Absorption of Lower Hybrid Waves by Alpha Particles in ITER

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Abstract Absorption of Lower Hybrid (LH) waves by alpha particles may reduce significantly the current drive efficiency of the waves in a reactor or burning plasma experiment. This absorption is quantified for ITER using the ray-tracing+2D relativistic Fokker-Planck code DELPHINE [1]. The absorption is calculated as a function of the superthermal alpha particle density, which is constant in these simulations, for two candidate frequencies for the LH system of ITER. Negligible absorption by alpha particles at 3.7 GHz requires $n_{\alpha,supra} \leq 7.5\ 10^{16}\ m^{-3}$, while no significant impact on the driven current is found at 5 GHz, even if $n_{\alpha,supra} = 1.5\ 10^{18}\ m^{-3}$.

INTRODUCTION

The absorption of lower hybrid (LH) waves by alpha particles produced by the fusion reactions may reduce the current drive efficiency significantly in a reactor or burning plasma experiment like ITER. To avoid absorption by the alpha particles, a high wave frequency should be used. A previous study, involving 1D quasi-linear calculations for both electron and alpha particle distributions in a simplified cylindrical geometry [2], suggested that the minimum frequency should be chosen as 5 GHz. Nevertheless, this high frequency is a source of technological constraints, and it would be much easier to build a LH system at a slightly lower frequency, i.e. 3.7 GHz, for which RF power sources already exist. Therefore it is an important issue to assess the choice of the frequency for the possible LH system of ITER, taking advantage of more recent tools (i.e. the DELPHINE package [1], wich includes ray-tracing in arbitrary geometry, 2D relativistic Fokker-Planck solver for the electron distribution function, and in which linear damping on alpha particles has been implemented).

EQUILIBRIA AND ALPHA PARTICLE DISTRIBUTION

Two different equilibria have been used in the simulations. Both correspond to the ITER non-inductive scenario. They have the same density and temperature profiles (see Fig. 1), but slightly different plasma current (respectively 9 and 7.6 MA). The qprofile is weakly reversed with a minimum at toroidal flux coordinate ρ = 0.6. This corresponds to the foot of an internal transport barrier, as shown by the high electron and ion temperature gradient inside this position. In the 9 MA case, 10 MW of LH waves are launched at a peak refractive index $n_{//0} = 2.0$. In the 7.6 MA case, 30 MW of LH waves are distributed among a co-current peak centered on $n_{//0} = 1.9$ (87 % of the power) and a counter-current peak centered on $n_{//0} = -3.8$ (13 % of the power) [3].

The alpha particle distribution follows the classical slowing down expression , $f(p) = \frac{c_0}{p^3 + p_c^3}$ where p is the alpha particle momentum, c_0 a normalisation constant, and the critical momentum is given by $\frac{p_c^2}{2m_\alpha}[keV] = 14.8 T_e[keV]\left(\frac{A_\alpha}{n_e}\sum_{j=ions}\frac{n_j Z_j^2}{A_j}\right)^{\frac{2}{3}}$ [4]. The distribution function drops to zero above an energy of 3.5 MeV, which is the kinetic energy of the alpha particles just after they are created by the fusion reaction. Since we do not take into account quasilinear effects for the alpha particles (i.e. a possible increase in the alpha particle energy due to the absorption of LH waves), we estimate only the lower bound of the absorption.

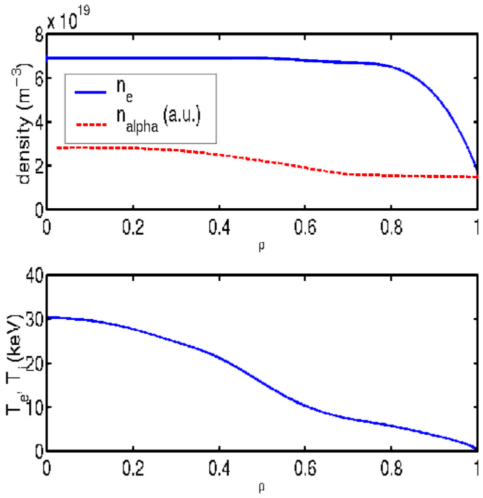

FIGURE 1. Electron density (m^{-3}), alpha particle density (arbitrary units), and temperature profiles.

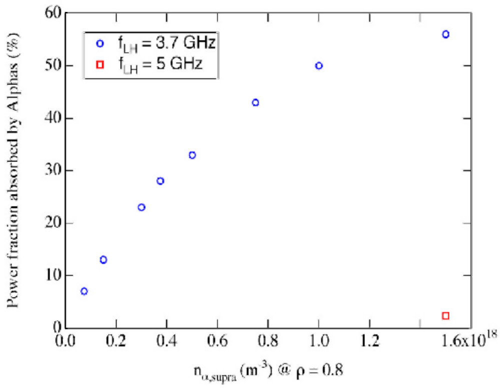

FIGURE 2. LH power fraction absorbed by alpha particles, 9 MA case, for LH frequency of 3.7 GHz (circles) and 5 GHz (square), as a function of the superthermal alpha particle density at the edge.

RESULTS

Though the details of the rays propagation are different between the two equilibria, the results on the LH power fraction absorbed by alpha particles is very similar (see Fig. 2). Significant absorption by alpha particles occurs for LH frequency of 3.7 GHz, except if $n_{\alpha,supra} \leq 7.5\ 10^{16}$ m^{-3}, while it is only of the order of a few percents for 5 GHz frequency and $n_{\alpha,supra} = 1.5\ 10^{18}$ m^{-3}. The power fraction absorbed by alpha particles for f_{LH} = 3.7 GHz increases linearly with their superthermal density for $n_{\alpha,supra} \leq 5\ 10^{17}\ m^{-3}$, then the slope of the curve flattens for higher densities. The amount of driven current is reduced approximately in the same ratio. The exception to this rule is when the absorbed power corresponds to the counter-current lobe, which drives in fact very few current (only 80 kA in the 7.6 MA case for f_{LH} = 5 GHz and n_α = 0, to be compared to the 2.1 MA driven by the co-current lobe). Therefore, even if in the 7.6 MA, 5 GHz case, the LH power fraction absorbed by alpha particles reaches 15 % for $n_{\alpha,supra} \leq 1.5\ 10^{18}\ m^{-3}$, it corresponds mostly to power in the counter-current lobe, and at the end there is a negligible reduction of the LH driven current.

The LH waves being damped on alpha particles by perpendicular Landau damping, the minimum alpha particle perpendicular velocity required to absorb LH waves is related to their maximum $n_\perp$ through : $v_{\perp\,\min} = c/n_{\perp\max}$, where c is the speed of light in vacuum. Since $n_{\perp\max}$ is higher at low LH frequency (in the electrostatic approximation, $n_\perp/n_{//} \propto 1/\omega_{LH}$) the interaction of the waves with the alpha particle distribution function may occur at lower energies. As shown on figure 3, for LH frequency of 3.7 GHz in the 9 MA case, there is a significant number of rays above the energy cut-off of the alpha particle distribution function (3.5 MeV, horizontal line on the figure). Absorption on superthermal alpha particles occurs, provided their density is not negligible. Conversely, since almost no ray propagates above the energy cut-off in the $n_\perp$ space at 5 GHz, the absorption by alpha particles is negligible (see Fig. 4). Figures 3 and 4 also show that the LH waves propagation in ITER is not purely single-pass, even though the electron temperature is high in the plasma core. For this reason, it is critical to take into account the toroidal $n_{//}$-upshift in a realistic geometry, in order to assess correctly the absorption of LH waves by alpha particles.

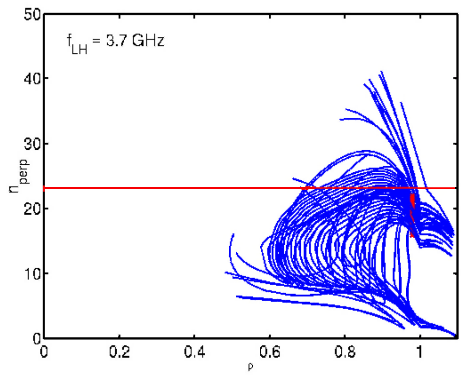

FIGURE 3. Perpendicular refractive index of the rays versus toroidal flux coordinate, 3.7 GHz and 9 MA case. The horizontal line corresponds to the perpendicular index required to have a resonance with alpha particles at their energy cut-off (3.5 MeV).

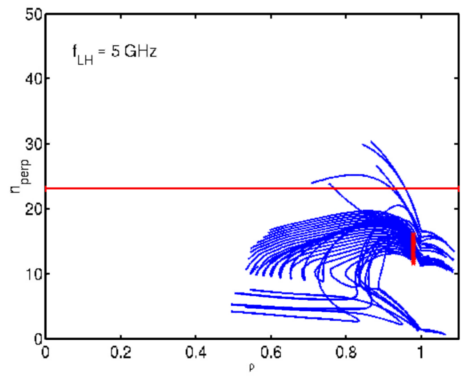

FIGURE 4. Perpendicular refractive index of the rays versus toroidal flux coordinate, 5 GHz and 9 MA case. The horizontal line corresponds to the perpendicular index required to have a resonance with alpha particles at their energy cut-off (3.5 MeV).

As shown on figure 5, for the 7.6 MA case, the local power deposition on alpha particles is of the same order of magnitude as the deposition on electrons in the low electron temperature region (ρ > 0.7), while electron absorption clearly dominates in the internal transport barrier region. In the 9 MA case, the power deposition profile on electron is broader in reason of a faster toroidal $n_{//}$-upshift, but still the damping of LH power on alpha particles is restricted to the low electron temperature region ρ > 0.7 (see Fig. 6).

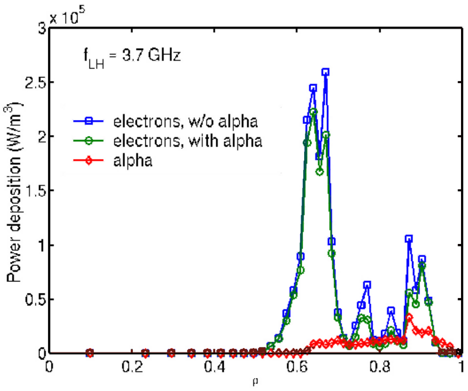

FIGURE 5. LH power deposition on electrons with no alpha particles (squares), on electrons (circles) and alpha particles (diamonds) for $n_{\alpha,supra}$ = 1.5 10^{17} m^{-3}, 3.7 GHz and 7.6 MA case.

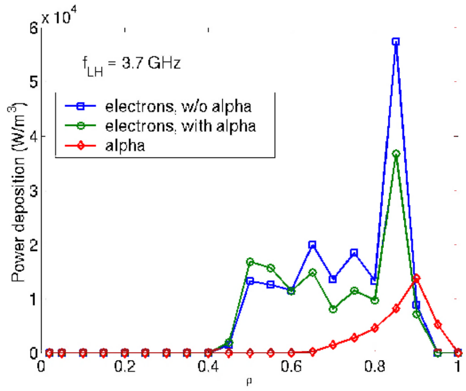

FIGURE 6. LH power deposition on electrons with no alpha particles (squares), on electrons (circles) and alpha particles (diamonds) for $n_{\alpha,supra}$ = 3.0 10^{17} m^{-3}, 3.7 GHz and 9 MA case.

CONCLUSIONS

In spite of slight differences due to the plasma current, both cases show the same trends : a LH frequency of 3.7 GHz may yield significant absorption of LH power by alpha particles, even at low superthermal alpha particle density, while at 5 GHz, there is a negligible current drive reduction due to superthermal alpha particles, even at high density. The counter-current lobes of the LH power spectrum drive very few current in the absence of alpha particles. Moreover they are easily absorbed by alpha particles, since their power deposition is localized in the low electron temperatue region. Ray-tracing in realistic geometry is a important tool to calculate the LH power deposition in ITER, since the LH waves propagation is not purely single-pass. The results presented here also show that the absorption on alpha particles occurs at the edge of the plasma (ρ > 0.7), where it is difficult to estimate the alpha particle distribution function. In this work, we used fixed alpha particle distribution function, and showed that the results are sensitive to its parameters, like the superthermal density and energy cut-off. Therefore, the next step is to develop a detailed modeling of the alpha particle distribution function in a burning plasma experiment, taking into account their specific trajectories and interactions with the various heating systems and the plasma.

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