Experimental Investigation of Magnetic Field Topology Influence on Structure of Accelerating Layer and Performance of Hall Thruster

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Abstract: The laboratory model of Hall thruster with rich capabilities of magnetic field topology transforming was developed. The discharge voltage of this Hall thruster is in the range of 300…700 V. The design of the thruster includes four coaxial magnetic coils and set of coaxial magnetic screens. The magnetic system allows changing during experiment of axial and radial position of a plasma lens and the shape of magnetic field lines by varying current's ratio in coils. To investigate the influence of magnetic lens topology on the structure and position of accelerating layer the thruster is equipped with set of near-wall Langmuir probes. The correlations between magnetic field parameters and performance characteristics including specific impulse and thrust efficiency are discussed.

I. Introduction

Hall thruster (HET) development could not be conceded now only as an engineering problem. The reason is that the modern numerical methods and the programs developed on their bases to simulate plasma in a Hall thruster discharge don't allow obtaining quite reliable results. That is why during designing and experimental adjustment the experience of the engineer and his intuition play a great role. Especially it corresponds to the problem of choice of the magnetic field magnitude and topology.

The magnetic field in Hall thrusters is mainly radial. The electric field is generally directed along the thruster axis. Electron collisions effective frequency in the discharge chamber is much lower than the Larmor frequency, so the electron motion could be considered as a drift in the crossed **E**x**B** fields. The azimuth rotation velocity of electrons is much greater than their drift velocity towards the anode. The main purpose of the magnetic field is to provide electron longtime presence in the discharge area. Longtime presence is necessary to achieve high gas ionization rate with relatively low discharge current values.

During first studies of the magnetic field topology influence on a Hall thruster operation modes[1] it was found out that the discharge characteristics essentially depend on the way the radial component of the magnetic field changes along the channel. It was experimentally determined that the lowest discharge current is obtained when the radial component of the magnetic field increases toward the thruster exit and reaches its maximum value nearby the thruster exit. In the thruster with so called "negative gradient" of the magnetic field (radial component of the magnetic field has its maximum nearby the anode and decreases towards the thruster exit) the increase of the

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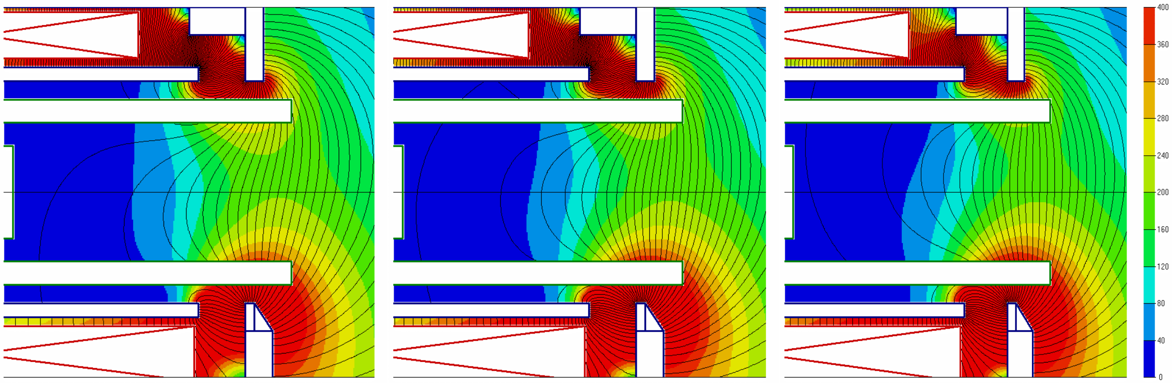
discharge current and its oscillation amplitude were observed. Theoretical studies of this effect[1,2] revealed that if the magnetic field decreases in the direction of ion motion it leads to the flow instability. These oscillations were named the gradient-induced oscillations.

The possibility to control the ionization and acceleration processes in a Hall thruster discharge with the use of magnetic field is based on the effect of “thermalized potential”[3]. In a Hall thruster discharge under typical conditions the electron mobility across the magnetic field is much lower than along the magnetic field lines. Moving along magnetic field lines the electrons are under Boltzmann balance: the forces of pressure gradient are counterbalanced by the force of the electric field. The potential difference along the field line and the electron temperature are equal in the order of magnitude. If the electron temperature is low, the potential difference along the magnetic field line is low too and the magnetic field line coincides with the electric field equipotential line. That is why changing the magnetic field topology one could affect the electric field and control the ion flow to achieve its best focusing. The base principle of the focusing is to create such magnetic field that the field lines will have convex shape and the so called “plasma lens” will be formed. This minimizes the ion losses on the thruster walls and provides high gas utilization and thruster efficiency.

The problem of choice of the form of magnetic field lines that will provide the best output parameters of the thruster is rather complicated. In a real Hall thruster discharge the electron distribution function is non-equilibrium and the electron temperature is rather high. It leads to the creation of radial component of the electric field and to the substantial violation of the magnetic field lines equipotentiality. Direct probe measurements showed[4] that the effect of “thermalized potential” is valid in the anode and cathode plasma areas only, i.e. in the regions where the electron temperature is low. In the ion acceleration layer the electron temperature has high radial gradient and the forms of the equipotential lines essentially differs from those of magnetic field lines.

The investigations carried out previously in Keldysh Research Center[5] showed that the magnetic field lines under optimal operation modes should be symmetrical relative to the central line of the discharge chamber. The symmetry violation leads to the increase in the discharge current and plasma plume divergence. But the field lines symmetry criterion is rather subjective and provides only qualitative conception to optimization of the magnetic field.

As an example the topology of the magnetic field of a Hall thruster laboratory model designed in Keldysh Research Center is considered. The thruster magnetic system has conventional design: the pole pieces placed near the discharge chamber exit and the magnetic screens form the so called “magnetic lens”(fig.1). Beside the magnetic field lines the magnitude of the magnetic field is shown in color. The introduced variants have different ratios of internal to external coils currents. The experiments showed that the variant b) provides maximum thrust at constant discharge power and discharge voltage.



a) b) c)

Figure 1. Field line topology (lines) and absolute value of magnitude of the magnetic force (color) at the current ratio in coils: a) 0.7; b) 1.0; c) 1.5

At the first sight the topology differences are quite negligible. Some changes in the field lines inclination relative to the central line of the discharge chamber could be mentioned, however both variants b) and c) comply with the qualitative symmetry criterion quite well. The axial distributions of the magnetic field radial component along the central line of the discharge chamber are almost identical (fig.2).

The difference between these variants could become more obvious if we define the function of two variables characterizing the gradient of the magnetic field rather then its absolute value. The function shows the rate at which the absolute value of magnetic field $\vec{B}(\vec{r}\,)$ changes along the direction perpendicular to the magnetic field lines:

$$F_B(\vec{r}) = \left| \frac{\left[\vec{B}(\vec{r}) \times \nabla \left|\vec{B}(\vec{r})\right|\right]}{\left|\vec{B}(\vec{r})\right|} \right|. \tag{1}$$

The results of calculation of this function for same three variants of the magnetic field are present in the figure 3.

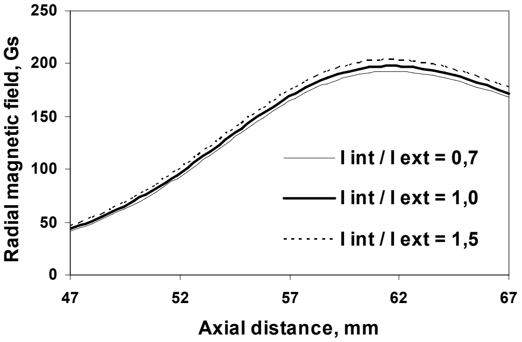
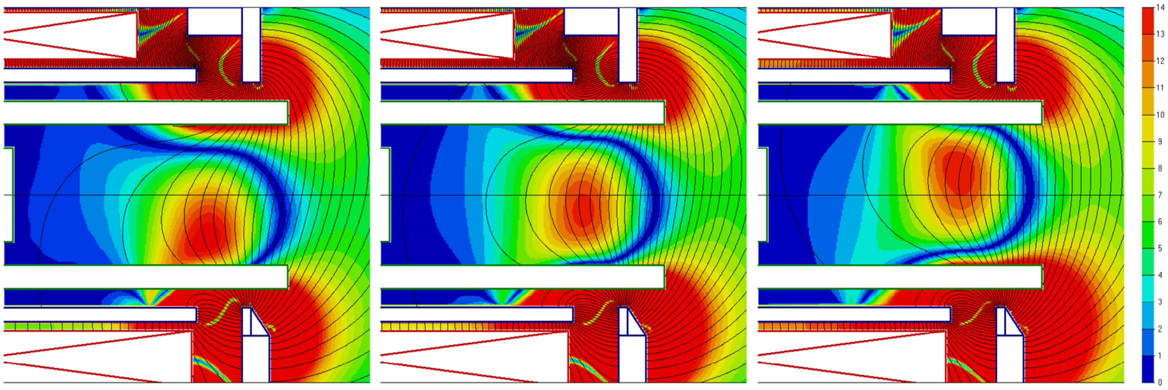


Figure 2. Radial magnetic field as a function of axial distance on discharge chamber centerline.



a) b) c)

Figure 3. Field line topology (lines) and function $F_B(\vec{r})$ (color) at the current ratio in coils: a) 0.7; b) 1.0; c) 1.5

Comparing the function distributions for these variants one could note that the area with the maximum gradient drifts in the radial direction while the ratio of current in coils changes. The optimal magnetic field corresponds to the maximum gradient position nearby the central line of the discharge chamber. So, the use of the function allow to characterize the field lines symmetry criterion more accurately. However the obtained dependence could turn out to be the property of this exact magnetic system geometry. The experience in the experimental investigations reveal that for some magnetic configurations slight changes of currents in coils lead to sufficient changes of the output parameters. Otherwise there are some configurations where the influence on the output parameters is low when the coil currents are changed in wide ranges. Maximum values (the magnetic field topology is optimized) of thrust and efficiency can differ greatly for these configurations. It is also known that if the thruster central line diameter is changed the scaling of the optimized magnetic system don't always lead to the required result and the magnetic system should be optimized again.

To provide the complex analysis of the magnetic field topology influence on the discharge parameters a Hall thruster model was designed in Keldysh Research Center. Its design allows changing the configuration of magnetic field lines sufficiently without stoppage of the experiment. The aim of the experiments was to define main rules for output parameters dependence on the magnetic field changes and to find quantitative criterion that will characterize the chosen magnetic field regardless of the thruster size and discharge chamber configuration. The thruster design, experimental tools and experimental procedure are described in the next chapter. The obtained results are reported further. Different approaches of criterion selection and argumentation are also discussed.

II. Thruster Description and Experiment Procedure

A. Four-Coils HET Design

The thruster magnetic system consists of magnetic circuit and four coaxially placed magnetic coils – two primary and two additional (fig.4). Additional coils are widely used in laboratory Hall thruster models to increase the opportunities to control the magnetic field[1,6,7]. More often the so called trim coil is used. It allows changing the position of maximum and the gradient magnitude of the radial component of the magnetic field.

The novelty of the scheme in fig.4 is in the use of two additional magnetic screens. They allow changing not only the position of maximum and the gradient magnitude but also the form of the field lines at constant position of the magnetic field maximum. It provides ground to investigate the influence of the magnetic field topology on the efficiency of the thruster operation mode more accurately.

The central line diameter of the Hall thruster discharge chamber was 64 mm and the height of the channel was 16 mm. The ceramic walls were made of composite material BN – SiO_2.

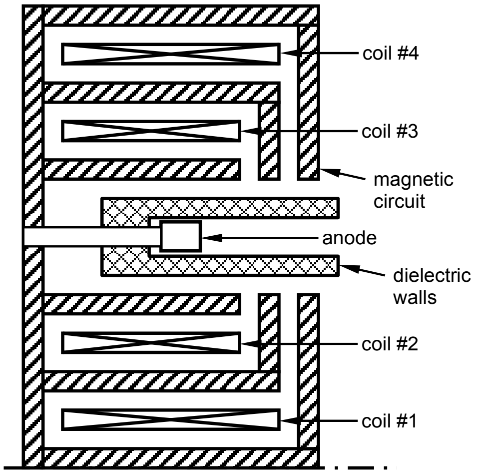


Figure 4. Four-coils Hall thruster scheme.

The outer wall of the discharge chamber was equipped with the near wall Langmuir probes. They allowed to measure the floating potential, and to estimate the plasma potential and the electron temperature.

B. Approach to Investigation

Systematic investigation of all possible magnetic field configurations for the discussed thruster is a very long work. Step by step changing current in four independent coils will amount in huge number of measurements. To narrow the research area and to obtain necessary information during reasonable time the following experimental procedure was developed.

Four parameters (according to number of the magnetic coils, i.e. according to the number of degrees of freedom of the magnetic system) of the magnetic field configuration were chosen to describe different variants. The first two of them p_1 and p_2 - it is the ratio of ampere turn number in the first and the second coils respectively (fig.4) to the total ampere turn number. The p_2 parameter can be negative because the current direction in the coil is taken into account. The current direction in the first coil is assumed positive.

To describe different variants of magnetic field configuration four parameters (according to the number of magnetic coils, i.e. the number of degrees of freedom) were chosen. The first two of them p_1 and p_2 is the ratio of the ampere turn number in the first and the second magnetic coil respectively (fig.4) to the total ampere turn number. The p_2 parameter could have negative values because the current direction in the coil is taken into account. The current direction in the first coil is assumed as positive. The third parameter is the maximum of the magnetic field radial component on the central line of the channel. The fourth one is the distance between this maximum and the outer edge of the discharge channel.

Series of experiments have been conducted. In each series the fourth parameter was fixed. The rectangular grid for the possible values of p_1 and p_2 parameters was set. The optimal value of the third parameter was selected in each knot of this grid. The value was considered as optimal if the maximum anode efficiency was achieved at the constant anode flow and discharge voltage. As a result of each series the dependences of thrust, anode specific impulse and anode efficiency on the p_1 and p_2 parameters were plotted. Then during the experimental data analysis the calculations of the magnetic field were conducted for the same grid and the correlation of thruster output parameters with different field criterion was investigated.

To fulfill this procedure a lot of calculations of magnetic fields should be conducted. So the computer program was developed before the experimental work. It works with the data base consisted of preliminarily calculated possible magnetic field configurations. During the experiments this program allowed to define the coil currents necessary to achieve four needed parameters.

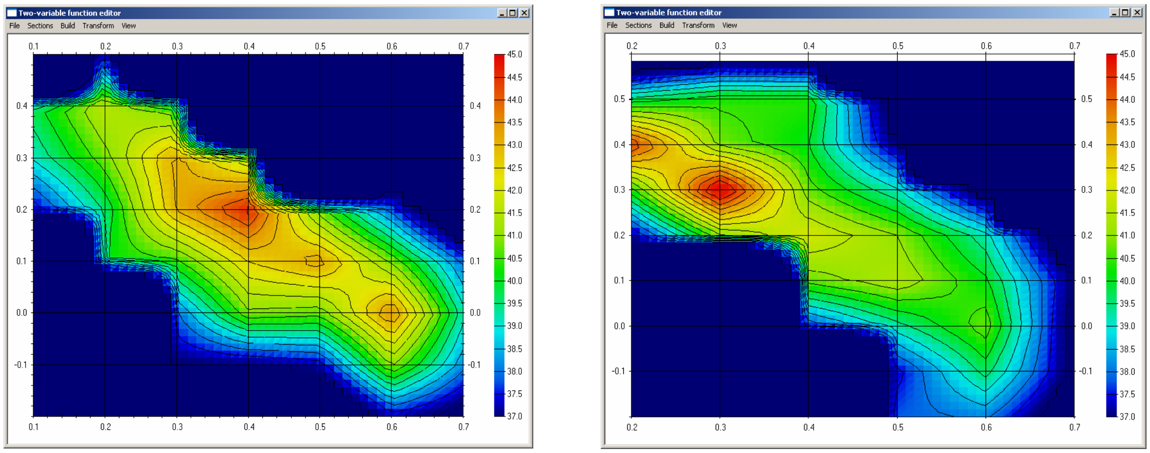
III. Experimental Results and Numerical Analysis

The experiments were carried out on the cryogenic vacuum facility CVF-90 in Keldysh Research Center[8]. The results of two experimental series are presented in this paper. In the first one the maximum of the magnetic field was 3 mm from the outer edge of insulators (series #1), in the second one – 4,5 mm (series #2). The range for p_1 and p_2 parameters investigated for both of these series is present in table 1. During all the experiments the discharge voltage and the anode flow were constant (500 V, 1,6 mg/s).

The results of anode efficiency and anode specific impulse measurements are present in fig.5 and fig.6 respectively.

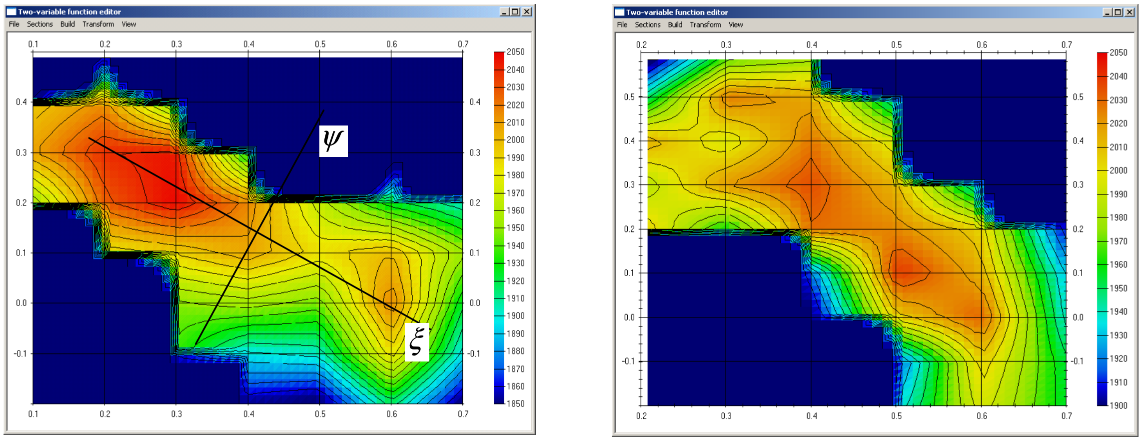
Table 1. The p_1, p_2 parameters range.

Series #1		Series #2	
p_1	p_2	p_1	p_2
0,7	– 0,2 ÷ 0,2	0,7	– 0,2 ÷ 0,2
0,6	– 0,2 ÷ 0,3	0,6	– 0,2 ÷ 0,3
0,5	– 0,2 ÷ 0,2	0,5	– 0,2 ÷ 0,5
0,4	– 0,2 ÷ 0,3	0,4	0,0 ÷ 0,6
0,3	– 0,1 ÷ 0,4	0,3	0,2 ÷ 0,6
0,2	0,1 ÷ 0,4	0,2	0,2 ÷ 0,6
0,1	0,2 ÷ 0,4		



a) **b)**

Figure 5. Anode efficiency in p_1, p_2 coordinates: a) test run #1; b) test run #2



a) **b)**

Figure 6. Anode specific impulse in p_1, p_2 coordinates: a) test run #1; b) test run #2

It is necessary to mention that not all combinations of the p_1 and p_2 parameters provide stable thruster operation. So the thrust measurements were made only for stable operation modes with relatively high output parameters.

The presented diagrams show that there is an optimal point in the investigated area for both anode efficiency and anode specific impulse. Two orthogonal directions could be chosen (fig.6a): $\vec{\xi}$ - the changes are small and don't exceed the error of measurements along this direction; $\vec{\psi}$ - the changes are significant along this direction.

Three variants of magnetic field topology are presented in fig.7, they correspond to the p_1, p_2 values a) 0.2;0.1, b) 0.3;0.2 and c) 0.4;0.3 for #1 experimental series. It is clear from fig.6 that mutual location of these points allows to analyze the magnetic field topology change in the direction close to vector $\vec{\psi}$. Besides the magnetic field lines the value of magnetic field gradient defined by equation (1) is present in color in fig.7.

The best parameters were obtained for the b) variant. If we use the symmetry criterion that was described in the introduction the best variant should be variant c). Position of maximum of the $F_B(\vec{r})$ function is closer to the central line of the discharge channel for this variant. So it is obvious, that one should use the parameter that describes the processes in the Hall thruster discharge more precisely to choose the optimal configuration of the magnetic field.

Let's analyze what properties of the magnetic field can have a main influence upon the thruster output parameters. The gas utilization efficiency is one of the key factors that affect the anode efficiency and anode specific impulse values. This influence becomes evident for specific impulse changes if the anode flow and the discharge voltage are kept constant.

If the multiple-charge ions are not taken into account the anode specific impulse of a Hall thruster is defined by the gas flow utilization efficiency and the mean ion beam velocity component in the axial direction[9]. So it is not enough to form well focused ion flow to obtain high specific impulse. On the contrary, the experimental results show[10] that changes of specific impulse at different thruster operation modes are mainly affected by changes of the gas utilization efficiency.

The gas utilization efficiency depends on the ionization area length, electron concentration and energy[9]:

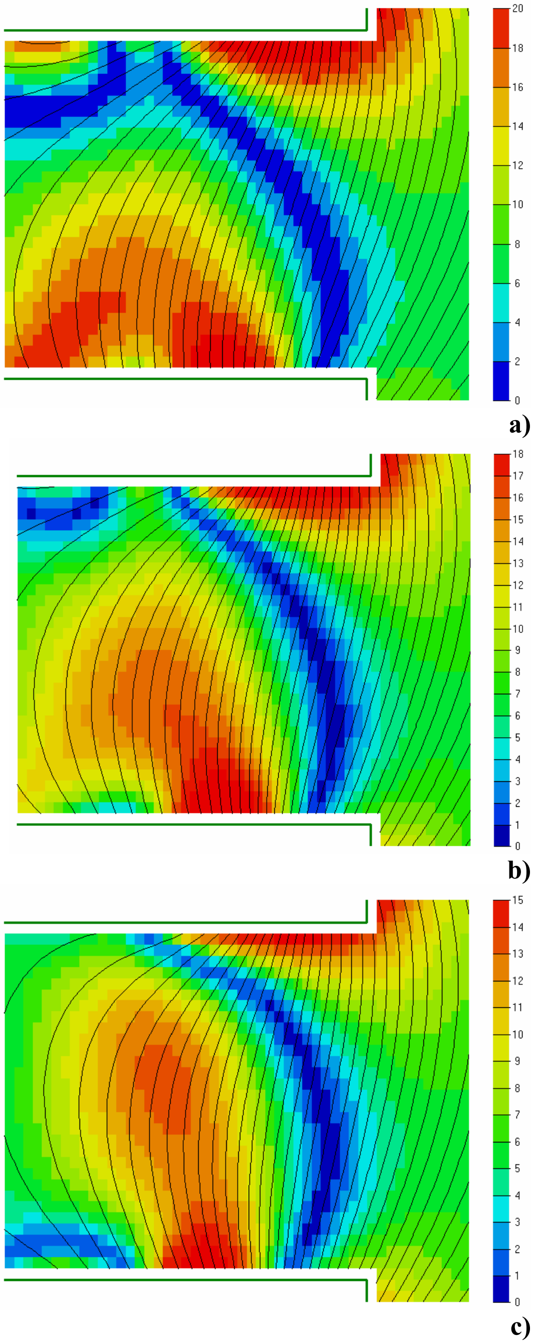


Figure 7. Field line topography at p_1, p_2 values: a) 0.2; 0.1 b) 0.3; 0.2 c) 0.4; 0.3

$$\alpha = 1 - \exp\left(-\frac{L_i}{\lambda_i}\right) = 1 - \exp\left(-\frac{L_i \langle \sigma_i v_e \rangle n_e}{V_a}\right) \tag{2}$$

where L_i - typical ionization area length, $\lambda_i = \dfrac{V_a}{\langle \sigma_i \upsilon_e \rangle n_e}$ - ionization free length for neutrals, V_a - neutral gas velocity, σ_i - ionization cross section, υ_e - electron velocity, n_e - electron concentration.

One of the key factors that affect the electron concentration is the efficiency of their keeping in the ionization area by the magnetic field. In the conventionally designed Hall thrusters the magnitude of the magnetic field is at its minimum nearby the central line of the discharge channel and grows towards the insulator ceramic walls (fig.1). Such field topology forms the so called "magnetic bottle" that prevents a part of electrons from the impact into the walls.

The condition of electron keeping is often described by the angle of losses cone. If the magnitude of the magnetic field is B_0 at some point $\vec{r}_0$ than only those electrons reach the discharge chamber walls moving along the field line which velocity has inclination angle to the field line lower than θ_0 at point $\vec{r}_0$. This angle is defined by the equation:

$$\sin^2 \theta_0 = \frac{B_0}{B_{wall}} \tag{3}$$

where B_{wall} - is the magnitude of the magnetic field at the point of intersection of the field line with the wall.

It is known that electron collisions with the wall lead to additional drift across the magnetic field under some conditions[11,12]. This effect is called "near wall conductivity". Moreover, if the electrons have enough high energy the collisions with the wall may be accompanied by secondary emission[13]. This means that the electron energy becomes lower, so does the ionization efficiency.

On the base of these argumentations the criterion that describes the efficiency of electron keeping in the ionization area could be defined. Let's determine a function in every point of area with the magnetic field that equals to the space angle external to the angle of losses cone:

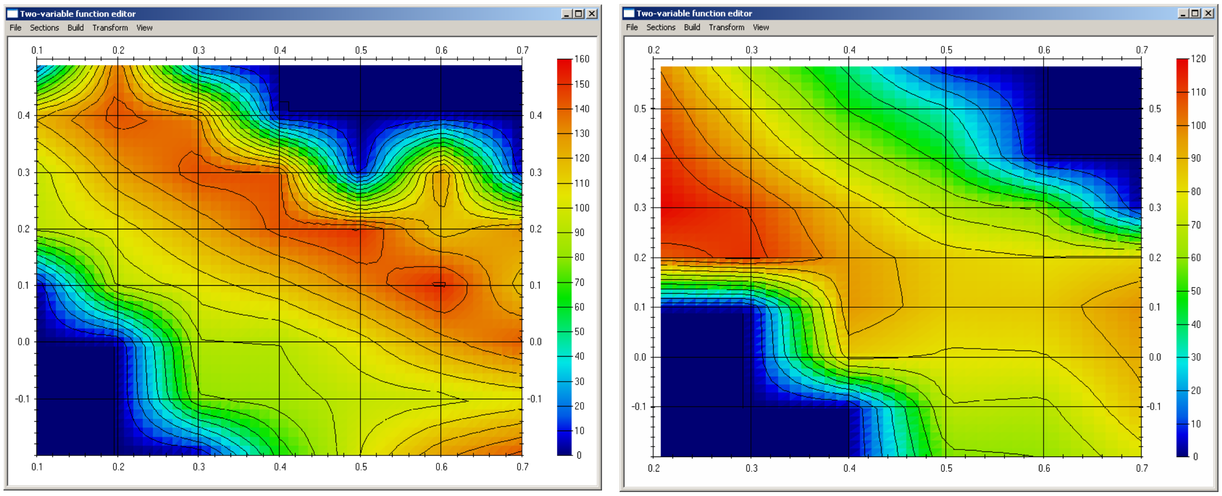
$$\Omega(z,r) = 4\pi \sqrt{1 - \frac{B(z,r)}{B_{wall}(z,r)}} \tag{4}$$

where $B_{wall}(r,z)$ - is the magnitude of the magnetic field at the point of intersection of the force line passing through the point (r,z) with the wall. According to our assumption the higher average value of this function in the ionization area is, the higher the efficiency of the electron keeping. To obtain quantitative criterion of the magnetic field quality across the whole area we should calculate an integral from the function (4) in the area of ionization:

$$G = 4\pi \int_{z_1}^{z_2} \int_{r_1}^{r_2} \Omega(z,r)\, dz dr \tag{5}$$

where r_1, r_2 - radii of the inner and outer dielectric walls respectively. Coordinate z integration limits are hardly defined. We will consider that the ionization area is located in the area with the positive magnetic field gradient, i.e. in the area where the magnetic field increases from the anode to the discharge chamber exit. We choose this area because, as it was mentioned above, if the magnetic field gradient is negative than the oscillations rather than collisions may play a significant role in the conductivity.

The dependences of the calculated criterion G on the magnetic field topology in p_1, p_2 coordinates for two series of experiments are presented in the fig.8.



a) b)

Figure 8. Quality factor G as a function of parameters p_1,p_2: a) test run #1; b) test run #2

A good correlation of calculated function and measured specific impulse (fig.6) could be noted for the series #1. Correlation in the series #2 is slightly worse. Some explanations could be found for this fact. The magnetic field maximum in the series #2 was located rather deep in the discharge chamber (4,5 mm far from the insulator edge). This could lead to the increase of ion losses on the walls and some changes in dependences that define gas utilization efficiency and thruster specific impulse.

Comparing function distributions in fig. 6 and 8 even for the series #1 one can note not enough correspondence in the location of the areas with maximum specific impulse and with maximum G criterion. In the second case the maximum is removed to the area with higher values of the p_2 parameter. For example, if p_1=0.2 the change of the field topology from p_2=0.3 to p_2=0.4 is accompanied by the decrease of the specific impulse but the G criterion at p_2=0.4 point reaches its maximum.

Let's return to the method of the angle of losses cone definition that was used for function (4) calculations to analyze possible reasons of such discrepancy. In this equation the magnitude of the magnetic field B_{wall} that defines conditions of electron collision with the wall is taken in the point of the field line intersection with the wall of the discharge chamber.

Strictly speaking this method is true only if the electron Larmor radius is infinitely small. In the real discharge the electron energy could be several tens of electronvolt. This means that their Larmor radii could be several millimeters, so it should be taken into account to calculate the angle of losses cone.

Since the electron trajectory doesn't coincide with the force line but twists around it, the electron can hit the wall earlier than the field line will cross its surface. That is why it is necessary to define $B_w(r,z)$ value not in the point of the force line intersection with the wall but in the "A" point (fig.9) that corresponds to moment when Larmor radius touches the wall while calculating the angle of losses cone. If the magnitude of the magnetic field in the "A" point is less than that on the wall the accounting of Larmor radius will lead to the losses cone increase. The strongest effect will be in cases when the magnetic field lines come to the wall under large angles, as it happened on the outer wall of the discharge chamber (fig.7).

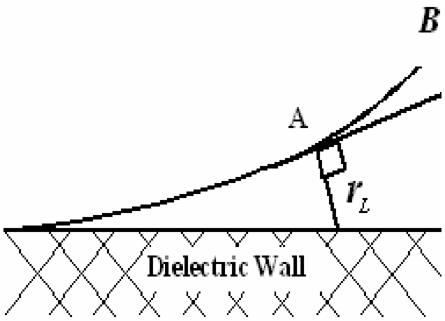
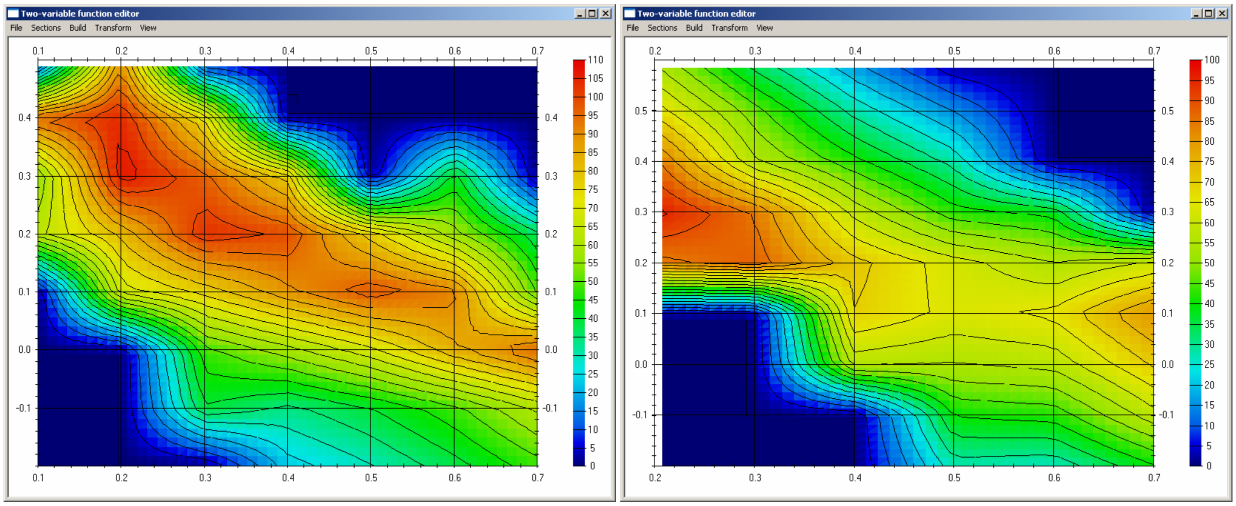


Figure 9. Electron-wall collision.

The exact calculations of the electron Larmor radius for the angle of losses cone definition is quite a complex problem because electrons move with different velocities and their distribution function is far from equilibrium one. Moreover not every electron collision with the wall leads to the drift across the magnetic field. One of the conditions of "near wall conductivity" is not specular reflection from the surface. This happens if the electron reflects from near wall potential barrier and the barrier width is much smaller than the typical size of the surface roughness. If the electron reflects specular it stays on the same force line though his trajectory despite its original trajectory was inside the losses cone. Another factor that leads to the electron drift is due to the secondary electron emission. Only with the help of kinetic modeling all these effects could be taken into account.

To obtain adjusted estimation of the G criterion using only the magnetic field topology data some averaged value of electron energy corresponding to their temperature could be set. The results of these calculations are presented in fig.10 for series #1 and #2 magnetic fields.



a) **b)**

Figure 10. Improved factor G as a function of parameters p_1,p_2: a) test run #1; b) test run #2

While calculating the adjusted G criterion the angle of losses cone was defined with Larmor radius of electrons with 50 eV energy. For the experimental series #1 the adjusted function has better correlation with specific impulse both in the $\vec{\xi}$ and $\vec{\psi}$ directions.

The developed method for the optimal magnetic field topology choice needs further improvement. During the G criterion calculations (5) the coordinate z integration limits were taken arbitrarily. Obviously this led to not enough correlation with the thruster output parameters for experimental series #2. The effective electron keeping by the magnetic field is necessary in the region of the most intensive ionization but it is quite hard to predict its location in the channel. One of the possible directions of the improvement of the offered method is the correct definition of the ionization area location, i.e. choosing the correct integration limits in equation (5). Moreover the offered criterion could not de used to define the absolute value of the optimal magnetic field. The G function monotonically increases with the increase of the magnetic field because the electron Larmor radius decreases and the losses cone becomes less. In Hall thrusters the magnetic field growth is accompanied by the output parameters increase till some threshold value. After that the discharge switches to another mode. In this mode discharge current is higher, thrust is lower and the plasma potential distribution along the channel changes significantly.

While carrying out the experiments the probe measurements of the plasma potential and electron temperature were made for some operation points. This was made with the help of near wall Langmuir probes placed in the outer wall of the discharge chamber. Particularly the correlation between the location of the acceleration zone and the position of the magnetic field radial component maximum on the central line of the discharge chamber was investigated. The dependence of maximum electron temperature on the discharge voltage was also studied. These results are interesting enough for special discussion and will be published later.

IV. Conclusions

1. The Hall thruster laboratory model with the new magnetic system design was made and tested. Four coaxially placed magnetic coils and set of magnetic screens allow varying the magnetic field topology in very wide range.
2. The sequence of experimental operations and obtained data handling provides systems approach to investigate the installation with a lot of freedom degrees.
3. The experimental series with comprehensive investigations of magnetic field influence on thruster performance were carried out.
4. The quantitative criterion, describing the magnetic field topology was proposed. This criterion defines the efficiency of electron keeping in the ionization area. A good correlation with output parameters is obtained. This criterion could find practical application for Hall thruster magnetic system design and optimization.

Acknowledgments

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