NUMERICAL MODELING OF PLASMA DYNAMICS IN NON-UNIFORM MAGNETIC FIELD

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The problem of interaction of a plasma flow with an inhomogeneous magnetic field is considered. The field is generated by magnetic coils. Field lines along the coil axis form a channel which is used to control the plasma flow. A two-dimensional axial-symmetric plasma model and 3D hybrid code has been used. The work results can be used for a study of processes taking place in a magnetic nozzle.

I. INTRODUCTION

A magnetic nozzle is an important component of propulsion plasma devices using a strong guiding magnetic field to control a plasma flow. It is a channel with a magnetic force tube of varying section connected to the plasma source. The nozzle has to accelerate the incoming plasma flow by a transformation of its inner energy into kinetic energy of directed motion. First, the tube section at the accelerating region along the channel is decreased, and then is expanded as the Laval nozzle. At the widening region of the tube the ejecting plasma has to become free from the field lines to create a propulsion. If the plasma stays frozen into magnetic field lines then no resulting propulsion can take place.

Separation of the plasma stream from the engine magnetic field is the key problem for numerous plasma engine devices with a magnetic nozzle. Therefore, research in this area is the important part of works dealing with a big class of plasma engine technologies in the space and requires detailed study.

There are two possibilities for solving the problem of plasma stream separation. The first one consists in the violation of the limiting frozen-in condition by a recombination or some other mechanism (Ref.1). The second possibility uses the frozen-in condition and assumes that the plasma stretches the magnetic field lines along the flow and is separated from the engine along with a portion of magnetic field. This scenario of magnetic field breaking resembles one which takes place in the solar wind during moving away from the Sun (Ref.2).

For understanding the separation mechanism it is necessary to investigate different configurations of the magnetic nozzle and determine the conditions of the "frozen-in separation" of plasma from the nozzle magnetic field.

A plasma flow outside the nozzle consists of two parts: an unperturbed main flow with straight magnetic field lines and a depression wave at the edge of the main flow. It had been shown in (Ref.3). that an ejecting flow is detached from the nozzle along with a residual magnetic field while the flow is superalfvenic. At the separation process the plasma expands and the flow partially loses its direction and becomes less collimated than the flow inside the nozzle. This radial expansion is caused by the balance violation between the magnetic field pressure and plasma pressure in the stream.

Two main factors influencing a nozzle efficiency are the geometric convergence of the nozzle magnetic field lines and additional radial propagation of the flow coming out on its edges. The relation of these factors, which limits a geometry of the magnetic nozzle, had been established in (Ref.3). The theoretical estimates show that the efficiency factor of a plasma engine can achieve 80%. On the current stage it is necessary to make numerical calculations to determine the efficiency factor of the nozzle for the considered magnetic field geometry used for the specific type of the plasma engine.

Results of numerical modeling for a plasma interaction with a non-uniform magnetic field are presented. Two models are considered. The first model is the two-dimensional axial-symmetric model, which is based on the complete system of Maxwell's equations. This model does not use any approximations and allows to obtain a complete description of the processes in a plasma magnetic nozzle. The second model is based on the three-dimensional hybrid plasma models in which a basic system of equations includes Vlasov's equations for the ion component of the plasma, hydrodynamic equations for electrons, and Maxwell's system. A method of solution is based on a method of particles in cells (PIC) and a splitting one for the finite-difference schemes. From the viewpoint of the numerical method theory, a realization of the method of particles in cells for kinetic models is steady and has a natural structure for parallel algorithms.

II. AXIALLY SYMMETRIC PLASMA MODEL

This model is based to the two-dimensional axial-symmetric plasma models, which is based on the complete system of Maxwell's equations and Vlasov's equations for the ion and electron components of plasma. This approach allows to avoid the difficulties to calculate intensity of electric field in the vacuum region. The Vlasov's equations are calculated by using particle in cell method, in which plasma is presented by set of model particles.

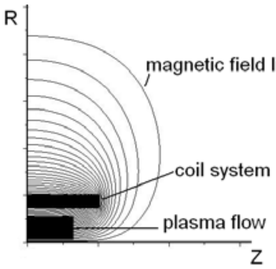

Fig. 1. Geometry of the 2-D problem

On the fig.1 the geometry of axially symmetric plasma problem is illustrated. The field is generated by a magnetic coil system (long bar in fig.1). The initial magnetic field is calculated by using the Poisson's equation. The magnetic force lines along the coil axis form a channel, which is used to control a plasma flow. The plasma particles (small bar in fig.1) enter to the region via left boundary. The initial velocity distribution is assumed to be uniform. At next time stages the plasma is accelerated by the influence of the magnetic field. The boundary conditions are as follows. Z-axis is the symmetry axis. For the field quantities the spatial differences of the normal components are set to be zero at the surface of the calculation region. When the plasma particles reach the calculation region boundary, the particles leave the region. The time levels of the particle position and field quantities are defined at integer time step, and the particle velocities and current density at a half-time step. The leap-frog method which is a time-centered difference scheme is adopted to solve the equations of motion. Maxwell's equations are solved by using difference scheme.

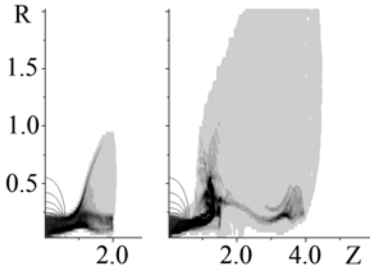

Fig. 2. The electron distribution in different time moments.

On the fig. 2 the electron distribution and magnetic field lines at difference time moments are presented.

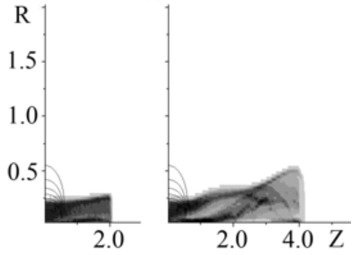

Fig. 3. The electron distribution in different time moments

The numerical results for the electron dynamics are shown in fig.2, where the electrons are projected onto RZ plane. One can see the shape of the electron cloud changes to follow the magnetic field lines. On the fig.3 the ion distribution and magnetic field lines at difference time moments are presented The fig. 3 illustrates that magnetic field is not enough to change ions trajectories considerable.

III. THREE-DIMENSIONAL HYBRID PLASMA MODELS

The three-dimensional problem of interaction of a plasma flow with an inhomogeneous magnetic field is considered. A geometry of the considered problem is illustrated in fig. 4. Here the Cartesian coordinates (*X,Y,Z*) are introduced. The field is generated by a system of infinitely thin magnetic coils with the radius R_c and the current I_c. The current coil centers are located on the X-axis at some distance *D* from each other. The magnetic force lines along the coil axis form a channel which is used to control a plasma flow.

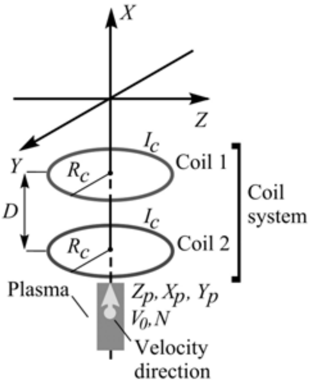

Fig. 4. Geometry of the 3-D problem

At initial time the plasma at the channel entrance has a parallelepiped shape. The plasma is characterized by linear scales (Z_p, X_p, Y_p), a location along the X-axis, an initial velocity V_0 along X-axis and, also, a big number *N* of model particles. The initial distributions of the particle positions and velocities are assumed to be uniform. The initial magnetic field is calculated by using the Bio-Savar-Laplace law. At the next time stages the plasma enters into magnetic channel. It accelerates there under the influence of the magnetic field.

In the present study the plasma dynamics at the magnetic channel outlet has been investigated. Also, the regimes, at which a plasma separation from magnetic force lines takes place, was studied.

Here we use the 3D hybrid PIC code (Ref.4) based on the numerical model given by (Ref.5). The hybrid code treats ions as individual particles and electrons as a fluid. This approach is valid when the system behavior is dominated by ion physics.

The model of collisionless plasma consists of the kinetic Vlasov's equation for an ion component, a momentum equation for an electron fluid and Maxwell's equations. To determine the electric field in vacuum the Laplace equation is solved. The current density involved in the Maxwell equations is calculated from the distribution functions of the ions.

The boundary conditions taken here for the field quantities are that the spatial differences of the normal components are set to be zero at the surface of the calculation region. When the plasma ions reach the calculation region boundary, the ion velocity is set to be zero.

Darwin approximation for the Ampere's law is used, which indicates that high-frequency electromagnetic waves do not exist. A quasi-neutrality is assumed.

The Vlasov's equation is solved by using PIC – method and Maxwell's equations are solved by using finite-difference scheme (Ref.6).

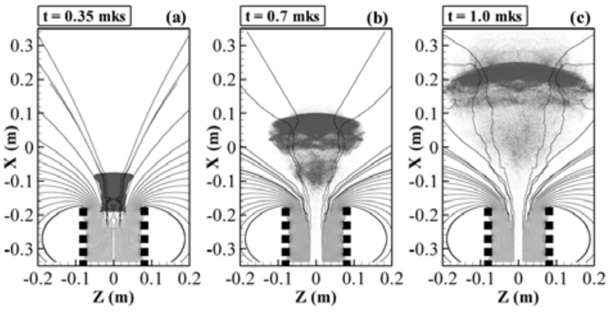

Fig. 5**.** The projections all plasma particle and the magnetic field lines projected on the ZX-plane: (a) *t=0.35mks*, (b) *t=0.7mks* and (c) *t=1.0mks*.

Fig. 5 illustrates the dynamics of all plasma particles and, also, the configuration of the magnetic field lines, which are projected on the ZX plane. From this graph it can be seen that the plasma carries along the magnetic field lines.

Fig. 6 illustrates the change of the plasma kinetic energy with time. First, on the energy graph one can see oscillations until the time of approximately 0.5 *mks.*

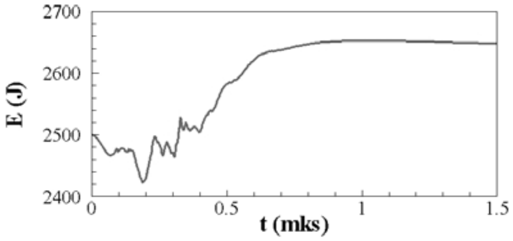

Fig. 6**.** Plasma energy.

This effect is connected with the fact that the plasma penetrating into magnetic channel slows down by the coil magnetic field and current. Then, the plasma flow escaping the magnetic channel is accelerated and gives its impulse to the system of the coils.

IV. CONCLUSIONS

For the modeling the interaction of the plasma flow with an inhomogeneous magnetic field the two-dimensional axial-symmetric plasma model and 3D hybrid code has been used. The results described in this article show that these models give the quality similar results and the magnetic field can accelerate the plasma flow. This work can be useful for the investigation of processes in magnetic nozzles.

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