Ways and Methods of Accuracy Increasing of Thruster Plasma Parameters Determining by an Electric Probe

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Abstract: **Inaccuracies of a technique, which is traditionally used for processing experimental Langmuir probe volt-ampere characteristics, are analyzed. Features of probe-plasma interaction in areas of strong and weak magnetic and electric fields are studded numerically. In both areas, based on a preliminary estimation of electron temperature, velocity of ions and plasma density, potential distribution in a layer nearby the probe is calculated from Poisson equation. As results of numerical experiment dependences of electron temperature, determined in traditional way, on probe potential and on probe orientation in plasma flow are determined.**

Nomenclature

B	=	induction of magnetic field
I_i	=	ion current in a plasma stream
m	=	mass of electron
M_i	=	mass of ion
n_e	=	electron concentration
q	=	elementary charge
R_L	=	Larmor radius
r_s	=	extent of a "double" sheath including radius of a probe
T_e	=	electron temperature
φ	=	potential of electric field
φ_{pl}	=	plasma potential
φ_{pr}	=	probe potential
φ_f	=	probe floating potential

I. Introduction

TO understand the processes that occur in plasma thrusters and on this basis to search for ways of its operation efficiency increasing it is necessary to diagnose its plasma. Among various methods of determining parameters of the plasma, generated by thrusters, the method of Langmuir electric probe[1] is widely used. The main advantage of

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this method is the opportunity to determine local plasma parameters, simplicity of a design of a probe and simplicity of a technique of processing measurement results, together with weak influence of a probe on plasma. In plasma of thrusters practically only by the method of electric probe it is possible to determine space (non-uniform in a radial direction) distribution of plasma potential, which is the major parameter, when researches of processes of a working substance ionization and acceleration are curried out. This research has been curried out to improve of a technique of plasma diagnostics by Langmuir probe.

II. Langmuir techniques of the probe V-I characteristics processing and real plasma conditions

Conditions (or assumptions) that are necessary to use of a technique of measurement results processing (probe volt-ampere characteristic - V-I measured like in Fig. 1) suggested by Langmuir, which can be named as "classical", are the following: - the charged particles fall on all receiving surface of a probe; - between a sheath of a spatial charge (in which the main potential drop is allocated) near to a probe and plasma, it is allocated extended quasi neutral area, so-called "presheath". In this "presheath" potential drop about $\sim T_e/2$ (due to which potential drop energy of the directed movement of ions increases on $T_e/2$) is allocated; - speed of ions on an input in "presheath" is determined by thermal energy of atoms; - the magnetic field does not influence on character of movement of particles; - the electric field of a probe does not bend a trajectory of movement of the charged particles near to a probe; - extent of a "double" sheath (including a sheath and "presheath") near to a probe is much less than sizes of a probe.

The analysis of real parameters of a plasma stream, for example characteristic for the Hall thruster (HT), shows that not always assumptions of Langmuir theory hold true. When the ion speed is large, breaking of plasma layer without formation of "presheath" can occur. In a zone of ionization gas and acceleration of ions the strong magnetic and electric field influence movement of electrons so that the size of a probe appears to be of one order with characteristic free path of an electron - height of a cycloid of its trajectory of movement. In these zones and also in a stream of plasma outside the thruster, extent of a sheath appears to be of one order with the sizes of a probe and consequently the electric field of a probe influences trajectory of movement of the charged particles so, that the part of an electron stream flow round a probe. Thus, for probe measurements practically in all area of a plasma flow complication of methods of processing probe measurement results is required by taking into account of the charged particles movement features near to a probe. Among the charged particles, it is necessary to take into account, at first, features of electron movement since the stream of these particles determines probe current and, finally, - result - parameters of plasma. To investigate features of electron movement the separate zones in HT plasma flow are allocated, depending on a power of influence of a magnetic and electric field on electron movement.

III. Specification of a probe technique in a zone of weak magnetic and electric fields

A. Modeling of processes in plasma near to a probe

We assume that as the equivalent of length of an electron free path should be used its Larmor (gyro) radius R_L or height of a cycloid $2R_L$ of its trajectory. Following this idea we shall determine the minimal value of magnetic field B_{lim} since which it is necessary to take into account its influence on features of electrons movement near to a probe, from a condition

$$R_L >> r_s, \qquad (1)$$

where: r_s - extent of a "double" sheath including radius of a probe (for a round probe); Larmor radius R_L of an electron is determined as $R_L = m \cdot v/(q \cdot B)$ at a magnetic field B; velocity of a particle v; weight and a charge of a particle - m and q. Then it is necessary what $B_{lim} << m \cdot v/(q \cdot r_s)$. Then the characteristic electron energy is in a range of 2 … 5 eV and velocities is about 10^6 m/s, concentration of the charged particles is about 10^{17} … 10^{18} m^{-3} and it is

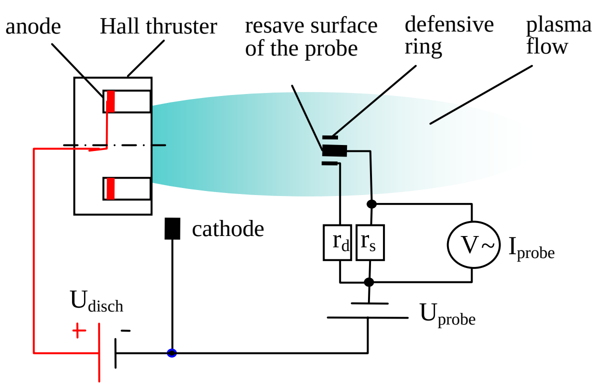

Figure 1. Electric circuit of the probe. r_d – balance resistance in the circuit of the defensive ring; r_s – resistance for probe current measurement, V – voltmeter.

characteristic $r_s \approx 10^{-3}$ m, the maximal value of an induction of magnetic field B_{lim} will be determined as $B_{lim} << B = m_e \cdot v_e / q \cdot r_s \approx 0.0056$ Tl. For the Hall thruster with the diameter of the discharge chamber channel of 70…100 mm this condition will hold true at distance more than 100…150 mm from edge of the discharge chamber.

We assume that in an investigated zone, in a stream of plasma, the ionization does not occur. Velocity of ions v_i of weight M_i on border of plasma and a sheath is determined by preliminary passed potential drop ΔU in an electric field of the thruster and by thermal energy of atoms T_a as

$$v_i = \sqrt{(2 \cdot q \cdot \Delta U + 2 \cdot k \cdot T_a)/M_i} \quad (2)$$

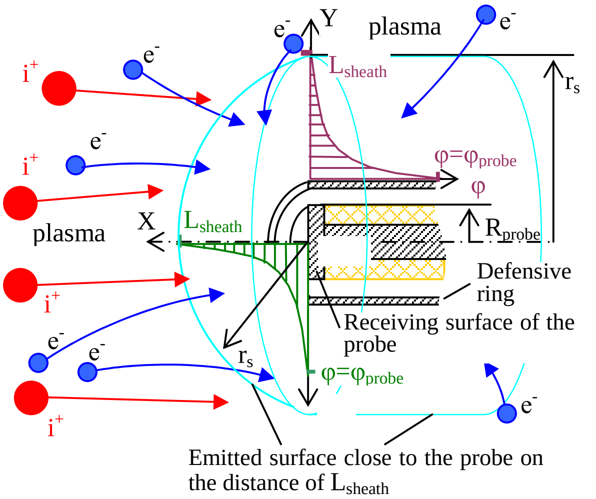

Figure 2. Potential distribution close to the probe and close to the surface of the defensive ring of the probe.

We also suppose that breaking of plasma layer without formation of "presheath" can occur. Taken the characteristic value of HT discharge voltage as about 300 V, the passed potential drop in an electric field of the thruster in studied area on distance more than 100 mm from the thruster is equal $\Delta U \approx 300$ V. We assume that intensity of an electric field in plasma does not exceed 10 V/m.

Let's conventionally allocate near to a probe a surface, which limits no disturbed plasma and we shall call it as emitting surface. We shall study features of movement of particles in a sheath near to a probe since this surface.

Distribution of potential φ(x) in a sheath near to a probe and extent of sheath L_l are determined by the Poisson equation in one-dimensional area as approached, and it is specified further on the base of results of numerical experiment. To solve the Poisson equation the following assumptions are done. It is assumed, that the electric field and potential of plasma on border of a sheath and plasma are close to zero, but can vary under influence of plasma heterogeneities (oscillations) with intensity of an electric field about T_e/l_D, where T_e - temperature of electrons, l_D – Deby length. Besides relative deviations in concentration of electrons and ions on border of a sheath up to $\varepsilon_n \approx 0{,}9999$ are possible. These boundary condition, reflecting real processes in plasma, can be use to solve the Poisson equation near to a flat probe.

Traditionally to solve the Poisson equation the Boltzman distribution of particles in potential field is used to determine distribution of concentration of electrons in a potential field of a probe. However, using Boltzman equation can lead to inaccuracies since in real conditions intensity of interaction of electrons among themselves within a sheath is not sufficient to apply this equation. Boltzman distribution was used by us as the approached distribution to solve the Poisson equation. Distribution of potential in a sheath was determined by the following differential equation

$$\frac{d^2\varphi}{dx^2} = -\frac{e}{\varepsilon_0}\left(\frac{I_i}{S_p \cdot e \cdot \sqrt{\frac{2 \cdot e \cdot \varphi(x)}{M} + v_i^2}} - \frac{\varepsilon_n \cdot I_i}{S_p \cdot e} \cdot \exp\left(-\frac{\varphi(x)}{T_e} \right) \right), \quad 3)$$

where v_i - velocity of an ion out a sheath of probe, is determined by equation (2); $2 \cdot q \cdot \varphi(x)/M$ - velocity which gets an ion with weight M, moving from border of plasma (where the potential is close to 0) in a direction of a probe up to section with coordinate x where the potential is equal $\varphi(x)$; I_i - an ion current in a plasma stream; S_p - the square of cross-section of a plasma stream; ε_n - a possible periodical relative deviation of concentration of electrons and ions; T_e - electron temperature.

Outcome of Poisson equation – $\varphi(x)$ distribution – is plotted in fig. 3.

Movement of the charged particles was modeled by system of the differential equations where: m - weight of the particle; $v_{x,y,z}$ - velocity; q - a charge of a particle; $E_{x,y}$ - superposition of intensity of an electric field of the thruster and a probe; $B_{x,y}$ - an induction of a magnetic field.

$$\begin{cases} m \cdot \dot{v}_x = q \cdot E_x - q \cdot v_z \cdot B_y, \\ m \cdot \dot{v}_y = q \cdot E_y + q \cdot v_z \cdot B_x, \\ m \cdot \dot{v}_z = q \cdot v_x \cdot B_y - q \cdot v_y \cdot B_x. \end{cases}$$

B. Numerical experiment

To study features of interaction of a probe with plasma numerical experiment on modeling processes in plasma near to a probe is carried out on the base of a Monte-Carlo method. One of the purposes of experiment was to determine influence of the limit sizes of a probe on results of determining plasma potential and electron temperature.

As boundary conditions characteristic experimental data of parameters of the plasma generated by HT, in area where the magnetic field weakly influences electron movement and results of measurements of a probe current are used. To carry out numerical experiment the temperature of electrons has been taken as $T_e=2.8$ eV on distance from the thruster of about 100 mm. Concentration of the charged particles on the same distance from an edge of the thruster $n\approx 2.2\cdot 10^{17}$ m^{-3}, and value of plasma potential concerning a basic electrode (cathode) - $\varphi_{pl}=30$ V. Radius of a reception surface of flat probe $R_{pr}=0.25$ mm (look fig. 4 a) and fig. 2), radius of a cylindrical probe is 0.125 mm (see fig. 4 b)) and length is 1 mm.

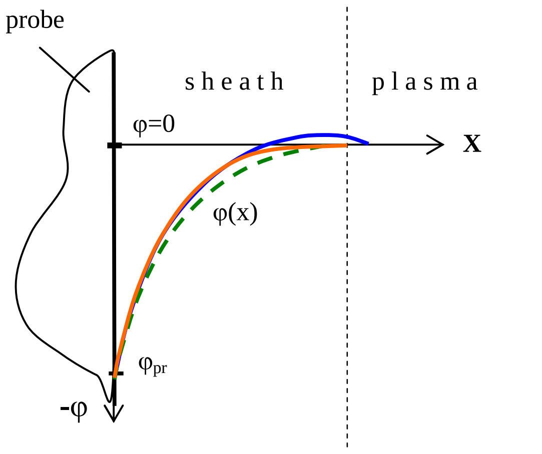

Figure 3. Curves φ(x) – outcome of Poisson equation than boundary condition, determined by plasma heterogeneities (oscillations), was sat as: $d\varphi/dx\neq 0$; $n_e\approx 0.9999\cdot n_i$.

By numerical experiment the emissive surface in plasma near to a probe has been shared conventionally in N parts, and it was assumed, that from each of these parts a separate stream of particles will start. Initial velocity of particles was set casually, but according to density of probability of Maxwell distribution function of particles on velocities. Range of determining electron distribution function on energy has been limited in a range from 0 up to $18\cdot T_e$.

By numerical experiment calculations were carried out in the following sequence. 1) As input conditions the plasma parameters determined by "classical" Langmuir technique were used. 2) On the base of Poisson equation extent of sheath L_l and distribution of potential near to a probe were calculated. 3) By numerical experiment were determined: electron I_e and ion I_i currents; the floating potential φ_{fl}; electron temperature T_e by a corner of an inclination of curve dependence $ln(I_e)$ from potential of a probe φ_{pr}; electron concentration as $n_e\sim I_e/(q\cdot T_e^{1/2})$ and plasma potential φ_{pl}. Distribution of the charged particles in a sheath was calculated by numerical experiment and was used for specification of extent of sheath L_l near to a probe and potential distribution in a sheath. These parameters can be specified repeatedly before numerical experiment until it will be received distributions of potential and concentration of charges in a sheath close to those that are set as initial.

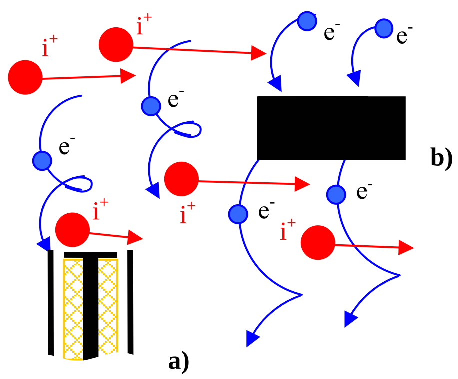

Figure 4. Some possible orientation of the probe with the flat receiving surface **a)** (flat probe) and cylindrical probe **b)** in a plasma flow.

Influence of conditions of numerical experiment (quantity of the particles used for modeling) on an electron probe current was analyzed. Results are resulted further.

C. The analysis of results of numerical experiment

By numerical experiments the ratio of the sizes of emissive surface R_{em} to a surface of probe R_{pr} has been chosen as $R_{em}/R_{pr}\geq 2$ when there is a saturation of a probe current at decreasing a probe potential.

Accepting as the "reference point" the plasma potential value of 30 V, it was determined the floating potential $\varphi_f\approx 22$ V and it was plotted V-I of a probe with a flat reception surface, directed as shown in fig. 4 b). To determine temperature of electrons, from a total probe current I_{pr}, determined during experiment, which is equal to a difference of electron currents I_e and ions I_i as $I_{pr}=I_e-I_i$, electron current I_e on a probe is allocated and dependence $ln(I_e(\varphi_{pr}))$, and then $T_e(\varphi_{pr})=-d\varphi/d(ln(I_e(\varphi_{pr})))$ was calculated. The difference between plasma potential φ_{pl} and the floating potential of a probe φ_f can be determined under the known formula

$$\varphi_{pl}-\varphi_f=T_e/2\cdot\ln(M_i/(2\cdot\pi\cdot m_e))\approx5.8\cdot T_e, \qquad (4)$$

where M_i and m_e - weights of Xenon ion and an electron.

The analysis of dependence $T_e(\varphi_{pr})$ (look fig. 5) shows, that the determined electron temperature is various in different ranges of φ_{pr}. The temperature determined in a range of a probe potential corresponding to the potential of plasma φ_{pl}, is equal $T_e=3.7$ *eV*. The temperature determined in the field of the floating potential φ_f $T_e=2$ *eV*. Reducing a probe potential below floating potential the temperature of electrons T_e increase and its error $\varepsilon=(T_{e1}-T_e)/T_{e1}\cdot100\%$ increase up to several hundreds percent increases.

Set by numerical experiment temperature of electrons $T_{e1}=2.8$ эВ to the greatest power there conforms to the temperature of electrons determined in a range from potential of plasma up to the floating probe potential, which is traditionally used for processing results of measurements.

Difference between plasma potential φ_{pl} and the floating potential φ_f is determined under the formula (4), following a "classical" technique. It was calculated $\varphi_{pl}-\varphi_f=5.8\cdot T_e=11.8$ V whereas in conformity with result of numerical experiment difference of plasma potential from the floating potential ≈11.6 V. Error of calculation of plasma potential by traditionally used technique will be equal to $(5.8\cdot T_e-11.6)/11.6\cdot100\%<2$ %.

Accepting as "reference point" the value of plasma potential of 30 V, the floating potential $\varphi_f\approx27$ V of a cylindrical probe (fig. 6), directed as shown in fig. 4 b), was determined, dependence of $T_e(\varphi_{pr})$ temperature on a probe potential and its error similarly to described above in this item, for a flat probe, was plotted. An observable significant error of temperature value, determining in various zones of dependence $T_e(\varphi_{pr})$, is the consequence of strong dispersion of electrons (overflowing a probe), when they move in a sheath near to a probe, that has the big curvature of a surface (look fig. 7).

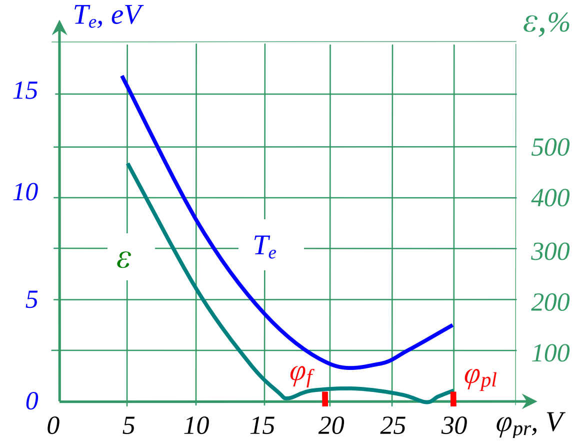

Figure 5. Dependence $T_e(\varphi_{pr})$ determined traditionally on the V-I characteristic calculated in numerical experiment in the **weak** magnetic and electric fields and its error ε. It was used **flat** probe and it was set electron temperature $T_{e1}=2.8$ eV in numerical experiment.

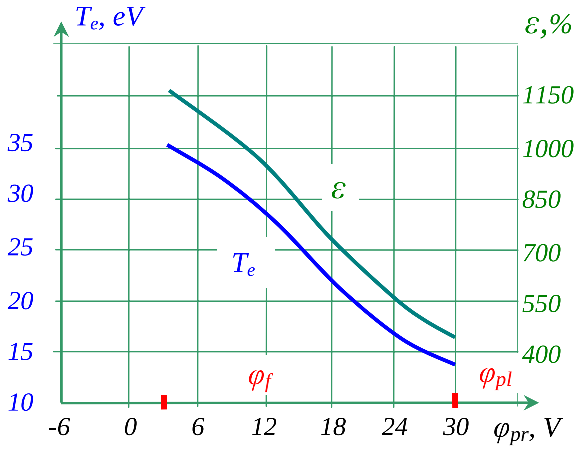

Figure 6. Dependence $T_e(\varphi_{pr})$ determined traditionally on the V-I characteristic calculated in numerical experiment in the **weak** magnetic and electric fields and its error ε. It was used **cylindrical** probe and it was set electron temperature $T_{e1}=2.8$ eV in numerical experiment.

IV. Determining plasma parameters in the field of strong magnetic and electric fields

A. Modeling of the electron distribution function formation process in crossed electric and magnetic fields

By modeling electron movement near to a probe in the crossed magnetic and electric fields, a separate important problem was "to create" group of electrons, which would have some (set before numerical experiment) temperature T_e. Thus, distribution of these electrons on energy should conform to (to be approximately equal to) Maxwell distribution function when they drift in the crossed electric and magnetic fields. Then, in numerical experiment it was enough "to start" these electrons in an investigated zone near to a probe. The problem was solved in some stages in the next way.

At the first stage, more simple situation was modeled. In area of the crossed electric and magnetic fields, electrons with the initial energy (that was chosen casually according to Maxwell distribution function and which had reference temperature T_{e0}) were "emitted". Their trajectory was determined by numerical differentiation of the electron movement equation system (look item **4.1**), where was used: $E_x << E_y = 300$ V/cm; $B_y << B_x = 15$ mTl.

During the casual moment of time, energy and components of an electron velocity recoded and dependence of density of the electron distribution function on energy (EDFE) f(ε) (lok fig. 8) was formed. Energy ε_1 to which maximum of EDFE is corresponds was determined. It was supposed, that true temperature of the electrons drifting in crossed electric and magnetic fields is equal to $T_e = \varepsilon_1$. Form of EDFE appears to be equal to f(ε), determined in numerical experiment, and essentially differs from Maxwell EDFE $f_M(\varepsilon)$ at temperature T_e (look fig. 8). Such difference is result of not taking into account processes of an electron energy exchange during modeling. It was supposed also, that such energy exchange can occur due to interaction of electrons with plasma fluctuations, which arise during the casual moment of time in a casual place. Accordingly to this idea, it was supposed, that slower electrons, passing through these of heterogeneity, can be displaced in phase space of EDFE in area of bigger energy and, thus, form of EDFE can be vary.

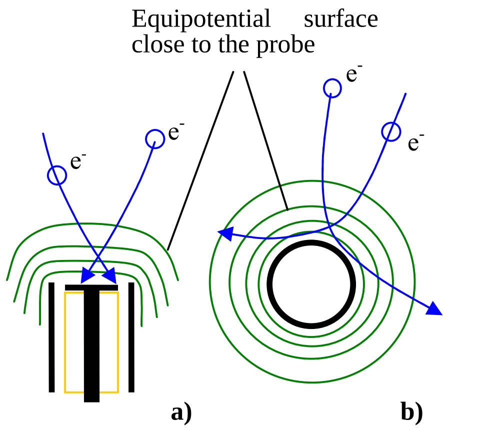

Figure 7. Dispersion of electrons in the sheft close to the flat probe **a)**; and in the shift close to the cylindrical probe **b)**, with a grate curve of equipotential surface.

At the second stage of modeling, to check up this hypothesis, special numerical experiment in which the system of the equations of electron movement was supplemented was carried out, periodically (linearly) changing in time, but arising in the casual moment of time has been carried out. These composed - intensity of an electric field (located in a place of heterogeneity of charges), which size is estimated as $E_{geter\ x,\ y,\ z}(\varepsilon) = \pm T_e / r_D$. The period of existence of this heterogeneity is estimated as $\tau \approx 2 \cdot r_D / V_e$ where $V_e \sim T_e^{1/2}$ - i.e. determined by time of flight of electrons with temperature T_e through this heterogeneity, which extent is of the order of Debye radius r_D. Accordingly to this idea, for modeling electron movement in plasma far from probe, the next electron movement equation system was used.

$$\begin{cases} m \cdot \dot{v}_x = q \cdot E_x - q \cdot v_z \cdot B_y + q \cdot E_{geter_x}(\tau) \\ m \cdot \dot{v}_y = q \cdot E_y + q \cdot v_z \cdot B_x + q \cdot E_{geter_y}(\tau) \\ m \cdot \dot{v}_z = q \cdot v_x \cdot B_y - q \cdot v_y \cdot B_x + q \cdot E_{geter_z}(\tau) \end{cases}$$

Result of numerical experiment - EDFE $f_{geter}(\varepsilon)$, determined in view of interaction of electrons with plasma heterogeneities, is plotted in fig. 8. Comparison of this EDFE $f_{geter}(\varepsilon)$ with Maxwell EDFE $f_M(\varepsilon)$ shows their good conformity. The described above technique of formation of electron group, when interaction of moving electrons with plasma heterogeneities is taken into account, was used in this research further.

For the electron movement modeling in the field close to a probe in numerical experiment when the electron probe current was determined $E_{geter\ x,y,z}(\tau)=0$ was set.

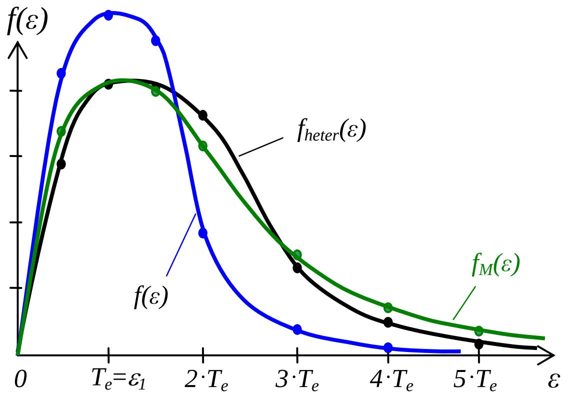

Figure 8. Density of the electron distribution function on energy *f(ε)*. $f_M(\varepsilon)$ – Maxwell distribution than T_e*=56 eV*. $f_{geter}(\varepsilon)$ – Distribution, determined in numerical experiment than plasma oscillations take into account. *f(ε)* – Distribution, determined in numerical experiment without plasma oscillations. *B=15 mTl, E=300 V/cm.*

B. Modeling processes in plasma near to a probe

Researched area - a zone of ionization and acceleration of a working substance in HT, in which characteristic parameters of plasma and magnetic field are the following. Concentration of the charged particles $n_e \approx 10^{17} \dots 10^{18}$ m$^-$

[3] and neutral particles - $n_a \approx 10^{20} \dots 10^{18}$ m^{-3}. Temperature of electrons in range $T_e = 10 \dots 50$ eV. Velocity of ions $v_i = 10^3 \dots 10^4$ m/s. Magnetic and electric fields are $B = 5 \dots 15$ mTl and $E \approx 10^4$ V/m.

As it was specified above, the analysis of the assumptions, which are necessary to use a "classical" technique of processing probe measurements, have to begin by determining some base parameters: characteristic free path of an electron λ_e or equivalent to it r_c - value of cycloid of an electron, which height is $2R_L$; extents of sheath $r_s \approx 10^{-3}$ m near to a probe including radius of probe R_{pr}. It is necessary, that $R_{Li,e} >> r_s$, following a condition (1), and $\lambda_e >> r_s$.

The free path of an electron λ_e before elastic dispersion on atoms or up to Coulomb dispersion is equal to several centimeters, i.e. greater then size of a probe and extent of a sheath. In a zone of ionization and acceleration condition $R_{Li,e} >> r_s$ does not hold true, as the characteristic size of a magnetic field ($B = 5 \dots 15$ mTl) is far from condition $B_{lim} << 5 \cdot 10^{-4}$ Tl, determined earlier as a limit, in spite of that energy of electrons reach several tens eV. Therefore, disturbed action of a probe will be extends out of sheath, which thickness is determined by the Poisson equation (3).

Therefore, the probe (the electric field) influence movement of electrons near to it and influence formation of a stream of electrons on a probe. So, to determine of parameters of plasma by an experimental method it is necessary to improve a technique of processing a probe characteristics.

By development of mathematical model of processes near to a probe, feature of a probe influence on formation of charge stream to a probe in the field of strong electric and a magnetic field has been analyzed in details. The model (scheme) of potential distribution of the electric field created by a probe and distribution of charges concentration near to a probe (look fig. 9) is suggested. It was supposed, that because of the directed movement of charges (accelerated ions and drifting electrons), near to a probe there is a zone, in which concentration of one charges exceeds another. It occurs, even when the potential of a probe equal to zero. Heterogeneities of electron concentration in this zone Δn_e, on distance of $L_{shift.Sh}$ from a probe, it is possible to estimate roughly on the base of the geometrical sizes of a probe R_{pr} as $\Delta n_e \approx n_e \cdot R_{pr}^2 / (2 \cdot L_{shift.Sh}^2)$. More exact distribution of charged particle concentration and potential near to a probe can be determined on the base of numerical experiment, however theoretical base which we now own, is not sufficient for the decision of this problem. Further in numerical experiment in this research, the specified features of charge concentration distribution and potential distribution near to a probe were not taken into account.

Carrying out of researches the mathematical model of movement of particles, which is described in item 4.1, has been used as base. By the numerical experiment the cylindrical probe and a probe with a flat reception surface and the security ring, directed just as is shown in fig. 4 (the reception surface was focused perpendicularly to a direction of drift of electrons), has been used.

Distribution of potential in a sheath and extent of a sheath near to a probe was calculated on the base of Poisson equation similarly to item 4.1. It is necessary to notice, that in investigated area, in the crossed electric and magnetic fields, using Boltzmann equation can be inaccuracy owing to action of Lorenz force (that aren't the potential nature) on electrons, except for action of an electric field. Therefore, distribution of concentration of the charged particles during a sheath was specified with use of results of numerical experiment. Then, the specified distribution of concentration can be used repeatedly to solve Poisson equation and to specify distribution of potential in a sheath. By the numerical experiment the sequence of calculations, similarly to item 4.2 and 4.3, was carried out. The potential of plasma (as the reference point) has been accepted as *250* V, determined in natural experiment. The floating potential $\varphi_f \approx -100$ V for a cylindrical probe and $\varphi_f \approx 0$ for a probe with a flat reception surface has been determined, and also dependences $T_e(\varphi_{pr})$ for such probes (see fig. 10 and 11) were plotted.

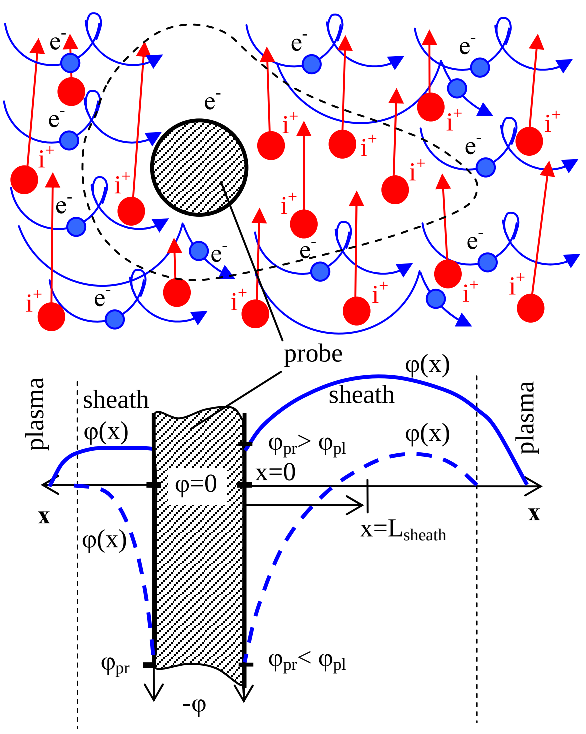

Figure 9. Prospective potential distribution φ(x) in area of "shadow" of a probe. Boundary conditions have been established as $d\varphi/dx \neq 0$, that can be determined by plasma fluctuations (heterogeneities).

C. The analysis of results of numerical experiment

The calculated curve $T_e(\varphi_{pr})$ (look fig. 10) shows, that the determined electron temperature, is various in different ranges of φ_{pr}. The temperature determined by a cylindrical probe directed as shown in fig. 4 b), in a range of potentials of a probe near to potential of plasma φ_{pl}, is $T_e=75$ eV). When reducing probe potential the temperature determined by a "classical" technique increases up to $T_e=130$ eV and its error $\varepsilon=(T_e-T_{e1})/T_{e1}\cdot 100\%$ exceeds one hundred percent when the temperature for the numerical experiment have been set by the value $T_{e1}=56$ eV. The error in determining electron temperature will be minimal if the probe potential close to the plasma potential. Using a traditional technique, , difference between potential of plasma φ_{pl} and the floating potential of a probe φ_f is determined by the formula (4) as $\varphi_{pl}-\varphi_f\approx 5.8\cdot T_e=754$ V for $T_e=130$ eV. According to the result of numerical experiment the difference between potential of plasma and the floating potential is ≈350 V. Then the error in determining potential of plasma by traditionally used technique will be $(5.8\cdot T_e-350)/350\cdot 100\%=115$ %. It is necessary to notice, that the orientation of a probe, used for numerical experiment, is not optimum, since the probe of 1 mm of length shunts sheaths of plasma, which have essentially various potential. As consequence, such probe can even influence an operating mode of the thruster.

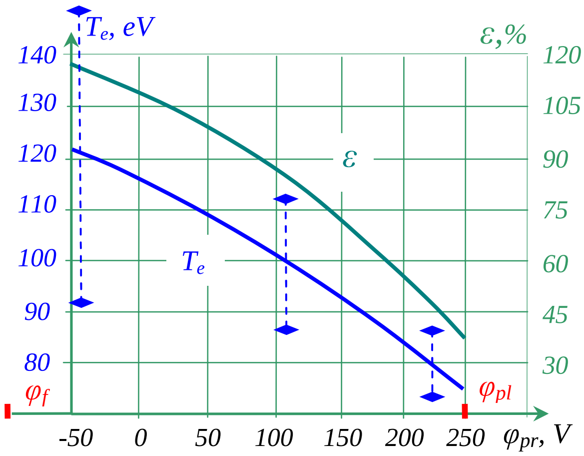

Figure 10. Dependence $T_e(\varphi_{pr})$ determined traditionally on the V-I characteristic calculated in numerical experiment in the **strong magnetic and electric fields**, its error ε and confidence interval. It was used **cylindrical** probe and it was set electron temperature T_e=56 eV in numerical experiment.

In fig. 11 results of the processing data, received in numerical experiment when it was used a probe with a flat reception surface of 0.25 mm diameter and directed as shown in fig. 4 a) are plotted. Processing experiment results is carried out similarly to how it was made for a cylindrical probe. As against results of researches with a cylindrical probe, dependence $T_e(\varphi_{pr})$ has the opposite tendency - the determined temperature is decreased as potential of a flat probe is increased.

Analyzing dependences $T_e(\varphi_{pr})$, shown in fig. 10 and 11, it is possible to conclude the following. Change of determining value of electron temperature depending on the probe potential is a consequence of physical process of overflow of a probe by a stream of electrons when the probe is under negative potential to plasma. Influence of this effect of overflow strengthen, if the cylindrical probe of small diameter is used and it is especially strengthen if thickness of a sheath is close to radius of a probe that is typical in area of the large temperatures of electrons - in a zone of ionization and acceleration of HT. The effect of a overflow can be weakened, than it is used the probe with a flat surface with a size which in some times is more than thickness of a sheath, that is typical in area of small temperatures of electrons - outside the thruster.

Idea about existence in low-temperature non-equilibrium plasma of two groups of electrons, which have various (in some times) temperatures[2], can be explained in the another way. Features of interaction of a probe with plasma (the overflow of a probe by a stream of electrons about which was spoken above), result in $T_e(\varphi_{pr})\neq const$ and it can create visibility of presence of electrons of several groups with different temperatures.

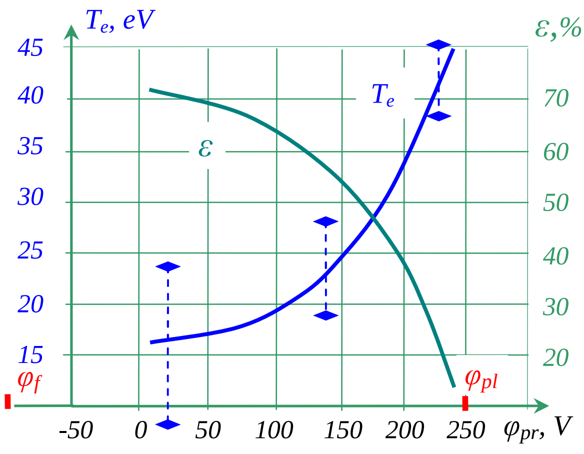

Figure 11. Dependence $T_e(\varphi_{pr})$ determined traditionally on the V-I characteristic calculated in numerical experiment in the **strong magnetic and electric fields**, its error ε and confidence interval. It was used **flat** probe and it was set electron temperature T_e=56 eV in numerical experiment.

One of the first reasons of the errors of numerical experiment results is the limited quantity of particles, which movement was modeled in the crossed electric and magnetic fields by a method of Monte-Carlo. The quantity of particles, sufficient for modeling, has been chosen on the base of the bright tendency to saturation of a current of electron components (look fig. 12) at increasing quantity of particles at various potentials of a probe. In numerical experiments 10^6 particles were used.

V. Specification of a plasma parameters determined in an experimental Hall thruster

Numerical experiment spoken above, has been carried out for specification of electron temperature and plasma concentration determined by the help of Lengmuir probe (shown in fig. 13) in plasma of the experimental Hall thruster (Fig. 14) operated with various Xe mass flow rate, at discharge voltage of 120 V and discharge current from 0.36 A up to 1.1 A. The probe was entered into discharge chamber plasma through the anode so that the axis of the probe has been directed along movement of ions and the probe was moved to the discharge chamber exit. Distribution of electron temperature and others plasma parameters along the discharge chamber, determined on a traditional technique (without specifications) is shown in fig. 15. Feature of such probe orientation consist in that the case of a probe created "shadow" and decrease concentration of ion in area of "shadow". Influence of "shadow" led to the decreasing of electron stream to a probe even when the potential of a probe did not differ from potential of plasma (like in Fig. 9). However, it is necessary to notice, that due to such probe orientation the probe directly did not influence processes in the discharge chamber upstream of electron flow and did not change thruster operation mode. To specify results of calculation of electron temperature and other plasma parameters (fig. 15) numerical experiment on studying of electron movement features in field near to a probe in view of charges in area of "shadow" was carried out. Results of this experiment are plotted in Fig. 15 by green curve.

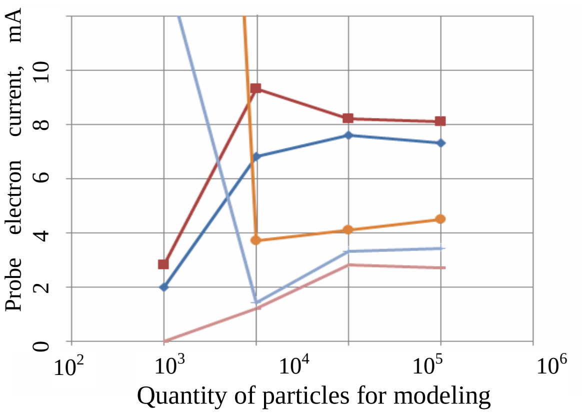

Figure 12. Dependence of probe electron current on quantity of particles used for mathematical modeling by various probe potential.

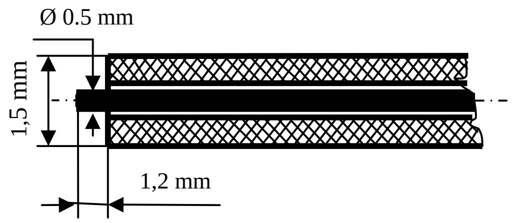

Figure 13. Schema of Lengmuir probe used in experiment.

VI. Conclusion

Researches of regularities of interaction of a probe with plasma by the method of numerical experiment, using the data of natural experiment, are carried out. By a method of numerical experiment it has been found, that an error of electron temperature determining and plasma potential determining in a case, when the traditional technique (suggested by Langmuir with co-authors) is used, can exceed 100%, because of a overflow of a single probe of the limited sizes by an electron stream. As consequence, the concentration of plasma determined on the base of electron temperature and an electron probe current will be underestimated. By numerical experiment it was found that the temperature of electrons, determined when potential of a probe close to the plasma potential would be of the minimal error. To find an error of plasma parameters determining by a traditional technique on the base of results of natural experiment, it is recommended to use these results as initial and to determine features of interaction of a probe with plasma in concrete conditions of a plasma flow by numerical experiment.

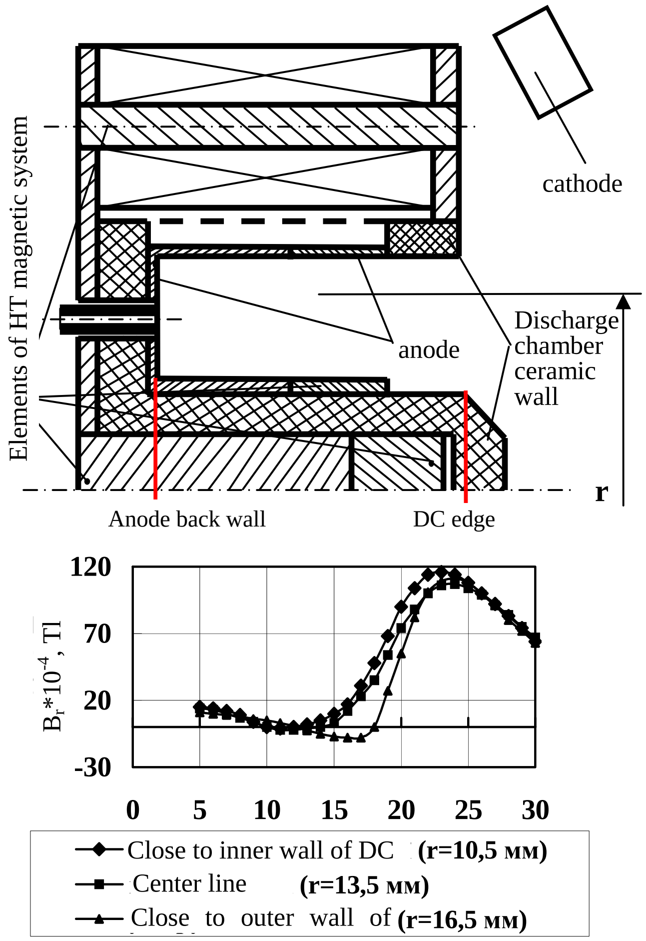

Figure 14. Diagram of experimentally determining HT magnetic field distribution.

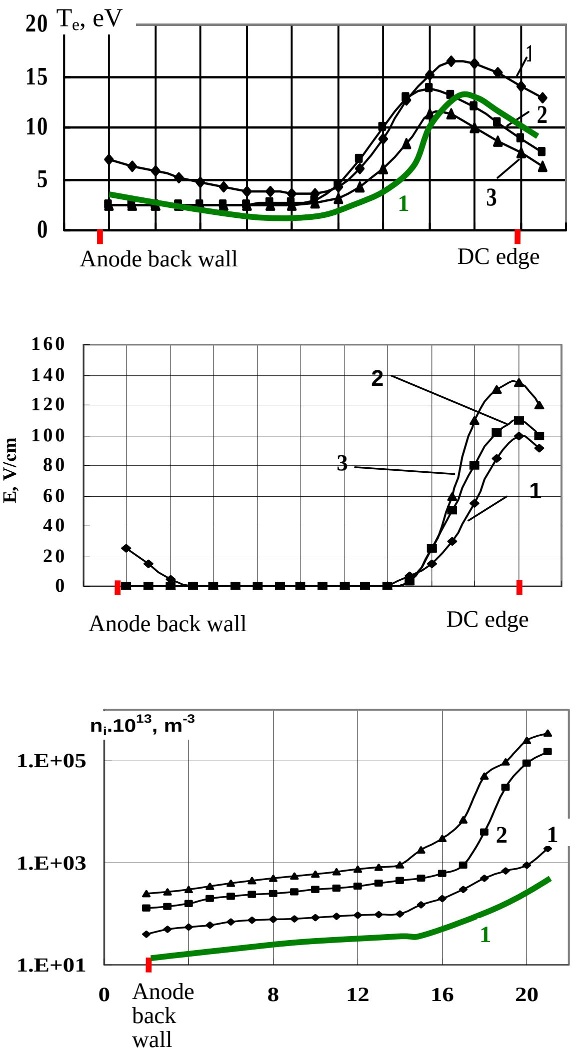

Figure 15. Electron temperature T_e, axial electric field E and plasma concentration n_i distributions along HT discharge chamber. 1– $\dot{m}$ =0,42 mg/s; 2– $\dot{m}$ =0,52 mg/s; 3– $\dot{m}$ =0,94 mg/s

Green curve – experimental data corrected by numerical experiment.

References

Books

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[2]Morozov A.I. and Savelyev V.V. "Fundamentals of Stationary Plasma Thruster Theory", Reviews of Plasma Phisics № 21 edited by Kadomtsev B.B. and Shafranov V.D., ISBN 0-306-11064-4, Plenum Publisher, New-York, 2000. P. 251 – 254.