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Elementary Processes Underlying Alpha Channeling in Tokamaks

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Abstract. Alpha channeling in tokamaks is speculative, but also extraordinarily attractive. Waves that can accomplish this effect have been identified. Key aspects of the theory now enjoy experimental confirmation. This paper will review the elementary processes of wave-particle interactions in plasma that underlie the alpha channeling effect.

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INTRODUCTION

One of the most exciting possibilities in energetic alpha particle interactions with waves in tokamaks is the release of the energy in these alpha particles to waves that then transfer or channel this energy to fuel ions rather than to electrons. This process, known as *alpha channeling* [1], is speculative, but in principle could make a significant difference in the economical feasibility of controlled fusion energy. It is only by channeling alpha particle energy directly to ions that the tokamak can operate in the so-called *hot-ion mode*, the tokamak parameter regime where ions are hotter than electrons [2]. The hot-ion mode regime has been so far achieved only through auxiliary heating of ions, either through heating by rf waves that resonate with ions or by means of neutral beams that tend to heat the ions preferentially. However, in a reactor the auxiliary heating would be small compared to the heating by energetic alpha particles, which preferentially slow down on electrons. Hence, only by channeling the alpha particle energy to ions can the hot-ion mode be achieved in a reactor. The hot-ion mode regime is, however, the regime in which by far the most spectacular performance results have been achieved to date.

The alpha channeling effect, achieved by waves that catalyze the transfer of alpha particle energy to fuel ions, is a robust effect in that the waves need not be coherent. This is because the waves need only diffuse particles to regimes of lower concentration from regimes of higher concentration. However, with the proper phasing of waves, diffusion in space can be linked to diffusion in energy. Thus, if the diffusion path goes from high energy in the tokamak center to low energy at the tokamak periphery, even an incoherent wave will force all alpha particles to the periphery, and capture their energy, through a diffusive process. That wave can then, also incoherently, damp on ions.

This paper will review at an elementary level the physical principles underlying the alpha channeling effect. After examining the features of a hot ion mode, we show how this mode might be produced by diffusive wave-particle interactions. Lastly, we briefly sketch how these wave-particle interactions might be implemented.

MHD and Energetic Particles
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HOT ION MODE

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 if fuel ions were much hotter than the electrons. This parameter regime is known as the *hot-ion mode* [2].

The reason that the effective reactivity increases in the hot-ion mode is because, in a tokamak, the total pressure of the confined plasma is limited by the pressure that the external magnetic fields can exert on the plasma. The limitation is on total pressure of the charged constituents of the plasma, meaning the sum of the partial pressures of fuel ions, electrons and impurity ions such as the fusion byproducts. At the same time, only the fuel ions participate in producing fusion events; the fusion power density released from the fusing of ions is a function only of ion temperature and density. The functional dependence on density must go as the density squared for binary interactions like fusion. And, for the temperatures in range of interest for fusion reactors, the functional dependence on temperature goes as the temperature squared. Since pressure is density times temperature, the fusion power density goes as the the ion pressure squared.

So if the total pressure of the ions and the electrons is limited by the available magnetic field strengths, then, if the electrons have less pressure, the ions can have more pressure. The ion and electron densities must be very nearly equal, since otherwise huge electric fields would restore the charge neutrality. However, the ion and electron temperatures can differ substantially. Thus, in a hot-ion mode plasma, the fusion reactivity can be much greater than in an equal-temperature plasma. If only the ions and electrons were sharing the pressure, and if the ions were twice the electron temperature, then the fusion reactivity would be a factor of 16/9 higher than if the temperatures were equal.

However, absent some active means, a fusion reactor tends to have electrons and ions of equal temperatures, or, in fact, electrons slightly hotter than ions. That is because the alpha particles slow down preferentially on electrons, so that the energy flow proceeds as depicted in Fig. 1. Since the ion heating occurs only through collisions with the electrons, to the extent that the alpha particles heat electrons and not ions, the electrons must of necessity be hotter than the ions, even if they radiate some heat away before heating the ions.

However, this collisional relaxation of the alpha particles can be interrupted. Collisional time scales are much slower than collisionless time scales; it takes several hundred milliseconds for alpha particles to slow dow in a reactor. That is plenty of time for wave instabilities that operate on a collisionless time scale to remove energy from the alpha particles before the alpha particles heat electrons. The alpha particles are born at high energy, in fact at 3.5 MeV, so their energy distribution is initially inverted, representing a free energy source. Assuming then that a wave exists that can tap into the energy inversion, that energy can be removed quickly from the alpha particles before they can slow down on electrons. If this wave were then collisionlessly damped by fuel ions, then the alpha particle energy would be effectively *channeled* to the ions.

In fact, it would be possible, and even more advantageous, if the tail of the fuel ion distribution, rather than the bulk of the fuel ions, damped this wave. Eventually, through ion-ion collisions, that energy will be distributed among all the ions, however, by delivering the energy first to the tail of the distribution the equilibrium distribution

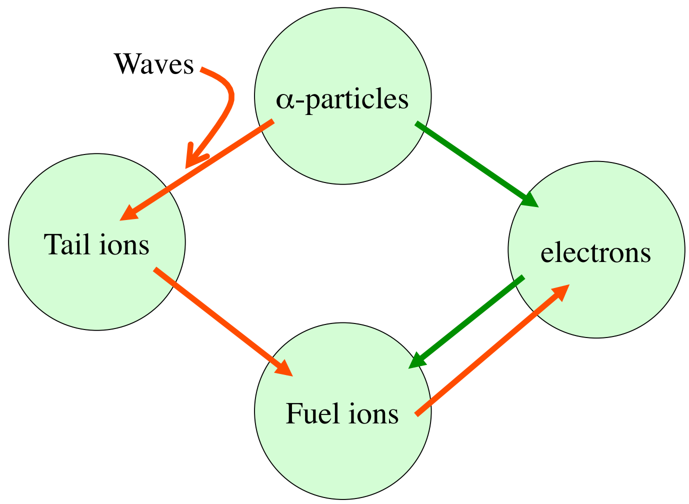

FIGURE 1. Power flow in fusion reactors. The normal power flow follows the green arrows, as alpha particles predominantly slow down on electrons. The electrons then heat the fuel ions on a collisional time scale. Under alpha channeling, this flow is disrupted. The red arrows indicate the flow of power when waves channel power from alpha particles to energetic fuel ions on a collisionless time scale. On a collisional time scale, the energetic fuel ions then equilibrate with the bulk fuel ions, which eventually heat the electrons.

of ions will not be Maxwellian; instead it will have elongated energetic tails. Since it is the superthermal ions that are much more likely to fuse than the thermal ions, this non-Maxwellian distribution will be more reactive than a Maxwellian distribution. Fig. 1 depicts the power flow under alpha channeling with the added benefit in delivering the alpha particle energy first to the tail ions.

Thus, under alpha channeling, the normal power flow is disrupted. The red arrows in Fig. 1 indicate the flow of power when waves channel power from alpha particles to energetic fuel ions on a collisionless time scale. Of course, under power flow in which the ions are heated first, the ions will always be hotter than the electrons. The electron temperature needs to catch up by collisions to the ion temperature. Hence, this flow path establishes the hot ion mode.

Of course, it is necessary to find a wave that will redirect the alpha particle power. But first, let us just suppose that such a wave exists.

If such a wave were to exist, namely a wave that produces the channeling effect, then it turns out that the resulting fusion power density can in fact be even greater than in the hot ion mode. First, as mentioned, the fusion reaction rate is higher than for a thermalized ion distribution because, through wave heating of the tail of the ion fuel distribution, the ion distribution develops superthermal ions with higher fusion cross-sections. Second, since the alpha particle energy is removed by the waves on a collisionless time scale rather than a much longer collisional time scale, there is no opportunity for alpha pressure to build up. That leaves more pressure for the fuel ions and electrons to share over and above what would be the case for a normal slowing down distribution of alpha particles. Typically, this could add about 15% to the available pressure, or, since the fusion power density goes as the pressure squared, about an extra 20% to the fusion power density.

TABLE 1. Two reactor design optimizations around ARIES I operating point

	No Channeling CD	**No Channeling Power**	**Channeling 75%**	**Channeling 75%**
T_i (KeV)	20	15	20	15
T_e (KeV)	20	15	12	12
n (10^{14}cm^{-3})	1.2	1.8	1.8	2.1
τ_i (sec)	2.0	2.0	2.0	1.0
τ_e (sec)	1.0	0.7	0.3	0.5
P_f (W cm^{-3})	4.7	6.1	10.9	9.7

Additionally, for power flows associated with the hot-ion mode, the electron energy loss mechanisms become less important. Under normal power flow, the ion temperature cannot exceed the electron temperature, so any radiative loss of the electron heat or transport to the periphery of the electron heat is then lost to the ions as well. However, if the ions heat the electrons, then heat losses from the electrons are less important. In fact, in order to maintain a large disparity in temperatures in the hot ion mode of operation, at least some leakage of electron energy is helpful; if there were no electron heat losses, then the electrons would catch up to the ions in temperature, thereby diminishing the available pressure for the fuel ions. On the other hand, the electron energy channel cannot be too leaky, or the ions would be too quickly cooled by the electrons. Thus, under alpha channeling, as opposed to the ions where the optimal heat loss rate is still zero, there is an optimal heat loss rates of energy from the electrons which is actually finite [3]. Any heat lost by the ions simply means that the ions are not optimally making use of the available alpha particle energy.

In Table 1, we show how reactors might have higher fusion power density near the operating points of present designs (based upon the ARIES tokamak reactor studies). Without alpha channeling, the design that optimizes for steady state current drive (column 1) has somewhat lower density than the design that optimizes for fusion power (column 2). In both cases of this 0-D calculation, the ion and electron temperatures are equal. The alpha channeling scenarios [3] assume that 75% of the alpha particle energy flows to the ions, and that the alpha particles affected are incidentally lost from the device in the process. One optimization (column 3), keeps the ions at 20 KeV, and maximizes the temperature disparity by having electron heat confinement times τ_e much smaller than the ion heat confinement times τ_i. Another optimization (column 4), about the ion temperature of 15 KeV, allows for higher plasma density. In both channeling cases, the fusion power density P_f can be seen to be significantly higher.

Because the electron heat loss is notoriously difficult to limit in any event, the fact that finite electron heat loss optimizes the hot ion mode under alpha channeling is significant. Electrons unavoidably radiate significantly in reactor-grade plasma. Bremsstrahlung radiation is unavoidable in dense hot plasma and synchrotron radiation is unavoidable in magnetized plasma. Second, whereas there are methods to limit the ion heat diffusion in a tokamak, for example through shear stabilization of unwanted turbulence, it is much more difficult to limit the electron heat diffusion because of the short spatial scales associated with electrons. Thus, it is highly advantageous that under alpha channeling moderate heat loss through electrons cannot only be tolerated but can in fact be useful.

As depicted in Fig. 1, the energy to maintain the plasma far from thermal equilibrium is supplied by the alpha particles. Ultimately, this energy is used to replenish the power lost through radiation and transport. However, it is the waves that redirect this energy, by being amplified at the expense of the alpha particles, so that the higher reactivity would then be reached without substantial external power. The alpha particle power is thus effectively *channeled* into a more useful form of power. Note that the redirection of power is doubly useful in the case of maintaining the hot-ion mode, since, in the absence of the channeling effect, the alpha particle naturally flows mainly into electrons, making electrons always hotter than ions. The power channeled to waves, however, could damp on ions, at once reducing the electron heating and increasing the ion heating.

It turns out that there are further advantages for producing the hot ion mode through alpha channeling. The free energy in the alpha particle distribution is then not available to drive modes that are deleterious to confinement. But this power is useful for other purposes, like using the waves for rf current drive [4]. In addition to incidentally exhausting the alpha particles, thereby making available more fuel pressure, the alpha channeling wave interactions tend to have the opposite but favorable effect on fuel ions, which start out cold: these waves heat fuel ions and incidentally drive them to the tokamak center.

WAVE DIFFUSION PATHS FOR ALPHA CHANNELING

Although, in principle, substantial channeling of α-particle energy can occur, exactly how to accomplish this effect is a challenging problem. For example, wave interactions that tend to drive particles in velocity space only tend not to extract much of the recoverable energy.

In fact, the alpha channeling effect was discovered precisely because we were worried that lower hybrid waves would actually be damped in a reactor due to interactions with alpha particles [5]. At that time, in the 1980's, the prediction that lower hybrid waves could efficiently generate toroidal current in tokamaks [6] was being verified on many of the then contemporary tokamaks. But those tokamaks verifying the drive effect were research devices, not using D-T fuel, and so fusion-produced alpha particles were essentially absent. But reactors are expected to have a significant density of alpha particles, and the worry was that the alpha particles would extinguish the lower hybrid waves and hence the lower hybrid current drive effect in a reactor. Under collisional slowing down, even though they are born with 3.5 MeV, the steady state distribution of alpha particles slowing down on electrons might well be monotonically decreasing in energy, which normally damps any waves. However, even an alpha particle distribution function inverted in energy, does not appear inverted for electrostatic waves like the lower hybrid wave when projected in velocity space onto the wave diffusion direction. The worry that alpha particles would damp the lower hybrid wave was confirmed also by quasilinear calculations that took into account the diffusion of the alpha particles by the waves in velocity space [7, 8].

However, what these calculations did not take into account is that the population inversion need not occur in velocity space only. Consider Fig. 2, which depicts a distribution of alpha particles monotonically decreasing in energy ε at various radii in a tokamak.

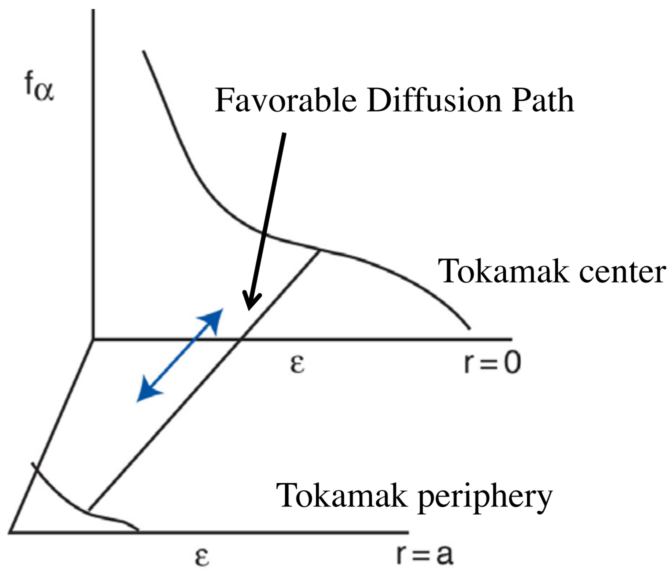

FIGURE 2. Schematic distribution of alpha particles vs. alpha particle energy ε at $r = 0$ (center of tokamak) and at $r = a$ (periphery of tokamak). At any radius, the alpha particle distribution function is monotonically decreasing in energy. However, there is a population inversion in energy along the indicated favorable diffusion path.

Most of the alpha particles are born near $r = 0$ (center of tokamak), where the plasma itself is most hot and and most dense. The alpha particles are therefore also most dense in the center, where they are born, and least dense near the periphery. But, as illustrated in Fig. 2, even for distribution functions monotonically decreasing in energy at each radius, there is nevertheless a population inversion in energy along the indicated favorable diffusion path. This diffusion path occurs in the joint energy-radius space. Thus, the population inversion can be exploited if alpha particles are removed at the periphery at low energy.

Note that alpha particles that are diffused along this diffusion path must leave the tokamak cold, because, absent collisions, that is the only way that they can stop interacting with the wave. Although the wave can diffuse them to higher energy, as well as to lower energy, it is only at lower energy that they are at the periphery; at higher energy they are in the tokamak center without the possibility of removal. The constraint on the rf diffusion is very strict; in the presence of rf waves producing the required diffusion paths, the alpha particles must exit cold. The energy extracted from the alpa particles is the birth energy minus the energy at the periphery. The question is whether such waves that produce the magical diffusion constraints exist and whether can be generated in a tokamak; the answer is that, in principle, such waves do exist and in principle they may be generated in a tokamak.

When one wave is used, there can be only one diffusion path, so that there are stringent constraints on the α-particle motion. If the path is chosen appropriately, then, if an α-particle gains energy, it must diffuse to the tokamak periphery; conversely, if it were to lose energy in interacting with the wave, it must diffuse to the tokamak center. The α-particle motion is constrained to lie on a one dimensional curve, a line. Thus, particles

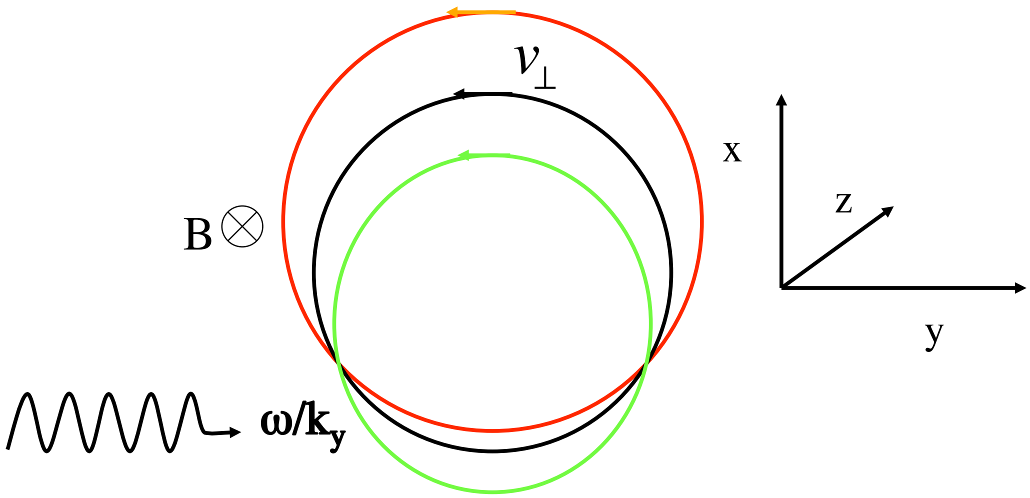

FIGURE 3. Ion orbits in a homogeneous magnetic field (into the paper) and in the presence of a resonant short-wavelength electrostatic wave traveling in the y-direction. If initially in the black orbit, the red orbit results when the ion gains energy from the wave; the green orbit results when the ion loses energy to the wave.

diffused by the wave to the tokamak periphery give up a precise amount of energy to the wave which is proportional to their distance traveled in reaching the periphery. This energy then ends up in the waves causing this diffusion.

TYING DIFFUSION IN ENERGY TO DIFFUSION IN SPACE

To see how the energy of the α-particles might be tapped by diffusing them simultaneously in energy and space, consider an ion in a uniform magnetic field B, as shown in Fig. 3. Here the magnetic field is into the paper, in the $\hat{z}$-direction, so that ions rotate in the counter-clockwise direction with frequency $\Omega = qB/m$ and with gyroradius $\rho = v_\perp/\Omega$.

Let us imagine an electrostatic wave with phase velocity ω/k_y. For simplicity, imagine that the wavelength is very short compared to the gyroradius, so that $k_y v_\perp/\Omega \gg 1$. (In point of fact, this simplification is not necessary, but it is easier to think of the resonance as a Landau resonance.) Thus, this waves interacts resonantly with ions through a Landau resonance such that $\omega - k_y v_y = 0$.

Note that so long as the ion is energetic enough, namely $v_\perp > \omega/k_y$, there will be two points on the orbit in which the resonance is satisfied. If $v_\perp = \omega/k_y$, then the resonance can only be satisfied at one point. And if If $v_\perp < \omega/k_y$, then no point on the orbit will satisfy the resonance condition, since, by construction, $v_\perp \geq v_y$.

So the ion (which we mean to be an alpha particle) executes circular motion until it encounters the wave resonance. When a particle encounters the wave, there is a particularly effective interaction if the wave phase velocity ω/k_y matches v_y, the particle velocity in the $\hat{y}$-direction, (like a surfer encountering a wave). When the resonance condition is satisfied, the particles gets an instantaneous kick in the $\hat{y}$-direction, which depending on the phase of the wave could be either to increase its energy or to slow it down. Thus, the velocity in the $\hat{y}$-direction changes instantaneously but randomly.

Suppose then that as a result of a random interaction with the wave resonance, the velocity in the $\hat{y}$-direction changes like

$$v_y \to v_y + \Delta v_y. \tag{1}$$

This change is presumed to occur instantaneously, and precisely at the point of resonance $\omega - k_y v_y = 0$. As a result of this acceleration, the perpendicular energy also changes instantaneously, so that, for small kicks Δv_y, the perpendicular energy changes as

$$E_\perp = \frac{m}{2}(v_y^2 + v_x^2) \to E_\perp + \Delta\varepsilon = E_\perp + m v_y \Delta v_y, \tag{2}$$

or we can say that the total energy change $\Delta\varepsilon$ can be written as $m v_y \Delta v_y$. Similarly, as a result of the velocity change in the $\hat{y}$-direction, the guiding center changes in the $\hat{x}$-direction like

$$x_{\mathrm{gc}} \to x_{\mathrm{gc}} + \Delta x_{\mathrm{gc}} = x_{\mathrm{gc}} - \Delta v_y/\Omega. \tag{3}$$

This change in the guiding center can be seen from Fig. 3, where if the energy decreases as a result of the interaction, then the radius must become smaller. In other words, if the ion beginning in the black orbit (central orbit) encounters a resonant interaction through which it loses energy, then that interaction sends it into the green orbit, which has a smaller radius and a smaller guiding center in the $\hat{x}$-direction. On the other hand, were the ion beginning in the black orbit (central orbit) to encounters a resonant interaction through which it gains energy, then that interaction would sends it into the red orbit, which has a larger radius and a larger guiding center in the $\hat{x}$-direction. The interaction in either case takes place at the point of resonance, so all three gyroorbits intersect at the two points of resonance with the wave. However, it is an entirely random even whether the ion gains energy from the wave or loses energy to the wave.

Now what is interesting is that the change in the gyrocenter in the x-direction, Δx_{gc}, is proportional to the energy absorbed $\Delta\varepsilon$. From Eqs. (2) and (3) , we have

$$\frac{\Delta x_{\mathrm{gc}}}{\Delta\varepsilon} = -\frac{1}{m\Omega v_y} = -\frac{k_y}{m\Omega\omega}, \tag{4}$$

where the last equality could be written since the interaction occurs instantaneously just when $v_y = \omega/k_y$. Note that the ratio of change in gyrocenter to change in energy 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 $\Omega \equiv qB/m$ is the α-particle gyrofrequency. In the slab case, upon repeated interactions with the wave, a particle will trace a line in $\varepsilon - x_{\mathrm{gc}}$ space.

But this is *exactly* what we have been looking for. Such a wave couples diffusion in energy to diffusion in position. Suppose that the plasma boundary is at $x = a$, i.e., α-particles can only leave at $x = a$. The plasma center is at $x = 0$, by which it is meant that no α-particles can leave at $x = 0$. For efficient channeling, one would then require $\Delta x_{\mathrm{gc}}/\Delta\varepsilon \sim a/\varepsilon_\alpha$, where a is the extent of the plasma and ε_α is the α-particle birth energy. If instead $\Delta x_{\mathrm{gc}}/\Delta\varepsilon \gg a/\varepsilon_\alpha$, then the α-particle would be extracted from the center with almost all its energy intact, whereas if $\Delta x_{\rm gc}/\Delta\varepsilon \ll a/\varepsilon_\alpha$, 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. And, of course, if the wrong sign of ω/k_y were taken, then α-particles would be heated as they were removed at the periphery and cooled as they moved to the center, which would obviously be a deleterious effect.

However, for the right choice of waves, namely with waves with the right phase velocity, if they are present long enough and if collisions are negligible, then remarkably all the energetic ions along the diffusion path must exit cold, leaving their birth energy to the wave. This is the strong constraint exhibited by Eq. (4); the only way that the alpha particles can be diffused is along this path, and the only way that they can exit this path is to do so with little energy.

TOROIDAL GEOMETRY

While the basic idea of the channeling effect can be explained most easily in slab geometry, and captured in Eq. (4), the diffusion path in a tokamak occurs in toroidal geometry [12]. In toroidal geometry, particles interacting with one wave trace a line in ε-μ-P_ϕ space, where $\mu = mv_\perp^2/2B$ is the magnetic moment, $\varepsilon = \mu B + mv_\parallel^2/2$ is the kinetic energy, and $P_\phi = R(mB_\phi v_\parallel/B - qA_\phi)$, is the canonical angular momentum, and where A_ϕ 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 $v_\parallel$, a passing particle orbit. Given ε, μ, and P_ϕ, and the sign of $v_\parallel$ for passing orbits, it may be determined if the orbit intersects the plasma periphery, thus losing the particle. Particles tend to follow closely the magnetic surfaces, i.e., surfaces of constant RA_ϕ, so that the particle position is largely determined by P_ϕ, especially for low energy particles.

Upon interaction with a wave with toroidal mode number n_ϕ, and absorbing energy $\Delta\varepsilon$, P_ϕ changes by

$$\Delta P_\phi = (n_\phi/\omega)\Delta\varepsilon. \tag{5}$$

Assume, as in the slab geometry, that the exchange of energy occurs only for particles satisfying the resonance condition $\omega - k_\parallel v_\parallel = n\Omega$, where n is an integer, then, upon absorbing energy $\Delta\varepsilon$, μ changes by

$$\Delta\mu = (nZe/m\omega)\Delta\varepsilon, \tag{6}$$

where e is the charge on an electron and, for α-particles, $Z = 2$. Thus, upon repeated interaction with one wave, the constants of motion, ε, μ, and P_ϕ, trace a line, with the possibility of extraction of the alpha particle at the periphery, as determined mostly by P_ϕ at low energy.

IMPLEMENTATION OF THE ALPHA CHANNELING EFFECT

In the foregoing, we showed the possibilities in channeling alpha particle power were a wave to exist with the proper wave characteristics. However, it remains to identify if the plasma can in fact support such a wave.

What makes the search for this wave easier than one might think is that it may be possible to use more than one wave to accomplish the channeling effect. With one wave, there is a very hard constraint on the motion of particles; with two or more waves, with overlapping resonances, the hard constraint is replaced by highly probabilistic behavior [9]. In other words, when one wave with the necessary phase velocity interacts with the alpha particle then if the alpha particle exits it must exit cold; however, under the influence of more than one wave with appropriate parameters, it may be that the alpha particle with very high probability will exit cold and with very low probability exit hot. For the purposes of producing a hot ion mode by effectively channeling most of the alpha particle energy, that may just be fine.

It turns out that, for tokamaks, it is advantageous to use two waves, one to move alpha particles out of the central region without extracting too much energy, and one wave to extract most of the energy in sending the alpha particle to the periphery. The mode-converted ion-Bernstein wave seems to be most appropriate for extracting most of the alpha particle energy [10]. This mode can grow at the expense of the alpha particle energy and then, in a DT plasma, as it reaches the tritium resonance, it damps on the tritium fuel ions [11]. In a reactor, simulations show that with two waves it would be possible to divert more than a half of the alpha particle energy through waves [12].

EXPERIMENTAL FINDINGS AND CURRENT EFFORTS

There were a number of interesting experiments performed on TFTR in the 1990's that showed that mode-converted ion Bernstein waves could produce diffusion paths in energy-position space. However, in those experiments, since there were few fusion-produced alpha particles, the wave parameters were chosen so that the diffusion paths connected cold in the center with hot on the periphery, diffusing 80 keV beams of deuterium ions so that they could be detected at 2.2 MeV at the periphery [13, 14]. This was of course not the cooling effect desired, but it did show that in principle the diffusion paths could operate as expected.

There was, however, one great surprise, and that is that the experimentally measured diffusion coefficient was a factor of fifty higher than expected. One possible explanation was that the tokamak was *ringing* like a high-Q cavity, with the mode-converted ion-Bernstein wave exciting an internal mode [15]. This explanation was not verified by directly observing the internal modes, because, by the time the explanation was offered, the TFTR experiment had already been shut down. However, that explanation gained support recently when related internal modes were observed on NSTX [16].

One recent and very promising direction of research is to optimize the alpha channeling effect together with transformer recharging, recognizing that the low density stage of transformer recharging is particularly suited for a driven hot ion mode [17]. Transformer recharging is a method of using rf current drive to recharge the toroidal current in a tokamak without letting the current itself reverse direction. There is a synergy in using alpha channeling with transformer recharging: the channeling effect is employed to get current drive, but then the transformer recharging optimizes the current drive effect. In achieving the hot ion mode together with current drive, it would be advantageous to use current drive mechanisms that heat ions rather than electrons [4].

The general concept of alpha channeling can be applied to other confinement devices as well. In different machines, different waves would be appropriate. Alpha channeling can be practiced in particular in mirror machines, where the concept of plasma periphery now includes the loss cone in velocity space [18]. In a mirror machine, contained modes can be utilized [19, 20], and the parameter space of possible waves can be extended by using minority ions to catalyze the channeling effect [21].

In supersonically rotating plasma, there is additional axial confinement due to the rotation, and there is also the opportunity to store energy in the plasma potential. A generalization of the channeling effect, in which some of the particle energy ends up in electric potential energy [22], can be useful in such centrifugal confinement devices for fusion [23, 24]. One of the technological advantages of employing such a channeling effect in supersonically rotating plasma is that it may be possible to use the (generalized) channeling effect to replace the electrodes that produce the radial potential.

However, until copious alpha particles are produced in a tokamak reactor with rf capability in the ion cyclotron range of frequencies, it will not be possible to check the complete alpha particle cooling and energy channeling scenario. One thing is certain, however: in order to reach the advantageous hot ion mode in a reactor, some form of alpha channeling will have to be employed.

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