UKRAINIAN SPT-20 HALL EFFECT THRUSTER: ANALYSIS OF THE PLUME BY OPTICAL EMISSION SPECTROSCOPY

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Abstract: The erosion of the ceramic made of Al_2O_3 of the SPT20 Hall effect thruster manufactured by the National Aerospace University "KhAI" has been studied by an optical method. The ratio of Al I, Xe I, Xe II emission lines was analysed using actinometry and coronal assumptions. The erosion rate of the ceramics has been evaluated for different operating conditions for the thrusters.

Nomenclature

$cp*$	=	thrust cost (W/g)
E_{rosion}	=	rate of erosion
I_{coil}	=	coil current (A)
I_{sp}	=	specific impulse (s)
U_{coil}	=	coil voltage (V)
$\dot{m}$	=	Xenon mass flow rate (mg/s)
U_d	=	discharge voltage (V)
I_d	=	discharge current (A)
P	=	power (W)
T	=	thrust (g)
η	=	global efficiency

I. Introduction

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The National Aerospace University “KhAI” has defined and manufactured a SPT-20 Hall effect thrusters (HET). This small HET operates with only one magnetic coil and the magnetic map has been adapted to focus the plume of ions and to decrease the plasma-wall interactions and the divergence of the plume. The annular walls are made of Al_2O_3 and the thruster works with xenon.

Small HET are today dedicated for precise scientific missions, for a use in clusters, for attitude control or also for the positioning of mini- or micro-satellites. Several models have been successively manufactured at KhAI in order to increase the performances. However, the efficiency of classic HET decreases with the size of the channel but a global efficiency up to 40% has been reached for the SPT-20 after an optimization of the thruster parameters[1]. In this paper, the SPT-20 is described and the performances as thrust, discharge current and efficiency for different discharge voltages, Xe mass flows and coil currents are briefly presented.

The Laboratoire de Physique des Gaz et des Plasmas (LPGP) from the University of Paris XI has developed a new optical method allowing to estimate the erosion rate of the ceramic of Hall effect thrusters. This method uses an actimometry and coronal assumptions in order to correlate the ratio of three emission lines (two from Xenon: Xe I, Xe II and one from the ceramic) to the erosion rate of the ceramic. The determination of the erosion rate of HET presents a great interest for the control of the behaviour of thrusters, to estimate the lifetime and to optimize the magnetic field topography: a large sputtering indicates an important divergence of the ion flux and consequently a loss of ions at the wall inducing a decrease of the ion flux involving to the thrust and an increase of the exchange of energy with the surface of the annular channel. Moreover, a large sputtering effect provokes re-deposition of neutral species on all the inner surfaces of the channel that can be modified the behaviour of the plasma discharge.

In first, the method has been tested with the PPS100-ML (French laboratory model) and PPS1350 Hall effect thrusters in the Pivoine facility (National Center for Scientific research, CNRS at Orléans – France). The ceramics of these thrusters was made of BN-SiO_2 and the three emission lines used to study the erosion rate were 828.01 nm Xe I, 484.43 nm Xe II and 249.72 nm B I. The optical method has been used to analyse the erosion rate for different thrusters operating conditions [2-3]. Recent experiments were performed with the PPSX000-ML thrusters also equipped with BN-SiO_2 ceramics[4].

The ceramics of the SPT-20 thruster are made of Al_2O3 and the emission lines used for the determination of the erosion rate was 828.01 nm Xe I, 484.43 nm Xe II and 396.15 nm Al I. The first results have been previously presented[5,6] and they shown the capability of the method for this ceramic. These first measurements have been performed with the SPT-20 model n°4 in the vacuum test facility of the KhAI mainly to estimate the possible overlapping of the lines. The second campaign has been done in 2007 with a new model of SPT-20 (model n°5) having best performances and similar to the flight model. The results obtained from this campaign are described in this paper.

After a short description of the facility and SPT-20 thruster (chapter II), the optical set-up is presented (chapter III) and the optical method and results obtained during the last campaign for different Xenon mass flow rates, discharge voltages and coil currents are presented and commented (chapter IV).

II. SPT-20 Hall effect thruster and facility

The KhAI ground test facility and the performances of the SPT-20 (model n°6) manufactured by the KhAI are detailed in the paper IEPC-2007-100. The facility consists of a cylindrical vacuum chamber made of steel with an inner volume of 1.9 m^3 (1m in diameter and 2.5m in length).

Figure 1. Plasma plume of the SPT-20 (model n°6) thruster

The vacuum is obtained by a two stage pumping system (primary and turbomolecular pumps) allowing a limit for the pressure of 6 10^{-6} torr and a pressure of $4..7\cdot10^{-5}$ torr with a Xenon mass flow rate of 0.3 mg/s.

The experimental facility consists of a stainless steel vacuum tank 1 m in diameter x 2.5 m long, prime and two turbo molecular pumps, several DC power supplies, thrust measurement system, single electrostatic probe and RPA with 3-axis positioning system, mini-spectrometer, different type gas supply systems, digital storage oscilloscope and other measurement equipment. The vacuum tank pressure is kept a range of $4..7\cdot10^{-5}$ torr under operations. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system.

Thrust is measured by a pendulum method. A HET is mounted on a thrust stand suspended with a titanium 3 m long bar, and the position of the thrust stand is detected by a CCD-sensor (non-contacting micro-displacement meter). It has high displacement sensitivity. Thrust calibration is conducted with a weight and pulley arrangement which is able to apply a known force to the thrust stand under vacuum environment. With this design, friction force was small, and it resulted in no measurable hysteresis. The estimating accuracy of the thrust stand is about 3%.

The SPT-20 thruster is a small HET (inner diameter of the outer ceramic of 20mm) with an axisymmetric channel made of Al_2O_3. The thruster operates with only one external coil set in the bottom of the channel. Fig.1 shows the SPT-20 (model n°6) plasma plume in the KhAI test facility. Compared to the SPT-20 (model n°4) – previously used for optical characterization of the plume – the magnetic field has been optimized to have a better focalization of the ions and to decrease the divergence of the jet and the plasma – walls interactions. Finally, a global efficiency up to 40% has been reached for the SPT-20 (model n°6).

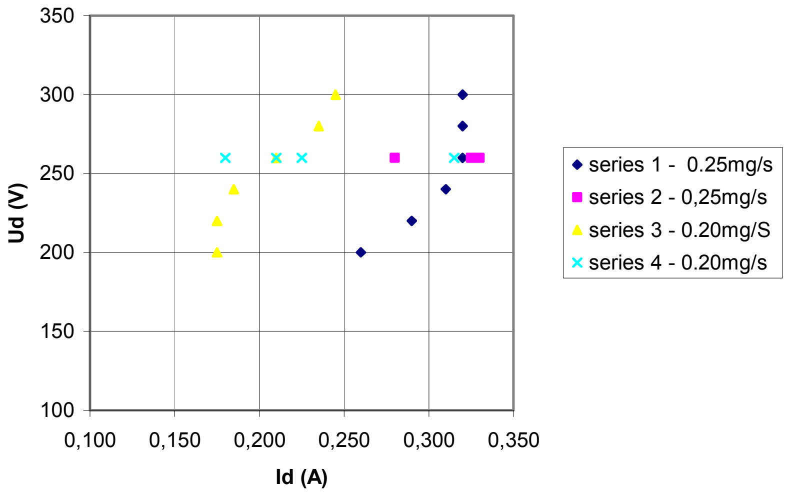


Figure 2. Discharge voltage (V) versus discharge current (A) associated to the operating conditions of the optical tests

The optical measurements was performed for a SPT-20 discharge voltage U_d between 200 V and 300V and for a coil current between 1.5 A and 3.0 A. All these measurements were associated to two Xenon mass flows $\dot{m}$: 0.20 mg/s and 0.25 mg/s. The series 1 and 3 was performed with a constant coil current (I_{coil} =2.4A). They show a increasing of the discharge current with the increasing of the discharge voltage and with the increasing of the Xenon mass flow rate: for U_d = 300V, the current is multiplied by 1.28 although the mass flow is multiplied by 1.25 (Fig.2). The series 2 and 4 was performed with different values of the coil current (I_{coil} =1.5A, 2.0.A 2.4A and 3.0A). The current appears as depending of the coil current but with an opposite effect for $\dot{m} = 0.20 mg/s$ and for $\dot{m} = 0.25 mg/s$.

For the same series, figure 3 displays the efficiency η defined by:

$$\eta = \frac{T^2}{2\dot{m}(U_d I_d + U_{coil} I_{coil})}$$

This parameter is calculated using the power of the coil but neglecting the cathode xenon mass flow. . The maximum (η = 0.353) of the SPT-20 efficiency is obtained for a discharge voltage of 300V and for Xenon mass flow of 0.25mg/s.

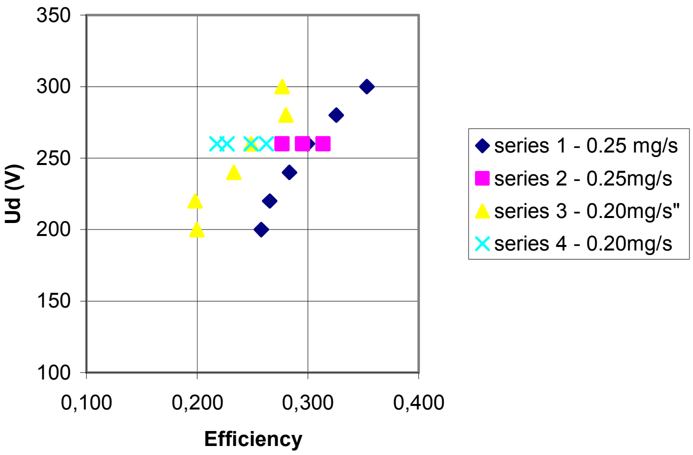


Figure 3. Discharge voltage (V) versus efficiency associated to the operating conditions of the optical tests

The variation of the thrust T (in g) is presented as a function of the power P (in W) on figure 4. The maximum value for the specific impulse is 1700 s and the maximum value for the thrust is 0.425 g (4.17mN). These two maximum are obtained for the same operating conditions ($\dot{m} = 0.25mg/s, U_d = 300V$). During the optical measurements, the SPT-20 operates in the power range of 57.8 W – 102.2 W.

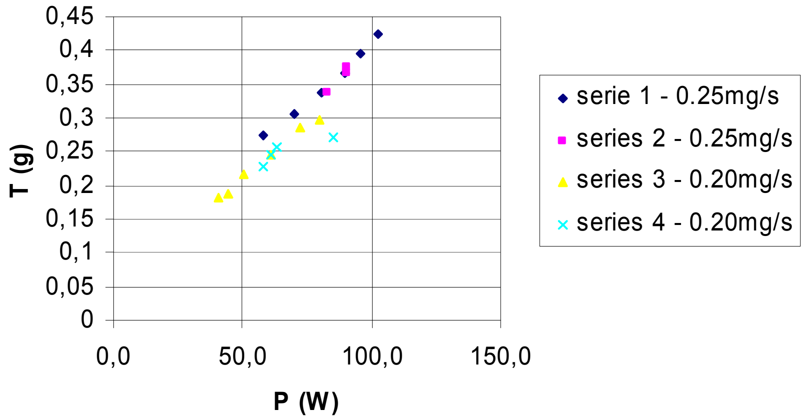


Figure 4. Thrust (g) and power (W) associated to the operating conditions of the optical tests

The table 1 shows the values of the parameters of the SPT-20 thruster associated to the four series of experiments.

$\dot{m}$, mg/s	I_{coil}, A	U_c, V	U_d, V	I_d, A	T, g	I_{sp}, s	cp*, W/g	η	P, W	
0,25	2,4	2,60	300	0,320	0,425	1700,0	240,6	0,353	102,2	series 1
0,25	2,4	2,60	280	0,320	0,395	1580,0	242,6	0,326	95,8	
0,25	2,4	2,60	260	0,320	0,366	1464,0	244,4	0,300	89,4	
0,25	2,4	2,60	240	0,310	0,338	1352,0	238,6	0,283	80,6	
0,25	2,4	2,60	220	0,290	0,305	1220,0	229,6	0,266	70,0	
0,25	2,4	2,60	200	0,260	0,274	1096,0	212,6	0,258	58,2	
0,25	1,5	1,63	260	-	-	-	-	-	-	series 2
0,25	2,0	2,17	260	0,330	0,376	1504,0	239,7	0,314	90,1	
0,25	2,4	2,60	260	0,325	0,366	1464,0	247,9	0,295	90,7	
0,25	3,0	3,25	260	0,280	0,338	1352,0	244,2	0,277	82,6	
0,20	2,4	2,81	300	0,245	0,298	1490,0	269,3	0,277	80,2	series 3
0,20	2,4	2,79	280	0,235	0,285	1425,0	254,4	0,280	72,5	
0,20	2,4	2,62	260	0,210	0,246	1230,0	247,5	0,248	60,9	
0,20	2,4	2,55	240	0,185	0,217	1085,0	232,8	0,233	50,5	
0,20	2,4	2,53	220	0,175	0,188	940,0	237,1	0,198	44,6	
0,20	2,4	2,50	200	0,175	0,181	905,0	226,5	0,200	41,0	
0,20	1,5	2,00	260	0,315	0,272	1360,0	312,1	0,218	84,9	series 4
0,20	2,0	2,45	260	0,225	0,258	1290,0	245,7	0,262	63,4	
0,20	2,4	2,62	260	0,210	0,246	1230,0	247,5	0,248	60,9	
0,20	3,0	3,65	260	0,180	0,229	1145,0	252,2	0,227	57,8	

Table 1

III. Optical emission set-up

The light emitted by the plasma plume observed though a quartz window (40mm in diameter, 5mm in thickness) by an optical set-up located outer of the vacuum chamber. The angle of sight is of around 60° compared to the vacuum axis and the plasma plume is observed just at the channel exit. The emitter light is collected and focussed at the entrance of a 1mm diameter optical fiber by a 10 cm focal quartz lens. The distance between the plasma and the lens was about 80 cm. The exit of the fiber was connected via a SMA connector to the spectrometer entrance slit. With a focal of 10 cm for the lens, the magnification was about 9. With an optical fiber of 1 mm diameter, the spatial resolution was about 9 mm diameter. So, a large part of the plasma inside the thruster channel and outside the exit plane of the thruster was covered by the optical set-up. The Optical Emission Spectroscopy (O.E.S) experimental set-up used for the analysis of the SPT-20 plasma is shown on Fig. 5.

The other extremity of the optical fiber was linked via a SMA connector to the USB2000 spectrometer entrance slit. The spectrometer is a mini-spectrometer manufactured by Ocean Optics (USA). It has been chosen in order to cover the used spectral range with a resolution (2nm) to permit a sufficient separation of the optical lines. Moreover, its characteristics in weight (600g), in size (15x11x5cm) and also in power consumption (100mA) define this spectrometer as a performing candidate for on-board satellite experiments in order to follow the evolution of the erosion of the ceramics and to analyse the optical spectrum of the plume.

The light entering the spectrometer is diffracted by a fixed grating towards a 2048-element linear array CCD detector. So, in one shot, this spectrometer provides a large 380-830 nm wavelength range spectrum but with only 2 nm resolution. The spectrometer is connected to a lap top computer by USB interface.

The computer control the parameters of the USB2000 spectrometer and a graphical interface gives on-screen spectrum which can be recorded on a text file.

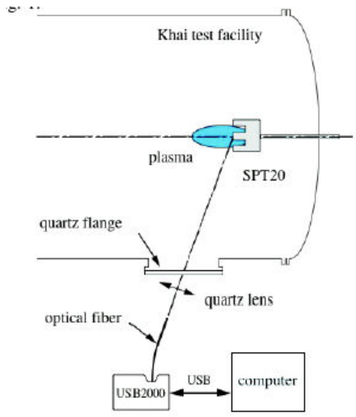


Figure 5. Experimental set-up with USB2000 spectrometer analysing the SPT-20 plasma.

IV. SPT-20 optical signal analysis

For the analysis of the erosion rate of a HET equipped with ceramics made of BN-SiO2, the retained lines are Xe I (828.01 nm), Xe II (484.43 nm) and B I (249.72 nm). The boron line is greater than the Si lines (four lines are however observed in the range 250 nm – 253 nm. These three lines have permitted the analysis of the erosion rate of two HET thrusters PPS100-ML and PPSX000-ML having a BN-SiO_2 channel[2]. Then, the erosion rate E_{rosion} was deduced from the following ratio of intensities of lines: $\frac{I(B\,I, 250nm).I(Xe\,I, 828nm)}{I(Xe\,II, 484nm)}$.

For the SPT-20 thruster with ceramics made of Al_2O_3, the emitted spectrum shows:

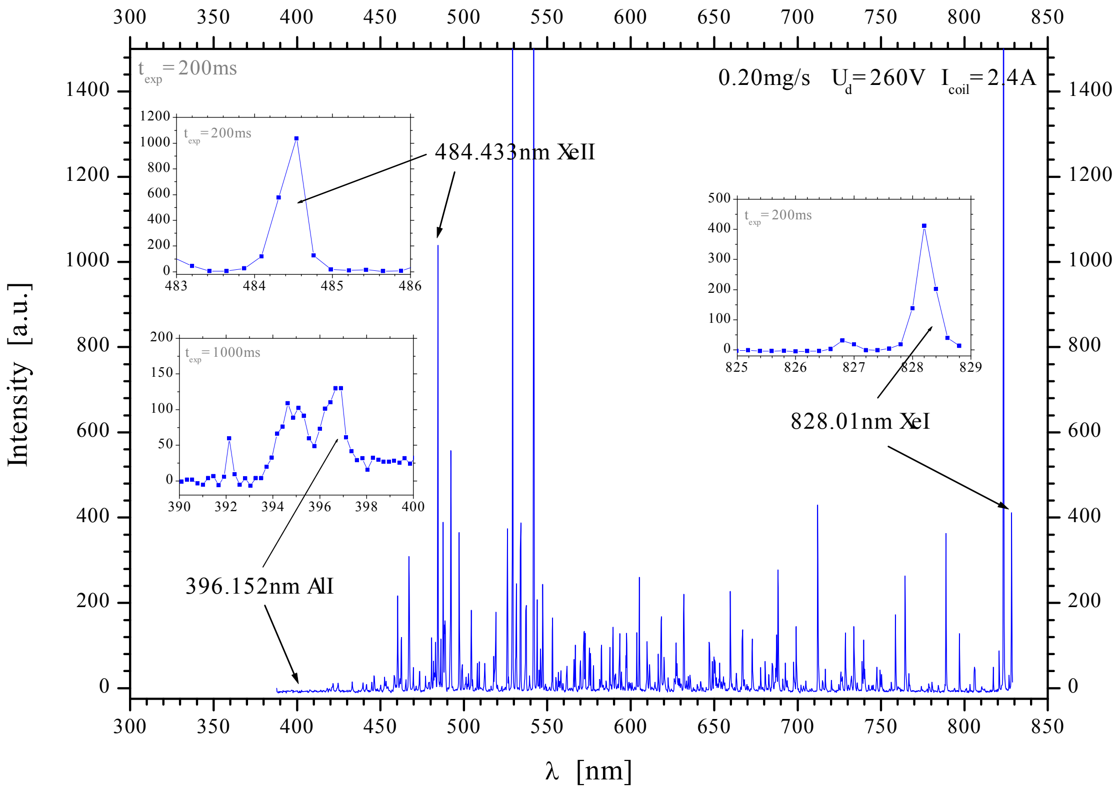
- neutral Xenon, Xe I: 828.012 nm
- ion xenon, Xe II: 484.433 nm
- neutral alumina Al I: 396.152 nm.

The emission of neutral Xenon is done by the transition: $5p^5(^2P^0_{3/2})6s - 5p^5(^2P^0_{3/2})6p$ with an initial level at 9.93eV (80118.962 cm^{-1}) and a final level at 8.44eV (68045.156cm^{-1}). The initial level of this transition is populated by electronic excitation from the ground state of Xenon.

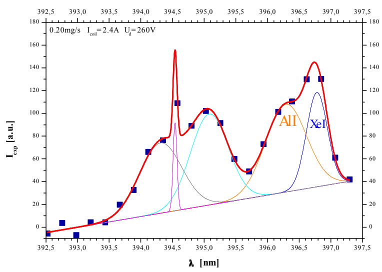
The emission of ion Xenon XeII is done by the transition: $5p^4(D^0_{7/2})6s - 5p^5(^2P^0_{3/2})6p$ at 484.43nm with an initial state at 14.10eV (113705.40cm^{-1}) and a final state at 11.54eV (93068.44cm^{-1}). The upper state $5p^4D^0_{7/2}$ is mainly populated by the two ionic metastable states of Xe^+ : $5d^4D_{7/2}$ and $5d^4F_{7/2}$.

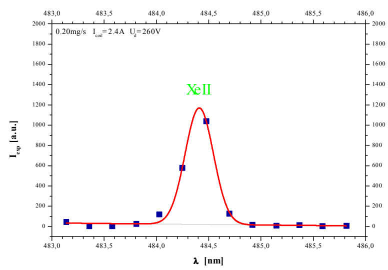
Two emission of neutral alumina are closed for the transition: $3s^2 3p - 3s^2 4s$ with an emitted level is at 3.14eV (25347.756cm^{-1}): the first one at 394.40nm and the second one at 396.15nm. The second quasi-resonant line is used. This Al I line is of light amplitude and located near Xenon II lines. The spectrometer has to be able to separate and to extract this lines from the others spectral lines due to the xenon plasma emission. A numerical procedure to fit the data by multi-peaks by Gaussian profile was used to extract the exact intensity value of the 396.15 nm Al I line (See Fig. 6b). The radiative state of alumina is also populated by electronic excitation from its ground state ($2P^0_{1/2}$).

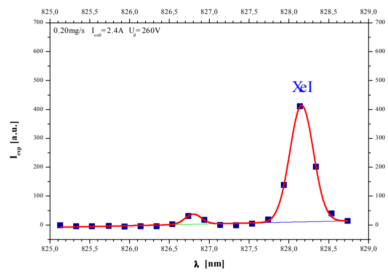
Fig. 6 presents the spectra of the light emitted by the plasma plume for AlI (396 nm), for XeI (828 nm) and for XeII (484 nm) for the such operating SPT-20 conditions: xenon mass flow rate of $\dot{m} = 0.20$ mg/s, coil current $I_{coil} = 2.4$ A, discharge voltage $U_d = 250$V. The variation of the Al I and Xenon lines (Xe I and Xe II) versus the discharge voltage is reported on Fig. 7 and Fig. 8 respectively.



a/ global spectrum







b/ Al I line *(in orange)* **c/ Xe II line** **d/ Xe I line**

Fig.6 Spectra of the light emitted by the plasma for AlI(396), for XeI (828) and for XeII (484) for $\dot{m}$ = 0.20 mg/s; I_{coil} = 2.4 A; and U_d = 260 V

The neutral line of alumina increases with the discharge voltage for a fixed mass flow rates (series 1: 0.20mg/s and series 3: 0.25mg/s) due to the increase of the energy of the Xenon ions. For a fixed mass flow and a fixed discharge voltage (I_d =260 V for the two series 2 and 4), the Al I line presents a different behaviour for the two mass flows: the variation of this line reaches a minimum value with 0.25mg/s and a minimum value for 0.20mg/s (Fig.7).

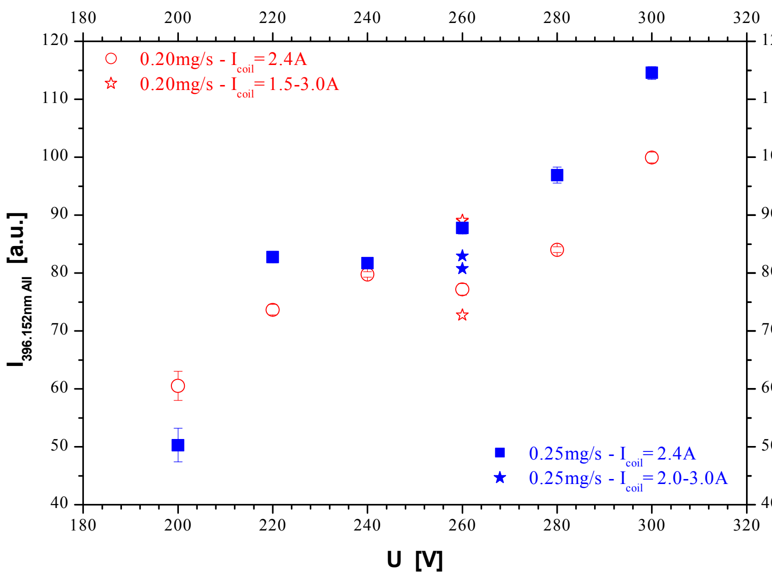
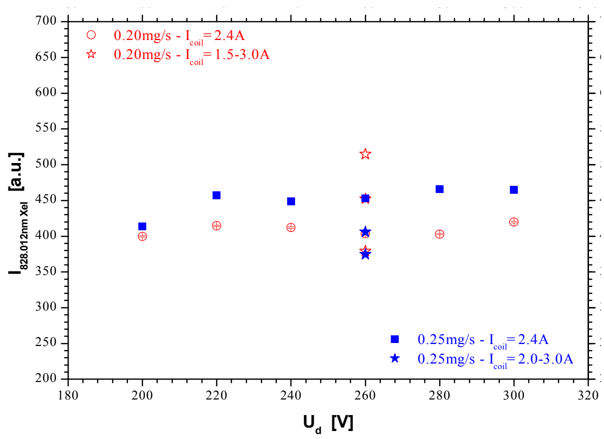
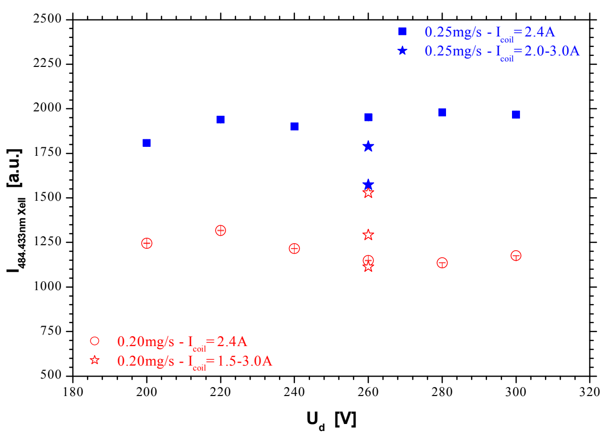


Fig.7 Neutral alumina line versus discharge voltage



a/ Neutral Xenon line



b/ Ion Xenon line

Fig.8 Xenon lines intensities versus discharge voltage

The erosion rate of the ceramics for the SPT-20 was deduced from the ratio of intensities of lines by $\dfrac{I(Al\,I,396nm).I(Xe\,I,828nm)}{I(Xe\,II,484nm)}$. The densities of the excited states are:

$$I_{Al}(396nm) \propto n_{Al}.n_e.k_e^{Al}$$

$$I_{Xe}(828nm) \propto n_{Xe}.n_e.k_e^{Xe}$$

$$I_{Xe^{+m}}(484nm) \propto n_{Xe^{+m}}.n_e.k_e^{Xe^{+m}}$$

where $n_{Al}, n_{Xe}, n_{Xe^{+m}}$ are respectively neutral alumina, neutral xenon and ionic metastable densities and where

k_e^{Al}, k_e^{Xe}, $k_e^{Xe^{+m}}$ are the electronic excitation coefficient for the respective upper states.
The line intensities ratio is used to determine the alumina density:

$$E_{rosion} = \frac{I(Al\,I, 396nm).I(Xe\,I, 828nm)}{I(Xe\,II, 484nm)} \propto \frac{n_{Al}.n_e.k_e^{Al}.n_{Xe}.n_e.k_e^{Xe}}{n_{Xe^{+m}}.n_e.k_e^{Xe^{+m}}}$$

Using the actinometry assumptions: ionic metastable density proportional to ionic density, close values for $k_e^{Al}, k_e^{Xe^{+m}}$ in reason of an equivalent variation of energy (a few eV), this ratio becomes:

$$E_{rosion} \propto \frac{n_{Al}.n_e.k_e^{Al}.n_{Xe}.n_e.k_e^{Xe}}{n_{Xe}\ .n_e^2.k^{Xe^+}k_e^{Xe^{+m}}} \propto n_{Al}$$

The values of this erosion rate are presented on the Fig.9 versus discharge voltages for the four series.

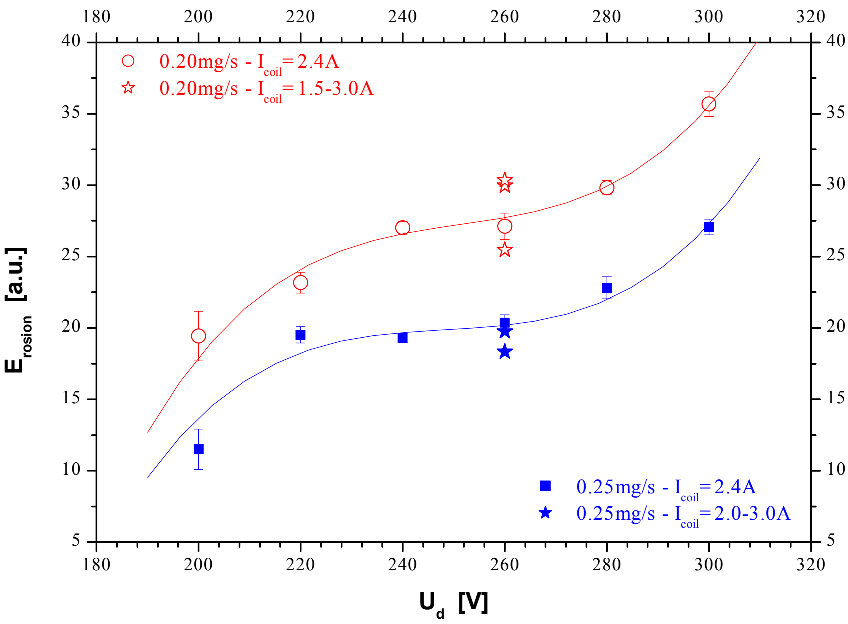


Fig.9 Ceramic erosion rate versus discharge voltage

Figure 10 shows the different behavior of the erosion rate as a function of the coil current for a constant discharge voltage of 260 V and for two Xenon mass flows (0.20mg/s and 0.25mg/s).

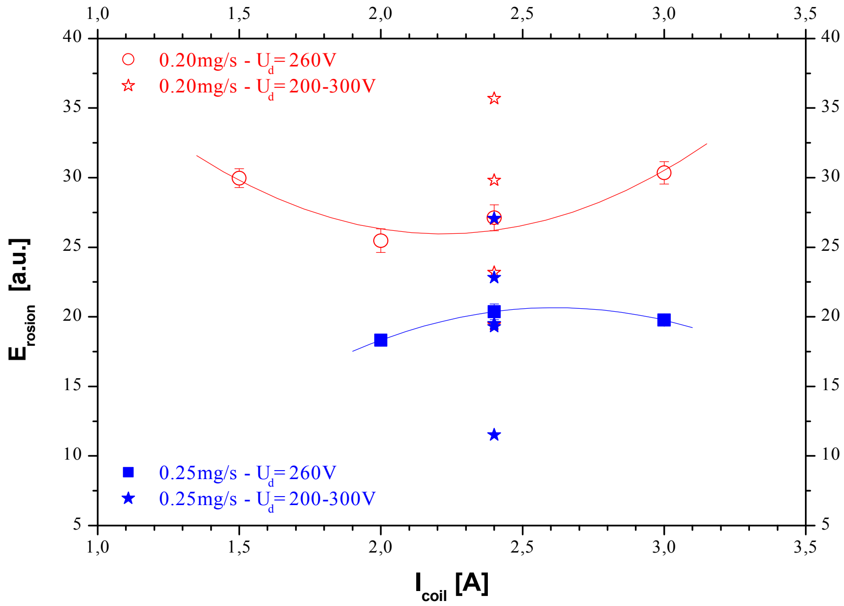


Fig.10 Ceramic erosion rate versus coil current

V. Conclusion

The feasibility to obtain the rate erosion of the ceramics of a Hall effect thrusters by optical emission is today clearly established after the measurements performed on PPS100-ML, PPSX000-ML (ceramics in BN-SiO2) and also on the SPT-20 from the KhAI institute at Kharkov. The O.E.S. is a performing tool to follow the influence on different thruster parameters on the erosion of the walls and the effects on the plume divergence. Consequently, it can be used with success to optimize new HET.

Some complementary researches have to be carried out to improve the quality of the measurements. They will be performed in future, by comparisons with the measurements obtained with a high resolution spectrometer. Moreover, a validation of the measurement will be done by micro-quartz balances. Comparisons between ground and on-board spectra will be required to increase the understanding of effect of ground test facilities upon the thruster performances. The small USB2000 spectrometer appears a good candidate for satellite on-board experiments. It has been tested for vibration space requirements by the manufactured and also tested in rarefied gas environment conditions.

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