

# Ablative Pulsed Plasma Thrusters R&D in Russia since the Beginning of the 90s

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**Abstract:** On December 14, 1964 Ablative Pulsed Plasma Thrusters (APPT) were first tested in the Zond 2 spacecraft and these were the first application of electric propulsion on any spacecraft. Successful launch and testing significantly increased the interest in the research and development of various types of electric propulsion. As a result, APPT about half a century ago fulfilled their role, paving the way for electric propulsion in space. After that several APPT have been used for attitude control and station keeping on a number of satellites. However, the applications of APPT in space constrained by the limited tasks for these thrusters. Since the early 90s the possibilities of APPT application to satisfy mission requirements were increased due to the miniaturization of space hardware. Typical needed total impulses are at the level of several kilo Newton-seconds. So, the appearance of small satellites (SSC) significantly expands the range of tasks that can address the APPT. Development and production of high efficiency plasma thrusters with power consumption at the level of 100 W or less for SSC attitude control and station keeping became promising. Accordingly, the activity of work in APPT R&D increased both in the world and in Russia. Beginning from 90s, a wide spectrum of works on APPT from basic research on physical processes in plasma up to space applications were initiated in Russia. Main activity was carried out in RIAME MAI, NRC “Kurchatov Institute” and “VNIEM” Corporation. So-called “side-fed” system of rectangular geometry, using two propellant (Teflon) bars was chosen as optimal for practical application.

## I. Introduction

On December 14, 1964 the Zond-2 spacecraft first used electric propulsion system. Ablative pulsed plasma thrusters (APPT) with electrothermal plasma acceleration, served to provide three axis attitude control. After successful launch and testing, the interest in the research and development of various types of electric propulsion significantly increased. As a result, APPT about half a century ago fulfilled their role, paving the way for electric propulsion in space. After that several APPT have been used for attitude control and station keeping on a number of satellites<sup>1,2</sup>. However, the applications of APPT in space constrained by the limited tasks for these thrusters. Since the early 90s the possibilities of APPT application to satisfy mission requirements were increased due to the miniaturization of space hardware. Typical needed total impulses are at the level of several kilo Newton-seconds. So, the appearance of small satellites (SSC) significantly expands the range of tasks that can address the APPT. Development and production of high efficiency plasma thrusters with power consumption at the level of 100 W or

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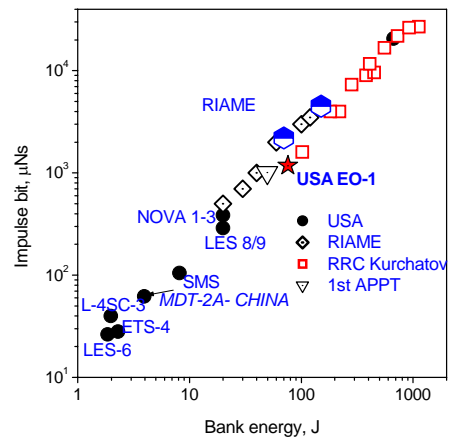
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less for SSC attitude control and station keeping became promising. Accordingly, the activity of work in APPT R&D increased both in the world and in Russia. Beginning from 90s, a wide spectrum of works on APPT from basic research on physical processes in plasma up to space applications were initiated in Russia. Main activity is carried out in RIAME MAI, NRC “Kurchatov Institute”(NRC KI) and VNIEM Corporation. So-called “side-fed” system of rectangular geometry, using two propellant (Teflon) bars was chosen as optimal for practical application<sup>3</sup>.

The experimental part of the work was pointed to the study of energy transferred from plasma to the surface of the propellant bar. We measured the propellant mass losses, discharge current and the voltage on the electrodes. The dynamics of boundary layer near the propellant surface, propellant mass, which does not take part in acceleration (late time ablated mass), parameters of the plasma flow in the accelerating channel have been studied.

2D time-dependent MHD model of plasma acceleration in a coaxial APPT has been developed. The main attention was devoted to the boundary conditions at the entrance of the accelerating channel, which largely determine the dynamics of the plasma acceleration. Propellant flow calculated from the kinetics of thermal decomposition of PTFE used the measured energy flow to the propellant surface. The experimental data were analyzed and approximated to use as the boundary conditions at the inlet APPT.

The improved APPT performance were obtained when the optimum correlation between the electric circuit parameters and the accelerating channel dimensions takes place together with aperiodic form of a discharge current. For further increasing of APPT efficiency, as well as to preserve the achieved efficiency during the development APPT flight prototypes, it is necessary to more clearly understand the physical processes in the accelerating channel. For this purpose a run of experiments was conducted to study the working process in the APPT. This made it possible to develop a new generation of high-efficiency APPT in a wide range of bank energies. Currently RIAME MAI developed a number of EPS with bank energy from 8 J to 155 J (electric propulsion APPT-95 was developed in conjunction with VNIEM Corporation), including two flight prototypes: APPT-45-2 and APPT-95M. Fig. 1 shows some Russian and foreign laboratory and flight APPTs in the coordinates: total impulse - bank energy.



**Figure 1. Impulse bit – bank energy dependences for experimental and space APPT.**

General respectable review on APPT<sup>1</sup> presents all over the world consideration. This paper presents the main activity in Russian Federation in the field of APPT R&D from 90s to present.

## II. Ablation-Fed Discharge Study

Ablation-fed discharge is studied in RIAME MAI and NRC KI. APPT, developed in RIAME<sup>4,5</sup> APPT have discharge channel formed by flat copper electrodes and Teflon bars of rectangular geometry. The APPT schematic and photo of electric discharge are shown in Fig. 2.

The simplest thruster comprising: a capacitor bank as a storage unit; electrodes; breach insulator, PTFE propellant and high-voltage spark plug. Electrodes, breach insulator and propellant form the accelerating channel. In thermal mode an efficiency of a thruster is very low and often less than a few percent. In NRC KI, the coaxial breach-fed APPT with high-energy electrical discharge of 100 - 10000 J and duration of 10 - 1000 ms are studied. The APPT schematic and photo of electric discharge are shown in Fig. 3.

### A. Electrical Discharge Characteristics

Electrical measurements (RIAME, NRC KI) include the discharge current, voltage and the magnetic field measurements. The discharge current was measured by the Rogowski coil connected to low inductance and low resistance shunt. The voltage across the capacitor bank and at other points was measured by capacitive voltage dividers. Energy fluxes dissipated in sample and calorimetric measurements used low dimension (1 mm scale) thermistor. Temperature and electron density are measured with use of spectral and interferometric measurements.

Side-fed thruster has capacity storage including several capacitors with energy (20-100) J. Thrust efficiency of the upgraded APPT at the energy of (20-100) J ranges from 12 % to 24%, accordingly. The typical discharge current

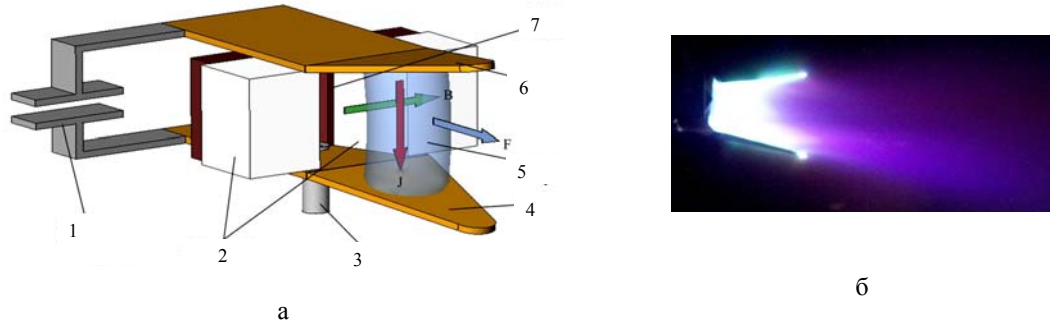


Figure 2. a-schematic of rectangular side-fed APPT, 1- electric circuit, 2- propellant, 3- spark plug, 4, 6- electrodes, 5- plasma blob, 7- breach insulator; b- photo of electric discharge.

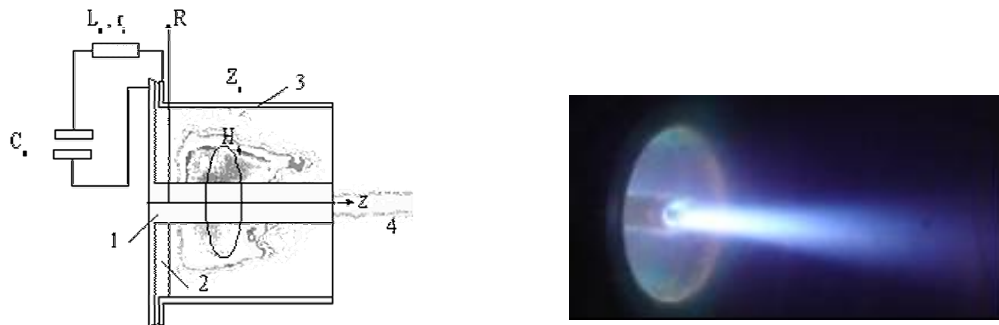


Figure 3. a-schematic of coaxial breach-fed APPT and photo of electrical discharge, 1- cathod, 2- Teflon propellant, 3- anode, 4- plasma flow, C, L, r – electric circuit parameters.

curve for such kind APPT is shown in Fig. 4. As it is seen discharge current is close to aperiodic. The data on discharge current, plasma component velocities and charged particle distributions, obtained by using the magnetic probe and optical spectrometer, show that in high efficient APPT the essential modification of the operating processes takes place<sup>6</sup>. It is shown that in a wide range of variation in stored energy upgraded APPTs provide near two fold increase of the thrust efficiency as compared with typical APPTs. Spectroscopic measurements as well as magnetic probing show the significant modification of APPT operating processes. Moreover the character of this modification clearly testifies about positive changes in processes of the propellant formation and acceleration as well as discharge current concentration zone motion along electrodes. As a result the better local-temporary compatibility of both mentioned processes was realized and it was also attained that most of propellant (up to 70 %) was accelerated by the action of electromagnetic force.

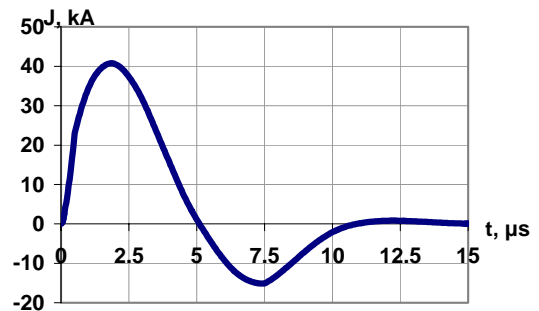


Figure 4. Time dependencies of the discharge current  $I$ , with 50 J capacitor bank.

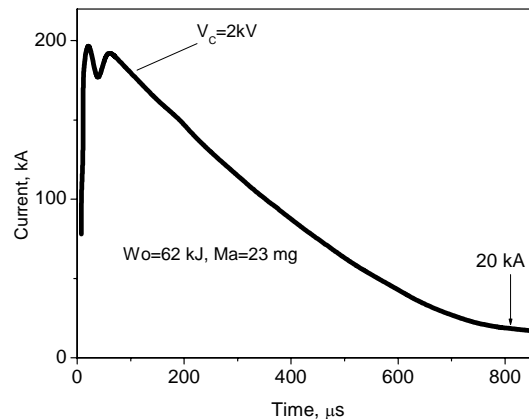
The developed semi-phenomenological numerical model<sup>7</sup> allows one to find the optimal operating conditions for APPT under which the maximal efficiency of energy conversion from the power source to the kinetic plasma energy is obtained. The calculated integral APPT-parameters (impulse bit, evaporated mass, efficiency) are close to the experimentally measured ones. The experimental results obtained give now the possibilities to process these on the base of APPT MHD model. It becomes possible to produce experimentation- modelling interpretation.

### B. Quasy-Steady Ablation-Fed Discharge. Millisecond discharge APPT

To study quasy-steady operation of APPT in wide range of discharge time<sup>8</sup>, coaxial breach-fed APPT was used. External and internal electrodes having 10 cm and 2 cm in diameters were manufactured from copper. It described in detail in<sup>9</sup>. APPT was connected to power source formed with two capacitor banks. First one is 30 kV with capacitance equal 97  $\mu$ F. Second has capacitance of  $3 \cdot 10^{-2}$  F with maximal charging voltage equal 5kV. In beginning the discharge arises after switching on high voltage bank discharge. Time of increase of a current in a discharge is near 10  $\mu$ s. At the time of maximum of a current second bank was connected to APPT by means of high current switches. Such a way we could realize experimentally ablation-fed discharge with wide range discharge current and millisecond discharge time.

APPT generate quasy-steady plasma flow within discharge currents in a range of 15 kA – 200 kA. During a discharge near 70% of energy stored in power source was transferred to APPT.

High speed photo registration near APPT outlet show that plasma flow with diameter of 2 cm is formed. This has lifetime near 1 ms. Divergence of plasma flow corresponds to a temperature of plasma near 2 eV. Calorimetric measurements have shown, that plasma flow contains, at least, 30 kJ, that makes about 53 % of the energy transferred to the discharge. Integral mass flow rate attains 23 mg. Discharge current in APPT is given in Fig. 5. Teflon behavior does not prevent long time (1 ms) existence of ablation-fed discharge more than for 100 firings.



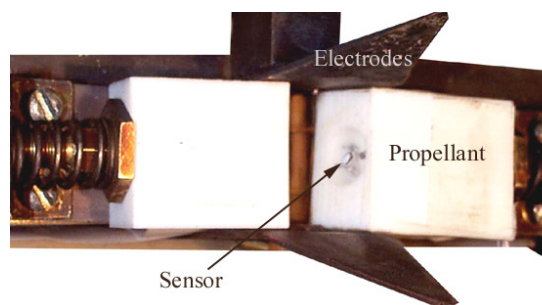
**Figure 5. Ablation-fed millisecond range quasi-steady discharge current.**

### C. Propellant Behavior Study

Measurement of energy bit dissipated in a propellant bar per one firing become possible if one uses thin separated Teflon film instead of propellant bar. Method of measurement of energy dissipated in skin layer is described in<sup>10</sup>, where the breech-fed model was studied. Discharge channel of studied side-fed model and placement of sensor are shown in Fig. 6.. Energy flux propagated to the propellant surface was measured with the tool based on low dimensions (1 mm scale) thermistor.

To measure energy dissipated in thermal skin layer the discharge was produced on the surface of thin Teflon film, which was closely pushed or glued to the sensor. Energy flux absorbed in the Teflon film transferred to the sensor. So, sensor absorbed energy bit produced temperature increase and a change in the sensor resistance.. Main purpose of this experiments is to obtain data connected with energy transfer to the propellant and its ablation.

Thermal energy dissipated per one discharge increases on 30% with increasing of bank energy from 16 J to 60 J. Such a way propellant receives near 0.1 J/cm<sup>2</sup> per one shot and main energy propagated from discharge to propellant is spent for evaporation (degradation). This value is near 0.4 J/cm<sup>2</sup> that yields 50  $\mu$ g/cm<sup>2</sup>. Accounted values are close to experimentally measured and weakly dependent on energy flux dissipated from a discharge. So, calculated energy



**Figure 6. Side-fed propellant accelerating channel.**

transferred to heating of propellant bar attains  $0.23 \text{ J/cm}^2$  and does not change with further increasing of total energy flux density.

The base of modeling<sup>11,12,13</sup> were several degradation mechanisms. All the quantitative data are referred to Teflon usually applied in the APPT. Example of modeling of propellant ablation is shown in Fig.7 where time dependencies of energy flux onto propellant,  $H$ , ablated mass,  $M_{ABL}$ , surface temperature,  $T_S$  and evaporation energy  $\epsilon$  are presented. The comparison of the calculated results with integral experimental data has a conditional nature. Really, the propellant surface area, from which PTFE- ablation goes on, depends on time. A change in the ablated area is affected on the efficiency of thruster operation and results in a change in the energy flux onto the propellant. However, there is a sufficiently good quantitative and qualitative agreement between the experimental data and the calculations.

#### D. Numerical Modeling

RIAME and NRC KI are working on the simulation of the plasma inside and outside the thruster. Presently 1D and 2D non-stationary MHD models are used in simulation of APPT plasma. One-dimensional models are useful for modelling of acceleration dynamics, connection with electric circuit, plasma formation near propellant surface. The results of numerical modelling in 1D are usually good analysed and interpreted. Numerous experiments show that the plasma flow in coaxial APPT is essentially two-dimensional; there are current loops in the accelerating channel, flow focusing towards the APPT-axis is observed etc. Therefore a 2D model is expedient to be used for an adequate representation of plasma flow geometry and focusing in such thrusters. In ideal case 2D model must obtain better correlation of calculated integral parameters of the thruster with experimental data. 2D MHD - model of plasma acceleration in APPT can additionally simulate phenomena connected with geometry of accelerating channel and flow<sup>14,7</sup>. The results of 2D numerical modelling are not simple for analysis and interpretation and often these needs to expand and repeat.

We developed the 2D MHD model of plasma acceleration in coaxial APPT<sup>7</sup> using experimental data. Main attention is devoted to conditions at the inlet of accelerating channel, which dramatically determine plasma dynamics in accelerating channel. Boundary conditions for propellant flow rate are based on the of energy flux propagated from a discharge to propellant. Propellant flow rate is accounted from kinetics of thermal degradation of Teflon with use of measured energy flux onto propellant. Data obtained is analyzed, approximated to be serving as boundary condition for APPT.

The objective of the works is to analyze the distinctive features of physical processes in APPT to study these through the use of different diagnostic methods, tests and numerical modeling. This makes possible to develop next generation APPT, with increased thrust characteristics. Developed numerical model is a tool to improve thruster parameters. Example of accounted plasma density distribution in coaxial acceleration channel is presented in Fig. 8. The model gives a correct qualitative picture of separate stages of discharge in APPT: plasma flow formation, appearance of tubular structure at the end of the central electrode, focusing of a flow, appearance of low accelerated mass near the zero of the bank voltage etc. The features of propellant flow rate determine monotonous character of distribution of density and especially axial velocity of plasma, and magnetic field in accelerating channel.

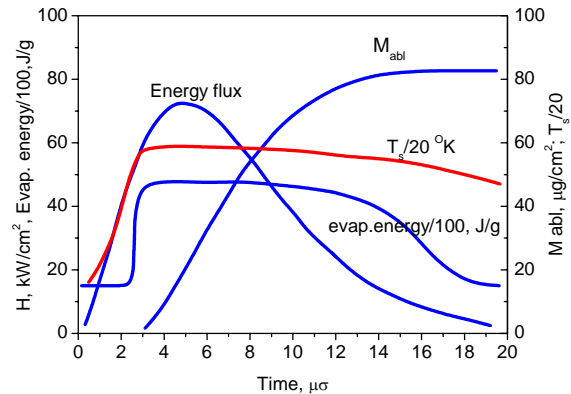


Figure. 7. Time dependencies of  $H$ ,  $M_{ABL}$ ,  $T_S$  and  $\epsilon$  for  $H_{MAX}=75 \text{ kW/cm}^2$ .

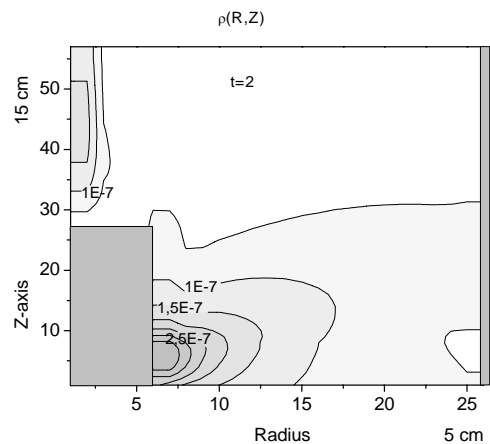


Figure 8. Plasma density distribution in APPT accelerating channel ( $t= 10 \mu\text{s}$ ).

## E. APPT Optimization

Optimization of APPT performance have been done due to finding the optimum relations between the electric circuit parameters and the discharge channel dimensions, realizing the quasi-aperiodic discharge in the thruster and optimising the current distribution in the discharge channel<sup>15</sup>. For further APPT efficiency increasing, especially for APPT having low bank energy, as well as for retaining the achieved efficiency under APPT manufacturing, it is necessary to understand more clearly the physical processes in thruster discharge channel. In particular, it is required to have adequate understanding of propellant ablation and ionization at the inlet of APPT to control this for APPT discharge optimization.

Development of APPT having high efficiency includes: a) reducing of propellant ablation, especially late-time ablation; b) optimization of a discharge, accelerating channel geometry and electric circuit parameters. The reducing of mass flow rate in APPT seems should be solved experimentally due to extremely complicated character of this problem for adequate modeling. Other part of work could be solved numerically.

Currently three directions seem could improve thruster performance: decreasing post-discharge evaporation or late-time ablation, increasing energy density in accelerating channel, optimization of energy transfer. Last two items have been studied in detail. Late-time ablation experimental studies meet difficulties due to small scale of interesting area. So, modeling is very important here. Developed models can explain the mass loss in a frame of thermal degradation kinetics, if maximum energy flux to the propellant exceeds 30 kW/cm<sup>2</sup> (integral flux more than 0.2 J/cm<sup>2</sup>). Moreover, it is necessary to have more experimental data of propellant ablation and ionization<sup>16</sup> at the inlet of APPT to control this for the discharge optimization. RIAME and NRC KI obtained extended data base for high efficiency APPT in bank energy range (20 - 1000) J. The thrusters are presented in Fig. 1 together with other known ones in bank energy - impulse bit diagram. It is seen that in a wide range of variation in stored energy of upgraded APPTs provide near two fold increase of the thrust efficiency as compared with typical APPTs. Spectroscopic measurements as well as magnetic probing show the significant modification of APPT operating processes. Moreover the character of this modification clearly testifies about positive changes in processes of the propellant formation and acceleration as well as discharge current concentration zone motion along electrodes. As a result the better local-temporary compatibility of both mentioned processes was realized and it was also attained that most of propellant (up to 70 %) was accelerated by the action of electromagnetic force. Mean current density become significantly lower than in discharge channel of the previous generation of APPTs.

APPTs with bank energy in a range (100-1000) J are often electric propulsion devices working in electromagnetic mode of operation, that have increased specific impulse on the level of (1500-4400) s. Experiments have shown relatively high efficiency of input energy transfer to energy of directed plasma flow. Main energy sinks for losses are in electrodes and energy source. Energy source losses can be significantly decreased. Typical parameters of the initial and upgraded APPTs: bank energy, impulse bit and efficiency are given in the Table 1.

**Table 1. Typical values of the initial and upgraded APPTs**

$W_{\text{bank}}, \text{ J}$	$P_{\text{bit}}, \text{ mNs}$	$P_{\text{bit}}, \text{ mNs}$ UPGR	$I_{\text{sp}}, \text{ s}$	$I_{\text{sp}}, \text{ s}$ UPGR	$\eta$	$\eta$ UPGR
20*	0,3	0,45	0,3	0,45	0,06	0,12
40*	0,7	0,9	900	1300	0,08	0,15
100*	2,2	2,7	1060	1600	0,12	0,22
102**		1.6		1500		0.25
182**		2.6		2400		0.23
284**		4.3		3100		0.29
557**		7.9		4370		0.30
728**		12.6		4370		0.45
921**		18.9		4490		0.68

\*Rectangular side-fed accelerating channel APPT in RIAME.

\*\* - Coaxial accelerating channel APPT in NRC KI.



### III. APPT models development

#### A. High Efficiency APPT development

Optimization of the electric circuit parameters and geometry of the accelerating channel allow to obtain the maximum possible contribution to the APPT efficiency with a relatively high specific impulse. Nevertheless, there is a significant temporary mismatch of input power and propellant flow rate. A significant part of a propellant enters the acceleration channel is already after the discharge is almost ended. This portion of propellant is accelerated only to thermal velocities, resulting in a reduction of the specific impulse and thrust efficiency. In general, despite the circuit and structural simplicity and cheapness, the new generation of high APPT requires typically long time and costly experimental refinement. Thus, depending on the set of optimization criteria, it is a necessary to find a compromise between the electrodynamic efficiency, correlation of input power and propellant flow rate to the discharge channel, and other characteristics of the thruster.

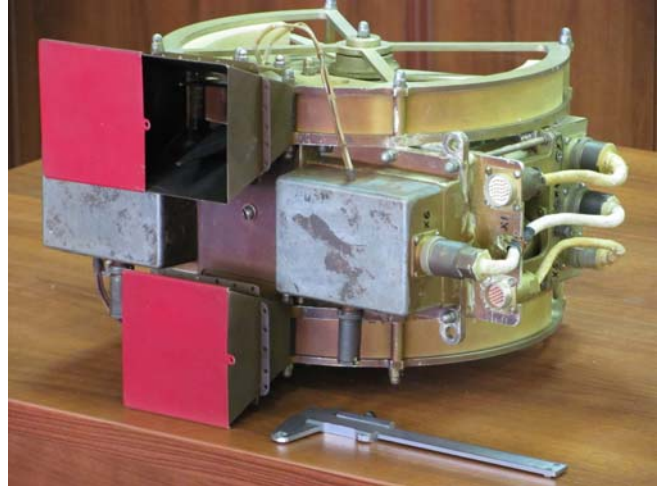


Figure 9. Appearance of EPS based on APPT-45-2.

Currently, RIAME has developed a number of propulsion systems with discharge energy from 8 J to 155 J. The main characteristics of the EPS are presented in Table 2. Appearance of one of the EPS, which took full range of ground experimental testing, is shown in Fig. 9. All propulsion systems designed to correct and maintain LEO SSC.

Table 2. Characteristics of EPS based on APPT developed in RIAME.

EPS Type	APPT-20	APPT -45-2	APPT -155	APPT -95
Status	Flight prototype	Flight model	Flight model	Flight model
Bank energy, J	20	55	88	155
Power, W	60	75...150	70...140	170
The number of pulses	$2 \cdot 10^6$	$1,67 \cdot 10^7$	$1,5 \cdot 10^7$	$1,5 \cdot 10^7$
Specific Impulse, c	716	1100	1320	1600
Thrust, mN	0,9	1,44...2,9	1,4...2,8	3,5
Total impulse, kNs	0,7	20	30	52
Total EPS mass, kg	3,0	10,5	14	20
Thrust/mass, mN/kg	0.3	0.274	0.2	0.175

Discharge energy directly determines the size of the acceleration channel, capacitor bank APPT and cross-sectional area of the propellant body. Therefore, as can be seen from Fig. 10 and Fig. 11, the discharge energy of the capacitor bank and total mass is uniquely determined the given total impulse. The average thrust of APPT almost linearly dependent on the power consumption. A slight deviation from linearity is due to increasing specific impulse with increasing discharge energy.

Currently, EPS based on APPT-45-2-155 and APPT APPT-95 are the most worked out. They passed total volume of ground testing and are in the process of acceptance testing<sup>17</sup>.

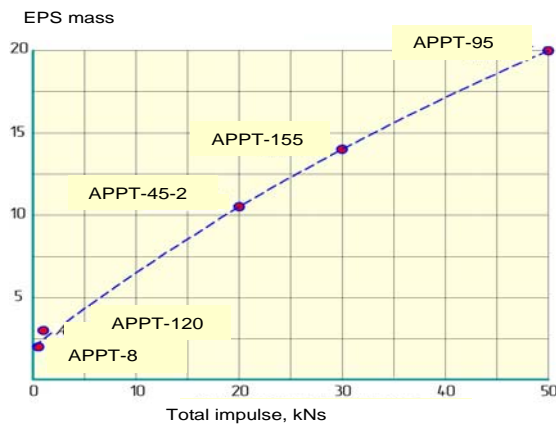


Figure 10. EPS mass dependance on total impulse.

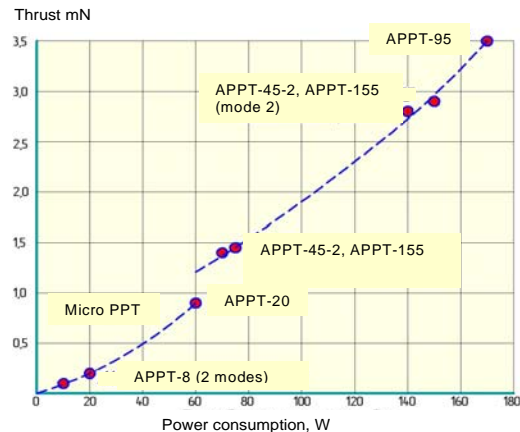


Figure 11. Dependence of thrust on power consumption.

### B. Micro APPT

Numerous expert estimations show that a lot of scientific and applied tasks in space in the near future will be dealt with the help of spacecrafts whose mass is 50 kg or less, including the so-called “minute” spacecrafts with mass of 10 kg. Such spacecrafts are most effectively used in orbital groups which vary from several to several hundred of SSC. In order to provide a quasi-continuous observation of a ground area and a real-time information delivery to the user, a multisatellite orbital space system based on use of minute spacecrafts should be utilized. A system like this is appropriate for the task because is cost-beneficial. Therefore, implementation of micro-spacecrafts-based space systems is a new, promising and essential space technology development line.

The need to conduct regular adjustments and to hold the orbit of micro spacecrafts during its whole running term implies the development of high-performance small-sized thrusters. Light-weight and low-price PS are preferred because of the strict manufacturing cost and operation limits, as well as the limitation of mass and electrical energy supply onboard the spacecraft. This kind of devices has high-efficient power consumption of up to 20W.

Micro ablation pulsed plasma thruster (micro-APPT) is a thruster capable of meeting a set of requirements imposed upon the low-power PS for micro- and nano-SC to the most extent. APPT is unique among the EP because it is capable of maintaining its working efficiency and work process stability using ~1J of electrical power. Unique design and technologic simplicity predetermining low construction and operation cost, operating capability at power consumption of about several W, and possibility for accurate thrust pulse control objectively provide certain advantages to APPT (with the discharge energy of up to 10 J) over low-power electric propulsions of other types. For this reason a number of laboratory models of APPT has been developed at RIAME, including APPT-8, APPT-5, APPT-5-3, APPT-It(m) with power range from 6 to 45W. The principle of their operation is based on the acceleration of plasma formed as a result of propellant ablation and ionization.

The typical performance parameters of the models are given on Table 3.

Table 3. Performance parameters of the Micro-PPT developed in RIAME.

Parameter	APPT-8	APPT-5	APPT-5-3	APPT-It(m)
Energy, J	8.4	4.5	3.8	5
Power, W	42.18	22.5	16.9	25
Trust Impulse bit, mNs	0.14	0.06	0.05	0.11
Consumption per pulse, $\mu\text{g}$	33.7	Not measured	12.7	35.3
Efficiency, %	3.4	Not measured	2.5	3.5

Micro APPT developed at RIAME has low power consumption while having higher resource and total pulse values. Therefore, it may be considered as the most promising micro propulsion system for orbital corrections of small-sized spacecrafts, as well as for other tasks in SSC movement control.



## IV. Applications

### A. APPT Propulsion Systems for SSC

Developments of APPT in energy range of 30 J -150 J with thrust efficiency from 15 to 40%, total impulse up to 50 kNs and with specific impulse up to 2500 s allow to consider the possibilities of applications in proposed and planned missions. In<sup>18,19,20</sup> Analysis has shown that number of missions can be satisfied with PS based on high efficiency APPT. In particular, the possibilities of application were analysed for many reference and known missions such as Kanopus-V, Gonets-M, Monitor-E, Victoria, Ionosfera etc. SSC in LEO Earth missions are the prospective candidates for APPT PS application. In series of joint papers VNIEM Corporation, RIAME, NRC KI proposed a number of APPT PS. It is shown that APPT based PS for a heavy spacecraft attitude control allows substantial savings in the required total pulse and propulsion system mass in general due to a small impulse bit.

Application of APPT based propulsion system for a small satellite station-keeping and attitude control is perspective also, because comparing to stationary thrusters it allows more precise station-keeping in the orbital point providing better opportunities for onboard equipment. Earth observing (EO) constellation based on eight 350 kg in mass satellites with orbit range 500-900 km have been described<sup>21</sup>. SSCs will be injected into SSO orbits by the launcher STRELA. The following tasks for SSC constellation to be solved: initial correction, phase equalization, orbit inclination and altitude maintenance. The total thrust impulse 77 kNs is necessary for SSC orbit control during its service life<sup>22</sup>. Two LEO Earth missions with circular orbits, 500 km and 900 km altitude were considered with spacecraft mass 350 kg and 1750 kg correspondingly. APPT-95 based EPSs meet the requirements for spacecraft insertion to working orbit and keeping this on sub polar circular orbits in a strip  $\pm (5 - 10)$  km during its service life<sup>23</sup>. As a whole, this works outline the area of APPT applications in LEO.

#### *IONOSFERE Satellite with APPT Based EPS*

Federal Space Agency creates space constellation (SC) "IONOZOND", intended to monitor the geophysical conditions ("space weather"), by measuring the basic parameters of the processes in the upper atmosphere, the ionosphere, magnetosphere, solar activity and the transfer of the data to the Earth for receiving, processing and dissemination of information for RF consumers.

Space segment "IONOZOND" includes 4 satellites "IONOSFERE" and 1 SC "ZOND". IONOSFERE satellites constellation is designed for the operational monitoring of the magnetosphere and ionosphere. The existence of single satellite IONOSFERE on the target orbit for the duration of lifetime is possible in uncorrected mode, but it needs to maintain a phase position of two devices. This requires the use of orbit correction propulsion system (OCPS). A comparative analysis of different types of OCPS showed that a relatively small total impulse (26 kN) required sustaining the phase shift between the two spacecraft can apply for these purposes OCPS based on APPT with redundancy of acceleration channel. This thruster named APPT-95 has been developed in RIAME. Based on the analysis of a number of candidate orbit correction propulsion systems for SC "Ionosphere", OCPS on the basis of APPT-95M was selected. APPT-95M OCPS flight model have been developed and designed. Qualifications testing of OCPS flight prototypes are carried out.

### B. Pulsed Plasma Injectors (PPI)

Modified APPT used as pulsed plasma injectors PPI during the so-called active space experiments, whose purpose is to study the Earth's ionosphere, by exposing it to high-velocity plasma flows. So, in 2009, on the basis of APPT-50 with the discharge energy 50 J at RIAME scientific apparatus was completed and tested. has been installed on the service module of RS ISS. Appearance of PPI-SM is shown in Fig. 12. The main design parameters and technical characteristics of PPI-SM close to the parameters and characteristics of the APPT-50<sup>19</sup>. In 2012, RIAME under orders of "RSC" ENERGIA" began to develop plasma injector PPI500 with input power up to 500 W. PPI-500 will be used as part of the space experiment "Impulse. Stage 2." The main objective of this experiment is to study the impact of high-velocity plasma flows with the ionosphere and to study ionosphere wave reaction to such impact. It was

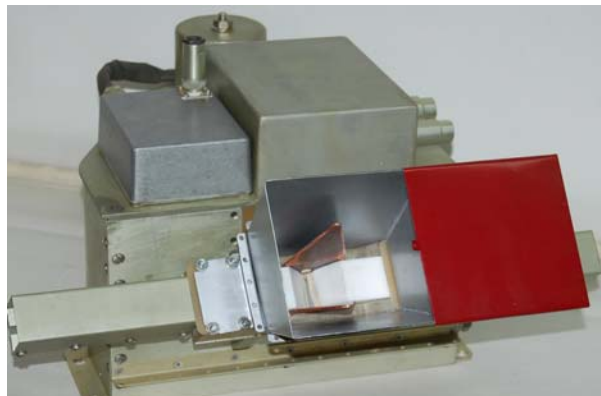


Figure 12. Appearance of PPI-SM.

decided to use coaxial breach-fed PPI-500. This configuration produces much better protecting of the injector from the influence of external factors. Appearance the PPI-500 is shown in Fig. 13.

### C. APPT for Ground Technology Applications

Plasma flow, having power density, which can exceed  $10^8$  W/cm<sup>2</sup> is formed in high power APPT. The pulse duration can be changed from microseconds to several milliseconds. Parameters of the plasma flow in the area of a sample may vary over a wide range. The velocity of the plasma flow with maximal concentration of about  $10^{18}$  cm<sup>-3</sup> reaches  $10^7$  cm/s, the efficiency of conversion of electrical energy into kinetic energy of plasma flow is about 40%, into thermal energy exceeds 60%.

Material processing by means of fluorocarbon plasma produced in APPT is of very limited interest. So, introduction of impurities is produced to enrich the plasma flow with elements required for material processing. The materials having high evaporation temperature are attractive for applications and can be evaporated in considered plasma flow due to its high power density. For these purposes special schema, based on the impact of a plasma flow with pellets, which are distributed in space in the form of dust-like structure is used<sup>24,25</sup>. Pellet dimensions are in a range of 0.1 – 70 μm. Throughout this process the plasma flow is enriched with impurities. Then this resulting flow interacts with the surface of metal sample. The photo of High power plasma flow interaction with micropowder and then with a sample is shown in Fig. 14.

Surface layer of steel CT-45 receive significant increase in hardness (max. - 3.4 times) under the effect of plasma flow in dependency of the number of plasma shots. Maximal microhardness value obtained for this steel is 904 kg/mm<sup>2</sup>. Electron microscope studies of surface layers in the metal (0.1 μm. deep), have shown that plasma processing resulted in an extremely strong reduction in the size of grains in the material. If the grain size in the initial state was near 20 μm, after the plasma processing it became smaller to - 0.1 - 0.2 μm. Under the plasma flow processing with impurities introduced in, maximal implantation has been obtained with the depth up to 4μm and with the impurity concentration of 2-4%.

Thermal behavior of pellets was analysed on the base numerical model.

## V. International Cooperation

Russian research teams cooperated with CNES in the frame of INTAS programs, EOARD in the frame of ISTC and INTAS grants. From 2007 the cooperation are also in the frame International PPT & iMPD Working Group. Group consists of international scientists from Europe, Japan, Russia, USA and research institutes working in the field of APPT's & iMPD's applications.

## VI. Conclusion

In Russian Federation since the beginning of the 90s effective R&D on Ablative Pulsed Plasma Thrusters have been completed. Wide range studies of ablation-fed discharge accomplished. A number of flight prototypes of APPT based EPS have been developed and tested. Developed and produce APPT and APPT-based plasma sources are used and planned for use in space and ground applications.

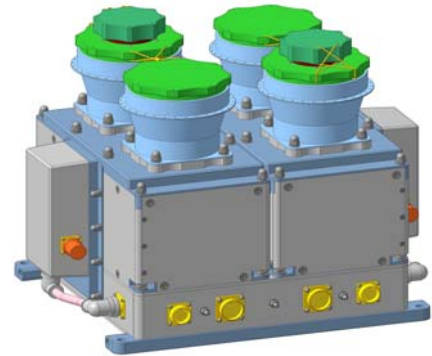


Figure 13. Appearance the PPI-500.



Figure 14. High power plasma flow interaction with micropowder and then with a sample. Pellets average dimension is 30 microns. Sample material is stainless steel. 1 – Initial plasma flow, 2 - pellets cloud, 3 – sample.

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