Power Processing Unit Activities at Thales Alenia Space in Belgium

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Abstract: Since 1996, Thales Alenia Space in Belgium designs, develops and produces Power Processing Unit (PPU) to supply Hall Effect Thrusters. The first PPU Mk1 flight heritage was provided by Smart-1 spacecraft which reached the Moon in October 2005, after 4 958 hours of PPU cumulated operation. Up to now, thirty five PPU Mk1 flight models were delivered to Airbus DS, ESA, IAI, OHB, Safran, TAS-F. Twenty six PPU Mk1 on flight on thirteen telecom satellites have cumulated more than 40 000 hours operation to perform North South Station Keeping.

To propose a more competitive product, TAS-B has developed and qualified, for the 100V bus platforms, the PPU Mk2, dedicated to Hall Effect Thrusters up to 2.5kW. The PPU Mk2 EQM was successfully coupled with the PPS1350-G at 1.5kW, the PPS1350-E at 2.5kW and the SPT-100. Sixteen PPU Mk2 flight models are ordered by two customers.

For Electrical Orbit Raising, TAS-B has developed and qualified in March 2016 the PPU Mk3 dedicated to 5kW Hall Effect Thrusters. The PPU Mk3 is based on the PPU Mk2 heritage but features additional optimizations to reduce cost. The PPU Mk3 development is consolidated by successful coupling tests with SPT140-D, PPS-5000 and XR-5 thrusters. In September 2019, a total of thirty six PPU Mk3 flight models have been ordered by four customers. Twenty one PPU Mk3 flight models have already been delivered; nine PPU Mk3 flight models are in-flight on three full electric satellites. After having completed their Electrical Orbit Raising, the PPU Mk3 in flight are now used for Electrical Station Keeping.

In order to prepare the next PPU generations, TAS-B is currently involved in three projects of the European Union's Horizon 2020 Strategic Research Cluster (SRC) on Space Electric Propulsion: CHEOPS, HEMPT-NG and MINOTOR. In the frame of the CHEOPS project, TAS-B is developing a 7kW PPU for Dual Mode HET dedicated to GeoTelecom and Navigation applications. In the frame of the HEMPT-NG project, TAS-B is developing a competitive 700W PPU for HEMPT dedicated to LEO applications. For the MINOTOR project, TAS-B investigates the impact of the disruptive ECRA technology on the PPU architecture and cost.

After an introduction of TAS-B heritage on PPU, the paper presents the on-going new PPU developments in TAS-B: the 7kW PPU for Dual Mode HET and the 700W PPU for HEMPT.

Nomenclature

CHEOPS	=	*Consortium for Hall Effect Orbital Propulsion System*
DM	=	*Demonstration Model*
ECR	=	*Electron Cyclotron Resonance*
EPS	=	*Electric Propulsion System*
EPTA	=	*Electric Propulsion Thruster Assembly*

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FU = *Filter Unit*
FMS = *Fluidic Management System*
HET = *Hall Effect Thruster*
HEMPT = *Highly Efficient Multistage Plasma Thruster*
MINOTOR = *MagnetIc NOzzle elecTron cyclOtron Resonance thruster*
PPU = *Power Processing Unit*
SPT = *Stationary Plasma Thruster*
SRR = *System Requirement Review*
TSU = *Thruster Selection Unit*
XFC = *Xenon Flow Controller*

I. PPU Mk1

The first TAS-B PPU product, the PPU Mk1, is dedicated to 1.5 kW Hall Effect Thrusters: PPS1350-G and SPT-100. It includes the SPT power supplies (anode, magnet, heater, ignitor), the XFC power supplies (valve driver and thermothrottle), a sequencer to schedule thruster operation (start-up, stop, regulated thrust, failure identification), a TC/TM interface (MIL-STD-1553 or ML16-DS16 or OBDH-RS485) and an internal Thruster Selection Unit (TSU) module allowing to drive one out of two thrusters.

PPU Mk1 (Fig.1) main features are:

- Efficiency in nominal operating conditions:
  - 91.6 % (Vbus = 50V) or
  - 92.4% (Vbus = 100V).
- Mass of PPU Mk1 including TSU: 10.9 kg.
- Dimensions: 390 mm x 190 mm x 186 mm.
- 8 900 hours lifetime test in space vacuum conditions coupled with SPT-100 thruster.
- 4 958 hours flight experience on Smart-1 launched in September 2003.
- 40 000 hours cumulated flight operation on thirteen geo-synchronous telecom satellites
- Thirty five flight models delivered to Airbus DS, ESA, IAI, OHB, Safran, TAS-F.
- Due to components obsolescence, the PPU Mk1 is now replaced by the PPU Mk2.

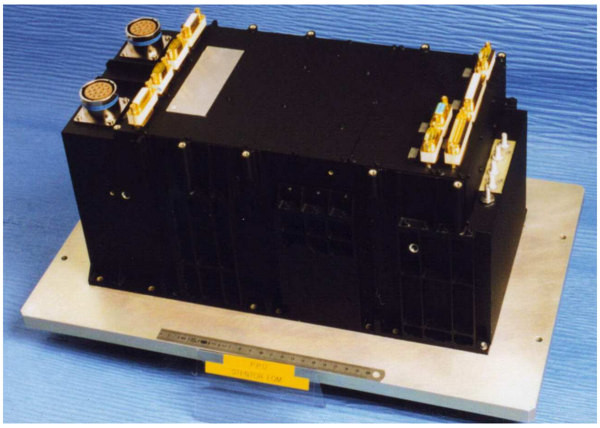

Figure 1. Stentor PPU Mk1 EQM

II. Filter Unit

In a standard Electric Propulsion System (EPS) configuration, a Filter Unit (FU) is implemented between PPU and thruster.

The aim of this passive filtering unit is to

- provide filtering on the thruster lines, the thruster behaving as noise generator at high frequencies;
- provide stabilization of the anode discharge current in order to avoid degradation of thruster efficiency with quasi-periodic oscillations in the 10-50 kHz range;
- limit the radiated emission inside the spacecraft;
- limit the conducted susceptibility at PPU level.

The FU, fully qualified through an EQM followed by a PFM, has been validated by successful coupling tests with PPU Mk1, PPU Mk2, PPS1350-G, PPS1350-E and SPT-100 thrusters.

TAS-B provides FU's flight models to 4 customers.

Figure 2. FU

III. PPU Mk2

A. PPU Mk2 Development

To replace PPU Mk1 by a more competitive and more powerful product, TAS-B has developed and qualified in July 2014 the PPU Mk2 dedicated to Hall Effect Thrusters up to 2.5kW (PPS1350-G, PPS1350-E, SPT-100), for the AlphaBus, Eurostar 3000 and SpaceBus 4000 platforms.

Taking benefit from the PPU Mk1 flight experience, the PPU Mk2 provides 1.6 times more output power (1.5kW → 2.5kW) and more flexibility to thrusters and platforms, with reduced manufacturing cost.

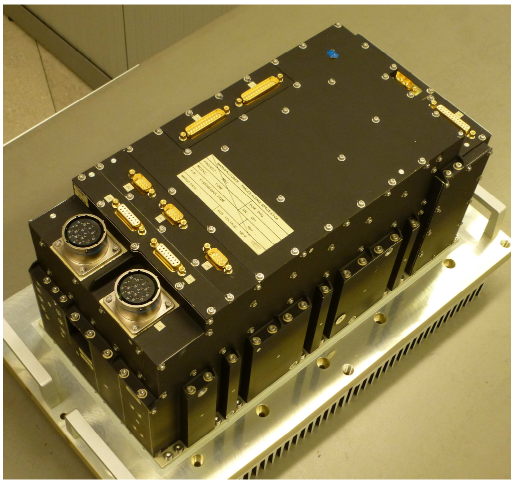

Figure 3. PPU Mk2 EQM

B. PPU Mk2 Description

PPU Mk2 (see Fig. 3) main features are:

- Bus voltage: 100V regulated
- MIL-STD-1553B interface
- Anode output characteristic is commandable in the range 220V – 350V, with short-circuit current commandable in the range 5A – 11A, see Fig 4 .
- Thruster type may be defined after PPU manufacturing, via external configuration straps.
- Standard start-up or soft start-up to reduce inrush current may be selected.
- PPU is robust to abnormal pressure increased inside satellite up to 1Pa, by mechanical design.
- Sequencer based on a FPGA provides more flexibility. The default values and major parameters are adjustable, the protections may be inhibited by telecommands
- Same baseplate size (390 mm x 190 mm) and fixation holes as PPU Mk1.

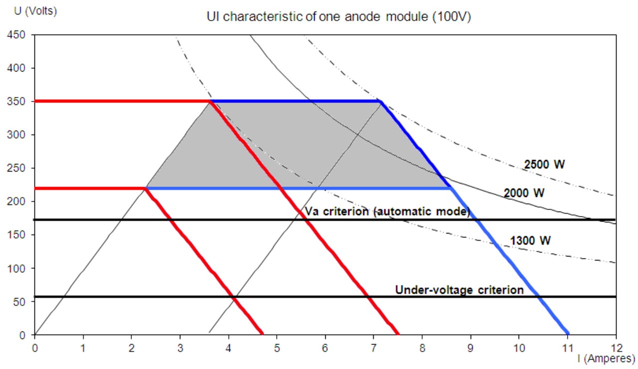

Figure 4. Anode output characteristic

C. PPU Mk2 Qualification

A Qualification Model was built and tested. Fig. 5 shows the efficiency measurements obtained on the Qualification Model in function of the discharge supply output power at a voltage of 350V with the valve driver and the thermothrottle supply active: above 94.4% up to 2.68kW.

After the PPU Mk2 mechanical qualification, including vibration and pyro-shock test, the thermal vacuum qualification tests were concluded by a pressure increase test up to 2 Pa to demonstrate PPU robustness to abnormal pressure increase inside satellite. The thermal vacuum campaign has been followed by a complete EMC test campaign including different LISN configurations to cover the SB4000, E3000 and Alphabus platforms. The Qualification Review was successfully held in July 2014.

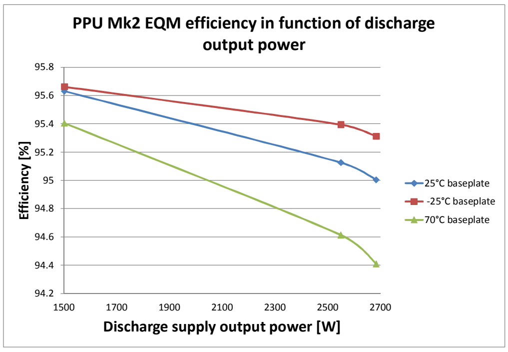

Figure 5. EQM efficiency at 350V

D. PPU Mk2 Coupling Tests and Flight Models

In July 2014, after the Qualification Review, the PPU Mk2 EQM was coupled with a SPT-100 thruster at CNRS Pivoine facility in Orléans, France.

In October 2014, the PPU Mk2 EQM and FU EQM were coupled with a PPS1350 thruster, in the Safran facilities at Vernon, France. Three operating points (250V/4.28A, 350V/4.28A and 350V/7A) were characterized.

In February 2016, the PPU Mk2 EQM and FU EQM were coupled with a SPT-100 thruster, in the Fakel facilities at Kaliningrad, Russia.

Sixteen PPU Mk2 flight models are ordered by two customers; ten are already delivered.

IV. PPU Mk3

A. PPU Mk3 Objectives

The objective of the PPU Mk3 development was to capitalize on the PPU Mk2 product to propose a cost-optimized solution, with a reduced time to market, to drive 5 kW-class HET. These high power thrusters enable an Electrical Orbit Raising of telecom satellites.

The PPU Mk3 objectives were:

- Competitive product,
- Dedicated to PPS-5000, SPT140-D and XR-5 thrusters.
- Dedicated to SpaceBus Neo, Eurostar 3000, NeoSat and Electra platforms.
    - o Bus voltage: 100V regulated
    - o MIL-STD-1553B interface
- Qualification and first flight models in 2016.

B. PPU Mk3 Description

The PPU Mk3 features all the supplies required to operate a HET which features a single cathode and a magnet coil independent from the discharge. It also features a switching function which enables to operate one out of two thrusters. It communicates with the satellite platform through a 1553 bus and receives its power from a 100V bus.

Figure 6 presents the functional diagram of the PPU Mk3.

The main functions of the PPU Mk3 are:

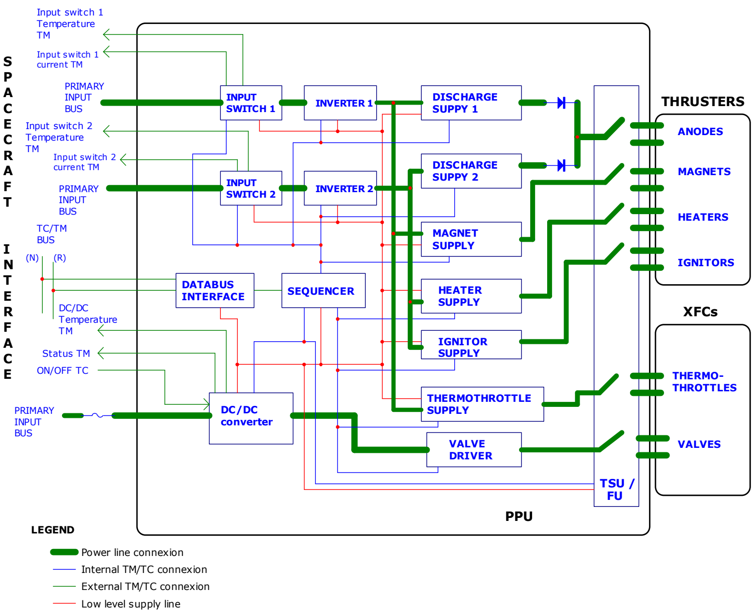

Figure 6. PPU Mk3 Functional Diagram

- 1553 data bus interface to communicate with the satellite.
- DC/DC converter which enables to supply the low-level circuits of the PPU. This DC/DC must be fused protected.
- Sequencer, which is implemented by a FPGA and which controls and monitors all the PPU supplies. The sequencer features an automatic mode where the sequencing of all the supplies is managed to start-up the thruster and operate it in steady mode. Telemetry based protections are also implemented in the FPGA. The sequencer includes a PROM which contains default values and valid ranges to operate different types of thrusters. Standard start-up or soft-start start-up sequence where the cathode is ignited and kept in sustain mode before applying the anode voltage to reduce inrush current may be selected. The sequencer also implements the regulation loop of the discharge current by controlling the setting of the thermothrottle supply.
- Input switch protections (one for each discharge supply) which enables to avoid any failure propagation to the satellite 100V bus in case of an internal failure.
- Two inverters with their transformer provide the insulated voltages required for the thruster. The inverter is a resonant topology in order to optimize the efficiency.
- Two discharge supplies operate in parallel with their outputs summed by diodes. They provide the anode voltage which is commandable from 100V up to 400V. The discharge supplies implement a power limitation: once the knee-current is reached, the voltage drops linearly as the current increases as presented in Fig. 7 which shows the anode supply output characteristic. The short-circuit current is commandable up to 22A. The anode supply, based on two modules of 2.5kW connected in parallel, delivers up to 4.74 kW. The power limitation is required because when the plasma forms at thruster ignition, it drains a lot of current. The linear increase of the current as the voltage decreases is required in order to avoid a lock-up with the thruster characteristic.

- Magnet supply drives the thruster magnet coils independent from the discharge, with current up to 7A.
- Cathode heater supply current capacity is 18A.
- Thermothrottle supply providing a current which enable to regulate the Xenon flow.
- The valve driver enables to control the XFC valves.
- The switching unit is relay-based and enables to supply two different thrusters, one at time.
- Two Filter Units are implemented inside PPU Mk3, downstream the TSU. This filter enables to limit the voltage ripple at PPU output due to the thruster noise. Indeed, when the thruster is fired, it generates significant noise. A telemetry providing an image of the thruster noise RMS current value is implemented.

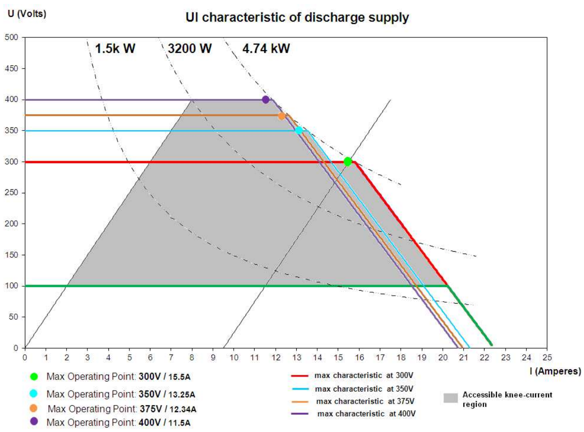

Figure 7. U-I characteristics of the Anode Supply

- The PPU Mk3 is robust to abnormal pressure increased inside satellite up to 1 Pa, by mechanical design.
- Mass of PPU Mk3 with TSU + 2 FUs: 18.6 kg.
- Dimensions: 390 mm x 315 mm x 263 mm.

C. PPU Mk3 Development

The PPU Mk3 development started in 2013, with a Study Phase, to issue and review PPU Mk3 specification with the thruster manufacturers and the primes. The PPU Mk3 architecture was optimized and new packaging was selected to reduce the number of modules and sub-assemblies in order to propose a more competitive product. This phase was concluded in January 2014 with the issue of the Technical Requirement Document which is the input for the following phase, the PPU Mk3 Development Phase.

During this phase, a 5kW anode and FU breadboard were coupled with a SPT140-D thruster, in Fakel facilities, at Kaliningrad, Russia, in October 2014, in order to secure the interfaces with the thruster. By powering the thruster up to 400V and 4.7kW, the anode supply output characteristics and output impedance were validated. The implementation of the FU inside the PPU Mk3 was also validated by testing different harness lengths between PPU, FU and thruster. With these results, the PDR was successfully closed in November 2014.

After the PDR, the PPU Mk3 Demonstration Model (Fig. 8), representative of future flight model (fit, form and function) was developed, manufactured and tested with representative load simulating the thruster and XFC, including hot and cold characterization.

Fig. 9 shows the evolution of PPU Mk3 efficiency, typically above 95%, with the output power and voltage. The measurements at 3 temperatures are above 94.7% up to 4.7kW. The PPU Mk3 DM was also tested up to 5.2kW in order to demonstrate 10% margin on the maximum output power.

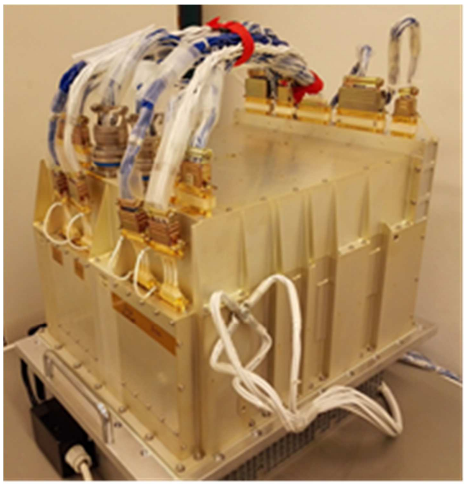

Figure 8. PPU Mk3 DM

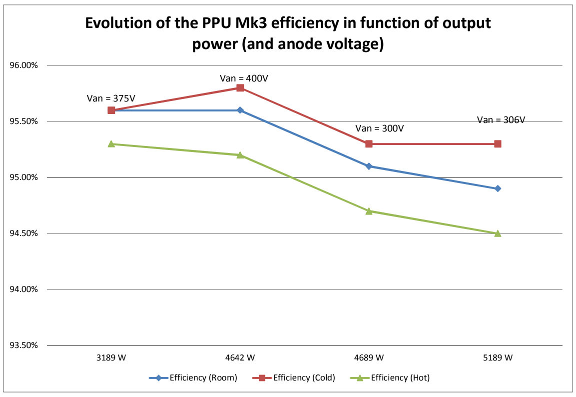

Figure 9. PPU Mk3 efficiency

D. PPU Mk3 DM Coupling Tests

In May 2015, the PPU Mk3 DM has been successfully coupled with a SPT140-D thruster at Aerospazio facilities, in Italy, in partnership with ADS. The coupling test results have supported the CDR closed in September 2015.

In October 2015, the PPU Mk3 DM was also successfully coupled with a PPS-5000 thruster at Pivoine facilities in CNRS Orléans, France.

In December 2015, the PPU Mk3 DM was also successfully coupled to an XR-5 thruster (without XFC) in the frame of an ESA contract led by ESP, at QinetiQ facilities in Farnborough, UK. This test involved experts from ESP, Aerojet Rocketdyne, Mars-Space and TAS-B.

E. PPU Mk3 Qualification

The PPU Mk3 EQM (Fig. 10) was submitted to a full qualification campaign.

The qualification tests first covered the mechanical environment: sine and random vibrations were applied and pyro shocks were performed along all three axis. The thermal and pressure conditions were validated during the thermal-vacuum test campaign as the EQM was submitted to three cold starts and 9 thermal cycles in vacuum conditions. At the beginning and at the end of the TVAC tests, a pressure increase test up to 2 Pa was performed to demonstrate that the PPU Mk3 is robust to an external pressure increase which can cause Paschen discharges in high voltage equipments.

Figure 10. PPU Mk3 EQM

The PPU Mk3 EQM was then submitted to a full EMC campaign including different LISN configurations to cover different platforms. The equipment conducted emissions were fully characterized both in differential and common modes. Conducted susceptibility tests were also performed to check the good behaviour of the unit in case of bus transient and with injections simulating the thruster worst-case noise. The radiated emissions were measured and radiated susceptibility tests were implemented. Direct ESD tests were performed on the PPU thruster outputs to check that they are robust to an electrical discharge occurring on the electrodes of the thruster. Bundle and ground plane ESD tests were also performed with success.

After the Qualification Review successfully held in March 2016, the PPU Mk3 EQM has been coupled with a SPT140-D thruster at Aerospazio facilities, in May 2016 and with a PPS-5000 thruster at CNRS facilities, in February 2017.

F. PPU Mk3 Flight Models

In September 2019, a total of thirty six PPU Mk3 flight models have been ordered by four customers. Twenty one PPU Mk3 flight models have already been delivered; nine PPU Mk3 flight models are in-flight on three full electric satellites. The first three PPU Mk3 in-flight since June 2017 on the first European full electric satellite have completed the Electrical Orbit Raising in October 2017. The Electrical Orbit Raising of the two other satellites is also completed, their PPU Mk3 are now used for Electrical Station Keeping.

G. PPU Mk3 Variant for XR-5

Similarly to PPU Mk1 and Mk2, the PPU Mk3 supplies the thermothrottle of the Xenon Flow Controller to adjust the thruster xenon flow. The thruster discharge is regulated by the PPU sequencer through control of the thermothrottle supply. As the XR-5 thruster is qualified with proportional valves (PFCV) instead of thermothrottle to adjust the xenon flow, TAS-B has performed a Neosat pre-development activity to validate TAS-B PPU Mk3 capacity to supply and regulate a Proportional Valve. TAS-B has developed and manufactured a breadboard model, that was successfully coupled to a PFCV in November 2015 at ESP/TAS-UK facilities in Belfast, UK. Thanks to this pre-development and the coupling test of PPU Mk3 DM with XR-5 thruster, the development of a PPU Mk3 variant for XR-5 thruster is secured.

V. H2020 Activities

In order to prepare the next PPU generations, TAS-B is currently involved in three projects of the European Union's Horizon 2020 Strategic Research Cluster (SRC) on Space Electric Propulsion (EP): CHEOPS, HEMPT-NG and MINOTOR.

A. Dual Mode PPU

In the H2020 CHEOPS project, TAS-B objective is to develop a dual mode PPU capable of driving a high power thruster up to 7kW either in a high thrust mode (lower voltage and high current), either in a high ISP mode (higher voltage and lower current) for Geo Telecom and Navigation applications.

The topology selected for the anode supply is a full-bridge with transformer based topology with several secondaries which can be configured in parallel or in series to enhance the current or the voltage capabilities. This topology, already validated and tested on breadboard in the frame of the Configurable High Voltage Power Supply project, enables to reduce the RMS current in the transformer by optimization of the transformer waveforms form factor. In parallel, thanks to the use of Digital Processor Controller (Fig. 11), developed and qualified by TAS-B for space applications, the implementation of numerical regulation which enables the zero-voltage switching conditions on the transistors, enables to obtain a high efficiency.

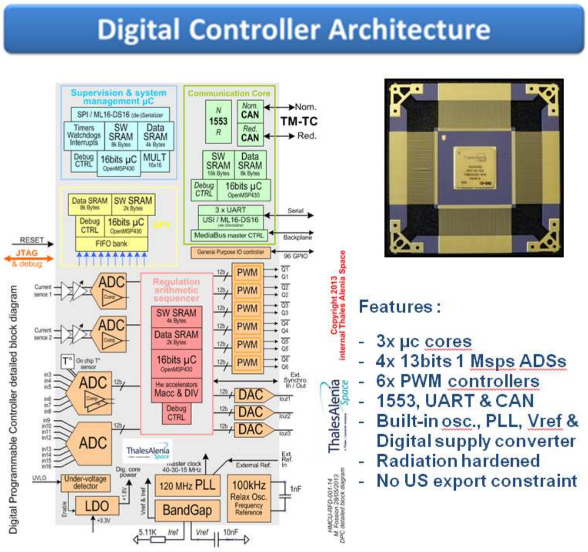

Figure 11. DPC Architecture

Innovative solutions in terms of magnetics and semi-conductors (wide band-gap transistors) as well as enhanced cooling devices are also used to optimize the power density and the cost.

The definition phase, with co-engineering sessions, was concluded by the SRR held with REA, Agencies, European Primes, Safran (thruster manufacturer) and Bradford (FMS manufacturer). The design phase is now completed; the development and manufacturing of the dual mode PPU breadboard is on-going to perform the coupling test with the dual mode thruster and the FMS early 2020.

The CHEOPS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730135.

B. LEO HEMPT PPU

In the H2020 HEMPT-NG project, TAS-B's activity is to develop a PPU capable of driving a HEMPT thruster for LEO applications.

The anode supply is designed to deliver 700W up to 900V. The objective is to develop a LEO HEMPT PPU with an optimized recurring cost in order to propose a competitive solution for the electric propulsion sub-system of constellation satellites. The PPU for HEMPT requires a higher anode voltage but TAS-B has experience in preventing Paschen discharges without the use of potting which penalizes the cost and power dissipation performances.

In order to achieve the cost objectives, topologies enabling the use of low cost planar transformer for the anode, neutralizer keeper and heater supplies has been selected and the use of COTS components is foreseen, as well as a Digital Processor Controller to schedule the different operation phases (thruster start-up, steady-state operation with regulation xenon flow, shut-down).

The definition phase, with co-engineering sessions, was concluded by the SRR held with REA, Agencies, European Primes, Thales Deutschland Electron Devices (thruster manufacturer) and TAS-D (FMS manufacturer). The design has been performed and the PDR has also been held. The LEO HEMPT PPU breadboard has been developed, manufactured and tested. It includes all the supplies required to

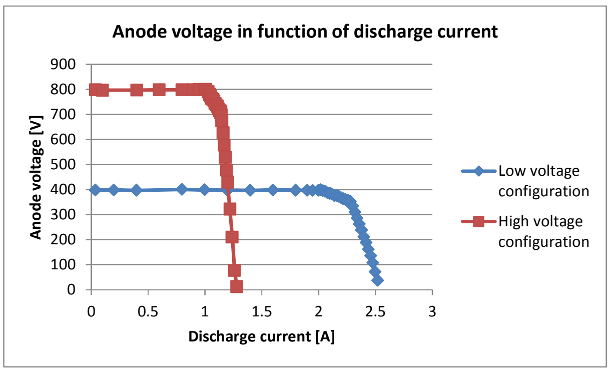

Figure 12. Anode supply voltage/current characteristics

drive the HEMP Thruster and FMS as well as their associated control implemented in a DPC. The Breadboard featured the digital regulation of the discharge current by action on the duty-cycle of the thruster valve.

Figure 12 shows the measured voltage/current characteristic of the anode supply low voltage configuration and in high voltage configuration. The adequate power limitation and current limitation curves were successfully implemented.

Figure 13 presents the efficiency of the anode supply at 800V and 400V.

A coupling test campaign performed with the collaboration of Thales Electron Devices was successfully performed at their facilities in Ulm. During those tests, the PPU implemented the thruster start-up sequence and supplied the LEO HEMPT in low voltage and high voltage mode from 300W to 700W. The compatibility of the different supplies (anode, heater, keeper and valves) with their respective load was checked. The PPU supported the thruster noise and was able to regulate the discharge current by controlling the thruster valve.

The HEMPT-NG project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730020.

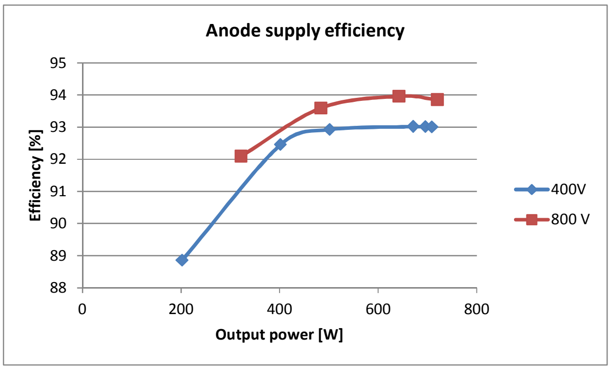

Figure 13. Anode supply efficiency

C. MINOTOR

The objectives of the H2020 MINOTOR project, led by ONERA, is to mature and increase the power of the disruptive Electron Cyclotron Resonance (ECR) thruster technology. In this project, TAS-B analyses the impact of ECR technology at system level, especially at power supply and control point of view.

The main impacts for the PPU are

- the replacement of the isolated high voltage DC/DC converter with power transformer by a RF generator and an RF power amplifier Solid State Power Amplifier (SSPA) with natural galvanic isolation thanks to the capacitive RF connection between amplifier and thruster.
- the absence of cathode in ECR technology which simplifies the PPU by decreasing the number of power supplies.

The simplicity of the ECR thruster induces simplifications, particularly for the PPU whose the cost is foreseen to be reduced by a factor two. The impacts of the insertion of an SSPA in the EPS needs to be further analysed, in term of cost, mass and efficiency.

The MINOTOR project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730028.

VI. Conclusion

Up to now, a total of 88 PPU flight models have been ordered to TAS-B by 8 different customers and 66 PPU flight models have already been delivered.

PPU Mk1 have already cumulated more than 45 000 hours in-flight operation. After the qualification in July 2014 of the PPU Mk2 dedicated to 2.5kW HET, TAS-B has qualified, in March 2016, the PPU Mk3 for 5kW-class HET. The first PPU Mk3 are in-flight since June 2017 and have already finished their EOR phase.

TAS-B is now preparing the next PPU generations thanks to the support of projects from the European Union's Horizon 2020 Strategic Research Cluster (SRC) on Space Electric Propulsion (EP).