Experimental Research of Deflection of SPT Thrust Vector

IEPC-2013-083

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

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Abstract: **The experimental researches on the deflection of the thrust vector of the stationary plasma thruster (SPT) with the help of magnetic field acting on the directed motion of jet ions have been carried out. The magnetic field has been created by the deflecting magnetic system, located behind the thruster exit. The measurements, carried out on the SPT laboratory model α-100 with the diameter of the outlet channel 100mm and the overall dimensions L=70mm and D=200mm, have shown that in the investigated range of the parameters variation the dependence of the turn angle of the thrust vector from the current value in the turns of the deflecting magnetic system is close to the linear one.**

Nomenclature

U_d	=	discharge voltage
$\dot{m}_a$	=	mass flow rate through the anode
I_d	=	discharge current
$\dot{m}_{cath.}$	=	mass flow rate through the cathode

The experimental researches on the deflection of SPT plasma jet with the help of magnetic field have been carried out using the developed in MSTU MIREA laboratory model SPT α-100 [1] with the overall dimensions L=70mm and D=200mm. Models of α class belong to the accelerators ATON family,[2] however for them the analogous with ATON configuration of the magnetic field force lines is obtained with the help of two magnetic coils (supplied from the independent sources) in the presence of six poles of the magnetic circuit.[3] Under measurements carrying out the model operates in the next mode: the xenon mass flow rate through the anode has been equal to $\dot{m}_a = 4.5 mg/s$, the discharge voltage has been equal to U_d=300V, the xenon mass flow rate through the cathode - $\dot{m}_{cath.} = 0.4 mg/s$. The currents in magnetic coils, corresponding to the minimum of the discharge current, have

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provided the model operation in the mode with the output jet in the cylinder shape, when the jet divergence is minimal.

The experiments have been carried out at MSTU MIREA vacuum stand. The stand vacuum chamber is of diameter 1m, length 3m and is equipped by four fore pumps НВЗ-20 and four diffusion pumps НВДМ-400 with the pumping speed 7000l/s for everyone. The pumping system has provided the initial vacuum $1 \cdot 10^{-5}$ mmHg and dynamic vacuum $2.4 \cdot 10^{-4}$ mmHg (on air) for the xenon mass flow rate $\dot{m}_a = 4.5 mg/s$. The thrust has been measured with the help of the torsion balance with the laser indicator and its relative error did not exceed 3%.

According to the measurements of the local plasma parameters in SPT jet, carried out for different SPT models (see, for example, Refs. 2, 4) under the discharge voltage 300V the electrons mean temperature in the jet from the model exit up to the distances of several calibers from the outlet is at the level 5eV (or slightly exceeds this value), therefore in carrying out estimations one may consider the electrons mean temperature in the jet equal to 5eV. For the given temperature the mean thermal velocity of electrons is equal to $1.3 \cdot 10^{6}$m/s, while the mean velocity of directed motion of the xenon ions in the jet at the given discharge voltage is equal to[1] $1.9 \cdot 10^{4}$m/s, therefore the directed motion of electrons “entrained” by the ions due to the plasma quasi-neutrality is negligible and one may consider the jet as the directed ions flow moving in the electron cloud. This allows to use the action of the magnetic field onto the ions directed motion for the turning of the plasma jet.

The outflow of the jet from the channel of the plasma accelerator is the complex physical phenomenon, both experimental and theoretical investigations are devoted to its treatment[2]. However such simplified representation about the jet turned out the reasonable one because it allowed, as we’ll see below, to make correct estimations and according to them to obtain the thruster vector turn by 5^0.

If the singly charged xenon ion with the initial velocity $\vec{V}_0$ flies in the region of the uniform magnetic field of extent *l* perpendicularly to the magnetic inductance vector $\vec{B}$, then after propagation through the field the velocity vector is turned by the angle α:

$$\sin\alpha = \frac{l}{R}$$

Here *R* is radius of the circle on which ion moves in the magnetic field:

$$R = \frac{1}{B}\sqrt{\frac{2m(U_d - \Delta U)}{e}},$$

where *m* – ion mass, *e* – elementary charge and the term *ΔU* takes into account the losses on the ionization. In order to take estimations in our case $\Delta U=50V$ (i.e. it is equal to a few ionization potentials of the xenon). Specifying the turn angle α and proceeding from the necessary values of the field length one may obtain the estimation for the value of the magnetic field. For the $U_d=300V$ the region of the extent $l=14cm$ provided the turn of the flow of the singly charged xenon ions by 5^0 under $B=0.016T$.

The deflecting magnetic system has been mounted on the accelerator body. The accelerator axis was horizontal, and the turn of the thrust vector in the horizontal plane to the right and to the left of the initial direction has been provided by the vertical component of the magnetic field of the deflecting system. The determined experimentally direction of the vertical component and direction of the turn of the thrust vector allowed to prove that just ions of the thruster plasma jet experience the turn under the action of Lorentz force.

Parameters of the deflecting system (its extent, shape and dimensions of the magnetic coils, the number of ampere-turns in them, the arrangement relative to the model) have been chosen and calculated in accordance with the dimensions of the plasma source and the parameters of the outgoing from it plasma flow. Numerous experiments and observations show that the outgoing from the accelerator plasma flow is the most formed at the distance of one-two calibers from the source, therefore the extent of the region of the “uniform” magnetic field *l* must be of the order of the accelerator caliber (that is equal to 100mm for the model α-100).

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[1] $\langle V \rangle = \sqrt{\frac{2e(U_d - \Delta U)}{m}}$, where *m* – ion mass, *e* – elementary charge and the term *ΔU* takes into account the losses on the ionization.

[2] Among the last we may note the investigations, in which the method of the description of the processes in the jet with the help of the model kinetic equations is suggested. [5]

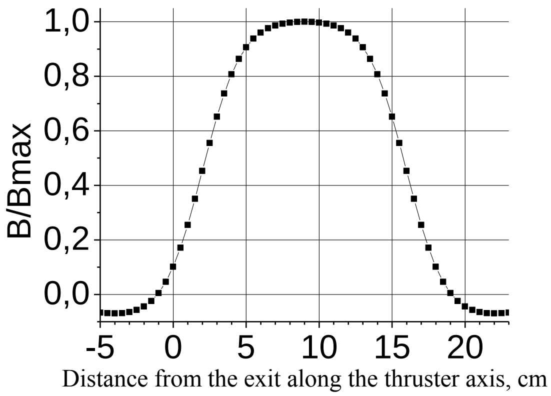

Figure 1. The distribution of the relative value of the vertical component of the magnetic field for the used in the experiment deflecting system along the thruster axis.

The distribution of the relative value of the vertical component of the magnetic field along the thruster axis for the used in the experiment deflecting system is shown in Fig.1. It is seen from the presented distribution, that generated by the deflecting system magnetic field has in the central part field of the length 100mm (along which the field decreases by 20%), which is necessary for the thrust vector turn. While in the fields which are at the distances of 100mm and more (caliber of α-100) from the central cross-section of the deflecting system the field decreases by the order providing the minimum of the influence onto the exit region of the thruster and accordingly onto its mode of the operation. The maximal value of the vertical component is equal to 0.02T under the current 10A in the turns of the deflecting magnetic system.

The probe measurements have been used in order to determine the direction of the thrust vector. The probe receiving surface with the area $5mm^2$ has been oriented perpendicularly to the plasma flow outgoing from the thruster. The probe has operated in the mode of the saturation in ions current. The probe has been located on the co-ordinate devise and moved in the horizontal plane perpendicularly to the accelerator axis.

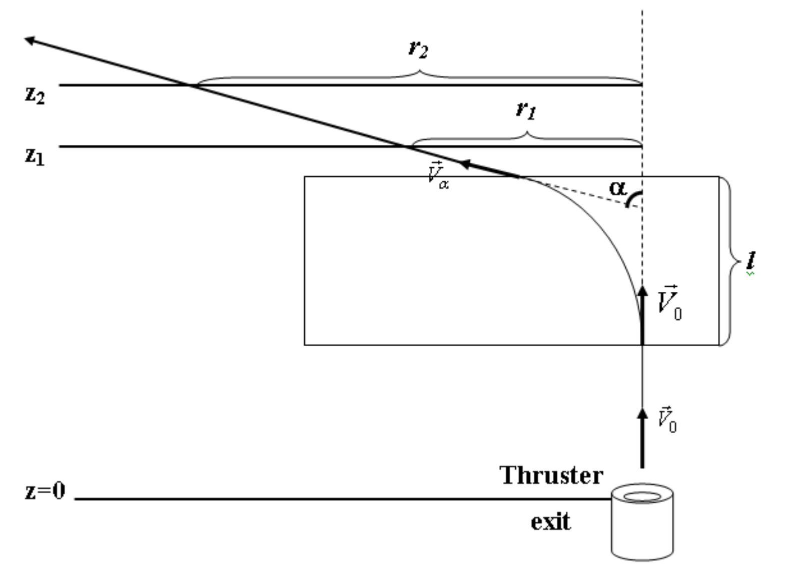

Figure 2. Measurement of the deflection angle α of the plasma flow after it has gone through the deflecting field with the length *l*.

Figure 2 explains the essence of the carrying out of measurements of plasma flow deflection angle by the radial distribution of the ions current onto the probe. It is seen from Fig. 2, in order to measure the deflection angle α of the source plasma flow after it has gone through the deflecting field with the length *l*, it is necessary to measure the coordinates r_1 and r_2 of the maximal values of the ion current onto the probe at the distances z_1 and z_2 from the thruster exit, respectively. In these experiments the measurements have been carried out at the distances $z_1=32cm$ and $z_2=40cm$ from the model exit in accordance with the length of the field deflecting the flow.

The dependence of the turn angle of the outgoing from the model plasma flow (i.e. thrust vector) from the current value in the turns of the deflecting system is represented in Fig.3. It is seen from Fig.3, that in the given range of the parameters variation this dependence is close to the linear one.

The integral parameters of the thruster measured for the different values of the current in the turns of the deflection system are represented in the Table 1. The following notations are used in the Table 1: *F* – the thrust generated by the accelerator, I_1 and I_2 – currents in the first and in the second magnetic coils, respectively. As it follows from the Table 1, under the current 10A in the turns of the deflecting system when the turn of the thrust vector by 5^0 is provided : 1) the configuration of the magnetic field in the model channel remains the same due to the constancy of the currents I_1 and I_2 in the magnetic coils, 2) the increase of the discharge current is below one

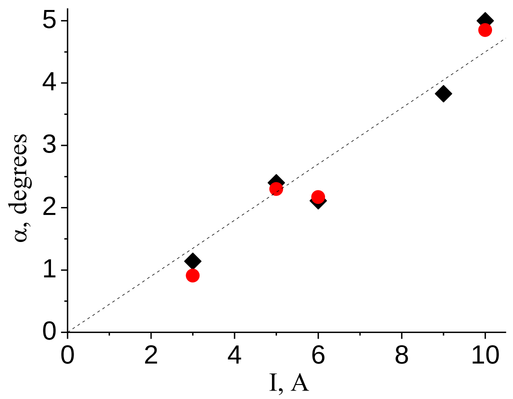

Figure 3. The dependence of the deflection angle of the thrust vector from the current value in the turns of the deflecting system. Rhombuses and circles corresponds to the opposite in sign currents in the turns of the deflecting system and, respectively, to the opposite deflection angles of the thrust vector.

percent from its value in the nominal mode, 3) the decrease of the thrust is equal to 3% from its value in the nominal mode. The turn of the thrust vector by 5^0 without changing its value in modulus could change the magnitude of the projection, measured by the balance, down to 80.6mN. The observed decrease of the thrust down to 78.5mN may be caused by the deviation of the model from the optimal mode, however it lies in the limits of the error of the thrust measurement.

Thus the possibility of the control of the thrust vector of the plasma accelerator with the help of the additional magnetic field is experimentally shown.

Table 1

Current in turns of deflecting system, A	$\dot{m}_a$, $\frac{mg}{s}$	U_d, V	I_d, A	I_1, A	I_2, A	F, mN
0	4.5	300	4.45	2.7	4.45	80.9
3	4.5	300	4.45	2.7	4.45	80.4
6	4.5	300	4.47	2.7	4.45	80.0
10	4.5	300	4.49	2.7	4.45	78.5

Acknowledgments

The study was partially supported by EDB “FAKEL” and by The Ministry of education and science of Russian federation, project 14.B37.21.1840 and project 14.B37.21.1291.

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