Self-consistent Simulations of the Interaction between Fusion Born Alpha Particles and Lower Hybrid Waves in a Tokamak

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Introduction

Fast particles are created in many scenarios where RF-waves are used for heating and current drive in fusion plasmas. Furthermore, they can interact with fusion born alpha particles. Consequently, it is important to have a capability to model the interaction between RF-waves and fast ions. Moreover, in order to carry out detailed predictive simulations, the modelling must integrate several codes. In order to address this problem, the orbit following Monte Carlo code SPOT [1] has been developed and integrated into to the transport code CRONOS [2]. Newly derived Monte Carlo operators account for the interaction of RF-waves and ions in SPOT [3]. As a first application, the interaction between alpha particles and Lower Hybrid waves has been studied. This has necessitated a self-consistent coupling of SPOT with the LH ray-tracing/Fokker-Planck (for the electrons) code DELPHINE [4].

In order to sustain steady-state or hybrid scenarios in future reactors, it might be necessary to have a capability to control the plasma current profile. One of the leading candidates for off-axis current profile control is Lower Hybrid Current Drive (LHCD). However, for this method to be viable in a fusion reactor, the parasitic absorption of LH power by fast alpha particles via the perpendicular Landau damping mechanism must be kept at acceptable levels. Since only those alpha particles with a perpendicular velocity above $\omega/k_\perp$ interact resonantly with the LH waves, the parasit absoption can be decreased by increasing the frequency. An important issue is therefore to determine the frequency that would be required to keep this parasitic absorption at an acceptable level. Today's Lower Hybrid (LH) systems operate with frequencies around $\omega/2\pi = 3.7$ GHz, and this might not be sufficiently high for ITER. However, higher frequency klystrons, while being developed, have not yet been extensively tested, and might involve extra costs. It is therefore of interest to evaluate the damping of LH wave on alpha particles via a comprehensive modelling.

In fact, to model the LH absorption by alpha particles, a number of effects must be taken into account in addition to the wave-induced velocity space diffusion. These include finite orbit width effects, the energy distribution of the alpha particle source, and wave-induced spatial transport of the alpha particles. Owing to the limited penetration of the LH waves in a high density reactor plasma, it is particularly important to take into account accurately finite orbit width effects, which influence the radial extent of the alpha distribution in the outer region of the plasma where the LH waves penetrate. Such effects are automatically taken into account in SPOT. Moreover, the Monte Carlo operators in SPOT representing resonant interactions between RF waves and fast ions account for the effect of wave-particle interaction on both the velocity and spatial distribution of the resonating ions.

The SPOT/DELPHINE package

In the coupling between SPOT and DELPHINE, the time-dependent evolution of the alpha particle distribution function and the LH power deposition is simulated in the following way: (i) rays are launched in DELPHINE and their trajectories are supplied to SPOT together with the LH wave numbers, (ii) SPOT evaluates the anti-Hermitian contribution from the alpha particles to the dielectric tensor along the rays; (iii) this information is used in DELPHINE, which calculates the power deposition; (iv) the absorbed alpha particle power deposition is used in SPOT to advance the distribution function of the alpha particles for a time step; the procedure is repeated until the end of the calculation.

Absorption of LH power for an ITER steady-state scenario

Results from simulations of a steady-state $Q = 5$ ITER scenario are presented. In this scenario the plasma current is $I_p = 9$ MA and the toroidal magnetic field $B_T = 5.1$ T. The profiles of density and temperatures are taken from [5], and are shown in figure 1. In the SPOT/DELPHINE simulation, 40 rays have been launched, and the directivity of them was taken to be 0.7 (70% of P_{LH} with $n_\parallel = 2$; 30% of P_{LH} with $n_\parallel = -3.6$) and the frequency 3.7 GHz, with a total LH power of 20 MW. The rays are illustrated in figure 2, as well as the positions along a ray where the alpha particle contributions to the dielectric tensor are calculated.

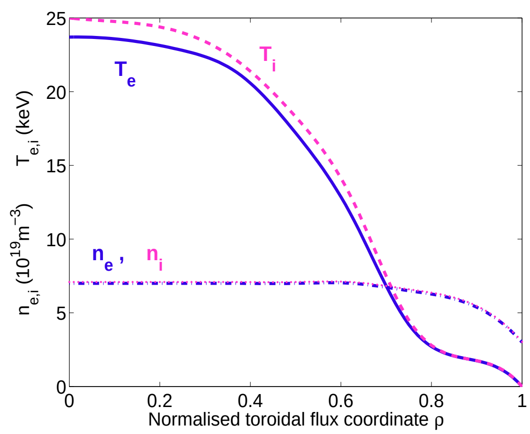

Figure 1: *Electron and ion temperature and density profiles used inside the simulation.*

The resulting absorption of the LH wave power by the alpha particles is presented in figures 4 (1D) and 5 (2D). These figures indicate that the LH absorption is concentrated around $\rho = 0.65$, i.e. as expected from figure 2, in the outer part of the plasma. The total amount of LH power absorbed by the alpha particles has been found to be around 3%,

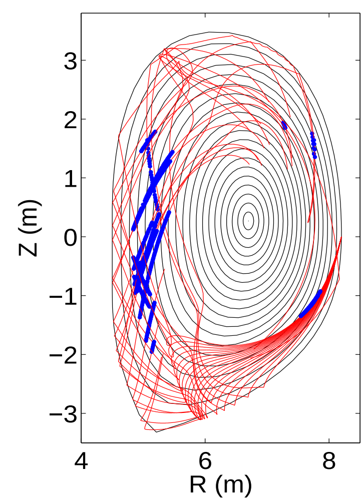

Figure 2: *LH rays provided by DELPHINE. Black lines represent the poloidal magnetic flux surfaces. Red lines are LH rays and blue points are the location of LH absorption by α particles.*

The above result can be compared to the recent simulations, based on a simplified Fokker-Planck model coupled to a toroidal ray-tracing code, presented in [6] for the same scenario above. They indicate a higher fraction of LH power absorbed by the alpha particles, of the order of 20% for an LH frequency of 3.7 GHz. In their case, 5 GHz would be required to reduce the alpha particle absorption to tolerable levels. A possible source for the discrepancy between the results could be the density profile of the fast alpha particles. In the simulations reported in [6], finite orbit width effects are modelled by an ad hoc broadening of the alpha particle profile, whereas they are intrinsically taken into account in SPOT. The alpha particle density profile of [6], including the ad hoc broadening, is compared to the one obtained by SPOT in figure 3.

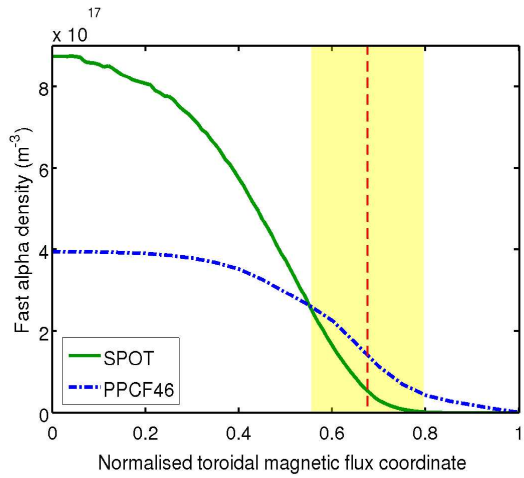

Figure 3: *Fast alpha density profiles coming from SPOT (solid) and ref. [6] (dot-dashed).*

As can be seen, there is a significant difference in the region where the alpha particle absorption takes place. In order to investigate if this difference is at the origin of the discrepancy between the fractions of LH power absorbed by the alpha particles, the alpha density profile of [6] has been forced as input to DELPHINE. The resulting LH absorption by the alpha particles then increases to about 16%, in good agreement with [6]. Thus, the main differences between the simulations presented here and those in [6] are caused by the difference in the alpha particle density profiles, which indicates that finite orbit width effects alone do not give rise to quite the broadening that is obtained with the ad hoc model used in [6].

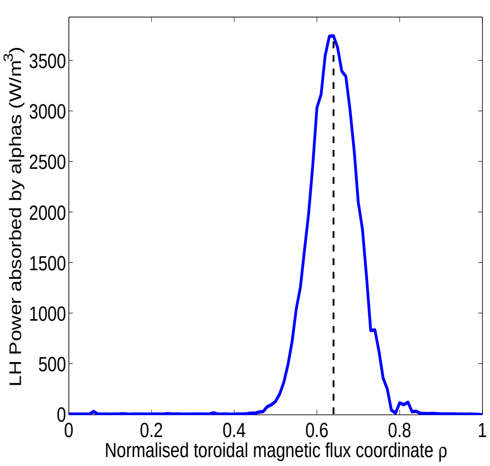

Figure 4: *1D profile of LH power absorbed by alpha particles.*

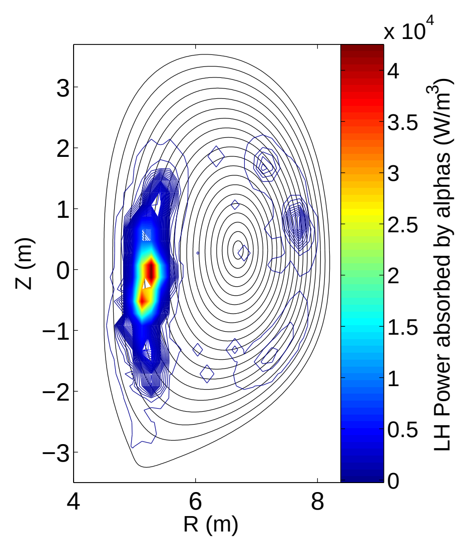

Figure 5: *Poloidal view of LH power absorbed by alpha particles.*

The effects of wave-induced spatial transport on the alpha particle absorption have been investigated by setting the toroidal mode number and the parallel wave number of the LH waves to zero in SPOT. This simulation has been compared to the case where the actual values calculated by DELPHINE were used. The differences were found to be relatively small.

The effect of the enhanced tail formation, due to the absorbed LH power, on the alpha distribution function, has also been investigated. For this purpose, the LH power has been increased to unrealistic levels so that about 30MW was absorbed on the alpha particles, leading the distribution shown in Fig. 6. The time evolution of the LH power damped on alpha particles was then studied to determine the influence of the tail formation. Again the effect was found to be moderate. Thus, we find that these effects are important for detailed studies, but that they do not change the order of magnitude of the alpha particle absorption.

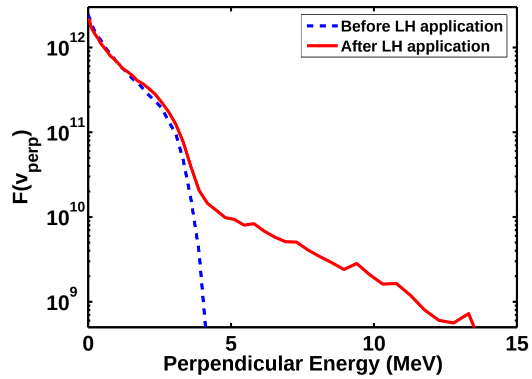

Figure 6: *Alpha distribution function with (solid) and without LH power (dashed), assuming 30 MW LH absorption by alphas.*

Conclusion

Modelling of interaction between RF waves and fast ions has been developed. As an application, a steady-state ITER scenario with $Q = 5$ has been simulated to study the absorption of LH wave power by alpha particles. The absorption, for an LH frequency of 3.7 GHz, has been found to be of the order of 3% for realistic alpha particle density profiles, including finite orbit width effects. Assuming that an acceptable level of parasitic absorption is below 10%, the results of the SPOT/DELPHINE coupling indicate that the use of 3.7 GHz klystrons for LH waves in ITER cannot be ruled out. However, higher frequencies will give a greater margin. It should also be kept in mind that there are uncertainties in the modelling. For instance, it is based on simulated plasma quantities, such as the density and temperature, and one cannot be sure how ITER will perform in reality. Moreover, we have not considered alpha particle transport induced by magnetic field ripple or Toroidal Alfvén Eigenmodes [7], which could have an influence on the alpha particle distribution in the outer part of the plasma (this should be the subject of a future study). The modelling would also benefit from benchmarking against JET experiments with LH heating and a detectable presence of fast particles.

References

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