FLUX DRIVEN TURBULENCE IN TOKAMAKS

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Abstract

This work deals with tokamak plasma turbulence in the case where fluxes are fixed and profiles are allowed to fluctuate. These systems are intermittent. In particular, radially propagating fronts, are usually observed over a broad range of time and spatial scales. The existence of these fronts provide a way to understand the fast transport events sometimes observed in tokamaks. It is also shown that the confinement scaling law can still be of the gyroBohm type in spite of these large scale transport events. Some departure from the gyroBohm prediction is observed at low flux, i.e. when the gradients are close to the instability threshold. Finally, it is found that the diffusivity is not the same for a turbulence calculated at fixed flux than at fixed temperature gradient, with the same time averaged profile.

1 INTRODUCTION

Turbulence simulations have received much attention during the recent years because they have impacted the formulation of transport models. Also simulations help to clarify some issues such as dimensionless scaling laws or fast transport events in fusion devices. Most turbulence simulations are done with fixed profiles, in order to provide predictive expressions for the transport coefficients as function of the gradients. However in any fusion device, fluxes are fixed and profiles fluctuate around their time average value. It was emphasized recently that instabilities governed by a threshold may lead to a "Self-Organized Critical" system by producing transport events at all scales, called avalanches [1,2]. These avalanches are due to local accumulation of energy (or particles), leading to an increasing gradient. Once the gradient exceeds the threshold, a burst of turbulence occurs, which radially expels the accumulated energy (or particles). This process can be renewed, much like a domino effect, leading to a large scale transport event. An avalanche as described above propagates down the gradient. It can be easily verified that a depletion of energy (or particles) propagates upward. These transport events may explain the fast transients which are sometimes observed in fusion devices. It was proposed [1] that they may cause the correlation lengths to scale as the machine size, thus leading to a Bohm-like transport instead of the expected gyroBohm scaling law. To investigate these issues, the results of four codes have been compared. This flux driven turbulence is investigated with specific codes in three regions. At the very edge, a 2D spectral code computes an interchange turbulence in the Scrape-Off-Layer of a tokamak. The drive is a particle source and the threshold a critical density gradient length [3]. In the standard "gradient" region, an Ion Temperature Gradient (ITG) turbulence is computed with a 2D [4] and a 3D [5] global code. The analysis of these two regions is bridged with a 3D global code to compute Resistive Ballooning Modes (RBM), which involve a critical pressure gradient length [6]. These codes yield a consistent description of transport processes from the small scale fluctuations to the equilibrium profiles. Several issues are investigated here: the existence of propagating fronts, similar to avalanches in SOC systems, the question of transport transients and scaling laws, and the consequences for turbulent transport.

2 AVALANCHES AND STATISTICAL PROPERTIES

The difference between simulations at fixed gradient and fixed flux is illustrated in the fig.1 for a 2D interchange turbulence in a tokamak scrape-off layer [3]. Here "fixed gradient" means that the equilibrium profile is not allowed to fluctuate, i.e. all density (or temperature) radial modes are removed except the equilibrium profile. The simulation at fixed flux clearly exhibits a bursty character, where each burst corresponds to a large scale transport event. The timescale of these radially propagating fronts is slower than the lifetime of vortices at fixed gradient. These fronts are observed as soon as radial modes are included in the simulation. Still this does not prove that fronts are poloidally and toroidally symmetric. The analysis of 2D interchange simulations shows that there are in fact spatially localized.

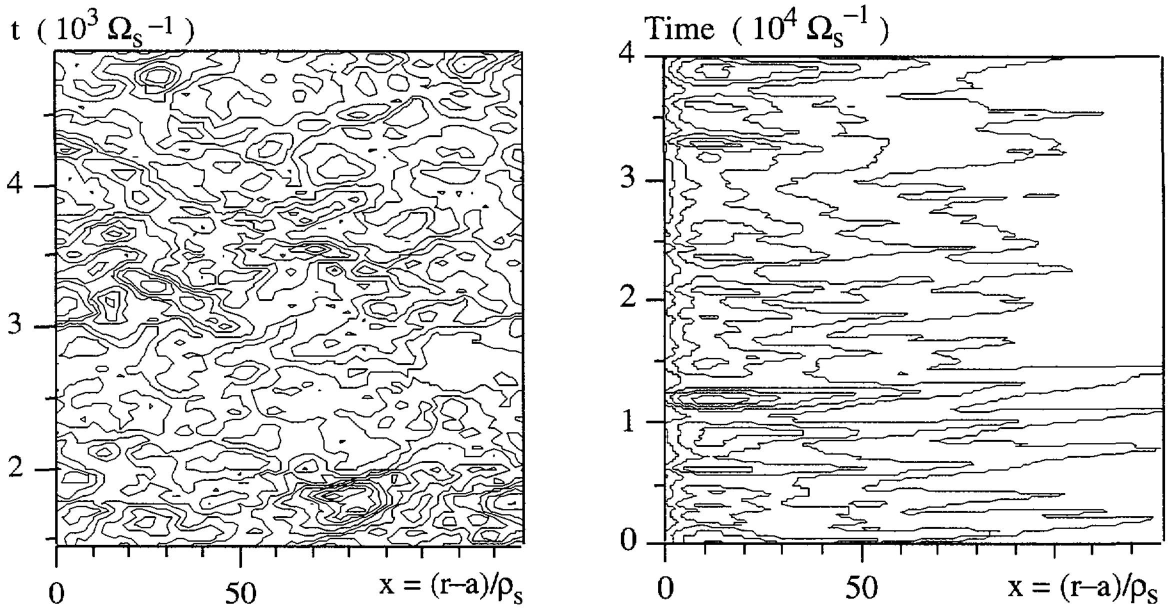

Fig. 1 : *Contour plots of the particle flux in the fixed gradient case (left) and fixed flux case (right) in the 2D interchange model.*

Radially propagating fronts are observed in most simulations. Only with the 3D ITG code, they were observed to be of rather modest intensity, propagating over a few radial correlation lengths. What causes the difference is at present not yet understood. Here we point out that the main differences between 2D and 3D ITG models is the presence in the latter of a Landau-fluid damping term in the temperature equation and of an additional equation for the parallel velocity. In the following, we focus our attention on the cases where avalanches are observed. Examples for 2D ITG and 3D RBM turbulences are shown in fig.2.

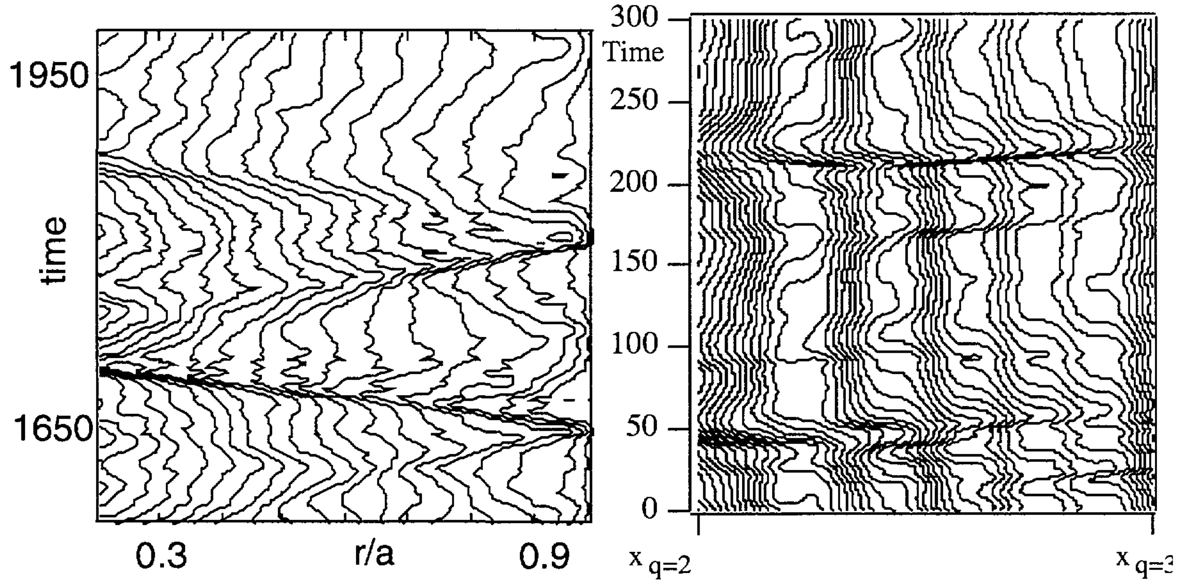

Fig.2: Contour plots of the pressure for a 2D ITG (left) and 3D resistive ballooning (right) turbulences. The pressure is an average over the poloidal and toroidal directions.

The propagation time of a front is typically of the order of 10 to 30 a/c_s, where $c_s=(T_0/m_i)^{1/2}$ is the acoustic speed and T_0 is a reference temperature. For realistic plasma parameters, this time ranges between 10 to 100μs, and is much smaller than a confinement time.

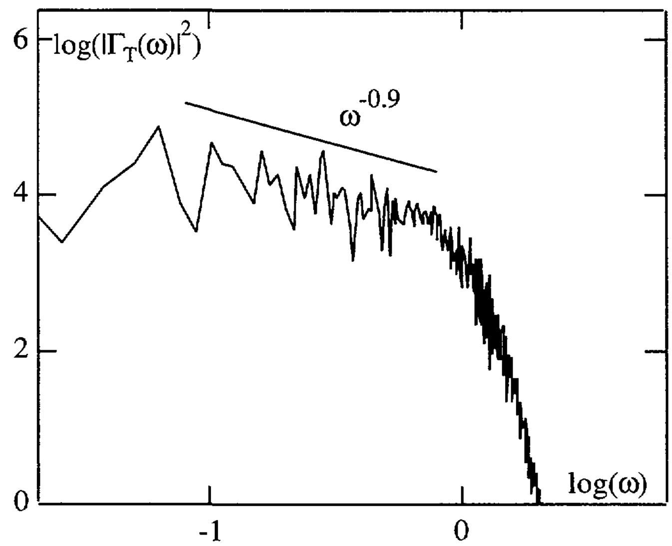

Fig.3:Frequency spectrum of heat flux for a 2D ITG turbulence at fixed flux.

At a given time, the radial profiles exhibit a sequence of steep and plateau regions. Plateau regions are locally stable whereas steep gradients are above the threshold. A linear stability analysis indicates that the time average profiles are supercritical, i.e. their gradient exceeds the threshold value everywhere. This behavior is different from sandpile automatons and previous fluid simulations of interchange modes in a cylinder [2], which are found to be subcritical. For low viscous dissipation and broad sources, part of the profile is subcritical (see [7], fig.2a corresponds to such a case).

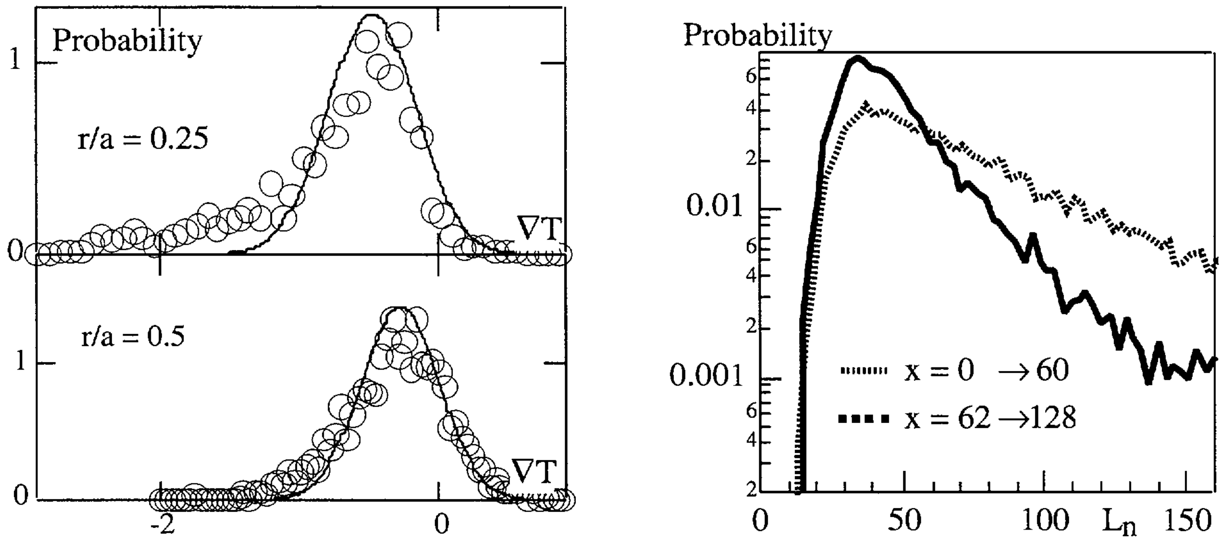

Fig.4: Probability Distribution Function of the temperature gradient for 2D ITG simulations close and far to the source (left). The solid line is a gaussian fit. The skewness (normalised third momentum) and flatness (normalised fourth moment) are respectively equal to -1.1 and 4.0 at r/a=0.25 and -0.3 and 3.3 at r/a=0.5 (values for a gaussian distribution are 0 and 3). Right: PDF of the density gradient length for a 2D interchange turbulence.

The experimental evidence of radially propagating fronts is a delicate issue. It has not been possible up to now to define a univoque signature of these fronts. Two tests, which are not definite proofs, can be suggested for an experimental investigation. First, the frequency power spectrum of the flux usually exhibits a shape with 3 slopes, typically f^0, $f^{-\beta}$ and $f^{-\delta}$, where β is of order 1 and δ>2 (fig.3). This type of spectrum is close to those observed in SOC systems [2]. The actual values of the slopes depend on the source and damping terms and also on the radial distance between the source and the position where the analysis is done. Note also that other situations than SOC systems exhibit a 1/f feature. Thus a power spectrum with a 1/f shape is an indication but not a proof of critical self-organization.

A second test consists in investigating the probability distribution function (PDF) of gradients and fluxes. These distributions are usually not gaussian in 2D interchange simulations. This is consistent with the intermittent character of the turbulence. For 2D ITG simulations, the departure from gaussianity is weaker (fig.4). A detailed analysis shows a near gaussian PDF far from the source (fig.4a), and a significant deviation from gaussianity close to the source (fig.4b).

Thus the distance of the measurement probes from the source is an important parameter in this case.

3 TURBULENT TRANSPORT AT FIXED FLUX

3.1 Fast transport events

Density or pressure perturbations are observed to propagate downward and upward the gradient. Events moving upward are usually less frequent than fronts moving downward. Note also that all of them correspond to positive perturbations of heat or particle flux. As already mentioned, these ballistic events propagate within a time of the order of 10 to 30 a/c_s, for an ion gyroradius normalised to the minor radius $\rho^*=0.01$. This behavior can be investigated by computing trajectories of test particles in a 2D interchange turbulence. Some of these trajectories are characterised by a ballistic radial motion (fig.5). A statistical study involving a larger number of particles remains to be done, in particular for ITG simulations where the plasma size is much larger than a radial correlation length. Such a behavior potentially explains the fast propagation of impurities which has been observed in Tore Supra for instance [8]. Also, starting a simulation with an equilibrium profile far from the relaxed one exhibits a fast relaxation over a time much smaller than a diffusion time. The relaxation time is again of the order of 30 a/c_s. However, it has not been possible up to now to simulate a core heating following an edge cooling such as those observed in Tore Supra [9].

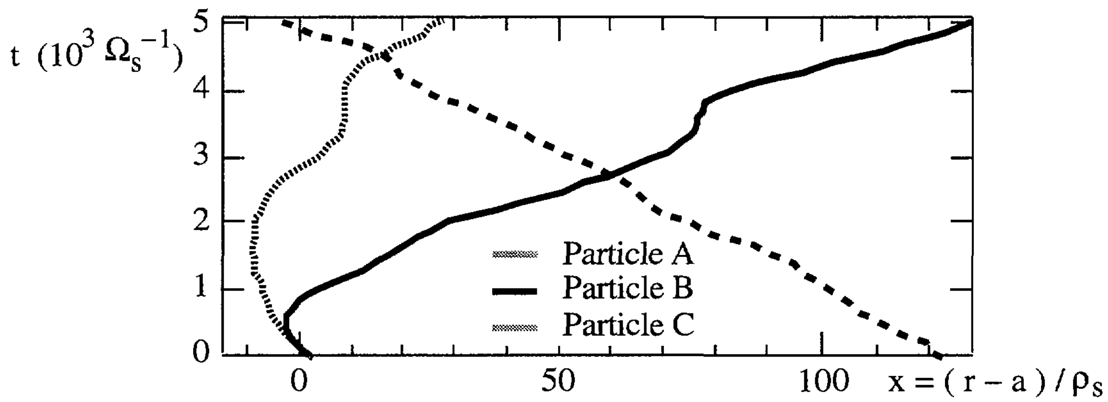

Fig.5 : *Three individual test particles trajectories in the 2D interchange model. The initial poloidal distance between particle A and particle B is equal to* ρ_s.

3.2 Dimensionless scaling laws

It is interesting to investigate the dependence of the confinement on the ion gyroradius normalised to the minor radius ρ^*. A traditional way to quantify this dependence is to express the heat diffusivity as $\chi_T = T_0/eB[\rho*]^\alpha$, where α characterises the scaling law (α=1 corresponds to the gyroBohm law and in the following χ_{gB} is defined as $\rho*T_0/eB$). 2D ITG simulations have been done for various values of $\rho*$. The control parameter S for the heat source is defined by the relation $P_{add}=3n_0T_0V(c_s/a)\rho*S$, where P_{add} is the additional power, n_0 a reference density (in ITG simulations, the density profile is flat) and V the volume. The source S has to be adjusted to maintain the same temperature profile when changing $\rho*$. Since the confinement time varies as a^2/χ_T, the source S must scale as $[\rho*]^\alpha$.

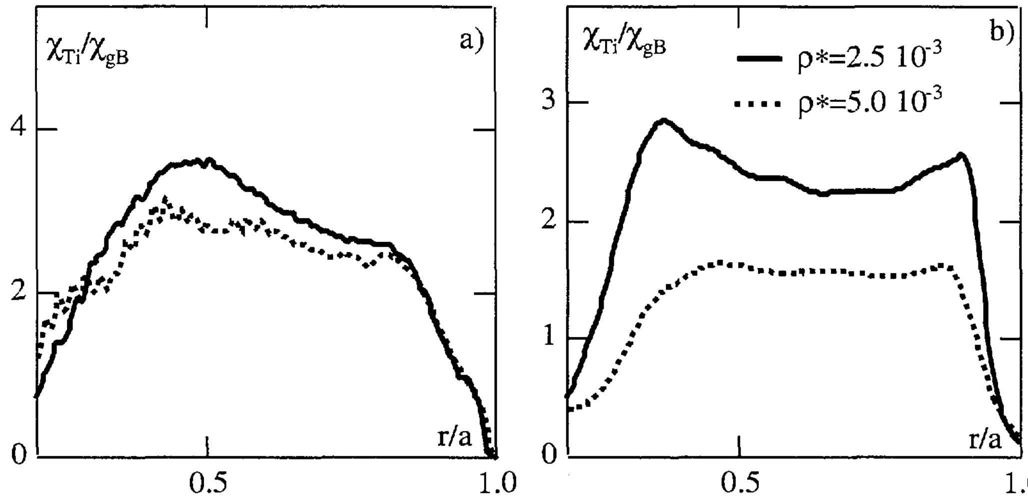

Fig.6: Heat diffusivities normalised to the gyroBohm value calculated with the 2D ITG code for two values of $\rho*$. *a) The heat source is large, the scaling law is close to the gyroBohm expectation. b)For lower heat flux, a departure from the gyroBohm expectation is observed.*

To find the value of α, the case ($\rho*=2.510^{-3}$,$S=5.10^{-3}$) has been compared to the case ($\rho*=5.10^{-3}$,$S=10^{-2}$). These two simulations exhibit the same temperature profile and are therefore characterised by a gyroBohm scaling law α=1. This is also verified by comparing the diffusivities normalised to the gyroBohm value which are the same for both cases (fig.6a). An interesting result is therefore that the presence of large scale transport events do not imply a breaking of the gyroBohm scale invariance. At lower fluxes, i.e. for a temperature gradient closer to the threshold, some departure from the gyroBohm expectation is observed (fig.6b). To maintain the temperature profile when doubling $\rho*$, the source is multiplied by 1.5 (from $S=10^{-3}$, $\rho*=2.510^{-3}$, to $S=1.510^{-3}$, $\rho*=5.010^{-3}$). This corresponds to a value α=0.6 (close to the so-called "weak gyroBohm" scaling law α=0.5). This value of α is recovered by comparing the normalised diffusivities (fig.6b).

This result is compatible with recent simulations for 3D global ITG simulations [5], which indicate a scaling close to gyroBohm well above and close to the threshold. Also a weak gyroBohm scaling is found for 2D interchange simulations. It has to be stressed here that the departure from the gyroBohm prediction is weaker here than in previous simulations at fixed temperature gradient [6]. In the later simulations, the departure from gyroBohm was attributed to the stabilising effect of diamagnetic rotational shear, which depends on ρ^*. However, the shear flow was externally controlled and larger than in the present calculations where the radial electric field balances the ion pressure gradient. Note that the ion pressure gradient tends to be smaller than actual values since the ITG fluid threshold is lower than the exact kinetic critical gradient. Thus the rotational shear is underestimated. This difference of rotational shear may explain the difference between simulations at fixed gradient or flux.

3.2 Consequences for transport predictions

An analysis of edge simulations show that the e-folding length of the Scrape-Off Layer exhibits parametric dependences which agree with some experimental observations, in particular there is weak dependence on the magnitude of the driving particle flux. Accounting for the convection associated to avalanches, an expression for the e-folding length is

$$\Delta_{SOL} = 3.9\ T_e^{0.36}\ R_0^{0.28}\ B_0^{-0.72}\ (10^{-3}\,\mathrm{m})$$

where T_e is the edge temperature.

Also, 2D interchange and ITG simulations indicate that the local diffusion coefficient with avalanches differs somewhat from the one calculated by freezing the equilibrium profile, thus forbidding radially propagating fronts. In practice, the diffusivity at fixed flux is found to be larger than at fixed gradient in the inner region, closer to the source, and smaller in the outer region (fig.7). This effect is attributed to a redistribution of the particle or heat source by avalanches. This has implications when comparing simulations at fixed gradient with those at fixed flux.

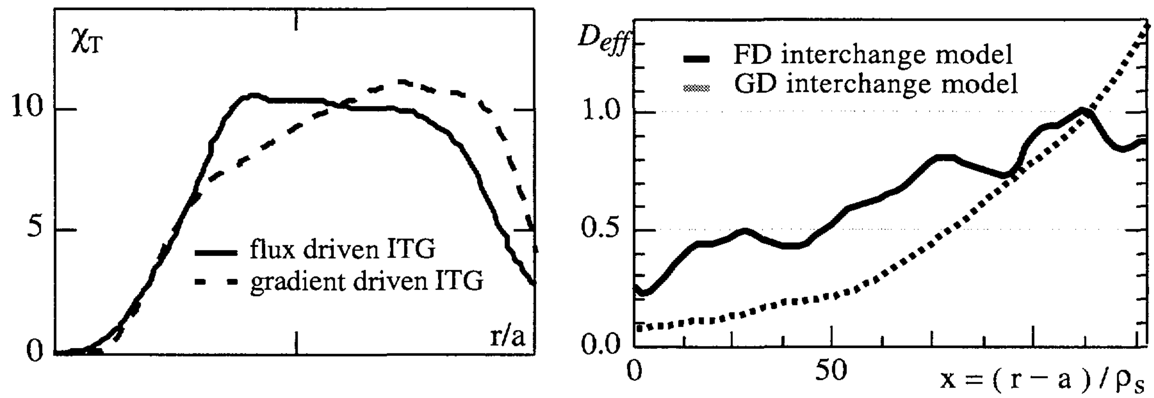

Fig.7 : Radial profiles of the turbulent diffusion coefficient in the 2D ITG model (left), and the 2D interchange turbulence (right). Results are given at fixed flux (bold line) and at fixed gradient (dashed line), with the same average gradient.

4. CONCLUSION

This work shows that a tokamak plasma turbulence does not behave necessarily in the same way depending whether fluxes or profiles are fixed. At fixed flux, many simulations exhibit some features of Self-Organized Criticality. In particular, radially propagating fronts are observed, similar to avalanches in SOC systems, moving upward and downward the gradient. The turbulent transport is found to be intermittent when these fronts are present. An exception is provided by 3D global ITG simulations, where avalanches are less pronounced and propagate only over a few radial correlation lengths. In all these simulations, the time average gradient exceeds the linear instability threshold, i.e. these systems are supercritical, in contrast with sandpile automatons and some previous fluid simulations, which were found to be subcritical at low fluxes. These propagating fronts provide a way to understand the fast transport events which are sometimes observed in tokamaks, for instance the fast penetration of impurities. It is also shown that the confinement scaling law can still be of the gyroBohm type in spite of these large scale transport events. Some departure from the gyroBohm expectation is observed at low flux, i.e. when the gradients are close to the instability threshold. Finally, it is found that the turbulent diffusivity is not the same for a turbulence calculated at fixed flux than at fixed temperature gradient, with the same time averaged profile. For predictive purposes, it is therefore preferable to perform simulations driven by sources.

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