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Nonlocal Modeling of Anomalous Transport in FRC Plasma

V.I. Khvesyuk, S.V. Ryzhkov, A.Yu. Chirkov

Bauman Moscow State Technical University
Moscow, 107005, Russia, e-mail: khves@power.bmstu.ru

A new approach to investigate electromagnetic field fluctuations and particles transfer in plasma with strong inhomogeneity of density and magnetic field is presented. Proposed theoretical analysis takes into account the real spatial structure of plasma and nonuniform magnetic field. Numerical model for particle dynamics and diffusion coefficient calculations for a field reversed configuration (FRC) is developed. Influence of magnetic field and plasma density profiles on diffusion is studied. Nonstationary electromagnetic field of the waves propagated in plasma is modeled. Calculations are carried out for the range of plasma parameters reached in FRC experiments.

This paper aims to study a new model of turbulent plasma. The most important distinction of this model from the standart transport model [1] is taking into account the real structure of plasma geometry and magnetic field. Influence of complex radial dependence of magnetic field $B(r)$ and density $n(r)$ on confinement time may be investigated by this approximation and resolved for various plasma areas where different types of instabilities are arising.

The plasma body is divided on a few layers which include several modes of drift waves. The number of layers is chosen from the value of magnetic field gradient and plasma density. The wave packet with radial profile of finite width is considered. Note, that potential profiles of nearest layers are overlapped. This nonlocal approximation allows to find the distribution of different modes along radial direction. Both the low frequency drift (LFD) and lower hybrid drift (LHD) instabilities are considered. The preliminary results on possible transverse transport of the charged particles across magnetic field with several modes of electromagnetic wave are received.

In the framework of the proposal approach we can estimate the anomalous diffusion coefficient in the case of stochastic particle motion [2]:

$$D(r) \approx \frac{\varepsilon^2}{\lambda |v_{ph} - v|} \left(\frac{kT_e}{eB} \right)^2 , \tag{1}$$

where $\varepsilon = |e\varphi_0|/(kT_e)$ is the relative level of the electric potential fluctuations, φ_0 is the electric potential of the wave (a factor of about maximum amplitude), e is the charge of the electron, k is the Boltzmann constant, T_e is the electron temperature λ is the maximum wavelength in the electric potential spectrum, v_{ph} is the wave phase velocity, v is the particle velocity (for magnetized particles, v is the velocity of the guiding center).

Using the diffusion coefficient (1) concerned with the parameters of the drift waves one can obtain global particle confinement time, that for FRCs can be written as

$$\tau = \text{const} \times \frac{eB_0 a^2}{\varepsilon^2 kT_e} \approx 10 \frac{eB_0 a^2}{kT_\text{t}}, \qquad (2)$$

where B_0 is a vacuum magnetic field of solenoid coil, a is the separatrix radius of the FRC, T_t is total temperature (here we assume $\varepsilon \sim 10^{-1}$). Numerical simulation compared with FRC experimental data for particle confinement time [3] is presented in Fig. 1.

The particle dynamics for broad range of the lengths of the waves: from $\lambda >> \rho_i$ to $\lambda \sim \rho_e$ (λ is a maximum wavelength for considered packet, ρ_i is the ion Larmor radius, ρ_e is the electron Larmor radius) is calculated. Both drift approach and decision of the dynamic equations are used for ions in long wave limit. Coincidence of typical values of the radial offsets of the ion under the action of pulse of the electric field is received in this limit. Preliminary expression for the diffusion coefficient coming from estimation of the values of the displacement is received consistent with calculation data.

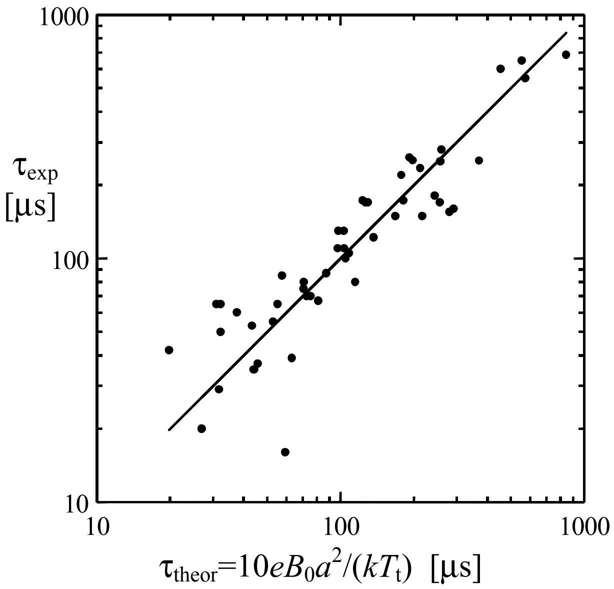

Fig. 1. Comparison of particle confinement time in a FRC between experiment and theory

In short-wave range ($\lambda \gtrsim \rho_e$), the influence of plasma parameters and different factors on the growth rate of the lower-hybrid-drift instability is investigated. The calculations have shown that the short-wave fluctuations render the weak influence on the energetic particle (the velocity vastly exceeds the thermal velocity). The diffusion coefficient decreases with growing of the energy of such particles, and does not depend on energy at low energy. The expressions for the diffusion coefficient taking into account the above mentioned theoretical and numerical analysis are offered.

The Figs. 2, 3 represent last results of the modeling of the particles behavior in FRC plasma from the mapping. Calculations were carried out for the model of the stochastic processes of particles interactions and electromagnetic (electrostatic) fluctuations. These fluctuations are packets of waves propagating along azimuthal direction of the nonuniform cylindrical plasma. The above mentioned approximations allow to obtain stochastic motion and orbits of charged particles. The samples of such microprocesses are shown below. These figures represent drift wave maps for ion with different start point: 0.89 r_s and 0.91 r_s, where r_s is the plasma/separatrix radius.

K_o, A, dQ, F_c are some coefficients using for the mapping picture. K is the factor taking into account the time of interaction between the particle and electromagnetic field pulse, $K=K_o+F$. In the general $F=F(r)=\pm Ar$ or $\pm Ar^2$. $dQ=d\Omega$ is the step between nearest frequencies/pulses. All parameters are dimensionless.

Unfortunately, dispersion relations derived in many papers [1, 4-6] consist (as we have discovered) no satisfactory assumptions to our model. The new nonlocal dispersion relation taking into account the fluctuations will be derived in the near future analysis.

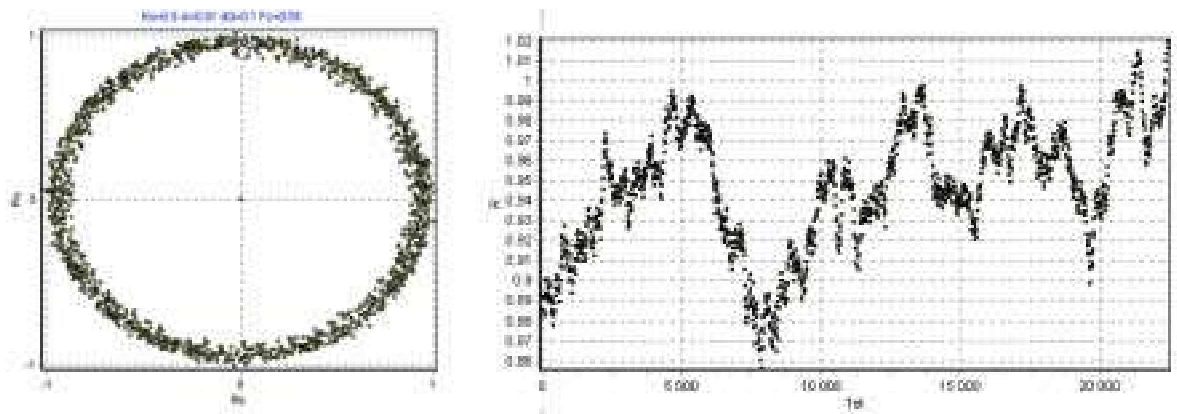

Fig. 2. General picture of chaotic motion in FRC plasma (left) and radial coordinate of the particle (ion) vs wave phase where theta is the dimensionless wave phase (right)

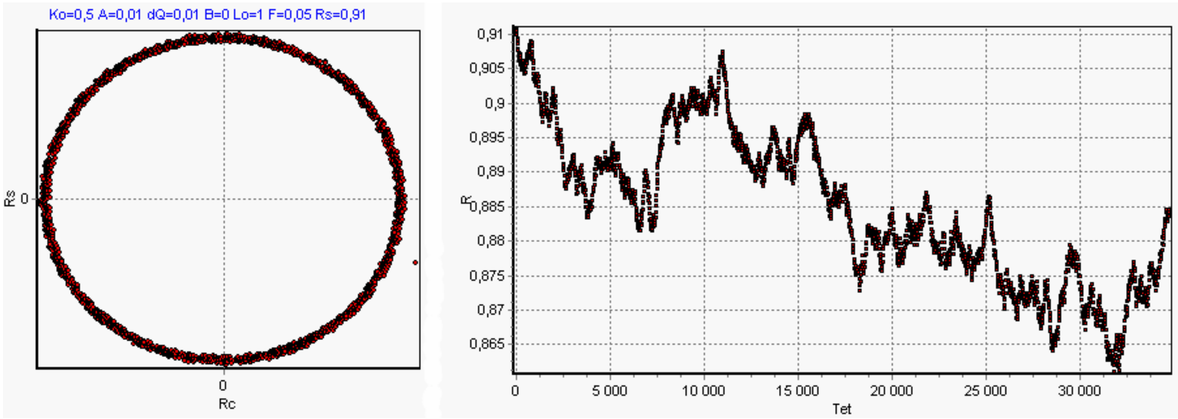

Fig. 3. Standart mapping picture for the ion with the initial radius r=0.91 r_s

Conclusions

A new model of transport in a FRC is developed. The main features of this model are taking into account complex field of drift waves propagating in plasma and analysis of motion of the particles interacting with field fluctuations. Preliminary comparisons using LFD and LHD theory show a reasonable correlation with experimental confinement times. It is proposed that combination of low frequency drift and lower hybrid drift instabilities leads to turbulence transport at the FRC plasma edge. Both LFD and LHD modes are responsible for explaining particle and energy transport and may be considered as a mechanism for anomalous transport. Although initial comparisons are favorable, a identification of the transport mechanism, diagnostic measurements in FRCs must be made.

Acknowledgements

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