globally, a regime of near-marginality is frequently inhomogeneous in time and in space, displaying a range of transport properties [9] as submarginal and turbulent patches coexist, with intermittent behaviour. Global-scale organisation of turbulence, from core ($\rho = r/a \lesssim 0.6$) to edge ($0.9 \lesssim \rho \lesssim 1$) is here investigated in such regimes, in the relevant low-heating limit of flux-driven forcing and using the gyrokinetic approach in Gysela [10, 11].

Gysela has recently been upgraded to account beyond the outer edge for SOL-like ($\rho \geq 1$) boundary conditions [12]. A sink is progressively added from $\rho = 1.05$ to 1.15 by enforcing exponentially-decaying density and temperature profiles. Though too crude to address SOL physics, these outer conditions introduce a coupling between the modeled confined plasma and the SOL-like sink region. Outward and inward plasma fluxes are self-consistently exchanged across $\rho = 1$ and fluxes beyond $\rho = 1.05$ are progressively damped. Self-consistent interplay of core and edge can be realistically investigated up to $\rho = 1$.

The steady increase, in L–mode, of the relative level of turbulent fluctuations $\delta n/n$, n being the plasma density, from the innermost core to the edge [13] is a universal feature of tokamak plasmas. Yet under-prediction of the fluctuation levels in the far-core near-edge region—sometimes dubbed the “No Man’s Land” owing to the difficult understanding of its dynamics and poorly estimated fluctuation level between $\rho = 0.6$ and 0.9—has been reported in various modeling attempts [14, 15]. This under-prediction of transport is sometimes referred to as the “transport shortfall” conundrum and though various attempts have been made to address it [16], its understanding remains troublesome. The way a hot stiff core interplays with the plasma edge is a central issue to combine high fusion performance and safe diverter operation.

The “spreading” of turbulence [17], i.e. the space–time propagation of patches of turbulence activity originated elsewhere in the plasma volume is amongst the possible mandatory ingredients to address this conundrum. Both core [18] and edge/SOL [19, 20] turbulence may indeed spread into the NM’sL, contributing to the fluctuation level there. In this paper, we step back from the specific problem of the possible “transport shortfall” and ask the general question of how much core and edge may interplay and how much core [resp. edge] turbulence levels may depend on distant edge [resp. core] turbulent activity.

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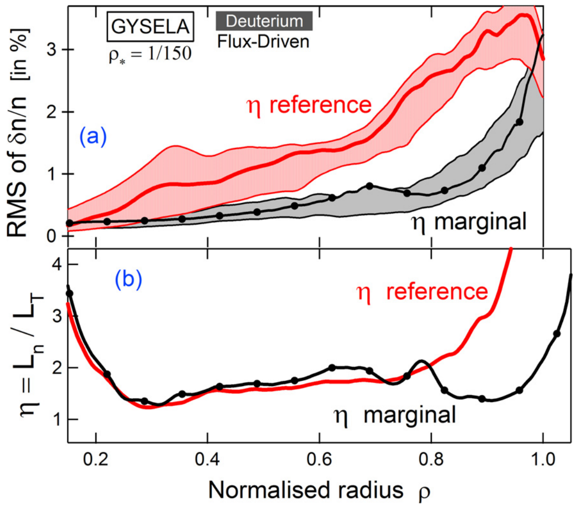

Fig. 1 Density profiles in both 'marginal' and 'reference' are the same for $\rho \leq 0.65$. A steeper, ITG-stabilising density gradient is chosen in the 'marginal' case for $\rho \geq 0.65$. Temperature profiles evolve freely in both cases and steady-state flux-driven η profiles are compared in Fig. (b). Edge turbulence activity spreads even deep in the plasma core: fluctuation levels, shown in Fig. (a) are remarkably different in the region $\rho \in [0, 0.7]$ despite similar gradients.

To this end we compare the radial distribution of Ion Temperature Gradient (ITG)-driven turbulence fluctuations in two different cases. In flux-driven Gysela, assuming for simplicity a Boltzmann response for the electrons, the temperature profile T freely evolves whilst the density profile, fixed, can be tailored to provide control of the threshold of instability. However, the statistical state of the system is always *a priori* unknown and dynamically self-organised, as T self-organises. Both 'reference' and 'marginal' cases in Fig. 1 (b) have the same density profile up to $\rho = 0.65$, typical of L–mode Tore Supra discharges. For $\rho \geq 0.6$, the density gradient is moderate in the 'reference' scenario and steeper in the 'marginal' one. Both cases are independently run until statistical equilibrium. The temperature profile organises differently in both instances, all other parameters (source, sink, boundary conditions) being otherwise the same.

The mean gradient drive $\eta = L_n/L_T$ is shown in Fig. 1 (b) for both cases, the corresponding turbulence fluctuation levels in Fig. 1 (a), with L_x the gradient length of quantity x: density n or temperature T. The usual flux–gradient paradigm [21] bijectively relates the local values for fluxes to the local values of the gradients. In flux-driven approaches this paradigm is challenged [5, 9, 12] as both fluxes and profiles evolve consistently and are unknown functions of the dynamics. The flux–gradient relation thus evolves in time, may become multivalued (different gradient drives may be associated to the same flux) and consequently non monotonic (a larger gradient drive may be associated to a lower flux). The observation of coherent structures, the onset of transport barriers [22] or of coherent patterns such as the $\mathbf{E} \times \mathbf{B}$ staircase [5–8, 12, 23] are signatures of the breakdown of the local flux–gradient paradigm.

Both 'marginal' and 'reference' core plasmas $\rho \leq 0.6$ in Fig. 1 (b) are marginally unstable. Beyond $\rho \approx 0.7$ the gradient drive η for the 'reference' case gradually increases, brought on by the decrease of T rather than the increase of ∇T whereas η for the 'marginal' case remains near marginal stability up to $\rho = 1$, then rapidly increases in the SOL-like region. Modification of the turbulence activity in the distant edge region deeply changes the core dynamics. Several conclusions can be drawn from Fig. 1:

(i). the density fluctuation levels in Fig. 1 (a) are much lower *everywhere* in the 'marginal' case, even below $r/a \leq 0.7$ despite a comparable or slightly higher gradient drive η. This clearly challenges the validity of the oft-used local flux–gradient paradigm: local knowledge of the plasma profiles does not allow to correctly predict local levels of turbulence intensity.

(ii). near-marginal plasmas appear prone to self-organise on a global scale and are responsive to details of the turbulence activity from even distant regions of the plasma volume. These facts stress the importance of a flux-driven description of near-marginal plasmas;

(iii). an edge reservoir of turbulence intensity appears to influence fluctuation levels even in the deep plasma core. As the gradient drive η for realistic profiles is bound to increase when approaching $\rho = 1$, inward spreading of turbulence intensity from the unstable edge is likely to play a key role in determining the radial distribution of turbulent fluctuations, globally;

(iv). inversely, outward spreading of near-marginal core turbulence appears to have a moderate impact.

Conclusions—Compelling evidence for edge–core interplay is found in the tokamak-relevant setup of a marginally unstable core plasma coupled to an edge region reservoir of turbulence activity. Inward spreading of edge turbulence intensity appears as the major contributor to global organisation of turbulence fluctuations as it affects fluctuation levels even in the deep confined core. Importantly, the oft-assumed bijection between local values for the plasma gradients and local values for the fluxes appears unreliable.

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