Transverse particle losses in an ambipolar plasma trap

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It is shown that the absence of axial symmetry of the magnetic field in an ambipolar trap leads to an appreciable growth of the transverse losses in comparison with the classical ones.

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An essential difficulty hindering the use of classical open traps[1] to obtain controlled thermonuclear fusion is, as is well known, the fact that the lifetime τ of the plasma in these traps does not exceed the time τ_i of the ion scattering by Coulomb collisions (see[2]). To overcome this difficulty, a new variant of an open trap was recently proposed, which differs from the foregoing in that to each end of an ordinary mirror trap is connected one more mirror trap with plasma of relatively high density (higher by approximately one order of magnitude than in the central mirror trap). With such a plasma density distribution, the ambipolar potential that maintains the density of the electrons equal to the density of the ions will be so distributed that a deep potential well is produced for the ions of the central mirror trap and prevents them from escaping along the magnetic field, and the lifetime of these ions becomes much larger than τ_i.

Of course, maintenance of a high plasma density in the external mirror traps calls for a definite energy consumption, but since the length of the central mirror trap can be increased without changing the lengths of the end traps, it is possible to make the energy released in the central mirror trap higher than the losses in the end traps. The corresponding concept was described in[3] (and later in[4]) and is recognized at present to be the only prospect for the development of open traps.

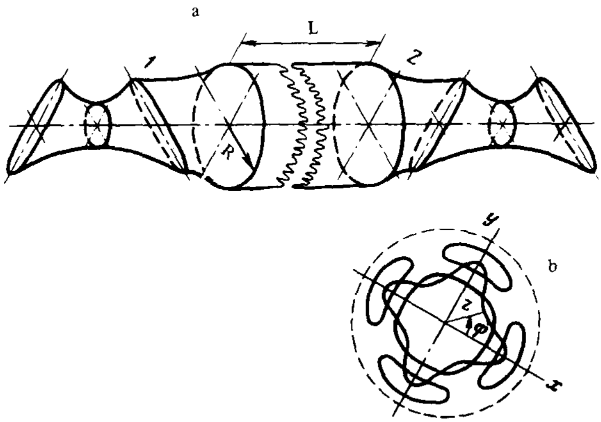

FIG. 1. Ambipolar trap. a) Geometry of magnetic fields: L—length of central part of the trap, R—radius of trap in the central part. b) Intersections of several drift surfaces of the ions with the equatorial plane of the trap; the formation of individual islands ("bananas") is typical of the case $\beta \equiv 8\pi n(T_e + T_i)/H^2 \sim 1$.

It is important that to ensure hydrodynamic stability of the plasma in an ambipolar trap it is proposed to use an axially asymmetrical magnetic field with the magnetic surfaces shown schematically in Fig. 1. In this communication it is shown that the absence of axial symmetry leads, generally speaking, to a strong increase of the transverse plasma losses in comparison with the classical diffusion.

Since the electric and magnetic fields are static, and the Larmor radius ρ_i of the ions is small in comparison with all the characteristic scales of the problem, the total energy ε and magnetic moment $\mu = m_i v^2 \sin^2\theta / 2H$ of the ions are conserved during the course of its motion (m_i and v are the mass and velocity of the ions, θ is the angle between the velocity vector of the particle and the magnetic field, H is the magnetic field intensity), and we can use the drift approximation to describe the motion of the leading center of the particle. In the motion along the long axially symmetrical section of the central mirror traps, the drift is produced, first, as a result of the radial electric field connected with the change of the density along the radius, and second, because of the radial inhomogeneity of the longitudinal magnetic field, due to the finite pressure of the plasma, and leads to rotation of the leading center around the magnetic axis.

We denote by $\Delta\psi$ the change of the polar angle of the leading center of the particle during one flight through the trap (we use a cylindrical coordinate system with a polar axis that coincides with the magnetic axis of the system, see Fig. 1). As will be shown below, the character of the motion of the ions and the rate of radial losses depend substantially on whether $\Delta\psi$ is large or small in comparison with unity.[1)] Let us examine these two possibilities in succession.

1. $\Delta\psi \ll 1$. In this case we have conservation not only of ε and μ, but also of the so called longitudinal adiabatic invariant $I_{\parallel} = \int v \cos\theta ds$, where the integration is along the force line between the particle reflection points (some of the ions are reflected by the magnetic mirrors of the central mirror trap, while the ions with the small values of μ are reflected from the potential barrier in the external mirror traps). The presence of this additional integral means that if the position of the particle and the values of ε and μ are specified at the initial moment, the drift surface is uniquely determined. It is important that the drift surfaces that pass through a certain force line are different for different ε and μ, see Fig. 1 (this effect does not occur for an axially symmetrical trap). Therefore when a particle is scattered at a certain point of space it goes over to a different drift surface, whose maximum distance to the axis can be larger than that of the initial one. Since, generally speaking, τ changes along the drift surface by an amount greatly exceeding ρ_i, the time of escaping of the ions to the wall is small in comparison with the estimate obtained by classical diffusion (thus, if the "spread" of the drift shells is comparable with R, then $\tau \sim \tau_i$). The situation in this sense is analogous with that in the "neoclassical" theory of transport processes in toroidal system (see[5]). In particular, we can separate here the Pfirsch-Schluter regime, the "banana" regime, and the plateau regime. A detailed analysis of these regimes will be presented in a separate paper.

2. $\Delta\psi \gtrsim 1$. In this case the particles execute several revolutions around the magnetic axis as they move from mirror to mirror. This means that $I_{\parallel}$ ceases to be an adiabatic invariant and an important role is acquired by stochastic effects.

Since the number of revolutions depends on ε, μ, and the radius r of the drift surface, the group of particles that occupies a small region of phase space near the mirror 1 (see Fig. 1) becomes smeared out in terms of the aximuthal angle ψ, and as it approaches mirror 2 it is transformed into a cylindrical layer. When reflected from the mirror, the particle does not return to the initial force line, but shifts in azimuth and, more importantly, in radius (the latter takes place only for an axially asymmetrical mirror). We denote by ψ_0 the polar angle of the particle directly prior to the entrance into mirror 2. The radial displacement Δr due to reflection depends on ψ_0, μ, ε, and r. If Δr is large enough, so that $|\Delta r\, \partial\psi/\partial r| \gtrsim 1$, then stochastic diffusion sets in[6], and the radial displacement of the particles can be described by the Fokker-Planck equa-equation for the ion distribution function $f(r, \varepsilon, \theta_0)$

$$\frac{L\, r}{v\,|\cos\theta_0|}\,\frac{\partial f}{\partial t} = -\frac{\partial}{\partial r}\, r f \langle \Delta r \rangle + \frac{1}{2}\,\frac{\partial^2}{\partial r^2}\, r f \langle \Delta r^2 \rangle,$$

where the angle brackets denote averaging over ψ_0, and θ_0 stands for the value of the angle θ in the central part of the trap. It turns out that in the linear approximation in the small parameter ρ_i/R we have $\langle \Delta r \rangle = 0$. On the other hand, the estimate of $\langle \Delta r^2 \rangle$ takes the form $\langle \Delta r^2 \rangle = \rho_i^2 R^2/L_m^2$, where L_m stands for the distance at which the magnetic field is doubled in comparison with the value H in the central region (we assume that the axially symmetrical and axially asymmetrical components of the field vary along z in accordance with the same scale L_m). Accordingly, we have for the ion lifetime

$$\tau \sim R^2 L / \langle \Delta r^2 \rangle\, v_{Ti} \sim L_m^2\, L / \rho_i^2\, v_{Ti}\,.$$

We note that τ does not depend on the collision frequency.

Under conditions when $\Delta\psi \gg 1$, but the inequality $|\Delta r\, \partial\Delta\psi/\partial r| \gtrsim 1$ is not satisfied, an important role is assumed by collisional diffusion of the "resonant" particles, i.e., of the particles for which $l\Delta\psi = k\pi$, $l, k = 1, 2, 3, \ldots$..

A situation is possible when the condition $\Delta\psi \gg 1$ is satisfied for the plasma ions, whereas for the other ions we have $\Delta\psi \ll 1$ (say, for particles with $\theta_0 \approx \pi/2$ we can have $\Delta\psi \gg 1$ and for particles with $\theta_0 \ll 1$ we can have $-\Delta\psi \ll 1$). Then the lifetime is determined by a combination of effects mentioned in items 1 and 2.

It appeared that in principle both effects can be decreased by using magnetic-field profiles (for example, by increasing the length of the mirrors). Of course, these profiles should be compatible with the plasma-stability conditions.

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1) We note that the case $\Delta\psi \gtrsim 1$ is typical precisely of ambipolar traps, in which a long ($L \gg R$) axially symmetric region is present; in the case of a classical probkotron trap with $L \sim R$ we usually have $\Delta\psi \ll 1$.

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