Synergic erosion of ceramic by electron and ion simultaneous irradiation of the Hall thruster channel walls

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Abstract: The Hall current thrusters are mainly used for space missions for their high efficiency in term of mass and energy use. Nevertheless, one limitation of such thrusters is the lifetime decrease due to the erosion of the discharge chamber wall. This study has investigated the possibility of a synergic effect on the erosion of the thruster walls. The results of this study clearly show that the electron current on the walls has to be taken into account to have an accurate assessment of erosion in HET. The results seem to demonstrate that the synergic effect could be a good candidate to explain the anomalous erosion present on the exit plane of a HET.

I. Nomenclature

γ = total emission yield (secondary emission and backscattered)
j_e = current density of ions
j_i = current density of electrons
j_{se} = current density of total emitted electrons

II. Introduction

THE Hall current thrusters (also called Hall Effect Thruster – HET) are mainly used for space missions for their high efficiency in term of mass and energy use. Nevertheless, one limitation of such thrusters is the lifetime decrease due to the erosion of the discharge chamber wall [1–4]. The erosion of the ceramics has been studied since years experimentally and numerically. Up of today, the numerical models and the ex-situ experiments developed have failed to provide a satisfactory assessment of the erosion rate of the ceramic materials in HET [5–8].

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This study has investigated the possibility of a synergic effect on the erosion of the thruster walls. In the erosion models used by the past, the effect of the electrons has been completely neglected. Only ions are taken into account. In other context, it has also been demonstrated that a synergic effect on erosion is possible by irradiating a sample with a combination (and simultaneously) of electron and ion beams [9,10]. This paper presents an experimental study that presents evidences of synergic erosion of SiO2 materials in condition representative of what it is encountered in a Hall Thruster. This paper will present in a first part an analysis of data coming from the scientific literature in order to define the plasma representative parameters to use in experiments. The second part will present the experimental protocol used at Onera to estimate the synergic erosion. The last part will show some evidences of synergic erosion increase on relevant materials for the Hall Thruster channel.

III. Plasma conditions at the walls

In order to estimate the synergic erosion effect, the first step is to obtain the plasma characteristic from the scientific literature. We also first define the order of magnitudes of the ions current, the electron current and the electron kinetic energy flux at the walls of the channel.

A. Plasma parameters in HET

In order to evaluate a possible effect of the synergic erosion, it is required to assess the plasma properties at the walls. It means that we need to evaluate the range of the electron and the ion flux at the walls. In order to limit the range of parameters and seeing the number of configurations used in the literature for the Hall Thruster, we limit our study de the SPT100 or PPS1350 thrusters in their standard configurations. This configuration has been extensively studied numerically and experimentally thus they benefit of a large number of data. The analysis of the plasma

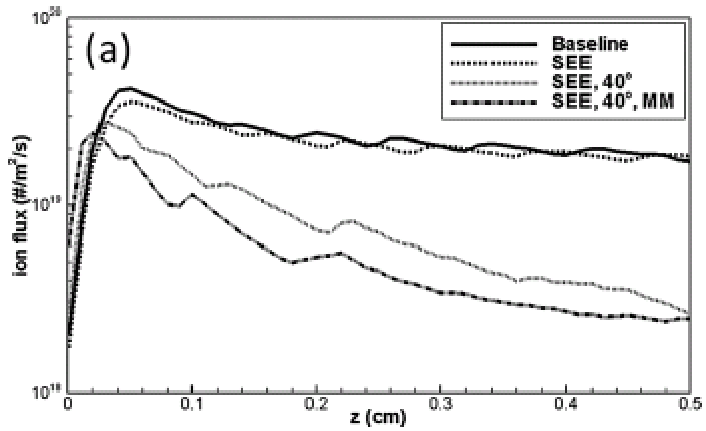

Figure 1. Ion flux at the wall as a function of the position in the channel for different secondary emission values (reproduction of the Figure 8(a) of Brieda paper [12])

conditions at the wall are based on numerical and experimental studies [11–15].

First, we need to estimate the ion and the electron currents going to the walls. It can be noted that, as the walls are thick dielectrics, these currents are not independent. A thick dielectric involved a small current leakage due to conduction thus the total current on the wall should be zero at the stationary state.

On Figure 1, a typical result extracted from simulations done by Brieda[12] has been represented. It shows that the ion current density at wall in Hall Thrusters is about 1 A/m². It can be notice that this current is about the same order of magnitude whatever the position in the channel.

Supposing the current conservation at the steady state, the total current can be written as follow:

$$J_e + J_{se} + J_i = 0$$

Where J_e is the electron current coming from the plasma, J_{se} is the secondary emission current and J_i is the ion current. Taking into account a secondary emission yield γ, the electron incident current at the walls should be deduced from the following expression:

$$J_e \sim -\ J_i \times \frac{1}{1-\gamma}$$

Due to the secondary emission, the electron current is higher than the ion current to the wall. Considering a secondary emission yield of 0.9, the electron current is 10 times higher than the ion current to the wall. It means that the order of magnitude of the electron current is about 10 A/m². This can note that the value of this current can be seen as overestimated with respect to electron current coming from modelling in the literature. In Figure 2, a simulation result from Barral[11] shows electron current and ion current with the same order of magnitude. This can be due to an underestimation of the secondary emission yields.

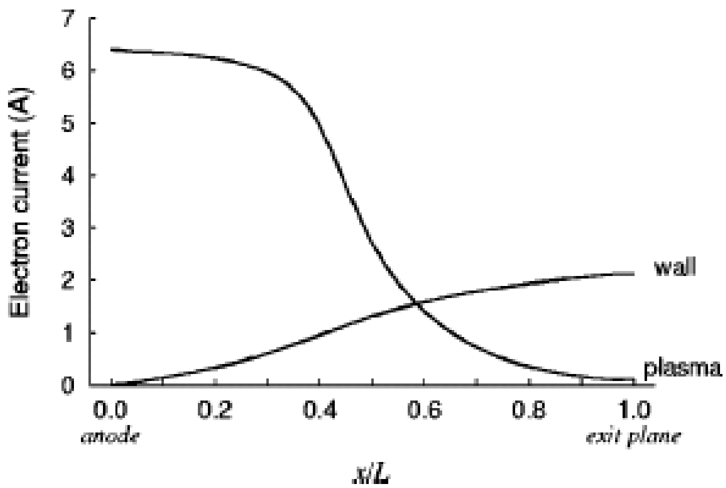

Figure 2. Electron flux at the wall as a function of the position in the channel (reproduction of the Figure 16 of Barral paper [11])

B. Energy deposition by electrons

Regarding the scientific literature about the energy flux at walls of a Hall thruster, the data are less abundant than for ion current estimation. Although, this data are very important to define as it is the energy deposited by the electrons on the near surface of the ceramic which is relevant for the synergic effect on erosion.

On modeling aspect, two papers have particularly investigate the electron energy flux toward the walls[13,14].

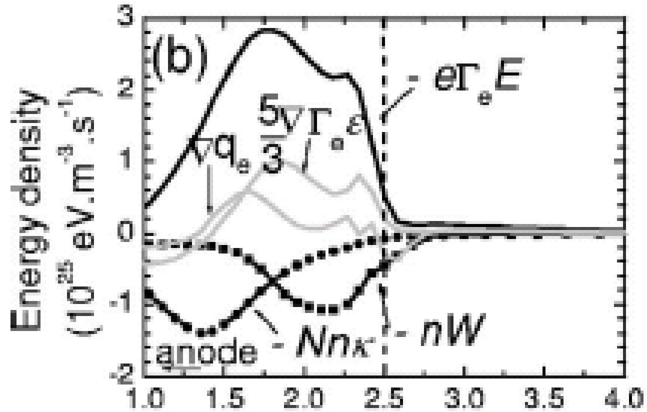

Figure 3. Energy term of the energy balance equation (reproduction of the Figure 3 of Garrigues paper [13])

On Figure 3, the different terms of the energy balance equation is represented by Garrigues[13] as a function of the axial position in the thruster channel. The term of energy loss at wall due to the electrons reach a peak of 10^{25} eV.m^{-3}.s^{-1}. It corresponds to a maximum power flux of electrons toward the walls of 20 kW/m². It seems quite surprising as a simple calculation tacking a current density of 10 A/m² (estimated previously from III.A) and electron temperatures of 30 eV lead to a power flux of 0.6 kW/m². There is more than a factor 30 between the both values. Others simulations results obtained by Parra[14] show the same values as estimated by Garrigues, i.e. about 20 kW/m².

This order of magnitude can be confirmed by experimental studies. In 2007, Mazzoufre[15] performed a study on the mean power flux at walls of a Hall Thruster as a function of the input power and the applied voltage. In this paper, the mean energy fluxes on the walls outside the channel and inside the channel are differentiated. It is shown that the mean energy deposited on the walls inside the channel for a 1500 W Hall Thruster is about 5 kW/m². It can be noted that nothing permits to differentiate the electrons from the ions contributions in the experiments. But, if we supposed that the major component come from the electron flux, the experimental result seems coherent with the simulations that are showing peaks around 20 kW/m².

The discrepancies between our simple calculation and the simulation and experiments results from the literature can be explained by an underestimation of the electron current. In fact, the temperature supposed for the electron is already high and would not be underestimated by an order of magnitude. It should also be supposed that the current density of electrons at wall is not 10 A/m² but 100 A/m². A factor of 100 between the ion current is not totally impossible, it just corresponds to a secondary emission yield of 0.99.

IV. Erosion

C. Anomalous erosion phenomena in thrusters

Anomalous erosion has been extensively studied in the past and numerous experimental results can be found in the scientific literature[1,6–8,16–23]. It is well know that this phenomena is a important limiting factor of the thruster lifetime[23]. But, up of today, it is difficult to get accurate predictions of the ceramic wall erosion in the channel of the thruster. The anomalous erosion phenomena has also been observed frequently at the exit plane of the thruster channel[1,16,18,19,23]. But, its origin is not really understood and the model does not really take into account the anomalous erosion.

Under the term of anomalous erosion, different phenomena or effects are defined and observed:

- An anomalous high erosion rate that decreases the lifetime of th channel walls of the thruster.
- The change of the surface state of the material. In such a case, only some microscopic change at the surface can appears. Some studies show that kind of changes on AlN material[19]. Some preferential zone are eroded that created king of spikes at the surface. Due to erosion, the roughness of the surface increases.
- The third phenomena observed are the striations at the macroscopic scale on the exit plane of the thruster[1,16]. This phenomenon is due to a preferred erosion of zone on the material. But this phenomenon is not due to the material composition as in the previous article.

These phenomena have been observed on numerous materials of thruster[18,24] and the wavelength of the striations is linked to the magnetic field. This effect is generally observed on material with oxygen and the wavelength of the phenomenon seems in agreement with an electron related phenomenon.

D. Synergic erosion in the scientific literature

Under electron irradiation, common of oxides (SiO_2, Al_2O3, MgO ...) are unstable. Indeed, the energy deposited by the electrons may break X-O chemical bonds. Many papers attested this effect. Indeed, the decomposition and the desorption of the oxygen of oxides under electron irradiation is intensively studied in electron beam etching technology and AES depth profiling and STM nanolithography[25]. Carriere and Lang[26] have studied the mechanisms of dissociation of an SiO_2 surface. Their study, which can extend on principle to other oxides, shows that the energy threshold of such a mechanism varies from 10 eV to 25 eV. The chemical process involved is as follows: (i) the incident electron of low or of high energy causes ionization of the target directly or indirectly by the cascade of secondary electrons. A high density of electron- holes pairs (e) (h) is then generated at the surface and immediately below the surface of the oxyde. In the ase of SiO_2, each silicon atom shares an oxygen atom with its neighbor. The breaking of a bond of Si-O-Si may result on the formation of Si-Si bond and the detachment of an oxygen atom that can be desorbed from the oxide surface. As a result, significant fraction of SiO_2 converts to SiOx. It was also demonstrated that the ion etching rate of SiOx is higher than of that SiO_2. Therefore, $_i$t is obvious that the simultaneous irradiation of an oxide by ions (and electrons synergetic effect) will result on higher etching rate than the commonly considered situation where only the ions are taken into account. From these analyses based on the literature we suspected that representative situation of HET plasma-walls interactions, the effect irradiation of the ceramics walls by electrons should be taken into account when the erosion effect is analyzed.

V. Experimental results

A. Experimental setup

In the frame of an experimental campaign performed at ONERA in the DEESSE vacuum chamber (Figure 4), the synergic erosion effect has been tested on two different materials used in the frame of electric propulsion. The two samples selected are BN-SiO2 M26 and HD-BN. These samples have been irradiated several tens of hours with representative conditions of ion and electron irradiation at the surface of the exit plane of a HET. During the experiment, the ion beam irradiates the whole sample and the electron beam a smaller surface (3 mm diameter) at the center. During the synergetic irradiation the relative residual gas composition was recorded with a help of high sensitive quadrupole gas analyzer. A flood low electron gun was used in conjunction with the ion irradiation gun to compensate the positive charge generated both by the ions and the incident electrons. Indeed, the used incident electron energy (higher than the first crossover energy) corresponds to the situation where the incident electrons induced a positive charging.

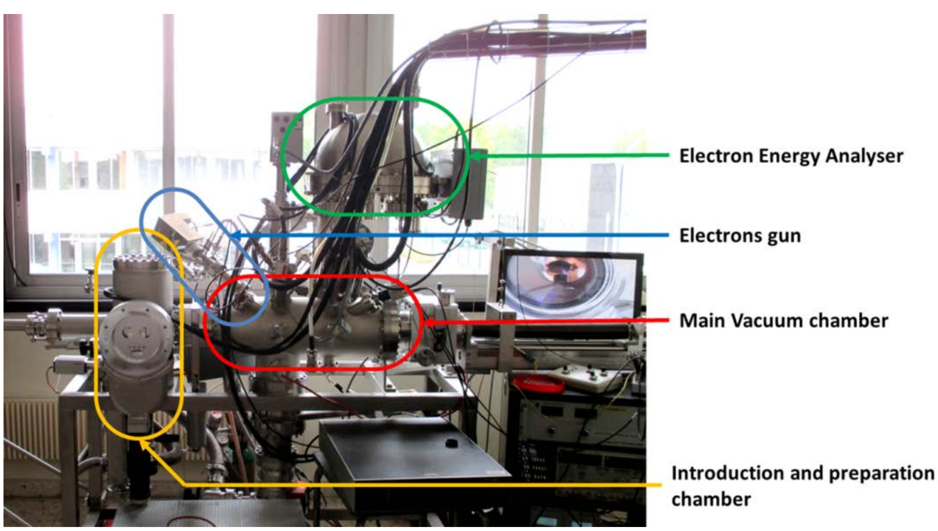

Figure 4. DEESSE facility

B. Residual gas analysis

The figure 2 shows the evolution of the composition of the residual gas in the analyses chamber during various experiments. This gas analyses is carried out under simultaneous irradiation of the sample by electrons (300 eV) and ions (400 eV) except at a particular time interval where the electron beam has been chopped off. The current density of the ions is about 65 µA/cm² (on the whole area) and the current density of electrons is about 490µA/cm² (corresponding to 35 µA on an irradiation diameter of 3 mm).

What appears to be the most interesting in the figure are the three hatched time intervals. These particular intervals are enlarged in Figure 5.

- Between t = 30 min and t = 40 min, the electron beam is cut: we then observe a net decay of the Si, O and H signals. (1)
- We observed the increase of the signals: Si, O when the beam is switched on (1) , then we again increased the electron current (2) and again observed an increase of the three signals.
- At t = 181 min the electron beam was cut (4) and after the ion source was cut off (5).

This experiment clearly shows that a significant fraction of the Si, O and H composing the residual gas is proportional to the incident electron flux. We therefore conclude that the electron beam clearly affects the erosion rate of the ceramic.

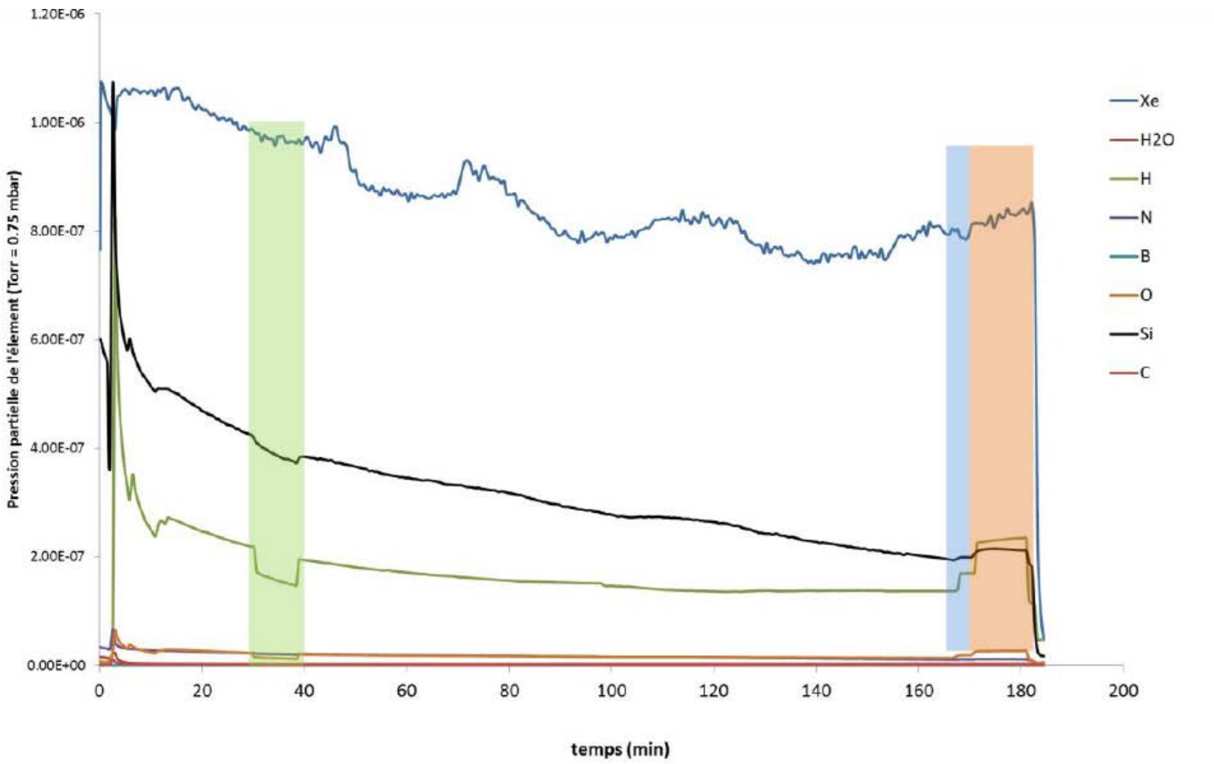

Figure 5. Residual gas composition during the ions and electrons irradiation of BN-SiO_2

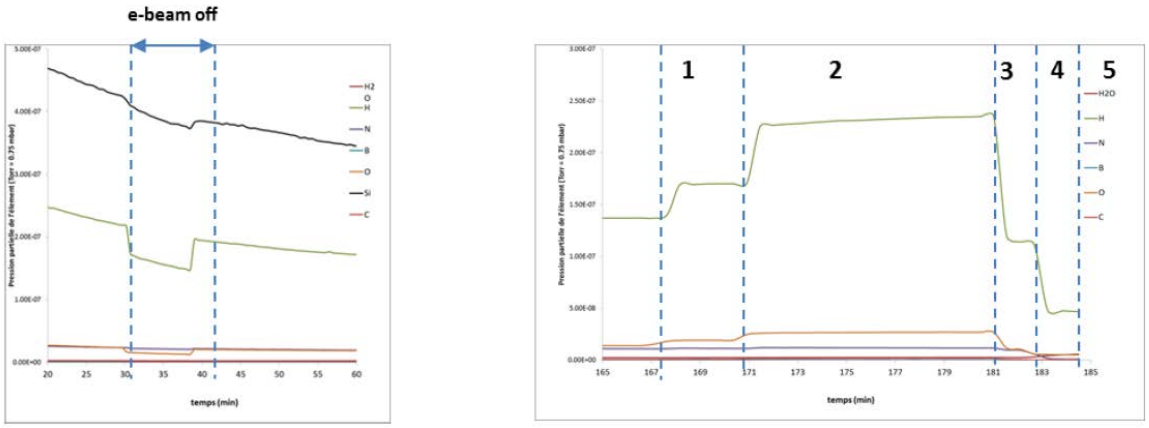

Figure 6. Residual gas composition during the ions and electrons irradiation of BN-SiO_2. On the left: effect of the switching off of the electron beam; On the right: effect of the variation of the incident current density of the electron beam

C. Erosion visual evidences

Finally, after the samples where removed from the vacuum chamber and visually inspected. On the Figure 7, the electron synergic effect is clearly visible. A step is clearly visible that demonstrate an increases of erosion where the electron beam is present. At the contrary, the HD-BN material does not contain oxides and no effects are visible. These visual evidences have been completed by surface analyses by electron been and in-situ analysis of residual gases resulting from erosion. These analyses have permitted to confirm the presence of synergic effect.

Figure 7. Synergetic erosion evidences – pictures of the sample M26 after 35 hours of irradiation

VI. Conclusion

On the exit plane of a HET (where there is an intensive erosion), the ion current density can be estimated in a range from 100 – 1000 µA/cm². The current density used in the experiment is a bit lower than the lower bound of the real range of ion current. Thus the ion flux here is underestimated. As the walls are dielectric, at the stationary state, the electron current has to be as large as the ion current to equilibrate the electron current. Due to the secondary emission phenomena (with a yield around 1 in this zone), in reality, the electron current can be one or two orders of magnitudes higher than the ion current. Thus the energy flux deposited by the electrons is very high. From the literature, this energy flux is estimated at around 10 kW/m². This kinetic energy deposited by the electron can be responsible of a synergic erosion effect. In the experiment, the power flux imposed corresponds to about 1.47 kW/m². This value is quite low compared to the energy flux estimated in the real situation.

In such a conditions, it is thus demonstrated that the irradiation by electrons is able to modify the structure of the SiO2 material [25]. This leads to a significantly increase the erosion rate by ions, this phenomena is called synergic erosion [9,10]. The present experiments show the visible effects after only 35 hours of irradiation.

The results of this study clearly show that the electron current on the walls has to be taken into account to have an accurate assessment of erosion in HET. The results seem to demonstrate that the synergic effect could be a good candidate to explain the anomalous erosion present on the exit plane of a HET.

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