

An Adaptable Power Control Unit for Ion Thruster Micro-Propulsion Subsystems

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Abstract

During recent years, different electrical propulsion thrusters in the micro-newton range such as Field Emission Electrical Propulsion thrusters (FEEP) and Radio-Frequency Ion Thrusters (RIT), in Europe, and colloid thrusters, in the U.S., have progressed and achieved considerable milestones both in development and qualification activities so that a significant number of space missions with applications requiring a very high level of controllability in the micro-Newton range (e.g. for drag-free experiments, fine pointing/attitude control or formation flying) are today really feasible.

Given that the electronic package is one of the key elements of any electrical propulsion subsystem, providing the electrical power to the thrusters, it actually plays an important role in the overall micro-propulsion performances. In fact, the electronic package (hereafter recalled as Power Control Unit – PCU), beyond being a driving factor for mass and power consumption, effectively allows the micro-propulsion subsystem to meet stringent thrust requirements in terms of resolution, accuracy, controllability and noise. From this perspective, this paper is presenting:

- An up-to-date status of the Power Control Unit (PCU) developed by SELEX Galileo to supply and control an electrical micro-propulsion subsystems making use FEEP technology.
- Review of the micro-propulsion subsystems aspects linked to the electronic package requirements.
- Finally, a review of the developed Power Control Unit for FEEP for its adaptability to different Ion thruster technology (e.g. micro-RIT technology).

Nomenclature

<i>EMC</i>	=	Electromagnetic Compatibility
<i>EQM</i>	=	Engineering Qualification Model
<i>ESA</i>	=	European Space Agency
<i>FEEP</i>	=	Field Emission Electrical Propulsion
<i>FM</i>	=	Flight Model
<i>HV</i>	=	High Voltage
<i>NA</i>	=	Neutraliser Assembly
<i>PCU</i>	=	Power Control Unit
<i>PFM</i>	=	Proto-Flight Model
<i>RFG</i>	=	Radio-Frequency Generator
<i>RIT</i>	=	Radio-Frequency Ion Thruster
<i>TC&TM</i>	=	Telecommand and Telemetry
<i>TRP</i>	=	Technology Research Program

I. Introduction

A. Micro-Propulsion Mission scenario

Different electrical propulsion thrusters in the micro-newton range such as Field Emission Electrical Propulsion thrusters (FEEP) and Radio-Frequency Ion Thrusters (RIT) in Europe, and colloid thrusters in the U.S., have gained significant development and qualification activities (up to flight model phase) so that a number of space missions requiring a very high level of controllability in the micro-Newton range (e.g. for drag-free experiments, fine pointing/attitude control or formation flying) are today feasible.

For instance, micro-propulsion technologies are mandatory in the frame of breakthrough experiments in fundamental physics (e.g. General Relativity) requiring Ultra-Precision metrology in space like the LISA Pathfinder and LISA (Laser Interferometer Space Antenna), in more detail:

- LISA Pathfinder, the technology demonstrator and precursor of LISA, is an experiment to demonstrate Einstein's geodesic motion in space and verify that the employed technologies are suitable for this task. The mission concept (see fig. 1) is to prove geodesic motion by tracking two test-masses nominally in free-fall through a laser interferometer measurement system with picometers distance resolution. The orbit is at the Earth-Sun L1 Lagrange point because provides a benign gravitational environment with stable solar illumination and freedom from eclipses and the spacecraft will stay in such an orbit for an operational lifetime up to 17 months. The micro-thrusters for this mission are in FEEP technology, which are presently under qualification.

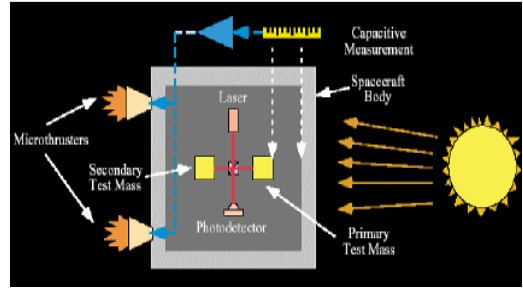


Figure 1. LISA Pathfinder concept

- LISA mission, the natural continuation of LISA Pathfinder and of its technologies, will have the primary aim to detect gravitational waves expected to be emitted by distant galactic sources, such as black holes; gravitational waves that are presently theoretical predicted only in the frame of Einstein's General Relativity. LISA mission (see fig. 2) should consist of three spacecrafts flying in a triangular formation but separated by about 5 billions of meters! and linked together by a laser beam in order to form a colossal interferometer not really feasible on the earth. So huge accuracy in spacecraft positioning need to be assured through high performance micro-propulsion technologies.

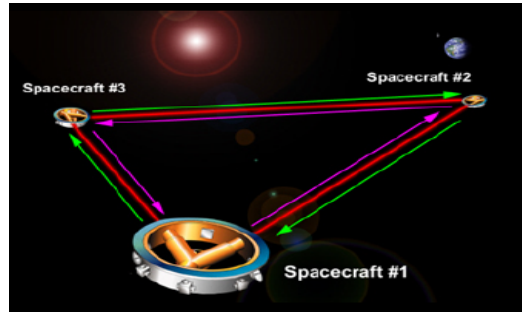


Figure 2. LISA concept

B. Micro-Propulsion main requirements

Based on the above described mission scenarios, it can be easily inferred that micro-thrusters are mainly used as actuators for fine pointing/attitude and drag-free operations in a closed-loop control: in these applications the

Table 1. Micro-propulsion requirements

Propulsion parameter	Requirement
Thrust range	0.1 μN to 150 μN
Thrust resolution	$\leq 0.1 \mu\text{N}$
Thrust accuracy	$\leq 2\%$ at max thrust
Thrust response time	$\leq 500 \text{ ms}$
Noise (from 1 to 10^{-4} Hz)	$\leq 0.1 \mu\text{N}/(\text{Hz})^{0.5}$

requested ultra-low thrust level is continually adjusted in order to respond and compensate any external disturbance (e.g. radiation pressure, particulate impacts, gravitational effect etc.), requiring, therefore, very high thrust controllability in term of thrust range, resolution, stability, linearity, response time and with actually noise-free behavior. The typical performances demanded to such Micro-Propulsion Subsystems are those shown in table 1.

In addition to the thrust requirements, it is demanded to provide multi-point thrust generation, robustness to failure conditions and relevant redundancy aspects; e.g. for LISA Pathfinder the micro-propulsion subsystem [1] is formed by three main multi-point thrust sections, which are allocated on the spacecraft at about 120 degrees between them, each one consisting of one cluster of four thrusters and two neutralizers both controlled and supplied by one Power Control Unit. It is worth noting that in all these aspects the PCU plays a fundamental role to achieve these challenging features.

II. Power Control Unit for FEEP technology

C. Power Control Unit for FEEP: General Description

To comply with the challenging micro-propulsion requirements and to match thrusters and neutralizers needs, a flexible PCU architecture able to control any thrust in the range 0.1 to 150 μN with a resolution better than 0.1 μN has been developed and qualified by SELEX Galileo

As far as the general description is concerned, the developed PCU can be adapted with different electrical and mechanical arrangements, providing the following main features:

- Control and management up to four independent FEEP thrusters working in hot redundancy with voltages up to 13.7 kV at very low currents from 0.5 μA to 2 mA and including power supplies for heaters.
- Control and management of two neutralizers working in cold redundancy.
- Single point failure tolerant architecture for its use as “primary” propulsion allowing at least three FEEP thrusters and one neutralizer fully operating in case of single failure (full redundancy applicable also for command, telemetry and power interfaces).



Figure 3. PCU for LISA Pathfinder

D. Power Control Unit for FEEP: Qualification

Based on the achievements of the PCU developed in the frame of an ESA TRP Contract [2], which was successfully functionally validated and tested in a wide range on environmental conditions including an accelerated endurance test on HV section, the PCU was updated for its potential use on Microscope program and submitted to a successfully qualification test campaign by means of a PCU Qualification Model [3].

Since the PCU mechanical arrangement for LISA Pathfinder was different of the previous ones, following redesign the overall qualification activity has been repeated and completed successfully according to the models philosophy with a EQM/PFM approach [4].

The qualification followed the general qualification rules as follows:

- o Initial Full Performance Test.
- o Mechanical Test (see table 2).
- o Thermal Vacuum Test (see table 3).
- o EMC Test (see table 4).
- o MIL-1553 validation.
- o Final Full Performance test.

Complementing the qualification flow, specific tests aimed at verifying capability to withstand launch and separation shock and confirming low DC magnetic moment (stringent on LISA Pathfinder because of the mission nature) have been also successfully performed.

It is finally noted that a set of PCU flight models have been already manufactured, tested and allocated into the LISA Pathfinder spacecraft.

Table 2. Vibration test conditions

Test type	Levels and equipment
Sine vibration	20 g EQM-PFM 16 g FMs
Random vibr. in-plane	14.1 grms EQM-PFM 11.3 grms FMs
Random vibr. out-plane	24.3 grms EQM-PFM 19.4 grms FMs
Shock (EQM)	Up to 1000 g at 10 kHz

Table 3. Thermal vacuum test conditions

Test type	Levels and equipment
Non operating temp.	-40°C to +60°C EQM-PFM -30°C to +50°C FMs
Operating temperature	-20°C to +60°C EQM-PFM -10°C to +50°C FMs
Temp. cycles (Qual.)	8 EQM-PFM and 4 FM

Table 4. EMC test matrix

Test type	Equipment
Bonding & Isolation	EQM; PFM and FMs
CE and CS (Power lines)	EQM; PFM and FMs
RE and RS (E - H)	EQM and PFM
ESD	EQM
DC Magnetic	EQM, PFM and FMs

III. Power Control Unit for general Micro-Propulsion Subsystem (design)

Starting from a qualified Power Control Unit developed for a specific micro-thruster technology, we will review as the developed PCU for FEEP previously described can be able to satisfy all tasks to obtain an adaptable Power Control Unit for a Micro-Propulsion Subsystems General Purpose. In order to focalize the paper on actual application, we will review the FEEP PCU design to be adapted mainly for a Radio-Frequency (miniaturized) Ion Thruster technology [5] considering, as baseline, the LISA Pathfinder general requirements so that, finally, a sort of “plug-and-play” approach is outlined.

E. PCU interface for micro-propulsion technology (a comparison)

FEEP and RIT thrusters are both falling in the category of the electrical propulsion making use electrostatic force; however, even if the acceleration takes place through electrostatic force for both, the ionization phase of the propellant is carried out by different means: for FEEP directly through the same electrostatic force from a liquid metal surface, while for RIT the propellant ionization takes place by applying a radio-frequency excitation (MHz range) in an ionization chamber before acceleration. Also the propellants are different: i.e. a metal (which is maintained in liquid form by means of heaters) in case of the FEEP, whilst a gas like Xenon is used for RIT.

Consequently, the impacts envisaged on the electrical interface between the PCU and the thrusters are:

- Electrical interface required for propellant acceleration: both technologies need one positive and one negative high voltage power supply even if with different levels of voltage (see table 5).
- Electrical interface for propellant ionization: in this case the FEEP does not require any PCU supplies (ionization occur directly through electrostatic force) but power supply sections for heating are necessary to maintain liquid the propellant; for RIT instead, is required a dedicated interface to supply a Radio-Frequency Generator (RFG), which is a stand-alone equipment outside the PCU and it is devoted to generate the radio-frequency excitation energy (see table 5).
- Propellant storage and propellant feeding system: the FEEP does not require specific supplies because a dedicated tank for each thrusters is allocated, while for RIT different approach for tank storage can be used: i.e. from an approach with dedicated tank for each thruster to a single common tank for the whole subsystem; it is important to note that independently of the storage approach implemented, the impact at PCU level is low because requires simple additional electronics like switcher (for latch valves), electrical interface for telemetry conditioning (pressure sensor) and a small supply section for tank heaters (for a common tank, this could be in charge of the system).
- Thrust control: according to the different ionization method, also the thrust control is slightly different, in fact for FEEP the thrust control is performed relying on the electrical impedance of the FEEP (where ionization occur directly in one single step) acting on the positive high voltage supply; for RIT instead, the control need to be performed during the ionization phase, in this case acting on the power delivered to the Radio-Frequency Generator (See fig. 4 for principle). However, even if the control operates in a different way, almost all the electronic is fully reusable reducing the number of modification and tailoring of PCU. It is also considered that the loop control is more useful to be allocated into PCU instead of the RFG because reduce connections and allows a more flexibility in the RFG allocation.

Table 5. PCU Electrical interface FEEP/RIT comparison

Parameter	FEEP	RIT
Positive voltage	up to 12 kV and 15 W	up to 2 kV and 4 W
Negative voltage	up to -4 kV and 4 W	up to 0.5 kV and 1 W
RFG auxiliary	12V / 6W (heater main)	12V / 2.5W
RFG power	12V / 6W (heater red.)	25V / 10W

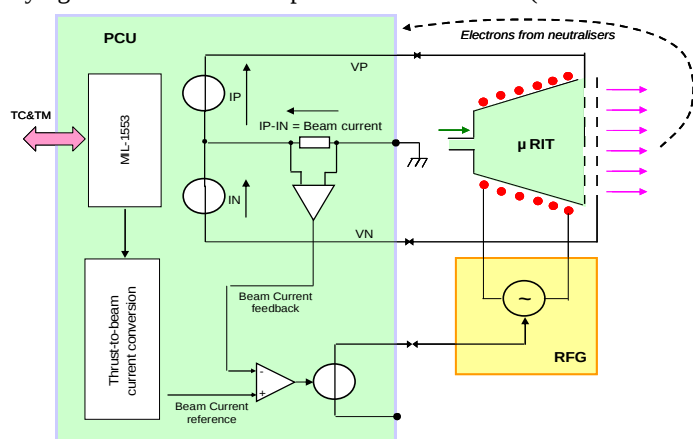


Figure 4. RIT thrust control principle

Based on the above review of interfaces, it can be noted that number of supplies and type of control are not significantly different between the two technologies making the PCU design appropriate for standardisation.

F. PCU General Architecture

The electrical architecture of a PCU for RIT can follow the same approach of the FEEP one: the system boundary conditions like four thrusters operating at the same time can be satisfied because modularity, location of the functions, approach to the interfaces can be easily reused revealing the high degree of flexibility of the PCU developed for FEEP.

The overall architecture of one cluster of four mini-RIT is shown in figure 6. Basically the PCU is constituted by seven boards as follows:

- One Mother-board (MB) for cross strapping among the all common interfaces.
- Two Control Boards (CB), one main and one redundant are used for the whole S/C interfaces (Main Bus, TC/TM), neutralizer supplies and control.
- Four Power Boards (PB), for all electrical interface of the thrusters; each one devoted to one RIT, one RFG and also including feeding system section.

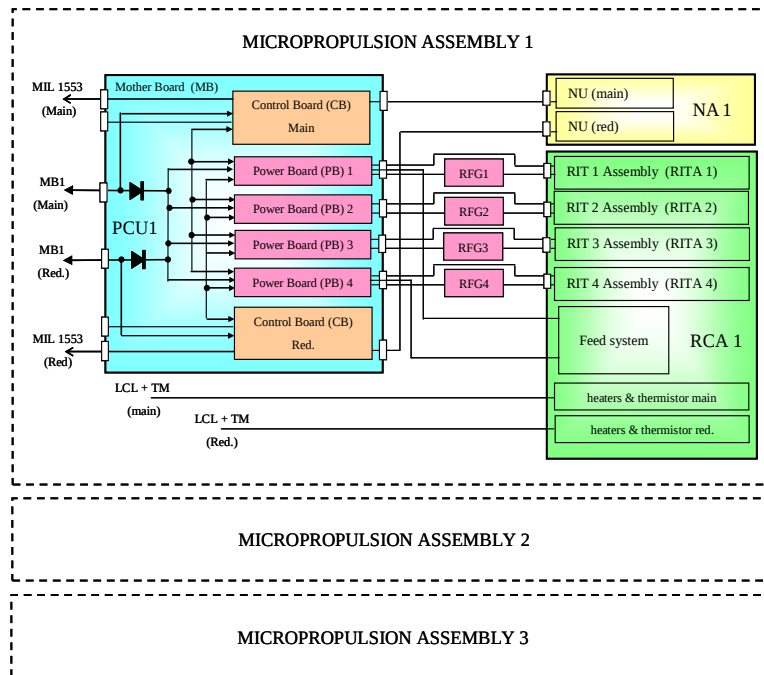


Figure 5. Block diagram of a complete subsystems with three cluster of four RIT's suitable for LISA Pathfinder mission

G. Spacecraft electrical interface

As for the generic spacecraft interfaces (Main Bus Power, Commands, telemetry etc.), the PCU for FEEP can be easily adapted for use on other micro-propulsion technologies thanks to its flexibility and communality of operation between micro-thrusters.

About electrical power from the spacecraft power distribution, the PCU is capable to operate either with regulated or unregulated main bus voltages (e.g. 28V regulated bus or 22 to 37V unregulated bus) since allocates dedicated dc/dc regulators on each main function directly connected to the main bus line. For LISA Pathfinder, PCU operates from 20.5 V to 28 V.

As far as command and telemetry (TC/TM) interfaces are concerned, the amount of signals required to manage FEEP thrusters and neutralizers (for monitoring, in-flight calibration and failure detection) led to have tens of commands and telemetries; this imposed the use of serial interfaces for their managing from/to the On-Board Computer (OBC). Also in this case the FEEP approach can be easily extended to other micro-propulsion technology so that almost all the functions are fully reusable. For interface flexibility, three different types of communication interfaces have been developed on the PCU [2], [3], [4] and can be implemented according to spacecraft needs:

- MIL-STD-1553 Data Bus interface (used in LISA Pathfinder application).
- UART Universal Asynchronous Receiver and Transmitter interface linked with RS-422 interface.
- ML/SD ESA standard serial data protocol linked with RS-422 interface.

About the protection philosophy, beside PCU internal protections for its safe operation (e.g. input and output current limiters), the automatic protections implemented inside PCU have been reduced to a minimum level: each thruster parameter exceeding the “nominal and safe” value that can lead to fault condition are protected at PCU level but managed at system level (i.e. On-Board Computer) in order to reduce at a minimum the interruption of FEEP operation. The only protections that are autonomously managed by the PCU are those necessary to avoid failure propagation in the subsystem and, possibly, propagating to the spacecraft.

The described protection approach, mainly driven by system requirements, can be extended for any micro-propulsion subsystem reducing the number of modifications and tailoring of the PCU.

H. Neutralizer interface

Neutralizers are required for space operation of ion thrusters in order to provide electrons for charge compensation upon ejection of positive ions so that the build up of electrostatic charge on the spacecraft surfaces is avoided. The PCU for FEEP developed for LISA pathfinder is able to supply two neutralizers operating in cold redundancy and each neutralizer has been designed to emit electrons for the operation of four thrusters at their maximum thrust for FEEP technologies (i.e. 6 mA). Such level of neutralization currents is also suitable for general micro-thrusters including mini-RIT application so the PCU already developed for FEEP with its own neutralizer interface is fully reusable without design change.

I. Mechanical and Thermal Architecture

The mechanical structure of the PCU for FEEP is constituted of a simple box (even if with profiles suitable to maximize robustness, meanwhile minimizing mass) made of Aluminum Alloy 7075: one baseplate, one front wall, one rear wall and a cover with C-shape, screwed one to each other with stainless still screw, mainly compose this standard box.

The FEEP PCU for LISA Pathfinder is fixed to the satellite panel by means of six mounting feet in order to provide adequate means of sustaining the specified environment (both mechanical and thermal). All the electronic parts are allocated on Printed Circuit Boards (PCBs) and are mounted and fixed to the mechanical structure by means of a dedicated frame, which provides the adequate stiffness to the board assembly and improve its thermal coupling to the box structure.

From that, different PCU mechanical arrangements can be made available (or can be tailored on specific needs)

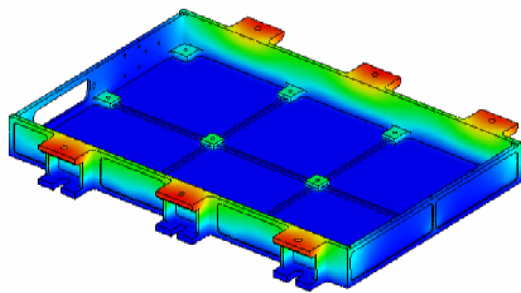


Figure 7. Temperature gradient between S/C and PCU baseplate for integrated structure

dissipation. These two main drawbacks have not considered critical though need to be managed carefully during design finalization.

Considering the good flexibility, the PCU mechanical design can be arranged with different subsystem configurations (e.g. two thrusters, one neutralizer operating with a single PCU without redundancy) in order to cope different mission scenario without jeopardizing significantly the qualification status.

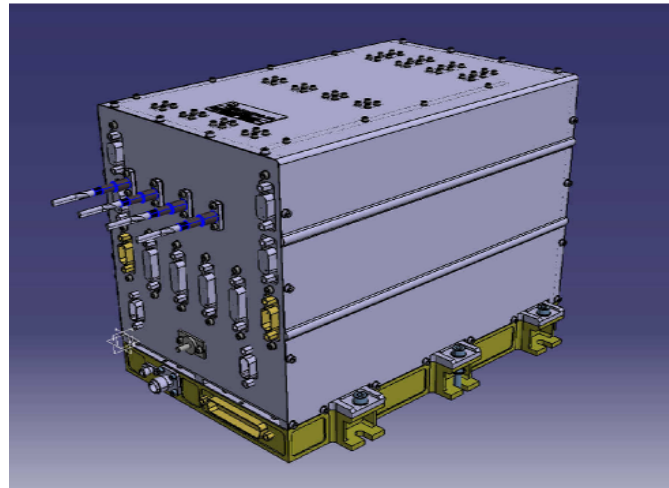


Figure 6. PCU & RFG integrated structure

thanks to the internal architecture adopted. In case of mini-RIT application and with the purpose to minimize the spacecraft mechanical interfaces (which lead to a significant cost effect at system level), a study to verify feasibility to implement an integrated mechanical structure between PCU and RFG units has been performed (see fig. 6): basically the RFG has been used in the bottom side of the integrated structure, whilst the PCU on top of it so maintaining the spacecraft mechanical arrangement as it is. As drawback of this configuration approach is the potential impact on mechanical and thermal design: in this view, the mechanical design of PCU need to be reinforced to withstand with adequate factor of safety the specified vibration environmental condition, while the thermal design of PCU parts are suffering of a little bit higher operating temperature (about 7 °C, as shown in fig. 7) due to additional RFG power

J. PCU Mass and Power Consumption

As far as the PCU mass is concerned, it is highlighted that mass is not changing significantly by change of thruster technology. For a PCU aimed to supply mini-RIT really a bit lower value of 10% is expected, this is due to the reduction of HV constraints since voltages are reduced significantly (i.e. from 12 to 2 kV) with respect to FEEP needs. In case of integrated PCU/RFG equipments, mass is increasing because of mechanical and thermal aspects described in section before, however mass estimation provides similar values of a PCU for FEEP.

For power consumption, similar PCU dissipation can be estimated for both FEEP and mini-RIT technologies because PCU power dissipation is mainly linked to fixed losses instead of converter efficiency due to very large number of power supplies required and therefore the associated control electronics consumption. In this perspective, a power model is considered a viable and reliable method to assess a realistic subsystem power budget in order to consider all the dissipating element according to the applicable operating condition (e.g. number of thrusters and neutralizers operating, thrust values either in term of peak and average etc.).

IV. PCU for RIT Micro-Propulsion technology (implementation)

In order to support the design considerations provided, a potential implementation of a PCU for a mini-RIT technology on available PCU hardware is presented. This implementation is very useful to support one of the most crucial step of a micro-propulsion subsystem verification: i.e. integration between the PCU and the thruster.

Starting from the discussed changes and thanks to the availability of elegant bread-board hardware from LISA Pathfinder project (i.e. PCU Elegant BreadBoard; see figure 8), the following changes are addressed in each type of boards in order to accomplish a PCU EBB tailored to mini-RIT:

- Control Board: this section implement all logic, command and telemetry interface and neutralizer section and it requires smaller changes in hardware and mainly relevant to logic section (i.e. FPGA, Field Programmable Gate Array), consequently can be fully reusable with small amount of wired modifications with reduced schedule.
- Mother Board: this section implement all cross strapping among the different PCU functions and implement a few components. Accordingly also this module is fully reusable with small amount of wired modifications.
- Power Boards: this is the area with major changes and need to be redesigned and manufactured. This is not an issue due to the reduced high voltages needs: the Printed Circuit Board area available for modification is sufficient for RIT interface implementation (about 20-25% of the area of the board is estimated left free). Schedule of this part is the driving factor of the hardware implementation, however, communality with electronics components with FEEP PCU design alleviate the manufacturing task.
- Electrical Ground Support Equipments: these items are of crucial importance both to simulate the spacecraft interfaces and to reproduce constraints and validate procedures of the thrusters. Different sets of equipments capable to support PCU EBB (one chain) and a full PCU equipment (four thruster chains and two neutralizers) were designed manufactured and tested in the frame of LPF. Due to high level of reusability of the spacecraft interface, these support equipments developed for LISA pathfinder can be adapted for mini-RIT PCU.

From the above, the tailoring of the available PCU hardware to achieve a mini-RIT PCU is confirmed as feasible and available in a short time, in order to:

- consolidate a design baseline;
- support integration activities with RIT, RFG and NA;
- early highlight (and, eventually, tackle) any technical risk present on the PCU versus Ion Thruster interfaces;
- provide hardware (fully representative of a potential PCU flight) capable of supporting a possible life-test demonstrator engine, thanks to suitable power supply and control features.

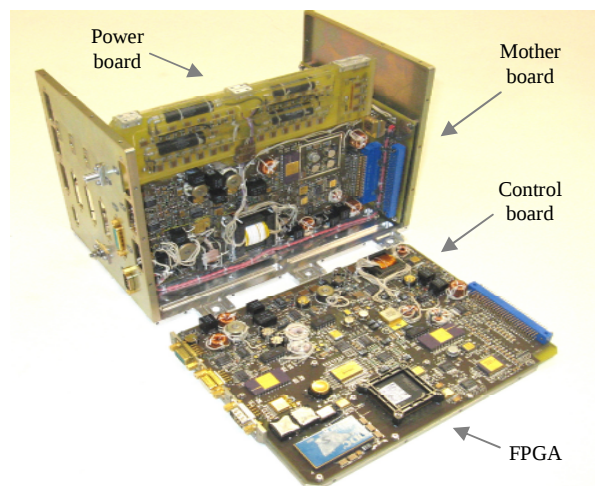


Figure 8. PCU EBB under tailoring to mini-RIT

V. Conclusions

The qualification activities successfully conducted in the frame of LISA Pathfinder mission, and presented in this paper, demonstrate SELEX Galileo capability to provide to a FEEP Micro-Propulsion Subsystem a PCU fitting with specific program and mission needs whenever a very high degree of thrust accuracy and stability is required. In the frame of LISA Pathfinder project, in addition to the formal qualification, the three PCU flight models required have been already manufactured, fully accepted and delivered to the LPF Prime (Astrium Ltd) during Summer 2010; they are currently supporting the system level testing activities after integration onto spacecraft.

The adaptability of this PCU design to different technologies (e.g. miniaturized RIT), has been presented not only from a theoretical point of view but with actual hardware, with the plan to make it available in very short time. Accordingly, the demonstration of the capability of this PCU to cope with the needs of different thruster technologies, without jeopardizing the PCU design and implementation, has been provided revealing a fine level of flexibility, well adequate to forecast potential use of this PCU for future missions.

The assessment lead to the conclusion that, in case the MAIT phase of a PCU for mini-RIT is authorized, the flight models manufacturing could be started without needing an extensive qualification test campaign, thus saving a model in case delta-qualification is carried-out on a mini-RIT PFM when considering the limited number of technical risks (at PCU equipment level) thanks to the solid coverage from LISA Pathfinder FEEP PCU EQM/PFM qualification campaign successfully achieved.

Finally, the availability of a PCU EBB level EGSE and two PCU FM level EGSEs, and their flexibility, can play a role: the former in bread-board verification, the latter in a potential PCU flight manufacturing phase – with significant cost containment.

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