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Research of electron distribution function traits in discharge chamber of ion thruster using "Particle-in-cell" simulation

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Abstract

Non-stationary kinetic PIC simulations had been performed for an ID-50 ion thruster. The analysis of simulation results revealed that electrons in a discharge chamber of an ion thruster have non-Maxwellian distribution. There are two basic mechanisms responsible for deviation of the electron distribution function from the equilibrium one. The first one is determined by a monoenergetic stream of primary electrons in the axial region of a discharge chamber. The second mechanism is a peculiarity of electron motion in the near anodic region. Only particles with near-zero component of velocity along magnetic field lines may exist there long enough.

Introduction

Keldysh Research Center is currently working on the subject of ion thrusters development [1-5]. Studying the physics of processes in the ion thrusters plasma and solving engineering problems, preliminary approbation of promising solutions and design improvement requires mathematical modelling.

A set of models describing plasma processes in electric propulsion systems has been developed at Keldysh Research Center [6-10]. The special PIC model has been developed to research plasma in a discharge chamber of an ion thruster. This model uses the experience of previous models development. At the same time, it has a number of innovations that make it possible to take into account the features of the system of interest.

Data on the electron velocity distribution function (EVDF) in the discharge chamber of the ID-50 thruster has been obtained as the outcome of modelling. This thruster has been chosen since there is a large amount of experimental data [11] available for validation of numerical results. The obtained simulation results are in good agreement with the experiment [12]. Also the ID-50 has small size so its simulation requires lower computational time.

Various features of EVDF such as its shape in different points of a discharge chamber have been explored via analysis of the obtained data set. The purpose of this work is to present results of this analysis. One should note that knowing the shape of EVDF and understanding the mechanisms causing this shape are of great interest. It provides insights in the physical picture of the discharge and it is useful while constructing adequate hybrid or hydrodynamic models of discharges typical for ion thrusters.

1. Model

The 2D3V-FullPIC model has been developed according to the classical scheme for PIC models. Plasma is considered as mixture of three components: neutrals, ions and electrons. The motion of the macroparticles is modelled under conditions of the self-consistent electric and stationary magnetic field. Elastic electron-neutral collisions, inelastic electron-neutral collisions, electron-neutral ionization collisions, Coulomb collisions of electrons and crosscharging collisions of ions with neutrals are included in the model. These reactions are simulated using Monte Carlo method. Bohm diffusion is modelled using additional elastic collisions [13] with a frequency that depends on the value of the magnetic field:

$$\nu_B = \frac{1}{16}\frac{eB}{m_e}. \qquad (1)$$

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The classical trick [14], based on tuning of the electric permeability coefficient (via multiplying it on some factor τ) in Poisson's equation is applied to ensure that the resolution of spatial and temporal scales are enough for the stability of numerical solution.

$$\nabla^2\varphi = -\frac{e}{\tau^2\varepsilon_0}\left(n_i - n_e\right) \tag{2}$$

In this equation φ is the electric potential, n_i and n_e are the concentration of ions and electrons respectively.

There is a number of peculiarities added to this model that make it different from the closest analogues [15,16]. Firstly, the model does not require specifying any plasma parameters from preceding experimental data or theoretical assumptions. Input data is a simple set of parameters defining thruster operating mode: geometry of the chamber, topology of the magnetic field, gas flow rate to the cathode and the gas distributor, discharge current, transparency coefficients of ion optics for ions and neutrals.

Secondly, near-wall plasma layers are included into the modelling area, being modelled directly via fine tuning of the coefficient τ. Consequently, their thickness in the simulation is greater than in the experiment. Nevertheless it does not influence the model physics considerably as long as the thickness of the layers remains small in comparison with the characteristic scale of the system.

The third feature is the technique for modelling the cathode as a source of primary electrons. The technique based on artificial maintaining of quasineutrality near the cathode boundary by adding new particles is used instead of specifying a stationary particle flux. Thus, the discharge receives just as many new electrons as it can "pull" out of the cathode plasma, which is a good approximation for the real physics.

The fourth distinctive quality implies taking into account the behaviour of the discharge power source operating in the current stabilization mode. The discharge voltage is automatically adjusted so as to keep the actual discharge current at the predetermined level.

All of the above model features made it possible to simulate plasma in a discharge chamber of ion thruster as a flexible self-consistent system in which the influence of unnatural constraints is minimized.

2. Input and output data of the simulation

Simplified scheme of the ID-50 ion thruster is shown in Figure 1.The cathode is on the left side of the gas-discharge chamber on the symmetry axis and the ion-optical system is on the right side. The annular anode wraps the chamber (bottom and top of the figure). The dashed line shows the axis of symmetry of the chamber, the solid curves present magnetic field lines.

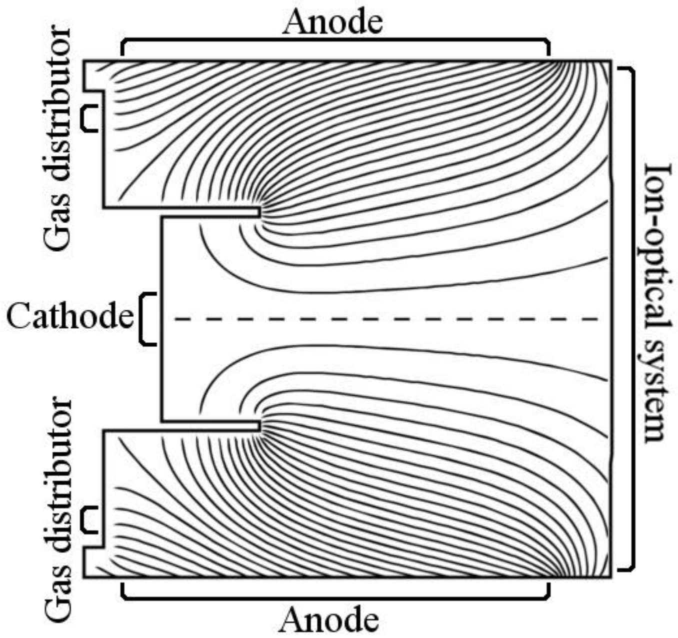

Figure 1. The scheme of simulated thruster discharge chamber.

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Several series of simulations for various operating modes have been carried out. The parameters of the regimes, the obtained simulation results and their comparison with the experimental data are described in [12]. Input parameters of the mode under consideration are shown in Table 1.

Table 1: Input parameters for simulation

Discharge current, A	0.72
Magnetic coil current, A	4.0
Gas distributor flow rate, mg/s	0.08
Cathode flow rate, mg/s	0.04
Base timestep, s	$5.0 \cdot 10^{-11}$
Macroparticle size	$1.0 \cdot 10^{8}$
Mesh scale, m	$0.5 \cdot 10^{-3}$
Parameter τ	7.5

Simulation output integral data and corresponding experimental data are shown in Table 2. It can be seen that the simulation results are in good agreement with the experiment. Such correlation allows us to believe that the model reproduces the physical picture quite accurately. The data obtained by modeling the nominal mode were used for the EVDF analysis.

Table 2: Simulation output integral data parameters and experimental data

	Experiment	**Simulation**
Discharge voltage, V	39.7	42.3
Plume current, mA	75.0	73.6
Ion production cost, W/A	381.1	413.9
Propellant utilization efficiency	0.83	0.82

Distributions of the plasma parameters for the mode obtained by simulation are shown in Figure 2.

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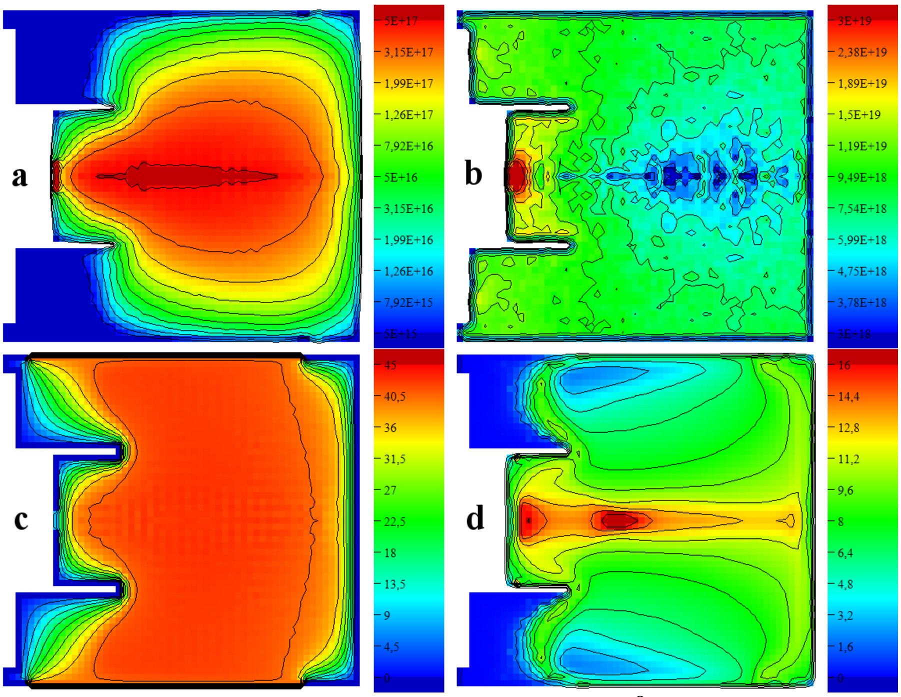

Figure. 2. Plasma parameters distributions: (a) plasma density, m^{-3}; (b) neutral gas density, m^{-3}; (c) plasma potential, V; (d) electron energy, eV.

Maximum of plasma density is located on the axis of the chamber and is adjacent to the cathode. Its location is determined by the trajectories of the primary electrons. The distribution of the neutral gas has the minimum in the central part of the chamber due to ionization. The distribution of electric potential has a shape of a flat plateau bounded by the near-wall layers. The electron energy distribution has a complex form with its maximum located in the central part of the chamber. The electron energy decreases toward the anode.

3. Electron velocity distribution function

The data of spatial distribution of electron temperatures along ($T_{\parallel}$) and across the magnetic field ($T_{\perp}$) have been analyzed to investigate the dependence of EVDF shape with respect to the position in the discharge chamber. Figure 3 shows the spatial distribution of the ratio $\beta = \frac{T_{\parallel}}{T\perp}$. The magnetic field lines are also shown in the figure.

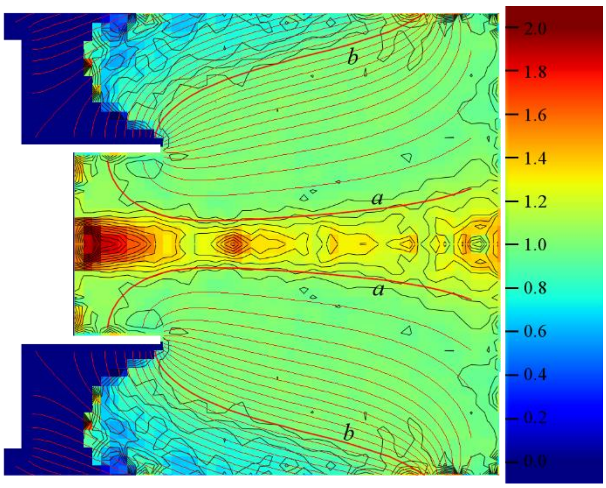

Figure 3. The ratio $\beta = \frac{T_{\parallel}}{T\perp}$ of the temperature along the magnetic field to the temperature across the magnetic field. Magnetic field lines.

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The value of $\beta \approx 1$ suggests that the EVDF is close to isotropic one. Small β indicates that the EVDF has a flat shape i.e. it is compressed in the direction of the magnetic field lines. Large β means the opposite: the EVDF is stretched in the direction of the magnetic field lines.

It can be seen from the given data that there is an extensive region, remote from the axis of symmetry, where the value of β is close to unity. This region is located between curves a and b in Figure 3. The EVDF in this region is isotropic.

The value of β decreases to almost zero and the EVDF flattens while approaching the anode. Herewith, the level curves of β correspond to the magnetic field lines. The mechanism for the appearance of this anisotropy is as follows. Electrons that are moving along the magnetic field quickly flow out via the anode. Consequently, in this direction the EVDF decreases, which makes its shape flat.

In the domain near the axis of symmetry bounded by curve a, the value of β significantly exceeds unity. EVDF is stretched across the magnetic field lines here. This is due to the presence of a beam of primary electrons in this region. These particles entered the chamber from the cathode plasma, thus gaining the energy of the cathode drop of potential. The large sections of the trajectories of the primary electrons coincide with the direction of the magnetic field lines, which causes such anisotropy of the EVDF. Note, that in this region the beam actively dissipates due to collisional and oscillatory processes.

In addition to the analysis of the spatial distribution of $\beta = \frac{T_\parallel}{T_\perp}$, the electron energy distribution function (EEDF) in various segments of the chamber has been studied. The exact arrangement of the segments in the discharge chamber is shown in Figure 4.The first segment denoted by I is the neighborhood of the symmetry axis. The second one marked with II is the region of isotropic EVDF. Segments III and IV are located close to the anode.

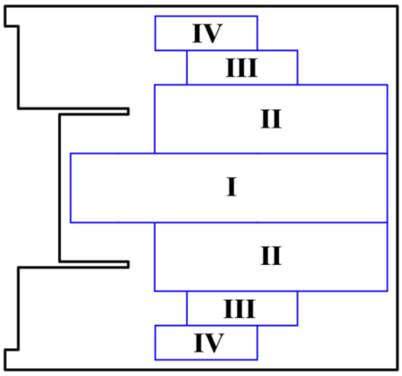

Figure 4. Arrangement of the segments in the discharge chamber

In each of these segments, the empirical EEDF was approximated by a gamma distribution

$$f_{k,T}(\mathcal{E}) = \frac{(1/T)^k}{\Gamma(k)} \mathcal{E}^{k-1} \exp\left(-\frac{\mathcal{E}}{T}\right) \tag{3}$$

with shape and scale parameters k and T respectively. Distribution functions obtained via simulation and their approximations for each segment are shown in Figure 5 (the blue histograms and green curves respectively). As can be seen from the figure, the green and blue curves almost coincide, thus the choice of the gamma distribution for approximation is justified.

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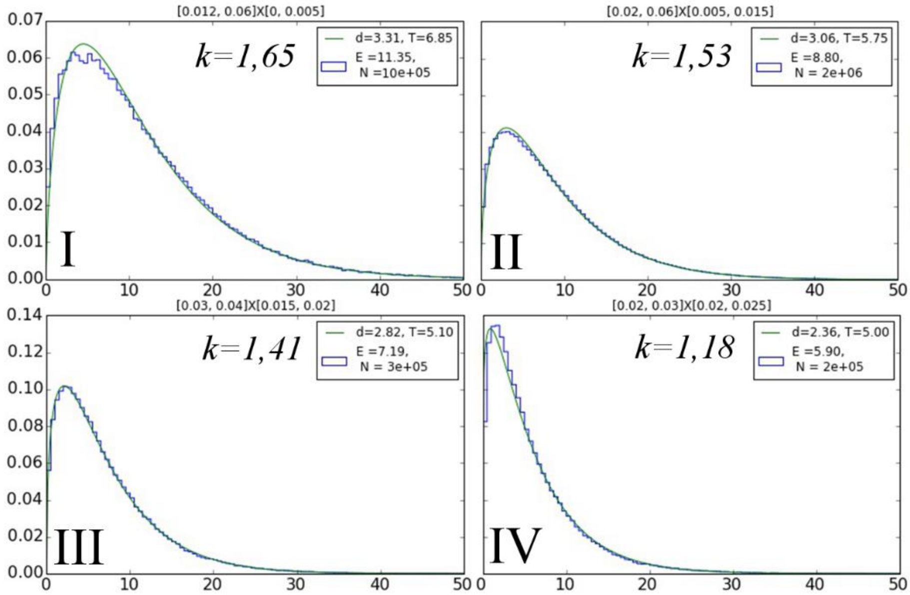

Figure 5 – The electron energy distribution functions (eV) in different segments of the discharge chamber

Here the Roman numerals denote the segments. The boundaries of the segments are indicated above each graph separately. In the picture, the parameters of the sample distributions (the amount of statistics, the sample mean), as well as the parameters of the approximating gamma distributions (form parameter $k = d/2$, scale T) are given.

It is known that the d-dimensional (for integer d) Maxwell distribution of kinetic energy with temperature T coincides with the gamma distribution $f_{k,T}$, where $k = d/2$. Thus, the latter can be regarded as a generalization of the Maxwell distribution to the case of non-integer degrees of freedom d. For $k \approx 1.5$, it is close to the standard Maxwell distribution with three degrees of freedom, and for $k \approx 1$ to the two-dimensional one.

In segment II, where the EVDF is isotropic, the parameter k is close to 1.5. Consequently, the EVDF in this segment is close to the Maxwellian one. The value of k decreases to unity while approaching the anode (segments III and IV). These values of k correspond to the two-dimensional Maxwellian distribution. Which means that the shape of the EVDF becomes flat. The EVDF in the direction of the magnetic field concentrates around zero and remains Maxwellian across the magnetic field.

The dependency of the EEDF shape from position in the discharge chamber can be seen in detail in Figure 6, where the spatial distribution of k in the modelling domain is shown.

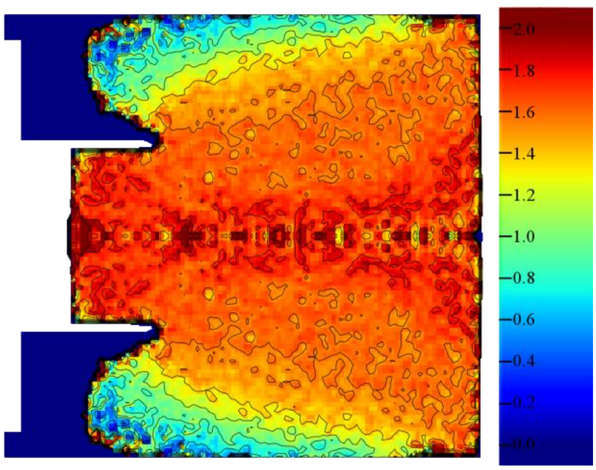

Figure 6. Distribution of the parameter k in the modeling domain.

These data correlate with the data on spatial distribution of β. The region where the parameter $k \approx 1.5$ coincides with the region where $\beta \approx 1$. The structure of the level curves of k(as well as of β) is determined by the topology of the magnetic field lines. This confirms and clarifies the earlier conclusions concerning the EVDF.

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Conclusion

This paper deals with the electron distribution function in the discharge chamber of the ion thruster ID-50. The study was carried out using the software package developed at Keldysh Research Center for modelling plasma in a discharge chamber of an ion thruster. The package is based on the 2D3VFull-PIC model.

It was found that the EVDF deviates from the Maxwellian distribution in certain regions of the discharge chamber. Two different mechanisms responsible for these deviations have been revealed. In the central part of the chamber the shape of the EVDF is determined by a monoenergetic beam of primary electrons. In the near anodic region a strong anisotropy in the motion of electrons is manifested due to the rapid loss of electrons moving along the magnetic field.

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