QCM and OES: two ways used to study simultaneously HET thruster chamber ceramic erosion. First QCM results on PPS100-ML validate previous OES measurements.

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Erosion of the accelerating chamber insulators by the xenon ions is the main limiting cause of the Hall-Effect Thrusters lifetime.

In the frame of the Groupement de Recherche CNRS/CNES/SNECMA/Universités "Propulsion spatiale à Plasma" a method to measure the HET ceramic wall erosion by means of Optical Emission Spectroscopy has been used on various thrusters.

In this paper, are presented first results about Quartz Cristal Microbalance erosion measurements. Two water cooled QCM were introduced into the Orléans PIVOINE tank at an angle of 70° from the motor axis in order to collect enough products of ceramics erosion but not much perturbating accelerated ions from the discharge. The quartz of the two QCM were polarised in order to repel the incoming ions, and the electrons attracted by this polarisation were trapped by a 600 G magnetic field produced by permanent magnets in front of the quartz. The QCM erosion measurements were used in order to test the validity of the OES technique previously used.

In the OES way, some hypothesis were made like corona and actinometric models because lack of datas about electron excitation cross sections. Due to the difficulty of the QCM technique and the lack of time, only one experiment has been made at 200 V discharge voltage, 2.0 to 3.6 mg/s xenon mass flow rate on PPS100-ML (former SPT100-ML). But the correlation between OES and QCM is very good for this experiment.

I. Introduction

Ceramic erosion appears as an important wearing process in Hall effect thruster. Ions are created inside the channel and accelerated outwards yielding the thrust. Part of this ion flux directed towards the walls of the channel produces the erosion of the ceramic. Material components are sputtered, mainly towards outside and much less inside which are deposited on the inner walls. Modelisation of the erosion is difficult because the radial distribution of the electric field inside the channel and the sheath potentials are not well known. In addition, the geometrical shape of the ceramic changes during the erosion process. Therefore an optical method to measure the material sputtered has been investigated to quantify the ceramic relative erosion.

Since 2004, in the frame of the Groupement de Recherche CNRS/CNES/SNECMA/Universités "Propulsion spatiale à Plasma" a method to measure the HET ceramic wall erosion by means of Optical Emission Spectroscopy has been used on various thrusters : SPT100-ML,[1] PPS1350-G,[2] PPS1350-TDS,[3] PPSX000-ML,[4] SPT-20M.[5] Results from these OES erosion measurements have been correlated with discharge parameters (discharge voltage, mass flow rate) with a good agreement, but the hypothesis (coronal model and actinometry) used in this OES

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method were not verified. The purpose of this paper is to report the first erosion measurements obtained by means of Quartz Crystal Microbalance and the comparison with the OES erosion method and its validity in the power range of the thruster investigated.

QCM is widely used in the PVD magnetron sputtering in order to control the deposition thickness of the metal layers on semi-conductor wafers. Ionised Physical Vapor Deposition is now used for filling high aspect ratio trenches as the feature size decreases. First, K. M. Green *et al*,[6] use a QCM behind a gridded energy analyser in order to determine the flux ionization fraction reaching the substrate. Several difficulties with gridded-energy analysers (as variation of the transparency) lead T. G. Snodgrass *et al*[7] to use a polarised QCM to repel the ions and collect only neutrals. In this IPVD experiment, the plasma potential was about 10 V and the front surface of the crystal was biased to 30 V to repel ions. In our experiment, the ions to be repelled was the xenon ions accelerated in the thruster channel. The ion energy was previously measured for SPT100 (now renamed PPS100) standard conditions (300 V, 5 mg/s) by means of Retarding Potential Analyser and was found equal to 260 eV.[8] This measurement was carried out only on the thruster axis, but it was found on this work that at a large angle (60-80°) from the thruster axis the ion energy is about the same as on the axis.

The polarised QCM was first calibrated then polarisation tested on the Orsay LPGP magnetron until 300 V. When introduced in the Orléans PIVOINE facility, the QCM deposition velocity signal was very unstable at high discharge voltage (> 200 V) or high mass flow rate (> 3.6 mg/s). So, the only parametric measurement carried out was for 200 V discharge voltage in the 2-3.6 mg/s mass flow rate range. A very good correlation was obtained when comparing with OES erosion measurements.

II. Apparatus

A. QCM apparatus design

The device used to measure the products of the ceramic erosion by impinging xenon ions was a standard water-cooled quartz crystal microbalance (Maxtex TM 400). Usually the front surface of the crystal is coated with a thin gold film and rests against the grounded surface of the crystal holder. The other side of the crystal is connected to the RF resonant circuit. In the device described here, a 76 μm Mylar foil was used in order to insulate the crystal holder from the grounded body of the QCM head. A variable dc voltage bias was supplied directly to the front surface of the crystal as shown in Fig. 1.

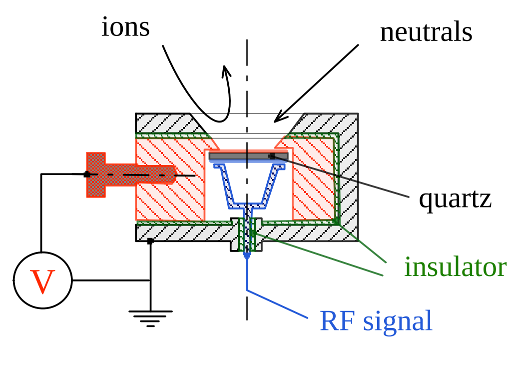

Figure 1. Quartz polarisation.

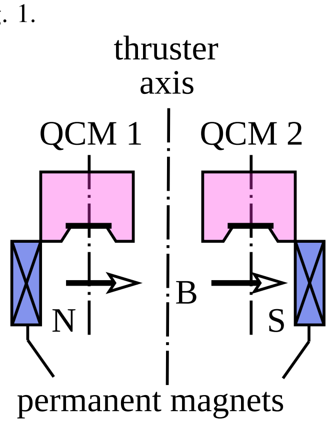

Figure 2. QCMs and magnets set-up.

The ions produced near the front exit plane have no much more energy than the one produced by the accelerating electric field of the discharge. Here the discharge voltage was 200 V and the front crystal face was biased to 300 V. The ions no longer have enough energy to reach the crystal and erode it. Only neutrals produced by the erosion of the ceramic inner walls impacted by the xenon ions are deposited.

When biased to 300 V the front crystal face could collect a large electron saturation current and would be heated and damaged. A magnetic field was used to trap the electrons before they reach the crystal. Two permanent magnets create an approximately 600 G magnetic field in front of the crystal collecting faces as shown in Fig. 2. The 2 cm magnet height is sufficient to trap the electrons which have a cyclotron radius less than 1 mm for a few eV energy and not sufficient for the 100/200 eV energy xenon ions which have a cyclotron radius of about 20/40 cm.

Two QCM was put at the same position (distance from the thruster axis, distance from the ceramics, angle from the thruster axis). The spare one was used as a control of the operational one. A displacement stage allows collecting angles ranging from 90° to 60° in relation to the thruster axis. For 90° angle, the distance between the crystal and the thruster axis is 26 cm (see Fig. 3).

The RF signal from the QCM head is connected to an oscillator relay by means of a Microdot cable. Due to a low RF signal, the Microdot cable lenght is limited to 70 cm. The oscillator relay is operating in air, then the two oscillator relays were put in a airtight box near the thruster and connected to a feedthrough by usual coaxial cable.

The frequency of the oscillator circuit is monitored by the Maxtex TM 400 which produces thin film thickness and a deposition rate with a very high sensitivity of 0.1 Å/s. The deposition velocity and thickness displayed by TM 400 depend on the acoustic impedance of the material laid on the quartz crystal. For alloyed materials as BN-SiO_2 the acoustic impedance is unknown and needs a calibration.

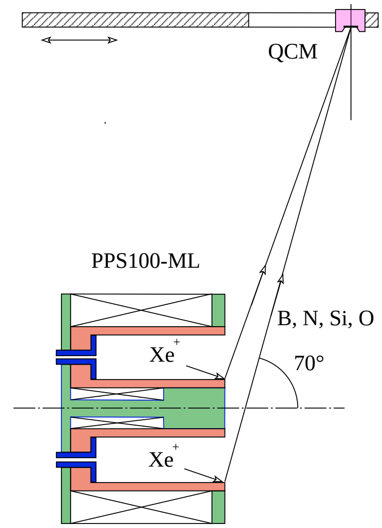

Figure 3. QCM moving above the thruster.

B. QCM calibration

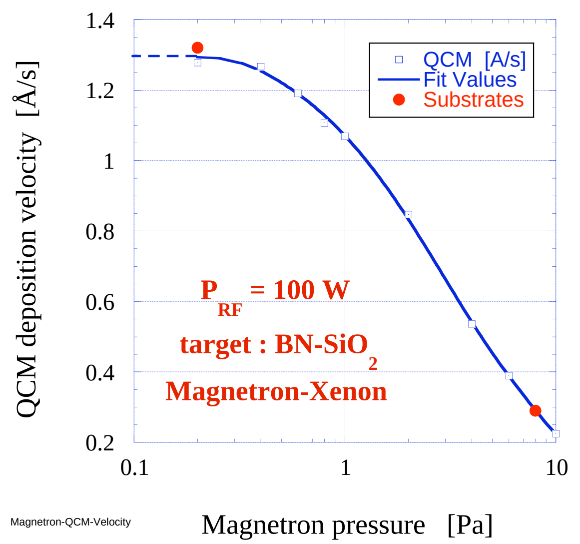

Figure 4. QCM deposition velocity versus argon pressure in a 100 W RF magnetron.

Before used to investigate the PPS100-ML thruster ceramic erosion, QCM deposition velocity and thickness were calibrated by means of a 32 mm diameter magnetron at LPGP. The QCM head was set in front of the BN-SiO_2 cathode (PPS100-ML like) of the magnetron. The 100 W RF discharge ranging from 0.2 to 10 Pa of xenon pressure allows cathode erosion by the xenon ions. The acoustic impedance of the BN-SiO_2 layer was determined by means of the measure of the silicon substrat thickness deposition by profilometry. The silicon substrat was set in front of the magnetron cathode and symmetrically to the QCM head from the magnetron axis. Two silicon substrat thickness depositions were performed for two xenon pressures: 0.2 and 10 Pa. Due to the high hardness of the BN-SiO_2 ceramic, 10 hours of cathode sputtering were needed to obtain measurable deposition thickness. During these 10 hours deposition, a good linearity was verified.

Fig. 4 shows the calibrated QCM deposition velocity when the magnetron pressure is varying and the two values obtained by the silicon substrat method. Both the two measures indicate the same 4 factor dynamic with a few percent accuracy.

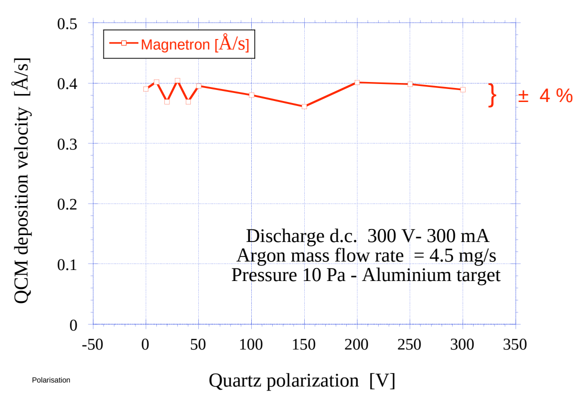

Figure 5. QCM deposition velocity versus quartz crystal polarisation.

C. QCM polarisation test

In order to estimate the influence of the quartz crystal polarisation on the QCM deposition velocity, a QCM head (as describe section II-A where the crystal holder is insulated from the grounded body of the QCM head) was employed in the LPGP magnetron. A 10 Pa argon pressure 300 V d.c. discharge was used for a better comparison with a d.c. thruster. This d.c. discharge involves a metallic cathode (here aluminium).

As shown in Fig. 5 the 0-300 V crystal polarisation had no influence on the QCM deposition velocity measurements.

D. QCM polarising and positioning

Before QCM erosion measurements and comparison with OES erosion results, QCM position has to be fixed in order to collect a quantity of erosion products sufficient for the QCM sensitivity but not to much xenon ions to avoid a too large QCM erosion. First experiment was to measure the quartz crystal erosion for both the QCM1 and QCM2 grounded when the collecting angles are ranging from 89° to 59° in relation to the thruster axis. The PPS100-ML discharge voltage was 200 V and the xenon mass flow rate fixed to 3 mg/s. Fig. 6 shows that the QCM deposition velocities are negative which indicates an erosion of the quartz crystal. This quartz crystal erosion is increasing when the angle from the thruster axis is decreasing as expected by previous divergence measurements of the xenon ion flux.[1]

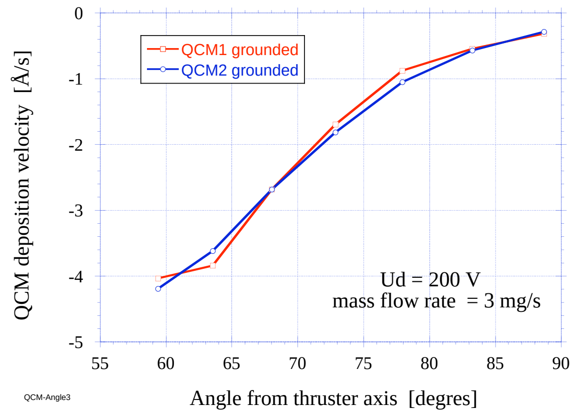

Figure 6. QCM grounded deposition velocity versus angle from the thruster axis.

The second experiment was the investigation of the QCM deposition velocity when the QCM1 is grounded and the QCM2 polarised from 0 to 300 V. The QCM were positioning at 60° in relation to the thruster axis.

The PPS100-ML discharge parameters were the same as previous (200 V - 3 mg/s). As shown on the Fig. 7 the QCM2 deposition velocity is negative for quartz crystal polarisation under 150 V and positive over 150 V. This behaviour can be easily explained by a quartz crystal erosion by the xenon ions when the polarisation is lower than 150 V and the xenon ion energy (not measured) is about 150 eV (for a 200 V discharge voltage). When the quartz crystal polarisation is higher than 150 V the xenon ions are repelled and the positive QCM deposition velocity indicates that the QCM is collecting the products of the erosion of the thruster ceramics.

The second QCM (QCM1) was grounded during this experiment and its deposition velocity should have been constant. This second QCM undergo the influence of the polarisation of the first one's.

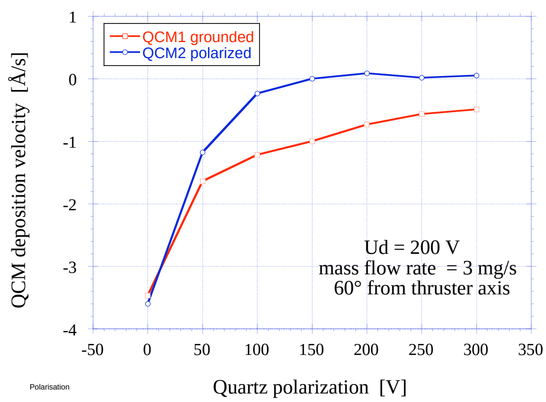

Figure 7. QCM deposition velocity versus quartz polarisation.

The third experiment was as the first one the measure of the QCM deposition velocity versus the angle of collection but with the QCM2 polarised at 250 V. Fig 8 shows that the QCM1 had the same trend as QCM1 and QCM2 in the first experiment but the QCM2 polarised at 250 V was collecting the products of the ceramic erosion. This collection is saturating when the angle from the thruster axis is lower than 65/70°, probably due to the angular distribution of erosion products diffusion.[4] Consequently an angle of 70° has been chosen afterwards. To avoid fast xenon ions to reach the quartz crystal, its polarisation was fixed to 300 V for security.

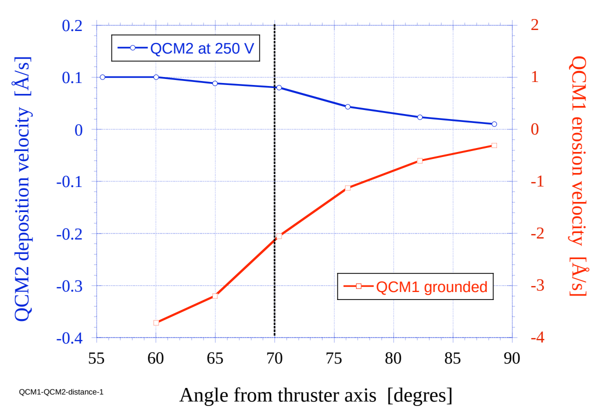

Figure 8. QCM deposition velocity versus angle from thruster axis.

It is interesting to compare the QCM deposition velocity (when polarised) to the QCM erosion velocity (when grounded). For example for a collecting angle of 70°, the erosion is by a 30 factor higher than deposition and there is no hope to collect erosion products without QCM polarisation. This ratio between erosion and deposition is varying from 25 at 80° to 37 at 60° due to the xenon ion flux divergence added to the angular distribution of erosion products diffusion.

III. Results

A. OES measurements

Study of the ceramic erosion has been carried out by means of Optical Emission Spectroscopy (OES) during the QCM measurements.

The light emitted by the xenon plasma, was collected by an external short focal quartz lens (10 cm). One end of a 500 μm diameter quartz fiber was set in the focal plan of the quartz lens. So, a spatial resolution of 1 cm was obtained thanks to a large optical magnification (20) in order to integrate possible displacement either of the plasma or erosion.

The other end of the fiber was connected to the entrance slit of a 750 mm imaging spectrometer (ACTON 750i) equipped with a CCD camera. A good spectral resolution of 0.10 nm was obtained with an entrance slit of 25 μm wide.

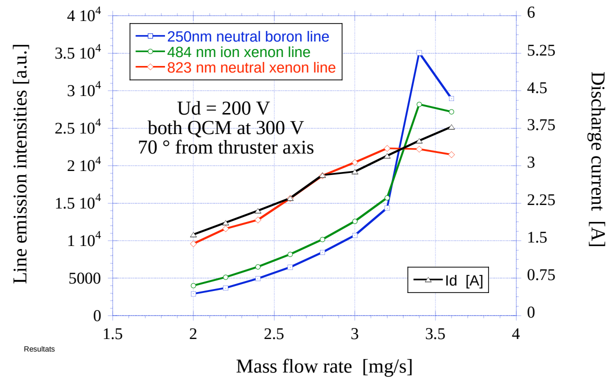

Figure 9. Line emission intensities and discharge current versus mass flow rate.

Xe, Xe^{+} and B lines emitted by the xenon plasma and by the sputtering of the BN-SiO_2 ceramic were used in conjunction with coronal model and actinometric hypothesis in order to obtain relative ceramic sputtering density (see Ref.[1] for more details). The line intensities are shown on the Fig. 9 when the discharge voltage was 200 V, both QCM at 70° from the thruster axis and 300 V polarised. Mass flow rate varying from 2 to 3.6 mg/s. On the same figure, the discharge current is reported in order to see how the line intensities are varying compare to the current. The neutral xenon line intensity variation is linear and about the same as the discharge current. The ion xenon and the boron lines have the same quadratic variation except for the 3.4 mg/s mass flow rate point.

B. QCM measurements

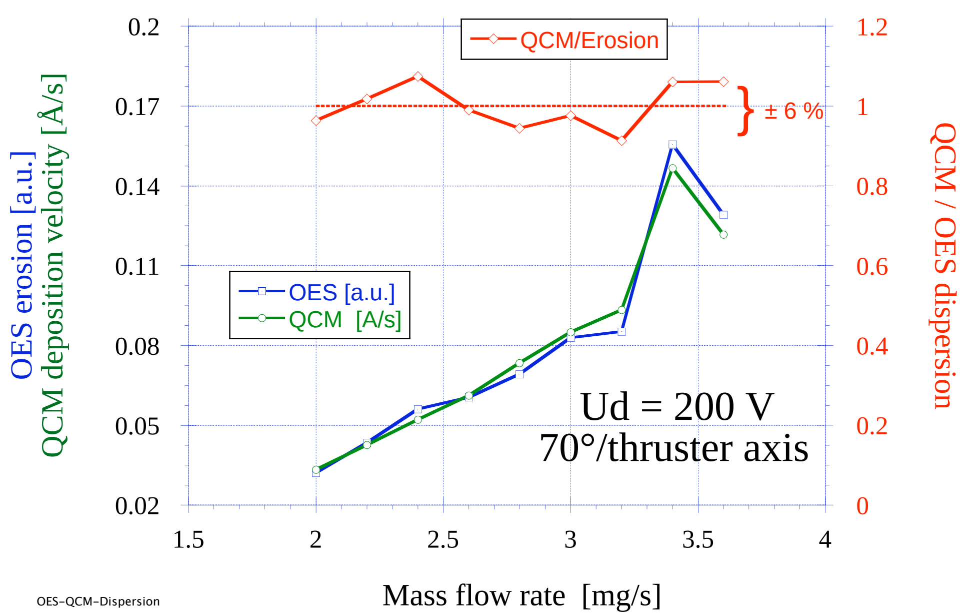

Figure 10. QCM deposition velocity and OES erosion versus mass flow rate.

In general it was found that a steady state was reached in approximately 10 min when increasing mass flow rate until 3.6 mg/s, in less 1 mn when decreasing.

As describe before, OES and QCM measurements were performed simultaneously for the same thruster parameters; 200 V discharge voltage, both QCM at 70° from the thruster axis and 300 V polarised. Mass flow rate varying from 2 to 3.6 mg/s. Fig. 10 shows the QCM deposition velocity and OES ceramic erosion results for the PPS100-ML ceramic erosion by xenon ions. The OES erosion measurement is relative and is here fitted by the QCM's. A very good correlation (std. deviation ± 6 %) is obtained between the two measurements including the peak for the 3.4 mg/s mass flow rate point which is certainly due to an increasing xenon ion flux nevertheless not observed on the discharge current.

IV. Discussion

Many ceramic wall erosion investigations have been made on various thrusters by means of Optical Emission Spectroscopy and related to discharge parameters, but it is the first time that another way (QCM) was used to measure this erosion. A Quartz Crystal Microbalance was used by L. Trevisani *et al*[9] mainly in order to avoid deposition on sensitive equipments as spacecraft solar cells. As their measurements are of the same order than ours, collecting only neutral species indicates that they have a better divergence of the xenon ion flux as ours. It can be explained by a higher mass flow rate in our experiment (2-3.6 compare to 1 mg/s).

Though only one QCM experiment was made, this one validates the erosion OES measurements in the range investigated. This validation must be next extended to larger discharge voltage and mass flow rate ranges.

Aknowledgments

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