Test particle approach of turbulent transport

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Test particle approach brings a complementary contribution to the understanding of the complex transport processes in turbulent plasmas, which is mainly obtained from large scale numerical simulations. This approach determines the diffusion coefficients as functions of the characteristics of the turbulence, not as functions of the gradients, and it deals with completely different physical quantities (mean square displacements, not average fluxes of density and/or temperature fluctuations). The condition of applicability consists of the existence of space-time scale separation between fluctuations and average quantities. The freedom in the modeling of turbulence that is characteristic to this approach permits to determine the transport regimes and to identify the dependence on parameters. We present here recent results obtained in realistic conditions for tokamak plasmas, using a semi-analytical approach (the decorrelation trajectory method [1]) that is able to describe trajectory trapping (eddying) in the stochastic potential. The model of the drift type turbulence developed in this study is based on the results of the numerical simulations and includes anisotropy and dominant wave numbers.

Low frequency turbulence (ITG, TEP, ETG) is characterized by similar shape of the spectrum. It has two (symmetrical) maxima in the poloidal wave number $k_y = \pm k_0$ and zero amplitude around $k_y=0$. The main difference consists in the typical wave numbers: $k_y\rho_i<1$ for ITG, $k_y\rho_i\sim 1$ for TEP and $k_y\rho_e\sim 1$ for ETG, where ρ_i, ρ_e are the Larmor radii for the ions and the electrons. The Eulerian correlation (EC) corresponding to these spectrum has zero integral in the poloidal direction, with negative domains and sometimes oscillatory behaviour determined by the dominant wave number. Also, the potential drifts with the effective diamagnetic velocity V_* (of the electrons or of the ions, depending on the type of turbulence). The EC corresponding to such spectrum can be modeled by

$$C(x,y,z,t) = \beta \exp\left(-\frac{x^2}{2\lambda_x^2} - \frac{|z|}{\lambda_z} - \frac{t}{\tau_c}\right)\frac{\partial}{\partial y}\left[\exp\left(-\frac{(y-V_*t)^2}{2\lambda_y^2}\right)\frac{\sin[k_0(y-V_*t)]}{k_0}\right] \quad (1)$$

where β is the amplitude of potential fluctuations divided by the confining magnetic field, k_0 is of the order of $1/\lambda_y$, τ_c is the correlation time and λ_i are the correlation lengths in the radial $i=x$, poloidal $i=y$ and toroidal $i=z$ directions. The cross sections of the EC for $x=0$ and $y=0$

are represented in Figure 1 (dashed lines). The parameters of the EC define the characteristic times: the diamagnetic time $\tau_*=\lambda_y/V_*$, which is of the order of the inverse of the typical frequency ω of turbulence, and the time of flight (or eddying time) $\tau_{fl}=\lambda_y/V_y$, where V_y is the amplitude of the electric drift. Since τ_c is of the order of the inverse of the growth rate γ and $\gamma \ll \omega$, the diamagnetic time is much smaller than the correlation time. Strong nonlinear effects in the transport are determined by trajectory trapping or eddying. The trapping parameter for drift turbulence is

$$K_* = \frac{\tau_*}{\tau_{fl}} = \frac{V_y}{V_*} \tag{2}$$

because the decorrelation is produced by the drift of the potential. We note that the Kubo number $K = \tau_c/\tau_{fl}$, which is the trapping parameter in other types of turbulence, does not play a major role in the drift turbulence, because $K > K_*$. Trajectory trapping is statistically important when $K_* > 1$.

The physical processes analyzed here are:

1) The effect of zonal flow modes on ion transport
2) The electron heat transport in multi-scale turbulence

A rich class of anomalous diffusion regimes appears in both cases when trajectory trapping is effective, i.e. when the combined action of the decorrelation mechanisms is weak enough. A very strong effect is produced by the drift of the potential with the diamagnetic velocity.

1. The effect of zonal flow modes on ion transport

We have shown in a recent paper based on an analytical approach [2] that the drift turbulence attenuation and the generation of the zonal flow are nonlinear effects determined by ion trajectory trapping in the moving potential combined with the ion polarization drift. The results are in agreement with the numerical simulations, but they do not agree with the predator-prey paradigm. Zonal flows are correlated with drift turbulence attenuation, but they are not the cause of this process. Their interaction with the drift mode is only indirect, through the modification of the diffusive damping. We study here the effect of the zonal flow modes on ion transport using the decorrelation trajectory method [1]

Zonal flow modes add to the EC of the potential (1) a function that has the same shape as that for the drift modes but with x and y interchanged, because the spectrum of the zonal flow modes has zero amplitude for $k_x=0$. There are three new parameters that appear in the EC: the relative amplitude $\beta_r = \beta_{zf}/\beta$, the dominant wave number k_{zf}, the correlation lengths λ_{zf}.

We note first that the zonal flow modes modify the shape of the EC, determining the decrease of the radial correlation length and the increase of the poloidal correlation length (Figure 1). This effect is not determined by the damping of the drift modes, but just by adding the potential of the zonal flow modes. Typical results for the transport coefficients are shown in Figure 2, where the diffusion reservoir that is the time dependent diffusion coefficient in the absence of the decorrelation is shown for the radial and poloidal directions. It was shown that the asymptotic diffusion coefficients as function of the decorrelation time follow closely these curves. Zonal flow modes determine the decrease of the radial diffusion coefficient and a strong increase of the poloidal diffusion. The poloidal diffusion becomes strong enough to produce a significant contribution to the drift turbulence attenuation. However, ion trapping combined with the drift of the potential have the main role.

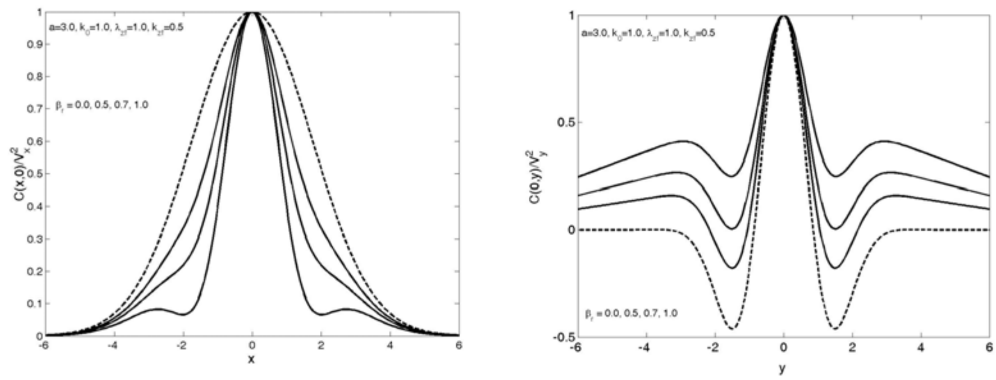
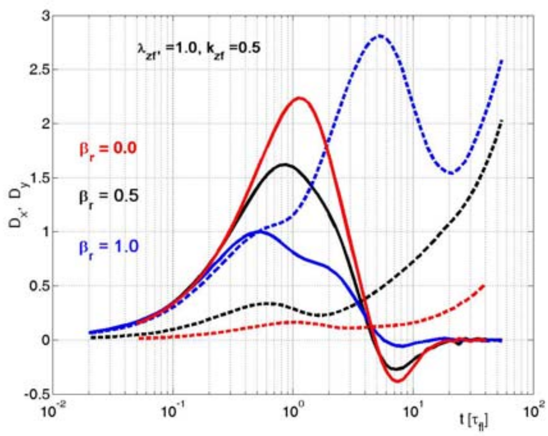


Figure 1. The radial (x) and poloidal (y) correlations of the drift type turbulence (dashed lines) and the modifications produced by adding the zonal flow contribution



Fiure. 2. The effects of the zonal flows on the radial D_x (continuous lines) and poloidal D_y (dashed lines) diffusion coefficients for two values of the relative amplitude.

Thus, the zonal flow modes have a direct effect on transport that is not mediated by the attenuation of the drift turbulence, but by the modification of the shape of the EC. This is in agreement with the experiments performed in the numerical simulations by eliminating the zonal flow modes where increase of the radial correlation length and decrease of the radial transport are observed.

2. The electron heat transport in multi-scale turbulence

We have considered a multi-scale spectrum of the stochastic potential, modelled by the superposition of two functions (1), one with small correlation lengths $\lambda_{xl}, \lambda_{yl}$ and the other with much larger correlation lengths $\lambda_{xL}, \lambda_{yL}$. The subscripts L for the large scale and l for the small scale were introduced in the parameters. The model is rather complex and contains 12 parameters that describe the turbulence plus the diamagnetic velocity V_* and the parallel velocity v_z.

The large scale determines local average velocities, which can strongly influence the electron transport provided that these average velocities are smaller than the amplitude of the electric drift produced by the small scale stochastic potential. A strong amplification of the diffusion along the average velocity appears in these conditions, due to the separation of the probability of displacements in two parts. The global electron heat transport, obtained by averaging the local diffusion coefficients over the local average velocity, increases from the small values corresponding to the small scale ETG turbulence to values of the order of the experimental ones.

The main conclusion of this work is that the electron heat transport in multi-scale turbulence can be much larger that in single scale turbulence. The physical process responsible for the increased transport is electron trajectory trapping combined with the existence of a large scale velocity. Our results show that the transport processes in two-scale turbulence are complex and that strong nonlinear effects appear in the presence of trapping. They suggest that simple well-defined scaling in the global parameters of the plasma and extrapolations cannot be obtained.

1. Vlad M., Spineanu F., Misguich J.H., Balescu R., Physical Review E 58 (1998) 7359.
2. Vlad M., Physical Review E 87 053105 (2013).