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Interaction between Fusion-born Alpha particles and Lower Hybrid Waves including Magnetic Field Ripple and Anomalous Transport Effects in ITER

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Introduction

In ITER and future fusion reactors, the control of the current profile could be essential to sustain high performance plasmas. For hybrid and reversed shear scenarios, a possible option is to use Lower Hybrid (LH) waves, taking advantage of their efficient off-axis current drive capability. However, initial difficulties to couple LH waves in plasmas with large ELMs has made it a lower priority for first ITER operations. Nevertheless, recent coupling of LH waves in JET high performance plasmas has been a success. Furthermore, many collaborations on this subject have led to a better understanding of LH physics together with the development of high performance LH launchers, as emphasized in [1]. An important issue is to find a suitable frequency of the launched LH waves, in order to limit the amount of LH power parasitically absorbed by fusion-born alpha particles, but using generators of reasonable cost. Another issue of this parasitic absorption is the possible formation of a high-energy tail of the alpha particle distribution function, which could lead to enhanced fast particle losses and therefore damage to the tokamak first wall.

In order to study these issues, finite orbit width effects have to be taken into account accurately to evaluate the radial distribution of alpha particles. Such a modelling is essential since LH waves are mainly absorbed at the edge of the plasma. Therefore, self-consistent simulations have previously been carried out [2] by coupling the SPOT orbit following Monte Carlo code [3] with the DELPHINE ray-tracing / Fokker-Planck package [4], to simulate the propagation and absorption of LH waves inside the plasma. This study indicated that the interaction between alpha particles and LH waves could be acceptable in ITER down to LH frequencies of 3.7 GHz.

However, effects like magnetic field ripple or interaction with plasma instabilities could lead to a further broadening of the alpha particle density profile, and thus increase the parasitic absorption. This paper presents the first attempts to quantify each of these effects for the main scenarios foreseen for ITER, i.e. standard H-mode, steady-state and hybrid scenarios.

Magnetic field ripple

The finite number of toroidal field coils in a tokamak (18 coils are envisaged for ITER, see e.g. [5]) leads to a ripple in the magnetic field, i.e. a periodic variation of the magnetic field in the toroidal direction. This leads to two different fast particle transport effects:

- *Ripple well losses:*

One can define the parameter $\nu = \frac{B}{B_R} N\delta$, where B and B_R are the magnetic field and its component in the major radius respectively, N is the number of toroidal field coils and δ the ripple magnitude (of the order of 1-2% at the edge of ITER plasmas). The condition $\nu > 1$ delimits the ripple well region, i.e. where particles may be trapped into local toroidal wells. For fast ions the most important process is collisionless trapping [6], which takes place when the turning point of poloidally trapped particles is in a region where ν increases along the grad-B drift direction of the ions (downwards in ITER), i.e. when

$dv/dz < 0$. The uncompensated grad-B drift of ripple well trapped ions leads to rapid losses of them. The ripple well region and the region where $dv/dz < 0$ are displayed in Fig.1.

The overlap between both regions (in red in the figure) represents the area where particles, trapped in ripple wells, have a high probability of escaping. However, owing to the downwards particle drift, most of the particles inside this region tend to reach the good confinement area before being lost. Therefore particles whose banana tips are in the region where $v > 1$ and $dv/dz < 0$ are not considered as directly lost, but simply vertically shifted towards the magnetic axis, to account for the enhancement of their drift motion by ripple wells.

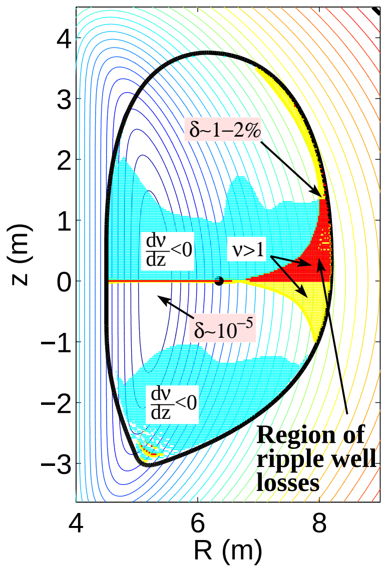

Figure 1: Plasma poloidal view; iso-ripple lines are displayed, as well as the ripple well region ($v > 1$, in yellow), and the region where trapped particles tend to escape ($dv/dz < 0$, in blue).

• *Ripple stochastic diffusion:*

The magnetic field ripple affects the orbits of fast ions even in the regions without ripple wells. The perturbations due to the field ripple tend to accumulate near the turning points of trapped particles, leading to a spatial displacement of the latter. For sufficiently energetic particles the turning point displacements become uncorrelated, resulting in stochastic diffusion [7]. This stochastic diffusion can be represented by the following accelerated Monte Carlo operator [8]:

$$\Delta\Psi = N_{acc}\frac{\partial D_{rip}^{\Psi\Psi}}{\partial\Psi} + \xi\sqrt{2D_{rip}^{\Psi\Psi}N_{acc}} \quad (1)$$

$$\text{with } D_{rip}^{\Psi\Psi} = \left(\frac{1}{2Ze}\right)^2\left[\frac{1}{2}mv_\perp^2\sqrt{\frac{2\pi N}{|\ddot{\phi}|}}\delta\right]^2\left(I_w^{stoch} + I_w^{coll}\right) \text{ and } |\ddot{\phi}| \simeq \frac{v^2}{2qR_0^3}\frac{z}{\kappa},$$

where $D_{rip}^{\Psi\Psi}$ is the stochastic diffusion coefficient, v and $v_\perp$ are the particle velocity and its perpendicular component respectively, q is the safety factor, z the vertical coordinate of the particle, ξ is a random number with a zero mean and unit variance, uniformly distributed in the range $[-\sqrt{3}, \sqrt{3}]$, and κ the ellipticity of the plasma. Coefficients I_w^{stoch} and I_w^{coll} represent the decorrelation between steps in successive bounces, associated with stochastic diffusion and collisions respectively (see e.g. [9]).

Anomalous alpha particle transport

Recent studies have shown that alpha particles may interact strongly with core ITG turbulence in ITER [10], leading to strong turbulent fluxes. This kind of interaction could lead to a widening of the alpha distribution function. In order to quantify the maximum tolerable magnitude of fast particle transport, with respect to the parasitic absorption of LH waves by alpha particles, a simple radial transport operator has been added, as shown in Eq.2:

$$\Delta\Psi = \frac{1}{\sqrt{g}}\frac{\partial}{\partial\Psi}\left(\sqrt{g}D_{ano}^{\Psi\Psi}\right)N_{acc}\Delta t + \xi\sqrt{2D_{ano}^{\Psi\Psi}N_{acc}\Delta t}, \quad (2)$$

where $\sqrt{g}$ is the jacobian of the coordinate transformation, Ψ is the poloidal magnetic flux coordinate, $D_{ano}^{\Psi\Psi}$ is the diffusion coefficient expressed as a function of the Ψ coordinate, Δt is the integration time step, N_{acc} is the factor related to the acceleration of the Monte Carlo operators (i.e. one simulated orbit represents N_{acc} orbits in reality), and $\Delta\Psi$ the radial transport of alpha particles induced by the plasma turbulence. Usually, the radial diffusion coefficient is expressed as a function of the plasma minor radius coordinate r rather than the Ψ coordinate; in the approximation of a plasma circular geometry, one can consider $D_{ano}^{\Psi\Psi} \simeq D_{ano}^{rr} \left(\frac{\partial\Psi}{\partial r}\right)^2$.

Simulations have been carried out with the following anomalous transport diffusion coefficients: $D_{ano}^{rr} = 0.1;\ 0.5;\ 1\text{m}^2/\text{s}$. These ad-hoc values cover the range of thermal particle transport. Hence, the value $D_{ano}^{rr} = 1\text{m}^2/\text{s}$ can be considered as an upper limit for fast ion transport.

Results

Magnetic field ripple and anomalous transport affect the alpha particle density profile, leading to a variation of the LH damping on alpha particles. The region of interest to study this effect is the plasma edge, owing to the low penetration of LH waves inside the plasma (due to the high electron temperature). Resulting alpha particle density profiles are shown in Fig.2 for $f_{\text{LH}} = 3.7$ GHz, for the three considered ITER scenarios. As can be seen, the only case in which the alpha particle density increases significantly at the edge is the steady-state scenario, in the presence of anomalous transport (only the profiles with $D_{ano}^{rr} = 1\text{m}^2/\text{s}$ are shown here). This is probably due to the higher gradient of the alpha particle density profile at the edge of the plasma, leading to an increased local diffusion.

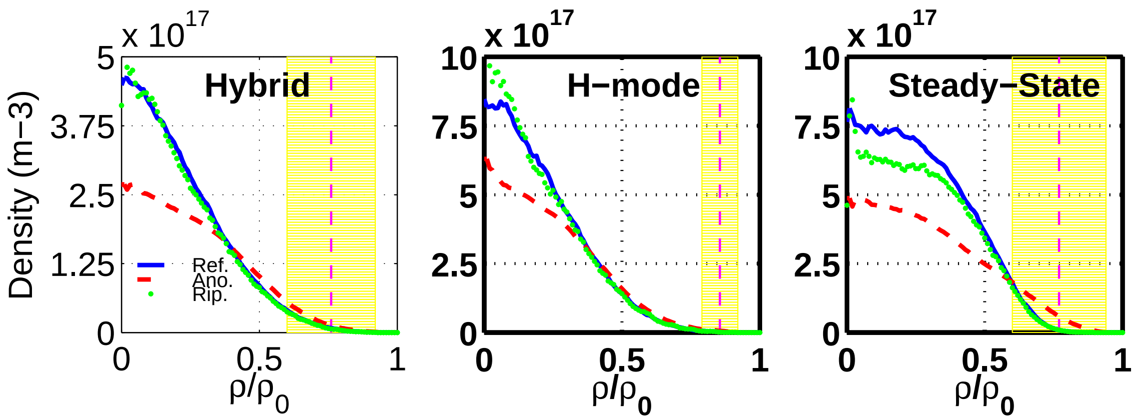

Figure 2: Alpha particle density profiles for $f_{\text{LH}} = 3.7$ GHz, for the three ITER scenarios: without ripple nor anomalous transport (reference, in blue); with magnetic field ripple only (in green), and with anomalous transport only (with $D_{ano}^{rr} = 1\text{m}^2/\text{s}$, in red) The colored area represents the region where LH power is absorbed by alpha particles.

The resulting LH damping on alpha particles, for $f_{\text{LH}} = 3.7$ and 5 GHz, is presented in the table 1 for magnetic field ripple, and in Fig.3 for anomalous transport. These results show that the magnetic field ripple does not increase the damping of LH power on alpha particles, whatever the LH frequency. It is even slightly reduced, due to the larger alpha particle losses coming from the plasma edge. These losses are presented in the table 2. They increase significantly in the presence of magnetic field ripple and anomalous transport, both for $f_{\text{LH}} = 3.7$ and 5 GHz. This can lead to a further damage of the first wall, but this is beyond the scope of this paper. On the other hand, regarding the effect of anomalous transport on the LH absorption by alpha particles, significant differences are observed with both LH frequencies. In the case of the steady-state scenario in the presence of large anomalous transport, the parasitic absorption can reach potentially unacceptable levels, i.e. around 8% with $f_{\text{LH}} = 3.7$ GHz, while it remains below 1% with $f_{\text{LH}} = 5$ GHz. However, as stated previously, this diffusion coefficient is rather unknown for fast particles and may be much lower. For instance, for $D_{ano}^{rr} = 0.1\text{m}^2/\text{s}$, this absorption is of the order of 2% for $f_{\text{LH}} = 3.7$ GHz, which remains negligible as well.

LH absorption (%)	f_{LH} = 3.7 GHz		f_{LH} = 5 GHz	
	wo ripple	with ripple	wo ripple	with ripple
Hybrid	0.6	0.5	0.04	0.04
H-mode	0.08	0.07	0.01	0.01
Steady	1.8	1.9	0.06	0.06

Table 1: Percentages of LH power absorbed by alpha particles, for each ITER scenario, with and without magnetic field ripple, for $f_{LH} = 3.7$ and 5 GHz (without anomalous transport).

Alpha power losses (%)	f_{LH} = 3.7 GHz		f_{LH} = 5 GHz	
	wo ripple	with ripple	wo ripple	with ripple
Hybrid	0.6	3.1	0.56	3.0
H-mode	0.4	2.3	0.41	2.3
Steady	0.1	6.7	0.12	6.6

Table 2: Percentages of alpha power losses, for each ITER scenario, with and without anomalous transport, for $f_{LH} = 3.7$ and 5 GHz (without anomalous transport).

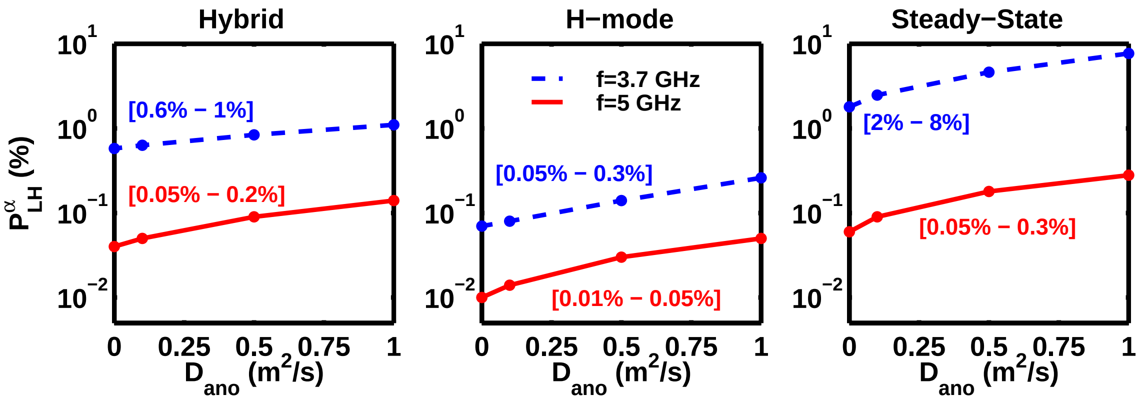

Figure 3: LH power asborbed by alpha particles as a function of the anomalous diffusion coefficient, for the three ITER scenarios, both for $f_{LH} = 3.7$ and 5 GHz (without magnetic field ripple).

Summary and conclusion

New SPOT simulations have been carried out, accounting for magnetic field ripple and anomalous alpha particle transport, using a simplistic model for the latter as a first step. The results show that, assuming an anomalous transport diffusion coefficient in the range $[0.1-1]$ m^2/s, the parasitic absorption of 3.7 GHz LH power by alpha particles may become significant for the ITER steady-state scenario (between 2 and 8%). However, as the anomalous fast ion transport is hardly known, this absorption is probably overestimated. Furthermore, for all other scenarios, the LH parasitic absorption remains negligible (<2%). On the other hand, for $f_{LH} = 5$ GHz, this absorption is negligible, whatever the scenario is. Regarding the magnetic field ripple, present simulations show no increase of the LH damping on alpha particles, whatever the LH frequency is. As a consequence, the use of 3.7 GHz klystrons in ITER cannot yet be ruled out. Furthermore, 5 GHz would be more than sufficient for all scenarios.

Present simulations indicate that both anomalous alpha transport and magnetic field ripple enhance the alpha particle losses, for both LH frequencies. This may lead to an increased damage to the tokamak first wall. Therefore, further studies will be essential to address this issue.

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