STATIONARY PLASMA THRUSTER (SPT)

DEVELOPMENT STEPS AND FUTURE PERSPECTIVES

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Abstract

The SPT concept was discovered in 1962. The engineering model was developped in 5 months while the first flight model was developped and integrated in 18 months. The first flight of EOL 1 on METEOR was a success. SPT is now on operational use on many Russian spacecrafts.

In parallel a permanent laboratory work was performed, enabling a better knowledge of the thruster physics.

Recently, the development of a second generation of SPT was started, involving a much higher efficiency.

The future perspectives of SPT development are presented.

Introduction

SPT design and principles of operation are well known now. They seemed to be rather natural and simple. Therefore, it is often imagined, that SPT turned out by itself, and real processes in SPT are also simple. But it is not so. Moreover, each significant step during the process of SPT investigation and improvement, required big efforts and to overcome many traditional opinions. In this report I shall dwell on the main results of past works and then I shall give my view on the perspectives of SPT development.

1.– Formulation of base principles, experimental verification

The Kurchatov Institute and its Department of Plasma Investigations, which was guided by an outstanding scientist, academician Lev Artsimovitch, played the role of scientific, and, in many cases, design center of electric propulsion activities in 1960–th and the beginning of 1970–th. The SPT concept appeared in my mind (I was the collaborator of this Department) in 1962, the first experiments began at the end of 1963. Initial prerequisites were my first theoretical papers [1,2], devoted to electromagnetic acceleration of plasma, in which I have shown, at first, the necessity of creation of sufficiently large electrostatic field in plasma volume, and, at second, the effect of "equipotentialization" of magnetic force lines in plasma, when $T_e = 0$.

$$\phi = \phi(\gamma) \qquad (1)$$

Where γ is index of magnetic force line. It is seen from (1), that, in plasma, one may regard magnetic force lines as equipotential patterns.

In this way, it was natural, that the wish for creation of ion thruster analogue, but with optics, consisted of "electrized" magnetic force lines, appeared. The significant stimulus for me were successful Ioffe–Yushmanov's investigations [3] of "ion magnetron", which were prolonged by A.Zharinov, who, additionally, has formulated the theory of "anode layers" [4], discovered in ion magnetron. By the time, when I began the working out SPT–principles, Zharinov tried to design anode layer thruster (ALT), based on principles, mentioned above.

But I didn't like the ALT conception of that time, based on ion magnetron ; the reasons were : high voltage (> 2 kV), necessary for stable operating, small clearances between electrodes, and, consequently, high electric field strength, high magnetic fields (> 0,1 T). Therefore, I have decided to stretch the region with electric field, making dielectric walls of channel, and to reduce significantly magnetic field (down to 0,02 T). In order to decrease the intensity of accelerated ions destruction on the walls, I, in accordance with [1], suggested to create magnetic field with force lines, convex to the anode, and increasing |H| towards the channel outlet. Nevertheless, the first experiments revealed, that, in principle, I was right, and that electric field in channel existed at distances much more than

electron Larmor radius as it was in anode Layers. The cause of this effect was the choice of nonuniform magnetic field, which increased towards the channel outlet (see below). It was expected, that we should be able, by these means, to wring out ions to the middle of channel. It may seems to somebody, that all mentioned above is rather natural. But the idea of using spatial E–field for ion acceleration and magnetic field for E – field structure creation and for suppression of electron current, has met with hurst of indignation from the authorities in gas discharge. They referred to unsuccessful 50–year experience of spatial electron conductivity magnetizing and to well know Bohm's formula.

2.– SPT space test

A very important work on investigations of processes in SPT, on optimization its design and characteristics had been done by the end of 1968. It became clear, that we have created a reliable and convenient engine, which was able to operate in wide power range (main investigation were performed in range 3 – 5 kW), had high characteristics for that time (efficiency up to 40 %, confirmed service life more than 50 hours etc). This achievement was the result of intense work of collaborators of my group. But I want to mention especially our mutual teacher, magnificient experimentator and wonderful man, chief of our sub–unit, German Yokovlevitch Stchepkin.

The achieved SPT parameters have put on the agenda the space test of SPT. The head of our Institude, accademician A. Alexandrov, undertook to organize our relations with chief designers of spacecrafts. In the middle of 1969 he had come to agreement with chief designer of "Meteor"–satellite, academician A. Iosiphyan, about placing our thruster on the Satellite. In December, 1969, we received form Iosiphyan the RFP on thrust unit with SPT. It was very tough RFP. We had to design thruster in, new for us, power range (400 W), economical neutralisers (cathodes–compensators), systems of gas storage and feed, systems of power supply and control, provide no less than 100 hours of continuous operation. And we had only 5 months for all work.

We have full filled the RFP requirements totally, and sent our thrust unit to EDB (Experimental Design Bureau) "Fakel" in May, 1970. There, under the guidance of clever chief designer R. Snarsky, the real design, based on our prototype, was created, it met all tough requirements to space systems. I must note, that our SPT–design remained practically unchanged. Last December, 1971, the "Meteor" satellite with SPT thrust unit "Eol 1" had been launched. Tests were carried out during January–February, 1972, and have passed brilliantly. These tests have proved the real thruster parameters, its compatibility with "Meteor" systems : thruster operated during 160 hours and spent all xenon, it gave the possibility to move the satellite to the nominal orbit, convenient for meteorological supervision. The "EOL" – unit and its operation are described in details in paper [5], 1974, one may note, that, among 18 authors of this paper, 12 are from Kurchatov Institude, 2– from EDB "Fakel", 4 – from Iosiphyan's Electromechanical Institude.

This flight had given a start in life for SPT as thruster and for EDB "Fakel" as specialized organization for EPT–design. From that time up to beginning of 1980–th, our Institute was scientific leader of the EDB, and I represented this leadership.

One additional note, relative to the paper [5] it contains an interesting plot, on which the increase of SPT –parameters, from year to year, is shown. In particular, not only "EOL" parameters, but parameters of 1974 year models are shown. Magnetic fields with more steep gradient were used in last models, it allowed to reach power 1kW with efficiency ... 50 %. I must note, that this level has maintained constant, up to this time, for SPT, which are exploited now (1993) (SPT 70 and SPT 100).

3.– New phenomena, discovered in SPT

Systematic physical investigations of phenomena in SPT began in 1964, soon after the design of the first model, and continue up to this time. Up to 1976, the main investigations were carried out at Kurchatov Institute (Morosov–Stchepkin's laboratory) and after mainly at MIREA (laboratory of A. Bugrova). A set of significant experimental studies were also carried out at CIAM (V. Fishgoit's laboratory), MAI (V. Kim and V. Shishklin's groups), EDB "Fakel", IRE (K. Kirdiashev's group), DSV (A. Kapulkin, V. Prisniakov et al) and at other organizations [6,7].

Investigations of phenomena were carried

out by means of electrotechnical, probe, spectral and VHF – methods, contractless inductive gauges, analysis of insulator erosion tracks, mass energy analysis of outlet flow etc. In parallel, theoretical analysis (A. Morosov, A. Shubin), numerical simulation (I. Melikov, S. Iakunin and, recently, V. Savelyev) were carried out [6, 7, 8, 9].

In parallel with expected behaviour, the most important, new physical phenomena and peculiarities have appeared and were discovered rather soon (already in 1960 th), first of all, the conditions of plasma flow stability in channel, relative to appearance of the most dangerous "rotating" instability were cleared up (rotating "spoke", which strikes through the channel, from anode to cathode). It was shown, first theoretically and then experimentally, that this instability may be suppressed, if we create magnetic field, which increases sufficiently rapidly towards the outlet [5].

$$(v\nabla)\,\underset{H}{n} < 0 \qquad (2)$$

The next important phenomenon is the deviation from simple dependence (1), when $T_e \neq 0$, due to plasma density gradient along force lines. The more accurate dependence is (see [10])

$$\phi - \frac{1}{e}\int \frac{dp_e}{n} = \phi^*(\gamma) \qquad (3)$$

Here γ "index" of magnetic force line,
$\phi^*(\gamma)$ is so called "thermalized potential".

Further, I have predicted a new mechanism of electron transfer across magnetic field, due to electron scattering on walls [6], which was called "near wall conductivity". Later it was corroborated brilliantly by means of set of delicate experiments, carried out in Pr Bugrova's laboratory [6]. It was shown also, that near wall conductivity plays a great role in electron transfer from ionization zone to the anode. Near wall conductivity curent pattern gives opportunity to obtain spectrum of electrons, reflected from wall, during the discharge. It was succeeded, with this pattern, to show, that Debye wall layer in SPT has mosaic structure [7]. The electron distribution function was very unexpected, it was also studied at first time at MIREA. It was shown, that this function bears no resemblance to Maxwellian, but contains three groups of particles, the most numerous group may be described by "Bugrova Splay" [7].

$$f_e\,(\text{e low}) = \frac{1}{N}\begin{cases} \mu - E^*, & E^* < \mu \\ 0 & ; E^* > \mu \end{cases} \qquad (4)$$

Here $E^* = \underline{m\,(v-u)}$
$\qquad\qquad 2$

$$\mu_o + e\phi - \underline{e}\,\psi = \mu$$
$\qquad\qquad\quad c$

$$U = C\,\underline{E}$$
$\qquad\quad H$

and $\psi \equiv \gamma A$ – magnetic flux fonction
It is shown, in particular, from (4), that the group of slow electrons rotates as a whole. This is a fundamental difference between classical ALT (ion magnetrons and two stage ALT) operating modes and those for SPT. I shall note also one fundamental fact, discovered at EDB "Fakel". During long time service life tests a new type of insulator erosion appears, it is due to electron collisions with insulator and consequent near wall conductivity [11].

Lack of time does not permit me to describe in details other, may be not so spectacular, but rather important phenomena in SPT, I shall note only, that total vast theoretical and experimental material of A. Bugrova, N. Maslennikov, and A. Morozov allows to formulate rather effective thruster scaling law, with aid of which one may express the main integral parameters of SPT, having various sizes, flow rates, voltages, working substances [12].

4.– Creation of second generation SPT (SPT "Aton")

At the beginning of 1992, the vice presidents of SEP, Mr Boulanger and Vignelles visited the Bugrova's laboratory and suggested her to create jointly the new SPT modifications. I have been invited to consult this new design. I and Bugrova had some ideas in reserve. The simplest was to create near ideal structure of electric equipotentials, basing on stored knowledge about processes in SPT channel, i.e those structure, which was already desirable for the first SPT model. After a year of rather intense and purposeful work has been done, (SEP collaborators were also took part in this

work), the second generation SPT model "Aton" appeared. It has unique parameters (for example, its efficiency is 70 % for SPT–70 size). We shall tell about it in details in another paper at this conference (EPC 93–223).

5.– Perspectives of SPT development

I shall not speak here about development of classical SPT, i.e about design of high power modules and its modifications for various special problems. There is no fundamental limitation in thruster size at least for power up to 500 kW. I should like to dwell on 3 methods of SPT modification, which will change these thrusters cardinally and will be new steps of their development.

a/ Phenomena on dielectric walls and near them influence drastically on integral parameters of SPT. It is explained by the fact, that these phenomena determine the look of electron distribution function, and, consequently the ionization, energy losses on walls, distribution of equipotentials in volume etc. At the same time, we, till now, have only qualitative ideas of near wall phenomena. It is obvious, that the creation of a realistic quantitative theory makes it possible to choose optimal structure and chemical composition of dielectric walls, this will give the effective instrument of electron component control, and, consequently, SPT parameters control.

b/ This time, the main disadvantage of SPT especially before creation of "Aton" was its dependance to the working substance. The best parameters may be obtained only with xenon. But xenon is very expensive, and, in addition, due to high atomic mass and limited voltages, applied to SPT, the flow velocity is at the level of 30 km/s. This velocity may be too low for a number of future problems (e.g interplanetary missions with high V requirements). The particularity of Xe was shown in paper of Morozov and Melikov [8], is due to good ionizing properties of this substance. One may overcome difficulties related to bad ionizing properties of other substances by mass flow rate increase. Inevitable thermal overloads may be reduced, for example, by operating with a low duty cycle. But, the transition to two stage accelerator seems also a perspective. But the choice of optimal design for the first ionizing stage requires serious investigations. Designs with effective ionization will permit not only to use cheap working substances, but, also to increase the plasma flow velocity. Thus, in principle, the attractive perspective of creation of SPT, operating with reactive gases, begins to be more clear.

c/ I am sure deeply, that, after some time, SPT will transform from modern rigid "monolith" to flexible "organism", which will check its operating and will be able to "self cure" fragments, which damage eventually. Self check may be realized today with set of gauges, which check integral and local parameters of operation modes, i.e. to provide health monitoring of SPT. These signals from gauges, when entering the SPT control unit, allow to provide automatic realization of a prescribed program. The next step is the transition to "self renovation" of elements, which wear during the long exploitation. It is known, that now the SPT service life is limited by erosion of dielectric walls near outlet. Of course, one can overcome this problem by having sufficiently large reserve of "redundant" SPT. But it is much more economic to "cure", in any case, the eroded edge. It may be done by means of many methods ; simply move the insulator forward, as it is ground off ; or it is more complicated during development, but may turn out to be most effective in future to make insulators as some porous structures and feed the liquid dielectric to the working surface through them [13]. Last time, SPT with movement of insulator as a whole provided by an electromechanical activation, was fabricated at MIREA. Such self–restored systems have the general name "phoenix" in Russian literature. It is important to note, that phoenixes not only reduce the service life problem at very great extent, but make rather easier the problem of its confirmation. In living organisms the wearing organs (teeth, skin, hair) operate according to phoenix–scheme. Three ways of qualitative development of SPT, mentioned above, do not exhaust all possibilities, of course.

I should like to emphasize, in conclusion, that SPT is the simplest representative of continuously

growing class of plasma systems with "organized" spatial electrostatic fields [5,6,7]. Replacement of metallic ion–optical systems of classic corpuscular optics by magnetic force lines (see [1] and [3]) is a too prospective and rich idea to reject it in future. In this way, there is little doubt that, in future, SPT type systems will be useful, in spite of concrete development of other electric propulsive thrusters.

New physical phenomena, discovered during SPT investigations, are an important part of fundamental plasma dynamics, are used more and more intensively in plasma technology, and, it is already unexpected, begin to be seriously analysed from the point of view of principally new circuit designs of fusion reactors [14,15].

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