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Kinetic Simulation of Heating and Collisional Transport in a 3D Tokamak

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Introduction

Transport and heating are usually described as separated processes, the former is customarily solved by fluid equations and the latter, that is considered as a source term of the transport set of equations, is calculated in the frame of kinetic theory. However, there exist several phenomena that show that transport is modified by the heating effects. For instance, the main effect of electron cyclotron resonance heating (ECRH) on transport is to cause an extra outward flux called pump-out, which is manifested through by density profiles.

In this work, we solve the transport and heating simultaneously taking advantage of the equivalence between the (linear) Fokker-Planck and Langevin equations [1]. The latter are Stochastic Differential Equations for a single particle, which means that the variation of any coordinate in phase space depends on a deterministic term, proportional to $\mathrm{d}t$, and on a random term proportional to $\mathrm{d}W$, which describes a Wiener process.

The Wiener process introduces diffusion phenomena in the system evolution. Using Langevin equations we can follow particle trajectories in the confined plasma, affected by electromagnetic fields using the guiding center approximation and collisions with other particles via Boozer and Kuo Petravic operator (see [2] and references therein). We include nonlinear evolution of the background temperature using an iterative method, updating the temperature at each step.

The Langevin Equations for Ion Dynamics

We start from ISDEP, a Monte Carlo code that solves the ion kinetic transport by following the guiding centre orbits, including electron-ion and ion-ion collisions [2], and we introduce a new term in the equations that estimates the microscopic wave-particle interaction equations that was first written in Langevin form in [3]. As we deal with ion transport, the heating method that we consider is Ion Cyclotron Heating (ICH) in the range of the second harmonic of ion cyclotron resonance frequency, which is based on launching a resonant electromagnetic wave

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from the edge of the confined plasma. In our case, the randomness represented by the Wiener processes of the interaction is related to the collisions with the background plasma and with the random relative phase between particles and waves. In this work we do not introduce any kind of turbulent transport yet. The wave-particle interaction is formally the same as in the ECRH case, i.e. it can be considered as a resonant diffusion in momentum space.

We use ISDEP to integrate a large number of independent trajectories and calculate the main confinement properties as the average energy, temperature, particle and heat fluxes, confinement time, etc. One of the main advantages of this code is that it scales perfectly in massive parallel clusters. In fact, all the calculations have been done using grid computing techniques. We choose a tokamak device with ripple instead of a complex 3D device, since we are interested in studying the influence of the heating on transport rather than on the confinement properties of a given magnetic configuration. The profiles are analytical, so we avoid any kind of numerical error induced by interpolation.

Linearizing the Boltzmann equation is equivalent to studying the test particles keeping static the background plasma. This makes the study of heating effects impossible because no temperature rising will be observed in the background although fast ions will transfer their energy. We will solve this problem using a self-consistent iterative method: we allow variations in the background temperature profile, given by the evolution of particle temperature. In this work we keep the background density constant, assuming that the sources are able to supplement the particle losses. As temperature we use the average square velocity: $v^2(\rho,t)$. Let q_i be the quotient of the kinetic energy in the i-th iteration with ICH and the energy without ICH. Then, in the iteration $i+1$ we take as temperature the initial profile multiplied by q_i:

$$q_i(\rho,t) = \frac{v_i^2(\rho,t)}{v^2(\rho,t)}, \qquad T_{i+1}(\rho,t) = T_0(\rho)\cdot q_i(\rho,t)\,. \tag{1}$$

Results

We stop iterating when we reach steady state and, therefore, we find a self-consistent profile in v^2 (fig. 1). The main results of this work are the comparison of fluxes, velocities and distribution function between simulations with and without heating. The evolution of the particle flux profile is plotted in fig. 2, which shows that this is always larger in the presence of heating, especially for $t > 10^{-3}$ s, which is the typical time scale for plasma heating to be relevant. The steady state flux is monotonic, as corresponds to the absence of sources or sinks. The heat flux profile evolution (fig. 2) is again monotonic in steady state ($t = 5\cdot 10^{-2}$ s), but the gradient in the centre of the device is much larger in the case of ICH than in the one without heating, since the heat

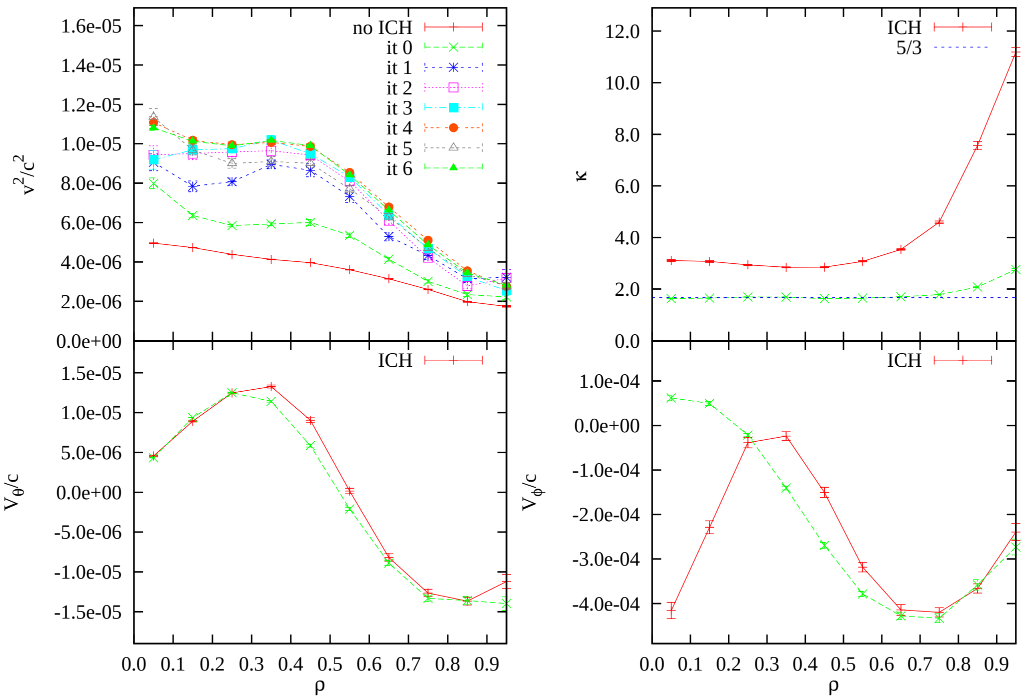

Figure 1: Iterations of the v^2 profile (upper, left), Binder cumulan (upper, right), poloidal velocity (lower, left) and toroidal velocity (lower, right).

source is located in $\rho = 0$. Also we calculate the toroidal and poloidal velocities profiles (fig. 1). We see that the poloidal velocity does not change because it depends mostly on the $\vec{E} \times \vec{B}$ drift, and it is not modified in the system. On the other hand, v_ϕ is strongly influenced by ICH, because if v^2 grows while v_θ is constant, then v_ϕ increases. This increment, focused on $\rho \simeq 0$, is propagated radially via diffusion processes.

We compute the probability distribution function ($v^2 \cdot f(v,\phi)$), in terms of v and ϕ (fig. 3). We find that with a small ripple (1%) $f(v,\phi)$ does not depend on ϕ in any case, which implies that the parallel transport is able to overcome the local heating produced by the antennae. It is clear

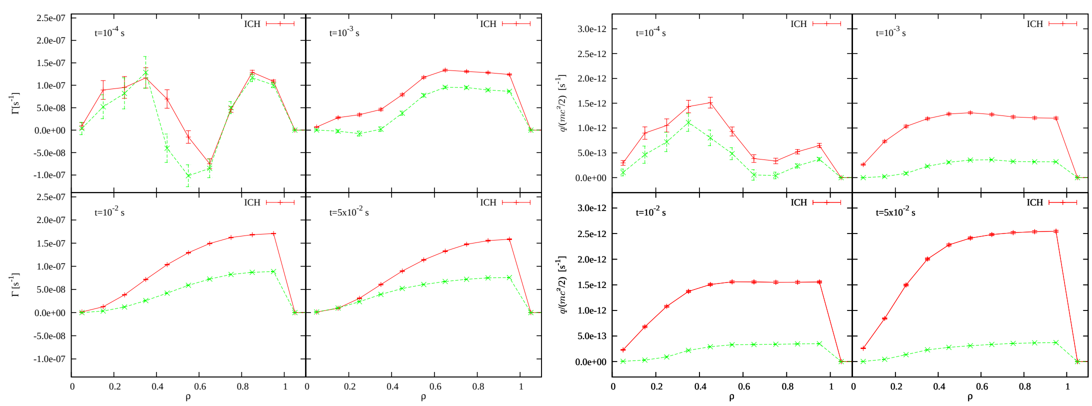

Figure 2: Particle fluxes (left) and heat fluxes (right)

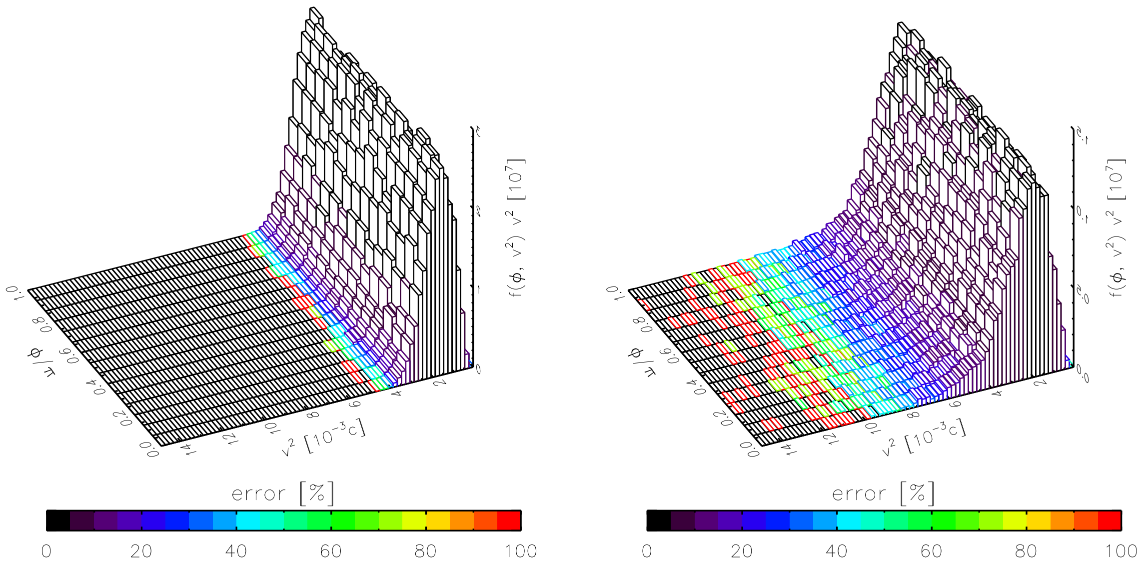

Figure 3: Velocity probability distribution functions, as a function of the velocity and the toroidal angle without (left) and with ICH (right).

that the effect of heating tends to make the distribution function wider , rising its tail and creating an important number of suprathermal ions. The Binder cumulant, defined as $\kappa := \langle v^4 \rangle / \langle v^2 \rangle^2$, measures deviations from the Maxwellian distribution (fig 1). In the plasma without ICH, the cumulant is equal to 5/3 at every time, except in the outer plasma radius where an increase of fast particles due to the transport is observed. The ICH plasmas show clear effects of heating with a cumulant larger than the Maxwellian value, with a local maximum in the centre of the device and an increase close to the plasma edge due to the effect of fast ion transport.

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