Mass-spectrometric measurements of a particle charge structure in the plasma jet of the stationary plasma thruster.

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Abstract: In this report the description of the mass-spectrometric measurements of a particle charge structure in the plasma jet of the stationary plasma thruster SPT-100 model and a modified SPT-100 model (PPS-1350) are given. A technique of measuring the particle charge structure in the plasma jet with a MX-7303 mass-spectrometer is represented, as well as the results of those measurements under the thruster operation with xenon in the range of discharges voltage 150–750V. An estimation of the beam structure changes under its transportation to a place of the measurements due to an interaction with neutrals Xe-atoms is given. The results of analyzing the formation of double-charged Xe-ions from the experimentally-produced plasma parameters in the PPS-1350-channel are also given.

Nomenclature

\( a_1, a_2 \) = coefficients allowing for exchange ions \( \text{Xe}^+, \text{Xe}^{2+} \)

\( D \) = external diameter of the accelerating channel

\( d \) = internal diameter of the accelerating channel

\( h \) = width of the accelerating channel cross-section

\( I_s \) = discharge current the thruster

\( I_i \) = ion current from the thruster

\( J_0 \) = total flows \( \text{Xe}^{2+} \)

\( J_1, J_2, J_3 \) = flows \( \text{Xe}^{2+} \) produced from the main, ion and exited states

\( J(z) \) = ion flow into channel

\( j \) = ion flux density from the thruster

\( j', j^{2+}, j^0 \) = ion flux densities \( \text{Xe}^+, \text{Xe}^{2+}, \text{Xe}^0 \) from the thruster, respectively

\( k_1 \) = coefficient takes account of a change in the display scale with respect to masses

\( k_2 \) = transmission coefficient for the mass-spectrometer probe with respect to masses

\( l \) = distance from the thruster “mouth” (outlet) to the anode

\( M \) = atom mass

\( m \) = mass flow rate

\( N \) = neutral gas density in chamber

\( n \) = densities of neutral atoms into a channel

\( n_e, n_i \) = densities of electron and ions, \( n_e = n_i \) in this case

\( n_{i0} \) = slow ion density

\( n_{i2+} \) = density of \( \text{Xe}^{2+} \)

\( P_e \) = pressure of neutral atoms in the chamber

\( P_b \) = pressure of neutral atoms in the beam

\( U_d \) = discharge voltage the thruster

\( R \) = external thruster radius

\( S_{ch} \) = area of the accelerating channel cross-section

\( T_e \) = electron temperature

\( t \) = time

\( v \) = slow ion velocity with which they escape from beam
1. Introduction

At present, for a whole number of promising space projects the usage of SPT operating with high specific impulses (3000s and higher) that will respectively require expansion in the discharge voltage range up to ≈ 1kV, is expected. The SPT-production, effectively operating in the high voltage modes, is rather complicated engineering problem which expects a wide cycle of physical studies. One should know a charge structure and an energy of particles outflying from the accelerating channel, as well as their space distribution, with a high accuracy for an analysis of the main operating processes inside and outside of the accelerating SPT-channel, such as the working gas ionization, acceleration, interaction with the wall, charge exchange, etc.

There are a number of publications devoted to such a kind of the studies \(^1\), however, in the studies either the measurements had executed at the low voltage conditions or the measurements had a local nature: in the vicinity to the beam axis, or the particle charge estimation in the beam had an indirect nature from the results of measuring the engine thrust, ion current magnitude etc.

The goal of the given study is determine a fraction of single- and multicharged ions, as well as that of neutral atoms, in the SPT-100 plasma jet within an expanded discharge voltage range (150–750V), as well as their angular and energy distributions across the beam.
2. Description of an experimental facility and a laboratory mock-up, SPT-100

A. Experimental facility

The studies were done at the E-1-stand, RRC ‘Kurchatov Institute’. The thruster was placed in a rectangular vacuum chamber, 1000 × 1000 × 2500mm in size; a high vacuum oil-vapour pump, H-200, with the air-pumping rate equal 200000 l/s, was used for its evacuation. The main part of the studies was done under operating pressure (1 – 2) × 10⁻⁵Torr (vacuum pressure values are given, according to the ionization gauge-meter, without recalculation for a working gas).

The power supply units with the voltage pulsation coefficient no higher than 1% were used for the power supply to the main SPT-discharge, magnetic system and to the cathode-compensator. The choke with the inductance of ≈30 mH, shunted by a resistor, ≈100 Ohm, and the capacity, ~2 μF, were used as matching elements in the circuit of the main SPT-discharge. The main electric parameters of the thrusters, such as a discharge voltage, \( U_a \), discharge current, \( I_a \), ion current, \( I_i \), were measured with the instruments within the accuracy range of 0.5%.

The working gas consumption was measured with a measuring vessel within the accuracy of about 5%.

B. Description of a laboratory mock-up, SPT-100

The design diagram of a laboratory SPT-100-model - under test in a given study - is represented in Figure 1. Its main dimensions are given in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>( D, \text{mm} )</th>
<th>( d, \text{mm} )</th>
<th>( l, \text{mm} )</th>
<th>( h, \text{mm} )</th>
<th>( l/h )</th>
<th>( S_{ch}, \text{cm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT-100</td>
<td>100</td>
<td>65</td>
<td>42</td>
<td>17.5</td>
<td>2.37</td>
<td>45.35</td>
</tr>
</tbody>
</table>

Here, \( D \) and \( d \) are external and internal diameters of the accelerating channel, \( l \) is the distance from the thruster “mouth” (outlet) to the anode, \( h \) and \( S_{ch} \) are width and the area of the accelerating channel cross-section.

The model was designed by the SPT – diagram - traditional for RRC KI - without magnetic screens but with a set of external and internal coils. The accelerating channel of the SPT-model was made of the ABN-insulator. The details of the magnetic system (poles, magnetic core elements) were made of soft magnetic steels, Sr.3-type. The coils were wound with a heat-resistant wire, PSDKT-type. A hollow gas discharge cathode, operating under automatic conditions, was used as a cathode-compensator. Tablets of \( \text{LaB}_6 \) were used as an emitter of electrons.

3. Technique of measuring the charged particle structure in the SPT-100 – plasma jet

A quadrupolar mass-spectrometer of a dynamic type, MX-7303, was used in a given study for estimating the ion change structure in the SPT-100 – beams.

The equipment disposition in the measurements is shown in Figure 2.

SPT-100 was placed upon a rotating platform inside the vacuum chamber to have an opportunity register the angular distribution of the measured parameters in the engine jet. The SS-shield protected the details of a vacuum lock against the SPT-100 ion beam effect. The shield with a mesh was necessary for cutting electrons off and for limiting the ion beam (1.5mm in diameter). A potential sufficient for repulsion all the electrons of plasma jet was applied to the screen grid. Then a beam consisting of ions and neutral atoms passed through the lens with a grid which could be used either as an electrostatic ion energy analyzer or as an electrostatic lock for the neutral particle passage only, when a high positive potential was applied to it. The ionizer was used, when
necessary, for an analysis of a neutral beam component and for the calibrating gas ionization under calibration of the mass-spectrometer with respect to masses (determination of the mass filter transmission factor). The analyzing grid located between the ionizer and the very mass-spectrometer (mass filter) could be used as an electrostatic energy analyzer respective to the energies of neutral SPT-beam particles. MX-7303 is a mass-spectrometer of a dynamic type 6, its principle of action is based on the fact that the ions of a definite mass (ions of a substance under analysis), passing through a hyperbolic high frequency electric field, have a limited amplitude of oscillations, meanwhile the amplitudes of other ion oscillations rise in time without any limits. These ions enter the surfaces of electrodes, being neutralized there. The ions with the limited oscillation amplitude are collected with the collection and their intensity is registered - via an amplifier - with a tape recorder.

The SPT-100 beam mass-spectrograms produced in operation with Xe are given in Figure 3. A considerable width of the isotope lines (all the lines are fused into one peak) is provided by a grate spread in the ion energies. In the treatment of mass-spectrograms the ion current value with this or that charge was determined as an integral over all the isotopes, i.e. as an area, $S$, under the intensity distribution curve, $f(M)$, with the corresponding coefficients, $k_1$ and $k_2$.

$$I = k_1 k_2 \int_{M_{min}}^{M_{max}} f(M) dM = k_1 k_2 S$$

Here, the coefficient $k_1$ takes account of a change in the display scale with respect to masses (for $Xe^+$ $k_1=1$, for $Xe^{2+}$ $k_1=2$); $k_2$ is the transmission coefficient for the mass-spectrometer probe with respect to masses. The coefficient $k_2$ depends on the mass-spectrometer adjustment conditions and the precise determination of this coefficient requires the mass-spectrometer calibration with respect to masses. However, in our experiments, when the mass-spectrometer operates under conditions of high sensitivity, this coefficient can be assumed to be equal: $k_2=1$ 6.

4. Experimental results.

The measurements of the charged particle structure in the SPT-100 plasma jet was done with the MX-7303-mass-spectrometer which was located at the distance of 800mm from the thruster butt end. At the first stage of the studies the measuring path of the mass-spectrometer concluded with a longitudinal axis of the accelerating thruster channel (angle $\alpha=0^\circ$). The measurements were done under voltage range, $U_e=150-750$V for three xenon supply values: $m=2.5$mg/s, $m=3.5$mg/s, $m=4.5$mg/s under an operating pressure not higher then $5\times10^{-3}$Torr with respected to Xe in the vacuum chamber.

Some typical mass-spectrograms taken in the SPT-100 beam at $U_e=500$V are given in Figure 3. One can see the presence of single-charged double-charged and triple-charged Xe-ions ($Xe^+$, $Xe^{2+}$, $Xe^{3+}$) on the spectrogram.

The results from the mass-spectrogram treatment are shown in Figure 4, where the relative $Xe^+$, $Xe^{2+}$, $Xe^{3+}$ -ion fractions in the ion beam component are represented under the thruster operation in the range $U_e=150-750$V. In this Figure one can see that the fraction of single-charged and multicharged ions in the beam are insignificantly charged in the ranges $Xe^+\approx85-90\%$, $Xe^{2+}\approx9-14\%$, and for $Xe^{3+}\approx3\%$.

For determining the summarized fraction of the ions with different charges one should know their distribution across the whole beam cross-section. In this connection, some mass-spectrograms under various angles respective to the accelerating channel of the thruster were registered. The results of these mass-spectrogram treatments are given in Figure 5 – for the conditions when $U_e=500$V. One can see that the ratio of the ion components with different charges in the SPT-
100-beam transversal cross-section in the angle range $\alpha = \pm 25^\circ$ is changed insignificantly, within the range of a few percents.

In Table 2 some average data of ions of various charging in the SPT-100 beam for a few characteristic modes: $U_a = 300V$, $500V$, $700V$; $m = 2.5mg/s$, $m = 3.5mg/s$ and $m = 4.5mg/s$, are given.

![Figure 5. Angular distribution of a relative $Xe^{2+}$ content in a SPT-100 plasma jet ($U_a = 500V$, $m \approx 4.2mg/s$).](image)

![Figure 6. Braking characteristics of the $Xe^+$ and $Xe^{2+}$ components and their energy spectra for the conditions with $U_a = 700V$, $m \approx 4.2mg/s$.](image)

<table>
<thead>
<tr>
<th>$U_a$, V</th>
<th>The ions $Xe$, %</th>
<th>$Xe^+$</th>
<th>$Xe^{2+}$</th>
<th>$Xe^{3+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m = 2.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>91</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>88</td>
<td>10.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>84</td>
<td>13</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>$m = 3.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>83</td>
<td>15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>82.5</td>
<td>15</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>80</td>
<td>17</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>$m = 4.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>86</td>
<td>13</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>86</td>
<td>12</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>82</td>
<td>15</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

One of the mine ion beam characteristics is an energy spectrum of the differently charged ions. In Figure 6 The braking characteristics of the ion components $Xe^+$ and $Xe^{2+}$ produced after the mass-spectrogram treatment and their energy spectra for the conditions with $U_a = 700V$ are shown. One can see that an average energy per charge unit for the $Xe^+$-ions is higher than that for $Xe^{2+}$ and equals for ions $Xe^+ \approx 0.9U_a$ and for $Xe^{2+} \approx 0.8U_a$.

A neutral component – fast and slow xenon-atoms ($Xe^0$) – has been detected besides the ion component in the SPT-100 beam. The measured fraction of the fast xenon atoms with an energy then 50eV was equal to a few percent from the ion beam component, however, the precise determination of the neutral atom amount was hard because of a low ionizer efficiency.

At final stage of the studies the ion charge structure measurements in the SPT-beam, PPS-1350 model (developed by the RIAME, an analogue SPT-100), has been carry out. As a whole, the results of the measurement confirm a closeness of the ion charge structures in the beams of both modes. Some results of the measurements are given in Table 3.

<table>
<thead>
<tr>
<th>$U_a$, V</th>
<th>The ions $Xe$, %</th>
<th>$Xe^+$</th>
<th>$Xe^{2+}$</th>
<th>$Xe^{3+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m = 2.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>89.4</td>
<td>9.3</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>$m = 3.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>91</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>83</td>
<td>15.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>$m = 4.5$ mg/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>88</td>
<td>11</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

5. A change in the beam structure components in the process of a beam transportation.

Experimental beam studies show that a content of the double-ionized $Xe$ ions is equal to 8-16% of the single-ionized ions and it is slightly changed within the limits of a discharge voltage from 150V to 750V.

As known, the beam structure in the process of its transportation can be change because the cross-sections of interaction for various ion varieties are essentially different from each other. Its is evident that one should take account of these conversions along the way of ions, following to the place of their measurements, in order to have an idea about the structure of a beam outgoing from the SPT.

The mass-spectrometer used for the studies was located at the distance of 80cm from the thruster cut. The measurements were done under pressure of $5 \times 10^{-5}$Torr with respect to $Xe$. This pressure was set out side of the beam spread zone. However, the $Xe$- pressure in the beam can be greater by a few reasons:

5.

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September 17-20, 2007
- because the ionization in the SPT-channel is less than 100% and the neutral gas flow outgoing from it is spread along the beam;
- an \( \text{Xe}^- \) – flow outgoing from the cathode compensator crosses the beam along 10–20 cm;
- beam ions entering the screen located in front of the mass-spectrometer are converted into neutral atoms and part of them enters back into the zone of a beam spread.

Considering the beam structure changes in the process of its transportation, let us proceed from the following assumptions:

1. The pressure of a neutral \( \text{Xe} \) along the beam path length is not changed.
2. The ion flux density is rapidly reduced because of a strong beam divergence and it can be represented by the following expression:

\[
j \sim I/\pi (R + \sigma \times \Phi)^2,
\]

where \( R \) is external thruster radius, \( I \) is the total ion flux from the thruster.

If the divergence agrees is \( \Phi = 50^\circ \), the beam density will be reduced by more than an order of magnitude at the distance of 80 cm.

3. Under collisions of the beam particles with slow ones the following interactions take place:
   - a) \( \text{Xe}^0 \) - charge exchange with neutral atoms, \( \sigma_{10} = 4.9 \times 10^{-15} \) cm\(^2\),
   - b) \( \text{Xe}^{2+} \) – with neutral atoms, \( \sigma_{20} = 2 \times 10^{-15} \) cm\(^2\),
   - c) \( \text{Xe}^+ \) - charge exchange from neutral atoms up to \( \text{Xe}^+ \), \( \sigma_{21} = 1 \times 10^{-16} \) cm\(^2\),
   - d) Stripping of fast neutral atoms from slow ions, \( \sigma_{01} = \sigma_{10} \).

It is evident that the \( \text{Xe}^+ \) and \( \text{Xe}^{2+} \) ion interactions with neutral atoms will be dominant processes. The density of the slow ions, which will appear as a result of this process, will be essentially lower than the density of neutral atoms.

Taking this into account, one can write a set of equations for produced in the beam transportation process:

\[
\begin{align*}
\text{div} \left( j^0 + \sigma_1 \cdot j^1 - j^1 + N \sigma_{10} \right) &= 0 \\
\text{div} \left( j^2 + \sigma_2 \cdot j^2 - j^2 + N \sigma_{20} \right) &= 0 \\
\text{div} \left( j^0 + \sigma_1 \cdot j^1 - j^1 + N \sigma_{10} \right) &= 0
\end{align*}
\]

where \( j^0, j^1, j^2 \) are the flux densities \( \text{Xe}^0, \text{Xe}^+, \text{Xe}^{2+} \), respectively; \( N \) is neutral gas density, \( n_{10} \) is the slow ion density.

It is evident that one should take account of their departure along the beam radius in the slow ion density calculations. Indeed, the beam potential is a positive one; as a result the slow ions will escape from the beam with the energy which will be dependent on the electron temperature.

The equation, which represents the slow ion density in the beam, can be written in the following way:

\[
j^1 N \sigma_{10} - j^1 n_{10} \sigma_{10} - 2 n_{10} v (R + \sigma \times \Phi \Phi) = 0
\]

where \( v = (T_e/M)^{1/2} \) is the slow ion velocity with which they escape from beam.

The electron temperature, \( T_e \), has been assumed to be equal 1–2 eV.

Solving the set of equations, one can obtain a change in the beam structure along the length of its transportation.

The solution results given in Figure 7, have been obtained under condition that the beam is spread in the chamber under pressure of 5 \( \times \) 10\(^{-2} \) Torr with respect to \( \text{Xe} \).

As one can see in Figure, under the gas pressure set in the chamber, the fraction equal to \( a = 0.4 \) of the single charged \( \text{Xe}^- \) – ion current along 80 cm is recharged and transformed into fast neutral atoms; as for the double-charge ions, their fraction is reduced by \( a = 0.2 \) only. I.e. in the process transportation noticeable change in the beam component towards an increase in the \( \text{Xe}^{2+} \) fraction takes place. If this fact is taken into account the content of the \( \text{Xe}^{2+} \) \( \beta \) ions which escapes from the thruster is lower respective to \( \text{Xe}^+ \) and equal

\[
\beta \beta^*(1-a_2)/(1-a_2),
\]

where \( \beta \) is the value obtained in the measurements a mass – spectrometer.

It means that the fraction of double-ionized ions is equal to 6–12% of a total particle flux outgoing from the thruster that is considerably lower than it follows from the mass-spectrometric measurements.
As noted above, the pressure of neutral atoms in the beam, $P_0$, can be higher than outside, $P_e$. Some estimates show that under certain conditions, when, in particular, the ion collector is located at a distance less than 1 m from the thruster, it is possible that $P_e/P_0=2–3$.

A relative change in the $Xe^{2+}$ flux dependent on the $Xe$ – pressure in the chamber is given in the Figure 8. One can see that the $Xe^{2+}$ content is increased 1.7 - times respective to the $Xe^{2+}$ – flux content, outgoing from the thruster, if the gas pressure in the transportation zone rises up to $1.5 \times 10^4$ Torr.

In this case one is forced to assume that a relative content of double-charge ions will be even lower and equal 5–9%.

### 6. Calculation of production double – charged ions into channels SPT.

It is evident that the main mechanism for the $Xe^{2+}$ - production are the double ionization from the main state and the ionization of a single- charged ionized ions.

In this case

$$n_iN_i<\sigma^{0}_{12}v_e> + n_e n_i <\sigma^{+}_{02} v_e> - \nabla n_i^2 <v_e^2> = 0,$$

Where $n_e$, $n_i$ are densities of electron and ions, $n_e=n_i$ in this case, $n$ is the densities of neutral atoms, $\sigma^{0}_{12}$ is the cross section of a double ionization from the main state, $\sigma^{+}_{02}$ is the cross section of a double ionization from the ion state, $v_e$ is the electron velocity, $v_e^{2+}$ is the velocity of $Xe^{2+}$, $n_i^2$ is the density of $Xe^{2+}$.

Taking this relationship into account, it is not difficult to produce the ion flow density for $Xe^{2+}$ which are produced in the channel $j_{i2}^{2+}=n_i^2 <v_e^{2+}>$.

As known, the excited neutral atoms produced in thruster channel, along with ions, and, in the collision of electrons with them, the emergence of $Xe^{2+}$ is possible. The cross-section of this process, $\sigma^{0}_{02}$, is much greater than $\sigma^{+}_{02}$. If the density of the atoms $n_0$ – gas is rather high, one should take account of this $Xe$ – production mechanism. It is easy show that the $Xe^{2+}$ - current will increased by due to the mechanism $n_i N_i <\sigma^{+}_{02} v_e> dz$.

The calculation of the double ionized ion production has been done, taking the following consideration into account.

The electron distribution function is a “Maxwellian” one with a cut tail of fast electrons. Under operating plasma parameters in the SPT- channel, frequency of electron collisions among themselves is lower then that with the channel walls, as a result, the fast electrons loose their activities “die”– upon the accelerator channel walls. It is evident that the channel walls are under a floating potential, the density of electrons having an energy greater than $4T_e$ is close to zero. Since $T_e$ does not exceed 50eV, in the discharge voltage range lower than 1000V, there will be no electrons with the energy greater than 200eV in the thruster channel.

Taking account of a limited amount of electrons having a high energy and the very fact that the ionization has a threshold nature, in calculations has been assumed that:

The $Xe^{2+}$ - production cross-section from the main state $\sigma^{0}_{12}$ is $3 \times 10^{-17}$ cm$^2$ with the electron energy change from 50eV to 200eV,

The $Xe^{2+}$ - production cross-section from the ion state $\sigma^{+}_{12}$ is $2 \times 10^{-16}$ cm$^2$ with the electron energy change from 30eV to 200eV. These values have been obtained from the data published in $^8$.

The data for the $\sigma^{0}_{02}$ – cross-section are absent, however, it is evident that the cross-section of this process should be some what lower, than $\sigma^{+}_{12}$, and the ionization threshold is somewhat greater than 30eV. Proceeding from these considerations, it has assumed that the cross section $Xe^{2+}$ - production from the excited state is $\sigma^{+}_{02}=1.7 \times 10^{-16}$ cm$^2$ with the electron energy change limits from 35eV to 200eV.

For ionization calculators one should know the neutral atoms distribution which is set in the device channel. It is easy to show that this value can be determined as

$$n=4(m/M - J(z)/e)/Sv_0$$

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*Figure 8. A change in the beam structure charge vs. pressure in the chamber. The transportation length is 80cm.*
Some examples of the plasma parameter distribution in the channel averaged over the channel radius are given in Figures 9 - 11.

The results of calculating the beam structure components are included into Table 4 for various discharge voltages $U_e$. The maximal electron temperatures are given in the row 2. Relative flows of the double-ionized ions produced from the main, $J_2$, and ion, $J_a$, excited, $J_b$, states are given in the rows 3, 4, 5. Relative flow $Xe^{2+}$ produced from the main, and ion, states in the row 6, and the total flow $Xe^{2+}$ are given in the row 7. In the calculations of ionization from the exited state it has been assumed that the density $N^0=0.015N$.

The thruster was operation at the expenditure of $3.5 \text{ mg/s.}$

![Figure 9. Distribution of the electron temperature along the channel. $U_e=700\text{V}$](image)

![Figure 10. Distribution of the electron density along a channel.](image)

![Figure 11. Distribution of the neutral atoms density along a channel.](image)

<table>
<thead>
<tr>
<th>$U_e$, V</th>
<th>300</th>
<th>500</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>20</td>
<td>27</td>
<td>35</td>
</tr>
<tr>
<td>$J_2/J_0$</td>
<td>0.024</td>
<td>0.041</td>
<td>0.072</td>
</tr>
<tr>
<td>$J_a/J_0$</td>
<td>0.0048</td>
<td>0.0093</td>
<td>0.015</td>
</tr>
<tr>
<td>$J_b/J_0$</td>
<td>0.004</td>
<td>0.0075</td>
<td>0.0095</td>
</tr>
<tr>
<td>$(J_2+J_a)/J_0$</td>
<td>0.029</td>
<td>0.05</td>
<td>0.087</td>
</tr>
<tr>
<td>$J^{2+}/J_0$</td>
<td>0.033</td>
<td>0.058</td>
<td>0.096</td>
</tr>
<tr>
<td>$(os. T_e)$</td>
<td>0.052</td>
<td>0.1</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The results of the calculations show that a fraction of the double-ionized ions is varied, dependent on the discharge voltage, in the range 3.3-9.6%. A growth of the $Xe^{2+}$-fraction with an increase in the discharge voltage is provided by a rise in the electron temperature as a result of which a number of electrons participating in the production process of these ions also rises. The main mechanism of $Xe^{2+}$-production is ionization from the ground state because the density neutral atoms in the channel is essentially higher then electron density. The $Xe^{2+}$-production from the excited state plays a noticeable role even at the density of the excited atoms equal to a few percents of the density of neutral atoms.

The $Xe^{2+}$-ions production from ion state at low discharge voltages, i.e. at low electron temperature is a few times greater than that of the $Xe^{2+}$-ions production from the main state. It is caused by a noticeable difference in the ionization thresholds for these two processes. It is evident that when $T_e<12.5eV$, the double – ionization from the main state is practically equal zero.

The estimation of the formation of double ionization $Xe$ was produced from the electron temperature measurements into the channel of thruster. These measurements were done by means of the method of time averaging. However some investigation showed that the electron temperature can vary depending on time along all channel, at all fluctuating temperature swing can amount a great deal relatively averaging’s. Such behavior of the electron temperature can increase the formation of the multi charge ions. To confirm these results the similar investigations to models SPT-70 has been doing.

The temperature dependence on time may calculate by difference in amplitude of a oscillations the floating plasma potential producing by emissive (heat) $V_h$ and cold probe $V_c$. Than the electron temperature is $T_e=e(V_h−V_c)/b$, here $b=−3.4$.

Figure 12 shows a schematic of the probe construction. The emitting portion of the probe was a filament made $0.02\text{mm}$- diameter tungsten wire. The ends of this filament were inserted down $150\text{mm}$ length of double bore alumina tubing along with cooper wire leads. The outer diameter tubing was $4\text{mm}$. The length of the emissive filament was $3\text{mm}$. A heat of the filament was performed by separating transformer. An oscilloscope for measuring the resulting floating
plasma potential plasma was connected by potential divider with a probe. Such schematic enabled to measure oscillations till 500 kHz.

The measurements accomplishing formerly showed that this oscillations were observed both into the accelerating channel and outside, at that it were in phase at the frequency below 80 kHz.

Model SPT, at which was been carry out that investigations, had large channel width and the probe inserting into its did not exert a significant effect on characteristic SPT. Fist experiments on this model, which did not have got some large channel width showed that in time inserting probe into channel takes place the significant perturbation to thruster operation. This has been note in other work\textsuperscript{11}. From this the electron temperature oscillations measurements had been perform only outside thruster (0–4mm from exit).

For comparison with the temperature dischage voltage and current oscillations also has been investigative. The results which is represented under have been produce at $U_a=200$V, $J_a=3$A, Figures 13–14 shows time evolution of both the plasma potential and floating potential. As seen amplitude of the plasma potential is 15–20V which largely exceeds the floating potential $V_c=1.2$–$1.7$V. It is can draw a conclusion that the plasma potential oscillation is the electron temperature oscillation. In range the period of oscillation increasing $T_e$ is greater on 30–40% than decreasing its. The peak value $T_e$ can increase of 5–6eV to 9–10eV.

The characteristic frequency is 25–30 kHz. It is note that the temperature oscillations also correlate with the discharge current oscillations.

On the basis of that can propose that at increasing $T_e$ corresponds to increasing ion current and in large part the appearance of the multi charge ions.

$$j_{\text{el}}^n = \frac{1}{l_0} \int_0^{l_0} \left[ \left( N(z) \right) \cdot (\sigma_{el} \cdot v_e(z,t)) + n_e^2(z,t) \cdot (\sigma_{el} \cdot v_e(z,t)) + n_e(z,t) \cdot N_e(z) \cdot (\sigma_{el} \cdot v_e(z,t)) \right] dz$$

If to believe that the amplitude $T_e$ constitute 30–40% from its average magnitude along all channel, then, how showed the calculation, the part of $Xe^{2+}$ increase on 20–30% and can constitute 5–12% from all ions (the results in the table 4) depending on the discharge voltage.

It is interest to note, that for varying $U_a$ from 500V to 700V the part of $Xe^{2+}$ increases only 2%. It is impossible this follows from that the electron distribution function has limitation from electron collision with ceramic channel. For large the electron temperature the part high energetic electrons with increasing $T_e$ increase not so greatly how for not large the electron temperature.

7. Conclusion

One should note the following data as the main results of the realized study:

1. The particle charge structure measurements in the SPT-100-plasma jet, operating in with $Xe$, in the discharge voltage range, $U_a=150$–$750$V, were realized with a modified mass-spectrometer MX-7303. Some single-charged, double-charged and triple-charged $Xe$-ions ($Xe^+$, $Xe^{2+}$, $Xe^{3+}$), as well as the fast and slow $Xe$–atoms (with the energy, greater or lower then 50eV), were detected in the beam.

2. In the whole discharge voltage range under study, the single-charged and multi-charged ion fraction in the ion beam components are insignificantly charged, being in the limits of 80–90% for the $Xe^+$, in the limits of 8–16% for $Xe^{2+}$ and in the limits of $Xe^{3+}$<3%.
3. The ratio of the differently-charged ion components in the transversal beam component, within the ±25° angle range is charged insignificantly, within the range of a few percents.

4. From the measured ion component energy spectra, under discharge voltages, $U_d=500–700\text{V}$, it has been produced that an average energy per the charge served for the $\text{Xe}^+$-ions is higher than that for $\text{Xe}^{2+}$ and equal for the $\text{Xe}^{3+}$-ions to $=0.9U_d$, and to $=0.8U_d$ for $\text{Xe}^{4+}$.

5. The ion charge structure measurements in the beam of a modified SPT-100 model (PPS-1350) confirm the proximity of the beam parameters for both models.

6. A beam transportation analysis to a registration place has shown that its structure can be changed due to an interaction of the beam ions with neutral atoms of the gas and it should be taken with account in the structure determination of a beam outgoing from the thruster.

7. Taking this into account, at fraction double – ionized $\text{Xe}$ outgoing from thruster, by estimation, is equal to 6-12% of the total ion beam.

8. An analysis of the double-ionized $\text{Xe}$ ions has been done experimentally – measured plasma parameters in the thruster channel for the PPS-1350-model. The ionization from the main, ion and excited states has been considered. In this approximation the calculations show that the beam structure depends on the discharge voltage, when it changes from 300V to 700V the $\text{Xe}^{2+}$-content in the beam should be changed from 3.3% to 9.9%.

9. Represent the evidence that into the thruster is the electron temperature oscillation pronounced amplitude relatively its average readings. The estimation shows that such behavior of electron temperature can increase the $\text{Xe}^{3+}$-content in the beam from 5.5% to 12%.

10. The calculation results show a close coincidence with the experimental ones. At the same time, one should note other ionization mechanism should be involved into such calculation, in particular, the autoionization cross-section, can exceed the shock ionization cross-section, and a threshold cross-section value is shifted to the zone of the lower energies. Unfortunately, there is not reliable data for those processes yet that provides some difficulties for a more detailed ionization analysis in the channel.

One should note the following data as the main results of the realized study within the INTAS-03-53-3358-Project and RFBR-06-08-000873-a-Project.

References


10. Smirnov V. Oscillation of the electron temperature $T_e$ into channel CDEA. A report at 3-th the Plasma Acceleration Conference, Minsk, 1976.