Characteristic Relationship between Dimensions and Parameters of a Hybrid Plasma Thruster

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Abstract: Research results on selection and optimization of the Hybrid Plasma Thruster (HybridPT) accelerator channel are presented here. Basic characteristic relationships between the ion formation area dimensions and optimum parameters of the operation modes of the new model of HybridPT, which can be considered as basic ones for creating a parametric series of the thruster of the given type, are stated.

Nomenclature

b_k = width of the discharge chamber;
L_k = length of the discharge chamber;
b_{no} = width of the beam in the accelerator area;
L_B = half-width of the B, magnetic field induction, distribution from the side of the discharge chamber to the section where B = Brmax;
b_a = width of the discharge chamber at the anode;
L_A = distance between the anode and the area of ionization and acceleration.

I. Introduction

Nowadays, two types of the plasma thrusters are well-known: Stationary Plasma Thruster (SPT) and Thruster with Anode Layer) TAL. In the early 90s, in order to increase efficiency of Electric Propulsion (EP), as well as to increase specific parameters and characteristics of the advanced EP, new constructive schemes were suggested[1] and approved. Plasma thrusters, which combine features and advantages of the known SPT и TAL, which, thus, are of a hybrid type, allow achieving of high levels of specific thrust impulse close to the ones of the ion thruster parameters.

Regarding the said direction, in the Experimental Design Bureau Fakel (EDB Fakel) (Kaliningrad, Russia), in 1999, on the base of modernized components of SPT-100 of 1350 W capacity and PPS 1350R of 1500 capacity thrusters, in cooperation with Atlantic Research Corporation (ARC, USA), in order to apply for the tender on creation of high impulse EP of 2.3 kW organized by NASA (USA), experimental model of high-voltage thruster SPT-1 was developed, where constructive scheme of HybridPT was implemented. Its constructive scheme features consist in high length of the metal part of the Acceleration Channel (AC) in relation to the ceramic one and configuration of the dielectric rings in their walls parts faced to the ionization and acceleration regions. In 1999, research tests of SPT-1 on the rigs of EDB Fakel were performed, and then, in 2000–2001, on the rigs of NASA's Glenn Research Center (GRC), successful demonstration tests were performed where in various operation modes with discharge currents of 2.07 to 5.09 A and voltages of 300 to 1250 V the following maximum parameters were

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achieved: efficiency η_a = 0.64, thrust F = 144.5 mN, Isp_a = 3661 s. In 2002, in EDB Fakel, after modification of the SPT-1 constructive scheme (Fig. 1), research tests with so-called hollow magnetic gas distributor anode were performed also.

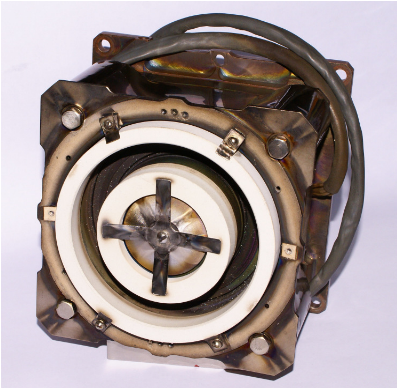


Figure 1. Anode Unite of SPT-1 Thruster with Magnetic Anode

Basic parameters and characteristics of several advanced EPs are shown in Table 1.

Table 1 – EP thrusters parameters and characteristics

Thruster	Thruster type	Status	Power, kW	Isp, s	Thrust, mN
SPT-1 ***EDB Fakel***	HybridPT[2]	Developed	Up to 2.3	2500–3500	Up to 115
HiVHAC NASA-103M.XL[3, 4] (USA)	SPT	Qualified	3.6	900–2900	20–150
BPT-4000[3, 5] "AeroJet" (USA)	SPT	Flight	3.6	900–1500	161–282
XIPS-25[6] (USA)	Ion Thruster	Developed	2.2–4.5	3500	79–165
NEXT[7] (USA)	Ion Thruster	Developed	6.9	4190	237
RIT-XT "ASTRIUM"[8]	Ion Thruster	Developed	Up to 7	4856	210
MELCO Hall[9, 10], "Mitsubishi Electric Corporation" (Japan)	SPT	Developed	5	1500	250
SPT-140DM ***EDB Fakel***	SPT	Under qualification	2.5–5.0	1600–2300	130–300
SPT-140 ***EDB Fakel***	SPT	Under qualification	4.5	1770	290
PPS-X000/PPS-5000[11, 12] "Snecma" (France)	SPT	Developed	5 (Up to 10)	2100	180–280
NASA-173Mv1[13, 14] GRC NASA (USA)	SPT	Under qualification	Up to 6	1800–3140	137–350
ROS2000[15] "ASTRIUM"	SPT	Laboratory model	2.5	1800	135
Prototype PlaS-40 ***EDB Fakel***	HybridPT	Developed	Up to 0.4	1000–1750	23.5
KM-7[13] Keldysh Research Center (Russia)	SPT	Developed	Up to 10	2100	180–280
D-80[16] TsNIMASH (Russia)	TAL	Developed	1–5	1500–4000	60–270
PlaS-120CM ***EDB Fakel***	HybridPT	Concept-model	Up to 4.5	Up to 4000	Up to 200

Analysis of several types of modern EPs presented on the summary diagram (Fig. 2) shows the level of parameters they achieved in wide power range. As we can see in the summary diagram, the basic advantage of the ion thrusters consists in providing high specific impulse, over 3,000 s.

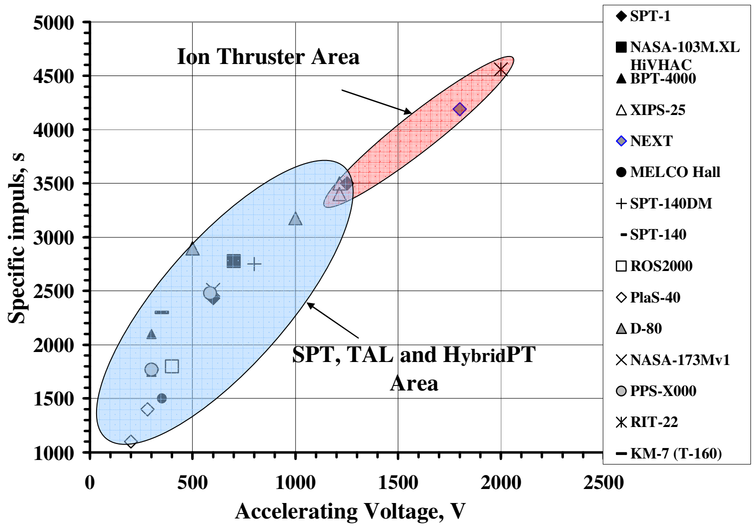


Figure 2. Diagram of Main Performances of Modern EP Thrusters (SPT-1 и PlaS-40 – Hybrid Plasma Thrusters)

As it was shown, HybridPT, in the higher power operation modes and enough high discharge voltages of 900 to 1250 V, e. g. SPT-1 model, also able to provide enough high values of the thrust specific impulse up to 3200 s and over, which, in turn, allows approaching the area of the ion thruster's specific impulses.

In order to identify the hybrid thruster as a new version of plasma thrusters and to determine its basic distinctive features in relation to other EP types, research tests of various nominal size and power consumption models were performed. In the course of the tests, AC configuration was optimized to determine basic characteristic relationships between the geometric dimensions and the parameters to be used in further constructive scheme and implementation of a parametric series of HybridPT.

So, the known SPTs and TALs differ mainly in constructive scheme of their ACs. SPT is based on an accelerator with closed electron drift and long acceleration region (Fig. 3). As is known, SPT is featured with: longer ceramic discharge chamber (DC) ($L_k/b_k > 1$), significant inductance variation within it ($L_k/L_B \geq 1$), possibility of significant changing of the magnetic field lines curvature and direct contact of the flow being accelerated with the walls $\left(\left(b_k - b_{n_0}\right)/b_{n_0} = 0\right)$[17]. Minimum distance from the anode to the ionization and acceleration region is a characteristic dimension of DC, which is about 18 to 20 mm in the known SPTs.

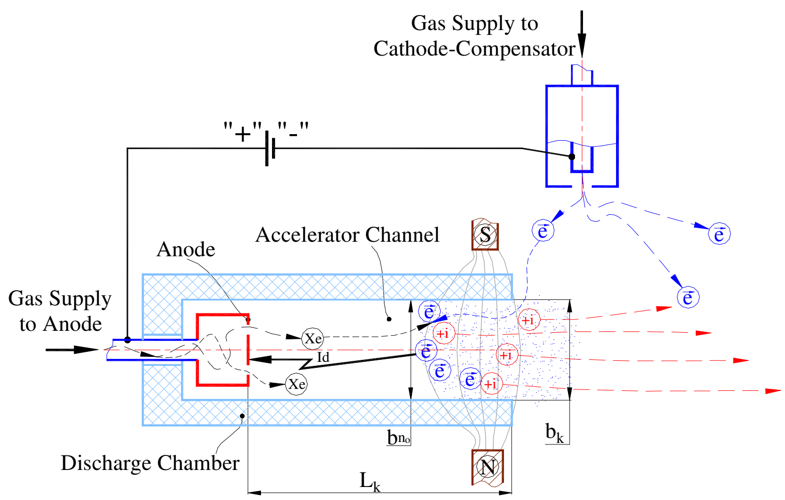


Figure 3. Stationary Plasma Thruster Constructive Scheme

It should be noted that at present in various sources different information on longitude of the layer of the DC magnetic field between the boundaries of maximum magnetic induction is presented. So, if the external boundary corresponds to $B_r$max, there is no common opinion on the internal boundary (from 05$B_r$max[17], 0.6$B_r$max[18], 0.7$B_r$max[19], up to 0.8$B_r$max[20]). Inside such long AC, anode is located (as a rule on the bottom of DC), which in most cases serves also as a gas distributor delivering propellant to AC and distributing it uniformly by azimuth in coaxial AC. Dielectric walls in the structure of this accelerator allow decreasing of the metal components atomization, especially in the beginning of the life time. In this case, however, the anode layer width extends due to increase of the lateral electrons mobility in the regions close to the walls.

TAL is based on accelerator with closed electron drift and long acceleration region also and has similar constructive scheme of AC (Fig. 4), which is formed with the use of coaxial metal DC, where the AC walls on the DC output can be made of non-metallic while current conducting rings made of graphite, for example.

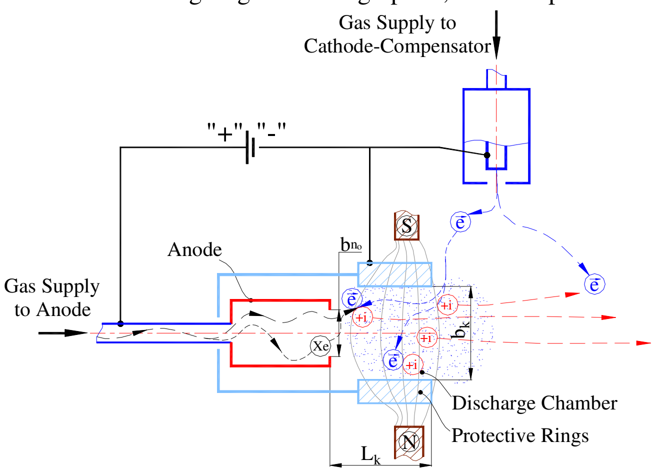


Figure 4. Thruster with an Anode Layer Constructive Scheme

As the such type accelerator structure includes hollow anode, we can somewhat optimize the problem of the working gas ionization near the anode layer boundary. Such metal DC operating under the cathode potential provides possibility of limit-narrowing of the anode layer thus decreasing loss of the plasma flow being accelerated at walls. On the other hand, intense atomization of the discharge chamber walls during operation of like thruster decreases its reliability due to increase of the risks related to the electrical strength of its structure. In comparison to SPT, the standard constructive scheme of TAL has relatively "shorter" chamber ($L_k/b_k < 1$),which within weaker magnetic field induction variation is provided ($L_k/L_B < 1$), as well the walls distant from the plasma in the acceleration region $\left((b_k - b_{n_0})/b_{n_0} \sim 1\right)$[17]. So, in TAL, the minimum distance from the anode to the ionization and acceleration region is of about 1 to 2 mm.

In the known thrusters of the both constructive schemes, enough high integral parameters and characteristics are achieved, but their operating modes are peculiar with non monotone variation of the discharge current oscillations intensity in relation to the discharge voltage variation, which oscillations are mostly of large amplitude (up to 2.0 A and over) and frequency of 20 to 40 kHz that is of enough low frequency range[21]. Those oscillations, as an ultimate result, increase probability of EP transition into unstable operation mode.

II. Research of HybridPT Models

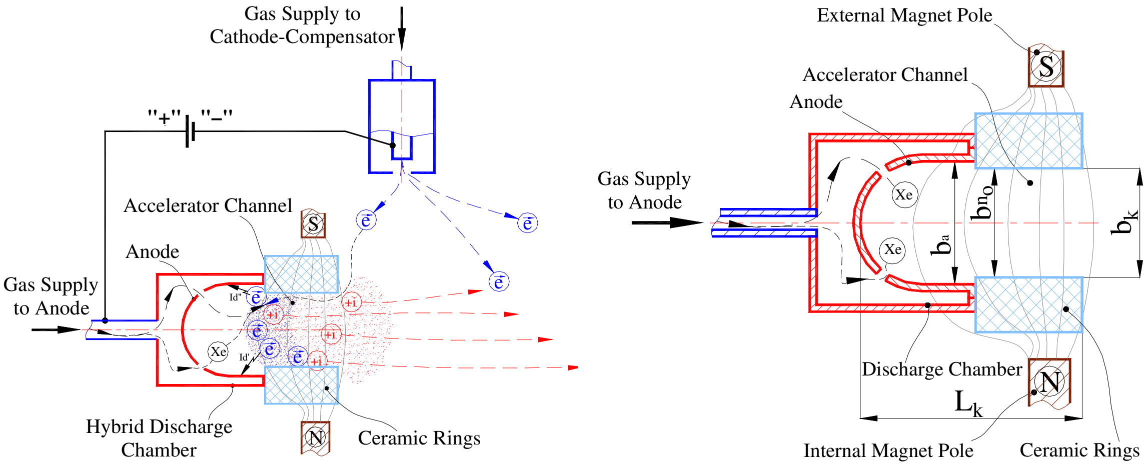
Construction diagram of DC with hollow gas distributor anode which is a part of hybrid thruster SPT-1 is given in Fig. 5. Detailed analysis of its constructive scheme shows that the basic geometric dimensions of the SPT-1 DC can be described with the following characteristic relationships[22]:

$$1 \le \frac{L_k}{b_k} < 2; \qquad \frac{L_k}{L_B} > 1; \qquad \frac{b_{n_0}}{b_k} = 1; \qquad \frac{b_k - b_{n_0}}{b_{n_0}} = 0.$$

The characteristic relationships show that the SPT-1 constructive scheme combines various criteria typical to both SPT and TAL, which confirm hybrid nature of SPT-1.

Thus, SPT-1 model has conformal distance from the anode bottom to the DC cut ($1 \le L_k/b_k < 2$) the same as the one of the standard SPT, which allows implementation of "direct" contact of the flow being accelerated with the walls $\left((b_k - b_{n_0})/b_{n_0} = 0\right)$. As we can see, the minimum distance from the nearest parts of the anode to the ionization and acceleration region in SPT-1, which can be determined by formula $L_A \min = (b_a - b_{n_0})/2$, is some less and is of 2.5 mm, which is typical to the TAL constructive scheme. Besides, that constructive scheme lead to more significant variation of the magnetic induction in AC ($L_k/L_B > 1$).

When comparing characteristic relationships of SPT, TAL and HybridPT SPT-1 dimensions, we can see, that SPT-1 thruster has three relationships similar to the ones of SPT and one changed individual feature. Dominating similarity of the SPT-1 model to the SPT thrusters is due to the fact that its constructive scheme is based on the structural assemblies of SPT-100B and PPS 1350R thrusters.



a) **b)**

Figure 5. Construction Diagram of HybridPT SPT-1 with the Combined Discharge Chamber and the Hollow Anode/Gas Distributor

In the another version of the HybridPT constructive scheme that is shown in Fig. 6, conventional thin-wall ring magnetic shields united by continuous bonding can be replaced with magnetic reflector[23] being a part of the hollow anode and electrically insulated from the rest components of the magnetic system structure. Implementation of the hollow anode with magnetic reflector allows creating of the DC magnetic field of the optimum configuration with larger gradient of the magnetic induction radial component.

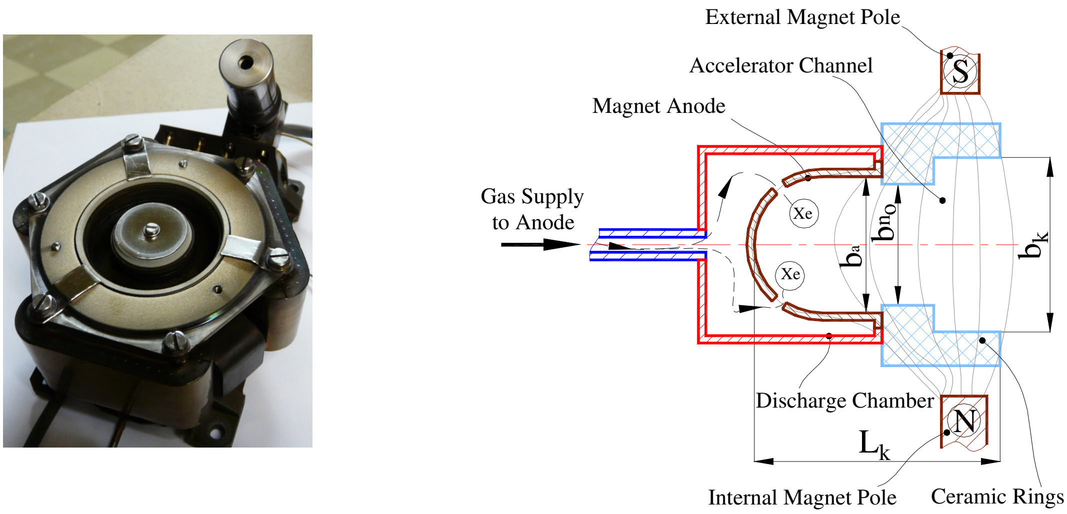


Figure 6. Overall View of the HybridPT Prototype PlaS-40 with the Hollow Magnet Anode and its Discharge Chamber Construction Diagram

In the case of HybridPT Prototype PlaS-40 shown in Fig. 6, the characteristic relationships between the dimensions somewhat differ from the ones for the constructive scheme implemented in the SPT-1 model previously:

$$1 \le \frac{L_k}{b_k} < 1{,}5\,; \qquad \frac{L_k}{L_B} > 1\,; \qquad \frac{b_{n_0}}{b_k} < 1^{24}; \qquad 0 < \frac{b_k - b_{n_0}}{b_{n_0}} < 1\,.$$

That HybridPT has relatively "shorter" chamber than the one of the standard SPT ($1 \le L_k/b_k < 1.5$), more significant variation of the magnetic induction ($L_k/L_B > 1$), as well as better possibilities of contact between the flow being accelerated and walls $\left(0 < \left(b_k - b_{n_0}\right)/b_{n_0} < 1\right)$. The minimum distance from the anode to the ionization and acceleration region for the HybridPT can be also determined by formula $L_A \min = \left(b_a - b_{n_0}\right)/2$ and amounts ~0.5 mm.

Comparative analysis of the obtained basic dimension relationships between HybridPT SPT-1 (with mid-diameter of AC equal ∅85 mm) and HybridPT Prototype PlaS-40 shows some more deep advance in the further structure improvement, generation of new constructive scheme and creation of a hybrid thruster. As we can see, Prototype PlaS-40 has three individual characteristic dimension relationships and the only similar relationship inherent to TAL.

At first, that version passed research test as a part of SPT-1 thruster with successful results similar to the ones for the original thruster configuration, which has passed demonstration tests. Then, that version of the DC construction was introduced in the developed thruster prototype PlaS-40, where, later. research test was performed in order to determine integral parameters and characteristics with stage by stage optimization of the constructive scheme and selection of low power operation modes in order to perform further limited durability test. The operating time amounted 200 hours of the test and was divided into two 100 hour periods with 200 and 400 W power.

In the known plasma accelerators, there exist some limitations of possibility to optimize efficiency and life time due to relatively long AC where the total distance to the anode and, respectively, to the working gas injection regions regarding the channel depth from the DC cut do not allow to control and affect the plasma concentration distribution starting but even the input of the ionization and acceleration region. Primarily, that is related to significant longitude of the DC walls in the ionization region and the region close to the anode where the ions and electrons recombination occurs mostly. It is known that due to the ions loss at the long walls, upon the average, half of the ions that come to the acceleration region had been subject to previous ionization, recombination on the walls and re-ionization which leads to corresponding increase of the energy consumption for the propellant ionization. Intense loss of the particles on the walls leads to uprise of significant gradients of the electron pressure which distort equipotential surfaces $\vec{E}$ -of the field so that significant part of the ions being accelerated interact with the walls in the acceleration region thus eroding the walls and increasing the energy losses in the plasma flow being accelerated.

The performed research test of PlasS-40 thruster and the data obtained in the course of the tests in the operating power range of 100 to 400 W as well as performed demonstration tests of the larger capacity SPT-1 thruster in the power range up to 2.3 kW has shown better stability (lower sensitivity) of the hybrid thrusters basic parameters and characteristics even when the magnetic field varies significantly as well as their ability to achieve high integral characteristics with various combinations of supply currents in the magnetic system magnetization sources thus allowing selection of the optimum combinations of ampere-turns on the basis of various constructive scheme criteria, e. g. mass of the EP components or possibility to include all magnetization sources connected in series into the EP discharge circuit. More stable operation of the various HybridPT versions exhibiting low discharge current and voltage oscillations is achieved due to arranging the anode in the extreme proximity to input of the L_A region of ionization and acceleration as well as due to providing, besides providing azimuth uniformity of the gas distribution, additional volume distribution of the working gas delivered to DC per AC depth meanwhile providing part of the gas delivery in direct proximity to input of the ionization region.

As per results of the performed research tests of several HybridPT versions of various nominal size and operating capacity of SPT-1 and Prototype PlaS-40, characteristic relationships (Table 2) for both geometric dimensions of DC and basic parameters of their optimum operation were determined.

Table 2 – Characteristic relationship between dimensions and parameters of the SPT, the TAL and the HybridPT

Thruster type	Discharge Chamber Geometry				Parameters			
SPT	$\frac{L_k}{b_k} > 1$	$\frac{L_k}{L_B} \geq 1$	$\frac{b_{n_0}}{b_k} = 1$	$\frac{b_k - b_{n_0}}{b_{n_0}} = 0$	$\frac{\lambda_{\text{И}}}{L_c} \leq 1$	$\frac{L_c}{L_B} < 1$	$\frac{L_c}{b_k} \sim 1$	$\frac{b_k - b_{n_0}}{L_c} = 0$
TAL	$\frac{L_k}{b_k} < 1$	$\frac{L_k}{L_B} < 1$	$\frac{b_{n_0}}{b_k} < 1$	$\frac{b_k - b_{n_0}}{b_{n_0}} \sim 1$		$\frac{L_c}{L_B} << 1$	$\frac{L_c}{b_k} << 1$	$\frac{b_k - b_{n_0}}{L_c} \sim 1$
HybridPT (PlaS)	$1 \leq \frac{L_k}{b_k} < 1{,}5$	$\frac{L_k}{L_B} > 1$	$\frac{b_{n_0}}{b_k} < 1$	$0 < \frac{b_k - b_{n_0}}{b_{n_0}} < 1$	$\frac{\lambda_{\text{И}}}{L_c} \leq 1$	$\frac{L_c}{L_B} < 1$	$\frac{L_c}{b_k} < 1$	$\frac{b_k - b_{n_0}}{L_c} \leq 1$

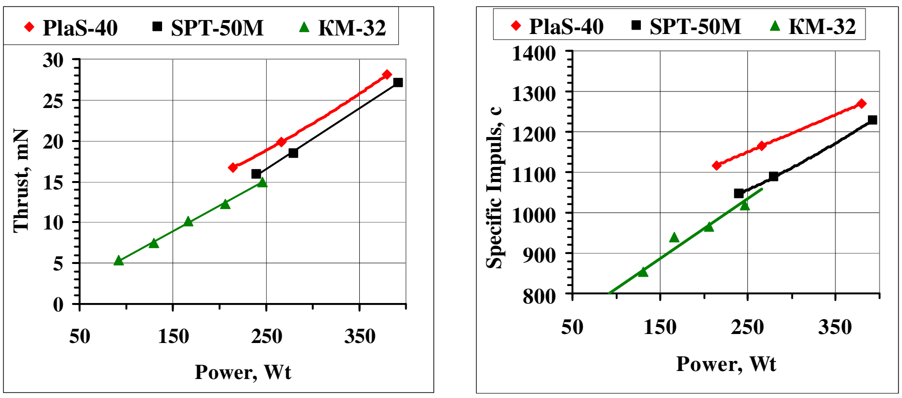
In 2010, EDB Fakel has performed also parametric tests of various thrusters of low capacity: Stationary Plasma Thruster SPT-50M and Hybrid Plasma Thruster PlaS-40 at the same conditions and with the use of the same low consumption experimental cathode compensator KE-1. The tests were performed at the discharge voltage of 160 and 220 V in the flow rate range of 1.25 to 2.00 mg/s in horizontal vacuum chamber at pressure during the thrusters operation not over $1{,}2 \cdot 10^{-4}$ mm Hg (regarding air).

For comparison, let's consider thruster KM-32[14] with mid-diameter of AC equal ∅32 mm and nominal capacity of 200 W developed in the Research Center named after M. V. Keldysh (Moscow). The said thruster constructive scheme features with implementation of DC as per the combined scheme where the DC walls are made of metal and are under floating potential while ceramic rings are installed close to the DC cut (output). The KM-32 thruster tests were performed on the rigs of Research Center named after M. V. Keldysh. The vacuum chamber diameter amounts 0.96 m, length 3.2 m, total volume 2.5 m^3. Typical pressure in the vacuum chamber did not exceed $2.5 \cdot 10^{-5}$ mm Hg. The thruster was tested at the discharge voltages of 200 to 350 V and in the range of the anode flow rate of 0.5 to 1.4 mg/s.

Table 3 – Analysis of the parameters of the low-power thrusters SPT-50M, prototype PlaS-40 and KM-32

Model	U_d, V	G_a, mg/s	C_t, W/mN	I_{sp}, s	I_i/I_d	I_i/I_m	Eff, %
SPT-50M	200	1.5	15.3	1088	0.75	0.89	35.0
PlaS-40	200	1.5	13.7	1144	0.74	0.83	40.5
KM-32[25]	200	1.4	16.4	1019	0.74	0.94	29.1

The comparison characteristics and parameters of the thrusters tested and under considerations of various constructive schemes are given in Figure 7.



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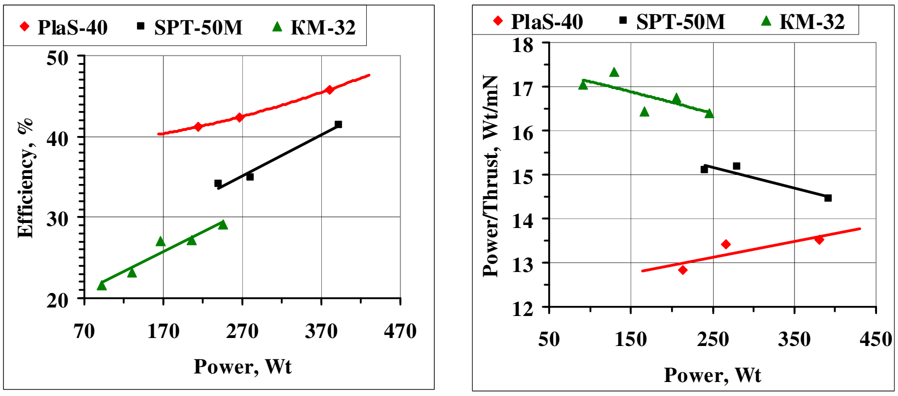

c) d)

Figure 7. Thrust, Specific Impulse, Efficiency and Power-to-thrust Ratio of the EPs of Various Constructive Schemes at the Discharge Voltage of 200 V

In 2011, on the vacuum rigs of EDB Fakel, research tests of the hybrid plasma thruster PlaS-120 conceptual model were performed (Fig. 8). The tests were performed in the operating modes with discharge voltage of 950 V in the flow rate range of 2.5 to 4.8 mg/s in horizontal vacuum chamber at pressure during the thrusters operation not over $1{,}2*10^{-4}$ mm Hg (regarding air). The rig vacuum chamber volume amounts 4 m^3, the chamber diameter is 0.9 m.

Figure 8. Overall View of the Concept-model HybridPT PlaS-120 after Manufacture

Comparative analysis of the basic parameters of the SPT and HybridPT versions of similar nominal sizes and capacities in high voltage and low voltage ranges are given in Tables 4 and 5.

Table 4 – Analyses of High-Capacity EP Parameters

Model	U_d, V	I_d, A	G_a, mg/s	F, mN	I_{sp}, s	N, W	E_{ff}, %
SPT-140 LM#1	300	4.5	4.7	78.5	1568	1350	44.0
BPT-4000QM[26]	300	10.0	10.1	203.0	1728	3000	57.0
PlaS-120CM	300	4.5	3.7	69.9	1451	1350	38.2

Table 5 – Analyses of High-Voltage EP Parameters

Model	U_d, V	I_d, A	G_a, mg/s	F, mN	I_{sp}, s	N, W	E_{ff}, %
SPT-140 LM#2	800	5.63	5.6	173	2750	4500	52.8
BPT-4000QM[27]	800	5.60	5.8	184	2620	4500	52.0
PlaS-120CM	550	4.65	4.15	101	1943	2558	38.5

The data obtained show that in the wide range of capacity HybridPT has better capacity due to better organization of the ion formation process in DC.

III. Conclusion

The obtained characteristic relationships between dimensions and parameters describing HybridPT allow identifying it as a new species of plasma thrusters, which can be used in the future for design of geometrically conformal versions being developed, e. g. for development of the thrusters parametric series: PlaS-40, PlaS-55 (or its modification PlaS-5510), PlaS-85 and PlaS-120, as well as of other nominal sizes of the thrusters of various capacities.

References

[1]I. B. Sorokin, V. V. Gopanchuk, EDB Fakel, Russia. Patent Application for a "Electric propulsion", Docket No. RU No. 2045134, filed 15 March 1993.

[2]David H. Manzella, David T. Jacobson and Robert S. Jankovsky "High Voltage SPT Performance", AIAA, CP3774, Salt Lake City, Utah, 2001.

[3]Randy M. Baggett, Wendy W. Hulgan, John W. Dankanich, Robert T. Bechtel "In-Space Propulsion Solar Electric Propulsion Program Overview of 2006", AIAA, CP4463, Sacramento, California, 2006.

[4]Peter Y. Peterson, Hani Kamhawi, David H. Manzella, David T. Jacobson, "Hall Thruster Technology for NASA Science Missions: HiVHAC Status Update", AIAA, CP5236, Cincinnati, OH, 2007.

[5]J. Fisher, A. Wilson, D. King, S. Meyer, K. de Grys, L. Werthman "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System for Geo Satellite Applications – status update", IEPC, CP295, Toulouse, France, 2003.

[6]Kuei-Ru Chien, William G. Tighe, Thomas A Bond, Rafael Spears "An Overview of Electric Propulsion at L-3 Communications, Electron Technologies Inc", AIAA, Sacramento, California, 2006.

[7]Michael J. Patterson, Scott W. Benson "NEXT Ion Propulsion System Development Status and Performance", AIAA, CP5199, Cincinnati, OH, 8-11 July 2007.

[8]Helmut Bassner, Rainer Killinger, Hans Leiter, Johann Müller "Development Steps of the RF-Ion Thrusters RIT", IEPC, CP105, Pasadena, CA, 2001.

[9]Kimiya Komurasaki, Hitoshi Kuninaka "Overview of Electric Propulsion Activities in Japan", AIAA, CP339, Cincinnati, OH, 2007.

[10]Toshiyuki Ozaki, Yukikazu Kasai, Yasutaka Inanaga, Takafumi Nakagawa, Hiroyuki Osuga, Takashi Itoh, Kenichi Kajiwara, Katsuaki Matsui "Electric Propulsion Development Activity at MELCO", AIAA, CP4321, Sacramento, California, 2006.

[11]Enrico Chestsa, Denis Arrat, Regies Bertrand, Frank Dannon, Stephani D'Escrivan, Nicolas Pielet "CNES Electric Propulsion activities overview: flight programs, R&T actions, novel mission constructive scheme", IEPC, Florence, Italy, 2007.

[12]J. Gonzalez del Amo, G. Saccoccia "Electric propulsion Activities at ESA", IEPC, PC237, Ann Arbor, Michigan, USA, 2009.

[13]R. R. Hofer "Development and Characterization of High-Efficiency, High-Specific Impulse Xenon Hall Thrusters", Ph. D. Dissertation, University of Michigan, 2004.

[14]O. A. Gorshkov, V. A. Muravl'ev, A. A. Shagaida, *Holl and Ion Thrusters for Space Vehicles*, under the editorship of the RAS Academician A. S. Koroteyev. M.: Mashinostroyeniye, 2008.

[15]G. Saccoccia "European Electric Propulsion Activities and Programmes", IEPC, Pasadena, CA, 2001.

[16]Semenkin A. V., Tverdokhlebov S. O., Garkusha V. I., Kochergin A. V., Chislov G. O., Shumkin B. V., Solodukhin A. V., Zakharenkov L. E "Operating Envelopes of Thrusters with Anode Layer", IEPC, Pasadena, CA, 2001.

[17]N. V. Belan, V. P. Kim, A. I. Oransky, V. B. Tikhonov, *Stationary Plasma Thrusters*, Kharkov: Kharkov Aviation Institute, 1989.

[18]Yu. M. Yermoshkin, *The Foundations of Theory and Design of Electric Propulsion and Thrusters*, 2003.

[19]A. I. Bugrova, V. P. Kim, *Current State of Researches in Physics regarding Accelerators with Closed Electron Drift and Long Acceleration Region* , Plasma Accelerators and Ion Injectors. M.: Nauka, 1984.

[20]Richard R. Hofer Peter Y. Peterson Alec D. Gallimore "A High Specific Impulse Two-Stage Hall Thruster with Plasma Lens Focusing", IEPC, PC36, Pasadena, CA, 2001.

[21] A. V. Gorshkov, V. A. Muravl'ev, A. A. Shagaida, *Holl and ion thrusters for space vehicles*, under the editorship of the RAS Academician A. S. Koroteyev. M.: Mashinostroyeniye, 2008, pp. 120–128

[22]V. V. Gopanchuk, M. Yu. Potapenko "Study of the impact of the discharge chamber configuration on characteristics of the hybrid plasma thruster", Trudy MAI, 2011, No. 42.

[23]V. V. Gopanchuk. EDB Fakel, Russia. Patent Application for a "Electric propulsion", Docket No. RU No. 2191487, filed 30 Nov. 2000.

[24]V. V. Gopanchuk, I. B. Sorokin, EDB Fakel, Russia. Patent Application for a "Electric propulsion", Docket No. RU No. 2209533, filed 10 Nov. 2001.

[25]Mikhail B. Belikov, Oleg A. Gorshkov, Evgeny N. Dyshlyuk, Aleksandr S. Lovtzov, Andrey A. Shagayda "Development of Low-Power Hall Thruster with Lifetime up to 3000 Hours", IEPC, PC129, Florence, Italy, 2007.

[26] J. Fisher, A. Wilson, D. King, S. Meyer, K. de Grys, L. Werthman "The Development and Qualification of a 4.5 kw Hall Thruster Propulsion System for Geo Satellite Applications – Status Update", IEPC, PC295, Toulouse, France.

[27]Richard R. Hofer "High-Specific Impulse Operation of the BPT-4000 Hall Thruster for NASA Science Missions", AIAA, PC6623, Nashville, TN, 2010.