32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, D-5.010 (2005)

Alpha Channeling in Mirror Machines

N. J. Fisch

Princeton Plasma Physics Laboratory, Princeton University, Princeton NJ, 08543, USA

Because of their engineering simplicity, mirror machines and related open-trap machines such as gas dynamic traps, are an attractive concept for achieving controlled nuclear fusion. Unfortunately, these concepts have not achieved to date very spectacular laboratory results, and their reactor prospects are dimmed by the prospect of a low Q-factor, the ratio of fusion power produced to auxiliary power. Nonetheless, because of its engineering promise, over the years numerous improvements and inventions have been proposed to enhance the reactor prospects of magnetic mirror fusion, such as tandem designs, end-plugging, and the design of electric potential barriers. Here, we suggest that the use of rf fields interacting with mirror-confined ions, such that the ions diffuse in the rf fields along highly constrained orbits, can make these open-trap concepts considerably more attractive as fusion devices.

The alpha channeling effect in mirror machines holds similar promise to alpha channeling in tokamaks, In tokamaks, where diffusion along highly constrained orbits might channel the alpha particle energy, the alpha channeling effect is implemented by exciting waves that diffuse resonant particles along diffusion paths connecting high-energy alpha particles in the tokamak interior with low-energy partcles in the periphery, so that a population inversion occurs along that path [1]. Because of the population inversion, the waves cause hot alpha particles to diffuse to the periphery and cool at the same time. These same waves, operating along similar diffusion paths, can simultaneously diffuse fuel ions from the periphery and heat them as they are brought to the tokamak center. This useful fueling and heating effect occurs because the population inversion for the fuel ions is opposite to that of the alpha particles. There are no MeV fuel ions in the center, but there are many relatively cold fuel ions near the periphery. So the diffusion path works to suck in cold fuel ions, heating them as they are diffused to the tokamak core. Thus, quite remakably, the same wave that taps alpha particle energy while rejecting the alpha particles to the periphery, also fuels the plasma by sucking in fresh fuel ions and heating them.

In a tokamak, by channeling 75% of the alpha particle energy, the effective fusion reactivity could be more than doubled [2]. The doubling of the reactivity occurs partly because the tokamak could be run in a hot ion mode (which in fact is the mode in which the tokamak has achieved to date by far the best performance parameters). Because of the alpha channeling effect, the fusion ash is advantageously removed quickly, and the ions are heated. It is also advantageous that, in principle, the alpha particle energy could be diverted to other good uses, like providing the current necessary for steady state operation. If these mechanisms can be implemented, they would impact significantly the cost of electricity by tokamak fusion [3].

In mirror geometry, the open geometry makes the mirror machine an advantageous geometry for similar alpha chaneling effects. Although both mirrors and tokamaks are devices with a symmetry direction, so that the diffusion paths can be written similarly, the most successful alpha channeling effects in a mirror machine will exploit key differences between a tokamak and a mirror. The periphery of the tokamak is defined very differently from that of a mirror machine, since as a closed field device, the periphery in a tokamak is past the last closed magnetic surface, particles get out of the device by diffusing across magnetic field lines. 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. In the following, we will assume for simplicity the “simple mirror", although the ideas will pertain to other mirror-type open-ended configurations as well.

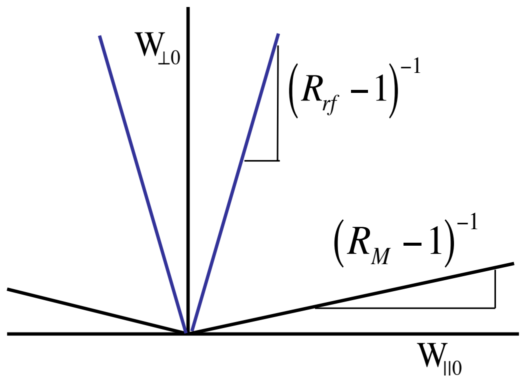

Figure 1: Mirror-trapping and rf-diffusion

Thus, to accomplish the alpha channeling effect in mirror geometry, suppose that mirror-trapped ions or alpha particles are wave-heated at axial position $z = z_{rf}$, where z is the axial direction along the mirror. The trapped particles can be described by their perpendicular and parallel energies, $W_{\perp 0} \equiv W_{\perp}(z=0)$ and $W_{\|0} \equiv W_{\|}(z=0)$, as they cross the mirror midplane at $z = 0$. The particles affected by the rf waves lie between the rays shown in Fig. 1. The lower ray represents the trapped-untrapped boundary for mirror ratio $R_M \equiv B_{max}/B_0$, where B_0 is the magnetic field minimum at the midplane and B_{max} is magnetic field maximum. The upper ray represents the boundary for particles reaching the region of rf power at $z = z_{rf}$, where the magnetic field is B_{rf}, with $B_0 < B_{rf} < B_{max}$. The upper ray is determined by the mirror ratio $R_{rf} \equiv B_{rf}/B_0$. Particles with higher perpendicular enery than the upper ray are mirror-reflected before reaching the region of rf, whereas particles with a lower perpendicular energy than the lower ray are not mirror-confined at all.

Upon interaction with the rf field at $z = z_{rf}$, the perpendicular energy $W_{\perp}(z_{rf})$ of the particle at $z = z_{rf}$ changes so that $W_{\perp}(z_{rf}) \to W_{\perp}(z_{rf}) + \Delta W_{\perp}$. The parallel energy similarly changes by $W_{\|}(z_{rf}) \to W_{\|}(z_{rf}) + \Delta W_{\|}$. Since the wave-particle interaction is a stochastic process, the velocity increments $\Delta W_{\perp}$ and $\Delta W_{\|}$ can be positive or negative, but they are related to each other through the diffusion path. For interaction by means of the resonance $\omega - k_{\|} v_{\|} = n\Omega$, the diffusion path obeys $\Delta W_{\perp} = \Delta W_{\|} n\Omega/(\omega - n\Omega)$. Here ω is the wave frequency, Ω is the cyclotron frequency, $k_{\|}$ is the wave parallel wavenumber, n is the harmonic of the resonance, and $v_{\|}$ is the wave parallel velocity, all measured at $z = z_{rf}$. For example, for Landau damping, we have $n = 0$, with $\Delta W_{\perp} = 0$, so that the diffusion occurs in the parallel direction only.

Ignoring for simplicity the plasma potential, but assuming adiabatic invariance of the magnetic moment, the energy kicks $\Delta W_{\perp}$ and $\Delta W_{\|}$ at $z = z_{rf}$ result in the midplane change

$$W_{\perp 0} \rightarrow W_{\perp 0} + \Delta W_{\perp}/R_{rf}, \tag{1}$$

$$W_{\| 0} \rightarrow W_{\| 0} + \Delta W_{\|} + \Delta W_{\perp}\left(1 - R_{rf}^{-1}\right). \tag{2}$$

Note that all of the parallel energy kick in the rf region is recovered in the parallel energy at the midplane, but, since $R_{rf} > 1$, not all of the perpendicular energy kick in the rf region is recovered in the perpendicular energy at the midplane, with some of that energy recovered as parallel energy at the midplane position.

For the more general resonance condition, $n \neq 0$, there are greater flexibilities in achieving the alpha channeling effect. However, for simplicity, we consider the case of perpendicular diffusion only, or $\Delta W_{\|} = 0$, which is realizable through $k_{\|} \rightarrow 0$. We show here that this important and simple limit offers sufficient flexibility to realize the alpha channeling effect with high efficiency. The channeling effect requires two conditions: First, the diffusion paths must connect high-energy particles in the interior with low-energy particles in the periphery of a confinement device, where the periphery is defined as a point of marginal confinement and the interior is defined as a point where particles are well-confined. In a mirror trap, one periphery would be the trapped-passing boundary. Second, the diffusion to high energy must be limited. We will show that both of these conditions can be satisfied in a mirror geometry.

First, note that from Eqs. (1) and (2), for $\Delta W_{\|} = 0$, the slope of the energy change in midplane coordinates, $\Delta W_{\perp 0}/\Delta W_{\| 0} = (R_{rf} - 1)^{-1}$, which is the same slope as the rf interaction boundary. This means that particles diffuse in energy due to the rf power parallel to the boundary. However, only particles resonant with the wave are affected. The resonance condition, $\omega - k_{\|} v_{\|} = n\Omega$, selects a parallel energy $W_{\| res}$ at $z = z_{rf}$, which is a function of the local wave and magnetic field parameters. The resonant region in midplane coordinates then obeys

$$W_{\perp 0} = \left(W_{\| 0} - W_{\| res}\right)/\left(R_{rf} - 1\right). \tag{3}$$

Thus, particles kicked by the rf wave at $z = z_{rf}$ diffuse along the trajectory indicated by Eq.(3). Since the slope of the diffusion path is the same as the slope of the resonance condition, particles remain in resonance as they are diffused.

By picking $W_{\|res}$ small, the energy lost at the boundary can be made small. Since particles diffusing to high energies are not lost, through coupled spatial diffusion they can be arranged to be limited by a maximum energy as in tokamaks [1]. However, the particles affected are only those in resonance, namely only those diffusing along the trajectory indicated by Eq.(3). At first glance, it appears that to affect a range of resonant parallel energies a large range of $W_{\|res}$ will be required, which would mean that the amount of energy lost at the trapped-passing boundary becomes large. However, interestingly, it is possible to access the full range of trapped particles by arranging for several regions of rf, but with a limited range of $W_{\|res}$. As shown in Fig. 2, this gives the optimum diffusion paths. In Fig. 2, we show two diffusion paths (dashed lines) due to two regions of rf, one at $z = z_{rf1}$ corresponding to the mirror ratio R_{rf1}, and one at $z = z_{rf2}$ corresponding to the mirror ratio R_{rf2}. Note that each diffusion path is parallel to its own corresponding trapped-passing boundary. Also note that although particles resonant at $z = z_{rf1}$ diffuse into the rf region $z = z_{rf2}$ before becoming untrapped, when they are in the rf region at $z = z_{rf2}$, their parallel velocity is not resonant with the rf waves at $z = z_{rf2}$. Thus, each set of resonant particles maintains the diffusion path set by one rf region. The resonance conditions are arranged at each axial location to correspond to the same relatively low parallel energy $W_{\|res}$. To the extent that $W_{\|res}$ is small, the diffusion paths become normal to constant energy surfaces, resulting in the most efficient cooling, since all particles cross the trapped-passing boundary (lowest solid line) at low energy. This arrangement of waves can be used both to tap alpha particle energy and to heat and trap fuel ions, thus facilitating mirror concepts relying on hot ions to achieve high-Q [4] or relying on disparate ion temperatures to minimize neutron production [5].

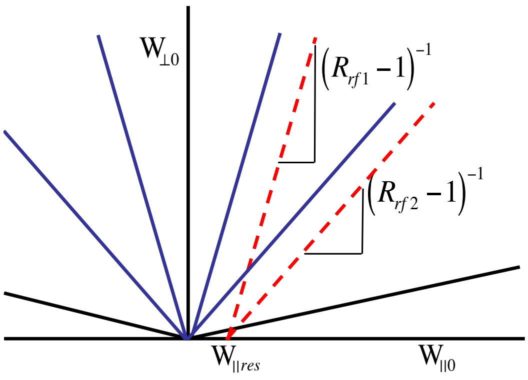

Figure 2: Diffusion paths

This work was supported by DOE contract DE-AC0276-CHO3073.

References

[1] N. J. Fisch and J. M. Rax, Phys. Rev. Lett. **69**, 612 (1992).

[2] N. J. Fisch and M. C. Herrmann, Nuclear Fusion **34**, 1541 (1994).

[3] G. A. Emmert, L. A. ElGuebaly, G. L. Kulcinski et al., Fusion Tech. **26**, 1158 (1994).

[4] R. F. Post, T. K. Fowler, J. Killeen and A. A. Mirin, Phys. Rev. Lett. **31**, 280 (1973).

[5] D. D. Ryutov, *D-3He Mirror Reactors*, Proc. 2nd Wisconsin Symp. Helium-3 and Fusion Power (WCSAR-TR-AR-9307-3), J. F. Santarius, compiler), p. 121 (1993).