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Improving the ion thruster scheme II. Optimization of the magnetic system

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To optimize the operation of the discharge chamber of the ion thruster, a modified configuration of the magnetic system was developed and manufactured, the distinctive feature of which is the use of a double cusp. The article describes the conditions and results of fire tests of the thruster using the developed configuration. The heterogeneity coefficient was 1,35, and the ion cost was equal to 234 W/A with a mass utilization efficiency of 91%, which shows the efficiency of the dual cusp and the developed configuration. Based on experimental data, the need to localize the magnetic field at the periphery of the discharge chamber is formulated not only to ensure high uniformity of the ion beam current density distribution, but also to ensure low ion cost.

Keywords: electric propulsion, discharge chamber, ion optics, ion beam, ion cost, mass utilization efficiency.

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Introduction

An ion thruster (IT) is among the most common types of electric rocket thrusters that are featuring indicative high values of specific impulse and lifespan. The main components of the IT include a gas discharge chamber (GDC), where plasma is formed by shock ionization of the working fluid's neutral component with electrons, an ion-optical system (IOS) that extracts ions from the plasma from GDC and generates thrust through their electrostatic acceleration, and a neutralizer that emits electrons into a beam of accelerated ions, compensating for its positive charge [1].

Nevertheless, ITs are classified mainly according to the type of GDC. This paper and the information below are focused on the GDC with the working fluid ionization in DC discharge illustrated as a part of the ion thruster schematic representation in Fig. 1. The task of increasing the efficiency parameters of this type of GDC is still relevant, which is largely due to the complexity of developing a sufficiently efficient magnetic system (MS) [1]. (MS) —is a component part of GDC that increases the residence time of charged particles in the plasma volume by reducing their mobility in the direction of some GDC surfaces [2]. MS can be made on the basis of electromagnets or permanent magnets. Further, only MS based on permanent magnets will be considered in this paper, since during their use higher efficiency parameters were achieved [3].

This paper outlines the continued investigation of dependence of ion thruster GDC parameters efficiency on the magnetic field characteristics; the previous stages of this investigation are described in papers [1,4]. The firing trials of ID-200PM thruster demonstrated that the increase in magnetic field induction in GDC was associated with an increase of the discharge voltage, as well as with lower homogeneity of the ion beam current density distribution and the ion value [1]. Evidently, as seen from [1], when one parameter was improved the other one was degraded. The reason for this was that higher closed-loop induction [1,5,6] was accompanied by an increase in the magnetic field induction modulus throughout the GDC volume, including near IOS, which resulted in lower homogeneity of the ion

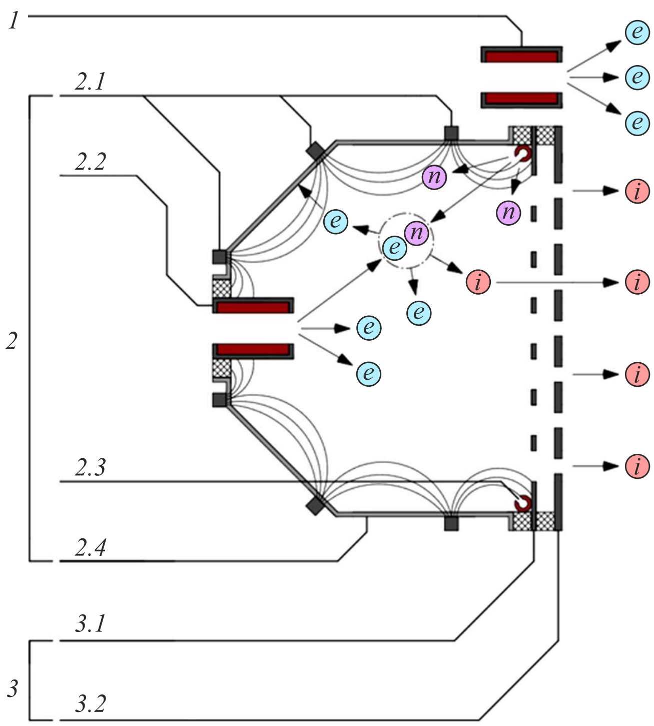

Figure 1. IT scheme: *1* — neutralizer; *2* — GDC; *2.1* — MS; *2.2* —cathode; *2.3* — anode; *2.4* — collector; *3* – IOS; *3.1* — emission electrode; *3.2* — accelerating electrode [1].

beam current density distribution. This study is focused on development of a MS configuration which, regardless of the magnitude of the closed-loop induction, will ensure a magnetic field induction modulus of less than 10 G near the IT. The developed configuration and the analogues created on its basis will have the ability to optimize the efficiency parameters independently of each other, thus, allowing to achieve their highest values.

1. MS rework methods

In terms of ensuring the lowest ion value, when developing MS, the largest closed-loop induction should be selected, in which the number of electrons required to maintain the discharge in GDC is absorbed by the anode [5,7]. From the standpoint of ensuring the greatest homogeneity of the ion beam current density distribution near IOS, the magnitude of the magnetic field induction modulus should be less than 10,G [8–10]. Since the surfaces that need to be shielded by magnetic field are adjacent almost directly to IOS, it is extremely difficult to develop an MS that fully meets both requirements and provides a sufficiently high radial gradient of the magnetic field induction modulus near IOS.

Currently, the magnetic field, which is itself a uniform arched structure, has become the most widespread, where areas with an induction modulus of more than 10 G are localized on the periphery of GDC. Such ion thrusters like XIPS-8 [11], XIPS-13 [12], XIPS-25 [13], NSTAR [5], NEXIS [6], NEXT [14], T6 [15] and etc. use various modifications of this field, since it provides a set of the highest efficiency parameters. The MS and magnetic fields of all the aforementioned thrusters are generally similar, but noticeable differences between them are present near IOS. Original technical solutions are applied to this part of the MS because homogeneity of the ion beam current density distribution depends mainly on the magnetic field in the vicinity of IOS [2,6,16]. As a rule, one of three methods is used to increase the radial gradient of the magnetic field induction modulus near IOS.

The first and most common method is to rotate the poles of a permanent magnet located near IOS [5,6,11–13]. In this case, this magnet is placed not on GDC housing, but on the flange of the emission electrode, and its magnetization axis is located at an angle of about 90° to the axis of the nearest magnet.

The second method is using a ferromagnetic flange which itself constitutes some kind of an additional pole in GDC at the boundary with IOS [1,15]. Most lines of magnetic field strength close on the flange due to its high magnetic permeability and, thus, weaken the induction modulus near IOS.

The third method is to add one or more additional permanent magnets to MS [17]. The field strength lines outgoing from the pole of one magnet are closed through the pole of another magnet, instead of extending deep into GDC. The closer the magnets are located to each other, the greater the gradient of the magnetic field induction modulus can be obtained.

A comparative assessment of efficiency of the aforesaid methods was carried out by their alternate application to the same GDC, while the rest of MS of which remained unchanged. The results of defining the magnetic field induction modulus in GDC are given in Fig. 2. The induction modulus magnitude near IOS —an area highlighted in Fig. 2 by a dashed line — was taken as a criterion for comparison. The larger the part of a given area where induction modulus was less than 10 G, the more effective was the method used. Since the rest of MS shall also be modified for the most effective use of each method, the comparison is more like a matter of judgment.

By estimating the computation results we see that the most effective method of increasing the radial gradient of the magnetic field induction modulus near IOS is the use of a double pole. Pole rotation is less efficient, but it also has a significant effect on the distribution of the induction modulus. In contrast to the two methods described above, when using a ferromagnetic flange the initial distribution of the induction modulus corresponding to the basic MS remains virtually unchanged.

2. Item under test

The prototype of IT-200PM thruster shown in Fig. 3 was tested in this study. This thruster was developed on the basis of the ID-200KR and has a power of 3 kW [4].

IOS of ID-200PM consists of emission and accelerating electrodes made of carbon-carbon composite material having a flat shape and a diameter of the perforated area 200 mm. Transparency of IOS of ID-200PM for neutral atoms is 17%. The calculated effective transparency of IOS for xenon ions during firing trials was about 63%. The GDC cathode and the thrust neutralizer are hollow cathodes with emitters made of porous tungsten impregnated with barium compounds. The GDC housing consisting of cylindrical and conical parts is used as an anode in ID-200PM. The diameter of the housing is 240 nm. The main part of the flow of the working fluid is supplied to GDC through a collector located near IOS, in addition, a fixed flow value enters the chamber through the cathode [1].

The MS configuration studied in this paper (hereinafter referred to as the D Configuration) was developed on the basis of the dual pole and configurations described earlier in paper [1]. At that, the ferromagnetic flange has also remained within MS. Its exclusion would require a redesign of the ion thruster, but, as shown above, it would not have any essential effect on distribution of the magnetic field induction modulus in GDC. Among the main objectives of Configuration D were an experimental study of the effectiveness of the dual pole and a demonstration of a possibility of creating MS configuration that meets the requirements set out in the abstract of this paper.

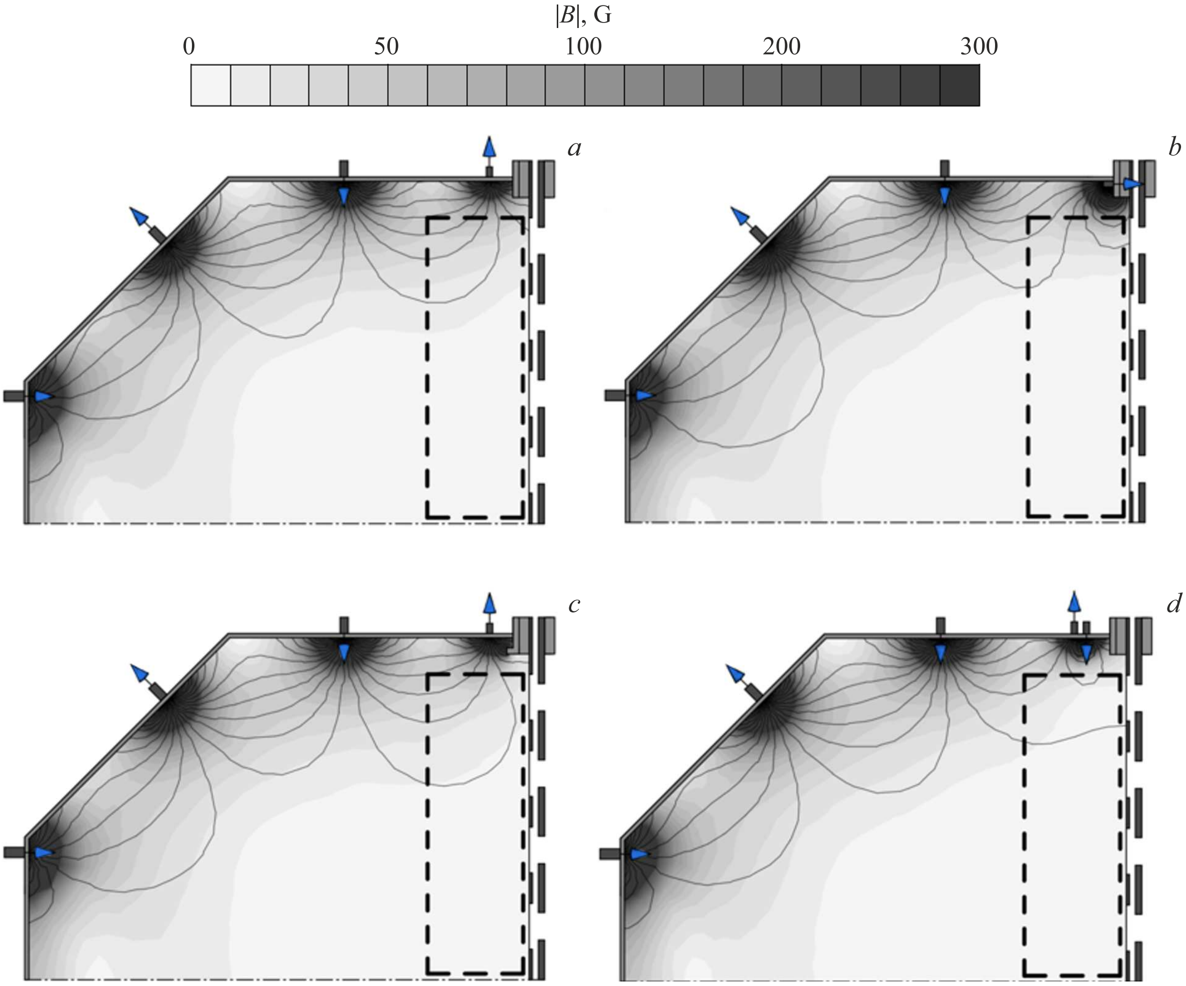

Figure 2. Distributions of magnetic field induction modulus $|B|$ in GDC when using methods of increasing the radial gradient of magnetic field induction modulus near IOS: *a* — basic MS; *b* — pole rotation; *c* — ferromagnetic flange; *d* — doubled pole.

Figure 3. Appearance of prototype of ID-200PM [1].

Distribution of the magnetic field induction modulus in GDC of ID-200PM corresponding to Configuration D is shown in Fig. 4. Configuration D provides induction of

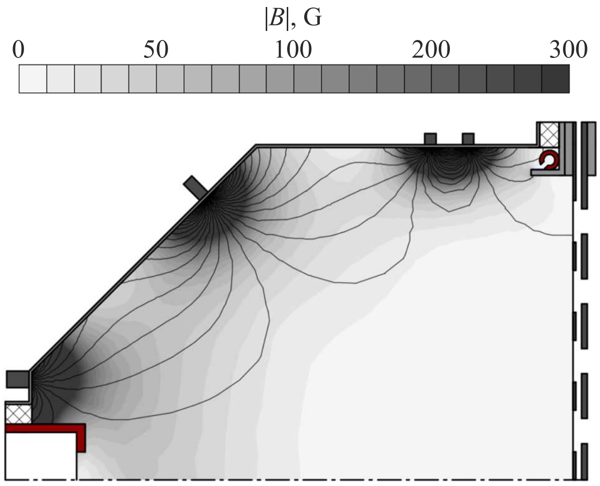

Figure 4. Distribution of the magnetic field induction modulus $|B|$ in GDC of ID-200PM corresponding to D Configuration.

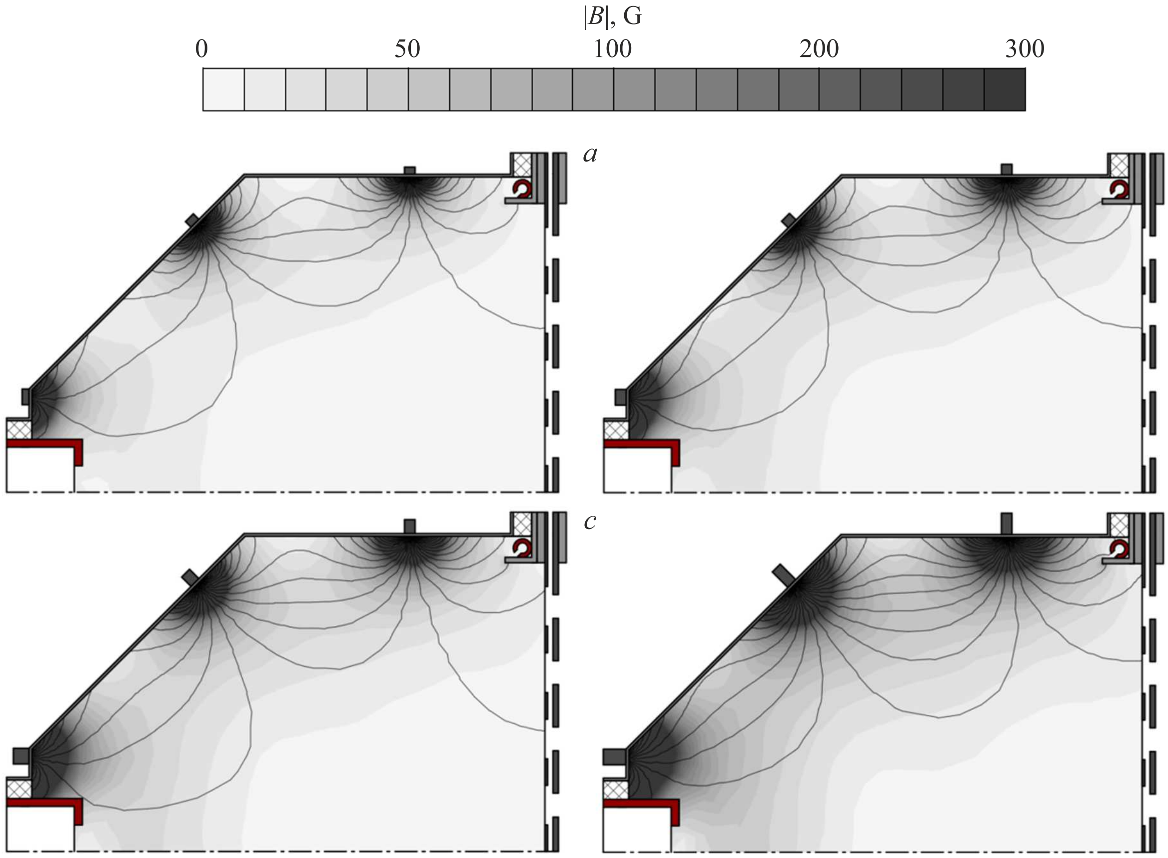

Figure 5. Distributions of the magnetic field induction modulus $|B|$ in ID-200PM GDC corresponding to the studied MS configurations: *a* — Configuration 1; *b* — Configuration 2; *c* — Configuration 3; *d* — Configuration 4 [1].

the closed-loop for the cylindrical and conical parts of the housing 30 and 50 G respectively. The differences in induction between the parts of the housing are due to the fact that the double pole has a high gradient of the induction modulus compared to a conventional permanent magnet, and its use required to strengthen the rest of MS. The induction values were selected based on the results of [1], where the lowest ion values were achieved with closed-loop induction of more than 30 G.

Tests for this study were performed using the test bench of „Keldysh Research Center" KVU-90, designed for testing electric rocket thrusters. An ion thruster control system with two stabilization circuits was used during testing: the first circuit maintained the ion beam current at 1.25 A by regulating the discharge current, the second circuit maintained the discharge voltage at a predetermined level by regulating the flow of the working fluid into the collector. The potentials of the emission and accelerating electrodes were 2000 V and −300 V, respectively. The support current of the GDC cathode was zero, the support current of the neutralizer was 1 A. Xenon was used as the working fluid. The pressure in the vacuum chamber did not exceed $5.0 \cdot 10^{-3}$ Pa [1].

During the tests, measurements of the discharge voltage and three main parameters characterizing the GDC efficiency of the ion thruster were carried out: ion value, gas efficiency, and homogeneity of the ion beam current density distribution, which was estimated using heterogeneity coefficient equal to the ratio of the highest current density to the average area of IOS. The methodology used in this study for testing and calculating efficiency parameters is identical to the one presented in the paper [1]. The efficiency parameters of the developed MS configuration was estimated by comparing them with configurations previously tested in the framework of [1]. The distributions of the magnetic field induction modulus in GDC of ID-200PM thruster corresponding to the developed configurations are shown in Fig. 5, *a, b, d*.

3. Test results

To simplify the comparative evaluation, the test results of the Configuration D studied in this paper are supplemented by the test results of the MS configurations studied earlier in [1]. Figure 6 shows the efficiency curves for the flow of the working fluid into the cathode 0.3, 0.35, 0.4 and 0.45 mg/s, respectively. The intervals of change of the discharge voltages, ensuring the range of gas efficiency from 75 to 95% are listed in the Table. The ion beam current

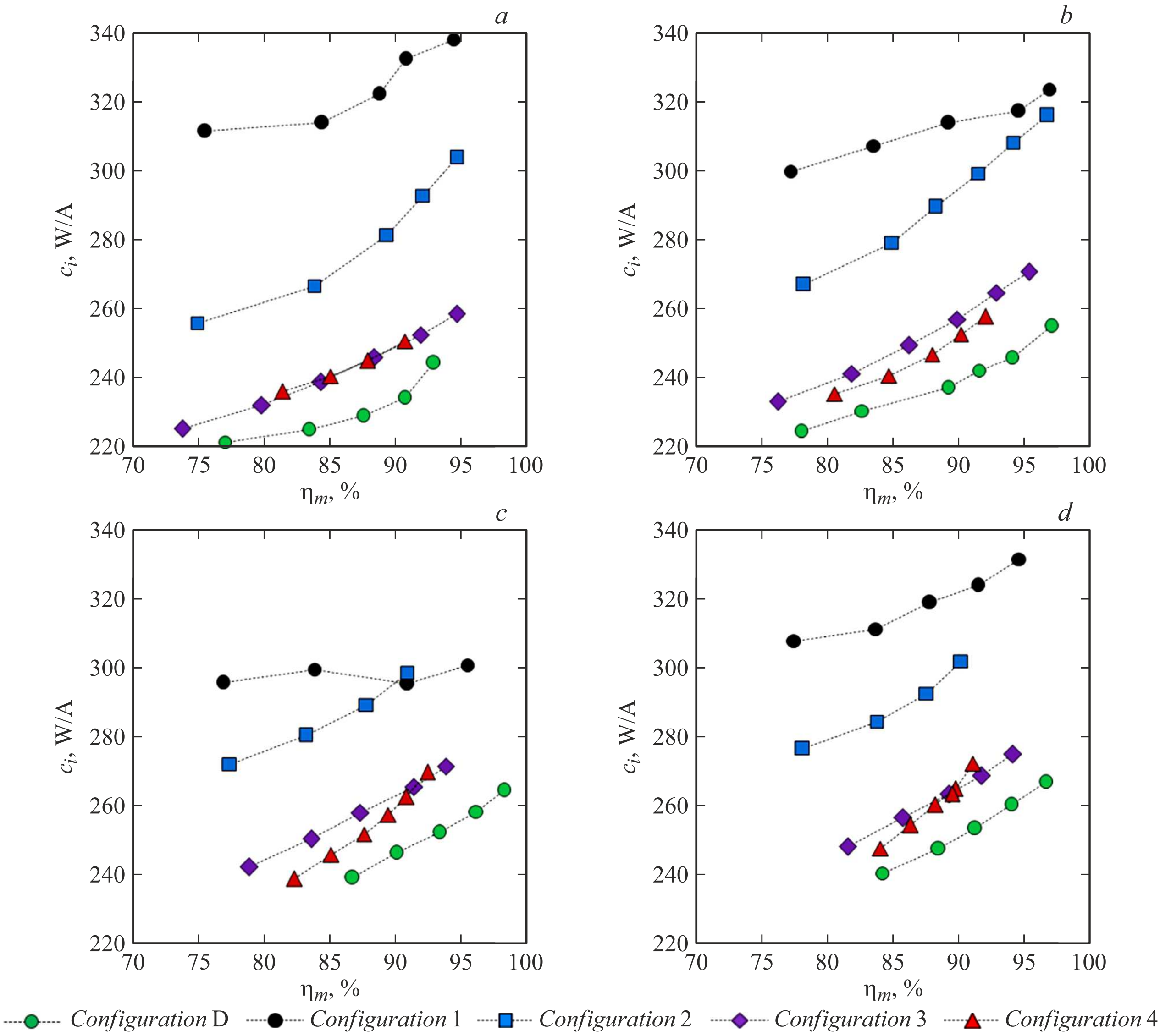

Figure 6. Dependences of the value of ion c_i on gas efficiency η_m (efficiency curves) for the studied MS configurations at working fluid flow in the cathode: a — 0.3; b — 0.35; c — 0.4; d — 0.45 mg/s.

density distribution in radial direction is illustrated as measurement results in Fig 7. The inhomogeneity coefficients corresponding to the obtained radial distributions of the ion beam current density are also listed in the Table.

4. Discussion of findings

The measurements showed that when using the D configuration, the ID-200PM thruster achieves the highest homogeneity of the ion beam current density distribution. Among the previously studied MS configurations, a similar distribution was obtained using the 1 Configuration. The D Configuration and Configuration 1 are different both, by the magnitude of the closed-loop induction and by the topology of the magnetic field. The configurations are similar in the magnitude of the induction modulus near IOS, which for both is less than 10 G in almost the entire region. Thus, the obtained result is consistent with the statement made earlier in this paper that it is magnetic field near IOS that the homogeneity of the ion beam current density distribution mainly depends on.

Since Configuration D has one pole more than the others, it was expected that it would correspond to slightly higher surface losses of charged particles, and, as a result, the ion value in comparison with the configurations 3 and 4 [3,18]. Despite this, according to the test results, when using the D Configuration, the ion value was in average by 10 W/A lower than when using the above-mentioned MS configurations.

Apart from the double pole, the most noticeable difference of Configuration D from Configuration 3 and Configuration 4 is the volume of GDC region in which the magnetic field induction modulus is less than 10 G. The volume of this region when using Configuration D is 1.5 times higher than when using Configuration 3 and almost 3 times higher than when using Configuration 4. It is most likely that the result obtained during the ion value measurement tests is related specifically to this difference.

In accordance with the 0-dimensional numerical model of GDC presented in [19], the ionization rate, i.e. the number of ions formed in GDC per unit time I_g, is calculated by the formula

$$I_g = n_e \cdot n_n \cdot (\sigma_i \cdot \upsilon_e) \cdot V + n_p \cdot n_n \cdot (\sigma_i \cdot \upsilon_p) \cdot V, \qquad (1)$$

where n_n — concentration of neutral component of the working fluid, [m^{-3}]; n_p — concentration of primary electrons, [m^{-3}]; n_e — concentration of secondary electrons, [m^{-3}]; σ_i — cross-section of ionization of the working fluid neutral component averaged in electrons energies distribution [m^2]; υ_p — average velocity of primary electrons, [m/s]; υ_e — average velocity of secondary electrons, [m/s]; V — plasma volume, [m^3].

Based on the results of probe diagnostics and numerical modeling, the plasma volume V in formula (1) is primarily determined not by the volume of GDC, but by magnetic field, since concentration of charged particles at the periphery is significantly lower than in the center of GDC [14,20–22]. The stronger is the magnetic field localized on the periphery of GDC, the larger is the chamber volume occupied by plasma. According to formula (1), it is possible that with a decrease in plasma volume, the concentration of electrons would increase inversely, and the rate of ionization would remain unchanged. However, studies show that in areas with the highest concentration of charged particles, there is a significant decrease in concentration of the neutral component of the working fluid due to the high rate of ionization [14,22–24]. In this case, a GDC with a smaller plasma volume will require either a higher consumption of the working fluid or more electron energy to create the required number of ions, which, in any case, will adversely affect the efficiency curve. Thus, an increase in the volume of GDC, in which the magnetic field induction modulus is less than 10 G, will be accompanied by an increase in the ionization rate and a decrease in the ion value. In addition, excessive electron retention in the center of GDC is accompanied by an increase in the number of double-charged ions, which will also lead to higher ion value, since it requires significantly more energy to create a double-charged ion than to create a single-charged one [5,16,22,25].

Since with Configuration D the ID-200PM achieved the highest efficiency parameters both collectively and individually, the superiority of this configuration over the others is obvious. Due to the fact that the only distinguishing feature of Configuration D is the presence of a double pole, the high efficiency of this method of increasing the radial gradient of the magnetic field induction modulus near IOS is also evident. At the same time, the permanent magnets

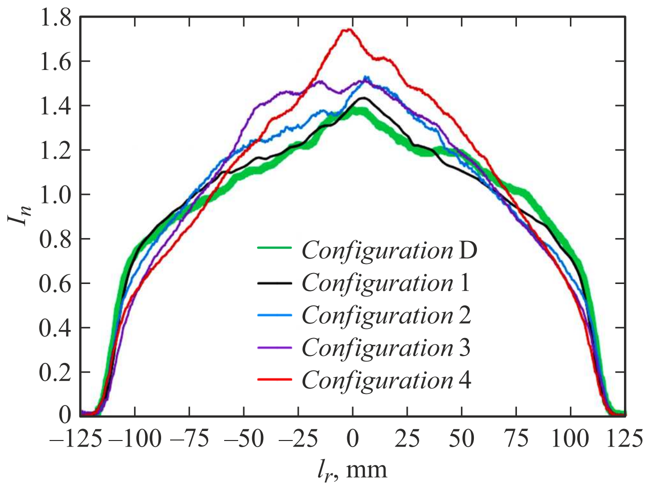

Figure 7. Normalized current to probe I_n versus distance from IT axis l_r for the studied configurations of MS.

forming a double pole in Configuration D are located at a relatively large distance from each other, which is related to limitations of GDC ID-200PM design. In the future, convergence of magnets can provide a higher radial gradient of the magnetic field induction modulus, and, accordingly, a slightly higher homogeneity of the ion beam current density distribution. In addition, since, apparently, a double pole can provide constant uniformity regardless of the magnitude of the closed-loop induction, configurations based on it are likely to be able to optimize efficiency parameters independently of each other.

One of the priority goals of subsequent research is to further improve the parameters of IT efficiency. Taking into account the accumulated theoretical and experimental groundwork, the simplest way to enhance efficiency is not to continue improving the MS, but to modernize the used GDC scheme. Probably, combining the poles of charged particle retention using the magnetic mirror effect and electrostatic retention would reduce the ratio of surface losses of primary electrons to surface losses of secondary electrons, and, accordingly, the ion value.

Conclusion

The paper outlines the findings of studies of the efficiency parameters of an IT with a modified MS configuration developed on the basis of a double pole — the most effective method for increasing the radial gradient of the magnetic field induction modulus near IOS. Firing trials of various MS configurations of the IT GDC constitute the main part of the study. The experimental prototype of ID-200PM thruster was tested in this study. The efficiency parameters of the developed MS configuration was estimated by comparing them with configurations previously tested in the framework of [1]. The MS configurations were compared based on the discharge voltage and three main parameters characterizing the efficiency of the IT GDC: ion value, gas efficiency and homogeneity of the ion beam current density distribution.

With the modified MS configuration ID-200PM thruster demonstrated the highest efficiency parameters during the tests. The inhomogeneity coefficient was 1.35, and the ion value reached 234 W/A under gas efficiency of 91%, which indicates that the double pole and the developed configuration in whole are efficient. Based on experimental data, the list of criteria previously used in the design of MS GDC has been supplemented. The necessity of the magnetic field localizing at the periphery of the gas discharge chamber is formulated, not only in terms of ensuring high homogeneity of the ion beam current density distribution, but also for the purpose of ensuring low ion value.

One of the priority goals of further research is to combine the poles of charged particles retention using the magnetic mirror effect and electrostatic retention, which is likely to reduce the value of the ion.

Conflict of interest

The authors declare that they have no conflict of interest

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