Optimal conditions for alpha channelling in burning plasmas

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Alpha-channelling [1] is a mechanism to extract the alpha particle energy through the interaction with mode-converted ion Bernstein waves (IBW) that are absorbed by the thermal ion population. In tokamaks, the resonant interaction between alpha particles and waves, $\omega = \vec{k}\cdot\vec{v}$, produces diffusion in the constant-of-motion (COM) space, defined by the energy ε, the magnetic moment μ and the toroidal angular momentum P_ϕ. Specifically, diffusion occurs along the following curves

$$\Delta\mu = \frac{Ze}{m\omega}\Delta\varepsilon \qquad \Delta P_\phi = \frac{n_\phi}{\omega}\Delta\varepsilon\,. \tag{1}$$

The generation of a net energy flow from alpha-particles to IBW requires that the particles crossing the plasma boundary are removed. As shown in Eq.(1) the variation of P_ϕ (related with the particle radial position) is proportional to the toroidal wave number n_ϕ thus in order to move particles from the center to the edge too high values of n_ϕ are required that cannot be realized in experiments [2]. To overcome this problem a second low-frequency wave can be used [3], that efficiently removes particles after they have released most of their energy to IBW. The investigation on the performance has been done through Monte Carlo simulations of the particles orbits [4], but limited evidence of alpha channelling has been found in experiments so far [5].

In order to gain a deeper understanding of the alpha channelling mechanism, a theoretical model has been proposed in [6] for a slab case and generalized to a tokamak configuration [7]. The model is based on a stationary solution of the Fokker-Planck equation including wave-induced diffusion, the slowing-down on electrons and the proper source term. The equation is solved in the limit of large diffusion coefficients and the low-frequency wave is modeled through a radial flux at the threshold perpendicular energy for wave-particle resonance. For simplicity, we considered an IBW localized on a thin region near mode-conversion (but the model can be extended to more generic configurations) implying that only those particles whose orbits cross such a layer can exchange energy with IBW.

The generic solution of the Fokker-Planck equation in the limit of large diffusion coefficient

D can be written as

$$F = d(w_1, w_2) - \int_{q_0}^{q} \frac{dq'}{D} \int_{q_0}^{q'} dq'' \, \tau \hat{C} d(w_1, w_2) - b(w_1, w_2) \int_{q_0}^{q} \frac{dq'}{D}, \tag{2}$$

q, w_1, w_2 being suitable coordinates for IBW-induced diffusion, with q along the diffusion paths and w_1, w_2 orthogonal to them, while τ denotes the period of the bounce-transit motion and $\hat{C}$ is the collision operator (in which the slowing-down operator provides the dominant contribution). The functions b and d are fixed by the boundary conditions in phase space and correspond to two physical effects: pure wave-induced diffusion, with a constant flux sustained by the particle source (it is the only contribution for those diffusion paths connecting the source with the plasma boundary), and wave damping, in which alpha particles extract energy from IBW and release it to electrons via collisions. The amount of alpha channelling can be quantified by solving a first-order PDE whose coefficients are some functions in COM space, that can be numerically computed given the poloidal flux ψ and the source profile.

We choose a specific form for both of them and we model the flux due to the low frequency wave by a parameter α ranging from $\alpha = 0$ (maximum flux) up to $\alpha = \infty$ (no transport due to the low-frequency wave). Hence, we solved numerically the PDE and we plot in figure 1 the total power flowing from alpha particles to IBW with respect to the ratio n_ϕ/N of toroidal wave number and harmonic number, while different curves correspond to different α values. The plot outlines the crucial role played by the flux associated to the low frequency wave: for negligible flux (*i.e.* large values of α - the lowest curve in Fig.1) the maximal power fraction transferred to the IBW is $\sim 25\%$ and it requires very high n_ϕ/N ($n_\phi \sim 700N$), while for smaller n_ϕ it becomes negative signaling the prevalence of wave damping. For larger values of the flux associated to the low-frequency wave, the transferred power fraction is larger and the maximum occurs at smaller n_ϕ/N values. The optimal case $\alpha = 0$ (solid line) is shown in figures 2 and 3.

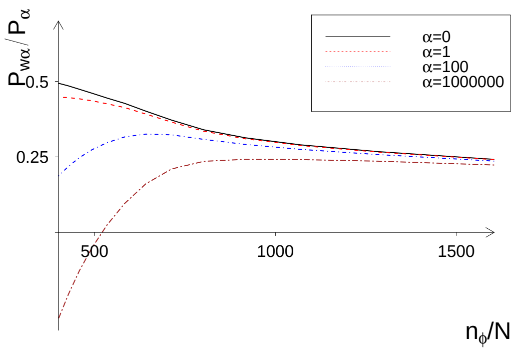

Figure 1: *The fractional power flowing from alpha particles to IBW.*

The three curves in figure 2 are obtained for different values of the distance r_{mc} between the magnetic axis and the mode-conversion layer (the ITER-like parameters are chosen with $2m$ minor radius, $6.2m$ major radius and $5, T$ the magnetic field on axis).

The position of the mode-conversion layer determines the fraction of those particles interacting with IBW, *i.e.* circulating and trapped particles with outer radii larger than r_{mc} and trapped particles with banana tips at radii smaller than r_{mc}. The largest alpha channelling effect is obtained for $r_{mc} = 0.5\,m$ (red curve) with about 55% of alpha particle power transferred to the IBW.

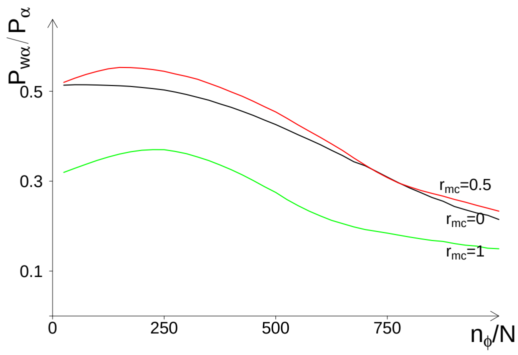

Figure 2: *The fractional power flowing from alpha particles to IBW in the optimal case* $\alpha = 0$.

In figure 3, the fractional power is plotted for different source profiles, parametrized by s as $\dot{N}_0 \propto \left(1 - \frac{\psi}{\psi^w}\right)^s$, $\dot{N}_0$ being the number density of alpha particles produced in a unit of time.

The source profile strongly affects the energy spectrum of the alpha particles crossing the plasma boundary, which is plotted in figure 4 for $n_\phi/N = 30$ and near each curve the corresponding energy flux is reported. Even though single alpha particles reach the wall with high energy, their flux is so small that the fraction of energy driven to the wall is negligible for peaked source profiles.

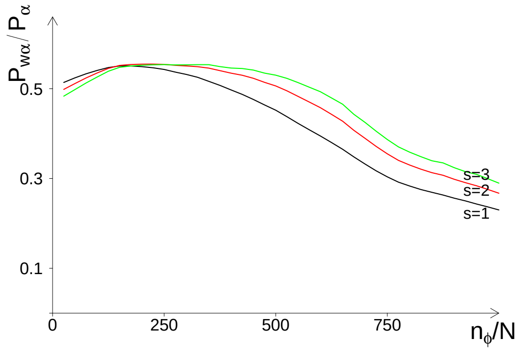

Figure 3: *The fractional power flowing from alpha particles to IBW in the optimal case* $\alpha = 0$.

Therefore, the process with two waves can reach high efficiency, with more than 50% of the total alpha particle energy channelled to IBW (and we expect this fraction to be higher by removing the thin layer approximation for the IBW amplitude), and low power released to the first wall of the chamber. However, this is only possible if the radial flux of alpha particles due to the low-frequency wave is comparable to the flux at the source.

With the aim of understanding if the Alfvenic turbulence could provide the required low-frequency flux of alpha particles, the form of the distribution function outside the region of resonant interaction with IBW has been derived. This analysis is the prelude for the investigation of the instabilities driven by the alpha particles, that will involve both a the-

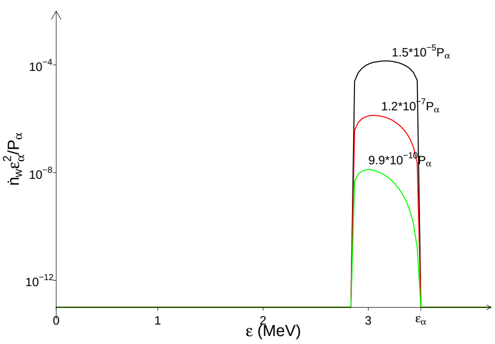

Figure 4: *The spectrum of alpha particles at the wall for* $n_\phi/N = 30$.

oretical description of TAE growth rate and the simulation of modes generation and evolution via the extended magneto-hydrodynamic gyrokinetic code (XMHGC).

Different scenarios for the IBW mode conversion and absorption have been studied in DT plasmas. The reference scenario corresponds to the excitation of a fast wave slightly above the D resonance at the plasma edge with conversion between the D and T resonance and absorption at the fundamental T resonance located at the plasma center. In order to avoid dominant absorption by electrons the poloidal and toroidal mode numbers of the injected fast wave must be such that the parallel wave vector at the mode conversion is minimized. Beyond the mode conversion surface the IBW propagates close to the equatorial plane. The ray equations have been analytically solved using asymptotic techniques [8] up to the region in which ion absorption takes place. Far from the ion resonance the ray orbits in phase space correspond to linear oscillations. As the ion resonance is approached the oscillations become nonlinear and there is a slow transition from closed to open trajectories.

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