A Concept of Development of Electric Thrusters with Thrust Vector Control

Valery Petrosov
Keldysh Research Center
Moscow, Russia
007-095-4564608
kerc@elnet.msk.ru

IEPC-01-15

The possibilities of development of electric propulsion (EP) with a thrust vector controllable (variable) on magnitude and direction are considered. The rational ways of solving the stated problem are shown and the specific technical decisions are suggested. In the nearest future all this allows one to develop a new-generation EP - single-channel Hall thrusters and polychannel Hall and Ion thrusters, in which, in particular, wide-range control of power or thrust magnitude and of an angle of thrust vector rotation (up to 10º and higher) can be performed.

Introduction

Electric propulsion (EP) is progressively gaining greater acceptance in space engineering. Now any perspective project cannot be competitive with the others if it does not foresee using the EP. Presently Hall-type (stationary plasma thrusters -SPT- and thrusters with anode layer - TAL) as well as Ion thrusters are deemed the most technically perfect and having the best characteristics. True, a certain stabilization (or even a slowing down) in further improvement has taken place after achieving some progress in development of EP of these types. Perhaps it would be more right to say so: strengthening the positions goes on the achieved results but not a winning over the new high levels. It is expressed in updating the construction and manufacturing process, improving the reliability, increasing the service life (lifetime), reducing the cost, etc. The thrusters are introduced into the spacecraft (SC), in so doing, the output characteristics do not vary much.

How are the most probable progress lines and directions in such more or less serious changes in the EP construction, output characteristics, and capabilities of the new thrusters?

It is convenient to illustrate these problems by the example of SPT as the most advanced in all lines thruster. Its typical magnitudes of the parameters for today are:

power N~0.5-5 kW, voltage U~300 V, current I~2-15 A, thrust F~30-300 mN, efficiency η~0.5, specific impulse I_{sp}~1400-1800 s, lifetime T~$(4\text{-}8)\cdot 10^3$ h, number of operating cycles n~$(4\text{-}8)\cdot 10^3$.

We can formulate the following possible lines of updating:

1. Increase of I_{sp} up to 2500 s or higher. Here there are at least two possibilities: 1) increasing U up to 600-800 V and higher, 2) transition to lighter working fluid (from Xe to Kr).
2. Increase of thrust at fixed power that is reducing I_{sp} down to magnitudes ~1000s. This task looks like sufficiently difficult because the natural way - reducing U - has failed: efficiency η declines already at U <200 V and gain in thrust has lost.
3. Derivative task from the first two ones - making bimodal thruster capable to operate at great and small specific impulse I_{sp}. In so doing, if we are dealing with one-mode thrusters in the first two cases here we are talking about controllable thruster.

Controllability (multi-mode operation) of the thruster can be considered in the other direction as well.

4. Variation of thruster power (or thrust) at constant magnitude I_{sp}.
5. Changing the direction of thrust vector action.
6. Variation of thrust vector on magnitude (on module) and on direction.

Apparently, the thrusters capable to vary their parameters (characteristics) over a wide range of magnitudes will be created in the nearest future. But presently all developed thrusters are one-mode in practice and it allows one to small forcing and throttling in power and absolutely are not capable to change the direction of thrust vector action.

We would like to consider the possible ways of making EP with changeable (controlled) thrust vector (tasks or directions 4,5 and 6).

Demand for EP with controllable thrust vector

A propulsion system apart from a thruster itself incorporates power supply system (this, for example,

solar array, converter, etc.) which generates power on SC for a thruster as well as for the other users also including payload, for example, radio equipment on communication satellites.
In the work process (we tell about functioning in space within 10-15 years) extremely different including contingency (when power supplied on thruster changes) situations arise. It can be related to the execution of two various tasks - transport and the task of stabilization, correction, orientation. In the first case (SC insertion into orbit, de-orbiting, orbital transfer) as a rule a great power (and thrust) of the thruster is needed. It is possible to generate increased power to the thruster (the other energy users are off). In the second case lesser power and thrust are required. Beyond this point the problems with electric power source, its gradual degradation, etc. can arise. Indeed thruster adapted to the operation in wide range of power (thrust as well) will be preferable.
In flight it is required to change the direction of thrust vector, for example, because of changing the location of SC center of gravity as propellant utilization or on the other reasons. As a rule it is sufficient to have a possibility to change the direction of thrust effort action only by several degrees. For this we are led to use a special mechanism of thruster steering regarding SC. Rotating (hinge) mechanism is heavy, complicated, unreliable and expensive. In the case of unavailability of the rotating mechanism we are led to apply the other means (for example, additional thrusters) which are not "free" too. So, presence of EP with controllable thrust vector and capability to change the direction of trust effort even in the range of several degrees is highly advisable onboard SC.
Thruster capable to solve the tasks of thrust vector rotation is convenient also because of making easier (simplifying) the preliminary technological development and updating the thruster at the stage of its making as well as it allows us to compensate the inaccuracy in manufacturing. Because of it the requirements imposed to a thruster on specification as well as the requirements while thruster manufacturing and a cost of a product reduce.
In brevi, making a thruster capable to operate without the deterioration of its characteristics in wide range of power and to change the direction of thrust vector is undoubtedly attractive. It expands the possibilities of EP, increase its value, usefulness and so the stimuli for introduction of such thrusters will grow.

Possible ways for the problem solving

The problem of making EP of wide-range in power does not seem very complicated in principle. More likely it is a technical (engineering) problem than a scientific. For example, this problem is solved at simple using a set of some similar thrusters capable to operate concurrently. In this case power (and thrust) can change in several times.
It is more complicated problem if the same result should be received in one module. Perhaps it should not follow this way too far. It is sufficient to have a thruster capable to work profitably in the range of power +/- (30-40)% from the nominal value.
The set of thrusters is suitable also because the necessity to test and develop a thruster of great power is not required.
A problem of making a thruster capable to rotate thrust vector looks like more complicated. Let us consider this problem in detail based on the example of Hall-type thruster (HT) of SPT-type.
Fig. 1 shows a variant of schematic diagram of such thruster. The thruster contains axisymmetrical channel 1 for ionization and acceleration. Internal 2 and external 3 walls bound it. Anode 4 is located in the channel in the area of its closed end. Anode 4 simultaneously plays the role of collector-gas-distributor. Magnetic system consists of inside and outside subsystem every of them contains correspondingly magnetic circuit 5 and 6, pole 7 and 8, source of magnetomotive force 9 and 10. Cathode 11 is placed outside channel near its open end. The area of annular channel 1 bordering on to anode 4 (that is to closed end of the channel) is an ionization zone, area near exit section (that bordering to open end of the channel) - is an acceleration zone.

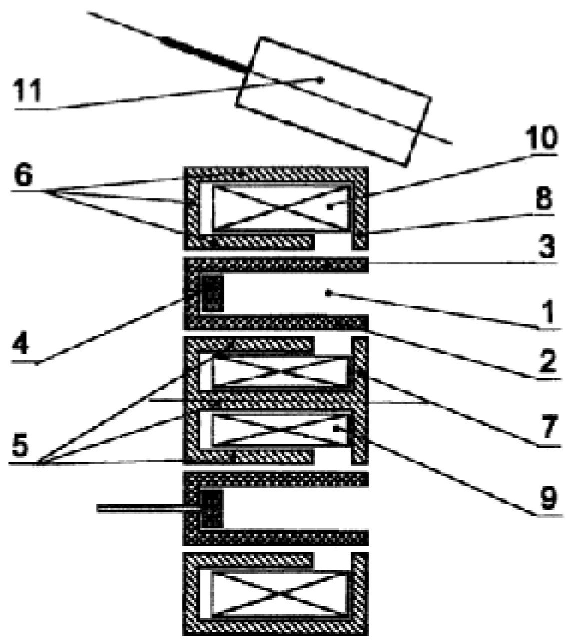

Figure 1.

If consider that HT is an axisymmetrical device generating force (thrust) strictly along the axis of symmetry, so it is necessary to induce the additional force in lateral (perpendicular to the axis) direction for rotation of thrust vector.

Label the direction along geometrical axis of thruster by "II" and in lateral direction by "⊥". So, the thruster generates thrust F_{II} or impulse I_{II} in the rated mode and force $F_{\perp}$ or impulse $I_{\perp}$ additionally appear at rotation of thrust vector by angle α. In so doing angle of rotation (or deviation from nominal position) will be:

$$\alpha = \text{arc tg } F_{\perp}/ F_{II} = \text{arc tg } I_{\perp}/ I_{II}$$

It is possible to imagine two possibilities for realization of thrust vector rotation in such device (without displacement or rotation of thruster itself)

1. Use of a special additional device located behind thruster exit and intended for change of movement of running out accelerating flow of the propellant (it is a remote device);
2. Organization of the working conditions in the thruster itself so that running out flow of the propellant can be directed not along the axis but under the angle to it.

At the beginning we consider the first possibility. Two ways can be used to change the direction of running out flow: remaining the axial velocity component as a constant, adding the transverse component and thus increasing the energy of running out particles; rotate the flow while remaining the energy of running out particles as a constant (that is the absolute magnitude of velocity vector). The first way means re vera creation of the second stage of the accelerator that is rather difficult, of course. The second way (without additional energy contribution) seems more preferable.
A device for realization of such rotation (it can be called as remote, autonomous in relation to the thruster itself) can be some magnetic system which typical size in radial direction should be greater than the diameter of running out jet. Longitudinal (along the flow) size λ depends firstly upon an angle of flow rotation and secondly upon a magnitude of the filed induced by this magnetic system and more exactly upon Larmor radius R_L.

$$R_L = V/\omega = V\cdot(Mc/He),$$

where V - flow velocity, ω - Larmor frequency and M - ion mass, H - magnetic field, $c=3\cdot10^{10}$ cm/s - light velocity, $e=4.8\cdot10^{-10}$ - electron charge in CGSE system. Let us assume, for example, velocity $V=1.6\cdot10^{6}$ cm/s, magnetic field H=150 Gs, Xenon ion mass $M=131\cdot1.66\cdot10^{-24}$ g, we get $R_L \approx 1.5$ m. So, at rotation of ion (or flow) through angle $\alpha\sim10°\sim0.17$ radn, the longitudinal size

$$\lambda\sim\alpha\cdot R_L=0.17\cdot1.5\approx0.25 \text{ m}.$$

Consequently, only working (useful) volume of remote device of thrust vector rotation will be of several litres. Then the volume of magnetic system will be lesser and the mass of such system will run into the tens of kg particularly taking into account that the rotation shall be implemented to any direction that is at least in two planes (directions).
We see that the remote system of thrust vector rotation will exceed on its sizes and mass (and in great extent) the corresponding parameters of the thruster. It is not acceptable. A propos, it has been justified by the direct attempts to develop such system (that has occurred heavy, large-size and inefficient).
So, we are forced to exclude the first possibility from the consideration and to dwell on the second one related to the organization of the process inside HT.

Analysis of the HT capabilities

At analysis of the capabilities of thrust vector rotation in HT itself we will try to base on the most common reasoning.
Clearly that it is necessary to disturb the symmetry (or to create asymmetry) for appearance of lateral thrust component $F_{\perp}$ in HT in any direction. But it is not enough. It is required also to find a source of thrust vector transverse component.

Azimuthal non-uniformities

The following possibilities (levers) are available to establish the azimuthal non-uniformity (asymmetry):

1. magnetic field H,
2. propellant flow rate m,
3. voltage U (or electric field E),
4. geometry G,

that is changing one of mentioned parameters along azimuth it is possible to establish asymmetry and expect of appearance of lateral thrust component. We have no the other levels. Let us consider these possibilities.
If we foresee the availability of azimuthal sections in magnetic system in the thruster design (as it has been made in [1]) and in collector-gas distributor (both have been realized in [2]) it is possible to provide varying on azimuth H and m. But here it should be taken into account that at break of azimuthal symmetry we disturb the important principles of HT work. Actually HT is an accelerator with closed (on azimuth) drift of electrons. In so doing the azimuthal current can exceeds the main (longitudinal) discharge current by an order or more. So, its availability leads to strong leveling of all parameters on azimuth. Artificially introducing the changes of parameters (H and m) on azimuth we will come into the conflicts with the normal operating conditions of Hall-type accelerator. That can have far-reaching implications. For example, it can lead to sharp increase in amplitude of discharge parameters variation and magnifying in magnitude of longitudinal electron current and it, in its turn, to either substantial decrease of the thruster efficiency or to break-down of distributed discharge and transfer to arc converging discharge with catastrophic consequences for the construction.
So, we come to the conclusion that the introduction of azimuthal non-uniformity of H and m should be very fine and in sufficiently limited range. But in this case the result cannot be substantial.

Besides, we should understand that introduction of azimuthal non-uniformity does not mean involuntarily thrust vector rotation. More likely it is only a pre-condition but not the fact of rotation itself. Actually if, for example, azimuthal non-uniformity m is made, so we can anticipate that re-distribution of axial thrust force will arise on azimuth and total vector F_{II} remains the same as the lateral component that is $F_{\perp}=0$ but in so doing the force moment occurs. its magnitude will be the fractions of $F_{II}\cdot R$, where R - typical (average) radius of the thruster channel (more precisely $\Delta F_{II}\cdot R$, where ΔF_{II} - characterizes azimuthal non-uniformity F_{II}).
In the light of all told about H and m it is easy to understand that making azimuthal non-uniformity of electric field E - is not a simple problem. Sectioning of the anode and using the several cathodes with simultaneous supply of various potential differences U on electrodes (or introduction of any additional electrodes) cannot be effective at azimuthal Hall current. Supply of various potential differences to azimuthal sections of the electrodes lose its meaning, i.e. these potential differences inevitably disappear owing to arising the shielding near-electrode layers. Keeping any considerable asymmetry of electric fields in space will require passing the great additional azimuthal currents between the sections of the electrodes. Consumed electric power will exceed the power consumed by the thruster in rated mode. In other words level E cannot give a result.
Using the forth level G - geometrical - in practice means the mechanically moving elements in the construction for making azimuthal non-uniformity. Finally such approach is the equivalent to use of thruster rotating mechanism. We should refuse from it to be logical.
So, actually there are only two levels for making azimuthal non-uniformity. They can be used at development of the thruster with thrust vector rotation, they are H and m.

Transverse component of the force

We repeat one more time - availability of azimuthal non-uniformity of any parameters does not guarantee appearance of thrust vector component that is necessary for rotation. Generally speaking, use of only non-uniformities without the other levels means the attempt to receive the positive effect from "losses", "wastes". In the best case we can reveal the effect but not get the effective decision.
In addition to longitudinal (axial) electric field E_{II} it is necessary to have the transverse component $E_{\perp}$ of electric field in the acceleration zone of HT for occurrence of transverse component of the force.
As lines of magnetic force in HT and equipotentials of electric field approximately coincide it is easier to make any configurations of electric field by making the corresponding configurations of magnetic field. Accepting such concept it is possible to plan two lines in activity for receiving of the needed result.
1. It is possible to make azimuthal non-uniformity H so as electric field $E_{\perp}$ arises - also azimuthal non-uniform. It will lead to appearance of transverse force $F_{\perp}$ [1,2].
2. It is possible to make azimuthal uniform field H so as electric field $E_{\perp}$ - azimuthal uniform - arises (aside from E_{II}). As a result the transverse component forces $F_{\perp}$ arise but at lack of azimuthal non-uniformity, the transverse components of ion impulses at the summation are compensated and total thrust vector will be oriented along HT axis. Occurrence of azimuthal non-uniformity under such conditions (for example, propellant flow rate m) will lead to non-zero total transverse impulse of all ions, i.e. thrust vector rotation is realized [3]. (Of course, combination of the 1st and 2nd is possible).
It is natural that the second approach is more effective. However both have one serious disadvantage. It is easy to understand if take into consideration the feature of the construction of HT using presently. Usually acceleration zone of HT is annular channel formed by co-axial cylinders. Occurrence of electric field $E_{\perp}$ (uniform on azimuth or non-uniform) leads to transverse, directed along radius (that is to the wall) force $F_{\perp}$. As a result it inevitably lead to the whole series of negative consequences: increase the interaction of plasma flow with the wall, thermal load on the wall and energy losses to the construction increase, erosion processes intensify, positive effect of thrust vector rotation reduces, etc.
It is possible to avoid all these negative consequences if to change the geometry of the channel. Actually, if middle line along the flow of propellant is not parallel with the thruster axis in the annular channel and it is inclined under angle β (see Fig.2), so under condition that the magnetic field is directed primarily normal to the channel wall, the electric field will be directed along this middle line, i.e. it will have radial $F_{\perp}$ in addition to axial component E_{II}. In this case at presence of non-uniformity, for example, of propellant flow rate m, the thrust vector rotation is realized and flow will not be directed to the wall [4].
So, it is necessary to consider the superposition of axisymmetrical (azimuthally uniform) electric field, non-parallel to the thruster axis, using the geometrical factor (annular channel with inclined middle line) and simultaneous making the azimuth non-uniformity, for example, m, is the best variant.
Simultaneous making azimuth non-uniformity of magnetic field H at the same azimuthal area should be highly useful to avoid the negative consequences of making the azimuthal non-uniformity m (- increase of oscillations and gain in longitudinal electron current) as well as with the purpose of providing the beneficial conditions for existing (realization) such non-

uniformity. Such effect can provide constancy in azimuth for Hall current j_φ (at non-constancy of particles concentration, n, in azimuth)

$$j_\varphi = encE/H.$$

The same effect can be achieved if azimuth non-uniformity of magnetic field with reverse sign (that is decreasing H instead of its increasing) will be made in additional in azimuth area.

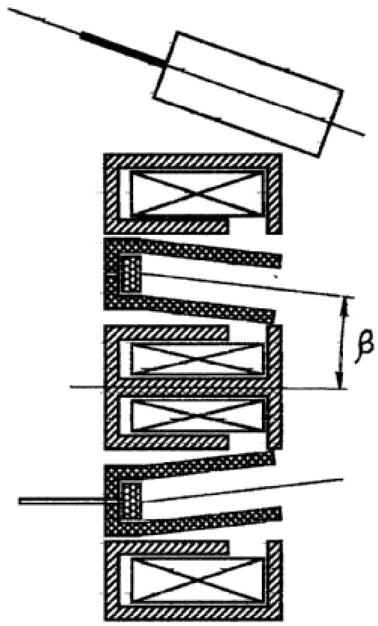

Figure 2.

Notice that we can change the magnitude of thrust vector deviation value (or transverse impulse magnitude) by two ways: 1) varying intensity (amplitude) of azimuthal non-uniformity and 2) varying time of its applying (duration of exposition).

Polychannel thruster

An idea to use geometrical factor can be modified and effectively realized at application of pack of thrusters or one polychannel thruster. For example, if four identical thrusters are located symmetrically relative to one common axis and the axis of every thruster, among available four, is inclined to the common axis at the angle α (see Fig.3), so the total thrust will be directed along the common axis of the device at simultaneous operation of all thrusters (or couples of thrusters located opposite to each other). If only one thruster is energized, so the thrust is directed at the angle α to axis of the device (however it is a quarter of thrust maximum). It is evident that varying the combinations of simultaneously operating thrusters (or accelerating channels in polychannel thruster) and duration of their work it is possible to rotate the thrust vector to any side and change the magnitude of rotation angle. At the same time it is possible to change power too (or total thrust).

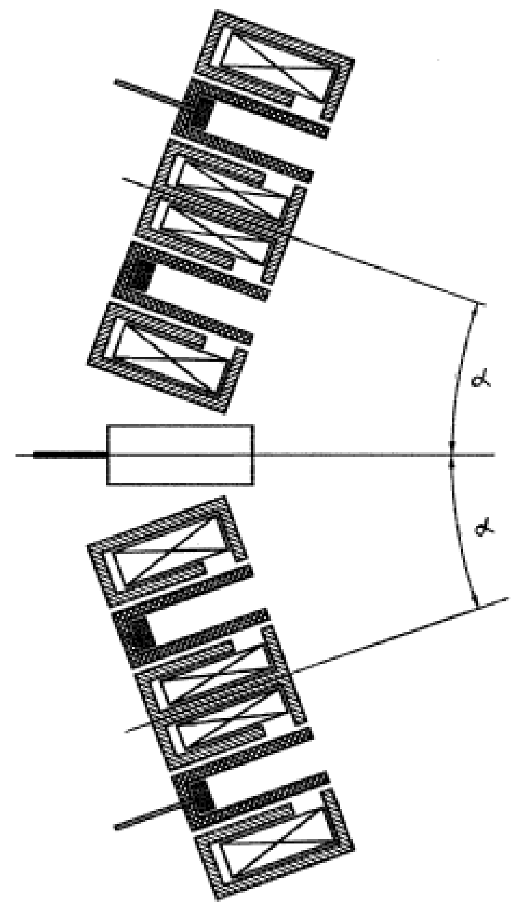

Figure 3.

Here the independent thrusters can be used or the device can be made in the kind of single polychannel thruster with one (or several) cathode and any other common systems. It is possible to use the Hall-type thrusters (both SPT and TAL) as well as ion thrusters, as the separate thrusters (or channels) [5].

We can consider the necessity to refine only single thruster (or channel) as a great advantage of this system, thrust vector control - on value and angle - is guaranteed automatically. In addition to it, high lifetime and reliability (because of duplication) are available in such polychannel thruster. We think the polychannel thrusters will be widely used in the nearest future.

Table

№	Reference	Where it has been realized	Method	Remarks
1m	**2**	**3**	**4**	**5**
1m	1, 1.1-1.4	KeRC, MMS, ISP	H_Δ	Determination of the intentions
2m	2, 2.1	KeRC, MMS	$H_\Delta m_\Delta$	In making progress towards resolve
3m	3	KeRC	$H_\Delta m_\Delta$ H_0	Solving the problem
4m	4	KeRC	$H_\Delta m_\Delta$ G_0 H_0	Stronger solving the problem
5p	5	KeRC	G_Δ G_0	Absolute solving the problem

Conclusion

We have reviewed the possibilities of building a thruster with thrust vector control. The brief summary of the results according to this analysis is tabulated. In the first column a number of the considered attempt (variant) in solving the stated problem is written; these attempts appeared in such sequence; letter m means one-channel (mono), letter p (poly) - polychannel. The second and third columns contain the references and organizations where the given decisions have been offered, the forth column - used method (level), the fifth - remarks with estimation of this attempt in solving this problem. Low index Δ means - azimuthally non-symmetrical, low index 0 - azimuthally symmetrical.

Notice, inducing the azimuthally uniform magnetic field H_0 in variant 3 (leading to appearance of $E_\perp$) on a command, i.e. at the moment of necessity in thrust vector rotation but not beforehand, is possible only in configuration when internal and external subsystems of magnetic system are independent [6]. Fig.4 presents such configuration where the evolution of magnetic system in SPT is from initial one (E-system) to classical (standard) widely used in HT and to the last new configuration [6] permitting us to change the direction (inclination angle) of force lines in magnetic field in the accelerating channel and to reach the optimal position.

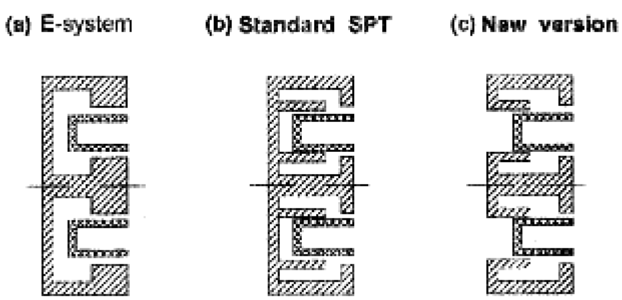

Figure 4.

Variant 4 is more perfect for one-channel thruster. It can work with field H_0 or without it. Here greater rotation angle can be obtained but it is unlikely exceed (4-5)°.

Polychannel thruster (variant 5) - is universal and supposedly the best technical decision of the thrust vector control problem. Such thruster is easy in development and use and while its application the greater rotation angle can be realized. So, 4-channel thruster where axes of the channels are inclined to the axis of the thruster at angle α=10° can realize the thrust vector rotation at 10° (maximum angle) at power (thrust) of 25 % of maximum (in so doing only one channel operates); at 50% power, the maximum rotation angle will be ≈ 7°. The losses in such polychannel thruster at lack of rotation are of very acceptable value - 1.5%(cos10° =0.985).

Presently at the KeRC the works on realization of the most advanced mono-channel thruster (variant 4) and polychannel thruster (variant 5) have been developing. The first results give hope.

References

[1] V.A.Petrosov, Y.M.Yashnov, A.S.Koroteev, A.I.Vasin, V.I.Baranov, J.-F.Poussin, J.-M.Stephan, P.A.Balaam, J.K.Koester, E.J.Britt. Hall effect thruster. Patent RU №2088802.

1.1. Hall effect motor. PCT WO 97/21923.

1.2. Steerable Hall effect thruster. EP 0778415.

1.3. Hall effect plasma thruster. Patent US №5845880.

1.4. A hall effect plasma thruster. PCT WO 97/37126.

[2] V.A.Petrosov, V.I.Baranov, A.I.Vasin, A.S.Koroteev, J.-F.Poussin, J.-M.Stephan. An ion accelerator. EP 1021073.

2.1. An ion accelerator. PCT WO 00/42827.

[3] S.G.Baidakov, V.I.Baranov, A.I.Vasin, Y.S.Nazarenko, V.A.Petrosov. Method of ion acceleration and device for its realization. Patent RU №2162624.

[4] V.A.Petrosov, S.G.Baidakov, V.I.Baranov, A.I.Vasin, Y.S.Nazarenko. Method and device for ion acceleration in hall-type plasma accelerators. Filed application RU №2000132952.

[5] V.A.Petrosov, S.G.Baidakov, V.I.Baranov, A.I.Vasin, Y.S.Nazarenko. Method of thrust vector regulation control of electric propulsion and device for its realization. Filed application RU №2000126566.

[6] V.I.Baranov, A.I.Vasin, V.A.Petrosov, Y.M.Yashnov. Plasma accelerator. Patent RU №2092983.

6.1. Plasma accelerator. PCT WO 97/37519.

6.2. A Hall effect plasma accelerator. EP 0800196.

6.3. Hall effect plasma accelerator. Patent US №5847493.

6.4. A hall effect plasma accelerator . PCT WO 97/37517.