Modelling the anisotropy of ICRH accelerated ion distributions with LUKE for ions

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Introduction - In magnetic confinement fusion, ion cyclotron resonance heating (ICRH) is a widely used auxiliary heating method. Ions accelerated by ICRH are known to exhibit strongly anisotropic velocity space distributions and modelling this anisotropy is an essential factor for comprehensive studies of the impact of ICRH on fusion plasmas. Examples include the interpretation of experimental results [1] and the study of instabilities driven by energetic particles [2].

For applications where rapid calculations of the distribution function of ICRH accelerated ions are required, e.g. in integrated modelling codes, the calculation of the distribution function limited to 1D in velocity space is desirable. This approach requires the use of simplified models to capture the anisotropy. Examples of codes that use this approach are PION [3], FoPla [4], Foppler [5] and SCENIC [6]. However, careful benchmarking of these models with results from a full 2D Fokker-Planck solver is largely lacking at present.

This work is aimed at contributing to such a benchmarking activity by testing the models against a new version of the LUKE code [7], which is widely applied for modelling electron cyclotron resonance heating (ECRH), lower hybrid current drive (LHCD) and runaway electrons. LUKE has now been adapted to solve the linearized bounce-averaged Fokker-Planck equation for ions by extending its collision operator to handle ions as the simulated species. Furthermore, a new quasilinear operator has been implemented for ICRH that uses wave fields from a full-wave solver.

In this paper, first results of LUKE for ions are presented. The code is applied to predict realistic pitch distributions for a JET-like plasma. The different models for the anisotropy mentioned are compared to a pitch distribution from LUKE for ions, and the parallel temperature is compared to Stix's prediction [8].

LUKE for ions solves the bounce-averaged Fokker-Planck equation in the thin orbit width limit, $\partial f_0/\partial t = C(f_0) + Q(f_0)$, where f_0 is the bounce-averaged distribution function of the resonant ion species. This distribution depends on the momentum, p, the pitch, ξ_0, at the magnetic field strength, B_0, on the outboard midplane, and the normalized radius coordinate, ρ_p, based on the poloidal flux. The collision operator $C(f_0)$ describes collisions against a thermal background plasma and the quasilinear operator $Q(f_0)$ [9] describes acceleration by ICRH. The wave fields and absorbed power densities are simulated by the full-wave solver FEMIC [10].

In the following, a JET-like plasma with a 3% helium-3 minority and deuterium majority is investigated. On the magnetic axis, the electron density is $8 \times 10^{19}\ \mathrm{m}^{-3}$, the temperature is 3 keV and the magnetic field is 2.7 T. The ICRH antenna provides 5 MW and is tuned for fundamental on-axis heating of ^{3}He, using a single mode number, $n_\phi = 15$. Under these conditions, FEMIC predicts the absolute value of the left-hand polarized component of the electric field, $|E_+|$, shown in Figure 1. The field is particularly strong along the L-cutoff located near $R = 3\,\mathrm{m}$. Based on the electric wave field and the absorbed power density from FEMIC, the quasilinear operator is constructed by LUKE for ions. The momentum-momentum component of the quasilinear diffusion tensor for ^{3}He is depicted in Figure 2 evaluated for the flux surface, $\rho_\mathrm{p} = 0.08$, marked blue in Figure 1.

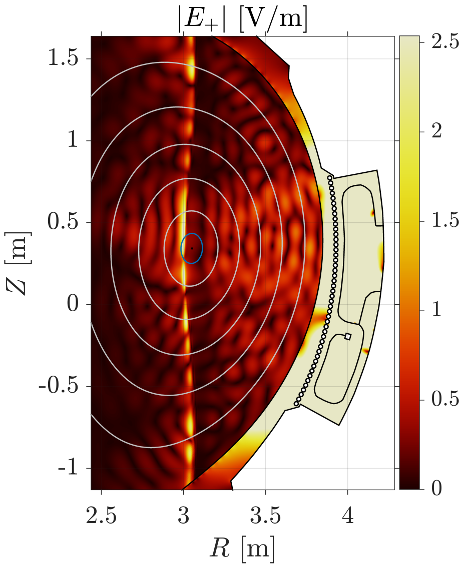

Figure 1: The left-hand polarized component of the electric field from FEMIC.

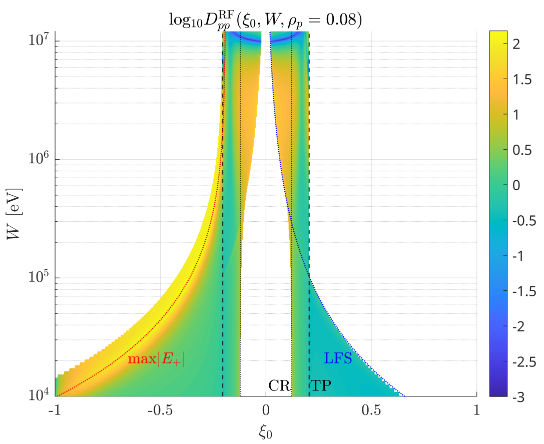

Figure 2: 2D plot of the momentum-momentum diffusion coefficient.

The cold resonance (CR), where $\omega = n\Omega_\mathrm{c}$ is satisfied, is marked as a vertical dotted line. Here, ω is the antenna frequency, Ω_c is the cyclotron frequency, and n is a harmonic number. The trapped-passing boundary (TP) is marked with a vertical dashed line. Note that in the trapped region, for $|\xi_0|$ smaller than the value at TP, the diffusion coefficients are symmetric with respect to the sign of the pitch. Additional curves indicate where resonances occur on the equatorial plane at the low field side (LFS), and at the location of strongest $|E_+|$. At 10 MeV, the finite Larmor radius (FLR) cutoff [11] can be observed.

Models for the anisotropy are described by the pitch distribution, which is defined as $\chi = f_0 / \langle f_0 \rangle_{\xi_0}$, where the pitch average is $\langle \ldots \rangle_{\xi_0} = \frac{1}{\ell} \int_{-1}^{1} \ldots p |\xi_0| \tau_B \mathrm{d}\xi_0$. In this expression, τ_B is the bounce time and $\ell = \int_{-1}^{1} p |\xi_0| \tau_B \mathrm{d}\xi_0$.

Different models for the pitch distribution, χ, are largely motivated by the fact that, in the absence of collisions, ions under ICRH diffuse along characteristics in phase space [12]. In the high-energy limit, the characteristics approach orbits whose turning point and resonance lie at the CR. Hence, the pitch distribution is expected to be peaked around these orbits at high energies. In this work, three different models for such peaked pitch distributions are compared.

The first model for χ is a Gaussian with respect to the normalized magnetic moment, $\Lambda = (1 - \xi_0^2)$, as used in e.g. [2]. The second model consists of two Gaussians with respect to the pitch ξ_0, both with the same variance and centred around the positive and the negative value of a mean pitch. This model is referred to as the smooth rabbit ear model. The third model is based on the Dendy model [13], which describes a bi-Gaussian with respect to the parallel and perpendicular velocity, $v_{||}$ and $v_{\perp}$, at the CR. The bi-Gaussian is characterized by the parallel and perpendicular temperature, $T_{||}$ and $T_{\perp}$. This model is then modified for deeply trapped orbits to ensure isotropy when $T_{||} = T_{\perp}$ [5].

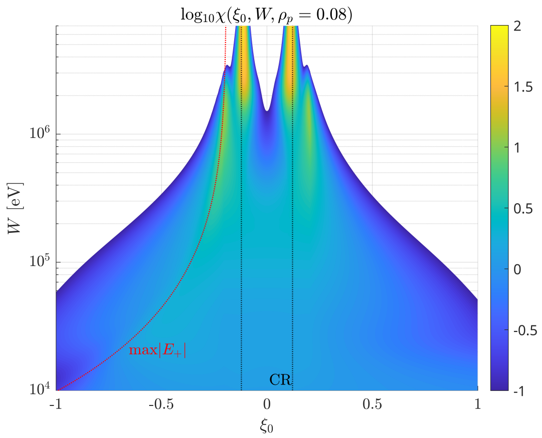

Figure 3: 2D plot of the pitch distribution.

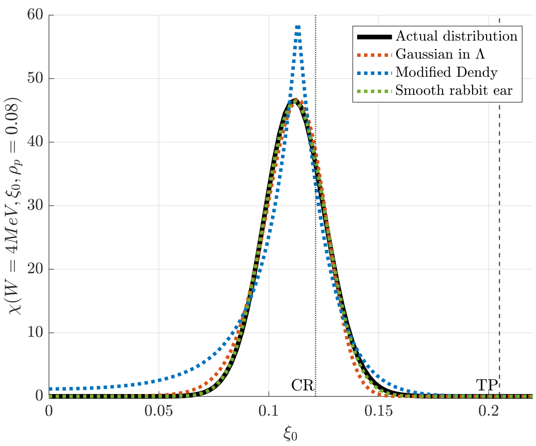

Figure 4: 1D plot of pitch distribution at an energy of 4 MeV with different models fitted.

Anisotropic pitch distributions are calculated by LUKE for ions using diffusion coefficients such as shown in Figure 2. For this particular case, the pitch distribution as well as the parallel and perpendicular temperature of ^{3}He are investigated. The results allow for three main observations.

First, the pitch distribution in Figure 3 is not simply peaked at the pitch of orbits with turning points at the CR. In fact, below 1.5 MeV the pitch distribution is peaked around the pitch of orbits with resonances at the maximum in the $|E_+|$. A shift of the peak location away from the CR is facilitated by a combination of strong local quasilinear diffusion accompanied by collisional pitch scattering.

Second, the smooth rabbit ear model and the Gaussian in Λ fit the single-peaked pitch distribution at 4 MeV well, as seen in Figure 4. In fact, they have the same shape at peak centre, and differ only slightly further away from it. In contrast, the modified Dendy model lacks the necessary smoothness at the peak location to be the best fit.

Third, the parallel temperature, $T_{||}$, remains close to the critical value $W_{\gamma}/4$ postulated by

Stix [8], as shown in Figure 5. The parallel temperature is measured as $T_{\|} = p_{\|}/n_{\|}$, where the density, $n_{\|}$, and pressure, $p_{\|}$, are moments of the distribution with respect to the parallel velocity, evaluated at a constant perpendicular velocity at the CR. The perpendicular temperature is estimated by the logarithmic derivative [5] of $n_{\|}$ with respect to the perpendicular energy $W_{\perp}$. Figure 5 shows the transition from the isotropic case, where collisional pitch scattering is efficient and ensures that $T_{\|} \simeq T_{\perp}$, to the anisotropic case, where $T_{\perp} > T_{\|}$ and collisional pitch scattering limits the parallel temperature, $T_{\|} \lesssim W_{\gamma}/4$. Only at $0.5 - 2$ MeV does $T_{\|}$ exceed the critical value. The increased parallel temperature is associated with a double peak in the pitch distribution, as seen in Figure 3.

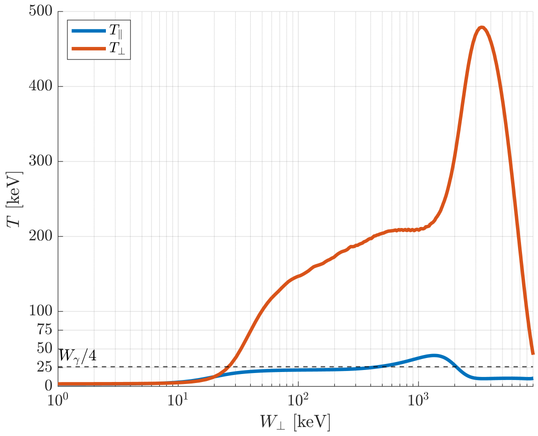

Figure 5: Parallel and perpendicular temperature at the cold resonance.

Conclusions - First results of LUKE for ions are presented. An illustrative example of a ^{3}He minority under ICRH in a JET-like plasma shows that pitch distributions can exhibit a peak that is centred away from the cold resonance ($\omega = n\Omega_c$). Different models for the pitch distribution from the literature are compared to such peaked pitch distributions. In this particular case, a Gaussian with respect to ξ_0 or Λ is found to be a good fit. Finally, it is shown that the parallel temperature is limited by collisional pitch scattering as postulated by Stix.

In the future, this work is going to be extended by comparing LUKE for ions to other Fokker-Planck solvers. Additionally, it is planned to develop an improved model for the anisotropy.

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.