DOI: 10.13009/EUCASS2017-139

Experimental studies of an ion optic system with improved mechanical strength

Sergey V. Madeev, Alexander S. Lovtsov* and Michael Yu. Selivanov**
** SSC FSUE Keldysh Research Centre*
8 Onezhskaya Street, 125438 Moscow, Russia

Abstract
Studies for development of carbon-carbon ion optic systems for ion thrusters are underway at Keldysh Research Centre. Screen grids have high transparency for ions, are thin and have thin spacers between apertures, so their mechanical strength decreases. Authors of this paper assume that keeping intact threads in the spacers by using rectangular apertures improves strength, however it may diminish the perveance range. This article presents the results of experimental studies of optics perveance range for circular apertures and for rectangular apertures having rounded corners. The data obtained proves the opportunity to replace the first with the latter.

1. Introduction

Increasing lifetime and efficiency are the most important tasks to be solved while developing modern ion thrusters. Those characteristics depend on the design of ion optics system (IOS), which is one of the important parts of an ion thruster.

The task of increasing the lifetime is usually solved by decreasing the current density of ions passing from the discharge chamber to the inner surface of the screen grid or by using carbon-based materials. Since the first method leads to enlargement of ion optics working part diameter, and, accordingly, increases size and weight of the thruster. Using of carbon-based materials while maintaining higher density values of the ion current is more promising.

The second task, namely the task of improving the efficiency of the thruster, is achieved by increasing the IOS transparency for ions. It may be implemented in two ways: by reducing thickness of walls between orifices in screen grid, i.e., increasing of the geometric transparency of IOS and by increasing the electric field between plasma discharge chamber and acceleration grid. For this purpose the screen grid thickness should be reduced while maintaining the minimal distance between the grids at which electric breakdown is absent.

All of the above ways are intended for changing the geometry of IOS, along with increasing lifetime and efficiency of the thruster, decrease the mechanical strength of the screen grid. Laser drilling of holes with classic circular geometry causes fiber cutting which leads to a further decline in strength. Square shape of apertures was prefered to add the number of intact fibers. In an earlier published work on the subject of computational studies [1] it was shown that square apertures decrease IOS range of perveance. At that, presence of rounded corners of square holes is required to restore the perveance range to the values observed in circular apertures. This paper presents the results of experiments performed on IOS with circular apertures and square apertures with rounded corners.

2. Experimental facility

The experiments for determining the perveance ranges of ion thruster IOS have been carried out at vacuum test facility with turbomolecular pumps (Figure 1). The total pumping speed for three pumps is 6000 l/s of nitrogen. At xenon flow rate equivalent to 20 mA the pressure in the chamber was at $\sim 5.3 \cdot 10^{-4}$ Pa. The tests were performed on a laboratory model of ID-100 ion thruster with 104 mm anode diameter and ionization in DC discharge (Figure 2).

DOI: 10.13009/EUCASS2017-139

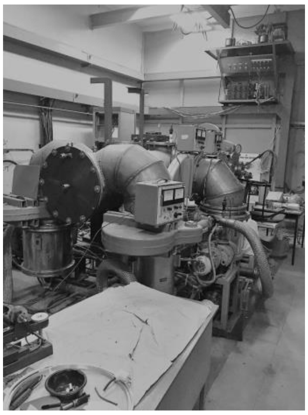

Figure 1: Experimental facility

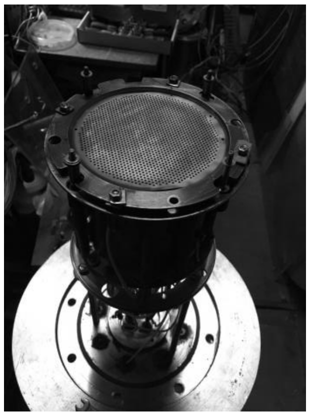

Figure 2: ID-100 ion thruster laboratory model

The perforated zone diameter of the screen grid was decreased in ~10 times in comparison with anode diameter. It allows neglecting radial distribution of ion density in the discharge chamber. Two-grid IOSs each consisting of a screen and an acceleration grid were tested in the experiment. Ion optic system parameters are presented in Table 1.

Table 1: Ion Optic System Parameters

Grid	Potential, V	Thickness, mm	Distance between centers, mm	Circular apertures	Square apertures with rounded corners	
				Aperture radius, mm	Square side, mm	Fillet radius, mm
Screen	1430	0.5	2.8	2.4	2.4	0.8
Acceleration	-200	1.0		1.7	1.7	0.5

2. Materials and Technique

The acceleration grids had been made of pyrolytic carbon. Blank electrodes had been manufactured by means of carbon deposition from gaseous media onto a heated core. Screen grids had been made of carbon-carbon composite. Holes had been cut in the blanks using a laser. Beam diameter was less than 0.3 mm. The screen grid minimal spacer thickness was limited by material properties and laser cutting mode [2].

The geometric transparency of grids with circular apertures is $Y_G = (2\pi/\sqrt{3})(r/h)^2$, where r – aperture radius, h – grid step. It equal to 0.67 for the screen grid and 0.34 for the acceleration grid. Geometric transparency for grids with square apertures with rounded corners is $Y_G = (b^2 - (4-\pi)r^2)/h^2$, where b – square side, r – fillet radius, h – grid step [1]. The transparency had been made equal to that of the grids with circular apertures. Grid steps are equal too.

Perveance range is also influenced by the accuracy of IOS assembly. When a shift of acceleration grid orifices relative to the screen grid orifices is present, the perveance range diminishes [3]. Intensity of electric field between the discharge plasma and the acceleration grid increases at decreasing the gap between the grids. It results in grows of extracted current density. The assembled ion optic system unit was photographed by optical microscope camera with subsequent image processing for measurement of non-concentricity between apertures of screen and acceleration grids (Figures 3,4). The results are given in Tables 2 and 3.

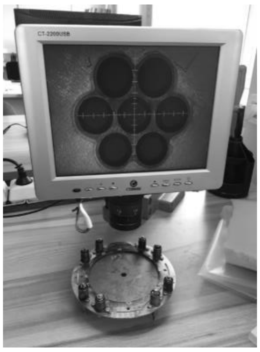

Figure 3: Photographing IOS unit with the optical microscope camera

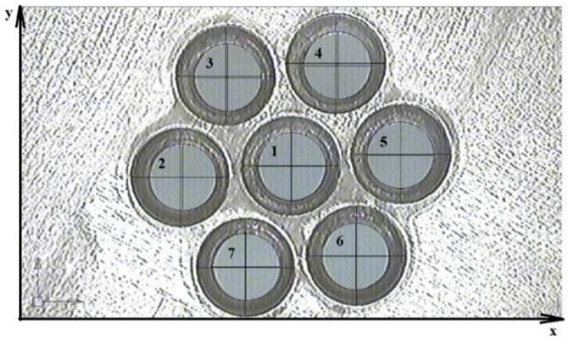

Figure 4: Image processing

Table 2: Shift of acceleration grid orifices relative to screen grid orifices in the IOS with circular apertures

Orifices	dx, mm	dy, mm	dl, mm
1	0.0221	-0.0205	0.030144
2	0.0619	0.0026	0.061955
3	0.052	-0.0348	0.06257
4	0.0469	-0.0536	0.071222
5	-0.005	-0.0249	0.025397
6	-0.0302	-0.0211	0.036841
7	0.0047	0.011	0.011962

Table 3: Shift of acceleration grid orifices relative to screen grid orifices in the IOS with square apertures with rounded corners

Orifices	dx, мм	dy, мм	dl, мм
1	0,012	0,021	0,024187
2	0,053	0,012	0,054342
3	0,053	-0,025	0,0586
4	0,032	-0,06	0,068
5	-0,011	-0,016	0,019416
6	-0,025	0,038	0,045486
7	0,012	0,027	0,029547

The inter-grid gap size was checked using the optical microscope and a micrometer with scale interval of 0.01 mm (Figure 5). In the beginning of the process the focal point of the optical microscope was being placed on the surface of the acceleration grid. Then the micrometer was being set to 0.00 mm position. Next the focal point was being moved to the surface of the screen grid. After that the acceleration grid thickness was subtracted from the micrometer readings. The measurement data is given in the Table 4.

DOI: 10.13009/EUCASS2017-139

Figure 5: Inter-grid gap measurement

Table 4: Inter-grid gap measurement results

IOS	Gap size according to 5 measurements, mm
Circular apertures	1,2 ± 0,03
Square apertures with rounded corners	1,2 ± 0,02

2. Perveance range comparison for circular apertures and square apertures with rounded corners

Range of perveance operational values for any IOS is determined by two limits. The upper value appears when the extracted current is relatively high and the IOS is unable to compress the ions into a narrow beam. It results in impacts of primary ions to the acceleration grid. The lower limit corresponds to low beam currents, at which the ions are coming to the central axis of the cell, the beam defocuses and ions reach the surface of acceleration grid. In this work an estimation is made for the normalized perveance range $P=J_i/J_o$, where J_i – ion current density in the discharge chamber, $j_o = (4\varepsilon_0/9)\sqrt{2q/M}\left(U_t^{3/2}/d^2\right)$ – normalizing current density, which is defined according to Child-Langmuir's law, ε_0 – electric permeability constant, q - charge of an ion, M – xenon atom mass, U_t – acceleration voltage, d – distance between the grids.

Beam current and acceleration grid current were measured in the course of the experiment. Since the perforated zone diameter was ~10 times less than the diameter of the discharge chamber anode, the current density in the perforated zone was considered the same. The current density on the entrance of the screen grid aperture was calculated according to the formula:

$$J_i = \frac{I_b}{\left(N_{ap} \cdot S_{ap} \cdot \sigma_{eff}\right)} \ , \qquad (1)$$

where I_b – beam current, N_{ap} – number of apertures in the screen grid, S_{ap} – aperture area, σ_{eff} – efficient transparency of the screen grid. The efficient transparency was computed using IOS 3D software [4]. Experimental data was used in the software in order to determine the efficient transparency $\sigma_{eff} = I_b/I_{dich}$, where I_{disch} – ion current at the entrance of the computational domain on the side of the gas discharge plasma. The dependencies $I_{acc}/I_b = f(P)$ for circular apertures and square apertures with rounded corners obtained from the experiments and from the calculations are given in Figures 6, 7, 8

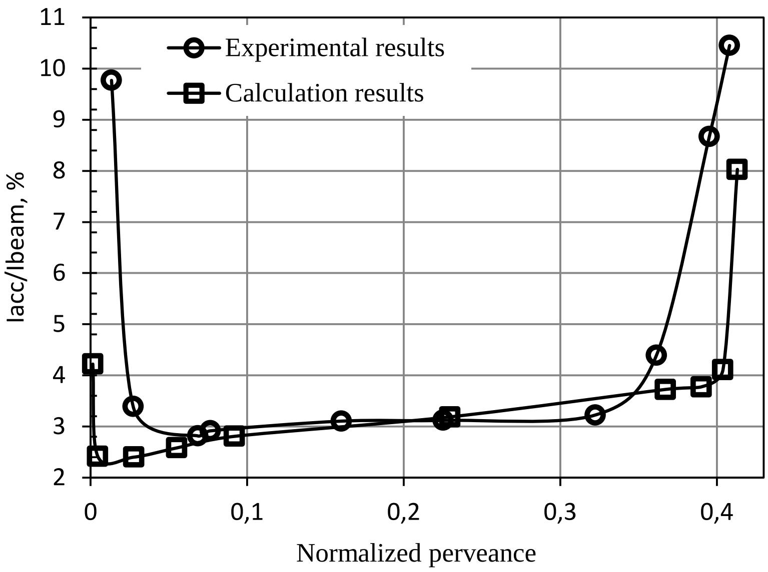

Figure 6: Comparison of experimental and calculated ranges of perveance for round apertures

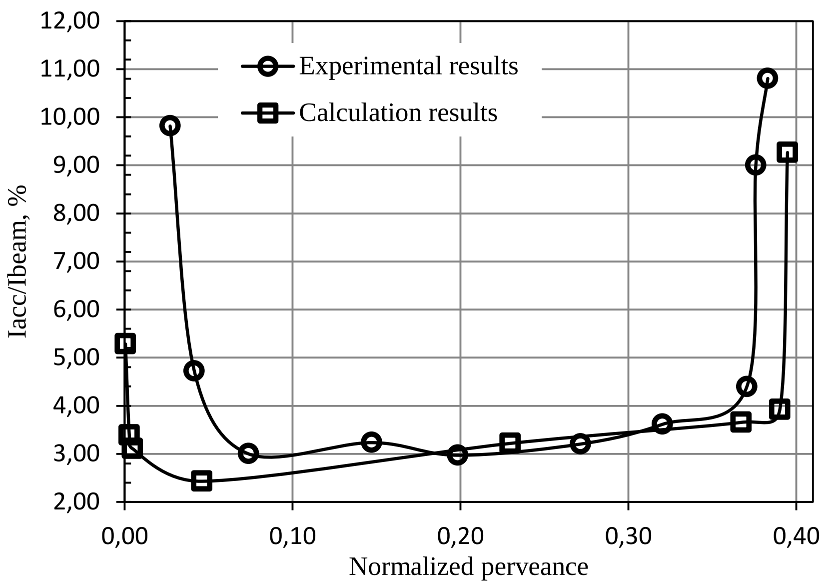

Figure 7: Comparison of experimental and calculated ranges of perveance for square apertures with rounded corners

.

DOI: 10.13009/EUCASS2017-139

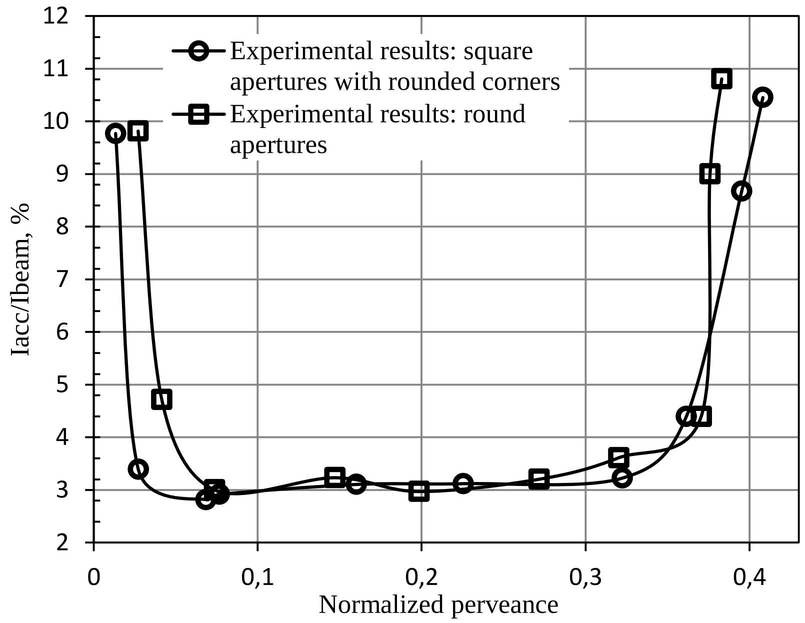

Figure 8: Comparison of experimental ranges of perveance for square apertures with rounded corners and round apertures

3.Conclusion

The obtained results demonstrate that for circular apertures and square apertures with rounded corners the experimental perveance ranges are lesser in comparison with the calculated values. Shift of the perveance ranges margin to the right at low current density may be caused by a taper in the orifices, namely, with narrowing of the orifice towards the beam plasma. Comparison of experimental ranges shows small decrease of the range for square apertures with rounded corners if compared to that of the circular. As a result, it may be concluded that utilizing grids with square apertures with rounded corners does not cause a significant decline in the range of perveance of an ion optic system. The subsequent activity will be dedicated to development of grid specimens for vibration tests in composition of an ion optic system unit.

References

[1] A. Shagayda and S. Madeev, 2016. Performance limits of ion extraction systems with non-circular apertures, Rev. Sci. Instrum. 87, 043301.

[2] S.V.Madeev, A.S.Lovtsov, I.N.Laptev, N.N.Sitnikov, 2016. Evaluation of operational characteristics of carbon\carbon composites for grids of ion engines, COMPOSITES and NANOSTRUCTURES, Volume 8, №2, p. 141–150.

[3] A. Shagayda*, V. Nikitin, D. Tomilin, 2016. Three-dimensional analysis of ion optics with misalignments of apertures, Vacuum 123, p. 140-150.

[4] A. Shagayda, 2014. “Simulation of charged particles in the ion-optical systems of ion engines (IOS-3D),” Software Package No. 2014610277.