ON SOME FEATURES OF THE BEHAVIOR OF A ROTATING PLASMA IN A TRAP WITH MAGNETIC MIRRORS

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Abstract

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V. I. VOLOSOV, V. E. PALCHIKOV, F. A. TSELNIK

ON SOME FEATURES OF THE BEHAVIOR OF A ROTATING PLASMA IN A TRAP WITH MAGNETIC MIRRORS

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It is known ([2,3]) that anisotropy of the ion distribution function in velocity space, unavoidable in a trap with magnetic mirrors, leads to the development of an instability that substantially limits the density of a plasma confined for a long time. On the other hand, it was shown already in ([1]) that the introduction into a trap with a mirror configuration of an additional radial electric field E reduces the anisotropy $f_0(v_\parallel, v_\perp)$.

Indeed, in the presence of a radial E that varies slowly in space, the adiabatic invariant is, as is not difficult to show, the quantity

$$\mu^* = r_0^2 \omega_H \sqrt{1+\alpha^2}, \tag{1}$$

where $\alpha^2 = 4eE/m\omega_H^2 r_0$; ω_H is the Larmor frequency, and r_0 is the initial radius of the particle. The magnetic field has axial symmetry.

Combining the indicated expression for the adiabatic invariant with the equations expressing the laws of conservation of energy and angular momentum, it is easy to obtain the equation for the boundary of the region of particle confinement in velocity space. For a sufficiently dense plasma (the electric potential is constant along a magnetic-field line), and assuming that the Larmor radius of a particle is small in comparison with r_0 (of the same order of magnitude as the transverse size of the plasma), this equation has the form:

$$v_\parallel^2 - (R-1)(v_\perp - v_g)^2 = \frac{R-1}{R} v_g^2, \tag{2}$$

where R is the mirror ratio, and $v_g = cE/H$ is the drift velocity of the particle.

The region of particle confinement is therefore bounded by a hyperbola whose axis is displaced by the amount v_g. Thus a mirror machine with a radial electric field represents an ideal trap for charged particles: if the initial kinetic energy is less than a certain value, then the particle is confined independently of the direction of the velocity and of the sign of the charge.

The development of an instability associated with anisotropy of the distribution function is possible because of the presence of "wings" of the confinement region with inverse population ($\partial f_0/\partial v_\perp^2 > 0$). We shall show, however, that the presence of a radial E leads to stabilization of the indicated instability in a certain range of plasma parameters. We restrict ourselves to the simplest case of a homogeneous (in space) plasma. In this case the dispersion equation has the form (for the notation and the conditions under which this equation is obtained, see (^{2})):

$$-\frac{\omega_{pe}^2}{\omega_{He}^2}+1=\frac{\omega_{pe}^2}{\omega^2}\frac{k_\parallel^2}{k^2}+\frac{\omega_{pi}^2}{k^2v^2}\left[F\left(\frac{\omega}{kv}\right)+\varphi(0)\right], \tag{3}$$

$$F(y)=-2\int_0^\infty dx\,\frac{\partial\psi}{\partial x}\,\frac{1}{\sqrt{1-x/y^2}}.$$

Let us choose, analogously to (2), a model of the initial distribution function in such a way that it vanishes at the boundary of the confinement region (at the same time omitting terms, insignificant in the present case, associated with the joint rotation of electrons and ions):

$$f_0(v_\parallel,v_\perp)=\left[\frac{R-1}{R}v_\varphi^2+(R-1)v_\perp^2-v_\parallel^2\right]^{1/2}e^{-{v_\perp}^2/\bar{v}^2}, \tag{4}$$

where $\bar{v}$ is the mean thermal velocity of the ions. The integral entering into (3) is equal to

$$\gamma F(y)=-2y^2+y(2\lambda^2-1+2y^2)Z(-y), \tag{5}$$

where $\lambda=\frac{1}{R}\frac{v_\varphi^2}{\bar{v}^2}$; γ is a positive constant factor; $Z(y)$ is the so-called plasma dispersion function [4]. Unstable states of the plasma correspond to those values of y for which $\operatorname{Im}F(y)<0$. Since $y=y_r-i\varepsilon$ ($y_r>0$, $\varepsilon>0$), we have $\operatorname{Im}Z(-y)>0$, $\operatorname{Re}Z(-y)<0$, and from (5) we obtain:

$$\gamma\operatorname{Im}F(y)=4\varepsilon y_r+y_r[2\lambda^2-1+2(y_r^2-3\varepsilon^2)](\operatorname{Im}Z(-y))+\varepsilon[2\lambda^2-1+2(3y_r^2-\varepsilon^2)]|\operatorname{Re}Z(-y)|. \tag{6}$$

For small ε, $\operatorname{Im}F(y)>0$ if $\lambda^2>1/2$, which is the condition for stabilization in view of the convective character of the instability. The specific form of this condition depends, of course, on the choice of the initial distribution function. For sufficiently large λ (in any case, one must have $\lambda>1$) the anisotropy of the distribution function disappears altogether, i.e., the quantity

$$\frac{\partial}{\partial v_\perp^2} \int f_0 \, dv_\parallel$$

turns out to be negative for all values of $v_\perp$. Since, on the other hand, one must have $R > 1$, it follows from the condition $\lambda > 1$ that $v_\varphi^2/\bar{v}^2 > 1$. The latter condition imposes a restriction on the choice of the method of creating the plasma. For example, in order to guarantee the absence of anisotropic instability, it is necessary to abandon methods of plasma creation in which the particles are born in the trap with zero initial velocity. The plasma must be introduced adiabatically from outside. If, however, from an analysis of the other branches of anisotropic instability it turns out that stabilization can be achieved for $\lambda < 1$, then for $R > 1$ it will be possible to create plasma directly in the volume of the trap.

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Note: Figure translations are in progress. See original paper for figures.

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