Investigation of the "back" and "radial" ion flows in the vicinity of the stationary plasma thruster exit plane

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Abstract: Results of experimental studies and simulation of the plasma parameter distributions and directed ion currents in the vicinity of the stationary plasma thruster (SPT) exit plane are represented in the paper.

Simulation was made with help of kinetic equations for the ion and neutral atoms dynamics and hydrodynamic approach for the electron dynamics description in 3D steady state problem statement to simulate such effects as influence of the neutral atoms flow through the side positioned cathode on the neutral atoms concentration space distribution and distribution of the charge exchange ion concentration and their directed flows near the thruster exit.

Experiments were made with the SPT laboratory models operating under different modes. Plasma and directed ion flow parameters were measured by electrostatic probes and retarding potential analyzer (RPA) positioned in the vicinity of the thruster exit plane.

Simulations show that the "back" ion flows onto reference plane consisting of the thruster exit plane have maximum values in the nearest vicinity of thruster and rapidly decreases with increase of radial distance over (1,5-2,0)D, where D is an external accelerating channel diameter and this is in agreement with the experimental data. Simulations show also that the local neutral atoms flow through cathode significantly changes neutral atoms concentration and charge exchange ions concentration spatial distributions and charge exchange ion flow field in the vicinity of the cathode.

Results of measurements in the radial ion flows in the vicinity of the mentioned exit plane show that ions in these flows have mean energies (100-120) eV and that these ions mean energy and current density weakly depend on SPT model operation mode. The most probable source of these ions in the SPT-100 type thrusters is the exit part of the accelerating layer positioned outside the accelerating channel.

I. Introduction

As it is well known [1], the stationary plasma thrusters (SPTs) are successfully used for the spacecraft orbit control. It is known also that during their operation an artificial plasma environment is created around spacecraft which has definite impact on the spacecraft surfaces potential due to interaction of the charged particles from the thruster plume with these surfaces [2]. Besides part of ions from the plume moves in the vicinity of the thruster exit plane in directions close to radial ones or in the upstream direction relative to the main ion flow direction forming the so-called "back" flows. These ions can get the spacecraft and thruster side surfaces changing their charge state. Moreover some ions at least in the "radial" flows can have significant energy and sputter structural thruster and spacecraft elements. Formation of the radial and "back" ion flows still was not studied fully enough. Particularly there was not studied formation of the spatial distributions of these ions concentration and energy distributions. Therefore it was reasonable to continue study of the considered ion flows. Some results of the theoretical and experimental studies of the mentioned flows in the vicinity of the reference plane consisting of the thruster exit plane are represented in this paper.

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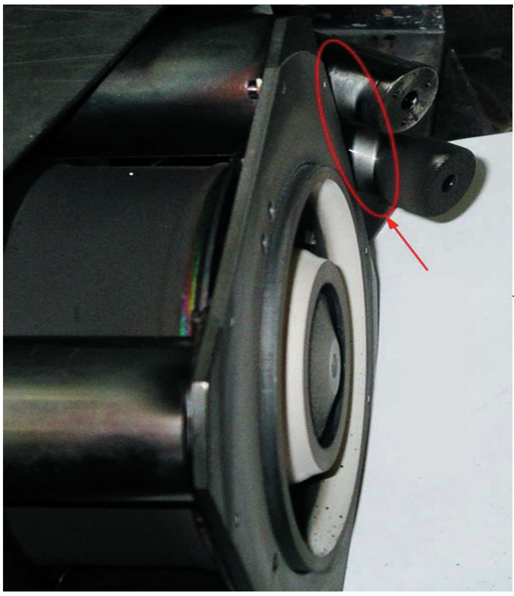
II. Some notes on processes in the SPT plume.

SPT plume consists of mainly the accelerated ions and neutral working gas atoms exhausting from the accelerating channel due to not full ionization of atoms incoming to this channel from the feed system. In addition there is the flow of the working gas atoms with small number of ions flowing out from cathode. The neutral atoms flow from the accelerating channel and from cathode each typically amounts (5-10) % of the total working gas flow through the thruster. The difference between them is that the first one flowing out together with the accelerated ion flow from the annular exit of the accelerating channel and the second one could be considered as flowing out from one point that is under typical side position of the cathode this flow has to create significant asymmetry of the neutral atoms concentration spatial distribution at least near the thruster exit.

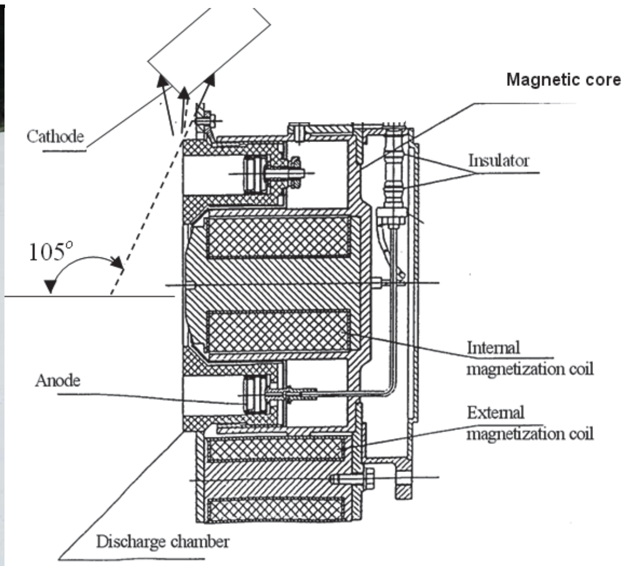
Some processes changing trajectories of the plume particles and their charges are going in the plume volume such as the charge exchange of ions with neutrals and other ions, elastic scattering of the accelerated ions on neutrals and other ions as well as the change of ion trajectories by the electric field in plasma. The most intensive process in the plume is the charge exchange of the singly charged ions on neutrals. This process creates ions with trajectories significantly different from that ones of the accelerated ions and form ion flows with trajectories directed approximately transverse to the trajectories of the accelerated ions main part and flows with velocities having mainly radial component and even component directed upstream of the main flow movement direction and resulting in appearance of the “radial” and “back” ion flows [3]. These ion flows are escorted by the flows of electrons required to ensure their quasineutrality, forming the plasma flows interacting with thruster and spacecraft surfaces and changing their charge state. The charge exchange process is the most intensive in the nearest vicinity of the thruster exit where flow densities and concentrations of particles are maximal. Therefore some theoretical and experimental studies of the directed ion flows formation in the mentioned thruster vicinity were done at RIAME MAI. And some results of these studies are represented in the given paper.

It’s necessary to note that the considered process can not give large enough energies of ions. But in the ion flows moving in the quasi radial directions some ions exist with energy sufficient to sputter structural elements. The first information indicating an existence of the high energy ions in the “radial” ion flows was obtained already during SPT-100 life time tests while side surfaces of cathodes were notably eroded [4].

Evidence of this process could be observed even after test of thruster during some hundred hours. For example, at RIAME MAI after the 300-hour test of the SPT-100 experimental model its igniting electrodes of cathodes were notably eroded in the parts positioned near plane consisting of the thruster exit plane [5] (Fig.1). Specifics of these erosion traces are that they had very clear boundaries. One of them was positioned closely to the thruster exit plane and another boundary approximately coincides with the strait lines in the longitudinal cross-sections of thruster touching the external edge of the discharge chamber external wall and with the edge of the external magnetic pole (see Fig.1). An off-axes angle relative to the main ion exhaust direction for the corresponding strait lines was estimated as 102-105 degrees.



a)



b)

Figure 1. Specifics of the cathode erosion during long thruster operation

Appearance of the first mentioned boundary could be explained by the following. The radial ion flows with the energetic ions sputter structural elements met by these flows. Because the exit parts of the discharge chamber walls are eroded by the accelerated ions bombardment, these walls are the source of the sputtered wall material. So, particles of this material are flying from the walls and part of them, mainly from the internal discharge chamber wall, are condensed on the end part of cathodes protecting them from the intensive sputtering. The significant part of these particles are neutrals [6] and flies along the strait lines. These neutrals can not get parts of the cathodes shadowed by the external discharge chamber walls. Therefore parts of cathodes not protected by the condensing material were eroded more intensively (see Fig.1). Therefore the first boundary of the eroded zone is to be close to the thruster exit plane what was observed after the mentioned above test. The end parts of cathodes were eroded also but with less rate due to protecting effect of the mentioned condensing material and results of this erosion after long thruster operation was also significant [4].

Concerning the second boundary of erosion traces one can conclude that it is created by the shadowing effect of the external magnetic pole for the "radial" ion flows having "back" velocity component. Appearance of this boundary indicates also that ions in the radial flows at thruster side have trajectories close to the mentioned above straight lines. So, one can conclude that these ions have trajectories with off-axes angles relative to the thruster axes around 102-105 degrees (see Fig. 1). Such trajectories indicate that one the most probable source of ions with such trajectories is the external part of the accelerating layer shifted in the SPT-100 type thrusters outside the accelerating channel to increase thruster life time [7].

An indication of existence of the high energy ions moving in the quasi radial and "back" directions in the SPT-100 plume was obtained also in the Ref. 8 by measurements made with help of the molecular beam mass-spectrometer system (MBMS). Particularly in the ion energy distributions measured at off-axes angles around ± 90 degrees there was found that the most part of ions have energies within the range (100-200)eV. To explain appearance of ions with such energies in the radial and "back" flows and high energy tail in the ion energy distributions in the plume core author of Ref. 8 supposed that such ions are created due to elastic scattering of the accelerated ions on the neutral atoms. But the RPA measurement results determined in the SPT-100 plume with use of the RPA obtained at distances (0.5-1,0)m from thruster and off-axes angles around ± 90 degrees [5,9] did not confirm existence of the mean energy ions, probably, due to small signal measured by RPA and high level of noises. It is necessary to note that at the mentioned distances and off-axes angles the measured by RPA ion flows consist of mainly the charge exchange ions from the significant part of plume. Therefore it was difficult to extract information on the mean energy ions from these data. In Ref. 8 it was mentioned also that another source of the mean energy ions in the radial and back ion flows could be the exit part of the accelerating layer. But preference was done to elastic scattering of the accelerated ions on neutrals in Ref.8. Taking into account all the mentioned it was interesting to measure ion current density and energy in the radial ion flows in the vicinity of the thruster exit plane at less distances to the thruster. I this case one can reduce input of the charge exchange ions because every RPA is collimated probe and reduction of the distance to thruster reduces the part of the plume volume where ions can get RPA collector from. Then, if source of the mean energy ions is a part of the main discharge, the level of the corresponding signal is to be significant enough to measure it with higher accuracy. Therefore some measurements of the radial ion flow parameters were made at RIAME MAI in the vicinity of the SPT-85 laboratory model with external accelerating diameter 85 mm at more close to thruster distance [10]. And results of these measurements are represented below.

III. Some results of simulations.

A. General information on the problem statement

Theoretical study of plasma parameter spatial distributions was made already by many authors including some authors of the given paper [3,5,11]. Particularly in the Ref. 3 there was made simulation of the plume processes in axisymmetric problem statement with kinetic description of the ion and neutral atoms dynamics taking into account charge exchange of ions on neutrals having the largest cross-section among ion and neutral collisions. As a result it was shown that appearance of the radial and back ion flows due to the mentioned charge exchange process causes deformation of the directed ion current lines. In Ref.5 and Ref.11 there were presented the results of more detailed simulation of the charge exchange ion flow formation in the vicinity of the thruster exit to estimate their spatial distribution and impact on the spatial distribution of the plasma concentration in different parts of the near field thruster plume. To solve this task there was used the developed earlier plume model [3] modified to simulate processes in 3D problem statement [11].

Geometry of the task is presented in Fig. 2. Parallelepiped $ABCDA_1B_1C_1D_1$ simulates the thruster body. All boundaries of this body are the solid surfaces excluding the annular hole in the center of the plane *ABCD* simulating the thruster exit. The plasma plume is exhausted from that mentioned exit. In the surrounding space it is possible to introduce other surfaces simulating spacecraft structural elements but in the Ref.11 the simulation was made without such elements. The side surfaces of the $KLMNK_1L_1M_1N_1$ parallelepiped in Fig. 2 represents the boundary of the calculation area. Calculations were made inside volume $D=KLMNK_1L_1M_1N_1\backslash ABCDA_1B_1C_1D_1$. For simulations there was used system of kinetic equations (SKE) for distribution function of ions in velocities f and distribution function g for neutral atoms in the main flow [5,11]

$$\begin{aligned} &\xi_j \frac{\partial f}{\partial x_j} + \frac{e}{m} E_k \frac{\partial f}{\partial \xi_k} = \nu_{in}(f_o - f), \\ &w_j \frac{\partial g}{\partial x_j} = \nu_{ni}(g_0 - g), \\ &k = 1,2,3;\ j = 1,2,3, \end{aligned} \quad (1)$$

where e,m are the charge and mass of ions, $x_1=x$, $x_2=y$, $x_3=z$ – are the space coordinates.
$\xi_1 = \xi_x$, $\xi_2 = \xi_y$, $\xi_3 = \xi_z$ are the velocity components of ions,
$w_1 = w_x$, $w_2 = w_y$, $w_3 = w_z$ are the components of the neutral atoms directed velocities,
$E_1 = E_x$, $E_2 = E_y$, $E_3 = E_z$ are the electric field intensity components.

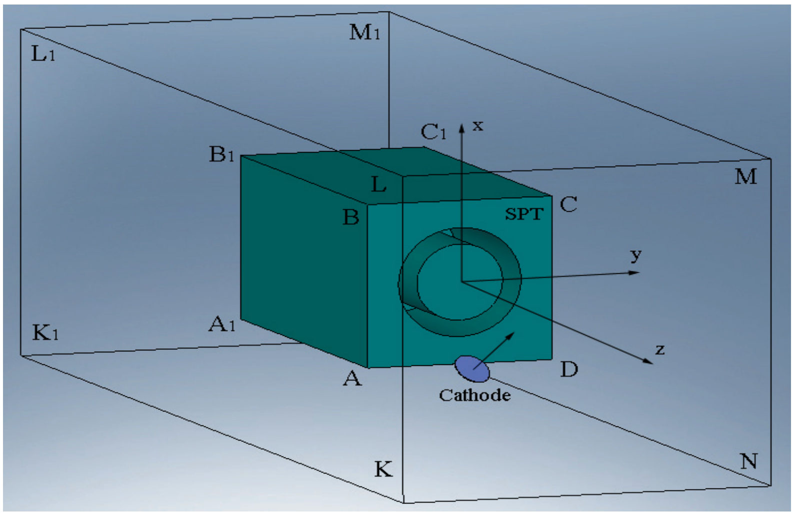


Figure 2. Scheme of the calculation area.

In the right parts of system (1) there are integrals of the ion–neutral and neutral-ion collisions. To calculate these integrals it was taken into account only the charge exchange collisions of ions with neutrals.

To determine the electric field components taking into account small expected changes of the electrons energy due to small plasma concentration n^i, small temperature T^e and mass of electron there was used the adiabatic approach for the "electron gas" dynamics description. Then, it is possible to obtain [5,11], that the electric field potential φ can be determined from equation

$$\varphi = \frac{5}{2}\frac{T_0^e}{e}\left(\frac{n^i}{n_0^i}\right)^{2/3}. \qquad (2)$$

For the system (1) as in Ref.5,11, it was assumed the maxwellian distributions of ions and neutrals incoming into the plume from the thruster exit with the specified temperatures $\bar{T},\tilde{T}$ and directed velocities $\bar{u},\tilde{u}$ for ions and neutrals, respectively, that is:

$$f = \bar{n}\left(\frac{m}{2\pi\bar{T}}\right)^{3/2}\exp\left\{-\frac{m}{2\bar{T}}\left(\vec{\xi}-\vec{\bar{u}}\right)^2\right\}, \qquad (3)$$

$$g = \tilde{n}\left(\frac{m}{2\pi\tilde{T}}\right)^{3/2}\exp\left\{-\frac{m}{2\tilde{T}}\left(\vec{w}-\vec{\tilde{u}}\right)^2\right\}.$$

The temperature was assumed as constant within the exit area. It was assumed also that concentrations of ions and neutrals within the exit area are changed according to the following laws:

$$\bar{n}(r) = 1-\frac{1}{2}\left(\frac{r-\bar{r}}{\tilde{r}}\right)^2,\ \tilde{n}(r) = \frac{1}{2}+\frac{1}{2}\left(\frac{r-\bar{r}}{\tilde{r}}\right)^2, \qquad (4)$$

where

$$r=\sqrt{x^2+y^2},\ \bar{r}=\frac{R_2+R_1}{2}\ \ \tilde{r}=\frac{R_2-R_1}{2}.$$

Ion velocity components were determined as

$$\vec{\bar{u}} = \frac{\vec{j}(r)}{\bar{n}(r)},$$

where the ion current density $\vec{j}(r)$ as in Ref. 3,5,11, was determined using results of measurements near the SPT-100 accelerating channel exit.

The directed velocity of neutrals was assumed constant and equal to zero.

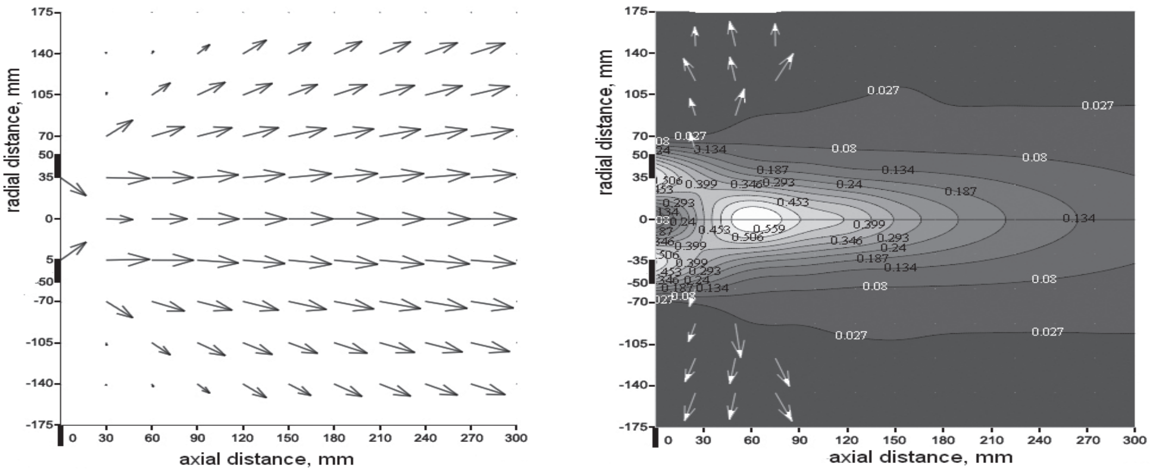
At side surfaces of the $ABCDA_1B_1C_1D_1$ area it was assumed diffusive reflection of neutrals with full thermal accommodation. It was assumed also that ions loose charge and are diffusively reflected as neutrals also with full thermal accommodation at surface. Conditions at infinity for ions and neutrals were transferred to the boundaries of the calculation area. Particularly it was assumed that at infinity there are no ions and neutrals have the maxwellian distribution function with the specified density, velocity and temperature.

For calculations the equations were transferred into dimensionless form using as a length scale the *ABCD* quadrate side length *a.* Solution was made numerically with usage of the characteristics method which is one of the main methods of the rarefied gas dynamics tasks solution. Detailed description of the calculation scheme was done in Ref.11.

B. Results of simulations.

1. General results of simulations not accounting for the cathode flow rate.

First the results of simulations of the plume parameter formation in the SPT-100 plume not taking into account the cathode mass flow rate are considered below. Obtained results show that simulation results reproduce the space distributions of the plume parameters well enough. For example, there was obtained realistic ion concentration distribution and ion current flow field [5] (Fig.3).



a) **b)**

Figure 3. Spatial structure of the ion current density (a) and ion concentration distribution in the near field zone of plume and ion current density structure (white needles) in the peripheral part of plume near the thruster exit for the SPT-100 operating with discharge voltage Ud=300V and discharge current Id=4.5A

As it's seen the main part of ions move within the range of off-axes angles ~45 degrees (see Fig.3) what is in correspondence with the experimental data [9]. Therefore the described plume model was used for study of the of the neutral atoms concentration distribution and its influence on the charge exchange ions dynamics including influence of the neutral atoms flow from the side positioned cathode on this dynamics. Particularly the distribution of the neutral atoms concentration was calculated (Fig.4) determining the rate of the charge exchange ion production as well as the distribution of the charge exchange ions concentration. It is evident that the rate of the charge exchange ion production is maximal at the thruster exit zone where densities of ions and neutrals are large. But there are some specific zones exist where concentration of the charge exchange ions has the local maximums near the exit plane with radius ~(1.5-2)D, where D is the external diameter of the accelerating channel (see Fig. 4) and at zones with off-axes angles around 30 degrees and distance from thruster around 1,5D. These particularities could be explained by the common influence of the neutral atoms concentration and accelerated ion current flow field.

Calculation of the relative charge exchange ion concentration shows that this concentration has to dominate in the vicinity of the reference exit plane at radiuses larger than (1.5-2) D.

Calculation of the ion "back" flow on to reference exit plane shows that this flow density reaches maximum value at radiuses equal to *(1-2)D* and that the "back" ion current density is rapidly reduced with increase of radius (Fig. 5). The most probable explanation of this behaviour is that this maximum is determined by the charge exchange ion flows from the mentioned above zones with local maximums of the charge exchange ion concentration (see Fig. 4).

Obtained results indicates that the side positioned cathode has to have significant influence on the plasma parameter distributions in the vicinity of the thruster exit. Therefore some simulations were made to study this influence. Results of these simulations are represented in the next part of paper.

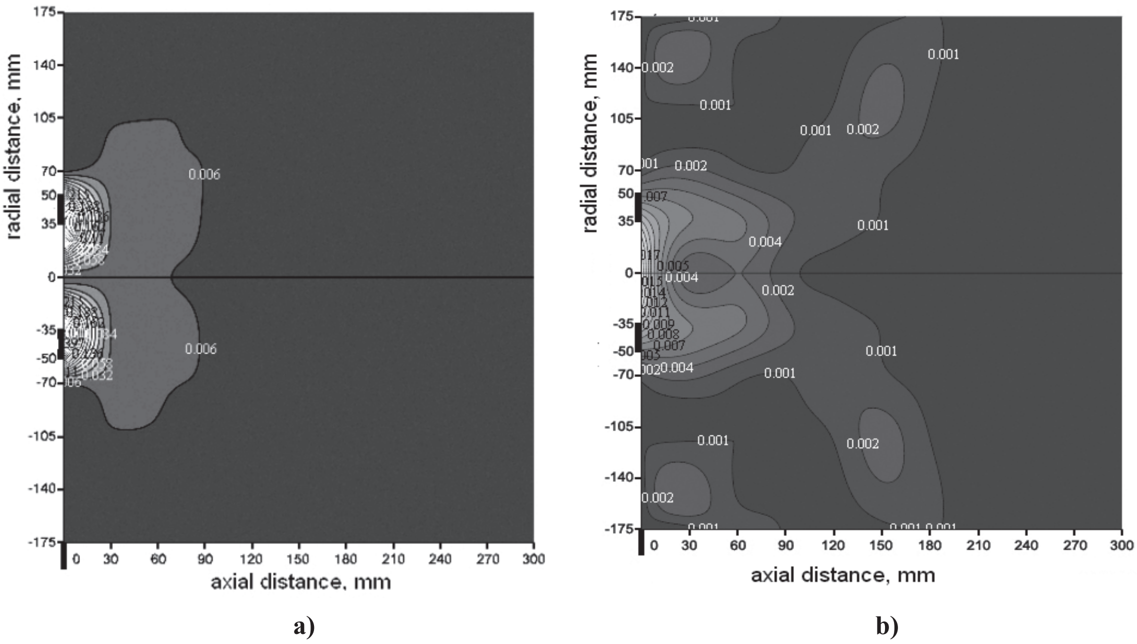


Figure 4. Space distribution of the neutral atoms (a) and charge exchange ion concentration (b) distributions

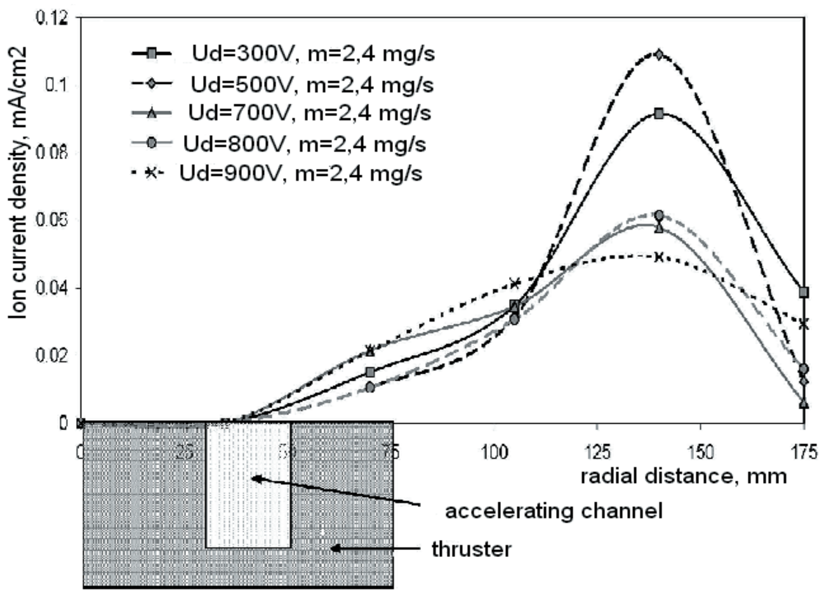
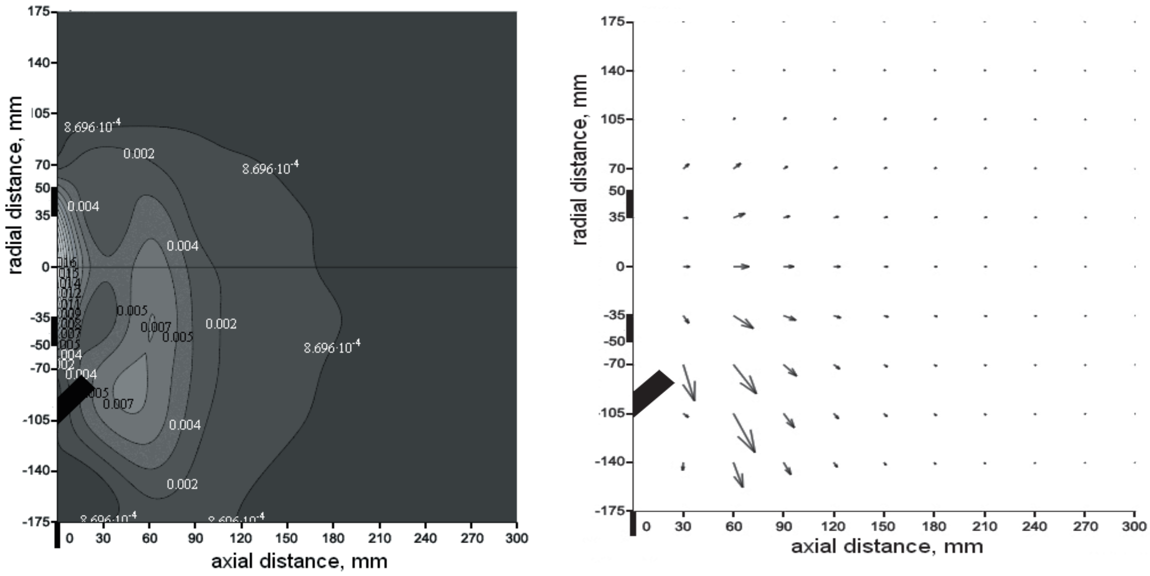


Figure 5. The 'back" ion current density distributions along the SPT-100 reference exit plane calculated for different operation modes

2. Results of simulations taking into account the cathode flow rate.

Cathode flow rate changes the neutral atoms concentration spatial distribution drastically because as was mentioned earlier its value comparable with flow rate from the accelerating channel and it is coming into plume locally. Therefore there is appearing the significant asymmetry in the concentration space distribution causing some additional effects like appearance of the local concentration maximum at definite distance from the cathode [5] (Fig.6a) and local increase of the charge exchange ion current density (Fig. 6b). The mentioned changes have weak impact on the spatial distribution of the total ion concentration in the plume core because the free pass of the accelerated ions in the near field plume is large enough and in the zone comparable with the thruster size the total rate of the charge exchange ions appearance is relatively small. But change of the charge exchange ionflow field is significant. Thus, the simulation of processes in the plume had given some new data on the spatial distributions of plasma parameters as well as on directed ion flows formation.



a) b)

Figure 6. Space distribution of the charge exchange ion concentration (a) and their current flow field (b)

IV. Some experimental data.

A. Results of the determination of the "back" ion flows onto the thrusters exit plane.

One of the experiments to study spatial distribution of the "back" ion flows was made at RIAME MAI with the SPT-140 type experimental model. The distribution of the "back" ion flows along the thruster exit plane was estimated with help of the several flat Langmuir probes positioned in different points of the mentioned plane (Fig. 7). In one series of experiments the collecting surfaces of these probes were oriented to the plume and ion currents densities J_{iz+} to these surfaces at their floating potential were measured. In another series the collecting surfaces were oriented in opposite direction and ion current densities J_{iz-} were measured. Then the 'back' directed ion current density components were determined as

$$\Delta J_i = J_{iz+} - J_{iz-} \tag{5}$$

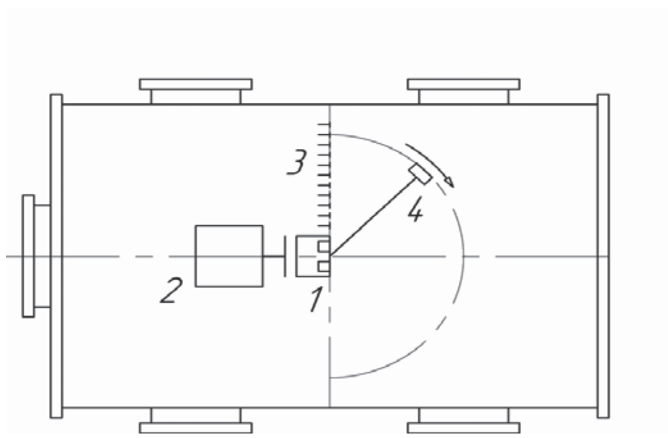


Figure 7. Scheme of measurements by system of the flat Langmuir probes

Measurements were made for several thruster operation modes with different mass flow rates $\dot{m}$ through the accelerating channel and different discharge voltages Ud (Fig. 8).

Obtained results show that ion currents have maximum values in the nearest vicinity of thruster with the characteristic size around 2D where D is the external diameter of the accelerating channel. Respectively, the "back" ion flows have also the maximum value in the mentioned thruster vicinity (Fig. 9). This is understandable because, as was mentioned above, the accelerated ion current densities and neutral atoms concentration are maximal in the vicinity of the thruster exit and are rapidly decreased with increase of distance from the thruster.

Fast reduction of the "back" ion current density with increase of distance to thruster over (1,5-2,0)D is in correspondence with the simulation results (see Fig.5).

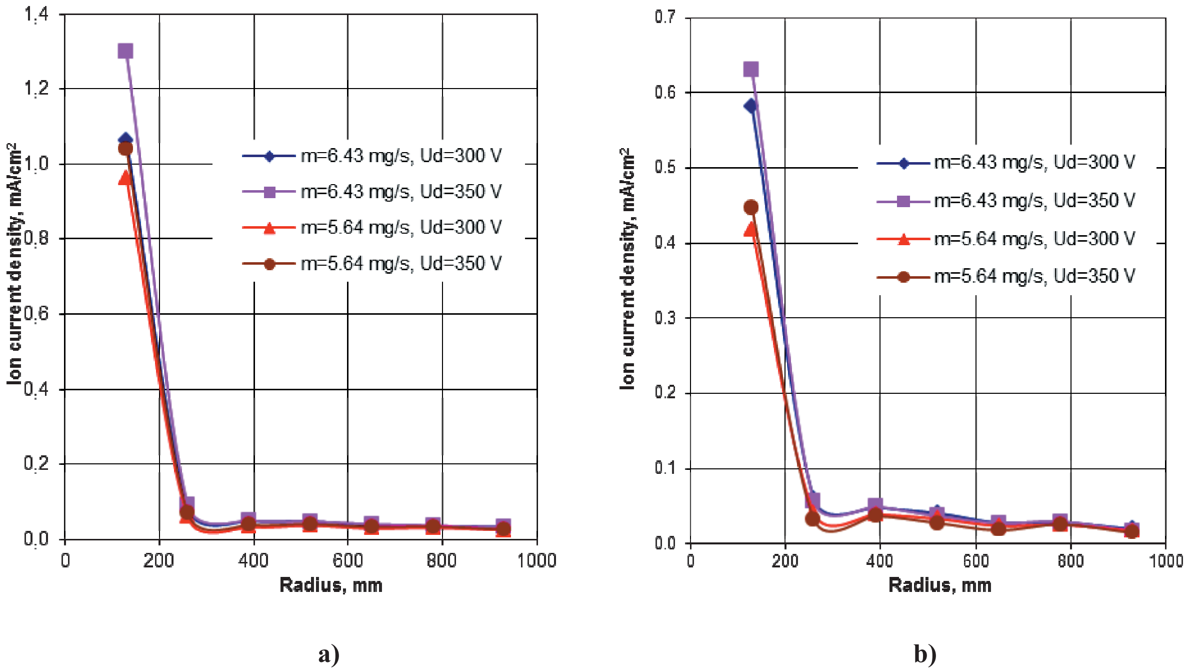


Figure 8 – Ion current densities were measured by different probes orientation to the plume (a) - J_{iz+} and (b) - J_{iz-}

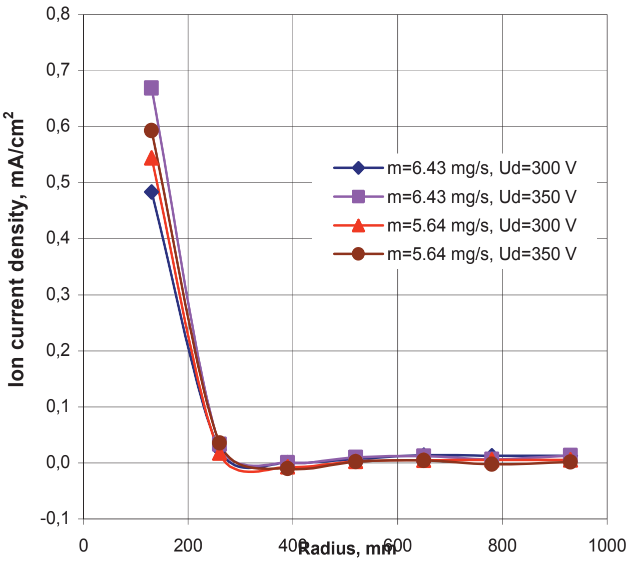


Figure 9. Ion current density distribution in "back" flow along the reference exit plane

B. Results of the ion energy determination in the radial ion flow.

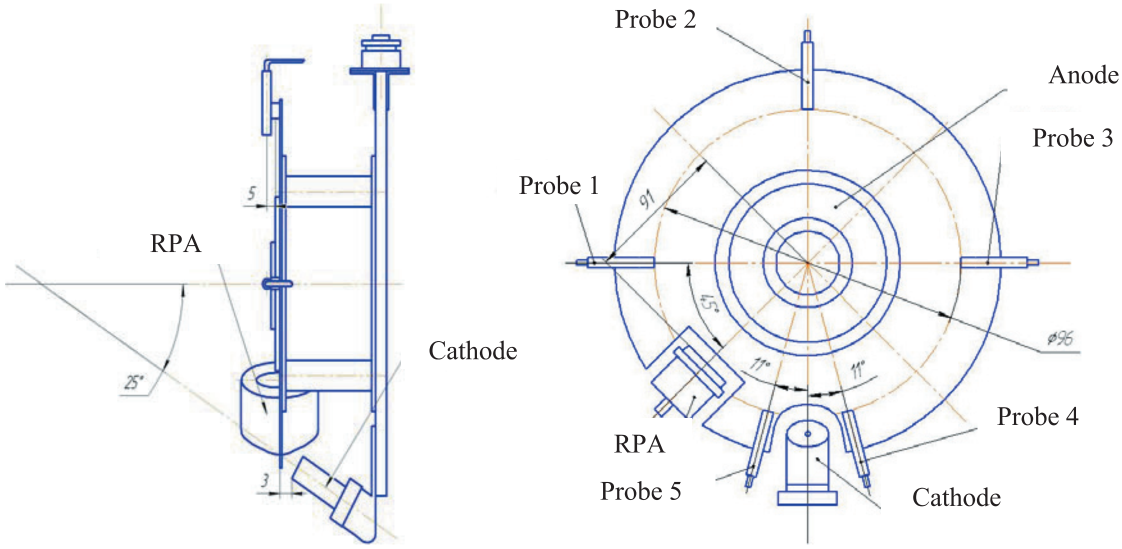
As was mentioned above the group of ions with medium energy is registered even at angles around ± 90 degrees and it was interesting to measure their characteristics at closer to thruster distances. Therefore some measurements were made at RIAME MAI for the SPT-85 laboratory model with external accelerating diameter 85 mm [10]. This model also has the accelerating layer shifted outside the accelerating channel. So, it has the same general features as the SPT-100.

The ion energy distribution in the radial ion flow was determined with help of the RPA positioned at distance around 90 mm from the thruster axes (Fig. 10). Several flat electrostatic probes were mounted also at distance ~96 mm from the thruster axes to estimate plasma parameters around the thruster.

At chosen distance of RPA from the thruster axes it measures current of ions in radial ion flow coming mainly from the nearest to thruster exit part of plume and part of the accelerating layer located just at the thruster exit. Obtained results (Fig. 11) show that in the vicinity of thruster the main part of the accelerated ions in the radial ion flow have energies within the range of (50-200) eV. It is interesting also that energy distribution of these ions is qualitatively similar to that one obtained in the plume core and significantly different from that one at distances (0.5-1.0) m. So, this is an indication of the medium energy ions appearance from the main discharge.

It is interesting also that the mean energy and current density of ions in the radial flow determined near thruster exit plane weakly depend on the discharge voltage (Fig. 12).

Depending on the operation mode and probe position the plasma potential values were varied in the range (5-15) V and the electron temperatures - within the range (1.0-2.5) eV.



a) **b)**

Figure 10. Scheme of the RPA position relative to the thruster model

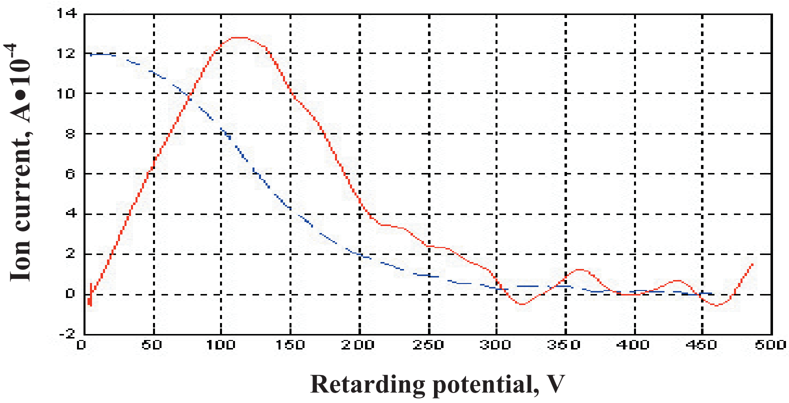


Figure 11. Retarding curve and energy distribution of ions in the radial ion flow

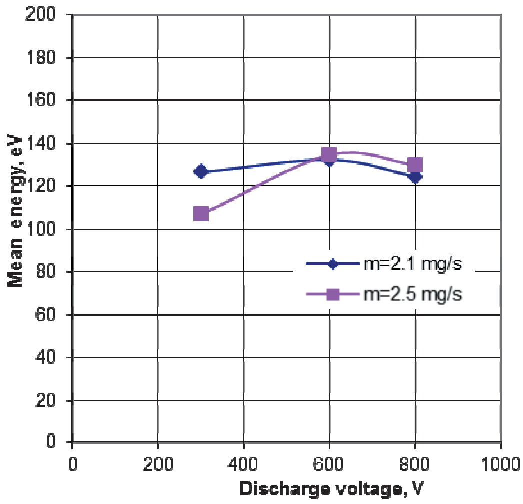
As was mentioned above the possible processes resulting in appearance of the medium energy ions in the radial ion flows are the following:

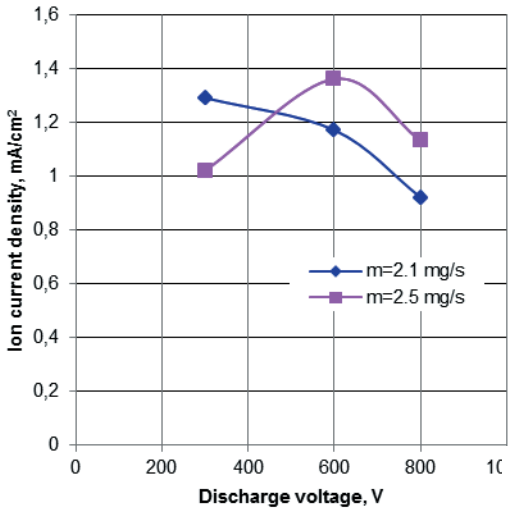
- An elastic scattering of the accelerated ions on neutral atoms;
- Acceleration of ions born in the exit part of the accelerating layer near side parts of this layer;
- Acceleration of ions in the plume by the potential difference due to difference of the plasma concentration in different parts of plume.

In order to move in radial direction in the vicinity of the thruster exit plane an ion appearing due to elastic scattering on neutrals or other ions is to be scattered within the relatively short distance from the mentioned exit plane. Estimations show that an elastic scattering cannot give the measured level of the medium energy ion current density. Then, energy of ions appeared in the place of measurements due to elastic collisions has to depend on the discharge voltage. But as was shown above dependence of the mean ion energy on discharge voltage is very weak and not regular.

Plasma parameter measurements show that difference in plasma concentration cannot give the measured energy of ions because as was mentioned above the plasma potentials in the points of the probe radial positions close to position of RPA (see Fig. 12) was in the range (5-15) V depending on the probe position and operation mode while the plasma potential in the plume core was within the range (15-25) V relative to vacuum chamber potential.

Thus, obtained results show that the most probable source of the considered medium energy ions is mainly the exit part of the accelerating layer. If so, they show also that the potential distribution in the exit part of the accelerating layer is conservative enough. This is another point to be studied further.





a) **b)**

Figure 12. Dependence of the ion mean energy and current density measured at different operation

V. Conclusion

The presented experiments and simulations had allowed obtaining of new data on the spatial distributions of the "back" ion flows and energetic characteristics of ions the radial flows moving in the vicinity of the SPT-100 type thrusters exit plane. These data could be used for the estimation of these flows impact on the charge state and erosion of the spacecraft and thrusters elements surfaces.

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