Spectral Investigation of SPT MAG Insulator Erosion

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Abstract: The opportunity of using the optical spectroscopy for the determination of the rate of the entrainment of the insulators material of the source of SPT type, operating on Xe, is investigated. The estimation of the total mass flux of the insulator, carried away from the exit of the source MAG-A2, has been obtained. Therewith with the increase of the discharge voltage, starting from approximately U_d=300V, the decrease of the channel erosion rate is observed.

Nomenclature

$\dot{m}$	=	mass flux of the given element
n_0	=	concentration of the neutral atoms of the given element at the source exit
m_{atom}	=	atom mass of the given element
$< V >$	=	mean velocity of the sputtered particles
S	=	cross-section area of the source channel
n_e	=	electrons concentration
U_d	=	discharge voltage
I_d	=	discharge current
$\dot{m}_{anode}$	=	anode mass flow rate
$\dot{m}_{cathode}$	=	cathode mass flow rate

I. Main Assumptions and Experiment Statement

The lifetime of Hall effect thrusters is one of its most important characteristic, which strongly depends on discharge chamber insulators erosion rate.

In order to estimate the mass flux of the sputtered substance from the source exit, in the first approximation, the following relationship has been used:

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

The mean velocity of the plasma flow at the exit of the source accelerating channel has been used as the mean velocity $< V >$.

The magnitude of the neutral atoms concentration has been determined using the absolute intensities of lines, radiated by the particles at the source exit. The absolute intensities of spectral lines have been experimentally determined by the standard procedure, which uses the calibration with reference source[1].

The suitability of the crown model to the source plasma has been validated in Refs. [2,3], which are devoted to the investigation of the radiation from the channel of the source and from its jet. It has been shown there, that under the conditions of its operation one may consider plasma as the optically thin one for nonresonance lines. Then the intensity of the spectral line I_{mk}, emitted by the transition from the level m to the level k, is written in the form:

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

where n_e, n_o are concentrations of electrons and atoms in the ground state; A_{mk} is the probability of the transition from the level m to the level k, $\gamma = \sum_{i<m} A_{mi}$ is reciprocal of 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.

The values of the electron temperature and density, needed for the determination of the concentration of the insulator atoms, have been obtained with the help of electrostatic probes, located in the investigated field of the source plasma[4,5].

The experiments on the investigation of the spectrum of the plasma radiation from the exit of the source MAG-A2[4,5] have been carried out at the diffusive stand in the nominal operation mode of the source: the mass flow rate through the anode has been equal to $\dot{m}_{anode} = 2.0 mg/s$; the mass flow rate through the cathode has been equal to $\dot{m}_{cathode} = 0.4 mg/s$; the discharge voltage - $U_d=350V$; the discharge current - $I_d=1.95A$. Xenon has been used as the propellant.

The radiation of plasma of the source jet, having passed through the quartz window in the vacuum chamber wall, has been focused by quartz condenser on the inlet slit of 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 written into the file on the computer. The tungsten ribbon lamp SIRSH 8,5-200-1 with an uviol inlet window has been used as a reference source in order to transfer to absolute intensities.

The experimentally obtained spectral band has covered (0,2÷0,8)mcm. The intensive line of boron atom BI with $\lambda=2497,7\,\mathring{A}$, corresponding to the transition between the levels $2p^2\,P^0_{\frac{3}{2}}$ (0,00189 eV) - $3s^2 S_{\frac{1}{2}}$ (4,964 eV), has been reliably fixed in identifying spectra, obtained from the exit of MAG-A2.

The calculation of the total cross-section of the excitation of the level $3s^2 S_{\frac{1}{2}}$ (4,964 eV) by the electron shock from the ground state has been carried out by Grysinski's formula[6].

By the data of the probe measurements the mean electrons temperature at the exit of the source MAG-A2 for the given mode is $T_e \sim 9eV$, and the mean electrons density in the same cross-section is $n_e \sim 14,4 \cdot 10^{11} cm^{-3}$.

II. Experimental Results and Their Discussion

A.

For the given above electrons parameters we obtain, that at the exit of the source MAG-A2, operating on the xenon in the nominal mode ($\dot{m}_{anode} = 2.0 mg/s$; $\dot{m}_{cathode} = 0.4 mg/s$; U_d=350V; I_d=1.95A), the flux of boron atoms is at the level $1{,}83 \cdot 10^{-8}$ g/s. However the boron mass part in the used ceramics is about 20%. Then the total flux of the insulator mass, carried away from the source exit, may be estimated as $\sim 1 \cdot 10^{-7}$ g/s.

According to the data Ref.7 the volume entrainment of insulators of SPT-100, starting from the values $6{,}5 \cdot 10^{-3}$ mm^3/s at the beginning of the tests, decreases by an order onto the values $7{,}0 \cdot 10^{-4}$ mm^3/s after 3500 hours of operation, that corresponds to the mass entrainment $1{,}3 \cdot 10^{-5}$ g/s at the start of the tests and $1{,}4 \cdot 10^{-6}$ g/s – after 3500 hours of operation (the density of the ceramics is considered equal to $2 g/cm^3$). Thus the erosion rate of insulators of the source MAG-A2 is significantly below the minimal one for the classic type of the source[††].

B.

We obtain from Eq.(2), that the ratio of the concentrations of boron neutral atoms at the source exit for two different modes (n_{01}^B и n_{02}^B, accordingly) is related to the lines intensities for these modes by the relationship:

$$\frac{n_{01}^B}{n_{02}^B} = \frac{I_1^B}{I_2^B} \cdot \frac{n_{e2}}{n_{e1}} \tag{3}$$

in the assumption, that $< \sigma V_e >_{om}$ at the source exit weakly varies for the given modes.

At the first approximation one may take the ratio of the electrons concentrations as the ratio of the mass discharge currents. Then, under the assumption, that the incident angle of the flow onto the insulator surface is the same, we obtain from Eqs.(1) and (3), that the ratio of fluxes of sputtered substance mass from the source exit in the different modes ($\dot{m}_1$ и $\dot{m}_2$, accordingly)may be considered equal to:

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{n_{01}^B}{n_{02}^B} \cdot \sqrt{\frac{U_{d1}}{U_{d2}}} = \frac{I_1^B}{I_2^B} \cdot \frac{n_{e2}}{n_{e1}} \cdot \sqrt{\frac{U_{d1}}{U_{d2}}}, \tag{4}$$

where U_{d1} and U_{d2} are the accelerating voltages for modes 1 and 2.

Therefore measurements of the line intensity of boron neutral atom BI ($\lambda = 2497{,}7\ \mathring{A}$) have been carried out under different discharge voltages and the mass flow rates through the source anode, and also the temporary dependencies of the intensity of this line have been obtained in the process of the source reaching the stationary heat operation mode.

The dependence of the insulator erosion rate from the discharge voltage under the constant mass flow rate through the source anode $\dot{m}_{anode} = 2.0 mg/s$ and the cathode $\dot{m}_{cathode} = 0.4 mg/s$ and under the invariable currents in magnetic coils of the source is shown on figure 1. The measurements in every point have been carried out under the source reaches the steady heat mode. The erosion rate in the nominal mode has been taken as the unit. It is seen from the figure 1, that with the increase of the discharge voltage, starting from U_d=300V, the decrease of the erosion rate of the source MAG-A2 channel ceramics is observed. Whereas according to the data Ref.7 for the classical sources M-100, this dependence is close to the linear one at this band of discharge voltages.

Analogous measurements have been carried out under the constant total discharge voltage U_d=350V and two different mass flow rates through the source anode: 2mg/s and 2,5mg/s. It has been obtained, that after the source reaches the steady heat mode, BI line intensity has been varied in directly proportion to the mass discharge

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[††] However it must be taken into account, that the values of the atom boron concentrations, obtained from the optical measurements, may be some undervalued due to the influence of reabsorption, which always takes place for resonance lines.

current. It means, that in the given case the increase of the anode mass flow rate, in the first approximation, has not result in the increase of the source channel insulators erosion.

The behavior in time of the relative intensity of the line BI (λ=2497,7 $\mathring{A}$), obtained during the operation of the source MAG-A2 in the mode: $\dot{m}_{anode} = 2.5 mg/s$; $\dot{m}_{cathode} = 0.4 mg/s$; U_d=350V, is represented on the figure 2 (the intensity of this line, after the source reaching the stationary heat mode, is taken to be 100%). The moment of the start of the source operation in this mode is taken as the zero moment of time, therewith the source has started in the cold state. For comparison the curve of variation in time of the source discharge current is represented on the same figure.

It is seen from the figure 2, that at first time the intensity reaches the value, close to the stationary one, in ~10 minutes after the start of the source operation, i.e. to the moment, when the discharge current obtains the steady magnitude. Finally the absolute intensity reaches the steady value approximately in 70 minutes after the source start. As the measurements of the heat fluxes have shown, just to this moment the heat regime of the source internal channel reaches the stationary one and, some later, whole source reaches steady heat mode.

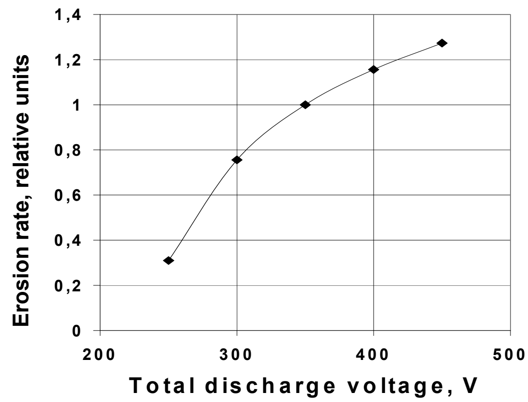

Figure 1. Dependence of the insulator erosion rate from the discharge voltage under the constant mass flow rate through the source anode $\dot{m}_{anode} = 2.0 mg/s$ and the cathode $\dot{m}_{cathode} = 0.4 mg/s$.

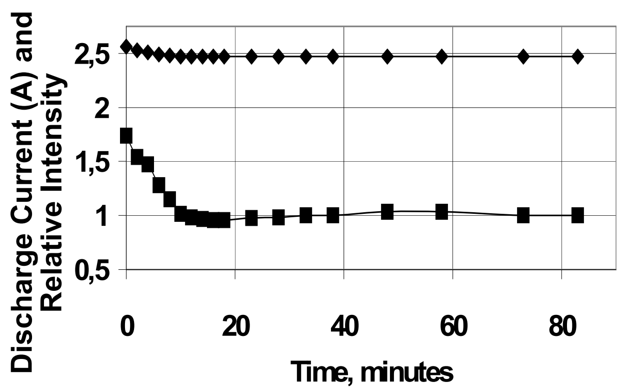

Figure 2. Discharge current (rhombus) and line BI relative intensity (squares) as a function of time under $\dot{m}_{anode} = 2.5 mg/s$; $\dot{m}_{cathode} = 0.4 mg/s$; U_d=350V.

III. Conclusion

Thus the spectral lines of the radiation of elements, which are in the source channel ceramics composition, may be used for the estimation of the insulators substance entrainment and also allowed to follow the variation of the erosion processes in time, not interrupting the source tests[8].

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References

[1] Haddlstone, R.H., and Leonard, S.L., *Plasma diagnostic techniques* Academic Press, New York-London ,1965.

[2] Bugrova, A.I., Danelia, I.A., Ermolenko, V.A., and Kalihman, L.E., «Determination of electron temperature of plasma jet of accelerator with closed drift of electrons (ACDE)», *Jornal tehnicheskoy phiziki,* Vol.47, No. 11, 1977, pp. 2310,2312.

[3] Bugrova, A.I., Ermolenko, V.A., and Sokolov, A.S., «Volume distribution of radiation energy of ACDE xenon plasma jet», *Teplophysika vysokich temperatur*, Vol.17, No. 3, 1979, pp. 642,644.

[4] Morozov, A.I., Bugrova, A.I., Desyatskov, A.V., Kharchevnikov, V.K., Priol, M., Jolivet, L., “Study of Two-Stage Thruster on the Base of SPT-MAG”, *Proceedings of 28th International Electric Propulsion Conference, 17-21 March 2003, Toulouse, France,* IEPC-290-03.

[5] Bugrova, A.I., Morozov, A.I., Desyatskov, A.V., Kharchevnikov, V.K., Priol, M., ”Investigation of physical processes in SPT MAG”, *Proceedings of 29th International Electric Propulsion Conference, October 31-November 4, 2005, Prinston University, USA,* IEPC –2005-146.

[6] Grysinski , M. *Phys. Rev.,* Vol.138, No.2A, 1965, p.353.

[7] Maslennikov, N.A., “Lifetime of the stationary plasma thruster”, *Proceedings of International Conference “Spacecraft Propulsion”, 8-10 Nov. 1994y.*

[8] Pagnon, D.,et al., “Control of the Ceramic Erosion by Optical Emission Spectroscopy” , *AIAA-2004.*