Erosion Rate Measurements of Hall Thruster with Nominal Power 1.6 kW in Throttling Modes

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Abstract
Spectroscopic measurements of erosion rate of a 1.6 kW Hall thrusters in throttling modes were carried out. Spectroscopic measurements were carried out in three different experiments with constant voltage 550 V and anode gas flow rate 2.3-3.7 mg/s. Moreover, in third experiment magnetic field optimization by spectral line intensity of sputtered boron atoms was carried out. Erosion rate values obtained in third experiment are significantly lower than appropriate values in experiments with nonoptimal configuration of magnetic field.

1. Introduction

Erosion of discharge chamber walls due to impact of high energy ions is the major lifetime limiting reason for Hall thrusters. 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.
The most reliable method of life characteristics determination is continuous lifetime test. However these tests require great amount of time and finances that significantly increase the cost of thruster design. Spectroscopic method of erosion rate measurements allows considerably reducing duration of lifetime tests at stage of thruster development and monitoring erosion rate variations during lifetest in real-time operation. The given method is based on investigation of spectral line intensities of propellant (Xe) and sputtered element (Boron) [1]. It is supposed that erosion rate is proportional to concentration of sputtered particles in region of observation.

2. Experimental apparatus

For carrying out of experiments Hall thruster with nominal power 1600 W and discharge voltage 550 V has been used. The thruster has a hybrid scheme of discharge chamber, consisting of metallic anode chamber and dielectric rings on the exit of the chamber. The average diameter of discharge chamber equals to 85 mm. In given experiments ceramic insulators made of BGP have been used. A hollow cathode with lanthanum hexaboride emitter was used as a cathode-compensator.
The experimental investigations were carried out in vacuum chamber KVU-90 of Keldysh Research Centre. The vacuum chamber has volume of 90 m^3 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^{-6} torr). Total productivity of a cryogenic pumping is equal to 66 m^3/sec. The KVU-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 to carry out measurements in a short-wave range of spectrum. The angle between direction of observation and thruster axis is 80°.
Spectral emission intensity 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.

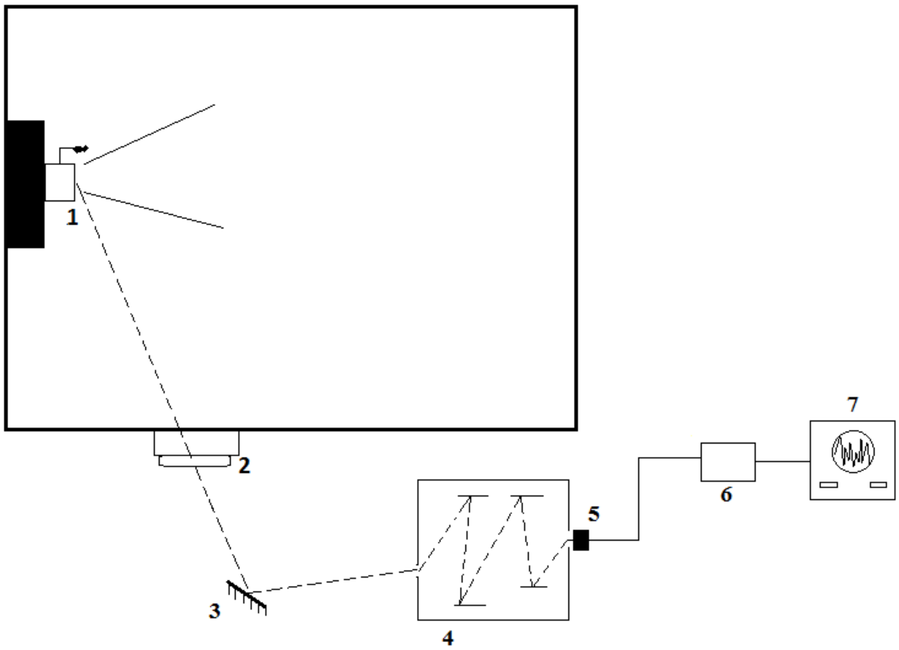

Figure1: Experimental setup: 1 – thruster, 2 – quartz side port, 3 – aluminium mirror, 4 – monochromator, 5 – photomultiplier, 6 – amplifier, 7 – oscillograph

3. Investigation of Hall thruster erosion regularity in throttling modes

Throttling that is variation of thrust due to variation of propellant flow rate while the discharge voltage is constant allows variate power and thrust of a Hall thruster in wide range. It can significantly increase flexibility of system, for example at variation of power supply parameters of propulsion system.
The use of data obtained by the spectral measurements underlies the spectroscopic method of erosion rate determination [1]. Spectral line intensities correlate with concentrations of radiating particles by Corona type model (CTM) interpretation [2] as follow:

$$I_S = C_S \int_0^{l_0} n_e n_S Q_S(f_e)\,dl \quad , \qquad \textbf{(1)}$$

where n_e and n_S are electron and radiating particles concentrations respectively, $Q_S = \langle \sigma_{ex} \upsilon_e \rangle$ 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_S is a constant that characterize transitions probabilities in given atom. Thereby we can find the expression for sputtered material concentration using formula (1) on the assumption that neutrals concentration and electron temperature changes insignificantly along integration path:

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

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

3.1 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 [3]. Formula for intensities ratio is written as:

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

where $C = \frac{C_{Xe828}}{C_{Xe834}}$ - is a constant that doesn't depend on external experimental conditions. It's assumed to be a Maxwellian velocity distribution function for electrons. Rate coefficients data for xenon is available in literature [4].

3.2 Determination of xenon atoms concentration in region of observation

Xenon concentration in Hall thruster 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» [5]. 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 [6] was used to determine the propellant utilization coefficient. The given method is based on Hall thruster plume diagnostics through the use of retarding potential probe and measurements of the anode efficiency η_a and discharge power N_d. Expressions for η_a and N_d have the appropriate forms:

$$\eta_a = \alpha\beta\gamma^2\frac{\left[1+(\sqrt{2}-1)p\right]^2}{1+p}, \qquad \textbf{(4)}$$

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

where β is a ratio of the beam current to the discharge current, γ^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 ions depends on the electron temperature which is in turn defined by the discharge voltage [7].

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

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

It was shown [8] that concentration of xenon neutrals escaping the thruster is of the order of gas concentration generated due to charge-exchange of xenon ions on the chamber walls. Therefore in order to determine the total neutrals concentration it's 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:

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

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]:

$$S \propto k(U_d)(n_{Xe}^{calc}(1-\alpha)+n^{meas})\left(\frac{Q_{Xe}(f_e)+Q'_{Xe}(U_d)+\frac{p}{\sqrt{2}}Q''_{Xe}(U_d)}{Q_B(f_e)}\right)\frac{I_B}{I_{Xe}}, \qquad (8)$$

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.

4. 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 didn't 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			

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 wasn't 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.

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

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.

5. Experimental results and discussion

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

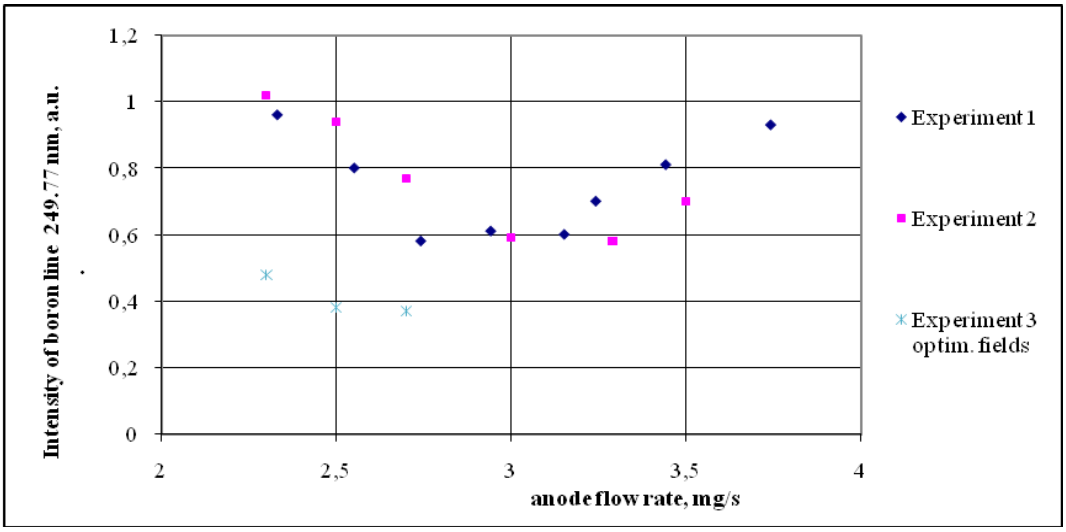

Figure 2: Sputtered boron atoms intensity

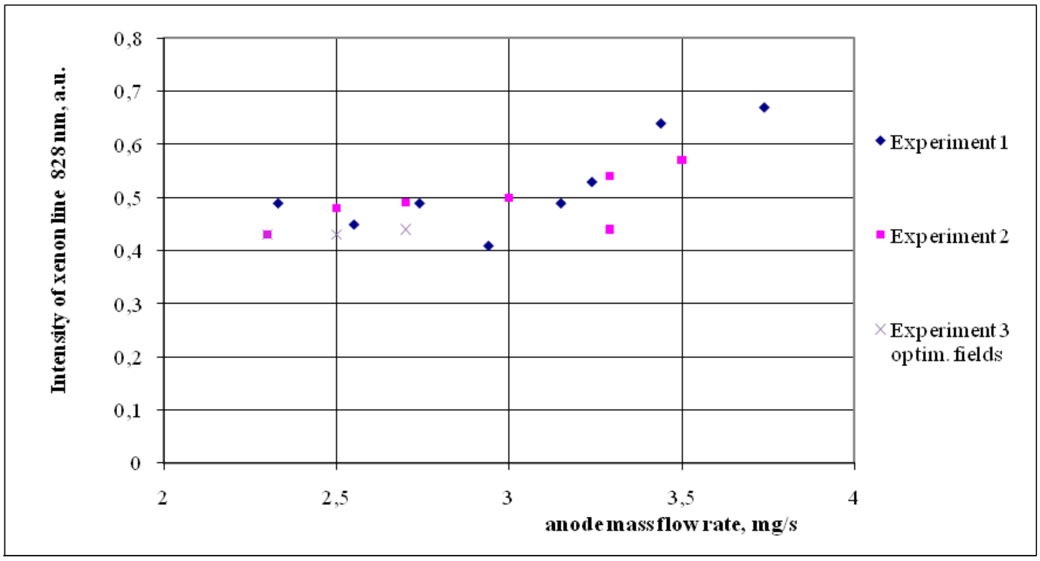

Figure 3: Xe line intensity corresponding to 828 nm

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 confirms 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 concentration. Increasing of xenon spectral line intensity as anode mass flow rate increases is probably specified by the electron concentration 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.

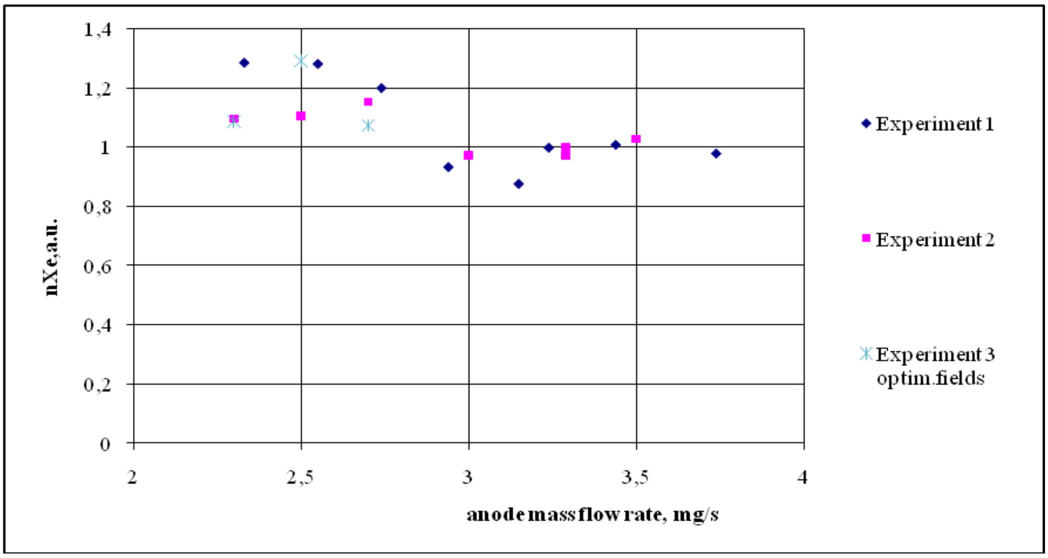

Figure 4: Xenon concentration in arbitrary units

All data in fig.4 is normalized to the concentration 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.

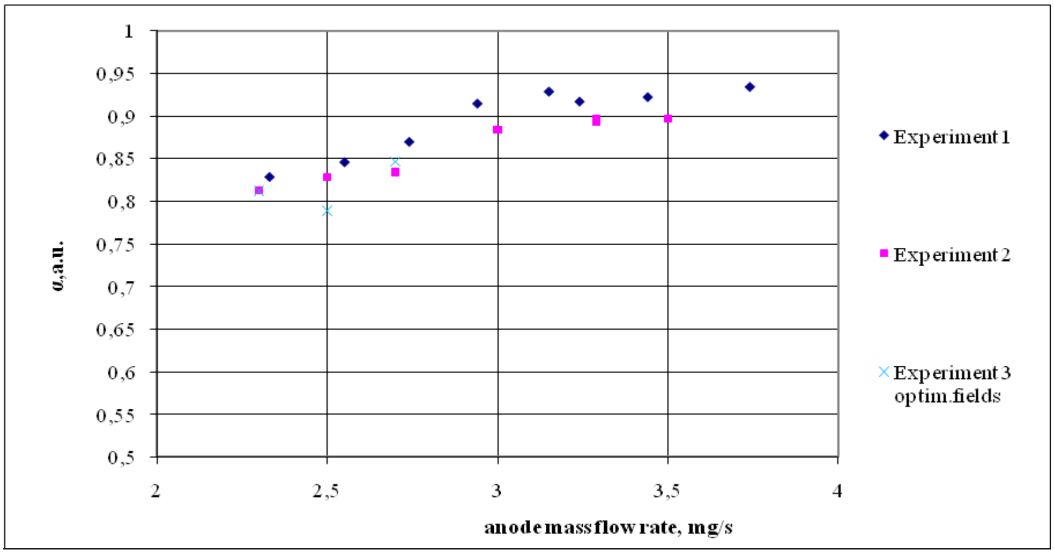

Figure 5: Propellant utilization coefficient dependency on anode mass flow rate.

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.

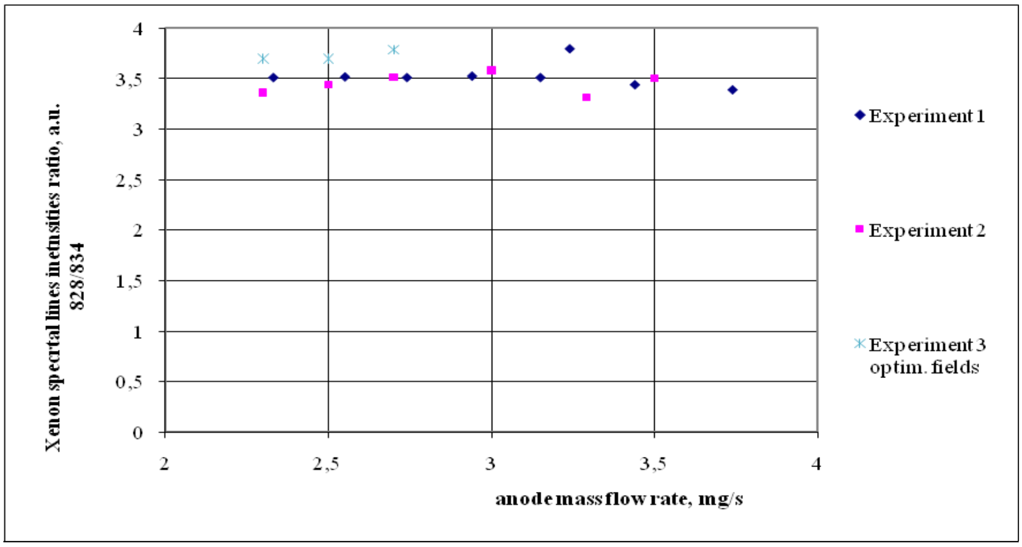

Figure 6: Xenon spectral lines intensities ratio dependency on anode mass flow rate.

As the obtained data shows intensities ratio doesn't 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.

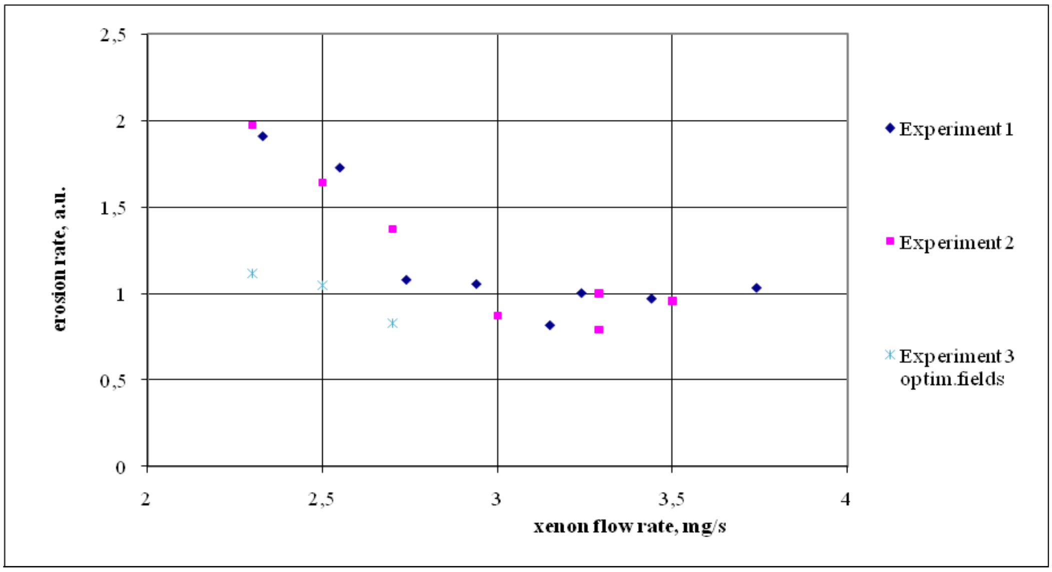

Figure 7: Relative erosion rate in different operation modes.

All values are normalized to the erosion rate in «nominal» operation mode (U_d=550 V, I_d=2.9A, 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. The specific characteristic in dynamics of obtained curves is an insignificant variation of erosion rate as xenon flow rate increase.

On basis of obtained data it can be concluded that at optimized magnetic fields erosion rate virtually doesn't depend on Xenon flow rate while discharge voltage is constant. That is 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. Thereby lifetime of thruster can be invariable or even increase at the increasing of power and vice versa decreasing of discharge power doesn't mean the increasing of lifetime characteristics. However it should be noted that this data obtained in the course of express diagnostics and require further investigation.

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