Influence of SPT magnetic field on life time characteristics of the thruster

IEPC-2013-51

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

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Abstract: The paper presents the research results of the relationship between the magnetic field parameters and geometry characteristics of erosion zones of the discharge chamber insulators of various stationary plasma thrusters (SPT) developed by Experimental Design Bureau "Fakel", Kaliningrad, Russia. It is shown that the boundaries of the erosion zones of the inner and outer walls of chambers are located at the intersection between those walls and single *boundary* magnetic field flux line, that passes through the point with induction value of $k\text{x}B_{\text{r max}}$ in the centerline of the acceleration channel, where $B_{\text{r max}}$ – is the maximum value of the magnetic field radial component, and k is the coefficient defined by thruster's operating mode. As per the experimental results, existence of zones with various mechanisms of sputtering also connected with the value and configuration of the magnetic field is noted.

Nomenclature

B_r = *radial magnetic field induction*
L_a = *longitudinal size (thickness) of ionization and acceleration layer*
L_e = *length of erosion zone*
U_d = *discharge voltage*
$\dot{m}_a$ = *anode mass flow rate*
n_a = *concentration of atoms*
S = *cross-sectional area of the discharge channel*
ν_u = *frequency of the ionization collisions*
ν_e = *frequency of electrons collisions*
m = *electron mass*
e = *electron charge*

I. Introduction

The operation of the most electric propulsion always associates with the erosion of those elements and nodes of the construction, affected by flowing-out plasma. The erosion usually results in various configuration changes of the elements and nodes up to their complete destruction. These changes may cause instability of thruster performance parameters during its long-term operation (lifetime test) and cause the complete loss of its operating capability.

Discharge chamber is one of the nodes in the Stationary Plasma Thruster (SPT) construction, determining its lifetime. As a rule, the prediction for SPT lifetime characteristics is based on the analysis of the erosion degree of the outlet part of the discharge chamber (DC) channel.

Erosion degree of the channel depends on the following factors: the distribution of the density and structure of the ion beam in the outlet part of the channel, and erosion resistance of discharge chamber material to ion sputtering.

The density and structure of the ion beam in the channel's outlet part depend on parameters of the ionization and acceleration layer (IAL). In its turn, the longitudinal size and position of the IAL with regard to DC channel cut are defined by the magnetic field parameters (induction distribution and field topology in the channel). It is known that

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IAL is localized in the part of the channel with maximum magnetic induction values, herewith the lower boundary of the layer (at the anode side) corresponds to the position of the kx$B_{\mathrm{r\ max}}$ value in the channel centerline, where k - is the numerical coefficient, and $B_{\mathrm{r\ max}}$ – is the maximum value of the magnetic induction. The certain numerical coefficient values can be found within quite a wide range: from k = 0,6 [1] to k = 0,7 ... 0,9 [2, 3]. Moreover, IAL's position depends on the thruster operating mode characterized by the discharge voltage and discharge current values [2].

The location of the erosion zone boundary in DC channel is directly related to the IAL position [3] and is determined by its length (L_e) - the distance from the erosion beginning to the discharge chamber cut. In most cases the erosion zone length is different on the inner (L_{ei}) and outer (L_{eo}) walls of DC. [4] illustrates that the erosion zone boundaries lie along two magnetic flux lines with ionization center (“core”) in between. Correlation between the erosion zone boundaries’ location and the magnetic field flux lines points to the functional connection of erosion processes and the magnetic field topology.

EDB “Fakel” received the results for both parametric and long-term tests for SPT of various sizes, as well as the results of the erosion zones geometric characteristics measurements for the same thrusters. These data allow to make analysis of the relationship between magnetic field parameters and erosion pattern, and to compare the outcome with previously obtained data.

II. Objects and Methods of the Research

For this analysis we used the tests results, including the ones of lifetime tests, received for the thrusters’ type SPT-50, SPT-70, SPT-100 and SPT-140 and their modifications. Parameters of thrusters operating modes are listed in Table 1. All thrusters were operated at the optimum current values in the magnetic systems coils (optimization to the minimum discharge current).

Table 1. Operating modes of examined thrusters

Model	Nominal Size	Channel width, mm	Discharge voltage, V	Discharge current, A
1	SPT -50	10	200	1,2
2		10	200	1,2
3	SPT -70	14	300	2,17
4	SPT -100	15,5	300	4,5
5		15,5	800	2,6
6	SPT -140	20	300	15
7		20	300	15
8		20	800	6
9		20	300	15

Parameters used in joint analysis:

- geometric parameters of erosion zones of thrusters’ DC walls, namely, length and shape of erosion zones (erosion profiles),
- the distribution of the magnetic field radial induction in the centerline of acceleration channel,
- magnetic lenses topology.

Erosion zones measurements were performed after the fire tests with the operating parameters that were maintained constant during the tests. The error in determining of erosion zones lengths did not exceed 0.1 mm. Erosion profiles coordinate error did not exceed 0,05± mm.

Parameters of the magnetic field – induction value and induction distribution along the SPT channel axis and magnetic lenses topology – were obtained by calculation.

For this purpose, the finite-element models of the magnetic systems were developed for all nominal sizes of thrusters and their modifications.

The magnetic field of the above models was calculated by EMAG module of NISA /DISPLAY application program package with the Maxwell's equations-based technique involving finite element method.

This method of magnetic induction calculation in the discharge chamber channel underwent verification which included examination of calculations compatibility with the results of magnetic field thrusters’ induction direct measurements. As per verification results the error of calculation did not exceed 7%, which was considered acceptable. Verification of the calculated magnetic field topology was performed by comparison method with the topology generated by iron filings. Comparison of the two topologies showed good compatibility.

III. Research Results of Relationship Between the Magnetic Field Parameters and the Erosion Zone Boundary Position

For the more accurate analysis of the relationship between the parameters of the magnetic field and the position of the erosion zone border we used measurements of erosion zones length on the inner (L_{ei}) and outer (L_{eo}) DC walls after practically the same firing operating time for all thrusters. The duration of operation was decided on the condition it’s sufficient to define precisely the boundaries of erosion zones.

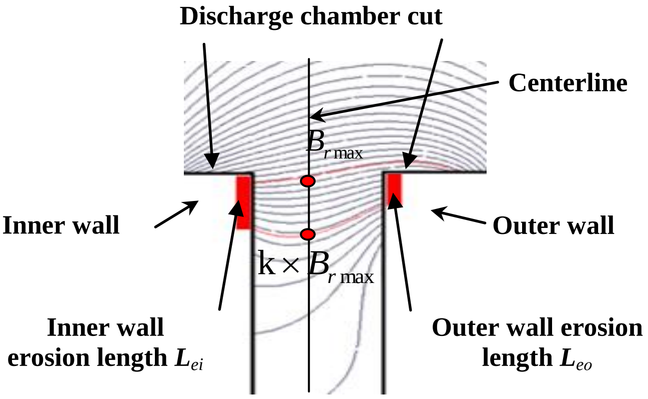


Figure1. Parameters used in analysis

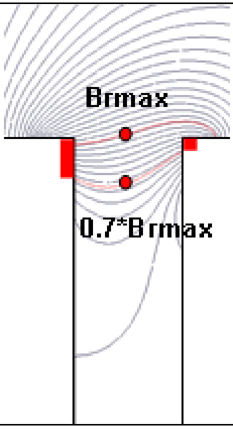
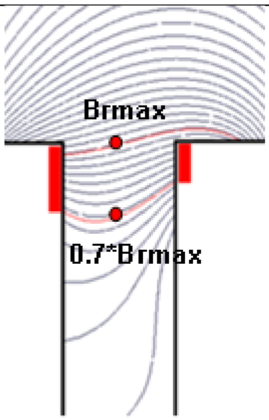
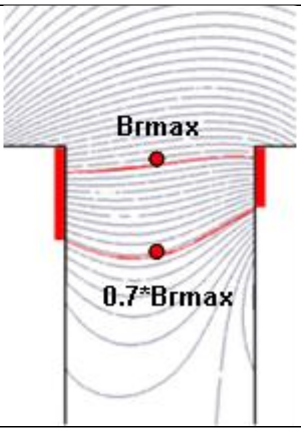
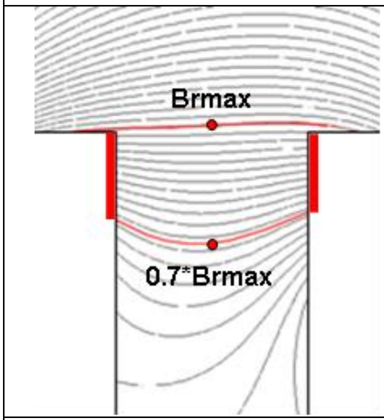
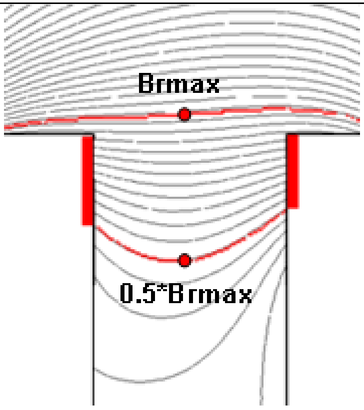
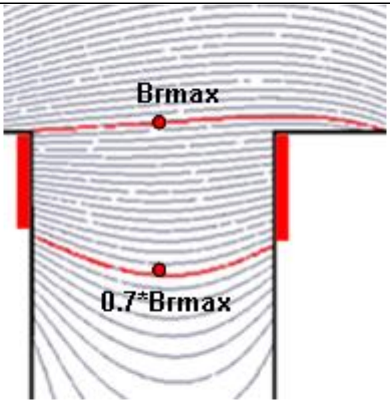
The parameters of the magnetic field, namely the topology and distribution of the radial induction along the centerline of the DC channel were obtained through the calculations results.

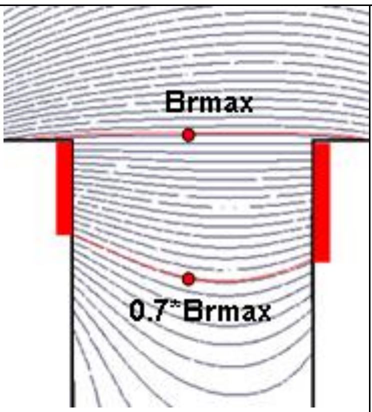
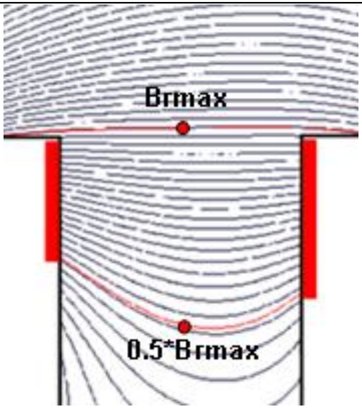
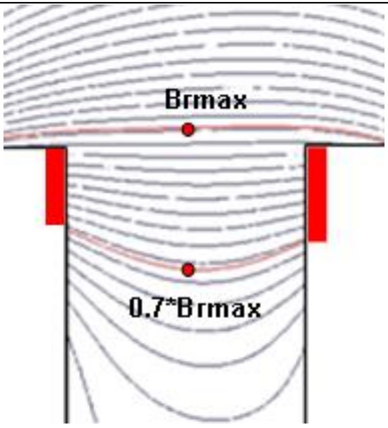
During the analysis, the magnetic field flux lines crossing the walls of the DC at the erosion zones boundaries obtained by the measurement results were defined. Then, the values of radial induction and *k* coefficient were determined at the intersection points of the channel centerline and found magnetic field flux lines along the radial induction distribution curve.

Figure 1 illustrates the scheme of the analysis with the parameters.

Table 2 illustrates the correlation results for the magnetic systems parameters and the length of erosion zones parameters for the examined thrusters.

Table 2. The relative position of the erosion zones boundaries and magnetic field parameters of the examined SPT (1-9: SPT models numbers)

		
1	2	3
		
4	5	6

		
7	8	9

The results from Table 2 show that erosion zones boundaries on the inner and outer walls of DC for all examined thrusters at anode side are located at the intersection of the channel walls with the one magnetic field flux line passing through the value $k\mathrm{x}B_{r\ max}$ along the acceleration channel centerline, whereas the coefficient k numerical values are different for each case. The note regarding SPT-50, SPT-70 and SPT-100: the position of the erosion zones boundaries located at the intersection with the DC walls magnetic field flux line $0{,}7\mathrm{x}B_{r\ max}$ is consistent with the previously known one [3], provided that the flux line shape (concave towards the anode) is taken into account.

It should be remembered that for the above analysis we used the thrusters of various sizes with different operating parameters. Previously, it was demonstrated [2] that both the value of magnetic induction in the DC channel and the thruster operation mode, especially the operating discharge current value, can affect the LIA position. Discharge current during thruster's operating in the optimal mode is directly related to anode mass flow rate. It was also demonstrated that the decrease in the propellant mass flow rate, provided all other conditions being equal, leads to expansion LIA in the direction of anode and of the corresponding displacement of the erosion zone boundary in the same direction [5,6]. Since the LIA position is generally determined by the magnetic field distribution, it can be assumed that the specified erosion zone boundary offset is associated with the increase of the LIA longitudinal length (size) by mass flow rate reduction.

LIA longitudinal size (La) behavior can be determined by the known A.V.Zharinov [7] formula applied to the anode layer thrusters:

$$\mathrm{L_a} \approx \sqrt{\frac{mU}{eB^2}\frac{\nu_e}{\nu_u}} ,$$

where:

- m, e - electron mass and electron charge,
- U - voltage drop in the layer,
- B - magnetic field induction,
- $\nu_e = \langle \sigma_{ea} \upsilon_e \rangle n_a$ - the frequency of electrons and atoms collisions resulting in change of their momentum and defining the electron mobility across the magnetic field, where n_a - is an average concentration of atoms in the layer,
- $\nu_u = \langle \sigma_u \upsilon_e \rangle n_a$ - frequency of ionization collisions, where $\langle \sigma_u \upsilon_e \rangle$ - averaged ionization rate coefficient over the electron distribution function.

The average value of atom concentration in the layer can be considered as proportional to the propellant mass flow rate through the accelerating channel density, i.e.

$$n_a \approx k_n \frac{\dot{m}_a}{\upsilon_a S} ,$$

where $\dot{m}_a$ - anode mass flow rate, υ_a - atom velocity, S - cross-sectional area of the discharge channel.

With reference to the SPT, the above expression for the effective frequency of collisions that change their momentum can be written as follows [1,6]:

$$\nu_e = \nu_{ea} + \nu_{ew} + \tilde{\nu}_e ,$$

where

$\nu_{ea} = \langle \sigma_{ea} \upsilon_e \rangle n_a$, and $\nu_{ew}, \tilde{\nu}_e$ - are, respectively, the frequency of electron-wall collisions and the effective frequency, indicating the impact of oscillation in the electron mobility across the magnetic field.

As known, the dependence of the net electron mobility across the magnetic field is considered complicated and under researched. But in this case it's important that the LIA longitudinal size depends on the neutral atoms concentration in the accelerating channel and, respectively, on propellant mass flow rate density.

Therefore, for examined thrusters the relation of the *k*-coefficient characterizing the value of the magnetic induction at the boundary flux line in the centerline of the acceleration channel to the density of the mass flow rate was analyzed. Obtained results for all analyzed SPT (regardless of the induction value, the magnetic lens' shape, discharge voltage and other factors) are shown in Figure 2.

As you can see from Figure 2, the obtained dependency of the magnetic induction boundary values from the specific mass flow rate fairly fits into a single curve.

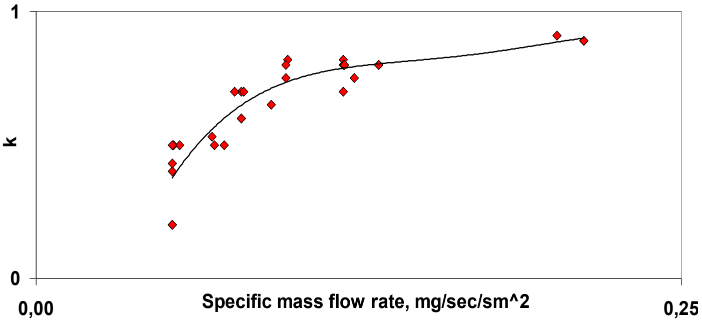


Figure 1. Dependency of *k*-coefficient on specific mass flow rate in examined thrusters

Therewith, the numerical values of the coefficient *k* decreases along with reduction of specific mass flow rate, i.e. erosion zones boundaries of the DC walls and the boundary of the LIA at anode side move depthwards the DC channel.

Thus, these results allow suggesting that one of the reasons of the spread in *k*'s numerical values cited earlier is most likely the difference in density of the mass flow rate in DC of examined SPT.

IV. Research Results of the Correlation Between the Magnetic Field Parameters and the Erosion Profile Shape

The results of the first tests of the SPT proved the existence of the relationship between the magnetic field topology and erosion profiles shape. Figure 3 illustrates as an example one of the SPT-100-type thrusters' magnetic field topology, rendering of which has been performed by iron filings. The same figure also shows the erosion profiles obtained for the different time points during long-term operation of the thruster. As you can see there is a qualitative dependence between the magnetic field topology and erosion profiles shape.

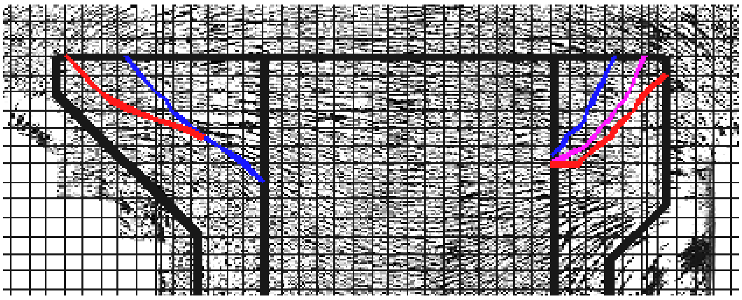


Figure 3 SPT-100 Magnetic field topology and erosion profiles

The further research was carried out to assess the quantitative relationship between these two parameters.

For this purpose we referred to the results of erosion profiles measurements of thrusters during their long-term tests at EDB "Fakel".

All thrusters were operated at discharge voltage 300 V and the constant currents in the coils of magnetic systems. The same calculation method used for the analysis of relationships between the parameters of the magnetic field and the erosion zones length of DC walls was used to determine the magnetic field parameters.

Figures 4-9 demonstrate the measured erosion profiles, the configuration of the magnetic flux lines, and marks of the corresponding *k* -values along the acceleration channel centerline.

You can see the erosion zones for the examined thrusters shift toward the anode as operating time increases. This process may be explained by broadening the DC channel during long-term operation and decreasing the specific mass flow rate of the DC outlet part.

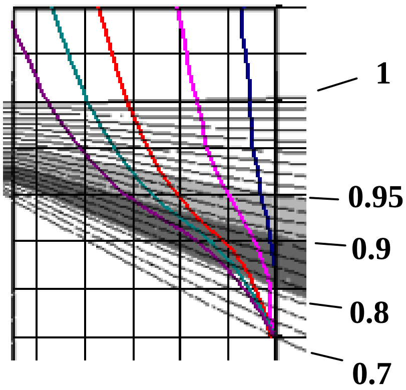


Figure 2. Erosion profiles of SPT-70 inner insulator; parameters and topology of the magnetic field

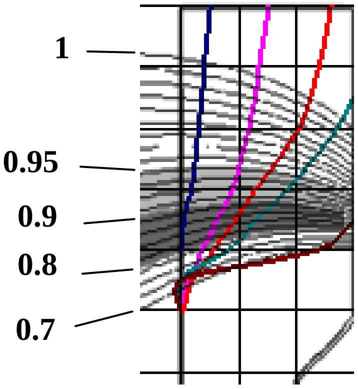


Figure 3. Erosion profiles of SPT-70 outer insulator; parameters and topology of the magnetic field

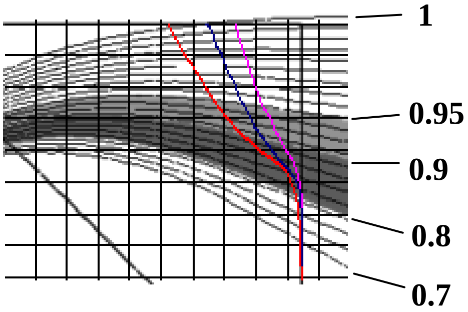


Figure 4. Erosion profiles of SPT-100 inner insulator; parameters and topology of the magnetic field

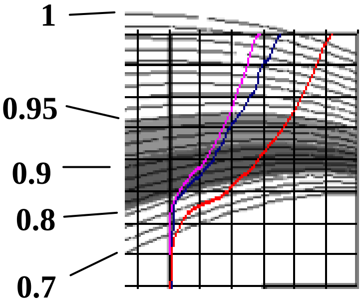


Figure 5 Erosion profiles of SPT-100 outer insulator; parameters and topology of the magnetic field

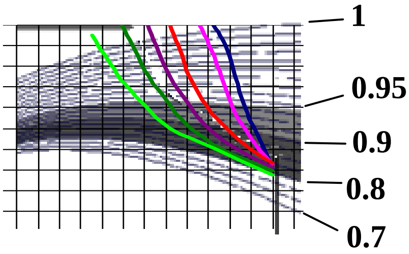


Figure 6. Erosion profiles of SPT-140 inner insulator; parameters and topology of the magnetic field

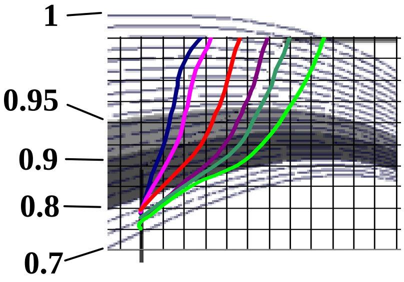


Figure 7. Erosion profiles of SPT-140 outer insulator; parameters and topology of the magnetic field

From the above table it is clear that inflection zones observed in the area of magnetic flux lines passing through the value of $0,8\mathrm{x}B_{\mathrm{r\ max}}$ in centerline channel are typical for all presented erosion profiles. We can suggest that in the area related to lower values of induction, there is no accelerated directional flow yet, and the motion of charged particles can occur in various directions. In the areas related to more than $0,8\mathrm{x}B_{\mathrm{r\ max}}$ induction values, the motion of the particles is directed toward the exit of the discharge chamber.

For more detailed analysis please refer to figure 10 that shows the magnetic field topology at the outer discharge chamber wall of one of the SPT-100 models and erosion profiles obtained during its long-term operation [8].

To make it simpler, the entire surface of each profile can be represented as a collection of individual elementary reception areas, where ions fall, provided that the areas are on cylindrical surfaces. It’s obvious that in the area of magnetic flux lines that corresponds to the induction values less than $0,8\mathrm{x}B_{\mathrm{r\ max}}$ in centerline of the channel, profile shape tends to repeat the form of flux lines.

In the area of flux lines corresponding to the induction values $(0,8..1)\mathrm{x}B_{\mathrm{r\ max}}$ in centerline of the channel, the direction of perpendicular to each elementary reception area is close to the direction of magnetic flux lines through these areas, and the direction of the profile of erosion for each elementary area is at an 60^{o} angle to the perpendicular.

As it is known that ions sputtering ability depends on the angle of incidence as well [9]. If the direction of the ions is random, the surface will be sprayed until the ions’ angle of incidence exceeds the certain limit, which for the test material of the examined SPT DC is equal 60 degrees. Thus, in this part of the chamber, wall profile configuration depends on the angle value corresponding to the maximum sputtering yield of the DC material.

Obtained results testify toexistence of two zones in the magnetic lens area: ionization zone and acceleration zone.

It can be assumed that if *k* is close to 0.8 there is a transitional layer between ionization and acceleration zones.

The value of k = 0,8, corresponding to the position of inflection profiles of considered SPT is not constant for all thrusters and is defined for each SPT depending on the operating mode.

Thus, the configuration profile is not the result of effect of ion beam directed from some fictitious center ("core"), but the result of different sputtering mechanisms.

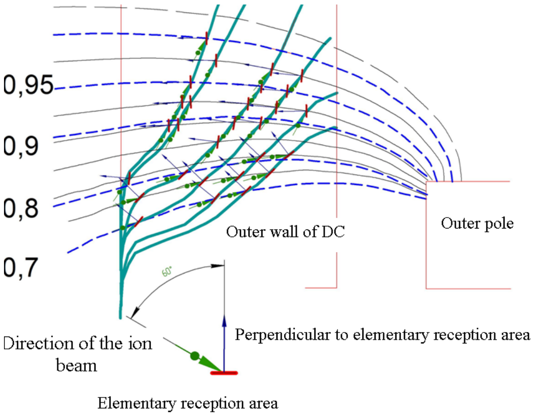


Figure 10. SPT-100 erosion profiles and magnetic field topology

This explanation is rather simplistic, but the purpose of the analysis was to determine the quantitative relationship between the geometrical characteristics of the erosion zones and the parameters of the magnetic field, rather than the study of physics processes occurring in the channel.

It should also be noted that during the long-term tests the entire area of the discharge chamber from the cut to the boundary magnetic flux line passing through the point $k\text{x}B_{r\ max}$ in the centerlineline of the acceleration channel, where *k* is determined by the value of the specific mass flow rate, will be eroded since the limit erosion profiles configuration close to magnetic flux lines.

This analysis was carried out only for the thrusters with acceleration channel bounded by the outer cylindrical side walls.

V. Conclusions

The studies show that:

1. Erosion zone boundaries on the outer and inner walls of the discharge chambers on the anode side are located at the intersection of a one boundary magnetic flux line and the walls regardless of the thruster size, the discharge voltage, the magnetic lens shape, the value of induction, etc.
2. The choice of this boundary flux line is determined by the radial induction value $k\text{x}B_{r\ max}$ in the centerline of the acceleration channel, where the coefficient *k* may have different values, depending on the specific propellant mass flow rate in the outlet part of the thruster channel. The dependence fits into a single curve.
3. As SPT operating time increases, length of erosion zone shifts to anode, which complicates the prediction of its end position.
4. Limit boundary erosion profiles of the discharge chamber are close to configuration magnetic flux lines. This fact confirms the conceptual possibility of existence of “immortal” SPT.
5. Zones with various mechanisms of sputtering exist in the insulators erosion zones.

The obtained results allow to make prediction about the erosion zones position based on magnetic field calculations results at the design stage and to assess the impact of various alterations of the magnetic system construction and the DC construction on the thruster erosion characteristics.

Acknowledgments

The authors are grateful to their colleague A.A. Komarov for criticism and participation in the analysis.

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