Simulation of Alpha Particles in Rotating Plasma Interacting With a Stationary Ripple

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***Abstract*—Superthermal $\boldsymbol{E} \times \boldsymbol{B}$ rotation can provide magnetohydrodynamic stability and enhanced confinement to axisymmetric mirrors. However, the rotation speed has been limited by phenomena at end electrodes. A new prediction is that rotation might instead be produced using a magnetic ripple and alpha particle kinetic energy, in an extension of the alpha channeling concept. The interaction of alpha particles with the ripple results in visually interesting and practically useful orbits.**

***Index Terms*—Magnetic confinement, plasma devices, plasma simulation, plasma waves.**

AXISYMMETRIC mirrors have many potential advantages as fusion reactors including high beta, steady-state operation, and a simple coil configuration [1]. The major issues that must be overcome by axisymmetric mirrors are magnetohydrodynamic (MHD) stability and excessive parallel energy loss. Both of these may be addressed by inducing superthermal $\boldsymbol{E} \times \boldsymbol{B}$ rotation, which provides MHD stability through velocity shear and increases axial confinement by the centrifugal force [2]–[4]. In past experiments, the rotation has been produced by electrodes in the mirror throat, and these electrodes limited the rotation speed to the Alfven critical ionization velocity (CIV) [2], [5], [6]. However, rotation might best be produced by waves rather than electrodes, allowing the CIV limit to be overcome [7].

The method of driving rotation with waves is an extension of the alpha channeling effect in tokamaks [8]. In alpha channeling, waves are injected which create a diffusion path connecting the hot core of the plasma to the cold edge. That is, there is coupled diffusion in energy and position. As alpha particles interact with the wave, they diffuse radially and may eventually exit at the outer edge. Because the radial diffusion is related to diffusion in energy by the wave properties, alpha particles can be made to exit at low energy, transferring their energy to the wave. The wave energy can then be used for heating ions or other purposes [9].

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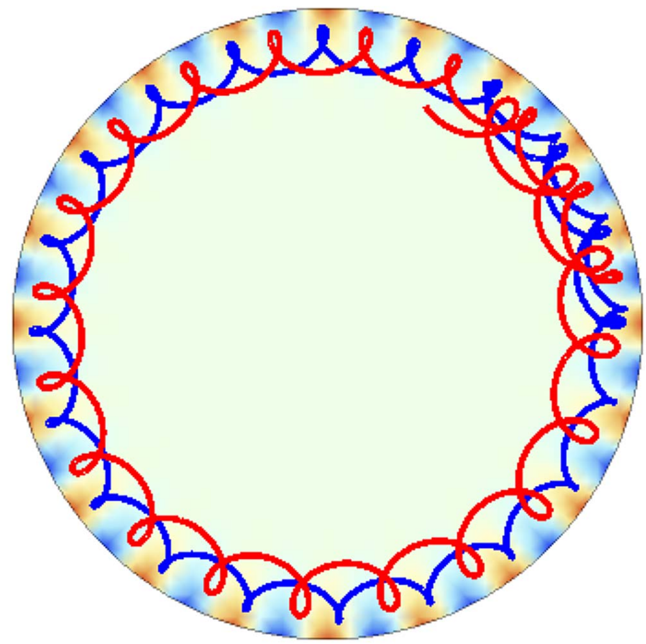

Fig. 1. Data from Fig. 2 projected into two dimensions. Particles start at the right side and move counterclockwise.

In a rotating plasma, there is a change in potential energy due to the change in radius [7]. It is therefore possible to convert the kinetic energy of alpha particles directly to potential energy. As the particles move outward, they reduce their perpendicular kinetic energy and move toward the loss cone. One can think of the wave as leading to nonambipolar diffusion of alpha particles, producing a radial current that maintains the rotation.

A wave that converts all kinetic energy into potential energy is a stationary magnetic ripple in the lab frame (a wave with $\omega = 0$) [10]. Because the ripple has no energy, it is simple to produce and maintain. In order to be resonant with alpha particles in the rotating frame, the wave must satisfy $\omega - k_{\|v\|} - m\Omega = \Omega_i$, where $k_\|$ is the parallel wavenumber, $v_\|$ is the particle parallel velocity, m is the azimuthal mode number, Ω is the rotation frequency, and Ω_i is the cyclotron frequency. For practical plasma parameters, this implies that high mode number ($|m| > 20$) waves must be used.

Figs. 2 and 1 demonstrate that these waves effectively lead to diffusion in potential and kinetic energies. Although high-m modes would decay like $r^{|\mathrm{m}|}$ in a vacuum, the decay is limited in the presence of a plasma. We use the cold plasma dispersion relation with 50/50 Deuterium–Tritium mix to determine the plasma response to the magnetic ripple (orange/cyan shading in

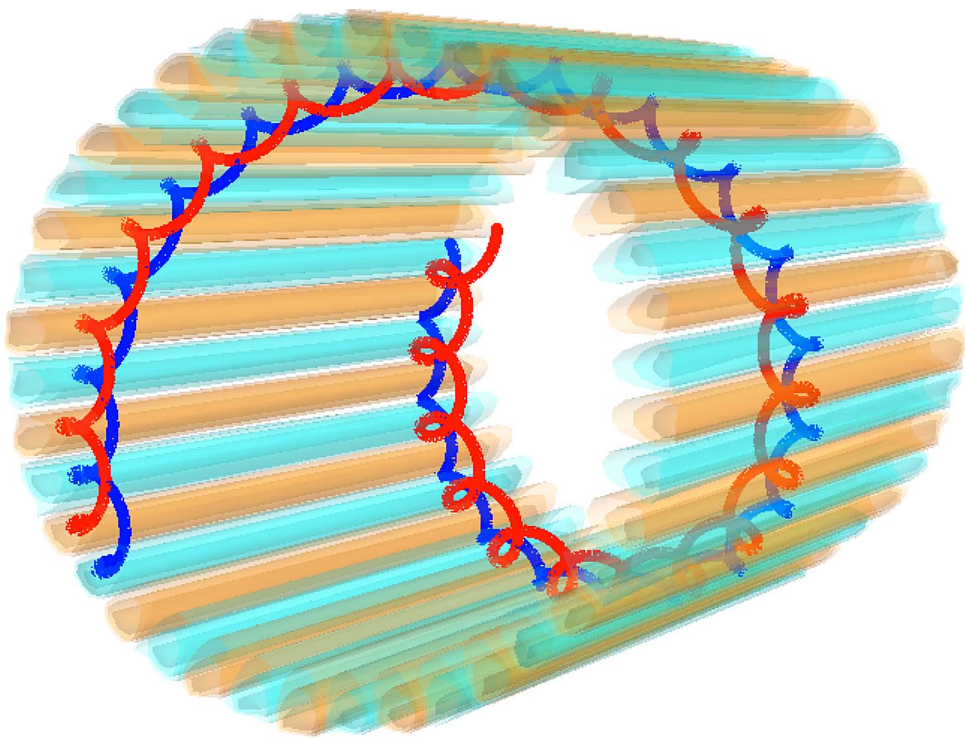

Fig. 2. Simulation of alpha particles in plasma, interacting with a stationary ripple. Orange/cyan shading indicates the magnitude of the ripple field, and the red and blue lines indicate the paths of alpha particles. The image at the left shows a 3-D view, with particles starting at the bottom left.

Fig. 2). The simulated magnetic field is 2 T, the plasma density is 7×10^{12} cm^{-3}, the rotation frequency is 5×10^6/s, and the plasma radius is 1.5 m. The ripple magnitude is 0.1 T, and $m = -20$. We then simulated the equations of motion of alpha particles in a rotating plasma moving through this ripple region (red and blue lines in Figs. 2 and 1).

The result is the inward drift and heating of one particle (red) and outward drift and cooling of another (blue). Particles that cool can be lost, but the heated particles are better trapped by mirror fields. Thus, after many interactions, there is a net cooling and outward diffusion of alpha particles. As they diffuse outward, the alpha particles transfer their energy to the potential. This maintains the plasma rotation. In fact, sufficient energy can be recovered to eliminate electrodes in a fusion plasma [10].

In conclusion, we have simulated alpha particles' equations of motion to demonstrate the coupled diffusion in kinetic and potential energies in a rotating plasma caused by introducing a high-m magnetic ripple. This could be used to produce rotation rather than relying on end electrodes, allowing higher rotation speeds and increased efficiency.

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