ANALYSIS OF DRIFT ORBITS IN CLOSED MAGNETIC CONFIGURATIONS WITH DRIFT ROTATION TRANSFORMATION

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A study is made of the dynamics of particles interacting with electromagnetic field fluctuations in a plasma in the presence of a magnetic field. Possible mechanism of anomalous transport is analyzed. Estimates of the diffusion coefficient are proposed based on the calculations of particle trajectories.
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1. INTRODUCTION

In this paper dynamics of charged particles is analysed to study the confinement properties of closed magnetic systems with planar magnetic field lines. Such a system can be presented as a set of linear and toroidal elements.

In closed magnetic configurations without rotational transformation of the magnetic field lines vertical drift appears due to the curvature of the magnetic lines in toroidal elements. To provide longtime confinement of the plasma particles in such systems the effect of the vertical drift can be balanced by the rotation of the particles around the magnetic axis. We consider a case of the rotation due to the guiding center drift rotation (drift rotation transformation). In the magnetic trap with high-beta plasma the guiding centers can rotate around the magnetic axis due to the ∇B-drift associated with the strong radial nonuniformity of the magnetic field in high-beta system [1]. Besides, radial electrostatic field can be used to create intensive $E\times B$-drift that increase the confinement efficiency.

Examples of Magnetic configurations with planar field lines are presented in Fig. 1. For the general analysis we consider configuration “racetrack” consisting of two linear and two toroidal elements. To consider the effect of the drift rotation we take into account guiding center motion associated with the following drifts: ∇B-drift around the magnetic axis due to the plasma diamagnetism, ∇B-drift due to curvature of the magnetic field lines in the toroidal parts, and $E\times B$-drift. The ion and electron guiding center trajectories are calculated to estimate confinement efficiency of the systems under consideration. Parameters of the trajectories allow to find condition corresponding to high efficiency of the confinement.

2. CALCULATION MODEL

In elements of magnetic field with curvature radius R we consider vacuum magnetic field

$$B_t = \frac{B_0}{1+\dfrac{r}{R}\cos\varphi}, \qquad (1)$$

where r is the distance from the magnetic axis, φ is the poloidal angle, B_0 is the magnetic field at the magnetic axis. In such magnetic field particles drift along the direction which is perpendicular to the plane of the magnetic axis. The velocity of this “vertical” drift is

$$V_t = \frac{mv_\parallel^2 + \dfrac{1}{2}mv_\perp^2}{qB(R + r\cos\varphi)}. \qquad (2)$$

Here q and m are the charge and the mass of the particle, $v_\parallel$ and $v_\perp$ parallel and perpendicular components of the particle velocity (respected to the magnetic field lines), B is the magnetic field inside plasma taking into account plasma diamagnetism.

In this work we consider we consider the possibility of the vertical drift compensation due to the drift particle rotation around the magnetic axis without rotation of magnetic field lines (as in tokamaks and stellarators). In discussed case magnetic field lines are planar.

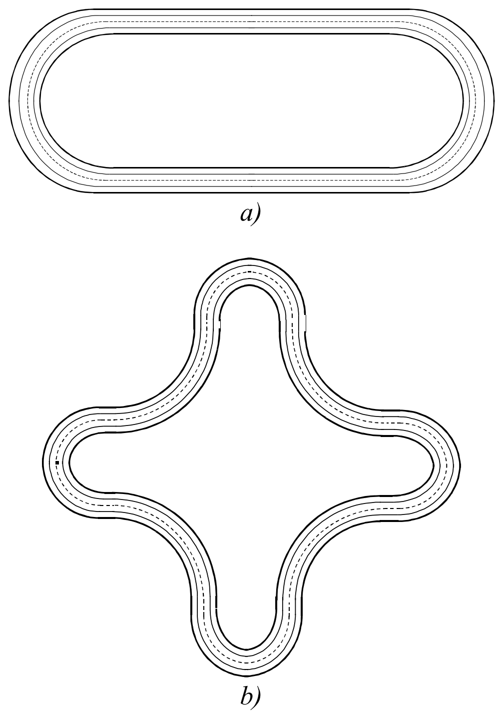
a) *b)*

Fig. 1. Magnetic configurations with planar field lines: a – “racetrack”, b – configuration with variable curvature.

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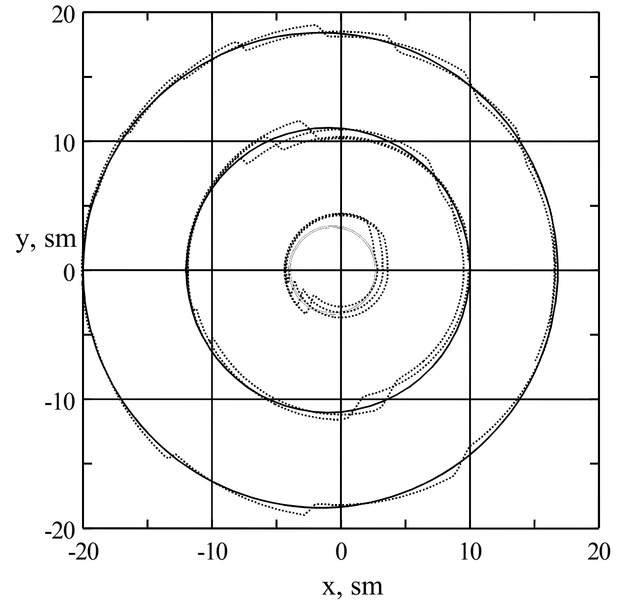

Fig. 2. Drift orbits of deuterium ions (- - - - -) and electrons (————) in "racetrack" configuration with no electrric field. B_0=2 T, B_1=1 T, a=0.2 m, R=0.8 m, the length of the straight section L_0=30 m, ε=1 keV, $ε_⊥/ε$=0.5.

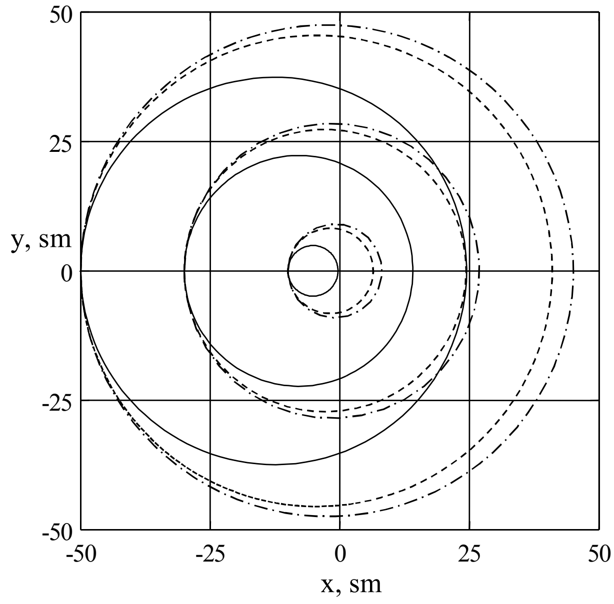

Fig. 3. Cross sections of the drift surfaces in "racetrack" with no electric field and different ratio $ε_⊥/ε$: $ε_⊥/ε$=0.2 (——), $ε_⊥/ε$=0.5 (- - - -), $ε_⊥/ε$=0.8 (– – – – –). B_0=5 T, B_1=2.5 T, a=0.5 m, R=2 m, L_0=65 m, ε=1 keV.

The drift rotation can be realized by applying of the radial electric field (*E*×*B*-drift) [2, 3].

We analysed high-beta systems ($\beta \lesssim 1$) with drift rotation due to the gradient drift (∇*B*-drift) associated with radial non-uniformity of the magnetic field. Taking into account diamagnetic weakness inside high-beta plasma magnetic field can be presented as

$$B = B_{\rm t}\sqrt{1-\beta}\ . \tag{3}$$

The drift velocity due to the plasma diamagnetism is

$$V_{\rm d} = -\frac{mv_\perp^2}{2qB^2}\frac{\partial B_{\rm d}}{\partial r}\,, \tag{4}$$

where the magnetic $B_{\rm d} = B_{\rm t} - B$ takes into account plasma diamagnetism.

For calculations of the particle orbits in the "racetrack" configuration we use the model dependance of the magnetic field inside plasma

$$B = B_{\rm t} - B_1\left[1-(r/a)^2\right], \tag{5}$$

where *a* is the radius of the plasma, B_1 is a constant. Note that in straight elements of the "racetrack" $B_{\rm t} = B_0$.

In special series of the calculations we consider the influence of the radial electric field. The model equation for the electric field is

$$E_r = \frac{2U_0}{a}\frac{r}{a}\,, \tag{6}$$

where U_0 is the potential difference between the magnetic axis and the plasma boundary.

To calculate drift orbits and corresponding drift surfaces we solve the following equations of the guiding center motion:

$$\frac{dr}{dt} = -V_{\rm t}\sin\varphi\ , \tag{7}$$

$$r\frac{d\varphi}{dt} = -V_{\rm t}\cos\varphi + (V_E - V_{\rm d})\,, \tag{8}$$

$$\frac{ds}{dt} = v_\parallel\,. \tag{9}$$

Here *s* is the coordinate along magnetic field line, V_E is the *E*×*B*-drift velocity $V_E = E_r / B$.

Solving Eqs. (7)–(9) we takes into account the invariance of $\mu = \frac{mv_\perp^2}{2qB}$ and $H = \frac{1}{2}m(v_\parallel^2 + v_\perp^2) + qU$ (*U* is the electric potential).

Calculated drift orbits (drift surfaces) are presented in Figs. 2–4, where (*x*, *y*) is the plane perpendicular to the magnetic axis.

From Fig. 3 one can see that the orbits shape depend on the part of perpendicular kinetic energy $\varepsilon_\perp = \frac{mv_\perp^2}{2}$ in total kinetic energy $\varepsilon = \frac{mv^2}{2} = \frac{m(v_\perp^2 + v_\parallel^2)}{2}$.

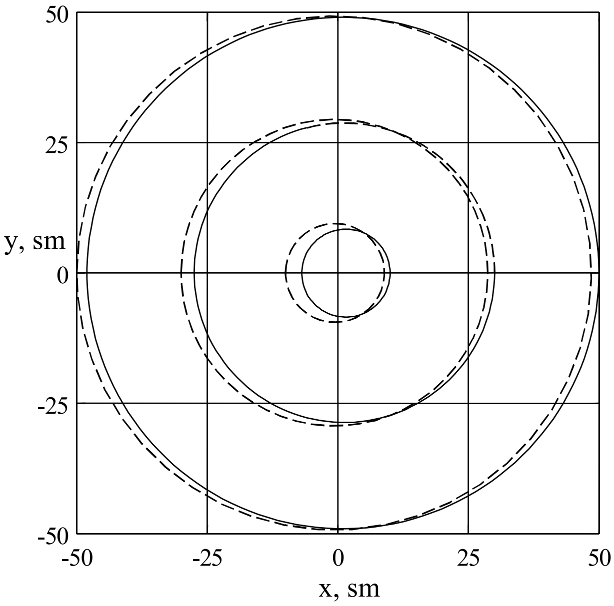

Fig. 4. Cross sections of the drift surfaces orbits of deuterium ions (- - - - -) and electrons (————) in "racetrack" with the electric field. B_0, B_1, a, R, L_0, ε see Fig. 3, $\varepsilon_\perp/\varepsilon$=0.5, U_0= -1 kV (electric field is directed inside plasma).

3. PARAMETERS OF DRIFT ORBITS

For the adopted here field geometry rotational velocity is equal to

$$\Omega = \frac{V_E - V_d}{r} = \frac{2U_0}{a^2 B} - \frac{mv_\perp^2 B_1}{qa^2B^2} = \frac{2(qU_0 - \mu B_1)}{qa^2 B}. \qquad (10)$$

In the (x, y)-plane guiding centers orbits are consist of circle arcs. In the linear sections the cnters of this circles lies on the magnetic axis. In toroidal sections the displacement of the circle center along x-direction is

$$\Delta_t = \frac{V_t}{\Omega} \approx \frac{\left(mv_\parallel^2 + \frac{1}{2}mv_\perp^2\right)}{2(qU_0 - \mu B_1)}\frac{a^2}{R}. \qquad (11)$$

If $\Delta\varphi = \Omega \frac{L_\Sigma}{v_\parallel} << 2\pi$ than one can assume that drift orbits are posed at some drift surface. High efficiency of the vertical drift compensation is achieved under the following condition:

$$|V_E - V_d| >> |V_t| \frac{L_t}{L_\Sigma}, \qquad (12)$$

where L_t is the length of toroidal elements, L_Σ is the total length of magnetic axis. The displacement Δ ($|\Delta| << a$) of the center of the drift surface in the "racetrack" system is

$$\Delta \approx \frac{V_t}{\Omega}\frac{L_t}{L_\Sigma} \approx \pi \frac{\left(mv_\parallel^2 + \frac{1}{2}mv_\perp^2\right)}{(qU_0 - \mu B_1)}\frac{a^2}{L_\Sigma}. \qquad (13)$$

This formula also cal be used for any configurations consisting of toroidal and linear sections.

Maximal displacement of the ion from the circular drift surface is about

$$\Delta y_{max} \approx \frac{V_t L_t}{v_\parallel N} \approx \frac{2\pi}{N}\frac{(mv_\parallel^2 + \frac{1}{2}mv_\perp^2)}{qBv_\parallel}, \qquad (14)$$

where N is the number of the similar elements (for the "racetrack" N=2).

CONCLUSIONS

A very important problem is the equilibrium of plasma in considered closed magnetic systems. This problem require next detailed study especially for areas with convex magnetic field lines. Note that equilibrium in such elements can be improved by the external current plats installed near the convex magnetic lines.

Carried out analysis show potentialities of the particle confinement in high-beta closed magnetic configurations with drift rotation transformation and planar magnetic field lines.

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