Visualization of the charged particles movement features in conditions, which are characteristic for the Hall Thruster discharge interval as the technique for the students training in space electric propulsion

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Abstract: During students training in electric propulsion of spacecraft, for exploration of features of charged particles dispersion and movement in the Hall thruster (HT) discharge interval the computer program of visualization was used. Such program allows investigating features of electron and ion movement lengthways Larmor trajectories, distributions of the charged particles and integral characteristic - thrust. It was set as a boundary condition: bi-dimensional distribution of magnetic field and a potential of an electric field, permanent distributions of the charged and neutral particles, close to the wall potential drop. The program enables to "turn off" collisions of electron-atom or electron - charged particles, to take or not to take into account an energy exchange at electron collisions that enables to study in details a role of separate processes in plasma of HT.

Nomenclature

B	=	magnetic induction
E	=	electric field strength, energy
I	=	current
M, m	=	ion and electron mass
n	=	concentration
P	=	probability
q	=	elementary charge
U	=	discharge voltage
V	=	velocity
σ	=	cross-section of some process
ε	=	electron energy
φ	=	potential of electric field
λ	=	length of electron run way

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I. Introduction

Progress in space electric propulsion technologies depends upon professional level of engineers and researchers, who solve scientific and technical problems. For successful preparation of the qualified experts, it is necessary to create conditions, in which students would have got already available knowledge in relatively short term, and on the other hand would have an opportunity to develop the creative potential as the future researchers. Representation of the information as accessible to understanding has the great importance during students training. Especially it concerns to that information, which is base and at the same time - complicated for perception. The problem can be solved by using computer program, which allow to visualize many important features of processes for example in discharge interval of Hall thruster (HT)

II. Mathematical model for detail studying of an electron movement in discharge interval of HT

Main principles of mathematical modeling as bases of the visualization program are the next.

The task was solved based on a Monte-Carlo method. The electron movement trajectory in discharge chamber (DC) is determined by numerical integration of the differential equations system of the charged particle movement with an charge - q, weight - m, in a crossed magnetic field with components B_z and B_x and electric field – E_z and E_x (Fig. 1):

$$\begin{cases} m \cdot V'_y = -q \cdot B_z \cdot V_x + q \cdot B_x \cdot V_z \\ m \cdot V'_x = -q \cdot E_x + q \cdot B_z \cdot V_y \\ m \cdot V'_z = -q \cdot B_x \cdot V_y - q \cdot E_z \end{cases} .$$

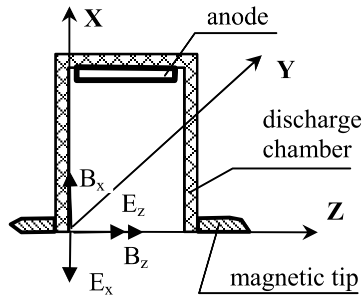

Figure 1. Coordinate system linking to the discharge chamber

Elastic and not-elastic electron collisions are considered: single ionization from the basic level and elastic dispersion on atoms and ion. The collision mechanism is modeled by probability P of an electron run way λ before realization of interesting process under the formula

$$P(\lambda / \lambda_0) = \exp(-\lambda / \lambda_0),$$

where λ_0 - average length of an electron run. Size λ_0 is defined as $\lambda_0 = V_e/(\beta \cdot n_e)$, where $\beta = \langle \sigma \cdot V_e \rangle$ - factor of process speed, σ - cross-section of process. In a case of coulomb dispersion on ion, the λ_0 in a range of angles from 0.1 up to 180 degrees is used. Estimate value λ_Θ as

$$\lambda_\Theta = \left[\left(q^2 / 8 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_e \right)^2 \cdot \Lambda \cdot \pi \cdot 2 \cdot n_e / \Theta^2 \right]^{-1}$$

(according idea[1]), where: q - an individual charge; ε_e - the energy determined by the speed V_e of charged particles mutual movement; Θ - a corner of dispersion; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ – constant, $n_e(x)$ - concentration of electrons. For λ_0 calculation the data of characteristic primary distribution of plasma parameters lengthways DC are used.

Electron-atom interaction is modelled in view of electron-atom angular scattering characteristic (Fig. 2) depending on kinetic energy ε_e like[1].

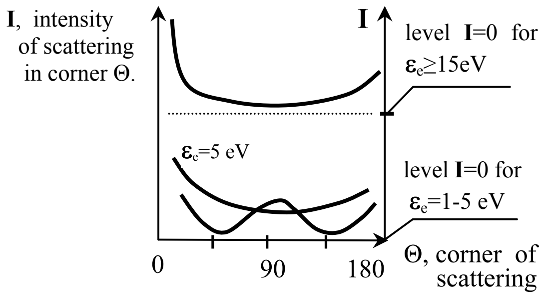

Figure 2. Quality characteristic of angular distribution of the electron (with energy ε_e) scattering intensity at elastic and non-elastic Xe atom collisions.

Processes recombination occurs only on surface DC at not-elastic collision of an electron with DC wall. SEE – secondary electron emission yield δ of surface (properties of acid Al_2O_3) was determined as

$$\delta = B \cdot E_p \cdot \left[14/5 \cdot E_g \cdot \exp\left(E_p / E_{pm}\right)\right]^{-1},$$

where: E_p - energy of a primary electron; B=0.68 for Al_2O_3; E_{pm}=512 eV - energy of a primary electron at which $\delta=\delta_m$ - it is maximum; $E_g\approx$9.9 eV - width of the forbidden zone.

III. Charge particles movement modelling

After beginning of the program, electrons from the cathode start consistently and their movement up to an input in DC or before their absorption by a surface is traced; or electrons from an input in DC start consistently and their movement before absorption by the anode or before absorption by a wall is traced. Features of movement of an electron and ion can be studied in bi-dimensional and three-dimensional space.

As a result of execution of the program characteristics of electrons penetrated in DC (three components of speed and coordinates) are recorded. Then these data are used as entry conditions to study features of electron movement inside DC. “Instant photos” of an electron trajectory – line of white color and for ion trajectory – line of red color are submitted in Fig. 3, 4 for SPT M-25 size type. Red points mark places, where ionization collision of an electron has been performed. The green points - places where there was an elastic electron-atom collision. Dark blue points mark places, where collision of an electron with the charged particle took place. Trajectories of electrons inside DC are shown in Fig. 3. Trajectories in area between the cathode and an input in DC are shown in Fig. 4.

Besides, during execution and after finishing of the program the data are formed: distribution of ion and electron in discharge interval, average electrons energy E_{ever}, average speed of electron movement along DC axis V_{axial} and integral characteristic – thrust for SPT M-70 type on nominal operation mode, like in Fig. 5, 6, 7. The program can be supplemented with other boundary conditions and techniques of data processing.

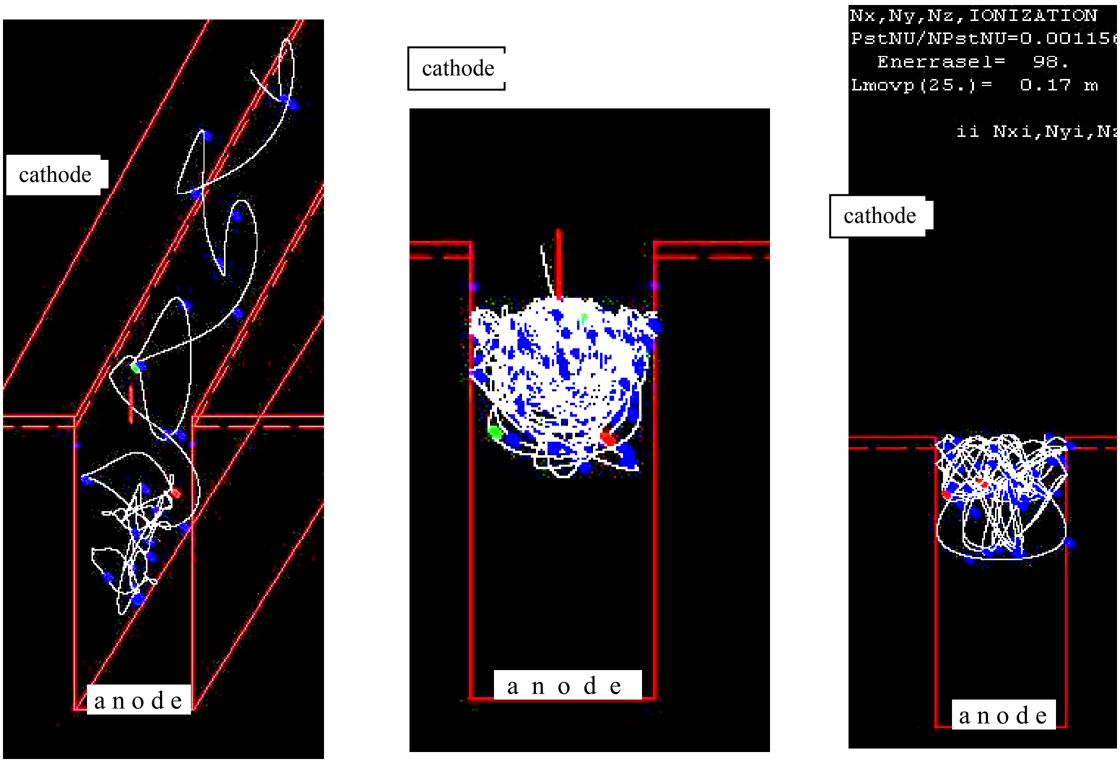

Figure 3. Trajectories of electrons inside discharge chamber of HT.
Color point – place of electron collision. Red points mark places of ionization collision. Green points mark places of elastic electron-atom collision. Dark blue points mark places, where collision of an electron with the charged particle taken place. Red lines – ion trajectories.

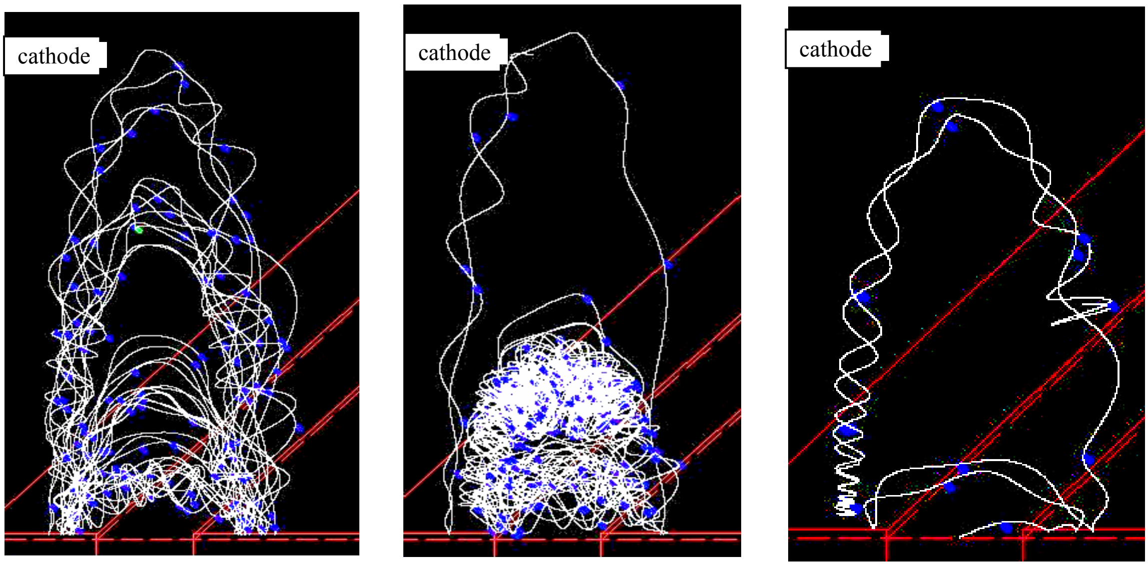

Figure 4. Trajectories of electrons in area between the cathode and an input in the discharge chamber of HT. *Dark blue points mark places of an electron collision with the charged particle.*

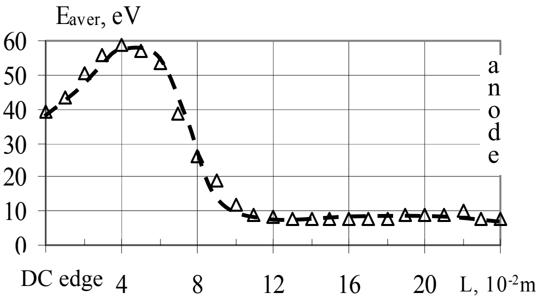

Figure 5. Average energy of an electron – E_{aver}.

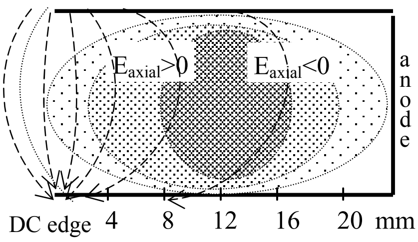

Figure 6. Electron concentration in DC.
--- *Line of equal electron concentration*
<-- *Magnetic field strength line in DC*

IV. Conclusion

Computer program for students training in spacecraft electric propulsion, which allow investigating features of electron and ion movement via visualization of its trajectories in discharge interval of Hall thruster, was development. The program enables to study in details a role of separate processes in plasma of HT by "tern off" some collisions or energy exchange. Due to the program students have got already available knowledge in relatively short term, and on the other hand have an opportunity to develop the creative potential as the future researchers.

References

[1]E.W., McDaniel. Collision phenomena in ionized gases, New York-London-Sydney, 1964, pp. 155, 781.

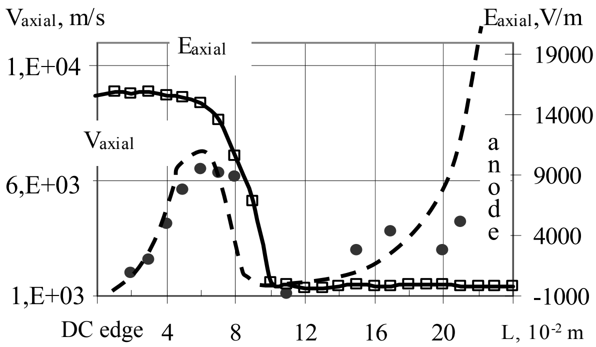

Figure 7. Electron velocity to the anode and electric field strength E_{axial}. *Thrust – 4.4 g.*