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Transport barriers and ELM's in flute mode turbulence

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The main cross-field transport in hot magnetized plasmas is anomalous, e.g., not diffusive, and ascribed to low frequency electrostatic fluctuations. It is generally recognized that self-consistently developing large scale poloidal - or zonal - flows strongly reduce the radial turbulent transport by "quenching" the turbulence. This mechanism is one of the main candidates for the rapid transition to an enhanced plasma confinement in toroidal devices, e.g., the H-mode regime [1]. This quiescent mode is often found to be intermittently disrupted by bursts in the transport, the so-called edge localized modes (ELM).

We consider the evolution and dynamics of transport barriers, in the form of zonal flows, and their interplay with the turbulent transport. An intermittent behaviour with very strong burst events is revealed. We employ a self-consistent model for pressure driven electrostatic turbulence of a plasma in an inhomogeneous, curved magnetic field [2]. This is a model of the outboard side of a toroidal confinement device. It captures the effects of unfavourable curvature in an energy preserving manner and describes consistently the evolution of profiles as well as fluctuations. Turbulence is sustained by a heat flux entering the system from the hot inside and leaving at the cold outside.

The normalized equations read:

$$\frac{\partial n}{\partial t} + \{\phi, n\} + \mathcal{K}(n + T - \phi) = \nu \nabla^2 n \,, \tag{1}$$

$$\frac{\partial T}{\partial t} + \{\phi, T\} + \frac{2}{3}\mathcal{K}(n + \frac{7}{2}T - \phi) = \kappa \nabla^2 T \,, \tag{2}$$

$$\frac{\partial \nabla^2 \phi}{\partial t} + \left\{\phi, \nabla^2 \phi\right\} + \mathcal{K}(n + T) = \mu \nabla^4 \phi \,. \tag{3}$$

Here $\{f,g\} = (\partial f/\partial x)(\partial g/\partial y) - (\partial f/\partial x)(\partial g/\partial y)$. The curvature operator, $\mathcal{K}$ simplifies for the slab configuration to $\mathcal{K}(f) = \omega_B \partial f/\partial y$, where $\omega_B = 2\rho/R_0$. Here $\rho = (\mathcal{T}/m_i)^{1/2}/\omega_{ci}$ is the spatial scale and R_0 the major radius.

In the in-viscid limit the equations possess Lagrangian invariants $l_\pm = \pm\sqrt{5/2}(n - B) + 3T/2 - n$, advected by the velocities $\mathbf{v}_\pm = \hat{z} \times \nabla[\phi - n - (1 \pm (5/2)^{1/2})T]$. A local linear stability analysis for equilibrium gradients in the x-direction, recovers the Rayleigh-Taylor instability when the pressure profile is steeper than $5B/3$ [2]. The growth rate in the long wave limit is $\gamma = k_y\sqrt{|N|}/K$, where k is the wave number and k_y its y-component, and $N \equiv \omega_B(n_0' + T_0' + \frac{5}{3}\omega_B)$ is the "buoyancy" frequency.

The model is solved numerically on a two-dimensional domain: bounded in x (radial coordinate) with length L_x and periodic in y (poloidal coordinate) with length L_y. The dissipation coefficients, ν, κ, μ were chosen equal ($= 10^{-3}$, typically). The turbulence is driven by an imposed temperature difference between the walls, using the boundary conditions $T|_{x=0} = T_0$ and $T|_{x=L_x} = 0$. The diffusive particle flux at the walls was set to zero by prescribing $\partial_x n|_{x=0,\,L_x} = 0$, and the potential ϕ was kept constant at the walls.

We performed runs for various values of the different parameters of the system. When T_0 is sufficiently large to drive the instability we observe the following general scenarios.

(i) For sufficiently large aspect ratio $\alpha \equiv L_y/L_x > \alpha_c$ (for $\mu = 10^{-3}$, $\alpha_c \approx 3.8$) the system develops into the socalled TEP-state [2], which corresponds to uniform mixing of the lagrangian invariants, $l_\pm$. In this case $n - B \approx const$ and $T - 2/3B \approx const$ regardless of the value of T_0, demonstrating profile consistency and resilience. There is a radial, turbulent heat flux, which is persistent but intermittent. This is the "L-mode" with flattened pressure gradient.
(ii) For smaller α a different behaviour is observed. In an initial phase the turbulence develops and establishes the TEP profiles with a high flux-level. Later on, the flux is interrupted, and for long periods the system is very quiescent, as seen in Figs. 1a) and 1b). This is the "H-mode" with steep averaged pressure gradient. However, sporadic bursts of flux are observed to occur with somewhat random intervals. The time scale of the quiescent periods between the burst is related to the viscous time scale. Increasing the viscosity we observe that the time intervals between the bursts decreases almost proportionally to μ^{-1}, as illustrated in Fig. 1b).

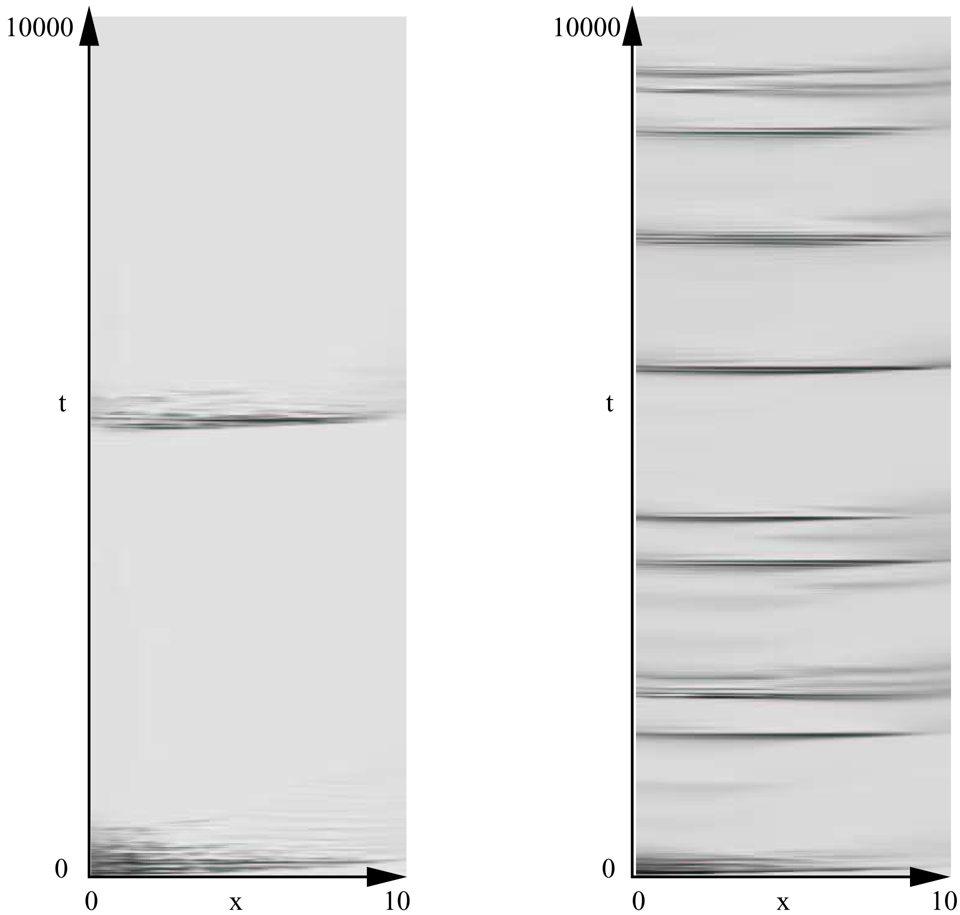

Figure 1: Poloidally averaged heat flux $\Gamma_T =< uT >$ versus (x, t) for aspect ratio $\alpha = L_y/L_x = 1$ and dissipation coefficients $\nu = \kappa = \mu = 10^{-3}$ (left frame) and 10^{-2} (right frame). The colour-scale is from -0.2 (light) to 0.5 (dark).

The quiescent periods are associated with the establishment of a strong poloidal mean flow - the zonal flow. This flow, which is strongly sheared and often only develops in a part of the domain, quenches the turbulence and acts as an effective barrier for transport and mixing. As there is no longer sufficient mixing by the turbulence to maintain the TEP profiles they start to steepen via the diffusive inflow of heat from the heated boundary. The zonal flow decays due to viscosity if the turbulence is quenched. This is seen from the equation for the evolution of the zonal velocity $V =< v >$:

$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial x} < uv > +\mu \frac{\partial^2}{\partial x^2} V \,, \tag{4}$$

where u, v are the radial and poloidal velocity components, respectively. The Reynolds-stress $R_{uv} =< uv >$ is related to the turbulence level. Thus, when the turbulence is quenched the flow is no longer sustained. After it has decayed sufficiently and the pressure gradient has built up, the basic instability may develop again, resulting in a strong burst of turbulence and heat flux. If the viscosity is larger, the zonal flow decays faster, and the turbulent bursts are therefore more frequent, as in Fig. 1b). Note that the linear growth rate of the Rayleigh-Taylor instability for the present parameters is on the order of 0.1; which explains the fast growth of the turbulence. This leads to a burst in the heat flux and an associated flattening of the temperature profile. The flux is first established near the heated wall and the onset of the flux propagates outwards as a sharp front accompanied by changes in the temperature profile. Again a zonal flow builds up, quenches the turbulence and the heat flux. The scenario then repeats.
We further note that a recent analysis by Benilov et al [3], demonstrates that an induced shear flow stabilizes the larger wave numbers of the RTI instability of an inversely stratified fluid. This implies that for a given aspect ratio, the shear flow may stabilize all modes allowed by the geometry $k > 2\pi/L_y$. This main explain the long quiescent periods - the H-mode - with the steep gradients that we observe for $\alpha < \alpha_c$.
In Fig. 2 we have examined the behaviour of the temperature and the vorticity during a strong flux event. For this case we have introduced a damping term on all the fields in the form δf, which is linearly increasing in the radial direction and acting in the outer 1/3 part of the domain. These terms serve as a model of the Scrape Off Layer (SOL). In Fig. 2 we observe very strong localized structures of temperature perturbations propagating outward through the "SOL". These temperature structures are accompanied by vorticity perturbations that takes the form of vortex dipolar structures propagating outward, with a velocity set by the vorticity in the dipolar vortex. The structures "survive" the damping in the "SOL" and they will represent a significant heat load on the divertor plates. These structures seems to be similar to the so-called "avaloids" or "IPO's" (Intermittent plasma objects) recently observed in the edge region of toroidal devices, e.g., the DIII-D tokamak [4].

In conclusion, we have shown that the nonlinear evolution of pressure driven turbulence in an inhomogeneous magnetic field depends strongly on the aspect ratio. We consider this as a crude but self-consistent and fully nonlinear model for turbulence on the outboard side of toroidal magnetic confinement devices. The aspect ratio in our model reflects that when moving poloidally one will cross the same magnetic field line after some distance L. This sets an effective poloidal periodicity length assuming perfect correlation along magnetic field lines. For low aspect ratio, which would correspond to either high irrational q or q values close to rational ones, the evolution is characterized by long lasting quiescent H-mode periods with the turbulent transport suppressed by a zonal shear flow that acts as a transport barrier. These periods are separated by short violent flux bursts (ELM) during which the zonal flow breaks down.

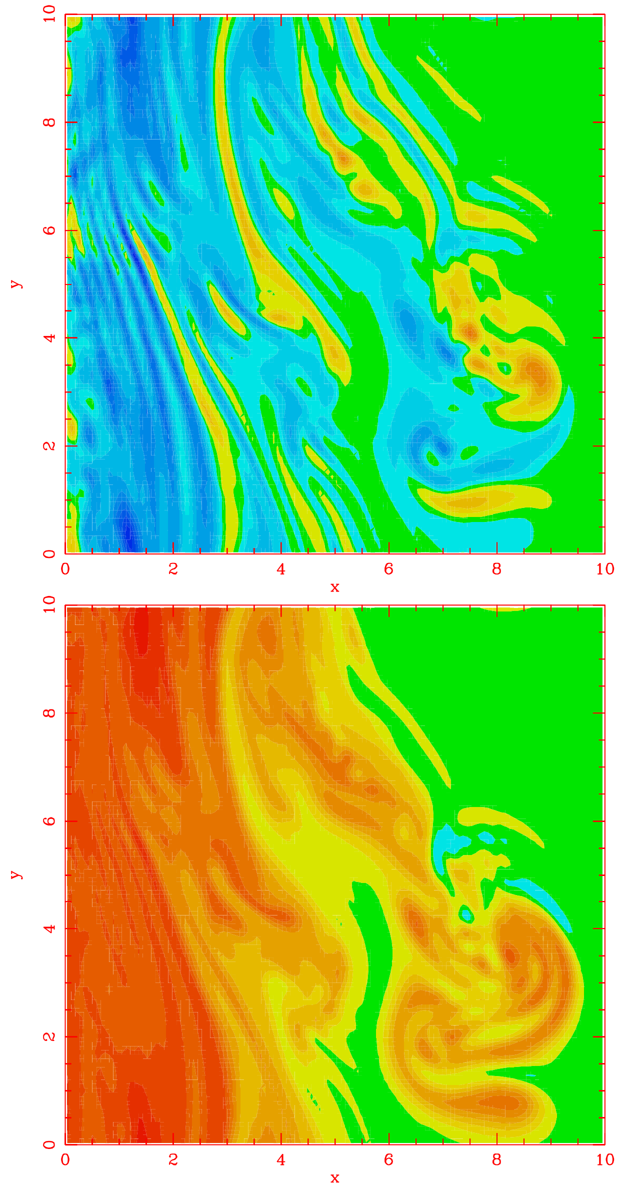

Figure 2: The vorticity (top frame) and the temperature (bottom frame) during a strong flux event for $\alpha = 2$ and $\mu = 10^{-3}$. The system is heated at the left boundary and a linearily increasing damping layer is introduced in the rightmost third of the domain. Red corresponds to positive values, while blue is negative.

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