

# Investigation of Discharge Power Influence on Erosion Rate of SPT Discharge Chamber using Spectroscopic Method

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**Abstract:** Discharge power influence on erosion rate of a SPT with nominal power 1.6 kW using spectroscopic method was investigated. Erosion rate measurements were carried out in three different experiments at constant discharge voltage 550 V. Variation of operational mode was realized by variation of xenon flow rate in all experiments. In third experiment magnetic field optimization by spectral line intensity of sputtered boron atoms was carried out. It is shown that erosion rate values in experiment with optimized configuration of magnetic field are significantly lower than appropriate values in other two experiments. Moreover as obtained data show at optimal configuration of magnetic field erosion rate changes insignificantly as anode flow rate increases.

## Nomenclature

$I_R$	=	spectral line intensity of radiating particles
$n_e$	=	electron density
$n_R$	=	radiating particles density
$n_{Xe}$	=	xenon atoms density
$n_B$	=	boron atoms density
$Q_{Xe}$	=	excitation rate coefficient for xenon atoms
$Q_B$	=	excitation rate coefficient for boron atoms
$f_e$	=	distribution function of electrons
$C$	=	constant that characterizes transitions probabilities in given atom
$dl$	=	length step
$I_{Xe}$	=	xenon spectral line intensity
$I_B$	=	boron spectral line intensity
$\eta_a$	=	anode efficiency
$N_d$	=	discharge power
$\alpha$	=	propellant utilization coefficient
$\beta$	=	ratio of beam current to discharge current
$\alpha$	=	propellant utilization coefficient
$\gamma$	=	thrust losses due to angle and energy distribution of particles
$p$	=	fraction of double charged ions
$\dot{m}_a$	=	anode mass flow rate
$M_{Xe}$	=	xenon ion mass
$U_d$	=	discharge voltage
$I_d$	=	discharge current
$R$	=	thrust

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$I_{int}$  = current in internal magnetic coil  
 $I_{ext}$  = current in external magnetic coil

## I. Introduction

At present the central tendencies of space craft development are increasing of spacecraft operational lifetime, specific payload mass and enlarging of power availability that in turn lead to need of creating of thrusters with high specific impulse as well as multipurpose thrusters that can variate operation mode in wide range.

Increasing of specific impulse of SPT leads to increasing of discharge voltage. Enlarging of  $I_{sp}$  in turn leads to higher erosion of discharge chamber walls of SPT and as a result decreasing of lifetime.

Erosion rate depends on many parameters: magnetic and electric field topology, geometry of discharge channel, operating mode, temperature of sputtering area, electron temperature, etc. Creating of model that can adequately describe process of sputtering becomes complicated because of variety of processes in discharge chamber of thruster that should be taken into account. In consideration of this fact experimental methods are used to determine erosion rate.

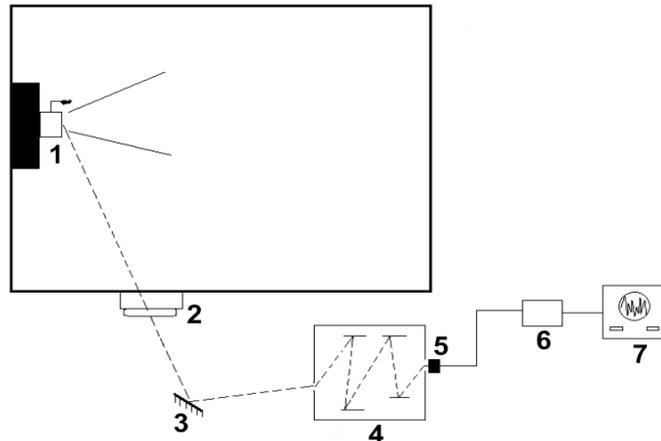
Continuous lifetime test is the most reliable instrument of lifetime characteristics determination. However such tests require great amount of time and finances that significantly increase the cost of thruster development. One of the methods that allows considerably reducing duration of lifetime tests at stage of thruster development and monitoring erosion rate variations during lifetest in real-time operation is a spectroscopic method of erosion rate determination. This method is not invasive and based on investigation of spectral line intensities of propellant and sputtered element.<sup>1</sup>

## II. Experimental Apparatus

For carrying out of experiments SPT with nominal power 1600 W was used. The thruster has a hybrid scheme of discharge chamber, consisting of metallic anode chamber and dielectric rings on the exit of the channel. The average diameter of discharge chamber equals to 85 mm. Ceramic insulators made of BGP has been used in given experiments. A hollow cathode with lanthanum hexaboride emitter was used as a cathode-compensator.

Spectroscopic measurements were carried out using MDR-23 monochromator equipped with photomultiplier tube (PMT) Hamamatsu R928. The one meter focal length quartz lens placed next to the quartz port was used to get picture of the thruster. Aluminium optic mirror was used to place the picture of thruster on the entrance slit of monochromator. After that the signal was amplified and registered on oscillograph. The arrangement of experimental setup is shown in Fig.1.

The investigations were conducted on Cryogenic Vacuum Test Facility CVF-90 of Keldysh Research Centre. The vacuum chamber has volume of 90 m<sup>3</sup> at diameter of 3.8 m and a high-productivity system of a cryogenic pumping which allows to achieve a high level vacuum (residual pressure in chamber is of the order of 10<sup>-6</sup> torr). Total productivity of a cryogenic pumping is equal to 69 m<sup>3</sup>/s. The CVF-90 is equipped with three windows, two of which are the side ports. One of the side ports made of quartz was used for spectroscopic investigations. It allowed carrying out measurements in a short-wave range of spectrum.



**Figure 1. Experimental setup: 1 – thruster, 2 – quartz side port, 3 – aluminium mirror, 4 – monochromator, 5 – photomultiplier, 6 – amplifier, 7 – oscilloscope.**

## III. Investigation of Erosion Rate Regularity in Throttling Modes

Throttling that is variation of thrust due to variation of propellant flow rate at constant discharge voltage allows to variate power and thrust of SPT in wide range. Thruster operation in throttling modes can significantly increase flexibility of system, for example at variation of power supply parameters of propulsion system.

Spectroscopic investigation of erosion rate tendency in throttling modes of operation is based on spectral line intensities measurements in every mode. Line intensity correlates with radiating particles density by Corona Type Model (CTM) interpretation<sup>2</sup> as follow:

$$I_R = C_R \int_0^{l_0} n_e n_R Q_R(f_e) dl \quad (1)$$

where  $n_e$  and  $n_R$  are electron and radiating particles densities respectively,  $Q_R = \langle \sigma_{ex} \nu_e \rangle$  is an excitation rate coefficient – a product of effective excitation cross-section from ground state and electron intensity averaged assuming Maxwellian distribution function  $f_e$ ,  $l_0$  is a path integration length along direction  $l$ ,  $C_R$  is a constant that characterizes transitions probabilities in given atom. Thereby we can find the expression for sputtered material concentration using Eq.(1) on the assumption that neutrals concentration and electron temperature changes insignificantly along integration path:

$$n_B \propto n_{Xe} \frac{I_B}{I_{Xe}} \left( \frac{Q_{Xe}(f_e) + Q'_{Xe}(U_d) + \frac{p}{\sqrt{2}} Q''_{Xe}(U_d)}{Q_B(f_e)} \right) \quad (2)$$

where  $n_B, I_B$  and  $n_{Xe}, I_{Xe}$  are intensities and concentrations of boron and xenon atoms respectively,  $Q_{Xe}, Q'_{Xe}, Q''_{Xe}$  are excitation rate coefficients of boron atoms by electrons, single and double charged ions respectively,  $Q_B$  is a rate coefficient of boron atoms by electron impact,  $p$  is a fraction of double charged ions,  $U_d$  is a discharge voltage,  $f_e$  is a velocity distribution function. Thereby to determine sputtered boron density as well as erosion rate, concentration of neutral Xe and electron temperature in region of observation are needed.

#### A. Electron temperature determination. Calculation of Rate Coefficients Variation.

Electron temperature was determined by «optical thermometer» method using two xenon lines 828.01 and 834.68 nm intensities ratio.<sup>3</sup> Formula for intensities ratio is written as:

$$\frac{I_{Xe828}}{I_{Xe834}} = C \frac{Q_{Xe828}(f_e) + Q'_{Xe828}(U_d) + \frac{p}{\sqrt{2}} Q''_{Xe828}(U_d)}{Q_{Xe834}(f_e) + Q'_{Xe834}(U_d) + \frac{p}{\sqrt{2}} Q''_{Xe834}(U_d)} \quad (3)$$

where  $C = \frac{C_{Xe828}}{C_{Xe834}}$  - is a constant that does not depend on external experimental conditions. It is assumed to be a Maxwellian velocity distribution function for electrons. Rate coefficients data for xenon are available in literature.<sup>4</sup>

#### B. Determination of Xenon Atoms Density in Region of Observation.

Xenon concentration in SPT channel depends on propellant flow rate, channel geometry and walls temperature. Xenon neutrals concentration is determined as a sum of gas concentrations due to gas streaming from thruster and residual gas in vacuum chamber. In given paper concentration of xenon neutrals proceeding from the thruster was calculated by the program «GASEL».<sup>5</sup> Concentration was calculated without taking into account of ionization. The ionization is taken into account after the propellant utilization coefficient is measured –  $\alpha = \frac{\dot{m}_i}{\dot{m}_a}$  - a ratio of ions number escaping discharge chamber to the total number of atoms entering the anode in unit of time.

The method developed at Keldysh Research Centre was used to determine the propellant utilization coefficient.<sup>6</sup> The given method is based on SPT plume diagnostics through the use of retarding potential probe and measurements of the anode efficiency  $\eta_a$  and discharge power  $N_d$ . Expressions for  $\eta_a$  and  $N_d$  have the appropriate forms:

$$\eta_a = \alpha\beta\gamma^2 \frac{[1+(\sqrt{2}-1)p]^2}{1+p} \quad (4)$$

$$N_d = \frac{\alpha}{\beta}(1+p) \frac{e}{M_{Xe}} \dot{m}_a U_d \quad (5)$$

where  $\beta$  is a ratio of the beam current to the discharge current,  $\gamma^2$  is a coefficient which is responsible for the thrust losses due to the angle and energy distribution of particles,  $M_{Xe}$  is a xenon atomic mass. Ions energy spectra measurements in the plume at different angles from the thruster through the use of retarding potential probe allow to determine coefficients magnitudes. The fraction of double charged ions depends on the electron temperature which is in turn defined by the discharge voltage.<sup>7</sup>

Concentration of xenon neutrals escaping the thruster with taking into account of ionization is defined as:

$$n_{Xe} \propto n_{Xe}^{calc}(1-\alpha) \quad (6)$$

It was shown in Ref.8 that concentration of xenon neutrals escaping the thruster is of the order of gas density generated due to charge-exchange of xenon ions on the chamber walls. Therefore in order to determine the total neutrals density it is necessary to take into account a pressure in the vacuum chamber. With a glance of charge-exchange xenon concentration in the region of observation is defined as:

$$n_{Xe} \propto n_{Xe}^{calc}(1-\alpha) + n_{Xe}^{meas} \quad (7)$$

where  $n_{Xe}^{meas}$  is a xenon concentration in the vacuum chamber during the thruster performance.

The total expression for relative erosion rate determination is written as [8]:

$$S \propto k(U_d)(n_{Xe}^{calc}(1-\alpha) + n_{Xe}^{meas}) \left( \frac{Q_{Xe}(f_e) + Q'_{Xe}(U_d) + \frac{p}{\sqrt{2}} Q''_{Xe}(U_d)}{Q_B(f_e)} \right) \frac{I_B}{I_{Xe}} \quad (7)$$

where  $k(U_d)$  is a coefficient which responses for the velocity and composition variation of sputtered boron atoms owing to discharge voltage variation. In order to determine this coefficient many calibration experiments during the lifetime tests and comparing with the results of spectroscopic measurements are required. Further data acquisition is required to carry out the experiments with high accuracy. Therefore in given paper spectroscopic method of erosion rate determination is applied with a constant discharge voltage. All parameters values will be presented in arbitrary units.

#### IV. Experiment Program

Intensities of atomic boron and xenon emission lines have been measured in three various experiments for the purpose to identify general correlation and verification of experimental data. Intensities have been measured in various operation modes in each experiment.

Variation of operational mode was realized by variation of xenon flow rate in first two experiments. Discharge voltage  $U_d$  was equal to 550 V. Currents in internal  $I_{int}$  and external  $I_{ext}$  magnetic coils were invariable and equal to 1.8 A. Performance parameters of the thruster in each experiment are presented in table 1 ( $\dot{m}_a$  - anode mass flow rate,  $I_d$  - discharge current,  $R$  - thrust). The type of discharge in all operation modes did not variate and was sort of spoke. At that magnetic field was equal to optimal at «nominal» operation mode (550 V, 2.9 A).

**Table 1. Performance parameters of thruster in first two experiments.**

Experiment 1			Experiment 2		
$\dot{m}_a$ , mg/s	$I_d$ , A	$R$ , mN	$\dot{m}_a$ , mg/s	$I_d$ , A	$R$ , mN
2,3	1,94	47,54	2,3	1,92	47,5
2,5	2,12	52,39	2,5	2,10	52,62
2,7	2,32	58,46	2,7	2,29	57,26
2,9	2,53	66,09	3	2,58	67,39
3,1	2,73	71,56	3,29	2,9	75
3,24	2,90	74,12	3,5	3,12	79,8
3,4	3,05	78,28			
3,7	3,38	86,36			

**Table 2. Performance parameters of the thruster in third experiment.**

$\dot{m}_a$ , mg/s	$I_d$ , A	$R$ , mN	$I_{int}$ , A	$I_{ext}$ , A
2,3	1,91	44,8	1,5	1,4
2,5	2,07	51	1,45	1,5
2,7	2,26	58,1	1,4	1,6

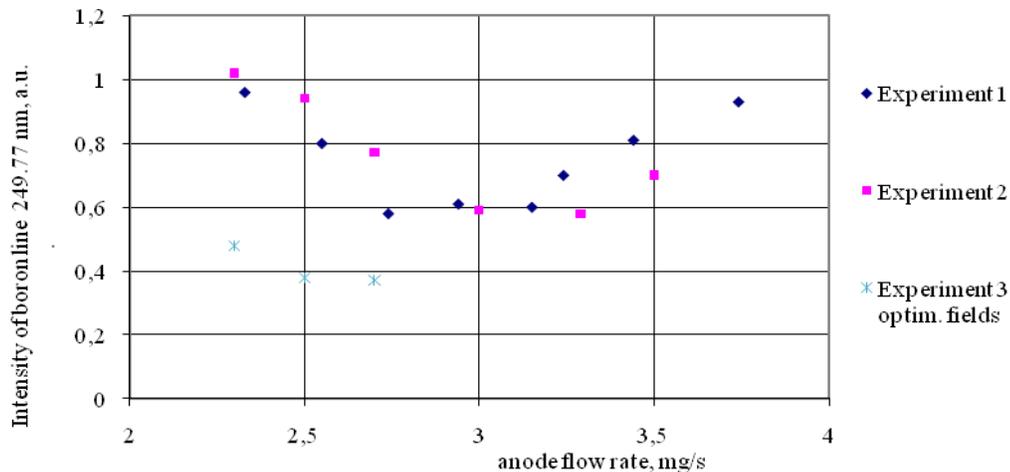
Operation mode optimization by intensity of sputtered boron emission line was carried out in third experiment. Current in magnetic coils were being variate to choose the minimum of the boron atoms intensity corresponding to the spectral line 249.77 nm in the real-time operation. The discharge current  $I_d$  before and after optimization was not changed practically. The discharge voltage was equal to 550 V. Table 2 lists anode mass flow rate, discharge current, thrust, currents in internal and external magnetic coils.

From Tables 1 and 2 one can see that thrust and discharge current with the same anode mass flow rate were changing during the optimization within 5 and 3% respectively that is comparable with measurement error. But at the same time boron atoms intensity as well as erosion rate were changing significantly

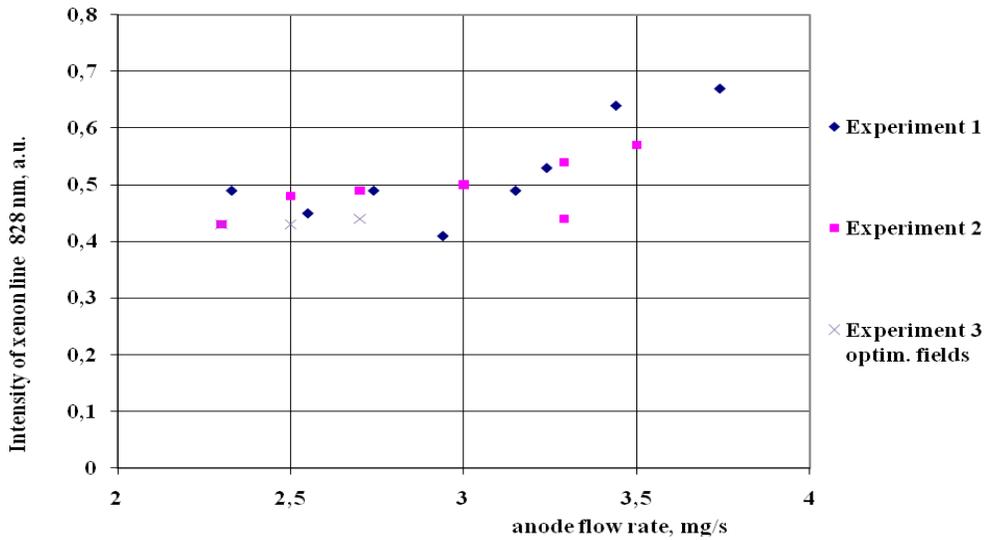
that will be shown later.

## V. Experimental Results and Discussion

Boron and xenon atoms intensities depending on anode mass flow rate are presented in Fig.2 and Fig.3.



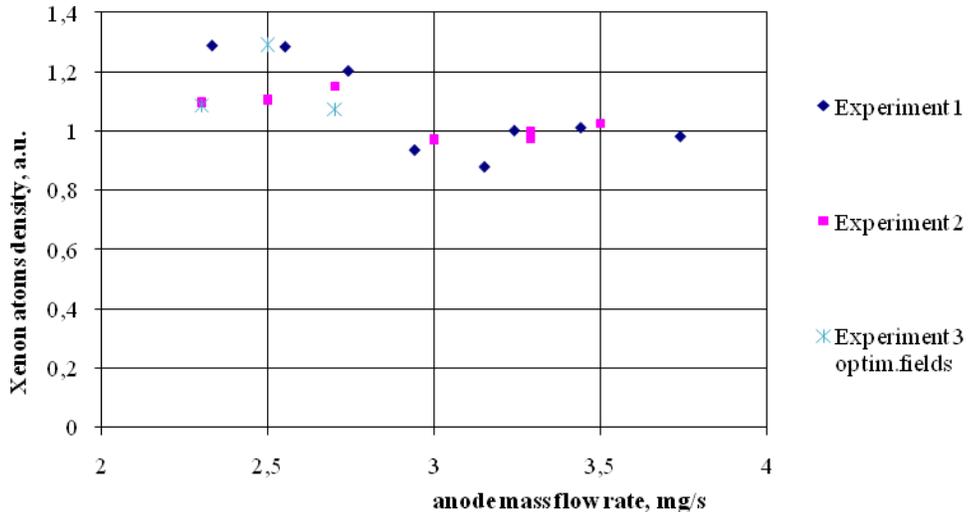
**Figure 2. Sputtered boron atoms intensity.**



**Figure 3. Xe line intensity corresponding to 828 nm.**

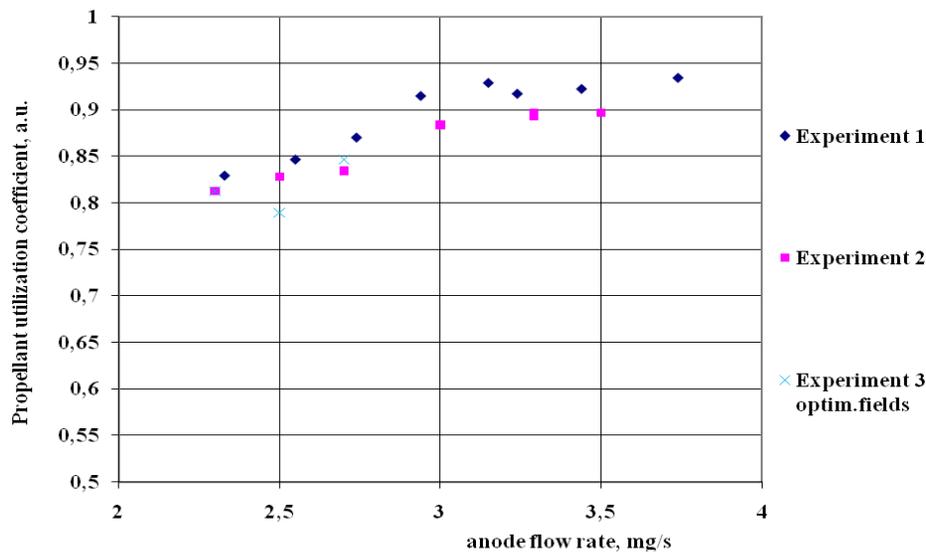
As follows from the obtained data boron atoms intensity has a minimum in first two experiments for operation mode in which optimization was carried out (550 V, 2.9 A). The higher boron intensity at low values of anode mass flow rate in comparison with «nominal» operation mode is probably associated with magnetic fields values in these operation modes. Experimental data obtained in third experiment in which magnetic field optimization was made confirm this fact. In given experiment the boron spectral line intensity at low values of anode mass flow rate is significantly smaller than in experiments 1 and 2 at the same anode mass flow rates.

A value of xenon spectral line intensity is specified by three basic parameters: xenon concentration, electron temperature and density. Increasing of xenon spectral line intensity as anode mass flow rate increases is probably specified by the electron density increase in the region of observation. At the same time xenon concentration decreases as anode mass flow rate increases. Xenon concentration dependency on the anode mass flow rate is presented in Fig.4.



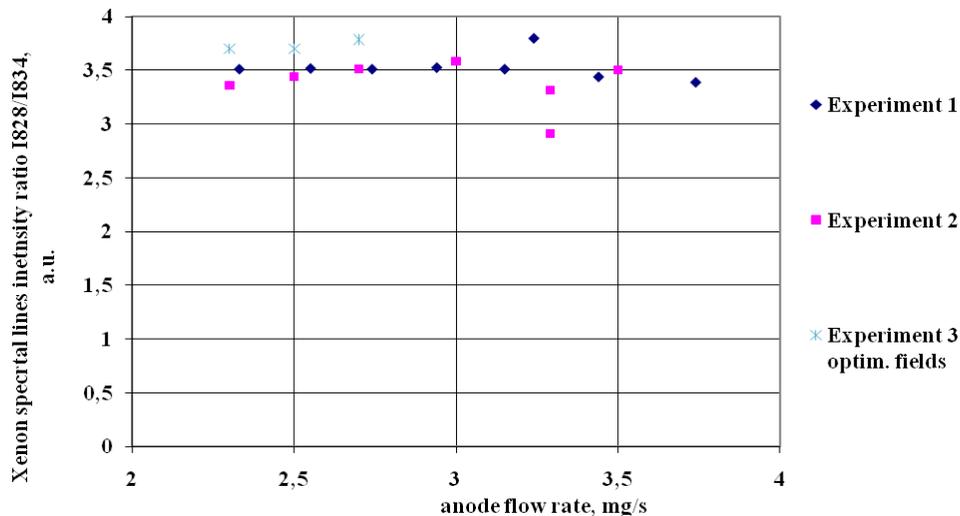
**Figure 4. Xenon density in arbitrary units**

All data in Fig.4 are normalized to the density in «nominal» operation mode. Xenon neutrals concentration decrease is specified by the propellant utilization coefficient increase. Calculated values of  $\alpha$  are presented in Fig.5.



**Figure 5. Propellant utilization coefficient dependency on anode mass flow rate.**

Electron temperature was determined by xenon spectral lines intensity ratio 828.01 and 834.68 nm. In Fig.6 the given ratio for different anode mass flow rates in each experiment is presented.

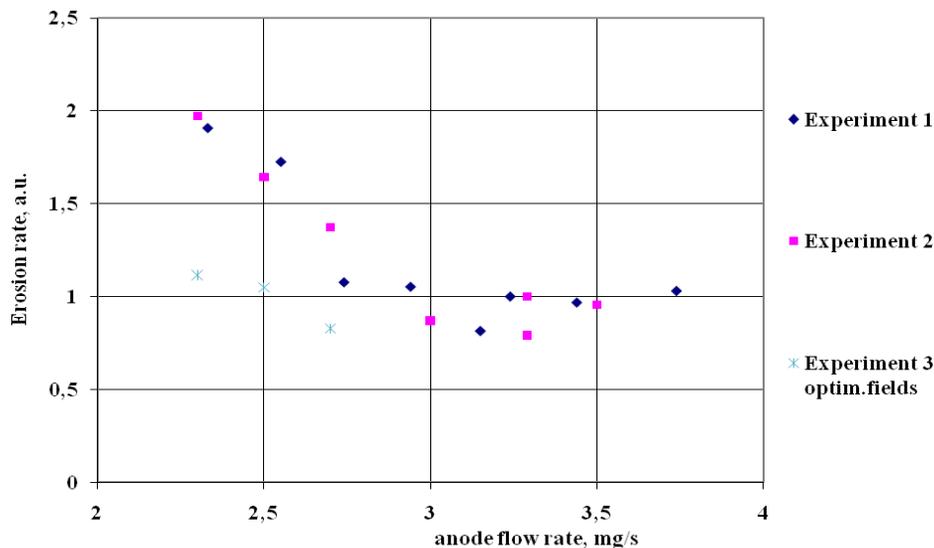


**Figure 6. Xenon spectral lines intensities ratio dependency on anode mass flow rate.**

As the obtained data show intensities ratio does not virtually depend on xenon flow rate that is electron temperature is constant in different operation modes. The average temperature is about 7 eV. Thereby coefficients variation in erosion rate determination is not taken into account in given experiments.

Erosion rate dependency on xenon flow rate is depicted in Fig.7.

All values are normalized to the erosion rate in «nominal» operation mode ( $U_d=550$  V,  $I_d=2.9$  A,  $I_{int}=I_{ext}=1.8$  A). Proceeding from the obtained dependencies for each experiment one can note a good repetition of experimental data. At low values of the anode mass flow rate in first two experiments increased values of erosion rate are observed. As it was noted earlier the main reason of increased erosion rate at low anode flow rates is nonoptimal magnetic fields. Erosion rate values obtained in third experiment at low anode flow rates are significantly lower than appropriate values in first two experiments at nonoptimal magnetic fields.



**Figure 7. Xenon spectral lines intensities ratio dependency on anode mass flow rate.**

On basis of obtained data it can be concluded that at optimized magnetic fields erosion rate virtually does not depend on xenon flow rate whereas discharge voltage is constant. The possible reason is that sputtering increasing due to ion flow increasing on the insulator walls is compensated by moving-out of ionization layer to the exit of thruster and decreasing of bombardment area.

## VI. Conclusion

Spectroscopic investigation of erosion rate tendencies in throttling modes revealed that magnetic field optimization can lead to considerable decreasing of erosion rate with insignificant variation of integral characteristics of thruster. Moreover experiments showed that at optimal configuration of magnetic field erosion rate depends insignificantly on anode flow rate at constant discharge voltage. Thereby lifetime of thruster can be invariable or even increase at the increasing of power and vice versa decreasing of discharge power does not mean the increasing of lifetime characteristics. However it should be noted that these data were obtained in the course of express diagnostics and require further investigation.

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