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One-way ponderomotive barrier in a uniform magnetic field

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The possibility of an asymmetric ponderomotive barrier in a nonuniform dc magnetic field by high-frequency radiation near the cyclotron resonance for selected plasma species was contemplated in [Phys. Plasmas **11**, 5046 (2004)]. Here we show that a similar one-way barrier, which reflects particles incident from one side while transmitting those incident from the opposite side, can be produced also in a uniform magnetic field, entirely due to inhomogeneity of high-frequency drive.

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In Refs. [1, 2], it was shown how an asymmetric barrier can be produced, for selected plasma constituents, by high-frequency (HF) radiation near the cyclotron resonance in an inhomogeneous dc magnetic field. The basic idea can be explained as follows. Under intense HF drive, a charged particle undergoes fast oscillations superimposed on the average drift motion. If the particle drift displacement on a period of these oscillations is sufficiently small, the average effect of the HF drive can approximately be replaced by particle interaction with an effective potential $\Phi(\mathbf{r})$ [3–5]. In the presence of a dc magnetic field $\mathbf{B}_0 = \mathbf{z}^0 B_0$, the quasi-potential $\Phi(z)$, which governs the particle drift along $\mathbf{B}_0$, is inversely proportional to $\Delta\omega = \omega - \Omega$, where ω is the frequency of the HF field, and $\Omega(z)$ is the local gyrofrequency. At the cyclotron resonance where $\Delta\omega(z_0) = 0$, $\Phi(z)$ experiences a singularity and changes sign. Hence, the average ponderomotive force on a particle, $F_z = -\Phi'(z)$, is repulsive at $\Omega(z) < \omega$ but attractive at $\Omega(z) > \omega$, and can reflect particles traveling in one direction while transmitting those traveling in the other direction. Putting aside the unavoidable resonant heating of transiting particles, such a barrier acts essentially like a Maxwell demon and can be employed in various applications, including selective separation of plasma species [6–9], confinement of one-component plasmas, enhancement of multiple-mirror plasma confinement [4, 10], and current drive [1, 2, 11, 12]. In particular, it was shown [1, 2] that the efficiency of driving currents in this manner could exceed the efficiencies of the leading current drive techniques [13], at least in principle.

The practical applications of the "Maxwell demon effect" (MDE) in a real plasma are limited though by the requirements imposed on suitable configurations of HF and dc fields [2]. In particular, collective plasma response impedes a maximum of HF electric field in the vicinity of the resonance. The purpose of this paper is to propose a novel scheme, in which this problem is eliminated by circumventing the requirement of the cyclotron resonance inside the interaction region. Namely, we show that MDE can rely entirely on the HF field inhomogeneity, and thus can be produced in a uniform (or quasi-uniform) magnetic field sufficiently far from the cyclotron resonance.

To show the effect, consider a particle driven by an intense HF field $\mathbf{E} = \mathrm{Re}\,\mathbf{E}_c$, $\mathbf{E}_c = \mathbf{E}_0 \exp(-i\omega t)$, assuming that the characteristic scale L of $\mathbf{E}_0(\mathbf{r})$ is large compared to the amplitude of the particle quiver motion. In this case, the average force on the particle can be approximately represented as $\mathbf{F} = -\nabla\Phi$, where the ponderomotive potential Φ is given by

$$\Phi = -\frac{1}{4}\left(\mathbf{E}_0^* \cdot \boldsymbol{\alpha} \cdot \mathbf{E}_0\right). \tag{1}$$

Here $\boldsymbol{\alpha}(\omega)$ is the polarizability tensor of the particle, and thus Φ is essentially the interaction energy of an oscillating dipole with a moment $\mathbf{d} = \mathrm{Re}\,[\boldsymbol{\alpha}\mathbf{E}_c]$ in the field $\mathbf{E}$. (We assume no energy dissipation as the particle oscillates in the HF field, so that $\boldsymbol{\alpha}$ is Hermitian.)

Eq. (1) can also be represented in an equivalent form

$$\Phi = \frac{e^2}{4m\omega^2}\sum_\nu \lambda_\nu |E_\nu|^2, \tag{2}$$

where e and m are, respectively, the charge and the mass of the particle; λ_ν are the eigenvalues of a dimensionless tensor $\mathsf{T} = -(m\omega^2/e^2)\boldsymbol{\alpha}$ corresponding to the eigenvectors $\boldsymbol{\tau}_\nu$, and $E_\nu = \mathbf{E}_0 \cdot \boldsymbol{\tau}_\nu^*$. For an elementary particle in vacuum, T is a unit tensor, and Eq. (2) yields the well known expression $\Phi = \Phi_{\mathrm{v}} \equiv (e^2/4m\omega^2)|E_0|^2$. However, in the presence of a dc magnetic field $\mathbf{B}_0 = \mathbf{z}^0 B_0$, the particle polarizability is modified, so that T can now be expressed as

$$\mathsf{T} = \begin{pmatrix} \frac{1}{1-b^2} & \frac{ib}{1-b^2} & 0 \\ \frac{-ib}{1-b^2} & \frac{1}{1-b^2} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{3}$$

where $b = \Omega/\omega$ and $\Omega = eB_0/mc$, and thus

$$\begin{aligned} &\boldsymbol{\tau}_{\pm 1} = (\mathbf{x}^0 \pm i\mathbf{y}^0)/\sqrt{2}, \qquad && \lambda_{\pm 1} = (1 \pm \Omega/\omega)^{-1}, \\ &\boldsymbol{\tau}_0 = \mathbf{z}^0, && \lambda_0 = 1. \end{aligned} \tag{4}$$

Note that for a wave with resonant circular polarization $\nu = -1$ (we assume $b > 0$), the magnitude of Φ increases in comparison with the vacuum case: $\Phi \sim \lambda\Phi_{\mathrm{v}}$, where the enhancement factor $\lambda \equiv \lambda_{-1}$ grows infinitely as the cyclotron resonance is approached. A large magnitude of the resonant ponderomotive potential renders a convenient tool for plasma confinement, employed, for instance, in magnetic mirror devices [4, 14–19]. On the

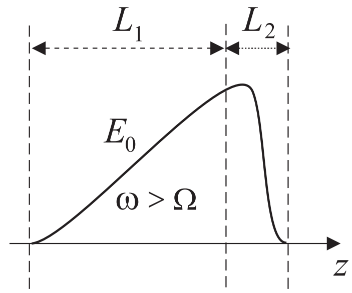

FIG. 1: HF field profile providing MDE in a uniform dc magnetic field: $L_1 \gg \Delta l \gg L_2$.

other hand, the same effect can be used for producing an asymmetric ponderomotive barrier, if the HF field is supplied with an appropriate spatial profile.

The effect can be explained as follows. The average ponderomotive force is proportional to the amplitude of the particle oscillation at the frequency equal or close to ω. Then, to "see" the potential Φ, the particle must have energy $\mathcal{E} \sim \lambda^2 \Phi_{\rm v}$, which is $\lambda \gg 1$ times *larger* than the height of the potential:

$$\mathcal{E} \sim \lambda\Phi \gg \Phi. \tag{5}$$

For a particle with kinetic energy less than Φ, to cross the barrier will require receiving the energy (5) from the HF field, for which process the characteristic time scale is $\Delta t \sim \lambda/\omega$. If, in a uniform dc magnetic field, the HF field region has a width $L \gg \Delta l$, $\Delta l = (\langle v_z \rangle/\omega)\lambda$, and the particle longitudinal (drift) and transverse (quiver) energies are less than or comparable with the height of the barrier $\Phi_{\rm max} > 0$, the particle will be reflected by the barrier, as if $\Phi(\mathbf{r})$ were a true potential. On the contrary, if $L \lesssim \Delta l$, the same particle will be transmitted, as its oscillatory motion will have no time to build up, and hence the repulsive ponderomotive force will have no time to establish.

Consider now a ponderomotive barrier in a plasma with temperature $T \lesssim \Phi_{\rm max}$, with HF field having a profile depicted in Fig. 1. Suppose that the left slope of the field has a scale L_1, which is large compared to the characteristic value of Δl for thermal particles. The barrier will then reflect particles incident from the left, preserving both their longitudinal and transverse energies. Suppose now that the right slope has the scale $L_2 \ll \Delta l$, so that each particle incident from the right is transmitted through the thin region of repulsive force without substantial energy change. After that, a particle finds itself on the top of the potential hill, from which it further slides off adiabatically, so that the resulting longitudinal and transverse energy changes are given by

$$\Delta\mathcal{E}_{||} = \Phi_{\rm max}, \qquad \Delta\mathcal{E}_{\perp} = \lambda\Phi_{\rm max}. \tag{6}$$

It is then clear that a ponderomotive barrier of a kind shown in Fig. 1 is asymmetric and acts essentially like a Maxwell demon, except that it increases the energy of transiting particles, as required by laws of thermodynamics. If employed for driving a current, such a current source would exhibit the efficiency close that by barriers in nonuniform magnetic field [1]. Contrary to those [2], however, the ratio $\Delta\mathcal{E}_{\perp}/\Delta\mathcal{E}_{||}$ is fixed in this case, and thus particle transverse heating cannot be reduced in comparison with longitudinal acceleration. Nevertheless, practicing MDE in a uniform magnetic field could be favorable over previously proposed techniques, as it does not require precise cyclotron resonance at the maximum HF electric field, and hence is more accessible technologically.

It is important to emphasize also that the contemplated effect is robust and can be achieved at finite ratio $L_2/\Delta l$ as well. The results of our numerical calculations (Fig. 2) for

$$\mathbf{B}_0(z) = \mathbf{z}^0 \left(1 - \frac{1}{\lambda}\right), \tag{7a}$$

$$\mathbf{E}_0(z) = \mathbf{x}^0 \, \frac{a}{2} \, \exp\left(-\frac{z^2}{L_1^2}\right) \left[1 - \tanh\left(\frac{z}{L_2}\right)\right] \tag{7b}$$

(field amplitudes are measured in units $m\omega c/e$), indicate that the effect persists up to $L_2/\Delta l \sim 1$, whereas at $L_2/\Delta l \gtrsim 1$ the barrier loses the asymmetry. Asymptotic values at $L_2/\Delta l \ll 1$ have also been checked numerically and have been found in agreement with our analytic predictions (6).

In summary, we showed that an asymmetric ponderomotive barrier can be produced by HF radiation near the cyclotron resonance for selected plasma constituents in a uniform dc magnetic field. Such a barrier can operate somewhat like a Maxwell demon, which reflects particles incident from one side while transmitting those incident from the opposite side. Unlike the methods contemplated in Refs. [1, 2] for the case of essentially nonuniform magnetic field, the proposed technique is technologically more accessible, as it does not require precise cyclotron resonance at the maximum HF electric field.

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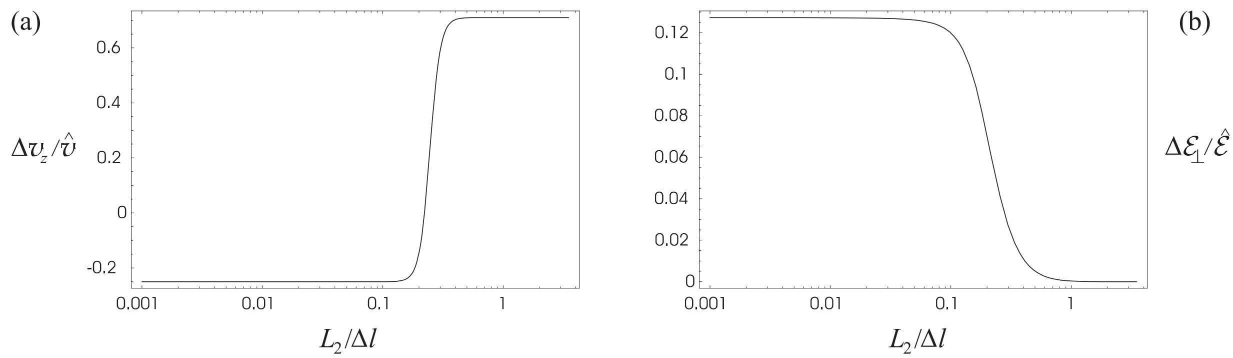

FIG. 2: Numerically calculated longitudinal velocity change Δv_z and transverse energy gain $\Delta\mathcal{E}_\perp$ (both interpolated) vs L_2 for a particle after scattering off a barrier depicted in Fig. 1 with $\mathbf{B}_0$ and $\mathbf{E}_0$ given by Eqs. (7). The particle initial velocity is $v_{z,0} = -\frac{1}{2\sqrt{2}}\,\hat{v}$; $\hat{v} = (eE_{\max}/m\omega)\sqrt{\lambda} \sim (\Phi_{\max}/m)^{1/2}$; $\hat{\mathcal{E}} = m\hat{v}^2 \sim \lambda\Phi_{\max}$; $\lambda = 100$. To compare, analytic predictions according to Eq. (6) for $L_2/\Delta l = 0$ and $L_2/\Delta l = \infty$ yield respectively: $\Delta v_z/\hat{v} \approx -0.26, 0.71$, $\Delta\mathcal{E}_\perp/\hat{\mathcal{E}} \approx 0.125, 0$. Particles incident with the same $|v_{z,0}|$ but from the left are reflected adiabatically.

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