UNDERSTANDING THE ExB DRIFT NONLINEAR EFFECTS ON TRANSPORT AND STRUCTURE GENERATION IN TURBULENT TOKAMAK PLASMAS

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1. Overview

1.1. Turbulent pinch and diffusion of impurities in tokamak plasmas

Impurity transport in magnetically confined plasma is one of the important problems in fusion research. This process is not completely understood and it represents a very active research field. We have found a new type of pinch, the ratchet pinch [1], which appears in turbulent plasmas due to the gradient of the confining magnetic field □B as an average velocity directed parallel or anti-parallel to □B, depending on the characteristics of the turbulence. We have shown [2], [3] that the pinch effect is dominant compared to the diffusive transport in the nonlinear stage of the turbulence characterized by trajectory trapping (or eddying) and that it can have in these conditions much stronger effects than the curvature pinch [4], [5]. The ratchet and the curvature pinch combine in determining the evolution of impurity density [3].

The ratchet pinch induced by the gradient of the magnetic field in turbulent plasma was developed from a fundamental idea toward a complex realistic model that can be used for specific tokamak plasma studies. The milestone for 2009 is the development of the model by including the mass-charge effects. The conditions for peaked density profiles were analyzed. The mass-charge dependence of the pinch velocity and of the diffusion coefficient was analyzed. A code that determines these transport coefficients for given impurity ions in a turbulence with realistic characteristics was developed. The pinch velocity was shown to be important only in the nonlinear stage of the turbulence when trajectory trapping is effective. The dependence on the impurity mass number is nontrivial in these conditions: as A increases the pinch increases, reaches a maximum at a value that depends on turbulence parameters and decays.

A new mechanism that produces impurity loss/accumulation was identified. It is a nonlinear affect that appears due to the poloidal motion of the impurity ions. The latter has two components: particle motion along magnetic lines in toroidal geometry and particle poloidal flows induced by the drift turbulence. Depending on the ratio of the two components, impurities can be accumulated or lost. The accumulation rate depends on impurity mass through the parallel velocity. It decreases with the increase of *A*.

1.1 Turbulent transport of energetic particles

Starting from our analytical estimation [11], [12] which shows that the turbulent transport coefficient of fast particles can be larger than previously generally accepted, this problem has attracted an increasing interest in the last three years. Numerical simulation were performed in several laboratories, both for given characteristics of the turbulence and in large-scale self-consistent simulations. There are controversial results and it is very important to understand this process. The enhanced transport can appear only as a nonlinear process. We have shown that in these conditions the diffusion coefficients for small energy ions are very sensitive to weak perturbations produced by other components of the motion. Thus, the first step for understanding fast ion turbulent transport is to develop the test particle model by taking into account other components of motion. The aim is to find if the enhanced transport persists in the presence of these components of ion motion and how they influence the diffusion coefficients.

The milestone for 2009 is the study of the effect of the parallel motion on the radial diffusion coefficient of energetic particles.

The first stage was the analysis and the improvement of the decorrelation trajectory method for fast particles. The gyromotion effect on the Eulerian correlation of the potential was determined and a modified subensemble average velocity was obtained. It was shown that the effects of trapping were overestimated in [11] and [12].

The diffusion coefficient was determined as function of the turbulence amplitude and characteristic parameters, geometrical parameters and particle energy. Domains of the parameter space with substantial turbulent diffusion were found. These studies will be continued by determining the effects of magnetic drifts, collisions and plasma rotation.

2. Detailed results

2.1. Turbulent pinch and diffusion of impurities in tokamak plasmas

The main step was to introduce in the test particle or passive field advection approach a realistic model of the turbulence in the strong nonlinear phase. Starting from our recent results [6], [7] (obtained in a different project), we have identified the main characteristics of the turbulence and we have developed such a model [L1].

We have shown that the trajectory stochastic trapping or eddying in the potential has very strong effects on the nonlinear evolution of the turbulence. This conclusion was drawn from a study of drift turbulence based on the evaluation of the growth rate of test modes on turbulent state [6], [7]. The trajectory structures [8] that are generated by trapping determine the increase of the size of the potential of the drift turbulence from the range of the Larmor radius to the average size of the trajectory structures, which is much larger. An important nonlinear effect due to trapping consists in the generation of ion poloidal flows by the potential that moves with the diamagnetic velocity. The trapped ions are advected by the moving potential while the free ones move in opposite direction with an average velocity that compensates the flux of the trapped ions. The ion trajectory structures and these ion flows modify the diamagnetic velocity determining an effective diamagnetic velocity V_{*eff} . The latter is obtained as function of the size of trajectory structures and of these ion (zonal) flows. These results provide a model for the turbulence that was introduced in the test particle study of the pinch and diffusion coefficient

The turbulent transport produced by the electrostatic drift is essentially independent of the characteristics of the impurity ions (mass, charge, energy). These parameters influence the effective diffusion coefficients through other components of the motion as collisions, parallel motion, magnetic drifts, etc. The first two effects were analyzed using the decorrelation trajectory method [9].

The collisional diffusion coefficient has a weak dependence on particle mass and charge numbers (it depends on A and Z only through the Coulombian logarithm). We have shown that collisions produce in the presence of trapping a strong effect on the ratchet velocity, in the sense that large variations of the pinch velocity appear for relatively small variations of the collisional diffusivity. We have estimated the dependence on the mass number A in the weak collisional regime that corresponds to ITER plasmas. A significative decrease of the pinch velocity with A was obtained in these conditions.

The parallel motion, although negligible as a decorrelation mechanism for the ions, has a strong effect in toroidal geometry. It determines, together with the poloidal flows induced by the potential that moves with the diamagnetic velocity V_{*ef} , a poloidal motion of the impurity ions. This motion brings periodically the particles from the low to the high magnetic field side of the magnetic surface. The average period is large and thus the local approximation (with constant magnetic field) can be used for determining the pinch velocity and the diffusion coefficient. But the distribution of displacements at large time has to include this periodic change of the transport coefficients, induced by their dependence on the magnetic field. The direction of the pinch velocity is toward the symmetry axis of the torus. The periodic poloidal motion determines a pinch velocity that change periodically from inside to outside of the plasma. For uniform poloidal rotation, the larger values of the peaking factor p inside torus determine a loss mechanism. If the poloidal rotation is not uniform, the loss mechanism can be amplified (for smaller rotation velocity inside the torus) or it can be attenuated or even transformed in an accumulation mechanism (if the rotation velocity is smaller outside the torus). The shape of the plasma also contributes to this mechanism. The toroidal geometry makes the magnetic lines shorter inside torus than outside. Thus the poloidal motion determined by the magnetic structure contributes to the accumulation of impurities. The diamagnetic velocity is smaller inside the torus and thus it has a loss effect. The zonal particle flows are important when the numbers of trapped and free particles are comparable. The poloidal motion is determined by both velocities. The first depends on particle mass while the second depends on the characteristics of the turbulence. The rotation velocity produced by the parallel motion decreases with the increase of the mass number and thus it is expected that the diamagnetic velocity dominates for large mass particles leading to smaller accumulation rate than in the case of small A particles.

The pinch velocity and the diffusion coefficient were obtained for rather large ranges of the parameters: $V_{*\mathrm{eff}}$, Kubo number K, turbulence amplitude V and particle mass A. The peaking factor depends in a complicated way on these parameters. Values in the range p□(0.2,5) were obtained. Large values of p appear only for $V_{*\mathrm{eff}} < V$, more precisely for $V_{*\mathrm{eff}}$ □ 0.2V. For this range of the effective diamagnetic velocity, the effect of collisions is rather strong as well as the dependence on impurity type. It is interesting that the dependence on the mass number is not always monotonically. In the range of parameters that correspond to trajectory trapping, as A increases the peaking factor increase and then it decreases. A maximum appears for a value of A that depends on the other parameters.

The semi-analytical calculations based on test particle approached were compared with results of a numerical study based on Hasegawa-Wakatani (HW) equation in collaboration with Universite de Provence [10].

In conclusion, the main results obtained in this period were:

- Development of a model for the drift turbulence evolution in the strong nonlinear regime and identification of the main characteristics of the turbulence that have to be included in the model of tracer or density advection. An important effect is produced by the poloidal motion of the potential, which determines average ion (zonal) flows in the nonlinear (trapping) regime.
- A new mechanism that produces impurity loss/accumulation was identified. It is a nonlinear affect that appears in toroidal geometry due to the poloidal motion of the impurity ions induced by the motion along magnetic lines and by the poloidal flows generated by the moving potential.

2.2. Turbulent transport of energetic particles

Based on calculations dating back to1979, the conventional wisdom is that, in the absence of long-wavelength MHD instabilities, fast-ion confinement is much better than thermal ion confinement. In particular, it is generally assumed that the alpha particles and high-energy neutral beam ions that will heat ITER will be well confined unless they drive Alfven waves unstable. The reason is that the effective motion of the guiding centers is determined by the average of the stochastic potential over cyclotron gyration, which is smaller than local values and goes to zero as the Larmor radius increases to values much larger than the correlation length. Starting from our analytical estimations [11], [12], which show that fast ion diffusion in turbulent plasma can be significative, even larger than for plasma ions, this problem was much studied in the last years (some of the papers published this year are [13]-[16]). These studies, most of them based on numerical simulations, have shown that the turbulent transport of fast particles is complex and that in some conditions it can be much larger than predicted by the classical theory.

The decorrelation trajectory method for determining the fast ion diffusion coefficients was improved. A smaller effective correlation length of the gyro-averaged potential was obtained, which determined diffusion coefficients smaller than in the first estimations [11]-[12]. The maximum possible diffusion coefficient is of the order D_{max}□ $V\lambda$, where V is the amplitude of the stochastic electric drift and λ is its correlation length. This rather large value can be attaint in special conditions that depend on the characteristics of the turbulence, on particle energy and on the other components of the motion as parallel motion, collisions, average velocity and magnetic drifts. The maximum diffusion appears for fast particles with $\rho >> \lambda$ when the effective Lagrangian correlation τ_L is of the order $2\pi\rho/V$.

In the nonlinear regime characterized by trajectory trapping, different perturbations of the ExB drift motion interact in a complicated way producing effects that are completely different of the superposition of their separate actions. We have shown this property in the case of drift transport and a similar behavior is expected for Lorentz transport.

The effect of the parallel motion was analyzed. The diffusion coefficients decrease with the increase of the parallel velocity in the quasilinear regime. The effect is reversed in the nonlinear stage when trajectory trapping is present. In these conditions, the diffusion coefficient is an increasing function of the parallel velocity. It also depends on the size of the tokamak (through the parallel correlation length) and on the correlation time.

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