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Propagating turbulence bursts and preferred location for transport barriers

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Introduction

A basic fluid model [1, 2] for the evolution of a turbulence field (e. g. the intensity of turbulent noise), when coupled to a diffusive field (e. g. plasma density) through the transport coefficient, conforms a reaction-diffusion system able to display many features in qualitative agreement with experimental findings: transport barrier formation, hysteresis [3], bursty behaviour and ELMy activity [4], non-local features under pellet injection [5], etc. This phenomenology arises from the three possible stationary states inherent to the model: high turbulent transport, low turbulent transport and an intermediate or marginal state where nonlinear features are most prominent [6]. Such description of transport has a notable interest because (i) it has room for describing all sorts of phenomena outside the purely diffusive paradigm and (ii) it does not involve essentially new approaches -like, e. g., kinetic level calculations- to the problem of transport but, rather, it simply extends traditional fluid-like transport models. However, these systems face two serious difficulties: the corresponding equations pose a complicated problem from the numerical point of view and the models that enter the evolution of the added fast, or turbulent, fields are far from trivial. While there is an ongoing work to solve these problems [7], the reaction-diffusion description of transport continues to yield new results of qualitative interest (e. g. [8]), which can only be made quantitative if (i) models of turbulent saturation and transport are sufficiently well-founded and (ii) analytical approaches support the numerical results to a satisfactory degree. It is acknowledged that non-linear systems of equations can accommodate very rich dynamics that may however be based on wrong physical notions. In an effort to falsify the model, it is useful to check for inherent features that have not been observed experimentally. In the present work we point to one such features.

Basic model. Propagation in the linear approach

The essence of the description of transport according to the paradigm proposed in Refs. [1] and [2] is that the flux of a diffusive field maintained by a fixed source P_0,

$$\partial_t N = P_0 + \partial_x (D \partial_x N),$$

is subject to a transport coefficient that obbeys the fast dynamics of turbulence, i. e., D scales with a turbulence field ε governed by timescales typical of micro-instability growth rates γ. For transport barrier phenomenology, it is mandatory that the conditions for increasing turbulence drive (let $\gamma = \partial_x N = N'$ be for simplicity) can, at some stage, force a drop of ε itself. This happens within the frame of ExB shear suppression physics [9] because, in the plasmas of interest here, the radial electric field shear will always have a contribution from the radial derivative of the diamagnetic force. Let us assume that N^2 can be associated to a pressure term. The radial derivative of the pressure gradient divided by N (a term representing the ExB velocity shear) would behave as N''. Therefore, ε evolves according to the sum of a forcing $\gamma\varepsilon = N'\varepsilon$, a non-linear saturation term that we write as $\alpha\varepsilon^2$ and a suppression term $\Omega = \alpha_2(N'')^2/\gamma$. This expression for Ω ensures that the condition for turbulence suppression is that the growth rate and the shearing rate are equal independently of the sign of the latter:

$$\partial_t \varepsilon = (\gamma - \alpha\varepsilon - \Omega)\,\varepsilon + D_\varepsilon \varepsilon''$$

The (constant) diffusivity in this equation limits spatial scales in ε. The parameter α_2 controls the strength of the suppression mechanism (via Ω). The equation can be simplified by direct linearization with respect to N, N', N'', ε, ε' and ε'' considering that perturbations in the second derivatives evolve faster than perturbations in first derivatives. The resulting linear system -in an infinite domain- allows for propagating solutions with velocity $V \propto N''$ whenever Ω and γ are comparable (marginal state). According to this, the second spatial derivative of the diffusive field dictates the direction of propagating fronts. The previous analysis is very simple and, if at all, should be valid in the first, linear stages of the development of marginal solutions. If, on the other hand, the feature of preferred propagation direction remains during the non-linear stages, then we should be able to find it making the system evolve in the marginal state.

Numerical calculations

The model of the previous section was formulated in planar geommetry. The following examples are based on the same paradigm, but have added levels of complexity. In the first case, we show the evolution of the ratio Ω/γ in cylindrical coordinates. An explicit numerical scheme is used here. The calculations are done with parameters that make the system stay in the marginal state, characterised by an effective competition between driving and suppression mechanisms. The radial region $0.1 < r < 0.3$ has $N'' > 0$ and there the pulses propagate outwards (Fig. 1); but where there is a marginal region with $N'' < 0$, the pulses propagate inwards (Fig. 2). In this second case, Ω is large enough in the region $0.65 < r < 0.8$ (where $N'' < 0$) and a transport barrier developes (ε vanishes in the region).

Another calculation (Fig. 3) is performed with real tokamak parameters ($R = 1.5$ m, $a = 0.8$ m, $B_T = 4.8$ T) and a rather complete transport model where, aside from ε, there are evolution equations for particle density, ion and electron temperatures and poloidal magnetic flux. The same property of propagation of the pulses towards the zones of smaller gradients is observed. This calculation has been done with the ASTRA transport shell [10].

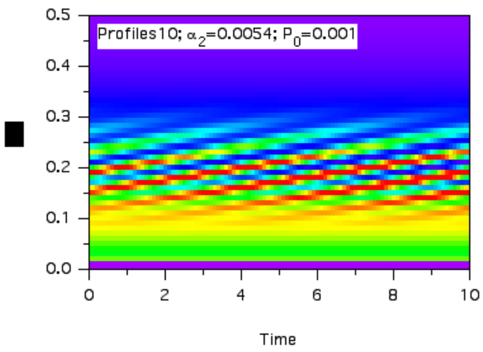

Figure 1: Time evolution of the Ω/γ profile starting from a steady state with $N'' > 0$. Values range from zero (purple) to 0.5 or higher (red).

A potential consequence of these results is that there is a preferred location for the formation of transport barriers: ExB velocity shear layers sided by steeper gradients. Intuitively, if we consider the pressure gradient to be the drive of turbulent transport and the plasma is close to conditions of ExB shear suppression, the turbulent bursts created by the reaction-diffusion system will tend to converge where there is a flattening of the pressure profile. Such a region may be expected around rational values of the safety factor.

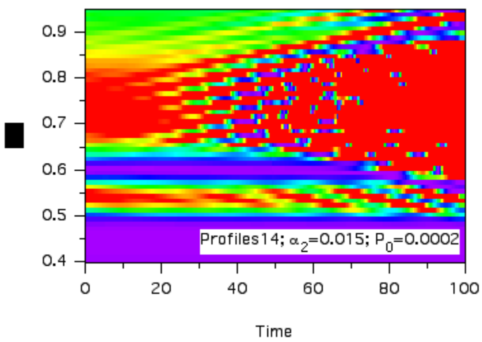

Figure 2: Same as Fig. 1 for a case where $N'' < 0$ in the region $0.4 < r < 0.6$. The term Ω overcomes γ as of $t \approx 50$ (arb. units).

It should be recalled, however, that for the dynamics of barrier formation to occur, the feedback mechanism that simultaneously increases gradients and suppresses turbulence must be active. Therefore, other transport mechanisms that limit the thermodynamic gradients independently of the level of turbulent fluid advection -like stochasticity in the lines of force- can in turn limit the process of barrier formation and sustainment. In any case, if the paradigm proposed in Refs. 1 and 2 is to represent transport physics of magnetically confined fusion plasmas, marginal states with propagating bursts should be found. These bursts would show preferred directions of propagation and here we suggest that they should move towards regions of flatter turbulence-driving gradients.

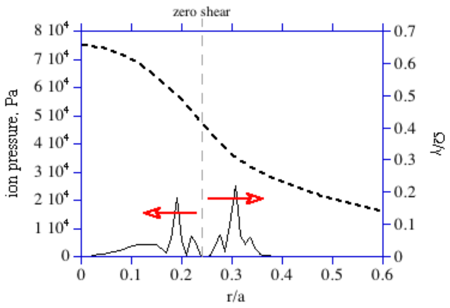

Figure 3: Evolution of the ratio Ω/γ in the frame of a tokamak transport system of equations with η_i model of anomalous diffusion. The simulated plasma is driven to marginality with 28 MW of on-axis heating power and a configuration of plasma current that reverses the magnetic shear in the plasma core. A radial grid of 200 points in the range $0 < r < a$ is used for the calculations. The arrows indicate the direction of propagation of the pulses in Ω/γ.

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