A Tutorial on α-channelling

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Abstract. One of the more ambitious uses of intense microwaves in tokamaks or in other magnetic confinement DT fusion devices would be to divert power from energetic α-particles to waves. This so-called "α-channelling" would be a large step towards achieving economical fusion power. The intense waves, amplified by the substantial free energy in the α-particles, damp on fuel ions, resulting in a hot ion mode, doubling the fusion power of the reactor at the same confined pressure. If the waves damp preferentially on electrons or ions traveling in one direction, current can be driven. This tutorial explains the key concepts and recent advances that lead us to believe in the plausibility of such an effect, at the same time showing how experiments to date give us a measure of confidence in both the simulations themselves, the underlying physical assumptions, and ultimately the reasonableness of the application of these ideas to α-channelling in a tokamak reactor.

1. Introduction

If only the cross-section for fusion reactions were larger, approaches to economical thermonuclear power production would be easier. There is, however, the possibility that the effective reactivity at constant confined pressure can be increased by departing from thermal equilibrium. For example, the fuel might have a higher effective reactivity if the fuel ions were "beamlike" rather than Maxwellian [1; 2], if the fuel ions were polarized [3], or if fuel ions were much hotter than the electrons (the so-called "hot-ion mode") [4]. In each case, while more power is produced, power is also required to maintain the departure from equilibrium in addition to that to replenish the power lost through radiation and transport.

If the power required to maintain the departure from equilibrium is external, none of these ways of increasing the reactivity is economically advantageous. There is, however, the possibility of using the free energy in fusion byproducts extractable by waves [5]; 3.5 MeV α-particles slow down on electrons in a reactor plasma in several hundred ms, which provides an opportunity to convert the α-particle power to wave power on a collisionless time scale. Waves are a useful form of energy that might then maintain the departure from equilibrium. Since the waves are amplified at the expense of the α-particles, the higher reactivity would then be reached without substantial external power. The α-particle power is thus effectively "channelled" into a more useful form of power.

The redirection of power is doubly useful in the case of maintaining the hot-ion mode, since, in the absence of the channelling effect, the α-particle power naturally flows mainly into electrons, making electrons always hotter than ions. Power channelled to waves, however, could damp on ions, at once reducing the electron heating and increasing the ion heating. This makes $T_i > T_e$ possible, conserving the fuel pressure for the ions. The process is shown schematically in Fig 1.

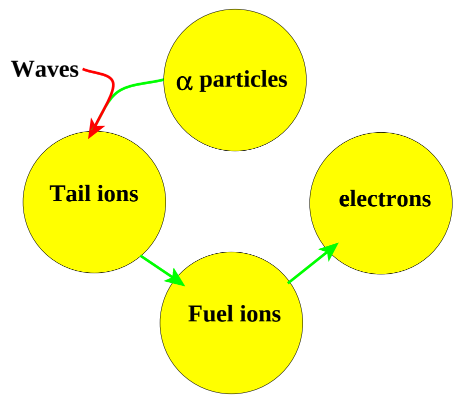

Figure 1. The α-channelling effect is used to redirect to the ions the α-particle power, which normally flows to electrons, thus increasing the plasma reactivity.

For example, if 75% of the α-particle power could be diverted to the ions via waves, a reactor operating at T_i = T_e = 20 keV could be operated instead at T_i = 20 keV and T_e = 12 keV [6]. This almost doubles the fusion power while retaining the same magnetic field and pressure. Other coincidental benefits might include ash removal, a reduction in the fast particle pressure (reducing the drive for undesirable instabilities), and, in principle, the waves used to divert the power may damp in such a way as to drive a current [7] or to control pressure or current profiles. These effects are typically optimized when the electron confinement time is short, and the ion confinement time is long. Such configurations might be attained naturally, for example, in enhanced reverse shear plasmas, where ion confinement is much better than electron confinement [8], or purposefully, for example, by injecting very high-Z impurities into the plasma to increase the radiated power, at the same time decreasing the heat load to the divertor.

2. Wave Characteristics for α-channelling

With the benefits apparent, the challenge is to identify the waves by which the α-channelling effect might be realized. The birth distribution of α-particles is monoenergetic, but isotropic, so wave interactions that drive particles only in velocity space tend not to extract much of the recoverable energy. But the free energy might be tapped by exploiting the population inversion along a path in both energy and space [9]. The channelling occurs when the diffusion path connects high energy α-particles at the plasma center to low energy α-particles at the plasma periphery, for example, as depicted in Fig. 2.

When one wave is utilized, there can be only one diffusion path, with stringent constraints on the α-particle motion. The α-particle motion is constrained to lie on a one dimensional curve, a line. If the path is chosen appropriately, then, if an α-particle loses energy, it must

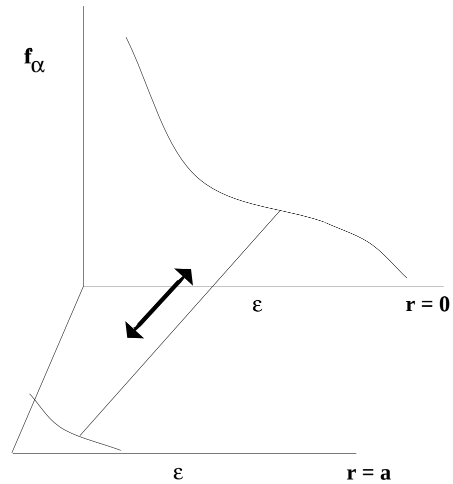

Figure 2. A diffusion path in energy and real space, along which energy is extracted from the α-particle distribution even though it is monotonically decreasing in energy at any fixed radius.

diffuse to the tokamak periphery; conversely, if it gains energy in interacting with the wave, it must diffuse to the tokamak center. Since α-particles exit only at the periphery, eventually they are diffused by the wave to the tokamak periphery where they give up a precise amount of energy to the wave which is proportional to their distance traveled in reaching the periphery.

The effect can be seen most easily in a slab with periphery at $x = a$ and "center" at $x = 0$, so that particles can escape only at $x = a$. (Here, x plays the role of the minor radius r in a tokamak.) Suppose a magnetic field in the z-direction, with α-particles exchanging energy with waves traveling in the y-direction. The ratio of displacement of the guiding center in the x-direction, Δx, to (perpendicular) energy absorbed, $\Delta \mathrm{E}$, is $\Delta x = -k_y \Delta \mathrm{E}/m\Omega\omega$. This quantity is determined by wave and particle parameters only; ω is the wave frequency, k_y is the wavenumber in the y-direction, m is the α-particle mass and $\Omega \equiv 2eB/m$ is the α-particle gyrofrequency. Upon repeated interactions with the wave, an α-particle will trace a line in x-E space.

For efficient channelling, one would then require $\Delta x/\Delta \mathrm{E} \sim a/\mathrm{E}_\alpha$, where E_α is the α-particle birth energy, 3.5 MeV. If instead $\Delta x/\Delta \mathrm{E} \gg a/\mathrm{E}_\alpha$, then the α-particle would be extracted from the center with almost all its energy intact, whereas if $\Delta x/\Delta \mathrm{E} \ll a/\mathrm{E}_\alpha$, then the α-particles are not extractable from the plasma center. In this case, a population inversion is not likely to occur, and the wave will not be amplified.

Thus, we search for waves with the following characteristics: (i) the waves must diffuse α-particles along a path in phase space, such that α-particles at high energy in the center diffuse to low energy near the edge of the tokamak; (ii) the waves must interact strongly enough with the α-particles that the α-particle energy is diverted before the α-particle collisionally transfers its energy to the electrons; and (iii) to achieve the hot-ion mode, the convectively amplified wave must then damp on ions. The necessary wave characteristic (i) is rather difficult to find in a single wave in a tokamak reactor. However, two waves might indeed extract energy from a full birth distribution of α-particles.

A qualitatively different picture emerges when more than one wave interacts with the α-particles; the α-particles are no longer constrained to a line in x-E space. For example, consider the interaction of α-particles with two waves in a slab, as sketched in Fig. 3, where $x = 0$ depicts the plasma center, and where $x = a$ depicts the periphery, with one wave causing energy diffusion only (horizontal paths) and one wave causing diffusion in position only (vertical paths). Note that $\Delta x/\Delta E$ is no longer fixed; a particle could move from the center to the edge and be cooled, even though neither wave diffusion path has the correct slope; but now it might also be heated as it is ejected from the plasma (Fig. 3a).

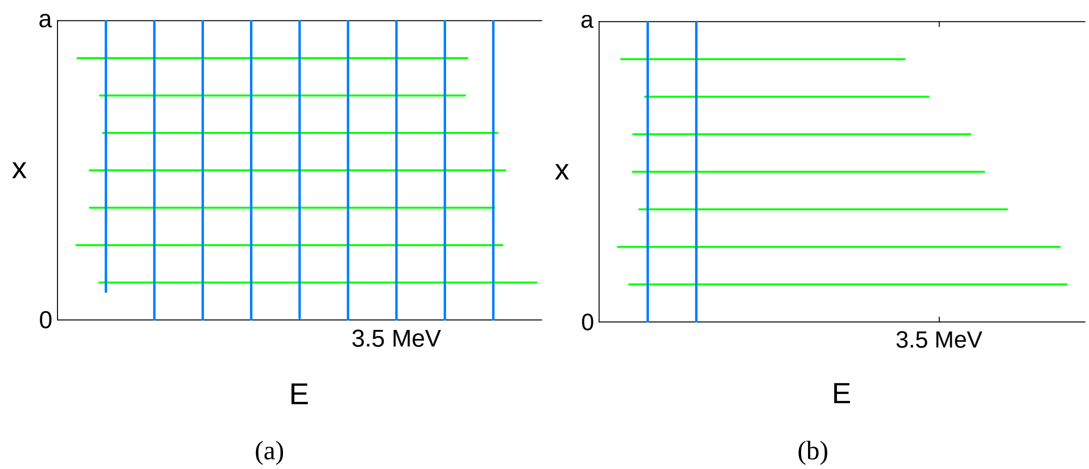

Figure 3. Diffusion paths of two waves, one along energy only and one along space only. (a) : paths allow particles to exit cooled or heated. (b) : paths arranged by means of resonance conditions and wave location, so that significant energy is extracted.

However, by selectively choosing where the diffusion paths exist in phase space (by means of resonance conditions and spatial localization of the waves), configurations of two waves can be created so that the α-particles are vastly predisposed to lose energy to the waves rather than to gain energy. To see that this is in principle possible, consider Fig. 3b, where the diffusion in space is energy dependent, so that significant spatial diffusion occurs only at low energy. Clearly, all α-particles must leave the plasma at low energy, so that there is net extraction of the α-particle energy.

Toroidal geometry is more complicated than a slab, but the considerations are similar. Particles interacting with one wave trace a straight line in ϵ-μ-P_ϕ space, where $\mu = mv_\perp^2/2B$ is the magnetic moment, $\epsilon = \mu B + mv_{||}^2/2$ is the kinetic energy, and $P_\phi = R(mB_\phi v_{||}/B - qA_\phi)$, is the canonical angular momentum, and where $\mathbf{A}$ is the vector potential. Each point in ϵ-μ-P_ϕ space represents a single guiding center orbit for trapped particles, and, for each sign of $v_{||}$, a passing particle orbit. Given ϵ, μ, and P_ϕ, and the sign of $v_{||}$ for passing orbits, it may be determined if the orbit intersects the plasma periphery, indicating that the particle exits.

Upon interaction with a single wave with toroidal mode number n_ϕ, and absorbing energy $\Delta\epsilon$, P_ϕ changes by $\Delta P_\phi = (n_\phi/\omega)\Delta\epsilon$. Assume that the exchange of energy occurs only for particles satisfying the resonance condition $\omega - k_{||}v_{||} = n\Omega$, where n is an integer; then, upon absorbing energy $\Delta\epsilon$, μ changes by $\Delta\mu = (nZe/m\omega)\Delta\epsilon$, where for α-particles, $Z = 2$.

Thus, upon repeated interaction with one wave, the constants of motion, ϵ, μ, and P_ϕ, trace a straight line.

While one wave diffuses along a line, several waves diffuse along a web in ϵ-μ-P_ϕ space. A good strategy for optimizing energy extraction is to choose one wave in the ion cyclotron range of frequencies, such as the mode converted ion Bernstein wave (IBW) [10], in order to break the invariance of μ and thereby access the particle's perpendicular energy. The IBW has $1 < \Omega_\alpha/\omega < 3/2$ in deuterium-tritium plasmas (see Fig. 4). The second wave should be at a low frequency, such as the toroidal Alfven eigenmode (TAE) [11; 12]. The low-frequency wave preserves μ, while moving the α-particles large distances with little energy exchange. The ion Bernstein wave may be excited by launching a fast wave that mode converts at the ion-ion hybrid resonance layer, or through other mode conversion techniques.

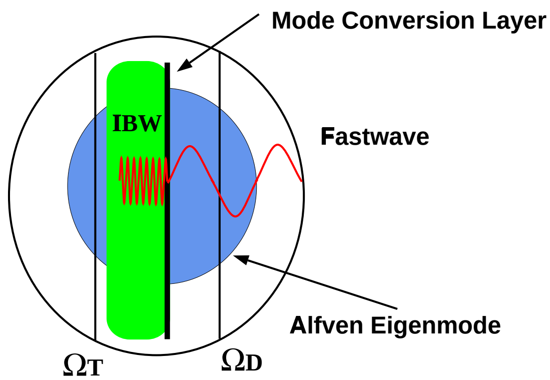

Figure 4. Minor cross-section of tokamak, showing placement of IBW and TAE.

3. Cooling α-particles in a Tokamak Reactor

While a single α-particle can be very effectively cooled by a combination of IBW and TAE [13], the goal is to cool substantially the full birth distribution.

Such a cooling effect is simulated numerically in a reverse shear tokamak reactor with $A = 3$, $R_0 = 5.4$ m, $B_0 = 6$ T, and $I_p = 16.3$ MA (this is a design which was consider by the ARIES-RS team). In this "advanced" reactor, 70% of the energy of the ejected α-particles (73% of those born) is diverted to waves, corresponding to 51% of the α-particle power if we use both MCIBW and TAE [14]. In Fig. 5, the birth locations of 1000 3.5 MeV α-particles are shown in a fixed-energy slice of ϵ-μ-P_ϕ space. Particles remaining in the tokamak are shown in solid black. Those that eventually reach the tokamak periphery are color-coded to show the total lost energy to, for example, just the IBW. Note that the IBW extracts the most energy from particles which have significant amounts of perpendicular energy. The TAE, which must conserve μ, extracts the most energy from those particles which have the most parallel energy.

Posing the problem in ϵ-μ-P_ϕ space enabled a highly efficient numerical simulation [15]. Only specific wave combinations exhibit the cooling effect as opposed to heating or ejecting particles without cooling. Together with isolating and visualizing the effect of each wave on each particle, the fast code enabled good parameter regimes to be found, including that with 93% of the α-particles ejected and cooled to 1/3 their birth energy!

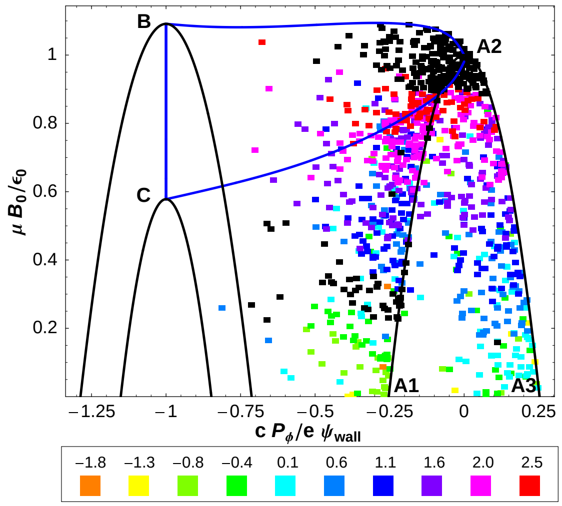

Figure 5. Energy extracted (MeV) by the IBW vs. initial location of particle in ϵ-μ-P_ϕ space. The IBW alone extracts an average of 1.14 MeV per ejected α-particle, the TAE extracts an average of 1.30 MeV.

4. Experimental Results

The numerical simulations that show significant alpha channelling rely on several key assumptions, including that the IBW indeed propagates and interacts with α-particles as expected from theory. The basic wave theory of IBW and TAE have enjoyed experimental verification. Experiments on TFTR demonstrated significant control in placing the IBW wave [16], as well as significant interactions with fast ions [17]. Experiments on JET include direct excitation of the TAE [18] as well as light damping of the TAE mode [19]. There are, however, other, more subtle, but critical wave features that these experiments have also elucidated. One is the so-called "$k_{||}$–flip," which has been predicted theoretically [20].

The $k_{||}$–flip occurs as follows: As the IBW emerges from the mode-conversion layer, there is a rapid increase, as a function of horizontal position, in k_x, the perpendicular wavenumber in the direction of the magnetic field gradient (here, the horizontal or $\hat{x}$-direction). Since the poloidal magnetic field has a component in the $\hat{x}$-direction, the parallel wavenumber can be written as $k_{||} = n_\phi/R + k_x\hat{x}\cdot\hat{B}$, where n_ϕ/R is the launched $k_{||}$, and where $\hat{B}$ is the direction of the magnetic field. Note that either above or below the midplane, $k_{||}$ may change sign from the launched $k_{||}$.

The flip is critical for two reasons: One, in flipping, the parallel phase velocity becomes infinite, so electron damping can be avoided. Two, α-particles will cool as they leave the plasma only for $n_\phi > 0$. From the resonance condition, $v_{||} = (\omega - \Omega_\alpha)/k_{||} > 0$. Since mode conversion in DT plasmas occurs to the high field side of the deuterium gyroresonance layer, $\omega < \Omega_\alpha$. Thus, to resonate with cogoing α-particles, $k_{||}$ must be negative, which is necessarily opposite in sign to the launched $k_{||}$.

In TFTR, in a D^{3}He plasma, large beam losses sometimes occurred when cogoing deuterium beams were injected along with IBW phased in the counterstreaming direction, but not in the costreaming direction. In a D^{3}He plasma, the deuterium resonance is on the high field side of the mode conversion layer, so $\omega > \Omega_D$. Thus, to affect cogoing particles, $k_{||} > 0$, which is opposite in direction to n_ϕ, hence "flipped" [21].

A second critical concern is the attainment of the collisionless limit in a reactor. A very rough estimate, assuming uncorrelated kicks by the IBW, predicts about 100 MW. Now in TFTR, deuterium beams with duration of only 50 ms were fired into discharges with varying amounts of IBW power [22]. The data, composed from the detection of heated beam ions at the periphery, is rich in detail; in addition to the poloidal angle, energy, and pitch angle of the exiting ions, there is now the time-history of this data as a function of rf power. The losses as a function of power should appear at a threshold power, related to overcoming collisional slowing down. Indeed, this is what is seen in simulations [15] and in the TFTR experiments [21].

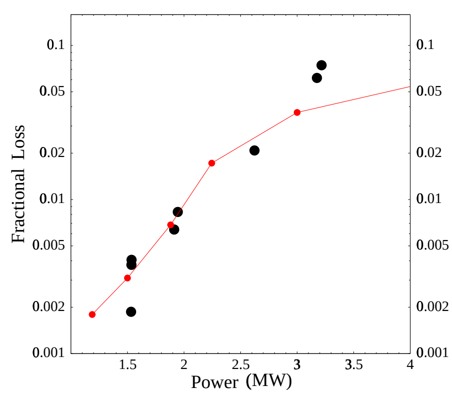

Figure 6. Fraction of the injected energy impinging on wall. The solid dots are the experimental data; the line connects the simulation results.

What is remarkable is that in order to get the simulation to exhibit even nearly the same threshold power as the experiment, as in Fig. 6, the wave diffusion coefficient must be 30–70 times the quasilinear theory! The possible explanations include the following: One, the simulation relies on 1D ray-tracing, which may be inaccurate (but it is hard to imagine such a large effect); two, kicks are not random, but correlated (but that requires correlations over at least 30 kicks); and three, geometrical optics is incorrect and the plasma is, perhaps, ringing at some internal eigenmode [23]. In any event, the collisionless limit is perhaps more easily accessed than previously thought.

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