Alpha power channeling using ion-Bernstein waves*

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An economically superior development path to a tokamak reactor may be possible, if α-particle power can first be extracted by plasma waves and then channeled to heat fuel ions. In principle, both increased reactivity and current drive could be accomplished at once. The most complete channeling is likely to be realized only through the excitation of a variety of waves, since α-particles at different velocities or at different locations within the tokamak interact most effectively with different waves. The necessary characteristics for these waves have been identified, but no specific implementation is yet at hand. The mode converted ion Bernstein wave, however, has a certain number of the required wave features, and is likely to play a useful role in helping to realize the channeling effect. © *1995 American Institute of Physics.*

I. INTRODUCTION

In a fusion reactor burning deuterium and tritium (D-T), the reaction is sustained by α-particle heating. There is an opportunity for significantly improved tokamak reactor performance by using the α-particle power to amplify waves that are then either absorbed by electrons traveling in one direction to accomplish current drive[1] or are absorbed by fuel ions for increased reactivity.[2] It may even be possible, through the amplification of an appropriate wave to achieve both the increased reactivity and the current drive at once if the wave is absorbed by tail fuel ions traveling in one toroidal direction. In the absence of the channeling, through Coulomb collisions, the α-particles heat mainly electrons, which is a less advantageous use of this power.

The mechanism of channeling relies upon the amplification of a wave at the expense of the α-particle energy. Amplification of the wave could occur if there is a population inversion in the α-particles along the wave diffusion path, where the diffusion path points from high energy α-particles in the plasma center to low energy α-particles at the plasma periphery. The wave need not be absolutely unstable; in fact, it is very unlikely that such a wave would be found. More likely, the wave might act in one of two ways: one, it could act as a catalyst, with growth due to the α-particles offset entirely by damping on ions; or, two, it might be convectively amplified by the α-particles and then damped heavily by the ions. Note that such waves would have to be excited in the tokamak, since any growth of the wave from noise would be limited.

There are two key wave criteria for the population inversion to occur and to be sustainable. First, almost the full energy of the alpha particle ought to be extracted as the wave diffuses to the periphery, or at least to a place where the particle can be removed from interacting with the wave. At the periphery of the tokamak, the α-particle might be most easily removed, thereby ensuring that the population inversion is sustained even as α-particles diffuse outwards. Second, the extraction of energy from a single α-particle must occur in a time short compared to the α-particle slowing down time, and the wave amplitude sufficient to induce this fast slowing down must not require too large a power input. The rapid slowing down by the wave ensures that the α-particle energy flows to the wave, rather than to collisional heating of the plasma. In practice, once an α-particle has slowed down considerably, it may become harder to extract energy from it. Fortunately, however, once most of the energy is extracted, the collisional slowing down then also favors energy transfer to ions rather than to electrons.

The above two wave characteristics are necessary to ensure that α-particles are extracted with nearly all their energy lost to the wave. However, the same waves that interact effectively on many or most α-particles might also interact in deleterious ways with other α-particles. For example, it will be important to ensure that in the process of extracting successfully the many α-particles born near the plasma center, the few α-particles born closer to the periphery are not ejected into the tokamak wall with almost all their energy left. The optimum wave maximizes the number of α-particles ejected with little energy left (soft landings), while minimizing the number of α-particles ejected with little energy extracted (hard landings).

Complete channeling of the α-particle power would result in about a factor of two in the fusion power density, where most of this increase is due to the operation in the so-called "hot-ion" mode.[3,4] Very preliminary estimates[5,6] suggest that, if the channeling works, the savings in a tokamak reactor could be about 35% in the cost of the tokamak and 15% in the cost of electricity. Taken into account in these estimates is the possible increase in fusion power density at constant pressure and the possible accomplishing of the current drive with the diverted α-particle power. Not included in these estimates are the possible savings in the incidental exhausting of the helium ash. Most of the savings probably comes from the possibility of using lower magnetic fields, with a large portion of the savings coming from the concomitant current drive effect.

This paper offers how the diverting of α-particle power might come about and sets forth some of the issues presently under consideration in assessing the possibility of diverting

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this α-particle power for useful purposes. On the basis of what is presently known, it is clear that a credible scenario for channelingα-particle power is not yet at hand. In fact, even a reasonably complete formulation of the issues is not quite in place. At the same time, however, neither does it appear that the requisite wave characteristics are beyond reach. Hence, the setting forth of the issues as we know them now is of necessity of a preliminary and tentative nature.

The paper is organized as follows: In Sec. II, we review energy extraction in slab geometry, which serves as a framework for discussing the required wave characteristics. These wave characteristics are introduced in Sec. III, with the ion Bernstein wave (IBW) discussed in Sec. IV. In Sec. V, we discuss the incidental spatial diffusion of the fuel ions that absorb the wave power. Section VI shows how, in principle, all α-particles could experience soft landings in the right wave environment. In Sec. VII, we introduce issues associated with approximating the wave-particle interaction as diffusive. Section VIII reviews the advantages of the channeling effect with reference to the specific use of the IBW. We conclude in Sec. IX with suggestions of what experimental evidence might be both important and relatively easy to obtain.

II. ENERGY EXTRACTION IN SLAB GEOMETRY

Although there is free energy in the energetic α-particles, how to tap a large fraction of this power is challenging. For example, wave interactions that tend to drive particles only in velocity space tend not to extract most of the recoverable energy.[7–9] A more promising way of tapping this power appears to be through a resonant quasilinear interaction with a poloidally and toroidally propagating short wavelength electrostatic wave.[1] Such a wave diffuses the α-particles both in space and energy, rather than just in energy.

Although tapping the α-particle power in a tokamak geometry introduces important complications, consider, for simplicity in illustrating the energy extraction process, a slab geometry, with an electrostatic wave propagating in the $\hat{y}$-direction. Let $\mathbf{B}=B\hat{z}$, with the gyrofrequency $\Omega\equiv qB/m$. The diffusion in energy is now coupled to diffusion in the guiding center in the $\hat{x}$-direction. To see this, begin with the Lorentz force equation,

$$\frac{d}{dt}m\mathbf{v}=q(\mathbf{E}+\mathbf{v}\times\mathbf{B}), \tag{1}$$

where $\mathbf{E}=-\nabla\phi(\psi)$, with $\psi=k_y y+k_z z-\omega t$. Consider now the evolution of the kinetic energy, ϵ, and the guiding center in the x-direction, $x_{gc}\equiv x+v_y/\Omega$:

$$\frac{d}{dt}\epsilon=\mathbf{v}\cdot\frac{d}{dt}m\mathbf{v}=-q\mathbf{v}\cdot\nabla\phi, \tag{2}$$

$$\frac{d}{dt}x_{gc}=-\frac{1}{B}\frac{\partial}{\partial y}\phi. \tag{3}$$

Using now $\partial\phi/\partial t=(\omega/k_y)\partial\phi/\partial y$, we find

$$\frac{d}{dt}[\epsilon+q\phi+(\omega qB/k_y)x_{gc}]=0. \tag{4}$$

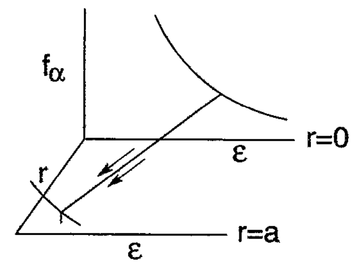

FIG. 1. f_α vs energy ϵ and radius r. Population inversion exists along diffusion path.

Since ϕ vanishes out of the wave region, a particle going through the wave region diffuses along the path in (x_{gc},ϵ) space such that

$$\Delta x_{gc}=-k_y\Delta\epsilon/m\Omega\omega, \tag{5}$$

which is a result that has been arrived at previously.[10,11]

Note that $\Delta\epsilon_{max}=mv_0^2/2$, where v_0 is the α-particle birth speed, so that the maximum excursion is

$$\Delta x_{gc}\bigg|_{max}=\frac{1}{2}(k_y\rho_0)\frac{\Omega}{\omega}\rho_0, \tag{6}$$

where ρ_0 is the initial gyroradius. Note that in extracting its energy, an α-particle can be made to move many gyroradii.

The diffusion path indicated by Eq. (5), however, is modified in toroidal geometry. Similar to the gyrocenter motion induced by perpendicular impulses, a velocity space impulse in the parallel direction results in banana center motion for toroidally trapped particles. Suitable formalism for studying these toroidal effects is found, e.g., in Refs. 12–15.

III. OPTIMAL WAVE CHARACTERISTICS

In a torus, the poloidal direction or $\hat{\theta}$-direction corresponds to the $\hat{y}$-direction in the slab model, the direction of wave propagation. The particle gradient is in the radial direction, which corresponds to the $\hat{x}$-direction in the slab. Correspondingly, Δr_{gc} is related linearly to $\Delta\epsilon$, so that, depending upon the sign of ω/k_θ, the particles are either diffused to larger radius and larger energy, or they are diffused to larger radius and smaller energy. The sign of ω/k_θ can and ought to be chosen to assure the latter event, for then α-particles are extracted cold at the plasma periphery, giving up energy to the wave. This is the situation depicted in Fig. 1, which shows a diffusion path such that α-particles are diffused from high energy at the plasma center $(r=0)$, to low energy at the plasma periphery $(r=a)$. Depicted here for didactic purposes is an α-particle distribution function f_α that is monotonically decreasing in energy on any magnetic surface, yet energy extraction takes place so long as there is a population inversion along the diffusion path.

Note that a population inversion along the diffusion path can normally be achieved with $\omega/k_\theta\to 0$. However, that would result in α-particles being ejected at $r=a$ with little change in energy, which, in fact, is highly undesirable. In the opposite limit, $\omega/k_\theta\to\infty$, the diffusion occurs in velocity space only, so that there is no population inversion (i.e., the

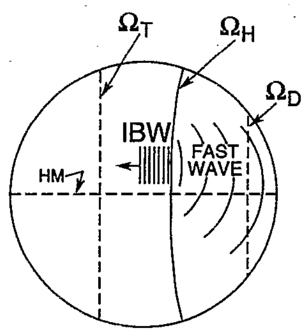

FIG. 2. Mode conversion of fast wave viewed in poloidal cross-section. Mode conversion occurs at the ion hybrid frequency Ω_H which exists between the deuterium gyrofrequency Ω_D and the tritium gyrofrequency Ω_T. The IBW emerges from the mode conversion with a short horizontal wavelength. For mode conversion above the horizontal midplane (HM), as depicted, the short horizontal wavelength is tantamount to a short poloidal wavelength.

wave is damped). The optimum choice of ω/k_θ, for α-particles born near the plasma center, results in $\Delta r_{gc}/\Delta\epsilon \simeq 3.5$ MeV/a, where clearly a population inversion occurs as α-particles may be extracted cold at the periphery. Fig. 1 depicts a nearly optimum diffusion path for center-born α-particles.

IV. THE ION BERNSTEIN WAVE

From Eqs. (5) and (6), certain necessary wave characteristics can be inferred immediately. For example, for a wave in the range of the lower-hybrid frequency, there is a requirement that $k_\theta\rho_0 \simeq (\omega_{\rm LH}/\Omega)(a/\rho_0) \gg 1$, something that in practice might be difficult to realize. In principle, such waves may exist in the tokamak,[16–18] but they may be subject to damping by electrons.[19] In addition, it would appear to be difficult to excite these waves, since a very high k_θ would need to be defined with slow wave structures at the plasma periphery.

Alternatively, to achieve the necessary $\Delta r_{gc}/\Delta\epsilon$, consider a wave in the ion-cyclotron range of frequencies. Such a wave has two advantages over higher frequency waves: First, the required poloidal wavenumber is reduced, since the same poloidal wavenumber achieves a lower poloidal phase velocity at the lower frequency. Second, it is possible to employ a vertical resonance layer to define a high poloidal wavenumber in the interior of the plasma, thus circumventing the need to define this wavenumber at the periphery. An attractive possibility,[20] depicted in Fig. 2, is to launch a fast wave that mode-converts at the ion-ion resonance surface into an ion Bernstein wave (IBW). The idea here is that the resonance surface is vertical, so the IBW emerges with a high horizontal wavenumber, which, if the mode conversion takes place sufficiently off the horizontal midplane, as depicted in the figure, is essentially with a high poloidal wavenumber. By poloidally phasing the ICRF (ion-cyclotron resonant frequency) antenna, the required sign of ω/k_θ can be accomplished.

The mode-converted IBW, excited on-axis, has been the subject of theoretical and experimental attention because of

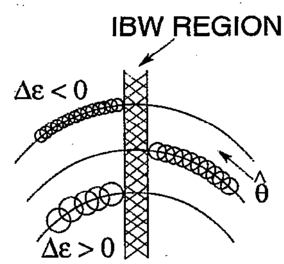

FIG. 3. Gyrating α-particle viewed in poloidal cross-section as it enters resonant region from right. The α-particle receives random kicks either to higher energy or to lower energy. With proper choice of the sign of ω/k_θ, subsequent motion is either along lower (more energetic) orbit or upper (less energetic) orbit.

the possibility of achieving the current drive effect.[21,22] Here, in contrast, for channeling α-particle power, it is important that the mode conversion occur off-midplane, ideally in a vertical line with the plasma center, where the horizontal wavenumber lies largely in the poloidal direction.

In Fig. 3, we depict the interaction of α-particles with the IBW, which occurs in such a narrow vertical slab. On any magnetic surface, essentially all the α-particles sample the wave region. Those α-particles satisfying the resonance condition as they pass through the vertical slab are kicked to a larger minor radius if they lose energy to the wave, and are kicked to a smaller minor radius if they gain energy from the wave. Particles are extracted as they near the periphery, so that a diffusion gradient is maintained along the path stretching from the center at high energy to the edge at low energy.

For the IBW, there can be a substantial upshift in poloidal wavenumber at the mode conversion surface. As calculated in Ref. 23, poloidal wavenumbers in the vicinity of 4 cm^{-1} appear to be achievable over a range of D-T (deuterium-tritium) mixtures, with ion temperatures of 20 keV and electron temperatures of 10 keV. These high wavenumbers are achieved by launching fast waves with $k_\parallel = k_{\parallel 0}$ at the antenna such that upon mode conversion, the upshifted k_x, projected on to the parallel direction, tends to cancel the launched $k_\parallel$. For a 50:50 D:T mix, however, the IBW is absorbed by electrons. To achieve diversion of the power to ions, the predominant damping must be on ions rather than on electrons. This can occur in about a 70:30 D:T mix, with the mode conversion occurring close enough to the tritium resonance that damping by tritium ions exceeds the damping by electrons.

Note that a 70:30 D-T mixture of Maxwellian ions is only 84% as reactive as a 50:50 mixture, so some benefit of the high reactivity in the hot ion mode is lost. However, the actual decrease from the maximum achievable reactivity may be somewhat less than this 16%, because of a number of compensating effects: First, the resulting distribution may be somewhat more reactive than the Maxwellian, since power is channeled to a hot tritium tail, which fuses with an enriched deuterium distribution. Second, the 70:30 mixture slows down the α-particles somewhat faster than the 50:50 mixture, so that the pressure taken up by the energetic α-particles is reduced, making more pressure available for

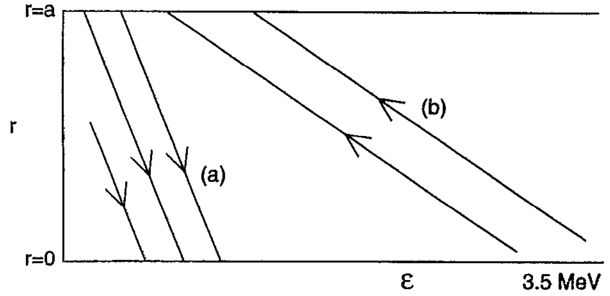

FIG. 4. Diffusion paths in energy ϵ and radius r space for fuel ions (a) and α-particles (b).

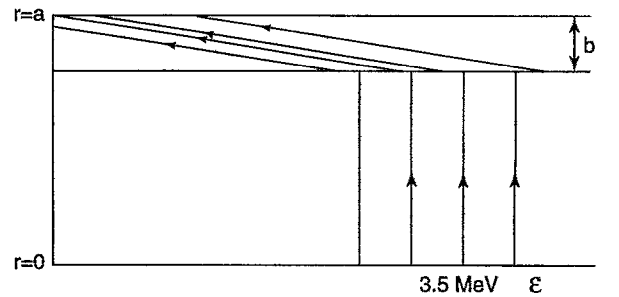

FIG. 5. Diffusion paths in energy ϵ and radius r space for α-particles showing the two-wave soft landing scenario.

reactive ions. Third, a very energetic tritium tail would absorb more of the IBW power than that calculated by linear theory,[23] so perhaps a fuel ratio closer to 50:50 could actually be employed. Thus, the precise decrease in the reactivity at 70:30, or how close to 70:30 is necessary so that tritium damping dominates over electron damping is not yet clear. Also, apart from the question of reactivity, there may be some advantage in operating at a 70:30 ratio because of the smaller tritium inventory in the tokamak.

V. DIFFUSION OF FUEL IONS

The fuel ions can diffuse in (r_{gc}, ϵ) space much in the same way that the α-particles do, that is, they diffuse along similar diffusion paths, except that the ions tend to gain energy and diffuse inwards, rather than lose energy and diffuse outwards. This happy difference means that ions tend to be heated, rather than to be cooled, and that they tend to diffuse towards the center. The reason for this can be seen by comparing the particle gradients of fuel ions and α-particles along their respective diffusion paths (see Fig. 4). Note, from Eq. (5), that the ions and the α-particles diffuse in the same wave along similar diffusion paths, except that, because the ions have half the ion charge state, $\Delta r_{gc}/\Delta\epsilon$ for the ions is twice that for the α-particles.

Fuel ions tend to diffuse inwards, even though the ion diffusion path is similar to the α-particle diffusion path, since the fuel ions tend to reside at the low energy end of these paths, and with less spatial concentration. In addition, the diffusion coefficient for particles tends to be a strong function of energy, which enters in two ways: first, the diffusion coefficient scales with perpendicular energy through $k_\perp \rho$, which tends to favor high perpendicular energy particles, and, second, only ions very energetic in the parallel direction see sufficiently Doppler-shifted waves to interact resonantly. As a result, only the very energetic ions interact with the wave. If as a result of the wave interaction, the ion loses energy, its interaction with the wave ceases, while if it gains energy, it remains interacting with the wave. Hence, the fuel ions tend to gain energy in diffusing to high energy.

The result is that the alpha channeling effect produces important heat and particle flows concomitant with the channeling of energy. First, the removal of energy from the α-particles also removes the α-particles to the tokamak periphery. If means are then found to remove them from the periphery, the important function of ash removal is accomplished. At the same time, the fuel ions diffuse towards the center, thus accomplishing fueling of the tokamak axis. Moreover, the ions reaching the axis will be heated as they arrive, thus producing a flow of heat. The heat flow is further helped by the interaction with the ion tail. Since the rf waves tend to interact with the fuel ion tail, it is the energetic tail fuel ions that will be heated and diffuse to the tokamak center. But the tail ions are already hotter than most particles by definition, so the removal of the tail particles from their original magnetic surface tends to cool that surface, resulting in a pinching of the heat.

VI. MINIMIZATION OF HARD LANDINGS

Note that the optimal diffusion path for α-particles born near the tokamak center, $\Delta r_{gc}/\Delta\epsilon \simeq a/3.5$ MeV, where a is the minor radius, does not optimize for α-particles born away from the tokamak center. In fact, if α-particles born in the center were to experience exactly soft landings at the plasma periphery, then α-particles born halfway to the periphery, if they were to experience the same ratio of spatial to energy diffusion, would experience rather hard landings at the plasma periphery with about half of the birth energy remaining at the periphery. In principle, however, a more careful programming of $\Delta r_{gc}/\Delta\epsilon$ can overcome this difficulty.

For example, to maximize the energy extraction from most α-particles, while minimizing the number of hard landings (α-particles hitting the wall with most of their birth energy), consider a "two-wave approach." Suppose, as shown in Fig. 5, that one wave, which exists only, say, within a distance b of the plasma periphery, diffuses α-particles along a path with a slope $\Delta r_{gc}/\Delta\epsilon \simeq b/3.5$ MeV. Pick b such that almost no α-particles are born in this peripheral region. Then pick a second wave, which exists only in the region from the magnetic axis up to the distance b from the plasma periphery, namely, pick the two wave regions to cover the plasma exactly and with no overlapping. Let the second wave induce diffusion along the path $\Delta r_{gc}/\Delta\epsilon \rightarrow \infty$, i.e., the second wave effectively deconfines theα-particles where the wave exists. Clearly, the combination of the two waves collects all α-particles to within the distance b of the periphery with their energy intact, after which the diffusion of all α-particles is optimized by the same ratio of spatial to energy diffusion. Hence, at least in this exemplary case, essentially all the α-particles experience soft landings.

VII. DIFFUSION OF THE α PARTICLES BY THE IBW

Depending upon their pitch angle in velocity space, α-particles traverse poloidally as much as 10^5 times in a slowing down time, and experience several to tens of gyro-orbits within the wave region, and several hundred gyro-orbits between kicks in the wave region. Assuming the kicks are uncorrelated, and estimating the kick size using a stationary phase calculation,[24] gives an energy diffusion of about an MeV^2/s at a power level of about 3 MW in Tokamak Fusion Test Reactor (TFTR). Assumed in this calculation is that the wave propagates through a ribbon with a vertical extent of about 20 cm and a circumference of the machine size, namely about 15 m. Scaling this to a reactor, in which the power levels would be about 100 times this power level, but over an area about four times as large (say double the height and double the major radius), gives a power density about 25 times larger, indicating diffusion over 3 MeV in about a third of a second, which is on the order of a slowing down time. This diffusion rate might be enhanced somewhat because the group velocity of the mode converted IBW turns around in the regime of interest, thus concentrating the field near the turning point. There are, however, a number of uncertainties in such a calculation.

First, the diffusion depends on the pitch angle of the α-particle, with the particles with the most perpendicular energy experiencing much larger diffusion than the particles with large parallel energy. Second, not all of the particles are strongly diffused by the wave; for example, for the IBW, where $\omega-\Omega<0$, only particles with $k_\parallel v_\parallel<0$ can be resonant. Since the mode converted wave is mostly of one sign of $k_\parallel$, this condition excludes the passing particles in the direction of $k_\parallel$. Third, the interaction may not be entirely stochastic.

Because many of the α-particles are not resonant or strongly diffused by the wave means that the IBW can divert directly at best power from only a portion of the α-particles.[25] On the other hand, if a portion of phase space is excavated, such as the trapped region, there may be instabilities that tend to fill in the excavated region. This, however, is by no means certain.

Effects that tend to randomize the kicks include the nonlinear phase shift of the particle upon traversing through the resonant region, the variation of the wave in the vertical direction as the particle is diffused in space, and the decorrelation of the fast wave itself as it propagates through a randomly fluctuating plasma from the antenna to the mode conversion layer. Nonlinear effects have been considered in similar contexts.[12,15,26,27] In the case at hand, these nonlinear effects tend to be, in themselves, insufficient to cause significant stochasticity. The other effects are unclear at present. Since there are several hundred gyroperiods between kicks, however, there is ample time, if it were desirable to have uncorrelated kicks, to decorrelate purposefully the wave excitation itself. It may be the case, however, that correlations, if they persist, could be useful. Several correlated kicks in a row result in an effectively larger diffusion coefficient for certain particles, so long as the excitation can be decorrelated after a number of kicks to assure the diffusive behavior.

Thus, the IBW can diffuse a fraction of the α-particles, mainly the trapped α-particles, over a distance of about 50 cm. It would appear to be difficult to extend this distance by a great amount, even if shorter poloidal wavelengths were to be found. First, it becomes difficult to diffuse over the larger distance in a slowing down time, not only because the diffusion rate is smaller, but also because the available power must be spread over a wider region, thus reducing the power density and the wave amplitudes. Second, in a toroidally axisymmetric geometry there arise constraints from the conservation of wave and particle toroidal angular momentum that either constrain the particle motion, or may constrain the flow of power into some of the waves.

VIII. ADVANTAGES OF THE ALPHA CHANNELING

There are a great many uncertainties with regard to the feasibility of channeling the α-particle power, but, if indeed this power can be channeled to the ions, the advantages are substantial. With 75% of the power diverted, the fusion power density roughly doubles.[4] If the power is absorbed, say, by passing tritium ions, there can, in principle, also be a helpful current drive effect.

As presently configured, however, this current drive appears not to be co-current, because the tritium ions that tend to absorb the IBW power tend to be counter-current. This can be seen as follows: if $\omega/k_x>0$ is picked so as to diffuse the α-particles properly, then $k_\parallel\simeq\mathbf{k}\cdot\mathbf{B}/B\simeq-k_xB_\theta/B<0$. The resonant tritium ions then obey $v_\parallel=(\omega-\Omega_T)/k_\parallel<0$. If the main current drive effect were to be through the minority species current drive,[28,29] then the heating of countermoving tritium tends to drive current opposite to the main current. This tendency might be reversed, if the heating of the countersteaming tritium ions caused them to become trapped, or if it were possible to channel the α-particle power into comoving tritium, say by offsetting $k_\parallel$. On the other hand, driving counter-currents might also be a desirable effect in controlling the current profile. Alternatively, if the power were to go into electrons, as would be the case in the 50:50 D-T mixture, then it would also be countermoving electrons absorbing the wave through a Landau resonance, and the resulting current drive effect is co-current.

A substantial increase in the fusion power density arises from the extra pressure available to fuel ions when the energetic α-particles are slowed down, thereby contributing less to the total pressure. This contribution, which could be as much as a 30% enhancement to the fusion power density, would be available even in the event that the α-particle power is directed into waves that merely damp on electrons, say, to sustain the plasma current. Incidentally, note that since the power required to drive the toroidal current is generally less than 10% of the fusion power output, whereas the α-particle power is 20% of the fusion power output, using even a fraction of the α-particle power to amplify the waves used for current drive can result in very significant savings in the required power for the current drive. A greater fraction of the α-particle power needs to be diverted to have a more substantial effect on the fusion reactivity.

Other advantages of diverting substantial amounts of α-particle power include those from the induced particle fluxes. As discussed above, both the ejection of α-particles from the core and the heat pinch of the fuel ions are benefits. Although these benefits have not been quantified, removal of the cool helium ash also results in significantly more pressure available to the fuel ions. Also contributing to the total reactivity, the heat and particle fuel pinches can contribute to more favorable pressure profiles. Finally, there is great advantage in simply removing the free energy source available in the undirected α-particle distribution that might fuel unwanted instabilities. This benefit, however, is also difficult to quantify.

IX. SUGGESTED EXPERIMENTS AND CONCLUSIONS

Although there is no specific scenario yet at hand for realizing the channeling effect, if such an effect were to be realized, it is likely that the mode converted IBW would be an important component. This wave appears useful for diffusing α-particles in the range of 50 cm, and, in principle, could exist both near the center of the tokamak or near the periphery. It does not appear to interact strongly with a large fraction of the α-particles, but the α-particles with which it does interact strongly might diffuse over the extent of the wave in a time short compared to collisional slowing down. It then becomes a matter of bringing other α-particles into resonance with this wave, perhaps to utilize it as the second stage wave discussed in Sec. VI.

In anticipation that the IBW wave might be such a useful component, it would be of interest to observe experimentally that such high k_θ waves exist. Simply to observe the attained wavenumbers requires neither unidirectional poloidal nor unidirectional toroidal phasing of the wave. If the high k_θ waves do in fact exist, then it would be of interest to at least have unidirectional poloidal or unidirectional toroidal phasing of the wave, so that a net diffusive effect might be observed. While it is not an absolute requirement, if it were possible to have both unidirectional poloidal and unidirectional toroidal phasing of the wave, then the wave power would be utilized more efficiently. It would be of interest to observe experimentally particularly whether there are any very quickly ejected α-particles or fast ions that might be associated with the superadiabaticity discussed in Sec. VII.

In conclusion, it should be emphasized that the ideas presented here are of a tentative and evolving nature. Detailed calculations are being carried out to support the descriptions offered here. It should also be realized that both the wave propagation and the requirements on the wave may change substantially if the magnetic configuration departed significantly from the low-beta tokamak with concentric flux surfaces envisioned here or if there were nonaxisymmetries in the tokamak. For example, both the propagation and the requirements on the wave are not clear yet in the presence of large plasma elongation or Shafranov shift. Also, it should be noted that although there may still be signficant other difficulties with aneutronic fusion, a reactor utilizing DHe^3 fuel stands even more so to benefit considerably from diverting charged fusion by-product power. In particular, the fusion reactivities go up also by factors of two or three,[4] and it would appear that because the protons are relatively lighter and more energetic than the α-particles, the channeling effect becomes relatively easier too.

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