PPS®X00 Thruster Development Status at Safran

IEPC-2019-241

Presented at the 36th International Electric Propulsion Conference
University of Vienna, Austria
September 15-20, 2019

J. Vaudolon*, V. Vial†, N. Cornu‡and I. Habbassi§
Safran Aircraft Engines, Electric propulsion directorate, 27200 Vernon, France

The development of the PPS®X00 Hall thruster is progressing at Safran, with the ambition to provide the market with a compact and highly cost efficient thruster in the early 2020s. The thruster is designed to span the 200 W 1000 W input-power range. The development is driven by time-to-market, design-to-cost and specific requirements imposed by LEO missions. Several innovations have been incorporated in the discharge chamber and magnetic circuit designs to propose a competitive and reliable product. This paper reports on the current status of the PPS®X00 development. The design approach and global roadmaps are presented. First tests on prototypes and analyses on the flight architecture are summarized, and future activities are described.

Nomenclature

CDR	= Critical Design Review
$CHEOPS$	= Consortium for Hall Effect Orbital Propulsion System
DM	= Development Model
EM	= Engineering Model
FM	= Flight Model
I_{sp}	= Specific Impulse
KP	= Key Point
LEO	= Low Earth Orbit
MEO	= Medium Earth Orbit
ML	= French acronym for Laboratory Model
PDR	= Preliminary Design Review
PPS	= Propulseur Plasma Stationnaire
PPU	= Power Processing Unit
QM	= Qualification Model
QR	= Qualification Review
StM	= Structural Model
TRL	= Technology Readiness Level

*Project Manager, julien.vaudolon@safrangroup.com
†Project Manager, vanessa.vial@safrangroup.com
‡Chief Engineer, nicolas.cornu@safrangroup.com
§Program Manager, idris.habbassi@safrangroup.com

I. Introduction

A. LEO market

The low earth orbit market is mainly driven by observation and telecom applications and ranges from large (above 1 t) to very small (under 100 kg) satellites. These platforms have a rather low delta-V in the order of 100 - 250 m/s for minimal station keeping and de-orbiting. The growing in-flight heritage of electric propulsion technologies and the specific requirements of these missions make the substitution of chemical propulsion lines by electric systems attractive.

A number of LEO constellation projects have emerged and open-up new opportunities for the electric propulsion market. The need of low-cost propulsion systems to equip hundreds of platforms for use on small or large constellations is however very challenging, be it from the technical, budgetary or production aspects:

- The system must be capable of operating for thousands of hours in LEO/MEO with a fair performance level at a few hundred watts.
- The challenging target cost imposes to change the design approach, which must rely on off-the-shelf components rather than developing specific high-end parts, when feasible.
- The production rates are about 10 to 100 times higher than those typically met for comsats.
- The market cyclical demand requires fast and efficient development approaches to meet the short time-to-market requirement.

B. Context

The CHEOPS[a] project (Consortium for Hall Effect Orbital Propulsion System) is part of the the European Union Horizon 2020 Framework Programme and includes the development of a whole LEO/MEO low power Electric propulsion system.
The CHEOPS consortium is led by Safran Aircraft Engines and is composed of representatives of the biggest European satellite manufacturers (Airbus Defence and Space, Thales Alenia Space-France, OHB AG), the full system supply chain throughout Europe (Safran Aircraft Engines, SITAEL, Bradford Engineering) and supported by several research centers (DLR, CNRS, UC3M, Chalmers University). Safran objective is to simplify the architecture of the propulsion system by developing a compact and plug-and-play system composed of the fluid regulator, the PPU and the thruster. The configuration is flexible, i.e. fully integrated or composed of separated subsystems. The design approach will facilitate its integration on a variety of satellite platforms, providing a competitive product for multi-mission and multi-customer environments and emerging markets of mega-constellations with possibly +1000 satellites.

C. PPS®X00

Based on these considerations, the PPS®X00 thruster development is progressing at Safran. The development approach, general design and justifications brought so far are presented in the next sections.

II. Thruster Development

The PPS®X00 thruster development was initiated in a two-year predevelopment activity started in early 2017, with the objective of reducing manufacturing costs and increasing robustness with respect to varying mission constraints, i.e., with a design objective consistent with operations over a wide range of operating conditions.
Figure 1 presents a summary of the hardware that has been manufactured and of the tests demonstrations performed so far. Demonstrations by tests and analyses are performed at each design iteration to provide a solid design justification ground for the rest of the development and industrialization to proceed. Several models have thus been manufactured and tested, see § III D.

The development activities are separated in several tasks: general design, maturing of new technologies, hardware manufacturing, tests and industrialization. Each task is driven by an ambitious schedule to meet

[a]CHEOPS is a European space project led by Safran Aircraft Engines that has received funding from the European Unions Horizon 2020 research and innovation program under Grant Agreement n730135

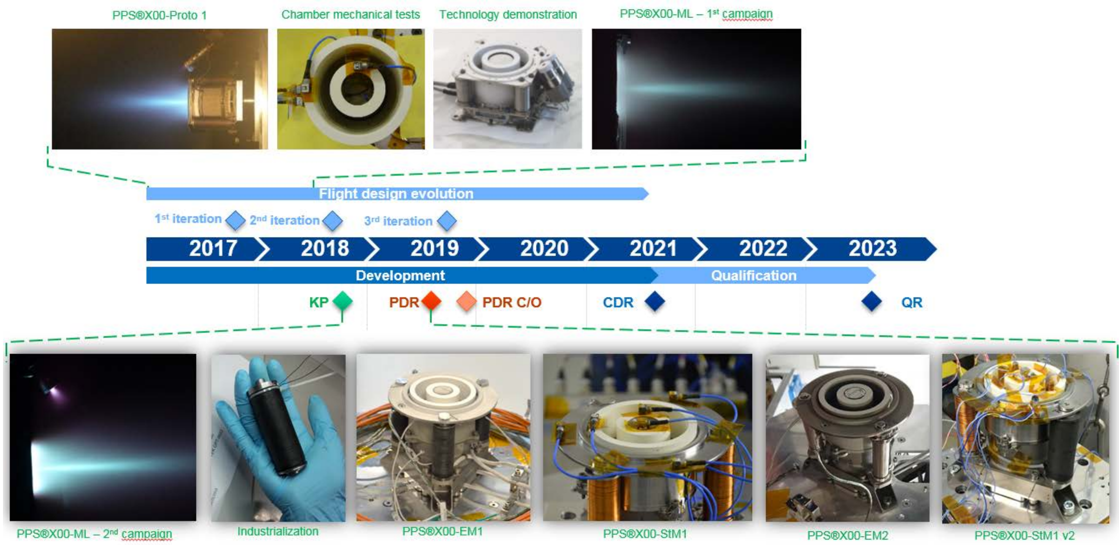

Figure 1. Illustration of the hardware that has been manufactured and tested during the preliminary design phase.

the time-to-market, and by risk mitigation.
Several internal reviews have been held in order to authorize the next design steps to be engaged.

- Concept review, in October 2017, to validate the pre-project architecture selected out of tens of concepts during the trade-off phase.
- Maturity review, in March 2018, to examine the technology and manufacturing readiness levels of the embedded technologies and criticize the maturity increase roadmaps.
- Materials and processes review, in July 2018, to present the material and processes lists, the need for characterization regarding the PPSX00 specification and the processes development plan.
- Preliminary Design Review in July 2019, to validate the technical specification and the preliminary design justifications.

Recoms raised have been implemented for further enhancing the thruster design and paved the way for preparing the preliminary design review close-out, which will be held at the end of 2019.

III. Engineering

A. Design philosophy

Reaching the target cost of the end-product is at the core of the design methodology and is monitored during each development phase and design iteration.
In order to extract the full benefit from the design-to-cost methodology, the thruster architecture design has started from the blank page. A trade-off between several discharge chamber designs, magnetic architectures, technologies, processes, manufacturing scheme and production costs has been made. Return on operating experience in manufacturing the PPS®1350 and PPS®5000 has guided the selection of the best concept.
The PPS®X00 design has been optimized with specific features to minimize the number of complex manufacturing processes while being capable of delivering a high performance, and as such presents significant differences with respect to actual Hall thruster designs operating in the same power range. Specifically, several innovations have been incorporated in the discharge chamber and magnetic circuit designs.

B. Operating envelope

The PPS®X00 is designed to span the 200 - 1 000 W power range, with an optimum design point at 650 W. The PPS®X00 operating envelope is presented in Fig. 2. This envelope has been established using a semi-

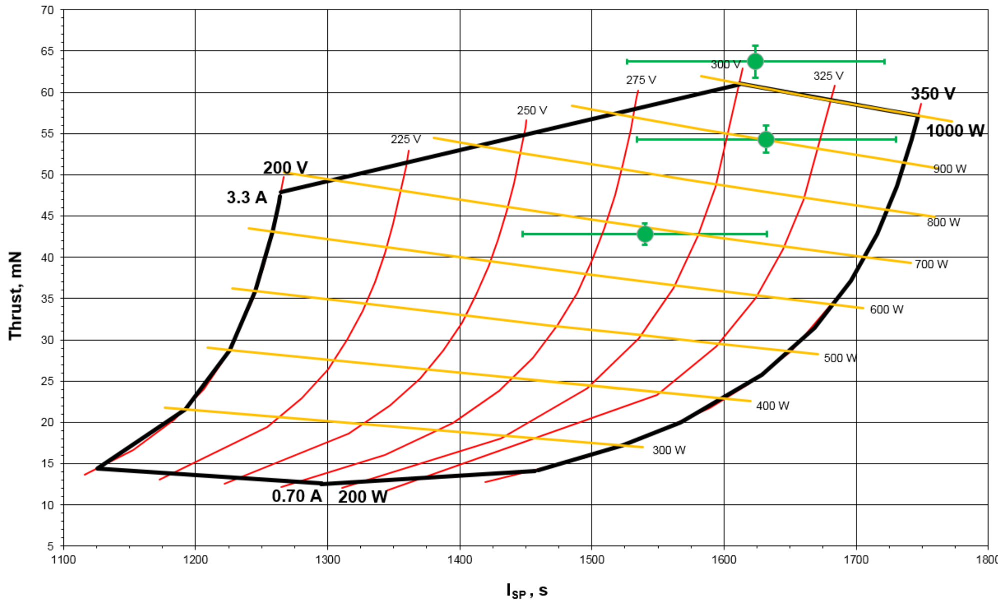

Figure 2. PPS®X00 operating envelope. Green dots: performance measurements at 300 V and 650 W, 800 W and 1 kW.

empirical discharge performance model and a first adjustment following the outcomes of the Laboratory Model test campaigns. It will be continuously adjusted during the development to fit the test results as the design gets closer to its final version.

The PPS®X00 performance target is to deliver 40 mN of thrust and 1 450 s of Isp at 650 W / 300 V (nominal set point). The expected total impulse is 1 MN.s, while actual thrusters do not exceed 0.6 - 0.7 MN.s. The Lab Model test results are very encouraging as the performance that has been measured is above the target: 43 mN of thrust and 1 530 s of Isp. This performance must now be reproduced on the flight architectural design of the thruster. The design iteration is in progress at the time of writing.

In order to deliver a high performance over a broad power range, the ratio of the channel width to mean diameter departs from the typical ratio observed on the vast majority of existing thrusters [Ref. 1].

It is well known that the thruster efficiency increases with its size. For a low-pressure plasma such as that of a Hall thruster, this is directly linked to the volume-to-surface ratio: plasma is produced in volume (so the thrust) and energy is lost on surfaces (i.e. channel walls) by way of particle bombardment and recombination.

The ratio of plasma losses to plasma production can be scaled to 2/h, where h is the channel width. Past research programs have confirmed that the wall losses decrease when the channel width is increased [Ref. 2]. This wall-loss management explains that the discharge can be maintained at low power and that the channel can endure a high-power operation. Additionally, a larger fraction of energy supplied to the device can be converted into ion production and axial ion motion, i.e. in useful thrust and specific impulse.

C. Analyses

Analyses have been made to support the justification file, with special focus on innovative internal parts which allow to span the entire power range or which are key to ease manufacturing and contain costs.

Mechanical, thermal and thermomechanical rounds of calculations have been made after each significant design iteration, the iteration being triggered by the recommendation of a previous technical analysis or by another element, for instance cost or manufacturing aspects.

The analyses have been performed with conservative assumptions where accurate data were not available, and tests supported the justification when analysis was not feasible nor acceptable. The mechanical tests performed at discharge chamber and thruster levels confirm that the design is robust. Likewise, the thermal adjustments following the Laboratory Model and Engineering Models test campaigns have confirmed the thermal margins.

D. Tests already performed

1. *Firing tests*

PPS®X00 Proto 1 The first test in the program was performed during the trade-off phase in early 2017 and involved the first PPS®X00 prototype developed during past R&T programs. During this test, several channel wall materials were tested. The thruster was also reconfigured during the campaign to measure its performance when equipped with thermal and neutral flow management parts. This test was successful and participated in the trade-off by indicating to what extent specific devices were able to optimize the performance delivered. The benefits of these devices were then compared to the induced cost, so that pre-project architectures could be refined with such implementations.

PPS®1350-G DT Another test of prime importance was that performed with the PPS®1350-G DT in the course of 2018, which has been used as a test bed for the maturing of the PPS®X00 ceramic. The PPS®1350 is the reference thruster of the PPS® family. It has been extensively characterized through years of successive developments and its behavior is well known.
The challenges posed by the PPS®X00 broad-range high-efficiency operation and low-cost design has imposed the choice of a different ceramic than those of the PPS®1350 and PPS®5000. As it is known, the ceramic has mainly three tasks to perform: withstand the mechanical loads, ensure a stable operation over the intended set points, and resist the ion bombardment.

The stable operation has been checked with the PPS®X00-ML, which has operated from the beginning with this ceramic to perform characterizations. The total impulse potential has been characterized with the PPS®1350-G DT prior to be able to engage a formal endurance test with the PPS®X00-EM. This test has significantly lowered the development risk early in the preliminary design phase.
The test has been successfully run for about 200 h at 2.5 kW and the erosion rate of the ceramic has been compared to that of current standard ceramics. The analysis confirms the ceramic life potential and reveals a very stable behavior even at the PPS®1350 power and geometrical scales.

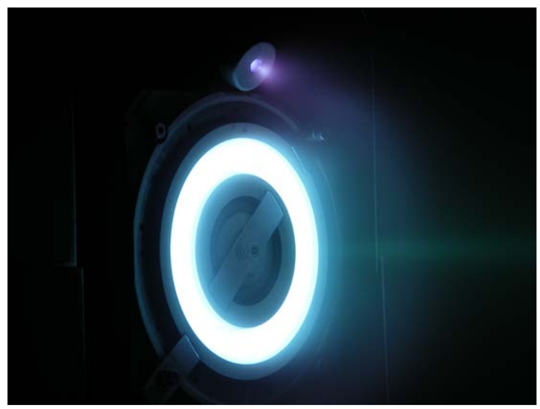

Figure 3. The PPS®1350-G DT firing with the PPS®X00 ceramic material.

PPS®X00-ML Two test campaigns are planned with the Laboratory Model of the PPS®X00, one of which having already been performed.

The first test campaign was performed in the CNRS PIVOINE-2g test bench in July 2018 and was dedicated to identifying and characterizing the magnetic configuration that must fulfil a number of constraints (stability in time and set points, power consumption among the most prominent). The test campaign was divided in two parts. During the first part of the test, the magnetic optimization was conducted using in-house experimental optimization tools and the simple observation of discharge parameters, such as the discharge and ion beam currents. The thruster initial performance was increased by more than 10 % in efficiency and almost 10 mN at the nominal operating point. Higher performance points were accessible at this set point but at the expense of achievable total impulse though. The magnetic configuration choice has been made according to the specification targets in terms of thrust, specific impulse, input-power, discharge power range and total impulse. During the second part of the test, the thruster was characterized between 200 W and 1 kW with the optimized magnetic configuration. The thruster behavior has been stable and reproducible over the entire test campaign, which lasted for several weeks. Notably, the discharge was stable over the target power range and even in high-voltage operating modes (operation up to 500 V during the test, limitation not imposed by the thruster).
The second test campaign has the objective of verifying the behavior of the magnetic setting over time (stability and lifetime potential). This test campaign is in preparation at the time of writing and results are expected Q1 2020.

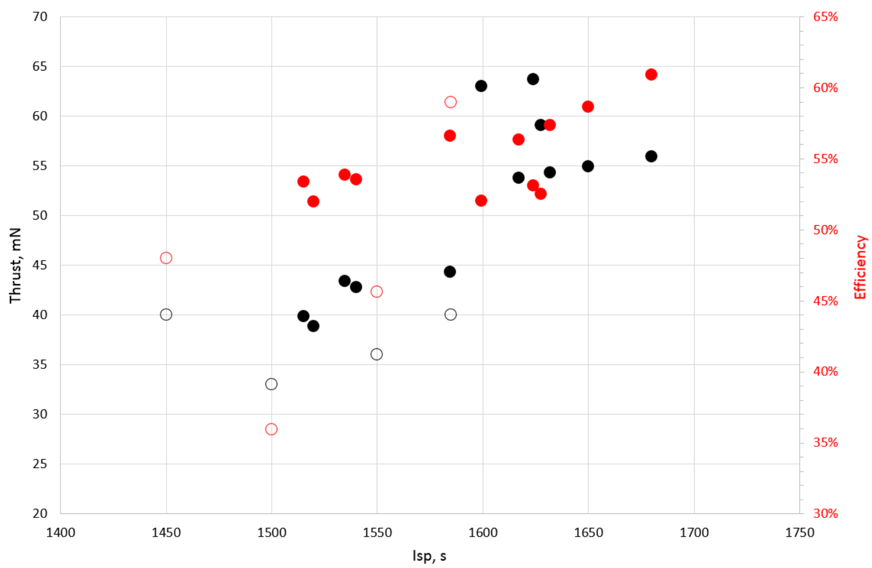

Figure 4. (Black) Thrust vs specific impulse. (Red) Efficiency vs specific impulse. Full symbols correspond to PPS®X00-ML performance measurements. Open symbols represent competitors performance extracted from the literature.

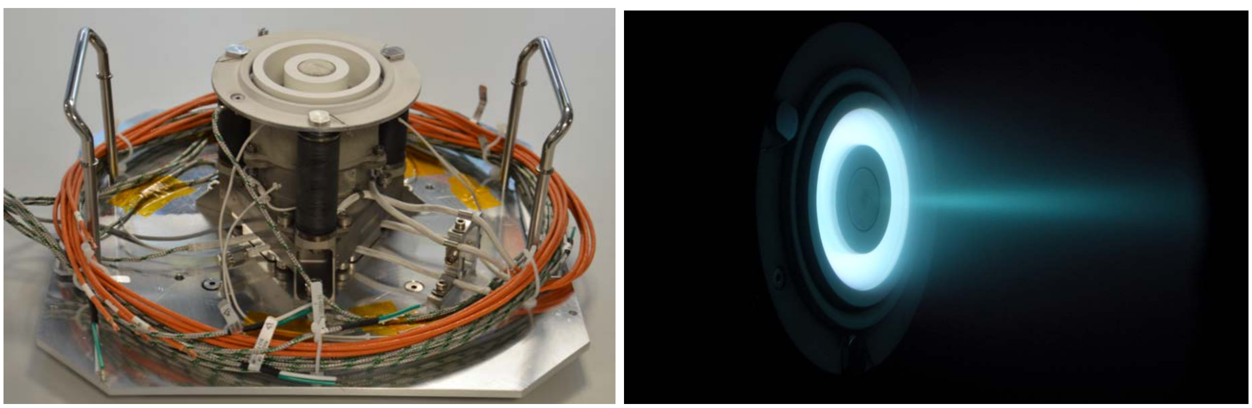

Figure 5. The first engineering model of the PPS®X00. Left: after manufacturing. Right: During firing in the PIVOINE-2g vacuum chamber.

A few characterization points are provided in Fig. 4, which presents the thrust and anode efficiency as a function of the specific impulse. These figures are compared to a variety of thrusters operating in the same power range, rating the PPS®X00 performance above state-of-the-art thrusters.
The performance characterization of the PPS®X00-ML is extremely satisfying, and brings a first validation of the innovations included in the design. This validation was crucial for the development as it provides confidence in the flight architecture functional design.

PPS®X00-EM Two engineering models of the PPS®X00 have been tasked with maturing the innovative technologies included in the design. As such it has been equipped with flight-representative hardware. Remarks made during the manufacturing and assembly of these models have slightly impacted the design to ease future production.
The engineering models have been characterized in the PIVOINE-2g test bench. The test campaign objectives were to characterize the discharge between 200 W and 1 kW, to participate in reaching TRL 5 on the embedded technologies and to adjust the thermal models. During this test, the anode block was coupled with the Sitael cathode HC3 [Ref. 3]. The test campaign has been successful, with slight design evolutions coming from the test analysis.

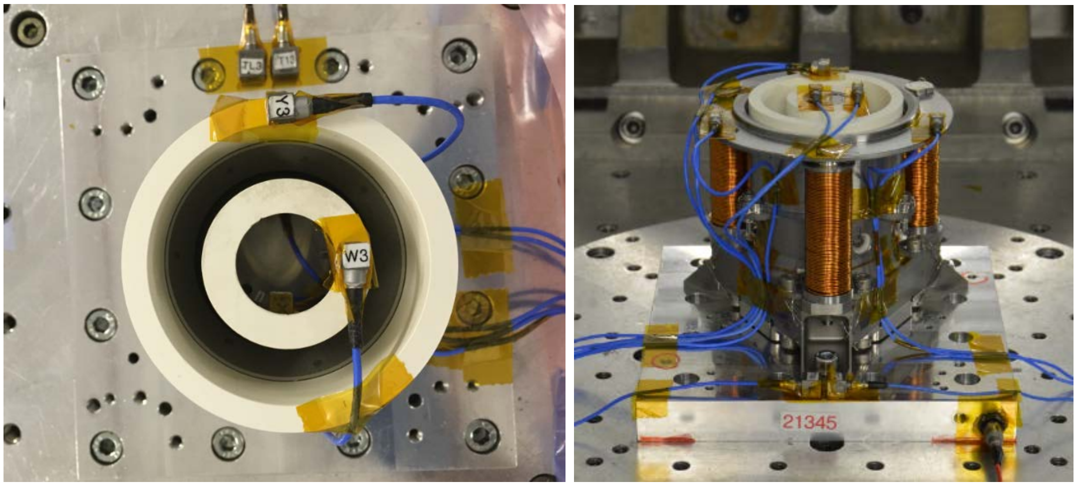

Figure 6. The PPS®X00 discharge chamber (left) and thruster structural model (right) during mechanical tests.

2. Mechanical tests

Vibration and shock tests have first been performed on the chamber plus thruster baseplate assembly only, to check its mechanical behavior. Following the development logic, these tests intended to bring the demonstration of the architecture viability as early as possible to lower the development risk and increase the technology readiness levels. Vibrations and shocks at qualification levels have been successfully performed during several tests campaigns (some of the parts were not changed in between campaigns and have thus cumulated a lot more sollicitations than required during service life).
Several mechanical tests at thruster level have then been performed, with the primary objective of adjusting the mechanical models. The hardware mechanical response was extremely close to that predicted by the models. This adjustment has allowed to secure the mechanical margins, and has highlighted the need of a design evolution for some of the parts within the thruster.
Some observations have been made during the test and led to minor redesigns on the hardware. Being able to perform mechanical tests and validations early in the development has allowed to test design variants of the thruster chamber and to determine to what extent the flight architecture is sound and where the margins are. This approach has been extremely beneficial and will be pursued.

3. Thermomechanical tests

Chamber assembly The vibrations and shocks have been followed by the thermal cycling of the chamber assembly to observe its behavior. Ten cycles have been performed between -70°C and +300°C on the full chamber assembly, and then ten cycles between -70°C and +500°C have been performed on the hottest subassembly of the chamber. All the cycles were performed under secondary vacuum. The test did not reveal any anomaly and validated the chamber assembly concept on the thermomechanical viewpoint.

Coils A significant work has been undertaken to lower the cost of the magnetic flux sources. As such, the coil design departs significantly from that of the PPS®1350 and PPS®5000 thrusters and risk mitigation action plans have been implemented. Analyses have allowed to select the three most promising off-the-shelf set of compounds constituting three possible configurations for the coils. Further refinement, i.e. selection of the flight design, has been done by tests. Vibrations and shock tests have been performed on the structural mock-up of the thruster, which on top of manufacturing requirements have allowed to narrow the selection process to two configurations, each configuration having two variants. The final design has been selected by performing 150 thermal cycling tests between -70°C and +475°C. Figure 8 shows the two coil configurations on the interface plate of the test chamber. Each configuration was composed of two variants, each composed of three identical samples. Each coil sample is connected to a power supply, a DAQ, and is equipped of at least one thermocouple. Figure 8 also shows the winding insulation characteristics with respect to ground

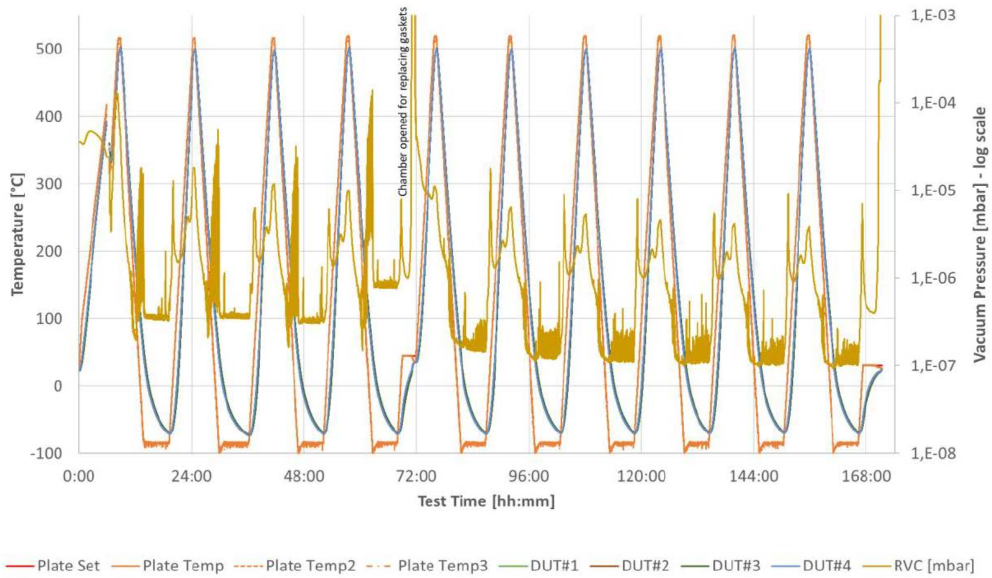

Figure 7. Illustration of the ten thermal cycles performed on the PPSX00 chamber assembly.

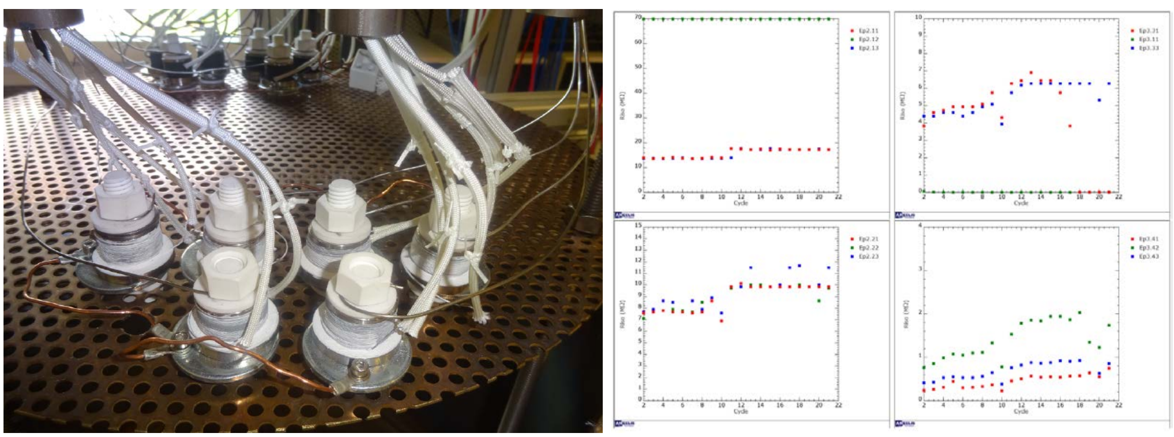

Figure 8. Coil thermal cycling test between -70°C and +475°C. Left: the two coil sample configurations on the thermal interface plate. Right: Insulation properties of the samples during the 25 first cycles.

during the first 25 cycles. The insulation properties as well as resistance characteristics (not shown) vary considerably between the configurations, allowing to narrow the selection process to one design.

IV. Conclusion and future activities

The development of the PPSX00 is progressing according to plan, and is currently in the final months of its preliminary design phase. The design validations already obtained mitigate the development top risks and confirm the design is on the right track to meet the market demands, be it on performance or cost aspects.

The development logic has been adapted to meet the very stringent time-to-market constraints placed on the PPS®X00. Figure 9 presents the high level milestones and main development models planned at this time.

The next step activities to further characterize and mature our technology is the endurance and coupled testing of the PPS®X00. Endurance tests of 4000 h and 4000 cycles are planned on the EM3 and DM, the latter being a full dress rehearsal of the qualification tests with the prospect of leading to minor design

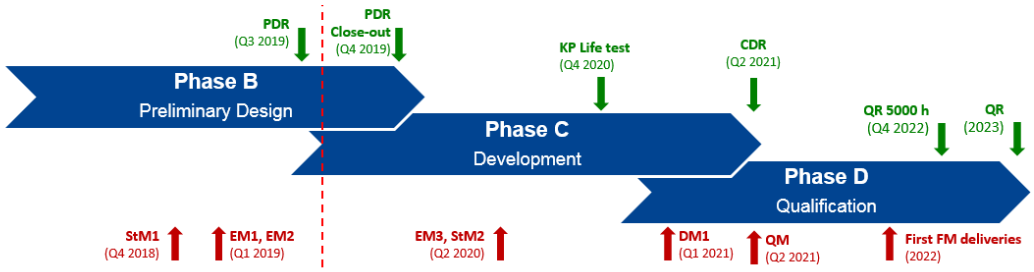

Figure 9. PPS®X00 development logic to meet the time-to-market demand.

modifications for the QM. These tests will extend through Phases C and D.

Industrialization has begun and will continue, through technical characterizations and the preparation of production of the first flight models. The procedures will be refined, the manufacturing chains consolidated and the operators will be trained throughout the production of the different development models.

Acknowledgments

The PPS®X00 development activities are achieved with the support of the CNES, the European Space Agency, the European Union and with internal fundings.

References

[1]A.A. Shagayda, "On scaling of Hall effect thrusters", IEPC-2013-056, 33rd International Electric Propulsion Conference, Washington, D.C., USA, October 6-10, 2013

[2]S. Mazouffre, G. Bourgeois, K. Dannemayer and A. Lejeune, "Ionization and acceleration processes in a small, variable channel width, permanent-magnet Hall thruster", J. Phys. D: Appl. Phys. 45 (2012) 185203 (7pp)

[3]D. Pedrini, F. Cannelli, R. Hadavandi, U. Cesari, C. Ducci, T. Misuri, F. Paganucci, M. Andrenucci, "Recent Advances in Low-Current Hollow Cathodes at SITAEL", IEPC-2019-782, 36th International Electric Propulsion Conference, Vienna, Austria, September 15-20, 2019