Electrostatic Turbulence and Transport with Stochastic Magnetic Field Lines

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Abstract. Electrostatic turbulence, associated convective transport and sheared flows at the edge of a tokamak plasma are strongly affected by magnetic perturbations with field line stochastization. Results from three dimensional numerical simulations of flux driven resistive ballooning turbulence are presented showing that (a) the level of convective flux associated with fluctuations is not quenched by the magnetic field perturbation despite a reduced pressure fluctuation level and (b) the poloidal plasma rotation is suppressed and zonal flows are reduced by an anomalous friction due to stochasticity. This inhibits the self regulation mechanism of large scale transport events and bursts are found to resist the magnetic perturbation.

1. Introduction

The impact of magnetic perturbations on electrostatic fluctuations and associated transport is an important issue for plasma confinement. The interest in this topic is twofold. First, it represents one part of the complete problem of electromagnetic turbulence and transport. Second, it applies to the interpretation and prediction of confinement with stochastic boundaries in fusion devices, e.g. ergodic divertors in tokamaks.

Some indications about the influence of magnetic perturbations on turbulence are available from simulations and theory of electromagnetic turbulence as well as from experiments. Numerical simulations assuming scale separability between fluctuations and background gradients show a stabilizing effect of magnetic perturbations due to the magnetic flutter [1]. Analytical investigations predict a reduction of zonal flows due to competition of the Reynolds and Maxwell stresses [2]. Experimental observations on TEXT [3] and Tore Supra [4, 5] in the ergodic divertor configuration show a decrease of density fluctuations in a region of stochastic magnetic field lines due to a stabilization of large scale structures. Surprisingly, there is no evidence of a reduced cross field diffusivity [6, 7] which is a beneficial effect as it keeps large the heat deposition patterns on the first wall elements.

In general, the scale separation assumption between fluctuations and profiles is not valid and turbulent transport is known now to be characterized by the interplay between large scale transport events and self-generated sheared mean and zonal flows [8, 9, 10, 11, 12, 13, 14]. In this work, three dimensional numerical simulations of resistive ballooning turbulence at the plasma edge are performed, driving the system by a constant incoming energy flux and allowing for a self consistent evolution of the profiles of pressure and electrostatic potential (and associated ExB velocity). It is found that convective transport associated with electrostatic fluctuations is not quenched by magnetic perturbations despite a reduction of pressure fluctuations. Furthermore, sheared plasma rotation is suppressed and zonal flows are reduced by a anomalous friction due to magnetic stochasticity. This mechanism is different from the Maxwell stress mentioned above. A direct consequence is the inhibition of the self-regulation mechanism of large scale transport events so that radially propagating bursts can resist the magnetic perturbation.

2. Characterization of Turbulent Transport

Let us first present results concerning turbulent transport in the absence of magnetic perturbations. The latter is found to be characterized by radially propagating bursts, regulated by self-generated sheared mean and zonal flows. Fig. 1a shows a snapshot of the pressure distribution in a poloidal plane. On the low field side (right part of the annulus), bursts can be observed that connect the high pressure region on the inner side with the low pressure region on the outer side of the annulus. A detailed analysis of the temporal behavior of such bursts reveals that they appear intermittently and propagate radially over large distances, transporting high pressure from the inner to the outer region or low pressure in the opposite direction. In Fig. 1a one recognizes that these events have a distorted shape. This is due to the self consistently generated sheared rotation of the plasma, indicated by arrows in Fig. 1a. The resulting adjacent zones of clockwise and counter-clockwise rotation lead to a distortion of the bursts. This can be demonstrated by a second simulation where sheared mean and zonal flows are artificially suppressed. In this case, a straight radial propagation of large bursts can be observed (Fig. 1b).

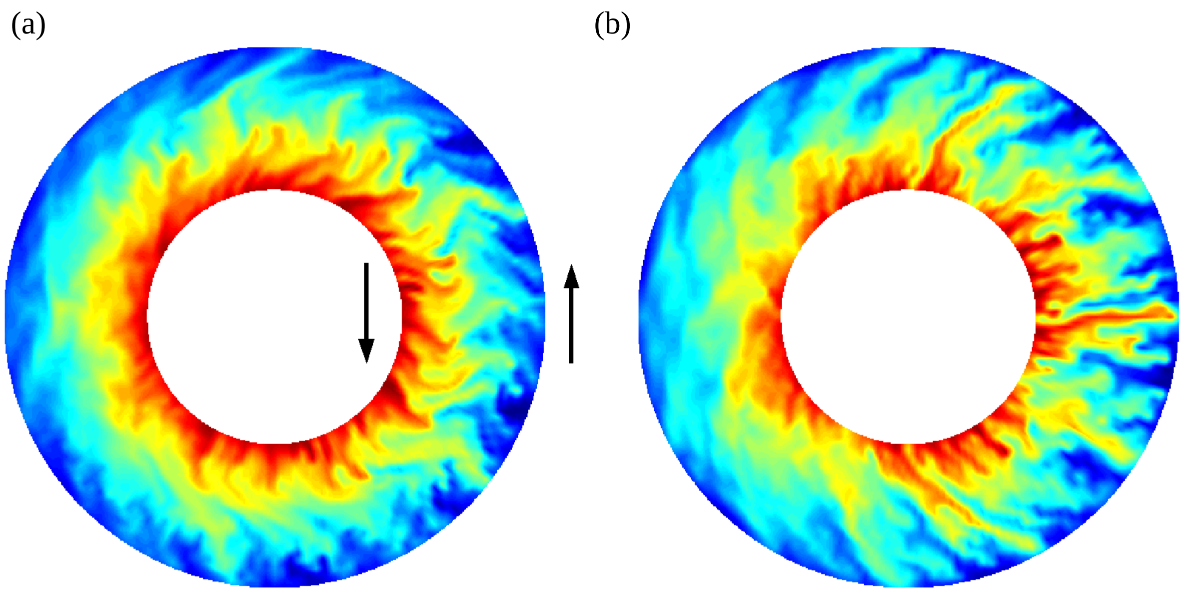


FIG. 1. Snapshots of pressure in a poloidal plane, the annuli represent the simulation region at the plasma edge, the plasma center is not simulated (but replaced by a constant energy source). In (a), the self consistent evolution of sheared mean and zonal flows is included in the simulation, in (b), these flows are artificially suppressed.

The regulation of radially propagating bursts by sheared flows can be quantified by comparing probability distribution functions (PDFs) and frequency spectra of the flux fluctuations in the self consistent case and in the case where flows are artificially suppressed. As can be seen from Fig. 2a, the curve of the PDF is broadened and shifted to lower fluxes when self consistent sheared mean and zonal flows are included. This results in a significant reduction of a large part of high flux events (for amplitudes of the turbulent flux roughly between 25 and 45 in Fig.

2a). The energy is evacuated by lower amplitude bursts that are fluctuating more rapidly, as can be seen from the comparison of the frequency spectra (Fig. 2b).

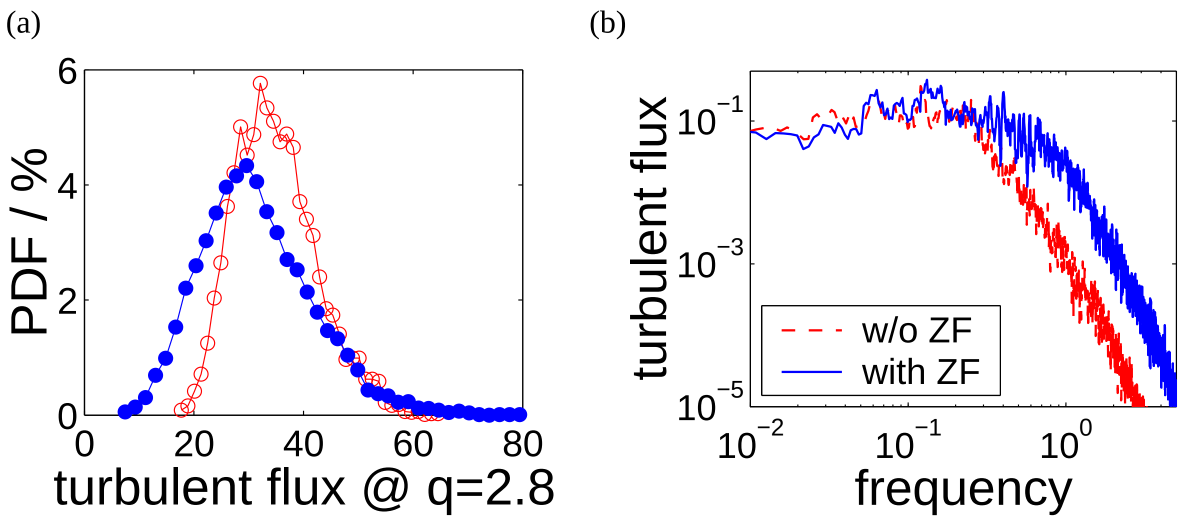


FIG. 2. Probability distribution functions (PDFs) (a) and frequency spectra (b) of the turbulent flux at a given radial position. In blue, the case with self consistent mean and zonal flows, and in red, the case where these flows are artificially suppressed.

3. Magnetic Field Perturbation

A perturbation $\delta\vec{B}$ is now added to the magnetic field which is given by

$$\vec{B} = B_\varphi \left(\hat{e}_\varphi + \frac{r}{Rq} \hat{e}_\theta \right) + \delta\vec{B}$$

in toroidal coordinates (r, θ, φ). R is the major radius, and the safety factor q is chosen to increase monotonically with minor radius r. The perturbation $\delta\vec{B}$ is written as a superposition of poloidal harmonics with mode numbers m,

$$\delta\vec{B} = \sum_m \vec{b}_m(r) \cos(m\theta - \bar{n}\varphi) \ ,$$

where $\bar{n}$ is the (fixed) toroidal mode number of the perturbation. Each harmonic m generates a chain of magnetic islands at the radial position where $q(r) = m/\bar{n}$, and for sufficiently high amplitudes $\vec{b}_m$, the radial overlapping of these islands leads to a stochastization of the magnetic field lines.

The radial profile of the perturbation is shown in Fig. 3, its amplitude is increasing with radius and reaches its maximum at the right boundary of the computational domain ($r = r_{q=3}$). At this position, the Chirikov overlapping parameter σ_{Chir} [15] reaches a value of 3. The onset of stochasticity ($\sigma_{Chir} = 1$) is located close to $r = r_{q=2.35}$, and field lines are highly stochastic with $\sigma_{Chir} > 2$ in the radial domain $r > r_{q=2.6}$. The details of the model are given in Refs. [16] and [17].

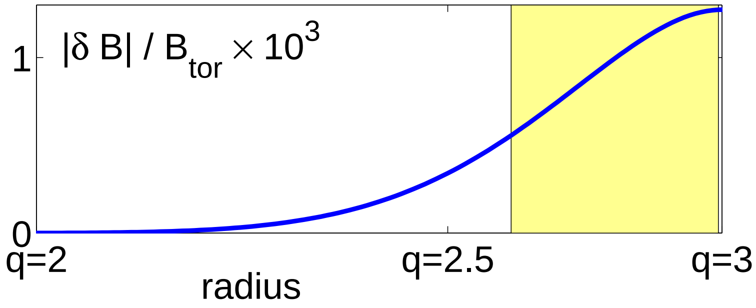
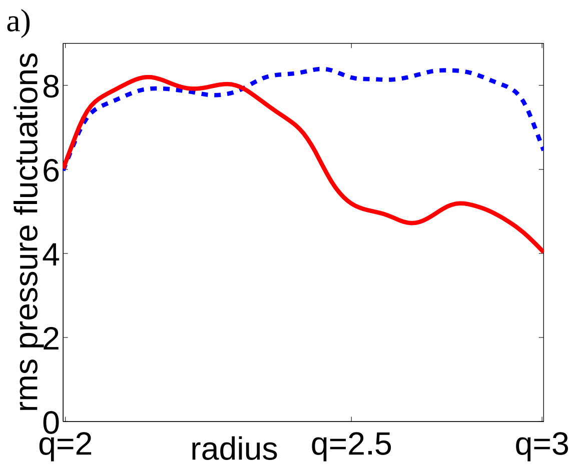
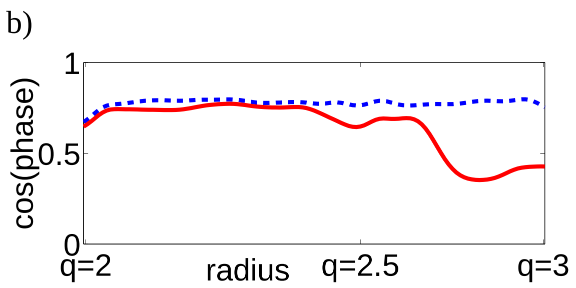


FIG. 3. Radial profile of the amplitude of the magnetic field perturbation. Field lines are highly stochastic in the region between $q = 2.6$ *and* $q = 3$ *(shaded).*

Two implications of the magnetic perturbation are directly visible in the model equations. First, transport parallel to the perturbed field now has a component perpendicular to the unperturbed field, i.e. down the pressure gradient. Second, an additional term appears in the equation governing the generation of mean and zonal flows. As will be shown in the following, this term plays the role of an anomalous friction due to stochasticity.

4. Impact of Magnetic Perturbations on Fluctuations





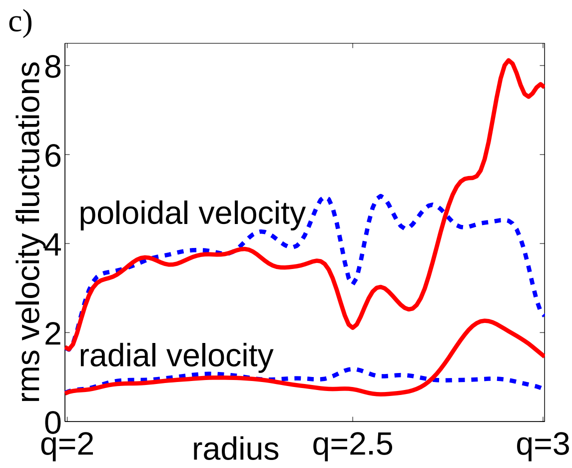


FIG. 4. Radial profiles of the amplitude of pressure fluctuations (a), the cosine of the cross phase between pressure and radial velocity fluctuations (b), and the amplitude of velocity fluctuations (c). The full red lines correspond to the case with magnetic perturbation, the dashed blue lines indicate a reference case without perturbation.

In the radial domain where magnetic perturbations are significant, a strong reduction of pressure fluctuations is observed (Fig. 4a). The cosine of the cross phase between pressure and velocity fluctuations is also decreasing (Fig. 4b), indicating a decorrelation of these fluctuations in the perturbed region. From these two elements, one expects a strong reduction of turbulent transport which is given by the product of the pressure and velocity fluctuation amplitudes and the cosine of the cross phase. However, it is found that velocity fluctuations can increase in the stochastic layer (Fig. 4c).

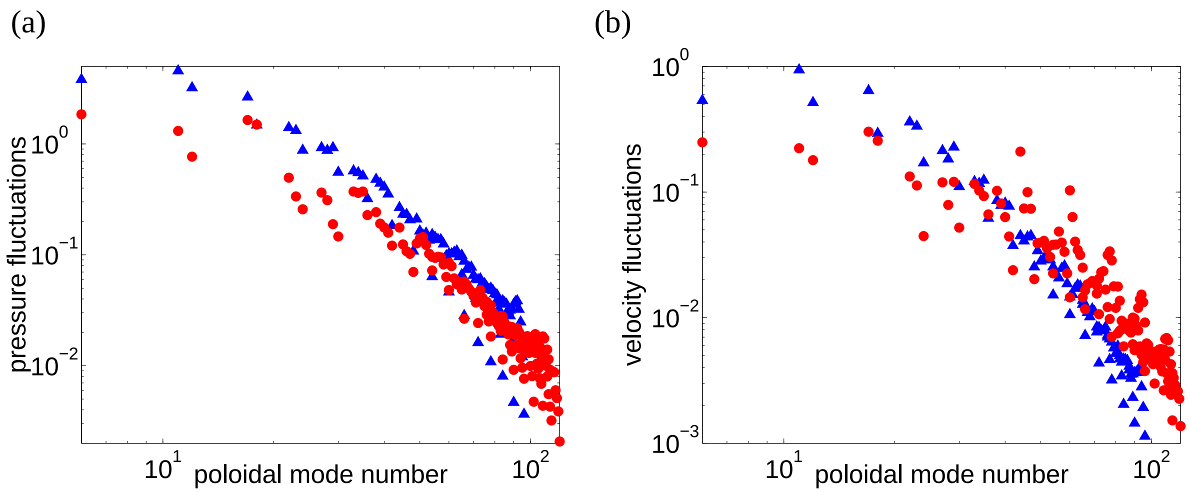


FIG. 5. Poloidal wave number spectra of pressure fluctuations (a) and velocity fluctuations (b) in the perturbed region between $q = 2.7$ and $q = 3$. The red points correspond to the case with magnetic perturbation, the blue triangles indicate a reference case without perturbation.

When looking at the poloidal wavenumber spectra, it gets clear that the reduction of pressure fluctuations comes from a stabilization of large scale structures corresponding to the low m contributions in Fig. 5a (except for $m = 17, 18$, see below). This is in agreement with density fluctuation measurements on TEXT [3] and Tore Supra [4, 5] when one assumes that pressure fluctuations in our model follow density fluctuations. The same is true for velocity fluctuations, but additionally, small scale (large m) velocity fluctuations tend to increase (Fig. 5b).

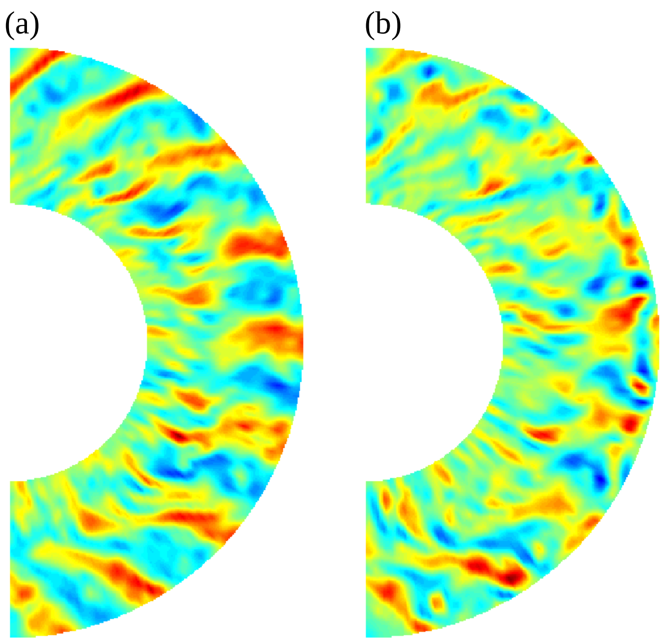


FIG. 6. Snapshots of potential on the low field side of a poloidal plane at two different time slices.

More insight into this behavior can be obtained from snapshots of potential fluctuations in a poloidal plane (Fig. 6). At a given time, the appearance of stationary eddies can be observed (Fig. 6a). These eddies are in resonance with one of the largest components of the magnetic perturbation, which explains the local peak at $m = 17, 18$ of the fluctuation spectra in Fig. 5. The stationary eddies turn out to be unstable with respect to a secondary instability that temporarily destroys these structures and generates fluctuations of a much smaller scale (Fig. 6b). These appear essentially in the radial domain close to $r = r_{q=3}$ which is highly stochastic. The fluctuations associated with these small scales then lead to an increase of velocity fluctuations in the stochastic region.

4. Impact of Magnetic Perturbations on Transport

The total effect on transport of the different modifications of electrostatic fluctuations is such that the convective flux associated to these fluctuations is not quenched by the magnetic perturbation. This can be seen in Fig. 7, showing that the amplitude of the total convective flux is close to the one in the reference case without perturbation. The total convective flux can be decomposed into two parts. The first corresponds to stationary eddies and is important in the region of onset of stochasticity. The second part is associated with turbulent fluctuations. It decreases when stationary eddies appear but increases when enhanced velocity fluctuations develop due to the secondary instability in the stochastic region.

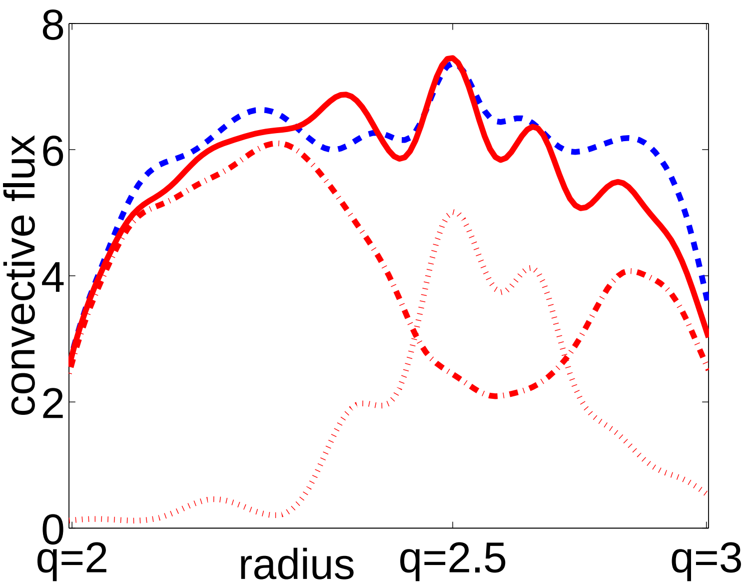


FIG. 7. Radial profiles of the total convective flux with magnetic perturbation (full red) and the parts corresponding to stationary eddies (dotted red) and turbulent fluctuations (dash dotted red). The flux in the reference case without perturbation is indicated by a dashed blue line.

Even if the level of convective flux is not quenched by the magnetic perturbation, the dynamics of radially propagating bursts and sheared flows is found to be modified significantly. In fact, the mean poloidal rotation of the plasma is completely suppressed in the perturbed region (Fig. 8a), and the amplitude of zonal flows is strongly reduced (Fig. 8b) by an anomalous friction due to stochasticity.

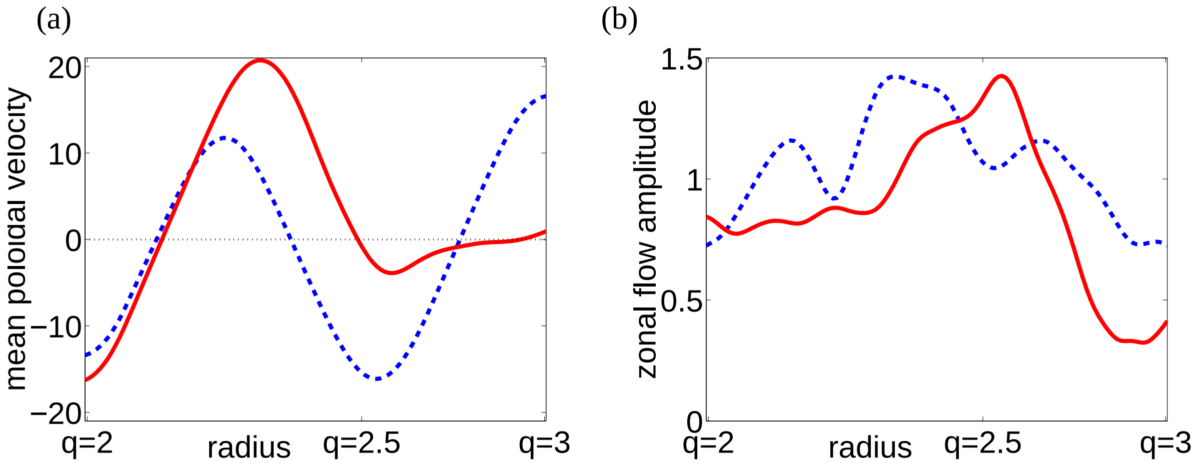


FIG. 8. Radial profiles of the mean poloidal velocity (a) and zonal flow amplitudes (b) for the case with magnetic perturbation (full red) and the reference case without perturbation (dashed blue).

From the discussion in Section 2, this modification of sheared flows is expected to have a strong impact on the dynamics of the turbulent flux. Indeed, the frequency spectra of the flux in the perturbed region show a similar behavior as in the case where sheared mean and zonal flows have been artificially suppressed (Fig. 9), i.e. a decrease of rapid fluctuations. From this, one expects large bursts to be present in the stochastic region and indeed, as can be seen from Fig. 10, radially propagating bursts can be found in the perturbed region. These are further supported by the appearance of stationary eddies that provide natural channels for the propagation of bursts.

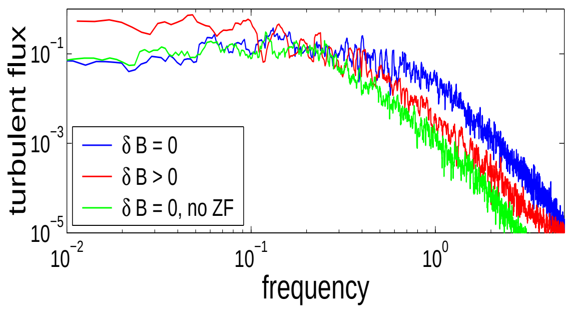


FIG. 9. Frequency spectra of the turbulent flux at a given radial position in the stochastic layer. In red, the case with magnetic perturbation, in blue, the reference case without perturbation, and in green, a reference case without perturbation and with artificially suppressed mean and zonal flows.

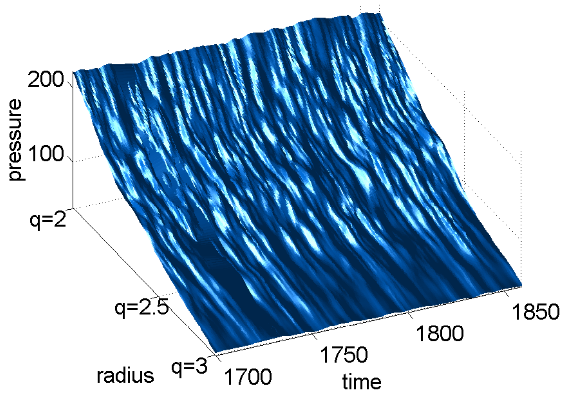


FIG. 10. Pressure profile as a function of radius and time. Fluctuations correlated over large radial distances appear, corresponding to radially propagating bursts. Some of these bursts propagate in the stochastic region.

5. Conclusions.

Turbulent transport is characterized by intermittent bursts, propagating radially over large distances. Self generated sheared mean and zonal flows regulate these events by broadening and shifting to lower fluxes the PDF of the turbulent flux, leading to an evacuation of energy by rapidly fluctuating small bursts.

A magnetic perturbation with field line stochastization has significant effects on electrostatic fluctuations, associated transport and sheared flows. Two main observations can be stated: First, the convective cross field transport is not quenched by the perturbation in spite of a reduced pressure fluctuation level. This is partly due to an increase of small scale velocity fluctuations. Second, mean poloidal shear flow is suppressed and zonal flows are reduced in the perturbed layer. This inhibits the self regulation mechanism of large scale transport events, and radially propagating bursts can resist the magnetic perturbation.

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