Development of stationary plasma thruster SPT-230 with discharge power of 10...15 kW

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Abstract: This article presents the results of development of the engineering model of the SPT-230 thruster with an operating power of up to 25 kW. Results of the initial phase of the research testing of the thruster are presented in the article as well as analysis of thruster performances and characteristics within the power range of 4.5 to 25 kW at a discharge voltage of 300 to 800 V and at a discharge current of up to 30 A. The model has demonstrated effective functioning in the modes of high-thrust reaching 1.0 N and high specific impulse reaching 3200 s while providing a thrust efficiency of not less than 55 %.

Nomenclature

I_d = discharge current;
U_d = discharge voltage;
G_a = anode propellant flow rate;
I_i = ion current;
I_e = electron current;
$U_{кз}$ = cathode-to-ground voltage;
K_i = propellant ionization coefficient;
$P_{v/c}$ = test stand vacuum chamber pressure;
F = thrust;
I_{sp} = specific impulse.

I. Introduction

Stationary plasma thrusters (SPT) are being more and more widely used on board of modern spacecraft (S/C). One of the topical modern tasks is the orbit raising or orbit-to-orbit transfer by means of SPTs. In connection with new projects related to creation of S/C with the mass of up to 5 - 6 tons and higher, there appears the necessity to create new high-power SPTs capable of providing a thrust of more than 500 mN. Such SPT with a power of 10 kW and more can be used not only as cruise propulsion to transfer S/C from a support orbit to the operating one, but as end organs in the S/C station keeping and attitude control systems for S/C of different purposes.

II. SPT-230 high-power plasma thruster

EDB Fakel is carrying out the activities related to creation of plasma thrusters of increased power in particular a SPT with a medial diameter of the acceleration channel (AC) of ∅230 mm and with an operating power of up to 25 kW, called as SPT-230 (Figure 1).

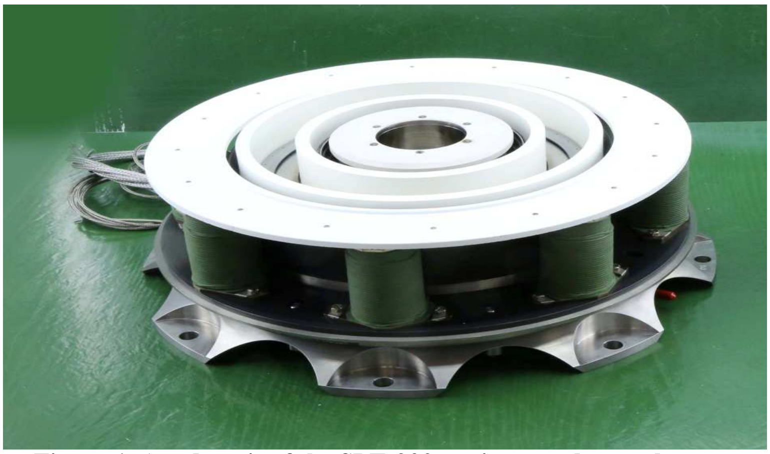

Figure 1. Anode unit of the SPT-230 stationary plasma thruster

A classical SPT scheme is the basis of the thruster design. The thruster anode unit traditionally contains magnetic and discharge systems. The magnetic system contains a magnetic circuit with magnetic screens, internal and external sources of magnetization of solenoid type, and magnetic poles. The discharge chamber represents an extended ceramic channel, in the depth of which an anode-gas-distributor is located.

When creating the SPT-230 thruster the experience of development of SPT-140-type thruster was taken into account. This thruster has passed qualification according to Russian programs and has a life of not less than 4500 hours.

To ensure high-efficiency operation of SPT-230, the magnetic system has been modernized. As a result of this modernization the losses in the magnetic circuit have been reduced and gradient of magnetic induction in the thruster acceleration channel has been increased. Also, taking into account thruster outline dimensions the gas supply system that supplies gas into the discharge chamber has been optimized to ensure high uniformity of operating gas distribution in terms of both azimuthal direction and along the whole width of the channel.

Specific feature of the SPT-230 as compared to its prototype is the possibility to locate the cathode-compensator along the thruster axis.

Two cathodes-compensators were designed for the SPT-230 thruster:

- A Unit K with the K-25M cathode operating at a discharge current of up to 25 A;
- A Unit K with the K-50 cathode operating at a discharge current of up to 50 A;

Both Units K represent sources of electrons made on the basis of a hollow cathode with the propellant going through it.

The external view of the cathode unit as well as parameters of the K-25M cathode are presented in Figure 2 and Table 1 respectively. The external view as well as parameters of the K-50 cathode are presented in Figure 3 and Table 2.

Table 1 - Parameters of the K-25M cathode developed by EDB Fakel

Figure 2. External of the Unit K with the K-25M cathode

Parameter	Value
Xenon flow rate, mg/s	(0.80±0.05)
Emitter material	Lanthanum hexaboride (LaB_6)
Heating power, W	<140
Discharge current, A	up to 25
Note	Engineering model

Table 2 - Parameters of the K-50 cathode developed by EDB Fakel

Figure 3. External of the Unit K with the K-50 cathode

Parameter	Value
Xenon flow rate, mg/s	0.90_{min}
Emitter material	Lanthanum hexaboride (LaB_6)
Heating power, W	<360
Discharge current, A	up to 55
Note	Engineering model

III. Experimental investigation of the SPT-230 thruster

A. Vacuum test stand description

The SPT-230 thruster was tested in the KVU-120 vacuum test stand of EDB Fakel (in Kaliningrad) at discharge voltages of 300 V to 800 V within the anode flow rate range of 4.5 to 30.0 mg/s and the cathode flow rate of up to 1 mg/s. External view of the KVU-120 test stand and its parameters are presented in Figure 4 and Table 3 respectively.

Table 3 – Parameters the KVU-129 test stand

Figure 4. External view of the KVU-120 test stand

Parameter	Value
Volume, m^3	120
Static vacuum pressure, Torr	less than $5.0 \cdot 10^{-6}$
Dynamic vacuum pressure, Torr	less than $2.0 \cdot 10^{-4}$
Pumping speed, l/s, Xe	100000
Discharge power supply:	
Current, A	up to 35
Voltage, V	up to 800

Xenon is supplied to thruster anode unit through a flow control module and two independent supply systems with flow regulators / flow meters are used to supply xenon to the thruster anode and cathode.

A balance-type thrust measuring device with a measuring range of up to 1.0 N was used in the vacuum chamber to measure the thrust.

B. Data processing procedures

Thrust and all the electrical parameters of the thruster were determined using a direct method, i.e. processing of appropriate data does not require any discussions. As to the thruster parameters that characterize thruster efficiency (specific impulse and thrust efficiency) it should be noted that when processing the data obtained during thruster operation the inflow of the operating gas from the vacuum chamber was taken into account. At that, to calculate the additional flow rate ΔG_a through the acceleration channel during thruster operation, a correction for vacuum proportional to the area of the thruster acceleration channel cross section was introduced. Taking into account the fact that according to EDB Fakel data for SPT-100-type thruster

$$\Delta G_a \approx 1500 \cdot P_{v/c} \qquad (1)$$

for SPT-230 thruster operating with xenon the coefficient in front of pressure in the equation (1) was taken equal to 3100.

Therefore, the SPT-230 anode flow rate with the account of the propellant backflow from the chamber was calculated using the following equation:

$$G_{\sum a} = G_a + \Delta G_a \qquad (2)$$

where $\Delta G_a = 3100 \cdot P_{v/c}$.

C. Reference performance test

During the test the thruster operated stably in the mode of "needle" that is characterized by a high value of thrust due to the increased discharge current value and, as known, due to a lower plasma plume divergence.

The thruster was tested at discharge currents of 15 to 30 A within the voltage range of 300 to 800 V. SPT-230 thrust, specific impulse, and thrust efficiency as a function of power and voltage are presented in Figures 6 – 9 below.

The maximum thrust value was registered when operating with the K-50 cathode at a discharge current of 30.0 A and at a discharge voltage of 800 V and was equal to 1030.00 mN. The maximum efficiency calculated taking into account correction for vacuum and the cathode flow rate was registered when operating with the K-50 cathode at a discharge current of 20.0 A and at a discharge voltage of 700 V and was equal to 72%.

Figure 5 shows the view of thruster plume in the vacuum chamber of the KVU-120 test stand.

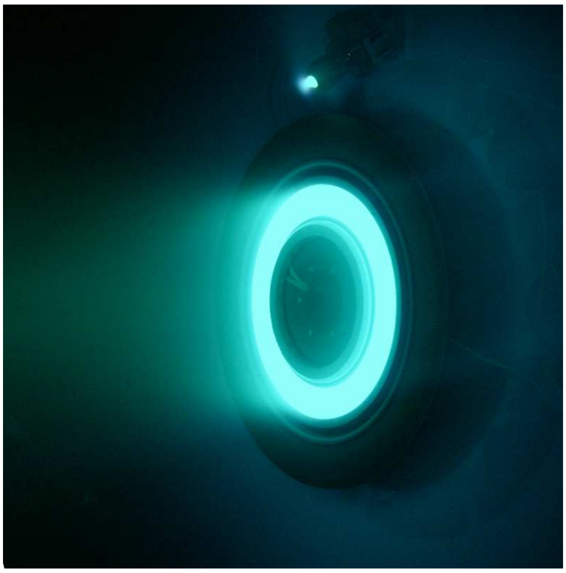

Figure 5. View of the SPT-230 plasma plume in the mode of 300 V / 25 A

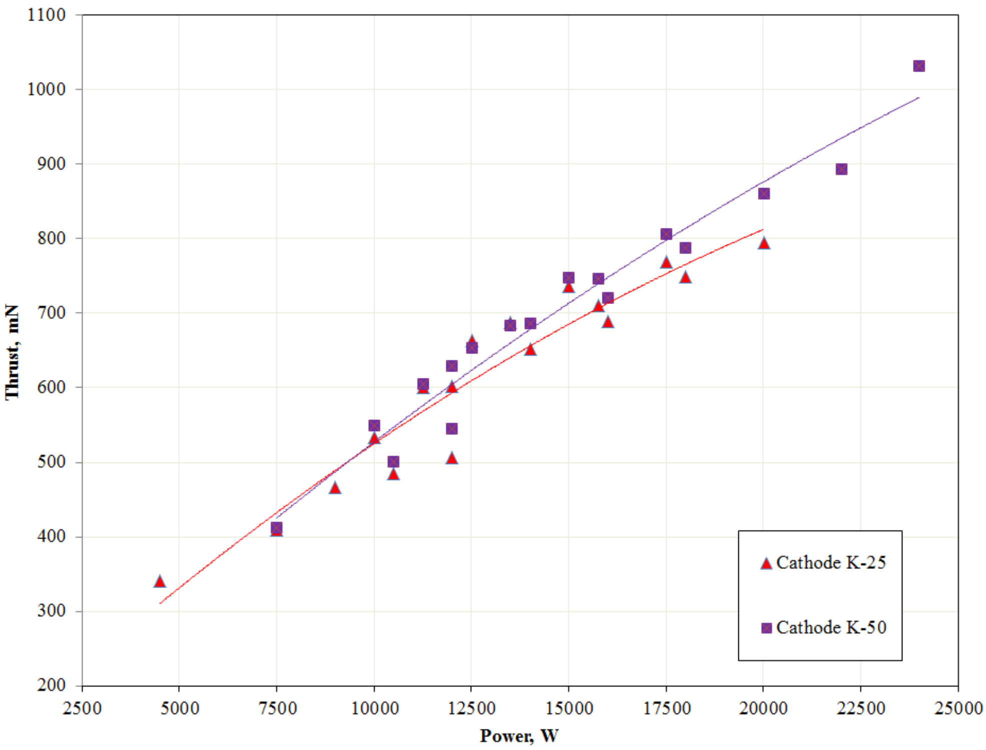

Figure 6. Thrust as a function of power when operating with K-25 and K-50 cathodes

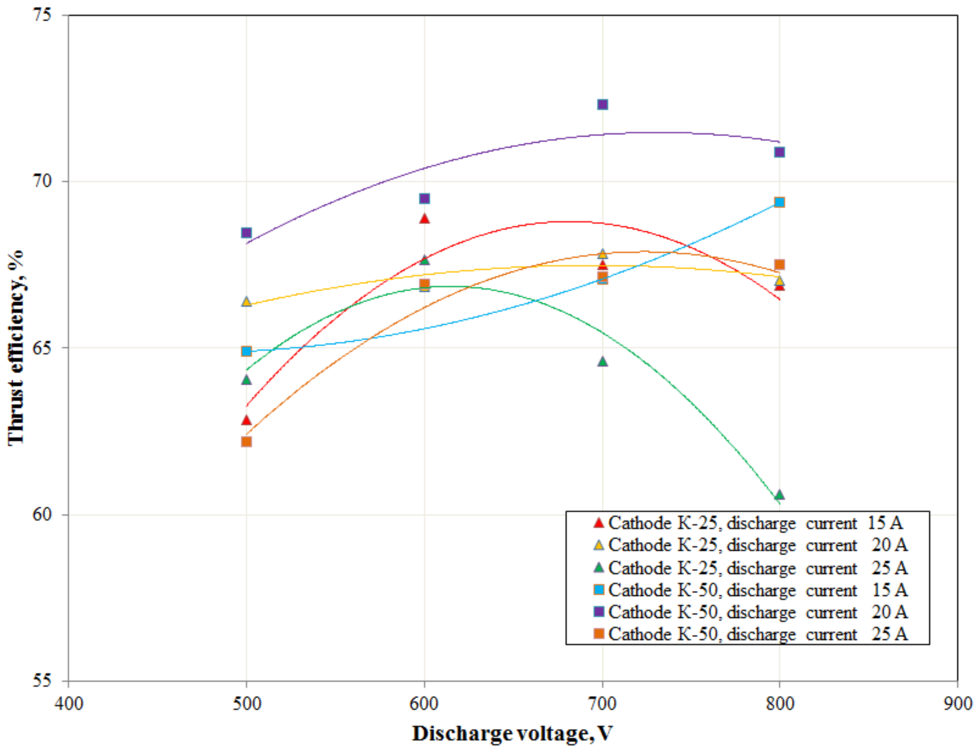

Figure 7. Thrust efficiency as a function of discharge voltage when operating with the K-25 and K-50 cathodes

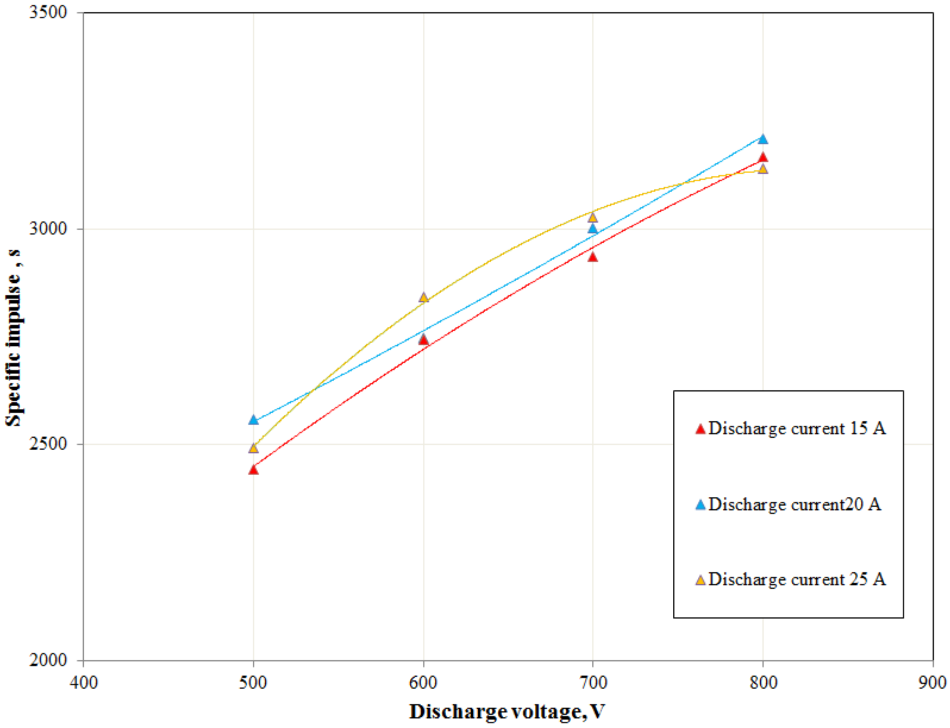

Figure 8. Specific impulse (of the anode) as a function of discharge voltage when operating with the K-25 cathode

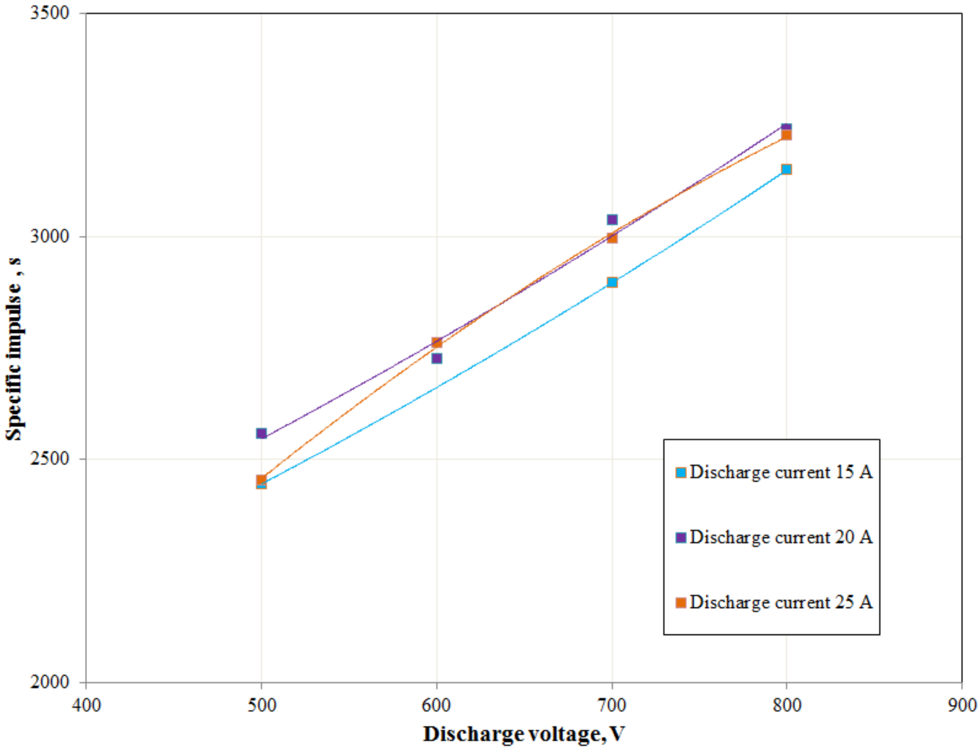

Figure 9. Specific impulse (of the anode) as a function of discharge voltage when operating with the K-50 cathode

D. Long-term operation

The thruster long-term operation was performed at a discharge voltage of (500±5) V and a discharge current of (25.0±1.0) A. The cathode heater current during the startup was (18.5±0.5) A. The test was performed in the modes of long firings – up to 8 hours. The total accumulated operating time during the test was 50 hours. The values of thrust and specific impulse during the test are presented in Figures 10 and 11 respectively.

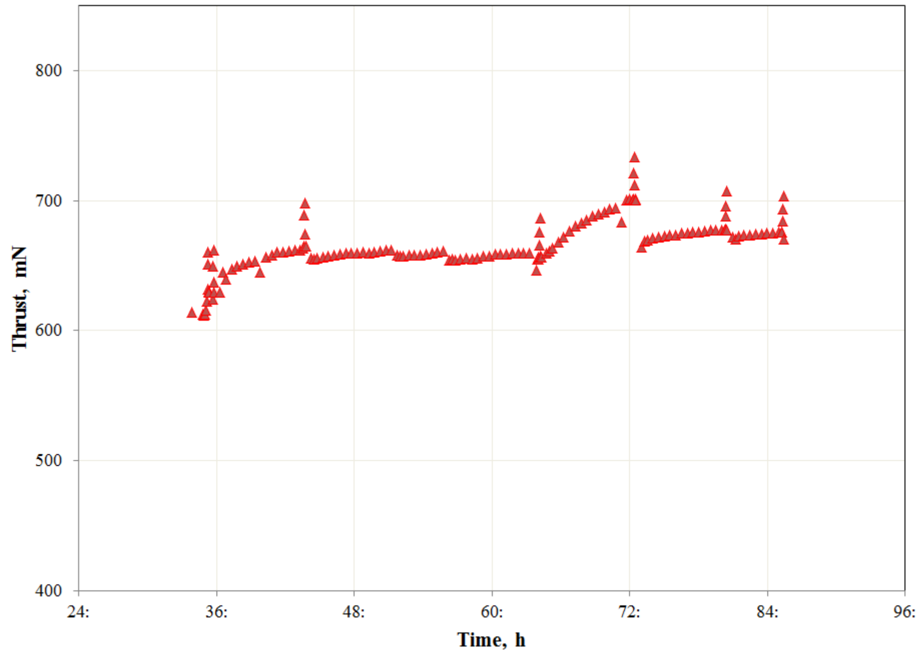

Figure 10. Thrust as a function of time during the long-term operation with the K-25 cathode

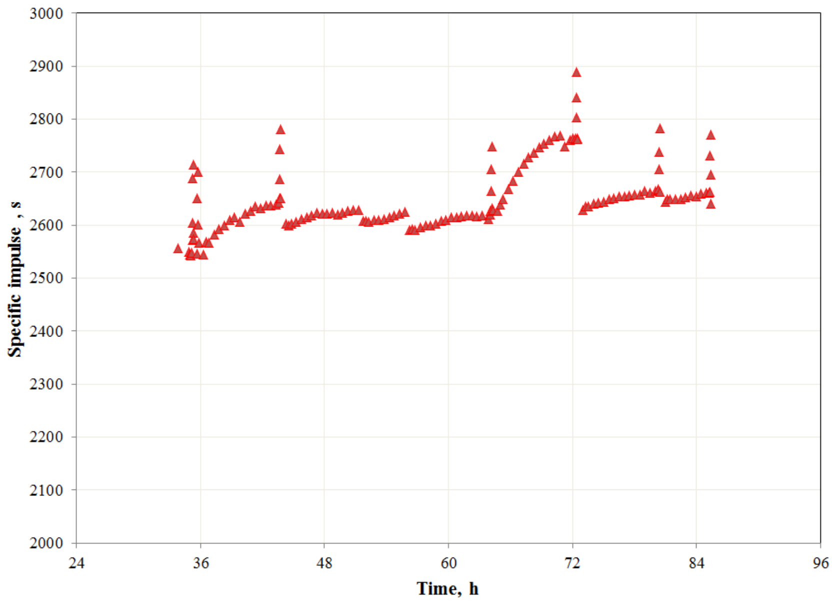

Figure 11. Specific impulse as a function of time during the long-term operation with the K-25 cathode

IV. Evaluation of the SPT-230 characteristics

Preliminary evaluation of SPT-230 characteristics during the thruster operation in the mode at a nominal discharge power was performed by comparing the rate of wall erosion at the edge of the discharge chamber of this thruster with the rate of wall erosion at the edge of the discharge chamber of the SPT-140 thruster which is the most close to the SPT-230 thruster in terms of dimension.

To determine the SPT-230 discharge chamber channel wall erosion rate, the erosion value was measured during full duration of the firing test, and the operating time equivalent to the operating time at nominal discharge power was determined. The measured erosion values for the internal and external walls at the discharge chamber edge were 1.5 and 1.0 mm respectively.

The calculated values of the erosion rate for the internal and external walls of the SPT-230 discharge chamber during the first 100 hours of operation in the mode of nominal discharge power were 0.017 and 0.011 mm/h respectively.

The comparative analysis of the obtained values of erosion rates for the SPT-230 walls and the values of erosion rates for the SPT-140 discharge chamber walls demonstrates that the values of erosion rates for the SPT-230 walls are close to the values of erosion rates for the SPT-140 discharge chamber walls. During the first 100 hours of testing of the SPT-140 thruster the internal wall erosion rate was 0.016 mm/h and the external wall erosion rate was 0.018 mm/h. These values of the wall erosion rates were obtained in the course of the SPT-140 life test with a duration of 1400 hours. Thus, to evaluate SPT-230 life characteristics, the SPT-140 life test results can be used.

Evaluations performed using the predicted SPT-140 life characteristics demonstrated that when operating in the mode of nominal discharge power the whole available thickness of insulator at the SPT-230 discharge chamber edge will be eroded in 7500 – 8000 hours what is not a limiting factor of the thruster life.

V. Conclusion

EDB Fakel has designed, manufactured, and tested a high-power SPT – SPT-230.

During the test of SPT-230 the possibility of thruster operation in the wide range of discharge voltages and xenon flow rates while ensuring thruster performances has been validated.

In future some additional tests of the thruster also with central location of the cathode are planned.