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ELECTROSTATIC TURBULENCE & TRANSPORT IN EDGE PLASMAS: BURSTS & ZONAL FLOWS, STOCHASTIC FIELD LINES, TRANSPORT BARRIERS

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Abstract. Turbulent transport at the edge of a tokamak plasma is characterized by the formation of two types of structures. The first are related to large scale radial transport events (bursts), the second are fluctuations of the poloidal velocity (zonal flows) that regulate transport events. These structures and their dynamics and interplay are studied by 3D numerical simulations of resistive ballooning turbulence. Additionally, a layer of stochastic magnetic field lines is considered where sheared poloidal flows are found to be strongly reduced and long lived eddies appear. As a consequence, the level of convective flux associated with fluctuations is not quenched by the magnetic field perturbation. Finally, the dynamics of transport barriers, generated by externally imposed shear flows is studied. They are found to be intermittently eroded by successions of large bursts, leading to relaxation oscillations of the barrier.

Introduction. It has been observed now in many different turbulence simulations [1, 2, 3, 4, 5] dealing with a variety of instabilities in different radial locations of a tokamak plasma, that electrostatic turbulence and associated transport are governed by the interplay between two types of structures. The first concern large scale radial transport events or "bursts" that are related to radially elongated convection cells called "streamers". The latter can appear due to a non-linear process when smaller eddies, moving arbitrarily in the turbulent velocity field, line up to form an elongated cell. Streamers give rise to ballistic transport events corresponding to radially propagating deformations of the density, temperature, and/or pressure profile. Such events are also interpreted in terms of "avalanches" [6] and studied in models including self organized criticality [7] or front dynamics [8]. The second structure playing an important role in self-organized turbulence are fluctuations of the poloidal velocity related to poloidally elongated convection cells called "zonal flows" [9, 10]. These flows are known to be stabilizing and are indeed found to regulate transport events. There are also some experimental evidences for the appearance of bursts [11, 12, 13, 14] and zonal flows [15, 16]. In this paper, we present results from 3D fluid simulations of resistive ballooning modes at the plasma edge.

Additionally, the impact of static magnetic field perturbations on electrostatic turbulence and transport is studied. The interest on this topic is twofold: First, the behavior of turbulent cross field transport in regions of stochastic magnetic field lines is highly important for the performance of ergodic divertors [17] as well as many other experimental situations such as the stochastic boundary of stellarators and transport in the vicinity of the separatrix of standard tokamak divertors. Second, the model of turbulence in the presence of magnetic field perturbations allows to study transport and poloidal flow modification due to the so called magnetic flutter [18, 19]. Experimental observations of density fluctuations on TEXT [20] and Tore Supra [21, 22] with ergodic divertor show a decrease of the fluctuation level and a stabilization of large scale structures in the stochastic region. Surprisingly, there is no evidence of a change of the turbulent cross field diffusivity [17, 23]. Furthermore, large scale transport events are expected to be affected not only directly by the shearing due to the magnetic field perturbation but also indirectly due to modifications of poloidal mean and zonal flows in the stochastic layer. These are in fact found to be competing effects.

Finally, transport barriers and their interplay with bursts are studied. These barriers play an important role in improved confinement regimes. They are associated with localized $E \times B$ velocity shear and/or zero magnetic shear. Here, a transport barrier is generated by an externally imposed strong velocity shear. The behavior of bursts in the presence of the barrier and the dynamics of the latter due to an intermittent erosion by bursts are then studied.

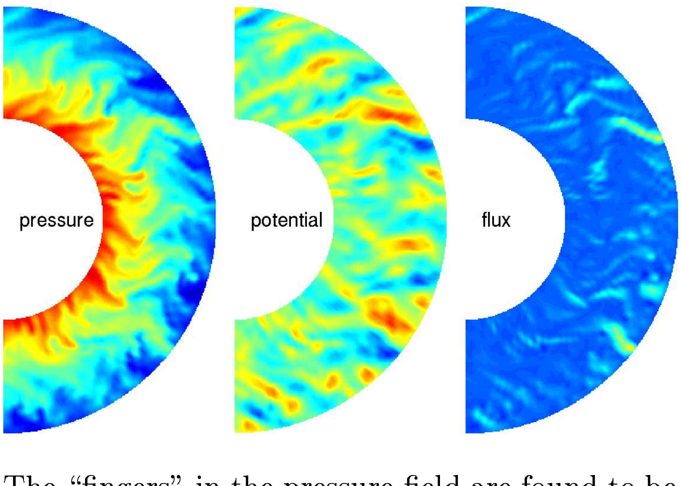
Model for resistive ballooning turbulence. The model consists of reduced resistive MHD equations for the complete fields of electrostatic potential ϕ and pressure p,

$$(\partial_t + \vec{v}_E \cdot \nabla)\, \nabla_\perp^2 \phi = -\nabla_{||}^2 \phi - Gp + \nu \nabla_\perp^4 \phi \;, \qquad (1)$$

$$(\partial_t + \vec{v}_E \cdot \nabla)\, p = \delta_c G\phi + \chi_{||} \nabla_{||}^2 p + \chi_\perp \nabla_\perp^2 p + S(r) \;, \qquad (2)$$

where $\vec{v}_E$ is the $E \times B$ drift, turbulence is driven by a constant incoming flux $\Gamma_{tot} = \int S\,\mathrm{d}r$, and the operator $G = \sin\theta\,\partial_r + \cos\theta\,\frac{1}{r}\partial_\theta$ accounts for the compressibility of diamagnetic current and $E \times B$ drift due to toroidal magnetic curvature. Diamagnetic drift is neglected with respect to $\vec{v}_E$ and no (self-consistent) magnetic fluctuations are included. The (unperturbed) magnetic field is written as $\vec{B}_0 = B_\varphi(\hat{e}_\varphi + \frac{r}{Rq}\hat{e}_\theta)$ in toroidal coordinates and the inverse of the safety factor q is linearly approximated at the vicinity of a reference surface $r = r_0$ at the plasma edge. Our computational domain covers the region between $q = 2$ and $q = 3$ and a slab geometry is introduced at the vicinity of $r_0 = r_{q=2.5}$. Finally, all quantities are suitably normalized [24]. The parameters ν, $\chi_{||}$, $\chi_\perp$, δ_c correspond to the collisional viscosity, parallel and perpendicular heat conductivity, and the ratio between a reference pressure gradient length and the large radius R, respectively.

Bursts & Zonal Flows. In a statistically stationary state, series of snapshots of pressure show localized regions of high pressure propagating radially outwards and regions of low pressure extending to the inner boundary of the computational domain. These intermittently appearing "fingers" corresponding both to events of positive radial flux, connect the inner and outer regions of the plasma over large radial distances (Fig. 1, left). The propagation can be visualized in plots of poloidally and toroidally averaged pressure or flux versus radius and time [4, 25]. When such an event appears, a large, radially elongated convection cell can be observed in the potential field (Fig. 1) which has been created by percolation of smaller, symmetric eddies.



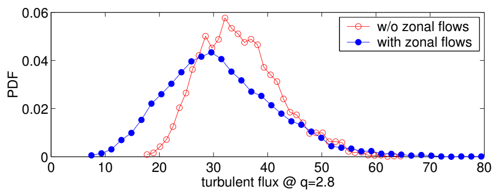
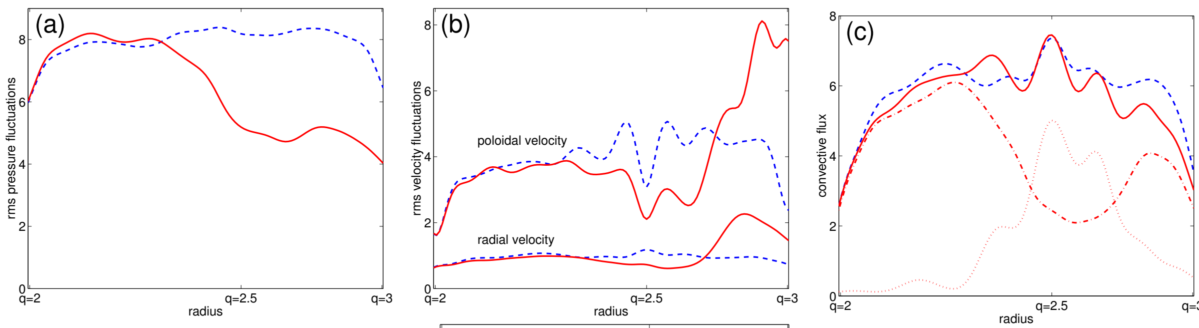


Fig. 1: (left) Snapshot of pressure, potential fluctuations and radial flux at the low field side of a poloidal cross section. The annulus has been stretched radially by a factor of 4. (up) Probability distribution functions of the turbulent flux at the radial position $r = r_{q=2.8}$.

The "fingers" in the pressure field are found to be distorted by zonal flows. In fact, when artificially suppressing mean and zonal flows, less small events and more large burst are observed. More precisely, a comparison of the probability distribution functions (PDFs) of the turbulent flux at a given radial position (Fig. 1, up) shows that the maximum of the curve is shifted to lower values and the PDF gets broader when zonal flows are included self consistently. This corresponds to an increase of small events and a reduction of a significant part of large bursts (for a turbulent flux between 30 and 45 in Fig. 1) due to zonal flows. This observation is qualitatively the same for all radial positions [25].

Stochastic Magnetic Field Lines. A perturbation is added to the magnetic field $\vec{B} = \vec{B}_0 + \nabla\delta\psi \times \hat{e}_\varphi$ where $\delta\psi$ represents a sum of different poloidal harmonics corresponding to overlapping island chains. The amplitude of $\delta\psi$ increases exponentially with radius and field lines become ergodic in the radial domain $q > 2.7$. The effect of such a perturbation on electrostatic fluctuations and associated transport is found to be threefold: First, non vanishing time averages of the fields of pressure and potential are observed that vary poloidally and toroidally and give rise to a positive convective flux. This is due to the appearance of long-lived stationary eddies. Second, time varying pressure fluctuations decrease (Fig. 2a) but velocity fluctuations tend to increase (Fig. 2b) especially in the region of strong magnetic perturbation (close to $q = 3$) where the stationary eddies are intermittently destroyed by a secondary instability. In total, this leads to a roughly unchanged convective flux due to fluctuations (Fig. 2c). Third, the mean plasma flow is suppressed (Fig. 2d) and zonal flows are strongly reduced (Fig. 2e) by an anomalous friction in the stochastic region. This effect, as well as the existence of long-lived eddies providing natural "channels" for the propagation of bursts, is beneficial for the appearance of large bursts that can be observed even in the stochastic layer [26].



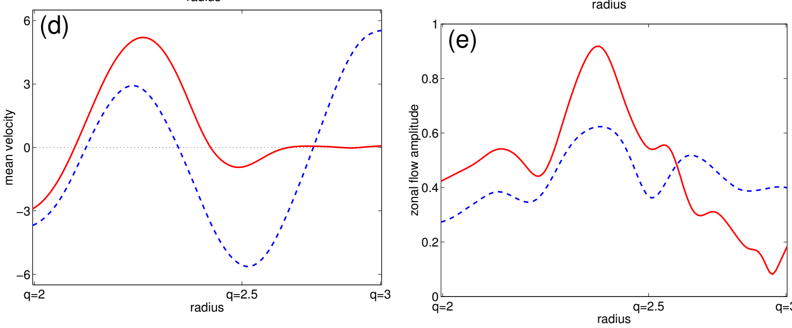


Fig. 2: Radial profiles of pressure (a) & velocity fluctuations (b), radial flux due to fluctuations (c), mean poloidal velocity (d), and zonal flows (e). Full red lines correspond to a simulation with magnetic field perturbation, dashed blue lines indicate a reference case without perturbation. In (c), the dashed dotted and dotted lines indicate the components due to long-lived stationary eddies and turbulent fluctuations, respectively.

Dynamics of Transport Barriers. Transport barriers are generated in our model by externally imposing a strong localized shear flow v_0. This is done by adding a driving term to the poloidally and toroidally averaged equation (1) which in fact is the equation governing the dynamics of the mean poloidal flow $\bar{v}_\theta = \partial_r\bar{\phi}$:

$$\partial_t\bar{v}_\theta + \partial_r\langle\tilde{v}_r\tilde{v}_\theta\rangle = \nu\partial_r^2\bar{v}_\theta - \mu\left(\bar{v}_\theta - v_0\right) \ . \tag{3}$$

The characteristic time scale μ^{-1} of the additional friction is chosen small compared to the viscous time scale $(\nu\sigma^2)^{-1}$ (where σ is the width of the shear layer) and to a characteristic non linear time of the fluctuations $\tilde{v}_r$, $\tilde{v}_\theta$. In this case, $\bar{v}_\theta$ relaxes rapidly to the imposed flow v_0 and time variations due to the Reynolds stress are negligible. It has been checked that for lower values of μ, where these variations of $\bar{v}_\theta$ become significant, the results do not change qualitatively. In the shear layer, the mean turbulent flux is found to be significantly reduced and the pressure profile steepens, i.e. a barrier forms. For strong velocity shear, relaxation oscillations of the barrier can be observed (Fig. 3): The pressure on the inner side of the barrier grows slowly during quiet phases that alternate with intermittent fast relaxation events. During quiet phases (for times typically of the order of the confinement time) low frequency components of the turbulent flux are strongly reduced and bursts are suppressed in the center of the barrier. During a relaxation event, the barrier is found to be eroded by a succession of large bursts.

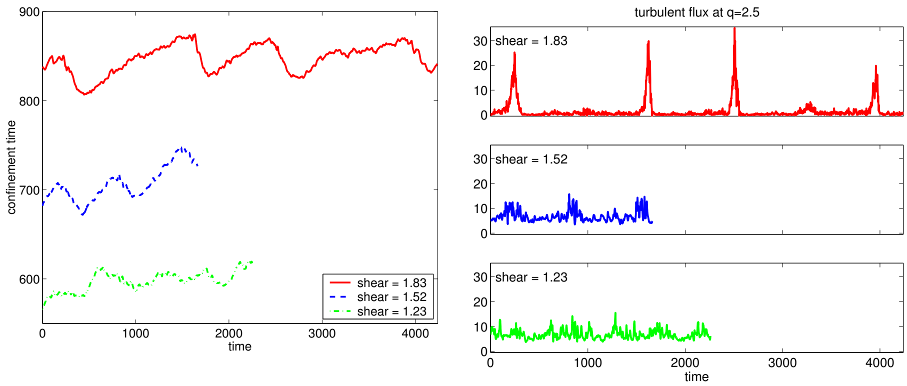


Fig. 3: Time evolution of the confinement time (left) and the turbulent flux at the center of the barrier (right) for three different values of the maximal velocity shear.

Conclusions. Turbulent transport is characterized by the interplay between large scale transport events and zonal flows. In a layer of stochastic magnetic field lines, transport associated to fluctuations is not quenched despite a lower level of turbulent pressure. Mean flows are suppressed and zonal flows are strongly reduced due to an anomalous friction. Transport barriers generated by a strong velocity shear exhibit relaxation oscillations where bursts do not cross the barrier during quiet phases but the latter is intermittently eroded by successions of large bursts.

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