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Shearing effects on density burst propagation in SOL plasmas

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ABSTRACT

SOL turbulence is characterised by intermittent ballistic transport of density fronts. The interaction of such density structures with velocity shear layers is found to yield shearing effects over scales that are comparable to those of the fronts. Enhanced diffusion transport governed by the thinning of the radial extent of the density structure governs the decay of such a structure over a Dupree time. Velocity shear layers extending poloidally over a fraction of the poloidal wave length can also exhibit a stopping capability due to the collapse of the radial velocity within the shear layer. The penetration of the density structure within such a barrier is of the order of five hybrid Larmor radius.

1. Introduction

A key issue for many aspects of the operation of the new generation of long pulse devices is that of the plasma flux to the wall of the main chamber. Indeed, it has been shown that turbulence as well as ELMs are characterised by long range propagation of density bursts, hence leading to an intermittent extension of the SOL width [1,2]. These events thus tend to blur the separation between the main chamber and the divertor. While there is ample experimental evidence that backs the existence of such density bursts, it is very hard to predict the associated fluxes in the ITER case. Indeed, this transport mechanism is based on the generation of self organised fronts combining a density burst and an electrostatic dipole that can only be described correctly from first principle plasma turbulence models.

Saturation of core turbulent transport by the self generated zonal flows is now a well established paradigm of core transport [3]. When considering the SOL turbulence this process is more difficult to identify since the poloidal symmetry is lost so that the concept of zonal flows does not hold. However, it can be seen in the simulations that shearing mechanisms still prevail but appear to result from interactions between the outgoing density burst and poloidal flow patterns that are generated in the wake of prior bursts [4]. The scope of this paper is to analyse the interaction between the density fronts and sheared poloidal flows in order to determine how the front ballistic motion is impeded. The paper is organised in three parts. In Section 2 the model and key properties are recalled. The underlying Hamiltonian properties are used in Section 3 to describe local barrier effects. Finally, the stopping capability of those layers is addressed in Section 4. Discussion and conclusion are found in Section 5.

2. Interchange model of SOL turbulence

We address SOL transport where turbulence ids governed by the SOL interchange instability [5]. We restrict the analysis to the density at constant temperature in the cold ion limit. The system is governed by two equations, one for the normalised density field and the other for the normalised electric potential. The flute assumption allows one to simplify the parallel transport which then takes the form of the loss terms at the sheath. Space coordinates, x and y, respectively the radial and poloidal coordinates, are normalised to the hybrid Larmor radius ρ_s, $\rho_s^2 = T_e/m_i$ (T_e is the electron temperature and m_i is the ion mass ratio), time to the ion cyclotron frequency $1/\Omega_i$. Although very simplified, this system, when flux driven, appears to be generic of SOL transport [6]

$$(\partial_t + \{\phi\} - D\nabla_\perp^2)\mathrm{Log}(N) - D(\nabla_\perp \mathrm{Log}(N))^2 = -\sigma e^{(\Lambda-\phi)} + S/N \quad (1a)$$

$$(\partial_t + \{\phi\} - \nu\nabla_\perp^2)\nabla_\perp^2\phi + g\partial_y \mathrm{Log}(N) = \sigma(1 - e^{(\Lambda-\phi)}) \quad (1b)$$

In this system the bracket term $\{\phi\}$ stands for the Poisson bracket, the Hamiltonian being the electrostatic potential ϕ, and represents the ExB convection. The various control parameters are the small scale transverse diffusion of particles, D, and velocity, ν, the average curvature drive, g, the parallel sheath loss term σ, and the potential Λ. The latter can depart from the floating potential when a biasing

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procedure is used. In particular, one can implement the structure presented in the following analytical calculation to perform the corresponding simulations. Only the source term on the right hand side of Eq. (1a) departs from a Log(N) dependence so that Log(N) appears to be the appropriate field. Indeed, the Vlasov equation, from which stems most of the terms of this equation, is homogeneous with respect to the distribution function and hence the density. This means that the density can be multiplied by any constant with no change of the equation. Consequently, the suitable representation of the density field is Log(N) except when collisional transport or non-linear source terms are dominant. In the present model, the source term, localised in a narrow radial region, does not depend on the density. Departure from a Log(N) behaviour can be expected in that region. Conversely, properties stemming from this Log(N) dependence should govern most of the transport properties of the system. In particular, Gaussian fluctuations of Log(N) will lead to a Lognormal PDF for the density. Such a skewed distribution function, reported experimentally and in simulations, can then be considered to be a signature of Gaussian fluctuations Let us now consider the parallel loss terms depending on the parameter σ. In the vorticity equation, this term stands for the characteristic time of parallel current losses out of a volume where the flute assumption is assumed to hold. When the parallel extent of this volume is smaller than the full connexion length between the limiting surfaces, the sheath loss term does not hold and the loss term governed by the plasma resistivity must be used. In fact, the latter regime will only be met when the collision frequency of the electrons is larger that the electron transit time, a situation that does not prevail for the hot SOL plasmas of interest as in JET or Tore Supra [7]. Regarding the density field, where one must take into account the ion transit time, the use of a sheath parallel loss term for the particles is more questionable. However, it can be shown that when the density structure is localised in the parallel direction, then the particle flux out of this structure is governed by a density front propagation in the parallel direction. This leads to a parallel loss comparable to the sheath boundary condition [8]. As a consequence, a departure from the flute conditions does not require a major change in the present model.

3. Propagation of a density front into a velocity shear layer

Let us decouple the evolution of the density front from that of the vorticity. The imposed electric potential Λ is a combination of two superimposed structures, $\Lambda_s(y) = -\phi_s \sin(ky)$ and $\Lambda_z(x) = \phi_z \exp(-(x-x_z)^2/(2\Delta_Z^2))$. The s subscript refers to streamer while the z subscript refers to zonal although the imposed electric potential does not originate from the basic mechanisms that actually sustain streamers and zonal flows. The Poisson bracket term in Eq. (1a) governs the convection of the density field. It combines therefore the radial convection with wave vector k and a velocity shear layer localised at $x = x_z$ and with an extent Δ_z. For such a poloidal flow, the shearing rate is also related to the width of the shear layer Δ_z. The ExB convection of the density is then governed by the Hamiltonian equations. It is important to note that taking into account a space dependence of the magnitude of the magnetic field (here found in the Larmor radius normalisation) requires to incorporate a drift term in the parallel velocity so that the parallel dynamics also depend on the transverse electric field. The problem cannot then be reduced to the 2D cross-field problem:

$$\dot{x} = V_{Ex} = -\partial_y \phi; \quad \dot{y} = V_{Ey} = \partial_x \phi \tag{2}$$

In the region such that $|x - x_z| >> \Delta_z$ the sheared poloidal flow is negligible so that the motion of the density structure is only governed by the radial velocity $V_{Ex} = k\phi_s \cos(ky)$ Provided the scale of the density structure Δ_y is small, $k\Delta_y << 1$, the radial velocity is constant $V_{Ex} \approx V_s = k\phi_s$. Let us consider a circular density structure such that $x_0^2 + y_0^2 = \Delta_0^2$ at $t = 0$. If the initial radial position is away from the poloidal shear layer this, structure will drift towards the shear layer at constant velocity. Upon reaching the shear layer the density structure will change shape, but this effect will take place at constant electric potential determined by the initial condition. Indeed, according to the equations of motion, Eq. (2) the potential ϕ is conserved as well as the surface of the density structure $S = \Delta_0^2$. With the assumptions discussed above, namely $|ky| < \pi/2$, $x_z - x_0 >> \Delta_z$ and for a sawtooth approximation of Λ_s one then obtains:

$$x = x_0 + V_s t; \quad y = y_0 + \frac{\phi_z}{k\phi_s} \exp(-(x-x_z)^2/(2\Delta_Z^2)) \tag{3a}$$

$$(x - V_s t)^2 + (y - \frac{\phi_z}{k\phi_s} \exp(-(x-x_z)^2/(2\Delta_Z^2)))^2 = \Delta_0^2 \tag{3b}$$

Furthermore, if the maximum potential of the shear layer ϕ_z is larger than the maximum of the electric potential away from the shear layer, ϕ_s, then no structure that originates from the region distant from the shear layer can cross the shear layer. Such a structure will get elongated a shifted poloidally until it reaches the region $|ky| > \pi/2$ where the radial velocity reverses sign and the structure will drift radially out of the shear layer back towards its initial radial position. This provides a criterion for the existence of a transport barrier governed by a velocity shear layer. The conservation of the electric potential during the motion then yields the closest approach distance to the centre of the shear layer:

$$\frac{x_z - x}{\Delta_z} = \left(2\text{Log}\left(\frac{\phi_z}{\phi_s}\right)\right)^{1/2} \tag{4}$$

One thus finds that the density structure is convected by the streamer like potential towards the shear layer, is elongated poloidally at constant cross-field surface and then reverses velocity as it reaches the point $|ky| > \pi/2$. The density structure thus bounces back and the shape changes reverse so that the density structure recovers its initial shape as it leaves the shear layer. Although several simplifications have been introduced to obtain Eq. (3), the evolution of the shape of the density contour given in Eq. (3b) remains difficult to analyse. To obtain the leading order change in shape, let us consider a linear shear layer where the velocity V_z and the velocity shearing rate $1/\tau_z = dV_z/dx$ are constant, hence $\dot{x} = 0$ and $\dot{y} = V_z + x/\tau_z$. In this calculation, the density structure is initiated in the velocity shear region with negligible radial velocity so that the shearing effect is time independent. With these assumptions one obtains the time dependent shape of the density structure $x^2 + (y - V_z t - xt/\tau_z)^2 = \Delta_0^2$ and its poloidal extent Δ_y (defined as half the distance between the two points with derivative $dy/dx = 0$).

$$\frac{\Delta_y}{\Delta_0} = \sqrt{1 + (t/\tau_z)^2} \tag{5}$$

The half radial extent of the structure can be deduced from the conserved surface $\Delta_x\Delta_y = \Delta_0^2$. The structure is thus thinned in the radial direction by the shear layer.

4. Stopping capability of the shear layer

In order to address the stopping capability of the shear layer one must introduce another process that will destroy the coherent structure. Chaotic mixing due to the interaction between several shear layers can provide such a mechanism; rather, we concentrate here on the diffusion process that does not require specific properties of the shear layers. In contrast to the surface of the density structure, one finds that the perimeter of the contour is not constant and behaves like $2\Delta_y(1 + \Delta_0^2/\Delta_y^2)$ while the poloidal density gradient will scale like $1/\Delta_y$ and the radial density gradient like

Δ_y/Δ_0^2. These geometrical properties will boost the diffusion process through the increase of the gradient in the radial direction and an increase of the surface transverse to that gradient. The net particle outflux, of the order of $DnL_{//}\Delta_y/\Delta_x$, will govern the decrease of the number of particles within the density contour $\partial_t(nL_{//}\Delta_0^2)$. Combining these expressions, one finds that the density within the contour will decay exponentially, $\delta n(t) = \delta n(t = 0)\exp(-t/\tau_d - t^3/(3\tau_D^3))$, where the diffusive time scale is $\tau_d = \Delta_0^2/D$ and τ_D, the Dupree time is $\tau_D = (\tau_d \tau_z^2)^{1/3}$. The thinning of the structure by the shearing effects governs the enhanced diffusive outflux and leads to the Dupree time [9]. Given the values of the parameters chosen for the simulations, one finds $\tau_D/\tau_d \approx 1/20$. In the turbulent self organised case with shear layers generated in the wake of prior fronts, one finds that the poloidal and radial Mach numbers are comparable, typically in the range of 0.03. The Dupree time is of the order of $\tau_D\Omega_i \approx 1500$ so that one finds that the poloidal distance covered by the density structure before its collapse is $L_D = \tau_D M_\theta \approx 45\rho_s \approx 13.5/k_\theta$. When considering a velocity shear barrier, the effect of diffusion is twofold. It governs a rapid depletion of the density structure but also allows particle transport through the barrier. For the same parameter values as used above, one finds that the coherent density structure will diffuse over typically $3\rho_s$ hence $\sim \Delta_z/3$. Since the front structure penetrates into the barrier, see Eq.(4), one finds that the electric potential of the velocity shear layer must be 25 % higher than the electric potential of the front dipole to ensure a proper transport barrier despite the diffusion transport through the barrier.

Going one step further when analysing the stopping capability of a velocity shear layer, one must take into account the impact of the shear layer on the build-up of the electrostatic dipole associated to the density front. Indeed, as the front is sheared and its poloidal extent increased, the drive term of the vorticity generation, the g term introduced in Section 2, yields a decreasing contribution that scales like Δ_0/Δ_y. The latter effect slows down the radial motion of the density structure and thus increases the relative efficiency of the velocity shear layer. Provided the vorticity build-up is governed by the g term only, the radial velocity is given by $V_{Ex} \approx \left(\frac{g\delta n}{n_0}\right)\frac{\delta t}{1+\Delta_y^2/\Delta_x^2}$. Assuming that the time δt for the vorticity build-up is governed by the radial motion of the front, hence $\delta t = \Delta_x/V_{Ex}$, one finds that: $\dot{X} = V_{Ex} \approx \gamma_{linear}F(\Delta_0/\Delta_y)$. The radial velocity of the density front is thus governed by the linear growth rate of the system $\gamma_{linear} \approx (g\delta n/n_0\Delta_0)^{1/2}$ combined to a geometrical effect that strongly reduces the growth rate, $F(\Delta_0/\Delta_y) = (\Delta_0/\Delta_y)^{1/2}/(1 + (\Delta_y/\Delta_0)^4)$. The decay of the radial velocity of the density contour is governed both by the density decay, and by the evolution of the geometry of the contour that reduces the polarisation of the density structure. Let us analyse the stopping capability governed by the latter effect, hence within the approximation of a long diffusion time compared to the characteristic shear time, $\tau_d >> \tau_z$. A simplification of the radial displacement equation is readily obtained when $\Delta_y^4 >> \Delta_0^4$, leading to $F(\Delta_0/\Delta_y) \approx (\Delta_0/\Delta_y)^{5/2}$. Upon time integration, the position of the density contour X is given by:

$$X(\tau) = \frac{\gamma_{linear}}{dV_z/dx}\frac{\tau}{\sqrt{1+\tau^2}}\left(1 - \frac{\tau^2}{3(1+\tau^2)}\right) \quad (6)$$

where $\tau = t/\tau_z$. The asymptotic time limit is readily computed leading to $X^* = \frac{2}{3}\frac{\gamma_{linear}}{dV_z/dx}$, the maximum penetration distance of the density structure within the velocity shear layer is about $5\rho_s$ and thus comparable to half the radial width of the shear layer. In such a turbulent regime, this indicates a strong stopping capability. Furthermore, when computing the poloidal displacement during the stopping process one finds that it is of the order of $1/k_\theta$.

5. Discussion and conclusion

SOL turbulent transport is characterised by strong fluctuations and intermittent propagation of density structures associated to electrostatic dipoles. The paradigm transport properties for such a system are strongly skewed PDFs associated to ballistic transport. It is shown here that the relevant field is the logarithm of the density that exhibits Gaussian fluctuations. Furthermore, the wake of density fronts can generate localised velocity shear layers that can strongly impact the front propagation. First, one finds that such layers can appear as transport barriers. Taking into account the diffusion process, one finds that the poloidal velocity shear will enhance the diffusive process leading to the Dupree life time for the density structure. Finally, it is found that the velocity shear layer can stop the radial motion of the density front over a very short radial distance (5 hybrid Larmor radii). Such a localised interaction between a density front and a shear layer only requires that the latter extends over a fraction of the poloidal wave length of the turbulence. In such a framework, the transport associated to the density structures appears like percolation where the media evolution strongly depends on the sub and over dense structures but also on the localised velocity shear layer build-up via the Reynolds stress. For such hot plasmas with weak damping of the latter flows, the blob paradigm appears to be more complex than usually considered, leading to significant non-linear regulation of the bursts of density. As pointed out by one of the referees, the correlation between local measurements of the poloidal and radial electric fields would allow one to test the shearing mechanism of density fronts proposed in this paper.

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