Three-Dimensional Analysis of Ion Optics with Deviation of the Apertures Geometry from Axial Symmetry

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Abstract: **A three-dimensional computer model for ion optics is described. The model is created for the project in which a space transport system with ion thrusters as the main engine will be developed. Simulation procedures solve the following tasks: solution of the self-consistent problem with calculation of the potential and space charge distribution; calculation of rarefied gas flows in the free-molecule approximation; modeling of charge-exchange collisions; calculation of surface erosion rate; prediction of the ion optics lifetime. In the present study, manufacturing tolerances on the mutual alignment of the apertures and inclination of their axes to the grid surface are investigated. The results from this computational model are compared with predictions of the linear optics theory. It is shown that the erosion pattern of the accelerating grid obtained in experiments can be used to measure the misalignment of apertures when the grids are in a heated state. An explanation of the observed asymmetry pattern of erosion on the periphery of the ion-optical system, which may arise even at perfect alignment of the apertures, is proposed.**

Nomenclature

e	=	elementary charge
E_1, E_2	=	potential gradients on the upstream and downstream sides of the accelerator grid, respectively
f	=	focal length
$\vec{F}$	=	beamlet thrust vector
h_d, h_u	=	downstream gap and upstream gap between beamlet edge and accelerating hole edge respectively
j	=	ion current density
I_k	=	current of k-th flux tube
K_B	=	Boltzmann constant
l_g	=	grid separation distance
M_a, M_i	=	atom mass and ion mass respectively
n_p	=	plasma number density
q_i	=	ion charge
T_a	=	atom temperature, K
T_e	=	electron temperature, eV
Δt	=	ion acceleration time
U_s, U_t	=	screen potential and total accelerating voltage respectively
V_a	=	atom velocity
V_i, V_{i0}, V_B	=	ion velocity, initial ion velocity, Bohm velocity respectively
$\vec{V}_k$	=	ion velocity of the k-th flux tube

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$V_{\perp}, V_{\parallel}$ = transverse and axial ion velocity respectively
x = axial coordinate
α = inclination angle of the holes axes to the grid surface
β = beamlet deflection angle
γ = ion initial velocity inclination angle
δ_h = relative holes displacement
ε_0 = permittivity of free space
ρ_i, ρ_e = charge density for the ions and the electrons respectively
φ = electric potential
φ_p = plasma potential

I. Introduction

A cooperation of Russian enterprises is working on the project "Development of a Transport and Power Generation Module Based on a Megawatt-Class Nuclear Propulsion Installation" within the Framework of the Presidential Commission for Modernization and Technological Development of the Russian Economy[1]. The main propulsion module of the nuclear space power system will be composed of ion engines IT-500 with a power of 35 kW, a specific impulse of 70000 m/s , thrust up to 750 mN and lifetime not less than 20000 hours. The ion optics of a single engine has diameter of 50 cm and is composed of two grids with circular apertures.

Most ion optics of ion engines, which were developed so far in Russia, has been made of refractory metals such as molybdenum or titanium. However, preliminary estimates showed that the requested lifetime could be achieved only when using graphite, as it has much lower rate of ion sputtering than refractory metals. It was therefore decided to develop the engines using grids made of refractory metal and in parallel to work off the technology of production of graphite grids. In present configuration, both screen and accelerating grids are made of titan. In the future, as soon as technology of graphite grid manufacturing will be available, the titanium will be replaced by graphite.

In the manufacture of ion engine with large diameter, the grids are usually spheronized. It provides mechanical strength necessary both to maintain the integrity of the grids during the vibrations on the stage of ascent satellite into orbit, and prevents possible short circuits because of electrostatic attraction of grids. Ensuring accurate mutual alignment of the holes in two grids having a large diameter is challenging. Besides, a significant issue in ion thrusters with ion optics that utilize refractory metal is thermal expansion of the grids during thruster operation, which may lead to mutual offset of the grid apertures. Misalignment of the apertures may also occur because of manufacturing tolerances, specific to a particular technology. The misalignment of apertures can produce unintended beamlet deflection. Besides, the range of operating values of perveance is reduced in this case, and interception of edge ions on the accelerating grid can be an issue[2]. A similar effect can arise also if the axes of the apertures are not exactly perpendicular to the grid surface.

To study the effects of thermal deformations, to determine the technological tolerances of grids manufacturing and for predicting real erosion rate and ion optics lifetime it is necessary to use three-dimensional numerical model. In addition, a three-dimensional model may be useful in the analysis of the test results. Determination of the presence of misalignment in a running engine is very difficult, and numerical simulations can be used to interpret the erosion pattern and find the values of misalignments in different parts of ion optics.

Many three-dimensional models have already been created to simulate the ion-optical systems in ion engines. The researchers were mainly focused on two aspects: firstly, the study of the possibility of the thrust vector control through mutual grid translation[3-5], and secondly, the analysis of the real three-dimensional erosion pattern for more accurate prediction of the lifetime[6-14]. However, to our knowledge, systematic study of the tolerance limits of apertures misalignments and axis inclination to the grid surface has not yet been performed. The erosion patterns on the downstream side of the accelerating grid in two-grid systems with misalignment of the apertures also have not been studied.

In this paper, we describe a three-dimensional ion optics computer model IOS-3D[15], which has been developed in support of creation of high power ion engines. The simulation model includes the following codes: a code of solution of the self-consistent problem with calculation of the potential and space charge distribution; a code of simulation of rarefied gas flows in the free-molecule approximation; a code of modeling of charge-exchange collisions; a code of calculation of surface erosion rate and prediction of ion optics lifetime.

The objective of this study is to explore the effect of the mutual displacement of the apertures and the apertures axis inclination to the grid surface, on the focusing properties of ion optics. We also examine changes in the erosion pattern in case of mutual misalignment of the holes. In addition, we investigate the possible causes of the asymmetry of the erosion pattern on the periphery of the ion-optical system, which is often observed in laboratory tests and perhaps is not related to the breaking of ion optics symmetry.

II. Numerical Model

The computer model IOS-3D performs calculating of the electric field and ion fluxes in three-dimensional domain with arbitrary geometry of the boundary surfaces. The electric field is calculated by solving the Poisson equation

$$\nabla^2 \varphi = -(\rho_i + \rho_e)/\varepsilon_0, \tag{1}$$

where φ is the electric potential, ρ_i, ρ_e are the charge densities of ions and electrons respectively, ε_0 is the permittivity of free space. The calculation of the potential is carried out by the finite difference method on orthogonal grid with seven-node pattern, which may have different steps in each of the six directions. The system of finite-difference equations is solved by an iterative method with Chebyshev acceleration. A boundary surfaces are described as a set of planar polygons. To calculate the potential the following boundary conditions may be specified: the Dirichlet condition with a constant potential; the Neumann condition with zero derivative of the potential along the normal to the boundary; the translational symmetry condition with the transfer vector parallel to one of the coordinate axes. The potential gradient is calculated from the values of the potentials using a bilinear interpolation. The self-consistent task is solved in the stationary approximation. To calculate the trajectories and the space charge of charged particles, the method of flux tubes is used.

The simulation approach to modeling of the ion extraction from plasma is inherited from earlier developed 2-dimensional simulation model GASEL[16]. Briefly, the method consists in the following. The area in the form of the box may be specified in the simulation domain, which may have subregion filled with plasma. Plasma parameters, namely its potential φ_p, number density n_p and electron temperature T_e should be indicated as an input data. In calculating the flux tubes trajectories, the following algorithm is implemented. Initial ion velocity is calculated from Bohm criterion:

$$V_{i0} = V_B \equiv \sqrt{eT_e/M_i}, \tag{2}$$

where V_B is Bohm velocity, e is the elementary charge, M_i is the mass of the ions, and the electron temperature T_e is expressed in eV. If the point, at which the trajectory is calculated, lies inside the box, and electric potential in this point is higher than the predetermined potential of the plasma ($\varphi > \varphi_p$), we assume that this point is located inside the plasma. In this trajectory point, we ignore the calculated value of the electric field. The electric field at this point is assumed zero, and space charge is reset to zero to ensure the condition of quasi-neutrality. If the potential is less than the specified potential of the plasma, the actual electric field is calculated by usual procedure with bilinear interpolation. In the last case, the negative space charge of electrons is added to the total space charge in given mesh node. The trajectories of electrons are not modeled. Instead, it is assumed that the electron density satisfies the Boltzmann equation:

$$\rho_e = -en_p exp[(\varphi - \varphi_p)/T_e]. \tag{3}$$

This method has been tested repeatedly in the program GASEL and showed good accuracy. When debugging a program IOS-3D, test calculations were carried out for axisymmetric geometries and were compared with GASEL results. Besides a flat two-dimensional problem was solved to check the formation of the flat ion extraction surface in a Pierce-type ion gun for theoretically predicted value of the perveance. These tests confirmed that the method gives correct results.

For calculating the density of neutral atoms, which enter the simulation domain from both the discharge chamber and the neutralization region, the method of flux tubes is used. As far as we know, this method has not yet been used for calculations of atom flows in ion-optical systems. We use it so that the same algorithm carried out the calculation of charged and neutral particles. The method consists of a cycle of successive iterations. At each iteration, the flow of neutral particles precipitating into the computational domain from each element of the boundary surface is represented as a predetermined number of flux tubes, with different directions of initial velocity. The total gas flow is distributed through the flux tubes according to a cosine law, while the velocity in each flux tube is set equal to the average value of the velocity modulus in the equilibrium gas with temperature T_a:

$$\langle V_a \rangle = \sqrt{8K_B T_a/(\pi M_a)}, \tag{4}$$

where K_B is the Boltzmann constant, M_a is the mass of the atoms, and temperature T_a is expressed in Kelvins. At the end of each iteration, new values of incident fluxes on the surfaces become known. These values are used in the next iteration, assuming the law of diffuse reflection of the atoms from the walls. The procedure of calculation of the atoms number density uses the same algorithm as in the calculation of the charge density of charged particles. That is, the flow of each flux tube is divided by the average speed, and the resulting density of the atoms is distributed to nearby nodes by bilinear interpolation. The testing of the algorithm has been carried out by comparing the calculation results with GASEL results. The code GASEL uses the proven method of integral iterations to calculate flows of atoms. In addition, a series of test tasks of the gas flow through the pipes, was used to compare the simulation results with known solutions. The comparison showed that described method gives the correct results. The numerical error approaches zero by increasing the number of flux tubes.

The program also has a subroutine for calculating the rate of volumetric formation of slow ions in charge exchange collisions and calculating the trajectories of secondary ions to their incidence on the boundary surfaces. At the end of the calculations of the primary ions and charge exchange ions, the calculations of the erosion rate of the boundary surfaces by ion sputtering is performed. The erosion rate is calculated taking into account the energy of the ions and incidence angle to the surface.

In what follows we plan to retrofit program algorithms with taking into account elastic collisions of ions with atoms, the presence of doubly charged ions and re-deposition of the scattered atoms.

III. Simulation results

In all calculations described here, the following nominal parameters of ion optics were used: screen hole diameter is 4 mm; screen grid thickness is 1 mm; screen grid potential is 4500 V; the nominal screen to accelerating grid gap is 2 mm; accelerating hole diameter is 2.8 mm; accelerating grid thickness is 2 mm; accelerating grid potential is -400 V; center-to-center hole spacing is 4.6 mm. Xenon was specified as propellant.

A series of calculations was performed to ensure that the simulation results do not depend on the grid step, the calculation domain length, the number of flux tubes and parameters of numerical procedures. In the final domain the upstream bound is located at a distance of 4 mm from the screen grid; the downstream bound is located at 10 mm from the accelerating grid. The numerical grid spacing in each direction was around 0.1 mm.

Throughout the text of the article, instead of the plasma density, as a parameter, we use the current density of ions, which move inside plasma toward the emission surface with Bohm velocity. This current density is specified in the program as a boundary condition on the surface from the part of plasma.

In calculations of the ion optics with ideal symmetry it was shown that there is no direct impingement of ions on the accelerating grid, when the ion current density in the discharge chamber is in the range from 10 to 140 A/m^2. Lower value corresponds to the so-called crossover limit, at which ions are deflected too strong, the upper value is the so-called perveance limit, at which the focusing of ions is not sufficient. On the part of neutralizing region the secondary ions current density was set to 0.5 A/m^2. The electron temperature was set to 5 eV in the discharge chamber, and to 2 eV in the neutralizing region. The plasma potential in the discharge chamber was set to 4530 V. In the neutralizing region, the plasma potential was set to 0 V.

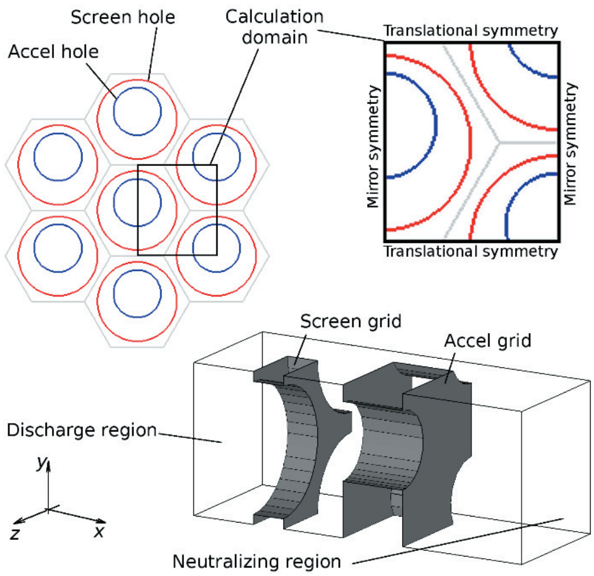

Figure 1. Calculation domain used to study the relative displacement of the holes.

A. Study of apertures misalignment

The schematic of calculation domain that was used in the analysis of the relative displacement of the holes is shown in Fig.1. The minimum possible elementary cell was chosen to reduce the volume of calculations. In this cell for two surfaces, which are perpendicular to the y-axis, the condition of mirror symmetry was specified. For two surfaces, which are perpendicular to the z-axis,

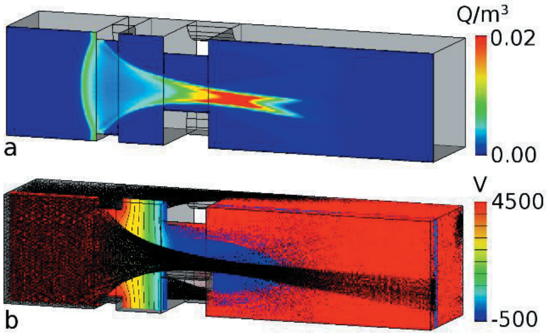

Figure 2. Example of simulation results of ion optics with holes offset: a) space charge distribution; b) plasma potential distribution and ion trajectories

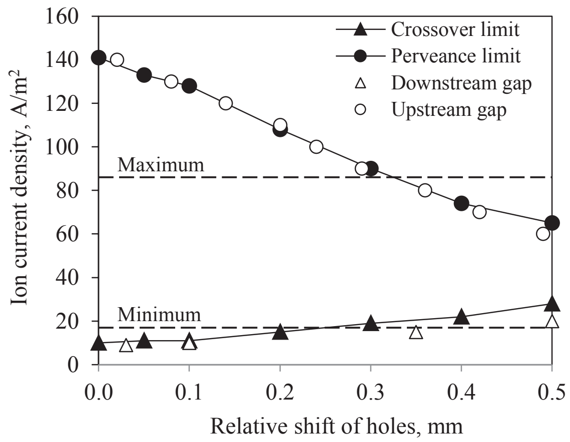

Figure 3. Limiting values of ion current density as a function of relative shift of holes.

the condition of translational symmetry was specified. Three-dimensional image of the computational domain is shown in the bottom of Fig. 1.

Figure 2 shows an example of calculation for the case of mutual holes displacement of 0.4 mm. The space charge distribution in a plane passing through the centers of the holes is shown using color map in Fig. 2(a). The color map gives a clear view of the ion extraction surface and shows beamlet deflection in the direction which is opposite to the shift of accelerating grid hole. The trajectories of beamlet ions, entering the calculation domain from discharge plasma, and back-flow ions entering from the downstream plasma, are shown in Fig. 2(b) by black and red colors respectively. A plasma potential distribution is shown in Fig. 2(b) using color map.

A series of calculations has been carried out to determine both the crossover and perveance limits of ion current density at different relative shifts of the holes. The results of these calculations are shown in Fig. 3. The allowable range of current density is shrinking with increase of the relative shift of holes. Fig. 3 also shows by dashed lines the minimum (17 A/m^2) and the maximum (86 A/m^2) values of ion current density that were measured in the ion thruster IT-500[17]. In the calculations, it was found that the maximum misalignment of apertures in which the engine operation is possible without direct ion impingement, is approximately 0.2 mm.

The results of modelling show that the shape of the beamlet in the gap between two grids varies little with mutual shift of the holes. In other words, the beamlet little "feels" misalignment, and if the hole in the accelerating grid moves relative to the screen hole, the beamlet remains nearly fixed with respect to the screen hole. Therefore, the allowable relative displacement of the holes can be estimated as the distance from the edge of the beamlet to the edge of the hole in accelerating grid, calculated in two-dimensional axisymmetric approximation.

Fig. 4 shows the results of calculations of the ion beamlet in the analogous axisymmetric region. The distances from the edge of the beamlet to the edge of the aperture in the accelerating grid which was defined as the upstream gap (h_u) and downstream gap (h_d) are also shown in Fig. 4. We have introduced two distances, since, at low current density, direct impingement takes place on the downstream side of the grid, and in the limit of high perveance, it takes place on the upstream side.

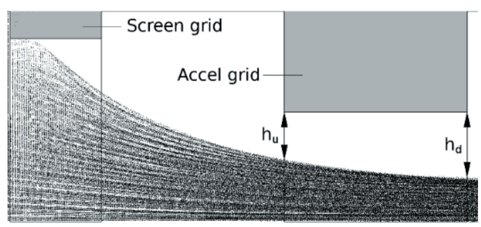

Figure 4. Upstream and downstream gaps in axial symmetric approximation.

The calculations of the distances h_u and h_d were carried out for a number of different values of the ion current density. The results of calculations are shown in Fig. 3 using unfilled markers. The abscissa values of these markers show the distances h_u and h_d, and the ordinate values are the corresponding ion current densities. It is seen that at given current density the shortest distance from the edge of the beamlet to the edge of the hole is close to the allowable mutual shift of the two apertures. In the perveance limit, coincidence is better than in the crossover limit. It is because direct ion impingement in crossover limit takes place in the downstream edge of the accelerating grid, where the ions come after defocusing in the lens, which is formed by accelerating hole. This noticeable changes their trajectories, i.e. decrease the distance between the trajectory and the edge of the accelerating hole.

The observed regularities are typical for linear optics theory, when ion-optical system is approximated by a set of thin lenses, and it is assumed that ions propagate between the lenses without experiencing deflecting impacts. From this point of view, it is useful to analyze the dependence of the deflection angle of the ion beamlet as a function of the relative shift of holes and compare it with linear optics theory predictions. In this theory the aperture in the accelerating grid of a two-grid system may be represented as a thin lens with a focal length, which is given by the expression[18]

$$f = 4\mathrm{U}_t/(E_2 - E_1), \tag{5}$$

where U_t is the total accelerating voltage; E_1 and E_2 are the potential gradients on the upstream and downstream sides of the accelerating grid, respectively. The beamlet deflection angle β is then given by

$$\beta = \delta_h/f, \tag{6}$$

where δ_h is the relative displacement of the holes. In Ref. 19 it was assumed, that E_1 equals to the total accelerating voltage divided by the grid separation distance, and neglecting E_2 compared to E_1, the following expression was obtained

$$\beta = -14.3 \cdot \delta_h/l_g, \tag{7}$$

where l_g is grid separation distance and angle β is expressed in degrees. In Ref. 20 space charge in the plane parallel-plate approximation was taken into account to refine the value of the electric field:

$$E_1 = -(4/3) \cdot \left(U_t/l_g\right), \tag{8}$$

and instead of (7) the expression

$$\beta = -19.1 \cdot \delta_h/l_g, \tag{9}$$

where angle β is expressed in degrees was used.

In our numerical simulations the deflection angle was calculated as an angle between *x*-axis and the thrust vector, for which the following expression was used

$$\vec{F} = (M_i/q_i) \cdot \sum_k I_k \vec{V}_k, \tag{10}$$

where the summation is over the flux tubes, M_i is ion mass, q_i is ion charge, I_k is the current of *k*-th flux tube, $\vec{V}_k$ is the ion velocity of the *k*-th flux tube at the exit of the calculation domain.

Fig. 5 shows the beamlet deflection angle as a function of the relative shift of holes for a number of ion current densities, obtained in numerical simulations, and two theoretical dependencies, given by the expressions (7) and (9). As can be seen, the theoretical estimation (9) with taking into account space charge, gives better agreement with numerical simulations than estimation with constant potential gradient. Thus, we can conclude, that the dependence (9) could be used for estimation of the deflection angle in wide range of ion current density.

The first experiments with 50-cm ion optics made of titanium have revealed an asymmetry of the erosion pattern in some regions on the downstream side of the accelerating grid. The example of such asymmetry is shown in Fig. 6 (a). It can be seen that erosion pattern is

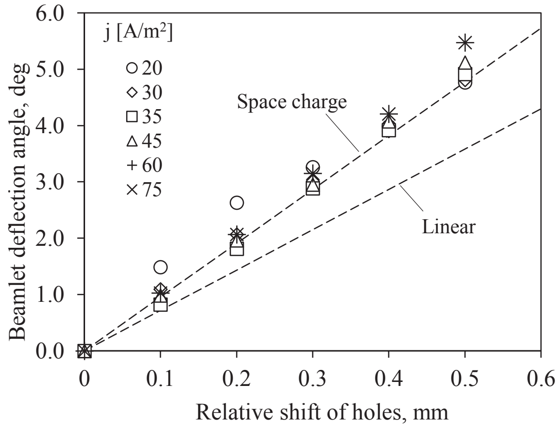

Figure 5. Beamlet deflection angle as a function of relative shift of holes.

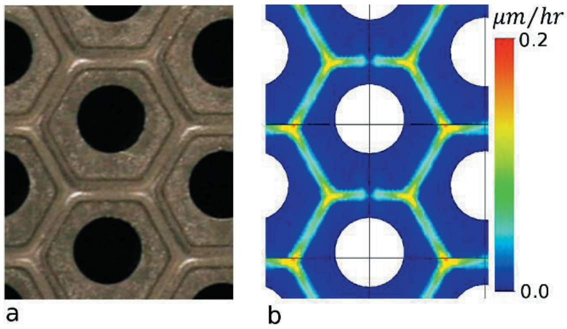

Figure 6. Erosion pattern on the downstream side of the accelerating grid: a) experiment; b) simulation.

shifted down and left with respect to the holes. The most likely cause of this asymmetry is local mutual shift of the holes in the screen and accelerating grids. For example, Fig. 6 (b) shows the erosion rate obtained in simulations, when the relative shift of holes is 0.2 mm and ion current density in the discharge plasma is 45 A/m^2. For better clarity, the picture in Fig. 6 (b) is made by layering multiple pictures calculated for the region shown in Fig. 1.

One of the causes of observed misalignment can be solution errors of thermal problem. The metal grids are experiencing noticeable thermal deformation during engine operation. Therefore, the coordinates of the holes were calculated to provide mutual alignment not in cold but in hot state. Accuracy of the solution of the thermal problem is not very high. This is because one of the main mechanisms of heat transfer is radiation, and the emissivity coefficients of the grid surfaces varies with time due to sputtering and deposition of the sputtered material. In addition, the distribution of the heat flux density from the discharge chamber is also a calculated value, and it may have an appreciable error. Therefore, misalignment of holes in a heated state could be caused by an error of the solution of the thermal problem that led to the error in calculating the coordinates of the holes on the cold grids. Another cause may be errors of manufacturing and assembly of ion optics.

It is difficult to measure directly the mutual displacement of the holes in the state of thermal deformation when the engine is in operation. Therefore, it is useful to clarify, whether you can use the observed pattern of erosion, to assess mutual misalignment of holes in a hot state. This information can help in the future to improve the accuracy of the ion optics manufacturing.

To reveal the dependence of the erosion pattern displacement on the mutual shift of the holes shift, a series of calculations was carried out. In these calculations, we varied the value of the mutual shift of the holes and ion current density in the discharge plasma. The shift of erosion pattern was measured as the distance between the erosion pit center and accelerating hole center in the direction parallel to the direction of holes shift. These values are shown in Fig. 7. The calculation results are shown in Fig. 8.

It can be seen that the erosion pattern displacement is approximately directly proportional to the holes displacement. At average and high ion current densities, which are usually observed in central part of ion optics, the shift of the erosion pattern weakly depends on the current density. For example, at a fixed holes offset, the pits offset differ in the range of the calculation error, when the ion current density changes between 45 and 75 A/m^2. At low ion current densities, which are encountered in the periphery of ion optics, the displacement is more sensitive to the ion current density. For particular geometry considered here, the accuracy of the holes misalignment, which can be

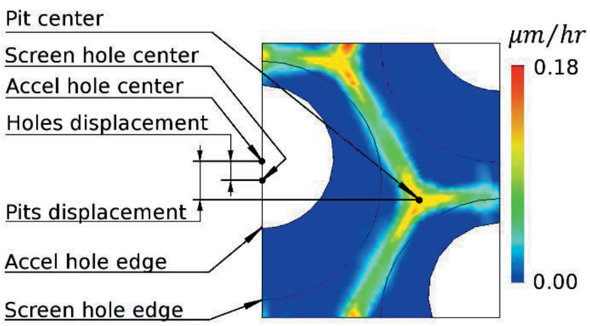

Figure 7. The way of calculating a shift of the erosion pattern.

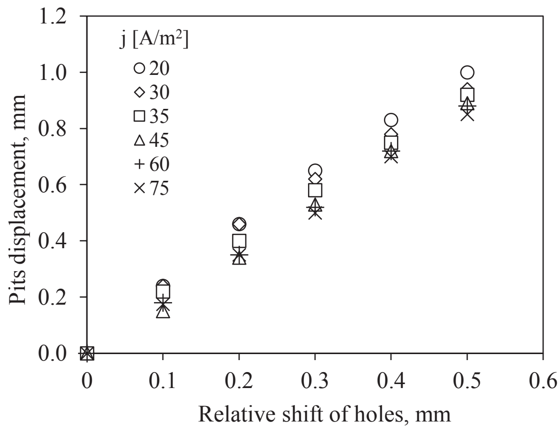

Figure 8. Pits offset as a function of the mutual holes shift.

obtained from the erosion pattern, vary from some hundredth to one tenth of a millimeter. Therefore, we can conclude that the pattern erosion shift can serve as a measure of the mutual offset of the holes.

B. Study of apertures inclination

The grids of large ion thrusters are usually make spherical, firstly to improve the mechanical strength of the ion optics, and secondly to avoid uncontrolled distortion of the grid due to thermal strains. Making holes which axes are strictly perpendicular to the surface of the large spherical grid workpiece, is rather complicated technological task. Therefore, it is useful to define the tolerances of the inclination angle of the holes axes, to the grid surface, at which the focusing properties remain at an acceptable level. It is also useful to investigate how the axes inclination to the grid surface influences on the beamlet deflection. If such an effect exists, it would be possible to reduce the total angular divergence of the ion beam by changing the inclination of the axes of apertures to the grid surface at the periphery of the ion-optical system. For example, Fig. 9 shows a variant of the inclination of the holes axis to the grid surface, at which the axis of the hole is parallel to the axis of the ion-optical system.

To simulate such ion optics, it is impossible to set the simulation domain with the exact boundary conditions, using a mirror symmetry and translational symmetry on mutually perpendicular surfaces. Therefore, the computational domain, representing half-size aperture, which is shown on the top of Fig. 10, was chosen for simulations. In this domain on all of the side surfaces, the condition of mirror symmetry was set. To identify the errors, which may arise because of not accurate boundary conditions, a series of comparative calculations for this computational domain and the domain consisting of three adjacent half-size apertures, shown in the bottom of Fig. 10, was carried out. Comparing the results of simulations showed that the deflection angles obtained in the first domain and in the central half-size cell of the second domain differed negligibly within the range of computational error. The erosion patterns on the downstream side of the accelerating grid surface were noticeably different. Therefore, the focusing and deflection properties of the ion optics were investigated in the computational domain representing a single half-size aperture, shown on the top of Fig. 10 with mirror boundary conditions on all side surfaces. The erosion pattern was not analyzed.

Figure 11 (a) shows the example of calculated ion trajectories, when the axis of the apertures has an inclination of 6 degrees to the normal of the grid surface, and ion current density in the discharge plasma is 60 A/m^2. Figure 11 (b) shows the distribution of the space charge in the plane, which passes through the centers of the holes. The beamlet deflection angle β was

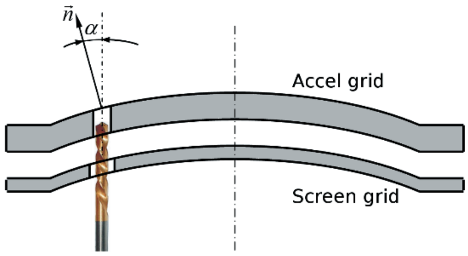

Figure 9. Inclination of holes axes to the grid surface.

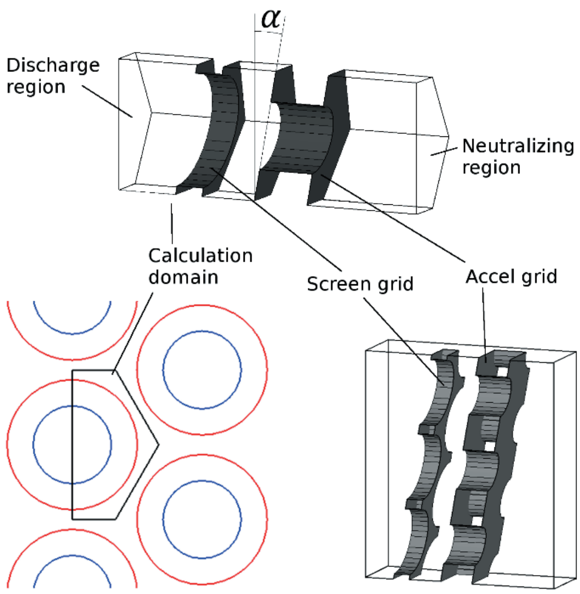

Figure 10. Schematic diagram of the region with holes axes inclination.

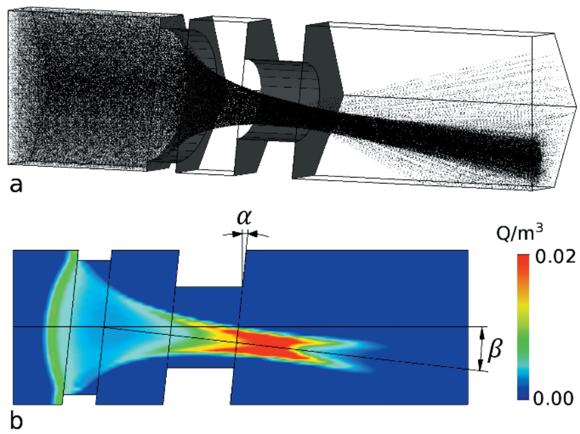

Figure 11. Example of simulation the ion optics with holes axes inclination: a) ion trajectories; b) space charge distribution.

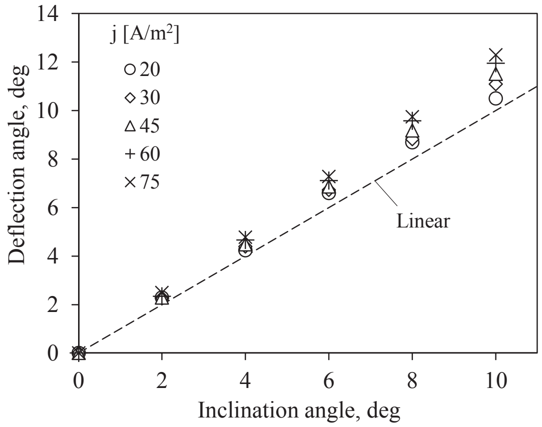

Figure 12. Beamlet deflection angle as a function of the axis inclination angle.

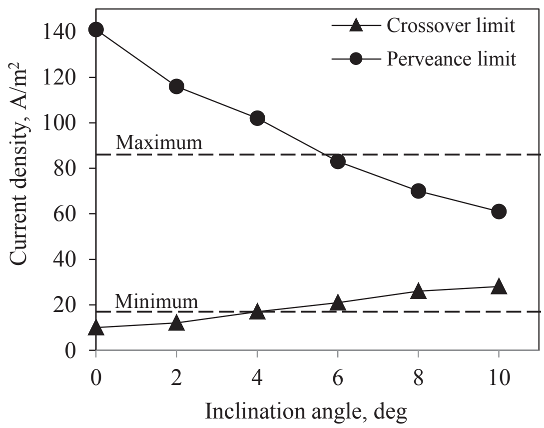

Figure 13. Limiting values of the current density as a function of the axis inclination angle.

defined as the angle between the centerline of the holes and the calculated thrust vector of the beamlet, as shown in Fig. 11 (b).

Beamlet deflection angle β was defined as the angle between the centerline of the holes and the calculated vector of the beamlet thrust, as shown in Fig. 11 (b). According to the conducted simulation, the inclination of the holes axis to the surface has little effect on the angle of beamlet. The direction of the accelerated beamlet is close to the direction of the normal to the grid surfaces. To demonstrate this we show in Fig. 12 the linear dependence $\beta = \alpha$ by dashed line. The deflection of the beamlet grows a little with increase of the inclination of the holes axis to the normal to surface. Therefore, we can conclude that the control of the beamlet deflection angle using the inclination of the holes axis to the normal to grid surface is not efficient.

The dependencies of the crossover and perveance limits of the ion current density on the holes axes inclination angle, obtained in numerical simulations, are shown in Fig. 13. According to obtained dependencies, the acceptable inclination angle for the considered particular geometry of ion optics must be less than 4°.

C. The slope of the initial velocity vector of ions

As experiments show, in the periphery of two-gridded ion optics with large diameter on the downstream side of the accelerating grid a nonsymmetrical erosion pattern is often observed. It occurs independently of the manufacturing quality or degree of mutual adjustment of the screen and accelerating grids. As an example, Fig. 14 shows the area of the accelerating grid of the ion thruster IT-500 near the edge of ion optics after some hours of operation.

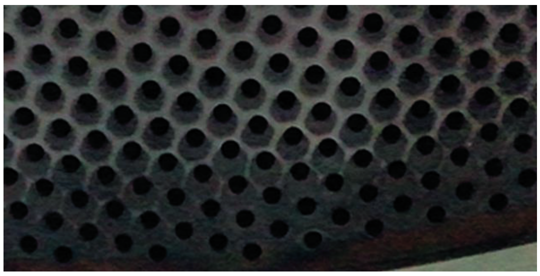

Figure 14. The edge of accelerating grid of the ion thruster IT-500.

As it was noted above, the asymmetry may be caused by mutual shift of holes in the screen and accelerating grids. However, we may note that the degree of the asymmetry drastically increases in the direction to the ion optics edge. To explain this erosion pattern by the thermal deformations it is necessary to assume very high nonuniformity of the grid temperature.

The observed asymmetry may arise also, because the Bohm velocity of the ions inside discharge plasma is not perpendicular to the screen grid surface. This effect was investigated earlier in two-dimensional approximation for slit-type ion optics using the computer code GASEL[21]. It was shown, that the inclination of the initial velocity of ions indeed causes the deflection of the beamlet. Therefore, for the correct interpretation of the experimental data, it is useful to analyze, how the inclination of the ion velocity affects on the beamlet deflection in the case of circular apertures. It is also of interest to study, whether this inclination causes a shift of the erosion pattern.

To investigate the effect of the ion velocity inclination on beamlet deflection, we used the calculation domain shown in Fig. 1, without relative shift of the holes axes. The vector of initial velocity of ions was situated in the plane *x*-*y*, and it had the angle γ with respect to the *x*-axis, as it is shown in Fig. 15. The absolute value of the ion velocity was calculated using the Bohm criterion. The condition of translational symmetry was set on both the top and the bottom surfaces of the computational domain. Figure 15 shows the example of simulation results for the case of ion velocity inclination angle $\gamma = 30°$ at the ion current density of 30 A/m^2. Black lines show the trajectories of primary ions, magenta lines show the back-flow ions. The potential distribution is shown using color map and lines of equal potentials.

The results of simulations are shown in Fig. 16. The beamlet deflection angle increases nonlinear with the inclination angle of initial velocity of ions. The less the ion current density, the higher the deflection angle.

We can estimate the deflection angle, using linear optics theory and regularities of acceleration of ion beam with space-charge limited current in a plane-parallel vacuum diode. If we assume that the deflection angle is caused by the transverse component of the initial ion velocity, and if this component is constant during ion acceleration, then the deflection angle approximately equals to the ratio of the transverse ($V_\perp = V_B \sin\gamma$) to axial ($V_\parallel = \sqrt{2q_i U_s/M_i}$) velocity:

$$\beta = V_\perp/V_\parallel = \sqrt{T_e/2U_s}\sin\gamma \qquad (11)$$

If in addition we take into account deflection of ions in the electrostatic lens formed by the hole in the accelerating grid, we should add to the angle (11) the angle, which is given by expression (6), where the value

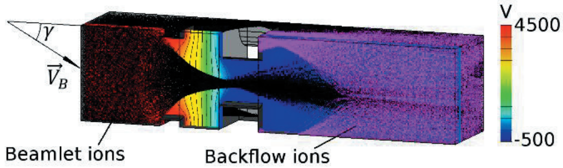

Figure 15. Example of simulation results in case of ion velocity inclination.

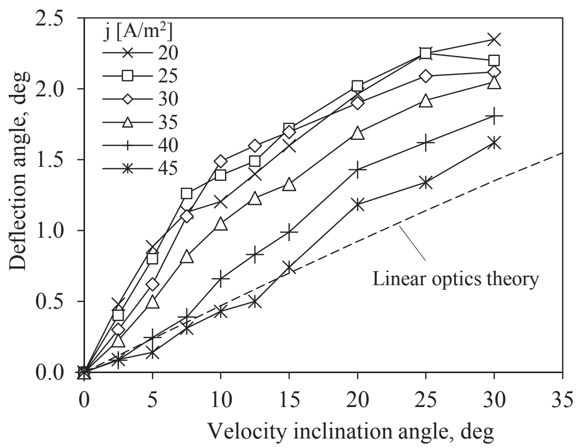

Figure 16. Beamlet deflection angle as a function of ions velocity inclination angle.

$$\delta_h = V_\perp \cdot \Delta t. \qquad (12)$$

is a transverse shift, which arises during the time of acceleration Δt. According to the laws of acceleration of ion beam in a plane-parallel approximation, when the ion current is limited by space charge, the potential increases along the direction of acceleration as[18]

$$\varphi(x) = U_t \cdot (x/l_g)^{4/3}. \qquad (13)$$

From this expression we can calculate the ion velocity

$$V_i(x) = \sqrt{2q_i U_t/M_i} \cdot (x/l_g)^{2/3}. \qquad (14)$$

and find the total time of acceleration

$$\Delta t = \int_0^{l_g} dx/V_i(x) = 3l_g\sqrt{M_i/(2q_i U_t)}, \qquad (15)$$

from which, using (2) and (12) we can find the total deflection angle with taking into account both the transverse component of the initial velocity and deflection of the beam in the electrostatic lens:

$$\beta = \sqrt{2T_e/U_s}\sin\gamma. \qquad (16)$$

Here, as in our previous estimates we neglect the accelerating grid potential compared with screen grid potential and use the approximate equality $U_s \cong U_t$. The obtained dependence (16) calculated for $T_e = 5$ eV, and $U_s = 4500$ V is shown in Fig. 16 by dashed line.

We see that linear optics theory gives a noticeably underestimated deflection angle. The lower the ion current density, the greater the deviation from the linear optics theory prediction. Analysis of the simulation results show that an unexpectedly high deviation angle of the beamlet is explained by deformation of ion extraction surface.

As an example, Fig. 17 shows space charge distributions in two cases: a) the vector of ion initial velocity is parallel to the axes of the holes; b) the angle between the vector of ion initial velocity and the axis of the hole is 30°. In the second case, we see little noticeable deformation of the ion extraction surface, which can be characterized as an inclination in the same direction as the inclination of the ion velocity vector.

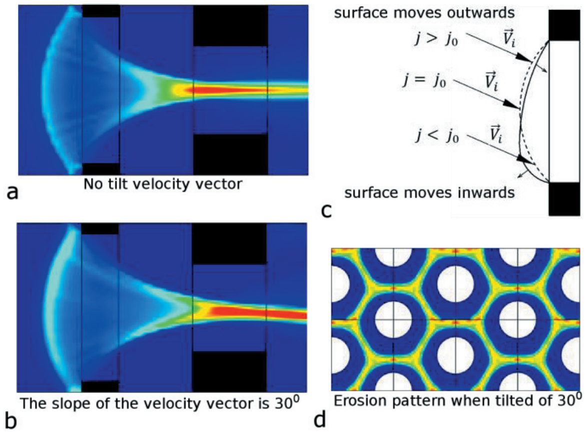

Figure 17. An explanation of anomalously strong beamlet deflection.

The deformation of the extraction surface may be explained as follows. The ion current density on the extraction surface is proportional to the cosine of the angle between the ion velocity vector and the normal to the ion extraction surface. If no tilt of velocity vector, the shape of ion extraction surface is close to spherical. The less ion current density, the higher the curvature of the ion extraction surface. If the angle of ion velocity changes in a way, as it is shown in Fig. 17 (c), the current density on the upper side of ion extraction surface increases due to decrease of the angle between ion velocity vector and normal to the ion extraction surface. On the bottom side of the surface, the current density decreases due to increase of this angle. According to Child's Law, increase of the current density moves the ion extraction surface ahead to reduce the distance of acceleration gap. In the bottom side, the ion extraction surface moves backward into discharge plasma due to lessen of current density. These movements of different parts of the ion extraction surface led to surface deformation, which enforces the ion beamlet deflection. As a result, the deflection angle is stronger than the prediction of the linear optics theory. The less current density, the more curvature of ion extraction surface, the more difference of the current density on upper and bottom sides of the ion extraction surface, the higher ion beamlet deflection, as it is seen in Fig. 16.

Fig. 17 (d) shows the simulated erosion pattern on the downstream side of accelerating grid when the angle of ion velocity inclination to the axis of the holes is 30° and ion current density is 25 A/m^2. As in all previous calculations, the backflow ion current density was set to 0.5 A/m^2. The electron temperature in the neutralization area was set to 2 eV. It can be seen noticeable offset of pit and grooves pattern, like it was, when the holes are not coaxial (see Fig. 6). Therefore, the non-symmetry of the erosion pattern, which is often observed in experiments near the edge of ion optics, may be explained by inclination of ion velocity to the normal to the surface. Perhaps it is not related to the misalignment of the holes.

IV. Conclusion

A three-dimensional computer model for ion optics simulation was developed that can be used to investigate arbitrarily complex ion-optical systems and to predict the erosion rate of the grids. A series of calculations has been performed to investigate the maximum tolerances, when manufacturing two-gridded ion optics. The main results obtained by numerical simulations can be summarized as follows.

The maximum allowable mutual shift of the holes in screen and accelerating grids may be estimated using results of two-dimensional axisymmetric simulations. It equals to the minimum distance from the ion beamlet to the edge of accelerating hole. The beamlet deflection in an ion optics with non-coaxial holes may be rather accurately predicted by linear optics theory, if to take into account space charge influence on the electric field in the accelerating gap. The erosion pattern on the downstream side of accelerating grid has a shift, which is proportional to the relative offset of the holes. The offset of the erosion pattern may be used to measure the local misalignments of the holes in hot ion optics, while it is rather difficult to make by direct measurements on the operating engine.

The inclination of the holes axis to the normal of the grids, with angle of the order of some degrees, dramatically decreases the current density range, at which the ion engine works without direct impingement of ions on the accelerating grid. The beamlet deflection from the normal to the surface in this case is too small to be used as a means of reduction of the ion beam divergence in ion optics with spherical shape of grids.

The asymmetry of erosion pattern on the downstream edge of accelerating grid that is usually observed on the periphery of ion optics may arise even in absence of holes offset. It may be a result of initial ion velocity inclination to the grid surface. The resulting deflection of ion beamlet in this case is stronger, than deflection predicted by linear optics theory, due to deformation of the ion extraction surface.

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