The main physical features of the Morozov's type SPT and Electric Propulsion classification

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Abstract: The ion acceleration mechanism in the stationary plasma thruster (SPT) of the Morozov's type as the base for the methodology of such thruster operation organization is considered in the given paper. Such consideration gives some outputs to the SPT title which is different in different countries and allows corrections of this title and EP classification. Particularly it is shown that SPT and thruster with anode layer (TAL) are the gas discharge devices with ions acceleration by an "resistive"electric field created with help of magnetic field within the inter electrode plasma as in a conducting medium by the voltage applied in between mentioned electrodes. That is why they could be positioned into separate EP class. It is shown also that such understanding of the mentioned mechanism had allowed development of the main principles of the modern SPT operation organization.

I.Introduction

As it is known nowadays the Electric Propulsions (EP) of several types are successfully used in space technology, and scales of their application are extended. In this connection already many years intensive enough investigations devoted to study of wide field of physical and technological EP problems are made. At the same time a small attention is paid to consideration of such basic things as the mechanisms of a propellant acceleration and the main physical features of EP thrusters (EPT) because it is seemed that all problems with them were already solved. But in connection with development of new scheme EPT's it is reasonable to return at least periodically to such consideration. It is important because definite understanding of the acceleration mechanism determines methodology of thruster operation organization and terminology. As an example the widely known stationary plasma thruster (SPT) is considered in the paper which is one of the most popular subjects of studies nowadays. Even for this thruster we have no common understanding of its main physical features and of the propellant acceleration mechanism. As indication of different understanding of the main physical bases of its operation one can consider usage of different titles for this thruster in different countries. Therefore an acceleration mechanism in SPT and the main principles of its operation organization are considered in the paper. Results of this consideration gives some outputs to EP classification. So, some attention is paid to this point also.

II.The main physical features of the Morozov's type SPT.

2.1. Mechanism of ions acceleration in SPT.

As was noted above one of indications of different thruster operation understanding is usage of different thruster titles for SPT. Indeed, at least several titles were used in USSR and Russia for this thruster such as:

1. "E-accelerator". It was the 1st SPT title in USSR and reflects the fact that ions acceleration is made in this thruster by electric field in plasma.
2. "Plasma accelerator (or thruster) with closed drift of electrons and extended acceleration zone". This title reflects the fact that trajectories of electrons within the circular accelerating channel are to be almost closed.

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"Definition "extended" was used to distinguish SPT and thruster with anode layer (TAL) having "short" accelerating layer.

3. "Plasma thruster with closed drift of electrons and acceleration within magnetic layer". This title reflects the fact that acceleration in SPT is made within the magnetic layer divided from anode (In contrary to thruster with anode layer where the accelerating layer is attached to anode).

In USA at the beginning the dominating title was "Hall ion thruster" and nowadays the title "Hall thruster" or "Hall effect thruster" is widely used for SPT and TAL outside Russia.

One can note that the 1st title reflects more fully the main physical feature of SPT. To illustrate this conclusion the mechanism of the propellant flow acceleration in SPT and TAL is considered below.

Under consideration of acceleration mechanism in EPT it is reasonable to distinguish conditions of acceleration and main forces acting on propellant particles to accelerate them. Concerning the mentioned conditions one can note that SPT is a plasma thruster that is acceleration of propellant flow in SPT is made in plasma. This condition distinguishes plasma thrusters from the electrostatic ones. In this connection it is reasonable also to remember statement of academician Lev Artsimovich, the famous USSR scientist in the field of plasma physics and fusion problem, made in the early 1960-th and declaring that plasma acceleration is really the ions acceleration. This statement reflects the fact that due to drastic difference in electron and ion masses a main part of energy for plasma acceleration is spent for ions acceleration. Concerning other conditions in acceleration zones of SPT and TAL one can add that acceleration of ions in SPT and TAL is made in gas discharge plasma within circular channel with mainly longitudinal electric field and radial magnetic field. It is known also that in SPT and TAL acceleration zones plasma is to be rarified that is all free passes for collisions of particles significantly exceed characteristic size of the acceleration zone. So, below some other known points will be repeated to clarify mechanism of ions acceleration in SPT and TAL.

As it is well known, acceleration of ion in plasma could be described by the following expression:

$$M\frac{d\vec{V}_i}{dt} = q_i\left[\vec{E} + \left(\vec{V}_i \times \vec{B}\right)\right] + \vec{F}_{ii} + \vec{F}_{ie} + \vec{F}_{ia}, \qquad (1)$$

where $M, \vec{V}_i, t, q_i, \vec{E}, \vec{B}, \vec{F}_{ii}, \vec{F}_{ie}, \vec{F}_{ia}$ are the ion mass, ion velocity, time, ion charge, electric field intensity, magnetic induction and forces acting on ion by other ions, electrons and neutral atoms, respectively.

Because plasma is rarified the last three forces in expression (1) are small in comparison with $q_i\vec{E}$ magnitude. Then, magnetic induction is to be such (see, for example, Ref.1) that

$$\begin{array}{l} R_{Le} \prec\prec L \prec\prec R_{Li} \\ \omega_e \tau_e \succ\succ 1 \end{array}, \qquad (2)$$

where $R_{Le}, R_{Li}, L, \omega_e\tau_e$ are the Larmor radii of electrons and ions, characteristic size (length) of the accelerating channel and Hall parameter, respectively.

Conditions (2) means that ions in these conditions are not magnetized and are moved mainly under impact of the electric field, that is

$$M\frac{d\vec{V}_i}{dt} = q_i\left[\vec{E} + (\vec{V}_i \times \vec{B})\right] \approx q_i\vec{E} \qquad (3)$$

Electrons in these conditions are magnetized and their main averaged movement is reduced to the so-called electric drift with velocity

$$\vec{u} = \frac{\vec{E} \times \vec{B}}{\vec{B}^2} \qquad (4)$$

Besides electrons can diffuse under influence of electric field along its direction due to collisions of drifting electrons with heavy particles and walls or due to impact of oscillations on their movement. The corresponding current density

$$j_{ez} \approx j_{e\perp} = \sigma_{e\perp} E_{\perp}, \qquad (5)$$

where $\sigma_{e\perp}$ is an electron conductivity transverse to magnetic field.

The last expression reflects the fact that electric field $E_{\perp} = j_{e\perp} / \sigma_{e\perp}$ in plasma in the case SPT and TAL is created due to plasma resistance in the acceleration zone and currents induced by applied voltage. That is this electric field could be called as "resistive"one. Typical values of this electric field intensity is around of some hundred V/cm.

There are two other sources exist in acceleration zones able to create an electric field in plasma with magnetized electrons: electron pressure gradient and Hall effect. Electron pressure gradient in SPT acceleration zone creates component of electric field at least by an order of magnitude lower than the mentioned "resistive" field intensity values. So, it is not a main playing factor in the SPT acceleration zone. Concerning Hall effect one can note that it is producing the Hall current due to the mentioned drift motion of electrons but not producing the Hall Electromotive Force (HEF) because electrons are almost free to move along $\vec{E} \times \vec{B}$ direction and their interaction with ions have small impact on ions movement because plasma is rarified. Therefore it is questionable to use electromagnetic mechanism of ions acceleration in SPT and TAL cases. Indeed, situation of conductor with current in transverse magnetic field is different from the case of the acceleration zones of SPT and TAL. Indeed, the classical electromagnetic force acting on conductor with current (Fig.1) is caused by shift of the moving inside conductor electrons – current carriers by the Lorentz force in the direction transverse to the directions of electric field in conductor determining their movement direction and magnetic field. But this shift is stopped by conductor walls what creates appearance of the HEF and Hall electric field transverse to the direction of the main electrons movement direction and direction of magnetic field[2]. This electric field is acting on ions in the same direction as direction of the electrons shift. Finally the moving within conductor electrons being current carriers are shifted by magnetic field and "draw" ions and conductor as a whole in the direction transverse to directions of current and magnetic field. This is a physical nature of the electromagnetic force.

In contrary to the solid conductor case, as was mentioned above, electrons movement in plasma within the SPT and TAL acceleration zones is not restricted in the drift direction under impact of electric and magnetic fields transverse to directions of electric and magnetic fields. Therefore they are almost freely moved in this direction forming the Hall current and can push ions in this direction only due to collisions with them. But in the case of SPT and TAL effect of this pushing is small and, even if it is, this pushing is directed into drift direction while ions are moved mainly along electric field direction (see Fig.1в).

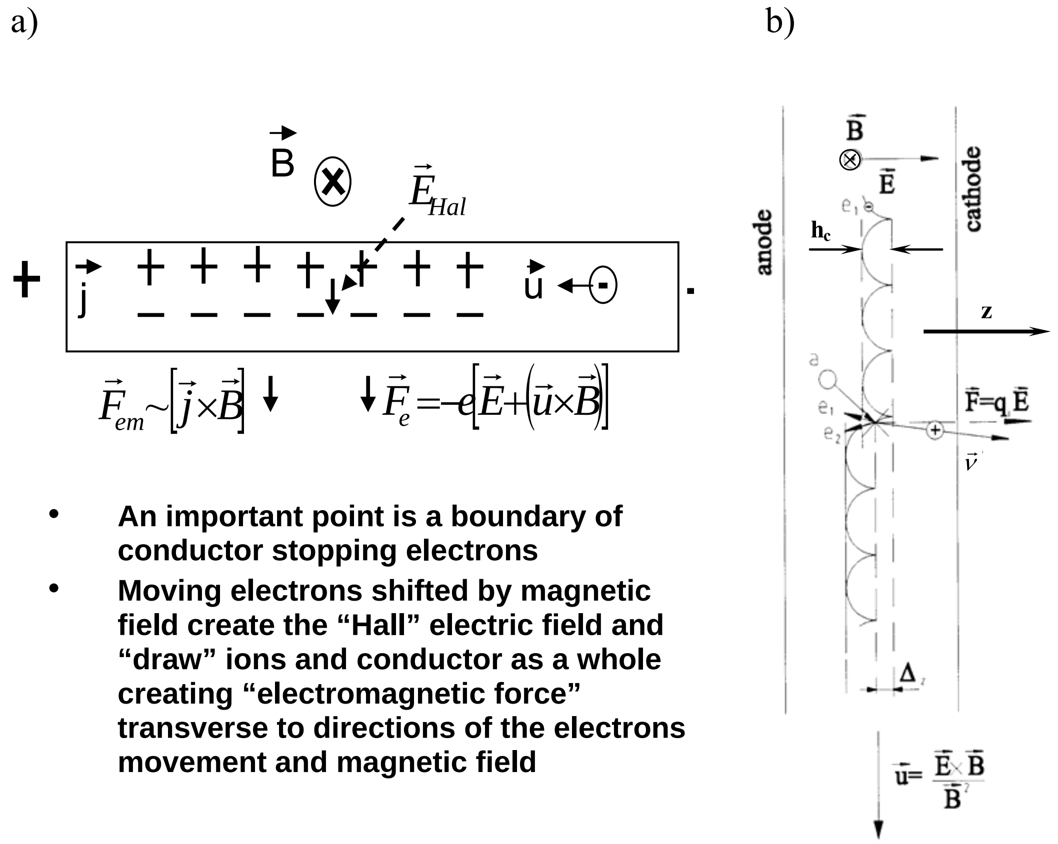

Figure 1. Scheme of the electromagnetic force appearance (a) and of the electrons movement in SPT(в)

Thus, in the case of SPT and TAL acceleration zones there is no HEF moving ions in the direction transverse to directions of electric and magnetic fields and the main ions acceleration is made by electric field along its direction. Moreover along direction of electric field electrons are gradually shifted in one direction and ions - in the opposite one. Consequently, electrons are not drawing ions which are accelerated mainly by electric field created in plasma as a conducting medium by voltage applied between anode and cathode and finally applied to plasma volume in the acceleration zone. So, there is no force acting on ions and similar to the electromagnetic force in nature. But induced currents in the accelerating layers of SPT and TAL are such that an electromagnetic force $\vec{f}_{em}$ calculated using the Hall current is equal to electric force $\vec{f}_{em}$ acting on electrons but is opposite to it in direction, that is:

$$\vec{f}_{em} = \vec{j}_{e\varphi} \times \vec{B} = -n\vec{u}e \times \vec{B} = -ne\frac{\left(\vec{E}\times\vec{B}\right)}{\vec{B}^2}\times\vec{B} = \\ = ne\vec{E}(\vec{B},\vec{B})\frac{1}{\vec{B}^2} - ne\vec{B}(\vec{B},\vec{E})\frac{1}{\vec{B}^2} = n\ e\vec{E} = -\vec{f}_e \tag{6}$$

where $n, e, \vec{f}_e = -en\vec{E}$ are the electrons concentration, equal to ions concentration, an electron charge and electric force acting on electrons, respectively.

Thus, an electromagnetic force $\vec{f}_{em}$, acting on electrons - Hall current carriers is acting in direction of the electric field and is compensated by electric force $\vec{f}_e = -en\vec{E}$ acting on electrons and total force acting on electrons flow is equal to zero:

$$\vec{f}_{em} + \vec{f}_e = 0 \tag{7}$$

Therefore electrons within the accelerating channel are in the steady state movement and have no drawing impact on ions which are moved by "resistive" electric field created in plasma as a conducting medium with help of external voltage source.

It is necessary to note also that due to quasineutrality of plasma the considered electromagnetic force is numerically equal to electric force acting on ions. So, in spite of the fact that there is no electromagnetic force acting on ions one can use the "virtual electromagnetic force" to analyze ions movement in the MHD approach.

Taking into account all the mentioned many Russian experts do not like titles "Hall thruster" or the "Hall effect thruster" for SPT and TAL. One can add that these titles do not characterize SPT and TAL specifics because Hall effect is realized in other stationary plasma thrusters too and even do not distinguish them. Concerning the title "Stationary plasma thruster" one can note that it is used already many years in many publications. Therefore it was proposed in Ref.3 to call these thrusters as the "Morozov's type SPT" or "Morozov SPT" taking into account great input of professor Morozov into their development and specifics of the modern SPT design. In this case we can use old title with addition reflecting the thruster specifics. This is similar to situation with Kaufman's type ion thruster or simply "Kaufman ion thruster" case. In the next part of paper the mentioned specifics of the Morozov SPT will be considered in more details to illustrate impact of the main acceleration mechanism understanding on principles of thruster operation organization.

2.2. The main ideas and methodology of the Morozov SPT operation organization.

Following idea of ions acceleration by electric field created in plasma volume Morozov had proposed to use "focusing" magnetic field lines (surfaces) geometry to create the corresponding electric field equipotential lines for the ion trajectories focusing within the accelerating channel (Fig. 2[3]). But electrons can move more or less freely along the magnetic field lines and can create the potential difference in between different points along these lines which could be estimated with usage of the so-called "thermalized potential" formula also proposed by Morozov[1] and could be rewritten as follows:

$$\Delta\phi(r,\gamma) = \frac{kT_e(\gamma)}{e}\ln\frac{n_0(\gamma)}{n(r,\gamma)}, \tag{6}$$

where $\Delta\phi(r,\gamma), n_0(\gamma), n(r,\gamma), kT_e(\gamma), e$ are the potential difference in between points with characteristic plasma concentration where, for example, concentration is highest, and other points along the mentioned line, characteristic plasma concentration and concentration in the interesting point, electron temperature and electron charge.

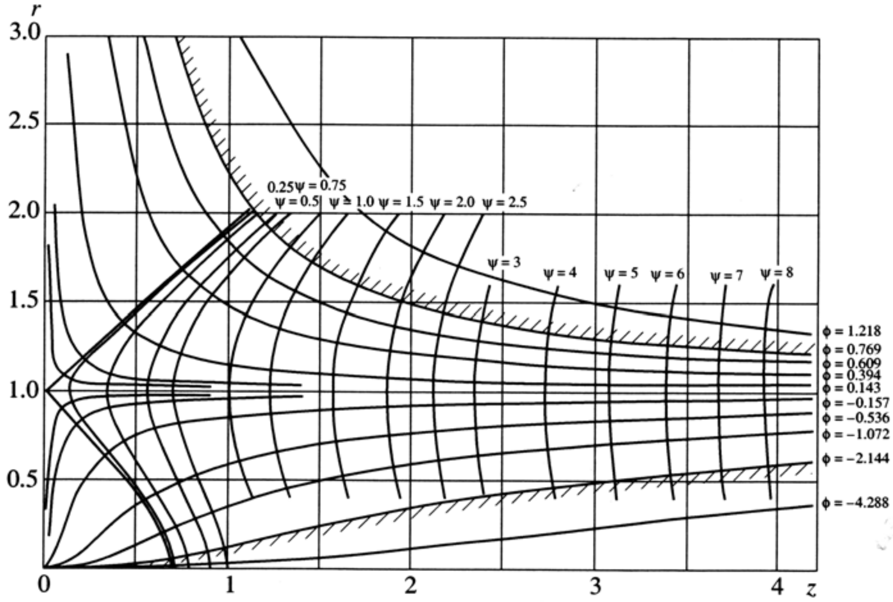

Figure 2 . Configuration of the magnetic field lines proposed by Morozov in early 1960-th[1]

This potential difference causes "defocusing" effect, and to reduce this effect Morozov had proposed to use dielectric walls having high secondary electron emission to reduce electrons temperature within the accelerating layer[3]. And nowadays one can confirm that discharge chamber walls in modern SPT's are made of ceramics and electron temperatures inside SPT channel is relatively low.

The considered ideas and magnetic field topology optimization made at the beginning at Institute of Atomic Energy (IAE) and Moscow Aviation Institute (MAI) had allowed notable improvement of the SPT performance and to reduce its plume divergence (Fig. 3-4[4-6]). Moreover, the "focusing" geometry of the magnetic field lines corresponds to increase of the magnetic induction within the space with such geometry of the magnetic field lines (see Fig. 3). And this feature allows more stable ion flow acceleration within the mentioned space what was explained 1st time by Morozov too[3]. Therefore in the modern SPT's the magnetic field with increasing magnetic induction from the anode to the accelerating channel exit is used.

It's necessary to note that Morozov had no definite ideas on usage of the plasma resistance to control electric field in SPT case. He was thinking that potential distribution could be introduced by special electrodes. The possibility to use plasma resistance to control electric field was recognized only on base of experimental studies of the local plasma parameter distributions which had shown that electric field is significant only in the parts of channel with high magnetic induction (see, for example, ref.7). Moreover it was recognized that changing magnetic field distribution one can change plasma resistance and plasma potential distributions within the accelerating channel. Moreover it was found that changing the magnetic induction distribution one can control position and width (thickness) of the accelerating layer[8-11](see for example, Fig.5[12]). Besides the performance improvement this possibility was used to position most part of the accelerating layer out of magnetic system counter[11] and to increase SPT life time.

One can add that the problem of plasma resistance or its electron conductivity had appeared already in early SPT type plasma thruster studies due to large fraction of electron current in the discharge current[13,14]. Since that time many approaches to explain this conductivity were proposed. But till now there is no strictly verified models of the electrons transport transverse to magnetic field in SPT. Following to experimental data one can assume only that in the near anode zone of the SPT discharge and in its part with reducing along acceleration direction magnetic induction the "Bohm's type" diffusion or mobility is realized. One can believe also that in the zone with large magnetic induction the conductivity could be assumed close to classical one (including the near wall conductivity), if one takes into account collisions of drifting electrons with ions, atoms and walls[10]. This point is supported by measurements of the Hall current and estimations of the effective Hall parameter giving for general SPT operation modes its values over 200[15] what is difficult to explain by the "Bohm's type" electrons mobility. In every case electron conductivity depends on magnetic induction magnitude and is to be small in the part of channel with large magnetic induction and this is a physical base for the potential distribution control in the modern SPT's.

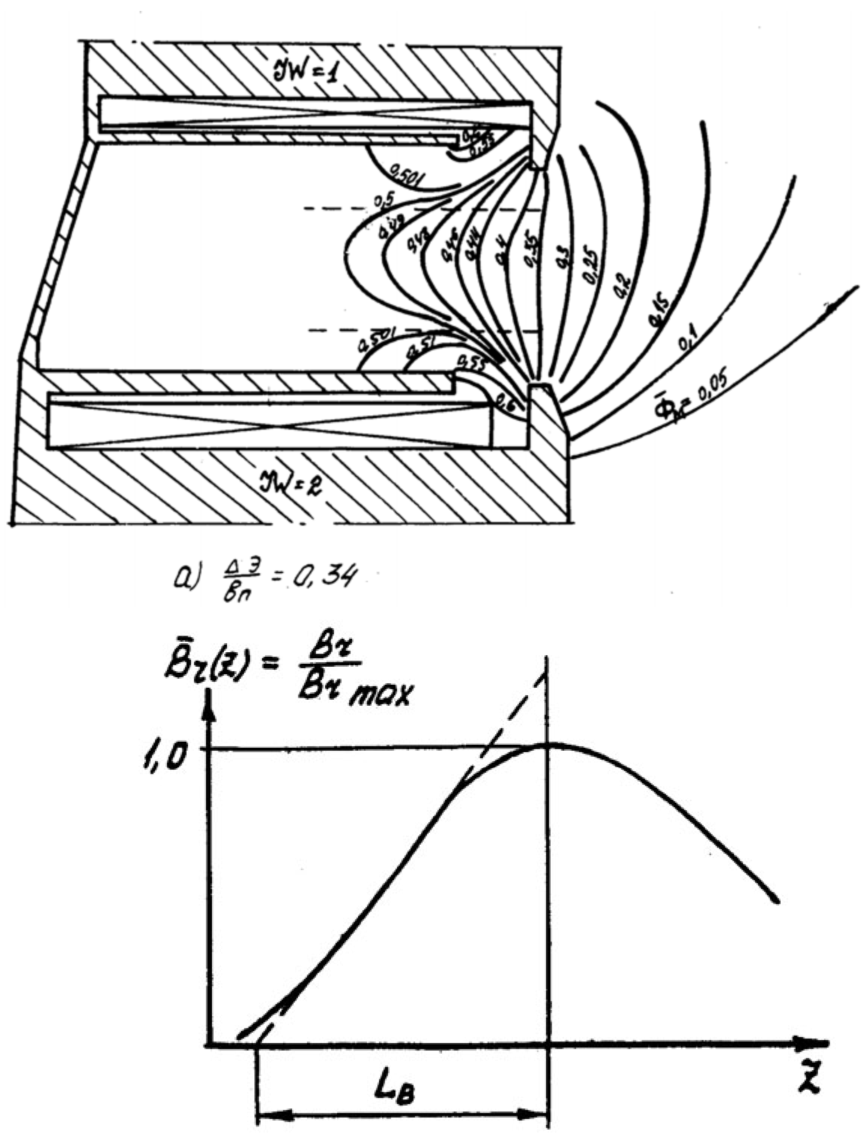

Figure 3. Magnetic field lines and radial magnetic induction component distribution along the mid surface of the accelerating channel of SPT.

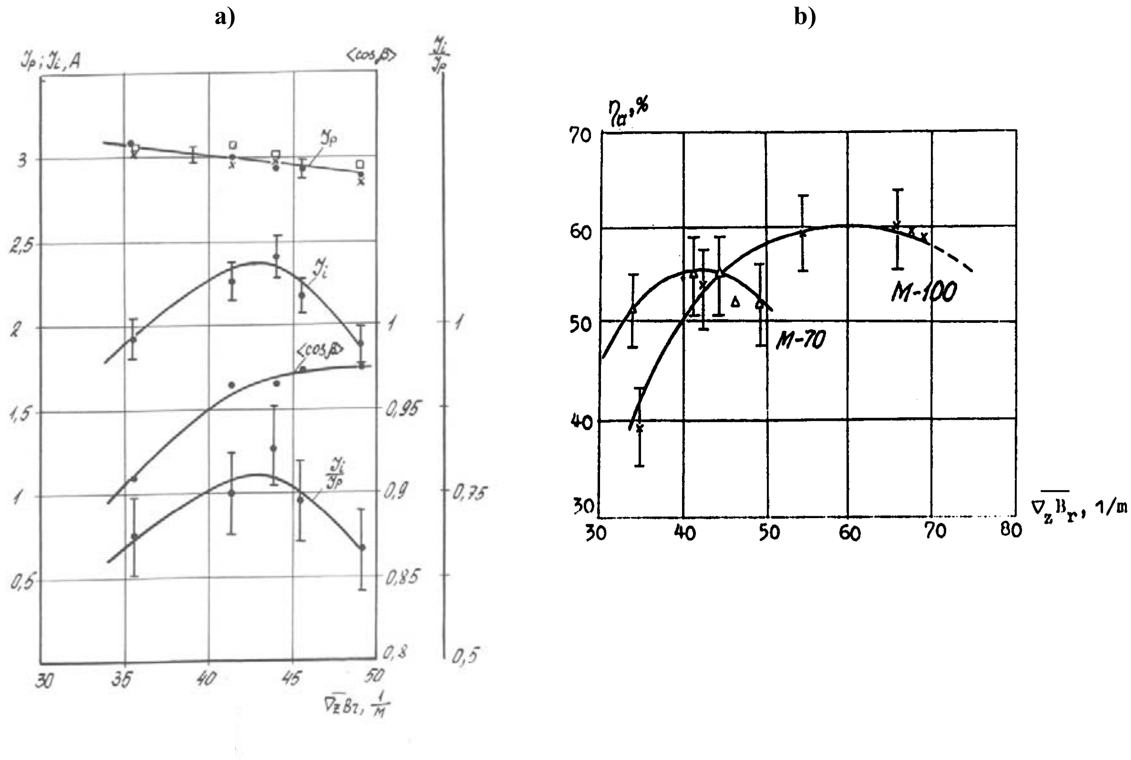

Figure 4. Dependence of thruster characteristics on the magnetic induction gradient for thruster model with external accelerating channel diameters 70mm(M-70) and 100mm (M-100)[4]:

- **a) discharge current Jp, ion current Ji exhausting thruster, mean value of the ion current density of-axes angle and ratio Ji/Jp versus the magnetic induction gradient for thruster model with external accelerating channel diameters 70mm(M-70)**
- **b) "anode" thrust efficiency for M-70 and M-100 thruster models**

One can note also that in the modern SPT's in spite of the magnetic topology optimization, the plume divergence is still significant enough (see, for example, Ref.16,17), that is a capability of the considered focusing approach is limited. Concerning the reasons of these limitations in the single stage thrusters one can state the following. Because the plasma conductivity in the part of the accelerating layer from the anode side is high, potential drop within this part of layer is relatively small. At the same time electrons traveling from the cathode side get maximum of their energy from electric field by this part of channel. Neutral atoms density is high here too. So, the ion production within this part of channel (which could be called as the ionization zone) has maximum rate. Combination of relatively small potential drop in longitudinal direction with high electrons temperature (see Fig. 4b) determines notable values of radial ion velocities within this part of channel due to significant radial potential drop according to expression (6). So, the significantly diverging ion flow is coming from the ionization zone into acceleration zone (see Fig.6), and it is difficult to focus this already partially accelerated flow of ions within the acceleration zone.

Focusing capabilities of the magnetic field are limited also due to the fact that electric field intensity is significant only in the part of channel where magnetic induction magnitude close to its maximum value and curvature of the magnetic field lines is small (see Fig.3).

As was noted above optimization of the magnetic field topology allows optimization not only position but thickness of the accelerating layer too (see option 2 in Fig.5a). Such optimization had given the optimum thickness of the accelerating layer ~1cm for external diameters of the SPT accelerating channels (50-300)cm. This thickness is significantly larger than Debye and Larmor radii. Thus, acceleration of ions in SPT is realized by electric field within the really extended plasma volume with focusing topology of the magnetic field bounded by dielectric (ceramic) walls. So, the main ideas of Morozov are realized in modern SPT's and this is one of the reasons to call SPT as Morozov's type stationary plasma thruster. It is also reasonable also to use title "Zharinov TAL" although title "TAL" already reflects some its specifics.

a)

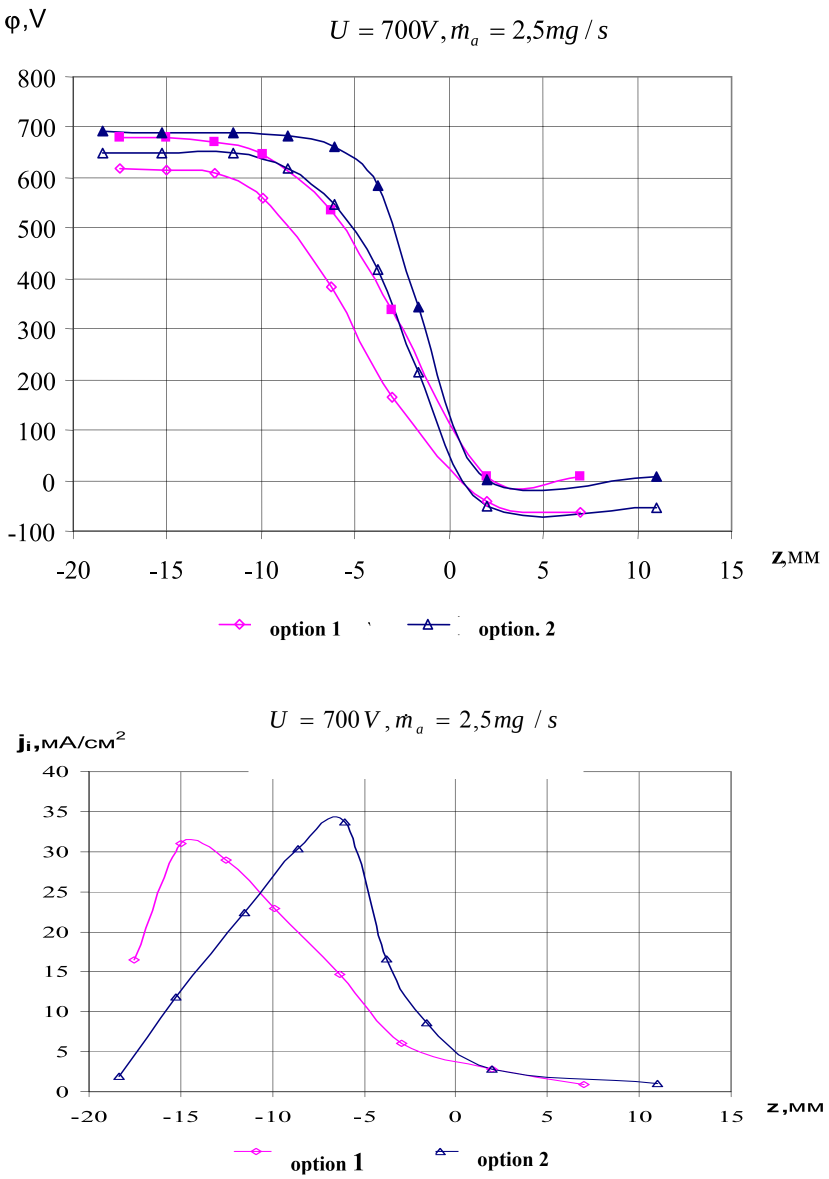

Figure 5. Distributions of plasma potential (φ_{pl}), probe floating potential (φ_0) and ion current to probe along the accelerating channel of the standard SPT-100 type laboratory model (option 1) and of the model with increased gradient of the magnetic induction and shifted to exit its distribution (option 2) measured by near wall probes[8].

opt.1 opt.2

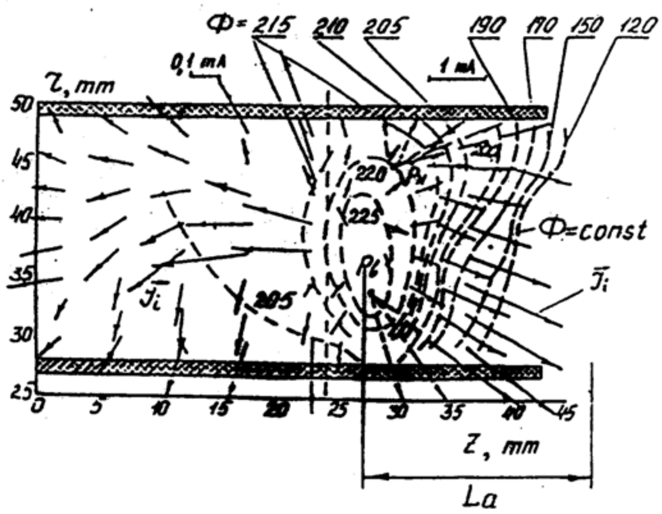

Figure 6. Typical directed ion flows structure within the SPT accelerating channel

So, control of the electric field formation as the main factor determining ions movement in the accelerating layer had allowed development of the SPT operation organization principles. As was shown this approach was productive enough and different from that ones used for the other stationary plasma thrusters where mainly the MHD approach was used for analysis and organization of processes. This is an illustration of the definite acceleration mechanism understanding impact on thruster operation processes analysis and control.

Ions acceleration by "resistive"electric field created within the plasma volume with help of magnetic field by application of the discharge voltage to the inter electrode gap is characteristic for TAL too. Acceleration of ions in plasma distinguishies SPT and TAL from ion thrusters and, as it is well known, due to this difference it is possible to obtain in the SPT and TAL acceleration zones drastically higher ion current densities. Therefore it is reasonable to remember that at the beginning of works SPT was called as E - accelerator. Therefore these thrusters could be classified as plasma (acceleration is made in plasma) thrusters with ions acceleration by "resistive"electric field or shortly as a "plasma thrusters with resistive E-acceleration" (PTREA).

III. Some notes on the EP classification.

The considered above examples show that under consideration of EP classification and elaboration of ways of thruster operation processes control it is very important to understand the main mechanisms and conditions of the ion acceleration within their acceleration zones. And it seems prospective to reconsider these mechanisms in the other stationary plasma thrusters with plasma creation and ions acceleration in the electric discharge in between thruster electrodes because the movement of electrons carrying and closing current within their accelerations zones could be considered as the steady state one. This means that an electromagnetic force acting on electrons as the current carriers should be in equilibrium with other forces acting on electrons including force created by the "resistive" electric field. So, this component of electric field can play notable role in ions acceleration and it is interesting to distinguish this role as it was done above in SPT case. Under such consideration, probably, one can find new ways to control operation of the mentioned thrusters. Naturally this consideration will take some time and it is out of frames of this paper. Therefore only small corrections of the EP classification are proposed below (Fig.7).

In this classification no changes are introduced in the the electrothermal thrusters (EThT) class represented by several subclasses or types: classical resistojets (RJT) and arcjet thrusters (AJT), as well as several types of thrusters with other ways of propellant heating (helicon - HThT, laser - LThT, general high frequency - HFThT, microwave heating –McWThT etc). Common their feature is exhausting flow acceleration by "thermal" expansion of the heated flow. Similar conclusion could be made for the electrostatic thrusters (EST) represented now by several types of ion thrusters with volume ionization (VIIT): Kaufman ion thrusters (KIT), radiofrequency ion thrusters (RIT), Microwave ion thrusters (McWIT). Then, we had or have ion thrusters with the surface ionization (SIIT), field emission ion thrusters (FEIT) and colloid thrusters (CT). Common feature of EST is an acceleration of charged particles of propellant by electrostatic field.

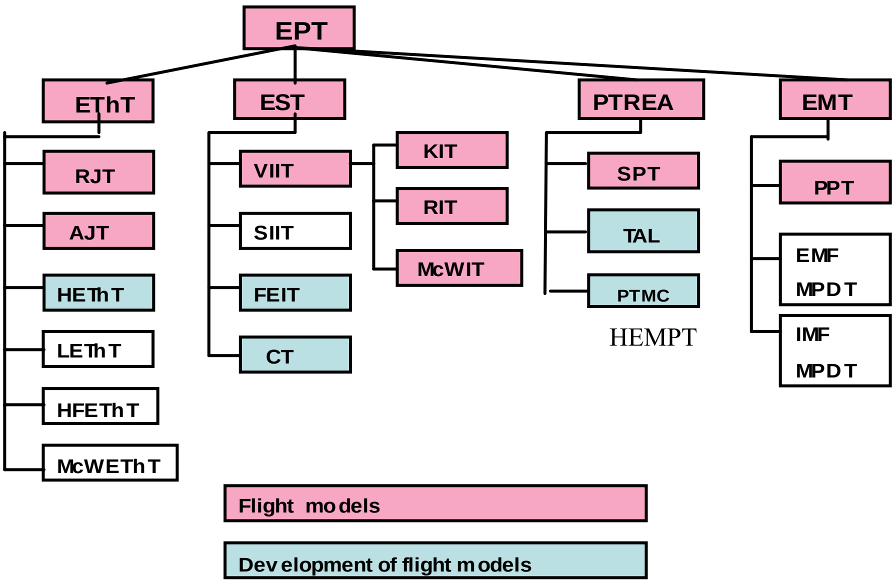

Figure 7. Scheme of the EP classification

Concerning the SPT and TAL they are removed from the electromagnetic thrusters (EMT) class and positioned into separate class of plasma thrusters with "resistive" E-acceleration (PTREA). It seems possible to have within this class also HEMPT[18] as the plasma thruster with ions acceleration by "resistive" electric field and magnetic confinement (PTMC).

MPD thrusters with external magnetic field (EMFMPDT) and induced magnetic field (IMFMPDT) as well as the pulse plasma thrusters (PPT) are left in the electromagnetic class.

It is natural that the proposed classification is not considered by author as the final one.

IV. Conclusion.

As it was shown in the paper acceptance of definite main mechanism of acceleration has definite impact on the methodology of thruster operation organization and that it is better to introduce the Morozov SPT and Zharinov TAL into new EPT class of plasma thrusters with ions acceleration by the "resistive"electric field. It seems prospective also to reconsider this mechanism in some other stationary plasma thrusters what, probably, could help to find new possibilities of these thrusters operation control and to correct EP classification and terminology, if necessary.

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