Analysis of Ceramic Erosion Characteristic in Hall-Effect Thruster with Higher Specific Impulse

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Abstract: The results of investigation of two materials - boron nitride-silicon oxide composition BGP and hot pressed boron nitride with boron oxide-calcium oxide binders BN-05 - sputtering by low energy Xenon ions are presented. The materials were sputtered both in plasma plume and as a part of insulators of 900 W Hall thruster with higher specific impulse. Dependencies of erosion rate on temperature (250; 480 °C), ion energy (300; 500 eV), angle of ion incidence (0^o-70^o) were measured on test samples is Hall thruster plasma. Then 500-hour life tests were carried out and life prediction was made which amounted to 3000 hours for both materials, in spite of greater erosion resistance of BN-05 in comparison with BGP in plasma plume. As a cause of observed effect several hypotheses are considered, namely differences in surface roughness of the insulators; different characteristics of near-wall plasma parameters, determining the value ion incidence angle and kinetic energy; differences in optimal magnetic field topology inside the discharge channel.

Nomenclature

HET = Hall effect thruster
I_{coil} = magnet coil current
γ = sputtering yield
φ_{pl} = plasma potential
φ_f = probe floating potential
T_e = electron temperature
n_e = plasma density
h_c = height of discharge channel
R_{pole} = radius of magnetic system pole
E_i = ion kinetic energy
α = angle between ion velocity and surface normal

I. Introduction

LATEST trends in commercial spacecraft development set up increased requirements to orbit correction propulsion systems HETs specific impulse and lifetime. In particular this means the increase of total specific impulse up to 3000s, discharge voltage up to 1000 V and lifetime up to 8-10 thousands hours. To satisfy these requirements it is necessary to modify discharge chamber geometry, magnetic field topology inside the discharge channel, materials of discharge chamber walls in comparison with existing HET-models with space flight experience optimized to operation at discharge voltages of 300-350 V.

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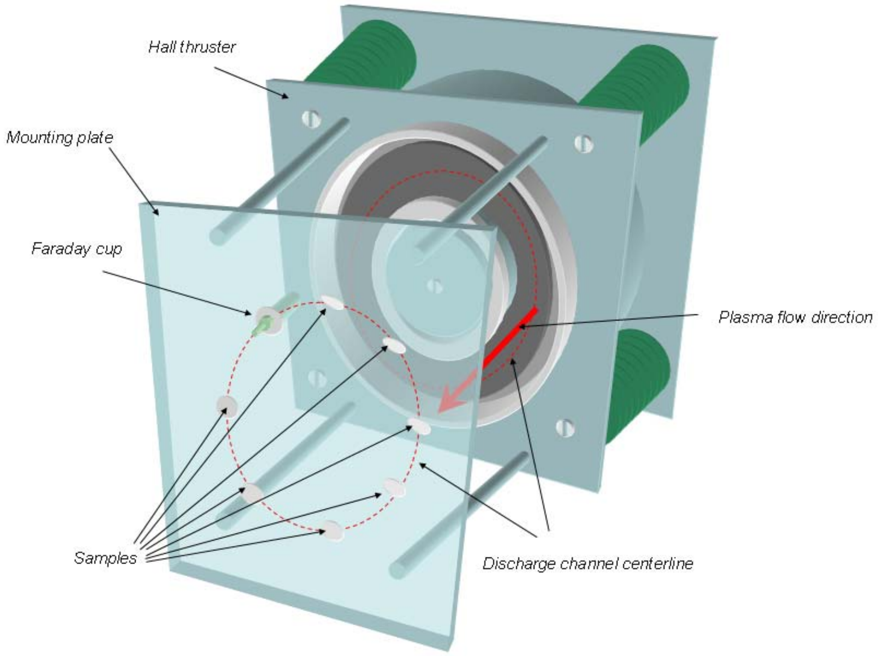

Figure 1. Principal scheme of sputtering yield measurement experiment.

Different experiments show, that application of BGP– material traditionally used for manufacture of HETs discharge chambers - is not always reasonable on thrusters with high specific impulse [1]. The search for new materials for discharge chamber insulator with increased erosion resistance and comparable output parameters with BGP was carried out in different laboratories[2,3,4]. Experiments conducted in KeRC and other laboratories shown, that boron nitride of high purity (more than 90%) is to be considered as most promising substitute for BGP. Boron nitride composites applied as discharge chamber material in these investigations were usually manufactured by process of hot pressure with different oxides or acids used as binders.

In a frame of work presented in this paper a hot pressed hexagonal boron nitride composition with less than 4% of boron oxide and calcium oxide used as binders named BN-05 was studied along with BGP. The experiments of sputtering yield measurement were carried out for both materials. The erosion sputtering yield for BN-05 was 1,5-18 times lower than BP one depending on ions energy and incidence angle. Then 900 W HET laboratory model with higher specific impulse and discharge voltage of 480 V was equipped with insulators made of both materials and optimization of magnetic field topology and discharge chamber geometry was carried out. Then short-cut and full time 500 hours comparison life tests were carried out for four HET models with different channel wall materials, magnetic field topology and chamber geometry. Predictions of full lifetime were made for investigated HET laboratory models with semi-empirical model described in[5]. For all HET models with BN-05 or BGP insulators full lifetime was 3000 hours.

Several causes of observed lifetime similarity were named: differences in surface roughness of the insulators; different characteristics of near-wall plasma parameters, determining the value of plasma flow to the walls, ion incidence angle and kinetic energy; differences in optimal magnetic field topology inside the discharge channel. The results of studying of these causes are presented in this paper.

II. Measurements of BN-05 and BGP sputtering yield in HET plasma plume

The experimental setup used for the investigation of sputtering yields is presented on fig.1. A 3kW HET laboratory model with 100 mm diameter of channel centerline was used as a source of ions. This thruster is capable of stable operation in discharge voltage range 250-1000 V for 40-50 hours without changes in voltage-current characteristic and ion current density in the plume.

The experiments were carried out inside the cryo-vacuum facility CVF-35 of Keldysh Research Center. This facility was designed for carrying out of electric propulsion fire tests, including prolonged life tests for thrusters with

Figure 2. Operation of sputtering yield measurement apparatus.

Figure 3. Mounting plate with samples and Faraday cup after exposition in plasma plume.

power up to 5kW. Vacuum chamber consists of main chamber and antechamber. Main volume has diameter of 3m and volume of 35 m^3. Antechamber volume is 3 m^3, diameter 1,6 m. Main chamber is separated from the antechamber by vacuum shuttle with 900 mm section. Residual chamber pressure is 4 10^{-6} torr. Vacuum pumping system allows keeping of Xenon working pressure of 4 10^{-5} torr with mass flows up to 3 mg/s. Time of continuous life test before the procedure of pump regeneration with Xenon mass flows up to 5 mg/s is 500 hours.

Tested samples were manufactured in a form of disks with 20 mm diameter and 3 mm height. They were positioned in the holders which provided their exposition to HET plasma plume at angles between the surface normal and direction of plasma flow 0 °, 20 °, 40 °, 50 °, 60 °, 70°. Holders also fix samples tightly, allow mounting of thermocouples, protect samples side surfaces from sputtering and redeposition of material from other samples or parts of the measurement equipment. On fig.2 the pictures of BN-05 samples loaded in holders on the mounting plate after the exposition in HET plume are presented.

The tested samples were positioned on the centerline of the HET discharge channel to provide surface bombardment with ions moving in the similar direction. Ion plume was collimated by 5 mm holes drilled in 10 mm thick graphite plate positioned 130 mm far from the HET exit in front of the mounting plate. The ion current density

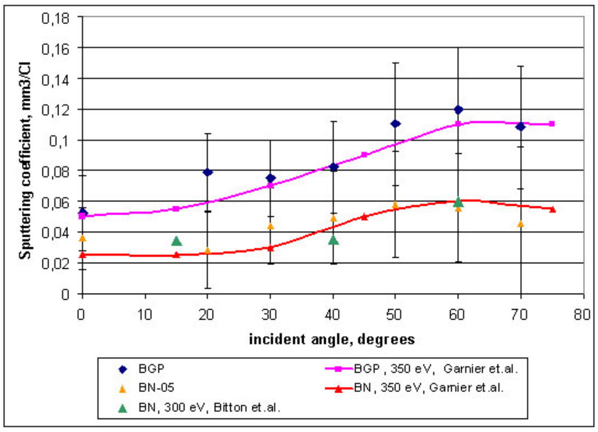

Figure 4. Sputtering yield for BGP and BN-05 comparison
Plasma generator discharge voltage - 325 eV. Results for similar conditions from[6,7] *are also given*

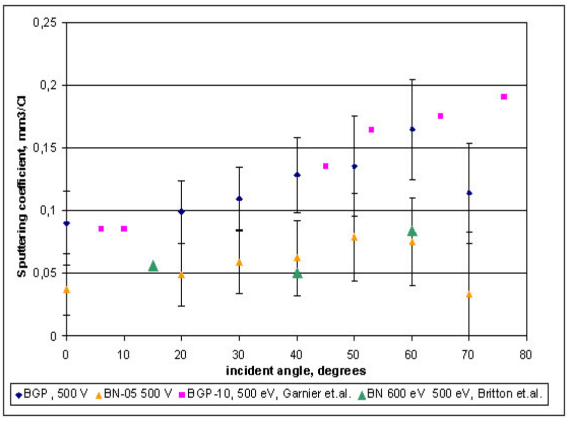

Figure 5. Sputtering yield for BGP and BN-05 comparison
Plasma generator discharge voltage - 500 eV. Results for similar conditions from[6,7] *are also given*

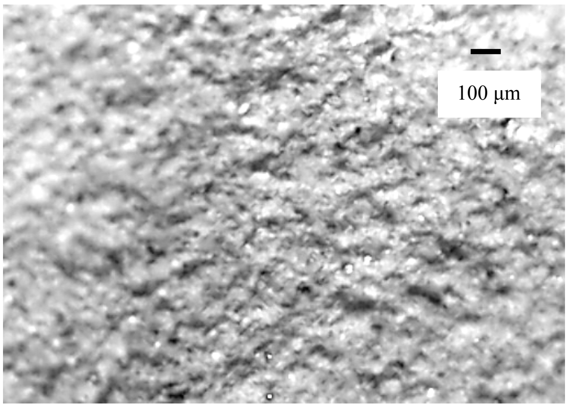

Figure 6a. BGP sample surface relief
Plasma generator discharge voltage - 500 eV, exposition length – 15 hours, current density 10 mA/m^2

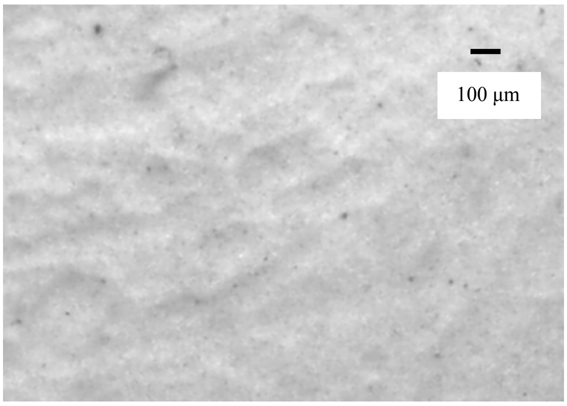

Figure 6b. BN-05 sample surface relief
Plasma generator discharge voltage - 500 eV, exposition length – 15 hours, current density 10 mA/m^2

inside the plume was measured by Faraday cup positioned in a same manner as tested samples. The graphite plate, mounting plate with holders, samples and Faraday cup were mounted on the HET front side. To control samples temperature thermocouples were mounted at their rear sides. So, as one can see, the presented apparatus allows exposition of seven samples at the same time, with constant control of bombarding ions current density at different angles of ion incidence on the samples.

Before the fire tests a control firing was carried out to measure the current density on each sample. To do this, seven additional identical Faraday cups were positioned on the mounting plate instead of samples and fire test was carried out. During that test HET regime operation was optimized to obtain maximum current density on the Faraday cups. Two operation regimes were selected with anode mass flow 3,25 mg/s and discharge voltage 325 and 500 V. The operating sputtering yield measurement device is presented on fig.3. Single exposition of samples to plasma lasted for 20-26 hours. For one material and one value of ion energy three expositions were carried out. Results of the first exposition were usually discarded because surface layer damaged during the samples polishing was removed at that time. Ion current density on the samples varied in a range 8-18 mA/cm^2.

The sputtering yield was measured in units of mm^3/Cl. The mass of eroded material was measured by samples weighting with laboratory balance with accuracy of 0,1 mg. During tests it was observed, that after BN-05 samples ejection from the vacuum chamber their weight varies in a range 0…+1 mg due to rapid adsorption of water vapor by the near-surface layer. To avoid the influence of this effect weighting samples was carried out after heating up to 180^o-200^oC.

Samples density was determined basing on size measured by conventional instruments with accuracy up to 0,01 mm and sample weight. Total charge adsorbed by the sample surface was calculated by multiplication of exposition time by ion current density value measured on the control Faraday cup multiplied by adjustment coefficients for each sample obtained during the control firing.

The measured dependencies of volumetric erosion sputtering yield on ion energy and angle of incidence in comparison with results published by Garnier et.al.[6] and Britton et.al.[7] are presented on fig.4-5. As one can see, the results for BGP and boron nitride are similar to published previously in absolute value, as well as in curves shapes. We should mention that differences in erosion sputtering yield obtained for 325 and 500 V lie within the measurement random error range for BN-05. Energy dependence of γ for BGP is stronger and is closer to ones published in[6,7].

The obtained dependencies of $\gamma(\alpha)$ for both materials are typical for borosils. The $\gamma(\alpha)$ curve maximum is greater than minimum at 0^o in 1,5-2,5 times. Curve maximum for BGP 300 and 500 V is situated on the angle of 60^o while curve maximum published in[6] for the same energy is situated at angles greater than 75^o.

Varying of the samples temperature from 280^oC to 480^o by application of additional heat screens and increase of HET discharge power didn't show any difference in γ for both materials.

Typical relieves formed on the samples surface after exposition in plasma are presented on fig. 6 a,b. On the fig. 6a the formation of periodical wave-like structure consisting of "peaks" and "holes" can be seen on the surface of

BGP. In[6] it was proposed that this structure occurs due to different erosion rate of BGP components: “peaks” are formed from sputter resistant grains of boron nitride, while “holes” appear on places of rapidly eroded zones filled with silicon oxide. The numerical model presented in[6] confirmed made proposition. Similar structures were described in[8] appearing after masking of metal surfaces by carbon, or erosion resistant admixtures. Period of the structures on fig.6 a,b varies between 30-130 µm. Quantity and size of “peaks” is much lower for BN-05 samples, than for BGP ones. Relief on BN-05 samples appears around traces of polishing instrument.

Height of “peaks” and their number per unit of sample area depends on ion angle of incidence for BGP samples. The most prominent structure is observed on the samples with $\alpha=0^{o}$. With increase of α “peaks” number per unit of area decreases and “peaks” height decreases also from 130-150 µm to 50-70 µm.

III. Results of insulator rings made of BN-05 and BGP fire tests and their discussion

When the measurements of sputtering yields of BN-05 and BGP were completed, shortened and full length fire tests of laboratory model HET with insulators made of these materials were carried out. Experiments were conducted inside the KeRC cryogenic vacuum facility CVF-90 providing operation vacuum of $3\text{-}5\cdot10^{-5}$ torr described in detail in[9]. The methods of shortened life test and lifetime prediction applied during these experiments were described in[5].

The life tests were carried out on a laboratory model HET with hybrid discharge chamber, where the chamber was manufactured from steel and magnetic system poles are protected by insulating rings. The laboratory model is optimized on operation with discharge power 900 W, with ability of stable operation in power range 500-1000 W. The magnetic system consists of two magnetic coils with separate power supplies. Life tests were carried out at regime with discharge voltage 480 V and discharge current 1,8 A. After standard procedure of operation regime optimization at minimum discharge current by variation of magnetic field topology, operation mode with maximum total specific impulse was chosen for life test.

Influence of channel height, magnetic field topology, and material properties on HET lifetime was investigated. Two sets of inner and outer rings were manufactured from BGP providing channel height of 13,5 and 15 mm to investigate the channel height influence, two sets of BN-05 rings providing channel height of 13,5 mm were manufactured also. Two HET models with identical magnetic coils and different magnetic poles (1st model $R_{\text{pole in}}/R_{\text{pole out}} = 18/42$, 2nd model $R_{\text{pole in}}/R_{\text{pole out}} = 16/40.5$) were manufactured to study the magnetic field topology influence on HET lifetime. After life tests of these two HET models with three different channel height-insulator material-magnetic poles size combination, third laboratory model HET with optimized number of turns in magnetic coils, discharge channel height 13,5 mm, magnetic poles identical to 2nd model and insulators ring made of BN-05 was manufactured and tested.

500 hours direct life tests were carried out for set of rings made of BGP with channel height 15 mm on the 1st laboratory model and one set of BN-05 rings on a 3rd laboratory model. 500 hours shortened life tests were carried

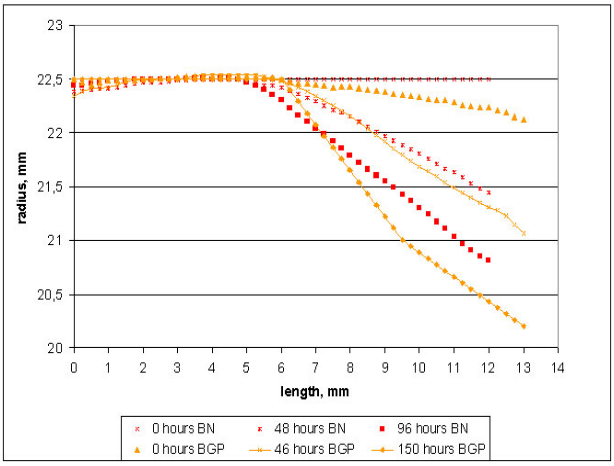

Figure 7. Inner insulator sputtering profiles
Materials: BN-05 and BGP. 2nd HET laboratory model

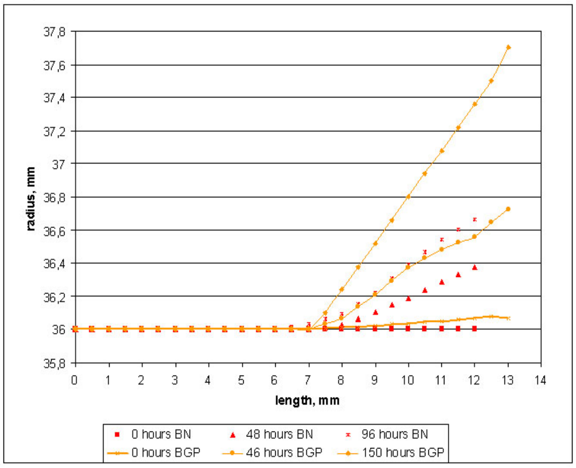

Figure 8. Outer insulator sputtering profiles
Materials: BN-05 and BGP. 2nd HET laboratory model

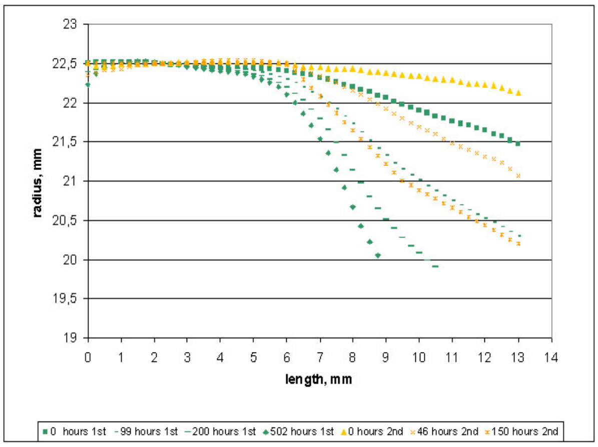

Figure 9. Inner insulator sputtering profiles
Material: BGP. 1st and 2nd HET laboratory models

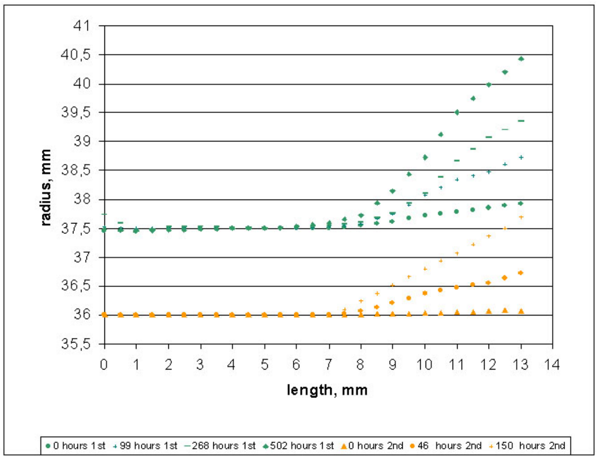

Figure 10. Outer insulator sputtering profiles
Material: BGP. 1st and 2nd HET laboratory models

out on 2nd laboratory model for BGP and BN-05 rings with channel height 13,5 mm. The shortened life test sequence was following:

- fire tests during 17-22 hours, choosing of optimal regimes of operation, measurement of insulators profiles in the atmosphere;
- fire tests during 50 hours, measurement of insulators profiles in the atmosphere, prediction of insulators profiles on 150 hours of operation, insulators modification to fit the predicted profile;
- fire tests during 50 hours, measurement of insulators profiles in the atmosphere, prediction of insulators profiles on 500 hours of operation, insulators modification to fit the predicted profile;
- fire tests during 50 hours, measurement of insulators profiles in the atmosphere, prediction of total HET lifetime.

Anode mass flow for all four variant of HET laboratory model varied in a range of 6%. Discharge voltage and current were kept constant. Insulators profiles obtained during life tests are presented in fig.7-12.

Results of shortened life tests for BGP and BN-05 rings for 2nd model are presented on fig.7-8. Coils made of BN-05 were 1 mm shorter, than BGP ones, due to instable operation of HET with 13 mm long rings. It can be seen, that outer BN-05 ring is sputtered approximately 2 times slower, than one made of BGP during first 150-200 hours of operation, but profiles predicted on 500 hours are very close. Profiles for inner insulators for both materials are close for most of the operation time. Optimal magnetic coils current was 25% higher for BN-05 insulators. HET operation was similar for BN-05 and BGP visually. The erosion zone boundary for BN-05 insulator lied closer than for BGP for outer ring (difference 0,5 mm), as well as for inner ring (difference 1 mm). The length of outer insulator erosion zone was smaller than one of inner insulator erosion zone by 2 mm for both materials.

Results of direct life tests four 1st model and shortened life tests for 2nd model are presented on fig.9-10. As one can see, the sputtering processes of outer insulator are different for these HET models. While profiles of inner insulator for 200 hours of operation of 1st model and 150 hours of operation of 2nd model are very close. Erosion zone of inner insulator of 1st model starts closer to the anode by 1,5-2 mm (depending on operation time) than one of the 2nd model. Length of outer insulator erosion was similar for both models. Difference between erosion zones length of outer and inner insulators was 2-2,5 mm for 1st model and 1,0-1,5 mm for 2nd model.

Profiles obtained during 500 hours direct life tests of 1st and 3rd models with insulators made of BGP and BN-05 respectively are presented on fig.11-12. The length of BN-05 rings was again 1 mm shorter, than BGP ones. During first 100 hours BN-05 is sputtered slower, than BGP, but inner insulator edge radius made for 105 hours of operation for BN-05 is smaller than BGP one by 0,4 mm. And further BGP is sputtered slower than BN. Similar picture is observed for outer insulator. Profiles for BN-05 at 105 and 204 hours of operation are close to 99 and 268 hours profiles for BGP. But profiles for 438 and 513 hours of BN-05 insulator lie above than BGP 502 hours profile. Both insulators erosion zone started 0,8-1,2 mm closer to anode for BGP, than for BN-05. Erosion zones boundaries moved closer to anode for both materials during life test.

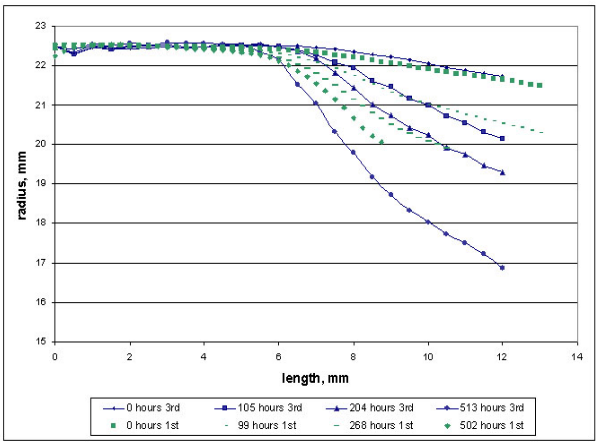

Figure 11. Inner insulator sputtering profiles
Materials: BN-05 and BGP. 1st and 3rd HET laboratory models.

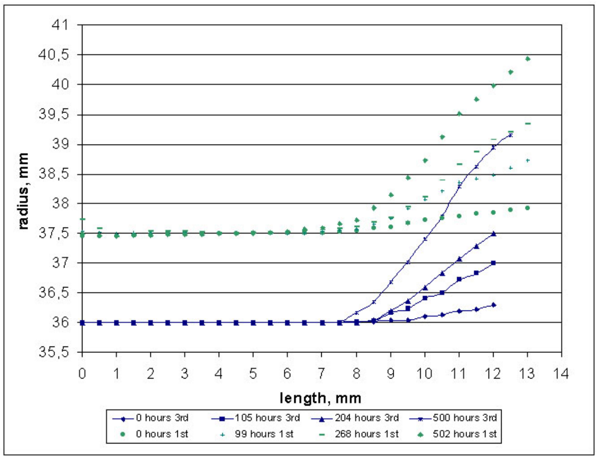

Figure 12. Outer insulator sputtering profiles
Materials: BN-05 and BGP. 1st and 3rd HET laboratory models.

So one can make several conclusions about processes of BN-05 and BGP insulators ion sputtering in the discharge channel plasma of HET with higher specific impulse:

1. Erosion during first 20-40 hours depends heavily on terms of manufacturing and history of insulator previous testing, for BGP, as well as for BN-05.
2. Erosion rate for both materials inside discharge channel is close in absolute value. In the first hours of operation (100-200 hors) erosion rate is either similar of BN-05 is sputtered slower. After 200-300 hours of operation erosion rate of BGP slows down and becomes lower than one of BN-05 (fig.13-14). This effect was observed for all investigated channel geometries and magnetic field topologies, for shortened life tests, as well as for full time life tests.
3. In case of similar discharge channel geometry insulators erosion zone for BN-05 starts closer to anode, than for BGP insulator.

Full life was predicted basing on results of 500 hours insulator profiles and was equal to 3000 hours for materials, shortened and full-length life tests. Life limiting factor was erosion of inner insulator, for both materials.

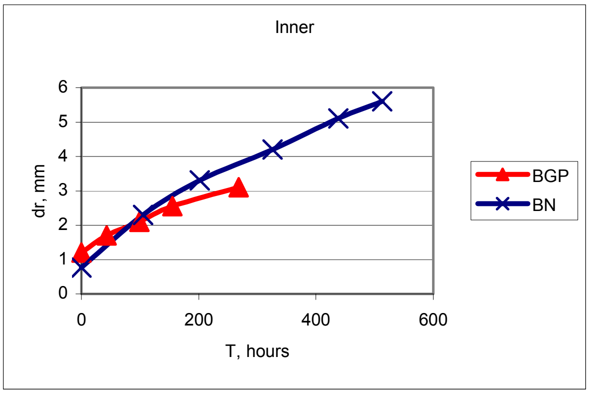

Figure 13. Dependence of inner insulator edge erosion on time.
Comparison of 1st and 3rd HET laboratory models. BGP curve ending at 270 hours caused by low thickness of the insulator

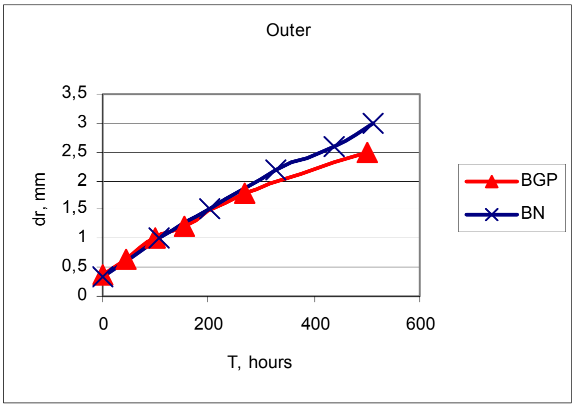

Figure 14. Dependence of outer insulator edge erosion on time.
Comparison of 1st and 3rd HET laboratory models

It was found out that degradation of total specific impulse during life tests for HET equipped with BN-05 insulators is 100 seconds lowed than for BGP after 500 hours of operation.

In this manner, one can state, that material erosion condition inside HET are different from ones, in which sputtering yields value for BN-05 and BGP were obtained. During the experiment it was impossible to obtain radical lifetime increase only by application of more sputter-resistant material. To explain this effect several hypotheses can be proposed:

- surface relief formed on BGP leads to different discharge organization and slows down sputtering, in comparison with BN-05;
- differences in near-wall plasma parameters distribution for BN-05 and BGP insulators, affect mean energy and angle of incidence of bombarding ions and lead to similarity of the erosion rate;
- different optimal magnetic field topologies cause increased flow of sputtering particles on BN-05 in comparison with BGP.

Let us consider each hypothesis in detail.

IV. Analysis of relieves formed on the insulators surface

It is well known that one of the distinguishing features of HET insulators made of BGP is formation of rough structure on the surface of the insulators in the first 20-30 hours of operation and following appearance of so called “anomalous erosion” pattern after 100-500 hours of operation. In paper[10] appearance of “anomalous erosion” was attributed to cease of discharge channel walls surface bombardment by “directed ions” and the effect was connected with “near-wall conductivity” of electrons. In paper[11] assumptions were made about continuous existence of two different sputtering mechanisms in HET plasma– “normal” and “anomalous”. First was attributed to bombardment of the wall by ions accelerated in HET acceleration layer, second – to standing wave of plasma density appearing due to interaction of axial ions flow and azimuthally directed electrons Hall current.

During life tests of 1st and 2nd HET laboratory models with BGP channel walls rough structure of “normal” erosion appeared after 30-40 hours of operation. Traces of “anomalous erosion” were observed only on 1st HET model after approximately 200 hours of operation. Insulators made of BN-05 during life tests had relatively smooth surface and never exhibited “anomalous erosion” patterns. On fig.15-16 pictures of 1st and 3rd laboratory models are presented after 500 hours of direct life tests.

On fig.17-18 surface patterns of outer BGP insulator after 500 hour of operation are presented. As one can see, the pattern consists of “peaks” and “holes” in the near-anode zone (fig.17). “Peak” height varies between 70-160 μm, “hole” diameter lies in the range of 100-300 μm. These dimensions are close to average size of material grain occurring as a result of hot pressure of quartz and boron nitride powders mixture – 20-200 μm depending on conditions of material fabrication. Pattern structure is similar to one observed during sputtering in the plasma plume (fig.6a). Estimations show that local electrons Larmor radius at the shown area is about 1500 μm, while Debye length is 30-50 μm.

On fig.18 surface pattern formed due to “anomalous erosion” is shown. It starts with axial grooves with typical

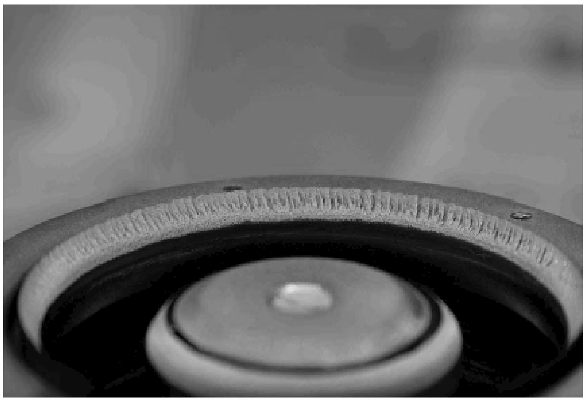

Figure 15. 1st HET laboratory model after 500 hours of operation
Insulators material - BGP

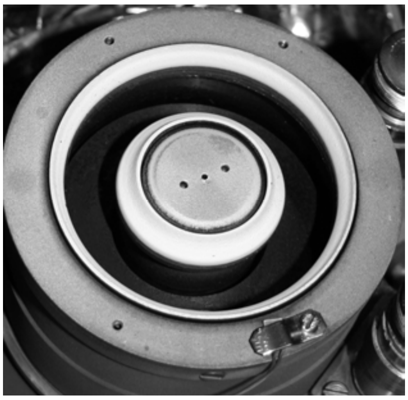

Figure 16. 3rd HET laboratory model after 500 hours of operation
Insulators material - BN-05

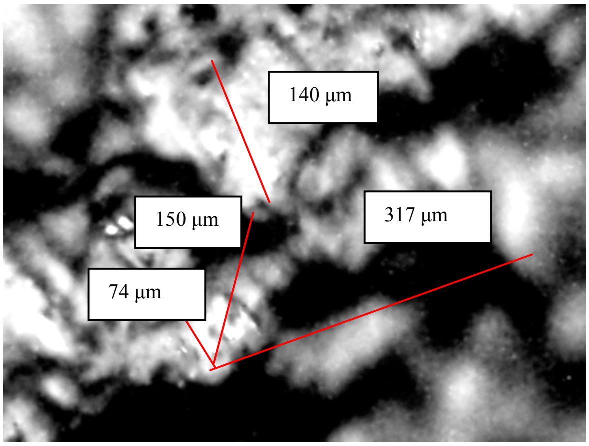

Figure 17. Insulator surface pattern after 500 hours of operation
BGP; magnification 200-times; near-anode erosion zone, "normal erosion"

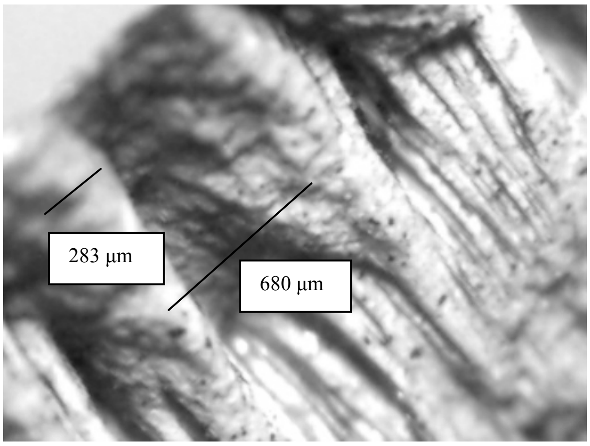

Figure 18. Insulator surface pattern after 500 hours of operation
BGP; magnification 200-times; insulator edge; "anomalous erosion" zone

width of 30-120 μm originating in the "normal erosion" zone and transforms to periodic "teeth" with period of 500-700 μm, length of 1500-2200 μm, width 250-350 μm. Larmor radius at the insulator edge is estimated to be about 500 μm at the top of the "tooth" and about 200 μm at its bottom, which lies closer to the inner magnetic pole. Debye length os estimated as 150 μm. The "teeth" are not oriented axially, but rather on the small angle to the thruster axis, which is common for "anomalous erosion" patterns.

The appearance of BN-05 inner insulator surface after 500 hours of life tests is shown on the fig 19. The formed structure is rather smooth in comparison with BGP. "Peaks" are lower, while "holes" are not observed at all. Distance between "peaks" varies in the range of 100-350 μm. "Peaks" height is 5-50 μm. This pattern remains constant for all the parts of eroded zones of both insulators.

So, the surface patterns of investigated materials have two main differences. First difference is the scale of "normal erosion" roughness. BGP pattern roughness is 3-6 times greater than Debye length that creates advantageous conditions for "near wall conductivity" according to paper [12]. Surface roughness of BN-05 is of similar size or smaller than local Debye length, which limits electrons "near wall conductivity" on surface heterogeneities and leads to different discharge conditions for BN-05 insulator than for BGP. Further studies should be carried out to clarify the influence of this phenomenon on HET discharge conditions and lifetime.

Second difference is lack of "anomalous erosion" for BN-05 insulators, which appearance according to[10,11,12] corresponds to abrupt decrease of BGP insulators sputtering rate. Results, obtained during the life tests, show decrease of BGP insulators erosion rate at the time of "anomalous erosion" pattern appearance, i.e. after 200 hours of operation. Neither "anomalous erosion" pattern, no decrease of erosion rate was observed for BN-05 insulators. May be different electrons conductivity mechanisms, or high composition homogeneity and surface smoothness of BN-05, do not give necessary conditions for "anomalous erosion" processes superiority over "normal erosion" ones, and decrease of erosion rate. This effect should be studied in the future.

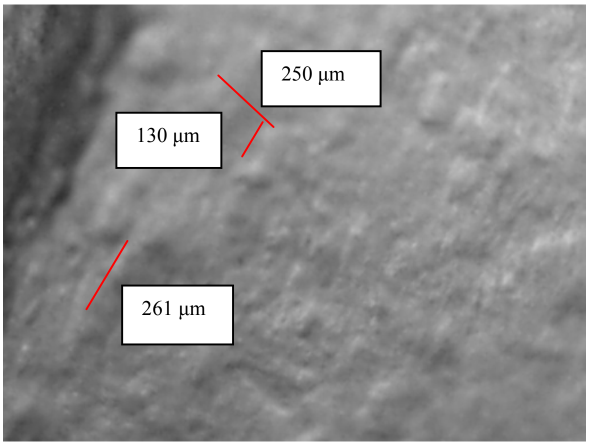

Figure 19. Insulator surface pattern after 500 hours of operation
BN-05; magnification 60-times; near-anode erosion zone

V. Analysis of near-wall plasma parameters of the investigated HET laboratory model

Hypothesis explaining the similarity of lifetimes of investigated HET models by differences in bombarding ions energy and ions incidence angle splits in two ones. Lifetimes can be close due to peculiarities of energy dependencies of materials sputter sputtering yield, or due to ions incidence angles for BGP are lower, than for BN-05. It is obvious that ions energy and incidence angle depends greatly on near-wall plasma parameters.

To study them the 1st laboratory model HET was equipped with eight near-wall flat Langmuir probes. Five of them were placed inside the discharge channel in the outer insulator, three – outside the thruster. Probes were made of tungsten-rhenium wire with diameter of 0,5 mm. Method of probe current-voltage characteristics measurement is described in[14].

Plasma parameters calculations were carried out according to standard methods for probes in Langmuir plasma[15,16], except recovery of ion current density to the probe at floating potential. Due to strong probe current-voltage characteristic non-linearity in zone of ion current decrease it was impossible to accurately recover ion current density basing on linear approximations. Ion current density at floating potential was accepted equal to electron current density, which was calculated, basing on known plasma density and electron temperature assuming Boltzman electron energy distribution.

It is understood that plasma parameters distributions obtained by this method can be considered as approximations only. First of all, probes are close to local Langmuir radius in size, which means that application of Langmuir probe theory without consideration of magnetic field effect is incorrect. Second, current-collecting area for plane probe increases with increase of probe voltage what in conditions of HET plasma introduces considerable changes in conditions of near-wall processes. Third, it is not well known how secondary electron emission sputtering yield for tungsten differs from one of BGP in conditions of near-wall layers of magnetized plasma, so it is impossible to estimate difference between particles flows on the probe and wall surface.

Several axial distributions of plasma parameters and particles flows on the surface of outer insulator are presented on fig.23-27. Obtained parameters are close in orders of magnitude to ones published in[16,17]. Among the peculiarities of local plasma parameters are relatively high electron temperature (up to 70 eV at discharge voltage of 500 V) and increased difference between the local plasma and floating potential, which changes from 30 V in near-anode region to 200 V near the HET exit.

It is possible to estimate local sputtering yield, at least in first hours of operation assuming the flow of particles collected by probe (fig.26) equal to flow, bombarding the wall surface with given volume of sputtered material, and time of operation. The linear approximation of sputtering yield dependence on energy is presented on fig.28. Sputtering threshold energy is assumed equal to 50 eV. On the same figure estimated mean energies of bombarding ions are given for three points inside the discharge channel. The sputtered material volume was calculated according to BGP 0 hour profile on fig.12. Time of firing was 20 hours. Digits on the graphics equals to distance from thruster exit to point, where estimations were made. Mean ions energy was estimated in approximation of incident angle

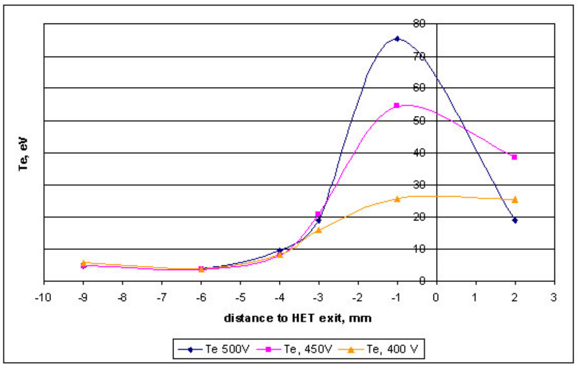

Figure 23. Dependence of T_e on distance to thruster exit

X=0 – thruster exit; anode mass flow 2.0 mg/s

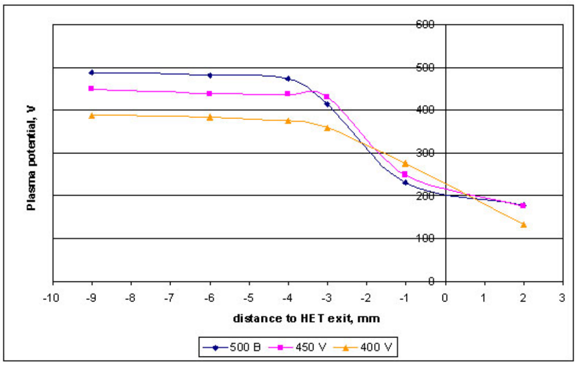

Figure 24. Dependence of φ_{pl} on distance to thruster exit

X=0 – thruster exit; anode mass flow 2.0 mg/s

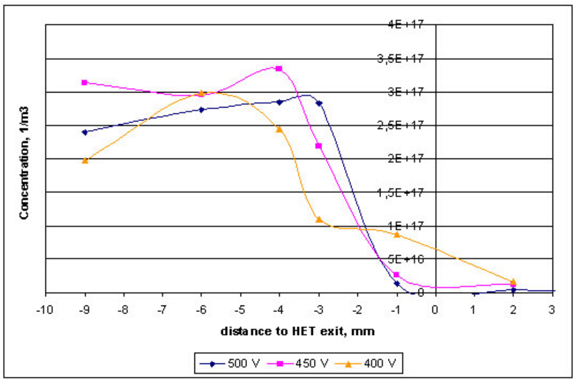

Figure 25. Dependence of n_e on distance to thruster exit
X=0 – thruster exit; anode mass flow 2.0 mg/s

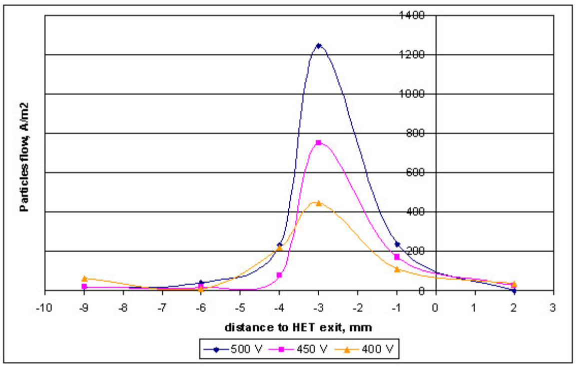

Figure 26. Dependence of particle flow to probe on distance to thruster exit
X=0 – thruster exit; anode mass flow 2.0 mg/s

α=0°, which gives energy upper estimate, because sputtering yield increases steadily with α increase up to α=60°-70°.

In table 1 kinetic energy values of ions originating from ionization zone and accelerated through acceleration layer and near-wall potential drop in the probe location is presented. E_i was calculated by following equation:

$$E_i = \varphi_{pl}^0 - \varphi_f \qquad (1)$$

where φ_{pl}^0 – mean value of plasma potential in ionization zone[16]; φ_f – value of local floating potential.

Table.2. Estimations of sputtering ions mean kinetic energy

Point location	Estimated energy , eV	$\varphi_{pl}^0 - \varphi_{pl}$,eV	$\varphi_{pl} - \varphi_f$,eV	E_i, eV (1)	α
-3	70	67	62	129	46
-1	200	251	200	451	48
0	340	281	170	455	52

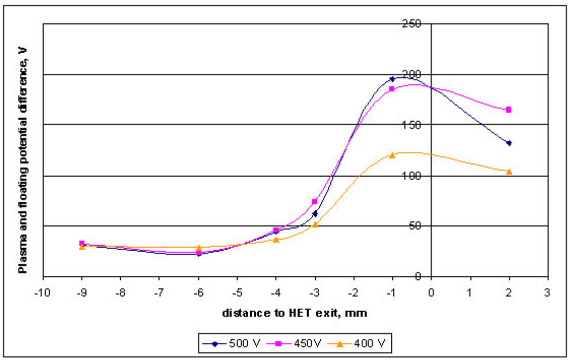

Figure 27. Dependence of φ_{pl} - φ_f on distance to thruster exit
X=0 – thruster exit; anode mass flow 2.0 mg/s

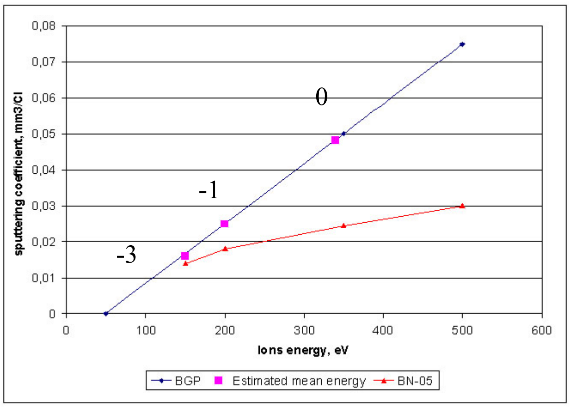

Figure 28. Dependence of γ on energy of bombarding particles.
BGP – linear approximation of experimental data; BN-05 taken from [18]

Table 2 shows, that estimated sputtering energy is at least 100 eV lower at the thruster exit, than E_i during first hours of operation, when the sputtering is most intense. It means, that walls are sputtered by ions, which did not pass through the full length of either acceleration layer, or near-wall potential drop.

The dependence of BN-05 sputtering yield on energy is also presented of fig.28. One can see, that with energy decrease difference between sputtering yields decreases also. So it seems quite reasonable to presume that insulators in studied HET were sputtering by ions with low mean energy (200-250 eV), which led to similarities in lifetimes of BN-05 and BGP insulators.

The value of α - angle between the normal to surface and bombarding ions velocity can be estimated by equation (2):

$$ctg\alpha = \left[\left(\varphi_{fl} - \varphi_{pl} \right) / \left(\varphi_{pl}^{0} - \varphi_{pl} \right) \right]^{1/2} \qquad (2)$$

Calculated values of α for points, where energy estimations were maid are shown in table 1. Sputtering yield values for obtained angles are 1,2 – 1,3, times higher, than for α = 0. Such small incident angles for BGP (less then 55^{o}) were obtained due to high difference between the local plasma potential and floating potential (up to 200 V). Estimations and results of plasma parameters measurements published in[19] allow presuming, that for BN-05 value of near-wall potential drop would be lower than for BGP, due to low secondary electron emission crossover energy[2] (32 and 53 eV, accordingly). Decrease of near-wall potential drop would lead to decrease of total kinetic energy, but to increase of α. To clarify which of these opposing effects would overcome it is necessary to carry out near-wall probe measurements of HET with BN-05 insulator. These experiments would be carried out in near future.

VI. Analysis of magnetic field topology influence on the insulators sputtering

In papers[20,21] the criterion of quantitative estimation of magnetic field quality was presented and dependence of axial erosion zone position on radial position of function F (magnetic induction gradient normal to magnetic field force line) maximum. Spatial distributions of F function for all four compositions of investigated HET models are presented on fig.29-32.

Results, published in[21] were obtained after experiments on HET laboratory model similar to 1st laboratory model described in this paper. Main results of[21] were confirmed during conducted life tests. Erosion zones borders lied on the magnetic field force lines, passing through the area of function F maximum. Shift of function F maximum location (2nd model in comparison with 3rd) to channel centerline led to shift of inner insulator erosion zone border to HET exit for BN-05.

Function F maximum radial location presented on fig. 30 and 31 (28 and 26 mm, accordingly) corresponds to

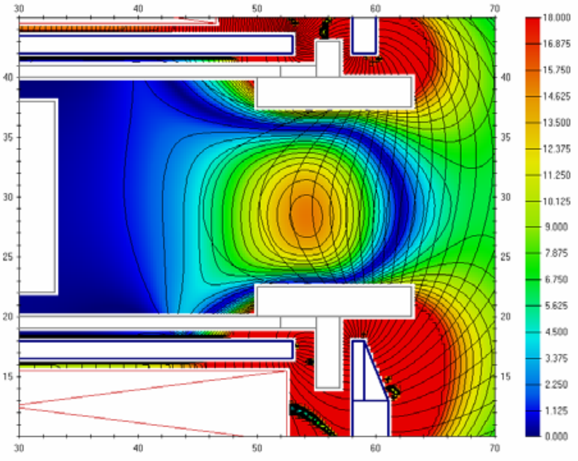

Figure 29. Function F distribution in the discharge channel
1st HET laboratory model

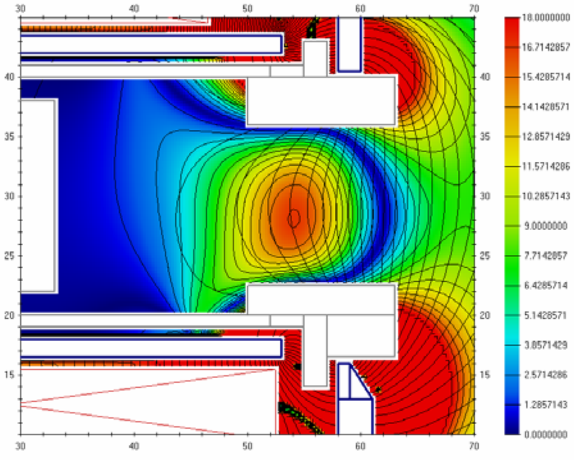

Figure 30. Function F distribution in the discharge channel
2nd HET laboratory model BGP walls

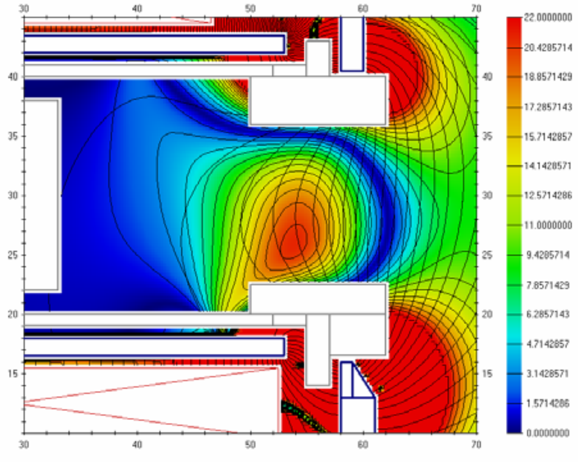

Figure 31. Function F distribution in the discharge channel
2nd HET laboratory model BN-05 walls

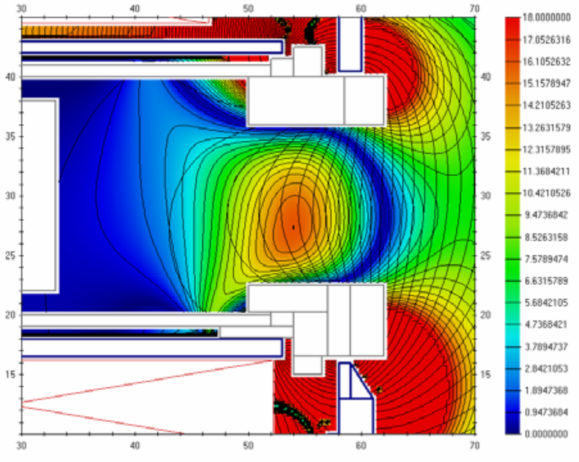

Figure 32. Function F distribution in the discharge channel
3rd HET laboratory model

erosion profiles presented on fig.7-8. For these magnetic field topologies erosion zone border for BN-05 inner insulator border lies closer to anode than BGP one by 1 mm. Sputtered zones borders for magnetic field topologies presented on fig. 30 and 32 lie on the same distance from anode for BGP as well as for BN-05. So one can state that tendency of sputtered zones borders shift in axial direction with shift of function F maximum area in radial direction is true for BN-05 and BGP insulators, and observed effect does not depend on insulator wall material if identical geometry is given.

In the same time, no differences in magnetic field topologies sufficient to explain the lifetime similarity with BN-05 and BGP were observed.

VII. Conclusion

Angular and energy dependencies of sputtering yields for two materials applicable as HET insulators - BN-05 and BGP - by low-energy Xenon ions were measured. It is shown that BN-05 is 1,7-2 times more erosion resistant in plasma plume, than BGP. 500 hours life tests are carried out for 900 W HET laboratory model with discharge voltage of 480 V with insulators made of both materials. It is shown, that application of BN-05 as an insulator does not increase HET total lifetime. However, degradation of output parameters, and especially specific impulse was observed to be lower for HET with BN-05 insulator.

Local plasma parameters investigations were carried out for HET laboratory model with BGP walls. Axial distribution of electron temperature, plasma density, plasma and floating potential, particles flows to the probes along the outer insulator were obtained. Using data of material sputtering obtained during life tests and particles flows to probes distribution, estimations of local sputtering yield and sputtering ion kinetic energy for outer insulator made of BGP was carried out. It was shown that main role in outer insulator sputtering play ions having mean energy 100-200 eV lower, than theoretically reachable, with acceleration in acceleration layer and near-wall potential drop, at least for BGP insulator in first hours of operation.

It was shown, that difference in sputtered zones boundaries axial position corresponds to differences of function F (magnetic induction gradient normal to magnetic field force line) maximum zone radial position. The connection between the magnetic field topology and similarity of lifetime for insulators made of BGP and BN-05 was not found out.

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