Ion Heating in transitions to CERC in the Stellarator TJ-II.

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Introduction

In stellarator devices, transitions to improved core electron-root confinement (CERC) are established in conditions of high Electron Cyclotron Heating power density [1]. These transitions are characterised by the appearance of a peaked electron temperature profile, a hollow density one, and a large positive electric field in the core plasma region. In TJ-II, an increase of the ion temperature is observed syncronized with that of the electron temperature during the transition [2]. Since the electron-ion energy transfer changes slightly after the temperature increase, the ion temperature rising should be attributed to an improvement of the ion confinement, which must be related to the increase of positive electric field in the centre that tends to reduce the typical ion orbit size. In order to explore this hypothesis, we estimate the ion collisional transport in TJ-II under the conditions established before and after the transition to CERC. Like in [3], we calculate a large number of ion orbits in the guiding-centre approximation considering the collisions with a background plasma, now composed of electrons and ions. This is a suitable approach since TJ-II is a medium size flexible heliac whose complex magnetic configuration makes the local approximation doubtful in some radial positions [3]. In the present case, the background temperature profile cannot be considered constant since, in such a case, the test particle temperature tends to the background one. Therefore, the ion temperature profile and the thermal flux are calculated in a self-consistent way, so that the change in the ion heat transport can be assessed.

The numerical method

In a previous work [3], we developed the computer code ISDEP (Integrator of Stochastic Differential Equations for Plasmas), which solves the guiding-centre equations in the presence of collisions with ions. The collision operator was the one introduced by Boozer and Kuo-Petrovic [4]: the Fokker-Planck equation for the phase-space distribution function f is linearized (as it depends on local features of the plasma) by neglecting the effects of the diffusive

particles on the collision rates. Thus, f will be the distribution function of test ions moving in (and colliding with) a thermal bath, described by experimentally fixed density, temperature and electrostatic potential profiles. Since there exists an equivalence between the Fokker-Planck equation and a Langevin one, we arrive to a set of five coupled stochastic differential equations (SDEs) that describe the trajectories of the test ions. In order to solve the SDEs, we use an algorithm developed by Kloeden and Pearson [5]. Details of the integration of long trajectories in the complex TJ-II magnetic configuration are given in [3]. In particular, the actual 3D configuration is considered by using a grid that fits the magnetic surfaces in the real space.

In this work, the collision operator of [3] has been extended following [6], in order to take into account the collisions of the test ions not only with field ions but also with electrons, which allows to estimate the heat transfer from electrons, which are heated by EC waves, to ions.
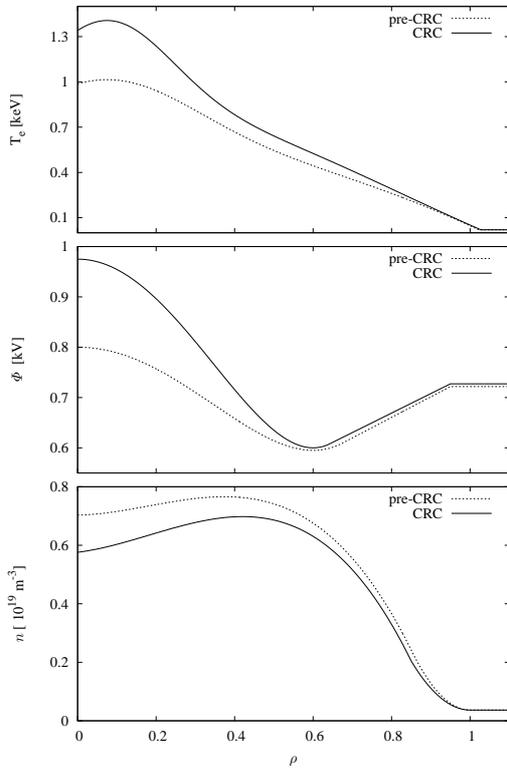

Figure 1: Plasma profiles

The initial distribution of the test ions is chosen to coincide with that of the thermal ions at $t = 0$ s. In order to estimate the ion heating, one cannot use a time-independent temperature profile for the field ions, since this infinite thermal bath will retain all the extra energy absorbed by the test ions from other sources, leading them back to the initial condition [3]. Moreover, since the test ions are expected to represent the whole ion distribution in the plasma (which, indeed, it is not an infinite thermal bath), the distribution of the field particles is allowed to evolve in a consistent way. We therefore perform an iterative calculation: in a time-independent field ion distribution f_0^{field}, we calculate the trajectories of $\sim 10^5$ test ions until $t = 0.01$ s. From the measurements over this ensemble, we obtain a time-dependent ion temperature profile, given by the distribution f_0^{test}. In the next iteration, $\sim 10^5$ ion orbits are calculated (again from $t = 0$ s to $t = 0.01$ s) in a time-dependent ion temperature profile given by $f_1^{field} \equiv f_0^{test}$. From these trajectories, we measure f_1^{test}. After several (~ 20) iterations of this scheme, we obtain a self-consistent ion temperature profile: the test ion distribution function evolves in equilibrium with that of the thermal bath (i.e. $f_\infty^{test} = f_\infty^{field}$), whose temperature increases in time due to the energy absorbed from the electron bath and, in a lesser amount, from the electric potential.

These calculations have been carried out for two different plasmas, representing the situation before and after the transition to CERC. We show their experimentally measured profiles in Fig. 1. The plasma after the formation of the CERC is characterized by a more peaked electron temperature profile and a higher positive electric field in the core region. In both cases, the potential profile, taken similar to those obtained by HIBP measurements, presents a minimum around $\rho = 0.6$, and is the result of the ambipolar condition. Here, $\rho \equiv (\phi / \phi_0)^{1/2}$ is the normalized radial coordinate. The initial ion temperature profile, taken from CX measurements, is almost flat and the distribution function is a Maxwellian with temperature $T = 100\,\text{eV}$. The density profiles are hollow, being the central density lower during the CERC phase.

Results

In Fig. 2 we plot the time evolution of the average temperature of the thermal ions for the two plasmas. For the CERC plasma, the final temperature is about 25% higher than the initial, and a 6% higher than that of the pre-CERC plasma. In both cases, the ion temperature rises at $t \sim 10^{-3}\,\text{s}$, which is the experimental time scale found in [2]. It was also shown in [3] that this is the characteristic time for the action of the electric field, which is the main responsible for the enhancement of ion confinement

Figure 2: Ion temperature evolution

that makes possible an extra ion heating by collisions with the electrons. Note that, due to numerical dispersion, after (~ 20) iterations of our numerical scheme, the initial temperatures are slightly different (about a 1%). Nevertheless, this cannot cause the final difference that appears in Figs. 3 and 4.
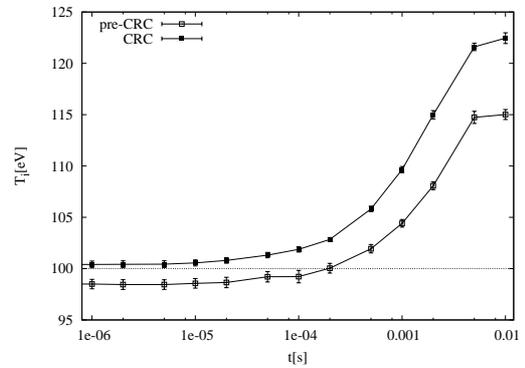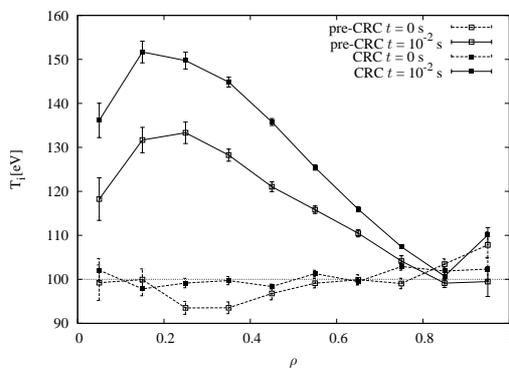

Figure 3: Ion temperature radial profile

In Fig. 3 we show the initial and final ion temperature profiles as a function of the radial coordinate. The main energy absorption takes place in a wide region around $\rho = 0.3$. This is due to the fact that the collisions with the electrons, which are more frequent in such zone of higher density, are the main responsible of ion heating, while the electric field mainly contributes by improving the confinement. Note that the slight difference in the initial condition (almost reduced to the zone around $\rho = 0.3$)

cannot be responsible for such difference of temperatures in the whole radial range.

In Fig. 4 we show the proportion of the ions in the plasma as a function of the radial coordinate. Here we find the difference between the two plasmas: the radial fluxes in the CERC conditions are such that, at the stationary situation ($t \sim 0.01\,\mathrm{s}$), the test density profile is more peaked. This implies that a higher proportion of ions has reached the area close to the minimum, absorbing energy from the electric potential. Furthermore, since the minimum is lower in this case, this amount of energy will be higher

Figure 4: Radial distribution

than in the pre-CERC plasma. Collisions with electrons will also play a role in the heating of this plasma, since the electron density and temperature are still high in this zone.
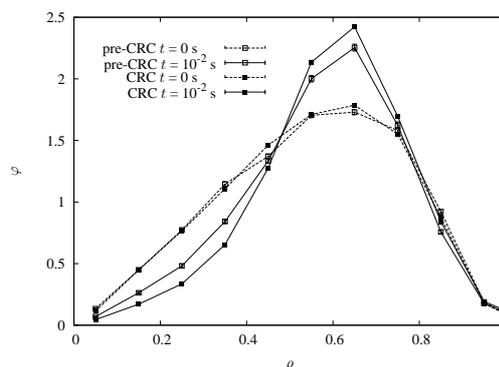
Conclusions

We have studied the ion collisional transport in TJ-II under the conditions established before and after the transition to CERC, using a numerical approach ideally suited for massive parallel computing. We have found differences in the radial fluxes which might be responsible for the experimentally observed rising of the ion temperature by means of a higher energy absorption, mainly from the electrons, due to an increase of the electric field, which also contributes to the ion heating.

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