MODELLING OF PLASMA FLOW IN CURVILINEAR DUCT

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The plasma flow in a curvilinear duct is modelled using particle-in-cell method in the cylindrical geometry. The curvature of magnetic field lines in the duct is simulated introducing centrifugal force acting on ions. The electrons are assumed magnetized while the action of the steady magnetic field on the ions is neglected. The electric potential is calculated self-consistently.

First the case when drift of the electrons is negligibly small is studied. There, starting from the certain plasma density, equilibrium can exist. It could be reached after some number of ions leaves the plasma column forming the potential well for the ions in the plasma core. An important point is that, at the equilibrium state, the distribution of electric potential is essentially asymmetrical.

To avoid the high voltage plasma oscillations the found equilibrium is used as the initial condition for further calculations with finite steady magnetic field. The calculations show that the distribution of the electric field in the plasma duct remains asymmetrical. This causes the electrons to drift to the wall of the duct mainly in vertical direction.

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INTRODUCTION

Vacuum arc discharge is widely used in coating technology. The typical scheme of such device is shown on Fig.1. There the discharge is sustained by the electric current flowing between the anode and the cathode. The major portion of current is carried by the electrons emitted from the cathode. The motion of electrons is strongly affected by the magnetic field of curvilinear duct. It is believed that they follow its lines of force. The electron beam charge is compensated by ions that appear from electron impact ionization of vapor arising from cathode. The ions are confined by the electrostatic mechanism inside the electron beam channel and transported along the curvilinear duct to the substrate placed at the opposite end of the duct. The role of curvilinear duct is to separate ions and electrons from droplets and dust which are much less affected by the magnetic and electric fields and, therefore, cannot reach the substrate in a straight line.

There is a number of papers addressing the theory of plasma flow in curvilinear duct (e.g. [1-2]). The most common feature of them is that the distribution of electric field inside the duct is not calculated self-consistently except analytical estimates given in [3]. In this report we present a simplest model for plasma flow in curvilinear duct with self-consistent account of the electric potential.

PHYSICAL AND NUMERICAL MODELS

We consider stationary flows electrons and ions in straight duct surrounded by the cylindrical metallic wall of radius r_w. The curvature of magnetic field lines of the duct is modeled by the centrifugal force $F_c = m_i \frac{v_z^2}{R} \vec{e}_x$ acting on ions. Magnetic field is assumed uniform and directed along the axis of the cylinder $B = Be_z$.

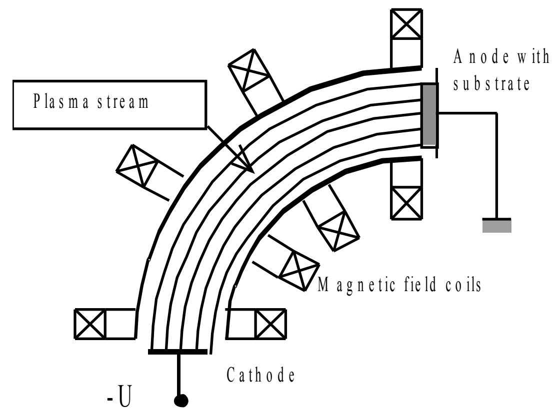

Fig.1. A scheme of toroidal duct

We consider the case when the ion Larmor radius is much greater than the electron beam channel radius and, thereby, neglect the action of magnetic field on ions. At the same time, the electrons are magnetized and obey the drift motion law. The electric field is assumed potential and, plasma collisionless. One more assumption is that the axial component of electric field is small. Accounting these, the kinetic equations for ions and electrons could be written in the following form:

$$v_z \frac{\partial f_i}{\partial z} + v_x \frac{\partial f_i}{\partial x} + v_y \frac{\partial f_i}{\partial y} - \frac{eZ_i}{m_i}\frac{\partial \Phi}{\partial x}\frac{\partial f_i}{\partial v_x} - \frac{eZ_i}{m_i}\frac{\partial \Phi}{\partial y}\frac{\partial f_i}{\partial v_y} = 0, \quad (1)$$

$$v_z \frac{\partial f_e}{\partial z} - \frac{c}{B}\frac{\partial \Phi}{\partial y}\frac{\partial f_e}{\partial x} + \frac{c}{B}\frac{\partial \Phi}{\partial x}\frac{\partial f_e}{\partial y} = 0. \quad (2)$$

The Poisson equation for potential reads:

$$\nabla_\perp^2 \Phi = 4\pi e\left(\int f_e d^3v - Z_i \int f_i d^3v\right). \quad (3)$$

For this problem there is a condition $f_{i,e}\Big|^{v_z<0} = 0$, which is satisfied everywhere including the right end of the duct $z = L$ what means full neutralization of arriving charged particles there. The similar boundary condition is applied at the cylindrical wall $f_{i,e}\Big|^{v_r<0}_{r=r_w} = 0$. The distribution functions at the left end of the cylinder are prescribed $f_{i,e}\big|_{z=0}^{v_r<0} = F_{i,e}(\vec{v},x,y)$.

The boundary condition for Poison equation is $\left.\frac{\partial \Phi}{\partial \varphi}\right|_{r=r_w} = 0$. The gauge constant for potential should be specified too. We combine this specification with the above-mentioned boundary condition assuming $\Phi\big|_{r=r_w} = 0$. Anyway, a proper constant could be added to the potential afterwards.

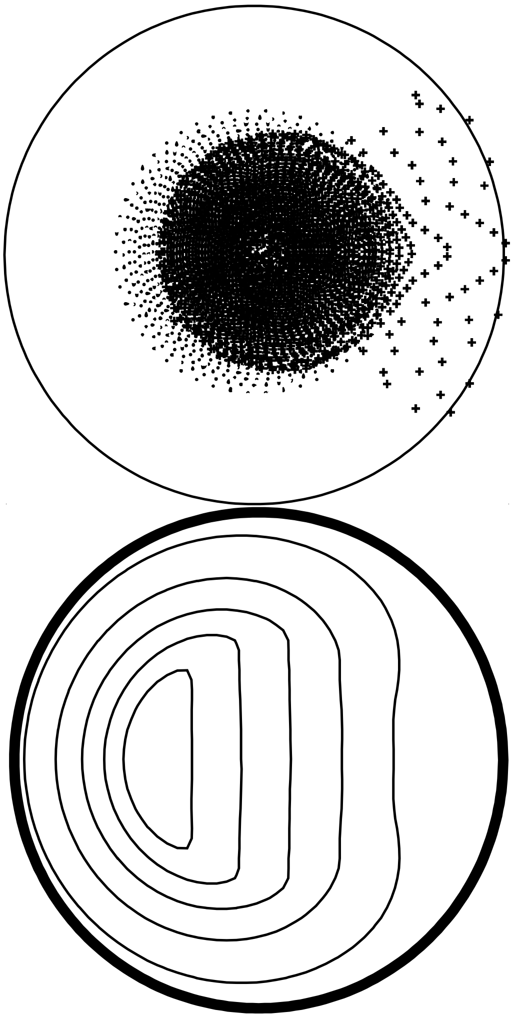

Fig.2. Upper chart: distribution of particles in the cross-section of the duct in static case. Ions are shown as crosses, electrons as dots. Lower chart: Contours of electric potential in the same cross-section

The system of equations (1)-(3) is solved numerically using the particle-in-cell method. First we notice that in the model the axial component of the velocity is conserved both for ions and electrons. So, z coordinate can serve as a parametric variable. The system of equations of motion for particles corresponds the characteristics of kinetic equations (1) and (2). In normalized form it reads:

$$\frac{d\vec{r}_{i\perp}}{d\tau} = A\vec{v}_{i\perp}, \quad (4)$$

$$\frac{d\vec{v}_{i\perp}}{d\tau} = -C\tilde{\nabla}_{\perp}\tilde{\Phi} + \vec{e}_x, \quad (5)$$

$$\frac{d\vec{r}_{e\perp}}{d\tau} = -D\tilde{\nabla}_{\perp}\tilde{\Phi} \times \vec{e}_z, \quad (6)$$

where $\vec{r}_{i,e\perp} = \frac{x_{i,e}e_x + y_{i,e}e_y}{r_w}$, $\tau = z/R$, $\vec{v}_{i,e\perp} = \frac{v_{(i,e),x}e_x + v_{(i,e),y}e_y}{v_z^{(i,e)}}$, $\tilde{\nabla}_{\perp} = r_w\nabla_{\perp}$, $\tilde{\Phi} = \frac{\Phi}{Z_iN_i}$; and constants are $A = R/r_w$, $C = \frac{4\pi e^2Z_i^2N_i}{m_iv_{i,z}^2}\frac{R}{r_w}$, $D = \frac{cReZ_iN_i}{v_{e,z}r_w^2B}$; R is the radius of curvature of the duct, Z_i is the charge of ion, N_i is the number of macro particles modeling ions at the entry point of the duct ($\tau = 0$). The Poisson equation reads:

$$\tilde{\nabla}_{\perp}^2\tilde{\Phi} = \frac{\sum_{n=1}^{N_e}\delta(\vec{r}_{\perp} - \vec{r}_{e\perp}^{\,(n)}) - \sum_{n=1}^{N_i}\delta(\vec{r}_{\perp} - \vec{r}_{i\perp}^{\,(n)})}{N_i}. \quad (7)$$

It is comfortable to introduce a staggered mesh in τ separating the coordinates and velocities. But in our case it is impossible because of the different character of equation (6). Therefore, a normal uniform mesh is used at the interval $\tau \in (0, L/R)$. The equations (4)-(6) are integrated using 2nd order Runge-Cutta method. The equation (7) is solved using Fourier series in azimuth. The integration in radial direction is performed following Galerkin method with 3rd order Hermite finite elements.

FIRST RESULTS OF CALCULATIONS

In first calculations we use the following set of parameters: $A = 5.0$, $C = 20.0$, $D = 0.0$, $L = R$,

$$F_i = \begin{pmatrix} 1 - 0.36\frac{r^2}{r_w^2}, & if\ r < r_w \\ 0, & if\ r > r_w \end{pmatrix}\delta(v_x)\delta(v_y)\delta(v_z - v_{i,z0})/Z_i,$$

$$F_e = \begin{pmatrix} 1 - 0.36\frac{r^2}{r_w^2}, & if\ r < r_w \\ 0, & if\ r > r_w \end{pmatrix}\delta(v_x)\delta(v_y)\delta(v_z - v_{e,z0}).$$

So, we consider monoenergetic ions with no perpendicular energy at the entrance of the duct. The electron influx is similar, but the parallel velocity is different. The charge density of both species is equal and distributed parabolically across the duct. The parameter D equals zero that means no electron drift. Under such conditions electrons move freely to the end of the duct not performing radial excursions. As the calculations show, ions also move there, but perform oscillations around the electrons in x direction. One could guess that there is a static state in which the potential does not oscillate and ion distribution is uniform along the duct. To find it we introduced anisotropic friction force between ions and electrons in perpendicular direction proportional to the ion perpendicular velocity. This causes the exponential decrease of oscillations.

The static state found is shown in Fig.2. The potential is negative inside the duct what prevents escaping of ions. This is because some ions leaved the column moving to the wall in x direction at the stage of relaxation. The charge separation is located at the outer edge of the plasma column. This separation forms almost uniform electric field inside it. This electric field compensates the centrifugal force acting on ions.

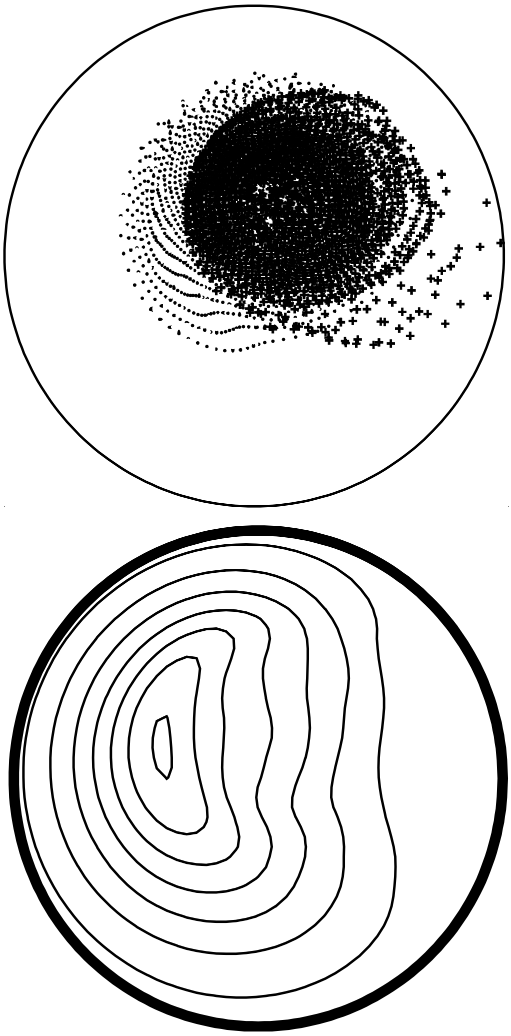

Fig.3. The same as in Fig.2, but for the case of finite magnetic field. The cross-section coordinate $\tau = 0.5$

In further series of calculations we use the static solution as boundary condition at the entry end of the duct. We introduce finite magnetic field setting $D = 10.0$. In Figs. 3 and 4 the distributions of particles and electric potential in middle and right end cross sections on the duct ($\tau = 0.5$ and $\tau = 1.0$) are shown. Remind here that Fig.2 shows the same at $\tau = 0.0$. We see that along the duct the electron channel shifts mainly up because of the drift of electrons in the electric field. While the core electrons move up, the boundary ones revolve. This causes the deformation of the column and the subsequent change of the distribution of electric potential.

CONCLUSIONS

We presented a two-dimensional kinetic model describing steady-state flow of ions and electrons in curvilinear duct. This model is realized numerically using particle-in-cell method. The distinctive feature of the model is self-consistent calculation of electric potential. First numerical results are presented and discussed. In fact, they confirm the importance of self-consistent account of the electric potential.

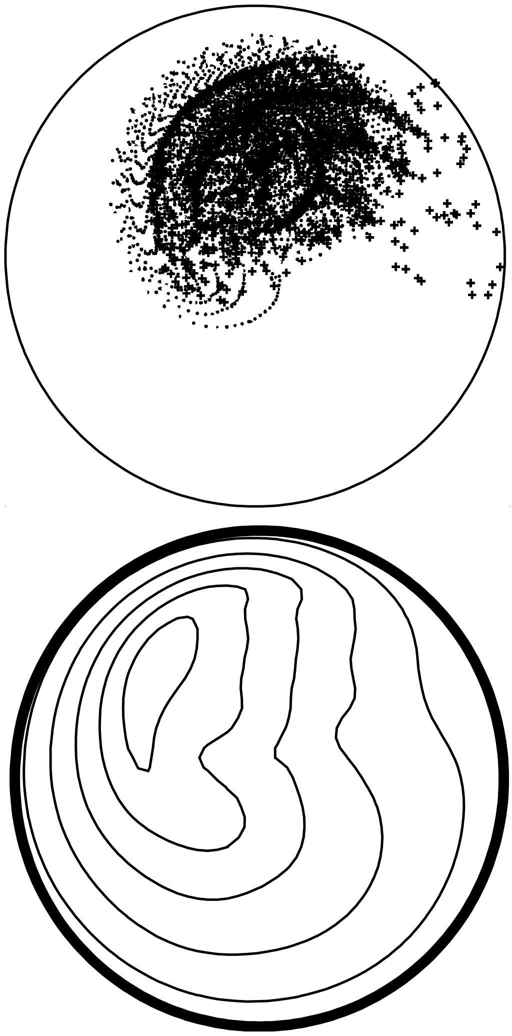

Fig.4. The same as in Fig.3, but for cross-section coordinate $\tau = 1.0$

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