Telemicroscopy Erosion Measurements of 5 kW-Class Hall Effect Thruster Channel Walls

IEPC-2015-348／ISTS-2015-b-348

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Tommaso Andreussi[1], Luca Pieri[2], Riccardo Albertoni[3], Mariano Andrenucci[4]
Sitael SpA, Space Propulsion Business Unit, Pisa, 56121, Italy

and

Olivier Duchemin[5]
Snecma, Space Propulsion Division, Safran Group, Vernon, 27208, France

Abstract: The present paper presents the erosion measurements performed on the Snecma PPS®X000 Technology Demonstrator Model using the Advanced EP Diagnostic (AED) system developed by Sitael. The PPS®X000 thruster has been operated for approximately 200 hours at the nominal power of 5 kW and at a discharge voltage of 1 kV. Channel profiles, taken by AED every ~30 hours of continuous operation, are reported and analyzed. Combined telemicroscopy and profilometer data show that the AED system allows for reliable measurements of the erosion evolution providing valuable insights into the nature of the erosion mechanisms.

I. Introduction

COMMERCIAL electric propulsion systems are now being considered as a cost effective solution for station keeping and orbit raising of large telecommunication satellites. Among the different electric propulsion systems, Hall Effect Thrusters (HET) are easily scalable and provide an optimal trade-off between specific impulse and thrust. Nevertheless, recent mission analyses have shown a need for thruster lifetimes for both Earth orbit raising and deep space applications in excess of 10000 hours. In particular, a thruster capable of both orbit-raising and station-keeping may become a key component in the development of all-electric satellites. In order to perform these tasks, a significant improvement in both thrusters operations and throttability is thus required. Together with the degradation of the cathode, the erosion of thruster ceramic walls due to plasma energetic particles represents the main limiting factor of the HET lifetime. Indeed, the progressive wear of the ceramic walls deteriorates the thruster's performance and eventually expose the magnetic circuit to the flux of plasma particles, leading to possible thruster failures. In this context, a better understanding of the erosion process and its evolution over time is needed to design devices able to properly operate for thousands of hours. Several theoretical models have been developed in the past years for predicting HET channel erosion[1,2,3]. However, validation with experimental data is of paramount importance to refine the models and to enhance prediction capabilities. In this context, the Sitael Advanced EP Diagnostic (AED) system is used to reconstruct the shape of the ceramic channel of the Snecma PPS®X000 Hall thruster when operated at high-I_{sp} (>2500 s). The thruster has been operated for about 200 hours at a nominal

[1] Project Engineer, Sitael SpA, tommaso.andreussi@sitael.com.
[2] Software Engineer, Sitael SpA, luca.pieri@sitael.com.
[3] Project Manager, Sitael SpA, riccardo.albertoni@sitael.com.
[4] Business Unit Manager, Sitael SpA, mariano.andrenucci@sitael.com.
[5] PPS®5000 Project Manager, Snecma, olivier.duchemin@snecma.fr.

discharge power of 5 kW and 1 kV discharge voltage in the Sitael IV10 vacuum facility. Erosion profiles have been recorded every ~30 hours of continuous operation to allow for a detailed 3D reconstruction of the channel erosion over time.

II. Experimental Setup

A. Thruster Description

The 5-kW-class PPS®X000 Technology Demonstrator is a versatile, reconfigurable Hall thruster optimized for discharge voltages of about 1 kV. This Technology Desmonstrator model was built to support the development of the PPS®5000, a flight design of equivalent scale. A detailed design and hardware upgrade activity has been carried out to enhance the thruster performance during high-voltage (high-Isp) operations. In particular, the PPS®X000 thruster used in the frame of the present test session underwent significant improvements in terms of maximum magnetic induction capability and confinement of the neutral xenon flow in the acceleration channel. Even though the standard-design PPS®X000 has already been tested at discharge voltages as high as 1 kV[3,4], operation at high voltage was not sustained beyond a few tens of minutes. In this context, the experimental activity performed at Sitael was aimed at verifying the stable and efficient operation of the new thruster design under high-voltage conditions. In addition, the empirical data gathered during the test campaign allowed for the evaluation of the main loss mechanisms at high voltage.

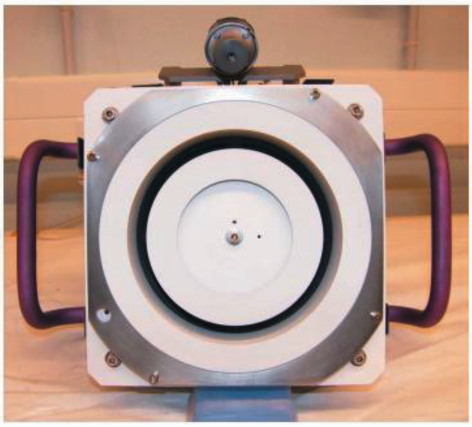
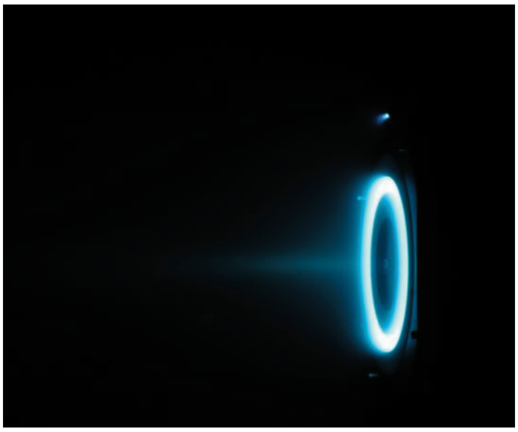

Figure 1: PPSX000 Thruster Assembly during Receiving Inspection (left) and Performance Characterization (right)

B. IV10 Test Facility

Sitael IV10 vacuum facility is the largest vacuum chamber currently available in Europe for EP testing. Vacuum vessel has total length 9.4 m, inner diameter 5.7 m and free internal volume of 160 m^3. The large size and the large volume available for the free expansion of the ion beam allows reducing the contamination of the thruster due to back-sputtering from the walls during endurance/life tests.

The vacuum chamber is equipped with LN_2 cooled bi-conical beam target which is accommodated on the opening cap of the facility in front of the thruster in order to damp the energy beam. The particular shape preferentially diverts the sputtered atoms directly towards the side walls instead of heading them back to the thruster. Moreover, all the critical surfaces undergoing significant bombardment from the thruster will also be lined up with Grafoil (purity > 99.9 %) in order to reduce the back-sputtering effects.

Figure 2: Sitael IV10 Vacuum Facility

The vessel is equipped with a large number of ISO standard flanges in order to provide the maximum flexibility when connecting pumping system, pressure sensors, residual gas analyzers, power / signal / gas feedthroughs, LN_2 pipes for thermal control, windows for optical observation.

The pumping system currently installed in IV10 permits to maintain completely oil free vacuum. The process of pumping down includes four main stages:

- Stage 1 (pressure $10^3 \times 10^{-2}$ mbar) 1 screw @ 630 m^3/hr (N_2); 1 roots (N_2)
- Stage 2 (pressure $10^{-2} \times 10^{-5}$ mbar) 2 turbo @ 2000 l/s (N_2); 2 scroll @ 25 m^3/hr (N_2)
- Stage 3 (pressure $10^{-5} \times 10^{-9}$ mbar) 2 cryo @ 5000 l/s (N_2)
- Stage 4 (pressure $10^{-5} \times 10^{-6}$ mbar) 5 cold panels @ 60000 l/s (Xe)

The total pumping speed is therefore in the order of 300000 l/s which ensured an ultimate pressure $< 1 \times 10^{-9}$ mbar and a chamber pressure in the order of $< 1 \times 10^{-5}$ mbar (Xe) during the test campaign.

C. Facility Configuration

The general facility configuration is shown in Figure 3. Briefly, the flow is metered and controlled via a facility propellant supply system (PSS). The power processing rack (PPR) delivered the required currents and voltages to the cathode heater and ignitor, electromagnet coils, flow valves, controllers and anode. A bench filter-unit (BFU) was placed on the anode line to facilitate discharge ignition and to decouple the voltage and current oscillations between the thruster and the anode supply. The BFU was a classical inductive-capacitive arrangement (L=250 µH and R=10 Ω). A Magna-Power TS1000-15 (1000V. 15A) power supply was used as anode supply. Data acquisition, PRR control and facility monitoring were performed via a LabVIEW-based computer system.

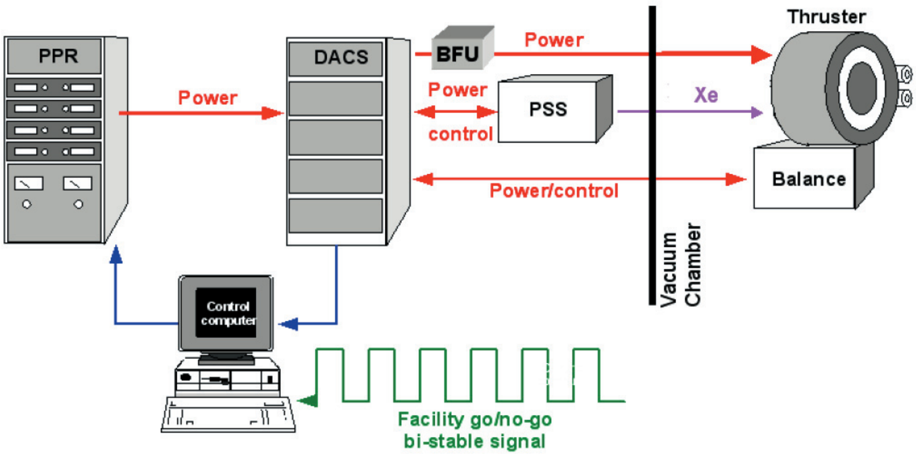

Figure 3: General Facility Configuration

The thrust measurement system consisted in a single axis thrust balance based on a double pendulum configuration, capable of sustaining the thruster weight with a degree of freedom along the principal direction. The sensing element is based on high-precision strain gages measuring the strain on the flexural elements. The thrust stand is mounted on a tilting platform actuated by a stepper motor. This system allows for thrust stand levelling during calibration and pre-firing operations. The thrust stand is also equipped with an electromagnetic calibrator, generating a reference force when requested. The calibrator is added to check the proper response of the stand during the test.

Finally, xenon flow rate through the PSS was controlled using a 500 mls/min (for the anode line) and 20 mls/min (for the cathode line) Bronkhorst mass flow controllers. The MFC units were calibrated for xenon at the factory by using air as surrogate gas and applying standard experimental correction factor. The calibration set points covered the range 10-100% of full scale and the specified accuracy is ±0.5% of full scale.

D. Advanced EP Diagnostic (AED) System

Erosion of the thruster ceramic walls was assessed by means of Sitael's Advanced Electric-propulsion thruster characterization Diagnostics (AED). AED is an automatic system, outlined in Figure 1, made up of two structured light vision systems, joined with a robotized rotating arm that allow the measurement of different profiles of the thruster. As shown in Figure 4, two laser-camera systems are used to perform the analysis of both the inner and outer ceramic walls of the thruster.

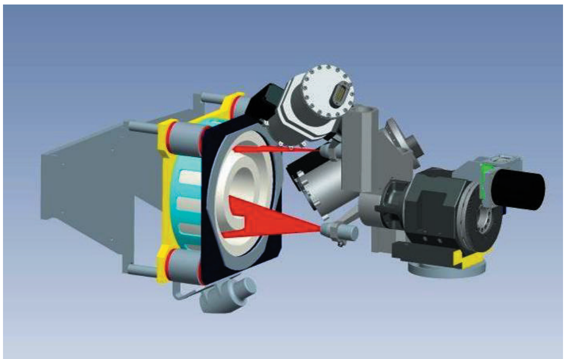

Figure 4: The Advanced Electric-propulsion thruster characterization Diagnostics (AED)

The system is placed inside the vacuum facility to have a perfect view of the thruster and to avoid any contamination due to the external environment when the erosion measurement is performed. More importantly, the system can perform erosion measurements without the need of breaking the vacuum. Figure 5 shows the experiment setup of the test campaign and, on the left, the AED system and the support structure used to move the system. The system is designed to remain in a parking position while the thruster is firing, in order to reduce the interference with the plasma plume. The movable support structure is connected to the thrust balance and can be rotated to place the AED system in front of the thruster. The camera viewports and the lasers are protected by metallic shutters, which prevent the deterioration of the vision system due to contamination or back-sputtering. When the thruster stops firing, the AED system is moved in front of the thruster and the shutters are opened. Then, the robotised arm that joins the cameras rotates and each camera records images of the insulator channel corresponding to different angular positions of the arm.

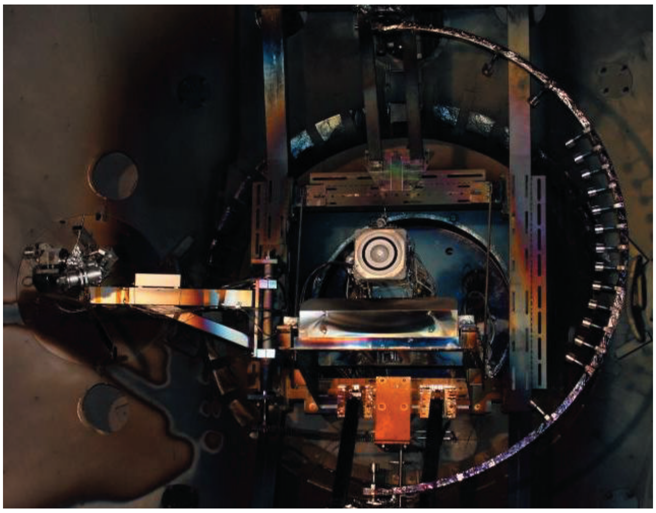

Figure 5: Test setup of the high-Isp configuration of the Snecma PPS®X000 Hall thruster. The picture shows the thruster and, on the left, the AED system.

E. Image Reconstruction Method

The use of structured light systems is a common technique to reconstruct the shape of three-dimensional objects.

When a narrow band of light (like the planar laser beams of the AED system) is projected on the object surface, the lighted line is deformed according to the 3D shape of the surface. If we look at the object through a camera we see a two-dimensional picture of the deformed line, which represents a simple projection of lighted points on the camera sensor. The calibration of the laser-camera system with a known target permits to assess the geometric parameters that define both the laser plane and the camera projection. Knowing the position of the camera reference frame and the laser frame it is thus possible to retrieve the 3D coordinates of the lighted line and reconstruct the surface shape.

The purpose of the AED system is to obtain the profile of the channel ceramic edges from the image of the projected laser lines. The calibration of two laser-camera systems, one for the outer ceramic wall and the other for the inner ceramic wall, is necessary to acquire all the key-parameters of the system, such as the laser plane orientation with respect to the camera optical axis. Since the overall accuracy of the measurement system is strictly dependent on the accuracy of the calibration procedure, each of the laser-camera system undergoes different steps of calibration. First, by using a reference calibration pattern, the internal and external camera parameters that compensate the distortion induced by optics and perspective are calibrated. A second calibration step is then performed by projecting the laser on a planar target. The target is translated by a calibrated actuator in the direction orthogonal to the surface and several pictures of the laser projection are acquired for different target positions. This permits the identification of the laser plane parameters with respect to the camera frame. Last, the geometric parameters needed to define the rotation axis of the robotized arm are calibrated on the reference thruster geometry. This calibration step is performed in the test environment, in the same condition of the successive measurements, and permit to obtain the three-dimensional shape of the ceramic surfaces. Knowing the precise channel geometry, the defects of alignment between the rotating arm and the channel axis can be compensated. Moreover, during this final calibration stage, a further refinement of the system parameters is performed.

The full calibration procedure makes possible to estimate the three dimensional scene starting from images acquired by the cameras: knowing the whole set of system parameters, it is possible to estimate by triangulation the points coordinates in 3D space with respect to the AED reference frame and, thus, to obtain the solid shape of ceramic walls.

After each images acquisition, the reconstructed 3D solid shape is aligned with respect to previous acquisitions by means of an optimization procedure. The alignment procedure permits the comparison of reconstructed shapes at different times and, consequently, the assessment of channel erosion.

It is important to notice that the final set up calibration and the alignment procedure are both based on the specific shape of the thruster and that the channel geometry (as defined in the technical drawings) is a necessary input of these procedures. Hence, small differences between the design geometry and the real geometry of the ceramics affect the reconstructed profiles.

III. Experimental Results

F. Erosion Measurements

In Table 1, images acquisitions performed by AED during the thruster endurance test are reported. Before the thruster characterization tests, a reference acquisition (called "Base" in the table) was made in order to calibrate the system.

AED Images Acquisitions	
Number	**Endurance total firing time**
Base	0 h 0’
#0	0 h 0’
#1	14 h 44’
#2	43 h 24’
#3	88 h 25’
#4	131 h 29’
#5	170 h 00’
#6	201 h 46’
#7	202 h 00’

Table 1: AED acquisitions and corresponding thruster total firing times

The rotating motion of the camera support around its own axis is fundamental for acquiring images relative to different thruster cross sections. In particular, pictures were taken every 15° starting from the cathode position, which corresponds to a set of 24 pictures per test and for each camera. The final erosion test (test #7) was performed after the post-endurance characterization tests, when the chamber was not in vacuum, i.e. in different environmental conditions with respect to the previous tests. This difference could affect the precision of the final profiles. However, due to the small difference of total firing times between test #6 and test #7, the measured profiles are almost identical and no significant degradation of the test accuracy is expected. Examples of the unprocessed images are shown in Figure 6 and Figure 7. These images correspond to the initial and final profiles at θ= 0° of the outer channel wall, Figure 6, and of the inner channel wall, Figure 7.

Figure 6: Outer channel wall at the beginning of the tests (left) and at the end of the experimental campaign (right)

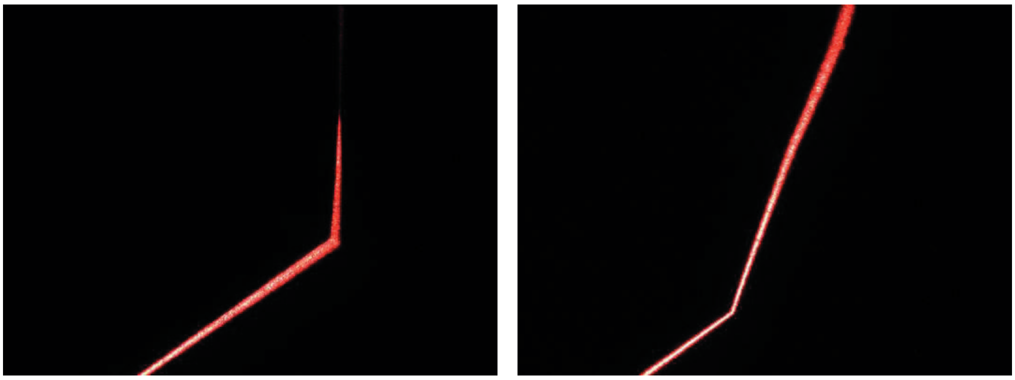

Figure 7: Inner channel wall at the beginning of the tests (left) and at the end of the experimental campaign (right)

For each picture, points lighted by the laser source are identified and averaged in order to obtain a curvilinear profile. The points of each profile are then triangulated to the 3D space and converted to a cylindrical coordinates system (r, θ, z) aligned with the thruster axis. The plane $z=0$ is arbitrarily set on the frontal edge of the ceramic walls at $t=0$.

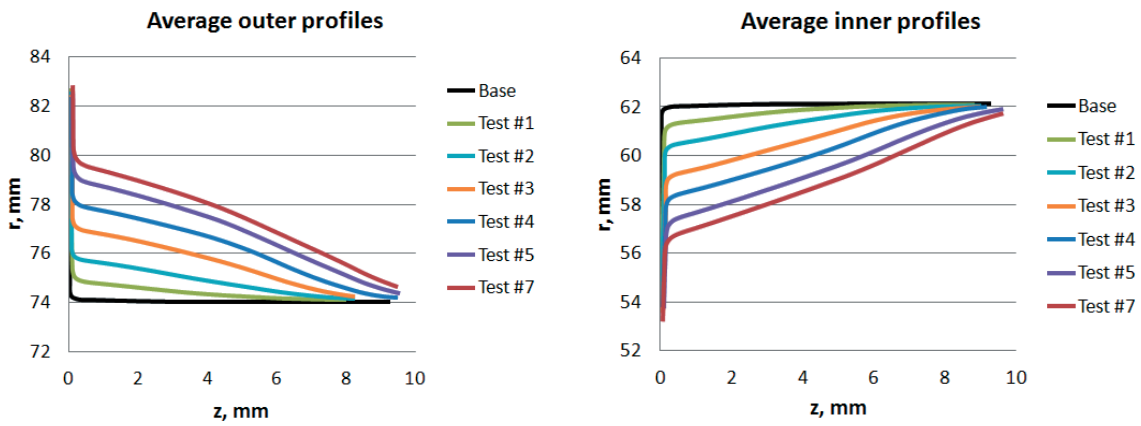

Figure 8: Average profiles of the outer ceramic wall (left) and inner ceramic wall (right) at different test times.

Results of the experimental campaign are summarized in Figure 8, which shows the reconstructed (*r,z*) profiles averaged with respect to the angular position. Due to high-voltage thruster operation, the measured erosion after approximately 200 hours is of the order of 5.5 millimeters for both inner and outer ceramics. Moreover, from the qualitative viewpoint, the erosion of the inner and outer walls shows a similar progression. After the completion of the test, the final shape of the ceramic walls was assessed by Snecma using a manual profilometer (post-test inspection). The comparison between the post-test inspection and the final measurement performed by the AED system is show in Figure 9. A small deviation between the two measurements can be observed for internal channel points. However, as shown in Figure 7, at the boundary of the picture frame the laser line became out of focus and a lower accuracy in the measurement of the laser centerline was expected.

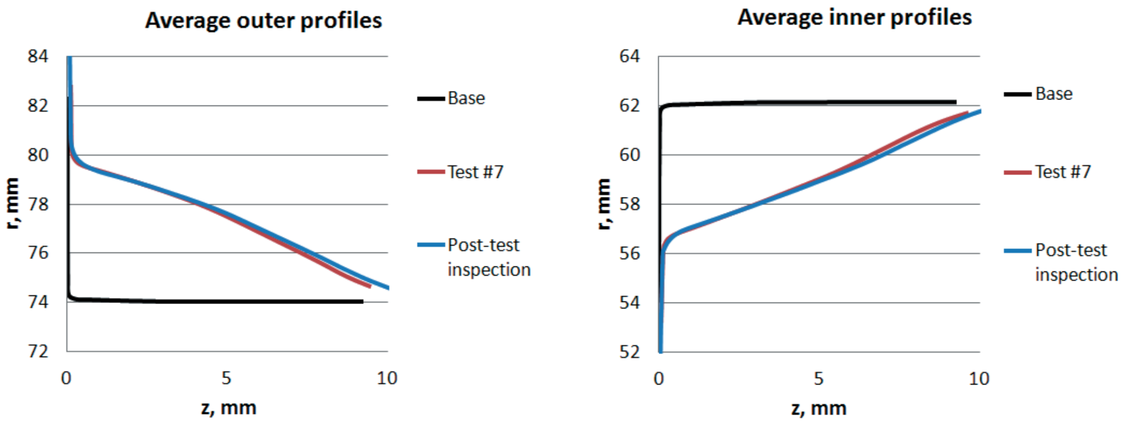

Figure 9: Comparison between the post-test channel profiles, averaged with respect to the angular coordinate, and the final AED measurements.

IV. Conclusion

The Sitael Advanced EP Diagnostic (AED) system has been used to measure the evolution over time of the erosion of the PPS®X000 technological demonstrator operated at 1 kV. Detailed measurements have been performed along both longitudinal and azimuthal directions providing a full 3D reconstruction of the eroded profile. Direct comparison between AED-measured data and profilometer data shows a very good accordance supporting the trustworthiness of the AED technology when used for high-power EP systems.

Acknowledgments

This work was performed within the framework of the “High-Voltage Single-Stage Hall-Effect Thruster” ESA Technology Research Programme under Snecma contract 752-015.

References

[1] S.Y.Cheng, M. Martinez Sanchez, “*Modelling of Hall Thruster Lifetime and Erosion Mechanisms*”, IEPC-2007-250, 30th International Electric Propulsion Conference, Florence, September 17-20, 2007.

[2] T. Tondu, V. Viel-Inguimbert, J.F. Roussel, “*Hall Effect Thrusters Ceramics Sputtering Yield Determination by Monte Carlo Simulations*”, AIAA-2008-5090, Joint Propulsion Conference, Hartford, CT, USA, July 2008.

[3] M. Gamero-Castano and I. Katz, “*Estimation of Hall Thruster Erosion Using HPHall*”, IEPC-2005-303, 29th International Electric Propulsion Conference, Princeton University, New Jersey, October 31 – November 4, 2005

[4] O. Duchemin, “*Stretching of the Operational Envelope of the PPSX000 Plasma Thruster*”, AIAA-2004-3605, 40th Joint Propulsion Conference, Ft. Lauderdale, Florida, July 2004.

[5] O. Duchemin, “*Testing the PPSX000 Plasma Thruster at High Discharge Voltage*”, ESA SP-555, 2004