# RESEARCH ON TWO-STAGE ENGINE SPT-MAG

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## ABSTRACT

Development and characterization of a Double Stage Hall Effect Thruster (DSHET) named SPT MAG is presented in this paper. Obtained integral characteristics of the thruster are a specific impulse $I \geq 2600$ s at $U_d \sim 500$ V, $\dot{m} = 2$ mg/s and a thrust $F \sim 120$ mN at $\dot{m} = 4$ mg/s.

## STATEMENT OF PROBLEM

The development and characterization of SPT-MAG has been initiated in order to achieve better operational characteristics than classical Hall Effect Thrusters. On the basis of a classical Stationary Plasma Thruster (SPT), a two-stage engine has been built. It would allow to:
1. Operate at high efficiency with different actuating mediums:
      a) cheaper gases(Kr, Ar, $N_2$)
      b) gases present in planet's atmospheres ($CO_2$, $CH_4$, $NH_3$).
      c) vapors of metals (from mid - Na, Mg, K, up to high-gravity - Hg, Pb, Br)
2. Decrease the divergence up to $\pm$ 3-5°.
3. Decrease the noise level inside the channel.
4. Increase the efficiency by decreasing the electronic current and the neutral density in the acceleration zone.
5. Increase the thruster lifetime by decreasing ionic and electronic (abnormal) erosion.
6. Extend the effective operating range.

To reach these aims, working process in SPT must be analyzed. As demonstrated by Kurchatov almost 30 years ago, development of classical SPT with power $W \leq 50$ kW is practically possible. Problem of lifetime is not a major limitation for engines with power $\sim 10$ W to 20 kW, at any rate till 10000 hours [1,2]. However, there are still three major problems: the increase of efficiency, which can theoretically reach $\sim 80\%$, divergence, which should be limited to $\left(\dfrac{a}{2}\right) \leq (5-10)^{\circ}$ and reduction of noise level, which can act on communication onboard satellite when thrusters are on.

In essence, there are two schemes of organization for working process in SPT:

In one case, basic ionization and acceleration take place near the exit plane. It results that the leaving flow has a wide scatter on energy and a large divergence. Process of ionization and acceleration are parted in space, and ionization takes place farther from the channel exit. The concentration of acceleration near the exit results in a dispersion of ion energy and ion angles.
In the other case, ionization and acceleration occur deeper in the channel and are spatially divided. Emitted ions are more focused. The ion flow does not strongly interact with the walls of the channel and the influence on the system lifetime is limited.

It is interesting, from the point of view of increasing the efficiency and decreasing the divergence, to organize a zone of ionization depth into the channel. Ionization and focalization of the ions would take place in this first zone. In the channel, there should be only the process of ion acceleration with focalization of the flow on the channel axis. Such a process would reduce the divergence angle and the noise level.

With classical SPT, basic ionization occurs near the anode [3,4]. Because of electron pressure gradient, magnetic field lines are not equipotential in the discharge channel and consequently, a large ion flux is

accelerated and lost onto the wall in the ionization zone. In the acceleration zone, the unfocused magnetic field lines lead to a large divergence and to energy losses (fig. 1). Consequently, the engine efficiency does not exceed 50 %, and the plume half-angle is close to 50°.
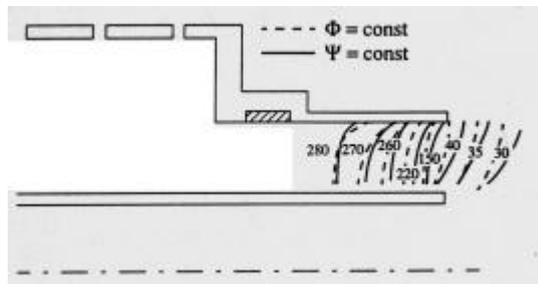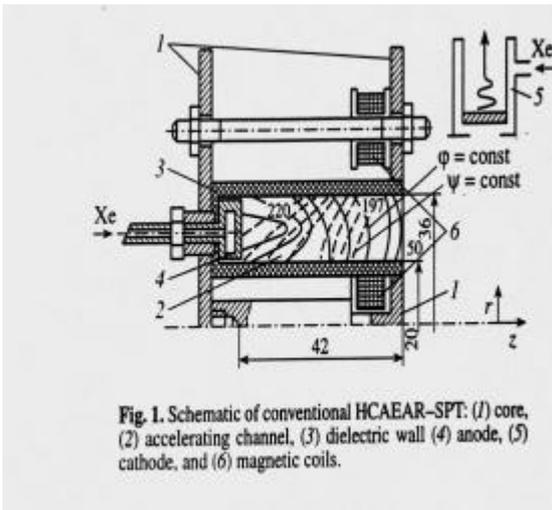


Fig. 1. Schematic of conventional HCAEAR–SPT: (1) core, (2) accelerating channel, (3) dielectric wall (4) anode, (5) cathode, and (6) magnetic coils.

**Figure 2 : distribution of magnetic-field lines ($Y$ = const) and equipotential curves ($F$ = const) for $\dot{m}$ = 3.0 mg/s and U = 300 V**

As first step to improve the engine, ionization zone and acceleration zone have been spatially separated resulting in the ATON thruster [5]. For this thruster, magnetic-field lines have been adjusted to be equipotential and ion flow into the channel has been focused (fig. 2). The integrated characteristics ATON are shown in fig. 3. Engine efficiency reaches value near 60% and the divergence half-angle has a value in the range $10^0$-$13^0$. However, ionization process in ATON was not optimized.
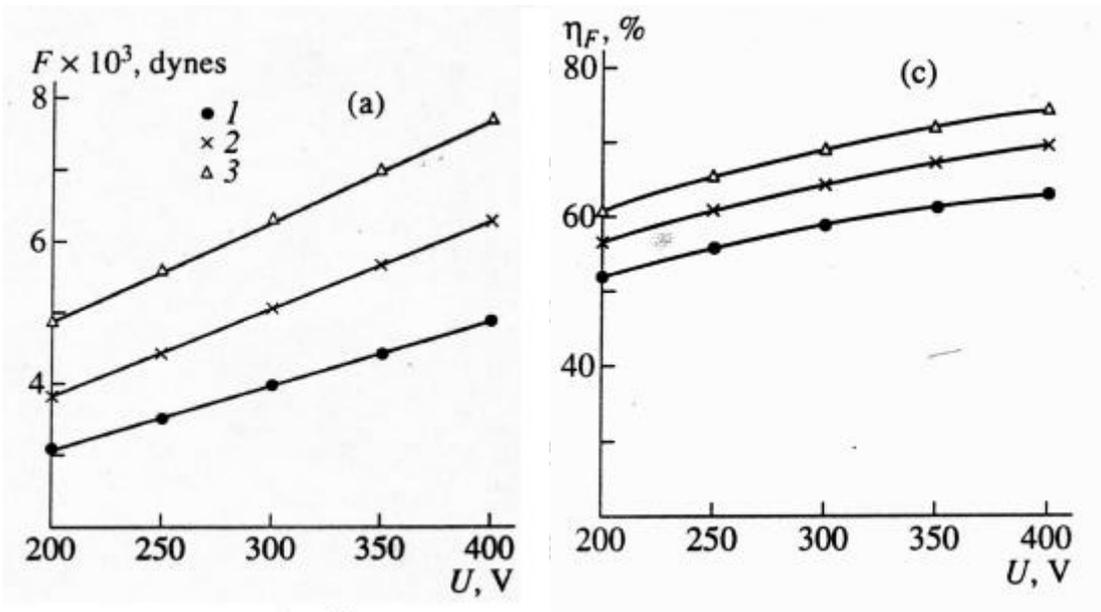


**Figure 3: thruster integral parameters for (1) $\dot{m}$ = 2 mg/s, (2) $\dot{m}$ = 2.5 mg/s, and (3) $\dot{m}$ = 3.0 mg/s.**

Further researches on the optimization of ionization process have resulted in the transformation of the buffer area in a separate first stage of the engine. The function of this first stage is to obtain an ionization rate of 100%. Created ions should have small energy that owes to focus them in the center of the channel with an appropriate electromagnetic field. In this case, at the entrance of the second stage, the ion flow would be almost monoenergetic and torn off from the channel wall. Therefore, engine lifetime would be increased, as the flow does not concern walls. Electronic current decreases as ionization does not take place in a zone of acceleration and so the efficiency $h$ is increased.

The first stage has only one function: create an extreme full ionization of actuating medium without limitations on the volume of the ionization zone. There is a real capability to achieve full ionization of almost any actuating medium without injecting atoms in the accelerating channel. Therefore, it is possible to work with any actuating medium. The second stage has for function to accelerate the flow with a high efficiency, it is the booster stage. At the entrance of the booster stage, the nearly monoenergetic ion flow, which is torn off from the wall, will be accelerated. Therefore, a high-energy ion flow is obtained at the exit of the booster stage. The engine lifetime, as the flow does not strongly interact with the walls of the channel, will be increased. The efficiency of the actuating medium is simultaneously increased. Because of the fall of ionization in the channel, the noise level decreases and the efficiency of the engine as a whole is increased.

## Basic characteristics of the system

The demonstration of physical principles and the assessment of functional properties of this kind of thruster compared to other systems were made on two-stage SPT MAG. The basic circuit of the device is shown in fig. 4. The model of the ATON engine is taken as a basis, but the buffer area of the ATON is transformed into a first stage of the engine. The work was carried out with Xe, the vacuum when engine is on is about $10^{-4}$ mbar. Vacuum in the chamber ($\Phi = 1$ m and $L = 2.5$ m) is obtained by diffusion pumps. A balance device measured the thrust with an accuracy of 3%. The magnetic field in the booster stage has been chosen in order to have a minimum of digit current. All characteristics are given for a stationary mode.
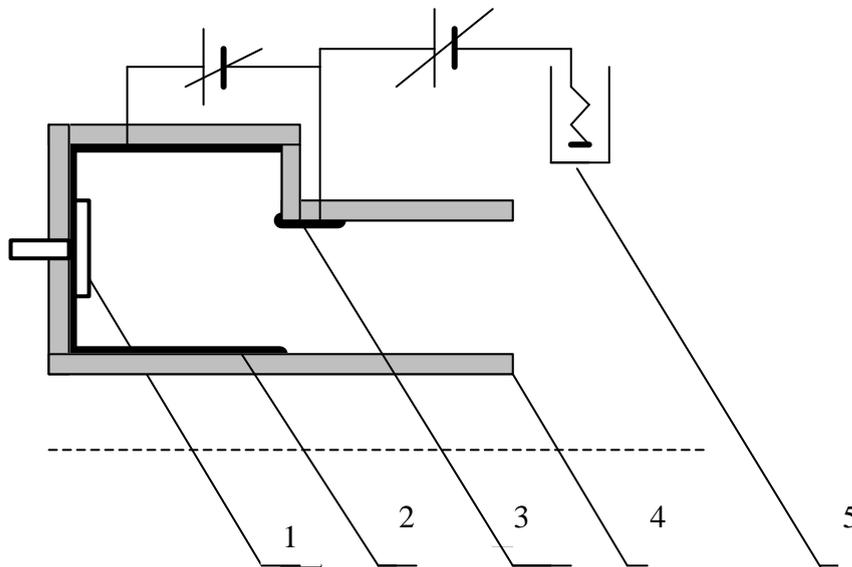
**Figure 4: schematic of SPT –MAG, 1- gas distributor, 2- buffer walls, 3- anode, 4- acceleration channel, 5-cathode.**

First, the operation of the first stage has been investigated. The ionization of the working substance and characteristic of the ion flow at the entrance of the second stage have been studied. Ion current arising in the first stage has been measured by a method of double directed probe. The double probe has two plane-parallel faces with an area $S = 0,07$ mm$^2$. The probe was placed in order to have the surfaces of the probe parallel to the surfaces of the engine then ion current was measured. The current on the wall is given by the equation:

$$J_{\perp i} = J_{i2} - J_{i1},$$

where $J_{i2}$ - current oriented toward the wall, and $J_{i1}$ - current oriented from the wall. A mechanical device allows positioning the probe at the required location. Measurements were made in the longitudinal direction with a step $\Delta z = 4$ mm and with a step $\Delta r = 4,6$ mm in a radial direction. The carried out measurements allow assessing the ion flow in the first stage and the ion current at the entrance of the second stage.

$$J_i^N = \sum_{k=1}^{N} \left( j_{i2}^k - j_{i1}^k \right) \Delta S^k ,$$

where $N$ - number of surfaces of the buffer volume, $k$- number of splitting, $\Delta S$ - elementary area of the surface. The experiment has shown, that a total current $J_i = 1,47$ A is obtained in the first stage. The ion current represents 97 % of the mass current $J_m = 1.52$ A ($\dot{m} = 2mg/s$). The engine worked in a mode: $\dot{m} = 2mg/s$, Xe, $U_d = 300$ V, $J_d = 1.98$ A. Thus, the experiment has shown, that in the first stage of the engine, there is practically complete ionization of the working substance.
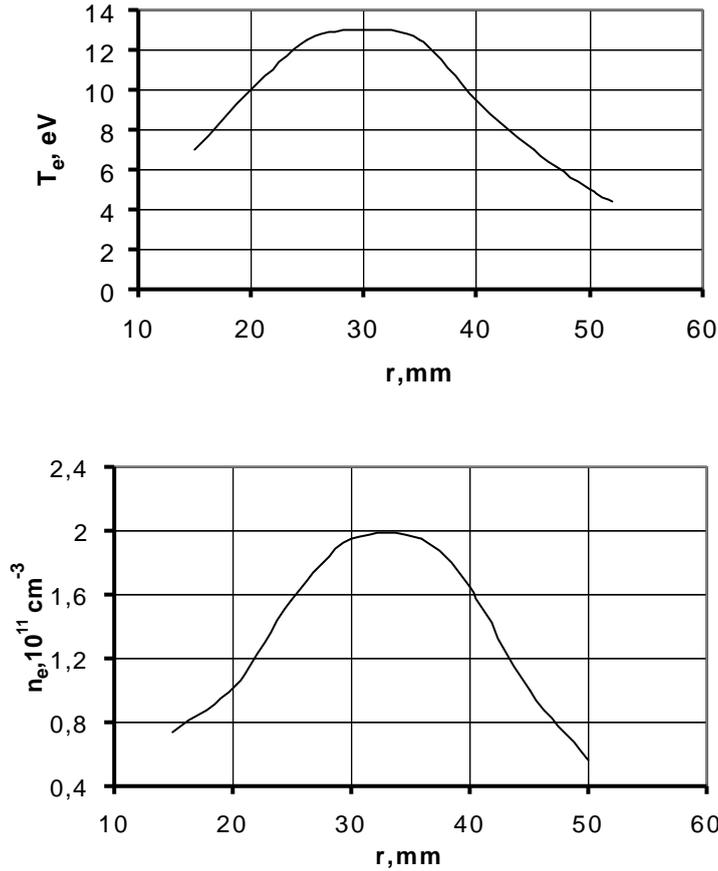




**Figure 5 : characteristics of plasma stream at the entrance of the acceleration channel, $U_d = 200V$; $\dot{m}_a = 2mg/s$.**

In fig. 5 is shown the electron density and the electron temperature in the channel booster. It means that at the channel entrance, there is a monoenergetic homogeneous flow of plasma. The integrated characteristics of the engine are given in fig. 6(a-d). The characteristic sizes of the booster stage are: $r_{average}= 63$ mm, internal diameter of external isolator 70 mm, length of the channel $L = 24$ mm.
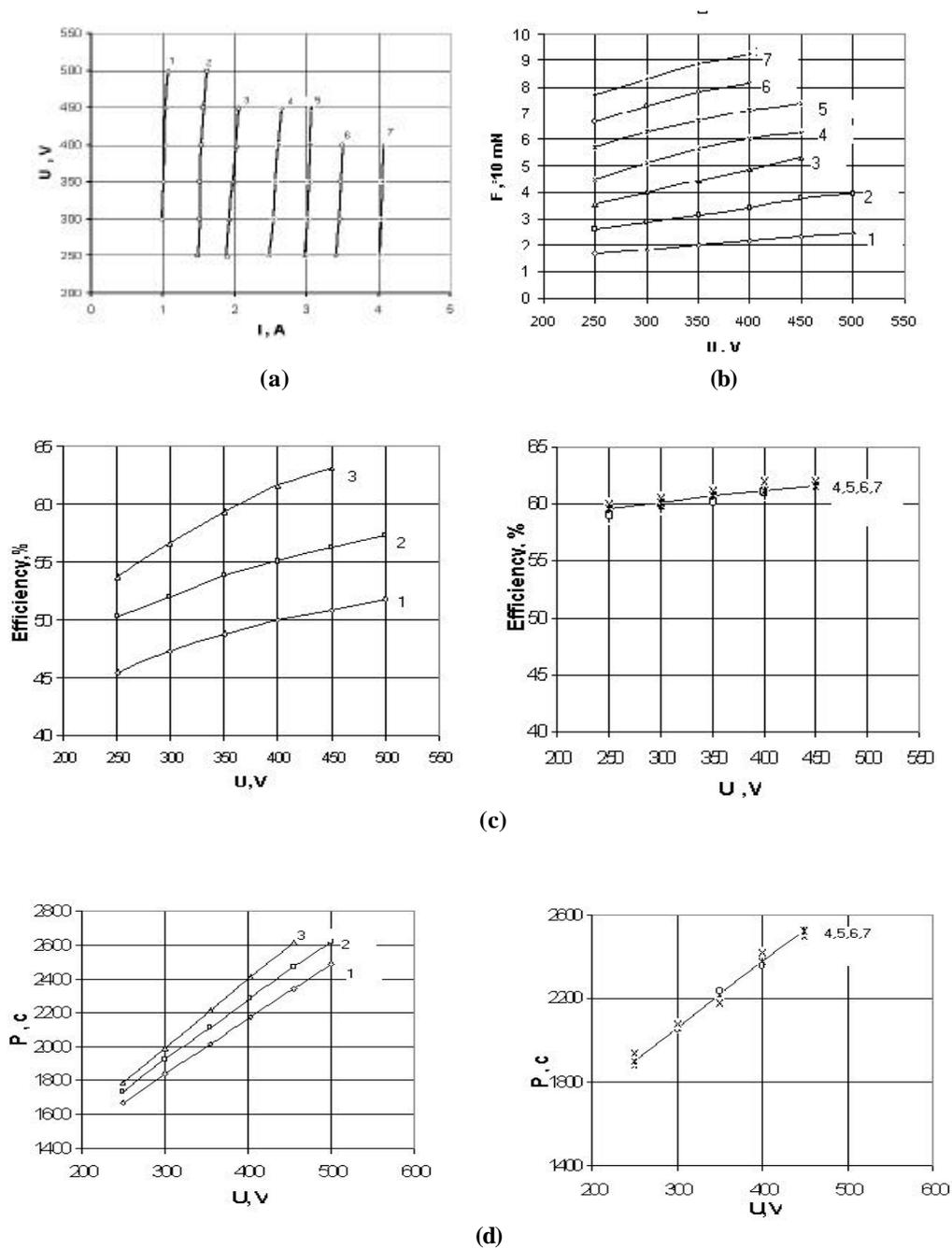
**(a)**



**(b)**



**(c)**



**(d)**

**Figure 6: integral characteristics of thruster MAG-A2. Voltage Current -a, thrust -b, efficiency -c, special impulse -d: 1-$\dot{m}_a$=1,0 mg/s, 2-$\dot{m}_a$ = 1,5 mg/s, 3-$\dot{m}_a$ = 2,0 mg/s, 4-$\dot{m}_a$ = 2,5 mg/s, 5-$\dot{m}_a$= 3,0 mg/s, 6-$\dot{m}_a$ = 3,5 mg/s, 7-$\dot{m}_a$ = 4,0 mg/s.**

Voltage-current characteristics of the engine are vertical (fig. 6-a). The functional range of the engine has been extended and has changed (in comparison with classical SPT) from 1 mg/s up to 4 mg/s with a channel size typical of  ? -70. Restriction on the voltage was only given by available equipment. The engine operated in two characteristic modes. The first mode was obtained with small flow rates $1 \leq \dot{m} \leq 3$ mg/s. In this mode, there is a linear growth of the specific impulse with the accelerating voltage. Therefore, for $\dot{m} = 2$ mg/s and $U_d \sim 450$ V, the specific impulse is $I = 2600$ s.
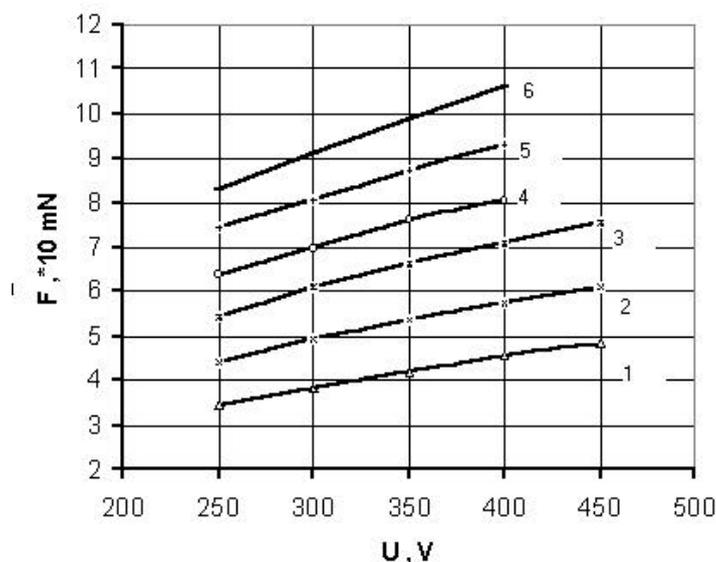
**Figure 7: thrust of MAG B thruster for different discharge voltages and mass flow rates with a propellant of xenon (??) (1- $\dot{m}_a$ =2,0 mg/s, 2- $\dot{m}_a$ =2,5 mg/s, 3- $\dot{m}_a$ =3,0 mg/s, 4- $\dot{m}_a$ =3,5 mg/s, 5- $\dot{m}_a$ =4,0 mg/s, 6- $\dot{m}_a$ =4,5 mg/s).**

For modes where $3 \leq \dot{m} \leq 4,5$ mg/s, with $\dot{m}$ = constant, the thrust increases with the voltage but the specific impulse changes poorly. The maximum value of thrust is 92 mN for $U_d$ = 400 V and $\dot{m}$ = 4 mg/s. By increasing the internal diameter of the external isolator to 90 mm for a channel width of 15 mm (MAG B), a flow rate $\dot{m}$ = 4.5 mg/s and a discharge voltage $U_d$ = 450 V will allow thrust up to $F$ = 120 mN (fig. 7). Flow divergence does not depend on the channel diameter. It must be emphasized that the level of fluctuation of the digit current for MAG engine in an optimum mode is less than for ATON model (5 to 8 %). The assessment of the plasma flow divergence was conducted with a double electrical probe. The probe was placed on a device apart with coordinate z = 35 cm from the engine and could be displaced in a radial direction. The measurements were made at different engine power settings. The profile of ion current was measured by using the probe and the half-angle of divergence was calculated.

Depending on the definition of the half angle ($\alpha/2$) (90 % or 95 % of the ion flow in a cone of half-angle aperture). We obtained that 95 % of the ion flow is in a cone with a semi-angle ($\alpha/2$) = $9^0$, and 90 % of the ion flow is in a cone with a semi-angle ($\alpha/2$) = $7^0$. The measurements were carried out for xenon with $\dot{m}$ = 4 mg/s and $U_d$ = 400 V.

By using krypton as actuating medium, specific impulse I=2900 s has been obtained for $U_d$ = 400 V and $\dot{m}$ = 4.0 mg/sec.

**Conclusion**

The two-stage SPT MAG design has been chosen on the base of existing SPT. The basic requirements for the physical processes have been assessed in each stage. The high overall performance of the engine has been demonstrated by tests in laboratory.

**Bibliography**

1. A.I. Morozov, V.V. Savelev, **"Fundamentals of stationary plasma thruster theory"**, Previews of Plasma Physics, 2000.
2. A.I. Bugrova and A.I. Morozov, **"Ionnye inzhektory i plazmennye uskoriteli (Ion Injectors and Plasma Accelerators)"**, Moscow: Energoatomizdat, 1990.
3. A.I. Bugrova, V.A. Ermolenko, A.S. Sokolov, **"Optical researches on neutral components for a plasma of xenon in nonequilibrium conditions"**.
4. A.I. Bugrova, A.I. Morozov, V.A. Ermolenko, **"Researches on ions created in the accelerator with the closed drift electron"**.
5. A.I. Morozov, A.I. Bugrova, A.V. Desyatskov, **"Fizika Plazmy"**, Vol. 23, No. 7.