Experimental Validation of RIT Micro-Propulsion Subsystem Performance at EPL

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ABSTRACT

In 2011 ESA's LISA Pathfinder (LPF) project decided to investigate propulsion technologies that could be an alternative to field emission electric propulsion (FEEP). A development program led by Astrium Ltd, the LPF Prime, and Astrium ST, as subsystem responsible, was initiated aiming at confirming the miniRIT Micro-Propulsion Subsystem (MPS) compatibility to LPF requirements and constraints.

Starting 2012 all equipment composing the miniRIT subsystem have been manufactured at Engineering Model level and tested as stand-alone or in coupled configurations to verify compliance to the stringent requirements imposed by LPF and future ESA science missions. Specifically, two EMs of the thruster capable to deliver thrust in the 10-100 µN range with their Radio-Frequency Generators (RFG) and one EBB of the Power Conditioning Unit (PCU) have been manufactured and tested.

The design of the EM thruster relies on the heritage from RIT10 flight design (ARTEMIS mission) and on the RITµX designed, built and tested by Astrium ST/University of Giessen (D) under previous ESA/DLR contracts.

The design of the EBB PCU is a modification of the LPF FEEP PCU design from Selex-ES (I), for which voltage and power levels have been adapted to the miniRIT technology. The present EBB PCU is able to control one thruster with its RFG and one neutraliser, the flight version will be able to control up to four or six 6 thrusters simultaneously. The neutraliser of thermoionic technology from Selex-ES (I) was previously developed and qualified within LISA Pathfinder.

Performance such as thrust range, thrust accuracy, thrust noise and stability, power consumption have been characterised by test and verified against LPF requirements.

A final subsystem verification test was performed at the ESA Propulsion Laboratory (EPL) to confirm the main subsystem performance and to verify the effectiveness of the proposed neutralisation concept. This will be achieved by testing an integrated miniRIT subsystem composed of one thruster, one RFG, one neutraliser and one PCU. This paper reports the results from this test.

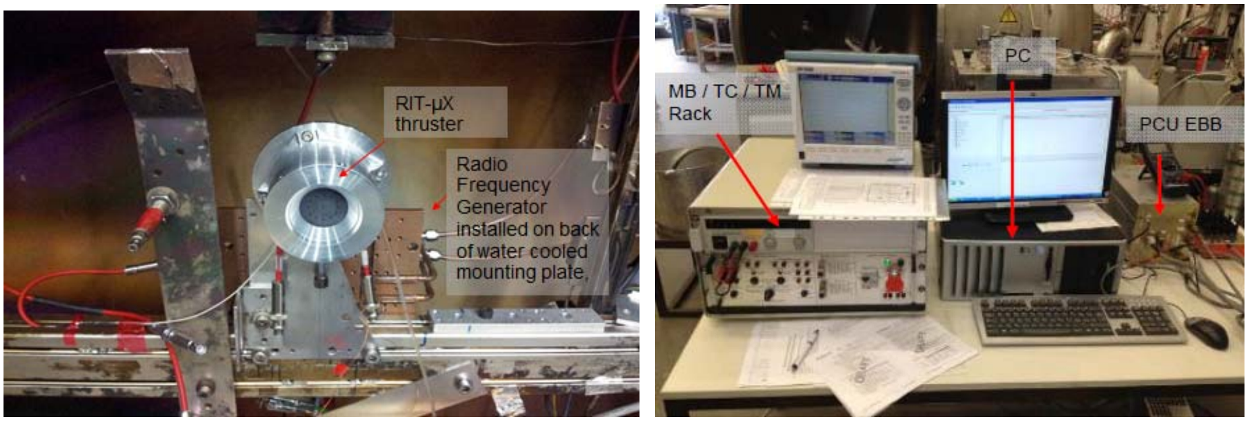


Figure 1: EM miniRIT and EBB PCU under test for LISA Pathfinder

I. Introduction

The Laser Interferometer Space Antenna (LISA) mission is aiming at detecting gravitational waves by measuring distortions in the space-time fabric. The LISA mission shall consist of three spacecrafts flying in a triangular formation with a side length of several million kilometers. The position of each satellite with respect to its two counterparts has to be controlled with an accuracy of 10^{-9} m to ensure sufficient accuracy of the scientific measurements. The extreme challenge in position control can only be satisfied with an ultra-precise propulsion system. LISA Pathfinder (LISA PF) is the precursor mission to LISA designed to validate the core technologies intended for LISA. The micro-propulsion system is one of the enabling technologies for LISA to be validated on LISA Pathfinder.

In view of the difficulties encountered in the development of the FEEP micro-propulsion system (MPS), LISA Pathfinder (LPF) Project decided to investigate alternative ultra-precise micropropulsion technologies. An initial ESA feasibility study of implementing a MPS based on the miniRIT in place of the FEEP technology was performed

[1]. In support to the study, Giessen University and Astrium ST built and tested four prototypes of different size to demonstrate compliance to the thrust range requirements of LISA Pathfinder, 10 to 100 µN.

Following the results of the LPF Micropropulsion System Review (MPSR), ESA requested ASTRIUM Ltd, the LISA Pathfinder prime contractor, to consolidate the finding of the study by performing a preliminary design of the system and all other necessary activities to remove all residual technical and programmatic risks before the start of the miniRIT subsystem procurement. LPF Project initiated a development program in 2011 led by the LPF Prime (Astrium Ltd) and Astrium ST as subsystem responsible, aiming at confirming the miniRIT MPS suitability to LPF requirements and constraints. In particular, the LPF development program aimed at:

- confirming the subsystem budgets,
- having all the miniRIT MPS units achieve TRL 5.

The following hardware items were manufactured, procured and tested for this purpose:

- 2 x EM miniRITs (also referred to by Astrium as RITµX) thrusters for the thrust range of **10 to 100 µN,**
- 2 x EM Radio-Frequency Generators (RFG),
- 1 x EM RFG of advanced design with reduced power consumption,
- 1 x EBB Power Control Unit (PCU),
- 1 x 5 µg/s and 1 x 10µg/s breadboard flow restrictors,
- 1 x EM Neutraliser of thermoionic technology from LISA Pathfinder.

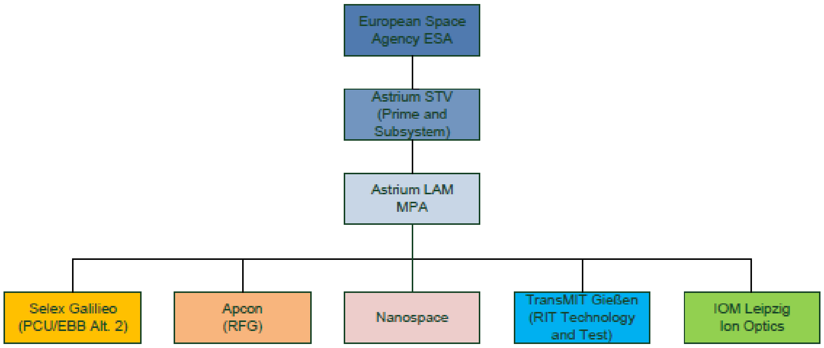


Figure 2: LPF miniRIT industrial set up

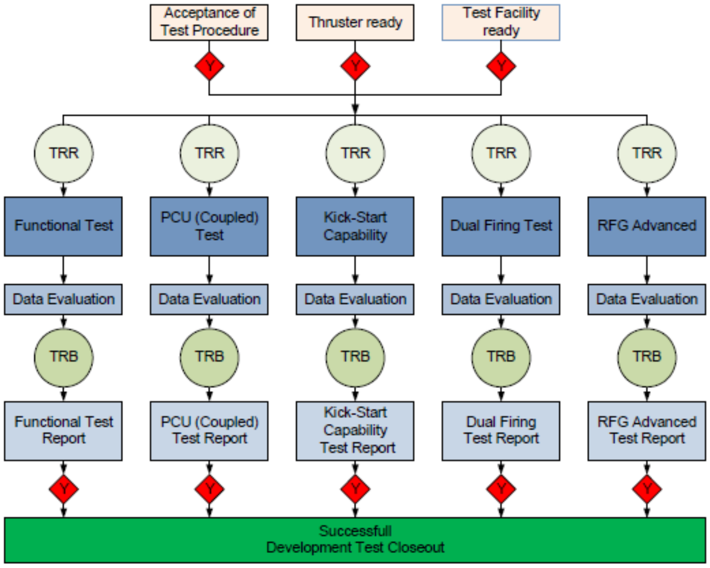


Figure 3: LPF miniRIT development test logic (roadmap to TRL 5)

The design of the EM thruster relies on the heritage from RIT10 flight design and from the RITµX designed, built and tested by Astrium ST/University of Giessen under previous ESA/DLR contracts.

The RFG design by Apcon is based on the model previously developed under past ESA/DLR contracts.

The design of the EBB PCU is a modification of the LPF FEEP FM PCU design, for which voltage and power levels have been adapted to that required by the miniRIT technology. The EBB PCU used for the development tests of miniRIT is able to control one thruster with its RFG and one neutraliser, while it is expected that its flight version will be able to control up to 4 or 6 thrusters at any time.

The flow restrictor design from Nanospace is based on the design of a more advanced xenon flow control module, which was developed in the framework of previous ESA contracts.

The Neutraliser from Selex-ES is of the same FM design qualified for LPF.

The LPF miniRIT industrial

team is depicted in Figure 2. In the framework of the LPF contract a sequence of tests were performed in order to demonstrate the suitability of the subsystem to the LPF requirements. The LPF development tests logic is summarised in Figure 3. The results for these tests are described in [10]. The neutralisation concept verification test was originally planned to be performed during the PCU coupled test. Due to the vacuum level required for the operation of the neutraliser it was lately decided to perform this test at ESTEC.

II. RIT micro-propulsion subsystem (MPS) architecture and system budgets

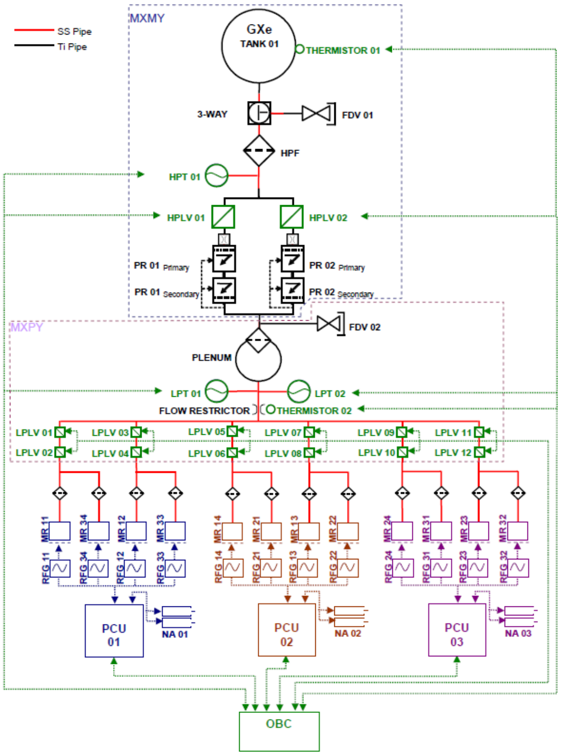


Figure 4: RIT subsystem schematic

The RIT MPS is an electric propulsion system, fed with gaseous xenon (GXe). Its main function is to provide small and calibrated thrusts, upon request of the AOCS. The RIT Micro-Propulsion Subsystem (MPS) is based on the RIT thruster technology. RITs generate thrust by the electrostatic acceleration of xenon ions. Since the middle 1960ies, RIT thrusters have been designed, built and qualified by Astrium ST (D) and University of Giessen (D). These thrusters cover the thrust range from 10mN to 250mN. RIT10 has been the first Western European ion thruster operated in space on EURECA (European Retrievable Carrier) mission and, since 2003, RIT-10 is flying in space onboard the ARTEMIS satellite.

The development of the miniRIT thruster, initiated in 2005, bases on the heritage in design, development, test and space operation of RIT10. Since 2005 several miniRIT prototypes have been built and tested to respond to the need of micro-propulsion systems capable of providing precise thrust modulation in the µN to low mN thrust regime. Results from previous development activities have been discussed extensively in [3], [4], [5], [6], [7], [8] .

The RIT MPS architecture for LISA Pathfinder can be considered in terms of four distinct assemblies: the xenon storage and feed system, the miniRIT thrusters each with its Radio Frequency Generator (RFG), the Neutraliser Assemblies (NAs) and the Power Control Units (PCU).

Xenon is stored at high pressure (up to 150 bar) in a single tank. The high pressure feed system is separated into parallel regulating branches to provide redundancy. The regulating branches both feed into a common low pressure section. The pipework downstream of the 12 LPLVs feeds xenon to the individual thrusters. The 12 thrusters needed to fulfil the mission requirements are arranged in clusters of 4, arranged in a way to give full control of manoeuvrability in all axes. The mini-RIT operates at a constant flow rate that is provided by a common flow restrictor (Figure 4). Originally the subsystem design had a common flow restrictor serving all thrusters. However, results from the development tests performed during LISA Pathfinder Project [10] indicated that a single flow restrictor for each thruster is necessary.

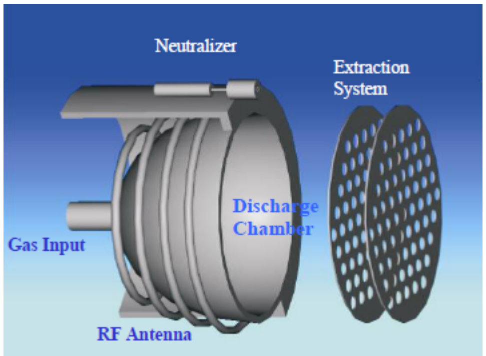


Figure 5: Functional principle of RIT

The MiniRIT generates thrust by the electrostatic acceleration of ionized xenon particles. For its operation the thruster requires propellant (xenon) and electric power. The RIT thruster needs two low voltage lines to operate the RFG for ionisation of the propellant and two high voltages lines for the acceleration of the ionized propellant in the thruster's grid system. Figure 5 shows the functional principle of RIT thrusters. Neutral xenon gas is injected into the thruster's ionisation unit via an integrated insulator and gas distributor. The ionisation occurs in a vessel made out of an insulating material (discharge chamber) and surrounded by the induction coil (RF Antenna) that is part of the resonance circuit of a radio frequency generator (RFG). The induced electric eddy-field accelerates electrons and generates a self-sustaining, electrodeless gas-discharge. From this plasma the ions are extracted, focused, and accelerated by a two-grid system ultimately generating thrust.

Figure 6 shows the RIT system block diagram.

The radio-frequency generator (RFG) is the driver for the ionization process inside the RIT thruster and the main control element of the thrust. Each thruster needs its own RFG.

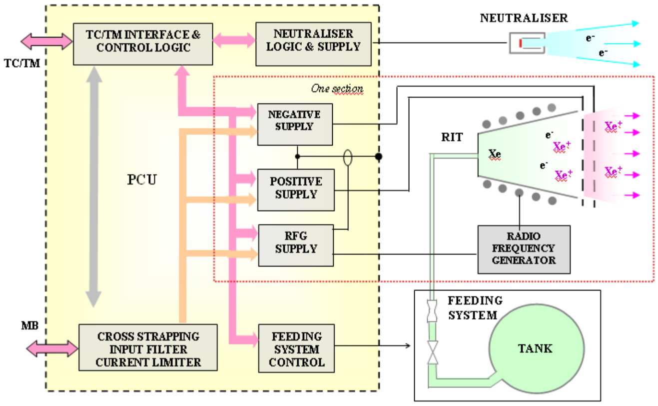


Figure 6: RIT system block diagram

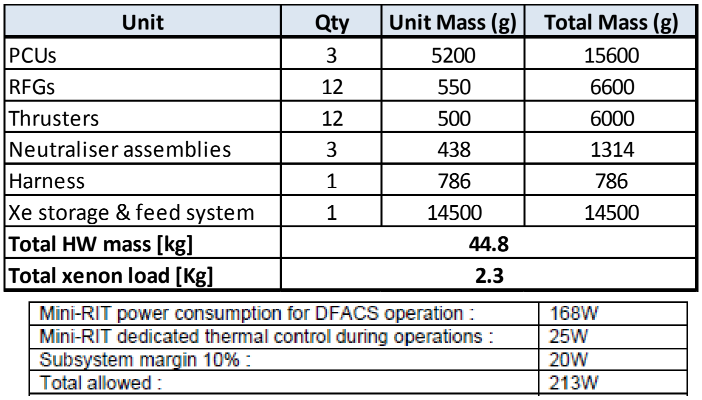
The PCUs are the only electrical interface of the miniRITs subsystem to the spacecraft. Each PCU controls four miniRITs, via each thruster's dedicated RFG, and one neutraliser assembly composed of a nominal and a redundant neutraliser.

The RIT PCU is based on the flight model design and qualified for the LPF FEEP with the following HW modifications:

- Control board: This section implements all logic, command and telemetry interfaces and the neutraliser section. It required smaller changes in hardware and mainly relevant to logic sections that are implemented into the FPGA (Field Programmable Gate Array), which was modified accordingly. As a result, this board was reused with small number of wiring modifications and replacement of components.
- Mother board: This board was reusable with small amount of wired modifications and components replacement.
- Power board: This is the section that was redesigned and manufactured due to the reduced high voltages needs.
- Mechanical frame containing all boards: fully reusable.

The LISA Pathfinder Neutralizer Assembly (NA), originally designed and qualified for the LPF FEEP MPS, consists of a self-contained unit of two neutraliser units mounted on a support structure. The neutraliser is necessary to nullify the spacecraft charge build-up due to the ion thruster operation. The neutralisation function is implemented by means of cold redundant hardware. The neutraliser produces a nominal electron current of 6 mA, suitable to counterbalance the electrical charge of up to 4 thrusters each delivering an ion beam current of 1.5 mA. The neutralisers are operated independently, and can be active at the same time, though normally they are operated one at a time. The neutraliser design is based on a moderately high perveance propellant-less electron gun. Its principle of operation has been described extensively in previous papers **[2]**.

The overall estimated mass budget of the RIT MPS was computed and it is reported in Figure 7. The baseline thruster operation is based on an almost constant flow rate for all operating thrusters, independent of actual thrust level. This is because thrust is varied by altering the RFG output, rather than the flow rate. The initial propellant budget has been calculated on the basis of a constant flow rate of 5 µg/sec per thruster over ~10000 hours of continuous firing. This gives a preliminary figure for the propellant mass of ~2.3 kg.



Unit	Qty	Unit Mass (g)	Total Mass (g)
PCUs	3	5200	15600
RFGs	12	550	6600
Thrusters	12	500	6000
Neutraliser assemblies	3	438	1314
Harness	1	786	786
Xe storage & feed system	1	14500	14500
Total HW mass [kg]	**44.8**		
Total xenon load [Kg]	**2.3**		

Mini-RIT power consumption for DFACS operation :	168W
Mini-RIT dedicated thermal control during operations :	25W
Subsystem margin 10% :	20W
Total allowed :	213W

Figure 7: RIT MPS mass & allowed budget

Initial RIT MPS power consumption has been based on the early test performed on the thruster and early analysis performed on PCU efficiencies. Verification of the power consumption estimates was performed during the development test activities.

III. Experimental validation of subsystem performance at ESTEC

Following a series of tests performed at unit and assembly level [10] an integrated miniRIT subsystem was tested at the ESA Propulsion Laboratory (EPL) in June 2013. The subsystem under test was composed of one RIT-µX EM thruster from Astrium ST, one 5 µg/s BB flow restrictor from Nanospace, one EM RFG Advanced from Apcon, one EM neutraliser and one EBB PCU both from Selex-ES (Figure 8).
The objectives of this test were to validate the overall subsystem performance and to verify the effectiveness of the neutralisation concept proposed for the mini-RIT propulsion subsystem on LPF.

Large ion thrusters have dedicated neutralisers to neutralise the ion beam of the thruster they are mounted on. In the case of the LPF spacecraft, the ion beam emitted by all operating thrusters is neutralised by 3 neutralisers running in parallel and referenced to a common grounding inside the PCU. In this configuration the neutraliser bias voltage is determining the overall spacecraft floating voltage. When heated, the neutraliser emits electrons until the overall spacecraft voltage is the opposite of the neutraliser bias voltage. When the thrusters are commanded ON, the emitted ion beam is added to the other existing charging mechanisms and electrons are emitted to neutralise the spacecraft (rather than the individual ion beam).

The test was performed in the GIGANT test facility (Figure 9) of EPL. This vacuum chamber is composed of two vessels isolated by a main gate. The hatch 0.4 m in diameter and 0.8 m in length. The main chamber is 1.5 m in diameter and 2.5 m in length. Both vessels are equipped with pumping systems and bake-out systems.
For a mass flow rate of 5 µg/s, the background pressure achieved in GIGANT was about 9.10-8 mbarA, which is below the 10-7 mbarA required for the functioning of the neutraliser.
GIGANT facility hosts three additional pieces of equipment:
- a target, located on the back-door of the main chamber, that can be cooled with LN2 to reduce backsputtering contamination;
- a diagnostics arm with 11 Faraday Cups , located in the main chamber, to map the ion beam;
- a linear motion drive, located in the hatch, to transfer the test item from the hatch into the main chamber.

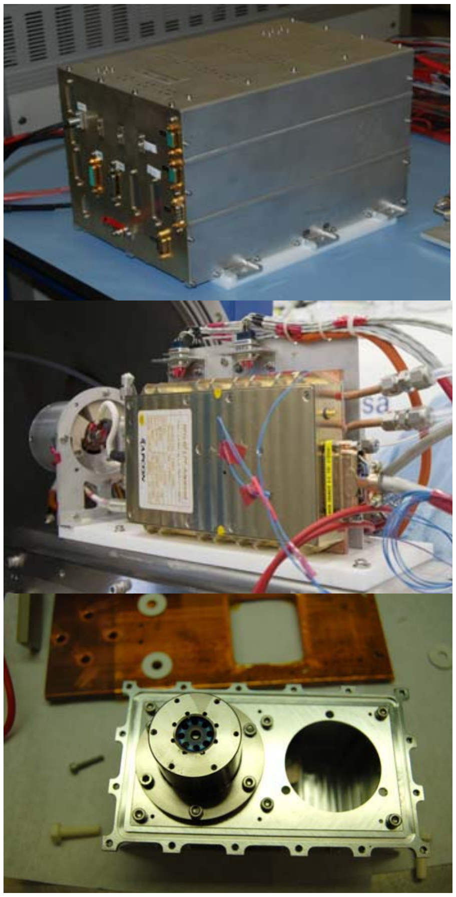


Figure 8: Test items (from top to bottom: PCU, thruster with RFG, neutraliser assembly)

Figure 9: EPL GIGANT facility with its diagnostic system of 11 Faraday Cups and the target

Main Results

Neutralisation concept verification.

The neutralisation verification test was intended to verify the neutralisation concept proposed for LISA Pathfinder. More specifically the test should demonstrate that at any time the neutraliser is capable to deliver an equivalent electron current to compensate the ion beam current emitted by the thruster.

In addition the test was also intended to verify the possibility to minimise/control the variation of the spacecraft floating potential over the beam current. The neutralisation test was performed at different bias voltage conditions.

The test was performed by testing an integrated miniRIT subsystem composed of one thruster, one neutraliser and the PCU, left floating with respect to the test facility. Figure 10 to Figure 12 report the results of the test. It can be noted that:

- For a bias voltage at 0V: neutralisation current was found tracking the beam current (Figure 10). The floating potential with respect to PCU chassis was found negative with significant variation in function of the beam current (Figure 11).
- For bias voltages of -50V,-100V,-150V and -200V: neutralisation current was found at maximum (for the selected neutraliser temperature of 1002°C) neutraliser emission capability of 8.5 mA. The floating potential with respect to PCU chassis was still found to be changing significantly as a function of the beam current (Figure 11). In order to minimise the variation of the floating potential the temperature of the neutraliser was lately decreased. Figure 12 shows an example of the measured floating potential for different polarization conditions (i.e. 0V, -50V, -100V and -200V) at reduced neutraliser temperature (931°C).

Verification of the self-adjustment neutralisation approach adopted for this integrated mini-RIT subsystem has been successfully performed. The results confirm what was already found in past neutralization test campaign using the same scheme but with different electrical micro-thrusters [9].

Neutralisation verification explored also the possibility to change the neutraliser setting and neutralisation electrical configuration (i.e. with different cathode emission through change of heater temperature or with different neutraliser electron emission through change of neutraliser bias conditions) in order to observe the effect on floating voltages

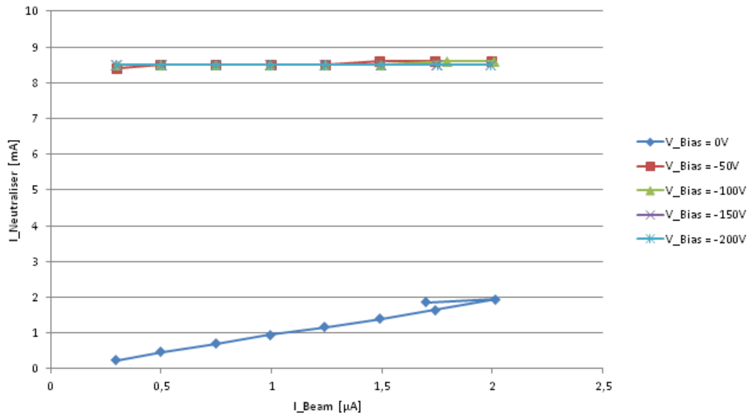


Figure 10: Neutraliser current at 1002°C

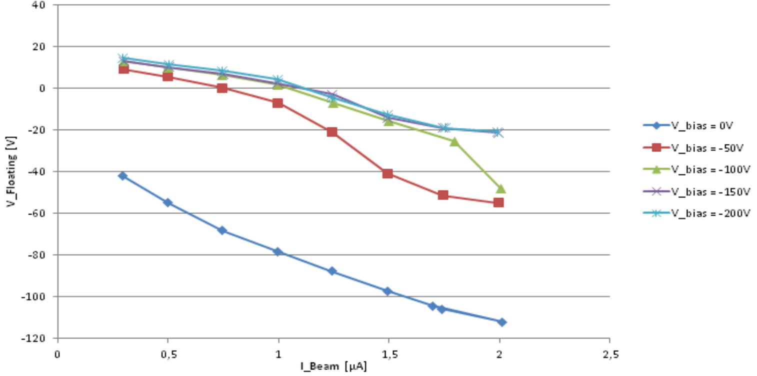


Figure 11: Floating potential at 1002°C

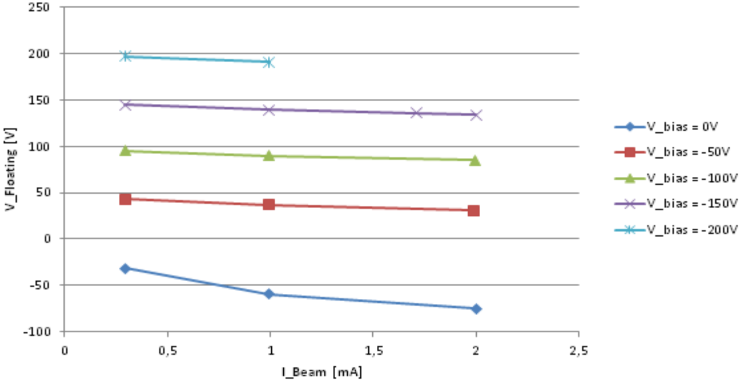


Figure 12: Floating Potential at 931°C

developed during thrust emission: also in this case test results confirmed the possibility to minimize/change the spacecraft potential with different levels of polarization. It is worth to mention that the capability to modify the neutralisation parameters is already implemented at PCU level.

Performance mapping and system power consumption measurement

The performance mapping was performed to derive the necessary data for computation of the system power consumption for any thrust level between 10µN and 100µN. In a miniRIT subsystem, the complete subsystem power consumption consists of:

- The ionisation power which is the input power to the RFG feeding the RF-coil;
- The RFG auxiliary power to feed the RFG control electronics;
- The high voltage power to feed the thruster's grid system;
- The neutraliser power;
- The PCU power dissipation including fixed losses, that are independent of the number of thrusters simultaneously operating (Bus interface, Control Unit, etc), and variable losses, that dependent on the number of thrusters operating (voltage converters, etc).

The overall measured power consumption of the integrated mini-RIT subsystem is ranging from 28W @10 µN to 45W @100 µN. Figure 13 (left) shows the measured values as a function of the thrust level differentiating power consumptions distributed over the different components of the subsystem (note: the RFG power includes the RFG electronics and the propellant ionisation dissipation).

Since a micropropulsion subsystem typically implements multiple thrusters, an example based on above measurements but scaled up to six thrusters (each one constituted of one RIT and one RFG), two neutralisers (to assure neutralization capability and redundancy) and one PCU is derived and provided in Figure 13 (right).

Of course, specific subsystem configurations can be required to satisfy different mission scenario (PCU is designed to be easily scalable): in this perspective, to help the reader to assess different applications, an overall power consumption for different number of thrusters is provided in Figure 14 (note: an average thrust of 50 µN per thruster is assumed).

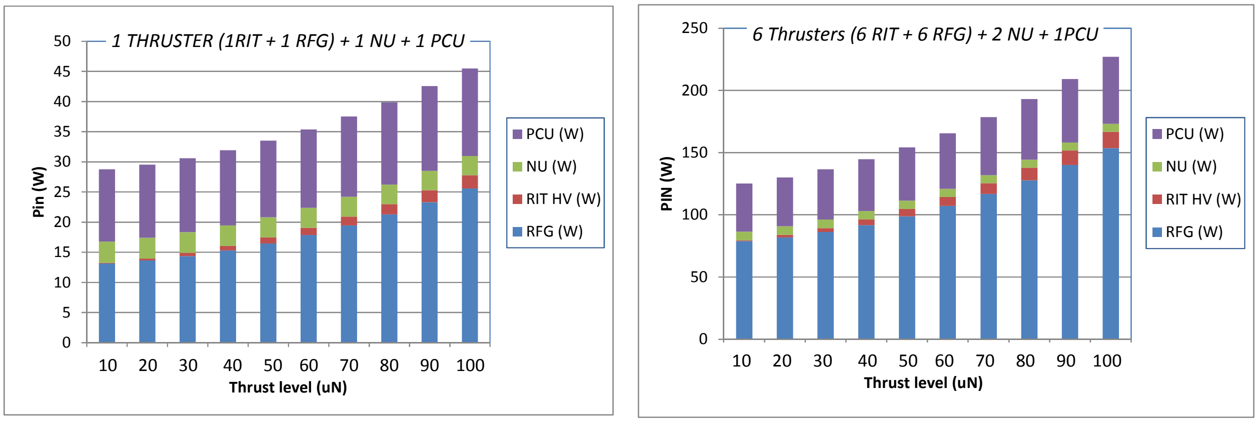


Figure 13: (left) Tested configuration; (right) Extrapolated for a system consisting of 6 Thrusters, 2 neutralisers and 1 PCU

Thrusters [N°]	Neutralisers [N°]	PCU [N°]	Thrust [uN]	Power Consumption [W]
1	1	1	50	33.5
2	1	1	50	56.6
3	1	1	50	79.6
4	1	1	50	102.7
5	2	1	50	131.2
6	2	1	50	154.3
7	2	1	50	177.4
8	2	1	50	200.4

Figure 14:Power consumptions for different EPL mini-RIT configuration

Beam divergence

The beam divergence of the RIT-µX thruster was measured during the test with the GIGANT beam diagnostic system. Results are summarised in Figure 16 where the divergence angle is plotted as a function of the thrust for different xenon mass flow rates. The divergence angle was higher for 10 µN than for the other thrust levels for which the beam divergence stayed below 20 º, as required by LPF.

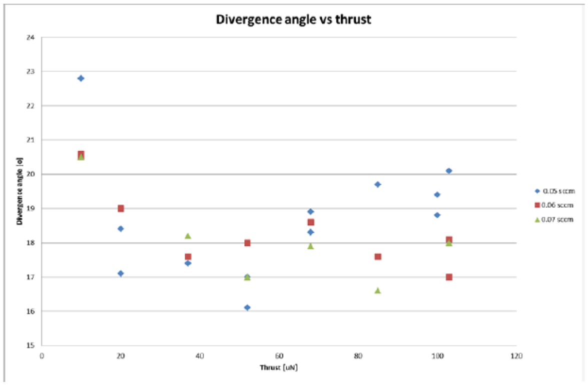


Figure 16: RIT-µX divergence angle vs thrust for different mass flow rates

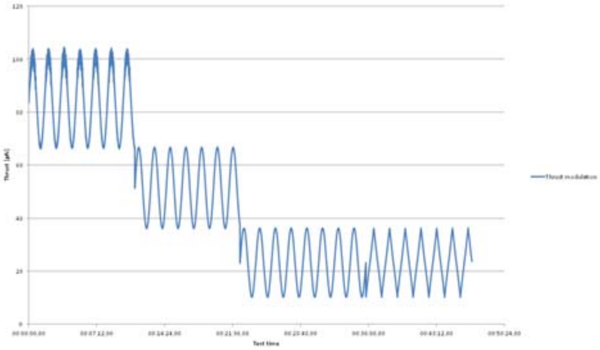


Figure 17: Thrust vs time demonstrating capability to continuously control the thrust level.

Thrust modulation .

For three ranges of thrust (103µN to 67µN, 67µN to 37µN and 37µN to 10µN) a sine thrust function was executed. Figure 17 shows the RIT-µX system response, well in line with the expectations.

Ignition by means of electrons injection

Large (high power / high thrust) RIT thrusters are conventionally equipped with a dedicated neutraliser, which is usually mounted close to the thruster's grid system. The discharge of large ion engines is conventionally initiated through the ingestion of electrons from the neutraliser into the discharge chamber.

In contrast, on LPF, one neutraliser, located far from the thrusters, is used to compensate the total ion current emitted by four thrusters. Therefore the conventional method to ignite thruster cannot be used and a novel ignition method, based on a combine power and pressure boost, has been adopted and verified [10] during the development tests. It is believed that the very low transparency of the RIT-µX grid system (less than 2%) is responsible as this does not allow a sufficient number of electrons to enter the discharge chamber to initiate the discharge.

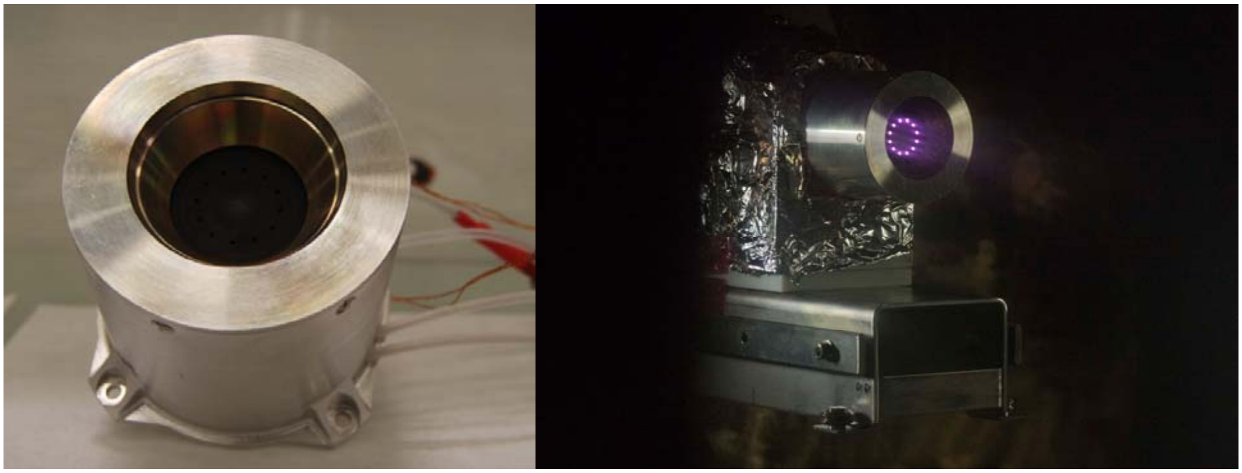


Figure 18: RIT-µX thruster before integration in the GIGANT VF (left) and firing during the test (right)

IV. Conclusion

The design of a RIT based Micropropulsion System has been performed and validated by test. All the equipment constituting the subsystem are ready to enter in qualification phase. The thruster design has demonstrated to be well suited for extremely fine position and attitude control applications.

Although LISA Pathfinder has decided to baseline a Micropropulsion System based on the Selex-ES GAIA cold gas thrusters, the interest in the Miniaturised RIT technology for future ESA missions remains.

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