Consistent modelling of ICRH using FEMIC-Foppler

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Introduction Modelling of ion cyclotron resonance heating (ICRH) requires that the wave field and the acceleration of fast ions are treated in a consistent fashion. In practice, this means that the wave electric field that accelerates the fast ions should be calculated including the dielectric response of those fast ions. Since the fast ions typically experience a larger Doppler shift and have larger Larmor radii compared to thermal ions, the inclusion of a fast ion response tend to widen the absorption region and enhance harmonic damping that relies on finite Larmor radius (FLR) effects.

In this paper the coupling of the wave- and fast ion physics is modelled using the wave solver FEMIC [1] and the Fokker-Planck code Foppler [2]. Here the non-Maxwellian populations in Foppler are approximated by a series of bi-Maxwellian distributions in FEMIC, which allow us to recover both the transition from the thermal population to the high energy tail, as well as the non-isotropic character of fast ions. While this model is not a fully consistent, we show below that it produces very similar absorption patterns in both the wave and the kinetic models.

The wave solver FEMIC The wave solver used in this work is FEMIC [1], which solves Maxwell's equations using hot quasi-homogeneous susceptibility tensors. FEMIC includes non-local effects, such as finite Larmor radius effects and parallel dispersion by pre-calculating an approximate wave vector. Here the parallel wave number is obtained from the toroidal mode number, while the perpendicular wave number is obtained from the local dispersion relation. FEMIC also has the capability of including the contributions from the poloidal mode spectrum to the parallel wave number [3]. However, this feature is not used in this report. The wave equation solved by FEMIC is given by,

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{\omega^2}{c^2}\left(1 + \sum_i \chi_i(f_{M,i})\right)\mathbf{E} = -i\mu_0\omega\mathbf{j}_{\mathrm{ant}} \quad (1)$$

where $\mathbf{E}$ is the wave electric field, oscillating with a frequency ω, and driven by an antenna current $\mathbf{j}_{\mathrm{ant}}$. The dielectric response of the plasma includes contributions from a set of plasma populations, i, through a susceptibility $\chi_i(f_{M,i})$, where $f_{M,i}$ is the bi-Maxwellian distribution function of the i:th plasma population. The concept of plasma populations is introduced to represent non-Maxwellian distribution function as an approximate sum of bi-Maxwellians with different temperatures, considering both ions and electrons.

The Fokker-Planck solver Foppler The Fokker-Planck model used in this work is the Foppler code [2], that solves 1D bounce and pitch angle averaged steady state Fokker-Plank equation on each flux surface. The Fokker-Planck equation is based on quasilinear theory for toroidal plasmas [4, 5], combined with a Dendy model for the pitch angle distribution function [6]. The Fokker-Planck equation for the slowly evolving (compared with the gyrofrequency) distribution function, $f_0 = \eta(v)\chi(v,\Lambda)$, is given

$$\frac{1}{v^2}\frac{\partial}{\partial v}v^2\left[(\kappa+\langle d\rangle)\eta+\left(\frac{1}{2}\beta+\langle D\rangle\right)\frac{\partial \eta}{\partial v}\right]=0 \tag{2}$$

where $\langle\cdot\rangle$ is the bounce and pitch angle average operator, κ and β are the Chandrasekhar coefficients for collisional advection and diffusion in velocity, and the quasilinear coefficients are

$$\begin{bmatrix}\langle D\rangle\\ \langle d\rangle\end{bmatrix} = C_P\sum_n\int_{\Delta_{\text{res}}}\left|\frac{L}{\ell}\frac{B}{B_\theta}\frac{1}{2k_\parallel v}\Lambda\right|\left|\frac{ZeE_{\text{e}}}{m}\right|^2\begin{bmatrix}\chi\\ \left(\frac{\partial\chi}{\partial v}+2\frac{\Lambda_{\text{res}}-\Lambda}{mv}\frac{\partial\chi}{\partial\Lambda}\right)\end{bmatrix}\mathrm{d}\theta_{\text{res}}. \tag{3}$$

Here ZeE_{e}/m is the gyro averaged acceleration, θ_{res} the poloidal angle at the cyclotron resonance in the resonance regions Δ_{res}, $\chi(v,\Lambda)$ is the Dendy distribution function [6] normalised such that $\langle\chi\rangle = 1$. Furthermore, $\ell = \sum_\sigma\int_0^{\Lambda_{\max}} v\tau_B \mathrm{d}\Lambda$ and L is the length of the field line in the poloidal plane. The quasilinear operator is normalised by a factor C_P that is adjusted, by iterations, such that the absorbed power matches the power computed by FEMIC on each flux surface. This ensures consistency between FEMIC and Foppler in terms of total power absorbed on each flux surface.

The coupled FEMIC-Foppler model The coupling of FEMIC and Foppler is achieved by using electric fields from FEMIC when evaluating the quasilinear operator in Foppler. In addition, the distribution functions calculated by Foppler are accounted for in susceptibilities used in FEMIC. The calculation of susceptibilities from non-Maxwellian populations is in general challenging. In this work we therefore adopt an approach similar to the one used in [7] and [8], where Maxwellians are used to approximate non-Maxwellian populations. The model used here extends this method by using a sum of bi-Maxwellian populations. Consequently, the model used here is able to describe both the thermal population, the Maxwellian-like tail that tends to form above the critical energy, as well as the distribution between the thermal energies and the critical energy.

In order to find an approximately consistent solution, the FEMIC and Foppler codes are run iteratively. These iterations are repeated until a convergence criteria is met, based on the variation in the absorbed power to each species, the collisional plasma heating, and the volume integrated fast ion energy.

Figure 1: Convergence of FEMIC-Foppler iteration loop with anisotropic (aniso) and isotropic (iso) models.

Modelling of ICRH in a (H)D plasma The modelling results presented below are for the heating of a 1% hydrogen minority in a deuterium plasma, using a JET-like geometry and plasma conditions. The on-axis electron density is 4×10^{19} m^{-3} and the temperature is 5 keV. The on-axis magnetic field is 3.4 T. The ICRH antenna is tuned for 10 MW of on-axis heating and using a single mode number, $n_\phi = 27$.

Figure 2: Power normalisation

Convergence When iterating FEMIC-Foppler, a sequence of approximate solutions are generated. As illustrated in Fig. 1, it takes 4 iterations until the absolute error or the relative error of absorption fractions, heating fractions and fast ion energy for all species is below a desired value. As shown on the top left, the deuterium absorbs only 26% in absence of the fast ions (first iteration) and 40% when the fast ions are included (final iteration). This is due to the deuterium absorption being an FLR effect. As a consequence, the deuterium fast ion energy content is increased, while the hydrogen fast ion energy content decreased, see Fig. 1. However, for an isotropic model, $\chi = 1$, the effects of the fast ions are exaggerated, see Fig. 1.

Figure 3: 2D power absorption [W/m^3] of hydrogen. a) FEMIC before iterations, b) FEMIC after iterations, c) Foppler after iterations.