ANOMALOUS TRANSPORT IN TURBULENT PLASMAS

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Results obtained in 2007

1. ELM modelling. (Provision of support to the advancement of the ITER Physics Basis)

Reduced models of ELM's provide a possibility to obtain statistical information on rare, intermittent and large amplitude events, where ab-initio numerical simulations of large tokamaks require huge parallel computing resources to collect reliable statistics. Intermittent events in ELM are related to heat load problems on plasma facing components in large tokamaks.

Milestone 1.1: ELM modeling by stochastic differential equations, study of intermittence effects.

The results of previous heuristic results on the mechanism of on-off intermittency from the work S. Aumaitre et all, P.R.L. 95, 064101 (2005) was generalized with rigorous proofs, by using the results from [1]. From the new model [2-4] a new stochastic mechanism for noise–driven relaxation oscillations, including ELM's was obtained. In this framework, the exact form of the asymptotic behavior of the stationary probability density was obtained and the study of the stochastic linear stability analysis was started. New mechanism for generation of the coherent structures was proposed and stochastic numerical approximation for the collision term in gyrokinetic codes was obtained. The work was done in collaboration with Dr. X. Garbet from C.E.A. Cadarache and will continue in 2008.

Milestone 1.2: Discrete time reduced deterministic models for relaxation oscillations.

The purpose of the study was to investigate the possibility of generating the same chaotic effects as with the external noise terms in the previous ELM models, by deterministic chaotic mechanism. The conclusion is that on-off intermittency behavior can be reproduced qualitatively by discrete time, 2 component versions of reduced ELM models, without external noise. This result is a new support for reduced stochastic models for on-off intermittency effects. The results were obtained in collaboration with Dr. X. Garbet from C.E.A. Cadarache.

2. Stochastic test particle dynamics.

New mechanism for particle transport in tokamak was studied in the framework of stochastic mechanism of instability growth in the edge plasma turbulence. From the mathematical study a new *method for the reduction of particle loss* from large tokamaks was derived. The improved numerical methods will be used in the optimisation of the gyrokinetic codes for ab-initio simulation of the large tokamaks.

Milestone 2.1: Test particle dynamics in stochastic electrostatic field, mathematical methods.

By new mathematical methods from [1] the large time asymptotic properties of the mean square displacement of test particles in random electromagnetic field generated by instabilities was studied. A new kind of transport, "extreme transport", was discovered. In this class of transport the mean square displacement increases according to $O(\exp(const \times t^{2H}))$, where the typical value of the Hurst exponent is $H \approx 0.75$. It follows that by reducing the value of the exponent H in tokamaks, the particle loss is largely reduced. The isotope effect paradox is explained and new limits on the guiding center approximation were obtained [5-7] in the frame of collaboration with Dr. B. Weyssow from ULB Belgium.

Milestone 2.2: Test particle dynamics in stochastic electrostatic field, elaboration of improved numerical methods.

The problem of extending the mean field approximation methods, by adding stochastic components determined from self-consistency conditions, for the study of interacting charged particles was considered. On simplified models the problem of replacing the deterministic electrostatic field in the Vlasov equation by a self –consistent field with stochastic component was studied. In the case of linear models the stochastic term restored the exact result. In order to perform extensive numerical test of the self-consistent stochastic approximation, the first step was the elaboration of specialized stochastic Runge-Kutta methods. The numerical stability of these schemes was studied and robustness criteria were derived in ref. [8]. The work was partially done in collaboration with Dr. B. Weyssow from ULB Belgium.

3. <u>Development of a Hamiltonian map for particle trajectories</u>.

The advantage of the mapping methods consists in the possibility to discover fine structures in the phase space of dynamical systems, like fractal structures, closely connected to the anomalous transport in tokamak. These fractal structures are related to the impurity transport, important for the optimisation of the large tokamaks.

Milestone: Formulation of a Hamiltonian map for particle trajectories. Application of the Hamiltonian map for particle trajectories to impurity transport.

This study was devoted to the transverse particle motion in turbulent electrostatic field with fixed magnetic field. The tokamak structure was modeled in the cylindrical approximation. The turbulent electrostatic field was modeled by linear superposition of Fourier components. The Poincare map was derived by using the non-commutative effects in the classical decomposition method in numerical integrations. The robustness of this approximation results from ref. [8]. The dependence of the impurity trapping effects on the spectrum of the turbulent electric field and specific charge was studied. The fractal structure, similar to Julia sets, of the domains of the trapped particles was observed. The reduction of the fractal dimension of the domain of trapped particles in tokamak, with the increase of the intensity of short wave components was observed. The work was partially done in collaboration with Dr. B. Weyssow from ULB Belgium.

4. **Anomalous transport of impurities in tokamak plasma**.

Milestones: Evaluation of the α-particle flux. Influence of the radio frequency heating on the quasineutrality condition.

The transport of impurities driven by the instabilities is modified in the presence of radio-frequency heating [6, 9-11]. The quasi-neutrality condition contains besides characteristics of instability wave, the characteristics of radio-frequency waves used for plasma heating and current drive. First we have evaluated the density perturbation given by the passing particles in the presence of ion cyclotron resonant heating (ICRH) in tokamak plasma with electromagnetic turbulence. For two different radial localization of the resonant layer we evaluated the radial variation of the density perturbation [12-13]. The results indicate a significant modification of the density perturbation for parallel heating wave number greater than 1/cm. It was also observed a disparity in the position of the resonant layer absorption compared with the radial position of a significant density perturbation. We used plasma parameters corresponding to ITER design. The obtained results are important for a better understanding of the turbulent particle transport in core tokamak plasma in ICRH regime. The work was partially done in collaboration with Dr. B. Weyssow from ULB Belgium and will continue in 2008.

5. **Electron transport in the presence of RF heating**.

Milestones: Evaluation of the electron density perturbation in plasma with rf heating.

Perturbation of electron density due to electrostatic turbulence in presence of radio-frequency waves (ECRF) was evaluated in the case of TEM (trapped electron mode) using kinetic formalism. This will be used in future study of the quasi-neutrality condition in presence of radio frequency heating.

6. **Theory related to specific models for particles and energy transport in SOL**.

Milestones 6.1: The study of the diffusion of a stochastic anisotropic sheared magnetic field lines using the decorrelation trajectory method.

The anisotropy in the magnetic fluctuation spectrum (stochastic anisotropy) and magnetic shear induces variations of global averaged quantities such as the running and the asymptotic diffusion tensors that can be investigated using a semi-analytical method [14]. The study considers ranges for the anisotropy parameter, magnetic Kubo number and shear parameter leading to contrasting dynamical behaviors. In particular, the trapping of the stochastic magnetic field lines is analyzed. An asymptotic 'poloidal' velocity larger for stronger anisotropy is obtained for the wandering of the magnetic field lines for different values of the parameters. The averaged Lagrangian poloidal velocity is represented in Figure 1 for different values of the y-stochastic anisotropy and for a single value of the Kubo number and the shear parameter $K_s = 0$ and $K_s = 2$. For $K_s = 2$ and for a short time interval the averaged poloidal velocity is negative whatever the anisotropy. The magnitude of the averaged velocity is constant and non-zero in the shearless cases and a fixed x-anisotropy ($\Lambda = 5$) when the magnetic Kubo number takes the values $2 > K_m > 0.5$. The presence of the shear ($K_s = 2$) changes the feature of the averaged velocity: the magnitude of the final velocity is greater than in the shearless case and grows when the level of magnetic turbulence grows. The space variation of the magnetic field, i.e. the magnetic shear, creates the average poloidal velocity even in absence of an initial velocity of the field lines. Thus the inhomogeneity of the magnetic field determines a directed transport because the magnetic potential depends on the 'z' coordinate, which plays here the role of time. In absence of the magnetic shear, for relatively small magnetic turbulence and different values of the stochastic anisotropy, the average poloidal velocity is zero.

This study shows that the mean magnetic shear and the stochastic anisotropy have an important role in the self consistently generated poloidal flow, known as reducing the radial turbulent transport. This mechanism contributes in large tokamaks like ITER to a rapid transition in an enhanced confinement regime, H-mode.

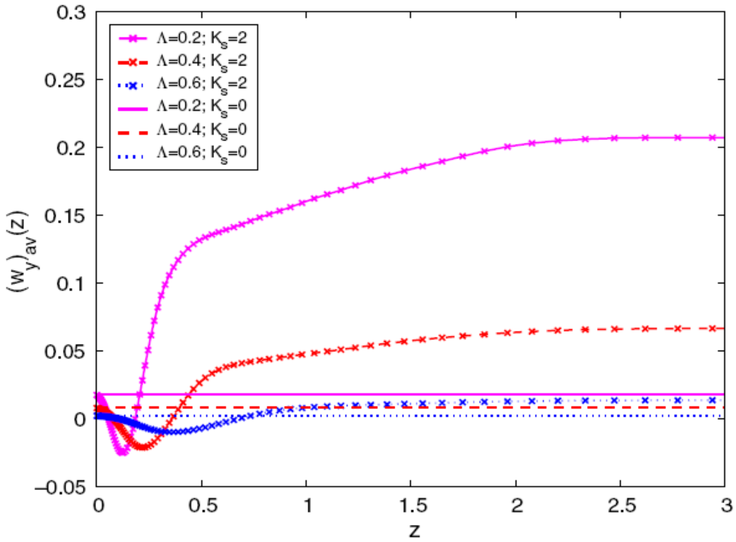

Figure 1: Average poloidal velocity for different values of the y-anisotropy. Other parameters are set to K_m=0.5 and K_s=0 or K_s=2.

Milestones 6.2: Theory related to specific models for particles and energy transport in SOL. Zonal flow case.

We have demonstrated that the growth of the diamagnetic Kubo number produces a suppression of the generation of the zonal flow in weak electrostatic turbulence [19]; it is an effect of the combined variation of the gradient length and of the stochastic characteristics of the electrostatic weak anisotropic turbulence. A real situation (e.g. a tokamak) is complex, but our model indicates that, under certain circumstances, the drift wave turbulence generates spontaneously a shear flow in the poloidal direction. The latter is random and is characterized by a correlation length that is much longer in the poloidal direction than in the radial one. We have also calculated global Lagrangian average of k, v_g and ω(θ) – Figure 2; their time evolutions have confirmed the tendency of suppression of zonal flow when the initial wave-vector is $k_{0x} = (0.8)^{1/2}$, $k_{0y} = (0.2)^{1/2}$. Our results give a contribution to the role of zonal flows in anomalous transport and creation of transport barriers, which are important for ITER.

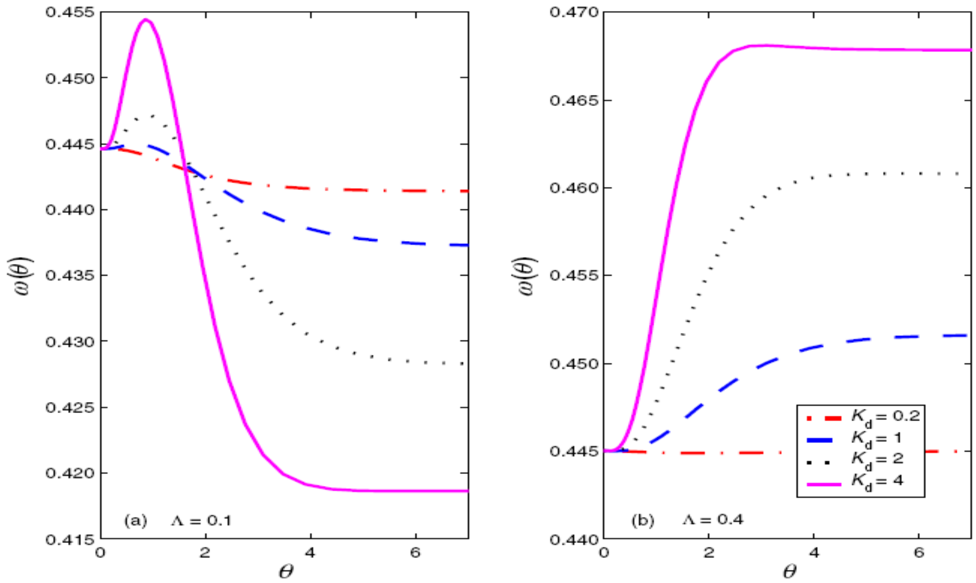

Figure 2: The Lagrangian global average of the normalized drift wave frequency for $k_{0x}= (0.2)^{1/2}$, $k_{0y}= (0.8)^{1/2}$, K=0.2, Λ=0.1 (subplot (a)) and Λ=0.4 (subplot (b)) and four values for the K_d.

Milestones 6.3: Particle dynamics and anomalous diffusion in stochastic electromagnetic field.

The electron diffusion induced by a two-dimensional electrostatic turbulence, in a sheared slab approximation of the toroidal magnetic geometry, is studied by direct numerical simulation. The 'radial' and the 'poloidal' running and asymptotic diffusion coefficients of electrons are obtained for physically relevant parameter values and the existence of an enhanced diffusion in the poloidal direction is observed in the presence of magnetic shear. The global effects of K^{sim} and K_S^{sim} on the running and asymptotic diagonal diffusion tensor components are exhibited using direct numerical simulation for a guiding center system in a first order of drift approximation. The radial running diffusion coefficient (Figure 3) starts with a linear part characteristic to a ballistic regime, $D_{xx}(\tau) \sim \tau$. In all of the cases a trapping effect appears for large enough values of K^{sim} and/or K_S^{sim}. We can conclude that an enhancing of the diffusion on poloidal direction and a relatively reduction on the radial one is caused by the presence of the magnetic shear for the same level of electrostatic turbulence. In our paper we have calculated the diffusion coefficients for the electrons by direct numerical simulation and we have found a very good qualitative agreement with the results obtained by the decorrelation trajectory method [15]. This conclusion gives a relatively certitude in order to apply DCT to other problems of interest where a Langevin treatment can be done.

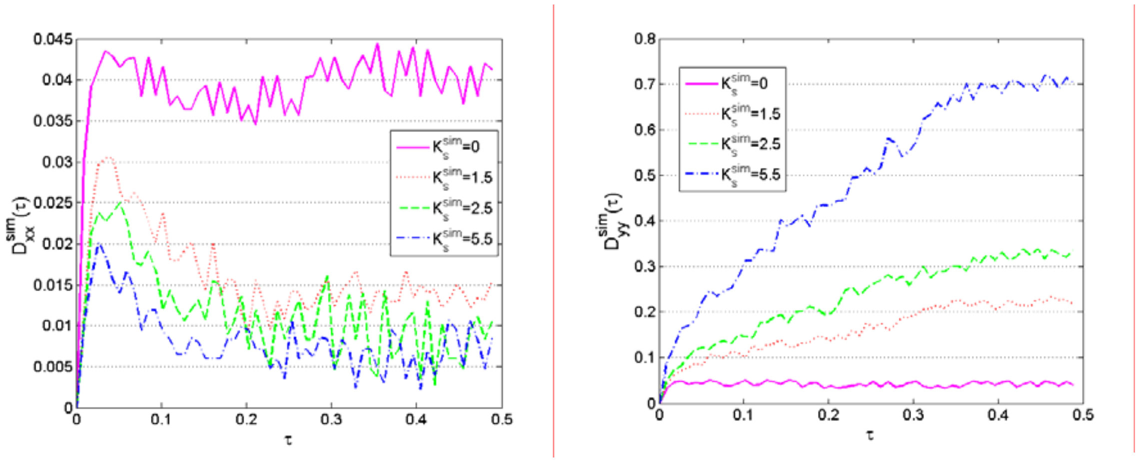

Figure 3: Diagonal running diffusion coefficients for $K^{sim} = 2.5$ *and different values for magnetic shear*

We have used in our various analyses the decorrelation trajectory method and the direct numerical simulations, which were performed mostly using the computing facilities of ULB-VUB Belgium and in collaboration with Dr. Boris Weyssow from ULB Belgium. Some comparisons between the results obtained by these two different methods were done and a good qualitatively agreement was emphasized [14-19]. In many cases, the magnetic shear is a key parameter. This feature has been shown in JET, ASDEX-Upgrade, TCV, FTU and TORE SUPRA, and is utilized to gain plasma stability. In consequence, all the reported results and the numerical simulations are important for "*Validation of physics-based transport models*" and "*Plasma edge characterization and modelling*", objectives for ITER.

7. Internal transport barriers, magnetic reconnection and anomalous transport in tokamaks.

Milestone 7.1: The study of the diffusivity of some magnetic fields using mathematical models generated by symplectic maps

The accuracy of some general mathematical models (discrete Hamiltonian systems) used for the description of the magnetic field configuration and of the charged particles' dynamics in tokamaks was systematically studied. The magnetic diffusivity of the magnetic field specific to ASDEX-Upgrade tokamak was computed directly from the mathematical models generated by symplectic maps. The conclusion was that the diffusivity is larger in the region where the dynamics of the magnetic field lines is chaotic (also called stochastic) and it is closely related to the chaotic indicators of the orbits [20-21]. The technique presented in [20] was applied in order to obtain a realistic model for the description of the charged particles' motion [22]. These results were obtained during the mobility at Universite Libre de Bruxelles. These dynamical features could be used in the theoretical description and mathematical simulation of internal transport barriers in large tokamaks, like ITER.

Milestone 7.2: The study of the influence of the reconnection on the transport.

By using the Tokamap model (specific to Tore Supra) we studied the influence of the safety factor on the formation of the magnetic transport barriers and on the main properties of the magnetic transport. It was observed that the stochastization of the magnetic field, generated by the reconnection, increases the diffusivity of the magnetic field and drastically modifies the transport properties [23-24]. The statistical aspects of the anomalous transport related to contamination of the tokamak plasma with multiply ionized impurities, elimination of the helium ash were studied during the mobility at ULB Bruxelles. The results are relevant for the estimation of the particle loss, heat load on the ergodic divertor plates, phenomena, which are partially caused by the anomalous transport generated by chaotic particle dynamics.

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