History of the Hall Thrusters Development in USSR

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V. Kim*
Research Institute of Applied Mechanics and Electrodynamics (RIAME), Moscow, 125871, Russia

K. N. Kozubsky† and V. M. Murashko‡
Design bureau Fakel, Kaliningrad, 236001, Russia

and

A. V. Semenkin§
Tsentral Research Institute of Machinebuilding (TsNIIMASh), Korolev, 141070, Russia

Abstract: As it is well known two types of the so-called "Hall Thrusters" had been developed in USSR, namely: the stationary plasma thrusters (SPT) and thrusters with anode layer (TAL). In the SPT and TAL the ions acceleration by an electric field within the gas discharge with crossed electric and magnetic fields and magnetized electrons is realized. Such mechanism of acceleration was proposed and the possibility to realize this mechanism was demonstrated by Askold Zharinov at the Institute of Atomic Energy (IAE) named after Kourchatov during 1959-1961. The TAL development based on the mentioned mechanism was started by team under leadership of A. Zharinov in 1962 at the Tsentral Research Institute of Machinebuilding (TsNIIMASh) and by the end of 1960th the powerful double stage TAL laboratory models were developed having good enough performance level under specific impulses till 8000 s at least. TSNIIMASh shared the TAL studies with Rocket and Space Corporation "Energiya", Bauman High Technology School (BHTSc) and others. Since late1970th the single stage TAL models were developed having competitive performance level within the power range (0.5-5) kW and all obtained results allowed development of TAL for different missions and for the 1st flight test on board of the US STEX satellite realized in 1998. The SPT development had been started during 1962-1963 also at IAE by team under leadership of another IAE scientist Alexey Morozov. The main idea of Morozov was creation of the electric field within the bulk of plasma with help of the transverse magnetic field and usage of this magnetic field to focus the ion flow during its acceleration. By mid of 1960th the first so-called E-accelerators (called later on as an SPT) were designed, created and tested. They were able to operate with gaseous propellants (Xe, Kr, Ar) within the discharge voltage range of (100-600) V and discharge powers (1-5) kW with thrust efficiency till 40% and specific impulses (1000-1800) s. Obtained performance level was estimated as prospective enough because it was higher than that one of the other EP types within the mentioned range of specific impulses. Therefore at level of the State Committee of Atomic Energy (SCAE) of USSR it was decided to realize the first SPT flight test and in 1972 SPT was successfully

* Chief scientist, professor, department of the stationary plasma thrusters, riame4@sokol.ru.
† Chief designer on EP direction, Dr, EPS design development department.
‡ General designer of EDB "Fakel", Dr.
§ Head of EP laboratory, Dr.

tested on board Meteor satellite. This test had given many interesting results and the main of them were demonstration of the reliable SPT operation in space and effective and fine satellite orbit correction with usage of SPT. Taking this into account it was decided to develop propulsion systems on base of the SPT for their regular application on board spacecrafts. And team of organizations including KIAE, Fakel, VNIIEM, MAI, TsIAM and others had continued efforts to solve this task. As result during 1970-1990 the great enough progress in the SPT studies, development and application was achieved. Thus, during 1970-1990 the powerful enough teams were involved into SPT and TAL development and many scientific results of their studies as well as the results of the technology development were already published. But there was no systematic publications on the applied studies. Therefore the main steps and results of applied studies only are considered in the given paper.

I. Introduction

Concerning EP history in USSR one can note that firstly the principal possibility to use electric propulsion for space transportation was considered by the province school teacher and great Russian scientist Konstantin Tsiolkovsky in 1902 [1,2]. The first real electric propulsion (EP) development was realized by Valentin Glushko in 1929-1933[3] but wide enough EP development in USSR was started after opening of the "space era" by launch of the 1st sputnik on October 4, 1957. It is worth to note that since 1957 at the Sergey Korolev's design bureau OKB-1 (nowadays the well known Rocket and Space Corporation "Energiya" – RSC "Energiya) the development of the heavy spacecrafts with nuclear electric propulsion had been started and due to initiative of Sergey Korolev the USSR Government decision was issued in 1960 obliging OKB-1, Tsentral Institute of Machinebuilding (TsNIIMASh), Research Institite of Thermal Processes (NIITP) and other institutions to develop powerful launchers, satellites, spacecrafts and many other things for the space activities including nuclear engines and EP[4]. One can add that Sergey Korolev at the end of 1950th had initiated more wide EP developments and his design bureau had tested the first electric propulsion system in space on board of "Zond-2" spacecraft[5]. An another important point is that great enough progress was achieved by that times in plasma physics in connection with the controlled fusion reaction studies. Therefore many first ideas and concepts of EP in USSR including the first pulse plasma thruster (PPT) tested on board of the "Zond-2" spacecraft, concepts of the SPT and TAL were born in the center of the nuclear and fusion problems studies – Institute of Atomic Energy (IAE) named after I.V. Kourchatov. So, history of the SPT and TAL concepts birth and of the first their laboratory models development are considered below first.

But development of the real space technology requires a lot of efforts. Therefore many scientists and engineers and many Institutions were involved into SPT and TAL development and studies. One can add also that many scientific and output thruster development results (performance and application data etc) were already published. Bur there was no systematic consideration of the applied studies and their results. Therefore the main steps and results of these studies and their connection with the technology development are considered in this paper.

II. TAL concepts birth and the 1st steps of their development

As was mentioned above the SPT and TAL based on the ions acceleration by an electric field within the gas discharge plasma with crossed electric and magnetic fields and magnetized electrons. To realize the mentioned mechanism it is necessary to create significant electric field in the plasma volume or at the boundary of plasma exhausting ions. Firstly an idea on the possibility to create significant electric field in the narrow double (electric) sheath at the boundary of the plasma injected near the axis of the magnetron type discharge was announced by Askold Zharinov in 1957[6]. This idea was born during the controlled fusion reaction studies while IAE scientists M.Ioffe and V. Telkovsky had proposed to use the magnetron type discharge for the filling of the magnetic trap by the hot ions. The mentioned idea of A.Zharinov among other things was confirmed at IAE by E. Yushmanov during his study of the mentioned magnetron type ions injection, namely: one of the his work results was the measurement of the plasma potential distributions along radius of the cylindrical magnetic trap while along axis of this trap the ion (plasma) flow was injected and permanent voltage of the several kV level is applied in between ion source and trap walls. Particularly it was demonstrated that under some operation modes the potential drop in plasma is really narrow enough[6]. And this was the promising point for the development of concept of the ions acceleration by an electric field without electrodes. This concept was verified during 1958-1961 at IAE by A. Zharinov with help of some others[7]. For such verification they had developed a cylindrical source of the hydrogen ions (Fig. 1) positioned in between magnetic poles so that its axis was parallel to the magnetic field direction. This source was ensuring the ~3 A ion current beam from the sleet of 1.2x4.7 cm^2 at the side source surface and the accelerating sheath was

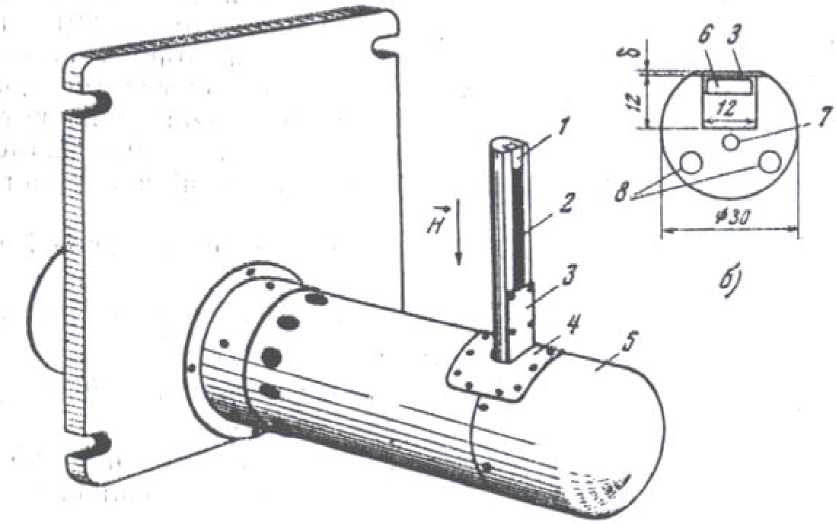

Figure 1. The proton ion source developed by Zharinov at IAE during late 1950th. *1 – plasma source, 2 – emitting sleet, 3, 4, 5 – structural elements, 6 – plasma source hollow, 7, 8 – auxiliary elements.*

located just at the boundary of plasma exhausted by the ion source. A.Zharinov had shown also that such acceleration of ions could be interpreted as an acceleration due to interaction of the external magnetic field with the Hall current induced within the narrow double electric sheath in the ExB discharge conditions with the magnetized electrons[7]. It is worth to note only that due to specifics of that times many results were published in open literature with delay from 1 till ~10 or more years depending on subject. Particularly the mentioned results were first time obtained before 1962 but they were published in open literature only in 1967[8] and 1973[9]. From the applied point of view all the mentioned was demonstration of the possibility to have electrodeless ions acceleration by an electric field within the narrow ExB sheath and basing on these results A. Zharinov had proposed the TAL basic scheme (Fig. 2).

Ideas of A. Zharinov were not supported by IAE management, and in 1962 he had left to TsNIIMash. One can remind that as was mentioned above since late 1950th at OKB-1, TsNIIMASh, NIITP, IAE and other USSR institutions the development of the powerful electric propulsion (EP) had been started. And one of the goals of these activities was the development of EP for the Mars mission[4]. In 1967 the first powerful double stage TAL model (Fig.3) was successfully operated. Later on the high enough performance level was achieved for such TAL models under operation modes with high thrust efficiency (till 0.75) under specific impulses till, at least, 8000s (Fig.4) and discharge powers up to 150 kW. Their characteristics were partially published in open literature in 1973[10] and 1974[11].

High efficiency of the double stage TAL was demonstrated under its operation with Cs, Bi, Cd, Xe[11]. So, the TAL concept was fully verified and prospective TAL laboratory models with high enough performance level were developed, created and tested. And this was the 1st significant step of the TAL development ending around mid of 1970th. These works were done by team of scientists

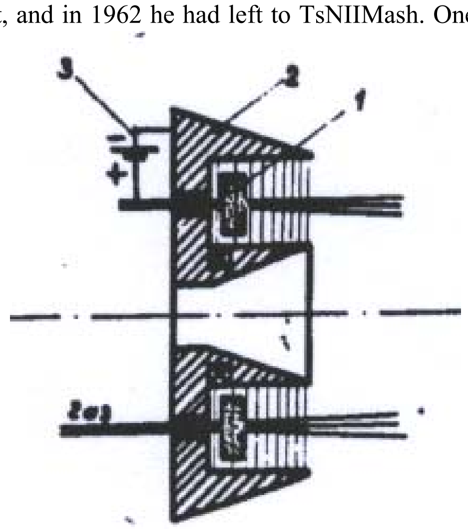

Figure 2. TAL basic scheme. *1 – anode, 2 – magnetic system, power supply source.*

and engineers V.Erofeyev, M.Abdyuhanov, E. Lyapin, V.Naumkin, I.Safronov and others. Serious of the analytic studies were made by A.Zharinov, Yu.Popov, Yu.Sanochkin, V.Kalashnikov and others. The main scientific results of this step including the discharge model and results of the physical processes simulation were presented at the All-union conferences on plasma accelerators[10-11] and were summarized in the books and journal papers [12-15].

The characteristic feature of the discharge in the developed thrusters was strong magnetic field with induction at level of (0.1-0.2) Tesla ensuring small magnitude of the electrons cyclotron radius and the possibility to concentrate the propellant flow ionization and acceleration within the narrow layers. But the ions Larmor radius calculated for the energy corresponding to full accelerating voltage was significantly larger than characteristic length of the ionization and acceleration stages.. So, length of the 1st stage was at level of 15-20 mm and length of the second stage ~10 mm. Due to strong magnetic field an electron current fraction in the acceleration stage did not exceed several percents of the ion current in spite of the high electric field intensity reaching ~10 kV/cm under some operation modes. And this was the key condition to obtain high ions acceleration efficiency.

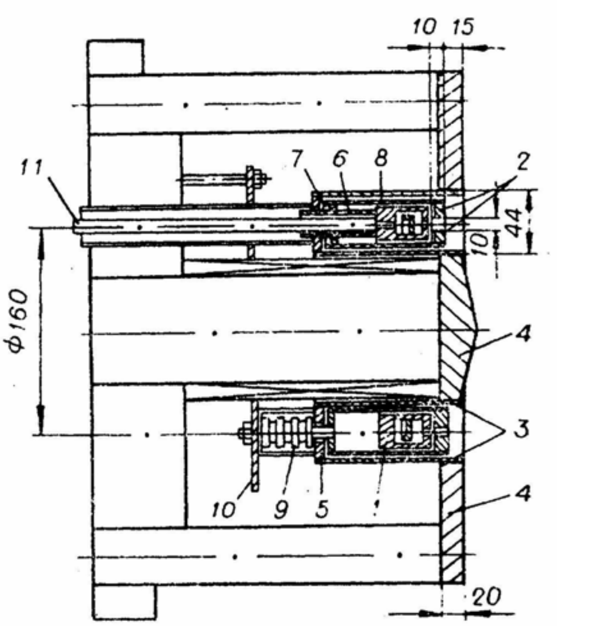

Figure 3. The double stage TAL design diagram. *1 – the 1st stage anode, 2 – the 2nd stage anode, 3 – guard rings, 4 – magentic poles, 5 – discharge chamber, 6 – insulator, 7, 8 – structural elements, 9 – insulator, 10 – flange, 11 – propellant feeding tube.*

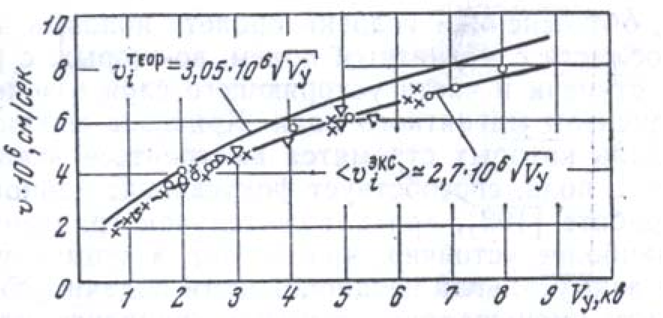

Figure 4. Dependence of the mean exhaust velocity longitudinal component on the accelerating voltage for Bi and Xe (the accelerating voltage is recalculated proportionally to the ratio M_{Bi}/M_{Xe}).

TsNIIMASh shared the TAL developmental works with RSC "Energya" and some studies with Bauman High Tech Scool (BHTSc), Kharkov Aviation Institute (KhAI), Dnepropetrovsk State University(DSU). The most interesting results of studies at BHTSc were devoted to the development of the so-called "hybrid" thruster where the ionization is to be realized in the SPT-like stage and acceleration – in TAL – like stage[16]. At KhAI the most interesting direction of investigations was devoted to studies of the double stage TAL operation under low (less than 1kV) accelerating voltages and possibilities to increase stability of such operation modes[17]. Interesting study of the "hybrid" type double stage accelerator with closed drift of electrons was fulfilled at DSU[18] where the 1st stage was equiped by hollow cathode and it was shown that such design allows obtaining of the high enough energetic efficiency ($\eta_{эф}$ in Fig. 5) under low enough discharge currents (J_p in Fig. 5).

Approximately by mid of the 1970th it becomes clear that the development of the powerful space power plants has to take long time. At the same time some spacecrafts already had ~1 kW level power could be used for the EP. And this possibility was successfully used by SPT (see below). So, it was reasonable to develop thrusters with relatively low power consumption and specific impulses within the range (1000-2000)s. The double stage TAL option did not ensure high performance level under specific impulses lower than 3000s. Therefore the single stage TAL development had been started. And by the end of 1970th under leadership of TsNIIMASh scientist E.Lyapin such TAL model (Fig. 6) with competitive performance level was developed[19-20]. The characteristic features of the single stage TAL is usage of the deep enough hollow anode (see Fig.6) and low magnetic induction inside the

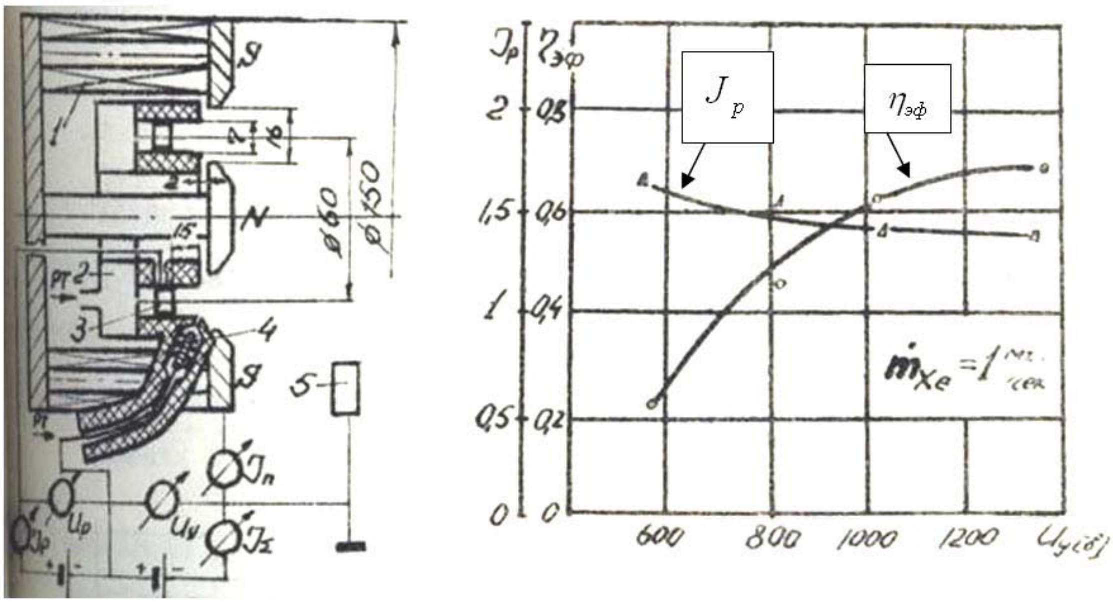

Figure 5. The scheme of the hybrid double stage thruster and its characteristics.

accelerating channel which was at level of (0.01-0.03) Tesla that is very close to the typical level realized in SPT. Study of this thruster operation specifics with usage of the sectioned anode had shown that discharge deeply penetrates into the anode hollow and that ~90% of the propellant flow ionization is happened inside this hollow.

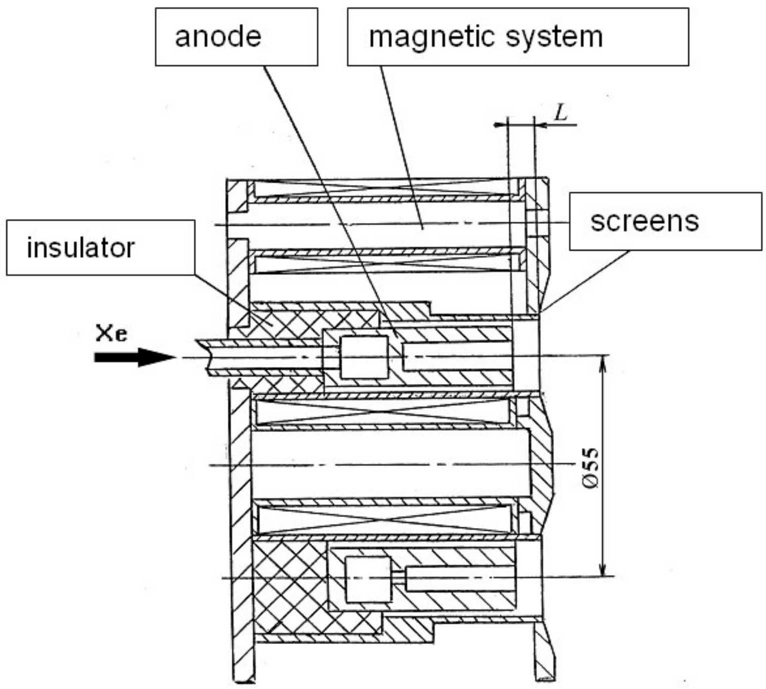

Figure 6. The D-55 single stage TAL design diagram.

Concerning the performance level it was very close to that one in the SPT case which was already tested in space and was intensively developed for the real applications (see part 2). Finally by the end of the 1980th the series of the single stage thruster models were developed and created including that one tested on board US STEX satellite[21-23]. (Typical characteristics some of them are represented in the Table 1).

Table 1. Some single stage TAL characteristics.

Thruster	Thrust F, мN	Power N, кW	Isp, s	State of development
D-38	6-100	0.1-1.5	1000-2850	Flight design which is under qualification for the experiments on board International space station
D-55	40-120	0.5-2.5	1000-2800	Engineering model used for the researches
TAL-WSF	18-100	0.3-1.5	600-2000	Flight design tested on board of the STEX spacecraft

During late 1980th development of the single stage TAL with the so-called shifted accelerating layer (Fig. 7) had been started at TsNIIMASh under leadership of A.Semenkin[24]. Principle used for this type TAL development was similar to that one used in the SPT case earlier (see part 2) and based on the fact that the accelerating layer (discharge zone with high electric field intensity) is localized in the zone of discharge with the maximum magnetic induction. Therefore shifting the magnetic field distribution it is possible to shift the accelerating layer outside magnetic system counter that is to reduce the accelerated ions interaction with the thruster structural elements and consequently to increase thruster life time. As in the SPT case it is possible to shift magnetic layer outside the magnetic system counter the so-called magnetic shunts (screens) are used (Fig. 8)

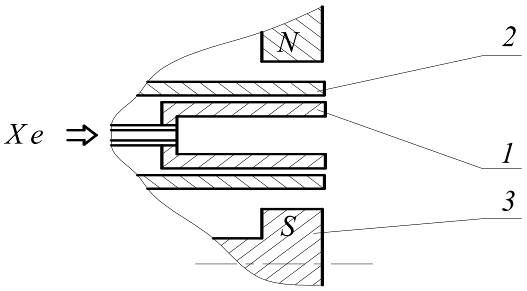

Figure 7. Design diagram of TAL with the shifted accelerating layer. *1 – anode, 2 – magnetic shunt, 3 – magnetic pole.*

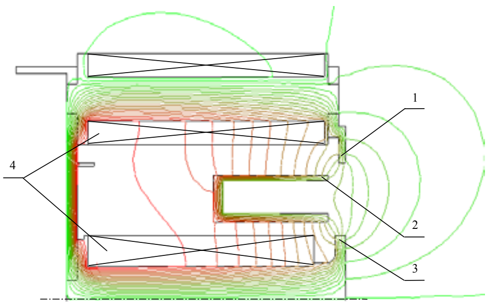

Figure 8. Magnetic field lines in systems with magnetic shunt. *1,3 – magnetic poles, 2 – magnetic shunt, 4 – magnetization coils*

Measurement of the plasma potential φ_{pl} and other plasma parameter distributions confirm that the accelerating layer could be really shifted outside magnetic system counter (Fig. 9).

During 1980th the double stage studies were also continued at TsNIIMASh under leadership of Sergey Tverdokhlebov and conditions ensuring high thrust efficiency and life time were found also.

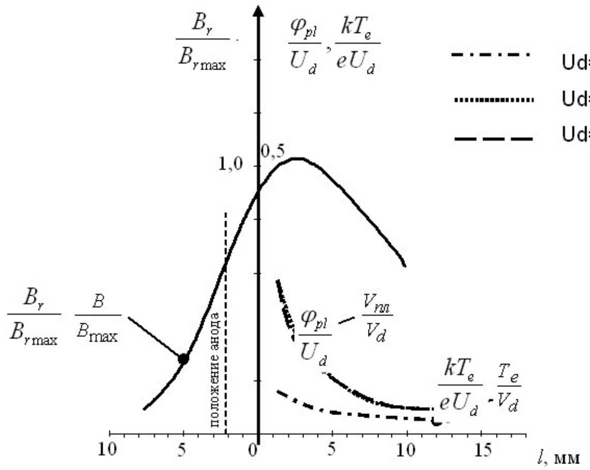

Figure 9. Longitudinal distributions of the plasma potential and magnetic field induction distributions in the model with the shifted accelerating layer (l=0 corresponds to the thruster exit plane).

So, by the end of 1980th the scientific and technological bases were created for development of the single stage and double stage TAL competitive with SPT and with the ion thrusters.

III. SPT development steps and the corresponding applied studies

A. First step of development

As was mentioned above the SPT development had been started in 1962 at IAE by team of scientists and engineers under leadership of Alexey Morozov. The main Morozov's ideas were as follows[25]:

- to create significant electric field within the bulk of plasma with usage of the transverse magnetic field;
- to use the magnetic field topology for the ion flow focusing taking into account that the magnetic field lines are almost equipotential ones, if an electron temperature is not high.

According to the last idea it was necessary to have within the accelerating zone the "focusing" geometry of the magnetic field lines[25-26] and relatively low electron temperature inside the accelerating channel. To get low temperature of electrons it was proposed to have dielectric discharge chamber walls ensuring relatively high level of the secondary electron emission and reduction of the electron temperature level. To distribute an electric field in plasma it was supposed to use system of the near wall electrodes but preliminary experiments had shown that these electrodes are not effective in the electric field control within the plasma volume and further they were not used. As result by 1964 the first so-called E-accelerator model E-1 (Fig. 10) was developed and tested[25] with external diameter of the accelerating channel ~100 mm. Gas flow was going through anode into the annular accelerating channel formed by the dielectric (quartz) walls. The magnetic poles were made with interpolar gap which was reduced to the channel exit to obtain the "focusing" magnetic field lines geometry.

To ensure the possibility to operate under large enough powers the discharge chamber walls and magnetic system elements were cooled by water. This model was tested with gaseous propellants within the discharge voltage

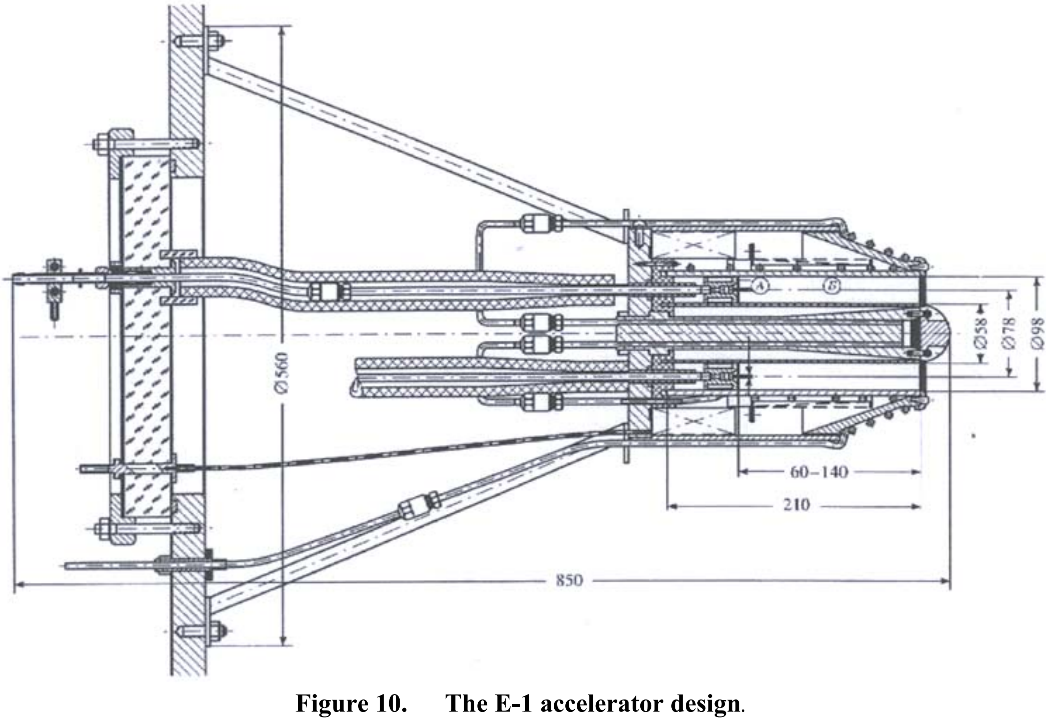

Figure 10. The E-1 accelerator design.

range of (100-600) V and the discharge powers till 5 kW ensuring the specific impulses (1000-1800) s and thrust efficiency (calculated not accounting for the cathode losses) till 40%[25]. Further the several basic analytic studies were made by A. Morozov concerning the plasma flow stability within the SPT accelerating channel, possibility to realize ions focusing by the magnetic field topology control, near wall conductivity[26]. Then, several models of the E-accelerators with thruster elements cooling by radiation were developed, created and tested including that ones for the study of the integral characteristics and their dependence on different factors, local plasma parameter distributions inside the accelerating channel and oscillations characteristics. And series of basic analytic and experimental studies of the SPT operation were made representing the scientific base for the 1st flown SPT development. Supervisor of the mentioned works was Alexey Morozov and they were fulfilled by team of the IAE scientists and engineers including Yu. Esipchuk, G. Tilinin, Yu. Sharov, A. Trofimov, I. Zubkov, A. Kislov, V. Smirnov and others at the IAE laboratory headed by German Shepkin. It is worth to remind only that due to specifics of that times many results were presented in the classified reports and published in open literature with delay from 1 till ~10 years (as in TAL case). Nowadays some first reports are declassified and according to these reports and open publications by the end of 1960th the laboratory models with ceramic discharge chambers fully cooled by radiation and having thrust efficiency (calculated not accounting for the cathode mass flow rate) till 35-40% and design life time over 1000 hours were created and tested[27]. One can add that under operation with specific impulses (800-1000) s accelerator was able to ensure the power to thrust ratio ("thrust cost') value less than 20 kW/N. This value was significantly less than that one for the ion thruster – one of the most popular subject of studies at that times. At the same time the mentioned specific impulse level was high enough and attractive in comparison with the chemical propulsion. Therefore A. Morozov had initiated an idea to realize the E-accelerator test in space. This initiative was supported by academicians Lev Artsimovich, head of the IAE plasma researches division, Anatoly Alexandrov, president of IAE and Andronik Iosiphian, president of the All-Union Institute of Electromechanics (VNIIEM) and chief designer of the Meteor type satellites. And in 1968 at level of the State Committee of Atomic Energy it was decided to realize the mentioned test on board the Meteor satellite. IAE was determined as supervisor of this test, future design bureau (FDB) Fakel was chosen for the development of the flight SPT version and of the corresponding experimental propulsion system, design bureau "Zarya was chosen for the PPU development and VNIIEM – for the integration of the SPT propulsion system on board satellite and test preparation. It was decided also to involve into the SPT studies and further development Moscow Aviation Institute – MAI, Tsentral Institute of the Motorbuilding – TsiAM. Later on and gradually this activity was joined by the Moscow Institute of Electronics and Automatics – MIREA (since ~1972), Sukhumi Physics and Technology Institute (during 1972-1980), BHTSc (during 1975-1990), KhAI(during 1975-1990), Moscow State University – MSU(during 1980-1985), NIITP(since ~1980) and some industrial enterprises producing special materials and parts. In total some years during 1970-1990 the full team consists of over 100 scientists, engineers and technicians. Involved Institutions had more than 15 test facilities with vacuum chambers from 1m3 till 150m3 available for the SPT and cathode studies and tests. And all they had more or less stable state support for their research activities. Therefore a lot of studies were done and it is difficult to review all obtained results within one paper. But many results of these studies were presented at several All-Union open conferences on plasma accelerators. One can add that some review papers were published also in the books[28-31] as well as in the periodic collections of papers "Plasma sources and accelerators" published by KhAI. Some references from these collections will be presented below. One can note also that:

- MIREA experts were dealing with the studies of the plasma parameter in the accelerating channel and in the SPT plume including the electrons dynamics and plasma optical radiation[32-37]
- BHTS had made studies of the SPT fed by alternating current as well as on the cathode operation, emitter erosion and development of the cathode accelerated test procedures[38-39];
- Kharkov Aviation Institute (KhAI) was involved into studies of the SPT and cathode studies and development[40-42];
- Moscow State University (MSU) was involved into the development of the plasma dynamics simulation model and tools[43-45]
- NIITP was dealing with the SPT operation and its elements erosion studies[46].

These studies had given significant inputs into understanding of thruster operation but had no direct impact on thruster design development. Therefore only some of their results consisting of the definite applied output are considered below.

Returning to the 1st SPT flight one can note that during 1970 the mock-up of the first experimental propulsion system "Eol-1"was developed, tested at KIAE and transferred to FDB Fakel. Thruster prototype (Fig. 11) was developed at IAE by Yu. Sharov and had power consumption ~450 W, thrust ~20 mN and specific impulse over 800 s[27]. Cathode (Fig. 12) developed at IAE by A. Trofimov with some others had cylindrical lanthanum gexaboride externally heated thermoemitter with the central capillary channel for the gas flow[27,47]. During 1970-1971 the flight version of the propulsion system was developed and upgraded by FDB Fakel team under management of the chief designer of the FDB Fakel Roald Snarsky and leading designer of the whole propulsion system K.Kozubsky. Principal thruster design diagram was remained as in the mock-up but some changes in design were introduced by

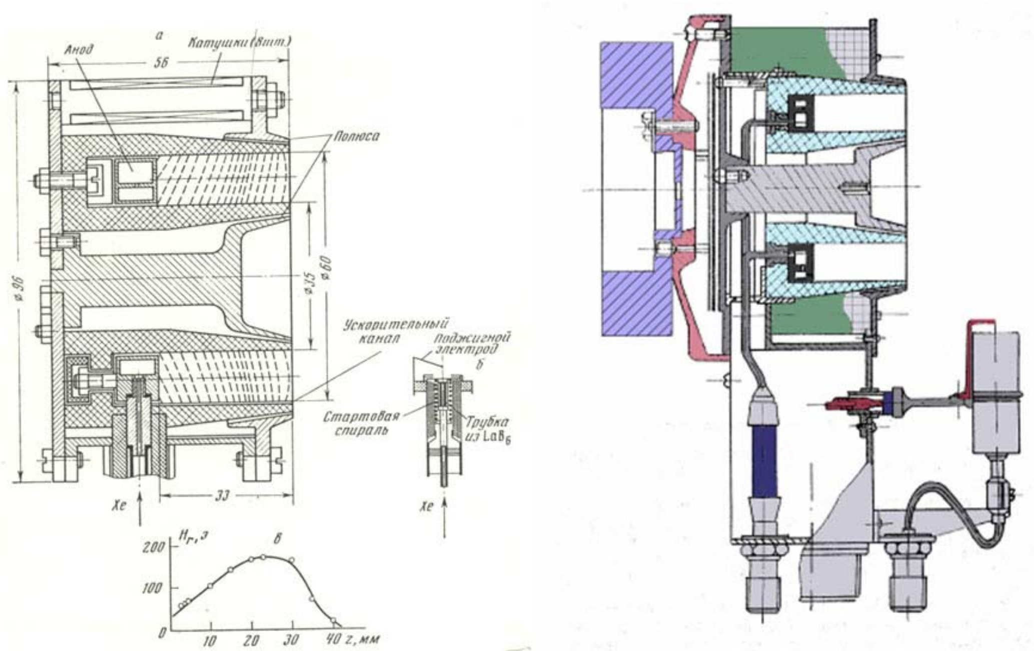

Figure 11. The mock-up developed at IAE in 1969 (left side) and the first flown SPT (right side) developed at Fakel.

Fakel designers V.Bryzgalin et al to meet requirements to flight design (see Fig. 11). As one can see the 1st flight version of SPT as the mock-up had several external magnetization coils, extended enough magnetic poles, electrically insulated gas feeding tube, two cathodes (for redundancy).

Cathode design was also significantly improved by B. Arkhipov, K. Kozubsky et al (see Fig. 12) what allowed to ensure its life time till 1000 hours at least. All parts of this propulsion system (excluding the PPU developed and manufactured by the design bureau "Zarya") were manufactured at Fakel, fully tested for flight вy Yu. Kondakov, G. Komarov, B. Merzlyakov and others and transferred by Fakel to VNIIEM. Integration of propulsion system on board satellite, preparation of the flight test program was realized by VNIIEM engineers and scientists Yu.Rylov, I. Barsukov, V.Khodnenko and others with attendance of Yu.Esipchuk, G Tilinin from IAE and K.Kozubsky and

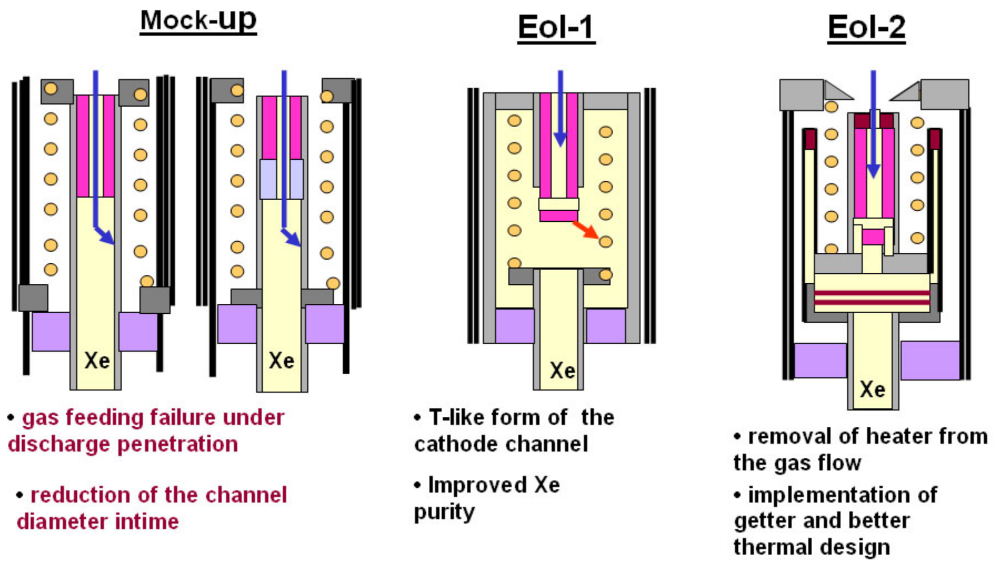

Figure 12. The cathode design improvements.

others from FDB Fakel. In December 1971 the Meteor satellite with SPT-based propulsion system (Fig.13) was launched and in 1972 the first SPT flight test was successfully realized by VNIIEM, Fakel and KIAE experts. Results of this test were fully enough published in 1974[27]. Therefore it is reasonable only to summarize the main of them what could be reduced to the following:

1. The reliable SPT operation in space during ~200 hours was demonstrated and good enough correspondence of thrust and other thruster parameters obtained in flight and during ground tests was shown. Particularly the thrust estimation was made using the satellite orbit parameter change and value of the torque moments due to thruster operation. The last estimation was possible by registration of the satellite attitude control system parameters.
2. The possibility to realize the fine satellite orbit correction with usage of SPT was demonstrated (it was impressive that ~1.3 t satellite orbit height was changed by ~17 km during ~170 hours of thruster operation with thrust ~20 mN). So, during 1hour thruster operation it was possible to change the satellite orbit height by ~100 m. Respectively, the satellite rotation period was changed very smoothly.
3. The compatibility of the operating SPT with the other satellite systems was shown. Particularly no any significant mulfunctions of the satellite systems were registered.

Figure 13. The "Eol-1" Propulsion system parts.

It is important also to underline that first time the Xe was chosen as an EP propellant what had allowed obtaining of the satisfactory thruster performance level, absence of the spacecraft contamination by the propellant flow, simplicity of the propellant storing as well as the low tank mass to propellant mass ratio in the future.

Thus, this test was fully successful and taking this into account it was decided at level of the SCAE that FDB Fakel in co-operation with IAE and other institutions has to develop SPT and propulsion systems on its base for regular application in space. Formally one can tell that the 1st flight had finalized the 1st stage of the SPT development. And the main its result was creation of the scientific and some technological bases for the new competitive electric propulsion development and demonstration of the possibility to effectively use it for the fine spacecraft orbit correction.

B. The 2nd stage of the SPT development

The second stage of the SPT development had been started in parallel with the mentioned test activities because the applied studies were continued at IAE and started at Fakel, MAI and TsIAM since 1969. They were devoted to:

- study of possibility to improve thruster performance and to extend its capabilities as well as to study of the SPT life limiting processes and of the accelerated test procedure development at IAE, MAI and Fakel;
- the cathode and plume studies as well as the investigation of the test conditions influence on the thruster operation and performance by thruster tests in the large test facility with the volume of the vacuum chamber (150m3) and great pumping speed had been made by Fakel, IAE, TsIAM and MAI;
- further SPT, cathode and whole propulsion system scheme and flight version designs improvement at Fakel.

Main directions of the thruster design improvement were as follows:

- magnetic field optimization to ensure high thrust efficiency and large life time;
- organization of the discharge within the accelerating channel with usage of additional electrodes and anode configuration;
- study of the life limiting processes and thruster design optimization (this task required taking into account complex of factors: magnetic field topology, accelerating channel configuration and discharge chamber design, materials of walls etc);
- development of the new design solutions allowing extension of thruster capabilities.

The most important applied results on the magnetic field optimization could be reduced to the following:

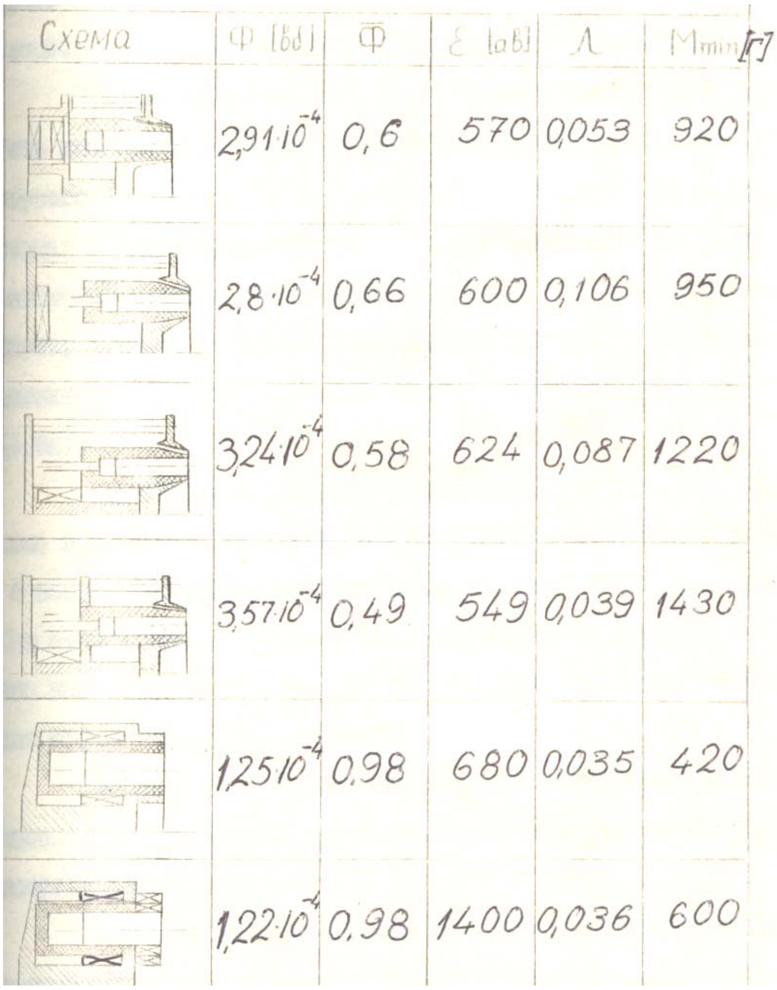

Схема	Ф [Вб]	Ф̄	ε [эВ]	Λ	Mmin [г]
	$2{,}91 \cdot 10^{-4}$	0,6	570	0,053	920
	$2{,}8 \cdot 10^{-4}$	0,66	600	0,106	950
	$3{,}24 \cdot 10^{-4}$	0,58	624	0,087	1220
	$3{,}57 \cdot 10^{-4}$	0,49	549	0,039	1430
	$1{,}25 \cdot 10^{-4}$	0,98	680	0,035	420
	$1{,}22 \cdot 10^{-4}$	0,98	1400	0,036	600

Figure 14. Schemes of the possible SPT magnetic systems.

1. During 1969-1970 V. Kim (principal investigator of all SPT works at MAI during 1969-1987), R. Thuyan, V. Serovaiski from MAI and K. Kozubsky from Fakel had made extended studies of the different schemes of magnetic systems (Fig.14) and of their capabilities with usage of the analogous simulation of the magnetic field[48].

The goal was to find magnetic systems allowing obtaining of the more "focusing" magnetic field topology and as the prospective one the magnetic system with two systems of the magnetization coils was recommended for the development of the second SPT flight version (Fig.15). This recommendation was supported also by an experimental study of the magnetic systems and better performance of model with such type magnetic system was confirmed[48]. Since that times all SPT flight versions have at least two systems of the magnetization coils.

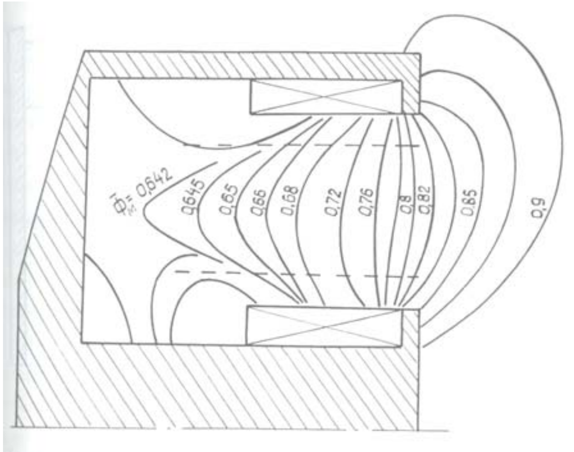

Figure 15. Magnetic system with two systems of coils.

As result an engineering model of the second (SPT-60) flight version with one external and one internal magnetization coil was developed, manufactured and tested at Fakel and first time thrust efficiency over 50% (calculated not accounting for cathode mass flow rate) under discharge voltage ~300 V was obtained.

2. During 1970-1972 at IAE the idea proposed by A. Morozov on the electromagnetic control of the thrust vector direction was studied by E. Petrov and V. Michailichenko and it was shown that such control allows thrust vector deviation by ~5 degrees[49]. But what was more important that during this study it was occasionally found that thrust efficiency could be significantly increased, if magnetic system has 'thin" magnetic poles (Fig.16) positioned just near the accelerating channel exit[49]. Analysis of this result and study of the thruster operation specifics with such magnetic system made by Yu. Esipchuk, E. Petrov and V. Michailichenko had shown[50] that the main reason of such improvement is an increase of the magnetic field gradient within the channel space in between anode and channel

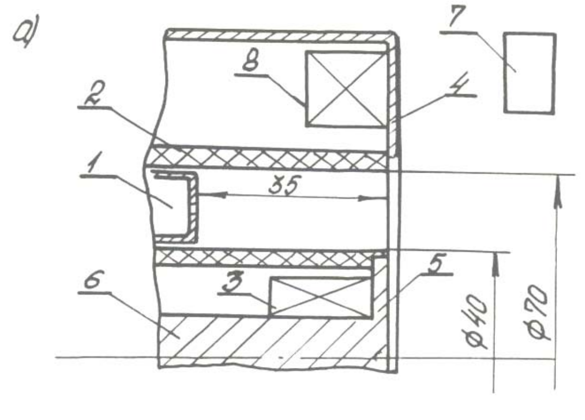

Figure 16. Magnetic system with "thin" magnetic poles.

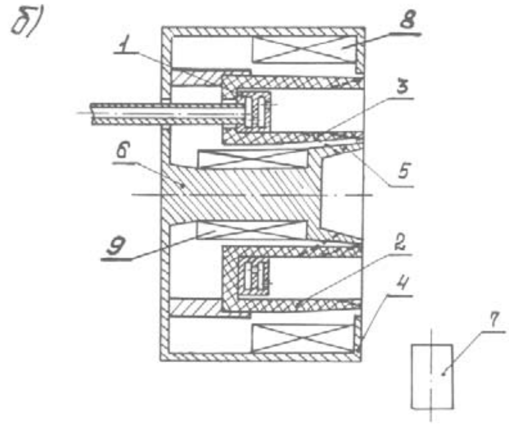

Figure 17. Magnetic system of the second flown SPT.

exit causing reduction of the accelerating layer thickness and its shift to the channel exit. Such changes cause reduction of the ion losses on the discharge chamber walls and corresponding increase of thrust efficiency. It is necessary to add that an increase of the magnetic field gradient was in correspondence with the Morozov's plasma movement stability criterion but this criterion did not give quantitative boundary allowing choice of the magnetic field characteristics. Therefore it was difficult to predict the mentioned effect and obtained result on the possibility to increase thruster efficiency by usage of the "thin" magnetic poles was not the expected one.

From the applied point of view it was important to implement the discovered effect into thruster design. The main difficulty was the following. To obtain increased magnetic field gradient by the magnetic system with "thin" poles it was necessary to have reduced interpolar gap (see Fig. 16) and respectively, thin discharge chamber walls. At the same time the discharge chamber wall erosion rate under comparable discharge conditions in the models with “thin” magnetic poles was higher than in the models with “wide” magnetic poles used in the first SPT models. Therefore an expected thruster life time for thruster models with “thin” magnetic poles was lower than in the case of “wide” magnetic poles and it was necessary to find the ways to ensure obtaining of the high thrust efficiency and large thruster life time with one thruster design. Nevertheless an attempt to implement “thin” poles was made during development of the second SPT flight model at Fakel. But after the 1st prolonged thruster test with such poles it was found that thruster operation in some time becomes unstable. Therefore it was decided to increase the internal magnetic pole width. Thus, the second flown SPT (“Eol-2”) was with “thin” external and “thick” internal magnetic poles (Fig. 17). Respectively it had an intermediate performance level.

3. For the further SPT development progress it was necessary to study rules controlling the thruster life time. More or less full study of the first SPT elements wearing was made at Fakel during 1971-1975. Particularly one sample of the 1st SPT flight version was tested during 1100 hours and it was found that the most intensive processes are the erosion of the discharge chamber walls and of the cathode emitter[51]. It was found also that the discharge chamber walls erosion rate is reduced in time. Sample of the 2nd SPT flight version was tested during 2200 hours. Having these data the head of the SPT laboratory at Fakel Yu. Kondakov had derived the following empiric law for the magnitude of the discharge chamber wall thickness change $\Delta\delta$ as a function of the thruster operation time τ :

$$\Delta\delta = C\tau^{2/3} \qquad (1)$$

In parallel at MAI the local plasma parameters measurements inside the accelerating channel were done by Andrey Bishaev and V. Kim. These measurements were made during 1972-1974[52] and published in open literature

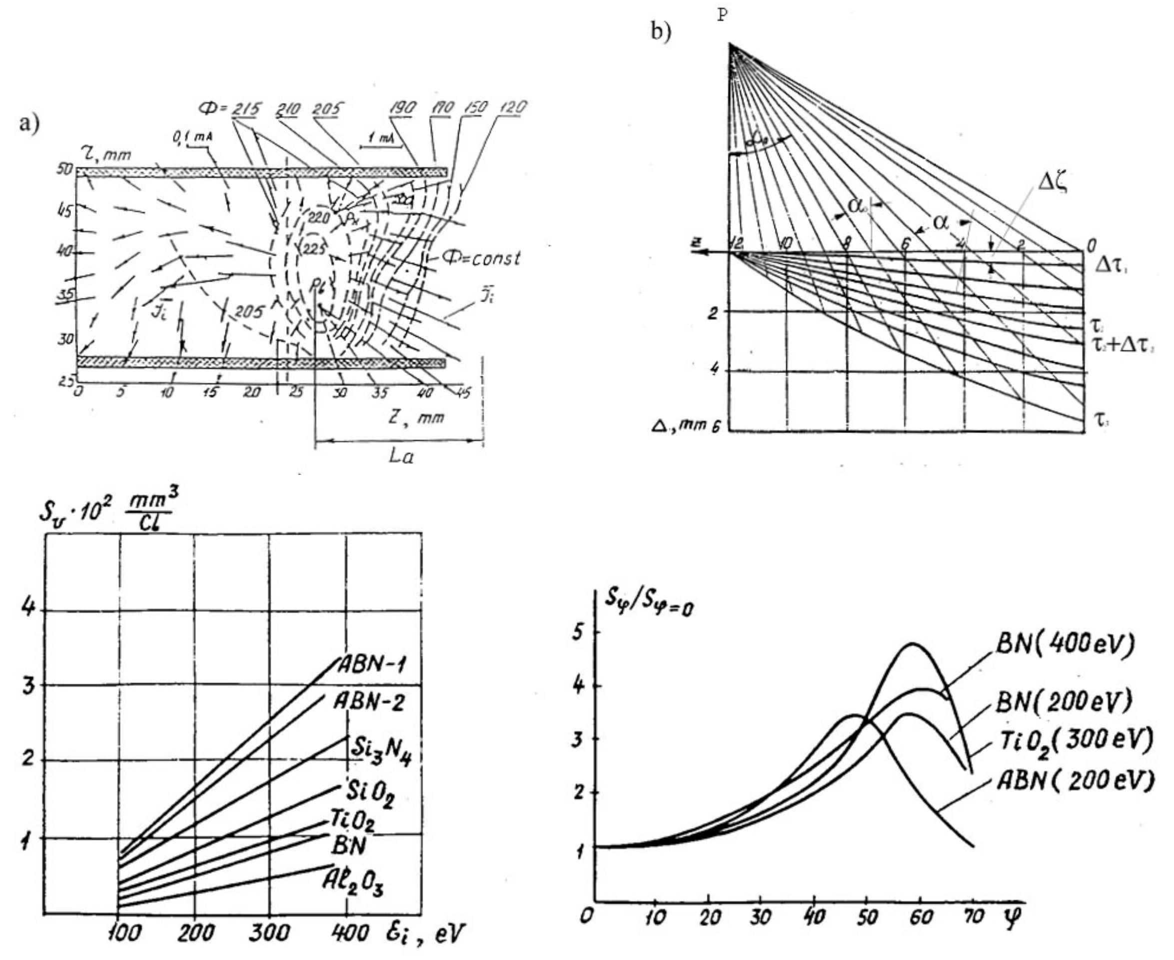

Figure 18. The ion flow structure (a, b) and ceramics sputtering characteristics (c).

in 1978[53] and in 1981[54]. They allowed obtaining of the 2D plasma parameter distributions and estimation of the energy losses for ionization inside the accelerating channel. Particularly it was shown that the total ion production cost in the SPT accelerating channel is at level of $(5-6)e\varphi_i / ion$. This means that SPT is the perfect ionizer and explains its good performance under relatively low specific impulses (1000-2000)s. Among other things the mentioned study allowed determination of the directed ion flow spatial structure (Fig. 18) and estimation of the ion flow density and mean energy of ions getting discharge chamber walls.

Then, the first determination of the sputtering rate of ceramics by the accelerated ion flow generated by the SPT-like plasma source was realized at MAI by team of scientist under leadership of I. Shkarban[55] (such studies were continued during 1970th-1980th, Fig. 18b[56]). Using obtained data on the ion flow density and energy of ions getting walls as well as the data on the sputtering factor the conclusion was made that the discharge chamber wall erosion represents the wall sputtering by the accelerated ions. Later on with usage of the mentioned results the simplified ion flow and wall erosion models were developed by V. Kim[51,57] explaining the mentioned reduction of the wall erosion rate and its dependence on time.

Concerning cathode the main problems were to improve its thermal design and to avoid the discharge penetration deeply into the emitter capillary channel (see Fig. 12). Under appearance of such penetration the discharge was touching the emitter keeping tube and destroying it. Therefore it was proposed to have the exit part of the capillary channel in the emitter connected with transverse channel[27,47] (see Fig. 12) which was in turn connected with the gas inlet into cathode. Usage of such channel design and improvement of the cathode thermal design allowed obtaining of the cathode life time not limiting thruster life time. As was mentioned above Fakel experts B. Arkhipov, K. Kozubsky, G. Komarov and others were involved into these cathode design improvements.

4. Different accelerating channel geometries were studied and it was found that pure cylindrical channel with constant width gives good enough results.

5. Different option of the anode configurations and discharge organization were studied also, including an attempt to control electric field in the near anode zone with additional electrodes (Fig. 19[51]) but they did not give significant results.

6. During 1972-1974 the propulsion system functional scheme and propellant storing and management units designs were also improved by the Fakel team under leadership of K.Kozubsky as well as the power processing unit scheme and design – by the leading designer of the first PPU's L.Novoselov and others at SPhTI. As result in 1974 the second SPT flight test was realized[58]. During this test thruster had operated during more than 600 hundred hours. The corresponding propulsion system (PS) "Eol-2" (Fig. 20) had already all features of the modern PS, namely:

- two thruster modules each equipped by two cathodes with life time over 2000 hours confirmed by the ground life time tests;
- propellant storing system with optimum Xe pressure in tanks;
- PPU with all control and telemetry subsystems allowing automatic thruster switching "on" and "off" and realization of the automatic cyclic thrusters operation.

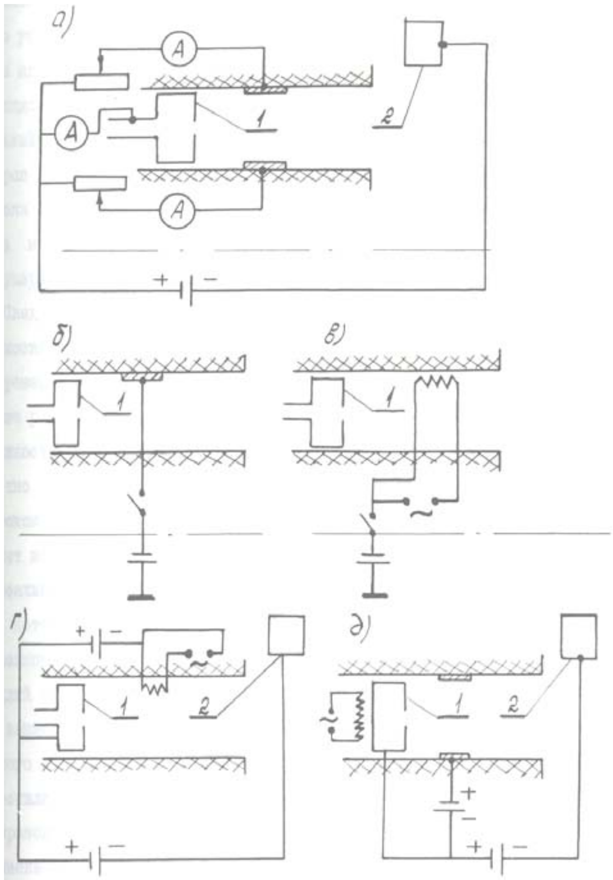

Figure 19. Schemes of different options of the discharge organization.

Respectively the more extended test program was realized during this test what allowed demonstration of the following[58]:

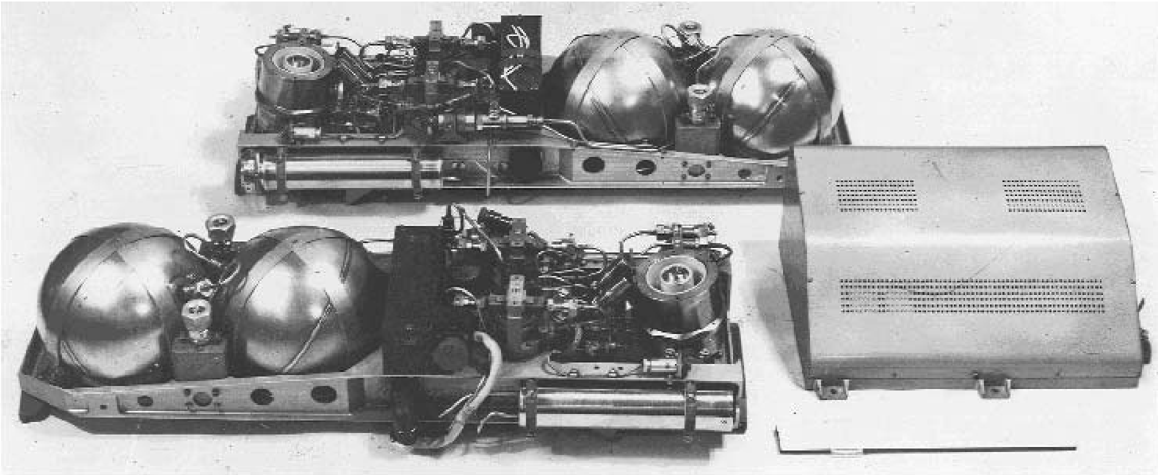

Figure 20. The "Eol-2" propulsion system parts.

- the possibility of the fine satellite orbit control was confirmed and the possibility of the orbit circularization was demonstrated;
- an impact of the thruster plume on the satellite solar panels (during over 300 hours) and on the attitude control system was checked;
- influence of the thruster operation on the level of noises at the satellite radiosystem receiver input was checked;
- reliable PS operation during more than 600 hours was demonstrated.

This test had fully confirmed effectiveness of the satellite orbit control by SPT and by the SPT – based propulsion system.

7. During 1972-1980 the further studies of the possibilities to ensure high thruster efficiency and life time in complex were continued. Particularly the following possibilities to ensure high thrust efficiency and life time were investigated:

7.1. Development of thruster design with movable discharge chamber walls allowing replacement of the eroded discharge chamber wall parts removed due to the walls erosion by the accelerated ions. In this case it was possible to use the magnetic system with "thin" magnetic poles to ensure high thruster performance level and to increase thruster lifetime significantly enough having sufficient margin of the movable discharge chamber walls. Idea of such principle proposed by A. Morozov was studied first at IAE by E. Petrov and V. Michailichenko. Then, the engineering models of thruster with such design were developed and tested at Fakel by V. Murashko and others. As result it was shown that such idea could be realized in practice but surely thruster design is more complicated and less reliable in this case.

7.2. Development of the magnetic system allowing obtaining of the magnetic field topology within the accelerating channel ensuring high thrust efficiency but under fixed width of this channel and increased interpolar gap. In this case it is possible to increase the discharge chamber wall thickness that is the margin for erosion and to increase thruster life time. Such solution first time was realized in 1973-1974 by V. Kim and A. Bishaev with usage of the magnetic shunts ("magnetic screens") and the first laboratory model with magnetic screens surrounding the discharge chamber were developed and tested at MAI[52] (Fig. 21). As result the possibility was shown to increase the wall thickness by 2-3 times and to obtain the same level of thrust efficiency as for the model with "thin" poles. Such increase of margin for erosion taking into account reduction of the erosion rate in time promised an increase of life time by 3-5 times. Therefore such solution was recommended to Fakel and since the 3rd SPT flight thruster SPT-50 developed at Fakel by N. Maslennikov (being head of the propulsion systems design development department), Yu. Gorbachev and others all further Fakel flight thrusters have magnetic screens (shunts) and increased thickness of the discharge chamber walls exit parts. The life time of the SPT-50 confirmed by ground tests exceeds 2000 hours for the same power level as was used for the first SPT flight model in spite of reduced overall sizes of the SPT-50 model[59].

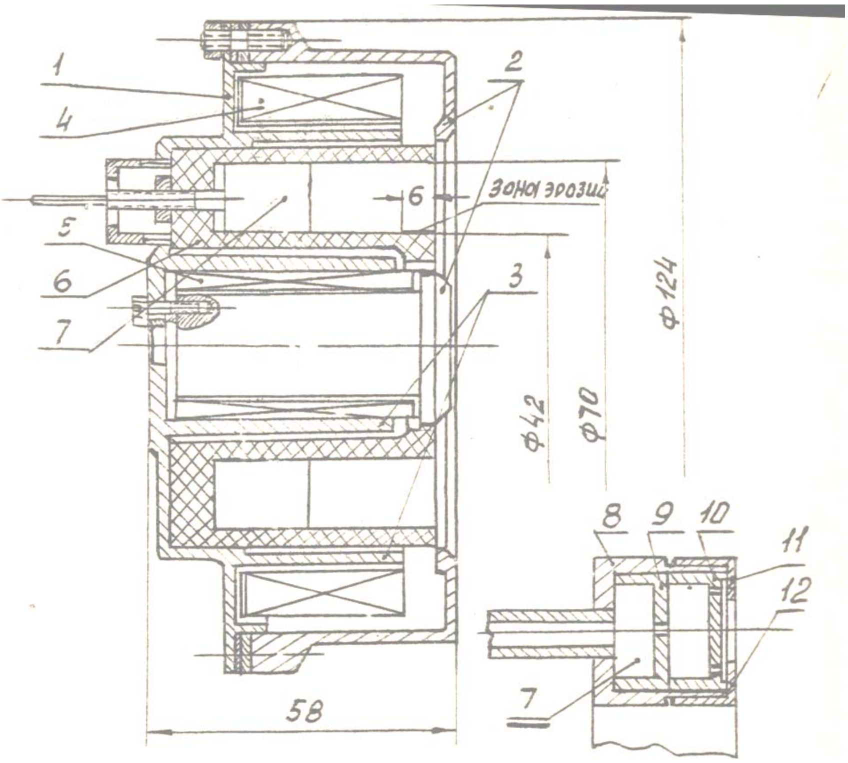

Figure 21. The first SPT model with the "magnetic screens", increased discharge chamber walls and high performance level.

7.3. During 1973-1975 V. Kim and V. Gavryushin had made an optimization of the magnetic field topology for thrusters with magnetic screens and external diameters (50-100) mm. Because the optimized magnetic field lines configuration was close to symmetrical relative to the accelerating channel mid surface, it was possible to use for the magnetic field topology characterization the magnetic induction distribution along the accelerating channel and characteristic width L_B of this distribution as well as the "magnetic field gradient" (Fig. 22):

$$\frac{1}{B_{\max}}\frac{\partial B_r(z)}{\partial z} \approx \frac{1}{B_{\max}}\nabla_z B_r(z) \approx \frac{1}{L_B} \qquad (2)$$

It was shown that for each thruster size one can find optimum magnetic field topology giving maximum ratio of the ion current at thruster exit to the discharge current, maximum of the thrust efficiency and minimum of the plume divergence[60] (Fig. 23). Plume divergence and total ion current were estimated by measurements of the axial and radial ion current components at the thruster exit (Fig. 24).

As a final applied result the SPT-70 engineering model with the external diameter of the accelerating channel 70 mm (Fig. 25) was developed[60]. This model passed some tests at MAI and in 1975 it was transferred to Fakel where full enough test campaign was realized including 1000hour test. On base of these test results it was decided to use the mentioned engineering model as the prototype for the flight SPT-70 design and such design was developed at Fakel by N. Maslennikov, G. Komarov and Yu. Gorbachev. This thruster design passed an additional optimization and full enough test

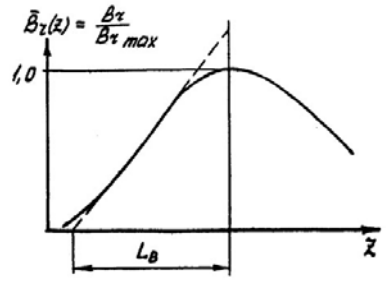

Figure 22. Scheme of the magnetic induction distribution along the accelerating channel.

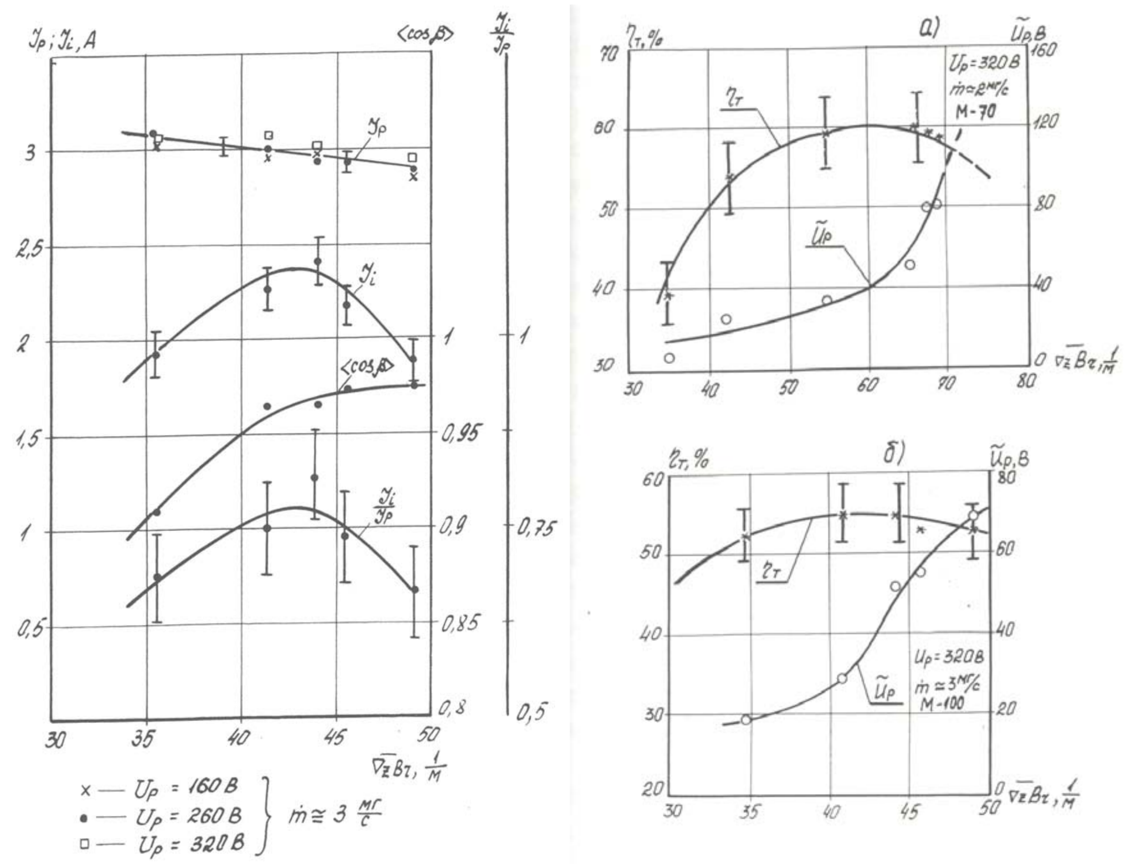

Figure 23. Influence of the magnetic field gradient on thruster characteristics and performance.

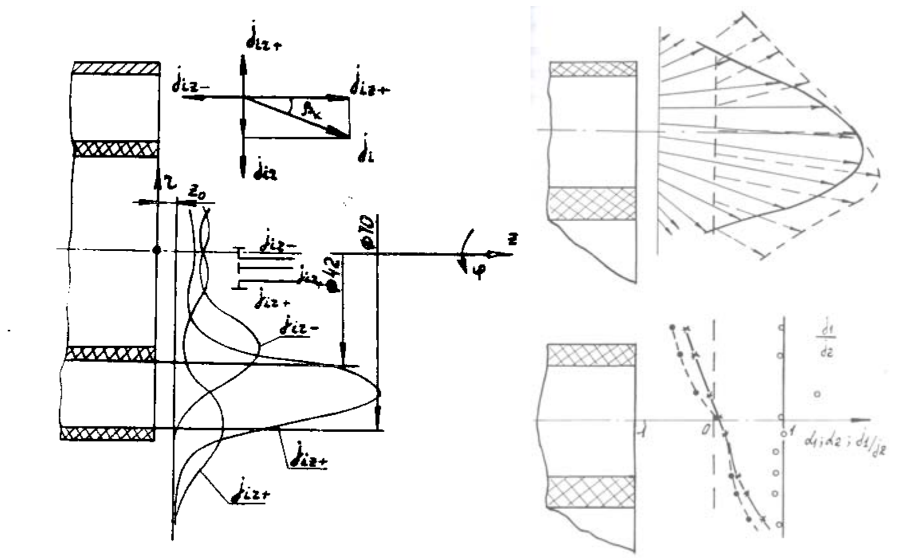

Figure 24. Sheme of the ion flow investigation at the thruster exit.

campain at Fakel including 3000 hour life time test and since 1982 it is in flight operation and still in the Fakel's serial production line[59].

7.4. During magnetic field optimization it was found also that with increase of the magnetic field gradient the oscillations intensity is changed significantly but till the definite level an increase of the discharge voltage oscillation intensity does not reduce the thruster performance (See Fig.23) and only under high level of the oscillations intensity they causes the decrease of thruster efficiency. The simple explanation of such decrease was the following: under large amplitudes of the discharge voltage significant part of time thruster operates under low voltages where its effectiveness is lower. Therefore the averaged effectiveness is lower than under lower level of these oscillations.

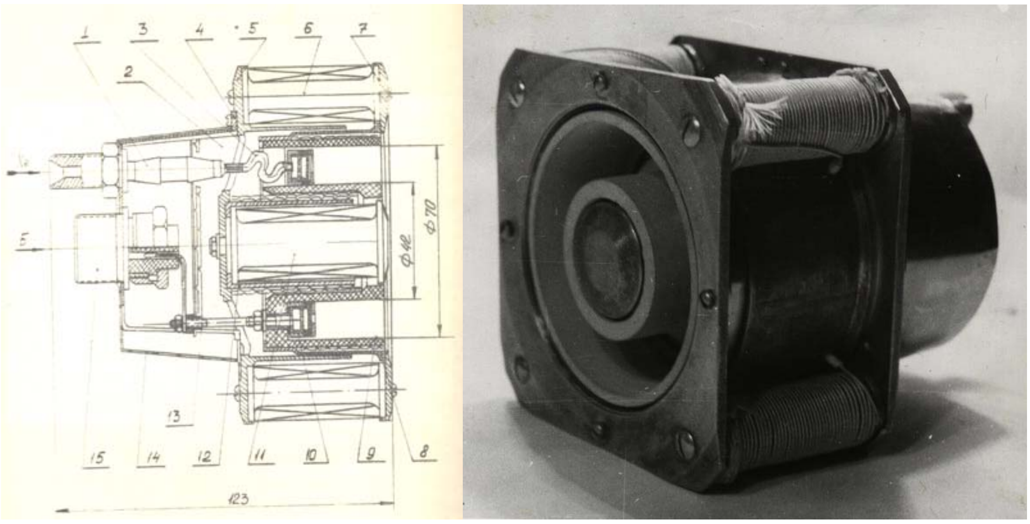

Figure 25. The SPT-70 thruster prototype design and general appearence.

Additional data were obtained during the long thruster operation while decrease of thruster efficiency was happened due to the oscillations intensity increase. To reduce this effect the Fakel engineer V. Kozlov had included the small capacity in between anode and cathode[61]. Such capacitor was reducing the scales of the discharge voltage oscillations and stabilizing the performance level during long thruster operation. This was in agreement with the fact that the discharge voltage oscillations are more dangerous than oscillations of the discharge current. Really it was the new matching element in between discharge and discharge power supply source. Influence of the possible matching unit scheme and possibility of the passive and active oscillations stabilization was studied at IAE, at MAI and Fakel and after some analysis and many experiments made at Fakel by K. Kozubsky and others the final matching (or "filter unit") scheme was chosen as an organization developing the whole propulsion system[62].

7.5. The next important step was the development of thruster design with the most significant increase of the life time capability by shift of the accelerating layer almost outside thruster magnetic system counter (thruster with "shifted accelerating layer"). This idea was first time proposed and checked at Fakel by engineer V. Kozlov and then it was more carefully studied and realized in the SPT-100 laboratory models by V. Kozlov (as PhD student) and V. Kim at MAI[61] during 1975-1978 (Fig. 26). This laboratory model was fully enough tested at MAI and IAE. During these tests the accelerated estimation of thruster life time with usage of the new methodology was realized. This methodology was based on combination of the erosion test, determination of the erosion rate and of the ion flow parameters with usage of the erosion rate data, prediction of the further wall erosion using the ion flow and wall erosion models for the period of time significantly exceeding the erosion test time, mechanical processing of the walls to simulate the predicted walls profiles for the time period significantly exceeding the erosion test time, new erosion test and repeating of all other steps by 2-3 times. Such accelerated test methodology gives acceptable accuracy and first time had allowed preliminary confirmation of the possibility to obtain the SPT-100 type thruster life time over 5000 hours [61]. On base of these results as in the SPT-70 case two different SPT-

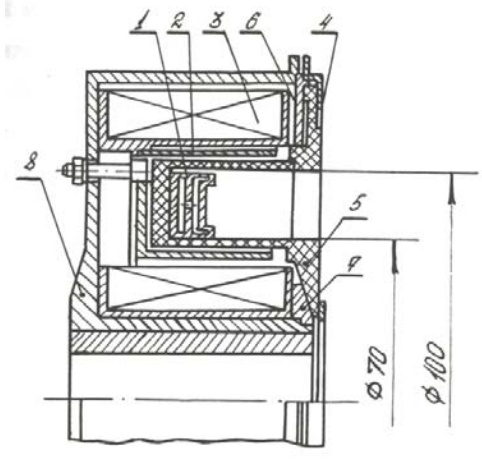

Figure 26. The SPT – 100 laboratory model.

100 engineering models with shifted accelerating layer were developed in turn and tested at MAI. Then they were delivered to FDB Fakel and were also fully enough tested and used during the SPT-100 flight version design development at Fakel as prototypes. This development and further design optimization were realized by N. Maslennikov, B. Arkhipov, V. Ivanov, Yu. Gorbachev and as it is well known now the SPT-100 had passed life time test ~9000 hours without failure[47]. It is operationally used in space since 1995[47].

7.6. It was very important for the SPT technology progress that since mid of 1970th the developments of SPT for real applications were supported by the Research and Production Association of Applied Mechanics (NPO PM). And as it is known the SPT-70 thruster is used operationally since 1982 on board of the geostationary satellites developed and produced by NPO PM for the East-West orbit corrections of the mentioned satellites and since 1995 NPO PM had started to use the SPT-100 for the final positioning and full geostationary satellites station keeping[47]. So, many problems appearing under development of propulsion systems for such applications and during their onboard operation were first time successfully solved by Fakel and NPO PM experts. It is worth to note also that by now the most part of SPT's flown in space were operating on board of the NPO PM satellites and by now NPO PM coupled the most reach experience of their usage.

7.7. As was mentioned above the optimized magnetic field near the accelerating channel exit of the modern SPT's has close to the "focusing" geometry of the magnetic field lines and close to symmetrical one relative to the accelerating channel mid surface. Therefore it was possible to use for the magnetic field topology characterization the distribution of the magnetic induction radial component Br(z) along the accelerating channel mid surface. Then using the erosion traces after long enough thruster operation it was possible to estimate position and width (along the accelerating channel) of the accelerating layer. Such approach in combination with results of the local plasma parameter measurements allowed finding of the fact that for thrusters of different sizes with optimized magnetic field the accelerating layer is localized within the space where the magnetic field induction radial component is at level of (0.8-1.0) Br_{max} (Br_{max} is the maximum of the radial magnetic induction component at the mid surface of the accelerating channel)[51]. Moreover by many experiments at IAE and MAI at least it was found also that electric field intensity is small in the near anode zone and in the zone of discharge with magnetic induction going down that is the accelerating layer in SPT as usual is devided from anode and cathode and localized within the zone with the maximum of the magnetic field induction. This is an indication of fact that the accelerating layer position and thickness is controlled by the electrons mobility transverse to the magnetic field. So, controlling the thickness and position of zone with maximum magnetic induction one can control the electric field distribution and the accelerating layer position what was really used during described above magnetic field topology optimizations and of the accelerating layer position control[51]. Taking this into account A. Morozov and V. Kim had proposed to call SPT as thruster with ions acceleration within the magnetic layer[63].

The mentioned studies had shown also that for each thruster scale one can find optimum magnetic field topology which is more or less similar for models of the different scale. This meant that it is possible to use for thrusters of different sizes the magnetic systems with rough geometrical similarity of their main parts. Taking into account some studies made at MAI for the thrusters models SPT-50, SPT-70, SPT-100, SPT-180 and at Fakel by N. Maslennikov, V. Murashko and others for thrusters of increased sizes[64], these results were summed by V. Kim as the principle of the geometrical similarity of the main magnetic system elements under preliminary thruster designing[51,65]. Surely such principle significantly simplifies the new thruster development.

It is worth to note that series of thruster models of different scales were developed and investigated at IAE by V. Michailichenko, E. Petrov, A. Veselovzorov et al, at DB Fakel by K. Kozubsky, V.Murashko, S.Kudryavtsev and others, at MAI by V. Kim, V. Gavryushin, S. Khartov[64]. Analyzing characteristics and potential application effectiveness of thrusters of different sizes N. Maslennikov being deputy chief designer of Fakel had proposed the SPT row to be developed for real applications. According to his analysis the possible application fields could be rationally covered by thrusters with characteristic diameters increased approximately by factor $2^{1/2}$ for the next thruster module in row. So, now the Fakel thrusters have the following row of the external diameters: 35mm, 50mm, 70mm, 100mm, 140mm, 200mm etc. And flight versions or laboratory and engineering models of thrusters of different sizes following the mentioned principle were developed at Fakel[59]. The most impressive was development of the SPT-290 (Fig. 27) realized at Fakel by V. Murashko, leading designer of this development, S. Kudryavtsev and others[64]. This model was developed as prototype of thruster for the electric propulsion system for the cargo and spacecrafts interorbital transfer vehicle. It had demonstrated high performance level and ability to operate long enough time under discharge powers till 35 kW.

7.8. The first detailed study of plasma parameters in the SPT plume at large enough distances from the thruster exit was made by TsIAM and MAI experts in the large vacuum chamber[66]. Particularly it was shown that the ion current density is changed with increase of the distance r from thruster as $\sim 1/r^2$ and that electrons temperature (at level of several eV) and plasma potential are slowly reduced with increase of the mentioned distance. These data were used for the analysis of the plume impact on the satellite solar panels.

7.9. During 1980-1985 V. Kim and V. Egorov had developed at MAI the SPT design with conductive inserts at the ceramic discharge chamber exit parts and it was shown that it is possible to increase thrust efficiency and to reduce notably its plume divergence by optimization of sizes and position of the mentioned inserts[51]. Later on an engineering model of such thruster was developed by RIAME and Fakel and this model had successfully passed 1000 hour life time test.

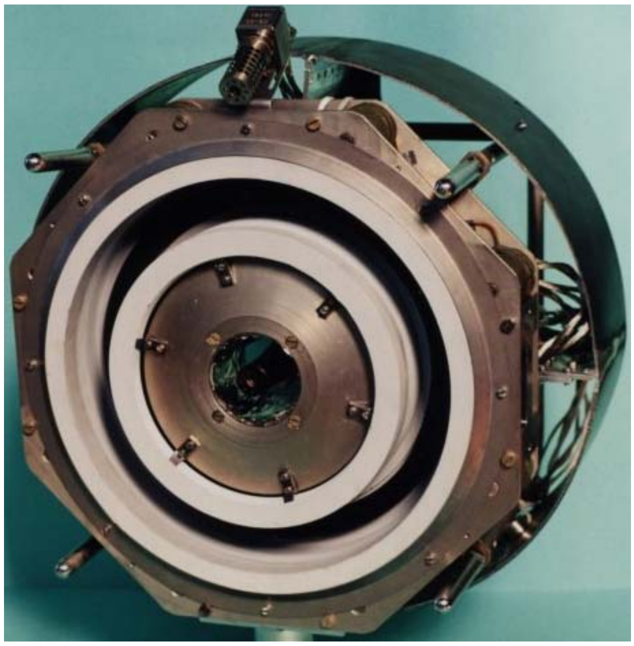

Figure 27. SPT-290 laboratory model.

During 1985-1989 the first development of the SPT with the metallic discharge chamber and ceramic outlet rings was realized by V. Kim and S. Khartov (Fig. 28)[67,51]. The main goal of this development was to reduce difficulties of the large ceramic peaces manufacturing. Obtained results had shown that such approach is realistic one, allows obtaining of the same performance level as the fully dielectric discharge chamber and that ceramic rings have as minimum to cover the part of channel where the accelerating layer is located that is they have to cover space where the magnetic induction has values close to maximum. This design allows also to introduce the conducting inserts at the discharge chamber outlet walls (see Fig.28). Its effectiveness was demonstrated on the SPT-70 and SPT-180 laboratory models with the external diameter 180 mm. Some works with such discharge chambers were made also at Fakel. Nowadays such discharge chamber schemes are used in US[68].

Considered above results had definite impact on the modern SPT designs. But there were some other activities

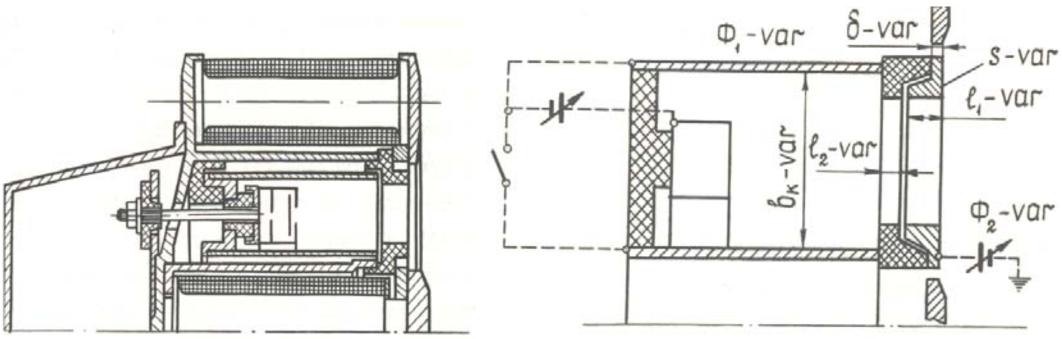

Figure 28. Design diagram of thruster with combined discharge chambers.

could be useful in the future. Among these activities one can distinguish the following:

1. Due to inintiative of A. Morozov first at IAE and then at KhAI the development and study of SPT operating in the pulse mode was made[43,69]. Particularly it was shown that thruster start time could be reduced till some ms, if one uses the special valve, and that in the pulse mode one can get higher thrust efficiency under operation modes with powers less than 100W due to possibility to operate thruster during pulse under conditions close to optimum and to maintain low average power consumption choosing duration of pulses. As it is known[70] in the steady state operation mode with low power it is difficult to reach such conditions.

2. At early 1970 the cluster of 9 SPT's of the SPT-70 scale was developed at IAE by E. Petrov and V. Michailichenko which was tested at TsIAM[51]. Particularly it was demonstrated the possibility to operate all thrusters of this cluster using one main power supply and one cathode.

3. Development and tests of thrusters operating with different propellants. As was mentioned the SPT studies had been started from the beginning with noble gases (Ne, Ar, Kr, Xe) and it was lucky choice. Later on many other

substances were checked as the possible propellants for thrusters and for plasma sources on base of SPT for the ground applications, namely[51]:

- S, H_2 and other substances were tested at IAE by A. Trofimov, A. Veselovzorov and others,
- Cs, Na-K eutectic, Li was tested at MAI by V. Kim, A. Bishaev, G. Alexeeyev, Yu. Melnikov and others,
- Cd was tested at Fakel by B.Trinchuk, S.Kudryavtsev and others.
- H_2, N_2, O_2, NH_3 and other gases were tested at IAE, MAI and other institutes for the ground applications.

The most interesting results were obtained for the Cs and Na-K eutectic, namely:

- Operation of SPT with Cs allowed to reduce the so-called accelerating mode till discharge voltages ~100 V and respectively to obtain low thrust cost (less than 10 kw/N) under specific impulses ~800 s. So, this propellant should be interesting while it is necessary to obtain maximum thrust;
- Operation of SPT with Na-K eutectic allowed obtaining of the high enough thrust efficiency and specific impulse under significantly reduced discharge voltages in comparison with the Xe case. So, this propellant could be used in the future propulsion systems with increased specific impulses operating in combination with the nuclear power plants;
- Both substances have low melting temperature.

An another advantage of the alkali metals as the SPT propellants is simplicity of the cathode design, possibility to obtain required electron current for low energy and mass consumption, large enough quantity of such substances on the Earth. The main disadvantages are the necessity to heat discharge chamber and propellant feeding line before thruster switching on to avoid propellant vapor condensation and possibility to contaminate spacecraft surfaces. But these problems could be solved and in the future missions such kind of propellants could be used.

4. Thruster models and plasma sources with the noncircular accelerating channels as well as with radial accelerating channel were developed and used[71,72]. Interesting scheme of discharge chamber with the so-called "prechamber" (Fig. 29) was studied at IAE and TsIAM. Particularly it was shown[73] that such discharge chamber configuration ensures the so-called "cylindrical" plume. But this configuration did not give significant improvement in thrust efficiency. Therefore the baseline for the SPT discharge chamber configuration was the standard one. One can add that such discharge chamber is used nowadays in the so-called ATON thruster design developed at MIREA[73].

5. An another line of studies was made at BHTSc and MAI related to the possibility to use the alternative current for the main discharge feeding[38,60]. Particularly it was shown the possibility to feed thruster discharge directly by the alternative current (without amplifier) and to receive the same thrust efficiency as in the direct current case. These results could be interesting, if in the future the powerful enough propulsion systems especially with turbo machinery power plants will be used in space.

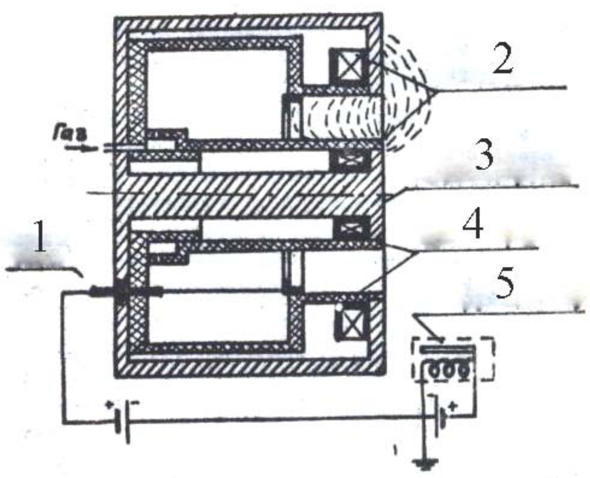

Figure 29. The SPT design with "prechamber".

So, this is not the full list of applied activities. The represented results were chosen by authors as the most interesting one.

IV. Conclusions

1. As it was shown above the so-called "Hall thrusters" had passed long enough history of their studies and development what allowed creation of physical and technological bases for the flight hardware development successfully used in space.
2. In the given paper authors considered only applied studies but in parallel with them a lot of basic studies were made in USSR related to the analysis and investigation of the general ExB discharge

properties, ionization and excitation processes, ions and electrons dynamics in the discharge and in the plume, oscillations, theoretical models and simulation tools development. As was noted at the beginning of this paper many results of these studies were published in open literature but often in very short form (abstracts etc). Therefore it seems reasonable to review results of these works too in a special paper or in the book.

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