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

IEPC-2007-144

A.N. Veselovzorov, E.E. Barkalov, A.A. Pogorelov, E.B. Svirsky, V.A. Smirnov

Russian Research Centre 'Kurchatov Institute' Moscow, Russia.

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 Xe^+, 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_a	=	discharge current the thruster
I_i	=	ion current from the thruster
J_0	=	total flows Xe^{2+}
J_1, J_2, J_3	=	flows Xe^{2+} produced from the main, ion and exited states
$J_i(z)$	=	ion flow into channel
j	=	ion flux density from the thruster
j^+, j^{2+}, j^0	=	ion flux densities Xe^+, Xe^{2+}, 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_i^{2+}	=	density of Xe^{2+}
P_0	=	pressure of neutral atoms in the chamber
P_b	=	pressure of neutral atoms in the beam
U_a	=	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

$\mathbf{v}_e$ = electron velocity
$\mathbf{v}_i^{2+}$ = velocity of Xe^{2+}
$\mathbf{v}_0$ = thermal velocity of atoms
z = distance
α = angle range
β = content of the Xe^{2+} ions which escapes from the thruster is lower respective to Xe^+
φ = divergence agrees
σ_{02}^i = cross section of a double ionization from the main state
σ_{12}^i = cross section of a double ionization from the ion state,

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 $\approx$ 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 [1-5], 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, $1000 \times 1000 \times 2500$mm 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 $(1 - 2) \times 10^{-4}$Torr (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 1.

Model	D, mm	d, mm	l, mm	h, mm	l/h	S_{ch}, cm^2
SPT-100	100	65	42	17.5	2.37	45.35

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, $St.3$–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 LaB_6 were used as an emitter of electrons.
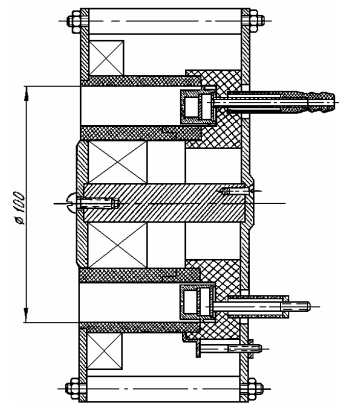

Figure 1. SPT-100 - diagram.

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
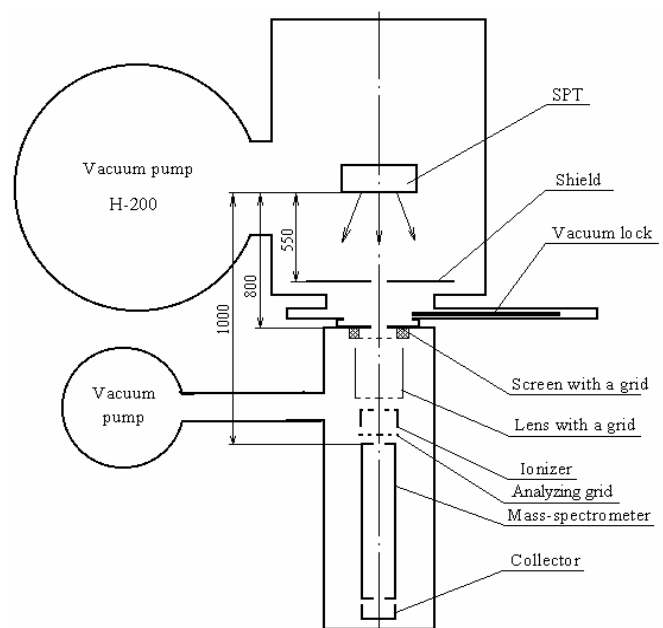

Figure 2. Circuit-diagram for measuring the mass (charge) composition of the SPT-plasma beam with a mass-spectrometer, MX 7303.

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, $j(M)$, with the corresponding coefficients, k_1 and k_2.

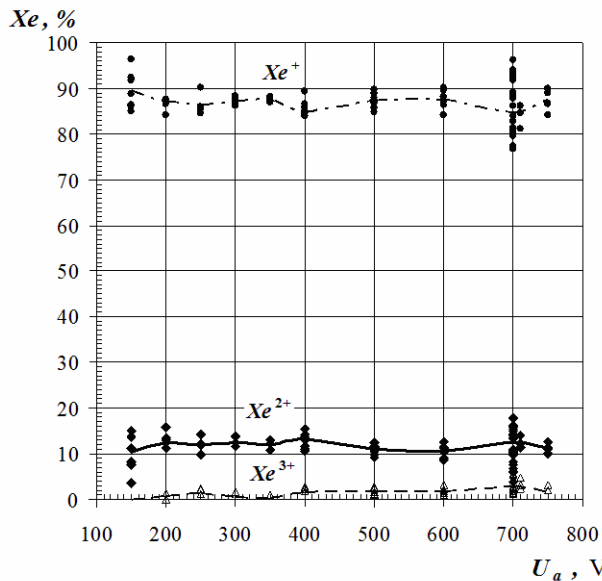$$I = k_1 k_2 \int_{M_{min}}^{M_{max}} j(M)dM = k_1 k_2 S$$
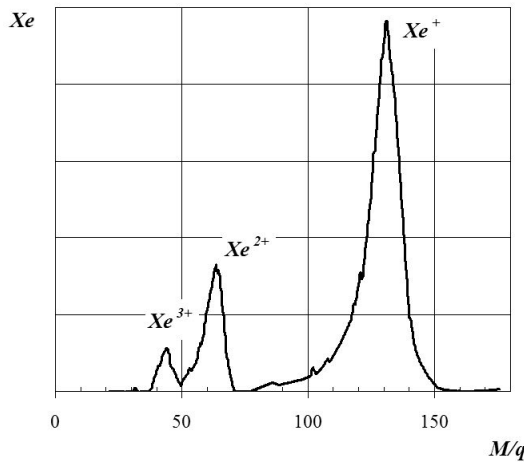
Figure 3. Mass-spectrogram of the SPT-100 – beam under operation with *Xe* (U_a=500V, $m \approx$ 3,5mg/s).

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: $k_2 \approx 1$ [6].

4. Experimental results.

The measurements of the charged particle structure in the SPT-100 plasma jet was done with the MX-7303-mass-spectrometerwich 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 $\alpha=0^0$). The measurements were done under voltage range, U_a=150–750V for three xenon supply values: m=2.5mg/s, m=3.5mg/s, m=4.5mg/s under an operating pressure not higher then $5 \cdot 10^{-5}$Torr with respected to *Xe* in the vacuum chamber.

Some typical mass-spectrograms taken in the SPT-100 beam at U_a=500V 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_a=150-750V, In this Figure one can see that the fraction of single-charged and multicharged ions in the beam are insignificantly charged in the ranges $Xe^+ \approx$ 85-90%, $Xe^{2+} \approx$ 9-14%, and for $Xe^{3+} <$ 3%.

For determining the summarized fraction of the ions with different charges one should known 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_a=500V. One can see that the ratio of the ion components with different charges in the SPT-

Figure 4. Dependencies of a relative Xe^+, Xe^{2+} and Xe^{3+} ion content in a SPT-100-plasma jet on the discharge voltage (m ≈ 4,2mg/s).

4

100-beam transversal cross-section in the angle range $\alpha=\pm25^0$ 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.

Table 2.
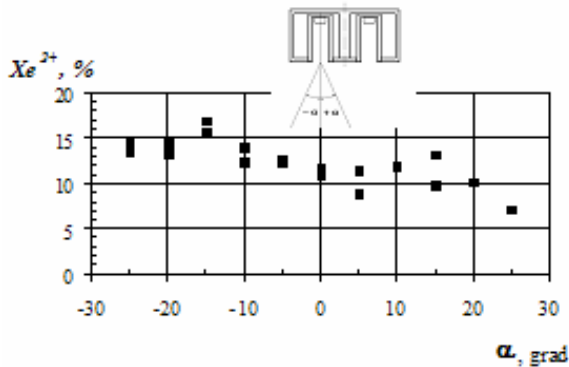
Figure 5. Angular distribution of a relative Xe^{2+} - content in a SPT-100 plasma jet (U_a=500V, m ≈ 4,2mg/s).

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

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 higher 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.
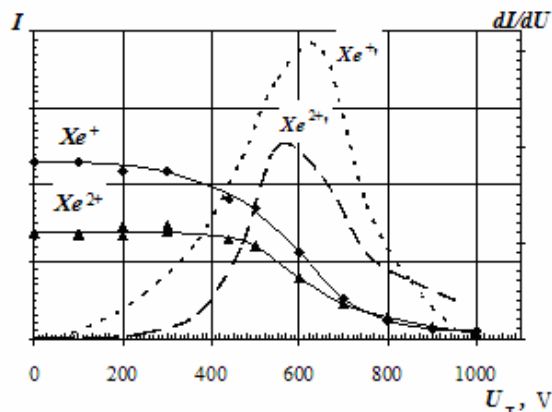
Figure 6. Braking characteristics of the Xe^+ and Xe^{2+} - components and their energy spectra for the conditions with U_a=700V, m ≈ 4,2mg/s.

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 3.

U_a, V	The ions Xe, %		
	Xe^+	Xe^{2+}	Xe^{3+}
	m =2.5 mg/sec		
500	89.4	9.3	1.3
	m =3.5 mg/sec		
300	91	9	
500	83	15.5	1.5
	m =4.5 mg/sec		
350	88	11	1

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 $5 \cdot 10^{-5}$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:

- 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 *Xe* – flow outgoing from the cathode compensator crosses the beam along 10–20cm;
- 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 *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:

$$j \sim I_i / \pi \cdot (R + z \cdot \mathrm{tg}\, \varphi/2)^2,$$

where R is external thruster radius, I_i is the total ion flux from the thruster.

If the divergence agree is $\varphi = 50^0$, the beam density will be reduced by more than an order of magnitude at the distance of 80cm.

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

It is evident that the Xe^+ and 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:

$$\mathrm{div}\, j^+ + j^+\, N \cdot \sigma_{10} - j^0\, n_{i0} \cdot \sigma_{01} - j^{2+}\, N \cdot \sigma_{21} = 0 \qquad (1)$$
$$\mathrm{div}\, j^{2+} + j^{2+}\, N \cdot \sigma_{20} + j^{2+}\, N \cdot \sigma_{21} = 0 \qquad (2)$$
$$\mathrm{div}\, j^0 - j^+\, N \cdot \sigma_{10} + j^0\, n_{i0} \cdot \sigma_{01} - j^{2+}\, N \cdot \sigma_{20} = 0 \qquad (3)$$

where j^+, j^{2+}, j^0 are the flux densities Xe^+, Xe^{2+}, Xe^0, respectively, N is neutral gas density, n_{i0} 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.
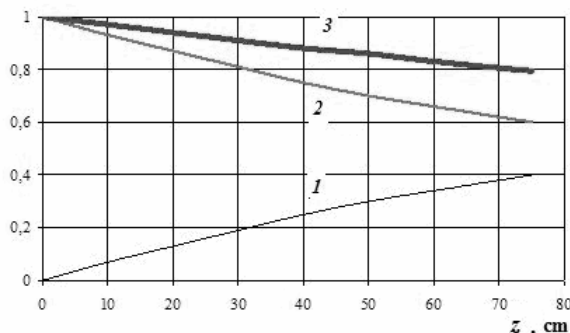
The equation, which represents the slow ion density in the beam, can be written in the following way:

$$j^+\, N \cdot \sigma_{10} - j^0\, n_{i0} \cdot \sigma_{01} - 2\, n_{i0} \cdot \mathrm{v}/(R + z \cdot \mathrm{tg}\, \varphi/2) = 0 \qquad (4)$$

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

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

Solving the set of equation, 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 $5 \cdot 10^{-5}$Torr with respect to *Xe*.

As one can see in Figure, under the gas pressure set in the chamber, the fraction equal to $a_1 = 0.4$ of the single charged *Xe* – ion current along 80cm is recharged and transformed into fast neutral atoms; as for the double-charge ions, their fraction is reduced by $a_2 = 0.2$ only. I.e. in the process transportation noticeable change in the beam component towards an increase in the Xe^{2+} - fraction takes place. If this fact is taken into account the content of the Xe^{2+} β ions which escapes from the thruster is lower respective to Xe^+ and equal

$$\beta = \beta_0 \cdot (1 - a_1)/(1 - a_2),$$

where β_0 is the value obtained in the measurements a mass – spectrometer.

Figure 7. Changes in the beam composition along the transportation length. (1- relative change in the flux of neutral atoms, 2- relative change in the Xe^+-flux, 3- relative change in the Xe^{2+}-flux).
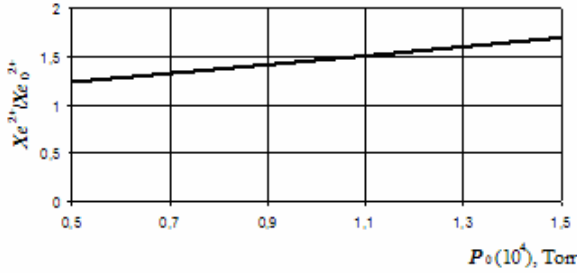
It means that the fraction of double-ionized ions is equal to 6–12% of a total particle flux outgoing from the thruster that is considerably lower than it follows from the mass-spectrometric measurements.

Figure 8. A change in the beam structure charge vs. pressure in the chamber. The transportation length is 80cm.

As noted above, the pressure of neutral atoms in the beam, P_b, can be higher than outside it, P_0. Some estimates show that under certain conditions, when, in particular, the ion collector is locates at a distance less than 1m from the thruster, it is possible that P_b/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 increases 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 $1.5 \cdot 10^{-4}$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

$$n_e N \cdot <\sigma^t_{02} v_e> + n_e n_i^+ \cdot <\sigma^t_{12} v_e> - \text{div } n_i^{2+} v_i^{2+} = 0,$$

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,
σ^i_{02} is the cross section of a double ionization from the main state,
σ^i_{12} is the cross section of a double ionization from the ion state,
v_e is the electron velocity,
v_i^{2+} is the velocity of Xe^{2+},
n_i^{2+} is the density of Xe^{2+}.

Taking this relationship into account, it not difficult to produce the ion flow density for Xe^{2+} which are produced in the channel $j_i^{2+} = n_i^{2+} v_i^{2+}$

$$j_i^{2+} = \int n_e N \cdot <\sigma^t_{02} v_e> \, dz + \int n_i n_e \cdot <\sigma^t_{12} v_e> dz$$

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, σ^0_{02}, is much greater than σ_{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 $\int n_e N^0 \cdot <\sigma^0_{02} v_e> dz$.

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 σ^i_{02} is $3 \cdot 10^{-17}$ cm^2 with the electron energy change from 50eV to 200eV,

The Xe^{2+}- production cross-section from the ion state σ^i_{12} is $2 \cdot 10^{-16}$ cm^2 with the electron energy change from 30eV to 200eV. These values have been obtained from the data published in [8,9].

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

$$n = 4(m/M - J_i(z)/e)/S v_0$$

where *G* is expenditure of a working substance through the thruster,

$J_i(z)$ - is the ion flow into channel,

S - is the thruster channel area,

v_0 - is the thermal velocity of atoms.

The atomic temperature has been assumed to be equal 400^0C.

An estimation of the j^{2+}- flow has been done for the PPS-1350 model for which the plasma parameter changes in the thruster channel are known[7] and for which the charged beam structure has been measured.

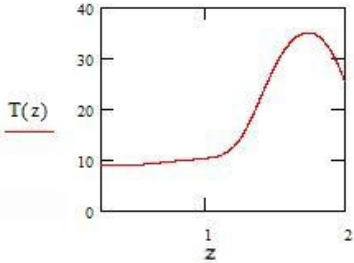The channel length for this model is 2cm, and the cross section area is 40cm^2.

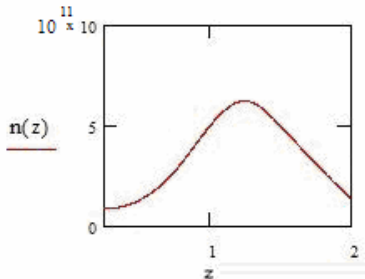**Figure 9. Distribution of the electron temperature along the channel. U_a=700V.**

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_a. The maximal electron temperatures are given in the row 2. Relative flows of the double-ionized ions produced from the main, J_1, and ion, J_2, exited, J_3, 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 mg/s.

Figure 10. Distribution of the electron density along a channel.

Table 4.

U_d. V	300	500	700
T_e	20	27	35
J_1/J_0	0.024	0.041	0.072
J_2/J_0	0.0048	0.0093	0.015
J_3/J_0	0.004	0.0075	0.0095
$(J_1+J_2)/J_0$	0.029	0.05	0.087
J^{2+}/J_0	0.033	0.058	0.096
J^{2+}/J (os. T_e)	0.052	0.1	0,12
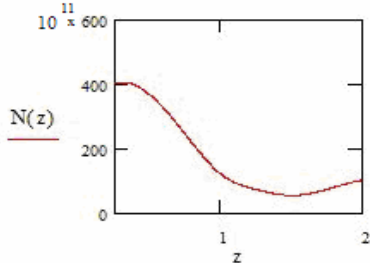
Figure 11. Distribution of the neutral atoms density along a channel.

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.
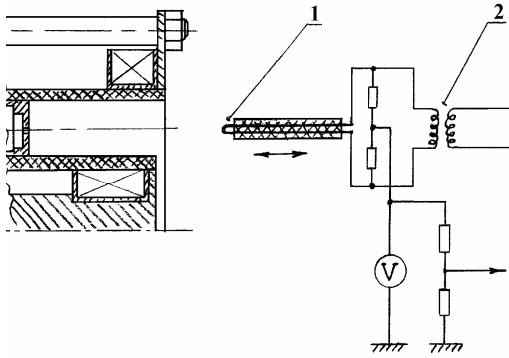
The Xe^{2+}-ions production from ion state at low discharge voltages, i.e. at low electron temperature is a few times greater than that of the Xe^{2+}-ions production from the main state. It is caused by a noticeable difference in the ionization thresholds for these two processes. It is evident that 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[10] 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.
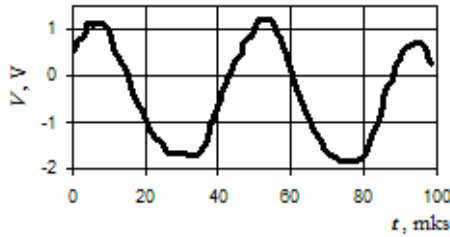
The temperature dependence on time may calculate by difference in amplitude of a oscillations the floating plasma potential producing by emissive (heat) V_h and cold probe V_c. Than the electron temperature is $T_e = e\cdot(V_h - V_c)/b$, here *b*~3–4.

Figure 12 shows a schematic of the probe construction. The emitting portion of the probe was a filament made 0.02mm- diameter tungsten wire. The ends of this filament were inserted down 150mm length of double bore alumina tubing along with cooper wire leads. The outer diameter tubing was 4mm. The length of the emissive filament was 3mm. A heat of the filament was performed by separating transformer. An oscilloscope for measuring the resulting floating
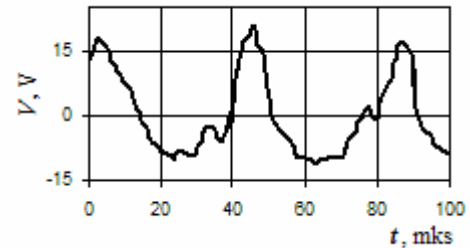
Figure 12. Schematic of the probe construction. 1 – probe, 2 – potential divider.

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[11]. From this the electron temperature oscillations measurements had been

Figure 13. Time evolution of the floating potential V_c.

Figure 14. Time evolution of the plasma potential V_h.

perform only outside thruster (0–4mm from exit).

For comparison with the temperature discharge voltage and current oscillations also has been investigative. The results which is represented under have been produce at U_a=200V, J_a=3A, 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=1.2–1.7V. 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.

$$j_i^{2+} = \frac{1}{T_0} \cdot \int_0^{T_0} \int_0^l (n_e(z,t) \cdot N(z) \cdot \langle \sigma_{02}^1 \cdot v_e(z,t) \rangle + n_e^2(z,t) \cdot \langle \sigma_{12}^1 \cdot v_e(z,t) \rangle + n_e(z,t) \cdot N^0(z) \cdot \langle \sigma_{02}^0 \cdot v_e(z,t) \rangle) dtdz$$

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=150–750V, 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 multy-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 $\pm 25^{\circ}$ angle range is charged insignificantly, within the range of a few percents.

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

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 Xe outgoing from thruster, by estimation, is equal to 6-12% of the total ion beam.

8. An analyses of the double-ionized Xe ions has been done the 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 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 Xe^{2+}-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

[1] Egorov V.V., Kim V., Mikheev S.Ju., Shkarban I.I., *Study of a charge structure in the CDEA beam.* In the book «Plasma Accelerators Physics and Engineering».MAI-edition, 1985.

[2] Vesselovzorov A.N., Svirsky E.B., *Charge-mass-energy analysis of the CDEA- particle flux.* Statements of the report from 6th All Union Conference on Plasma Accelerators and Ion Injectors. Dnepropetrovsk, State University, 1986, p.42.

[3] King L.B., Gallimore A.D., *Mass Spectral Measurements in the Plume of an SPT-100 Hall Thruster.* Journal of Propulsion and Power, Vol.16, №6, 2000, pp. 1086-1092.

[4] Morosov A.I., Bugrova A.I., Desyatskov A.V. and other, *Stationary Plasma Accelerator – the thruster ATON.* Plasma Physics, 1997, V. 23, № 7, pp. 635-645.

[5] Bugrova A.I., Lipatov A.S., Morozov A.I., Baranov C.V., *Effect of a ratio between the ions of various charge multiplicity upon the integral SPT-parameters, ATON-type.* Thesis's of reports to the XXXII. Zvenigorod Conference of Plasma Physics and on Controlled Fusion, 2005, p.228.

[6] Slobodenuk G.I., *Quadrupolar mass-spectrometers.* Moscow, Atomizdat, 1974.

[7] Kim V., Kozlov V., Skrylnikov A. etc. Mid-term report, project N 03-53-3358, p.43-45 Orleans May 4, 2005.

[8] Egger F., Mark T.D., Naturforsch Z., Teil. A33 1111 (1978).

[9] Physics of Ion – Ion and Electron – Ion Collisions edited by F. Prouillard and J.W. McGowan, p184, Moscow, Mir, 1986

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

[11] James M. Haas and Alec D. Gallimore. Physics of Plasmas, V.8, No.2 (2001).