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Citation: AIP Conference Proceedings **1689**, 020001 (2015); doi: 10.1063/1.4936463
View online: http://dx.doi.org/10.1063/1.4936463
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1689?ver=pdfcov
Published by the AIP Publishing

The Alpha Channeling Effect

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Abstract. Alpha particles born through fusion reactions in a tokamak reactor tend to slow down on electrons, but that could take up to hundreds of milliseconds. Before that happens, the energy in these alpha particles can destabilize on collisionless timescales toroidal Alfven modes and other waves, in a way deleterious to energy confinement. However, it has been speculated that this energy might be instead be channeled into useful energy, so as to heat fuel ions or to drive current. Such a channeling needs to be catalyzed by waves Waves can produce diffusion in energy of the alpha particles in a way that is strictly coupled to diffusion in space. If these diffusion paths in energy-position space point from high energy in the center to low energy on the periphery, then alpha particles will be cooled while forced to the periphery. The energy from the alpha particles is absorbed by the wave. The amplified wave can then heat ions or drive current. This process or paradigm for extracting alpha particle energy collisionlessly has been called alpha channeling. While the effect is speculative, the upside potential for economical fusion is immense. The paradigm also operates more generally in other contexts of magnetically confined plasma.

EARLY HISTORY

The so-called *alpha channeling* effect is a stochastic wave-particle interaction in which energy is channeled from a particle to the wave by virtue of an inversion in the particle energy distribution function along the wave diffusion path in energy-position space [1]. The particle distribution of most concern in this regard is the α-particle distrbution in DT reactors; hence, the nomenclature: *alpha channeling*. Since α-particles, the byproducts of the DT fusion reaction, are born at 3.5 MeV, they initially have an inverted energy distribution irrespective of the diffusion path. However, in a tokamak reactor, they slow down through collisions mainly on electrons. Their distribution then tends to be monotonically decreasing in energy on any flux surface. Hence, to extract energy from the α-particles, it is generally necessary to recognize the population inversion along wave diffusion paths in energy-position space.

The α-channeling effect thus contemplates injecting waves with diffusion paths that recognize this energy inversion in a desirable way. There may be other waves that could be excited due to natural energy inversions along other wave diffusion paths. However, those excited waves might have undesirable properties, like ejecting the α-particles before their full energy is recovered. By injecting waves with the desired diffusion paths, the α-particle energy can be extracted along the favorable diffusion paths before the naturally occurring instabilities have a chance to develop.

The motivation for identifying these diffusion paths came in response to a disquieting calculation [2]. The prediction that lower hybrid current drive could efficiently generate toroidal current in tokamaks [3] enjoyed, in the 1980's, substantial experimental verification. The tokamaks verifying at that time the current-drive effect, however, were research devices, not using D-T fuel, and so fusion-produced α-particles were essentially absent. It was then predicted that in a reactor the lower hybrid waves would actually be damped by the α-particles [2]. The damping of the wave on the α-particles would extinguish the wave before it could drive current, motivating ways to circumvent the damping.

Indeed, the steady state distribution of α-particles slowing down on electrons might well be monotonically decreasing in energy, which normally damps any waves. Moreover, even if the α-particle distribution function were inverted in energy, it would not appear inverted for electrostatic waves like the lower hybrid wave when projected in velocity space onto the wave diffusion direction, meaning that the lower hybrid wave would invariably suffer damping even without the collisional relaxation of the α-particle velocity distribution.. The worry that copious production of α-particles would lead to damping of the lower hybrid wave was confirmed also by quasilinear calculations that took into account the diffusion in velocity space of the α-particles by the waves [4, 5].

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AIP Conf. Proc. 1689, 020001-1–020001-10; doi: 10.1063/1.4936463

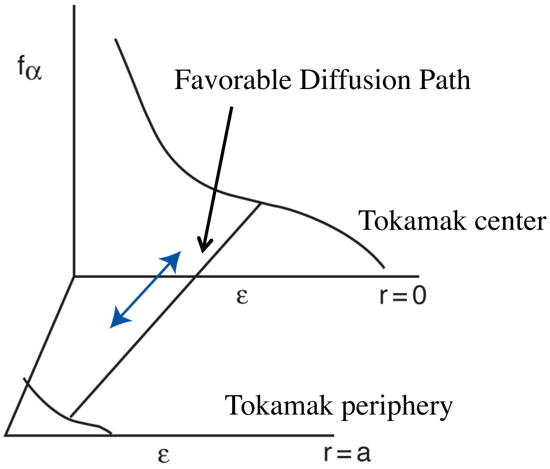

FIGURE 1. Schematic distribution of α-particle phase space density f_α vs. α-particle energy ϵ at $r = 0$ (center of tokamak) and at $r = a$ (periphery of tokamak). At any radius, the α-particle distribution function might be (as shown) monotonically decreasing in energy. However, it remains the case that there is a population inversion in energy along the indicated favorable diffusion path.

However, the population inversion need not occur in velocity space only. In fact, in a density gradient, the damping effect of the α-particles can be reversed [1]. Consider Fig. 1, which depicts a distribution of α-particles monotonically decreasing in energy ϵ at various radii in a tokamak. Most of the α-particles are born near $r = 0$ (center of tokamak), where the plasma itself is most hot and and most dense. The α-particles are therefore also most dense in the center, where they are born, and least dense near the periphery. But, as illustrated in Fig. 1, 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 α-particles are removed at the periphery at low energy.

Note that α-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 can reach the periphery; at higher energy they are stuck 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 α-particles must exit cold. The energy extracted from the α-particles is the birth energy minus the energy at the periphery. The diffusion path illustrated in Fig. 1 is rather optimal in this regard, since the slope is such that a large proportion of the initial energy appears to be extracted. Certain waves that can be generated in a tokamak can produce these strict and useful diffusion constraints, creating the possibility to release the energy in these α-particles to waves that then transfer or channel this energy to fuel ions rather than to electrons. This *alpha channeling* effect is speculative, but in principle could make a significant difference in the economical feasibility of controlled fusion energy.

KEY ADVANTAGES

First, by channeling α-particle energy directly to ions, the tokamak can operate in the so-called *hot-ion mode*, the tokamak parameter regime where ions are hotter than electrons [6]. So if the total pressure of the ions and the electrons is limited by the available magnetic field strengths, like in magnetic confinement fusion, then, if the electrons have less pressure, the ions can have more pressure. For fuel ions much hotter than the electrons, the effective reactivity at constant confined pressure can be increased significantly, with significant cost savings in building a reactor. The hot-ion mode regime has been so far achieved only in experimental devices, not in DT plasma, 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 α-particles, which preferentially slow down on electrons. If the electrons absorb the α-particle energy, then the ions only become hot by virtue of collisions with the electrons. Then the ions cannot become hotter than the electrons. Thus, in a reactor, where the plasma is maintained by α-particle heating, only by channeling the α-particle energy to ions, can the hot-ion mode be achieved. The benefit of channeling say 75% of the α-particle energy to fuel ions in a DT reactor could, result in ions being about twice as hot as electrons, which could double the fusion reactivity [7].

Second, in the hot-ion mode, the electron energy loss mechanisms become less important. This feature could solve or alleviate the problem of electron heat confinement. 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 are hotter than the electrons, then heat losses from the electrons are less important. In fact, in order to maintain a large disparity in temperatures, 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 α-channeling, there is an optimal heat loss rates of energy from the electrons which is actually finite [7]. That finite electron heat loss optimizes the hot-ion mode under α-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. Also, whereas there are methods to limit the ion heat diffusion in a tokamak, 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 α-channeling moderate heat loss through electrons cannot only be tolerated but can in fact be useful.

Third, it is in the hot-ion mode where by far the most spectacular performance results have been achieved to date. Thus, it stands to reason that the extrapolation of the most promising present day experimental results to tokamak reactors can be made with the greatest confidence if reactors were operated in the hot-ion mode.

Fourth, many natural instabilities in tokamak reactors, deleterious to plasma confinement, might could grow at the expense of the α-particle energy. If, however, the α-particle energy were removed through the channeling effect, then this source of energy would be unavailable to power these naturally occurring, but deleterious, instabilities.

Fifth, the α-channeling effect can help in plasma fueling and plasma heating. Note that the α-channeling effect relies on a diffusion path that connects high-energy α-particles in the tokamak center to low-energy α-particles at the periphery. But the same diffusion (or very similar) path connects high-energy fuel ions in the tokamak center to low-energy fuel ions at the periphery. For example, for deuterium, which has the same charge to mass ratio as the α-particle, the diffusion path would actually be the same. Now, in the case of the α-particles, there is greater abundance of high-energy α-particles in the tokamak center than low-energy α-particles at the periphery. Hence, the α-particles tend to diffuse in the wave fields towards the periphery, losing energy to the wave. However, there are very few high-energy fuel ions in the tokamak center, but, under gas puffing at the periphery, there could be very many low-energy fuel ions at the periphery. Hence, the fuel ions would diffuse in the very same wave fields towards the center, gaining energy from the wave. In effect, the same wave fields that grow through ejecting α-particles while absorbing their energy, also bring fuel ions from the tokamak periphery to the plasma center while heating them to high energies. Once in the center, they would represent also a nonthermal population with higher reactivity (for the same energy content) due to the enhanced tail population.

Sixth, along the lines of fueling while heating, further advantages might be realized through maintaining nonthermal ion distributions. Under α-channeling, the α-particle energy is captured first in an amplified wave that can damp on ions. In principle, it would be possible for the amplified wave to be damped by the tail of the fuel ion distribution, rather than the bulk of the fuel ions. 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 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. Coupled with the hot-ion mode to begin with, this effect increases further the fusion reactivity.

Seventh, along the lines of ejecting the α-particles while extracting their energy, there is considerable advantage in cleansing a reactor of the α-particles, which are essentially the ash of burning deuterium and tritium. This cleansing is important, even without the extraction of the α-particle energy. Suppose for example that α-particles comprise 10% of the ion density in a reactor. Since there are two electrons for each α-particle, that means that the electron density associated with the α-particles is 20% of the total electron density, meaning that, if all plasma constituents have the same temperature, then the total pressure associated with α-particle ash is close to 15% of the total pressure. That means that, since the fusion reactivity goes approximately as the square of the pressure, that the α-particle ash of 10% is enough to cause a 30% reduction in the fusion power density. Thus, an additional significant advantage of the α-channeling effect of ejecting the α-particles is that they no longer pollute the fuel.

Eighth, in addition to producing a hot-ion mode or otherwise to increasing the fuel reactivity, the amplified wave might also drive toroidal current. In principal, if the amplified wave mediating the α-channeling is injected with

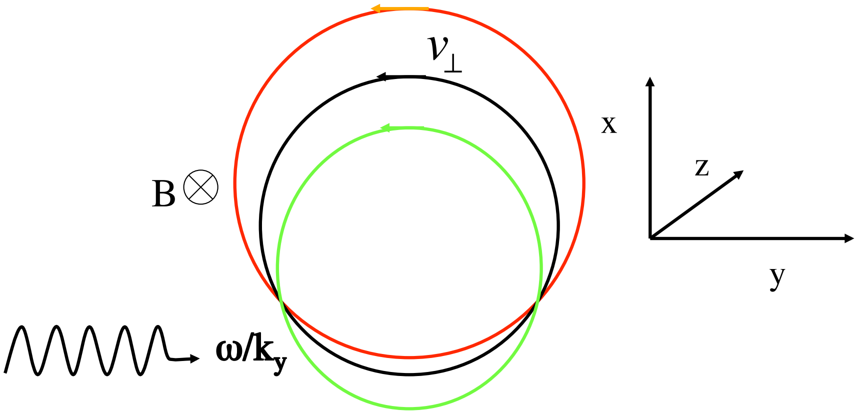

FIGURE 2. Ion orbits in a homogeneous magnetic field (into the paper) and in the presence of a resonant short-wavelength electrostatic wave traveling in the y-direction. If initially in the black orbit, the red orbit results when the ion gains energy from the wave; the green orbit results when the ion loses energy to the wave.

toroidal asymmetry, it could drive current using any of a number of wave-particle interactions [8].

The advantages of α-channeling enumerated above are indeed substantial. There may be more advantages yet, since the free energy in the waves might also be used to drive currents that do other good things, like to stabilize tearing modes [9]. The first and most important question is to identify waves that can accomplish the α-channeling effect. The next set of questions should be to address to what extent these advantages might be realized simultaneously. This review follows earlier reviews of the α-channeling effect, including the physical processes underlying the effect [10], a tutorial [11], and a review including the channeling effect in mirror machines [12]. Other recent, relevant reviews include energetic particles in tokamaks [13, 14] and wave-particle resonances [15]. While the fundamental physics behind this effect will also be reviewed here, what is emphasized here is recent advances in the theory, including both synergies recognized with other effects as well as new applications.

TYING DIFFUSION IN ENERGY TO DIFFUSION IN SPACE

Let us review how the energy of the α-particles might be tapped by diffusing them simultaneously in energy and position [1]. Consider an ion in a uniform magnetic field B, as shown in Fig. 2. 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 $\rho = v_\perp/\Omega$. 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 $k_y v_\perp/\Omega \gg 1$. Thus, this waves interacts resonantly with ions through a Landau resonance such that $\omega - k_y v_y = 0$. 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 α-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

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

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

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

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

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

This change in the guiding center can be seen from Fig. 2. If the energy decreases as a result of the interaction, then the radius becomes 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.

What is interesting is that the change in the gyrocenter in the x-direction, $\Delta x_{\rm gc}$, is proportional to the energy absorbed $\Delta\epsilon$. From Eqs. (2) and (3) , we have

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

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 $\epsilon - x_{\rm gc}$ space. 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 $\Delta x_{\rm gc}/\Delta\epsilon \sim a/\epsilon_\alpha$, where a is the extent of the plasma and ϵ_α is the α-particle birth energy. If instead $\Delta x_{\rm gc}/\Delta\epsilon \gg a/\epsilon_\alpha$, then the α-particle would be extracted from the center with almost all its energy intact, whereas if $\Delta x_{\rm gc}/\Delta\epsilon \ll a/\epsilon_\alpha$, 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. This constraint can also be extended to more general, possibly nonstationary, discrete systems [16].

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 [17]. 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, $\epsilon = \mu B + mv_\parallel^2/2$ 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 $\Delta\epsilon$, P_ϕ changes by $\Delta P_\phi = (n_\phi/\omega)\Delta\epsilon$ 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 $\Delta\epsilon$, μ changes by $\Delta\mu = (nZe/m\omega)\Delta\epsilon$, 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.

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 [18]. 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 [19]. 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 [20]. 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 [17].

Experiments performed on TFTR in the 1990's that showed that mode-converted ion Bernstein waves could produce diffusion paths in energy-position space [11, 21, 22]. Since there were few fusion-produced α-particles, mainly what could be verified was the existence of diffusion paths that connected cold in the center with hot on the periphery. The experiments consisted of using the mode-converted ion Bernstein waves to diffuse 80 keV beams of deuterium ions so that they could be detected at 2.2 MeV at the periphery This was of course not the cooling effect desired, but it did show that in principle the diffusion paths could operate as expected. Interestingly, these experiments also showed that the mode-converted ion Bernstein waves also exhibited an important wave feature, namely a flip in $k_{||}$, which had been predicted as important to avoid electron damping [20]. There was one great surprise, namely 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 [23]. 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, the fact that related internal modes were observed on NSTX lends further support to that explanation [24].

SYNERGY BETWEEN ALPHA CHANNELING AND CURRENT DRIVE

Broadly speaking, what the α-channeling effect does is to capture the energy of the α-particles and channel it into a more useful form of energy. The advantages that then accrue are a function of what is done with that energy. At the very least, the thought is that it should first be absorbed by ions rather than electrons. In that case, the hot ion mode would be produced, which would capture the most important advantages.

However, one can ask whether it might not also be possible to use the α-particle power to generate on the cheap the toroidal current. Here the idea is to channel the α-particle into waves which have a toroidal asymmetry. These waves can then damp on ions or electrons, thereby to generate the plasma current.

The most efficient and the most researched current-drive effects might involve currents produced from waves that interact with superthermal electrons, such as the lower hybrid wave [3] or the electron cyclotron wave [25]. But if the current drive mechanism is via electrons, particularly through the tail electrons, then the electron tail heating creates a substantive superthermal electron population [26, 27, 28, 29, 30] . This tail population may represent significant enough electron heating so as to act in opposition to the hot-ion mode. To avoid electron tail heating, it may be preferable to employ instead for the current drive other electron-based methods that operate on the bulk electrons [31, 32]. Even better, to avoid the electron heating altogether, and to channel the α-particle power directly to the ions, it might be most desirable to drive the current using an ion-based method, such as minority species current drive [33]. The minority species current drive effect enjoys some experimental confirmation [34, 35], but it is by no means as efficient (or as well scrutinized) as electron based methods. However, if the current drive effect is indeed powered directly by the α-particle energy, then a current drive method with modest or even poor efficiency could be effective by leveraging the α-particle power. In the case of minority species current drive, if substantial α-particle-power can be channeled, then not only might the full current be driven, but the ions would be made hotter than the electrons, achieving the hot ion mode. Furthermore, the minority species current drive effect contemplates wave interactions with tail ions, which further enhances the fuel reactivity.

Suppose, for example, that steady-state might be provided by rf waves in a tokamak at a dissipated power cost of 10% of the recirculating power, which might be achievable in principle with electron-based current drive methods. Of course, the cost of converting the recirculating power to the wave power means that more than 10% of the fusion power would have to be recirculated. However, since 20% of the fusion power comes as α-particle-power, if half of that can be channeled to amplify the waves, then in the example considered here the current drive comes essentially for free. If the current drive were less efficient, such as with an ion-based rf method. then the cost of the current drive might still be rendered insignificant, if enough of the α-particle power could be used to amplify the rf waves. Thus, while electron-based methods are more efficient, it remains that there may be greater synergy with increasing the fusion reactivity in using an ion-based method.

Now the current drive efficiency might be made far greater, in principle, if quasisteady steady-state, rather than completely steady-state operation, is sought. The quasisteady state method, also called *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 [8]. The phenomenon of tokamak recharging by rf waves was established on the PLT tokamak [36, 37], and has since been confirmed on many other tokamaks [38, 39, 40], including in a recent campaign on Tokamak EAST [41, 42, 43]. It turns out that there is a synergy in using α-channeling together with transformer recharging [44]. To see this, first consider how transformer recharging can increase the effective current drive efficiency, absent the α-channeling. Suppose two stages, a current generation stage, when the current is generated by, for example, lower hybrid current drive (LHCD), and a current relaxation stage in which there is no current drive so that the current decays in an L/R time, where L is the tokamak plasma inductance and R is the resistivity. The generation and relaxation cycles then repeat. However, even as the current does not deviate much from its average value, the average power dissipation can be much less if the plasma parameters in the two stages are different. In principle, these other parameters can be changed on time scales short compared to the L/R time, because the particle and heat confinement times are of the order of a second in a tokamak reactor, whereas the L/R time is about three orders of magnitude longer.

During the current-generation stage, the current is increasing, so there is an induced electric field that opposes the increase in the current. The density in this stage should be relatively small to increase the current drive efficiency. The resistivity, which is is independent of the density, should be relatively large to reduce the induced counter current. This can be arranged through small electron temperature or large effective ion charge state. On the other hand, during the current decay stage, choose the resistivity to be relatively small and the density large so that the induced electric field supports the rf-generated current at high density which also means high fuel reactivity. The savings on the average current drive efficiency by this means can be very substantive; a few percent in the oscillation of the current can give factors of 10 in the efficiency. The synergy with α-channeling occurs because, in the current generation stage, the density is low, so the electron and ion temperatures equilibrate more slowly, facilitating the hot- ion mode. In the hot-ion mode, the fusion reactivity is greater, so the fusion power production can be made more uniform in the generation and relaxation stages, reducing the thermal fatigue. There is also a synergy with LHCD, because in low-density plasma the LHCD effect is not only more efficient , but the waves can better penetrate to the tokamak center.

One open question in tokamak recharging is how to keep the resistivity low if fast-electron-based methods, such as LHCD or ECCD, are employed, because there is an additional conductivity proportional to the rf power [45]. Also, when the current is ramped-up quickly, there is production of the so-called *backwards-runaways*, or electrons that reach high energy but carry current opposite to the desired current [30]. One speculative method to limit the electron conductivity might be through a transport mechanism that operates solely on the energetic backward-going electrons, possibly through some resonant mechanism, like the stochastic instability suggested as responsible for restraining energy in runaway electrons [46]. The idea is to remove electrons contributing to the high conductivity. Alternatively, accomplishing the tokamak recharging with ion based methods would limit the presence of high energy electrons.

It is worth noting that, while there have been a number of studies to optimize LHCD [47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59], the joint optimization of LHCD and α-channeling was considered only recently [60], where it was pointed out that launching the LH wave from the tokamak high-field side facilitated the joint optimization. This study was stimulated by the recent proposal using high-field launch so that the LH wave would penetrate more deeply the plasma core, with the waveguide better protected from the plasma [61, 62].

ALPHA CHANNELING IN OPEN FIELD GEOMETRY

The concept of α-channeling can be applied also to open field geometries, such as mirror machines [63]. The effect might even be used in Z-pinches, where Knudsen layer losses [64, 65] might be controlled [66]. The advantages accrued in an open-field devices are generally different. Fueling and ash removal are easier than in tokamaks. However, it is more important to capture the α-particle energy quickly, since α-particles tend quickly to give up energy to relatively cold electrons. As opposed to the tokamak, where α-particles take up valuable plasma pressure, in a mirror machine, the fusion ash can be thought of as taking up valuable electric potential, making important the quick ejection of the α-particles. In fact, a key application is mirrors, because recirculating power requirements are only marginally satisfied, so that improvements could affect the very viability of the mirror as a self-sustaining fusion reactor.

Both mirrors and tokamaks are devices with a symmetry direction, so that the diffusion paths can be written similarly. However, the most successful α-channeling effects in a mirror machine will exploit the fact that the periphery

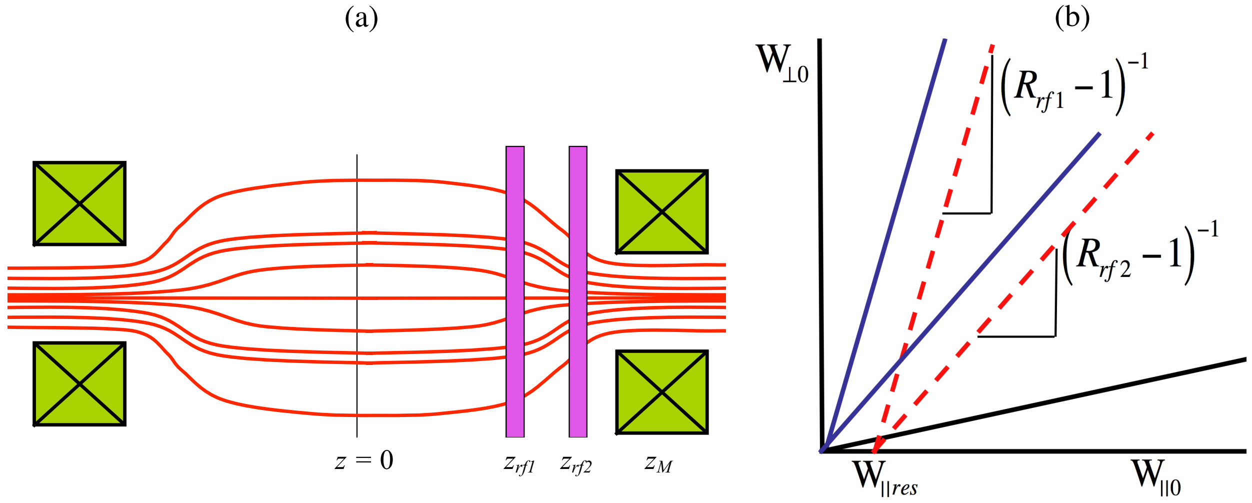

FIGURE 3. (a) Mirror field with field maximum at $z = z_M$; rf regions at axial positions $z = z_{rf1}$ and $z = z_{rf2}$. (b) Diffusion paths in midplane energy coordinates. The solid rays are the particle coordinates for particles mirroring at $z = z_{rf1}$ (upper ray); $z = z_{rf2}$ (middle ray); $z = z_M$ (lowest ray). The dashed rays are the diffusion paths for particles, resonant at instantaneous parallel energy $W_{||res}$, at $z = z_{rf1}$ (upper ray) or $z = z_{rf2}$ (lower ray), parallel to the associated solid rays and offset by the resonant parallel energy.

of the mirror machine is defined very differently from that of a tokamak. The tokamak periphery lies past the last closed magnetic surface, so particles exit the device by diffusing across magnetic field lines. In mirror geometry, the open geometry defines a periphery in the phase space that includes both configuration space and velocity space. Particles can also leave a mirror machine across field lines through radial diffusion, but they are more likely to leave through the open field lines at the ends of the mirror through velocity-space diffusion. For example, consider a simple mirror geometry as depicted in Fig. 3a, where two regions of rf interactions are shown. In Fig. 3b, we show the resulting diffusion paths, in midplane coordinates, resulting from diffusing α-particles in perpendicular energy $W_\perp$ in each region, assuming the same resonant parallel energy $W_{|||res}$. The local mirror ratio R_{rfi} denotes the ratio of the local field in region i to the magnetic field at the midplane; the mirror ratio (R_M is the ratio at z_M, where the magnetic field is at its maximum. The lowest solid ray, with slope $1/(R_M - 1)$, indicates the trapped-passing boundary.

In each region, resonant α-particles gain or lose energy, remaining on the indicated diffusion path, until exiting at low energy upon crossing the trapped-passing boundary (lowest solid ray). By linking diffusion in space to diffusion in energy, diffusion to high energy is limited by the spatial extent of the resonant region. Thus, the α-channeling effect is accomplished, as all resonant α-particles must eventually leave the mirror machine a low energy. It can be seen that, with multiple rf regions, suitable diffusion paths may be arranged to cover nearly all of the trapped α-particles. It remains, of course, to find suitable waves. Certain contained modes can be utilized [67, 68, 69], and the parameter space of possibly useful waves can be extended by using minority ions to catalyze the channeling effect [70].

In supersonically rotating plasma, there is additional axial confinement due to the rotation, creating the basis for centrifugal fusion schemes [71]. The rotation is caused by an imposed radial potential, resulting in $E \times B$ rotation. Now for α-channeling along diffusion paths, there is the new opportunity to support the plasma potential by diffusing α-particles to higher potential energy. Thus, a generalization of the channeling effect in rotating plasma contemplates some of the α-particle energy channeled to electric potential energy and some channeled to the wave energy [72]. The proportion of energy channeled to the potential depends on the wave characteristics. Like in a simple mirror, waves can be set up in a centrifugally rotating mirror plasma that eject α-particles while capturing their energy in the wave fields [73, 74]. However, waves with low frequency, which includes a fixed azimuthal perturbation (zero frequency), can be used instead to support the radial potential [75]. Producing the radial potential through this (generalized) channeling effect, rather than through endplate electrodes, represents an important technological advantage. This advantage also accrues in a rotating plasma centrifuge [76]. Here, instead of extracting energy from waves, the effect can be run in reverse with wave energy supporting the plasma radial potential.

Recently, the plasma centrifuge has been advanced for high-throughput nuclear waste separations [77]. Here the idea is to separate large mass difference elements, rather than isotopes, as a step to minimizing the volume of radioactive waste needing burial. A variation of the centrifuge, exploiting the mass dependence of the axial confining forces in rotating plasma, confers the additional advantage of axial separation [78, 79, 80]. The use of high-throughput mass separation, as a supplement to chemical separation techniques, may be critical to process economically large amounts of nuclear waste. Processing this waste is now seen as an issue of increasing urgency and expense.

CONCLUSION

The tokamak is a special case of the general paradigm: Suppose a box of hot, magnetized plasma. We shine waves into this box in such a way that the waves resonantly interact with one species of ions in the box. If the ions gain energy, they move to the center of the box; if they lose energy they move to the periphery. Thus, if we shine such waves into the box for long enough, then absent collisional effects, all of the resonant ions leave the box cold. For fusion applications, the ion species is α-particles. Opportunities through α-channeling confer substantial advantages for tokamak reactors. They also challenge the basic assumptions about the viability of both mirrors and centrifugal mirrors as fusion reactor concepts. Furthermore, this paradigm or methodology might be useful in a variety of settings, including, but not limited to, nuclear fusion. However, until copious α-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 α-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 α-channeling will have to be employed.

ACKNOWLEDGMENTS

This work was supported by the U.S. DOE under Contract No. DE-AC02-09CH11466.

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