33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.180 (2006)

Turbulence amplitude reduction as the main effect of a shear flow

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Introduction

The formation of transport barriers in magnetically confined fusion plasmas is strongly related to the reduction of turbulent transport by sheared mean $\mathbf{E}\times\mathbf{B}$ flows and zonal flows. Several works addressed analytically the determination of the dependence of the radial flux Γ, square amplitude of fluctuations $\langle p^2 \rangle$ and cross-phase $\cos\delta$ between the scalar field and the velocity field on the shear rate for a mean shear flow [1, 2], and for random zonal flows [3]. In this paper we investigate the role played by the reduction of the amplitude of turbulence and cross phase in regulating the radial transport using numerical calculations and compare our results to the theoretical works [1, 2].

Passive scalar model in a shear flow with linear profile

We consider the advection of the passive pressure field p by a turbulent flow $\mathbf{v}$ (the $\mathbf{E}\times\mathbf{B}$ velocity field) and a shear flow $\mathbf{V} = V(x,t)\ \hat{\mathbf{y}}$ with linear profile ($\partial_x V$ independant of x), in the local poloidal plane perpendicular to a magnetic field $\mathbf{B} = (0, B_y(x), B_0)$. We study the following physically relevant cases, (i) a mean shear flow with constant shear rate $\omega_E = k_y(dV/dx) = Cte$, where k_y is the poloidal wave number; (ii) a random zonal flow with shear rate $\Omega(t) = k_y\ \partial_x V$.

The Fourier transform of the zonal flow shear rate is: $|\Omega_\omega| \exp(i\varphi_\omega)$ where φ_ω is a random phase. The equation describing this model is the following: $\partial_t p + \nabla\cdot(p\mathbf{u}) = \mu_\parallel \nabla_\parallel^{\mathbf{2}} p$, where $\nabla_\parallel = B^{-1}(\mathbf{B}\cdot\nabla)$, $\mu_\parallel$ is the dissipation parallel to the field lines and $\mathbf{u} = \mathbf{v}+\mathbf{V}$ with $\mathbf{v} = -B^{-1}\nabla\phi\times\hat{\mathbf{z}}$. The electrostatic potential ϕ is a turbulent field modeled by a random source $S \sim \partial_y \phi$. We consider a perturbation of the form $p = \tilde{p}(x,t)\exp(ik_y y - ik_z z)$ which is resonant at the position $x = 0$, i.e $\nabla_\parallel \tilde{p}|_{x=0} = 0$ or $k_y/k_z = B_y|_{x=0}/B_0$. A linear approximation of B_y around $x = 0$ leads to $\nabla_\parallel \tilde{p} \sim ix\tilde{p}$. The equa-

	$1 \ll \frac{\tau_D}{\tau_C} \ll \frac{l_D}{L}$	$\frac{l_D}{L} \ll 1,\ \frac{\tau_D}{\tau_C}$
Γ	ω_E^0	ω_E^{-1}
$\langle p^2 \rangle$	$\omega_E^{-2/3}$	$\omega_E^{-5/3}$

Figure 1: Mean shear flow scaling laws of the radial flux Γ and the square amplitude of turbulence $\langle p^2 \rangle$ for different flow regimes in the strong shear limit

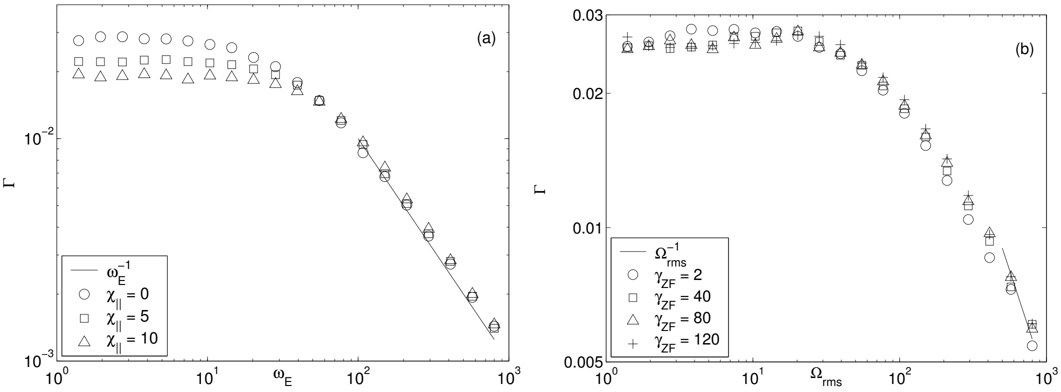

Figure 2: Radial flux Γ, *(a)* as a function of mean shear rate ω_E for different values of $\chi_\parallel$; *(b)* as a function of zonal flow shear rate Ω_{rms} for different values of γ_{ZF}.

tion governing the passive scalar fluctuations $\tilde{p}$ takes the following form:

$$\partial_t \tilde{p} = \chi_\perp \partial_x^2 \tilde{p} - \chi_\parallel x^2 \tilde{p} - i\,\Omega(t) x\tilde{p} + S(x,t) \tag{1}$$

Here, $\chi_\perp$ and $\chi_\parallel = k_y^2\ \mu_\parallel$ are the perpendicular and parallel diffusivities. We solved equation (1) numerically by considering a source with spectrum $S_{k\omega} = |S_{k\omega}|\exp(i\varphi_{k\omega})$ where $\varphi_{k\omega}$ is a random phase. The power spectrum $|S_k|^2$ is localized in k with correlation length $\frac{1}{\alpha}$ (Lorentzian power spectrum): $|S_{k\omega}|^2 = \frac{2\alpha}{k^2+\alpha^2}|S_\omega|^2$. We use two different types of source: (i) a source with a localized (Lorentzian) frequency spectrum $|S_\omega|^2 = 2\gamma_k/(\omega^2+\gamma_k^2)$ and (ii) a source corresponding to a delta-correlated flow ($|S_\omega|^2 = Cte$). We also used the following Lorentzian shape for the zonal flow spectrum: $|\Omega_\omega|^2 = 2\gamma_{ZF}/(\omega^2+\gamma_{ZF}^2)$ In order to derive the scaling laws analytically, we focus on case (i) without parallel diffusion ($\chi_\parallel = 0$). Equation (1) can be written in Fourier space ($\chi = \chi_\perp$): $-i\omega\ p_{k\omega} + \chi k^2 p_{k\omega} + \omega_E\ \partial_k p_{k\omega} = S_{k\omega}$ The solution of this equation satisfying the boundary condition $p_{k\omega} \to 0$ for $k \to -\infty$ is given by $p_{k\omega} = \frac{1}{\omega_E}\int_{-\infty}^{k} dk'\, S_{k'\omega} \times \exp\left[-\frac{\chi}{3\omega_E}(k^3-k'^3) + \frac{i\omega}{\omega_E}(k-k')\right]$. The expressions for the radial flux Γ and square amplitude of turbulence $\langle p^2\rangle$ are as follows: $\Gamma = \int_{-\infty}^{+\infty}\frac{dk}{2\pi}\int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}\langle p_{k\omega}S_{k\omega}^*\rangle$ and $\langle p^2\rangle = \int_{-\infty}^{+\infty}\frac{dk}{2\pi} \times \int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}\langle p_{k\omega}p_{k\omega}^*\rangle$. We focus on the physically relevant case of a localized spectrum $\langle S_{k'\omega}S_{k\omega}^*\rangle = \langle S_{k'}S_k^*\rangle\frac{2\gamma_k}{\omega^2+\gamma_k^2}$. The key parameters in the present model are a characteristic length $l_D = \left(\chi\omega_E^{-1}\right)^{1/3}$, a characteristic time $\tau_D = \left(\chi\omega_E^2\right)^{-1/3}$, the correlation length α^{-1} and the correlation time $\tau_C = \gamma_k^{-1}$ of the source, together with a inhomogeneity length L defined through the relations $\langle S_{k'}S_k^*\rangle = |S_k|^2\ C(k-k')$ and $\int_{-\infty}^{+\infty} dk\ C(k)e^{ikx} \sim e^{-|x|/L}$. In the strong shear limit $\alpha l_D \ll 1$, two dimensionless parameters $\frac{l_D}{L}$, $\frac{\tau_D}{\tau_C}$ define different flow regimes. Depending on the value of these parameters, we derive two different sets of scaling laws for the radial flux and square amplitude of turbulence as shown in Fig. 1.

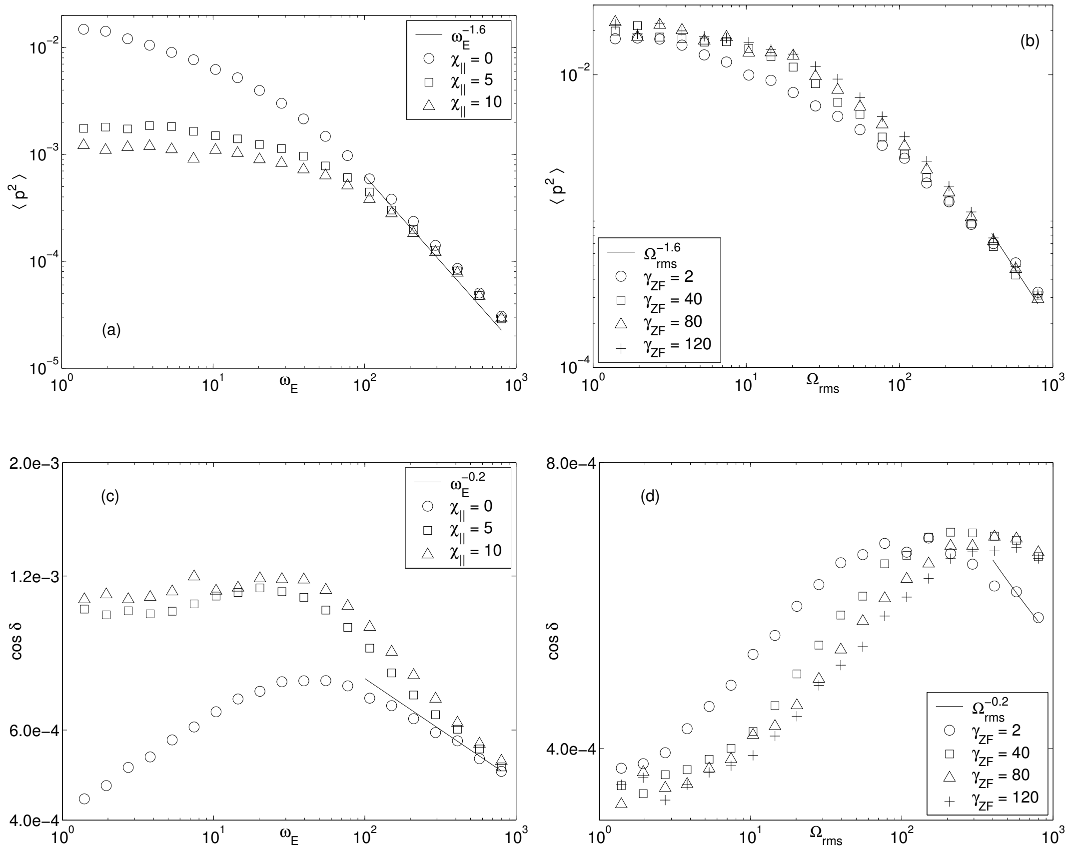

Figure 3: Square amplitude of turbulence $\langle p^2 \rangle$ and cross-phase $\cos\delta$ in the localized spectrum case as a function of *(a,c)* mean shear rate ω_E and *(b,d)* zonal flow rms shear rate Ω_{rms}.

In the delta-correlated flow ($1 \ll \frac{\tau_D}{\tau_C} \ll \frac{l_D}{L}$) and localized spectrum ($\frac{l_D}{L} \ll 1$, $\frac{\tau_D}{\tau_C}$) regimes, we find, using another method, the same results $\omega_E^0, \omega_E^{-2/3}$ and $\omega_E^{-1}, \omega_E^{-5/3}$ for the scaling of the flux and square amplitude as Kim & Diamond [2].

Discussion

Results showed that the reduction of fluctuation amplitude is the main effect of a strong shear flow, and that this reduction depends on the statistics of the turbulent flow as well as on the statistics of the shear [Figs.2,3]. Concerning a sheared turbulent flow, in the strong shear limit, with localized frequency spectrum, our numerical simulation provides the scalings $\Gamma \sim \omega_E^{-1}$ for the radial flux [Fig. 2], $\langle p^2 \rangle \sim \omega_E^{-1.6}$ for the square amplitude of turbulence and $\cos\delta \sim \omega_E^{-0.2}$ for the cross-phase [Fig. 3], in the case of a mean shear ω_E. These results confirm the analytical scalings of, respectively, ω_E^{-1}, $\omega_E^{-5/3}$ and $\omega_E^{-1/6}$. We also studied the effect of the parallel diffusivity $\chi_\|$, which controls diffusion along the magnetic field lines. In the strong shear limit, parallel diffusion has no effect on radial transport, and the latter scalings are recovered. However, in the weak shear limit, an increase of $\chi_\|$ is shown to reduce the radial flux compared to the case where $\chi_\| = 0$. This reduction of transport is due to a decrease in fluctuation amplitude, despite an increase of the cross-phase, yielding a decreased radial flux, thus pointing out the important role of parallel diffusion as a general stabilizing mechanism in the weak shear limit.

In the case of random zonal flows and for low shear rates $\Omega_{rms} \simeq 10$, the square amplitude of turbulence becomes less sensitive to the shearing as the zonal flow bandwidth γ_{ZF} increases, therefore showing that the correlation time $\tau_{ZF} = \gamma_{ZF}^{-1}$ of zonal flows plays an important role. As τ_{ZF} becomes shorter, the zonal flow has less time to act on an eddy, therefore yielding an increase of the fluctuation amplitude. However, in the strong shear limit, the mean shear scalings $\Gamma \sim \Omega_{rms}^{-1}$, $\langle p^2 \rangle \sim \Omega_{rms}^{-1.6}$, and $\cos\delta \sim \Omega_{rms}^{-0.2}$ are recovered, independently of the value of γ_{ZF}. The reduction of the amplitude of turbulence observed in this passive-scalar model computation, may be the key feature for the formation of transport barriers.

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