Periodical plasma structures controlled by external magnetic field

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Abstract. The plasma of Hall thruster type in external magnetic field is studied in 2D3V kinetic simulations using PIC MCC method. The periodical structure with maxima of electron and ion densities is formed and becomes more pronounced with increase of magnetic field incidence angle in the plasma. These ridges of electron and ion densities are aligned with the magnetic field vector and shifted relative each other. This leads to formation of two-dimensional double-layers structure in cylindrical plasma chamber. Depending on Larmor radius and Debye length up to nineteen potential steps appear across the oblique magnetic field. The electrical current gathered on the wall is associated with the electron and ion density ridges.

1. Introduction

Recently some methods to control the Hall thruster characteristics with applying the oblique magnetic field with respect to the channel walls are widely discussed [1,2]. Nevertheless with increasing the inclination of the magnetic field, discharge plasma properties can essentially change. For example, a several stationary, magnetized, two-dimensional weak double-layers were observed in a laboratory experiment for this type of plasma [3]. The double-layer potential drops were found to be followed across any given potential profile. In [4] it was shown in PIC simulations that weak magnetization results in the double-layer electric-field alignment of particles accelerated by these potential structures and that strong magnetization results in their magnetic-field alignment. A morphological invariance in two-dimensional double-layers with respect to the degree of magnetization observed in [4] implied that the potential structures scale with Debye lengths rather than with gyroradii. In this work, in kinetic simulations we consider the direct current discharge plasma in the external oblique magnetic field at low gas pressure, $P=10^{-4}$ Torr. The purpose is to study the plasma structure modification with changing the electron temperature, magnetic field strength and incidence angle for the conditions similar to the Hall thruster.

2. The physical model and simulation algorithm

In our simulations, the plasma is embedded in a cylindrical metallic chamber with the radius of 4 cm and the height $H=10$ cm. The calculation domain is shown in Figure 1. The cathode made from metal material with the radius of 3 cm is placed 0.3 cm apart from the chamber bottom. All walls of the chamber made from stainless steel are grounded and the cathode is biased with $-90$ V. A plate made from Al₂O₃ is placed near the side wall. In some variants we considered the secondary electron emission (SEE) effect on the sheath near the wall.
The external magnetic field \( B \) is assumed to be constant over the plasma volume. The magnetic field is axially symmetrical. To avoid the singularity at \( r=0 \), we took the magnetic field angle \( \alpha_B \) in the following form: \( \alpha_B = 0 \) at \( r<r_1 \), \( \alpha_B = \alpha_0 \) at \( r>r_2 \), \( \alpha_B \) is approximated by a quadratic spline function at \( r_1<r<r_2 \). In simulations, we took \( r_1=0.3 \) cm and \( r_2=0.6 \) cm (see Figure 1). The \( \alpha_0 \) ranges from 0 to 77° in different variants, the strength of magnetic field \( B \) is from 25 to 100 G.

The magnetized plasma is described with the system of equations including the Boltzmann equations for electrons and ions and fast neutral atoms. The distribution functions for electrons \( f_e(t,x,v) \) and ions \( f_i(t,x,v) \) are calculated by solving the Boltzmann equations

\[
\begin{align*}
\frac{\partial f_e}{\partial t} + v_e \cdot \frac{\partial f_e}{\partial x} + \frac{e(E + v_e \times B)}{m_e} \frac{\partial f_e}{\partial v_e} &= J_e, \\
\frac{\partial f_i}{\partial t} + v_i \cdot \frac{\partial f_i}{\partial x} + \frac{e(E + v_i \times B)}{m_i} \frac{\partial f_i}{\partial v_i} &= J_i,
\end{align*}
\]

and the Poisson equation for the electric potential \( \varphi \) is also solved:

\[
\Delta \varphi = 4\pi \varepsilon (n_e - n_i), \quad \mathbf{E} = -\frac{\partial \varphi}{\partial \mathbf{r}}.
\]

where \( v_e, v_i, n_e, n_i, m_e, m_i \) are the velocity vectors, densities and masses of electrons and ions respectively, \( \mathbf{E}, \mathbf{B} \) are the electrical and magnetic field vectors, \( J_e, J_i \) are the collisional integrals for electrons and ions. The Particle in Cell Monte Carlo Collision (PIC MCC) method [5] was applied to solve the Boltzmann equations, which are two-dimensional in space and three-dimensional in velocity space. The system of equations are solved self-consistently with PlasmaNOV code [6]. For the electrons, the model includes elastic scattering, excitation and ionization collisions are accounted; for ions, the resonant charge exchange collisions with background argon gas are included. Additionally, the external ionization is included as electron-ion pairs generation with the Maxwellian distributions with the electron temperature \( T_e \) from simulation and the ion temperature \( T_i = 0.05 \) eV. The calculation grid is uniform over \( z \)-direction and nonuniform over radius condensing with increasing \( r \).

Figure 1. Scheme of calculation domain. \( B \) is the magnetic field vector, \( \alpha_B \) is angle between \( B \) and the normal to the side wall.

Figure 2. Distribution of potential \( \varphi \) (V) for \( B=50 \) G, \( \alpha_B=65^\circ \) and \( T_e=5 \) eV.
3. Results

The periodical structure with ridges of ion and electron densities is observed for larger inclination of magnetic field. For $\alpha B$ smaller than $27^\circ$ shown in Figure 3(a), the electron density is almost uniform in the central part of the chamber. In general, the plasma looks very similar to the case of $\alpha B = 0$. The developed sheath forms near the cathode, with the potential drop of approximately 90 V. A weaker sheath screens plasma from walls of the chamber with the potential drop of $\approx 3$ V. The sheaths can be seen in Fig.3 as areas with the depleted electron density.

With increasing $\alpha B$ the periodical plasma structure becomes clearly visible (see Figure 2 and 3). The electron and ion ridges are shifted with respect to each other and double–layer structure appears across the magnetic field and along the potential rise. The double-layers structure forms due to a distortion of local quasineutrality in the presence of inclined magnetic field. The electron is shifted from the ion in the direction normal to the magnetic field and a local charge appears. The structure occupies the quasineutral part of plasma in which the electrical field is small. Within the cathode sheath it does not appear even for large $\alpha B$. More complex situation takes place in the wall sheath. As the potential drop over the wall is small (3 - 8 V), the Lorentz and electrical forces are comparable there. Therefore the wall sheath becomes modulated by B-field with increasing $\alpha B$.

In Figure 4(a), the electron current $j_e$ near the wall is shown for two values of $\alpha B$. It is seen that the currents approaching the wall are affected by a variation of $\alpha B$. The $j_e$ profile over $z$ taken at $r = 3$ cm is almost uniform for $\alpha B = 10^\circ$ and has peaks for $\alpha B = 65^\circ$. Each electron current peak is splitted with a scale of $2r_L$, where $r_L$ is Larmor radius. The ion current near the wall also exhibits peaks for larger $\alpha B$. This effect can lead to an additional local erosion of wall material.

Figure 4(b) shows the potential distribution across B-field. The charge distribution has negative and positive ridges, since the sheets of large negative and positive charges appear in quasineutral plasma due to relative shift of $n_e$ and $n_i$ in the direction of increasing potential and across B-field. This structure is called as double-layers and characterized with the non-monotonic potential distribution. Cross sections of the potential distribution in Figure 4 are taken along the dashed lines which start at $r=0$ and $z= 7$cm, 8 cm and 9 cm. For this case the potential bumps across magnetic field is about 0.5 V. The presence of magnetic field enhances the charge separation. For this case we can distinguish seven double-layers. The double-layers form due to a distortion of local quasineutrality in the presence of oblique magnetic field. When electron-ion pair appears after an ionization event an electron begins
Larmor gyromotion. The electron is shifted from the ion in the direction normal to B-field and a local charge appears.

The characteristics of plasma structure such as the number of peaks, gap between them, their broadening depend on the Larmor radius $r_L \sim T_e^{-0.5}/B$, Debye length and the size of quasineutral plasma. The structure exists within some ranged of $r_L$ and $n_e$. With increasing $r_L$ and decreasing $n_e$, the density peaks begin to overlap due to increasing broadening and the plasma loses the periodical structure.

In conclusion, the 2D3V PIC MCC simulations of dc discharge plasma in the cylindrical chamber at low gas pressure have been performed. The plasma was maintained by external ionization and confined by inclined magnetic field. The periodical structures with ridges of ion and electron densities have been found for larger inclination of magnetic field. The electron and ion ridges were shifted with respect to each other and periodical double-layer structure appears across magnetic field vector and along the potential rise. The flow channels of current to side wall are associated with ridges of electron and ion densities.

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