# Understanding the mechanism of alpha channelling

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The production of a stable energy flow from alpha particles produced in nuclear reactions to the bulk ion population (known as alpha channelling [1]) has been conjectured in order to enhance the performance of fusion devices. Proper carriers of such an energy flow are those mode-converted Ion Bernstein waves (MCIBW) [2] having parallel phase velocity very large and opposite in sign with respect to the launched wave ($k_\parallel$ flip), thus preventing damping on electrons. The extraction of alpha particle kinetic energy by waves is based on wave-particle interaction $\omega = \vec{k}\cdot\vec{v}$, providing the following kicks in the Constant-of-Motion (COM) space

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

$\varepsilon$, $\mu$ and $P_\phi$ being the energy, the magnetic moment and the toroidal angular momentum of alpha particles. As a consequence, alpha particles loose energy in favor of the wave while moving towards the plasma periphery, where they are removed. The associated diffusion has been simulated for a realistic tokamak configuration via a Monte Carlo approach [3]. The main conclusion is that the toroidal wave number is too high for a single wave to extract energy and move particles to the plasma edge and it has been proposed in [4] to combine a high-frequency wave, such as MCIBW, extracting most of the energy, with a low-frequency wave, like toroidal Alfvén modes, moving particles towards the plasma edge. However a better understanding of alpha channelling and of its dependence on plasma and wave features is required, since only very limited evidences have been found in experiments [5] as well as in numerical simulations [6]. A novel analysis on alpha channelling has been proposed in [7] and applied to the slab case, *i.e.* for straight magnetic-field lines. It is based on the analytic solution of the stationary Fokker-Planck equation governing phase space diffusion for alpha particles interacting with electrostatic waves under the assumption of very large diffusion coefficient. This analysis provides the explicit expressions of the stationary distribution functions and of the power flowing from alpha particles to the wave.

In order to extend the analysis in [7] to a toroidal tokamak configuration, let us consider a MCIBW whose amplitude is non-vanishing in a thin vertical layer near the mode conversion layer. The wave has positive toroidal wave number $n_\phi$ and frequency smaller but very close to the alpha cyclotron frequency, $\omega \sim \Omega_\alpha$. Under the assumption of $k_\parallel$ flip the resonance condition $\omega = \vec{k} \cdot \vec{v}$ for wave-particle interaction holds only if the velocity has positive component along the magnetic field. Each time these particles cross the mode conversion layer, they receive the kicks (1), which, if stochastic, provide a diffusion term in the Fokker-Planck equation for the distribution function $F$ of alpha particles. Diffusion paths can be conveniently labeled by two variables $w_1 = \varepsilon - \frac{m\omega}{Ze}\mu$ and $w_2 = \frac{m\omega}{Ze}\mu - \frac{\omega}{n_\phi}P_\phi$, which do not change under the kicks (1), while a third variable $q$ can be taken along diffusion paths, so that $\Delta q = \Delta\varepsilon$. By including also a slowing-down contribution $\hat{C} = \nu \partial_{\vec{v}} \vec{v}$, $\nu$ being the collision frequency, and a source term with production rate per unit volume $\dot{N}_0$, the full Fokker-Planck equation reads [8]

$$\partial_t F = \frac{1}{\tau}\partial_q D \partial_q F + \hat{C}F + \frac{\dot{N}_0 m}{4\pi v_\alpha}\delta(\varepsilon - \varepsilon_\alpha)\,, \tag{2}$$

where $D$ denotes the diffusion coefficient, $\varepsilon_\alpha = 3.5MeV$ is the birth energy of alpha particles and $\tau$ is the period of the poloidal motion. The geometry of COM space is simplified by neglecting the term proportional to the parallel velocity within the expression of $P_\phi$ and by taking the high inverse-aspect-ratio limit. The solution of the stationary Fokker-Planck equation in the limit $D \to \infty$ can thus be written explicitly and it exhibits different behavior depending on the considered region of COM space (see figure 1).

In region II particle experience pure wave-induced diffusion between the source and the wall, where they are removed. The diffusion flux is constant and the distribution function vanishes at the leading order of the $D^{-1}$ expansion. In region I, the solution is determined by the flux $\vec{S}$ due to Alfvén waves on the surface $\mu = \mu_{min}$, where $\mu_{min}$ is the minimum magnetic moment for wave-particle resonance ($\omega = \vec{k} \cdot \vec{v}$). We consider the two limiting cases:

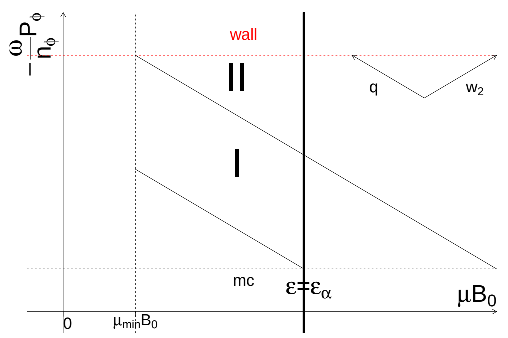


Figure 1: *COM space on section of constant* $w_1$.

- 1) $\vec{S} = 0$: the distribution function in region I does not vanish and the total particle flux is the sum of the wave-induced contribution, which decreases from the source to $\mu = \mu_{min}$ where it vanishes, and of the slowing-down term.

- 2) $|\vec{S}|$ is maximal, *i.e.* all the particles reaching the surface $\mu = \mu_{min}$ are removed, so that in region I there is a vanishing distribution function and a constant wave-induced flux from the source to $\mu = \mu_{min}$, similarly to region II.

In case 1) the fractional power from alpha particles to IBW, *i.e.* the fraction of alpha particle energy channeled to the wave, is plotted in figure 2 as a function of the parameter $x = \frac{\omega}{n_\phi}\frac{Ze}{c}\frac{\psi^w - \psi^{mc}}{\varepsilon_\alpha}$, where $\psi$ is the poloidal flux, the superscripts $^w$ and $^{mc}$ denotes quantities evaluated on the outer midplane at the plasma boundary and at the mode conversion layer, respectively.

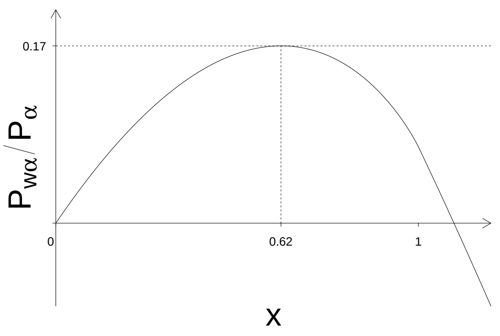


Figure 2: *The fractional power from alpha particles to the wave in absence of external flux.*

It is worth noting how it exhibits a maximum $\sim 17\%$ at $x = 0.62$, while the energy flow reverse for $x > 1.03$. This reversal is due to the energy lost in collisions, which is balanced by an equal amount of energy extracted from the IBW resulting in wave damping. Case 2) is the best scenario for alpha channeling and the corresponding fractional power is shown in figure 3. The maximum is now reached for $x \gg 1$, at which the whole perpendicular energy of alpha particles is released to the wave. The two limiting cases shown in figures 2 and 3 outline the impact of the flux due to Alfvén modes on the energy flow from alpha particles to the MCIBW.

In this respect, we are currently investigating the possibility of deriving a self-consistent expression for the flux $\vec{S}$ due to Alfvén waves. The idea is to initialize the distribution function according to the solution of the Fokker-Planck equation (2) and to use the extended magneto-hydrodynamic gyrokinetic code (XMHGC) to simulate the generation and evolution of Alfvén modes. Since, as pointed out above, the initial distribution function depends on $\vec{S}$, the interplay between the high-frequency IBW and the low-frequency Alfvén waves is highly non trivial.

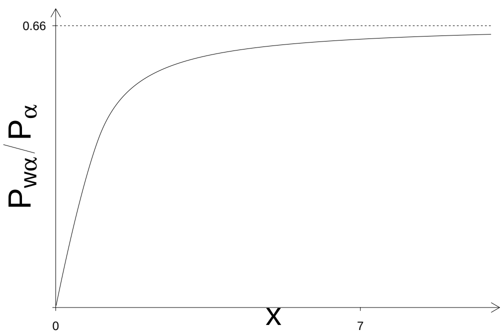


Figure 3: *The fractional power from alpha particles to the wave in the optimal case.*

The IBW is excited via mode conversion of a fast wave at the ion-ion resonance layer and it propagates towards the ion cyclotron resonance interacting with both ions and electrons. In the present analysis the ray tracing equations have been solved using the full dispersion relation for the IBW wave [9]. A simplified low-beta equilibrium with circular flux surfaces is used here.

Following previous analyses [10] analytical studies of the propagation and (linear) absorption of the IBW have been also performed using a simplified IBW dispersion relation in toroidal geometry. Results are shown in Fig.4 and 5 where the parallel wavenumber and the ray trajectory are reported for $n_{\|} \sim 0$ and $q = 0$ at the mode conversion layer. The analysis is ongoing to determine the best conditions to optimize the transfer of power from the alpha particles to the thermal ions via the IBW.

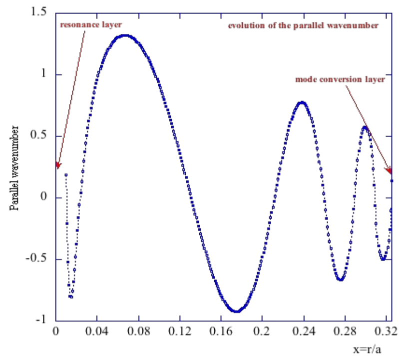


Figure 4: *The poloidal wave number as a function of the minor radius.*

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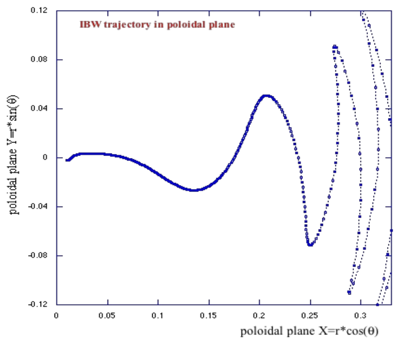


Figure 5: *IBW trajectory in poloidal plane.*

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