New Generation of SPT-100

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Abstract: **The paper presents the results of the works carried out in EDB "Fakel" on SPT-100B thruster upgrading. Two developmental prototypes of the upgraded thruster (SPT-100M) were developed and tested. Their design used at least 85 % of SPT-100B units and parts. In the operating mode with discharge voltage of 300, at discharge current of 4.5 A, SPT-100M, thrust was 88…91 mN at a specific impulse of 1680…1710 s, which is by 6…8 % higher than the corresponding parameters of SPT-100B. SPT-100M plume divergence semi-angle – 30°. The possibilities of improving SPT-100M life time characteristics were investigated. The thruster life expectancy is at least 10 000 hours with the number of firings being at least 14 000.**

Nomenclature

Id	=	discharge current
Ud	=	discharge voltage
Nd	=	discharge power
F	=	thrust
Psp	=	specific impulse
B	=	magnetic field induction
Br max	=	maximum radial induction values in the centerline of channel
Ji	=	ion current

I. Introduction

At present, the most significant success in Russia was achieved in development and practical application of electric propulsion systems (EPS) on the basis of stationary plasma thrusters (SPT) designed in EDB "Fakel". SPT is a source of accelerated flow of the plasma generated and accelerated in the discharge burning in crossed electric and magnetic fields. A relative simplicity of the EP design, its power supply and control systems, as well as the thruster high thrust characteristics make SPT competitive with other EPs, both at spacecrafts (SC) maneuvering in the near-earth space and for interplanetary flights.

SPT-100 is one of the best in terms of the output characteristics, reliability and the degree of flight testing, stationary plasma thruster. The first spacecraft with such a thruster was launched in 1994. Since 1995, it has been successfully used in the correction system of downlink synchronistic SCs of "Gals", "Express", "Express-A", "Express AM", Sesat and other types developed by RIAME, LLC "ISS" named after academician Reshetnev (the

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town of Zheleznogorsk). Since 2003, thruster SPT-100 (SPT-100B) has been applied in foreign synchronistic SCs of Inmarsat, Intelsat-X, IPSTAR-II, Telstar-8 and other types for the purpose of bringing SC to the operating point, stabilizing its position in that point, changing the operating point, if necessary, and removal from the operation point once the operation is over. By now, more than 200 thrusters aboard 18 Russian and 14 foreign SCs have been in operation. It is due to its efficiency and rather a high reliability that SPT-100 is so popular.

SPT-100B thruster has significant regulating range margins, both in terms of power and discharge voltage[1] which enabled improvement of both thrust power and life time characteristics of the thruster.

Upgrading of SPT-100B was carried out in the following directions:

1. Computation and experimental works on optimizing the magnetic system with the aim of improving the thrust and specific parameters.
2. Development, manufacturing and testing (determination of thrust, specific and plume parameters) of upgraded thruster (SPT-100M) developmental prototypes.
3. Determination of life time improvement possibility.

II. Upgrading of SPT-100B Thruster Magnetic System

SPT thrust, specific and life time characteristics are known to be primarily determined by the parameters and configuration of the magnetic field.

SPT-100 was designed in the late 80's – early 90's on the basis of those times' ideas of the operating processes in the thruster[2, 3, 4].

During the upgrading, the modern vision of the magnetic field optimal parameters and configuration[5, 6], as well as the experience of EDB "Fakel" in SPT-type thrusters development were taken into account.

The basic philosophy used for determining the field optimality was the "plasma lens" philosophy, its main idea consisting in shaping a special "focusing" field configuration with a larger positive gradient of the magnetic field. Such a configuration allows for the necessary ions focusing with their minimum on the discharge chamber walls. Thus a higher propellant utilization factor is achieved and thruster efficiency factor is increased.

In terms of life time characteristics, the field optimality was determined by the position of the maximum radial induction values Br max in the centerline of channel, and the position of the area boundary of (0.5-0.8) Br max.

With this in mind, the main objectives of the magnetic system upgrading were the following:

1. creating a more focusing configuration of the magnetic lens with a larger magnetic field gradient;
2. ensuring a higher offset of the magnetic induction maximum position beyond the acceleration channel cut;
3. shaping the magnetic saturation margins of the structure with the aim of ensuring thruster functioning in a number of modes including those with a high specific propulsion impulse.

The parameters and configuration of SPT-100B and the variants of its improvement were analyzed by computation and experiment.

A number of magnetic system design options were studied, and magnetic field parameters were calculated for them (such as induction distribution among the magnetic systems elements, magnetic field induction distribution along the discharge chamber channel). Field configurations in the discharge chamber channel (magnetic lens shapes) were calculated.

The computations were carried out using of 3D modeling of one fourth of the magnetic system (Figure 1) due to the symmetry of the structure in EMAG module of application package NISA/DISPLAY Version 17[7].

On the basis of the computations results, the magnetic system configuration variant meeting the requirement mentioned in the upgrading objectives was selected.

The configurations of the magnetic field lines of the basic SPT-100B model and the upgraded SPT-100M model are shown in Figure 2. Figure 2 shows that SPT-100M magnetic field lines have a larger curvature, which is indicative of an improved focusing force of the lens. Magnetic lens SPT-100M is shifted towards the DC output and is shorter, which means an increased magnetic field gradient in the channel.

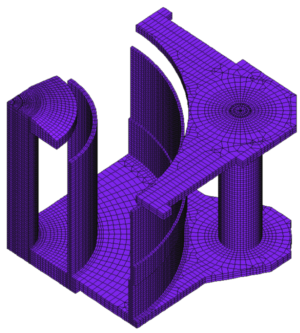


Figure 1. Computed model of SPT-100M magnetic system

Distribution of the design values with radial induction along the centre of the discharge channel for SPT-100B and SPT-100M is shown in Figure 3. Compared with SPT-100B, in SPT-100M, the position of magnetic field radial component maximum is shifted by about 1 mm towards the channel output.

Position (0.5–0.8) Br max for SPT-100M is shifted by about 2 mm. A large position offset of Br max and (0.5–0.8) Br max towards the channel output is likely to improve the life time of the thruster discharge chamber isolator.

Induction around the anode position of SPT-100M is lower compared with that of SPT-100B. The magnetic field gradient has been increased, which is likely to improve focusing of the ion flow from the thruster.

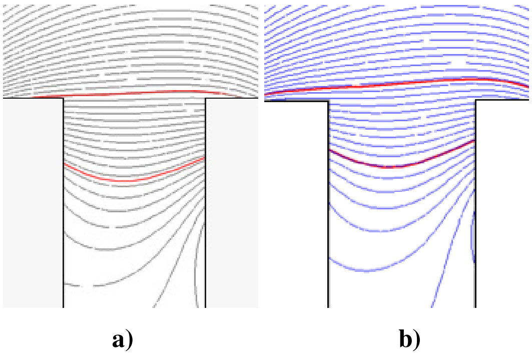


Figure 2. Field lines configuration in the thruster channel: a) SPT-100B, b) SPT-100M

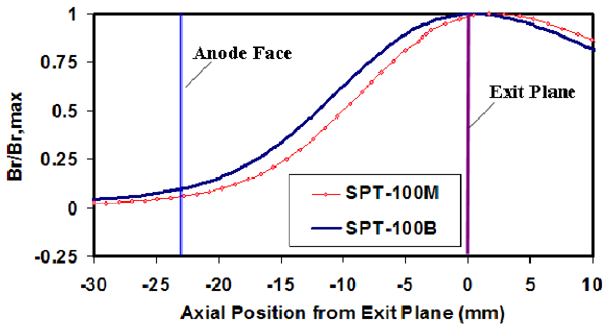


Figure 3. Normalized radial magnetic fields on centerline for the SPT-100B and SPT-100M

Figure 4 presents the diagrams of magnetic field distribution in the channel of SPT-100M.

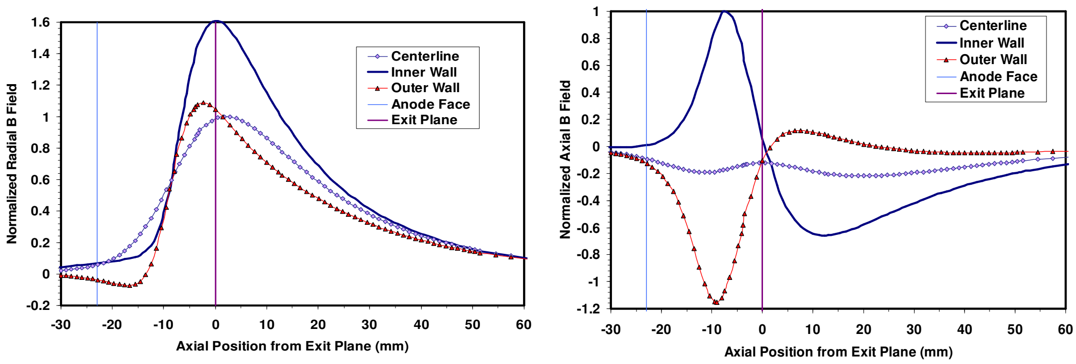


Figure 4. Normalized magnetic fields in the SPT-100M. The radial fields are normalized with the peak centerline value. The axial fields are normalized by the magnitude of the peak field on the inner wall

The induction along the discharge chamber channel centerline is minimum, and it increases closer to the channel chamber. Such a configuration shapes a so called “magnetic bottle” which limits the speed of electrons drift towards the anode, thus ensuring a higher degree of propellant ionization.

III. The Results of SPT-100M Prototypes Parameters Studies and of Works on Improvement of its Characteristics

A. Description of the prototypes used in the studies

In order to check the parameters of upgraded SPT-100M thruster, two developmental prototypes were designed and manufactured. In the both thruster prototypes, the configuration of the magnetic system was in accordance with the variant selected. The number of turns in the coils and their ration allowed for including the magnetic coils into the discharge circuit when the thrusters are working in the mode with the discharge current of 4.5 A and discharge voltage of 300 V. There was a possibility of connecting an outer source of coils power supply in order to optimize the current in them with the operation at other discharge modes.

At least 85 % of the previously qualified units and technologies used at production of SPT-100B thruster are used in the both prototypes.

The general view of the first prototype (SPT-100M EM1) is shown in Figure 5. This prototype was used for preliminary parameters check of the thruster with an upgraded magnetic system, during the tests aimed at selection of new materials for discharge chambers isolators and during tests aimed at optimization of the cathode compensator position in the new configuration of the magnetic system.

The second prototype (SPT-100M EM2 thruster) differed from SPT-100M EM1 in mechanic and thermal interface and the external pole shape. This prototype was used for checking the parameters in an expanded working range during tests aimed at determination of the plume parameters and during the tests aimed at determination of the thruster units thermal modes.

All the tests of the both developmental prototypes SPT-100M were carried out at the stands of EDB “Fakel”.

The tests aimed at determination of the thrust and specific parameters were carried out using a stand equipped with a cryogenic pumping system. The capacity of the pumping system allowed for a maximum pressure in the vacuum chamber of $1.1 * 10^{-4}$ mm hg (by air) at tests with a total flow to the thruster of 5.3 mg/s. The thruster thrust and xenon flow were measured with a maximum error of 2.5 %. Prior to the start of the tests, the thrust and flow meters were additionally calibrated.

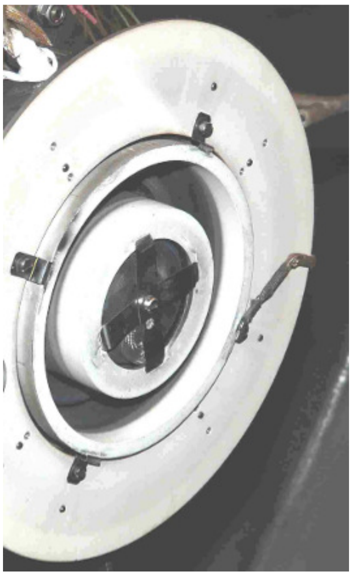


Figure 5. SPT-100M EM1 thruster general view

For plume parameters determination, the equipment previously applied at SPT-100B[8] thruster qualification was used.

B. The results of the tests aimed at determination of the thrust and specific parameters

The tests aimed at determination of the thrust and specific parameters of the both SPT-100M prototypes involve the operation of the thruster in a wide range of discharge currents and voltages at the discharge power from 400 to 1800 W.

As the control points for determining the efficiency of SPT-100B thruster upgrading, the parameters of the models were used, which had been obtained at operation in the nominal mode of SPT-100B thruster with a discharge power of 1350 W (a discharge current of 4.5 A at a discharge voltage of 300 V) and in the mode close to the nominal working mode of PPS-1350 thruster with a discharge power of 1500 W (discharge current of 4.25 A at a discharge voltage of 350 V).

The results of SPT-100M EM2 thruster tests with the working points parameters are given in Table 1. To facilitate the comparison, the table also provides the parameters of SPT-100B and PPS-1350 thrusters nominal modes.

The thruster tests results for other current values at discharge voltages of 300 and 350 V, in particular, for the working mode with a discharge voltage of 660 W are provided in Table 2.

Table 1. SPT-100M EM2 parameters at the test points

Mode		Thruster	Parameters	
Id, A	Ud, V		F, mN	Psp, sec
4,5	300	**SPT-100M**	**90,2**	**1734**
		SPT-100B	83	1600
4.25	350	**SPT-100M**	**93.3**	**1865**
4.28		PPS-1350	88	1720

Table 2. SPT-100M EM2 parameters within the regulating range

Mode			Parameters	
Id, A	Ud, V	Nd, Watt	F, mN	Psp, sec
4,5	350	1575	98,8	1876
4	350	1400	87,8	1850
2,2	300	660	43,4	1520

At the tests of the both thrusters prototypes, engineering model XFC was used for supplying the propellant. Therefore, the values of the specific impulse are provided in the tables with due consideration of the total flow to the thruster.

A comparative analysis of SPT-100B and PPS-1350 parameters versus SPT-100M EM2 parameters at the control points shows that the thrust and specific impulse values of the upgraded SPT-100M EM2 are higher by 6…8 %.

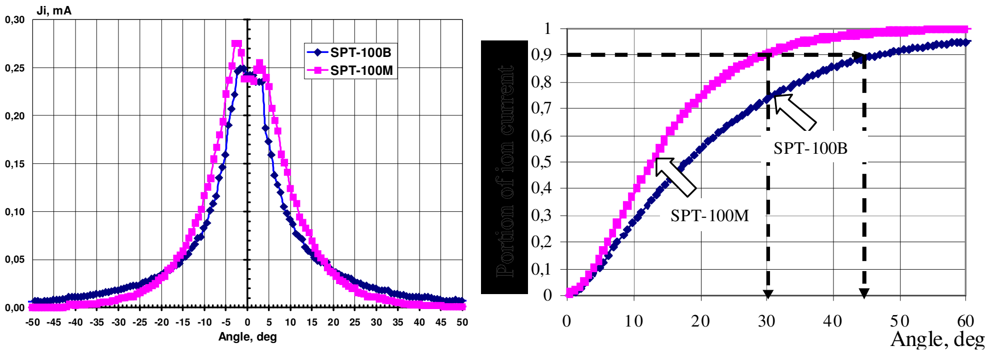
C. Plume Parameters Study Results

The configuration of plasma plume of SPT-100M EM1 and SPT-100M EM2 thruster is more compact compared with SPT-100B plume. The general views of operating SPT-100M EM1 and SPT-100M EM2 thrusters operation are shown in Figures 6 (a) and 6 (b) respectively.

a) **b)**

Figure 6. SPT-100M EM1 (a) and SPT-100M EM2 (b) in operation

For the purpose of correct comparison of SPT-100M EM2 and SPT-100B plumes, a series of plume parameters tests were carried out for SPT-100M EM2 thruster and one of SPT-100B thruster prototypes. The both thrusters were working with a discharge current of 4.5 A at a discharge voltage of 300 V. The plume parameters were carried out with use of an energy analyzer probe. The energy analyzer probe was located at a radius of 1.11 mm relative to the line passing through the intersection of the thruster longitudinal axis with the discharge chamber cut. The probe was isolated from the thruster and all the reference voltages were supplied relative to the ground. For cutting off electrons, a negative potential of 20 V was supplied to the probe first mesh. For cutting off thermal ions, a positive potential of 20 V was supplied to the collector. As the probe was moved, the ion current distribution changed. The results of ion current distribution changes were used for determining the plume divergence semi-angle for the both thrusters. The ion current distribution for the both thrusters is shown in Figure 7 a), where the reference for the angle is the thruster longitudinal axis. The result of the numeric integration of the ion current values over the spherical surface is shown in Figure 7 b).



a) **b)**

Figure 7. The distribution of the ion current and the total ion current value in the plumes of SPT-100M EM2 and SPT-100

Considered as the plume divergence criterion was the half of the space angle, into which falls 90 % of the ion current.

The comparison of the measurement results for ion current distribution of the thrusters shows that the plume central area (up to 20° from the thruster axis) of SPT-100M EM2 is much larger compared with the same area of SPT-100B thruster. This result shows that the plume divergence of SPT-100M EM2 is much less than that of SPT-100B. This conclusion is also confirmed by the results of the divergence angle numeric computation: the divergence semi-angle (90 % of ion current) for the plume of SPT-100M EM2 thruster is 30º, and for that of SPT-100B thruster – 45º.

D. Studies of life time Improvement Possibilities

The life time of SPT-100B thruster is confirmed at a number of thrusters prototypes[9, 10, 11]. The longest operating time for SPT-100B is currently 9066 hours, the total impulse produced being 2.67 kN s.

For further durability improvement of SPT-100B thruster, a series of studies of new materials for discharge chambers isolators has been carried out. The erosion resistance of one of the materials is at least 1.3 times as high as that of BGP-10 used at present in SPT-100B. With due consideration of the erosion tests results, the lifetime expectancy for the thruster is at least 10 000 hours with production of the total impulse of at least 3000 kN·s.

Also, studies were carried out in order to optimize the cathode compensator position relative to the new magnetic system configuration of SPT-100M thruster. When selecting the location of the cathode compensator, the results of 3D modeling of the thruster magnetic field periphery, as well as the results of thrusters life tests were used. In the position selected for SPT-100M, the plasma plume effect on the cathode compensator structure is minimized. The results of the computation and experimental studies have shown that, with the cathode optimized position, the sputter rate of its ignition electrode will be 5 times less than that in SPT-100B thruster.

In order to increase the firing number margins, a cyclogram of cathode pre-firing preparation was tried, which decreased the effect of thermal shocks which occur at the incandescence power supply to the cathode on the cathode structure. This cyclorgram was used for testing two cathode compensator prototypes. At each of them (integrated in the thruster), 14 000 firings 5 s long and 14 000 heating modes with a pause of 15 min were performed.

IV. The Results Discussion

Plume divergence is one of the limiting factors limiting SPT configuration at a spacecraft (SC). The peripheral part of the plume can spray SC structural elements and solar cells. Plume divergence semi-angle for SPT-100B was 45º. For that reason, SPT-100B thrusters intended for correction by the "north-south" direction are generally located on SC at an angle of 45º (Figure 8). As a result, the effective thrust and specific impulse are decreased $\sqrt{2}$ times, and, consequently, the thruster operation duration is increased. Correspondingly, the thrust efficiency factor is decreased approximately 2 times.

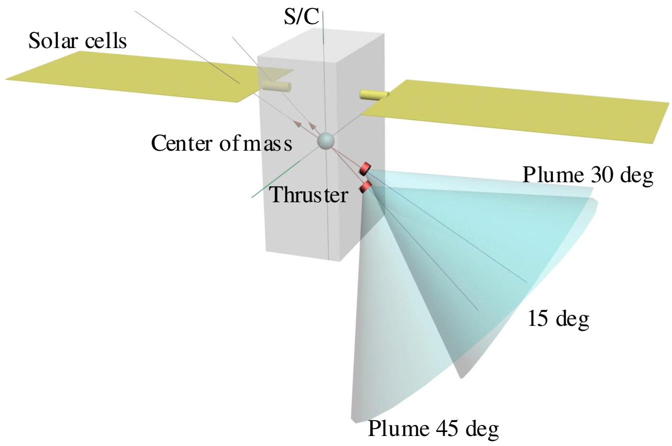


Figure 8. A Diagram of the Thruster Configuration on Board the SC

The plume divergence semi-angle for SPT-100M is 30º. A smaller plume divergence assembly of SPT-100M will allow for a better configuration of the thruster aboard the SC – it will be possible to install it at a smaller angle, which will significantly increase its application efficiency. SPT-100M installation at an angle of 30º, the efficient thrust and specific impulse are increased by 20 %.

If we take into consideration even higher parameters (by 6–8 %) of an upgraded thruster, its thrust and specific impulse at SC will be increased by ~ 30 % compared with SPT-100B. At the same time, the thruster operation duration will be decreased by one third.

V. Conclusions

In EDB “Fakel”, a developmental prototype of a new generation thruster SPT-100 has been developed, which ensures an increase of integral parameters by 6–8 % at a power of 1350 W and a discharge voltage of 300 V, with the plume divergence semi-angle decreased down to 30º.

The results will be implemented in a QM level model, which is planned to be designed and qualified in future.

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