Two Approaches to the Studying of a Hall Thruster Discharge Chamber Erosion Process

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Abstract: The problem of Hall thruster (HT) discharge chamber (DC) ion sputtering that restricts HT life-time is analyzed. Two approaches to study regularities of an ion flow to the DC wall that lead to destruction of DC are studied. According to the first approach ions directed to walls mainly owing to radial component of the electric field in all DC space. According to second idea DC sputtering by ions moving to DC surface owing to it‘s chaotic velocity. Near to DC surface ions are accelerated owing to close to the wall potential drop. To calculate flow of ions sputtering DC surface the radial component of electric field was set of various values. Operational characteristics of HT schema like model M-70 (worked out by design bureau "Fakel" in former USSR) was used to test result of erosion processes mathematical modeling and in further to estimate life-time of HT M-40 type designed in Ukraine in National State University in Dnepropetrovsk. Researches include the following interconnected parts. 1. Calculation of potential distribution between the anode and cathode of HT including two intervals: in the DC and outside it base on hydrodynamic 1D model. 2. Calculation of potential drop in close to the wall layer, including discussion of a problem of limiting electron temperature in ceramic DC. 3. 2D modeling of an ion origin process in DC base on Monte-Carlo method. 4. Modeling of ion movement in DC and DC wall erosion process.

Nomenclature

B = magnetic field induction
I_{e0} = electron current from the cathode to the discharge chamber
I_d = discharge current
h_c = height of cycloid
n_{pl} = plasma concentration
n_h = concentration of charges in the field of plasma heterogeneity
S = square of cross-section of discharge chamber, square of discharge chamber segment surface
T_e = electron temperature
T_s = discharge chamber surface temperature
V_y, V_r, V_x = components of electron velocity

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U_c = cathode potential drop
U_d = discharge voltage
$\Delta\varphi_h$ = potential drop because of plasma polarization in the field of charges heterogeneity

I. Introduction

BASIC HT circuit has been created more than 50 years ago and due to a good combination of operational characteristics of the first models (high operational efficiency, high reliability) HT is exploited already tens years. For further HT modernization it is necessary to increase HT life-time by effecting to discharge chamber erosion processes. A base for this purpose is the understanding of a role of the basic processes (factors), which influence DC erosion. These are the following. 1. Distribution of electric potential and corresponding values of radial and axial a component of an electric field. 2. Formation of close to the wall potential drop. 3. Distribution of concentration and temperature of electrons. 4. Distribution of ion origins intensity in DC.

In the second section of paper the distribution of a discharge potential along an axis was determined on the basis of hydrodynamic 1D model on two sites: in DC in a zone of ionization and outside DC up to the cathode-neutralizer (CN). We offer the equation, which should be used for potential distribution determining in a radial direction of DC. However we are not ready to offer full model for the decision of this separate task. By numerical calculations we have varied a radial component of an electric field so that results of calculations obviously did not contradict known results of experiments. *In the third section* we determine the value of close to the wall potential drop and we try to overcome the contradiction between known data of experiments that the electron temperature in DC can surpass 40 eV and the assumption that because of effect of secondary electronic emission from DC surface the electron temperature cannot surpass a limit in 30 eV. *In the fourth section* we yield results of Monte-Carlo modeling of plasma parameters distribution in DC - average energy and concentration of electrons, intensity of ion origin process (quantity of ions born per second per unit of volume). *In the fifth section* we yield results of calculation of DC destruction within 1000 hours as test calculation for HT M-70 type.

Using the developed techniques of an estimation of DC erosion, it is planned to predict resource of HT M-40, developed in Ukraine in Dnipropetrovs’k National State University.

II. Features of HT plasma processes 1D hydrodynamic modeling

The basic applicability 1D hydrodynamic model consist in determining of potential drop on two sites of a discharge interval: first - from the cathode-neutralizer (CN) up to DC edge - a zone of acceleration of ions (ZA) with potential drop U_{za}; second - from DC edge up to section inside DC, in which the potential reaches a maximum - a zone of ionization of gas (ZI) with potential drop U_{zi} (Fig. 1a). Features of model consist that the following balance equations are written for two major sites - ZI and the ZA, and also for their border.

To determine of an electron stream in DC probably to use some approaches. One of them is the following.

By development of model it was assumed that electrons emitted by CN and that reached DC, passing area ZA (Fig. 1a) mainly due to distortion of close azimuthal drift - being displaced at each collision (with atoms, ions, in local plasma fluctuations, on ion beam boundary) to DC edge on size $h_c=2\cdot R_l$ (height of a cycloid equal to twice Larmor radius). Should occur at least N_{min} collisions that electron has reached DC edge. Probably to look electron movement from the cathode to DC as likelihood process, believing that probability of electron displacement to DC on size of a cycloid after one collision - P_c. Then the resulted probability P, that electron emitted by the cathode have reached DC

$$P = (P_c)^{N_{min}}, \qquad (1)$$

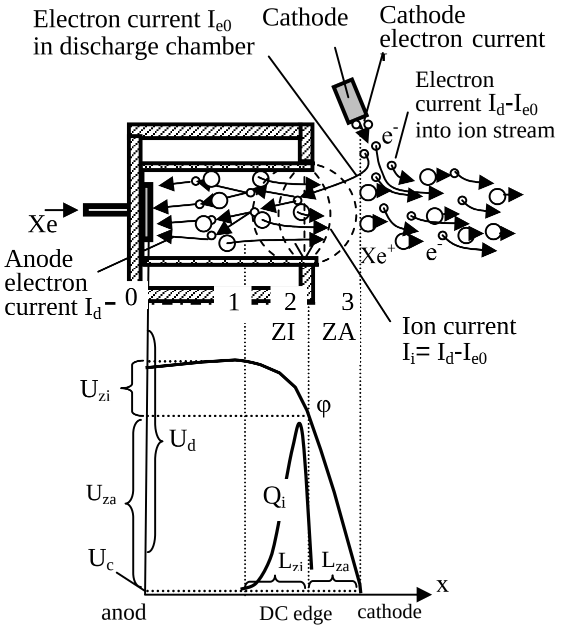

Figure 1a. Electron currents distribution. Potential φ and ion origion intensity Q_i distributions in the HT discharge interval.

where: $P_c=f(\varepsilon_e)$ - probability that electron (ε_e - energy) was displaced on a height of a cycloid $h_{c=}2\cdot R_l$ to DC edge due to any collision; N_{min} - a minimum quantity of electron-atom collisions, necessary to reach DC at the L_{za} distance from cathode

$$N_{min} = \int_3^2 \frac{dx}{h_c} . \tag{2}$$

Allocating among all electron flow I_d/e (I_d - electrons emitted by the cathode is total discharge current) part I_{e0}/e - electrons reached DC, a ratio of these flows is determined as

$$I_{e0}=I_d\cdot(P_c)^{Nmin}. \tag{3}$$

Other approach to determine electron stream in DC is the following. It is supposed, that carry of electrons across a magnetic field occurs because of dispersion of electrons on plasma heterogeneities, extended in an axial direction (see a Fig. 1b). These heterogeneities of plasma arise in a zone of ionization in DC because of heterogeneity of gas concentration in DC Δn_a, so $\Delta n_a/n_a\approx0.01$. The value if heterogeneity of gas concentration is determined by non-uniformity of distribution of gas in DC through apertures in the anode-gasdistributor (nearby 5 … 10 mm that corresponds to distance between apertures in the anode). After ionization of gas, in which there are heterogeneity, in plasma arise heterogeneity of charge concentration Δn_i, so $\Delta n_i/n_{pl}\approx0.01$. Extent of these areas of heterogeneity of charges concentration is determined by Debye screening distance $r_D\sim(T_e/n_i)^{1/2}$. At that there is an ionization of gas in the field of heterogeneity, and in same time, the ions born in DC, are accelerated and leave DC. Therefore heterogeneity in a stream of plasma are kept in the form of extended along an axis tubes with the increased concentration of plasma until atoms "burn out" in a zone of heterogeneity of gas in DC. Owing to electron drift in an azimuthal direction outside of DC there is magnetized electrons, there is a polarization of charges in the field of local heterogeneity of plasma and there is a local azimuthal electric field. Under influence of it close drift of electrons can be braked. "Slow" electrons can be displaced in a direction to DC creating an axial current from the cathode in DC.

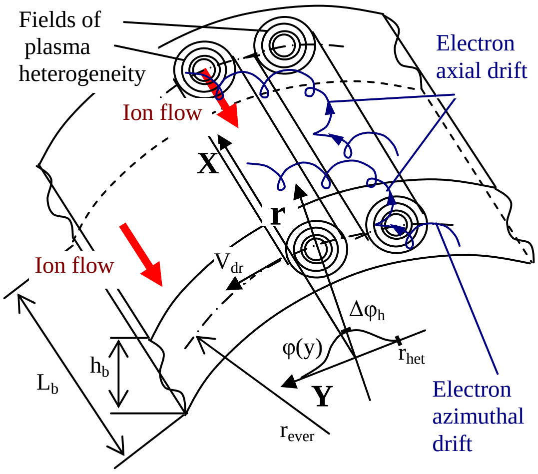

Figure 1b. Axial electron drift because of dispersion of "slow" electrons on plasma heterogeneities in a stream of ions.

Potential drop in the field of heterogeneity can be estimated from the equation, taking that azimuthal electron flow retard due to potential drop $\Delta\varphi_h$ appeared because of plasma polarization in the field of charges heterogeneity (look in Fig. 1b)

$$\frac{n_{pl}}{n_h} = \int_{\sqrt{\Delta\varphi_h\cdot q\cdot 2/m}}^{\infty} \frac{V_y-\sqrt{\Delta\varphi_h\cdot 2\cdot q/m}}{V_y}\cdot f(v_x,v_y,v_r,T_e)/n_{pl}\cdot dv_y\cdot \int_{-\frac{r_h\cdot v_y}{2\cdot 6\cdot R_l}}^{\frac{r_h\cdot v_y}{2\cdot 6\cdot R_l}} dv_r\cdot \int_{-\infty}^{\infty} dv_x$$

where: n_{pl} – plasma concentration; n_h - concentration of charges in the field of plasma heterogeneity, can be estimated on heterogeneities of atoms; $\Delta\varphi_h$ – potential drop because of plasma polarization in the field of charges heterogeneity; R_l – Larmor electron radius; r_h - the value of plasma heterogeneity, a boundary condition for V_r that allocates electrons, which cannot flow round heterogeneity of plasma; $f(V_x, V_y, V_r, T_e)$ – density of function of electron distribution on velocities in plasma of ion flow.

Electron current I_{e0} in an axial direction across a magnetic field because of electron dispersion on plasma heterogeneities, under the order of electron stream from the cathode in DC, can be estimated as

$$I_{e0} = r_{ever} \cdot \pi \cdot h_b \cdot q \cdot \int_0^{\sqrt{\Delta\varphi_h \cdot q \cdot 2/m}} v_y/2 \cdot f(v_x, v_y, v_r, T_e) \cdot dv_y \cdot \int_{-\frac{r_h \cdot v_y}{2 \cdot 6 \cdot R_l}}^{\frac{r_h \cdot v_y}{2 \cdot 6 \cdot R_l}} dv_r \cdot \int_{-\infty}^{\infty} dv_x \cdot \left(\frac{2 \cdot \pi \cdot r_{ever}}{r_h} \cdot \frac{h_b}{r_h} \right),$$

where: h_b - width of ion stream, q - electron charge, r_{ever} - average radius of ion stream.
Current I_{e0} exists owing to electrons, which have not overcome retarding potential $\Delta\varphi_h$.

For calculations we used the first approach described above. However, neither first, nor second approaches do not solve all the questions connected with electron maxwellisation and specific influence of a magnetic field on HT discharge current.

Equation of energy flow in zones ZA and ZI of discharge interval.

Electron temperature $T_e(x)$ on distance x from DC edge was determined by balance

$$d(q_e(x) \cdot 5/2 \cdot e \cdot T_e(x))/dx = q_e(x) \cdot e \cdot E(x) - Q_{wall}(x) - Q_{ion}(x), \qquad (4)$$

where: $q_e(x)=V_{eX}(x) \cdot n_e(x)$ – electron flow, collected by electrons in an electric field E, V_{eX} - axial electron velocities, n_e – electron concentration;

$Q_{wall}(x) = 2 \cdot T_e \cdot e \cdot \sqrt{\frac{T_e \cdot e}{2 \cdot \pi \cdot m}} \cdot \exp(-\varphi_w/T_e) \cdot \frac{2 \cdot \delta}{(r_{out} - r_{in})^2}$ – energy flow to the DC wall, δ – width of the layer ion flow to the DC wall mainly come from, r_{out} – radius of the DC outer wall, r_{in} - radius of the inner wall;

$Q_{ion}(x) = q_e(x) \cdot \varphi_i \cdot e \cdot \sigma_i \cdot n_a(x) \cdot V_e(x)/V_{eX}(x)$ - energy flow spent for atom ionization, $V_e = \sqrt{3 \cdot e \cdot T_e(x)/m}$ - full electron velocity, σ_i – ionization cross section, φ_i – ionization potential of atom, n_a – atom concentration.

Equation of electron and ion velocities in cross-section 2.

Axial electron velocity V_{eX2} in cross-section 2 at the DC edge, in view of: full electron velocity V_{e2}, total collision cross-section σ_Σ, atom concentration n_{a2} taking into account cathode $\dot{m}_c$ and anode $\dot{m}_a$ mass flow rates was determined as

$$V_{eX2}=V_{e2} \cdot \sigma_\Sigma \cdot n_{a2} \cdot h_{c2} \cdot P_c. \qquad (5)$$

Full electron velocity V_{e2} at the DC edge is determined by the electron kinetic energy, taking into account, that electrons reach DC mainly due to elastic collisions

$$V_{e2} = \sqrt{3 \cdot e \cdot T_e/m} \cdot \qquad (6)$$

Equation for discharge current determining.

The anode discharge current I_d is determined by the current I_{e0} avalanchely increased in ZI from section 1 to 2 so, that

$$I_d = I_{e0} \cdot Z, \quad \text{wherevalue } Z = \exp(\int_2^1 \alpha(x) \cdot dx)' \qquad (7)$$

where: α(x) - number of ionization collisions per unit of length of electron run along axis X

$$\alpha(x) = n_a(x) \cdot \sigma_i \cdot \frac{V_e(x)}{V_{eX}(x)}. \qquad (8)$$

Equation for determining of atom concentration decreasing in zone ZI because of ionization.

Concentration $n_a(x)$ in any section on distance x from section 2 was calculated as

$$n_a(x) = \frac{\overset{\bullet}{m}_a}{M \cdot V_a(x) \cdot S} - \frac{I_d - I_{e0} \cdot \exp(\int_2^x \alpha(x) \cdot dx)}{M \cdot V_a(x) \cdot S \cdot e}, \tag{9}$$

taking into account:

"burning out" of atoms in DC ionization process, anode mass flow rate $\overset{\bullet}{m}_a$ and that $\overset{\bullet}{m}_a$ /M/S - atom flow through the DC area of cross-section S with axial atom velocity V_a;

$I_d - I_{e0} \cdot \exp(\int_2^x \alpha(x) \cdot dx)$ – ion flow in section x.

Equation for electron and ion concentration determining in cross-section 2.

Ion - n_{i2} and electron - n_{e2} concentrations are equal and were determined at the DC edge as

$$n_{i2} = \frac{I_i}{V_{i2} \cdot e \cdot S} = \frac{I_{e0} \cdot (X-1)}{V_{i2} \cdot e \cdot S} = n_{e2} = \frac{I_{e0}}{V_{eX2} \cdot e \cdot S}. \tag{10}$$

where V_{i2} - ion velocity at DC edge is determined roughly by $U_{zi}/2$ – the average potential drop in ZI ion accelerated due to

$$V_{i2} = \sqrt{e \cdot U_{zi} / M}. \tag{11}$$

Equation of potential drop balance in discharge interval.

Balance of the HT discharge voltage is calculated on equation

$$U_d = U_c + U_{za} + U_{zi}. \tag{12}$$

Processes in the cathode were not studied separately and cathode potential drop U_c was set to follow typical experimental dependence on discharge current I_d, adjusting constants a and b

$$U_c = a + (I_d - b)^2. \tag{13}$$

The following boundary conditions were taken. We suppose that back potential drop on a site (01) much less when potential drop in ZI. The HT magnetic system is included in a discharge circuit, but we neglect potential drop

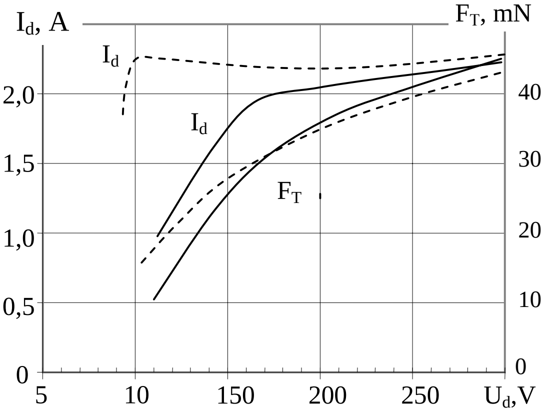

Figure 2a. HT M-70 type V-I characteristic and thrust F_T in the stationary mode.

—— Calculated on hydrodynamic model

- - - - Experimental measurements

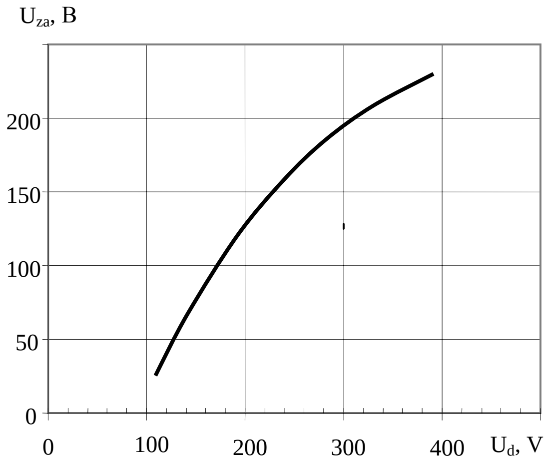

Figure 2b. Potential drop U_{za} in zone DC edge – cathode-neutralizer at various discharge voltage U_d, calculated for HT M-70 type.

on magnetic coils. We believe, that ions and electrons will be neutralized on DC walls and thus the stream of electron on DC wall is determined by the retarding potential at a wall of value $\Delta\varphi_w=2.5T_e$.

Forms of the curves of magnetic and electric field distribution are typical for wide range of discharge voltage. These curves were taken from the experimental researches, but the value of potential drop was calculated.

Volt-ampere characteristic of HT was determined by calculation of Eqs. (1 – 13). As a test, HT integral characteristics (Fig. 2) of model M-70 have been calculated in a nominal discharge mode: Xe mass flow rate through cathode-neutralizer – 0.3 mg/s; through the anode gas-distributor – 2.5 mg/s. Cathode-neutralizer is located on the distance of 7 mm from a DC edge. Magnetic coils are included in a discharge circuit. The deviation of calculated and experimental data dependences of a discharge current (Fig. 2a) reflect inexact determination of the mechanism of electron conductivity in a interval cathode-neutralizer – DC edge. Potential drop U_{za} on site of acceleration (from edge DC – up to cathode) is shown in Fig. 2b.

III. Electron distribution along a magnetic field force line

It is known that distribution of an electric field is described by Poisson equation, which, however, is difficult to use directly for HT plasma when plasma concentration is 10^{17} … 10^{18} m^{-3}. So-called equation of “thermolized potential”, offered by A. Morozov is usually used

$$\varphi_\gamma=\varphi_\gamma^0+T_e\cdot\ln(n_\gamma/n_\gamma^0),$$

where φ_γ - potential in a running point on force line γ, φ_γ^0 - potential in a point on an average line of DC on magnetic field B force line γ, n_γ – electron concentration with temperature T_e in a running point on B force line γ, n_γ^0 - concentration электронов in a point on an average line of the channel on B force line γ.

It is necessary that electrons move free along a B force line of magnetic field. However in HT magnetic field distribution is characterized by an essential gradient in a radial direction. Increase of an induction from 15 mTl up to 22 mTl during 1 cm creates known effect of "a magnetic mirror” that is not considered by the equation “thermolized potential”. It, certainly, leads to errors by determining of an HT electric field potential distribution that is corrected by various researchers.

We suggest to consider effect of "a magnetic mirror” as follows. Electron stream электронов $q_e=\langle v_r\cdot n_e\rangle$ and electron concentration n_e along a B force line of a magnetic field can be certain, considering that

$$(V_y^2+V_x^2)/B=\text{const}$$

where V_y and V_x - components of electron velocity, perpendicular to a B force line (Fig. 3). Then electron stream from a point, where an induction - B_0 and potential φ_0 in a point, where an induction B and potential φ is determined,

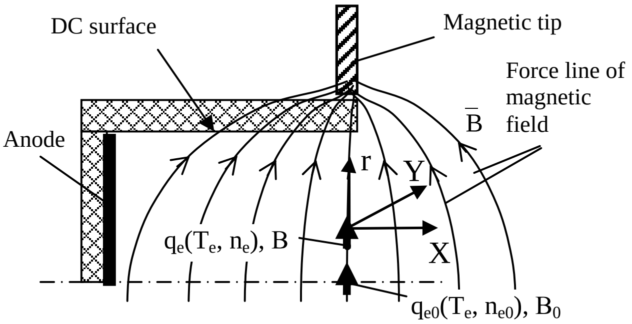

Figure 3. Electron stream q_{e0} along a force line of a magnetic field.

$$\int_{\sqrt{\Delta\varphi\cdot q\cdot 2/m}}^{\infty} v_r\cdot f(v_x,v_y,v_r,T_e)\cdot dv_r\cdot 2\cdot\int_0^{\left(\frac{V_r}{\sqrt{B/B_0-1}}\right)} dv_x\cdot 2\cdot\int_0^{\sqrt{\frac{V_r^2}{B/B_0-1}-(V_y^2+V_x^2)}} dv_y=\langle v_r\cdot n_e\rangle=q_e$$

where v_r - a component of electron velocity along a force line of a magnetic field, $\Delta\varphi=\varphi_0-\varphi$ – potential drop.

It has been calculated numerically q_e/q_{e0} in some ranges of $\Delta\varphi$, B/B_0, T_e and yield are resulted in a Fig. 4, 5.

IV. Potential drop in close to the wall layer

It is expected[5], that electron temperature will not surpass 30 eV if DC of HT is made of ceramics. Since temperature becomes more than this limit close to the wall potential drop becomes zero owing to strong secondary electronic emission of DC surface. At this critical value of the SEE coefficient the charge-saturation regime is reached. Data of experiments that electron temperature in DC surpasses 40 eV are known also[3, 4]. In our opinion this contradiction can be solved as follows. We assume that electron distribution function on energy (EDFE) is close to Maxwell, but is not precisely Maxwell. The deviation consists that there is no so-called "tail" with electron of high energy. Probably, that EDFE it would more precisely be described by Druvestain distribution. Now there is no explanation of physical processes, which would confirm the fact of electron Maxwellization in DC of HT for the period of electron movement from a wall to wall of DC. Data about EDFE, received from probe measurements, cannot capture a range of energy more than (5…6)T_e since in this range the ion current to a probe is close to value of an electron current to a probe.

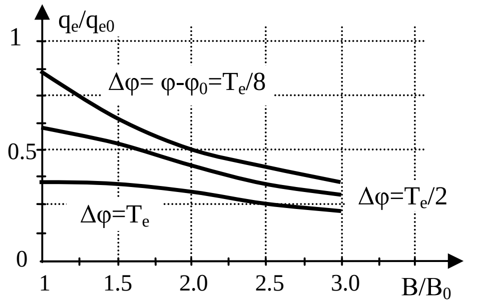

Figure 4. Ratio q_e/q_{e0} of electron stream moving along a force line of a magnetic field from a point, where an induction - B_0 and potential φ_0 in a point where an induction B and potential φ, electron temperature T_e=40 eV, B_0=15 mTl.

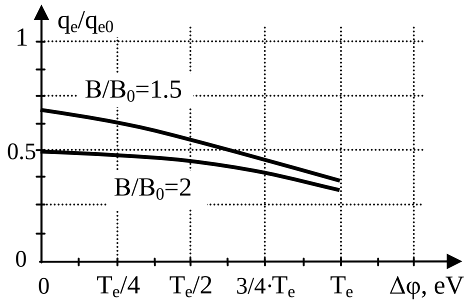

Figure 5. Ratio q_e/q_{e0} of electron stream moving along a force line of a magnetic field from a point, where an induction - B_0 and potential φ_0 in a point where an induction B and potential φ, electron temperature T_e=40 eV, B_0=15 mTl.

In our calculations we suppose that electrons with energy more when $3\cdot T_e$ are absent in EDFE.

Potential drop $\Delta\varphi_w$ between plasma and DC wall in so-called close to the wall layer in some range of electron temperatures T_e (Fig. 6) is determined. For this purpose it is suggested the equation of balance of radial streams of ions and electrons to the DC surface, in view of emission properties of the DC surface

$$\int_{\sqrt{\Delta\varphi_w \cdot q \cdot 2/m}}^{V_{lim}} v_r \cdot [1 - S(\varepsilon)] dv_r \int_{-\infty}^{V_{lim}} dv_x \int_{-\infty}^{V_{lim}} f(v_x, v_y, v_r, T_e) \cdot dv_y = < V_{ir} \cdot n_i >$$

where: $f(v_x, v_y, v_r, T_e) = A \cdot \exp(-\varepsilon/T_e)$- electron distribution function close to Maxwell, electron velocity limit - $v_{lim} = (\varepsilon_{lim})^{1/2} = (3 \cdot T_e \cdot 2./m)^{1/2}$; $S(\varepsilon) = S_{max} \cdot \varepsilon / \varepsilon_{max} \cdot e^{2\cdot(1-\sqrt{\varepsilon/\varepsilon_{max}})}$ - factor of secondary electron imission, where $\varepsilon = (v_x^2 + v_y^2 + v_r^2) \cdot m/2$ - energy of electron falling to the DC surface, S_{max}=2.5 and $e_{max=}$500 eV for material BN-S_iO_2[1]; the stream of ions $<V_{ir} \cdot n_i>$ is certain on border of plasma and close to the wall layer. Radial component of ion velocity V_{ir} is determined by the next: chaotic energy of atom (100 … 200 m/s) and the energy accumulated by an ion owing to ion acceleration by the radial component of an electric field in DC space outside of a layer; and also by the energy accumulated owing to acceleration in a preshift ~$(T_e/2)^{1/2}$ - Bohm velocity. In plasma before the preshift concentration of ions and electrons are equal $n_e = n_i$. Took into consideration, that ions are born in all DC space and move to a wall in increasing (from DC axis to DC walls) radial electric field E_r=2…3 V/mm of value. Being based on results of preliminary calculations, average speed of ions $<V_{ir}>$ in a stream directed to a wall on border of close to the wall layer is estimated as (1 … 5) ·1000 m/s.

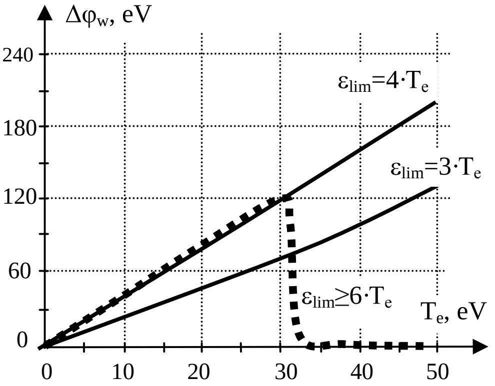

Figure 6. Dependence of potential drop $\Delta\varphi_w$ in close to the wall layer on electron temperature T_e for material BN-S_iO_2. The maximal electron energy in EDFE does not surpass ε_{lim}.

V. DC plasma parameters calculation

The intensity of ion origin process Q_i (quantity of ions born per second per unit of volume) and average electron energy ε in a discharge interval was numerically calculated base by Monte-Carlo (M-C) method modeling. By modeling the forms of the curve of magnetic and electric field's distribution (Fig.1) were taken (base on experimental data) as typical for the HT, but the value of potential drop was calculated on 1D hydrodynamic model in section II. By plasma parameters calculation the value of a radial component of electric field E_r was varied. Calculation on M-C model was curried out with time step of integration dt=0.05/w, where w – electron cyclotron frequency. By calculation the HT thrust created by all ions born in DC and accelerated in ZA was determined in a test task in diapason from 4 up to 4.4 grams, when the experimental value is 4 gram. It was required six hours operation of the personal computer to reach satisfactory repeatability of results of calculation.

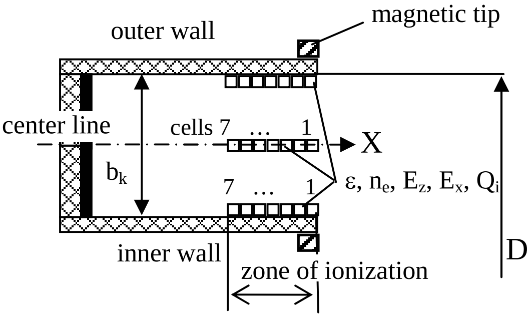

Figure 7. Numbering of cells in DC modeling area.

Results of plasma parameters calculation in DC (look in Fig. 7) HT type M-70 (with external diameter D=70 mm, width of the channel b_k=15 mm, at a discharge voltage 280 V; an induction of a magnetic field 16 mTl; Xe mass flow rate through the anode block of 2.5 mg/s are shown in Tables 1-3. In tables: Q_i - quantity of ions born per second in cubic millimeter in space of ZI in DC; ε - average electron energy; E_r, E_x - radial and axial components of an electric field. By calculation of DC erosion it was accepted that electron temperature T_e=ε.

Similar calculations have been curried out when Er=0.

Table **1**. Cells close to the auter wall (Fig. 7)

Distance from DC edge, mm	1	2	3	4	5	6	7
E_x E_r V/mm	27 2.4	27 3.5	14 4.0	6.8 4.1	2.9 4.1	0.8 4.2	0 4.2
ε, eV	41	36	23	13	12	8	8
Q_i, 10^{14} part/s/mm^3	2.1	2.5	1.8	1.3	0.9	1.0	0.9

Table **2**. Cells close to the inner wall (Fig. 7)

Distance from DC edge, mm	1	2	3	4	5	6	7
E_x E_r V/mm	27 2.5	27 3.6	14 4.1	6.8 4.2	2.9 4.2	0.8 4.3	0 4.3
ε, eV	48	36	20	12	10	9	9
Q_i, 10^{14} part/s/mm^3	2.1	5.0	5.3	3.9	3.0	1.6	0.5

This artificial situation has been created to estimate a role of radial component of an electric field in DC space for strengthening DC wall erosion. Results of calculation of plasma parameters in DC are yield in Tables 4-6. It is necessary to notice that only 55 % of the Xe mass flow rate was ionized when E_r=0 and the settlement value of thrust was 2.6 gram, whereas experimental value - 4 grams under condition of E_r#0.

Table 3. Cells close to the center line (Fig. 7)

Distance from DC edge, Fig. 6	1	2	3	4	5	6	7
E_x E_r V/mm	29 0	29 0	14 0	6 0	1.6 0	0.2 0	0 0
ε, eV	25	18	10	9	8	8	7
Q_i, 10^{14} part/s/mm^3	6.5	8.0	5.5	7.8	5.9	4.1	2.2

Table 4. Cells close to the auter wall (Fig. 7)

Distance from DC edge, mm	1	2	3	4	5	6	7
E_x E_r V/mm	29 0.1	29 0.1	14 0.1	6 0.1	1.8 0.1	0.1 0.1	0 0
ε, eV	67	36	20	8	6	6	6
Q_i, 10^{14} part/s/mm^3	1.0	0.75	0.93	1.4	1.4	1.2	0.46

Table 5. Cells close to the inner wall (Fig. 7)

Distance from DC edge, mm	1	2	3	4	5	6	7
E_x E_r V/mm	27 0.1	27 0.1	14 0.1	6.8 0.1	2.9 0.1	0.3 0.1	0 0
ε, eV	80	48	18	10	10	10	10
Q_i, 10^{14} part/s/mm^3	0.6	0.9	0.79	0.68	0.68	0.68	0.62

VI. DC erosion profile calculation

It is known that the DC material sputtering yield strongly depends on surface temperature. Therefore for calculation of DC wall erosion it was calculated temperature distribution along DC working surface on the basis of balance of energy stream which is brought with particles from plasma to the DC surface, and which is radiated from this surface in outer space. By calculation of radiation of a surface with square S at temperature T_s on well-known Stefan-Boltzmann's relation for a grey body

Table 6. Cells close to the center line (Fig. 7)

Distance from DC edge, mm	1	2	3	4	5	6	7
E_x E_r V/mm	29 0	29 0	14 0	6 0	1.8 0	0.1 0	0 0
ε, eV	90	91	78	80	26	15	17
Q_i, 10^{14} part/s/mm^3	2.6	2.5	2.5	2.8	2.8	2.5	2.4

$$N_{rad}=S\cdot\varepsilon\cdot T_s^4\cdot\sigma$$

Factors $\varepsilon=0.5$ and $\sigma=5.6\cdot10^{-8}$ W/(m$^2\cdot$K^4) were used. To calculate temperature T_b of a surface, which does not contact to plasma, transfer of heat N_{con} to this surface from a wall contacting to plasma in view of factor of heat conductivity of DC material $\lambda=0.44$ W/(K·m) is considered. The scheme of thermal streams is shown in Fig. 8. We used the following equation to determine of an energy stream N_e, which is bring by electrons to DC surface, considering that electron with temperature T_e and a charge q overcome retarding potential $\Delta\varphi_w$ of close to the wall layer

$$N_e=n_e\cdot\exp(-\Delta\varphi_w/T_e)\cdot(T_e\cdot2\cdot q/\pi/m_e)^{1/2}.$$

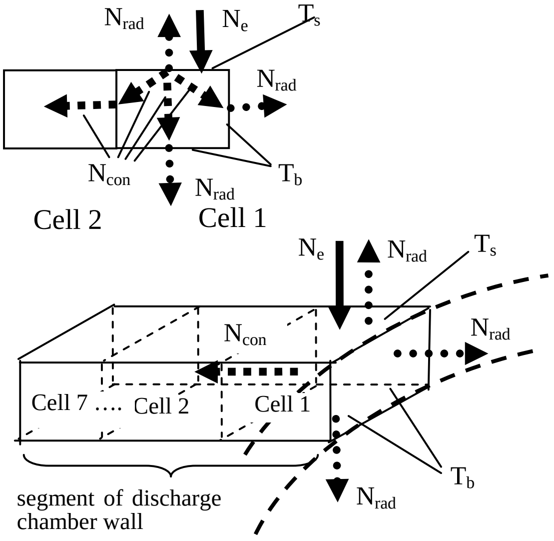

Figure 8. Heat balance through borders of cells allocated in DC body.

At the DC input this stream brings ≈0.1 W of energy on 1 mm^2. Dependence of potential drop $\Delta\varphi_w$ on electron temperature has been determined early (Fig. 6.) Analyzing value of energy stream to a DC wall it is possible to results that more than 90 % of energy bring to a DC surface by electrons.

By calculations of DC erosion process movement of ions was modeled, considering: 1) that initial ion velocity is equal to velocity of atoms, which are distributed on Maxwell function; 2) data on Q_i (in Tables 1-6) – quantity of ions born per second in 1mm^{-3} in ZI of DC. Distribution of potential φ(r) lengthways close to the wall layer (perpendicular to DC surface) was determined on the basis of Poisson equation. The ion trajectory in view of potential distribution φ(r) in close to the wall layer was calculated.

Dependence of factor Y of DC material sputtering yield on a corner of Xe ion falling to DC surface and on Xe ion energy is considered[2] (look in Fig. 9 and 10). By calculation the value of a radial component of electric field E_r outside of close to the wall layer was varied. It was taking into account that in process of DC destruction (as width of the DC channel increase) intensity of an ion birth Q_i decreases in again appeared areas of the channel (removed from an average line in a radial direction) because of decreasing of neutral particles concentration in these areas.

Outcome of calculations for variants (when radial a component of electric field E_r it is not equal to zero and when E_r=0) are resulted in a Fig. 11 and 12 where the calculated temperature T_s of DC surface also is specified.

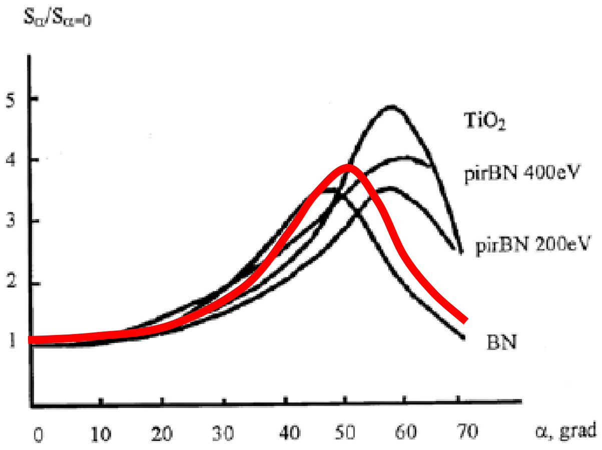

Figure 9. Dependence of DC material sputtering yield[2] on a corner of Xe ion falling to DC surface. Red curve - was used for calculations.

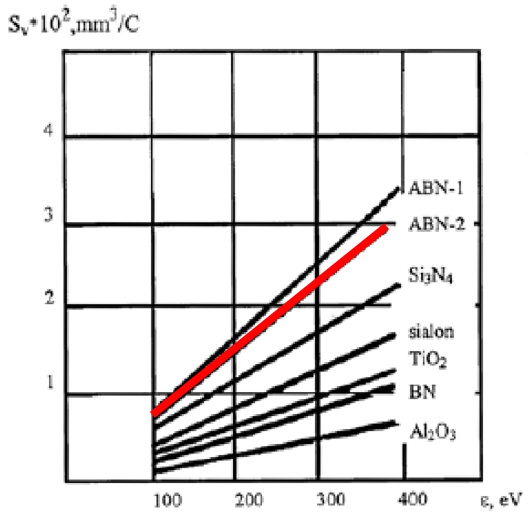

Figure 10. Dependence of DC material sputtering yield[2] on Xe ion energy. Red curve - was used for calculations.

VII. Discussion and Conclusion

Life-time of HT M-70 type has been estimated in design bureau "Fakel" by 3500 hours, when thickness of DC wall is 3 mm. Our calculations of DC erosion (Fig. 11 and 12) show that rate of erosion is approximately 1.5 … 2 times surpasses the erosion rate, which is supposed by manufacturer. The most probable direct reason of a deviation of our results of calculations (it is specified above) consists that the DC surface temperature has been overestimated. It has occurred as result of limitation of electron distribution function energy range by value of $3T_e$.

To explain experimental data about existence of electrons with temperature 40 eV and more it has been assumed that electron energy is limited by value of $3T_e$. Then existence of close to the wall layer with potential drop (not zero) is possible at electron temperatures more than 30 эB. This layer prevents an unlimited electron stream to a DC wall and cooling of electrons. As a result of calculations it has appeared that electron stream to a DC wall with concentration about 10^{17} m^{-3} in a zone of ionization (when electrons overcome the retarding potential drop in close to a DC wall layer and interact with a wall owing to what electrons move to the anode) in some times surpasses value of an axial electron current in DC (nearby 1 A). Thus, we have received inconsistent results: electron current to a DC wall considerably exceeds an axial electron current. The most probable reason of the overestimated value of an electron current to a DC wall consist in error of potential drop in close to a DC wall layer determining. It is the consequence of that electron energy was limited by value of $3T_e$. To correct calculation it is necessary to increase electron energy limit of distribution function up to $4T_e$ … $5T_e$. Then also would exist potential drop in close to the wall layer at T_e> 30 eV and more. Then the electron current to DC surface would be in some times less. And, as consequence, DC surface temperature, which strongly influences DC sputtering yield, would be less.

Operation mode when Er→0 is artificially created for calculation of DC erosion. It has enabled to examine a hypothetical situation and to analyze whether costs aspires to create HT designs, in which E_r→0. Results of calculations show that radial component of an electric field considerably reduces electron stream to a DC wall. It limits DC surface temperature and reduces erosion rate. When E_r→0 the big stream of electrons to a DC wall surface leads to heating of a DC wall and to cooling of electrons that in turn reduces intensity of a birth of ions and reduces thrust of HT.

Being based on results of calculations, we can summarize the basic features of discharge chamber erosion: the basic role in formation of the directed stream of ions to ceramic walls of chamber plays a radial component of an electric field, especially in the field of where a longitudinal component is small; the basic role in increasing of energy of an ions, which bombard the chamber walls, plays close to the wall potential drop; mainly due to electrons heating of the chamber walls that conducts to strengthening of erosion is going.

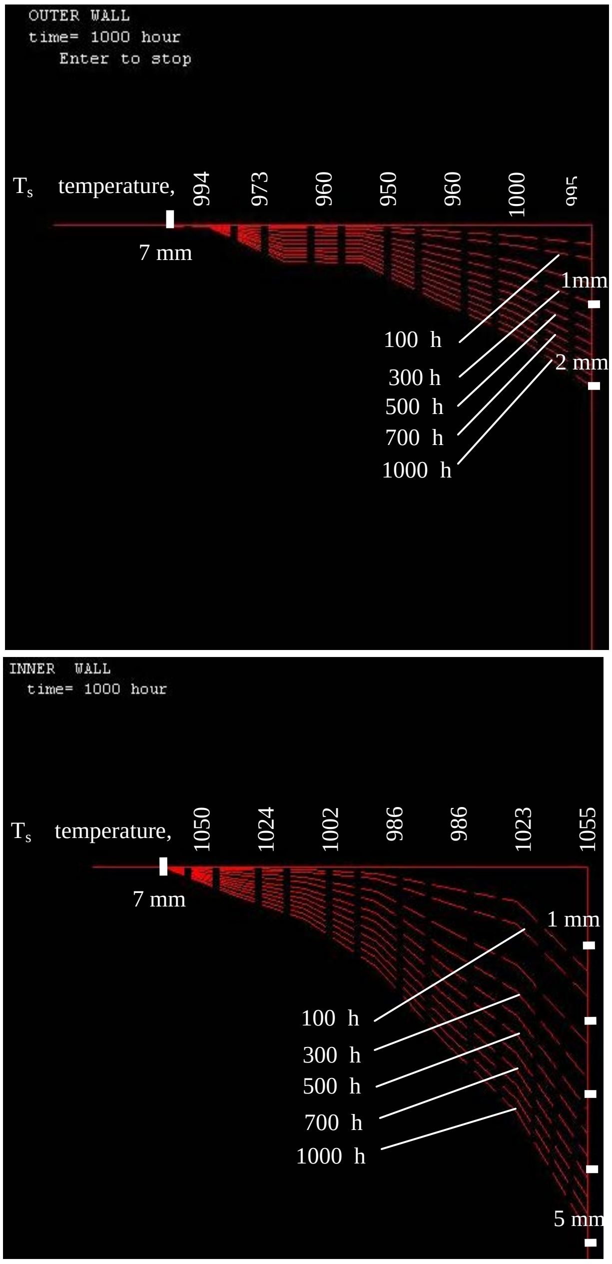

Figure 11. Distortion of the wall of HT M-70. DC surface temperature T_s. Radial component of electric field E_r#0. Thrust was calculated as 4.2 grams.

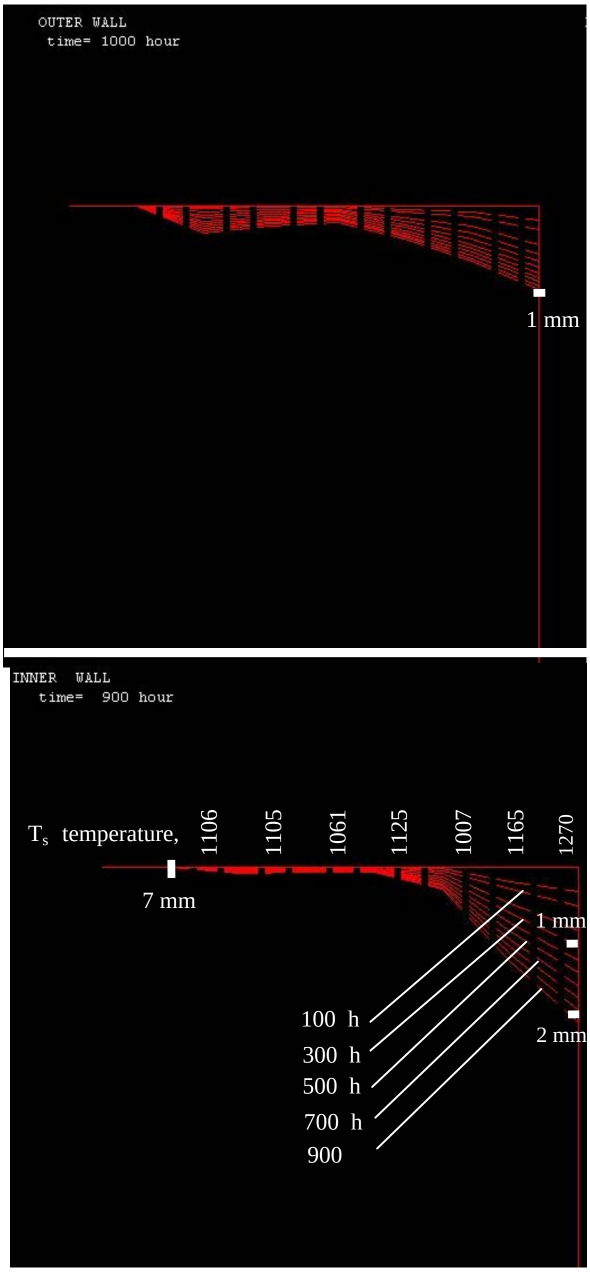

Figure 12. Distortion of the wall of HT M-70. DC surface temperature T_s. Radial component of electric field E_r=0. Thrust was calculated as 2.6 grams.

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