ИВМиМГ

Numerical Simulation of Ion Beam Evolution in Magnetized Plasma

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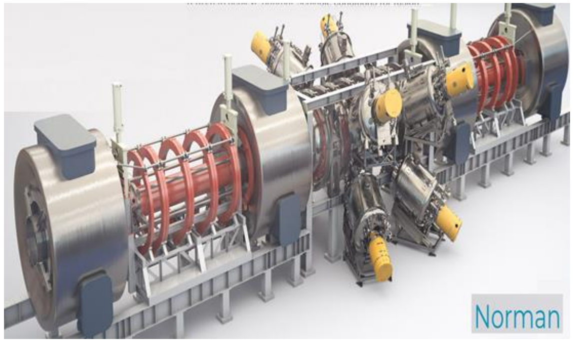
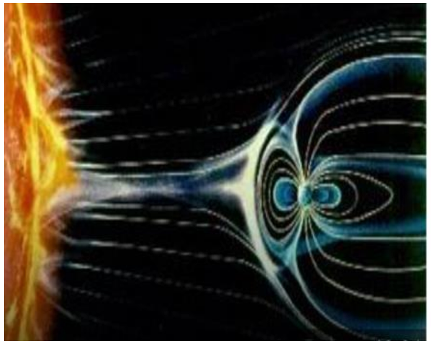
Introduction

The problem of interaction of injected beam with plasma is very relevant for all types of gas discharge and laboratory experiments with magnetic traps.





The interaction of the beam with the plasma also plays a fundamental role and determines the nature of such astrophysical phenomena as supernova explosions, the interaction of the solar wind with the Earth’s magnetosphere, and solar flares.

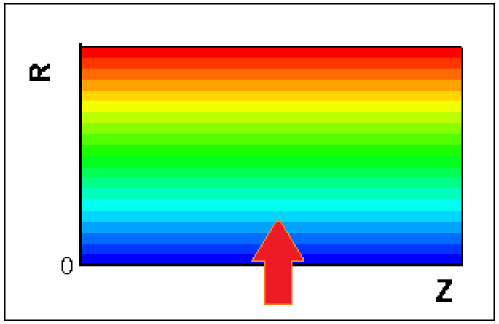
The difficulties of the theoretical analysis of the problem are related to the nonlinear nature of the processes under study and the need to take into account the large ion gyroradius and the stochasticity of the particle orbits. The task requires the use of numerical simulation based on high-level mathematical models that are adequate to the processes under study.

Abstract

- The problem of the interaction of high-current ion beam with plasma is investigated on the basis of computer simulation. The two-dimensional axisymmetric hybrid numerical model is based on the MHD approximation for electrons and the particle-in-cell method (PIC) for the ion beam and plasma ion component.
- To solve the Vlasov equations by the PIC method, a transition to Cartesian coordinates and back to cylindrical coordinates is used.
- The evolution of the ion beam depending on its energy and current, is studied. The formation of a region with a low plasma density and a displaced magnetic field is shown.

STATEMENT OF THE PROBLEM

At t=0, a hydrogen background plasma of uniform density n_0 = const was placed inside a cylindrical chamber of radius R_0 and length L. constant magnetic field was directed along the z- axis $\boldsymbol{B} = (0, 0, B_0)$.



Magnetic field lines, t=0.

At a point $R = 0$, $z = L/2$, an ion beam is generated, its current J is determined by the number of injected ions and their speed $\boldsymbol{V} = (Vr, 0, Vz)$. The injected beam has a temperature T_b; the background plasma are assumed to be cold: $T_e = 0$, $T_i = 0$.

Due to axial symmetry, the problem is considered in a two-dimensional cylindrical formulation. To solve this problem, a hybrid numerical model applying the particle-in-cell method (PIC) is used.

Statement of the Problem

The system of equations : Vlasov equations for the ions MHD equations for the electrons and Maxwell equations:

$$\frac{\partial f_i}{\partial t} + \boldsymbol{v}\frac{\partial f_i}{\partial \boldsymbol{r}} + \frac{\boldsymbol{F}_i}{m_i}\frac{\partial f_i}{\partial \boldsymbol{v}} = 0,$$

$$\boldsymbol{F}_i = e\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right) + \boldsymbol{R}_i,$$

$$e\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{V}_e \times \boldsymbol{B}\right) - \frac{\nabla p_e}{n_e} + \boldsymbol{R}_e = 0$$

$$\frac{3}{2} n_e\left(\frac{\partial T_e}{\partial t} + (\boldsymbol{V}_e \cdot \nabla)T_e\right) = -p_e \nabla \cdot \boldsymbol{V}_e + Q_e$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j}, \quad \nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t},$$

$$\nabla \cdot \boldsymbol{B} = 0. \quad \boldsymbol{j} = ne(\boldsymbol{V}_i - \boldsymbol{V}_e) \quad n_e = n_i = n$$

$\boldsymbol{B}$ $\boldsymbol{E}$ – magnetic , electric fields

f_i – the ion distribution function

$\boldsymbol{V}_i = \int f_i(\boldsymbol{r}, \boldsymbol{v}, t)\boldsymbol{v}\, d\boldsymbol{v}/n_i$ – ion velocity

V_e – the electron velocity

p_e – pressure , T_e – temperature

$\boldsymbol{R}_e = -m_e(\boldsymbol{V}_e - \boldsymbol{V}_i)/\tau_{ei}$

τ_{ei} ion-electron collision time $\sigma = ne^2/m_e\nu$

Heat generated in electrons is $Q_e = j^2/\sigma$

collision force $\boldsymbol{R}_i = -\boldsymbol{R}_e$

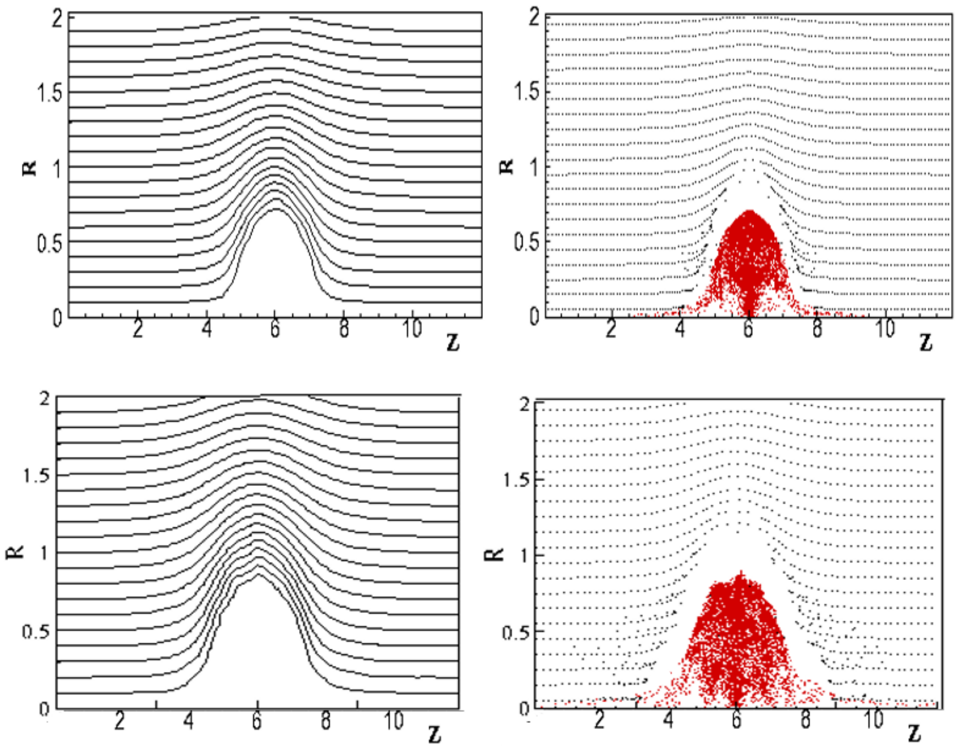
Here it is assumed that the frequency of collisions $\nu = 1/\tau_{ei}$ caused by anomalous processes of scattering on fluctuations of electromagnetic fields and do not depend on the parameters of the plasma and magnetic field ($\nu = const$).

Statement of the Problem

- To solve the Vlasov kinetic equation, the author's modification of PIC is used *. To solve the MHD and Maxwell equations, finite-difference schemes of the first order of accuracy are used.
- To solve the heat balance equation for electrons the up-wind scheme is used. In hybrid models, the condition of plasma quasi-neutrality is assumed to be $n_e=n_i$ (the scales under consideration are larger than the Debye radius), and displacement currents are also neglected, only low-frequency processes are considered.
- The electric field is determined from the equation of motion of electrons under the assumption $m_e = 0$. This approximation ignores the dispersion effects associated with the electronic component.

**Yu.A. Berezin, V.A.Vshivkov. Particle method in the dynamics of rarefied plasma. - Novosibirsk: Nauka, 1980 (in Russian).*

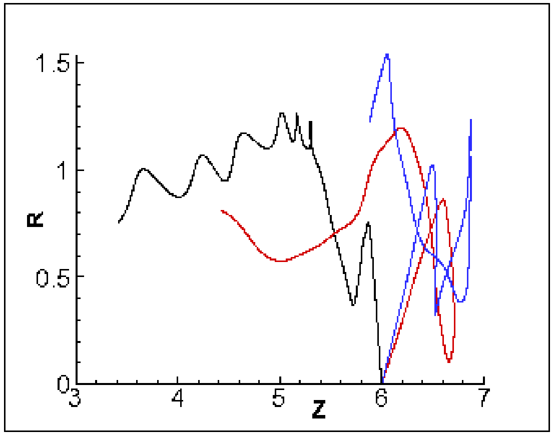
Results of Simulation



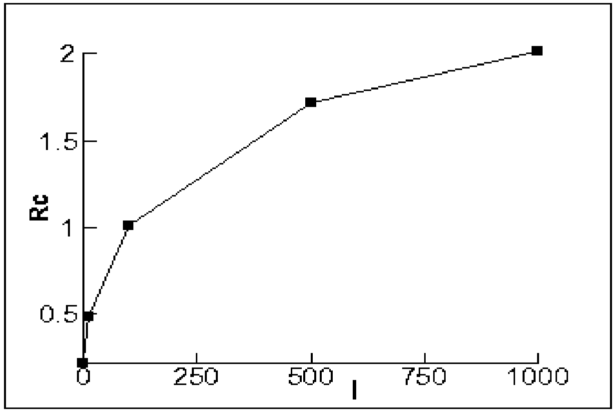
Map of magnetic field lines- (left column), distributions of the injected-beam ions (red points) and the background plasma (black points-(right column) at *t*= 40 and t= 160 (top and bottom row respectively) .

The spatial dimensions are expressed in units of c/ω_{0i}, *the time - in* ω_{iH}^{-1}, *the velocity is normalized to the Alfven speed* $V_A = B_0/\sqrt{4\pi n_0 m_i}$, *where* n_0 *- the density of the background plasma at the initial time t=0.*

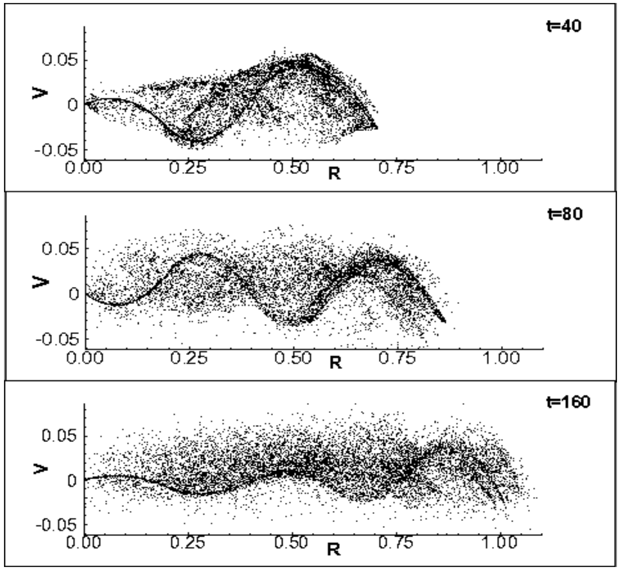
Results of Simulation



The trajectories of individual ion beam (0<t< 200).



The dependence of the size of the cavity of the magnetic field on the current of the beam .



Ion phase space (V_{φ}, R) at at t=40, 80, 160 (from upper to bottom).

Conclusion

- On the basis of numerical modeling, nonlinear processes of continuous injection of an ion beam into the plasma, immersed in the magnetic field are investigated.
- As a result of computer simulation, the evolution of the ion beam depending on its energy and current, magnetic field and plasma density is studied.
- The possibility of forming regions with a low plasma density and a displaced magnetic field is shown.