Fast Ion Simulations in Stellarators

A. Bustos[1,2], F. Castejón[1,2], M. Osakabe[3], L. A. Fernández[2,4], V. Martin-Mayor[2,4]

[1] *National Fusion Laboratory, EURATOM-CIEMAT, 28040 Madrid, Spain*

[2] *BIFI, Zaragoza, Spain*

[3] *National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan*

[4] *Complutense University, Madrid, Spain*

Introduction

NBI heating plays a crucial role in the physics of most fusion devices, since it is a valuable method for ion heating and plasma fuelling. The understanding of the transport of the fast ions that come from NBI is very important since the heating efficiency depends strongly on their confinement and they carry a significant fraction of the total energy. The NBI fast ion distribution function is calculated for LHD and TJ-II plasmas using the orbit code ISDEP. In the present work the fast ion population is considered as a perturbation to a static plasma background and its dynamics given by the guiding center movement and collisions with ions and electrons.

The orbit code ISDEP [1] (Integrator of Stochastic Differential Equations for Plasmas) is used to perform simulations of fast ion transport. ISDEP is a linear Monte Carlo code that solves the Fokker-Panck equation for the test particle population integrating ion guiding center equations of motion in 5D phase space taking into account i-i and i-e collisions with the background plasma. ISDEP avoids approximations on the size of the orbits and on the diffusive nature of transport. In fact, interesting non-diffusive features have been found for neoclassical dynamics in complex geometries like the TJ-II one [2]. ISDEP uses cartesian coordinates, overcoming in this way the limitations of the magnetic coordinates and allows the inclusion of geometries with magnetic islands or ergodic zones. As a consequence, the properties of ion transport in the scrape-off-layer can be studied as well as the hit points on the vacum chamber of the device, as was done in Ref. [3] for TJ-II. This collisions with the vacum vessel are the only test particle losses. Using Green's function formalism, the steady state distribution function is calculated for stationary source.

The plasma background equilibrium in the two stellarators studied is obtained with VMEC considering the typical plasma profiles for this type of discharges. The scrape-off-layer is simulated by an extrapolation of the equilibrium.

Simulations for LHD

Even though in LHD most of the NBI heating power comes from tangential injection, in this work we simulate fast ions injected perpendicularly by NBI line number 4 (6 MW power) in order to compare with experimental results in future works. The ions are initialized following the distribution function provided by the code HFREYA (three peaks in energy at $\sim 35, 18, 12\,\mathrm{keV}$). In these simulations the electric field is disregarded. The plasma parameters are roughly $T_i = T_e \sim 1-2\,\mathrm{keV}$, $n \sim 2\cdot 10^{19}\,\mathrm{m}^{-3}$ for the standard configuration with magnetic axis $R_0 = 3.60\,\mathrm{m}$.

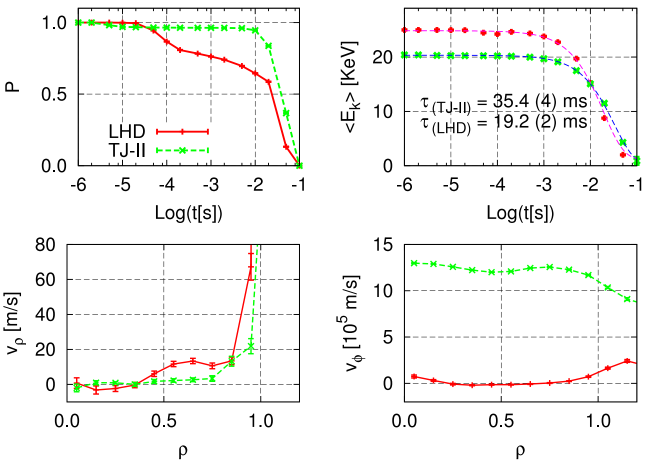

Figure 1: Persistence of the test particles and average kinetic energy as a function of time (up). In the steady state, radial velocity and toroidal rotation profiles are plotted (down).

All the properties of the fast ion confinement can be taken from statistical measurements on the trajectories of the launched particles that interact with the background. The first important quantity we can estimate is the slowing down time, which is defined as the time that the average energy of the whole beam takes to reach the background temperature. Fig. 1 shows the time evolution of the beam average energy and this curve is fitted by an exponential whose time constant gives the slowing down time. The big slope in the persistence $P(t)$ at $t \sim 10^{-4}$ s is caused by prompt losses. The radial velocity v_ρ is proportional to the fast ion radial flux. The radial profile indicates the existence of three zones of different particle confinement: for $0 < \rho < 0.4$ the confinement is very good, it gets worse for $0.4 < \rho < 0.9$ and becomes very bad when $\rho > 0.9$. The toroidal rotation, given by the toroidal velocity v_φ, presents a strong shear, changing sign twice while moving in the radial direction.

The distribution function of the fast ions is plotted in Fig 2. ISDEP can not provide absolute values of f, so the results are presented normalized so $\int d\rho\, dv_{||}\, dv_\perp J(\rho, v_\perp) f(\rho, v_{||}, v_\perp) = 1$. Nevertheless, real values can be calculated multiplying with the incoming flux of particles. Traces of the continuous injection of high energy ions can be seen everywhere but in the outer position. Thermalization occurs in a similar time scale as particle confinement (see Fig. 1). It means that the energy slowing down time is not purely collisional because it includes particle losses effects.

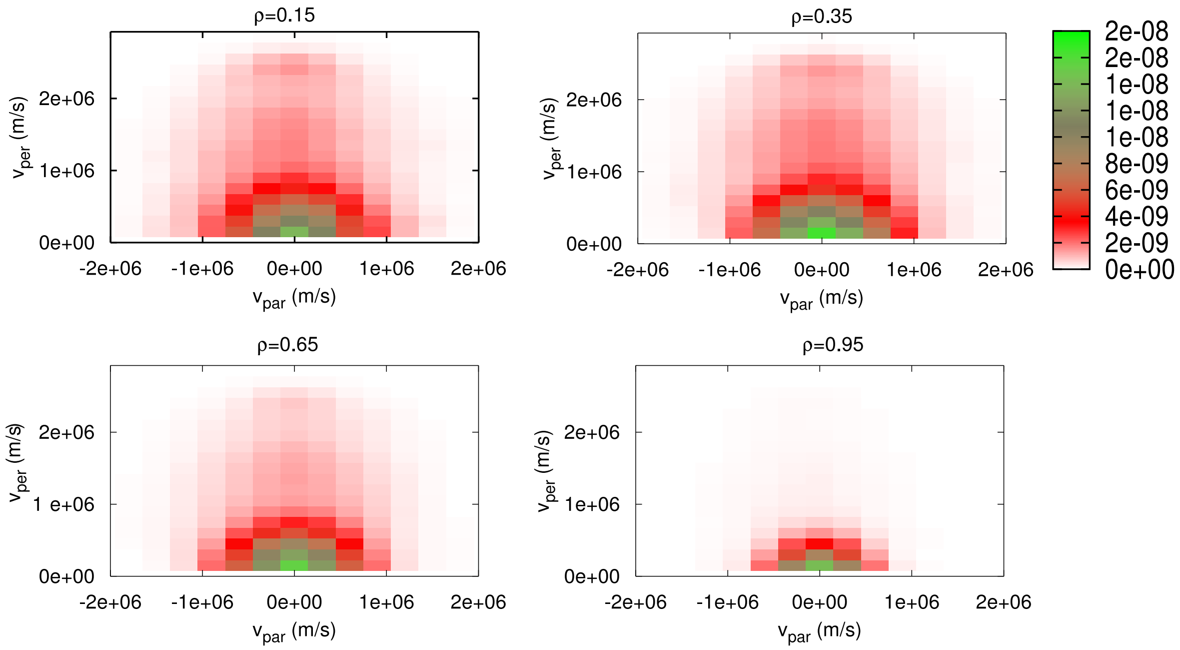

Figure 2: LHD. $f(\rho, v_{||}, v_{\perp})$ for four different radial positions in the steady state.

Simulations for TJ-II

In this case we deal with tangential injection of fast ions from one of the two lines of TJ-II. The birth points are estimated with the FAFNER code. The plasma background corresponds to the standard magnetic configuration and typical ECRH discharge profiles: $T_i \sim 100\,\text{eV}$, $T_e \sim 1\,\text{keV}$, $n \sim 0.6 \cdot 10^{19}\,\text{m}^{-3}$. As expected, Fig. 1 shows that v_φ is much higher in TJ-II than in LHD and direct losses are much smaller, $\sim 20\%$ in LHD compared with $< 5\%$ in TJ-II. In Fig. 3 the distribution function $f(\rho, v_{||}, v_{\perp})$ is plotted. Most of the energetic particles are located near the axis (green zones in the spectra). In this case, thermalization is slower than in LHD and many particles escape before transfering energy to the plasma, decreasing the heating efficiency.

Summary

The confinement properties of the NBI fast ions are studied for stellarators using the global MC code ISDEP. The main result is the calculation of the fast ion distribution function $f(\rho, v_{||}, v_{\perp})$ for two different NBI lines and plasmas: perpendicular injection for LHD and tangential for TJ-II. The energy slowing down time presented in this work includes several processes: particle losses, geometrical features and collisional processes with thermal ions and electrons. With this definition, NBI4 of LHD is a more efficient heating system than the injector in TJ-II. Several other quantities can be measured in this Monte Carlo simulation. As an example, the particle loss cone is plotted in Fig. 4 for the two devices. Comparison with experimental data [4, 5] measured with NPA's (Neutral Particle Analyzers) will be done in the near future. From the time

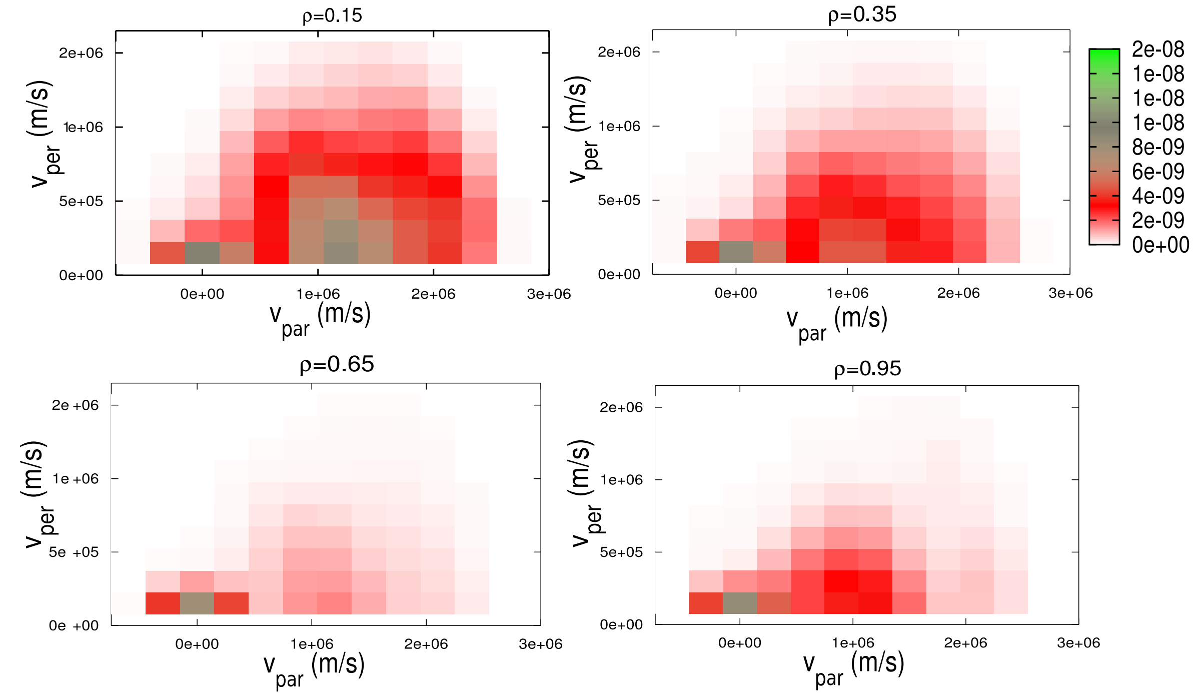

Figure 3: TJ-II. $f(\rho, v_{||}, v_{\perp})$ for four different radial positions in the steady state.

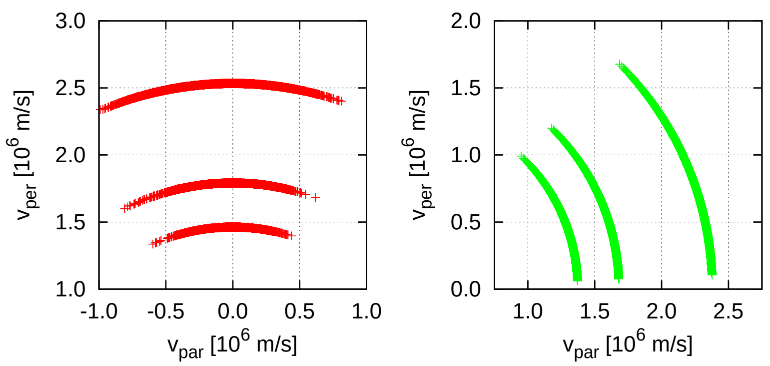

Figure 4: Loss cone for LHD (left) anf TJ-II (right).

evolution of f it is possible to estimate the momentum and energy transfer to the background plasma. Computing resources have been provided by the EULER cluster at CIEMAT.

References

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