

# Development and Research of the Plasma Thruster with a hollow magnet Anode PlaS-40

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M.Yu. Potapenko<sup>1</sup>, V.V. Gopanchuk<sup>2</sup>  
FSUE EDB Fakel, Kaliningrad, 236001, Russia

**Abstract:** This paper presents the results of development and mass-energy optimization of the Plasma thruster design with a hollow magnet Anode PlaS-40. The stability of thruster operation in the power range of 100 to 650 W is demonstrated. PlaS-40 ensures higher performances in comparison with its analogue dimension types, as well as the level of performances comparable with other SPTs of bigger dimension type. Application of new PlaS-type thrusters for similar tasks solved by SPTs abroad spacecraft allows to reduce mass and volume occupied by them as part of S/C almost by 40 %.

## Nomenclature

|                |                                                                                             |
|----------------|---------------------------------------------------------------------------------------------|
| $B_{r,max}$    | = maximum value of the magnet induction radial component in a gap between the magnet poles; |
| $\nabla_z B_r$ | = axial component of gradient of the magnet induction radial component;                     |
| $I_d$          | = discharge current;                                                                        |
| $U_d$          | = discharge voltage;                                                                        |
| $G_a$          | = anode gas flow rate;                                                                      |
| $I_i$          | = ion current;                                                                              |
| $I_e$          | = electron current;                                                                         |
| $U_{K3}$       | = "cathode-ground" voltage;                                                                 |
| $K_i$          | = gas ionization rate.                                                                      |

## I. Introduction

One of the leading tendencies in the modern space branch is an increasing expansion of application range of electric propulsion (EP) of various power, in particular, Hall-Effect and ion thrusters aboard spacecraft (S/C). Along with the Plasma Stationary Thrusters (SPT) of the classical scheme there appear more thrusters with the discharge chamber (DCh) of a new constructive scheme, which allows to reach higher thrust performances. Thruster schemes with composite DCh have already been applied in the thruster BPT-4000 by Aerojet (USA), "BHT" thrusters by Busek (USA), parametric family of "KM" thrusters by SSC Keldysh Research Centre (Russia), and also in experimental models of the thrusters by RIAME.

The scheme of thruster with so-called "hybrid" DCh - Plasma thruster with a hollow magnet anode - has been developed<sup>1,2</sup> by EDB Fakel. This thruster called PlaS is a version of Morozov's type Plasma thruster<sup>3</sup>. Prototype of the PlaS type thrusters is the experimental plasma thruster SPT-1, which constructive scheme first proposed by EDB Fakel<sup>4</sup>.

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1 Design Engineer

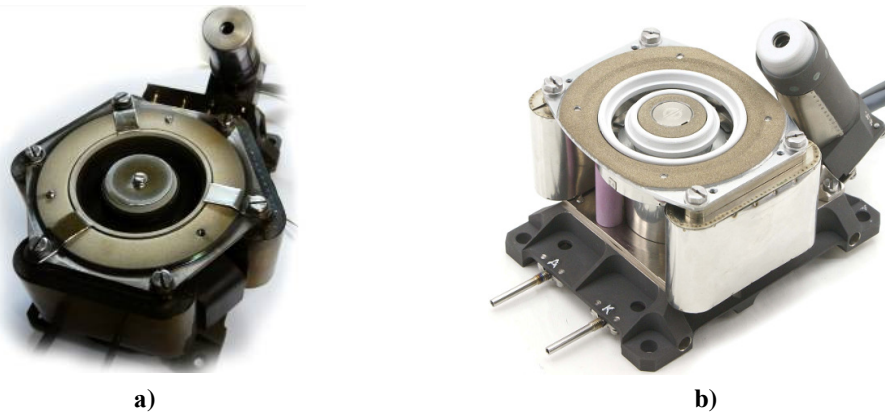
2 Leading Designer

## II. Development and optimization of the PlaS-40 thruster design

The principal distinctive design feature of the PlaS type thrusters consists in the composite design of its DCh, the exit of which is formed by dielectric rings and its metal bottom is formed by the walls of an adjoining hollow gas distributing anode, which is electrically insulated from other structural elements. Advantages of the DCh scheme with a hollow magnet anode consist, first, in minimization of plasma longitudinal oscillations, due to facilitated process of the electrons shorting to the anode, and, second, in the generation of the magnet lens of optimal “focusing” geometry with a high gradient of a radial component of the magnetic induction  $\nabla_r B_r$  in the accelerating channel (ACh) by ensuring of the minimal magnet stray fields.

Characteristic relationships of similarity between the main geometric dimensions and operating parameters which are basic for the configuration of thrusters of this type<sup>1</sup> are defined for the family of PlaS type thrusters

Due to modern tendencies of space techniques progress, one of which perspective direction is development and application of small S/C, EDB Fakel is developing a plasma thruster with a hollow magnet anode of low power PlaS-40, its middle diameter of ACh is 40 mm. Tests of the thruster laboratory model (fig. 1a)) demonstrated high thrust performances and stability of thruster operating in the power range from 100 to 600 W<sup>1</sup>.

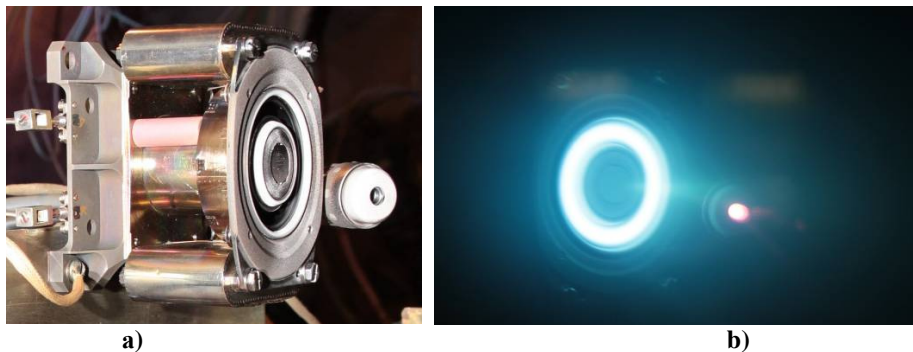


**Fig. 1. External view of the PlaS-40 a) laboratory model (LM) and b) engineering model (EM)**

Optimization of the mass-dimension and energy characteristics was performed for the PlaS-40 EM (fig. 1b)). This optimization allowed to reduce mass by 25 % and its outline dimensions (see table 1), and also to reduce consumption of energy needed to generate magnet field and gas ionization processes.

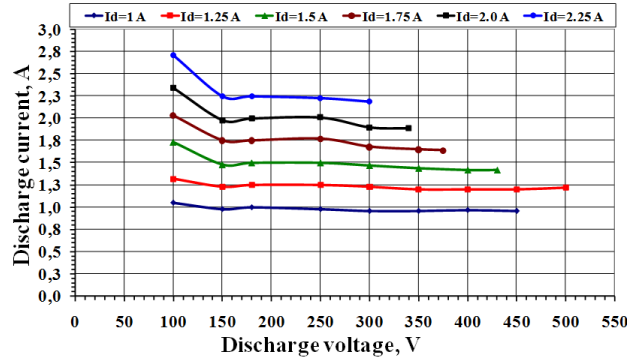
## III. PlaS-40 thruster experimental research

PlaS-40 was tested at discharge voltage from 100 to 500 V in the anode flow rate range of xenon from 1.25 to 2.5 mg/s and the cathode flow rate of 0.18 mg/s in the horizontal vacuum chamber at dynamic pressure not more than  $1.2 \cdot 10^{-4}$  mm Hg (in terms of air). External view of the thruster during test is shown in figure 2.



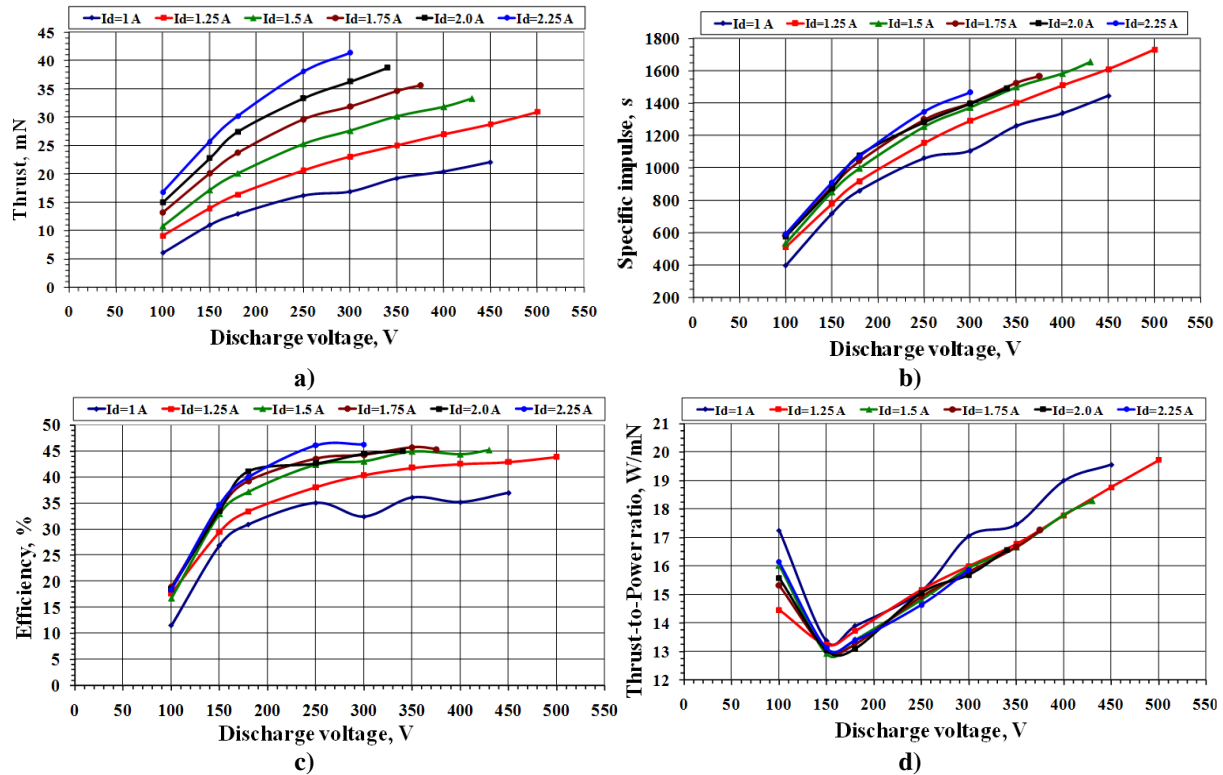
**Fig.2. Thruster PlaS-40 a) after life test and b) during life test**

Current-voltage characteristics (fig. 3) were measured at the specified anode flow rate, which corresponds to the ensured discharge current of 1.00 to 2.25 A with an increment of 0.25 A. Magnetic field has been optimized by minimum discharge current at each operating point. Figure 3 shows that discharge current decreases insignificantly at the discharge voltage increase of more than 250 V, which is most probably caused by the reduction of gas ionization process efficiency.



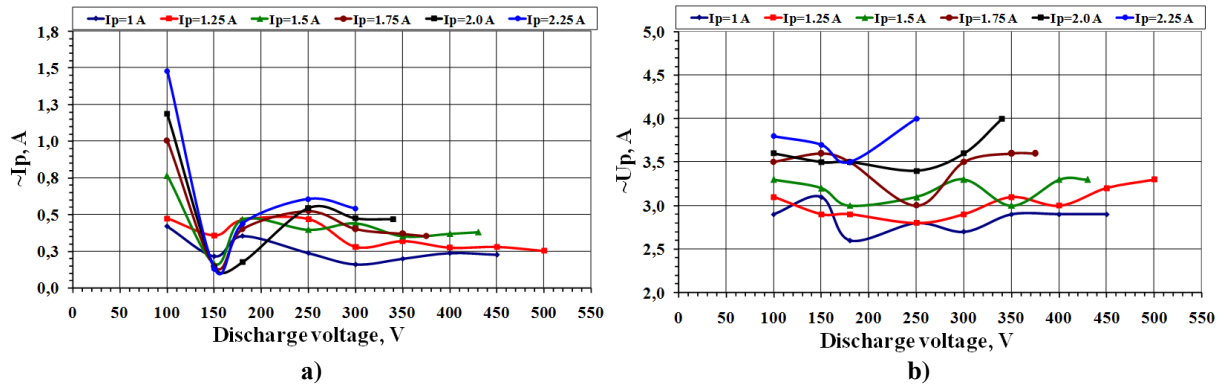
**Fig.3. Current-voltage characteristics**

Efficiency increases significantly at the discharge voltage increase up to 250 V followed by stabilization of the value up to ~35% for anode gas flow of 1.32 mg/s and ~47% for anode gas flow 2.58 mg/s. Stabilization of the efficiency value at the discharge voltage of 250 V is accompanied by the discharge current decrease (fig. 3).



**Fig.4. a) Thrust, b) specific impulse, c) efficiency and d) thrust-to power ratio dependence on discharge voltage**

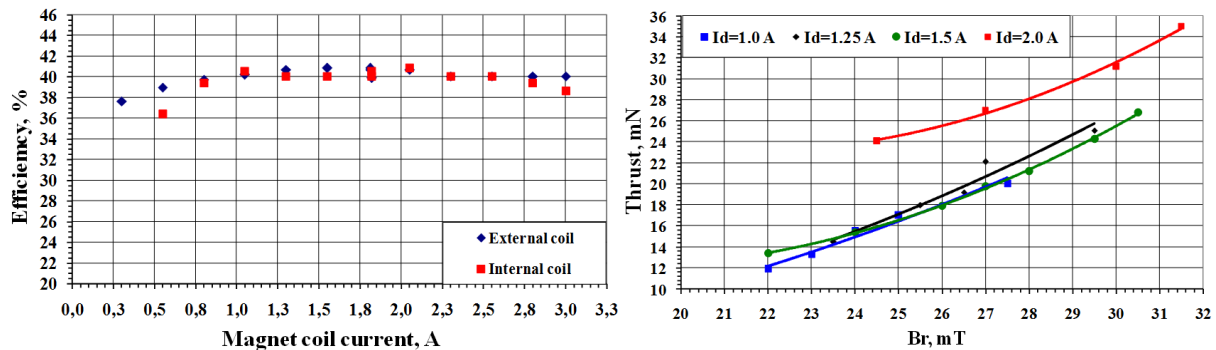
RMS discharge voltage and discharge current amplitude are shown in figure 5. Discharge current oscillations decrease sharply by the discharge voltage increase (fig.5a)), which minimum was detected at the discharge voltage  $U_d=150$  V. Minimum of the Thrust-to-Power ratio was defined at this discharge voltage also. Discharge current oscillations change insignificantly by the voltage increase (fig.5b)).



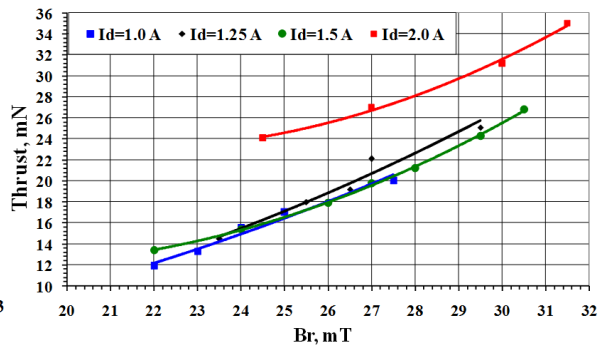
**Fig.5. RMS a) discharge current and b) discharge voltage amplitude dependence on discharge voltage**

As a result of PlaS-40 researches it is determined that thruster has wide range of magnet field stability, and its high performances are reached at various combinations of magnet coil currents (fig. 6). During operation stability test at magnet field change followed by magnetizing current optimization at operating point of  $I_d = 1.25$  A and  $U_d = 180$  V, current of one coil was kept constant of 1.82 A, while current of the other magnet coil varied.

Researches of the thruster operating efficiency with magnet field variation in ACh (fig.7) showed that thrust increases and is similar to linear dependence at magnet field and discharge voltage increase at operating points with flow rate of less than 2.0 mg/s. Sharp increase of the thrust level is also observed at operating point with gas flow rate of more than 2.0 mg/s (relevant to  $I_d = 2.0$  A), what was caused by narrowing of the Ionization and Acceleration layer, and also by its displacement to the ACh outlet, what allows to reduce ion loss on the ACh walls and to enhance plasma jet focusing at the end.



**Fig.6. Thruster efficiency dependence on magnetic coil current**

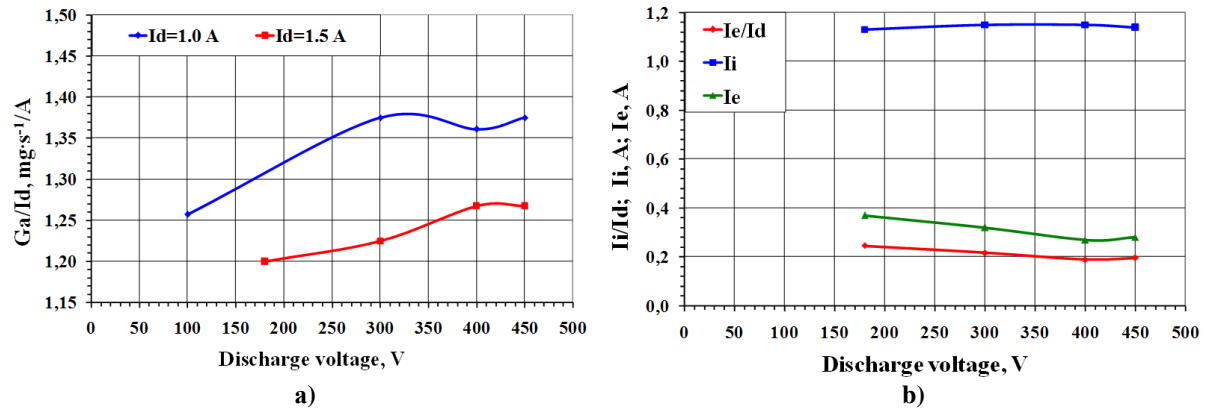


**Fig.7. Thrust dependence on radial component of magnet induction in the ACh**

Analysis of gas utilization was made with flow rate-to-discharge current ratio  $G_d/I_d$  (fig. 8). For PlaS-40, this ratio is more than 1 ( $G_d/I_d > 1$ ), and it is more preferable, because the value of spurious electron current is low given gas ionization is fully ensured. It should be noted that  $G_d/I_d$  value is somewhat overrated by partial gas ionization.

Electron value has been estimated by test at the operating point with gas flow rate of 1.8 mg/s. Its dependence on discharge EM is shown in figure 8b). Such function usually decreases monotonous and reaches “saturation” for PlaS-40 EM given the discharge voltage is more than 400 V. Similar tendency was also observed in PlaS-40 laboratory model (LM), but the “saturation” was reached at the discharge voltage of about 250 V. When saturated, this  $G_d/I_d$  value is 1.36.

Electron Current-to-Discharge Current relation is also shown in figure 8b), which relation doesn't exceed 20 %, what is indicative of good gas ionization and acceleration processes. According to the tests results, gas ionization rate has been determined, and its value varies in the range of 0.70 to 0.86, what is indicative of partial gas ionization. It is necessary to note also that at such values of the ionization rate (which values are lower than those typical for SPTs) much higher Efficiency values are reached in PlaS-40 EM.

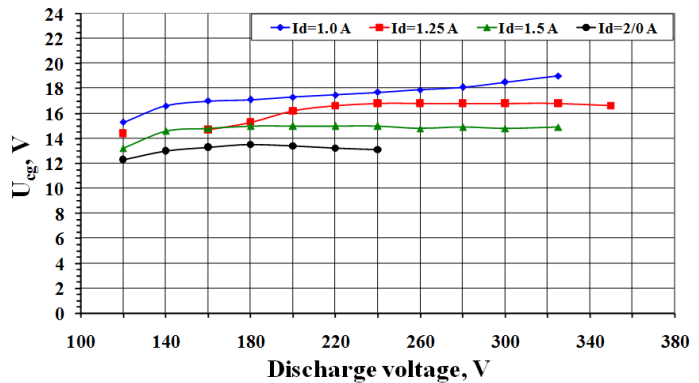


**Fig.8. PlaS-40 characteristics: a)  $G_a/I_d$  and b) ion current, electron current and its part (at  $G_a=1,8 \text{ mg/s}$ ) dependences on discharge voltage**

The low-flow rate cathode KЭ-1H has been applied in PlaS-40 thruster, which external view is shown in figure 9. Distinctive feature of KЭ-1H cathode design is its multiple cavity emitter of a new configuration made of lanthanum hexaboride. This cathode is able to operate at gas flow rate up to 0.05 mg/s. During test Cathode operated stably at the cathode flow rate of 0.18 mg/s. There is dynamics of the "Cathode-ground" voltage  $U_{cg}$  in figure 10. This parameter defines cathode operation efficiency at operating points with different discharge current.  $U_{cg}$  decrease at high discharge current is typical for hollow cathode.



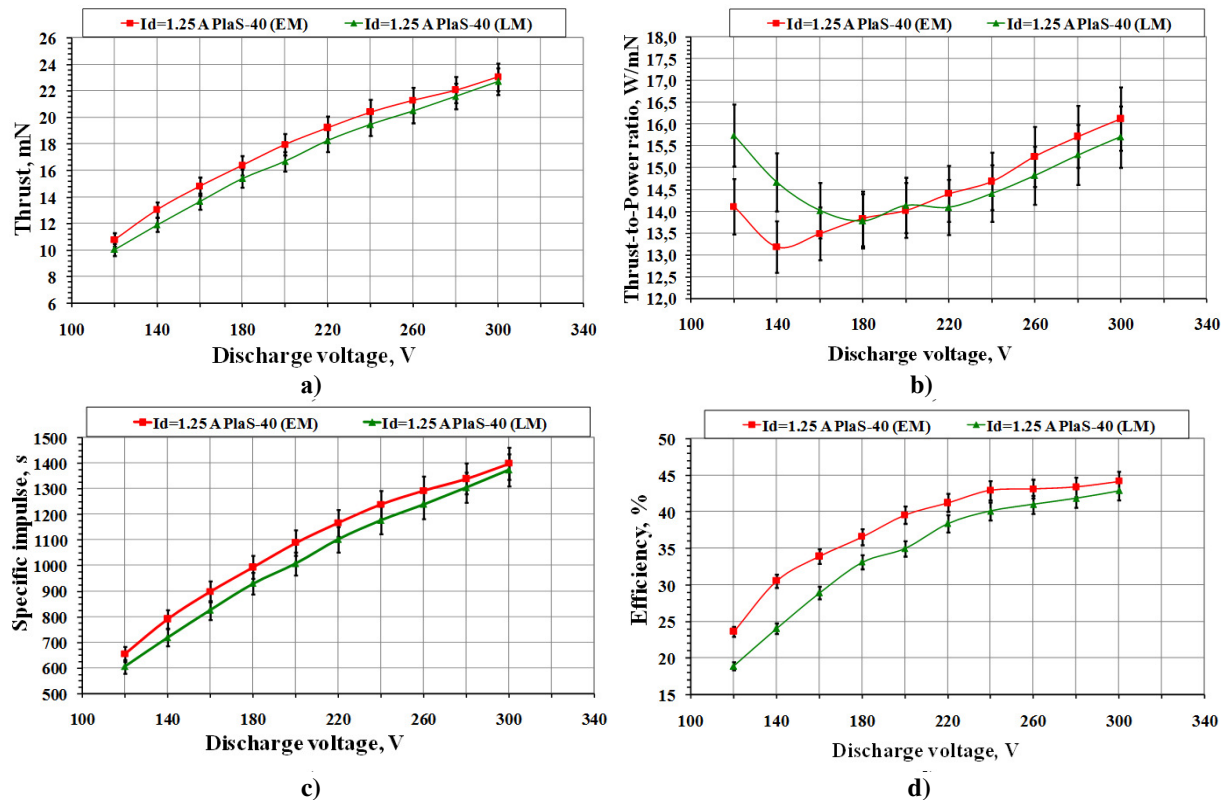
**Fig.9. External view of the cathode KЭ-1H**



**Fig.10. "Cathode-ground" voltage  $U_{cg}$  dependence on discharge voltage**

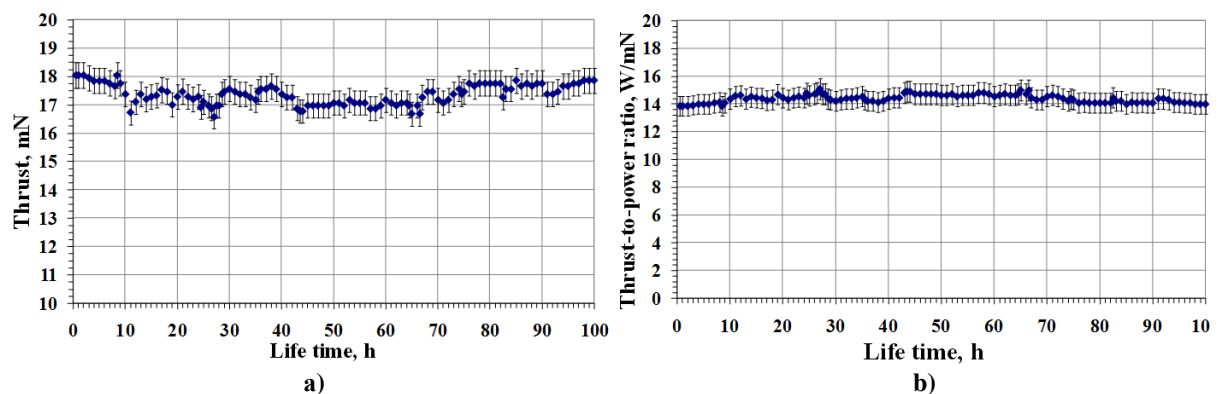
Optimization of the PlaS-40 constructive scheme, in particular its magnet system, and mass-size characteristics minimization allowed to reduce mass of the engineering model by average increase of reached performances level by 5-8 %. Comparative characteristics of the PlaS-40 laboratory model and engineering model at operating point with discharge current of 1.25 A are shown in figure 11.

Dependences type has not been changed, but it is determined, that minimum of the thrust-to-power ratio reached at lower discharge voltage for updated thruster, what was accompanied also with Efficiency increase more 5 %.

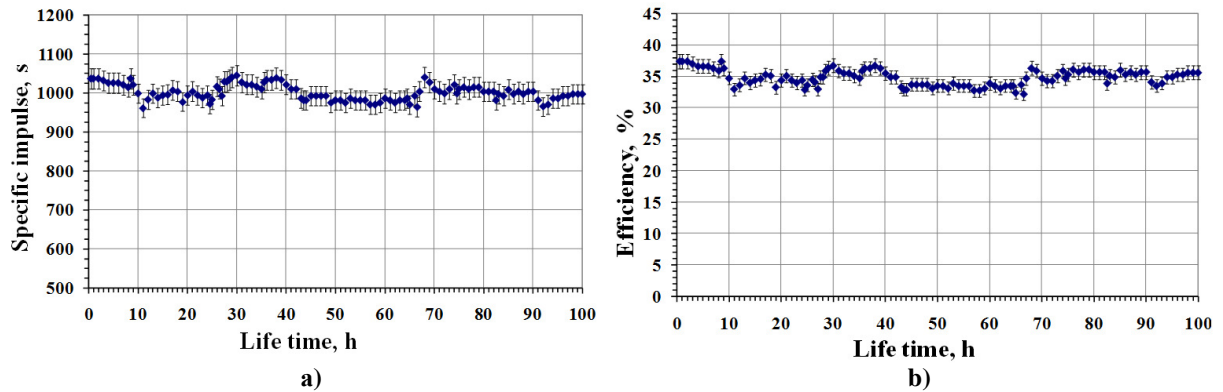


**Fig.11. Performances of the PlaS-40 Laboratory model (LM) and Engineering model (EM):**  
a) thrust, b) thrust-to power ratio, c) specific impulse and d) efficiency dependence on discharge voltage

PlaS-40 has also been tested during 100 hours at operating point with discharge voltage of 200 V and discharge current of 1.25 A. Variation of the thrust, thrust-to-Power ratio, specific impulse and efficiency during life test is shown in figures 12 and 13. Average value of the thrust during life test amounts to 17.1 mN, average value of the specific impulse calculated with allowance for the discharge power and power consumption for magnet field generation, and also with an allowance for cathode flow rate and adjusted for level of a vacuum chamber pressure is 1000 s. Average value of the total efficiency is 34.7 %, thrust-to-power ratio is 14.4 W/mN. Total impulse of the PlaS-40 thruster after 100 hours operation amounts to 6.2 KN·s.

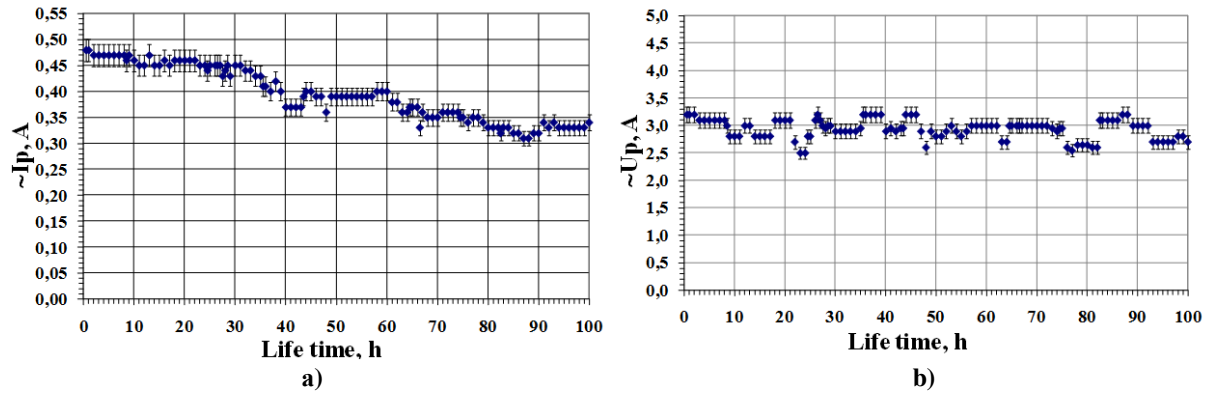


**Fig.12. Performances of the PlaS-40 engineering model during life test:**  
a) thrust and b) thrust-to-power ratio



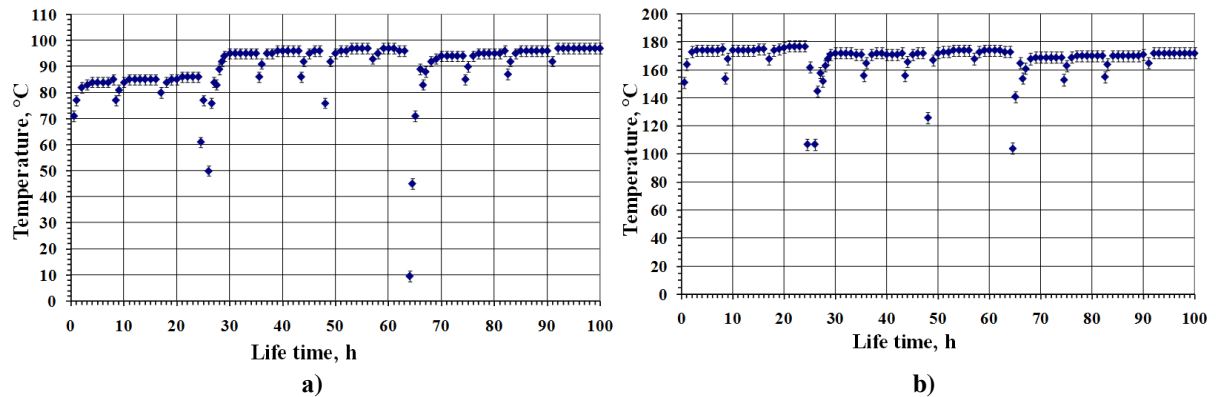
**Fig.13. Performances of the PlaS-40 engineering model during life test:**  
a) specific impulse and b) efficiency

During life test decrease of the discharge current oscillations was noted, its connects with thruster running-in (fig. 14). It is expected that RMS discharge current amplitude will be stabilized about value of 0.35 A. Level of the discharge voltage oscillations did not change during test.



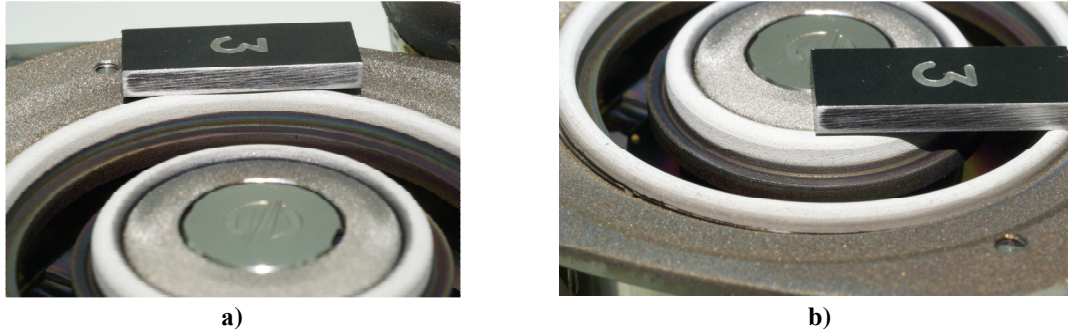
**Fig.14. RMS a) discharge current and b) discharge voltage amplitude dependence on discharge voltage of the PlaS-40 during life test**

Temperature of the PlaS-40 mounting surface and its external magnet pole has been controlled also during life test (fig.15). Mounting plate temperature by thruster operate at the discharge power of 250 W did not exceeded 100 °C. Temperature of the external magnet pole was less than 180 °C.



**Fig.15. Temperature variation of a) the mounting plate and b) the external magnet pole during life test**

Depth of the erosion rate was also measured after test. Measurement was performed in 8 sections. Average value of the erosion rate depth for external ring made of the ceramic BGP-10 is 2.5 mm, for internal ring it is 3.0 mm (fig. 16).

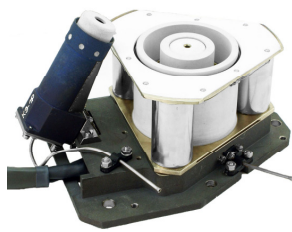


**Fig.16. External view of the DCh erosion rate of the PlaS-40 Thruster with a measured standard sample №3 a) external and b) internal wall of the DCh**

#### IV. Comparative analysis of the thruster PaS-40 and its analogies

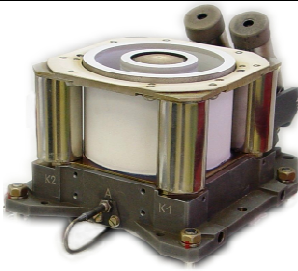
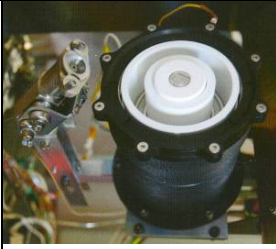
Nowadays one of the actively developing direction in the modern space branch is creation and application of the small-sized S/C of up to 500 kg by weight. The creation of small-sized S/C is primarily attractive for the reduction of the financial expenditures and those on manufacturing, for the mitigation of the risk of launch failure, and it is also attractive for the usage of the light-type launch vehicles dedicated for S/C injection into orbit. Application of the small-sized S/C constellations allows to solve a range of specific tasks by means of SPTs.

Low-power thruster SPT-50 has been developed at EDB Fakel, which is applied in the Electric Propulsion System "Canopus-V"<sup>5</sup>. Comparative analysis of the PlaS-40 and its analogues shows that PlaS-40 has 8-10 % higher performances at the same or similar operating points.

|                                                                                                                                                                                                                                       | <i>SPT-50 (Canopus-V)</i>                                                           | <i>PlaS-40 LM</i>                                                                    | <i>PlaS-40 EM</i>                                                                     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                                       |  |  |  |
| <b>Main performances*</b>                                                                                                                                                                                                             |                                                                                     |                                                                                      |                                                                                       |
| Discharge voltage, V                                                                                                                                                                                                                  | 180                                                                                 | 180                                                                                  | 180                                                                                   |
| Discharge voltage, A                                                                                                                                                                                                                  | 1.20                                                                                | 1.25                                                                                 | 1.25                                                                                  |
| Discharge power, W                                                                                                                                                                                                                    | 220                                                                                 | 225                                                                                  | 225                                                                                   |
| Thrust, mN                                                                                                                                                                                                                            | <b>14.0</b>                                                                         | <b>15.3</b>                                                                          | <b>17.0</b>                                                                           |
| Specific impulse, sc                                                                                                                                                                                                                  | <b>860</b>                                                                          | <b>940</b>                                                                           | <b>1010</b>                                                                           |
| Efficiency, %                                                                                                                                                                                                                         | <b>26</b>                                                                           | <b>34</b>                                                                            | <b>37</b>                                                                             |
| Thrust-to-power ratio, W/mN                                                                                                                                                                                                           | 16.0                                                                                | 13.6                                                                                 | 13.8                                                                                  |
| Mass, kg                                                                                                                                                                                                                              | 1.23                                                                                | 1.6                                                                                  | 1.2                                                                                   |
| ACh External diameter, mm                                                                                                                                                                                                             | 50                                                                                  | 50                                                                                   | 49                                                                                    |
| Overall dimensions, mm<br>(Volume, cm <sup>3</sup> )                                                                                                                                                                                  | 160×120×91<br>(1.75·10 <sup>3</sup> )                                               | 213×117,5×94<br>(2.3·10 <sup>3</sup> )                                               | 167×100 ×87<br>(1.50·10 <sup>3</sup> )                                                |
| Note: * - Performances value specified with allowance for the discharge power and power consumption for magnet field generation, and also with an allowance for cathode flow rate and adjusted for level of a vacuum chamber pressure |                                                                                     |                                                                                      |                                                                                       |

**Table 1. Low-power SPT performances**

Tests of the thruster PlaS-40 showed that it is capable of reaching the level of performances, which is typical for thrusters of a bigger dimension type (table 2). For comparison, there is a thruster SPT-70 made as classical SPT and developed by EDB Fakel for Aerojet, and also the same dimension type SPT HT-400 developed by Alta S.p.a. (Italy) as shown in the table. Discharge chamber of the HT-400 is also made as a classical SPT constructive scheme. Its distinctive feature consists, first of all, in the usage of permanent magnets as external and internal magnet coils, and this is known to allow reducing power consumption and temperature of the internal constructive elements. Secondly, magnet screen of the magnet system covers DCh from the external side with magnet gaps relative to the elements of operating magnet circuit<sup>6</sup>.

|                                                                                                                                                                                                             | <b>SPT-70</b><br><i>(delivery to AeroJet)</i>                                     | <b>HT-400</b><br><i>(Alta S.p.A)</i>                                               | <b>PlaS-40</b>                                                                      |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                                                                                                                                                                                                             |  |  |  |
| <b>Main performances*</b>                                                                                                                                                                                   |                                                                                   |                                                                                    |                                                                                     |
| Discharge voltage, V                                                                                                                                                                                        | 300                                                                               | 300                                                                                | 300                                                                                 |
| Discharge current, A                                                                                                                                                                                        | 2.23                                                                              | 2.25                                                                               | 2.20                                                                                |
| Discharge power, W                                                                                                                                                                                          | 669                                                                               | 675                                                                                | 652                                                                                 |
| Thrust, mN                                                                                                                                                                                                  | <b>39.2</b>                                                                       | <b>33.0</b>                                                                        | <b>41.5</b>                                                                         |
| Specific impulse, s                                                                                                                                                                                         | <b>1468</b>                                                                       | <b>1500**</b>                                                                      | <b>1470</b>                                                                         |
| Efficiency, %                                                                                                                                                                                               | <b>43</b>                                                                         | <b>45**</b>                                                                        | <b>46</b>                                                                           |
| Thrust-to-Power ratio, W/mN                                                                                                                                                                                 | <b>17.0</b>                                                                       | <b>20.5</b>                                                                        | <b>15.5</b>                                                                         |
| Mass, kg                                                                                                                                                                                                    | <b>2.0</b>                                                                        | <b>1.1**</b>                                                                       | <b>1.2</b>                                                                          |
| ACh External diameter, mm                                                                                                                                                                                   | 70                                                                                | 62                                                                                 | 49                                                                                  |
| Overall dimensions, mm<br>(Volume, cm <sup>3</sup> )                                                                                                                                                        | 198×146×98<br>(2.8·10 <sup>3</sup> )                                              | 90×113×95<br>(1.0·10 <sup>3</sup> )**                                              | 167×100×87<br>(1.5·10 <sup>3</sup> )                                                |
| Note: ** - There are specified performances of the HT-400 Anode Unit<br>(without allowance for the discharge power and allowance for cathode flow rate and adjusted for level of a vacuum chamber pressure) |                                                                                   |                                                                                    |                                                                                     |

**Table 2. Mean-power SPT performances**

## V. Conclusion

As a result of PlaS-40 researches it is determined that thruster operates stable in the range of power of 100 to 650 W at the discharge voltage of 100 to 500 V and at the discharge current of 1.00 to 2.25 A, and also during life test. High performances are reached at different combination of magnet coil currents.

Thruster PlaS-40 allows to reach high level of performances, which are ensured with the thruster of a bigger dimension type as, for example, SPT-70. An application of the new PlaS type thrusters for the similar tasks solved by SPT allows to reduce mass and taken volume occupied by them aboard S/C by ~40%. By applying several PlaS type thrusters aboard the S/C Electric Propulsion System, the overall advantage will significantly increase.

In terms of obtained results of the researches and the mass-energy optimization of the PlaS-40 design, the next improvement of the PlaS type constructive scheme and also development of the bigger dimension type thruster model as, for example, PlaS-55 and PlaS-85 and theirs performances research will be further proposed.

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