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Applying Alpha-Channeling to Mirror Machines

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The α-channeling effect entails the use of radio-frequency waves to expel and cool high-energetic α particles born in a fusion reactor; the device reactivity can then be increased even further by redirecting the extracted energy to fuel ions. Originally proposed for tokamaks, this technique has also been shown to benefit open-ended fusion devices. Here, the fundamental theory and practical aspects of α channeling in mirror machines are reviewed, including the influence of magnetic field inhomogeneity and the effect of a finite wave region on the α-channeling mechanism. For practical implementation of the α-channeling effect in mirror geometry, suitable contained weakly-damped modes are identified. In addition, the parameter space of candidate waves for implementing the α-channeling effect can be significantly extended through the introduction of a suitable minority ion species that has the catalytic effect of moderating the transfer of power from the α-channeling wave to the fuel ions.

I. INTRODUCTION

In devices designed to produce controlled nuclear fusion through deuterium-tritium reactions, α particles are born with 3.5 MeV energies and tend to dissipate their energy by colliding with electrons and also through excitation of plasma instabilities [1–6]. A fraction of this energy eventually ends up in fuel ions, sustaining the reactor operation; however, both of the dissipation mechanisms are generally deleterious. Any energy ending up in electrons is somewhat precarious, since, before being transferred to the ions, this energy can be radiated away or transported away through collisions. Moreover, in different magnetic confinement devices, there are different specific deleterious effects of energy residing too long in the α particles or in the electrons. Similar to instability effects driven by α particles in the tokamak [7–9], mirror instabilities, likewise stimulated by the energy in the α particles, might also diminish confinement of the plasma [10–13].

A further issue is that, in a tokamak, the electrons and α particles take up valuable pressure that could have been utilized for fuel ions. A similar issue occurs in mirror machines: in a mirror machine, the collisional slowing down of α particles does not remove them from the trapping region, so a positive potential builds up and hinders the input of fresh fuel ions into the machine. In both cases, having more fuel ions instead of fusion byproducts would make the fuel more reactive thereby reducing confinement costs.

Alleviating these problems is the so-called α channeling technique, which redirects quickly the α particle energy to waves, which then transfers it rapidly to fuel ions such that the electrons are not heated and the fusion ash is quickly extracted from the reactor [14]. By *quickly* what is meant is a collisionless rather than a collisional time scale. Considerable theoretical attention has been given recently to how these colisionless effects might occur[15–18]. Were they to occur, and were the energy to be successfully redirected, the tokamak reactor could be made significantly more economical [19].

While originally proposed for toroidal plasmas, the concept may also apply in mirror machines [20, 21]. In a simple mirror [22], just the extraction of fusion ash alone is predicted to increase the reactivity by a factor of 2.8 [20]. However, this energy can be redirected to do more useful things in mirror machines, particularly in more complex mirror geometries [23, 24], including preventing collisional energy loss to electrons and heating ions in desirable locations, such as, in the case of the tandem mirror, in the end cell.

The α channeling effect can be implemented by externally exciting unstable or weakly damped cyclotron waves. These waves cause rapid α particle cooling, accompanied by ejection of cold α particles. However, the excited waves are not necessarily the fastest-growing instabilities. When any wave that accomplishes the channeling effect is excited, the free energy contained in the steady-state α-particle distribution is significantly reduced, so that this energy is not available to other potentially destructive instabilities.

The objective of this paper is to review the fundamental theory and practical aspects of α channeling in mirror machines, and to assess the present state of understanding. In addition, certain opportunities for improvement or advancement of this technique are identified.

The paper is organized as follows: In Sec. II, the basic concept of α channeling is introduced, including the way diffusion paths are employed both to transport particles to lower energy at the periphery and to limit their gain in energy, with particular application to mirror machines. In Sec. III, the dynamics of distributions of α particles is simulated in practical geometries, but with idealized waves, to motivate the desirable wave properties for achieving the channeling effect. In Sec. IV, a method is outlined for finding contained plasma modes, satisfying the wave dispersion relation, that in fact can be used to practice the effect. Section V outlines some of the more immediate opportunities for experimental investigation of aspects of the α-channeling technique. In Sec. VI, a new technique is discussed for redirecting the energy of these waves to fuel ions such that a broader parameter space of waves is useful for achieving the channeling effect. In Sec. VII, the main conclusions of the present work are summarized and speculations are advanced concerning the further applicability of the concepts that proved useful here in producing the α channeling effect in simple mirror geometry.

II. DIFFUSION PATHS

In order to extract cold α particles while leaving the even colder deuterium ions (characterized by the same charge-to-mass ratio) and hot α particles trapped in the device, the excited waves should affect particles with different velocities differently. Specifically, the quasilinear diffusion in the particle phase space caused by such waves should induce flows between the hot α particles in the device interior and cold particles near the loss boundary, while not affecting other regions of the phase space. For a tokamak, the loss boundary is the physical boundary of the device and hence the "diffusion paths" along which particle random walk is induced, should connect hot center with a cold periphery. For a mirror machine, on the other hand, the diffusion paths do not necessarily have to lead particles to the plasma boundary, instead they may connect the regions of hot trapped particles with a low-energy part of the loss-cone.

Using waves to affect a localized region of the particle phase space is possible due to the selective nature of the wave-particle resonance. Indeed, only particles satisfying the resonance condition $\omega - \ell\Omega_0 - k_\parallel v_\parallel = 0$, *i.e.,* travelling with the parallel resonance velocity $v_{\rm res} = (\omega - \ell\Omega_0)/k_\parallel$, are in resonance with the wave. Here ω and $\boldsymbol{k} = k_\parallel \boldsymbol{B}/B + \boldsymbol{k}_\perp$ are the wave frequency and wavevector, $\boldsymbol{B}$ is the background magnetic field, Ω_0 is the particle gyrofrequency, $\boldsymbol{v}$ is the particle velocity, and integer ℓ is the cyclotron resonance number. For resonant particles, the change of the particle energy E, magnetic moment μ and gyrocenter position (X, Y) are connected through [25–27]:

$$\frac{\dot\mu}{\dot E} \approx \frac{\ell}{\omega}, \qquad \frac{\dot p_\parallel}{\dot E} \approx \frac{k_\parallel}{\omega}, \qquad \frac{\dot X}{\dot E} \approx \frac{k_\perp}{m_0\Omega_0\omega}, \tag{1}$$

where m_0 is the particle mass and $\boldsymbol{k}_\perp$ is assumed to be directed along the y axis. It is therefore possible to arrange resonant interaction with only hot α particles, avoiding perturbation of the background fuel ions and coupling α particle cooling to the particle drift. Note also that substituting $k_\parallel \ll \omega/v$ in Eqs. (1), one obtains $\dot p_z/\dot p_\perp \ll 1$ and the resonant particles stay close to the resonance while losing or gaining energy. Therefore, in the presence of a single homogeneous wave with constant ω, $\boldsymbol{k}$ and some randomization mechanism, resonant particles will diffuse strictly along the so-called "diffusion path," where $v_\parallel = v_{\rm res}$.

The application of this principle to the α-channeling to mirror machines [20, 21] envisioned the excitation of several distinct localized ion-cyclotron waves with $v_i \ll v_{\rm res} \ll v_\alpha$ and $k_\parallel \ll \omega/v$. The first condition is necessary to avoid interaction with the background ions and to permit significant cooling of α particles. The employment of several rf regions is required to capture α particles within a wide range of pitch angles. Indeed, consider a wave localized near $z = z_{\rm rf}$. The corresponding diffusion path in the local energy space $(W_\parallel, W_\perp)$ is a finite-width "stripe" $W_\parallel \approx m_0 v_{\rm res}^2/2$ (the finite width arises from the finite-width wave spectrum, the magnetic field inhomogeneity, and the wave profile). In the midplane energy space $(W_\parallel^0, W_\perp^0)$, however, the same diffusion path satisfies $W_\parallel^0 \approx (B_{\rm rf}/B_0 - 1)W_\perp^0 + m_0 v_{\rm res}^2/2$. In other words, it is again localized near a straight line with an inclination dependent on the magnetic field magnitude at the rf region location. By arranging several wave regions with identical $v_{\rm res}$ along the device axis, it is therefore possible to create a population inversion between the region of high-energetic α particles with different pitch angles and a low-energy part of the mirror loss cone (Fig. 1). If all waves are sufficiently strong and if the particle diffusion is limited at high energies [20, 28], before slowing down on electrons, the fusion α particles will diffuse along the paths and eventually must leave the device through the loss cone, transferring nearly all their energy to the α-channeling waves.

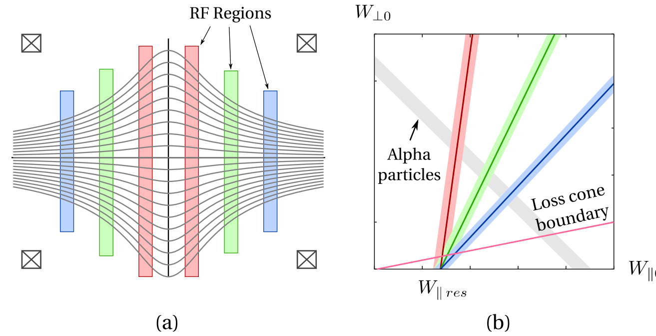

FIG. 1. (Color online) Layout of rf regions in a simple mirror machine together with the corresponding set of diffusion paths: (a) six localized rf regions placed along the device axis; and (b) diffusion paths induced by the given rf regions. The gray region indicates the α particle birth distribution.

III. PRACTICAL ISSUES

In practice, the magnetic fields are inhomogeneous, so the diffusion path will be broadened as depicted in Fig. 2. The broadening will allow a larger fraction of α particles to interact with the waves, so that only several monochromatic wave regions need be imposed. However, the broadening can also lead to the overlapping of several diffusion paths near the loss cone. As a result of the overlapping, Eqs. (1) are no longer satisfied precisely in the intersection region, so that a more complex model of

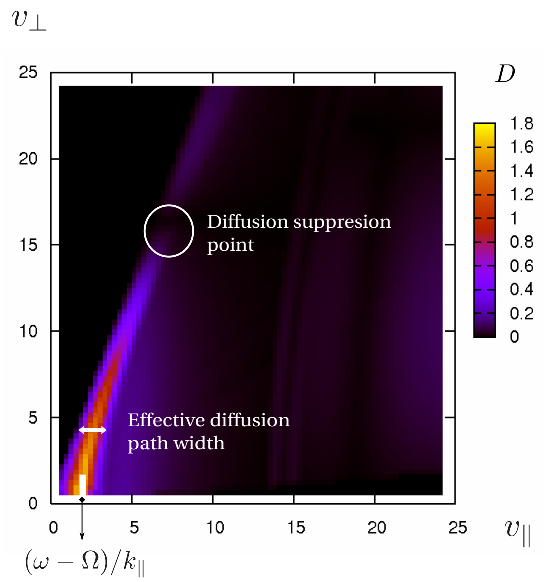

FIG. 2. (Color online) Dependence of the diffusion coefficient D on the particle midplane velocity $(v_{\|}, v_\perp)$ calculated numerically by integrating the equations of motion for particles in a simple mirror with length $2L = 20\,\mathrm{m}$ and a single rf region at $B_{\mathrm{rf}} = 1.2B_0$ [28]. The finite width of the path and the region of suppressed diffusion (due to finite-$k_\perp\rho$ effects) are shown.

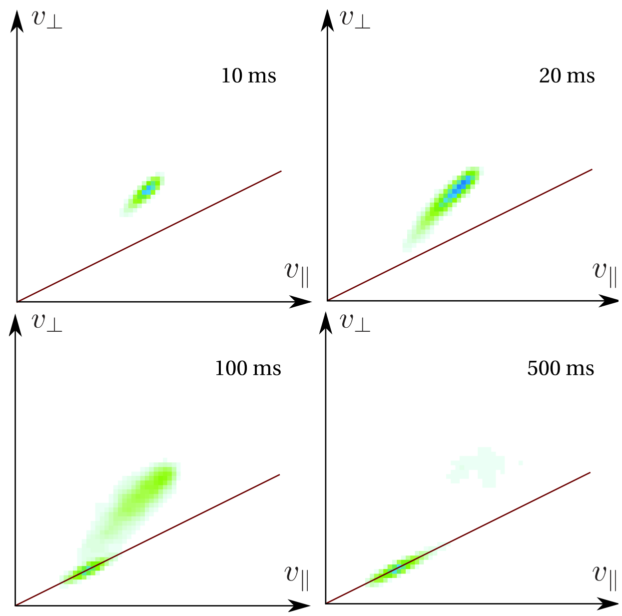

FIG. 3. (Color online) Evolution of the particle distribution function in a mirror machine of length $2L = 20\,\mathrm{m}$ and a single rf region located at $B_{\mathrm{rf}} = 2B_0$ [28]. Most of the particles initalized on the path diffuse to the loss cone in a finite time.

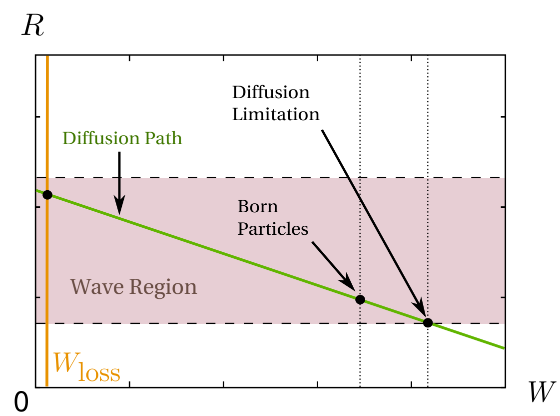

FIG. 4. (Color online) A diffusion path in the configuration-energy space (R, W), where R is the radial particle position and W is the particle energy. Particle diffusion along the path is limited at high energies as the particle reaches the wave region boundary.

α particle diffusion in the phase space is required.

To account for these effects, the dynamics of α particles in realistic geometry was modeled numerically, both by solving the Fokker-Planck equation and by tracking trajectories of individual particles [28]. The particle drag and diffusion coefficients entering the Fokker-Planck equation were calculated numerically for each rf region using either full, or gyroangle-averaged equations of particle motion. The numerical simulations confirmed that the limitation of the α particle heating along the diffusion path (Fig. 3) could be achieved via finite-$k_\perp\rho$ effects [28, 29] or via the radial α particle drift accompanying particle energy diffusion [20] (Fig. 4), in both cases leading to efficient channeling of the α particle energy to the waves.

A rough numerical optimization of α-channeling efficiency with respect to rf region parameters (ignoring restrictions imposed by the plasma dispersion relation) for a system with limited particle heating, confirmed that extraction of up to 80% of all trapped α particles, accompanied by channeling of 75% of their energy to the wave, might be possible (Fig. 5) in a simple mirror. Thus, the simulations demonstrate channeling of up to 60% of the total energy of trapped α particles. The remaining 40% of the energy is partially the residual energy of α particles that escaped the device and also, partially, the energy that remained inside the device and presumably would eventually be shared by the background plasma as a result of collisions. The response of the background fuel ions to the α-channeling waves was also simulated, showing that using higher cyclotron resonances and choosing rf regions with smooth longitudinal profiles (resulting in narrower spatial Fourier spectra) minimizes the effect of the waves on the fuel ions. However, injecting fuel ions near the loss phase-space region for α particles [20, 30, 31] results in the heating of fuel ions by the same waves that channel the α particle energy, with the fuel ions diffusing into the mirror rather than diffusing out of the mirror [28]. This effect might be particularly useful in devices with many cold fuel ions near the trapped-passing boundary [32].

IV. CONTAINED MODES

The waves extracting energy from α particles can be either convectively or absolutely unstable in response to the density inversion along the diffusion paths of α particle distribution function. Hence, two approaches to the α-channeling implementation are possible. The first approach is realized by shining high-amplitude convectively unstable waves into the device. These waves are expected to first encounter an α particle resonance region, extracting energy from α particles, and then pass through a region of resonance with fuel ions, thereby damping all extracted energy on the background plasma, for example, on the tritium resonance [33]. In the second approach, an unstable cavity mode grows off the α particle free energy until it is nonlinearly stabilized through damping off of the background plasma, for example through the reduction of the growth rate due to the quasilinear flattening of the α particle distribution function along the diffusion paths. Since it grows off of α-particles while it is being damped by the background plasma ions, the cavity mode both extracts and redirects the α-particle energy. These cavity modes can be formed as a result of rf wave reflection from the device periphery conductors or internal reflections from plasma density or magnetic field gradients (Fig. 6). Despite being more difficult to identify, the weakly-damped cavity modes can be more advantageous than the strongly damped convectively unstable waves since they may require less external power for their excitation. Furthermore, once the device is operating and the fusion α particles are produced, this mode reaches saturation, requiring virtually no energy to sustain it.

Assuming the validity of the WKB approximation [35], a method of finding all contained weakly-damped electromagnetic modes [36] propagating primarily along (Fig. 7) or across (Fig. 8) the background magnetic field was proposed [34, 37]. Applying this method to several practical device designs including the fusion reactor prototype [38] and the Large Plasma Device [39], several contained weakly-damped modes with parameters close to those required for efficient α channeling were found. Those modes, identified as fast and shear Alfvén waves and also ion Bernstein waves, have cutoffs both radially and longitudinally, while the parallel wave vector component $k_\parallel$ is limited by $|k_\parallel| < k_0$ with $\omega/k_0 \gg v_{\mathrm{th}\,e}$, where $v_{\mathrm{th}\,e}$ is the electron thermal velocity. The identified modes are therefore trapped in a mirror machine, typically near a local minimum of B_0 and extend to a region over which B_0 changes by several percent. Should a device allow for multiple regions like that, the arrangement of multiple modes interacting with α particles within a single machine would be possible [34].

On the other hand, since the contained modes are sensitive to the magnetic field perturbations, excitation of such modes in a strongly-fluctuating plasma can be challenging. Thus, other modes may turn out to be more practical, including those propagating at other angles with respect to B_0, those having large $k_0 v_{\mathrm{th}\,e}/\omega$, or those unstable convectively.

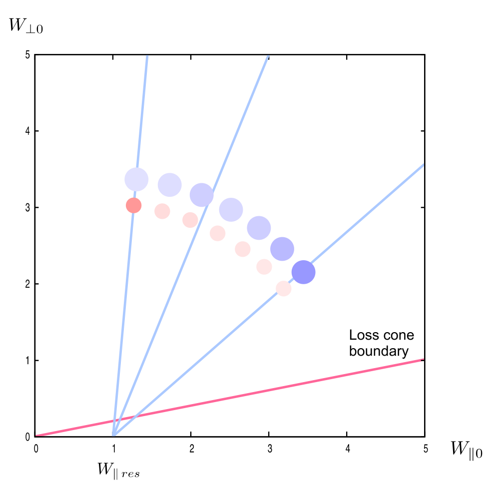

FIG. 5. (Color online) Dependence of the channeling time (small circle) and the average output energy (large circle) on the initial pitch angle of the α particle in a mirror machine of length $2L = 40$ m with 8 rf regions arranged along the device axis [28]. Darker shades correspond to larger values.

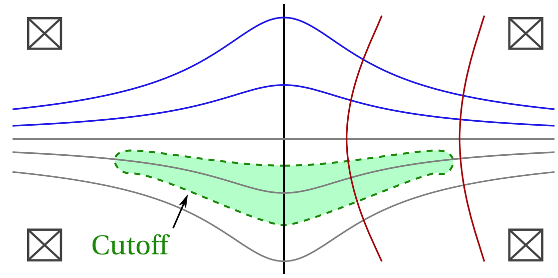

FIG. 6. (Color online) A region of the wave propagation in case if a contained α-channeling wave experiences cutoffs in both radial and longitudinal directions.

V. POSSIBLE EXPERIMENTS

Although fully testing the α-channeling effect in a mirror machine requires copious amounts of fusion-born α particles, it is worth noting that many of the key ideas of the α-channeling technique, in particular the characteristic properties of the wave-particle interaction and existence of suitable contained modes, might be investigated experimentally on existing devices, such as the Large Plasma Device (LAPD) [39].

The verification of the α-channeling effect could be performed by arranging the interaction between the injected ions and the shear Alfvén wave launched by the internal antenna. Similar experiments carried out for free-streaming particles confirmed many properties of the resonant wave-particle interaction [40, 41]. Creating a mirror trap in this system and trapping resonant particles

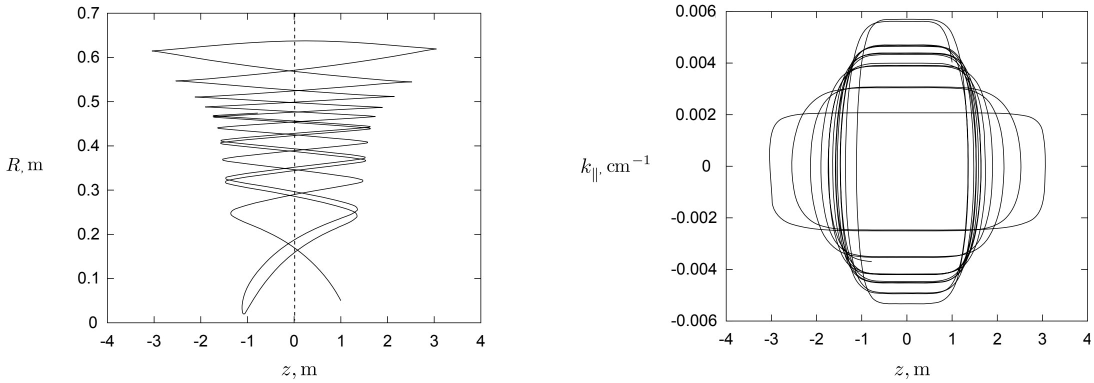

FIG. 7. A ray trajectory for the identified ion Bernstein wave propagating primarily along the magnetic field lines: (a) ray trajectory in (R, z) coordinates, (b) ray trajectory in $(k_\parallel, z)$ coordinates. The system parameters are $\omega \approx 5.8 \times 10^7\,\mathrm{s}^{-1}$, $T_e^0 = T_i^0 = 4\,\mathrm{keV}$, $n_e \approx 7.4 \times 10^{12}\,\mathrm{cm}^{-3}$, $n_D^0/n_T^0 = 1$, $\kappa = 0.15$, $m = 1$, $B_{\min} = 1.5\,\mathrm{T}$, and $B_{\max} = 5B_{\min}$ [34]. The ray launched with $k_\parallel = 0.004\,\mathrm{cm}^{-1}$ and $z = 1\,\mathrm{m}$ experiences cutoffs both radially and longitudinally.

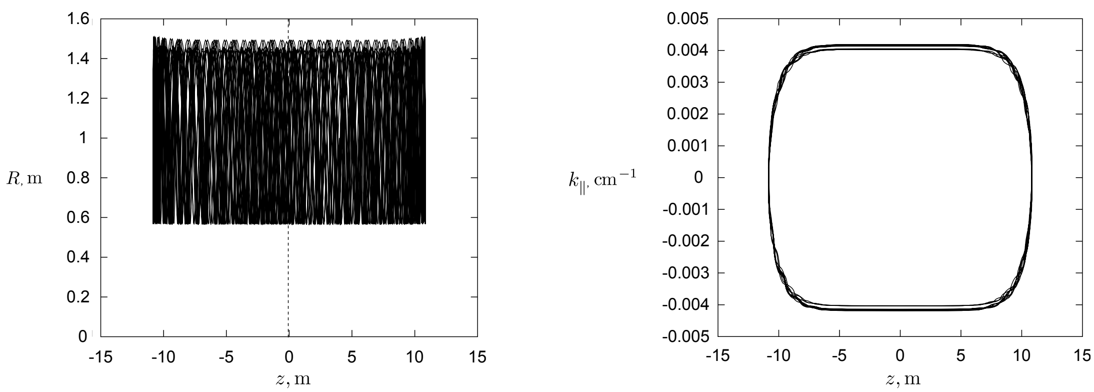

FIG. 8. A ray trajectory for the fast Alfvén wave propagating primarily across the magnetic field lines: (a) ray trajectory in (R, z) coordinates, (b) ray trajectory in $(k_\parallel, z)$ coordinates. The system parameters are $\omega \approx 5.8 \times 10^7\,\mathrm{s}^{-1}$, $T_e^0 = T_i^0 = 2\,\mathrm{keV}$, $n_e \approx 9.8 \times 10^{12}\,\mathrm{cm}^{-3}$, $n_T^0/n_D^0 = 1.5$, $\kappa = 0.15$, $m = 1$, $B_{\min} = 1.5\,\mathrm{T}$, and $B_{\max} = 5B_{\min}$ [34]. The ray trajectory experiences cutoffs both radially and longitudinally.

could, in principle, let one observe the radial drift accompanying particle energy diffusion. Note that using particle energy spectrum analyzers could be important to observe the full α-channeling effect in this case.

The existence of some of the predicted contained modes could also be verified using the LAPD device. The ongoing fast Alfvén wave launching campaign could provide one with an opportunity to study coupling, propagation and reflection of such waves, as well as excitation of the contained fast Alfvén modes. At the same time, the LAPD device is also suitable for studying shear Alfvén waves [42]. Recently, the existence of the so-called ion-ion hybrid shear Alfvén wave resonator was demonstrated in the LAPD plasmas [43, 44]. This contained mode exists due to the fact that the fast Alfvén wave experiences the cutoff at the ion-ion hybrid frequency, which may be realized inside the device. Since the same mechanism is responsible for longitudinal reflection of one of the modes identified as suitable for α channeling, the experimental observations discussed in Refs. 43, 44 does represent important evidence supporting the existence of such modes.

VI. MINORITY ION CATALYSIS

The effects predicted might be made more robust by introducing a minority ion species. The idea is to channel energy from α particles to fuel ions without demanding that there be a wave that is resonant with both species, even if in different spatial locations. Keeping the operating wave in resonance with both α particles and tail ions imposes significant restrictions on plasma parameters suitable for the channeling effect. In particular, even weak variations of the dc magnetic field can lead to resonant interaction between the wave and the bulk fuel ions, resulting in strong damping and plasma pump-out [10, 11].

Thus, to remove the restrictions on the waves in the straightforward α-channeling technique, the technique can be modified using a "catalytic" effect of minority ions [45]. Specifically, minority ions injected into plasma can act as mediators, extracting the energy resonantly from the operating wave (Fig. 9) and then transferring

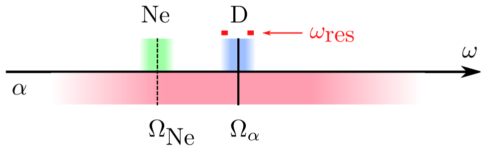

FIG. 9. (Color online) Doppler-broadened cyclotron frequencies of three plasma species: fuel ions, minority ions (Ne) and α particles. The range of frequencies for waves capable of resonant interaction with both α particles and tail fuel ions (not the bulk fuel ions) is shown with two bars.

it through collisions to fuel ions but not to electrons. As long as the energy of the catalytic species is not too high, the collisional relaxation of the energy of the catalytic species will be preferentially on fuel ions. For typical deuterium-tritium fusion scenarios, this means that the catalyst energy does not exceed about 1 MeV. This approach can be particularly useful for mirror concepts in which the fuel ions are much hotter than electrons [46].

One feature of this approach is the possibility of using wave frequencies ω sufficiently far from the fuel ion gyrofrequency Ω_i. As a result, despite the inhomogeneity of the magnetic field in the wave propagation region, and despite possible field fluctuations, the resonance between the wave and the bulk fuel ions can be avoided, thereby decoupling the fuel heating by waves from the channeling of energy from the α particles. In fact, the magnetic field inhomogeneity extends the parameter space of useful α-channeling waves. Indeed, the resonant interaction between the wave and the minority ions occurs at $\Omega_m(z) = \omega$, where Ω_m is the minority gyrofrequency. The bandwidth of operating waves can therefore be as large as $k_\parallel v_{m\,\parallel} + \delta\Omega_m$, where $\delta\Omega_m$ (which is typically much larger than the Doppler width $k_\parallel v_{m\,\parallel}$) is the variation of the minority gyrofrequency across the desired region of interaction and $v_{m\,\parallel}$ is the parallel thermal velocity of minority ions.

To ensure that the wave is in resonance with deeply trapped α particles, but is not Landau damped on electrons, heavy minority ions such as ^{22}Ne or ^{21}Ne are indicated [45]. The amplitude of the employed waves must be sufficiently large to cause fast α particle extraction, but small enough that the bulk plasma is not perturbed significantly. At the same time, the steady-state minority ion temperature (depending on the wave amplitude) should be larger than that of the fuel ions, but much smaller than 1 MeV to avoid collisional heating of electrons. Finally, the energy flux leaving the device with escaping minority ions must be much smaller than the α particle energy transferred to ions. In Ref. 45, the possibility to satisfy all these conditions simultaneously was demonstrated through Fokker-Planck simulations of both the α-particle and ion dynamics for the system with the following parameters: $B_0 \approx 0.9\,\mathrm{T}$, $n_e = 3\times10^{13}\,\mathrm{cm}^{-3}$, $n_D = 0.9n_e$, $n_T = 0.1n_e$ and $T_e = T_D = T_T = 10\,\mathrm{keV}$. The minority ions were prevented from overheating because the polarization of the fast Alfvén waves used for α channeling is opposite to the direction of ion gyration.

Note that, in the catalytic method discussed here, there is the added benefit of working with minority ions whose distribution is more easily controlled than that of fuel ions. The minority ions are fewer in number and may be injected at the precise point where they are maximally useful for the catalytic effect. There are advantages also in applying these catalytic methods in α channeling to tokamaks. Like in mirrors, the use of α channeling increases the fusion reactivity [47], and catalytic methods should enlarge the parameter space of useful waves for α channeling in tokamaks over and above those waves already considered which interact only with the fuel ions [33, 48–51]. A further advantage of the catalytic effect in tokamaks would be that, to the extent that the excited wave has phase velocity in one toroidal direction only, the minority ions would not only heat preferentially the fuel ions, but also produce a net electrical current useful for confining the plasma [52].

VII. SUMMARY AND DISCUSSION

The α-channeling effect entails the use of radio-frequency waves to expel and cool high-energetic α particles born in a fusion reactor; the device reactivity can then be increased even further by redirecting the extracted energy to fuel ions. Originally proposed for tokamaks, this technique as described here also benefits open-ended fusion devices. The α cooling effect arises from wave diffusion paths in energy-position phase space that connect high energy α particles born in the center of the device to low energy α particles that exit at the periphery. In a tokamak, the center is literally the physical center or magnetic axis, and the periphery is the last closed flux surface. However, in mirror machines the confinement occurs outside a loss cone, with a peripheral surface in energy space. In either case, α particles give up energy to the waves on a collisionless time scale as they are forced to leave the device.

Here, the theory of α channeling in mirror machines was reviewed, with particular attention paid to practical aspects, including the influence of magnetic field inhomogeneity and finite wave region size. Simulations showed that most of the α particle energy can be extracted by waves that drive out most of the α particles. In mirror machines, however, the channeling effect is produced by waves different from those that exist in tokamaks. In particular, contained ion Bernstein, shear and fast Alfven modes were identified that are effective in achieving the channeling effect in open geometry. Also identified was how a larger parameter space of waves could be made useful for achieving the channeling effect if a minority species were introduced. The minority species acts as a catalyst, being heated by the waves that extract energy from the α particles, but then quickly transferring this energy to fuel ions rather than to electrons. Although the simulations here were carried out for the simple mirror, it can be imagined that the same or very similar waves should work for more complex open system geometries, including mirror devices with centrifugally-confined supersonically-rotating plasma, which could benefit from channeling α particle energy to support the supersonic rotation [53, 54].

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