

Investigation of Discharge Channel Wall Material Influence on Lifetime of Hall Effect Thruster with High Specific Impulse

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ABSTRACT

Results of 500 hours life tests of 900 W Hall thruster laboratory model with specific impulse of 2000 s are considered. The thruster discharge channel walls were manufactured of 60% BN + 40% SiO₂ and >90% BN hot pressed ceramics. Predicted total lifetime was ~3000 h for both wall materials in spite of greater erosion resistance of pure BN in comparison with BN-SiO₂ mixture. To clarify observed phenomenon following research was carried out: insulators surface microstructure and composition was investigated by means of electron microscopy and X-ray fluorescence analysis; near wall plasma parameters were studied with flat Langmuir probes; obtained plasma parameters distributions were compared with results of discharge channel 1-D stationary hydrodynamic modeling.

1. INTRODUCTION

Recent trends in commercial spacecraft development set up increased requirements to Hall effect thrusters (HET) used in orbit correction propulsion systems specific impulse and lifetime. In particular this means the increase of total specific impulse up to 3000s with lifetime more than 3000 hours. Serious modifications of existing HET-models with space flight experience are required to satisfy these requirements. It is necessary to change discharge chamber geometry, magnetic field topology inside the discharge channel, materials of discharge channel walls.

Most of HETs applied in space missions today are equipped with discharge channel walls made of BGP – ceramic consisting of ~60% BN and ~40% SiO₂. While this material provides excellent mechanical and insulating properties its sputter resistance to xenon plasma is hampered by relatively high fraction of SiO₂ [1]. The search for new materials with increased erosion resistance and comparable HET output parameters with BGP is carried out in different laboratories [2-4]. Experiments conducted in Keldysh Centre and other laboratories show, that boron nitride of high purity (more than 90%) is to be considered as most promising substitute for BGP.

In a frame of work presented in this paper a hot pressed hexagonal boron nitride ceramic (h-BN) with less than 4% of boron oxide and calcium oxide used as binders named BN-05 was studied along with BGP as materials for HET discharge channel walls. The laboratory model of HET with power of 900 W and specific impulse of 2000 s was equipped with insulators made of both ceramics and 500-hours life tests were carried out for each material [5]. The specific impulse degradation during life test was 100 s lower for BN-05 walls than for BGP ones. The full lifetime predicted with semi-empirical model [6] for both materials was ~3000 hours.

Obvious causes of observed phenomenon, namely similarity of sputtering yield for both materials and differences in discharge channel walls macrostructure were considered in [5]. It was shown, that BN-05 had 1,5...2 times less sputter yield than BGP for Xe ions energy range 250...500 eV for ion beam incidences range 0°...70°. Furthermore it was shown that during first 500 hours of operation “anomalous erosion” structure appears on the BGP walls while BN-05 walls surface remains relatively smooth (fig.1).

This paper is dedicated to clarification of physical mechanism beyond the similarity of lifetime for Hall thrusters with different sputter resistant discharge channel wall materials. The wall surface microstructures and compositions of different HETs developed in Keldysh Centre are investigated and near-wall plasma parameters are measured for BGP and BN-05 walls.

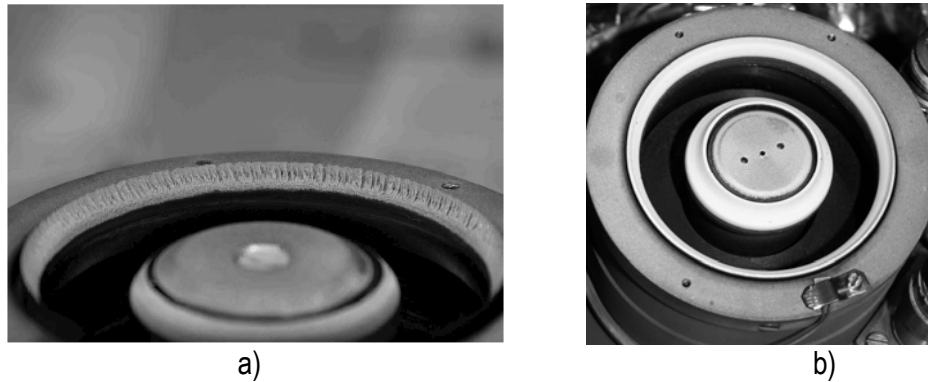


Fig.1. 900 W HET after 500 hours of operation at discharge voltage of 500 V: a) BGP walls; b) BN-05 walls.

A simple 1-D stationary hydrodynamic model of Hall thruster plasma in discharge chamber is introduced to explain the obtained results.

2. WALL SURFACE MICROSTRUCTURE AND COMPOSITION INVESTIGATION

The walls surface investigation was carried out using Environmental Scanning Electron Microscopy (ESEM) method, which allowed studying of insulating ceramics without deposition of any conductive coating and conventional X-ray Fluorescence Spectroscopy (XRFS) analysis. Due to relatively low mass of atoms composing studied ceramics and small scale of considered microstructures results of XRFS are qualitative while ESEM pictures are considered as reliable source of quantitative information.

It is well known [7] that during prolonged operation of HET with BGP discharge channel walls at discharge voltage 300-350 V two kinds of macrostructures appear on the insulators surface: first regular peaks and holes called normal erosion and later periodic grooves oriented axially at the cathode side of walls called anomalous erosion. Normal erosion structure appears after 5-10 hours of operation. Similar structure appears during ceramic sample sputtering in a plume of a Kaufman plasma source or a HET [1,5]. It was proposed that normal erosion is caused by differences in sputtering yield of BN and SiO₂ grains of BGP [1]. While physical mechanism beyond the anomalous erosion is not so clearly understood appearance of anomalous erosion structure is important indicator of HET operation mode. Usually it is connected with major decrease of channel walls sputtering rate [7]. Both normal and anomalous erosion structures were observed on the walls of tested HET laboratory model made of BGP after 500 hours of operation at high specific impulse mode. ESEM images of these structures are presented at fig.2 a,b.

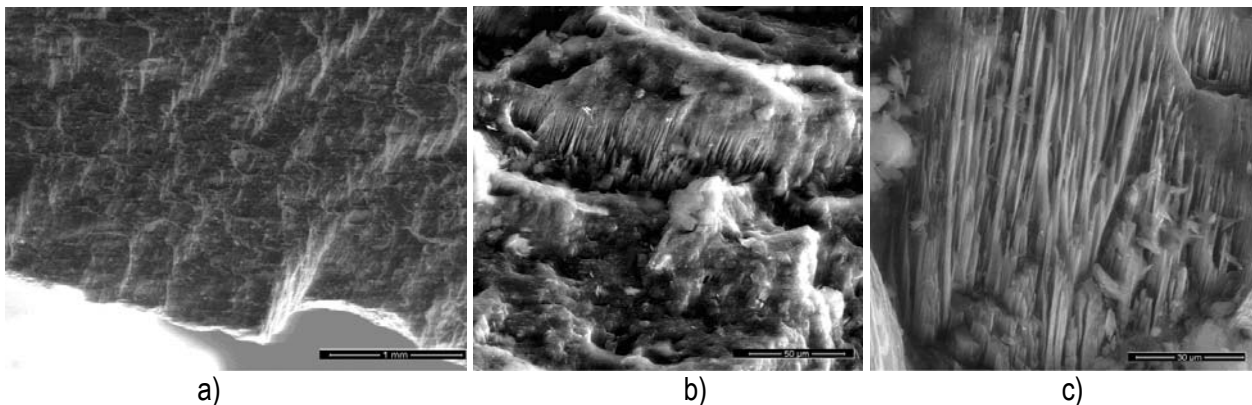


Fig.2. ESEM results for BGP walls structure at different magnification levels: a) anomalous erosion structure (size ~1mm); b) normal erosion element (size ~150 μ m); c) fine structure needles (diameter 50...600 nm, length 100...1600 nm).

XRFS analysis showed that material composition at the top of normal erosion peaks anomalous erosion groove was generally similar to composition of non-sputtered material (B, N, Si, O atoms). The bottom of normal erosion holes usually consisted of Si and O atoms. Walls of the hole were often covered with scales composed of redeposited material from its bottom. Anode side of discharge channel walls was covered with dark-brown and black films composed of mainly of Si and O with traces of B, N, C, Al, Fe and Xe atoms.

At greater level of magnification the “fine structure” of normal and anomalous erosion patterns was detected on BGP walls. This structure consists of needles with diameter of 50-600 nm and length of 100-1600 nm (fig.2 c.). Erosion “fine structure” needles were located at the sides of anomalous and normal erosion elements covered from the direct HET plasma plume bombardment, i.e. generally at the cathode-oriented side of these structures. There were no such structures observed on the samples sputtered in HET plasma plume. So it was supposed that these needles appeared due to plasma-enhanced redeposition of sputtered material from one channel wall to another. The intensity of Si and O atoms radiation lines in the XRFS spectrum of these needles was much greater than in spectrum of unsputtered material.

The presented results of XRFS and ESEM analysis showed that BGP walls structure and composition change greatly with HET lifetime. These changes should be considered during HET modelling and development. Possible mechanisms of “fine structure” influence on the HET operation require detailed investigation. At glance such structures can affect plasma electrons transportation through changes in wall emissive properties.

The typical structure of 900 W thruster BN-05 wall obtained by ESEM is presented in fig.3 a. As one can see, the structure consists of flat grains bound together, with thin edge oriented normally to the picture plane. The size of observed grains is close to the size of h-BN powder particles used for manufacturing of the BN-05 ceramics. The axis of the hot pressing was oriented from the top of the figure to its bottom. XRFS analysis of BN-05 wall structure didn't show any radical changes in material composition in comparison with unsputtered material.

To find out reasons behind the lack of anomalous erosion structure on the 900 W HET model walls another HET model – KM-32 – equipped with BN-05 walls was investigated with ESEM method. The KM-32 thruster was designed for operation in power range 100...300 W, discharge voltage range 250...400 V and successfully passed 180-hours life test with BGP walls and 500-hours life test with BN-05 walls [8]. Results of ESEM for outer wall of KM-32 are presented in fig.3 b,c. The anomalous erosion structure can be clearly seen on both figures, however the structure appeared 200...250 hours later on BN-05 walls, than on BGP ones. The structure period is of similar size (~200 μm) for both materials.

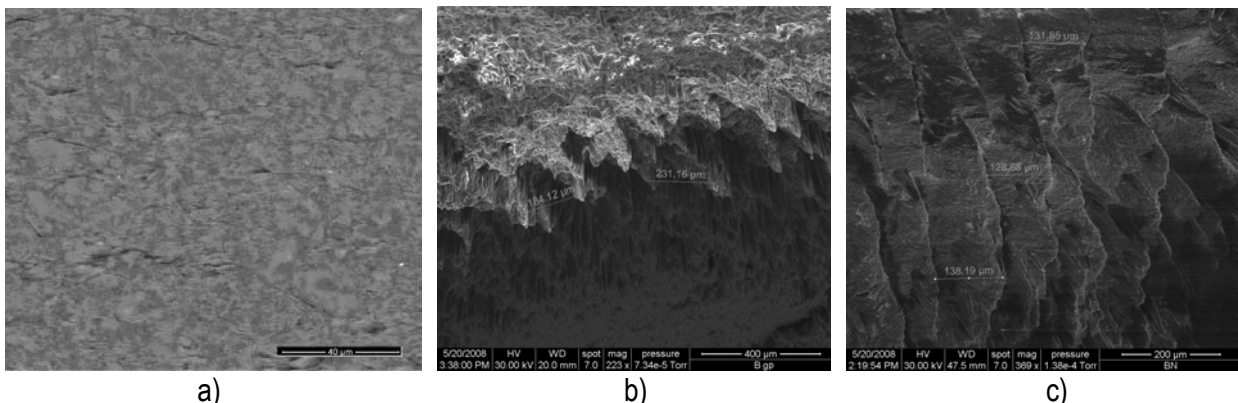


Fig.3. ESEM results for BN-05 and BGP walls structure of different HETs: a) 900 W HET, discharge voltage 500 V, lifetime - 500 hours, normal erosion elements (size ~3...5 μm); b) KM-32, discharge voltage 250 V, BGP walls, lifetime - 180 hours, anomalous erosion structure (size ~200...250 μm); c) KM-32, discharge voltage 250 V, BN-05, lifetime - 500 hours, anomalous erosion structure (size ~200...250 μm).

The phenomenon may be caused by the differences in the intensity of normal erosion for investigated materials, while anomalous erosion is quite similar in intensity and resulting structure composition[7].

3. NEAR-WALL PLASMA PARAMETERS MEASUREMENT

First results of analysis of near-wall plasma parameters for the investigated 900 W HET laboratory model were described in [5]. However, the values of ion current on the walls were estimated with several assumptions proved to be erroneous for high voltage modes HET operation for probes located in the acceleration zone, i.e. area where the plasma potential drop is observed. The measured values of plasma potential were also overestimated. The analysis of data obtained and observed systematic errors lead to following conclusions: temperature of electrons can be measured with lowest error, following by the floating and plasma potentials, which can be affected greatly by very low frequency oscillations (2-3 Hz), changes in HET operation mode due to thruster heating and parasitic currents in the data acquisition system. Currents of electrons and ions are measured with greatest errors and can be considered only as auxiliary qualitative data. Basing on these conclusions following experiments were carried out.

Flat Langmuir probes were installed into the outer discharge channel walls to obtain local plasma parameters distribution for 900 W HET laboratory model equipped with BN-05 and BGP walls. The volt-ampere characteristics of the probes were collected after 3 hour of HET operation at chosen mode. The power source allowed rapid decrease of probe voltage from 50 V higher than plasma potential to the ground potential. The signal from the probe was visualized on the recording oscilloscope and volt-ampere characteristic was chosen for further processing manually. The value of floating potentials for all probes was constantly controlled during the experiment.

The measurements error is estimated as 25...30%. It includes errors due to changes of probe geometry during the measurements, uncertainty of probe positioning relatively to the wall inner surface, non-Maxwellian electron energy distribution and periodic plasma parameters changes during the experiment.

The distributions of electron temperature for different operation modes are presented in fig 4a. The corresponding plasma potential distributions are presented in fig.4b. Position of outer magnetic pole and outer discharge channel wall are also presented in the figures. The cause of the two-hump electron temperature distribution in case of BN-05 walls is unclear. One can see, that areas of maximum electron temperature and electric field are located 1-1,5 mm closer to the anode in case of BN-05 walls. Maximum of electron temperature is higher for BN-05 walls, which corresponds to results published in [9].

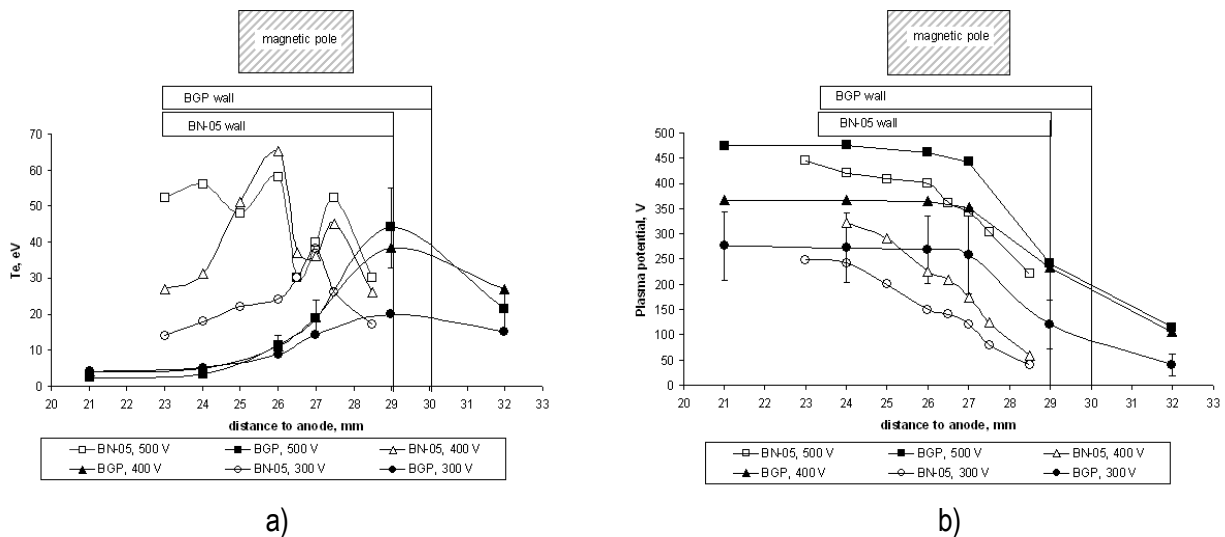


Fig.4. Plasma parameters distribution of 900 W HET laboratory model at different discharge voltages and anode mass flow of 1.8 mg/s: a) electron temperature; b) plasma potential.

Basing on presented data, we can presume that ionization and acceleration zones for BN-05 walls are located closer to the anode than ones of BGP walls. So the ion flux bombarding BN-05 wall should be higher in absolute value and ions mean energy should be higher than in case of BGP walls. This phenomenon is recognized as main cause of equal lifetime for both materials.

4. 1-D MODEL OF DISCHARGE CHAMBER

To obtain quantitative criterion of ionization and acceleration zones position dependence on the wall properties a simple 1-D stationary model was developed. The approach was similar to one used in [10]. Plasma of discharge channel with height h and cross-section area S was modelled. The model included following components of plasma: electrons, single charged ions and neutral atoms. Elastic electron-neutral scattering, inelastic electron-neutral excitation, electron-neutral ionization, ions loss to the wall and electron energy loss to the wall collisions were modelled. The neutrals were injected through anode-side of the model region, their temperature and velocity were constant. All the mentioned collisions were modelled by appropriate frequencies:

$$\begin{aligned} v_{iw} &= \alpha_w \cdot \frac{1}{h} \cdot 2 \cdot \frac{1}{n_i} \cdot \Gamma_i \\ v_{ew} &= \alpha_w \cdot \frac{1}{h} \cdot 2 \cdot \frac{1}{n_e} \cdot \Gamma_e \\ v_i &= n_n \sigma_i \left(\frac{8kT_e}{\pi m} \right)^{1/2} \left(1 + 2 \frac{kT_e}{E_i} \right) \exp\left(-\frac{E_i}{kT_e} \right) \\ v_n &= n_n \sigma_n \left(\frac{8kT_e}{\pi m} \right)^{1/2}, \end{aligned} \quad (1)$$

where m - electron mass, v_{iw} - frequency of ions loss to walls, v_{ew} - frequency of electron collisions with walls, v_i - frequency of ionization, v_n - frequency of electrons elastic collisions with neutrals, $\alpha_w = 0,3...0,003$ - attenuation coefficient, introduced for accounting of magnetic confinement of electrons between walls, $\sigma_n = 2,7 \cdot 10^{-19}$ - mean cross-section of elastic electron-neutrals collisions, $\sigma_i = 3,6 \cdot 10^{-20}$ - mean ionization cross-section, T_e - electron temperature, $E_i = 12,1$ eV - ionization potential Xe, Γ_i, Γ_e - ions and electrons flows to the walls, n_n, n_e, n_i - concentrations of neutrals, electrons and ions.

Near-wall potential drop φ_w was calculated according to [11]:

$$\begin{aligned} \varphi_w &= -\frac{kT_e}{e} \left(\frac{1}{2} \ln \left(\frac{MT_e}{mT_i} \right) + \ln(1 - \delta) \right); \delta < 0,997 \\ \varphi_w &= -\frac{kT_e}{e}; \delta \geq 0,997 \end{aligned} \quad (2)$$

where e - electron charge, δ - integral secondary electrons yield.

For δ exponential approximation was used:

$$\delta(\varepsilon) = \left(\frac{\varepsilon}{\varepsilon_1} \right)^\alpha, \quad (3)$$

where ε - total kinetic energy of electron, ε_1 (31 eV for BN-05, 53 eV for BGP [12]), α (0,57 for BN-05, 0,64 for BGP [12]) - experimental coefficients.

Ions flow to the wall equaled electrons flow to the wall with the deduction of secondary electrons flow:

$$\Gamma_i = \Gamma_e(1 - \delta) = \left(\frac{kT_e}{2\pi m}\right)^{1/2} n_e \exp\left(\frac{e\phi_w}{kT_e}\right)(1 - \delta); \delta < 0,997$$

$$\Gamma_i = \Gamma_e = \left(\frac{kT_e}{2\pi m}\right)^{1/2} n_e; \delta \geq 0,997$$
(4)

where $T_i = T_n = 1000^\circ K$ ions and neutrals temperature, M - xenon atom mass.

In this manner a possibility of space charge saturation (SCS) mode occurrence was taken into account.

Ions mass and momentum conservation equations were solved with given electron temperature and magnetic field distribution inside the discharge chamber:

$$\frac{d(n_i V_i)}{dz} = n_e v_i - n_i v_{iw}$$
(5)

$$\frac{d(n_i V_i^2)}{dz} = \frac{e}{M} n_e E + n_e v_i V_n - n_i v_{iw} V_i$$
(6)

Electrons motion equation was reduced to:

$$V_e = -\left(\frac{e}{m} \left[\frac{v_n + v_{ew}}{\Omega_e^2} \right] + \frac{\alpha_{Bohm}}{B}\right) \cdot E = -\mu_e E,$$
(7)

where μ_e - axial mobility of electrons, E - electric field, V_e - electrons axial velocity, B - magnetic field, $\Omega_e = eB/m_e$ - electron cyclotron frequency, $\alpha_{Bohm} = 1/160$ - coefficient of anomalous diffusion of electrons.

Equations of discharge current continuity, heavy particles global mass continuity, plasma quasi neutrality were also solved:

$$I_d = const = e \cdot S \cdot (n_e V_e + n_i V_i), n_n V_n + n_i V_i = const = \dot{m}_a / (MS), n_e = n_i,$$
(8)

where I_d - discharge current, $V_n = const = \left(\frac{5 kT_n}{3 M}\right)^{1/2}$ - neutral velocity, \dot{m}_a - anode mass flow rate [kg/s].

Initial degree of ionization was assumed 0,01. To determine the physical mechanism of observed experimentally difference in acceleration zone position distribution of electron temperature was selected equal for both materials and close to measured experimentally for BGP. Results of numerical integration of equations (1-8) are presented in fig.5 a-d.

Despite simplicity of proposed model, results of calculations allowed seeing difference in ionization zone position and conditions of ions acceleration. The difference was caused by realization of SCS mode in case of BN-05 walls, while in case of BGP walls this mode was not realized. Strong difference in electrons-walls collisions frequency for BGP and BN-05 (fig.5 d) caused increase of electron conductivity in latter case, shift of ionization frequency and electric field maximum to the anode. Varying initial T_e distribution one could realize SCS mode for both materials or for none.

If SCS mode was not realised then differences in axial position of ionization and acceleration zones were similar to fig. 5. If SCS mode was realized for both materials then ionization and acceleration zones of BN-05 and BGP became indistinguishable.

Today the described model is not a reliable instrument for calculation of self-consistent plasma parameters of HET. There are non-realistic oscillations of ion velocities in the anode-side of modeled area, and obtained value of plasma potential drop inside the channel is too large in comparison with one observed in the experiment. To improve the model it is needed to include the electrons heat balance equation in the calculation, to calculate α_w using results of magnetic field 2-D modelling, to model realistic neutrals velocity and density distribution.

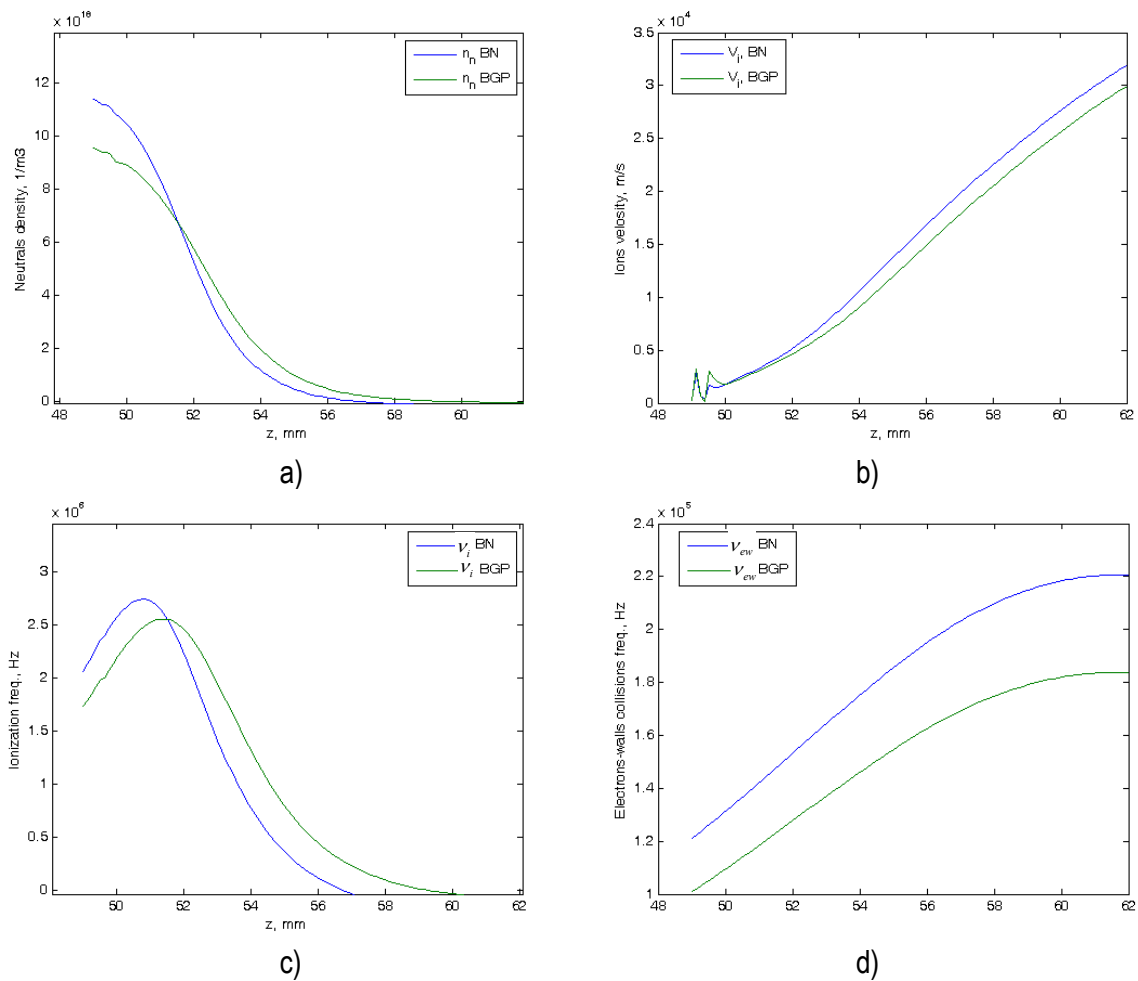


Fig.5. Results of axial plasma parameters distribution calculation ($I_d = 1,8 \text{ A}$, $\dot{m}_a = 2,11 \cdot 10^{-6} \text{ kg/s}$, $T_{eMax} = 50 \text{ eV}$): a) neutrals density; b) ions velocity; c) ionization frequency; d) electrons-walls collision frequency.

5. CONCLUSION

Results of 500 hours life tests of 900 W Hall thruster laboratory model with specific impulse of 2000 s and discharge channel walls made of BN-05 and BGP ceramics are considered. It was shown that application of more sputter resistant material, as an insulator did not increase HET total lifetime. Possible causes of observed lifetime similarity were considered in this paper: differences in wall surface morphology and composition and dependence of near-wall plasma parameters on wall material properties.

The walls surfaces were investigated using Environmental Scanning Electron Microscopy (ESEM) method and conventional X-ray Fluorescence Spectroscopy (XRFS) analysis. BGP and BN-05 different walls parts atomic composition was investigated.

It was shown that besides well known normal and anomalous erosion structures the “fine structure” composed of needles with diameter of 50-600 nm and length of 100-1600 nm exists on BGP walls after 500 hours of HET operation. It was also shown, that anomalous erosion structure can appear both on BN-05 and BGP walls. The period of the initial grooves looks similar, while time of appearance is 200...250 hours later on BN-05 walls, than on BGP ones.

Near-wall plasma parameters distributions were measured for both walls materials using flat Langmuir probes. It was shown, that areas of maximum electron temperature and electric field are located 1-1,5 mm closer to the anode in case of BN-05 walls. It was proposed, that this phenomenon was responsible for lifetime similarity obtained for 900 W Het laboratory model with BN-05 and BGP walls.

To obtain quantitative criterion of ionization and acceleration zones position dependence on the wall properties a simple 1-D stationary model was developed. It was shown that difference in electrons-walls collisions frequency for BGP and BN-05 caused increase of electron conductivity in latter case with shift of ionization frequency and electric field maximum to the anode. The difference in electrons-walls collision frequencies was caused by different secondary electron emission yield of BGP and BN-05.

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