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End-to-End Testing of the PPS®5000 Hall Thruster System With a 5-kW Power Processing Unit

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Abstract: **A coupled, or "End-to-End", system test was performed in the electric propulsion testing facility of Snecma, Vernon, France, in June 2014. During that End-to-End test, an Engineering Model of the 5-kW-class PPS®5000 Hall thruster in development was operated successfully over its entire operating range while being coupled to a BreadBoard Model Power Processing Unit and a Xenon Pressure Regulation Feed System. In particular, the tests highlighted the strong influence of the applied thruster startup procedure on the transient discharge current inrush.**

Nomenclature

CRP	=	Cathode Reference Potential, or coupling voltage (V)
EGSE	=	Electrical Ground Support Equipment
FU	=	Filter Unit
Id	=	discharge current (A)
Itt	=	thermothrottle current (A)
P_{Xe}	=	xenon pressure upstream of XFC (bar)
XFC	=	Xenon Flow Controller
XRFS	=	Xenon Pressure Regulator and Feed System
ΔV	=	delta-V, or increment of orbital velocity (m/s)

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I. Introduction

THE use of Electric Propulsion (EP) on board commercial geostationary (GEO) satellites has become commonplace because it permits significant mass savings over all-chemical systems. Since its progressive introduction in the 1990s and until 2012, however, EP had essentially been confined to North-South Station Keeping (NSSK) duties, whereas chemical propulsion was preferred for orbit transfer and, in some cases, for other on-orbit maneuvers or for redundancy purposes for part of the NSSK mission. Since 2012, however, a decisive move has been triggered in the community toward using EP for all on-orbit propulsion needs.

This change in mission applications in fact changes dramatically the typical top-level requirements that the EP system must fulfill: not only does the orbit raising ΔV constitute more than 70% of the total spacecraft mission ΔV, but also this particular mission is subject to transfer time duration constraints at a prescribed power level larger than the power available once the telecommunications payload has entered service.

As a consequence, the technical requirements for the EP system have been driven toward dramatically larger total impulse capability; higher maximum power level; and throttleability to high thrust-to-power ratio, i.e. moderate specific impulse.

The renewed interest toward more-electric GEO comsats is exemplified in Europe by the Neosat program, approved at the European ministerial conference of November 2012. In this context, the development of the PPS®5000, a 5-kW Hall-effect (stationary plasma) thruster based on earlier Technology Demonstration programs[1,2] has begun in January 2013. An Engineering Model (EM) of the thruster has been designed, manufactured and tested. The thruster Preliminary Design Review (PDR) was held in July 2014.

Key to the availability and competitiveness of the Plasma Propulsion System, a Power Processing Unit New Generation (PPU NG) is also under development at Airbus Defence & Space. The purpose of a coupled test between the PPU NG BBM and the PPS®5000 EM at an early phase of the development was to adjust, on the first PPU hardware model and with representative 100-V bus and thruster interfaces, a number of technical solutions and such development parameters as the discharge closed-loop control or the startup sequence. An inductive-capacitive electric Filter Unit (FU) was also implemented, with the capability to adjust its inductance L and capacitance C.

In particular, the test objectives were to test several automatic startup sequences at 300 V as well as 400 V of thruster discharge voltage; verify the behavior of the cathode coupling voltage, or CRP, through cathode pre-heat and ignition phases; verify the PPU power supply regulations performance; and perform fine characterization of startup and shutdown transients, as well as steady-state operation.

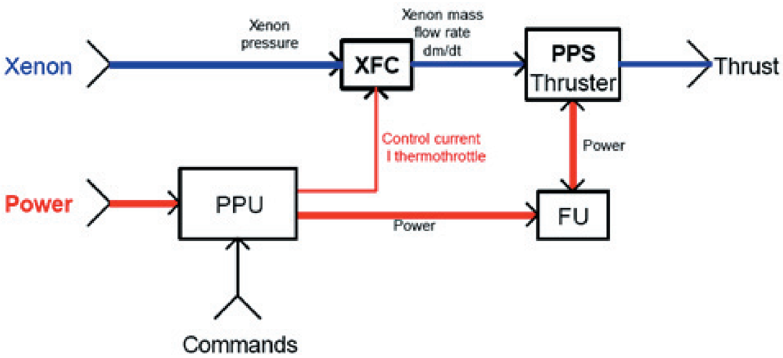

Figure 1. Functional schematic of closed-loop control.

Verification of the stability of the discharge current regulation was performed by coupling the Xenon Flow Controller (XFC), which is part of the Thruster Unit, to a Xenon Pressure Regulator and Feed System (XRFS). Because this system relies on a principle of pulsating ON/OFF valves, the pressure regulation also generates pressure spikes with each valve cycle. These pressure spikes are then only partially filtered by the XFC and excite the closed-loop discharge current control electronics and software located inside the PPU.[3] This process is partly represented in Figure 1.

Section II of the paper will describe the PPS®5000 Hall Thruster System under development. Sections III and IV, respectively, provide a description of the PPU and XRFS. Finally, Section V provides an overview of the coupled, or End-to-End, test.

II. The PPS®5000 Hall Thruster System

The PPS®5000 design, depicted in Figure 2, is optimized with specific patented features to handle large thermal loads,[4] and as such presents very significant differences with respect to previous-generation HET designs. Its operating domain ranges from 2 – 5kW in discharge power.

The PPS®5000 was first developed up to PDR in 2003-2004 within the framework of an ESA ARTES-8 contract. This Advanced Research in Telecommunications Systems (ARTES) element was dedicated to the *Alphabus* platform. A first iteration on the PPS®5000 flight design was thus proposed for the *Alphabus* (extended range) pre-development activities and the PDR milestone was reached in December 2004. However, the PPS®5000 development was placed on hold because of the combined modification of the *Alphabus* propulsive needs and extension of the smaller-scale, 1.5-kW PPS®1350-G endurance qualification, such that the PPS®1350-G became capable of meeting the near- to mid-term need of the *Alphabus* program. The PPS®1350-G thruster was thus selected for flight on *Alphasat,* the first spacecraft based on this platform, which was launched in July 2013 and has been in operation since.[5]

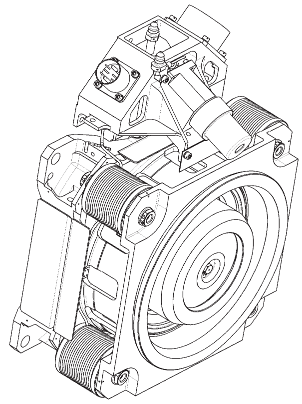

Figure 2. The flight-design PPS®5000.

As a consequence, the PPS®5000 development was put on hold until the need was revived for 5-kW-class Hall thrusters. In 2013, the ESA *Neosat* program was initiated within the framework of a French national Investment Plan for the Future (PIA) managed by CNES and focused on all-electric spacecraft. The *Neosat* program specifically addresses the technology building blocks for GEO communications satellites in the range of 3 – 6 tons at launch, which represents 80% of the telecommunications satellite market, and with an objective to improve competitiveness by at least 30%.

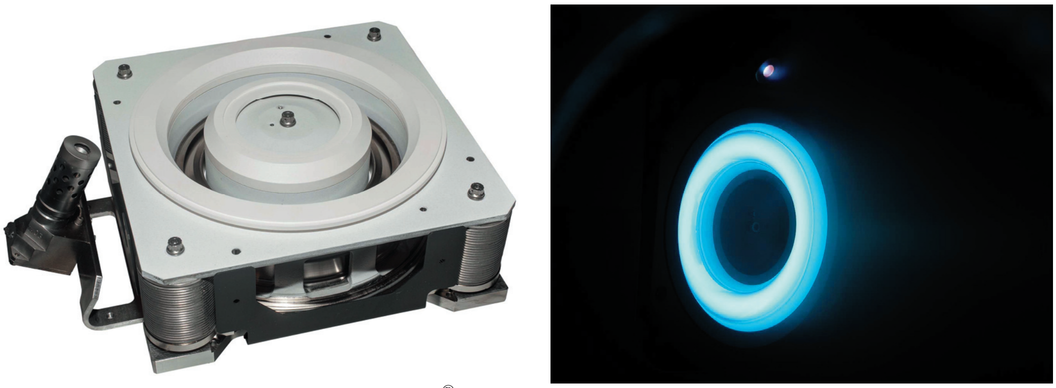

Figure 3. The PPS®5000 Engineering Model (EM).

A second round of PPS®5000 design optimization was performed post-PDR in 2006, with the support of CNES, and further technology validation was achieved throughout ESA Technology Research Programs (TRP) contracts in 2007-08 and 2013-14. This permitted testing of improved design features under largely varying conditions on the PPS®X000 Technology Demonstrator model.

Finally, an Engineering Model (EM) for the PPS®5000 (Figure 3) was designed, built and tested over the course of 2013. A number of testing campaigns have been carried out since, including the coupled tests described in this paper, and to date the EM has cumulated over 3,300 hrs of operation, mostly at 300 V and 5 kW of discharge voltage and power, respectively. In particular, the PPS®5000 EM completed in early June 2015 a final partial endurance test of close to 1,800 hrs, including a last leg of about 200 hrs to verify transition to the candidate operating conditions for NSSK of 375 V and 3 kW of discharge voltage and power, respectively. This overall pre-development history is summarized in Figure 4.

In summary then, the PPS®5000 development relies on a solid pre-development heritage accumulated through a coherent combination of internal and Agency resources. Three functionally representative development models have been built to scale, i.e., the PPS®X000 Technology Demonstrator; the PPS®X000-ML Laboratory Model; and the PPS®5000 EM, and the combined test heritage amounts to about 6,300 hrs of firing over a variety of operating conditions as shown in Figure 4.

The tests described in this paper were carried out on the PPS®5000 EM in June 2014, just before the thruster design passed a new PDR held against the *Neosat* requirements. This new PDR process was initiated in July 2014 and was flowed down to the levels of the cathode, XFC, and dual-valve subassembly which constitutes part of the

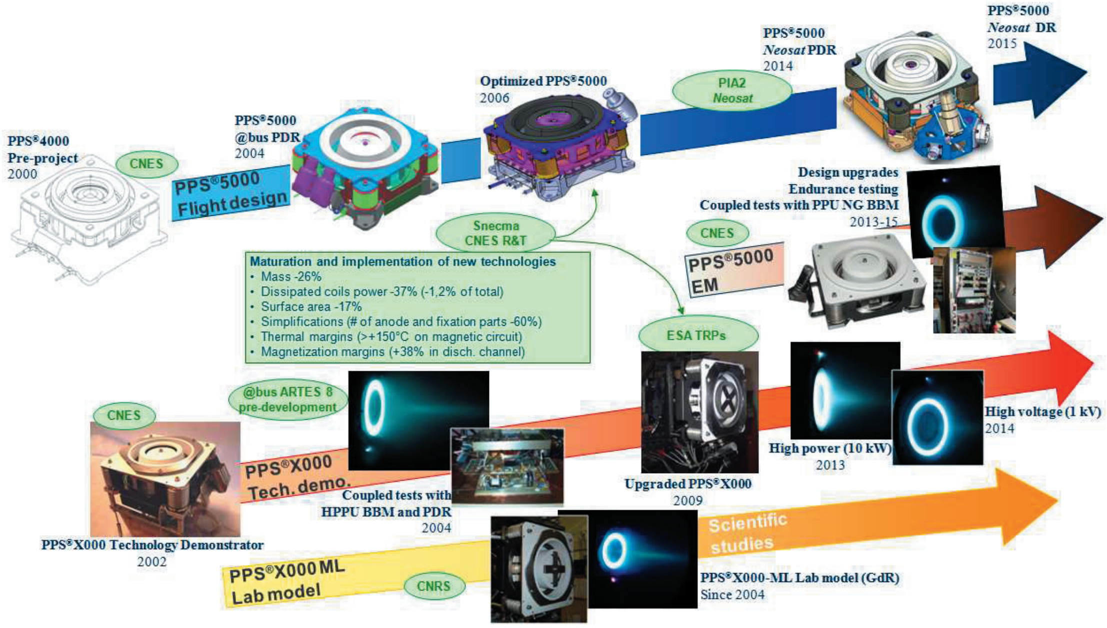

Figure 4. Pre-development heritage of the PPS®5000.

XFC (Figure 5). All three distinct subsystems were therefore submitted to a dedicated PDR – as well as CDR for the dual-valve subassembly – within the frame of the *Neosat* program.

In April 2015, the PPS®5000 Thruster Unit passed an intermediate Design Review as well as a Manufacturing Readiness Review, authorizing manufacturing activities to proceed toward the production of two Engineering Qualification Models (EQM).

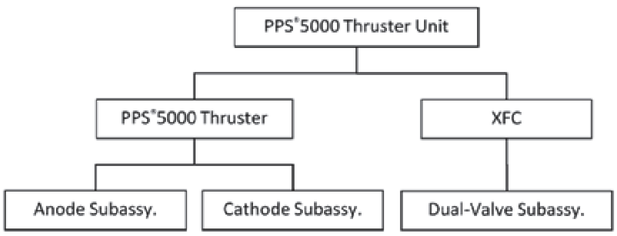

Figure 5. PPS®5000 Thruster Unit product tree.

III. Power Processing Unit

The Power Processing Unit interfaces the platform power and data buses with the Hall-effect thruster. It provides all electrical supplies necessary for thruster startup and thruster operational domain control for orbit raising and station keeping operation.

The development of the PPU NG between Airbus DS Elancourt (France) and Airbus DS CRISA (Spain) has led to a new innovative concept of PPU, capable of adapting to a wide range of EP subsystem configurations.

The PPU NG offers:

- A minimized recurring price thanks to a Design For Manufacturing (DFM) approach and an innovative architecture;
- A flexible and modular equipment, same solution able to deliver from 1.5 kW up to 20 kW. The PPU NG is thus able to drive a Hall thruster system up to a maximum power of 20 kW (four thrusters);
- The capacity to answer orbit raising and station keeping needs, with various operating points of a HET: 300 V to 400 V (optimize Isp vs thrust);
- A flexible design compatible to all main HET thrusters in the market;
- A single platform communication bus able to manage all thrusters of the platform;
- An increased reliability thanks to internal redundancies.

Compatible with a 100-V power bus (standard for Telecom Satellites), it may easily be adapted to other power bus voltages.

The electrical architecture is presented in Figure 6. The main principle of this architecture is that all functions which are not used permanently in the subsystem, such as the cathodes power supplies (Heater, Keeper and Ignitor), as well as sequencing of the overall PPU, are gathered in a module called HKISeq. This module is able to address up to six cathodes. All other functions (Anode 5 kW power supply, Magnet and Xenon Flow Control supplies) are gathered in the module called Anode module. Filter/Thruster Switching Unit (FTSU) modules are used to filter and switch the Anode power supplies towards two thrusters.

All modules are physically independent and the communication between HKISeq and Anode modules is made by a CAN bus through a harness. Thus, the modules can be assembled altogether with standard fixing points (no specific tie-rods) to form a single unit, or they can be implemented separately. Examples of the possible configurations are presented in Figure 7 and Figure 8. This modular approach aims to largely facilitate the accommodation of the PPUs for the satellite prime contractors.

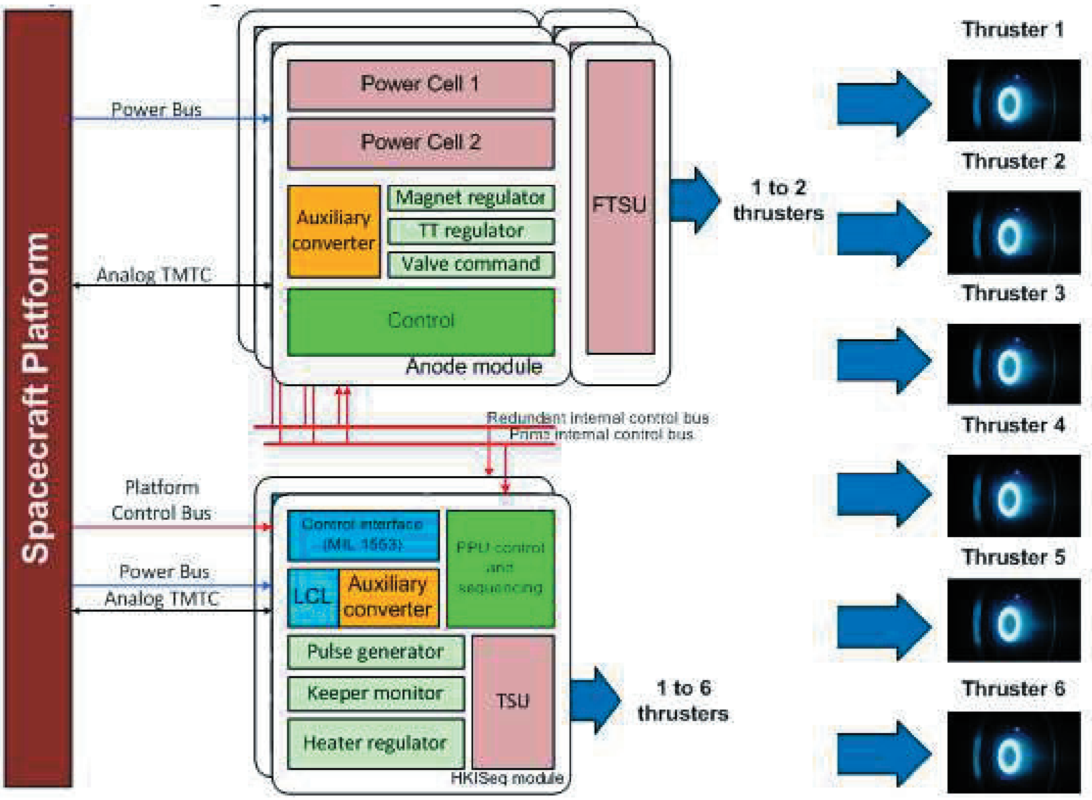

Figure 6. PPU NG architecture.

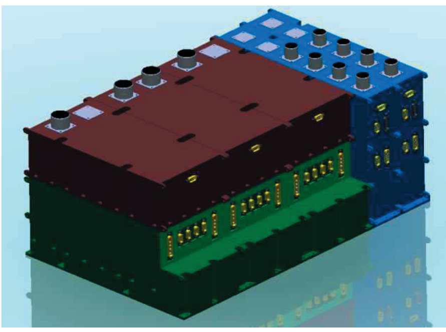

Figure 7. Assembled 15-kW PPU.

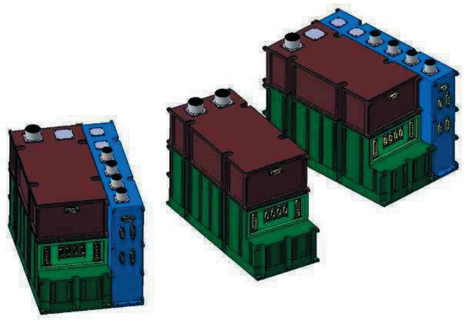

Figure 8. 15-kW PPU distributed modules.

A breadboard model was built in less than six months time, with Anode and HKi modules which are representative of the final design regarding power supplies topologies and hardware protections, and have demonstrated the functionality and performance during the coupling test with the PPS®5000.

The development of the PPU NG is on-going and the PDR has been held successfully in September 2014. The CDR is foreseen in the third quarter of 2015, the QR in the first quarter of 2016, and delivery of the first flight set is scheduled in the second quarter of 2016.

IV. Xenon Pressure Regulator and Feed System

The XRFS ensures the regulation of the xenon pressure from the high pressure in the xenon storage tank down to thruster working pressure. It provides a filtered supply of xenon to the XFC within a tightly-controlled pressure band.
A picture of the XRFS EQM is shown in Figure 9.

The regulator incorporates a system of valves, a plenum volume, pressure transducers and flow restrictors and embeds a "bang-bang" control of pressure. This control is obtained by actuating one regulation valve, followed by a small plenum volume, located downstream of the valve, which provides a damping of resulting pressure ripple to acceptable limits for the thrusters. This technological approach, which uses high pressure components, provides flexibility on the outlet pressure setting.

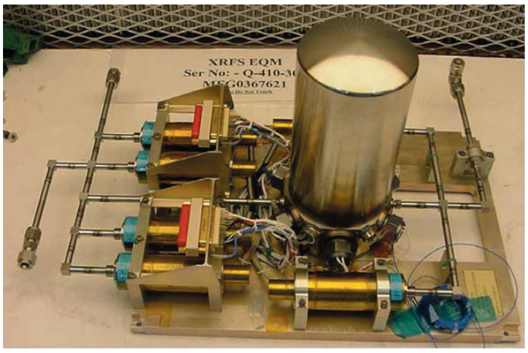

Figure 9. The XRFS EQM.

V. Coupled Test Setup and Main Results

A. Facility and test setup

The tests were carried out in the LIC test facility of Snecma, Vernon operations. The test facility includes a cryo-pumped vacuum chamber 2.2 m in diameter and 7.5 m in length. Under operation of the thruster at full power (5 kW and 17 mg/s of discharge power and total xenon mass flow rate, respectively), the background pressure was maintained lower than 1.2×10^{-4} mbar. This facility is visible in Figure 10.

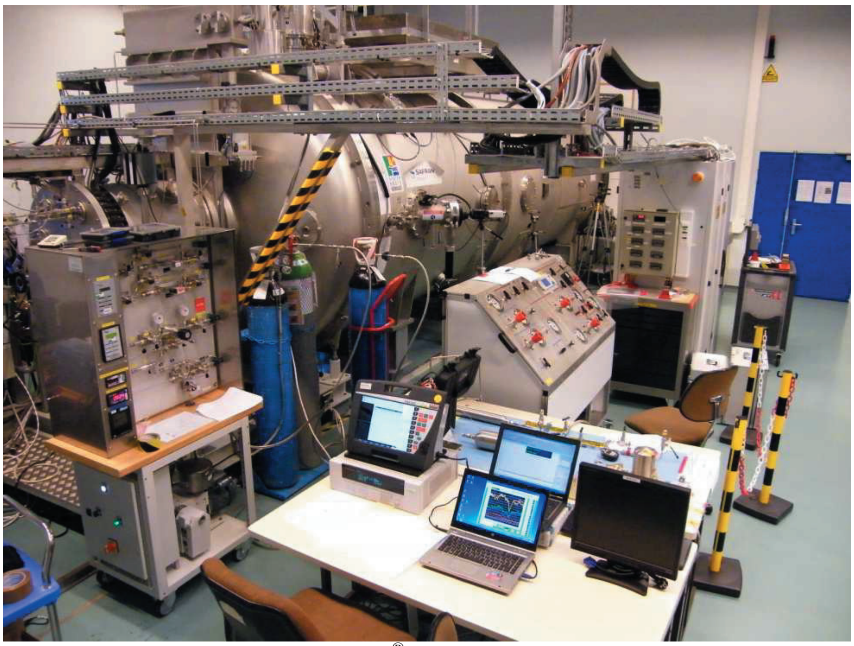

Figure 10. The LIC test facility with the PPS®5000 EM / PPU BBM / XRFS End-to-End test setup.

Since the PPS®5000 EM performance was already well characterized over its operating domain, the thruster was not installed onto a thrust balance. This was in fact rendered necessary because a representative electrical harness was used, the stiffness of which was not compatible with mating on the thrust measuring device.

The test setup (Figure 11) comprised the PPU BBM, the PPS®5000 including a functionally representative XFCs, the XRFS, and a high-pressure xenon cart with compressor directly interfaced with the xenon bottle. The compressor raised the xenon pressure up to 120 bars, corresponding to the inlet pressure of the XRFC.

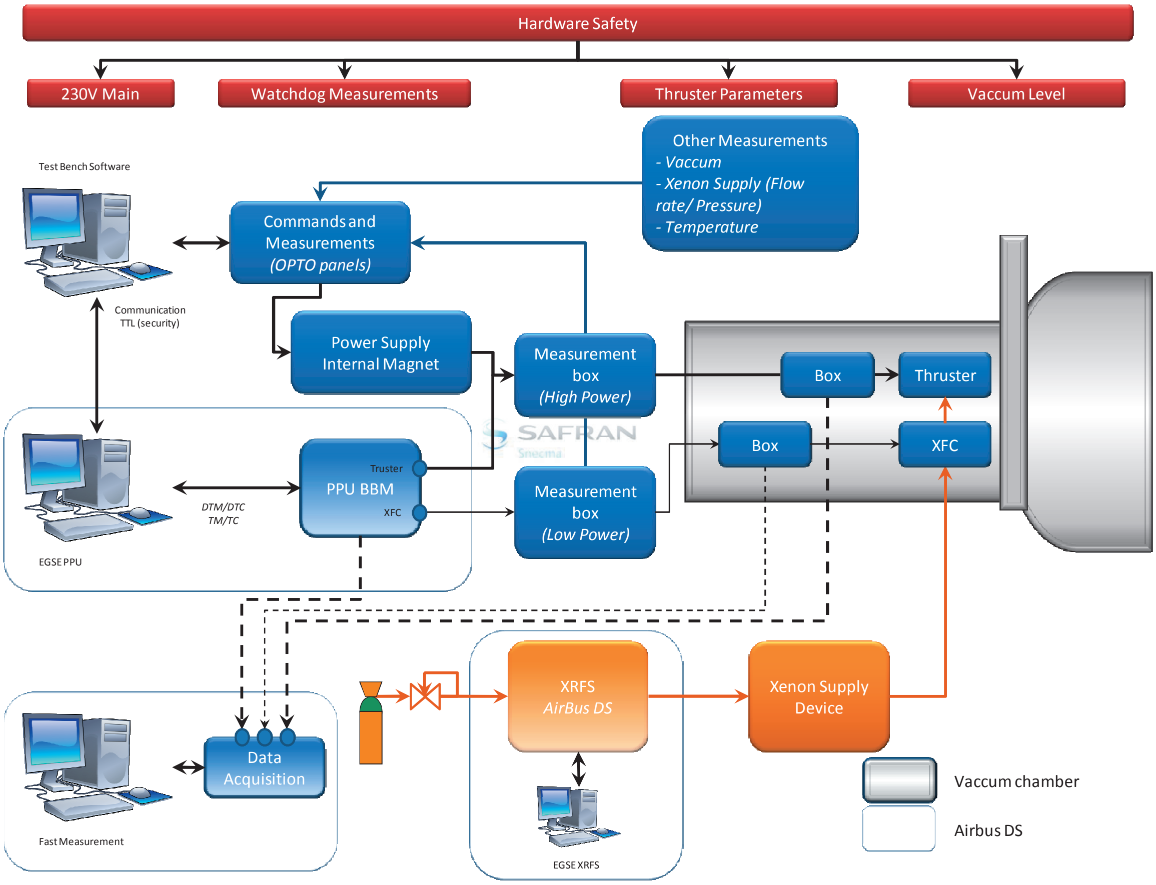

Figure 11. Principle schematic of coupled test setup.

The PPU NG BB comprises all PPU specific electronics boards (anode, heater, ignitor, magnets, thermothrottle, XFC valves) and was itself supplied by laboratory power through an Electrical Ground Support Equipment (EGSE). The only exception was the inner electro-magnet coil, which was supplied directly by a laboratory power supply because it needs a current slightly different from that of the inner coil on the PPS®5000 EM, whereas both coils currents are identical on the flight design. The PPU NG BBM is presented in Figure 12.

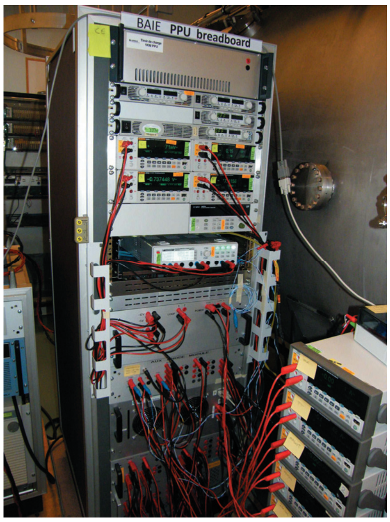

Figure 12. The PPU NG Bread-Board model.

B. Main Test Results

The tests were carried out in the second half of June 2014 and lead to about 34 thruster ignitions and 34 hours of thruster discharge operation. Overall, the behavior of the system under test was found to be excellent.

The discharge current regulation performances have been validated on flight representative scenario in terms of XFC pressure profiles and change of HET operating points. The tests allowed to:

1) Characterize accurately the thermothrottle dynamical behavior in open loop (in response to thermothrottle current variations and XFC pressure variations)
2) Validate the PPU NG discharge current regulation loop implementation and functional behavior
3) Tune the regulation loop gains.

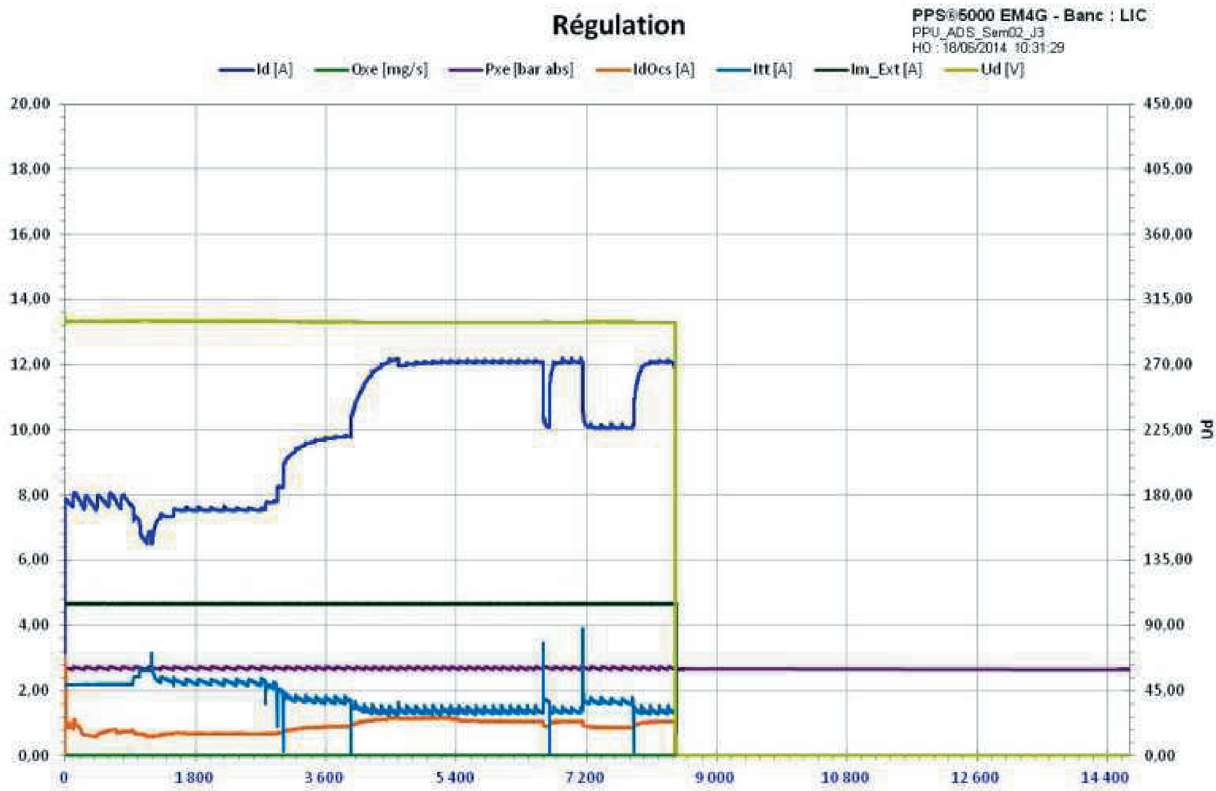

Figure 13. Effect of XRFS-generated pressure spikes on thermothrottle current *Itt* and discharge current *Id*.

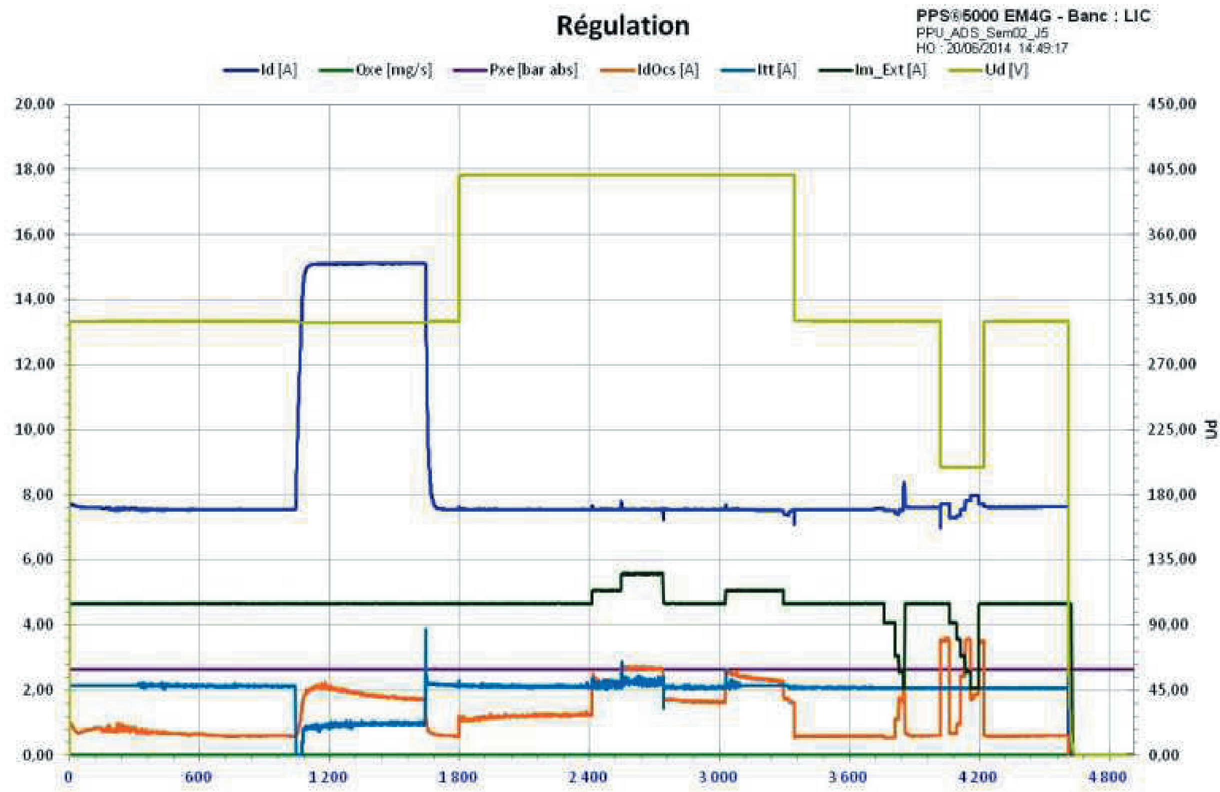

Figure 14. Exploration of operational range and testing of parameters sensitivity to electromagnet coils current.

For example, Figure 13 highlights the typical effect of the pressure spikes (P_{Xe}) generated by the pulsed operation of the XRFS valves during the bang-bang cycles. In this Figure, the discharge current set point is changed with excursions between 6.5 A and 12 A under constant discharge voltage and magnet current conditions. The effect of the transient pressure spikes generated by the XRFS is readily visible on thermothrottle current *Itt*, on xenon pressure P_{Xe} upstream of the XFC, and on discharge current *Id*. Because the time constant of the thermothrottle is on the order of 10 sec., the XRFS cycles generate a discharge current perturbation with a visible reaction of the thermothrottle current (*Itt*) via the regulation loop of Figure 1.

Figure 14 in turn shows the discharge parameters during exploration of the operating domain of the PPU / Thruster system between 400 V and 200 V of discharge voltage and up to 4.5 kW of discharge power. In this test sequence, as visible on the Figure, the sensitivity of the discharge and electrical parameters was tested against variations of electromagnet coils current.

The PPU NG showed a fully satisfactory behavior with respect to thruster startup automatic sequences. In particular, three different ways of starting the thruster were tested:

- Normal start, where the anode voltage and nominal magnet current are applied as a preliminary before discharge ignition;
- Soft start, where the nominal magnet current is applied as a preliminary before cathode ignition, and where anode voltage is applied when discharge appears on the cathode;
- Magnetic soft start, where a reduced magnet current is applied as a preliminary before cathode ignition, and where anode voltage is applied when discharge appears on the cathode.

Figure 15, Figure 16, and Figure 17 respectively show the typical behavior during the startup procedures described above, and in particular the impact of the procedure on the discharge current inrush.

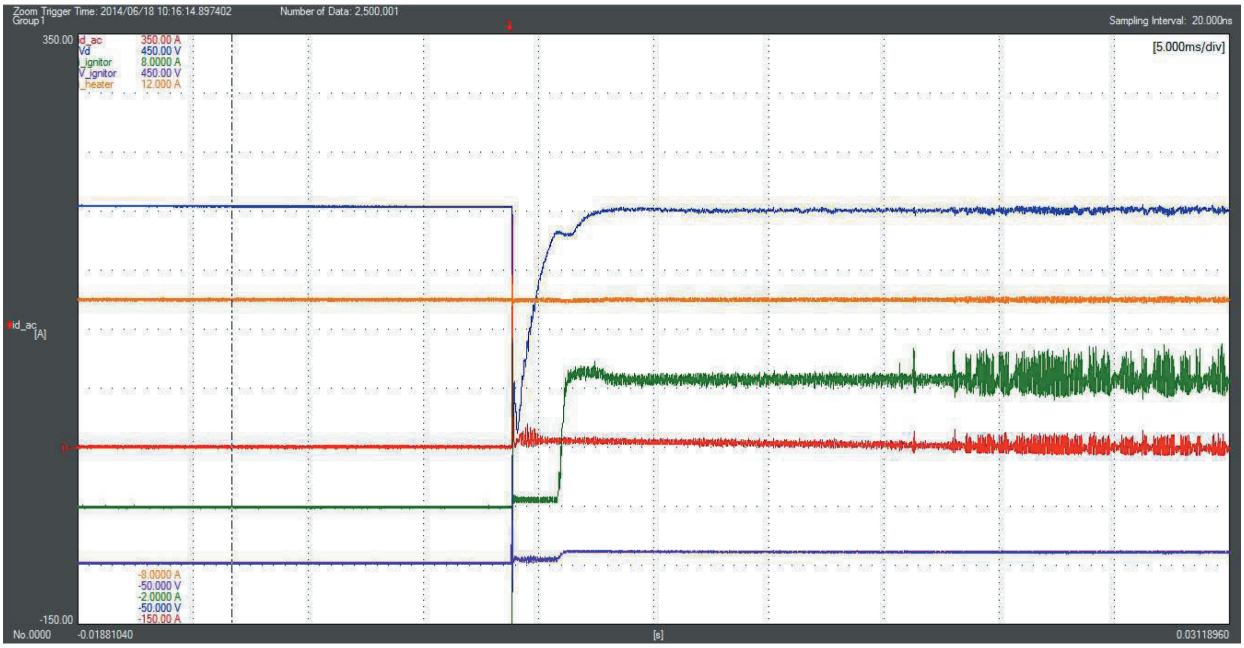

Figure 15. Normal startup sequence. Inrush on discharge current: 195 A.

Beyond the tests of startup procedures as described above, the anode power supply was fully characterized and validated at various operating points: 300 to 400 V of discharge voltage; and up to 5 kW of discharge power. A characterization of the power limitation was also performed, and efficiency of the anode module was measured to be around 96%.

VI. Conclusion

An "End-to-End", or coupled test was performed on development models of a 5-kW Hall plasma thruster system, in support of a PPU development activity at Airbus Defence & Space, and in the frame of the PPS®5000 Thruster Unit development at Snecma. The test involved an EQM Xenon Pressure Regulation and Feed System, a BreadBoard Model PPU, and an Engineering Model Thruster Unit.

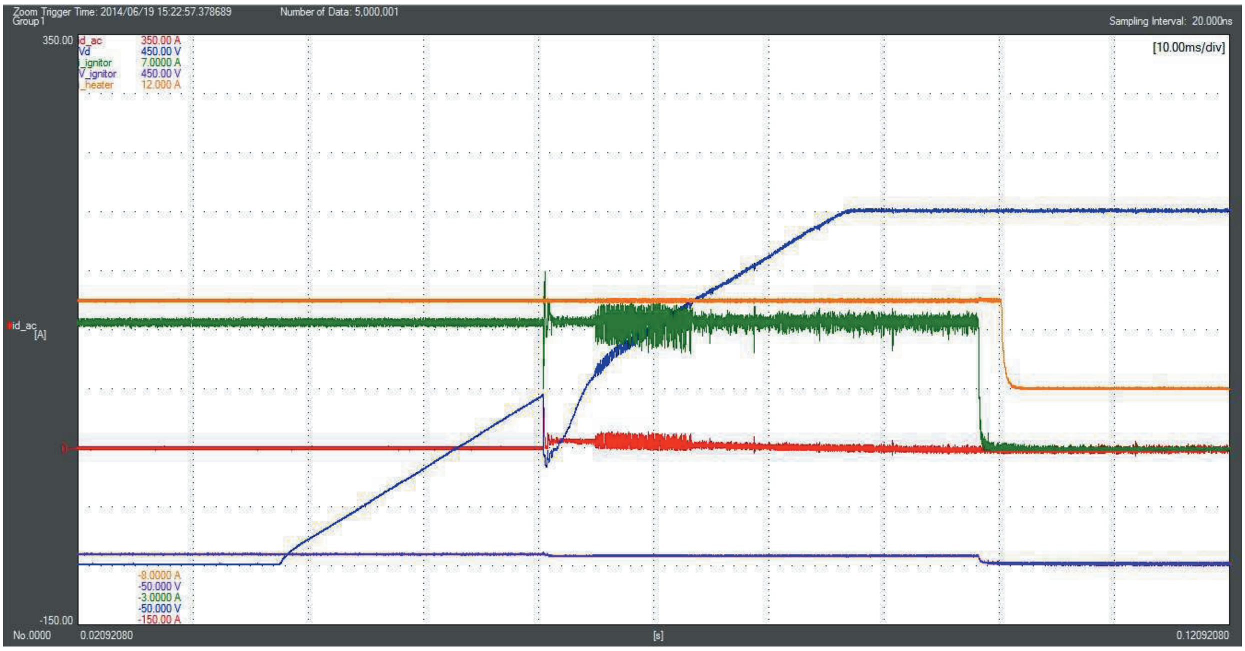

Figure 16. startup sequence. Inrush on discharge current : 45A..

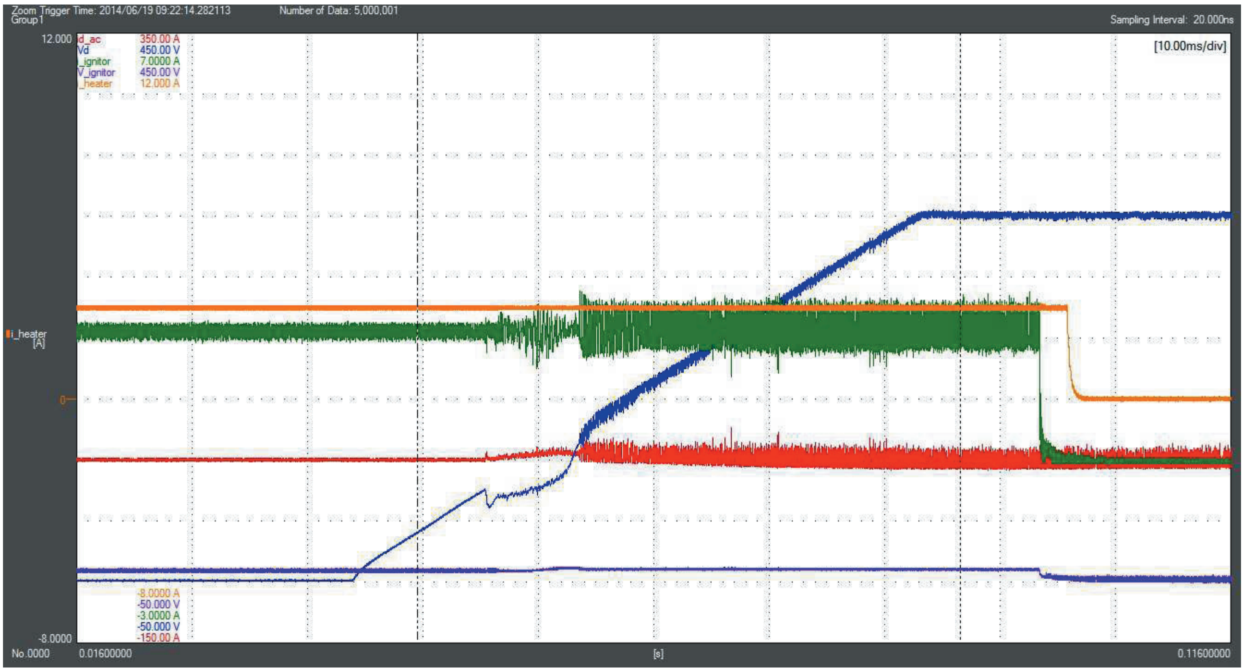

Figure 17. Magnetic soft startup sequence. Inrush on discharge current: 7A.

The tests were performed within two weeks as planned in June 2014, and served to finely characterize system behavior during startup and shutdown transients, as well as verify steady-state operation with the discharge regulated by the PPU closed-loop control in the presence of XRFS pressure spikes.

The tests were completed successfully, and other coupled tests are planned with higher-fidelity models on different PPU options before the end of 2015 as development activities proceed closer to system qualification.

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