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Interaction of Ion Cyclotron Range of Frequencies Wave with Energetic Particles

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1. INTRODUCTION

Ion Cyclotron Range of Frequencies (ICRF) heating is an auxiliary heating system that can provide a significant fraction of bulk ion heating in a reactor tokamak [1]. However, to maintain a high ion heating fraction during the burn phase, when the concentration of fusion products will be beyond 10%, the parasitic absorption of ICRF power by alpha particles has to be minimised. As several heating scenarios are envisaged for reactor operation in a D-T mixture, it is important to assess the efficiency of these scenarios in terms of bulk ion heating. One is therefore led to carefully study the interaction between the wave and the energetic particles. Within the quasi-linear approximation, the effect of ICRF heating on the resonating ion distribution function can be viewed as a diffusive process in phase space. The resulting diffusion coefficient is therefore intimately linked to the efficiency of the wave particle interaction. This paper compares two models for calculating the ICRF induced quasi-linear diffusion coefficient, and discusses the salient features for correctly assessing the efficiency of the wave particle interaction.

2. LOCATION OF THE WAVE PARTICLE RESONANT INTERACTION POINTS

At high energies, the width of ion orbits can be of the same order as their distance to the magnetic axis. A correct description of the wave particle interaction therefore requires an accurate description of the particle trajectories [2]. The unperturbed motion of fast particles is well described by three constants of motion, such as the energy, E, the magnetic moment, μ, and the toroidal momentum P_ϕ. In this paper, we use the same set of constants of the motion that was utilised in ref 3. These are a combination of E,μ and Pϕ:

$$Q_1 = 2v^2R_0 - v_\perp{}^2R$$
$$Q_2 = v_\perp{}^2R - v^2R_0 \qquad (1)$$
$$Q_3 = \psi - v_{//}R$$

The resonance condition between the particle and the wave can be expressed as

$$\omega = \omega_c - k_{//}v_{//} \qquad (2)$$

From equations 1 and 2, it is possible to express the resonance condition in terms of ψ, Q_1, Q_2 and Q_3 only. For given Q_1,Q_2,Q_3, this gives a second degree polynomial in ψ, from which it is possible to determine ψ at the resonance. From ψ, one can compute, R and Z, obtaining the location of the Döppler-shifted resonance point for any trajectory.

3. COMPUTATION OF ICRF-INDUCED DIFFUSION COEFFICIENTS

At a given resonance point, using an eikonal expansion of the wave field and a first order expansion of the particle motion in the neighbourhood of the resonance, the energy exchange between the particle and the wave can be written approximately as:

$$\Delta E = q\sqrt{\frac{2\pi}{n|\dot{\omega}_c|}}\, v_\perp^{res}\left[E_+ J_{n-1}(k_\perp\rho) + E_- J_{n+1}(k_\perp\rho)\right]^{res}\cos(\Delta\phi) \qquad (3)$$

where ω is the wave pulsation, $\Delta\phi$ is the phase difference between the cyclotron motion and the wave at the resonance crossing, the time derivative of the cyclotron frequency is taken at the resonance, E_+ and E_- are respectively the co- and counter- rotating components of the ICRF electric field, $k_\perp$ is the perpendicular component of the wave vector **k**, ρ is the Larmor radius and J_n is the n-th order Bessel function.

Assuming that the cyclotron phase varies very quickly and is decorrelated between two successive resonances, through collisions or non-linearly, the energy transfer between the particle and the wave can be described as diffusive process, whose diffusion coefficient is given by $D_{QL}=\Sigma\sigma(\Delta E)/\tau_b$, where the summation is over the different resonances the particle encounter during one poloidal revolution, $\sigma(\Delta E)$ is the variance of the change in energy and τ_b is the poloidal bounce time.

When $\dot{\omega}_c$ is close to zero, the expression for ΔE given in equation 3 becomes singular. For trapped particles, this corresponds to cases when the resonant point is close to the banana tip of the particle trajectory. This can also happen when the resonance is tangent to the trajectory, which can occur for both passing and trapped particles (see figure 1). In this case, the first order expansion of ω_c around the resonance point is no longer appropriate, and a second order expansion around the extremum point of ω_c is required. The expression for ΔE obtained in this way involves Airy functions and is continuous for $\omega_c^{resonance}=\omega_c^{extremum}$

The connection between the coefficient obtained from the first order expansion and the one coming from the second order expansion is illustrated in figure 2.

To take into account a complete toroidal spectrum, the individual contribution of each wave number is summed with weights corresponding to the power of each antenna mode.

$$D_{QL}^{total} = \Sigma P(k_{//}) D_{QL}(k_{//}) / \Sigma P(k_{//}) \quad (4)$$

This model has been implemented in the SPECO code, which computes the ICRF-induced diffusion coefficients of fast particles interacting with a complete toroidal spectrum.

4. COMPARISON OF THE MODEL WITH A COMPLETE CALCULATION

The results of the model discussed in paragraph 3 have been compared with those of a complete calculation obtained with the MOKA code [3]. MOKA computes the complete trajectories of the particles with an equilibrium magnetic field calculated with the IDENT code and the ICRF electric field that is obtained from the ALCYON code [5]. Thus, the full poloidal and toroidal structure of the wave perturbation are retained. Computations are made in six dimensions, keeping finite orbit width effects (including the Larmor orbit) and correlation effects.

The first case we study is for trapped particles interacting with a single toroidal wave number. Figure 3a shows the results of SPECO: the diffusion coefficient is actually the sum of two contributions: one from the inner leg of the orbit that is Döppler shifted towards the low field side (LFS) and one from the inner leg that is Döppler shifted towards the high field side (HFS). The LFS contribution peaks for particles having an energy of 600 keV and then drops dramatically. At this energy, the Döppler shift makes the resonance tangent to the particle trajectory, and the interaction is therefore maximum. At higher energies, the Döppler shift is such that there is no more resonant interaction between the wave and the particle. The contribution of the inner leg increases steadily with energy. The diffusion coefficient obtained with MOKA is consistent with the above observations (figure 3b): it peaks at the same energy as the SPECO LFS coefficient and remains almost constant at higher energies.

The second comparison concerns trapped and passing particles interacting with a complete spectrum. In both cases, the coefficients increase strongly up to 1 MeV and are almost constant for higher energies. Though $\sigma(\Delta E)$ increases with energy for a given wave number, fewer and fewer wave numbers interact resonantly with the particle, as the Döppler shift gets larger. The agreement between the SPECO model and the MOKA simulations is

good. The only significant discrepancy comes for trapped particles at energies under 500 keV. These particles absorb power both at their banana tip and at their tangent point. The focusing of the wave as it penetrates the plasma will therefore be important for the relative strength of the energy exchange at the resonance points. However, this focusing is poorly described by the simple wave structure used by SPECO, which at least partly explains the discrepancy .

The comparison shows that at high energies, the geometry of the particle orbit and its Döppler shifted interaction points with the wave play a crucial role for an accurate modelling the diffusion coefficients. In comparison, the poloidal structure is of lesser importance, because the effects are averaged over the whole toroidal spectrum.

5 . SUPERADIABATICITY

From the MOKA simulations, it is possible to compute diffusion coefficients averaging over ten poloidal revolutions instead of one poloidal revolution. In the limit when the decorrelation hypothesis is valid, the diffusion coefficient should be the same regardless of the number of poloidal revolutions. However, when stochastization is not sufficient to ensure wave-particle phase decorrelation between successive resonances, the energy transfer can no longer be treated as a diffusive process [2,3,6] and the coefficient averaged over ten poloidal revolutions diverges from the one computed over one poloidal revolution. Figure 3 shows that over 1.2 MeV, the correlation effects makes the diffusion coefficient averaged over ten revolutions drop under the value averaged over one revolution. This is characteristic of non-diffusive behaviours resulting in a reduction of the wave-particle energy transfer.

6 . CONCLUSION

This paper discusses frequently made assumptions for the treatment of the wave particle interaction. It particularly stresses the importance of taking into account a complete toroidal mode spectrum. At high energies, Doppler shift effects spread the resonant points over the whole particle orbit. Because of these shifts, the absorption at the LFS equatorial plane crossing of the trajectory can be more important than the absorption at the banana tip for trapped particles. The SPECO model also emphasises the importance of finite orbit widths effects, showing that non standard orbits can play a significant role in assessing the efficiency of the wave particle interaction (for example, on Figure 3, counter passing particles absorb power very efficiently, even at low energies).

The efficiency of the RF heating is also affected by cyclotron phase correlation effects, which play a role at high energies, especially for passing particles. Whereas this effect is not likely to play a large role in present day tokamaks, it could strongly change the absorption of RF power by alpha particles in a reactor tokamak, and this parasitic absorption should be evaluated in the light of the diffusion reduction due to superadiabaticity.

References

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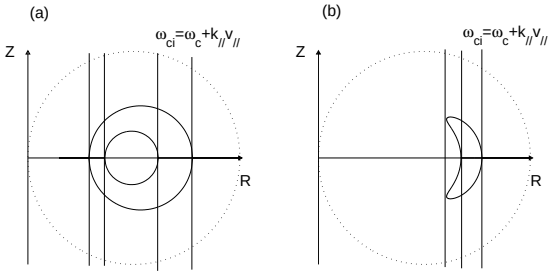

Figure 1: Tangency points for passing (a) and trapped (b) orbits.

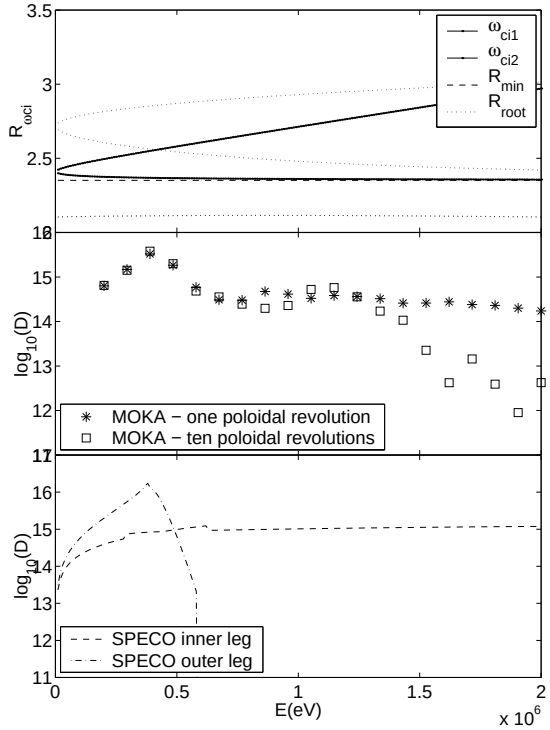

Figure 3 : SPECO and MOKA simulation for trapped particles interacting with one wave number N=20. The first plot gives the location of the resonance points(ω_{cI}), the banana tip(R_{min}) and the equatorial plane crossings (R_{root}.). The second plot gives the diffusion coefficients as a function of the energy as computed by MOKA. Crosses correspond to the quasilinear diffusion coefficient, averaging over one poloidal revolution, and circles to the diffusion coefficients obtained with statistics over ten poloidal revolutions. Lastly, SPECO coefficients are given, one corresponding to the crossing of the resonance on the inner leg of the banana trajectory, the other one to the outer leg.

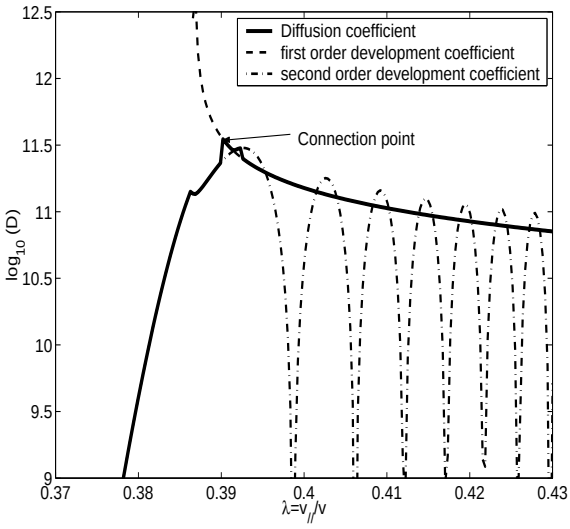

Figure 2 : Connection between the diffusion coefficients computed with the first order development of ω_c and the second order development. The coefficient used for the calculations is given in full line.

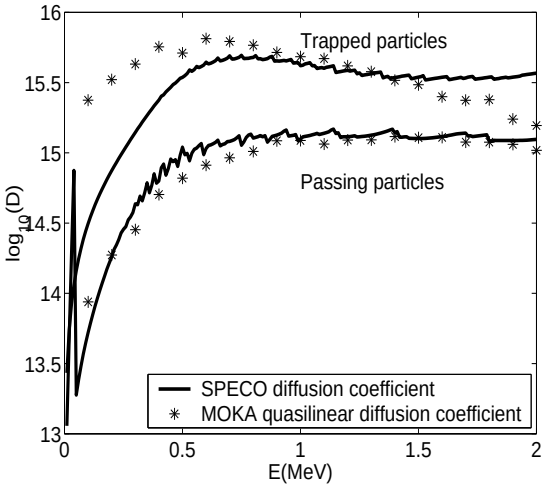

Figure 4 : SPECO and MOKA simulations for trapped and passing particles interacting with a complete spectrum