Forecast of Erosion Rate of SPT K-0 Channel Insulators by Spectral Measurements

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Abstract: The channel insulators erosion of K-0 plasma source is estimated by the relative spectral measurements using the calibration curve plotted by the weight measurements.

Nomenclature

U_d	=	discharge voltage
$\dot{m}_{anode}$	=	anode mass flow rate
$\dot{m}$	=	mass flux of the given element
n_0	=	concentration of the neutral atoms of the given element at the source exit
M_B	=	boron atom mass
M_{Xe}	=	xenon atom mass
$< V >$	=	mean velocity of the sputtered particles
S	=	cross-section area of the source channel
n_e	=	electrons concentration
F	=	thrust generated by the source
T_e	=	electron temperature

I. Introduction

IN connection with the broad spectrum of the tasks for which plasma sources are used at present time and for which their using is planned in future, the problem of the sources life time and means of its increase is one of the

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most current importance. The weight measurements have been traditionally used for this purpose. However in this case we are obliged to resort to the source periodic cutoff. After that the unavoidable influence of the chamber vacuum components on its working surfaces in the hot state and of the air atmosphere - in the cold state - takes place. These processes may cause the disturbance of the source operation mode under its following switching on. In this connection the using of the optical measurements for this purpose is the most attractive. The value of such measurements has especially increased when the obtaining of the information about the mass loss of source channel ceramics under its operation during a few thousands hours without the contact with an atmosphere has been required. In the simplest case the photographing (through the bull's-eye in the vacuum chamber wall) of the source exit cross-section [1,2] has been carried out in the different time, and by this way the curves of the discharge chamber external and internal insulator width in time are obtained.

Bringing of the data of emission line intensities of the insulator components for the investigation of the source insulator erosion in the different modes of its operation seems to be convenient and perspective. The main component of ceramics intended for using in the sources of the given type (especially under its operation at high powers and at high discharge voltages) is boron nitride. Therefore using of the boron line radiation for the investigation of the source ceramics erosion seems to be the most perspective.

Ref. 3 has been devoted to the opportunity of using of the data on the intensity of boron atomic line BI with the wavelength λ=249.8nm, radiated at the exit of SPT of ATON type [4], for the investigation of the source insulators erosion. It has been obtained the line intensity increases proportionally with the discharge voltage under the same mass flow rate through the anode, and also it increases at the increase of the volume flow rate from 0.2cm^3/s up to 0.25cm^3/s under the same discharge voltage. However any quantitative data on the insulator mass loss are not represented in this work. And the question about the accordance of the data on the insulator mass loss, obtained by the spectral measurements, to those from the weight measurements remained the open one.

The radiation of the boron atoms BI with the wavelength λ=249.8nm has been registered by the authors in the earlier carried out spectral investigations of the plasma emission at the exit and in the channel of the given type sources [5].

However the calculation of the absolute values of the source channel insulator loss directly from the optical measurements involves large errors due to the error of the definition of line excitation function and electron distribution function.

In order to increase the reliability of the data on the source insulator erosion, obtained by the optical measurements it is more correctly to use the optical measurements for the calculation of the relative mass loss of the eroded substance in the different modes, and for the turning to the loss absolute values – to use direct weight measurements carried out in a few calibration modes.

Because of this, in the given paper the erosion of the source K-0 insulators is estimated by the relative spectral measurements relying on the calibration curve plotted by weight measurements. The advantage of this procedure is in the fact that it allows to carry out the proximate forecast (express-prediction) of the source life time in the different modes without carrying out of prolonged tests (30 and more hours) in every mode.

II. Experimental Statement and Main Assumption

SPT K-0 is developed in MIREA and designed for the low power (<300W) laboratory model [4, 6]. The required configuration of the magnetic filed is produced using two magnetic coils and six poles of the magnetic core. The source K-0 has the following overall dimensions: the diameter is equal to 85mm, the length is equal to 43mm. The length of the discharge chamber channel is equal to 15mm, the width of the gap between the internal and external insulators – 11mm. In this model the gas distributor and the anode are separated in space. The gas distributor is in the buffer volume with diameter 60mm. The internal diameter of the outer insulator is equal to 45mm. This model can operate both in stationary and in “machine-gun” mode with the pulse duration of several tens of milliseconds [7].

The investigations have been carried out for the source K-0 working in the stationary mode at the anode xenon mass flow rates $\dot{m}_{anode} = 0.7 mg/s$, $0.8 mg/s$, $0.9 mg/s$ and for the discharge voltages U_d=200V, 250V and 300V. The input power has been varied from 130W up to 240W.

The radiation of the source jet plasma, having passed through the quartz window in the vacuum chamber wall, has been focused by quartz condenser on the inlet slit of grating monochromator MDR-23 with the scanning of spectrum. The light signal at the exit of monochromator has been converted into the electrical one by photomultiplier, and then it has been converted into the digital one by ADC and has been recorded into the file on the computer.

In order to study the source K-0 insulators erosion by the spectral method, the radiation of the boron atom line BI with the wavelength λ=249.8nm (corresponding to the transition between the levels $2p^2\,P^0_{\frac{3}{2}}$ (0,00189 eV) - $3s^2S_{\frac{1}{2}}$ (4,964 eV)) has been registered at the source exit, in the jet for the different modes of the source operation in the input power from 130W up to 240W.

In order to plot the calibration curve there have been used the data of the weight measurements on the insulators mass loss of the model K-0, carried out in the stationary mode under the xenon anode mass flow rate $\dot{m}_{anode} = 0.8mg/s$ and for three discharge voltages U_d=200V, 250V and 300V (according values of the input power were equal to 140W, 175W and 210W).

The weight measurements have been carried out by the following procedure. Before the experiment realization the ceramics has been scrubbed by the abrasive paper and the weighing of the external and internal channels has been carried out separately with the help of the analytical balance (allowing to measure mass in the grams up to the forth significant digit after the comma). After this the model has operated during some hours under the same input parameters ($\dot{m}$, U_d). After completing the source operation in the given mode the channels have been weighed again, and the mass loss during the given interval of its operation time has been determined. The source K-0 had about 30 running hours for every mode.

In order to estimate the mass flux of the sputtered substance from the accelerator exit, in the first approximation, the following evident relationship may be suggested [8, 9]:

$$\dot{m} = n_0 \cdot M_B \cdot <V> \cdot S\,, \tag{1}$$

where n_o is the atom boron (or any other eroded element) concentration at the source exit, M_B is atom boron mass (or any other eroded element), $<V>$ is the mean velocity of the eroded substance atoms at the source exit, S is the cross-section area of the jet at the source exit (it is practically the cross-section area of its channel).

Under the conditions of an applicability of the coronal model to the plasma of the source [10], the boron atoms concentration n_o at the source exit is related to the spectral line intensity I_{mk}, emitted by its atoms under the transition from the level m to the level k, by the formula [11]:

$$I_{mk} = \frac{A_{mk}}{\gamma}\frac{hc}{\lambda_{mk}} n_e n_o < \sigma V_e >_{om}\,, \tag{2}$$

where n_e is electrons concentration, A_{mk} is the probability of the transition from the level m to the level k, $\gamma = \sum_{i<m} A_{mi}$ is a magnitude reciprocal to the life time τ of the level m, $<\sigma V_e>_{om}$ is the velocity-averaged cross-section of the excitation of the level m by the electron shock from the ground state.

In order to verify the applicability of the formulae (1) and (2) to the calculation of the relative mass loss of the source insulators in the different modes, using BI line radiation intensity, the relative mass loss of the source insulators has been calculated for those modes, in which the weight measurements have been carried out (i.e. under the anode mass flow rate $\dot{m}_{anode} = 0.8mg/s$ for three discharge voltages U_d=200V, 250V, 300V and input powers equal to 140W, 175W, 210W accordingly; the mass loss under input power 175W has been taken as a unit).

Using formulae (1) and (2) we obtain the ratio of the insulators mass losses $\dot{m}^{(I)}$ to $\dot{m}^{(II)}$ in the modes (I) and (II) accordingly:

$$\frac{\dot{m}^{(I)}}{\dot{m}^{(II)}} = \frac{I_{mk}^{(I)}}{I_{mk}^{(II)}} \cdot \frac{n_e^{(II)}}{n_e^{(I)}} \cdot \frac{<V^{(I)}>}{<V^{(II)}>} \cdot \frac{<\sigma V_e^{(II)}>}{<\sigma V_e^{(I)}>} \tag{3}$$

Let us consider the ratio of the boron atoms mean velocities at the accelerator exit in the modes (I) and (II) is equal to ratio of the plasma flow mean velocities [12] and has been calculated from the thrust measurements:

$$\frac{<V^{(I)}>}{<V^{(II)}>} = \frac{F^{(I)}}{F^{(II)}} \cdot \frac{\dot{m}_{Xe}^{(II)}}{\dot{m}_{Xe}^{(I)}}\,, \tag{4}$$

where $F^{(I)}$ and $F^{(II)}$ are the thrust values in the modes (I) and (II), $\dot{m}_{Xe}^{(I)}$ and $\dot{m}_{Xe}^{(II)}$ are the xenon mass flow rates through the source anode in the modes (I) and (II) accordingly.

The electron temperature values at the source exit needed for the determination of velocity-averaged cross-section of the excitation of the level by the electron shock, have been obtained with the help of electrostatic probes measurements at the source exit and have been equal to: T_e=6.3eV under mass flow rate $\dot{m}_{anode} = 0.8 mg/s$ and discharge voltage U_d=200V; T_e=7.3eV under $\dot{m}_{anode} = 0.8 mg/s$ and U_d=250V; T_e=8.4eV under $\dot{m}_{anode} = 0.8 mg/s$ and U_d=300V. The averaging has been carried out under the assumption of an applicability of Grysinski's formula [13] to the total cross-section of the shock excitation of the level $3s^2S_{\frac{1}{2}}$ (4,964 eV) of boron atom BI from the ground state and Maxwellian distribution function for electrons.

The mean electron concentration values in the calibration modes, obtained at the source exit by the probe measurements, agree within error limits with the ions concentration (and, by virtue of quasi-neutrality, with electrons density), calculated from the thrust measurements by formula:

$$< n_e > \approx < n_i > = \frac{(\dot{m}_{Xe})^2}{M_{Xe} \cdot F \cdot S} . \tag{5}$$

Therefore the relationship (5) has been used for the turning to the electrons densities in the modes, different from the calibration one and which integral parameters have been known.

III. Experimental Results and Their Discussion

The obtained array of the experimental values of the BI line (with λ=249.8nm) intensity at the source K-0 exit in the different modes of its operation is shown in the Fig.1. It is seen from the Fig.1 that, firstly, for all indicated values of mass flow rates the line intensity varies in proportional to the anode voltage; secondly, the inclination of linear dependence increases with the increase of the mass flow rate; and, thirdly, the intensity of BI line radiation increases with the increase of the mass flow rate under the given discharge voltage.

The values of the relative mass loss rate of the source insulators, obtained by the formulae (3), (4) using optical measurements (the measurement error was about 16% in this case) in the stationary mode of the source operation under the anode mass flow rate $\dot{m}_{anode} = 0.8 mg/s$ for input powers 140W, 175W, 210W, and also the calibration straight line, plotted for the same modes using weight measurements, are represented in the Fig.2. It is seen, that within limits of error we obtain concordant results, and, hence, one may use formulae (1) and (2) for the comparison of the source channel insulators erosion rate at the different modes of its operation.

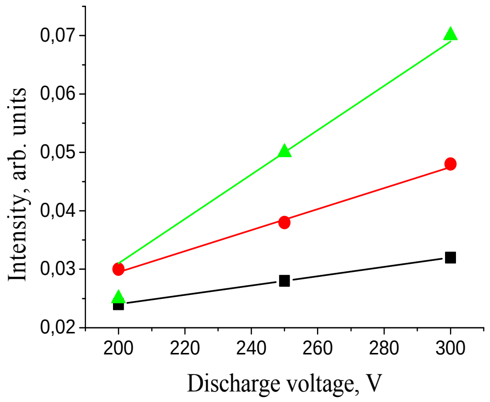

Figure 1. BI line (λ=249,8nm) intensity at K-0 exit in the different modes of its operation:
■ - $\dot{m}_{anode} = 0.7 mg/s$ **;**
● - $\dot{m}_{anode} = 0.8 mg/s$ **;** ▲ - $\dot{m}_{anode} = 0.9 mg/s$ **.**

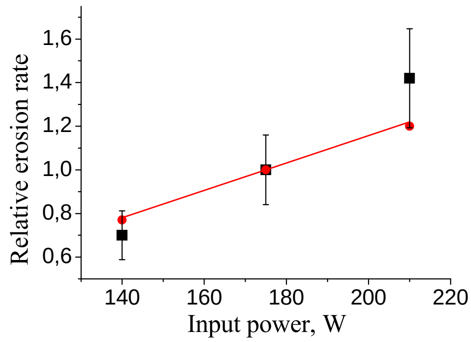

Figure 2. Relative erosion rate of model K-0 insulators as a function of input power under $\dot{m}_{anode} = 0.8 mg/s$ **:**
■ - **from optical measurements;**
● - **from weight measurements.**

The obtained by spectral measurements dependency of the erosion rate of the source K-0 insulators from the input power is represented in the Fig.3. It is seen from the figure the source insulators erosion rate varies within error limits in proportional to the input power.

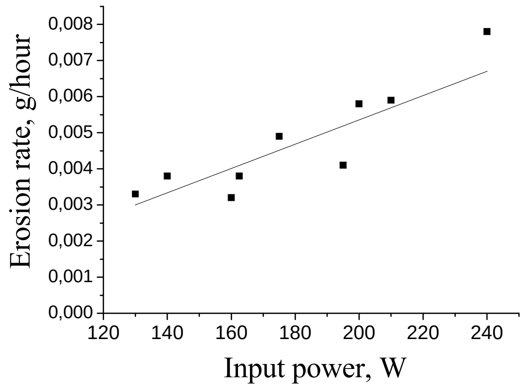

Figure 3. Model K-0 insulators erosion rate as a function of input power.

Let us, using the experimental data on the mass loss of source channel ceramics, estimate K-0 life time under the continuous operation of the accelerator in the stationary mode and under the width of the walls of the external and internal insulators equal to 3mm.The mean mass losses of the external $\dot{m}_{ext}$ and internal $\dot{m}_{\mathrm{int}}$ insulators of K-0 channel obtained by the weight measurements under $\dot{m}_{anode} = 0.8mg/s$ and for three discharge voltages U_d=200V, 250V, 300V are represented in the Table 1.

Table 1

$\dot{m}_{anode}, mg/s$	0.8	0.8	0.8
U_d , V	200	250	300
$\dot{m}_{ext}, g/hour$	0.0014	0.0019	0.0023
$\dot{m}_{\mathrm{int}}, g/hour$	0.0024	0.0030	0.0036

It is known from the literature [14, 15, 16] during a few hundreds of hours (~500hours) the radial erosion increases in time by the linear law, then the erosion rate decreases. This follows, in particular, from the data on life time tests of the model SPT-100. Basing on experimental data, there is proposed the logarithmic dependence of the forecasted radial erosion in Ref. 15:

$$\Delta r = A \cdot \ln(1 + \beta t), \tag{6}$$

for the radial erosion rate we have:

$$\Delta \dot{r} = A\beta / (1 + \beta t), \tag{7}$$

where A and β are the empirical coefficients chosen so in order that experimental points optimally correspond to this curve. For some modifications of SPT-100 these coefficients are equal to: for the external channel insulator A=4.656mm, β=0.00219 hour $^{-1}$; for the internal channel insulator A=3.912mm, β=0.00234 hour $^{-1}$.

Let us use the approximation (6) for the forecast of K-0 lifetime. For small values of time t (0≤t≤500) formula (6) takes the form:

$$\Delta r = A \cdot \beta \cdot t \tag{8}$$

On the other hand, the calculation of the volume loss of the outer and inner insulators of K-0 channel gives the next equations for their radial erosion for these times (0≤t≤500):

$$\Delta r_{ext} = \frac{\dot{m}_{ext} \cdot t}{\pi \rho l_{ext} r_{ext}} \tag{9}$$

$$\Delta r_{\mathrm{int}} = \frac{\dot{m}_{\mathrm{int}} \cdot t}{\pi \rho l_{\mathrm{int}} R_{\mathrm{int}}} \tag{10}$$

Here ρ is the ceramics density, r_{ext} – the internal radius of the external insulator before the start of model K-0 operation, R_{int} - – the external radius of the internal insulator before the start of model K-0 operation, l_{ext} and l_{int} is the length of the erosion zone ("erosion belt") of the external insulator and internal insulator accordingly. The values of these parameters for K-0 operation mode $\dot{m}_{anode} = 0.8mg/s$, U_d=250V are represented in the Table 2.

Table 2

r_{ext} , mm	$\dot{m}_{ext}, g/hour$	l_{ext} , mm	R_{int} , mm	$\dot{m}_{\mathrm{int}}, g/hour$	l_{int} , mm	ρ, 10^{-3} g/mm^3
22.5	$1.9 \cdot 10^{-3}$	4.5	11.5	$3 \cdot 10^{-3}$	10	2.2

In accordance with the data of the Table 2 the formulae (9) and (10) for this K-0 operation mode take the form:

$$\Delta r_{ext} = 0.0027 \cdot t, mm \tag{11}$$

$$\Delta r_{\mathrm{int}} = 0.0038 \cdot t, mm \tag{12}$$

Assuming K-0 model erosion rate under the times t > 500 hours decreases by the same way as SPT-100 erosion rate we obtain empirical formulae for the radial erosion and the radial erosion rate of the external and the internal insulators of K-0 model channel for this operation mode:

$$\Delta r_{ext} = 1.233 \cdot \ln(1 + 0.00219t) \tag{13}$$

$$\Delta \dot{r}_{ext} = \frac{0.0027}{1 + 0.00219 \cdot t} \tag{14}$$

$$\Delta r_{\text{int}} = 1.620 \cdot \ln(1 + 0.00234t) \tag{15}$$

$$\Delta \dot{r}_{\text{int}} = \frac{0.0038}{1 + 0.00234 \cdot t} \tag{16}$$

Using formulae (13) and (15) we obtain the times t_{ext} and t_{int}, under which the radial erosion of the external and internal channel is equal to 3mm, i.e. to the width of the ceramics. For this mode of K-0 their values are equal to: $t_{ext} \approx 4700 hours$ and $t_{\text{int}} \approx 2300 hours$. These values of K-0 lifetime are in agreement with the value of SPT-50 lifetime, which is equal to 2250 hours.

Using data of insulators mass erosion rate obtained by spectral measurements for all K-0 operation modes listed above, the mean mass losses of the external $\dot{m}_{ext}$ and internal $\dot{m}_{\text{int}}$ insulators of K-0 channel per hour have been calculated (assuming the external and internal mass losses are in the same ratio as for calibration curve). Then using formulae analogous to (13) and (15) with the empirical coefficients A and β taken for the listed above operation modes, the time of K-0 continuous operation during which the radial erosion at the source exit is equal to 3mm for the external t_{ext} and internal t_{int} insulator has been calculated. The results of these calculations are given in the Table 3.

Table 1

$\dot{m}_{anode}, mg/s$	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9
U_d , V	200	250	300	200	250	300	200	250	300
$\dot{m}_{ext}, g/hour$	0.0012	0.0015	0.0016	0.0014	0.0019	0.0023	0.0012	0.0023	0.0031
$\dot{m}_{\text{int}}, g/hour$	0.0021	0.0023	0.0025	0.0024	0.0030	0.0036	0.0020	0.0035	0.0047
t_{ext} , hours	21000	9500	7800	12000	4700	2900	21000	2900	1600
t_{int} , hours	5600	4400	3500	3900	2300	1600	6400	1700	1000

IV. Conclusion

The proposed method of the calculation of the relative mass loss of the source K-0 channel insulators at its different operation modes by the radiation intensity of the boron line BI with the wavelength λ=249.8nm has been successfully verified by the weight measurements.

It has been obtained the source insulators erosion rate varies within error limits in proportional to the input power.

With the help of the spectral measurements there has been obtained the forecast of the erosion rate of the source K-0 channel insulators for six not investigated in erosion modes.

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References

[1] Brophy, J.R., Garner, C.E., Polk, J.E., et.al. "Performance Evaluation and Life Testing of the SPT-100". *Proceedings of 23rd International Electric Propulsion Conference, 13-16 September, 1993, Seattle, USA,* IEPC-93-091.

[2] Cornu, N., Darnon, F., and Estublier, D. "The PPS®-1350 qualification demonstration 7500h on ground, about 5000h in flight". *Proceedings of 29th International Electric Propulsion Conference, October 31 – November 4, 2005, Princeton University, USA,* IEPC-2005-209.
[3] Minea, T., Bretagne, J., Magne, L., et al. "Spectroscopic Evidence of the Ceramic Erosion in a Stationary Plasma Thruster". *Proceedings of. 2nd European Spacecraft Propulsion Conference, 27-29 May 1997, Noordwijk,* ESA SP-**398**, 259.
[4] Morozov, A.I., Bugrova, A.I., Desyatskov, A.V., et. al. "ATON-Thruster Plasma Accelerator". *Plasma Physics Reports*, Vol.23, No. 7, 1997, pp. 587-597.
[5] Bishaev, A.M., Bugrova, A.I., Desyatskov, A.V., and Kozintseva, M.V. "Radiation Characteristics of the ATON Plasma Thruster". *Proceedings of SPIE,* vol.4187, pp. 79-83.
[6] Bugrova, A.I., Lipatov, A.S., Morozov, A.I., Baranov, S.V., and Daren, Y. "SPT operation in "Machine-gun" mode". *Proceedings of 29th International Electric Propulsion Conference, October 31 – November 4, 2005, Princeton University, USA,* IEPC-2005-161.
[7] Lipatov, A.S., A.I., Desyatskov, A.V., Bugrov, G.E. and Kozintseva, M.V. «Integral Parameters of ATON Stationary Plasma Thruster of Low-Power in Stationary and "Machine-gun" Modes». *Kosmonautika i Raketostroenie*, No. 3(52), 2008, pp. 69-74 *(in Russian)*.
[8] Isaev, Y. A., Oranskii, A.I., and Titov, A.A. "Investigation of the hole cathodes erosion by the optical spectroscopy method". *Scientific and Technical Collected Articles "Rocket and Space engineering",* No.3 (131), 1991, pp. 170-175 *(in Russian)*.
[9] Brain, A. Rock, Maris, A. Mantenieks, and Michael, L. Parsons "Rapid Evaluation of Ion Thruster Lifetime Using Optical Emission Spectroscopy". *AIAA Paper,* 1985, N2011.
[10] Bugrova, A.I., Ermolenko, V.A., and Sokolov, A.S., «Optical Investigations of the Neutral Component of Xenon Plasma in Nonequilibrium Conditions». *Teplophysika vysokich temperatur*, Vol.25, No. 6, 1987, pp. 1080-1086 *(in Russian)*.
[11] Haddlstone, R.H., and Leonard, S.L., *Plasma diagnostic techniques* Academic Press, New York-London,1965.
[12] Czanderna, A. W. (ed.), *Methods of Surface Analysis,* Vol.1, New York, 1975.
[13] Grysinski , M. *Phys. Rev.,* Vol.138, No.2A, 1965, p.353.
[14] Morozov, A. I., *Introduction into Plasmadynamics,* Fizmatlit, Moscow, 2006 (in Russian).
[15] Baraniv, V., Petrosov, V., et al. "Prediction of Electric Thrusters Lifetime". *Proceedings of 23th International Electric Propulsion Conference, 1993, Seattle, Washington, USA,* IEPC-93-099.
[16] Yim, J.T., Keidar, M., Boyd, D. "A Hydrodynamic-Based Erosion Model for Hall Thrusters". *Proceedings of 29th International Electric Propulsion Conference, October 31 – November 4, 2005, Princeton University, USA,* IEPC-2005-013.