DYNAMICS OF PLASMA PARTICLES INTERACTION WITH ELECTRIC FIELD FLUCTUATIONS

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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

The paper is devoted to analyzing the dynamics of charged particles in inhomogeneous magnetized plasma in their interactions with wave packets propagating transverse to the magnetic field and to the plasma density gradient. This approach makes it possible to consider the processes of particle scattering by electromagnetic field fluctuations. Similar problems arise in the study of anomalous transport in plasmas.

Here, a possible mechanism for the onset of anomalous transport under the action of drift instabilities [1, 2] in a plasma is discussed in terms of the motion of individual particles. In the presence of multimode perturbations, the motion of particles can become stochastic due to their interactions with fluctuations, in which case the particle confinement in a magnetic field is governed by collisionless diffusion [3–7]. We are interested in the particle interaction with moving, spatially localized, soliton-like fluctuations.

2. ANALYSIS OF THE PARTICLE DYNAMICS

We consider a two-dimensional (r, θ) configuration that is uniform along the z-axis and in which the magnetic field B depends only on the radius r and is directed along the z-coordinate. We assume that the waves are electrostatic and propagate along the azimuthal angle θ. The components of the electric field of each wave packet have the form

$$E_\theta^{\sim} = -\frac{1}{r}\frac{\partial \varphi^{\sim}}{\partial \theta}, \qquad (1)$$

$$E_r^{\sim} = -\frac{\partial \varphi^{\sim}}{\partial r}. \qquad (2)$$

Here, the electric potential $\varphi^{\sim}$ is represented as a sum of many harmonics:

$$\varphi^{\sim} = -\sum_n \varphi_{0s,n} g_s(r) \cos\left[n(\omega_s t - \theta) + \psi_{s,n}\right], \qquad (3)$$

where s is the number of the wave packet, n is the azimuthal wavenumber, ω_s is the angular phase velocity of the packet, $g_s(r)$ is its radial profile, and $\varphi_{0s,n}$ and $\psi_{s,n}$ are the amplitudes and initial phases of the electric potential harmonics of the packet.

We take into account the radial electrostatic field $E_r(r)$. Such a field can appear due to an ambipolar effect of the ion and electron fluxes in the plasma. Besides, the radial electric field (of any polarity) increases, the radial displacement of the particle decreases substantially and, accordingly, the radial scale of the diffusion becomes shorter [6].

The particle trajectories are obtained by numerically solving the following equations of particle motion:

$$m\frac{dv_r}{dt} = q\left[E_r^{\sim} + E_r(r) + v_\theta B\right], \qquad (4)$$

$$m\frac{dv_\theta}{dt} = q\left(E_\theta^{\sim} - v_r B\right), \qquad (5)$$

where m and q are the mass and charge of a particle and v_r and v_θ are the radial and azimuthal components of its velocity.

An important characteristic of anomalous transport is the radial displacement of a particle in its interaction with localized fluctuations. In computations, it was assumed that the electric field of the wave is localized along the azimuthal angle θ in a sufficiently narrow region of width δ_θ. The maximum potential difference $\Delta\varphi$ across this region (or the maximum potential amplitude) satisfies the condition

$$\varepsilon = \frac{|e\Delta\varphi|}{kT_e} < 1, \qquad (6)$$

where ε is the relative amplitude of the wave potential, e is the charge of an electron, k is Boltzmann constant, and T_e is the electron temperature.

The features of the particle motion under the action of the low-frequency drift (LFD) and lower-hybrid drift (LHD) fluctuations are shown in Figs. 1–3.

The time during which a particle interacts with the electric field of a single wave packet is equal to

$$\Delta t = \frac{\delta_\theta}{u}, \qquad (7)$$

where u is the particle velocity with respect to the wave.

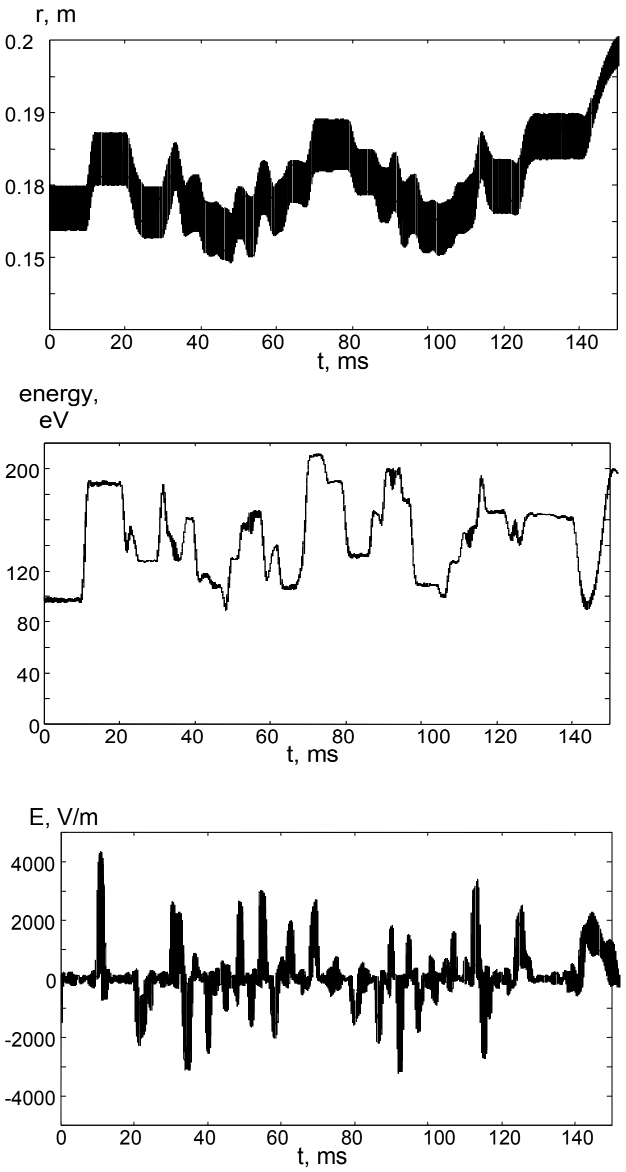

Fig. 1. Radial coordinate of the particle (proton), its energy, and the azimuthal component of the electric field acting on the particle (LFD). Magnetic field at the plasma boundary B_0=1 T, plasma radius a=0.2 m, magnetic field gradient dB/dr=12 T/m, ε=0.05

For the case $\delta_\theta >> \rho$ (ρ is the cyclotron radius of the particle), we have $u=|v_{ph}-V_{dr}|$, where v_{ph} is the wave phase velocity and V_{dr} is the drift velocity of the particle guiding center. For opposite case $\delta_\theta << \rho$, we have $u=|v_{ph}-v_\theta|$.

In the geometry adopted here, the drift velocity V_{dr} may be caused by both the electric field and the magnetic field gradient:

$$V_{dr} = \frac{E_r(r)}{B} - \frac{mv^2}{2qB^2}\frac{dB}{dr}\,. \tag{8}$$

During the interaction time Δt, a magnetized particle is displaced in the radial direction by a distance of about

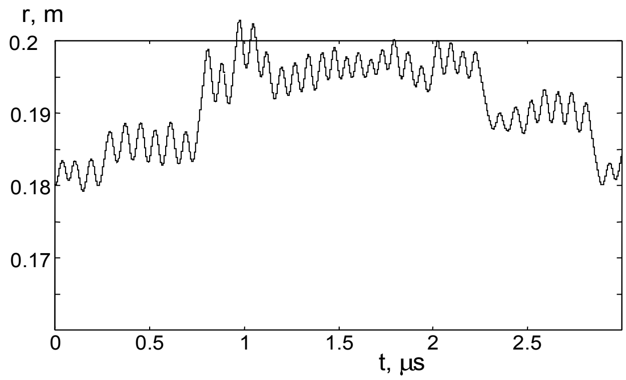

Fig. 2. Radial coordinate of the particle (proton) under the action of LHD-waves. B_0=1 T, a=0.2 m, dB/dr=12 T/m, ε=0.1

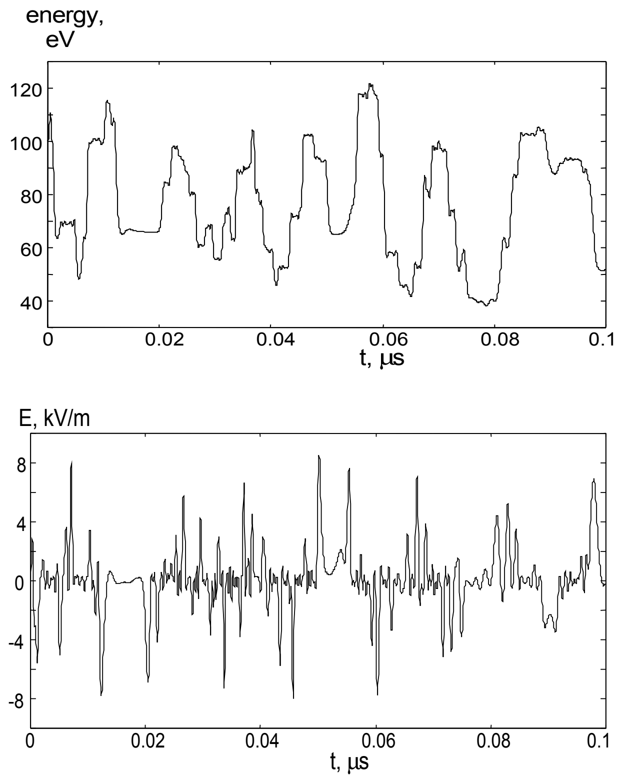

Fig. 3. Time dependencies of the particle energy, and the azimuthal component of the wave electric field acting on the particle during one gyroperiod for the condition of Fig. 2

$$\Delta r \approx \frac{E_\theta^{\sim}}{B}\Delta t \approx \frac{\Delta \varphi}{Bu}\,. \tag{9}$$

Our numerical calculations show that estimate (9) is valid for both $u << v_\theta$,and $u \gtrsim v_\theta$. The time between the interactions of a particle with two successive wave packets is equal to

$$\tau_0 = \frac{\lambda}{u}\,, \tag{10}$$

where λ is the maximum (under the conditions adopted here) wavelength in the electric potential spectrum (3).

Using relationships (9) and (10), we can estimate the maximum anomalous diffusion coefficient in the case of stochastic particle motion:

$$D(r) \approx \frac{(\Delta r)^2}{\tau_0} \approx \frac{\varepsilon^2}{\lambda u}\left(\frac{kT_e}{eB}\right)^2 . \qquad (11)$$

Estimate (11) shows, in particular, that the diffusion coefficient can be lowered (and, accordingly, the anomalous transport can be suppressed) when $|V_{dr}|>>v_{ph}$. The drift velocity V_{dr} can be increased by applying a strong radial electric field, which gives rise to the E×B drift.

The phase velocity of the low-frequency waves, as well as of the lower hybrid drift waves [2], is equal to

$$v_{ph} \approx \frac{kT_e}{eB\delta_n} , \qquad (12)$$

where δ_n is the radial scale of the plasma density gradient. For such waves, we have $\lambda \sim \delta_n$.

Using relationships (11) and (12), fore the limiting case $|V_{dr}|<<v_{ph}$ one can obtain the Bohm-like diffusion coefficient:

$$D(r) \approx \varepsilon^2 \frac{kT_e}{eB} . \qquad (13)$$

Note that the confinement time estimated from diffusion coefficient (13) coincides with that obtained in [3, 5] in analyzing the quasi-Hamiltonian dynamics of the guiding centers of the ions during their stochastic motion under the action of low-frequency drift waves.

3. CONCLUSIONS

In conclusion, we have analyzed the ion dynamics under the conditions of a stochastic regime of anomalous diffusion. Both qualitative consideration and computational results allow to estimate the coefficient of anomalous diffusion.

We emphasize that we have neglected a possible decrease in the oscillation amplitude ε due to the radial electric field and assumed that ε lies in the range ε =0.01…0.1, corresponding to the experiments on different magnetic confinement device. Presumably, the value of ε should be determined from the self-consistent solution to the corresponding problem.

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