High Throughput 1.5 kW Hall Thruster for Satcoms

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Abstract: In order to increase the lifetime of Hall thrusters, a "Low erosion" approach is described, consisting in moving the magnetic poles upstream the end-of-life eroded profile of discharge chambers. The erosion rate of the ceramic chambers is lowered but not cancelled. The same magnetic topology as for original thrusters is imposed in the discharge channel in order to benefit from former qualifications. A Low Erosion PPS®1350 was manufactured and tested. The comparison between standard PPS®1350 thrusters, qualified at 1.5 kW and 2.5 kW both at 3.3 MN.s, has shown identical thrust and Isp. Moreover the new total impulse of the Low Erosion 1.5 kW thruster was evaluated at about 12 MN.s with a 700 kg xenon throughput but requires the implementation of a longer lasting cathode, like the PPS®5000 cathode. Because of their high xenon throughput, Low Erosion thrusters may offer new opportunities for low and mid power thrusters as for example, all electric propulsion of small GEO telecommunications satellites or redundancy options for high power satellites.

Nomenclature

EOL	=	End of life
Id, Ud	=	Discharge current and voltage
Um	=	Voltage applied to power the coils in series
LE	=	Low Erosion design of a Hall thruster
MS	=	Magnetic Shielded design of a Hall thruster
PPU	=	Power processing unit

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I. Introduction

IN recent years, Safran Aircraft Engines has made concentrated efforts to diversify its offer of Hall thrusters. The first Hall thruster initially qualified was the PPS®1350-G at 1.5 kW. This thruster was initially developed for North-South Station Keeping maneuvers of geostationary satellites. With an average thrust of 87 mN and an average specific impulse above 1633 s, the PPS®1350 demonstrated a total impulse of 3.3 MNs under various and extreme environmental conditions. A total ground qualification time of 10 532 hours was reached in 2007, representing a total xenon throughput of 206 kg[6].

From 2012, it was recognized that the use of EP on the commercial market, in conjunction with the emergence of a broadening offer for launch services, would lead the market towards "all-electric" spacecraft where most, or essentially all, propulsive maneuvers would be assigned to the EP system. Aiming at performing both orbit raising and station keeping, the qualification of a 5 kW thruster, the PPS®5000, was then initiated by Safran Aircraft Engines. This thruster was designed with a lifetime requirement leading to a minimum total impulse capability of 11.7 MN.s, with the objective of reaching 14.5 MN.s. This amounts to a total xenon throughput of 825 kg. More recently, the emergence of constellations has resulted in the need of lower power hall thrusters for LEO. In order to cover this emerging market, a 650 W thruster, the PPS®X00, is currently under development by Safran Aircraft Engines.

In parallel to the widening range of electric power of thrusters, a significant increase of total impulse was also required, underlining the need of developing high throughput Hall thrusters. It is well known that the operational lifetime of HETs is determined by the amount of time the thruster can operate before the plasma within the channel damages the magnetic system. Next figure 1 shows a photograph of an aged PPS®1350 during qualification. After a complete beveling of the dielectric discharge channel exit, ion plume interacts with the inner and outer magnetic poles and generate a progressive erosion of the magnetic circuit. This moment is often called "soft failure". Hall thrusters continue operating after the magnetic poles are first exposed without performance changes. A definitive stop of thruster operation is named "hard failure". In 2009, a breakthrough eliminating this erosion of the magnetic circuit was proposed[1] by the NASA/JPL. A new magnetic topology called "magnetic shielding" (MS) was described to reduce drastically the channel erosion which could lead to eliminate this failure mode of Hall thruster.

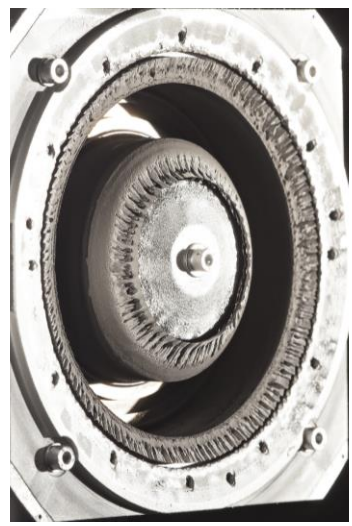

Figure 1. Erosion of the ceramic discharge channel and magnetic poles of an aged PPS®1350.

With co-funding of ESA and CNES, Safran Aircraft Engines has developed a high throughput version of the PPS®1350 Hall thruster, increasing the margins before appearance of an erosion of the magnetic poles. This publication describes the proposed design methodology, named "Low Erosion" (LE). A 1.5 kW prototype was manufactured and tested in order to estimate the thruster performances and erosion rates of both ceramics and magnetic poles. Finally, the increased capabilities of the low erosion Hall thruster are also discussed for Satcom applications.

II. High Throughput Hall Thrusters

The lifetime of Hall thrusters has historically been limited by erosion of the discharge channel caused by ion impacts. In order to eliminate the channel erosion as a failure mode, NASA/JPL proposed a concept called "magnetic shielding"[1] reducing by several orders of magnitude the discharge channel erosion, due to the ion bombardment. The magnetic shielding exploits the isothermality of magnetic field lines that extend deep into the acceleration channel, which marginalizes the effect of plasma density and temperature in the thermalized potential. From a practical point of view, a magnetic circuit is designed in order to obtain parallel magnetic lines to the ceramic inner and outer walls. An empirical approach was first followed, based on trial-and-error. The cancellation of the ceramic ring erosion was demonstrated, however the displacement of the plasma acceleration zone downstream the thruster exit lead to a small erosion of the magnetic poles[2,3].

In order to increase significantly the timescale corresponding to a full beveling of the ceramic rings of a standard thruster and before starting erosion of the magnetic poles, an alternative methodology is proposed here with the aim of significantly increasing the xenon throughput of Hall thrusters. The approach is named "Low Erosion" and is described in the next paragraphs.

A. Low Erosion Hall thrusters

In order to design high throughput thrusters, several criteria were defined as follows:

1) Allow but minimize erosion of the dielectric discharge channel in order to clean the outlet of the ceramic rings at EOL. Qualifying a thruster means firing a qualification model during several thousand hours in a vacuum test facility. Because of ion jet impacts with the vacuum facility walls, significant eroded material is backsputtered to the thruster walls and to the discharge channel. Because of the important role played by plasma – wall interactions in Hall thrusters (for example secondary electron emissions), a low erosion rate of the ceramics but greater than the backsputtered yield of pollutants to the ceramics is sought.
2) In the discharge channel, specify a magnetic topology corresponding to a standard thruster, (identical to the topology of the qualified PPS®1350 thruster). In order to benefit from the previous 10 532 qualification hours, a magnetic topology "as close as possible to the PPS®1350 topology" was imposed in the ionization and acceleration zones of the "Low Erosion" thruster. The main objective was to guarantee the same thrust, Isp and jet divergence, as a follow-up to the former version of the PPS®1350.
3) Shift the magnetic poles upstream the EOL profiles of the discharge channel. This shifting aims at increasing the thruster throughput before "soft failure" occurrence.

Figure 2 compares the Low Erosion approach to the standard topology of the former PPS®1350 and the MS design of Hall thrusters. One can infer that the LE concept generates an intermediate magnetic topology, between the standard and the magnetically-shielded topologies.

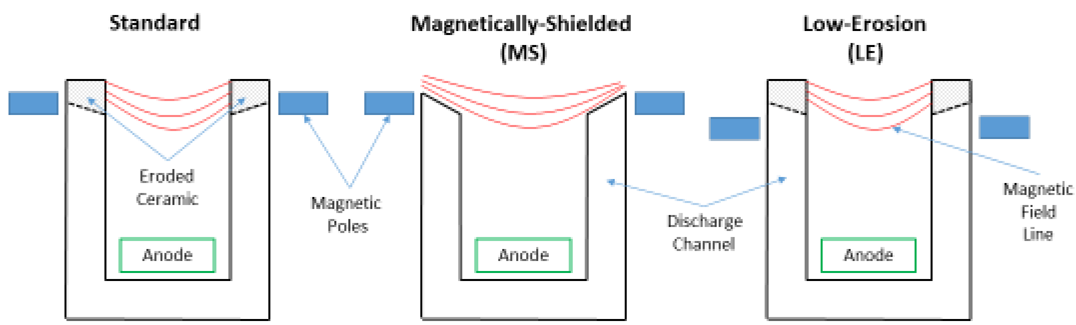

Figure 2. Comparison of the Standard, "Magnetically-Shielded" and "Low-Erosion" concepts.

When designing a LE thruster, three main issues are to be solved. Firstly, one needs to determine the EOL profiles of the discharge channel in order to specify correctly the upstream recess of the magnetic poles versus the ceramic exit plane. Currently, correlations are used to predict these profiles but a specific software will be developed in the future. Secondly, guaranteeing an erosion rate higher than the pollution yield of the test facility is tricky and is dependent of the materials, size and design of the facility walls. In order to minimize the thruster pollution due to facility contaminations, carbon plates were installed in Safran's vacuum test facilities. Moreover, Quartz Crystal Microbalance were installed in the test facility to quantify the backsputtering rate of pollution and the low-intrusiveness of the vacuum facility. The measured pollution rate inside the test facility is equal to about 11 µm/kh. Erosion yields of the discharge channel can also be measured by successive in-situ ceramic profile scans with adequate spatial resolution and uncertainty quantification of the selected diagnostic. During our tests, ex-situ 3D digitalization were performed by a scanner having a 50 µm resolution. Finally, the design of LE thrusters is essentially driven by an optimization of the magnetic circuit and poles. This issue was addressed by the development of a specific design software, relying on optimization algorithms and is described in the next paragraph.

B. Optimization of Hall thruster magnetic circuit

Optimal design of electromagnetic systems and more specifically the design of a LE magnetic circuit can be understood and formulated as an inverse problem. Many electromagnetic problems require determining the spatial distribution of an unknown quantity (material distribution in space or the source; e.g., the current density) which produces a specified quantity (the effect, e.g. the magnetic field, the induced current density or the electrodynamic force) in a specified region of the space. These problems belong to the class of inverse problems. An inverse problem can be resolved as an optimization problem. The developed design method uses a parametric optimization algorithm with a resolution using a finite elements method in order to achieve an optimized geometry; see Ref. 5. The finite elements model takes as an input the geometric parameters of the structure and it will output the values of the field for an optimal current configuration. An evaluation criterion for the optimization function is then calculated to assess the correlation between the field values obtained and the initially target set values of the magnetic field. Assumptions conventionally used of azimuthal homogeneity of the field in the thruster channel (invariance of the Flux density along the circumference of the channel) allow reducing this model to a 2D model, which represents a considerable saving of time because many functions are called for the evaluation criterion and derivatives during the optimization procedure.

Here, the starting structure is represented by the standard PPS®1350 magnetic circuit (see Fig. 3) because the objective is to reproduce the same magnetic topology of this magnetic circuit but with additional constraints. This approach is focused on the optimization of magnetic poles shape, magnetic screens dimensions and also current values in the coils. The variables of the problem are represented in Fig. 3 and they are identified by control points (green dots) that define magnetic poles, heights of magnetics screens, horizontal position of external screen and coils currents.

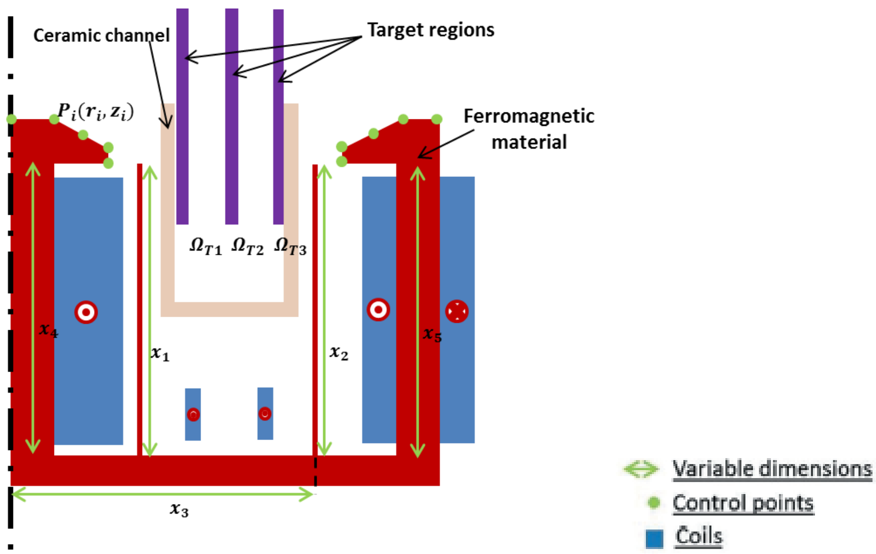

Figure 3. Optimization of the magnetic circuit of Low Erosion thrusters.

Thus, we have three types of variables: control points, dimensions and currents in the coils. There are ten control points, three variable dimensions and three variable currents (internal coil, external coil and trim coil current). The goal is to reproduce the same magnetic mapping of the PPS®1350 with a new LE shape of the entire magnetic circuit. This new shape must be "shorter" than the classical shape and as consequence with pole pieces lower than the standard version but at the same time with the same magnetic topology. To achieve this goal an innovative optimization method was employed. This methods is divided into three different optimization steps:

1) A first optimization step with the algorithm named ATOP (Algorithm To Optimize Propulsion) was performed; see Ref. 7 for more details. In order to adapt the entire structure to the new architecture, the algorithm modified the structure leaving the magnetic field unchanged.
2) After this first step, the magnetic target was satisfied except for the magnetic lens that was too high. A second optimization step was then necessary to improve the magnetic lens. A topology optimization process was applied to the external pole piece to find a new shape of the iron volume. The goal was to improve the magnetic lens and at the same time generate a lower structure with no change in the targeted magnetic topology.
3) After the topology optimization step, a new innovative shape for the external pole piece was found. This new shape allowed to generate the targeted magnetic topology with the specified magnetic lens but with a lower structure to remove iron and copper from erosion areas. A third parametric optimization step was necessary to adapt this new shape to the industrial manufacturing needs.

After this iterative process, a new Low Erosion architecture was proposed. It should be underlined that this process is more difficult to follow if applied to small thrusters (up to 300 W) because the magnetic circuit is closer to magnetic saturation in the inner coil and circuit parts.

III. Design and testing of a Low Erosion PPS®1350

In order to validate the LE methodology and to evaluate the magnetic circuit designed previously, a new thruster was manufactured. It should be noticed that the standard PPS®1350 was designed at 1.5 kW (i.e. Ud+Um = 350 V; Id = 4.28 A) but a qualification test of an upgraded version of the PPS®1350 at 2.5 kW (Id = 7 A and Ud+Um = 350 V) was also realized in 2013 and 2014. A cumulated duration of 6722 hours was reached and when averaging over the qualification test campaign, the following performances were obtained at 2.5 kW: thrust 140 mN; total Isp 1820 s; total efficiency 50%. The jet divergence was equal to 39°. Projected lifetime, based on the test results, showed a total impulse of about 3.4 MNs, similar to the qualification at 1.5 kW. As expected for a standard thruster, a significant erosion of the discharge channel was measured. The PPS®1350 at 2.5 kW and at EOL was chosen for validation of the LE design, with the aim of performing a follow-up test of the LE prototype with EOL profiles.

A. Manufacturing of the Low Erosion PPS®1350 prototype

The EOL ceramic profiles of the PPS®1350 at 2.5 kW were digitalized and post-processed in order to manufacture a discharge channel for the LE prototype. As expected, abnormal erosion led to striations of the discharge chamber but an axisymmetric ceramic profile, averaged from the 3D digitalization, was specified in order to be easily machined from a ceramic ingot.

A new magnetic circuit was also manufactured and the magnetic field generated by this new circuit was compared to the magnetic topology of the original standard thruster. The radial magnetic profiles are shown on Fig. 5. Minor differences were measured on the outer ceramic wall but as a whole the magnetic field inside the discharge channel is accurate enough compared to the standard PPS®1350. A photograph of the manufactured prototype is presented Fig. 4. This thruster, named PPS®1350-LE, was then evaluated in the Pivoine test facility, described below.

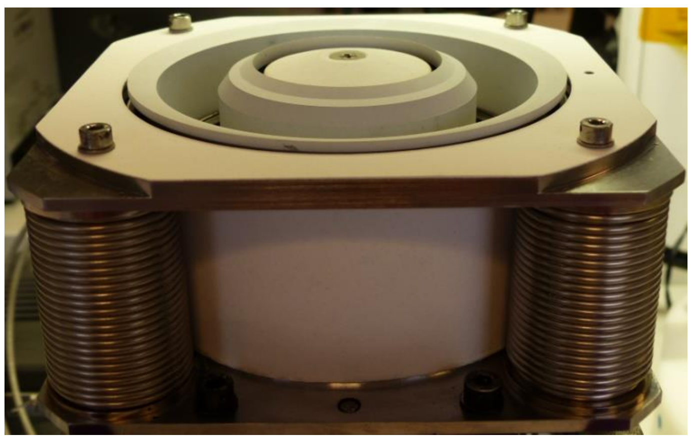

Figure 4. LE Prototype of PPS®1350 with EOL profiles.

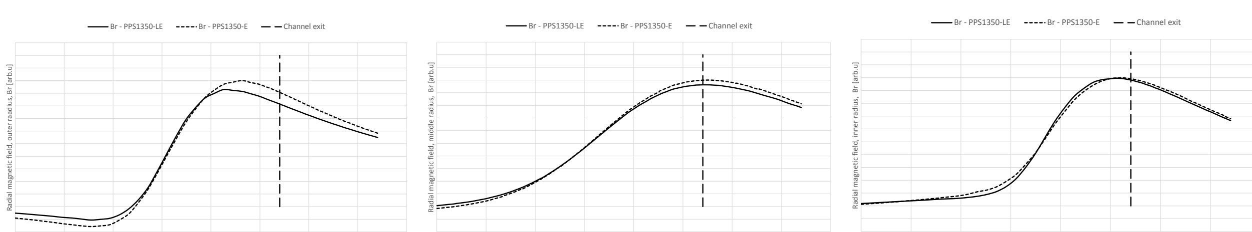

Figure 5. Comparison of the radial magnetic profiles between standard PPS®1350 (solid line) and LE version of the PPS®1350 (dashed line). Respectively outer, middle and inner profiles.

B. Pivoine Test Facility

The Pivoine test facility was built in 1997 with the support of the French space agency CNES, the "Région Centre" council and Safran Aircraft Engines. This facility is dedicated to research activities in the field of electric propulsion and enables different research teams to test Hall thrusters, to develop new diagnostics and to characterize experimentally thrusters. In 2007, an upgraded version of the Pivoine test facility was built. The current version is made of two cryogenic stages, optimized for xenon as a propellant. The first stage enables to test 5 mg/s thrusters at a pressure of 2.10^{-5} mbar. With both stages operating, 21 mg/s thruster tests can be performed at 2.10^{-5} mbar. The test facility is equipped of different diagnostics, like a thrust balance, plasma probes and several acquisition systems. A cylindrical test port was mounted along the main axis of the chamber. A photograph of the test facility is shown Fig. 6.

Figure 6. Pivoine test facility of CNRS

The test facility was upgraded in 2018 in order to perform automated 24 hours a day tests. An automatic control system was developed and validated, monitoring both thruster and test facility parameters. This new system was implemented during our tests, in order to age the PPS®1350-LE prototype for high discharge voltages; see paragraph E.

Several topics were addressed during these tests: comparison of the thruster performances (thrust, Isp, jet divergence) between the qualified standard PPS®1350 and the LE prototype at both 1.5 kW and 2.5 kW; evaluation of the erosion rate of the ceramics and the increase of total impulse and throughput. In a second phase, the capability of the thruster to operate at higher discharge voltages than 350 V was also evaluated.

C. Tests results of the Low Erosion version of the PPS®1350 prototype at 350 V

The first wear test with the PPS®1350-LE was carried out, aiming at comparing performances of LE and standard PPS®1350 versions at 1.5 kW and 2.5 kW. A total of 1020 hours was reached, enabling the measurement of erosion rates of magnetic poles and channel. The thruster was taken out of the test facility several times and 3D digitalization were realized to measure the eroded profiles. Three scans were performed after 270 hours, 590 hours and 996 hours of cumulated operating time at 2.5 kW and 350 V. During the test, the thrust and jet divergence were measured both at 1.5 kW and 2.5 kW every 24 hours. Next figure 8 shows the evolution of thrust, efficiency and Isp with time.

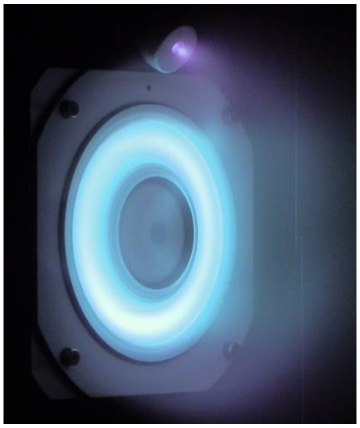

Figure 7. PPS®1350-LE at 2.5 kW and 350 V

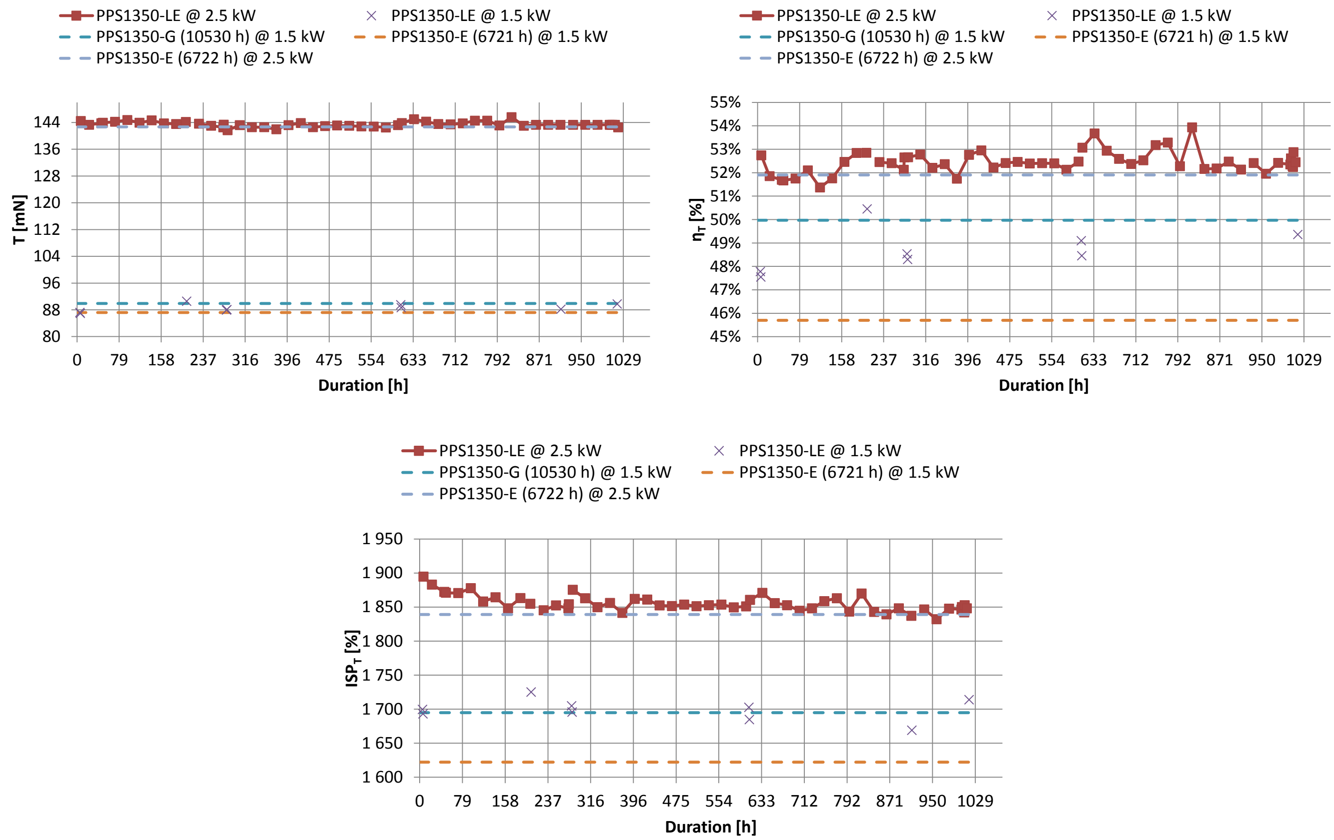

Figure 8. Evolution of performances during the PPS®1350-LE wear test at 2.5 kW and Ud+Um = 350 V

From the measured data, it was concluded that the LE prototype performances remained very stable over the 1020 h wear test. Thrust and Isp are identical to the EOL performances of the standard PPS®1350, qualified respectively at 2.5 kW (EOL at 6722 h) and 1.5 kW (EOL at 10530 h). Table 1 summarizes the performances obtained for the prototype at 1.5 kW and 2.5 kW and are compared to the standard PPS®1350 qualification models. No notable differences were identified.

Table 1. Overview of the PPS®1350-LE averaged performances at Ud+Um = 350 V

Thruster	Ud+Um [V]	P_{TOT} [kW]	T [mN]	η_T [%]	Isp_T [s]
PPS®1350-LE	**350**	**1.5**	**89**	**49.4**	**1700**
PPS®1350 1.5 kW (EOL)	**350**	**1.5**	**90**	**50.0**	**1700**
PPS®1350 2.5 kW (EOL)	**350**	**1.5**	**87**	**46.0**	**1620**
PPS®1350-LE	**350**	**2.5**	**143**	**51.8**	**1849**
PPS®1350 2.5 kW (EOL)	**350**	**2.5**	**143**	**51.7**	**1847**

A picture of the magnetic poles is shown in Fig. 9. A comparison of the different scanned profiles was performed and the erosion rates were deduced after post-processing the data. These erosion yields for the inner and outer walls are plotted on Fig. 10. A higher erosion rate was measured at the beginning of the wear test. It can probably be explained by the smooth and averaged profile chosen for the machined ceramic chamber, without anomalous erosion patterns. The maximum erosion rates measured at the end of the wear test are for the inner wall 30 µm/kh ± 123 µm/kh and for the outer wall 220 µm/kh ± 123 µm/kh. However the erosion rates were not fully stabilized and tended to decrease over time. To consolidate these values, more hours of wear test would be necessary.

Figure 9. Inner and outer magnetic pole after 1020 h

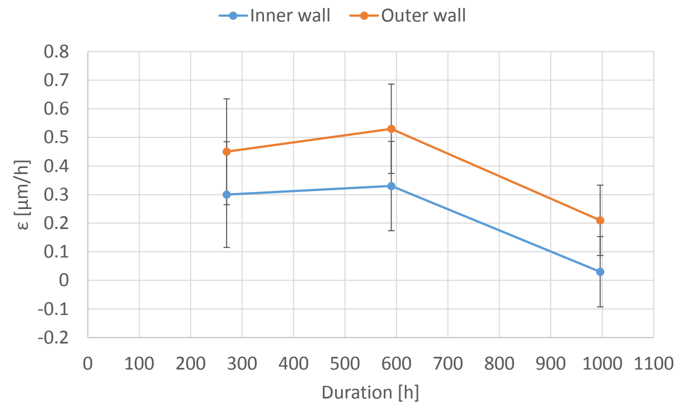

Figure 10. Evolution of the maximum erosion rates during the wear test for the discharge channel

The magnetic poles were also digitalized and no erosion was quantifiable. Both inner and outer magnetic poles were covered by carbon deposits and became almost fully black; see Fig. 9. It was concluded that the magnetic poles were pushed back upstream the discharge channel at an adequate distance.

Based on the last erosion measurements, the potential lifetime and throughput of this thruster will be discussed in next paragraph.

D. Throughput evaluation of the Low Erosion version of the PPS®1350

The lifetime estimation of the Low Erosion PPS®1350 is based on evaluating the duration needed to fully erode the remaining ceramic of either the inner or the outer part of the channel. The EOL time is consequently considered at "soft failure" occurrence. The lifetime of the thruster is limited by the outer wall owing to an erosion rate seven times higher (220 µm/kh) than the inner wall (30 µm/kh) and less ceramic available. However, it should be noticed that the erosion rate of the inner wall is within the resolution capabilities of the 3D digitalization scanner. Assuming a mean thrust over life equal to 140 mN and 1845 s for the total Isp, table 2 summarizes the lifetime for the inner and outer walls as well as the corresponding total impulse and throughput. Thus, the estimated total impulse of the LE PPS®1350 is of about 12 MN.s with about 700 kg for the throughput. An additional life test should be required to refine this estimation because a steady erosion rate could not be reached after this test campaign. Moreover the probability to get a longer lifetime is to be consolidated further because the erosion rate tends to decrease over time (see Fig. 10). Compared to the standard PPS®1350 at 2.5 kW, the lifetime gain of the discharge channel is of about 4. This increase is however not compatible with the lifetime of the 1.5 kW cathode but the implementation of the PPS®5000 cathode can resolve this limitation.

Table 2. Lifetime estimations of the PPS®1350-LE at 2.5 kW and 350 V

PPS®1350-LE	Averaged estimations at EOL (soft failure)
Inner wall	~ 180 kh
Outer wall	**~ 25 kh**
Total impulse	~ 12 MN.s
Throughput	~ 700 kg

It is also important to notice that the definition of EOL in Table 2 is very different from the EOL criteria for the former PPS®1350 versions. For the LE thruster, the lifetime criteria corresponds to a "soft failure" when for the standard PPS®1350 at 3.3 MN.s, erosion of the magnetic pole were observed, meaning that the previous EOL lifetime are actually between "soft" and "hard failure" EOL lifetimes.

E. Tests results of the Low Erosion version of the PPS®1350 prototype at higher discharge voltages

Further to the 1020 hours at 2.5 kW and 350 V, a second wear test has been carried out with the LE prototype. The discharge channel of the thruster was changed by a new one made of pure boron nitride. The aim was to explore the limit of the thruster at higher voltage for station keeping maneuvers during a short wear test.

The thruster was tested successfully up to 1000 V but an unstable behavior of the discharge was noticed at high voltages. During further discharge voltage explorations, the operating point 2.5 kW and 500 V was finally selected. A short test of about 85 hours was then performed. Next table and Fig. 11 show the measured performances.

Table 3. Performances of the PPS®1350-LE at 2.5 kW and higher Isp

Total power [kW]	Ud [V]	F [mN]	Isp_T [s]	η_T [%]
2.5	500	115	1930	43

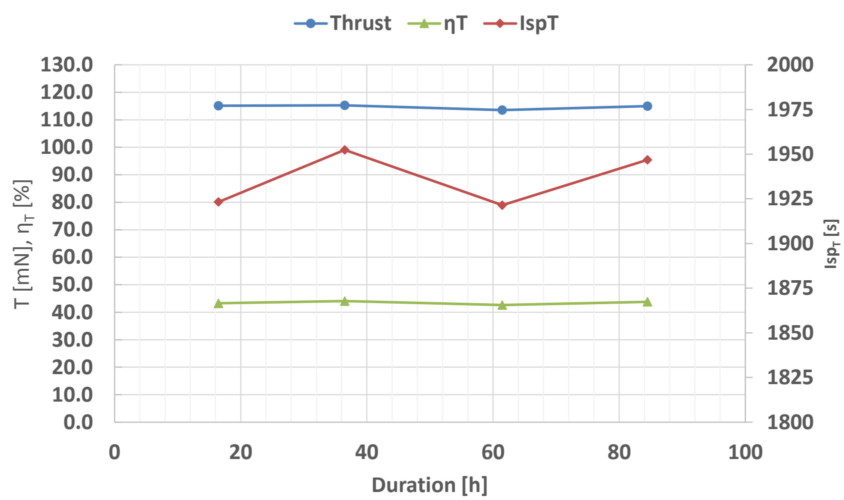

Figure 11. Evolution of the performances during the PPS®1350-LE test at 500 V and 2.5 kW

The thruster performances remain stable and constant at 500 V. Erosion measurements could not be realized because of the too short test duration and consequently erosion of the ceramic rings.

IV. Discussion: Low Erosion Hall thrusters for Satcoms

Previous results and tests of the PPS®1350 prototype have shown that a Low Erosion magnetic circuit can significantly increase the lifetime of Hall thrusters, assuming that the cathode has the lifetime capabilities. However, it is obvious that specifying an infinite xenon throughput for a thruster is not mandatory because of finite lifetime and finite mass of xenon onboard telecommunication satellites. In this paragraph, we propose to estimate the maximum throughput need for Hall thrusters used onboard satcoms. Hereafter, we will rely on averaged data in order to obtain orders of magnitude rather than absolute estimations.

If M_{wet} [kg] denotes the wet mass and P_{PL} [W] the payload power of a spacecraft, the following relationship is proposed[8]:

$$M_{wet} = 4.6\, {P_{PL}}^{0.73} + 140 \qquad (1)$$

The previous equation[8] is not specific to full EP satellites and relies on chemical propulsion systems, so that we assume that the mass gain due to EP will be used to increase the payload mass and not to reduce the spacecraft wet mass. Moreover we assume that the xenon mass onboard the satellite is equal to 20% of the spacecraft wet mass. From previous assumptions, next curves can be plotted for communications satellites.

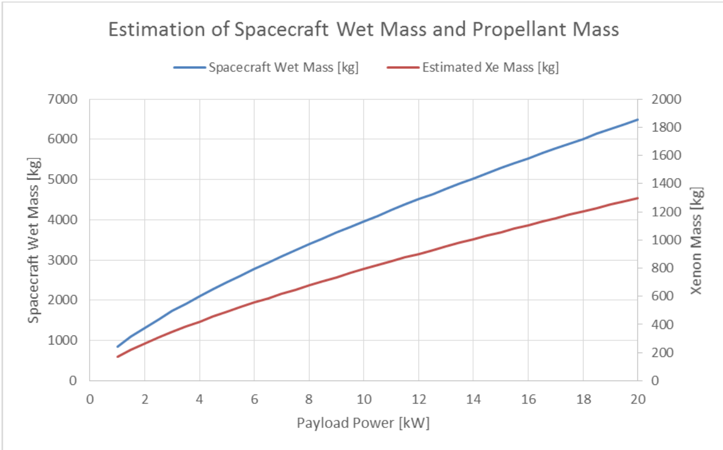

Figure 12. Estimation of spacecraft wet mass and xenon mass as a function of payload power for communications satellites

The xenon throughput of standard and low erosion Hall are now estimated. The lifetime of standard Hall thrusters is proportional to the size of the discharge channel but it should be noticed that the lifetime estimation given hereafter corresponds to an estimation of the "soft failure" time.

Let *D* [mm] denote the discharge channel mean diameter, *Pd* [kW] the power discharge, T [mN] the averaged thrust, η_t the total efficiency, *LT* [kHours] the thruster lifetime. At first order, the current correlations can be established:

$$Pd = \frac{D^2}{4200} \; ; \; T = 56 * Pd \; ; \; \eta_t = 0.049 * \ln(Pd) + 0.466 \; ; \; LT \sim 0.1 * D \qquad (2)$$

From previous equation set (2), the total impulse and the total xenon throughput of a thruster can be estimated. Next figure 13 shows the evolution of both quantities for a standard Hall thruster.

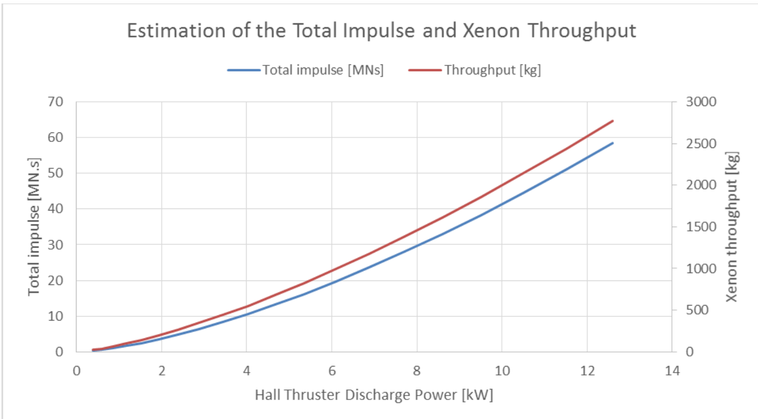

Figure 13. Total impulse and xenon throughput of standard Hall thrusters; EOL estimated at "soft failure" time.

Comparing xenon mass onboard satellites to thruster throughputs shows that a single standard thruster designed for high discharge power can consume the total xenon mass of the satellite. This unit ratio between propellant mass and throughput is obviously very severe because several thrusters are implement on satellite platforms but we aim to impose significant margins. Consequently, low erosion designs are mainly of interest for telecommunications satellites making use of mid and low power thrusters.

At “soft failure” EOL time, the PPS®1350-LE has an estimated throughput of ~ 700 kg versus ~150 kg for the original version. Defining the LE mass gain by the ratio of the xenon throughput between LE and standard thrusters, the minimum LE gain is equal to ~ 4. As mentioned previously, the PPS®1350 cathode will not be able to reach such a high throughput so that the PPS®5000 cathode is to be used.

For the current 5kW PPS®5000 thruster under qualification, a Low Erosion architecture was also designed for the anode block but the thruster lifetime will be set by the cathode. The throughput targeted for the qualification test campaign is 825 kg to be compared to ~ 700 kg of a standard thruster. The actual LE gain of the PPS®5000 thruster was not determined experimentally up to now but a LE gain of at least 2 or 3 can be expected for the anode block. This leads to a throughput of about 1 700 kg, significantly higher than the total xenon mass stored onboard current large telecommunications satellites. However, as mentioned previously, the lifetime expectation of the thruster is no more limited by the anode block but by the cathode. The current cathode was not designed to achieve a 1.7 ton throughput so that a full PPS®5000-LE will need to redesign an improved cathode.

Currently, a 650 W Hall thruster, the PPS®X00, is also under development. The specified throughput for this thruster is ~ 90 kg. This value corresponds to a LE gain of ~ 3.

Next figure 14 summarizes the potential throughput of Low Erosion versions of the PPS® X00, PPS®1350 and PPS®5000.

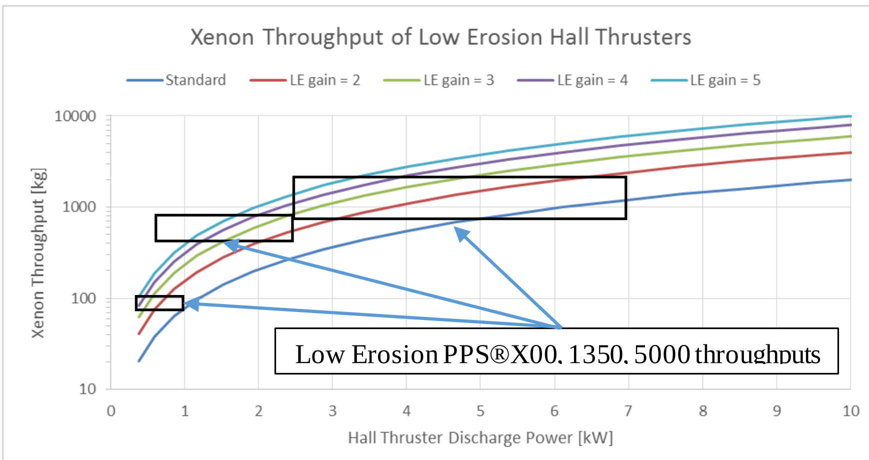

Figure 14. Estimation of xenon throughput of Low Erosion Hall thrusters

The enhanced potential of high throughput 1.5 kW Hall thrusters make it an attractive option for telecom satellite missions. Two examples can be given:

1) Small GEO Satcoms. Assuming total propellant mass of 400 kg, PPS®1350-LE thrusters could provide both orbit-raising to geosynchronous orbit and on-orbit station-keeping with significant margins for an all-electric satellite.

2) High power Satcoms. Satellite platforms often implement dual thrusters used at full power during orbit raising and at mid power during station keeping. In case of failure of a thruster during operation, remaining thrusters still guarantee the propulsion needs. Alternative configurations can be considered, using high power thrusters with optimized thrust-to-power ratio for orbit raising and high throughput low power thrusters for station keeping. In case of failure of the orbit raising propulsion system, the low power thrusters may be used for both orbit raising and station keeping. This propulsion system could also benefit from more versatile capabilities of PPU’s. Recent development efforts within the field of PPU’s have aimed at proposing different architectural configurations, making the use of several independent power modules for one or two Hall thrusters, but managed by a common unit for the spacecraft communication links and the different power modules. In this manner, a PPU configuration with multiple power modules, each capable of sourcing one (or two) thrusters can be constituted thus capable of feeding several thrusters, either one at the time or several in parallel. In the future, to meet the demands of all-electric spacecraft configurations, i.e. the use of EP for the orbit raising as well as the station keeping phase, PPU configurations capable of handling power output ratios of at least 5:1 to 10:1 will be necessary. The intention is to be able to assure the orbit raising phase with a single high-power

thruster and the station keeping phase being maintained by high throughput low power thrusters. This means that the PPU equipment itself must be able to re-configure its different power modules (or power cells) in a serial/parallel scheme that allows to draw full benefit of the embarked power capability in an optimized way. This will also maintain the EP system's availability at a higher level if redundancy is needed. In this case a re-configuration of the PPU could be performed to switch the effort of the orbit raising task to the station keeping, although at a lower power level. This scenario requires of course that the station keeping thrusters can be re-oriented to the required spacecraft thrust axes (Z-axis) or that the spacecraft can assure the adequate orientation during this re-configuration maneuver.

V. Conclusion

Aiming at increasing xenon throughput, a Low Erosion concept is proposed for enhancing the capabilities of Hall thrusters. In order to benefit from previous thruster qualifications, the magnetic topology in the discharge chamber is unmodified and corresponds to a standard Hall thruster topology. The lifetime increase is obtained by shifting the magnetic poles upstream the end-of-life profile of the eroded discharge chamber. As the main redesign effort is focused on the magnetic circuit, a specific optimization software was developed and applied to the definition of a low erosion circuit of a PPS®1350 thruster. In the past, two PPS®1350 qualification models, powered respectively at 1.5 kW and 2.5 kW, reached both a total impulse equal to 3.3 MN.s. A low erosion PPS®1350 prototype was manufactured here and was fired during 1020 hours at 350 V and 2.5 kW. Measured thrust and Isp were identical to the qualification models at EOL. The erosion rate of the discharge channel was quantified and the new total impulse of the Low Erosion PPS®1350 was estimated at about 12 MN.s. This lifetime increase is not compatible with the PPS®1350 cathode and the implementation of a 5 kW thruster's cathode is proposed. When considering telecommunication satellites, the Low Erosion approach is of interest for thrusters with low and mid electric power and can increase by a factor 2 to 4 the xenon throughput of a thruster. This improvement provided by low erosion designs offers new opportunities for mid power hall thrusters. Examples are propulsion of all electric small GEO spacecraft or redundancy by station keeping thrusters if failure of high power, high thrust-to-power, orbit raising thrusters.

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