Advanced simulation of energetic ion populations in the presence of NBI and RF sources

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Accurately computing fast ion distribution functions in the presence of external heating methods is essential for reliable predictions of fusion plasma performance. Whereas injecting auxiliary power is mainly aimed at increasing the plasma temperature and driving non-inductive current, it has been shown that controlling fast ion populations in phase space can be used to enhance the rate of nuclear reactions, influence MHD phenomena and also possibly turbulence. Such control is achieved by tuning NBI and RF power sources to target ion populations with potential to significantly influence such processes. In practice, accurate simulation of the resulting fast ion population is only possible by including at least 1) the modification of the quantities characterizing the particles under the influence of collisions and wave/particle interactions, 2) the modification of the wave electromagnetic field under the influence of these non-thermal populations. This must be done in a self-consistent fashion by integrating both part of the calculation not only numerically, but also by adopting a consistent mathematical framework.

For this purpose, a library, called RFOF, is under development. It is capable of reading the wave field computed by a wave code as an input, and generates Monte Carlo operators to be used by a Fokker-Planck code as a RF source[1]. A special effort is being devoted to the improvement of the employed Monte Carlo algorithms in order to ease the numerical implementation of the various terms describing the stochastic processes, and to speed up the existing library by using new numerical approximation methods for the stochastic differential equations[2]. Although RFOF has been designed to be versatile enough to accommodate various code combinations, we report here on its first use as an interface between the ICRF full wave code EVE[3] and the Monte Carlo Fokker-Planck code SPOT[4]. This code combination has been tested on a DT(^{3}He) scenario relevant to the activated phase of ITER, which has already been used as a basis for wave code comparisons in Ref. [5]. In this scenario, the DT plasma contains 3% of ^{3}He ions which absorb a large part of the power at the fundamental ICRF resonance. In Fig. 1 is shown the right-handed polarized electric field obtained when injecting $P_{RF} = 20$MW

at frequency $f = 52.5$MHz for a single toroidal mode, $n_\phi = -27$. Unsurprisingly, the wave damping is almost complete in a single pass and as a result, the damping on minority ions, shown in Fig. 1(b), is well localized, in the vicinity of the magnetic axis.

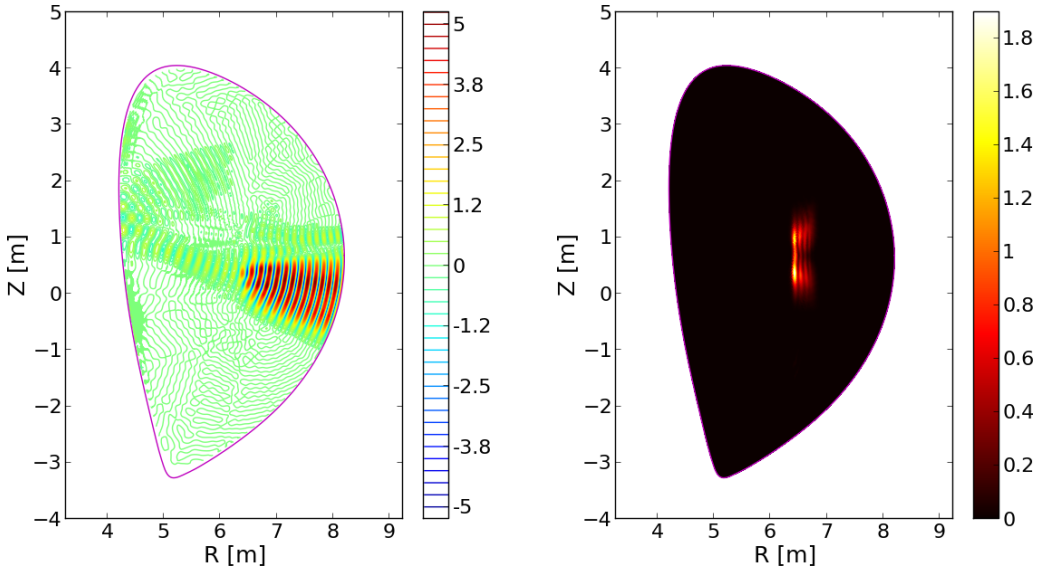

Figure 1: (a) Right-handed polarized electric field E_- in ITER, in kV/m. (b) Power density absorbed by helium 3 ions, in MW/m^3.

SPOT is an orbit-following Monte Carlo code which has been extensively used to describe fast particles originating from NBI or fusion reactions[4]. It uses a collision operator valid at arbitrary, non-relativstic, energies and an acceleration scheme in order to speed-up the calculations, although the latter has been switched off for development purpose in the presented simulations. It has been employed to describe the ^{3}He tail driven by the ICRF power in the ITER scenario described previously. Practically, this is accomplished by using the wave field computed by EVE in RFOF, which builds the adequate Monte Carlo operators for SPOT. Fig. 2(a) shows the power density in SPOT corresponding to the RF kicks of helium 3 ions. These kicks are found to be localized around the ICRF resonance, as expected. The obtained pattern differs slightly from the one shown in Fig.1(b) because EVE and SPOT have used different equilibria, and also because of the difference between the point of absorption and the region where the orbit-redistributed collisional power transfer to the bulk plasma takes place. Fig. 2(b) shows the time evolution of the injected power, the power transferred by fast ions to thermal particles by collisions, and the escaping power. Whereas the injected power is switched on instantaneously, the fraction transferred to thermal species increases on a collisional timescale, consistent with the development of the ^{3}He fast ion tail. Finally, it should be mentioned that fast ion losses are compensated by injecting thermal particles in these simulations, but the escaping power is found to be negligible.

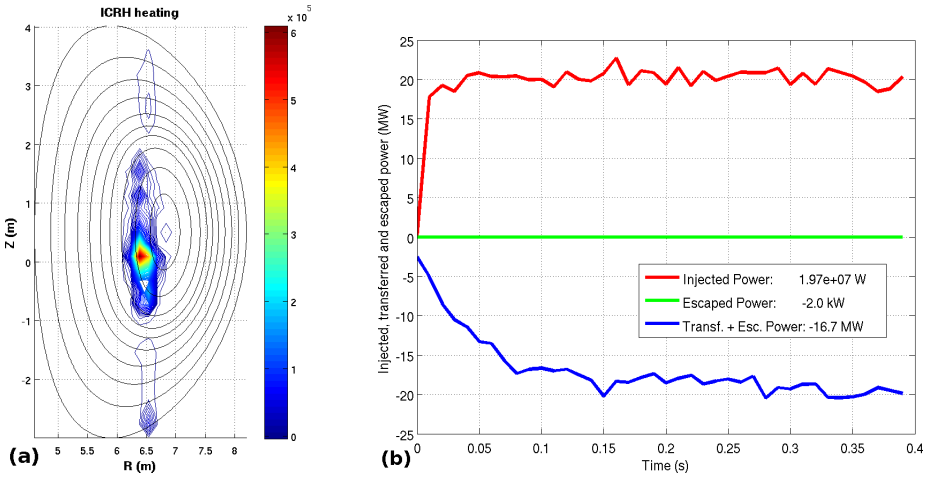

Figure 2: (a) Absorbed power density in W/m^3 absorbed by ^{3}He ions in ITER. (b) Time evolution of injected power, redistributed power and escaping power after the ICRF switch-on.

In order to reach self-consistency between the wave and the Fokker-Planck calculations, another requirement is the capability of the wave code to handle non-Maxwellian distributions. Previous versions of EVE have used equivalent Maxwellians to mimic fast ion populations features, including in the ITER simulation presented above. Although this is known to be fairly adequate in many situations, it can also yield inconsistent results, especially in the presence of NBI and ICRF sources[6]. Recently, the capability of handling non-Maxwellians has been added to the code. More precisely, EVE can now make use of arbitrary distributions specified in terms of invariants, i.e. $f \equiv f(E, \Lambda, P_\phi, \sigma)$ with E the particle energy, Λ the normalized magnetic moment, P_ϕ the canonical toroidal momentum and $\sigma \equiv \pm 1$ depending on whether the considered particles are co- or counter-passing. This distribution function is mapped in terms of local parallel and perpendicular velocity $(v_\parallel, v_\perp)$ at space locations (ψ, θ) where the Maxwell's equations are solved, with ψ the poloidal flux and θ the poloidal angle[3]. The required velocity integrals are then performed numerically, which is costly in terms of computation time, but remains within acceptable limits on parallel architectures by using efficient algorithms for the dielectric response calculation[7].

This new version has been tested by comparing simulations using an analytical or a numerical Maxwellian specified on a discrete $(v_\parallel, v_\perp)$ grid. This case corresponds to a standard D(H) heating scenario in the Tore Supra tokamak, assuming all species are thermal, including the hydrogen ions. Fig. 3(a) shows a comparison of the power damped by electrons, deuterium and hydrogen ions between the analytical and numerical Maxwellians on a velocity grid $(n_{v_\parallel}, n_{v_\perp}) = (301, 100)$. Both distribution functions yield indistinguishable results (the power density profiles are found to agree within less than 0.1%). On the other hand, the calculation time is increased

by a factor 8-10. However, it should be mentioned that this simulation uses a fairly coarse grid in space $(n_\psi, n_\theta) = (51, 128)$, and poloidal numbers ($n_m = 33$). As a result, the time spent by the code in precomputing the dielectric response is a large part of the overall time. We expect this ratio to be lower in forthcoming, more accurate simulations.

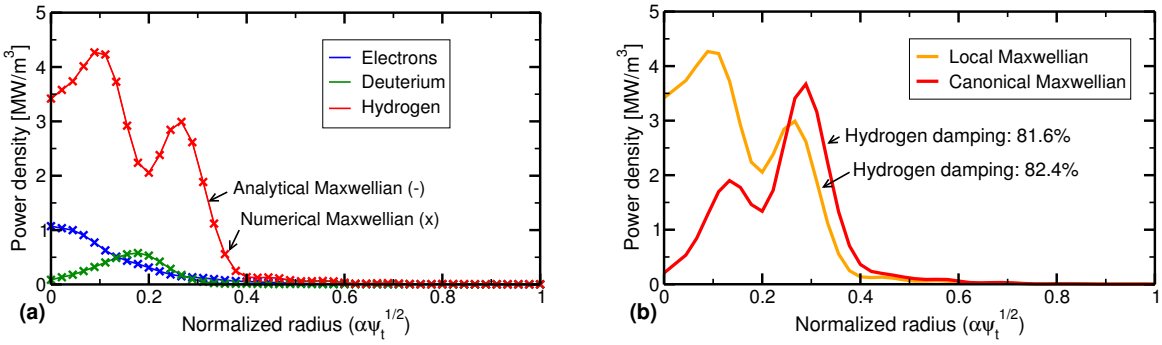

Figure 3: (a) Power deposition profiles obtained with an analytical (line) or a numerical (crosses) Maxwellian. (b) Power absorbed by hydrogen ions when using a canonical Maxwellian, or an equivalent "local" Maxwellian with $T_\perp/T_\parallel = 5$.

Finally, to illustrate the importance of an accurate description of the distribution function in the wave-field calculation, we have compared two simulations of the ICRF scenario shown in Fig. 3 using $T_\perp/T_\parallel = 5$ with $T_\perp$ (resp. $T_\parallel$) the perpendicular (resp. parallel) temperature. In the first simulation, we use a canonical Maxwellian:

$$f(E,\Lambda,\psi) \equiv A \exp\left\{-\frac{E}{T_\perp}\frac{\Lambda B_{res}}{B}\right\} \exp\left\{-\frac{E}{T_\parallel}\left(1-\frac{\Lambda B_{res}}{B}\right)\right\}, \quad (1)$$

with $B_{res} = B(\psi, \theta_{res})$ the magnetic field at the ICRF resonance location and $T_\perp(\psi, \theta_{res})$ represents the perpendicular temperature at this point. In the second simulation, we use an equivalent Maxwellian with constant $T_\perp/T_\parallel$ on a given magnetic surface. This distribution features a dependence in θ and is thus not canonical. As shown in Fig. 3(b), although the total absorbed power is the same in both situations, the resulting deposition profiles differ appreciably.

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