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Ion kinetic transport in presence of collisions and electric field in TJ-II ECRH plasmas.

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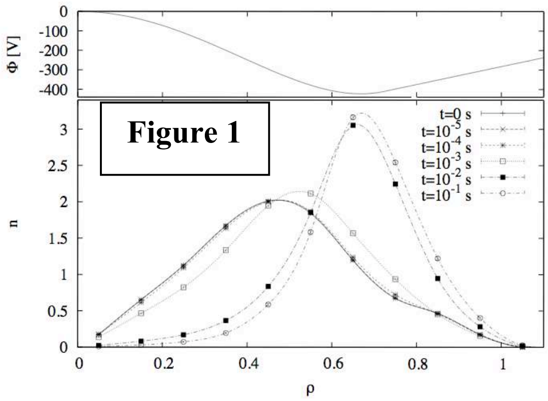
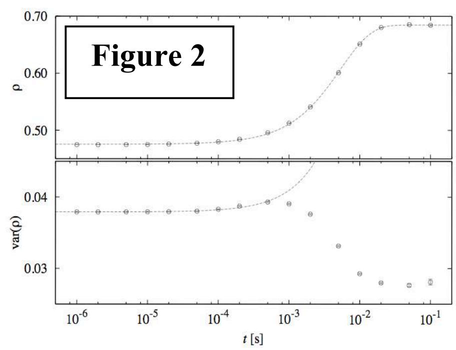
1. Introduction. The customary neoclassical transport estimates (DKES and Monte Carlo codes) assume that transport coefficients depend only on local plasma characteristics: magnetic structure, electric field and collisionality, i. e., the typical size of trajectories performed during a collision time is assumed to be small. TJ-II is a medium size stellarator of the flexible heliac type (R=1.5 m, a<0.22 m) characterized by its complicated magnetic configuration. Ion confined in TJ-II, in the lmfp regime, perform large radial excursions, thus visiting plasma regions with very different characteristics and making invalid the local approximation. In a previous work[1], global transport properties were estimated by following the trajectories of a large number of protons during two collision times. In this work, we improve over the latter study by considering collisions. Specifically, we follow the trajectories of 10^6 ions in TJ-II ECRH plasmas, for times up to 0.1 s (in order to describe the stationary part of the TJ-II pulse, that lasts about 0.3 s). The temperature profile, taken from CX measurements, is almost flat for these low density plasmas[2], and the electron density profile is hollow. The potential profile, taken similar to those obtained by HIBP measurements, presents a minimum around effective radius $\rho \approx 0.7$. The 3D magnetic configuration is considered by using a grid that fits the magnetic surfaces in the real space and does not need to assume nested surfaces, although no islands are considered up to now.

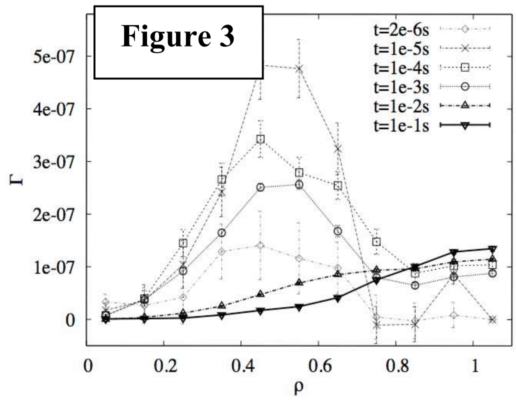
2. The model. We have developed a computer code, with name ISDEP (Integrator of Stochastic Differential Equations for Plasmas), that solves the guiding-centre equations in presence of collisions. The collision operator is the one introduced by Boozer and Kuo-Petrovic[3] by linearising the Fokker-Planck equation for the phase-space distribution function *f,* which is the distribution function of test particles moving in (and colliding with) a stationary thermal bath, described by experimentally fixed density, temperature and electrostatic potential profiles. We have chosen *f* at *t=0* according to the underlying bath. From the equivalence between the Fokker-Planck and Langevin equations, we arrive to a set of five coupled stochastic (Stratonovich) differential equations with uncorrelated multiplicative Gaussian noises. After a thorough study of the error induced by time and space discretisations, we have used the Kloeden and Piersen algorithm[4] (first order and weak convergence with multiplicative Gaussian noises) for solving the equations. Particles may *die*, when they collide with the groove and the walls of the vacuum chamber or when they go beyond ρ=1.5. We define the persistence up to time *t*, *n(t)*, as the fraction of trajectories that are still *alive* at time *t*. The estimated evolution of *n(t)* is not purely exponential: at short times, some curvature is observed for $t< 0.02$ s but the persistence decays exponentially, $n(t) \propto e^{-t/\tau}$, for later times. Fitting to a purely exponential decay from *t=0.0075* s on, we find: $\tau_{E=0} = 0.0090(1)\ s$ and $\tau_{E\neq 0} = 0.0286(1)\ s$. Although in TJ-II the field is indeed present, the calculation has been made both with and without radial electric field. Our computer experiment allows us to conclude that the radial electric field tends to improve plasma confinement by a factor three. These results can be compared with the experimental particle confinement time of 21(3) ms [5].

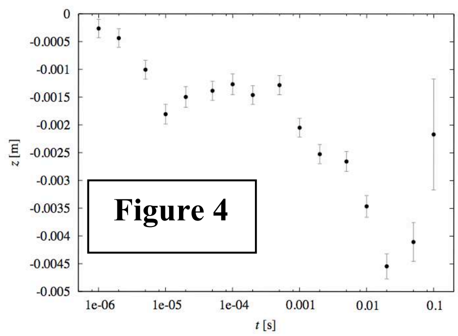




3. Results and non-local transport features. The evolution of the average effective radius of all the particles shows that, in presence of collisions, ions tend to accumulate close to the minimum of potential. In Fig. 1 we plot the ion density as a function of the effective radius for several times (note that the curves are normalized to unit area). We also show the electrostatic potential profile. In Fig. 2 we show the time evolution of the average and the variance of ρ of the ions present in the plasma. If transport were diffusive, we would expect the variance of the radial coordinate to have a linear evolution in time, var(ρ) ~ *t*. This seems to be true for early times, t<10^{-3} s (see the linear fit), but not for longer ones: despite of taking into account the collisions, the ion global transport is not diffusive during the process of accumulation close to the minimum of potential. Once the equilibrium is reached at long times, the diffusive behaviour is recovered. Moreover, one can fit the time evolution of the average ρ to $\langle\rho\rangle = \rho_f + (\rho_0 - \rho_f)\exp(-t/\tau)$, finding an exponential approximation to equilibrium from ρ to ρ_f, with $\tau \sim 5\times10^{-3}$ s.

A more detailed insight can be obtained by studying the particles and energy radial fluxes integrated to every magnetic surface (see Fig. 3). At every selected time, the curves are normalized by the total number of remaining particles. For a broad range of time, 10^{-6} s< t <10^{-2} s, there is a wide maximum in the $0.4 < \rho < 0.7$ region, when the ions are drifting to the minimum of the potential. The energy flux shows the same qualitative behaviour. Thus, it seems that all the ions, no matter its kinetic energy, are affected by the field, although the most energetic particles will be less sensitive to the field effect. The reason is that the height of the minimum of plasma potential is about *400* eV, several times the mean kinetic energy of ions. For greater times, the flux profiles increase monotonically to the edge. This is related to the process of particle escapes, which occurs mostly at long times. This last result (obtained taking into account the actual geometry) cannot be explained in the frame of the local ansatz: The standard calculation methods predict a non-monotonic behaviour with a maximum close to $\propto -0.3\,\tau\,0.4$.





The complexity of the magnetic configuration and non-local transport are in the origin of several non-negligible asymmetries, some of which have been observed experimentally[6]. In particular, difference between up/down fluxes leads to different density of particles in the upper and lower half of the device. Fig. 4 shows the time evolution of the average z-coordinate of the ions. Starting with approximately equal amount of ions at each half of the device, $\langle z\rangle$ decreases monotonically at early times and immediately separates from zero. Nevertheless, for 10^{-5} s < t < 10^{-3} s, the proportion of up/down ions remains nearly constant. In the same interval (see Fig. 3), there is a broad maximum in the flux at medium ρ, when the ions are being attracted towards the minimum of the potential, so the electric field has a clear symmetrising effect. The time evolution of $\langle z \rangle$ in absence of electric field supports this affirmation: the proportion of up ions decreases monotonically with no plateau.

We define a new poloidal angle, $\theta = \chi - 4\phi$, in order to take into consideration the TJ-II geometry (τ and ϕ are the usual poloidal and toroidal angles). Now, $\tau = \neq$ corresponds to the groove region. Fig. 5 shows the density as a function of θ for several times. The profiles are normalized by the initial value, thus taking into account the volume in real space of the θ intervals. For $t > 10^{-3}$ s there is a non-negligible accumulation of particles in the vicinity of the groove. This happens when ions losses become important and makes important to remove the usual assumption that the large parallel transport is able to homogenize the magnetic surfaces. Thus, it is questionable that collisional transport can be approximated by a 1.5D geometry in the lmfp. The flattening of ion temperature profile in this low collisionality regime, previously observed experimentally[2], is other of the global transport consequences. Ions visit distant parts of the plasma along their lives, in the extremely lmfp regime, thus mixing the low and the high energy ones and giving a flat energy profile, which is also a feature of the non-diffusive transport. Despite the presence of collisions, the ion distribution function becomes non-Maxwellian due both to selective losing of particles in velocity space and to the presence of electrostatic potential that provides an increase of kinetic energy when particles approach the minimum of potential. In a further work, we plan to study higher collisionality plasmas to find out what of these non-local features can still be found.

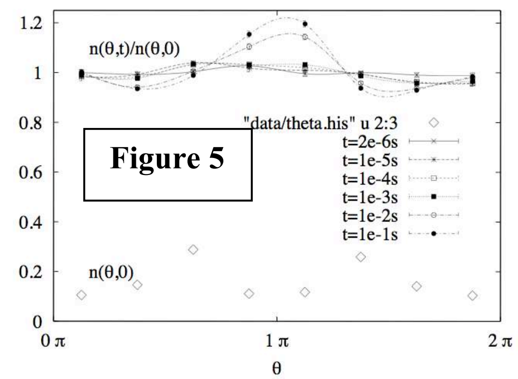


Figure 5

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