INFLUENCE OF HIGH-FREQUENCY POTENTIAL OF A TOROIDAL ELECTRIC FIELD ON THE TRAPING OF CHARGED PARTICLES IN A CLOSED MAGNETIC TRAP

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Several recent theoretical papers [1 - 3] have been devoted to the influence of a constant longitudinal electric field on the motion of particles and on plasma transport processes in closed magnetic traps. It is also of interest to study the influence of a high-frequency (HF) electric field on the motion of charged particles in magnetic traps, in connection with the possible use of HF electric fields to decrease the neoclassical diffusion of weak-collision plasma [4] and to stabilize the instability [4 - 6]. In the present paper we call attention to the fact that the toroidal inhomogeneity of the longitudinal electric field, possessed by closed traps, can lead in the case of an HF electric field to an increase of the "degree of trapping" of the particles and to a deterioration of their containment.

Let us consider a closed trap with a helical magnetic field and a longitudinal HF electric field $E = E_0(1 - \varepsilon \cos \phi) \sin \omega t$ (E and ω are the amplitude and frequency of the electric field, $\varepsilon = r/R_0$ is the toroidal ratio, R_0 is the major radius of the torus, and ϕ is the polar angle in the meridional section of the torus). Owing to the toroidal inhomogeneity of the electric field, a field gradient is produced along the helical trajectory of the particle. If the particle oscillation amplitude $qE_0/M\omega^2$ is much smaller than the characteristic dimension of the variation of the electric field along the trajectory, then the particle is acted upon by an additional force $\vec{F} = -\nabla U$, connected with the high-frequency potential $U = q^2E^2/4M\omega^2$ [7] (q and M are the charge and mass of the particle). In the case of an axially symmetrical magnetic poloidal field $\vec{F} = (q^2E_0^2\iota\varepsilon \sin \phi/4\pi M\omega^2 R)\vec{\ell}$ (ι - angle of rotational transformation of the magnetic force lines, $\vec{\ell}$ - unit vector along the trajectory). When $\omega \ll \omega_H = qB/cM$, the magnetic moment of the particle is an adiabatic invariant and the condition for the trapping of the particles is given by

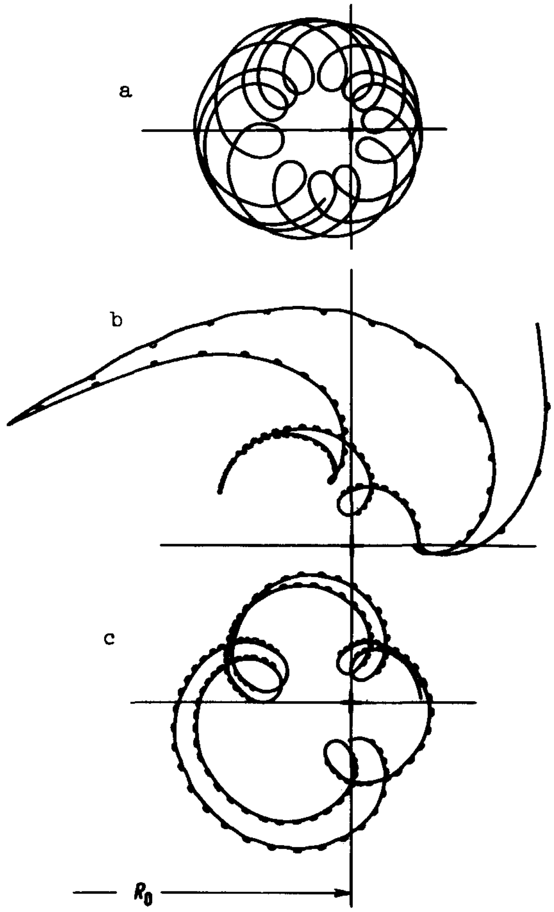
$$\frac{M}{2}\left(\bar{V}_1^2 - \frac{B_2}{B_1}\bar{V}_{\perp 1}^2\right) < \frac{q^2(\hat{E}_1^2 - \hat{E}_2^2)}{4M\omega^2} \qquad (1)$$

where $\hat{E}$ is the projection of the electric field intensity on the particle trajectory, B is the magnetic field intensity, $\bar{V} = (\bar{V}_\parallel^2 + \bar{V}_\perp^2)^{1/2}$ is the total particle velocity averaged over the HF oscillations, and the indices 1 and 2 correspond to the values of the quantities in the initial position of the particle and at the reflection point. From the condition (1) we can obtain an expression for the boundary separating the regions of the trapped and untrapped particles

$$\frac{\bar{V}_\parallel}{\bar{V}_\perp} = \left[2\varepsilon\left(1 + \frac{\tilde{V}^2}{\bar{V}_\perp^2}\right)\right]^{1/2}, \qquad (2)$$

where $\tilde{V} = qE_0/\omega M$ is the amplitude of the oscillatory velocity. We note that when the magnetic moment is conserved the value of $\bar{V}_\perp$ is close to the transverse velocity $V_\perp$ in the absence of the HF field, and consequently when $\tilde{V} \sim \bar{V}_\perp$ the region of the trapped particle in velocity space broadens greatly compared with the case without the HF field.

The foregoing considerations are confirmed by a numerical calculation of the particle trajectories in a double-entry circular stellarator, the parameters of which correspond to the RT-2 stellarator [8]. The equations of motion of the particle were integrated in the drift approximation. We considered the motion of the protons whose Larmor radius, determined from the total initial velocity, was 0.031 (the unit of length was the maximum separatrix radius, equal to 4.7 cm). The initial positions of the particle were chosen at the points of minimum magnetic field. The toroidal HF electric field, having a single component parallel to the magnetic axis, was specified in the form $E = E_0(1 - \varepsilon \cos \phi)\sin(\omega t + \phi)$. The chosen frequency of variation of the electric field $\omega = 1.26 \times 10^7$ rad/sec satisfied the inequality $\omega_b \ll \omega \ll \omega_H$, where ω_b is the frequency of passage of the particle through the periods of the poloidal magnetic field. We assumed in the calculation three values of E_0, corresponding to $\tilde{V}/V_0$ = 0.065, 0.26, and 0.65. The range of initial values of $V_\parallel/V_\perp$ was chosen such as to encompass at $E_0 = 0$ all the groups of particles having different forms of trajectories, namely the untrapped particles and the particles trapped in the mirrors of the toroidal and poloidal magnetic fields.



Projections of the trajectories of particles with initial values $V_\perp/V_0 = 0.9$ on the meridional plane. a - Trajectory of untrapped particle in the absence of the HF electric field; b - trajectory of particle in the absence of a toroidal HF electric field, $\tilde{V}/V_0 = 0.65$. The small-scale structure is connected with the drift in the crossed fields E and B; c - particle trajectory obtained without allowance for the toroidal character of the electric field, $\tilde{V}/V_0 = 0.65$.

The results of the calculations at $E_0 = 0$ show that the boundary of the trapping of the particles is determined by the toroidal inhomogeneity of the magnetic field, and consequently the results presented below are applicable to the case of an axially symmetrical poloidal field, for which expression (2) was obtained. The influence of the HF potential on the trajectory was very weak when $\tilde{V}/V_0 = 0.065$. At $\tilde{V}/V_0 = 0.26$, the influence on the particle trajectories was noticeable, although the region of trapping of the particles in velocity space remained practically unchanged. At $\tilde{V}/V_0 = 0.65$, the fraction of particles that were untrapped in the absence of the HF electric field (Fig. 1a) becomes trapped. In this case there is a noticeable increase in the region of trapping of the particles and its new boundary is in satisfactory agreement with expression (2). A typical trajectory of such a particle is shown in Fig. b. A control calculation performed for a particle with the same initial conditions but in the case of an electric field homogeneous over the cross section shows that the particle remains untrapped (Fig. c). For particles that are untrapped in the absence of an HF field, the deviation of the drift surfaces from the initial magnetic surfaces increases in comparison with the case without the HF field. This is connected mainly with the increase of the time of revolution of the particle about the magnetic axis. The HF potential has a particularly strong influence on the deviation of the drift surfaces of the untrapped particles that are close to capture. In accordance with the foregoing, the containment of the particles in the trap becomes worse.

In conclusion, we note that at the same particle energy averaged over the period of the HF field, the value of $\tilde{V}/V_0$ is larger by a factor $\sqrt{M_i/M_e}$ in the case of electrons that for singly-charged ions. Therefore the influence of the HF potential on the trapping of the electrons may become manifest at relatively small values of the electric field intensity, which are characteristic of plasma experiments.

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INFLUENCE OF LONGITUDINAL STREAMS OF CHARGED PARTICLES ON THE DIFFUSION OF PLASMA IN A STELLARATOR

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The rates of decay of plasma injected by an external source, observed in experiments with the double-entry stellarator of the Physics Institute of the USSR Academy of Sciences L-1 [1], have not yet been reconciled with calculations performed within the framework of any theoretical model [1, 2].

Undertaking the next attempt to explain the mechanism of plasma loss in closed traps, we turn in the present article to a phenomenon observed in the L-1 [3, 4], namely the existence of an average velocity of the ion component (u_{z_i}) along the minor axis of the toroidal chamber (the Z axis). A qualitative analysis and a rigorous theoretical analysis carried out in [4] and [5] enable us to state that the longitudinal ion streams should of necessity arise in closed traps in the regime of weak-collision plasma with a radial electric field E_r. The cause of the directional streams is the recoil momentum acquired by the "untrapped" ions as a result of the increased velocity of the drift of the "trapped" ions, which have at $E_r \neq 0$ an average axial velocity $\bar{v}_Z \simeq V_E/\Theta$ ($V_E = cE_r/H_Z$). The measurement procedure used in [3] and [4] has made it possible to determine the average directional velocity only for the ionic component. However, the plasma as a whole takes part in the rotation about the principal axis of the torus. Dragging of the electrons along the Z axis should be caused by the ion-electron interaction.

The axial velocity acquired by the electronic component can be estimated from the relation