Power Processing Units - Activities in Europe 2015

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Abstract: For European space missions the importance of electric propulsion is strongly growing and has recently experienced a real burst in the telecom market. The initial drivers of this development were programs of the European Space Agency and projects of the European national space agencies. In addition, electric propulsion is now on the priority list of European commercial satellite manufacturers. Actual programs target orbit raising and station keeping with full electric propulsion for telecom satellites. European space industry, represented by individual companies, has developed specific and generic solutions for the electronics dedicated to powering and controlling electric propulsion systems.

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I. European Missions and Technology

THE first European space mission with electric propulsion has been flown in 1992. Since this time a variety of propulsion (EP) concepts have been studied and many of them have been implemented in recent, actual and coming missions. Latest successful milestone in European EP achievements is the GOCE satellite operating with the QinetiQ T5 ion engines for drag compensation in low earth orbit. It has reached its end of life after a very successful mission from 2019 to 2013. Another great example is AlphaSat where electric propulsion is used for North-South Station Keeping (NSSK), which is in orbit since July 2013. Close to launch are the BepiColombo and Small Geo spacecraft. A key element accompanying the various thruster evolutions is the development of electronic equipment, dedicated to operate the thrusters by providing power, often at high voltage level, with their challenging impedance behavior and demanding control functions.

European electric propulsion engines are developed and/or manufactured for example by the companies AIT (Austrian Institute of Technology) Seibersdorf in Austria (Indium-FEEP, Pulse Plasma Thruster), AIRBUS-DS in Germany (RIT with RIT-10 and RIT-22, µN-RIT, Indium FEEP with AIT Seibersdorf), AIRBUS-DS in UK with the ROS2000 (Hall Effect Thruster), SITAEL in Italy (Cesium-FEEP, HT 100, HT 400, HT 5k Hall Effect Thrusters, and xenon-optimized resistojets and arcjets) SNECMA in France with the PPS-1350-G, PPS-1350-E, PPS-5000 (Hall Effect Thrusters), QinetiQ in UK with the T5 and T6 Kaufmann ion engines and Thales in Germany (HEMP-T 3050). Furthermore, Hall Effect thrusters (SPT-100) from FAKEL in Russia are also used.

Companies currently providing highly developed products of PSCU and PPU electronic equipment in Europe are:

- ASP Advanced Space Power Equipment, Germany
- CRISA in Tres Cantos, Spain
- Airbus DS in Friedrichshafen, Germany
- Airbus DS in Elancourt, France
- Selex ES (formerly Galileo Avionica and Selex Galileo) in Nerviano, Italy
- SITAEL in Pisa/Bari, Italy
- Thales Alenia Space Belgium (ETCA) in Charleroi, Belgium

The Table 1 gives an overview of actual and recent European electronics developments for EP with reference to thruster applications and status. More details on the mission and the related development on the electronics are given in the following chapters. Details on the successful ARTEMIS mission and the PCU developed by Selex ES driving the RIT-10 can be found in reference [1].

I. ASP - Advanced Space Power Equipment GmbH in Germany

THE company has been founded in 2002 by experienced space power engineers and has established a broad range of space power products in the meantime.

For electric propulsion a development was made regarding a PPU for iMPD thrusters [2]. The focus of the development is put on a high efficient light weight design.

The PPU provides two independent high voltages for the iMPD thrusters. The charge output provides a voltage of 1,3kV to charge up the capacitor of the iMPD. This ignition output provides a voltage of 20kV and is connected to the cathode of the iMPD in order to ignite the thruster. A special charge up circuitry provides a constant power charge up to the capacitor with the advantages of reduced required peak power at the input and reduced input filter requirements. For safety reasons a proper insulation is mandatory on the parts with High Voltage. Internal needed low level auxiliary voltages are generated by the PPU itself. The Input Voltage range is 24 to 32 V, input power is 100Wmax and the Ignition Frequency 1Hz.

The PPU is designed to charge up the capacitor in less than 1s. This allows a firing rate of the thruster of 1Hz. The efficiency of the PPU is approx. 85%. In standby mode the PPU consumes less than 1.3W. The PPU is controlled via three galvanic isolated bi-level commands via optocouplers inside the PPU. For monitoring the status of the PPU three galvanic isolated open collector and two analog signals are provided.

The PPU has been developed to support researching activities in the context of the Magneto-PlasmaDynamic thruster. It fulfills the TRL of an elegant breadboard. The model is shown in Figure 1. The design is principally fit for space use, even if that is not foreseen for this particular PPU. In order to provide a cost effective solution commercial level EEE parts will be applied. The PPU was delivered in 2012.

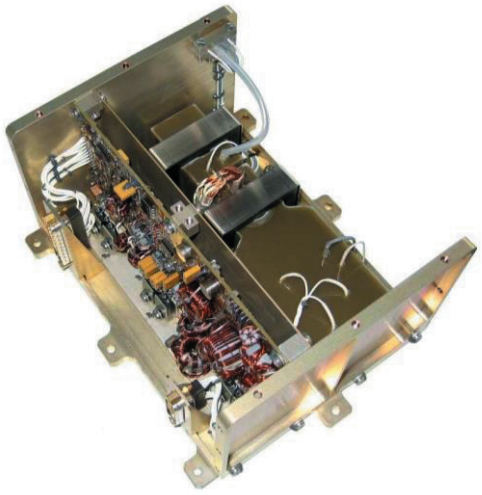

Figure 1 PPU for an iMPD Thruster

Company Equipment	Max. Voltage	Power	Application/Functionality	Year of Delivery/Use	Status
ASP (Germany)					
PPU for iMPD	20kV& 1.3kV	100W	EBB for thruster research (design & packaging suitable for space)	2012	Elegant Breadboard
CRISA (Spain)					
GOCE IPCU	1200 V	620 W	PPU for the ESA GOCE Mission 2 QinetiQ T5 Ion Engines	Flight since 2009-2013	Full Qualification performed Mission already finished and spacecraft decommissioned without any incident concerning EP.
HPEPS PSCU	1850 V	5100 W	Optional High Power Thruster for the ESA ALPHABUS Platform using the QinetiQ T6 Ion Engines	On-going	Coupling test campaign performed Qualification Program Started
BepiColombo SEPS PPU	1850 V	6400 W	Main Thruster for the ESA BepiColombo Mission using the QinetiQ T6 Ion Engines	Flight in 2018	Qualification still in progress, flight hardware manufactured and ready for acceptance.
EGEP PPU	1850 V	5100 W	Industrialization of the BEPI PPU in the frame of Galileo second generation to drive a T6 thruster.	EM on mid 2016	Industrialization in first stages
Airbus Defense & Space (France)					
Joint development between Airbus DS Elancourt (France) and Airbus DS CRISA (Spain)					
PPU NG for HET thrusters	400 V	4 * 5 kW	Development of a new PPU for EOR subsystems based on HET thrusters.	First flight models will be delivered in Q2 2016	PDR held successful. 2 coupling test campaigns have been performed with SPT140D (Fakel) and PPS5000 (Snecma).
Airbus DS (Germany)					
GOCE MPE	13 kV	10 W	FEEP of AIT Seibersdorf	2003	Breadboard
GOCE IBCV	1200 V	520 W	Ion Beam Converter as part of the ASTRIUM CRISA IPCU (see above)	Flight since 2009-2013	Full Qualification performed Mission already finished and spacecraft decommissioned without any incident concerning EP.
µN-RIT PSCU	1..2 kV	100 W	Power Processing Unit EBB for µ-RIT / RIT µX	2009/2013	Predevelopment Power Processing Unit for µN-RIT
Improvement of Building Blocks for T5 Ion-Beam Supply	2000V	1500 W	Improvement and concept for industrialisation of ASTRIUM PPU (IPCU) for QinetiQ thruster T5	2013	EM for further tests on Subsystem Level
SGEO HEMP PSCU	1050 V	1500 W	ESA SGEO Mission 2 HEMP3050 Thrusters	delivered in 2013, flight opportunity on H2Sat	Coupling test campaign performed Qualification Program Started
HPEPS PSCU Beam Supply Modules	1850 V	4410 W	Beam Supply Unit as part of the ASTRIUM CRISA PPU for the ESA ALPHABUS Platform (see above)	delivered in 2012	Coupling tests campaign thruster performed. Qualification for Beam Supply Modules in progress and Flight Program Started
BepiColombo PPU Beam Supply Modules	1850 V	5600	Beam Supply Unit as part of the ASTRIUM CRISA PPU for the ESA BepiColombo Mission using the QinetiQ T6 Ion Engines	Beam Supply Modules delivered in 2013 Flight in 2018	Qualification still in progress, flight hardware manufactured and ready for acceptance.
Selex ES (Italy)					
Artemis PCU	1200V	600 W	Full power processing for ESA ARTEMIS	Launched in 2002	In flight RIT-10 successfully contributed to ARTEMIS orbit raising into GEO
Microscope PPCU	13 kV	70 W	Full power processing for CNES/ESA Microscope mission	Qualification completed in 2008	Qualification completed
Lisa Pathfinder PCU	13 kV	76 W	Full power processing for ESA LISA Pathfinder mission	Qualification completed in 2010	Qualification completed Flight Models delivered
µN RIT PCU	2 KV	57 W	Full power processing for LISA Pathfinder mission	Completed	Elegant Breadboard Coupling test performed with ASTRIUM RIT-µX and neutralisation concept verified with Selex ES
mN RIT PPU	2.5 KV	140 W	Full power processing for a 2.5 mN RIT for Euclid and future space missions	On-going	Design of Elegant Breadboard on going

Table 1 (Part 1): Overview of European Propulsion Electronic Developments and Applications

Company Equipment	Max. Voltage	Power	Application/Functionality	Year of Delivery/Use	Status
Sitael (Italy)					
Cs-FEEP HVPS	7k V	14 W	High Voltage Modules (S9044 &S9045) for SITAEL Cs-FEEP Thruster Simulator on Rubin II	Flight proven in 2002	In flight successfully demonstrated in 2002.
In-FEEP HVPS	11.3 kV	9 W	High Voltage Modules (S9032 and S9071) for AIT In-FEEP Thruster	Flight Models delivered to ARC in 2004	Test with In-FEEP thrusters performed in 2004.
PPU for SPT-20	350 V	350 W	PPU (S9093) for clusters of low power HETs	EM in 2009	Coupling test performed with a cluster of 4 low power Fakel SPT-20 HET in 2010.
PPU for HT 100 and CAM-200	400 V	300 W	PPU for SITAEL HT 100D and Rafael CAM-200 Hall Effect Thrusters	On-going development	Coupling test performed with SITAEL HT 100D. Coupling test with Rafael CAM-200 in July 2015. EQM in 2016.
PPU for HT 5k and PPS-5000	450 V/ 900 V	5 kW	PPU for SITAEL HT 5k and Snecma PPS-5000 Hall Effect Thrusters	On-going development	Coupling test performed with SITAEL HT 5k. Coupling test with Snecma PPS-5000 planned June 2015. Target for EQM 2016.
Thales Alenia Space Belgium (ETCA) (Belgium)					
PPU for SPT-100 and PPS1350-G	350V	1500 W	Full power processing for Fakel SPT-100 and Snecma PPS1350-G Hall Effect Thrusters	Qualification in 1999 Various Flights since 2002	Qualification on Stentor 26 flight models delivered **7 satellites in flight** 3 satellites to be launched
SMART1 PPU	350V	1225 W	Flight Program ESA SMART-1 mission with Snecma PPS1350-G Thruster	Flight 2003 till 2006	Qualification and **Flight** completed
AlphaBus PPU	350V	1500W	ESA AlphaBus platform	Flight since July 2013	Full Qualification performed and 2 flight models delivered for AlphaSat, satellite in orbit since July 2013
Small GEO PPU	350V	1500W	PPU for the OHB Small GEO platform, with SPT-100 thrusters	Flight in 2015	2 flight models delivered, satellite to be launched
PPU Mk2	350V	2500W	Full power processing for 2.5kW Hall Effect Thruster	First FM delivery in 2015	Qualified in July 2014. Coupling test performed with SPT100, PPS1350-G, PPS1350-E
PPU Mk3	400V	5 kW	Full power processing for 5kW Hall Effect Thruster	First FM delivery in 2016	PDR successfully held. CDR is on-going. Coupling test performed with SPT140-D.
HPPU	400V/ 800V	5 kW	Generic Development of High Power PPU for Snecma PPS-5000, Fakel SPT-140, Astrium ROS-2000 compatible with Snecma PPS1350-G and Fakel SPT-100.	Development Model in 2004	Coupling test performed with Snecma PPS-X000
PSCU	2 kV	4.5 kW	Generic Development of High Power PPU for Ion thrusters like Astrium RIT-22 and HEMP-T 3050	Development Model in 2004	Coupling test performed with RIT-22 and Thales HEMP-T 3050

Table 1 (Part 2): Overview of European Propulsion Electronic Developments and Applications

II. Power Processing Unit for HET Thrusters by Airbus Defence & Space in France

IN response to the rapidly evolving Satcom market towards full Electrical Propulsion (EP) solutions, capable not only to perform SK (Station Keeping) maneuvers, but also OR (Orbit Raising) and transfer, Airbus Defence and Space initiated a project internally called PPU NG in order to answer these needs targeting 5 kW class Hall-Effect Thrusters (HET). This joint development between Airbus DS Elancourt (France) and Airbus DS CRISA (Spain) has led to a new innovative concept of PPU, capable to adapt to a wide range of EP subsystem configurations.

The PPU NG offers:

- A minimized recurrent 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. PPU NG is thus able to drive with max. power of 20 kW (4 thrusters).
- The capacity to answer OR and SK needs, with various operating points of a HET: 300 to 400V (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 100V power bus (standard for the Telecom Satellites), it could be easily adapted to other power bus voltages.

The electrical architecture is presented in Figure 2. The main principle of this architecture is that all functions which are not used permanently in the subsystem (Cathodes Power Supply: Heater, Keeper and Ignitor and sequencing of the overall PPU) are gathered in a module called HKISeq. This module is able to address up to 6 cathodes. All other functions (Anode 5kW 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 2 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 the Figures 3 and 4. This modular approach aims to largely facilitate the accommodation of the PPUs for the Satellite Primes.

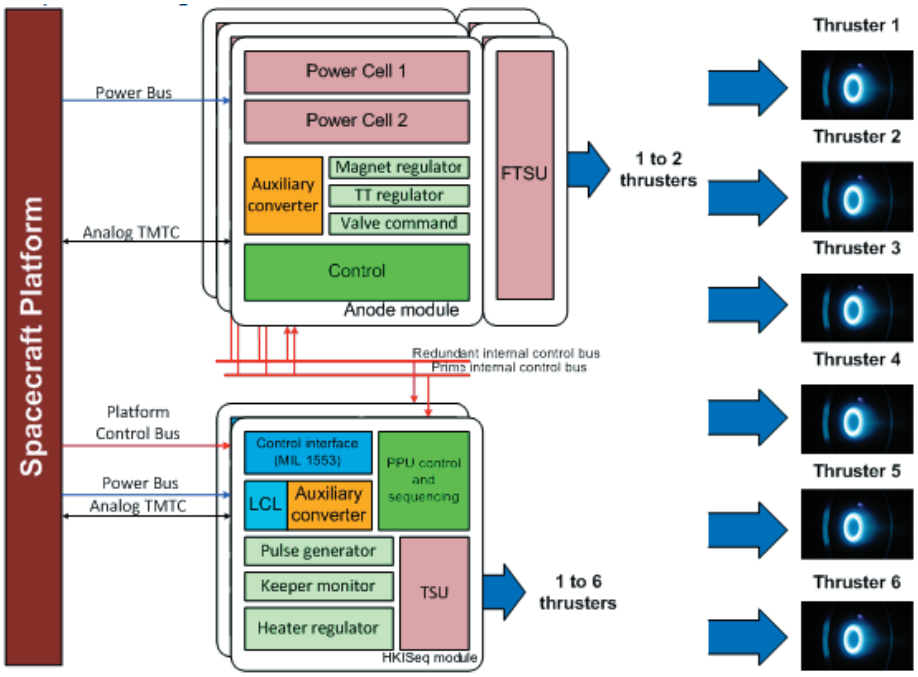

Figure 2 PPU NG Architecture

The development of the PPU NG is on-going and the PDR has been held successfully in September 2014. A breadboard model has demonstrated the functionality and performances. The efficiency was measured around 96% and a characterization of the power limitation has been performed.

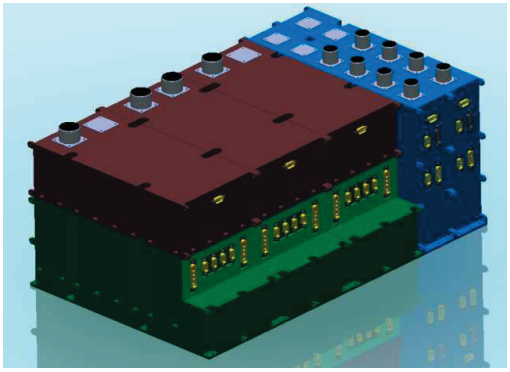

Figure 3 15 kW PPS Assembled Together

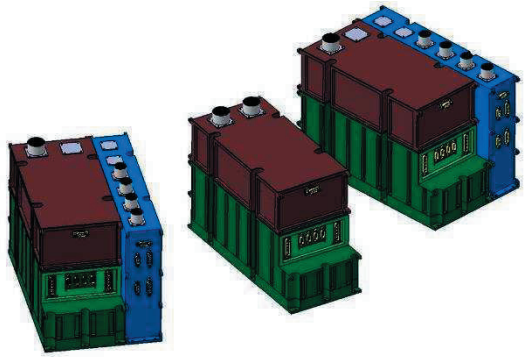

Figure 4 15 kW PPS Distributed Modules

Moreover, two successful coupling tests have already been performed between the PPU NG BB, the SPT140D from Fakel and the PPS5000 from Snecma. The anode power supply has been fully characterized and validated at various operating points: 300 to 400V, up to 5kW.

The CDR is foreseen in Q3 2015, the QR in Q1 2016 and delivery of the first flight set in Q2 2016.

III. HEMP-Thruster PSCU and Generic High Voltage Power Supplies in Airbus Defense and Space, Germany

AIRBUS DS (former Astrium GmbH) in Germany has made contributions to programs EURECA, GOCE, AlphaBus, BepiColombo and Small GEO delivering either complete PPU's or core elements based on their "Generic High Voltage Power Supply – Next Generation" (HVPS-NG). HVPS-NG provides a "tool box" of functional blocks and modules – with a very efficient high voltage converter as core element [3,4]. This " tool box" is continuously further developed, improved and extended.

The actual generation of modules is used for the Anode Supply Modules for HEMP3050 plasma thruster and the Beam Supply Module (BSM) of the QinetiQ T6 Ion thruster showing an overall efficiency of >95% @ 1000V (HEMPT)/1850 V (T6) operating voltage at 1400 W output power.

The qualification program was successfully finalized. The In-Orbit-Demonstration will follow within the H2Sat for HEMPT and for T6 in BepiColombo program. Further Airbus DS Germanys product roadmap comprises customizable complete Power Supply & Control Units and HVPS modules for various thruster types as HEMP, plasma and gridded ion thrusters. The development of a new generation of the generic High Voltage Power Supply has been started in 2013 in order to meet the needs of Orbit Raising applications. The main technology developments and improvements are:

- Increase of power from 1,4 kW up to 5 kW
- Modular approach (1,4/2,5/5 kW)
- Configurable output voltage to optimise the efficiency for orbit raising and station keeping
- Design for manufacturing / cost
- Planar transformer & AMB / direct bonded copper (Figure 5).

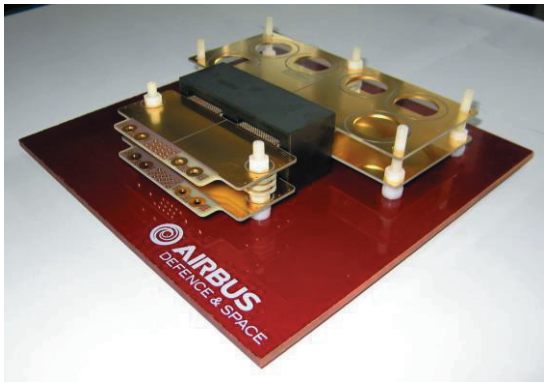

Figure 5 New Key Element: High Power Planar Transformer up to 17 kV.

Some landmarks for recent and ongoing developments are detailed in the following:

GOCE

Two EP electronics developments have been made for GOCE: A demonstrator was built comprising high voltage power conditioning module for a FEEP subsystem (Field Emission Electric Propulsion) providing 13 kV for a total of 96 micro-Newton thrusters [5].

The other electronics is the Ion Beam Converter being part of Airbus Crisa's PPU supplying the main power of the thruster 190 W to 420 W at 1176 V (see chapter 4).

ALPHABUS & BEPICOLOMBO

A team of Airbus CRISA and Airbus DS Germany has provided the Beam Supply Modules (BSMs) of the QinetiQ T6 ion thruster. 2 + 1 BSM's are used in parallel for the PSCU of AlphaBus (High Power Thruster option). 3 + 1 BSMs are used in parallel for the BepiColombo, in total 2 PPU's are operated in parallel. Each BSM is able to provide 1400W output power at 1850V with a bus input voltage of 100V

µN-RIT

Targeting new ESA earth observation and science missions, a development of electronic power supplies for µN-RIT was performed in the frame of an activity of University of Giessen funded by the DLR German Space Agency and ESA. It comprises of a Positive High Voltage Supply (PHV), a Negative High Voltage Supply (NHV), the Radio Frequency Generator Supply (RFG) for plasma generation, a Neutralizer Supply and the Beam Current Controller Further it is prepared to accommodate a Flow Controller (FCU) Supply, An EBB has been tested in a representative test with a µN-RIT.

Figure 6 Qualification Model of a HEMP PSCU

SMALL-GEO & H2.

In the frame of an On-Orbit Demonstration opportunity the HEMP3050 thruster from THALES was developed targeting SGEO. The already qualified hardware is now foreseen for a first light within the German Heinrich-Hertz (H2) mission.

The Astrium PSCU is designed as a modular concept (see Figure 6), composed modules providing

two high voltage power supplies (Anode Supplies) in parallel and operating as main supply for the thrusters, each delivering 1000V / 1400W [4].

RIT-22 PPU

This PPU is developed within Airbus DS Germany, together with Airbus Crisa. A breadboard has successfully tested coupling with the RIT-22 thruster in 2014. An adaptation of the high voltage module to the RIT-10 thruster is planned.

IV. PPU's by Airbus DS CRISA

AIRBUS DS Crisa, Spain started working in the field ESA GOCE satellite from 2001 on [6, 7].

IPCU for GOCE

The IPCU was successfully flown on the GOCE satellite su to 20 mN with a resolution of 12 µN is the main asset of th

IBCV performances	
Input Voltage Range	20V – 34V
Output Voltage Precision	1200V ± 1.5V
Output Voltage TM	0V – 1291,87V (12bits)
Output Current TM	0A – 0,484A (12bits)

Table 2: Ion Beam Converter Summary

Fig. 7 GOCE IPCU - Mass: 17 kg – Size: 380 x 270 x 205 mm^3

PSCU for QinetiQ T6 Engine as AlphaBus High Power Op

The Power Supply and Conditioning Unit, PSCU, has been developed as parallel contract to AlphaBus (ESA under ARTES Program). This contract was awarded to Crisa (and Airbus DS Germany for 1850 Vdc Beam Supply Modules and hv transformers) teaming with QinetiQ (T6 thruster supplier) as lead company and Marotta, UK, (Xe-- Flow Control Unit).

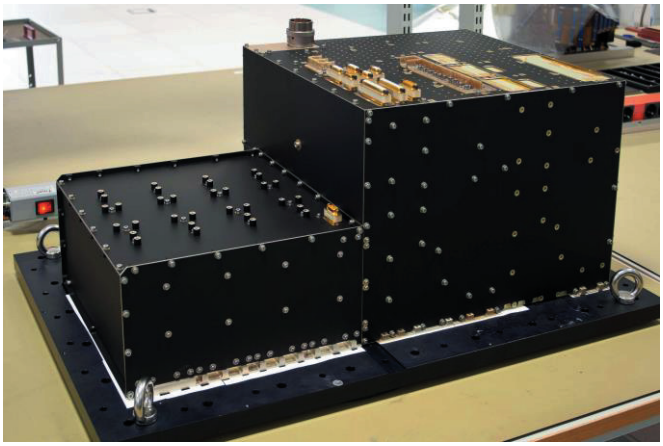

Figure 8: PSCU EQM

The unit mass is 43 kg for 785 x 420 x 355 mm^3 overall dimensions. The overall efficiency is 94,5% @ 5000 Watts

The PSCU (see Figure 8) is composed of two Accelerator-Neutralizer Supplies (DANS), housed in single box together with the Beam Supply (BS). The BS, composed by 3 BSMs, is providing the High Voltage for the Discharge chamber of the thruster. The DANS is providing power to the thruster and Xenon Flow Control Unit, XFCU, and controls the BS. Each DANS is able to switch between two thrusters.

PPU for QinetiQ T6 Ion Engine for the BepiColombo Mission

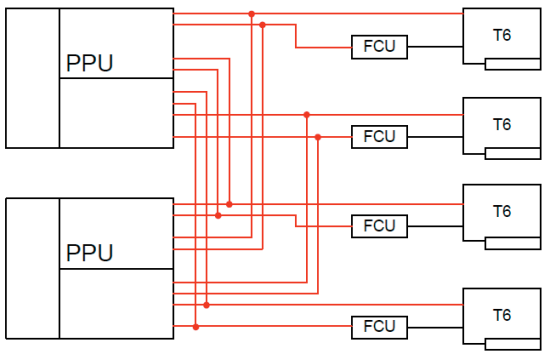

Figure 9: BepiColombo EP Architecture

For the ESA BepiColombo mission to Mercury, Crisa is developing an evolution of PSCU identified on this program as Power and Processing Unit (PPU). It is based on Alphabus PSCU design but in configuration of redundant operation of 4 T6 thrusters. Figure 9 shows the architecture enabling [8]:

- Single operation of any one of the 4 thrusters, and:
- Simultaneous operation of any 2 of the 4 thrusters.

The BEPI PPU EQM has been successfully coupled with the thruster. The EQM is now under qualification and the flight models are manufactured and a ready for acceptance testing.

Innovative Building Blocks

For improvement and in order to establish a concept for industrialization Crisa with Airbus DS Germany has performed a development under ESA contract. The scope is an optimization of the PPU (IPCU) for QinetiQ T5 thruster, mainly by reducing the number of internal supplies from 11 to 5 and an optimization of the mass and manufacturing cost.

An elegant breadboard (see Figure 10) has been successfully tested. The results obtained are being used now in some studies of new missions based on T5 thruster.

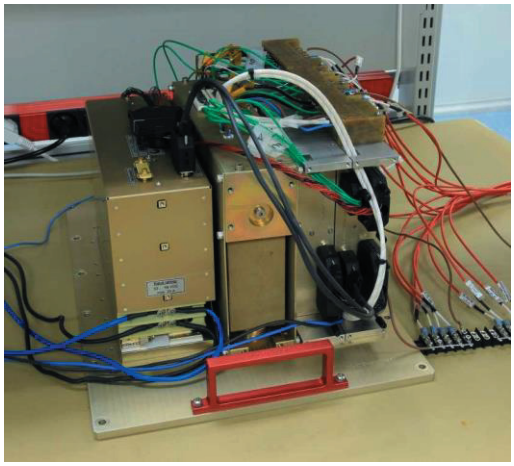

Figure 10: IBB EM

EGEP PPU

In the frame of the European GNSS Evolution Program (EGEP), Airbus DS Crisa together with Airbus DS Germany is performing the industrialization of the BEPI PPU Unit.

This activity is aiming a competitive EP system based on T6 engine targeting Galileo Second Generation platform. In contrast to the BEPI PPU this unit will not include any type of internal redundancy and will be connected to a single Thruster /FCU making it much simpler in terms of hardware. The different power supplies as well as the overall electrical architecture will be optimized in order to minimize the recurrent cost while improving overall performances.

Some of the main goals of this industrialization are: Cost minimization, Mass below 20 kg, efficiency higher than 95 %, volume smaller than 400mm x 350mm x 200mm, simplification of physical interfaces with thruster

The electrical features of this PPU are. Power bus: 100 V, Voltage: 1850 V, Delivered power: 5 kW

This industrialization program is already running, the delivery of an EM is scheduled for mid 2016 followed by a coupling test with the thruster. The program shall be completed at end 2016.

V. Power Control Unit for µN Propulsion by Selex ES

Power Control Unit for µN FEEP Propulsion Subsystem

Field Emission Electric propulsion (FEEP) is one of the potential key technologies for those space applications where very high controllability at low thrust level is required, e.g. drag-free experiments, fine pointing/attitude control or formation flying.

The main performances of a FEEP thruster are a high thrust range of 0.1 µN to 150 µN, with a good setting accuracy of ≤ 0.1 µN, thrust accuracy of ≤ 2%, a response time of ≤ 500ms and a low thrust noise figure.

Selex ES has developed a flexible PCU architecture able to control any thrust in the range 0.1 to 150µN with a thrust resolution better than 0.1µN providing the following main features: - Control and management up to four independent field emission thrusters (hot redundancy) in a cluster structure, providing operating voltage range up to 13kV at very low currents (from 0.1µA to few mA).- Control and management of two neutralizers. - Single point failure tolerant architecture for its use as "primary" propulsion allowing three thrusters and one neutralizer operating in case of single failure at FEEP Subsystem level. 3 FM's as shown in Figure 11 has been delivered for LISA Pathfinder [9].

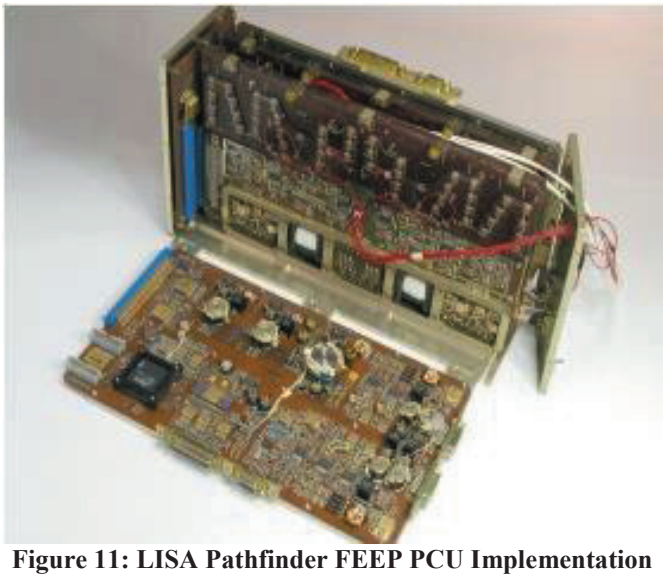

Figure 11: LISA Pathfinder FEEP PCU Implementation

Power Control Unit for µN RIT thruster

Based on the PCU developed and qualified for FEEP, the adaptation for a miniaturized RIT thrusters has been designed, hardware implemented and finally tested. The main performances data are shown in Table 3 and 4. The available elegant bread-board (EBB) PCU from LISA Pathfinder project has been adapted to the µN RIT interfaces via

a few hardwired modifications (control board and mother board), a new power board and the replacement of the FPGA to implement the µN RIT control algorithms (see Figure 12).

The EBB of the PCU has been submitted to a dedicated stand-alone electrical test campaign before its integration with a RIT-µX thruster, its companion Radio- Frequency Generator (RFG) and the neutralizer (also this item of the thruster subsystem is a Selex ES product).

Performance	Requirement
Thrust range	5 µN to 150 µN
Thrust resolution	≤ 0.3 µN
Thrust response time (from 5 µN to 150 µN)	≤ 100ms
Noise (1 - 10^{-4}Hz) @ 100 µN	≤ 1 µN/(Hz) 0.5

Table 3 Thrust Performance Requirement

RIT Interface	Requirement
Positive voltage	up to 2 kV and 4 W
Negative voltage	up to 0.5 kV and 1 W
RFG auxiliary	12V / 2.5W
RFG power	25V / 10W

Table 4: µN RIT thruster to PCU interface requirements

The integration between the EBB PCU and the RIT-µX thruster has been successfully carried out and confirmed the expected performances.

Power Processing Unit for mN RIT thruster by Selex ES

The combination of experience from above micro-Newton thruster PCU development, joined with past flight heritage in the milli-Newton range (RIT-10 for Artemis) shows an appealing capability of such an electrical propulsion technology to support thrust in a wide range of space applications from very fine attitude control up to deorbiting of small-medium satellites.

Therefore, the extension of the application range of the PCU developed for µN RIT to 2.5 mN has started under ESA TRP "Development of a miniaturized gridded ion engine subsystem for future missions".

An enlarged thrust range (i.e. from 10-100 µN to 50-2000 µN) requires to implement the following modifications to the µN PCU:

- Increase of the power capability of the high voltage electrical supply to increase the energy applied to the accelerator electrostatic field (the typical power-to-thrust ratio for this technology is 30W/mN)
- Increase of the current neutralizer interface power capability to cope with the increased neutralization current requirement
- Implementation of the functions devoted to Xenon Flow Control Unit (XFCU) interfaces.

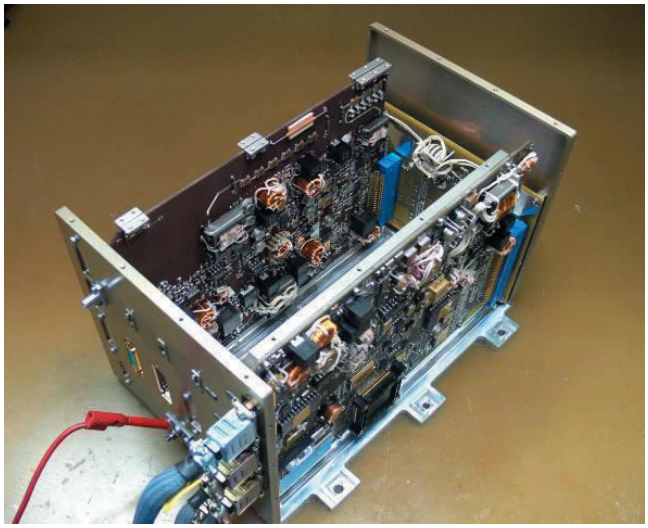

Figure 12: Modified Elegant Breadboard (EBB) for µN RIT

The resulting mass estimate is 5.4 Kg for a complete PPU driving four thruster assemblies (i.e. mini-RIT and RFG), two neutralizers and relevant Spacecraft Interfaces (MB power and TC/TM). The converters efficiency is 85%.
The PPU design has been completed. The PPU EBB manufacturing is on-going and integration with the mini-RIT thruster, the Xenon Flow Control Unit (XFCU) and the neutralizer will be completed by July 2015

VI. Power Processing Unit Activities in Thales Alenia Space Belgium (ETCA)

SINCE 1996, Thales Alenia Space Belgium designs, develops and produces Power Processing Units to supply Hall Effect Thrusters from Fakel (SPT-100) and Snecma (PPS-1350) [10, 11,12].

Current PPU Mk1 Product

Current PPU Mk1 for SPT-100 and PPS1350-G Hall Effect Thrusters as shown in Figure 13 includes: SPT power supplies: anode, magnet, heater, igniter, XFC power supplies: valve driver, thermo throttle, sequencer performing automatic control, TC/TM plug-in module available for MIL-STD-1553, ML16-DS16 and OBDH-RS485 (RUBI) communication busses

In combination with a Thruster Selection Unit (TSU) the PPU allows driving one out of two motors; this module is typically used for North-South station keeping application on geo-synchronous satellite.

The main characteristics are: Maximum thruster discharge power: 1500 W with an overall efficiency in nominal operating conditions up to 92.4% for 100V regulated power bus version. The mass for one PPU including TSU is 11 kg

The unit is fully qualified according to environment specifications of Europeans platforms Eurostar 3000, Spacebus 4000 and AlphaBus. It has heritage of 8900 h lifetime test in space vacuum conditions coupled with SPT-100 thruster, 4958 h flight history on Smart-1 and flight experience of 16 PPU's on 8 geo-synchronous telecom satellites with more than cumulated 28.800h flight operation. A total of 30 flight models have already been delivered for Stentor, SES, Smart-1, Intelsat, Inmarsat, Eutelsat, SmallGEO, AlphaSat, Yahsat, DirecTV, Sky Brasil and Amos.

SMART-1 PPU

Launched in September 2003, Smart-1 spacecraft has reached the Moon after 4958 hours operation of a PPU driving a single PPS1350-G Hall Effect Thruster with variable power from 306W up to 1225W.

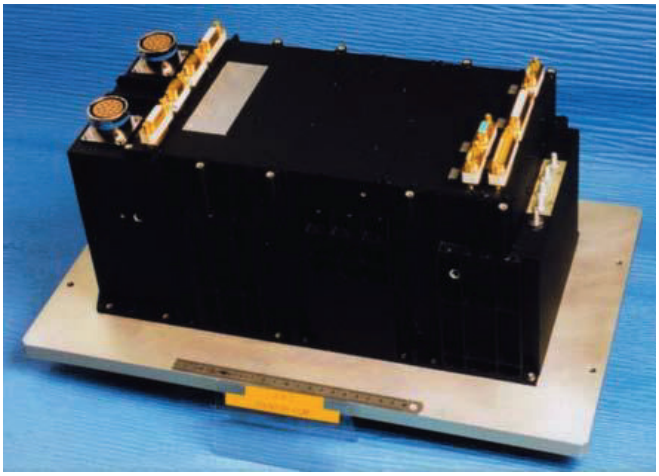

Figure 13 Power Processing Unit for Hall Effect Thruster

HPPU

In 2003, TAS-B (ETCA) has started the development of the High Power Processing Unit to drive high power Hall Effect Thrusters: Snecma PPS-5000, Fakel SPT-140, Astrium ROS-2000 and compatible with the current Snecma PPS-1350-G and Fakel SPT-100.

The HPPU is constituted of several 2.5kW discharge supplies interconnected in parallel or series. Each discharge supply interfaces the input power bus with the plasma discharge circuit. The output voltage and output short-circuit current of each module are adjustable by serial telecommand up to 400V and up to 12A. So, it is possible to adapt the anode voltage depending on the thruster type or the mission phase (orbit raising or attitude control).

The HPPU discharge supply was successfully coupled during 2 weeks with the Snecma PPS-X000 thruster at QinetiQ facilities, in October 2004

PSCU

In the frame of AlphaBus Predevelopment activities, TAS-B (ETCA) has started the development of Power Supply and Control Unit to drive the high power Astrium-ST gridded Ion Thruster RIT-22.

The Positive High Voltage Converter (PHVC), the more powerful supply, provides 4.5kW regulated positive high voltage commendable up to 2kV to the thruster screen grid with output current limitation commandable up to 2.6A.

The two PHVC modules were successfully coupled with the EADS-ST RIT-22 thruster at Giessen facilities, in October 2006. In March 2007, one PHVC module (1kV / 2.5A) was successfully coupled during one week with the Thales TED HEMP-3050 thruster, in Ulm facilities. Steady state operation in the range 500V – 1kV was characterized

PPU-Mk2

In the frame of AlphaBus extension program TAS-B (ETCA) has developed an optimized and more competitive product; the PPU Mk2. The PPU Mk2 addresses SPT-100, PPS1350-G and Hall Effect Thrusters up to 2.5kW and is dedicated to AlphaBus, Eurostar 3000, SpaceBus 4000 platforms. PPU Mk2 provides 1.6 more output power (1.5kW → 2.5kW), more flexibility to thrusters and platforms, with reduced manufacturing cost.

- Thruster type may be defined after PPU manufacturing, via external configuration straps
- Anode output characteristic is commandable in the range 220V – 350V, with short-circuit current commandable in the range 5A – 11A, Figure 14.
- Standard start-up or low power/low voltage start-up to reduce inrush current may be selected
- Sequencer based on a FPGA provides more flexibility. By telecommand, the default values and major parameters are adjustable, the protections may be inhibited.
- Optional magnet supply
- Same baseplate size (390mmx190mm) and fixation holes as current PPU Mk1 (see Figure 15).

The qualification was completed in July 2014, followed by a coupling test campaigns with SPT100, PPS1350-G (1.5kW) and PPS1350-E (2.5 kW) thrusters. The PPU flight models are in production: 8 ordered and 4 anticipated; first delivery in 2015.

PPU Mk3

In line with this SATCOM market evolution, the satellite manufacturers foresee the use of Electric Propulsion to perform Orbit Raising with 5kW-class Hall Effect Thrusters. In response to this demand, TAS-B (ETCA) develops the PPU Mk3 based on its significant heritage with the objectives are:

- Competitive product,
- Dedicated to SPT140-D, PPS5000 and XR-5 thrusters.
- Dedicated to SpaceBus Neo, Eurostar 3000, NeoSat and Electra platforms with 100V regulated Bus voltage and MIL-STD-1553B interface.

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 more competitive product. During the Development Phase, a 5kW anode and FU breadboard were coupled with a SPT140-D thruster, in Fakel facilities, in October 2014, and operated up to 400V and 4.7kW. With these results, the PDR was successfully closed in November 2014.

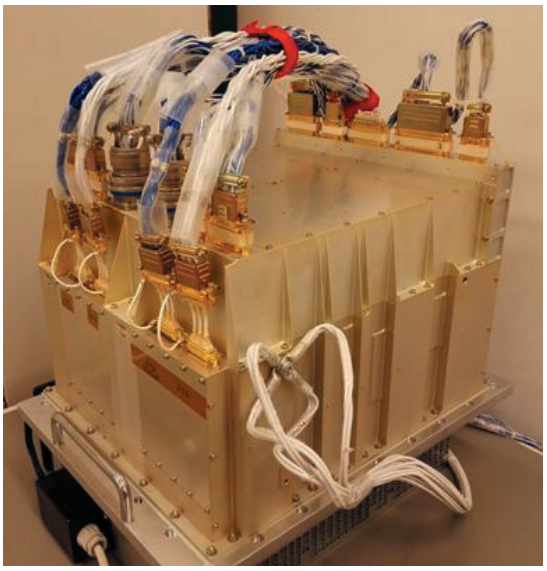

Figure 14 PPU Mk3 DM1

The PPU Mk3 Demonstration Model 1 (Fig 14), representative of future flight model, was developed, manufactured and tested with representative load simulating the thruster, including hot and cold characterization. The PPU Mk3 efficiency is typically above 95%. In May 2015, the PPU Mk3 DM1 has been coupled with a SPT140-D thruster at Aerospazio, in Italy. This coupling test supports the CDR initiated in April 2015. Further coupling test with PPS5000 and XR-5 thrusters are also foreseen.

The procurement and manufacturing of the PPU Mk3 EQM is initiated with the objective of qualification in 2015. Nine PPU Mk3 flight models are already ordered with first deliveries in 2016.

VII. Power Processing Unit Activities in Sitael (Italy)

SITAEL has made several developments in the field of PPU within the past 20 years with a focus on power electronics for FEEPs and PPUs for Low and High Power Hall Effect Thrusters. PPU activities grew up through the years until the recent acquisition of Alta by the Angelo Investment Group and the consequent merging into SITAEL by the end of 2014. SITAEL represents today a unique example in Europe of a company able to provide complete Electric Propulsion Systems for different class of Satellites, from Microsatellites up to Large GEO Platforms. Moreover, the close coordination between PPU and thruster designers in the same company, allows to explore the most innovative solutions to improve affordability and compactness of such space systems.

High Voltage Power Supplies for FEEP Thrusters

SITAEL involvement in power electronics for Electric Propulsion started with the development in the early 2000s of High Voltage switching-type DC/DC converters for FEEP Thrusters developed by Alta (today SITAEL Advanced Propulsion Division).

In the frame of a contract with OHB-CGS, SITAEL developed the Power Processing and Control Unit (PPCU) HV power supply system for the Alta Cesium µ-Newton FEEP to be proven on Rubin II technology demonstrator.

The S9044 (-5 kV / 0.15 mA) and S9045 (7 kV / 2 mA) power supplies were successfully proven in 2002 on board of the satellite connected to a simulator of the ALTA Cs-FEEP.

In 2003, SITAEL developed the Flight Models of S9032 (-1 kV / 0.4 mA) and S9071 (+11.3 kV / 0.76 mA) HV modules to supply AIT Indium FEEP Thrusters (see Figure 15)

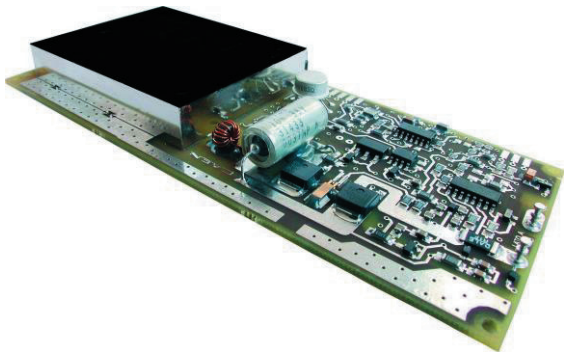

Figure 15: HV Module for FEEP

PPU for Low Power HET Cluster

In 2009 SITAEL developed the Engineering Model of a PPU for Fakel SPT-20 HET. The S9093 PPU is composed by three sections: Data Processing Unit (DPU), Power Conditioning and Distribution Unit (PCDU) and Flow Control

Unit (FCU). Developed for the unregulated 28 V bus, the PPU has been successfully tested controlling a cluster of 4 SPT-20 (75-80 W each, 350 W total) operating in vacuum environment.

PPU for Low Power HET System for Small Satellites

In the frame of the ESA/ISA MEPS project led by SITAEL and RAFAEL, SITAEL is responsible for the development of a PPU for a low power and low costs 300 W HET-based propulsion system for small satellites (< 300 kg).

MEPS PPU functional blocks are:

- 2 PCMs (PPU Control Module)
- 2 PPMs (PPU Power Module)
- TSU (Thruster Switching Unit)
- 2 FUs (Filter Unit)

The PPU has an efficiency higher than 93% and is compatible with non-regulated 28 V power bus including in-rush/bus-switch protection controller. The power limitation is programmable up to 600 W.

Furthermore is provides a MIL-STD-1553B interface., the ability to independently command, control and monitor two thrusters (with their cathodes) , to command and monitor the PMA , the ability to select two independent thrusters (with cathode) through its TSU

The PPU is suitable for SITAEL HT 100D and Rafael CAM-200 Hall Effect Thrusters with full redundant design.

The redundancy strongly improves reliability, making the solution suitable also for critical applications. If redundancy is not required, the two thruster driver installed in the PPU can be used to supply two different independent thrusters at the same time, thus increasing flexibility of the PPU. The anode voltage is adjustable in the range 250 V ÷ 400 V and Magnet supply is based on a 3.5 A – 40 W current source.

For the MEPS project, a heater-less cathode is used. This configuration allows reducing the electronic parts, at the same time increasing the reliability of the whole system. Because of heater-less cathode, an high voltage power supply is used for ignition. The ignition voltage is programmable in the range 600 V ÷ 1200 V, able to sustain 50 A peak current providing more than 1.2 mC of energy to ignite the cathode.

The sustain module is a current source able to provide 1 A (30 W power limitation). Ignition rate is programmable in the range 1 Hz ÷ 50 Hz. An Elegant Breadboard was completed in 2014 and coupling test with SITAEL HT 100D was successfully performed. Coupling test with RAFAEL CAM-200 is planned for July 2015. The PPU EQM will be delivered in 2016.

PPU for High Power Hall Effect Thrusters

SITAEL is developing a 5 kW PPU for SITAEL HT 5k and Snecma PPS-5000 Hall Effect Thrusters. An Elegant Breadboard is available (see Figure 16) since end of 2014 and a coupling test with HT 5k was successfully performed. A coupling test with Snecma PPS-5000 is planned for June 2015.

The PPU has an efficiency higher than 92% at 100 V bus, It is equipped with MIL-STD-1553B, in-rush/bus-switch protection controller, programmable power limitation, XFC management, TSU able to select two independent thrusters (with cathode)

With an Anode voltage adjustable in the range 250 V ÷ 450 V, the PPU provides full power all over the operating range in order to satisfy both high ISP and high thrust.

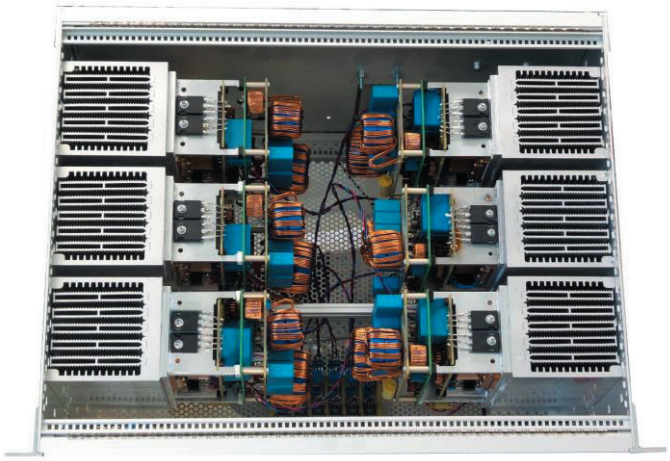

Fig. 16: Modular 7.5kW Power Supply BB for Thruster Anode

Currently SITAEL PPU power density is higher than 1.5 kW/l, but the EQM development is ongoing, targeting a cost effective and innovative PPU based on a single 5 kW Anode module. The Magnet supply is based on a 7 A – 350 W current source. Ignition module is able to provide 400 V ignition pulse in the programmable range 10 Hz ÷ 85 Hz. The heater supply is able to provide up to 18 A programmable (46 V max. voltage).

The qualification is planned in 2016, and the EQM is targeting considerable reduction of mass, volume and cost.

VIII. Conclusion

SEVEN European suppliers of PPU's – ASP Advanced Space Power Equipment, CRISA, Airbus DS France, Airbus DS Germany, Selex ES, Sitael and Thales Alenia Space Belgium have made remarkable developments to fulfill the needs of the ambitious European space missions as well as to enter the commercial market of telecom

satellites.

Significant flight experience has been achieved with the PPU's from Thales Alenia Space Belgium (ETCA) combined with Hall Effect thrusters from FAKEL (SPT100) and Snecma (PPS-1350-G). This is including the full electric propulsion flight to moon (SMART1-mission) and several telecom missions in orbit. Based on PPU Mk1 flight experience and numerous coupling tests, TAS-B (ETCA) has qualified the PPU Mk2 and started the development of PPU Mk3 dedicated to 5kW Hall Effect Thrusters for full EP satellites with EP Orbit Raising

CRISA and Airbus DS Germany have qualified a PPU for the QinetiQ T5 Kaufmann engine, completed operation on GOCE satellite from 2009-2013. Both companies are qualifying together PPU solutions for the QinetiQ T6 high power Kaufmann engines to be operated on the BepiColombo flight probe to Mercury as single propulsion system for its 5 years journey. Furthermore, CRISA is exploring together with QinetiQ further optimization of ion gridded PPU

Airbus DS Germany has qualified a PSCU for the Thales HEMP 3050 Thruster and developed generic solutions for high voltage power supplies and dedicated developments for µN thrusters (RIT). A next generation of High Voltage Power Supply is expected to use planar transformer technology delivering 2500W per module.

Selex ES has provided a qualified PCU for FEEP application for both, the Indium FEEP as well and the Cesium FEEP. Moreover Selex ES develops a PCU, based on the FEEP one, for the Astrium Germany µN RIT thruster as a potential candidate for the EUCLID mission. An upgrade of this PCU to extend the application range up to 2.5 mN is currently on going.

ASP Advanced Space Power Equipment company in Germany has developed breadboard PPU for Pulsed Plasma Thruster (iMPD). The design is capable for pulse operation at 1.3kV of a thruster firing at a frequency of 1Hz. The efficiency of the PPU is 85% at an input power of 100W.

SITAEL has been active on Power Electronics for FEEP and PPUs for Hall Effect Thrusters. A range from 80 W to 5 kW has been explored, with 5 kW PPU already coupled with the HT 5k thruster, and a very flexible PPU with up to 600 W of power tested with the HT 100D thruster in the frame of the MEPS project. Target qualification for both PPUs is planned for 2016.

In addition to these core developments all electronic equipment supplier are aiming a cost-efficient, scalable and modular approach in order to serve different thruster types and power classes with an optimum design and maximum of recurrent elements

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