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Spreading of edge plasma turbulence in transport barriers

G. Ciraolo[1], Ph. Ghendrih[1], Y. Sarazin[1], G. Darmet[1], P. Tamain[1]

[1] *Association Euratom-CEA, CEA-Cadarache, 13108 St Paul lez Durance, France*

Introduction

Turbulence spreading, namely the interplay between plasma regions that are linearly unstable and neighboring regions that are linearly stable, can have a relevant role in determining properties and nature of plasma transport in magnetic fusion devices. Two main effects are relevant for an ITER scenario: firstly, penetration of turbulence from the edge region (Scrape Off Layer) to the core region, crossing the H-mode barrier, can lead both to a narrowing of the transport barrier and to a destabilization of the pedestal stable region. Secondly, large bursts of turbulence can overshoot in the far SOL, like plumes, eventually producing overloading and localisation of heat deposition on plasma facing components not designed to sustain large heat fluxes.

In this paper the phenomenology of spreading in SOL turbulence is analysed with the flux driven code *Tokam* which is a $2D$ non-linear code for density and electric potential governed by interchange instability [1, 2]. In the next section the 2D model is recalled as well as its transport properties. Then the effect of turbulence spreading on the properties of transport barriers is investigated.

Flux driven turbulence in the Scrape Off Layer

SOL turbulence is specific with respect to core turbulence due to the sheath boundary conditions that strongly reduce the parallel current flowing on each flux tube. Regimes with reduced parallel current are then very sensitive to charge separation via the curvature drift since the parallel current is less effective to balance the charge separation. In fact, the interchange instability, hence curvature charge separation combined to a density gradient, in conjunction with the sheath resistivity have been proposed to explain the very large fluctuation levels reported in the SOL [3, 4]. We consider here this model of SOL turbulence in the limit $T_i \ll T_e$. Two balance equations are used, the particle balance that governs the density transport, and the charge balance which takes the form of an evolution equation for the vorticity $\Delta\phi$, where ϕ is the electric potential, due to the ion inertia terms. Further simplifications are introduced in the flute limit, hence with weak parallel gradients such that the average along the field lines can be performed. The system is thus reduced to a $2D$, r, θ, and 2 field model, n the density and ϕ the plasma potential normalised to T_e/e.

$$\left(\frac{\partial}{\partial t} - D\nabla_\perp^2 + \{\phi\}\right) n = \sigma_n n + S \quad (1)$$

$$n\left(\frac{\partial}{\partial t} - \nu\nabla_\perp^2 + \{\phi\}\right) \nabla_\perp^2 \phi + g\partial_y n = \sigma_\phi n \quad (2)$$

Time is normalised to the ion Larmor frequency and space to the so-called hybrid Larmor radius ρ_s. D and ν stand for the collisional transverse diffusion and viscosity (normalised to the Bohm values), S is the density source term, here localised radially and constant in time and along the poloidal angle θ. σ_n and σ_ϕ are the sheath controlled particle flux and current to the wall, $\sigma_n = \sigma\ exp(\Lambda - \phi)$ and σ_ϕ=$\sigma\big(1 - exp(\Lambda - \phi)\big)$ where $\sigma = \rho_s/qR$ stands for the normalised saturation current. The operator $\{\phi\}F = \{\phi, F\} = \partial_x\phi\partial_y F - \partial_y\phi\partial_x F$ is the electric drift convection term. At first order in the fluctuation magnitude, sheath loss terms can be linearised to yield the Hasegawa-Wakatani coupling term $\sigma(n-\phi)$ [5]. Turbulence is generated by an unstable density gradient and then overshoots into a stable density region [1, 2, 6]. This is reminiscent of the physics reported in experimental observations in the deep SOL [7] with intermittent turbulent transport in regions with flat density profiles. Thus, turbulence spreading, i.e. the existence of turbulent transport in regions that are linearly stable, does seem to play a role in SOL turbulence.

Transport barriers and SOL turbulence spreading

Turbulence spreading, when considering the interplay between SOL turbulence and the H-mode transport barrier (or pedestal), will also change the properties of the pedestal. A comprehensive analysis is not possible since one lacks of a complete theoretical understanding of the onset of the H-mode transport barrier. Here we propose to analyse the spreading effect on transport barriers generated by two different mechanisms: in the first case we set g in Eq. (2) to 0 over a chosen radial extent Δ_{linear}, here set at $32\rho_s$. This corresponds to switch off the turbulence drive in a selected region producing a very artifical transport barrier [8]. In the second case, more realistically and following similar studies for core plasma turbulence [9], we drive a barrier imposing an external sheared electric potential V_{bias} over the selected spatial region. These two cases allows us to study the barrier properties when they are governed by a linear analysis criterion on the one hand and, on the other hand, when a complex non-linear effect due to the plasma response is present.

For what concerns the first case, i.e. the $g = 0$-case, a linear analysis, presented in Fig. 1 (top panel), is performed with equal poloidal and radial wave vectors ($2\pi/15$) that maximise the growth rate and a prescribed density gradient, $\nabla n/n|_{linear} = \langle\nabla n/n\rangle - 5\big(r.m.s.(\nabla n/n)\big)$

where $r.m.s.(\nabla n/n)$ is the root mean square of the fluctuating density gradient. With the chosen parameters for this simulation, one finds that the turbulence is sub-critical, namely that the mean density gradient is smaller than the critical density gradient $|\nabla n/n|^* = |\langle \nabla n/n \rangle| + 2.55\big(r.m.s.(\nabla n/n)\big)$. Hence, from the linear point of view, the whole simulation region is stable. The turbulent activity that is sustained can therefore be considered as penetration of turbulence in a stable media, a situation that is comparable to the spreading of turbulence in the flat density SOL.

The effective pedestal width is analysed in terms of an indicator, namely the ratio of the radial turbulent flux $\Gamma_{turb.} = -\partial_y \phi\ n$ to the total radial flux $\Gamma_{total} = \Gamma_{turb.} - D\partial_x n$, that is $I(x,y,t) = \Gamma_{turb.}/\Gamma_{total}$. This indicator allows one to discriminate regions with large turbulent fluxes $|I| \gtrsim 1$ from that with weak turbulent flux. The indicator $I(x,y,t)$ is proportional to $\Gamma_{turb.}$ and exhibits large fluctuations with a skewed *PDF* [1, 2]. The time and poloidal average of this indicator $\langle I(x,y,t)\rangle_{(y,t)}$ provides a profiles with a clear signature of the transport barrier. Indeed, while $\langle I(x,y,t)\rangle_{(y,t)} \lesssim 1$ away from the barrier, $\langle I(x,y,t)\rangle_{(y,t)}$ is significantly reduced within the pedestal as shown on Fig. 1 (bottom panel). It drops from the order of 98 % to less than 3 % but departs significantly from the square shape that would result from the linear analysis represented on Fig. 1 (top panel). Associated to the decrease of the turbulent flux, one observes a steepened density gradient, Fig. 1 top panel, leading to a standard tanh like profile.

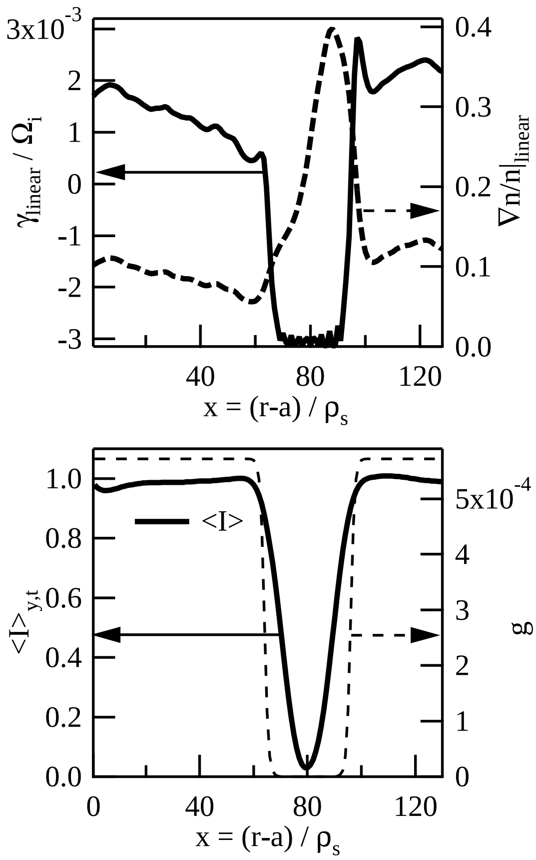

Figure 1: *Top panel: Radial profile of the linear growth rate γ_{linear}, left axis, computed with the density gradient $\nabla n/n|_{linear}$, right axis. Bottom panel: Radial profile of the mean turbulence indicator $\langle I(x,y,t)\rangle_{(y,t)}$, left axis, and of the curvature drive g, right axis*

The reduction of the transport barrier width due to turbulence spreading is observed also when the barrier is generated by an external bias. Moreover, the plasma response produces a further shearing of electric potential on small regions on the two sides of the barrier where the turbulent transport is thus reduced. In Fig. 2, left panel, this effect can be observed on $\langle I(x,y,t)\rangle_{(y,t)}$ that is the poloidally and time averaged ratio between the

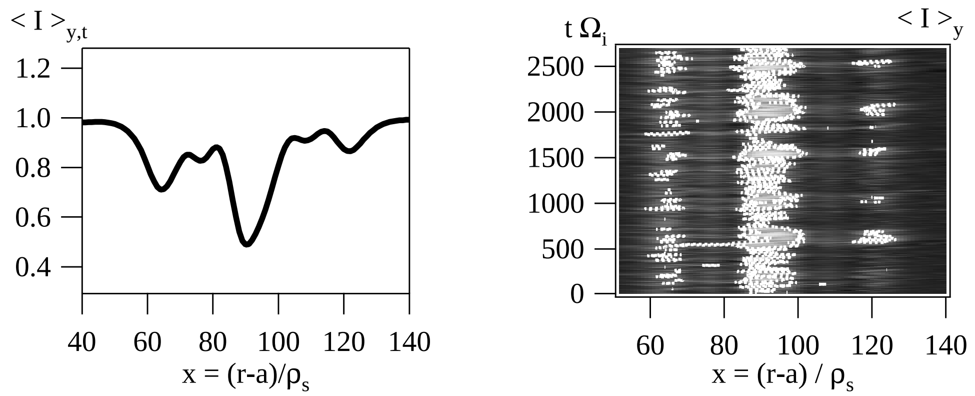

Figure 2: *Left panel: Radial profile of the mean turbulence indicator* $\langle I(x,y,t)\rangle_{(y,t)}$. *Turbulent transport is reduced in the central region by an external bias but also on the two sides of this region where the plasma response causes a less intense but still efficient shearing of the electric potential. Right panel: 2D map of* $\langle I(x,y,t)\rangle_{(y)}$ *function of time (y-axis) and radial position (x-axis). The contour* $\langle I(x,y,t)\rangle_{(y)} = 0.5$ *is indicated by dotted lines.*

radial turbulent flux and the total radial flux. If only the poloidal average is performed, this ratio will depend also from time and gives insight on the dynamics of the barrier, its width vs time, its boundary and shape fluctuations. As expected, due to the intermittent nature of the turbulent transport, intermittent variations of the barrier width are observed (Fig. 2, right panel). When the magnitude of the turbulence is large enough, the larger events can cross the transport barrier thus bridging the edge to the core region. The modification of the plasma potential governed by such events is then large enough to modify the structure of the transport barrier leading to long transients where the biasing potential is balanced by the plasma potential thus suppressing the stabilising effect of the external drive.

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