Development and Industrialization of the RIT 3.5

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The miniature ion thruster, neutralizer and harness sub-system are critical elements of a high specific impulse propulsion system required to enable the use of CubeSat's and other small spacecraft for deep space or interplanetary missions by providing a high total impulse propulsion system for large delta-V maneuvers, with the emphasis of providing a plug-and-play thruster/neutralizer solution for different classes of missions. Through an ESA-funded project, MSL is currently identifying the required steps for the advancement of the engine to a higher TRL status, including industrialization of the hardware in conjunction with the development of thermomechanical and ion optics models. In addition, further thruster elements, such as harness and pipework will be included in the higher TRL activities.

I. Nomenclature

FCU = *Flow Control Unit*
EoL = *End of Life*
GOCE = *Gravity field and steady-state Ocean Circulation Explorer*
M-ARGO = *Miniaturized-Asteroid Remote Geophysical Observer*
NGGM = *Next Generation Gravity Mission*
NTR = *Neutralizer*
PPU = *Power Processing Unit*
RFG = *Radio Frequency Generator*
RIT = *Radiofrequency Ion Thruster*
TRL = *Technology Readiness Level*

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II. Introduction

The miniature ion thruster, neutralizer and harness sub-system are critical elements of a high specific impulse propulsion system required to enable the use of CubeSat's and other small spacecraft for deep space or interplanetary missions by providing a high total impulse propulsion system for large delta-V maneuvers. Mars Space Ltd (MSL) has recently acquired the design rights to the RIT3.5 engine, which is a miniaturized radio-frequency ion thruster that was originally developed at TransMIT GmbH up to TRL 5 through the development of an engineering model that was capable of operating in the thrust range of 50 µN to 2.5 mN at quantization of 0.2 µN[1]. Thanks to the excellent performances, the RIT3.5 is ideally placed to support cubesat applications [20], as well as more complex and demanding scientific missions, such as NGGM[1].

The main activities of this technology development include such things as ion optics optimization to suit SI, thrust range and power requirements; lifetime analysis will be performed in conjunction with a dedicated endurance test; a number of neutralization concepts will be developed and trade-offs will be performed, including lifetime assessment; the development of the harness and pipework to meet the requirements of the sub-system elements, along with analysis of lifetime performance degradation and power and radiation budgets.

The above activities will result in the establishment of a reliable supply chain and the creation of a robust and dedicated production line. The qualification/industrialization approach for the subsystem elements will be presented and discussed in this paper.

In parallel, MSL will be defining the requirements for the other subsystem elements, namely power processing unit (PPU), radio-frequency generator (RFG) and flow control unit (FCU). Iteration of the requirements will be performed to support different applications and budgets. This will culminate in the planning of a dedicated coupling test of the key subsystem elements, including the assessment of neutralization concepts for multiple thruster heads.

III. RIT 3.5 Description

A. Design Description and Heritage

While typical Gridded Ion Engines can deliver a dynamic thrust variation ratio of between 1:5 or 1:10 in the best cases, from minimum to maximum thrust, the miniaturized Radio-Frequency Ion Engine RIT3.5 delivers a dynamic thrust range with a minimum to maximum thrust variation ratio of 1:50. The main reason for this feature is the unique design that was developed from scratch within the [18] to satisfy very demanding requirements, primarily for the Next Generation Gravity Mission.

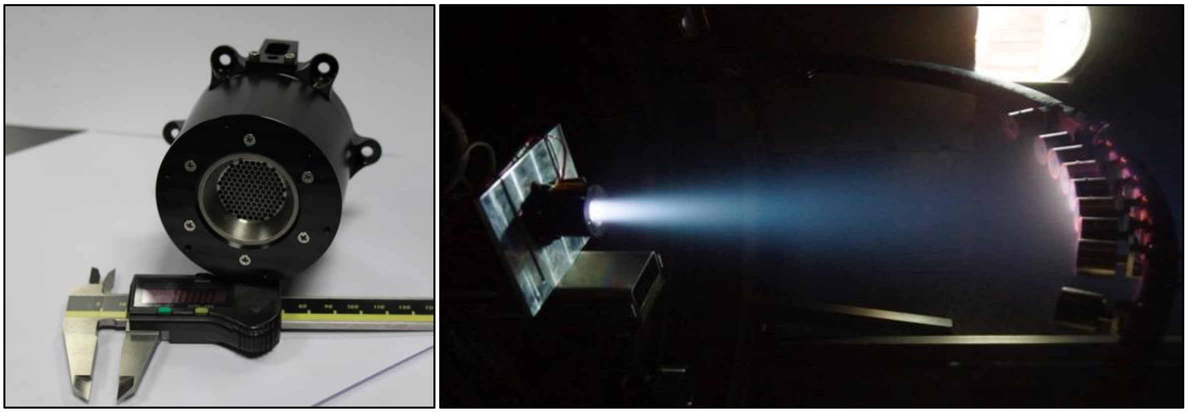

Figure 1: RIT3.5 EM miniaturised Radio Frequency Ion Thruster (mRIT) (left) and its operation in ESA ESTEC EPL (right).

A thruster performance model, comprising performance parameters of various RIT thrusters, RIT scaling laws and basic plasma and electric propulsion physics, was developed and allowed for a precise determination of the major design features including sizing and shaping of the individual parts and sub-assemblies that would lead not only to required thrust/power/Isp relationships but also the effective thermo-mechanical properties. The fundamental thruster design has not changed since it was first completed back in 2013, and every test campaign performed since increased the confidence level with respect to that design.

The design of the RIT3.5 is of course based on a standard configuration of inductively coupled plasma source. The thrust generated is equivalent to the net force acting on the grid electrodes due to the extraction and acceleration of the ions. The RIT3.5 grid system comprises three electrodes to better accommodate the requirements related to the mission lifetime and thus total time of the thruster operation. Performance has been estimated and later demonstrated considering two different configurations for the propellant flow control: variable flow control and fixed flow control in order to support mission scenarios coming from the NGGM mission analysis and design.

The first development project accommodated an extensive experimental program divided in two sequences of characterization and endurance tests, including development and verification of performance, thermal, mechanical and lifetime models of the RIT3.5.

Characterization tests, included performance mapping, thrust range, thrust resolution and thrust noise qualification, thrust fall/rise time definition, as well as the verification of the thermal model prepared by Thales Alenia Space in Turin, coupled with a heaterless hollow cathode neutralizer to get very first assessment on the possible variation in thruster operation and especially lifetime expectations with and without a neutralizer. Finally, evaluation of the facility effects was carried out through the performance mapping in two different vacuum facilities. The endurance test included 1000 h of direct firing of the thruster with periodic determination of the grid erosion evolution that was then used to validate the endurance model set-up by IOM in Leipzig and to project End-of-life (EoL) expectations for the RIT3.5.

Thermal and mechanical models were both developed by Thales Alenia Space in Turin. That allowed a comprehensive study of the thruster thermal behavior throughout the NGGM expected mission scenario, taking into account satellite configuration and various solar activities, and thus confirming the suitability of the thruster thermo-mechanical design.

One of the most challenging requirements repeatedly emerging from the NGGM mission analysis is the necessity to deliver a specific impulse as high as possible, especially in the very low thrust regimes. Unfortunately, it is well understood that physical limitations of the Gridded Ion Engines (and pretty much of any other electric propulsion technology) would not allow for extremely high Isp and the necessity of maintaining it over a broader thrust range represents an even stricter limitation. To overcome this, a variable Isp grid system has been proposed. This technology has been implemented on the RIT3.5 and proven to deliver extended performances within a dedicated ESA project [19].

In the frame of that activity, the capabilities of the existing RIT3.5 thruster design were extended with minimum changes to utilize 4 potentials within its already existing three grid system, instead of the nominal 3 potential configuration. The purpose of these modifications was to decouple the ion extraction and acceleration processes, allowing for quasi-independent control of thrust and specific impulse, without significant losses in the overall performance. The project was concluded successfully, although demonstration of performances in the lower thrust region was only partially successful due to limitations in the flow control units.

The experimental campaign for the Variable Isp Project was divided into Characterisation and Endurance test sequences. During the characterisation tests, performances were directly compared between baseline and variable Isp control by switching from 3 to 4 potential application during the same facility run. A comprehensive performance characterisation was then carried out demonstrating a dynamic thrust range of 1:300 (between 10µN and 3mN), with a very broad selection of specific impulses for each thrust level. To validate the performance model of this configuration, some operating points were precisely predicted beforehand. Setting the exact input parameters from the model into the experiment resulted in the achievement of the expected performances with a maximum 1.5% deviation from the model predictions.

During the project, the thruster was tested in three different facilities, including two facilities at the ESA Electric Propulsion Laboratory (EPL) in ESTEC.

The Endurance test campaign was carried out at the worst-case conditions identified during the performance characterisation carried out in the first phase of testing. The selected operating point therefore exceeded the baseline conditions by at least 20% for ion energy and around 25% for current density load. However, the overall grid erosion trend has been demonstrated to be similar to that obtained for nominal thruster operation at maximum thrust level, demonstrating a far more efficient extraction process in the Variable Isp concept.

Recently, a new class of missions has been studied by ESA: interplanetary missions based on CubeSat form factor. The specified propulsion requirements demonstrated that Miniaturized Gridded Ion Engines could be suitable candidates for such an application. The preliminary definition, development and testing of Hybrid Propulsion System for M-argo based on RIT3.5 thruster has been performed in the frame of the ESA project [4]. Within this project, the RIT3.5 operating parameters were adjusted to suit the identified mission requirements and it has been demonstrated that the baseline configuration without major, if any, design changes could successfully fulfil such a demanding set of requirements. Of course, interfaces and sub-system configurations to match that class of missions are entirely different than Class-1 ESA missions, like NGGM, which Mars Space Ltd are currently addressing in an overall system architecture definition.

B. RIT3.5 Performances

1. Power, thrust and Isp envelopes

Figure 2 summarizes the operating envelope for the original and variable Isp configurations of the RIT3.5 thruster targeting NGGM Phase-0 requirements. The figure does not reflect the possibility of the thruster to operate at higher thrust levels, as this was not required by the mission requirements at the time.

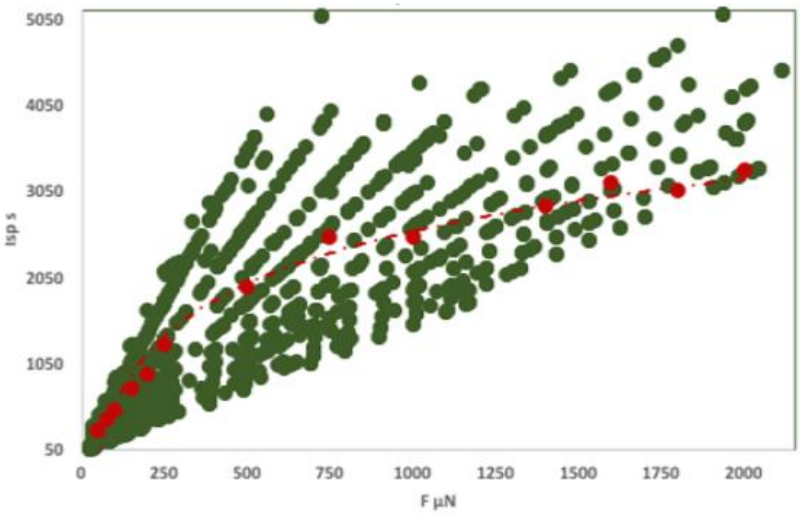

Figure 2: The Isp of the thruster for different thrust levels up to 2mN in nominal configuration (red) [2] and Variable Isp configuration (green) [3] for NGGM Phase-0 preliminary requirements.

While for the nominal configuration power-to-thrust relationships are straight forward to understand (see Figure 3), the relationships between power and the thrust for Variable Isp configuration are way less intuitive. However, acquired data allow thruster design authorities to select optimum operating conditions following the mission request as there are overall dependencies between necessary power and used flow at the given thrust level.

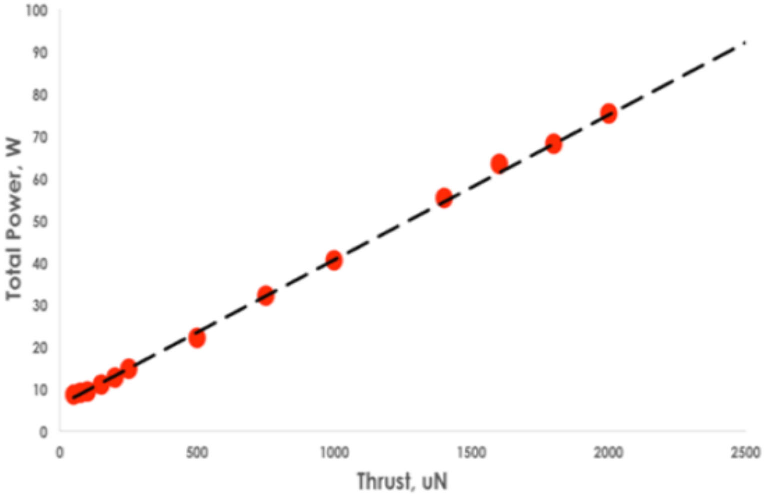

Figure 3: The Total power of the thruster only (at thruster level) for different thrust levels up to 2 mN in nominal configuration (red) [2]

As the interplanetary CubeSat stand-alone mission requirements are majorly driven by the factors of size and mass and, understandably, the benefits from simplification of various elements, it has been clearly identified that simplification of the extraction-acceleration process could benefit RIT3.5-based propulsion system. Co-engineering activities between satellite/mission authorities and propulsion system experts, followed by RIT3.5 performance evaluation and modelling, led to the preliminary conclusion that utilization of non-variable voltages within extraction system of the thruster would be sufficient to deliver the required operating performances without lifetime reduction. Successful hybrid chemical-electric propulsion system test campaign confirmed those predictions. Figure 4 shows the operating envelope of the RIT3.5 adjusted for the M-ARGO mission.

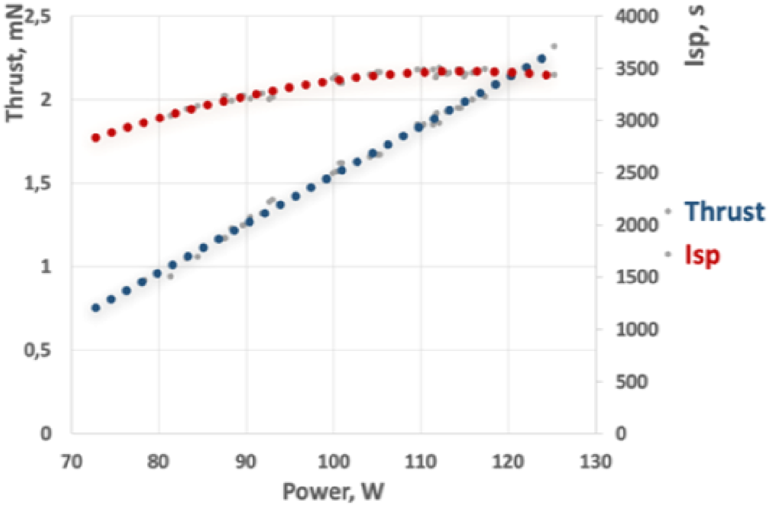

Figure 4: The Thrust (800µN - 2200µN) and Isp (2900s - 3600s) for given power consumption (bus level including all the necessary sub-systems) of the electric propulsion system [3].

As for some applications the use of Xenon as propellant might become problematic, one of the optimization directions is the use of a Krypton-based RIT3.5 configuration. The very first experimental assessment of the performances of this configuration has been carried out at the end of 2021. It was aimed to derive thruster performances without any hardware change in comparison to Xe. The results obtained support further optimization and development of the system operating with Krypton. Figure 5 compares the operating envelope obtained running the thruster with Xenon and Krypton.

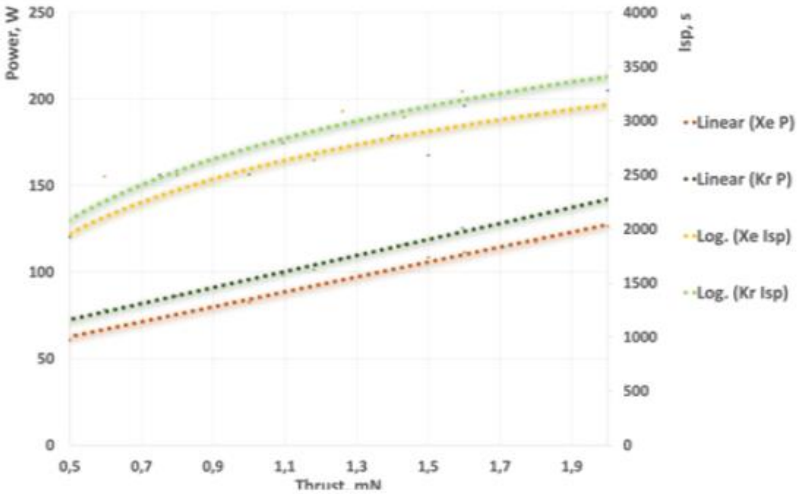

Figure 5: Power consumption and Isp for given thrust level of the electric propulsion system [3].

C. Industrialization

As mentioned above, MSL has recently acquired the rights to the design of the RIT3.5 and is currently leading an activity funded by ESA, for the development and qualification of a miniaturized ion thruster sub-assembly. The ultimate aim of this development contract is to reach TRL6 for the entire RIT3.5 sub-assembly (i.e. thruster and neutralizer, harness and pipework). In order to achieve TRL6 at sub-assembly level it will be necessary to reach at least TRL6 at unit level, and in addition to perform adequate testing and verification at sub-assembly level. In particular, the neutralizer for this sub-assembly is based on a dry-neutralizer technology currently being developed by Mars Space and further detailed in section IV-B [12]

To support the progression to TRL6, Mars Space is developing internal modelling tools (e.g. mechanical, thermal, performance and ion optics) in harmonization with the design iteration activities (e.g. optimization, robustness and implementation of lessons learned) and interface definition (mechanical, electrical and fluidic), along with the implementation of a robust supply chain.

To help support these activities, Mars Space are collaborating with the expertise from TransMIT, in particular for the thruster elements and interface with other EP subsystem elements, such as the RFG and PPU. In addition, Mars Space will use TransMIT's support to execute a number of optimization exercises to suit the target operating parameters. The objective is to establish the end-to-end performance and lifetime definition and allow for different input parameters, including not only thrust, Isp and power relationships, but also such things as system complexity, minimisation of physical design changes, variety of mission scenario within the same mission concept.

This section provides a brief overview of the industrialization activities on the RIT3.5 that Mars Space are undertaking to address the design features of both the thruster sub-assembly elements.

Figure 6 shows the thruster development and qualification roadmap as envisaged by Mars Space to achieve the TRL maturities as explained above and in addition further developments required to achieve TRL7/8.

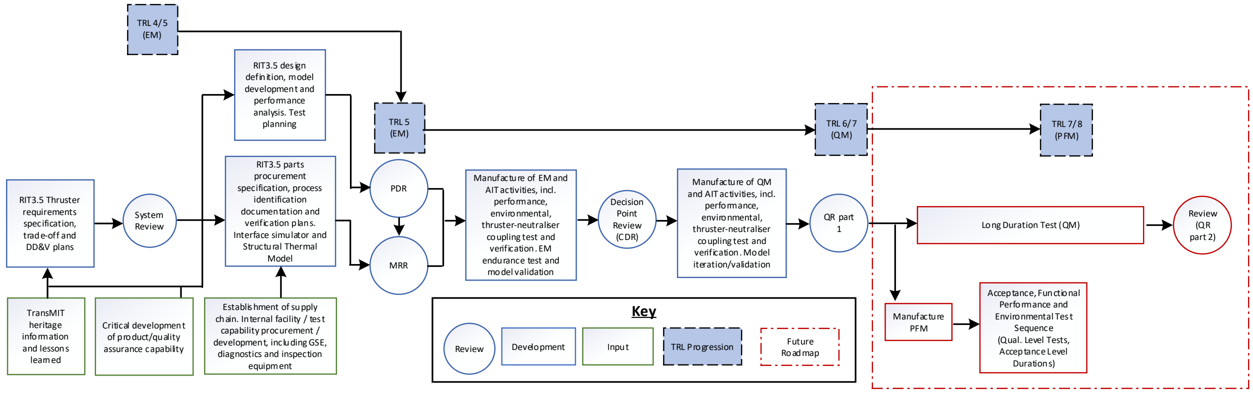

Figure 6: RIT3.5 Thruster Development and Qualification Plan.

Figure 7 shows the dry neutralizer development logic and qualification roadmap as envisaged by Mars Space to achieve TRL6 and in addition further developments required to achieve TRL7.

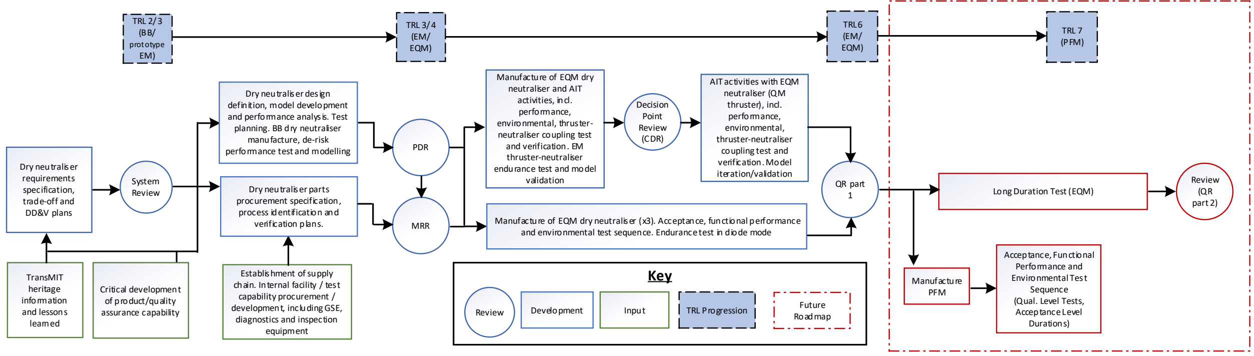

Figure 7: RIT3.5 Dry Neutralizer Development and Qualification Plan.

Mars Space are overall responsible for the harness design, which will include performing the following activities:

- Defining harness requirements (length constraints, electrical characteristics, thermal characteristics, flexibility and lifetime)
- Functional design definition (harness interface definition, electrical performance, materials and processes)
- Radiation Analysis (Mars Space will engage with specialist support from the harness provider for this aspect

Similarly, Mars Space are overall responsible for the pipework design, which includes performing the following activities:

- Defining pipework requirements (length constraints, pressure rating, flowrates and leakage)
- Functional design definition (tube bore size, wall thickness, mechanical fittings, materials and processes)

In addition, the following inputs are required to fulfil the Harness and Pipework design definition:

- Specification of the mechanical environmental levels
- Thermal design. This shall include thermal analysis (TBD) necessary to establish the design
- Routing constraints (including minimum bend radius)
- Resistive torque requirements (in case the thruster is mounted on a pointing mechanism)

Figure 8 and Figure 9 provide an overview of the logic foreseen for the harness and pipework development and qualification. The basic logic approach can be summarised as:

- Preliminary design and analysis
- Harness and Pipework Interface Simulator & STM build and test
- BB Harness Sample Test (included radiation testing if needed above that of the cur-rent capability)
- EM#1 Harness and Pipework Build & Integrity Test
- QM#1 Harness and Pipework Build & Test, Integrity Test and Integration to QM#1 Sub-Assembly
- QM#2 Harness and Pipework Build, Integrity Test and then be subjected to a stand-alone endurance test

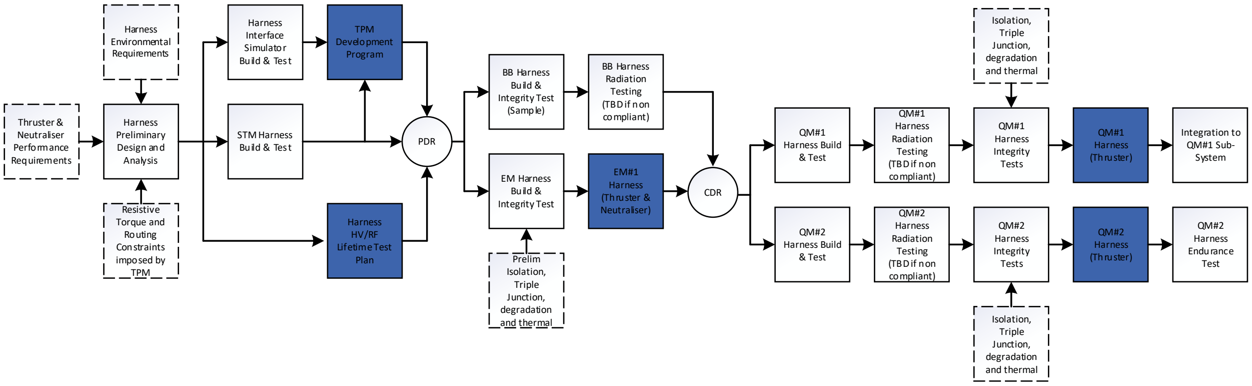

Figure 8: RIT3.5 Harness Development and Qualification Plan.

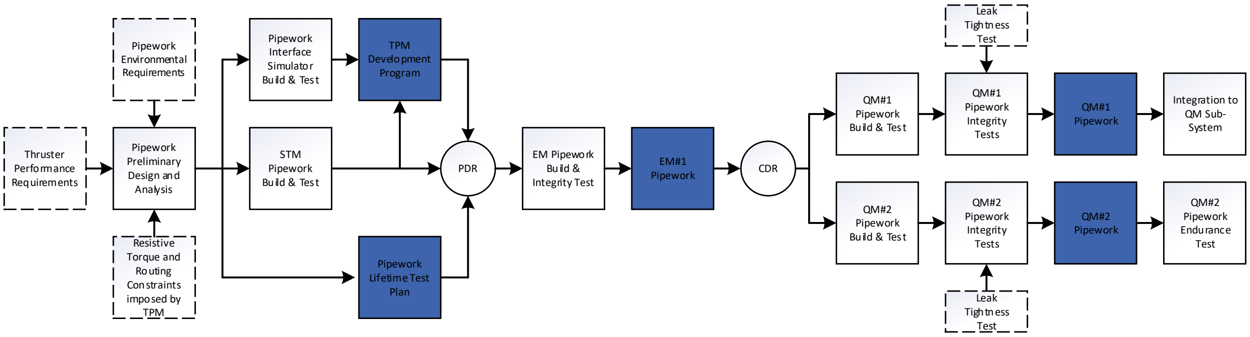

Figure 9: RIT3.5 Pipework Development and Qualification Plan.

In a parallel pre-development contract with the European Space Agency, Mars Space are developing an EP system for the NGGM mission, based on the RIT3.5 thruster. In the frame of this activity, Mars Space is collaborating with the Agency and with system primes in the definition of the system requirements and will subsequently lead the engagement with suppliers for the down-selection of critical sub-system units, such as the RFG, PPU and FCU. In the context of this activity, which foresees the use of multiple RIT3.5 engines, Mars Space have baselined the usage of an existing hollow cathode to neutralize multiple thrusters. The hollow cathode, which was selected over the dry neutralizer technology to meet the development timescales and achieve the lifetime specified for the mission, is an evolution of the T5/T6 hollow cathode that were used on the GOCE and BepiColombo missions, further described below in section IV-A.

IV. RIT 3.5 Neutralization Concepts

A. Hollow Cathode

MSL are currently working in collaboration with ESA, on the development of a Hollow Cathode Neutralizer based on the T5 (GOCE) design heritage. MSL has in fact recently acquired a license to manufacture, commercialize and further develop the T5, T6 and T7 thrusters, including the associated cathode technology. This technology development project is focused on re-establishing QinetiQ's T5 hollow cathode technology and manufacturing capability at MSL, followed by technology development according to the NGGM mission specification. The project brings with it the benefit of flight heritage and lessons learned from GOCE and BepiColombo. The T5 neutralizer technology may be considered for coupling with other EP engines in the scope of NGGM. The T5 hollow cathode neutralizer is at TRL9, however, modifications are required to meet the NGGM specifications and the required emission current depending on the neutralization concept selected (i.e. single neutralizer common to single / multiple engines). Part of the ESA pre-development Project is to explore coupling of multiple RIT3.5 engine(s) with the NGGM hollow cathode neutralizer.

Mars Space have currently built two breadboard models to assess the optimization of the orifice size / flow rate / keeper current that will be required to neutralize the engines and analysis of the neutralization concept associated with the engine configuration, these are shown in Figure 10.

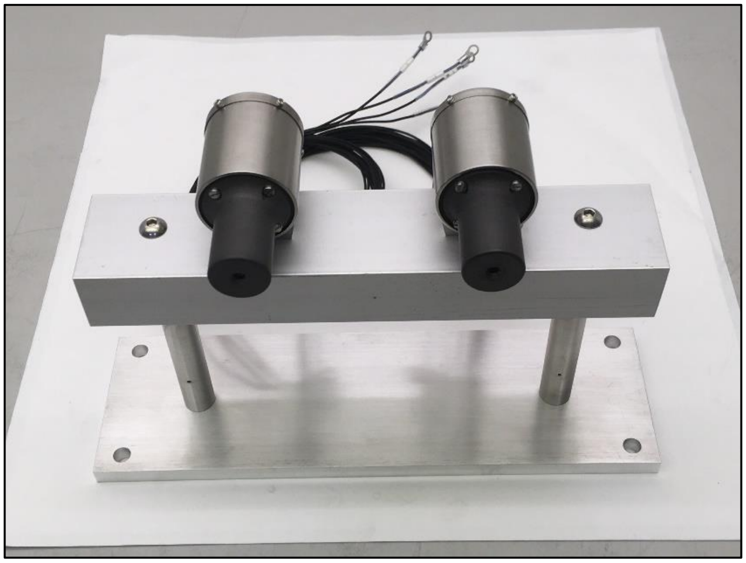

Figure 10 Breadboard Hollow Cathode Neutralizers built by Mars Space

The Hollow Cathode Neutralizer design concept proposed for the NGGM mission application is closely based on the hollow cathode technology used in the T5 Kaufman ion thruster originally developed by QinetiQ, and which achieved significant flight heritage through the GOCE mission. The T5 thruster design features two integrated hollow cathodes; one used to provide an electron current to the main discharge, the other used for neutralization of the ion beam. The hollow cathodes that formed part of the GOCE satellite's primary thruster were operated for a total of over 36,000 hours whilst successfully executing the required thrust operations over the course of the mission. A scaled-up version of the same hollow cathode technology is also currently in operation as part of the T6 ion thrusters propelling the BepiColombo spacecraft to Mercury. All of these cathode benefit from a highly robust, reliable and long-life barium oxide emitter technology, originating from Philips, which has been extensively demonstrated on the ground and in flight.

The Hollow Cathode Neutralizer is illustrated in schematic form below in Figure 11. Propellant (normally xenon gas) is fed into a tantalum tube leading to a cylindrical porous emitter which is impregnated with a low work function material, in this case barium oxide. At the downstream end of the tube (the cathode tip) there is a narrow opening referred to as the cathode orifice. The cathode tube and emitter are surrounded by a heating element which is isolated from the tube using a high temperature machinable ceramic, and which is used to initiate thermionic emission in the emitter. The cathode can then be ignited by applying a voltage to the keeper electrode, after which the plasma discharge is able to sustain without direct heat input due to the energy input provided by ion bombardment.

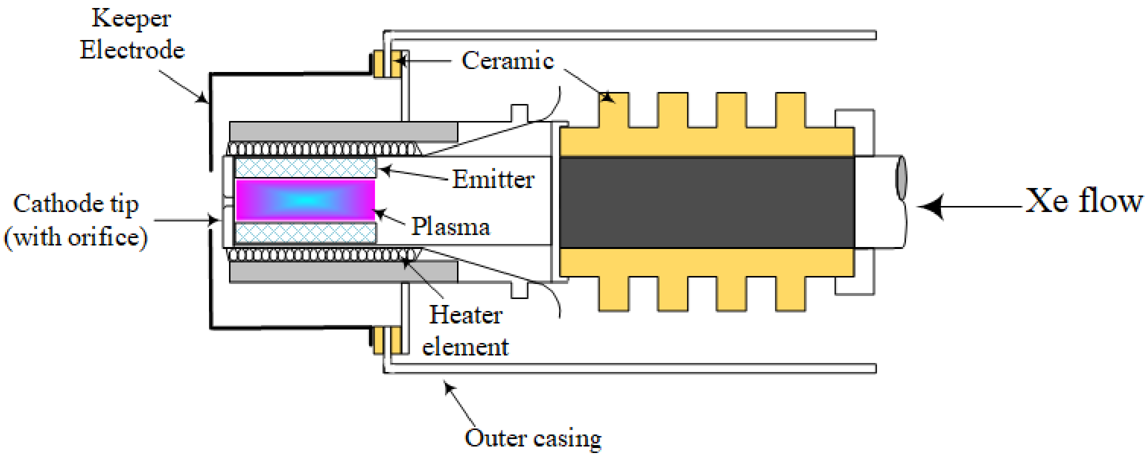

Figure 11 Schematic of Hollow Cathode Neutralizer

In order to make maximum use of the GOCE flight heritage, Mars Space's proposed neutralizer design shares its core design configuration (comprising the cathode's emitter, tubes, heater assembly and xenon feed assembly) with the T5 discharge cathode. In this way, the cathode's functional design has been preserved. The main exception to this is the tip orifice design, which needs to be tailored for the neutralizing function in accordance with the specific mission requirements. Other changes to the design have been implemented as follows:

- The neutralizer used in the GOCE T5 thruster was electrically connected to ground rather than having a dedicated electrical return path. However, for a robust system design it is essential that the neutralizer is able to float relative to ground. This was achieved firstly by using the T5 discharge cathode design configuration, which already features an isolator in its gas feed line, as the basis for the new design. Secondly, an isolated mounting design concept was adopted which ensures that the neutralizer body, keeper and grounded mount are all electrically isolated from each other whilst ensuring a robust mechanical connection. This concept is derived from the design adopted on QinetiQ's larger T6 neutralizer and on their standalone version of the T5 cathode technology.
- For the NGGM application the neutralizer is required to be a separate standalone device rather than integral to the thruster as per T5. The main neutralizer assembly is therefore mounted to the spacecraft via an enclosure tube, which also provides thermal isolation to the spacecraft and to the neutralizer's electrical interface.
- QinetiQ performed a comprehensive review of lessons learned from GOCE and other more recent projects, particularly development of the larger T6 thruster for BepiColombo, and compiled a set of recommendations for consideration by Mars Space. Mars Space assessed and implemented these recommendations throughout the NGGM neutralizer design. As a result, the design benefits not only from the extremely valuable GOCE heritage, but also QinetiQ's extensive hollow cathode development

experience, addressing known major risks identified subsequent to the GOCE mission as well as other minor improvements to design specifications, manufacturability and quality.

Because MSL's approach relies on the re-use of an existing mature technology, many of the functional design parameters (particularly the overall sizing of the neutralizer) are effectively frozen and will not be altered, in order to maximize heritage, read-across to the new design. However, to achieve the desired performance it is essential to optimize the orifice design. Due to the planned spacecraft altitude, and the resulting thrust range needed to achieve dynamic drag compensation, the NGGM neutralizer requirements specify operation at lower emission current compared to GOCE, even where a single device is used to neutralize multiple thrusters simultaneously. Furthermore, it is essential to minimize as far as possible the xenon flow rate in order to meet the overall xenon budget. These requirements, together with the need to maintain stable emission over life whilst operating in electrically floated configuration, are expected to lead to the selection of a much smaller orifice compared to GOCE.

At present, the available data to support the orifice selection is limited. Hence, Mars Space has embarked on the following activities:

- Two breadboard neutralizers have been manufactured (see Figure 10), each with a slightly different orifice size. The performance of these devices will be characterized in order to inform the orifice size selection and confirm the operating parameters and associated margins.
- MSL will use an internally developed erosion model to predict the evolution of the orifice profile over life. The model consists of a 0D insert region and a 1D orifice region (see Figure 12) and was validated against experimental data available in the literature (see Figure 13 and Figure 14) [13][14].
- One of the two breadboard devices will be selected to be subjected to long duration testing; orifice profile measurements will be taken periodically for comparison to the model predictions.
- An 'end of mission' neutralizer, featuring a representative orifice, will be manufactured and tested to confirm that the required performance can still be achieved, including stable operation in spot mode.

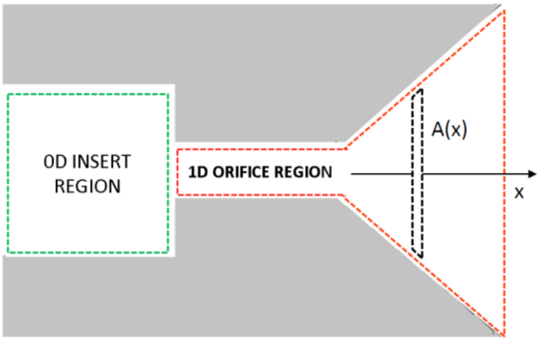

Figure 12 Simulation domain geometry, 0D insert region and 1D orifice region

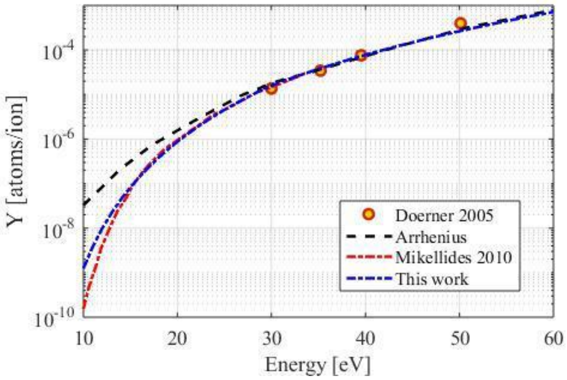

Figure 13 Sputtering yields of W versus Xe ion energy, experimental data from Ref. [15] and numerical extrapolation from Ref. [16]

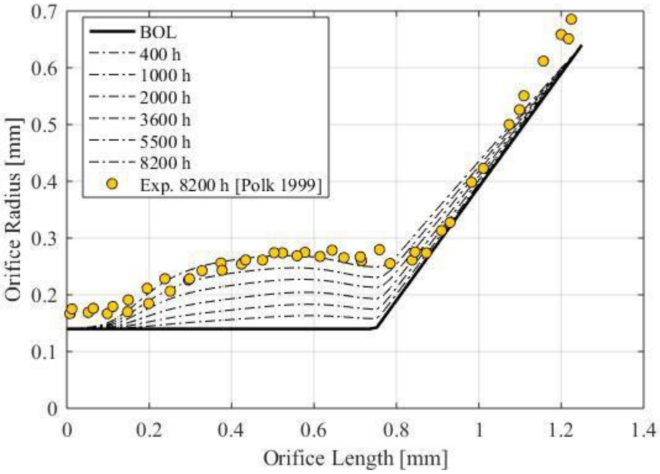

Figure 14 Orifice radius profiles at different simulation time steps, experimental data from Ref. [17]

In order to inform the design process, Mars Space has also developed finite element models and a thermal model of the standalone neutralizer design. These models benefit from data supplied by QinetiQ in relation to the work conducted for GOCE; however, MSL is implementing a far greater level of detail commensurate with the extensive modeling activities performed more recently for projects such as BepiColombo, noting that the T6 hollow cathode technology used on BepiColombo is a scaled-up version of the T5 technology such that many of the modelling techniques employed for that project are directly applicable.

B. Dry Neutralizer

Within the framework of the RIT3.5 Sub-Assembly Development, a dedicated dry Neutralizer (RIT3.5 NTR) is being designed, developed, and tested. The RIT3.5 dry NTR development is the focus of a companion paper [12], thus only a brief overview of the development is provided here. The RIT3.5 dry NTR is being designed to be capable of delivering an emission current of 10-50 mA at a max voltage bias of <400 V with a power consumption <10 W and a lifetime of more than 25,000 hours.

As it has been determined that there is not an off-the-shelf solution suitable for the project NTR requirements, a development activity has been defined and undertaken to create an in-house NTR solution specifically tailored to the NTR requirements. Operation within this current range is inefficient for hollow cathodes that are typically employed for >0.5 A and require propellant flow, dry emitters such as field emission emitters have been used for µA to 10 mA and have not demonstrated practical operation within the required range. Ultimately, following a full review of cathode technologies it was determined to adopt a dry thermionic cathode in a Pierce Gun configuration for the development program.

Several conceptual designs and approaches to the solution were formed, with thermal, structural, and electrostatic modelling parametric analysis supporting the design definition, as outlined in the companion paper [12]. A prototype breadboard system, which allows for empirical parametric analysis has now been constructed and is set to be tested in a simplified diode configuration as depicted in Figure 16. The first phase of testing is set to provide validation to the modelling design tools utilized and provide indication of performance compliance with the derived requirements. Following this testing, development will commence on an engineering model of the RIT3.5 Dry NTR.

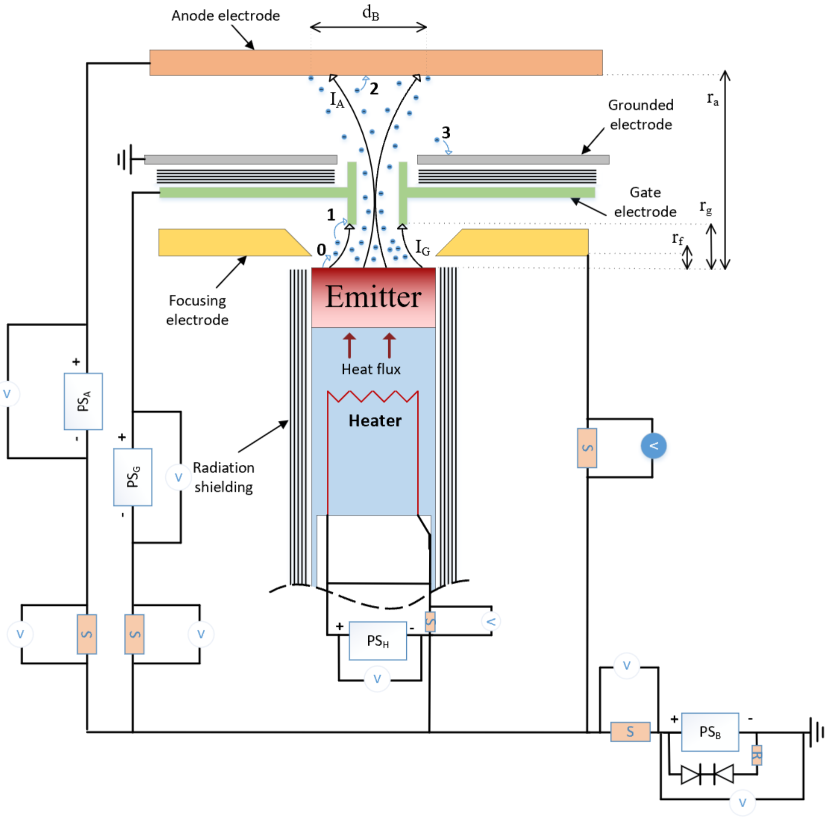

Figure 15 Dry Neutralizer Electrical Representation

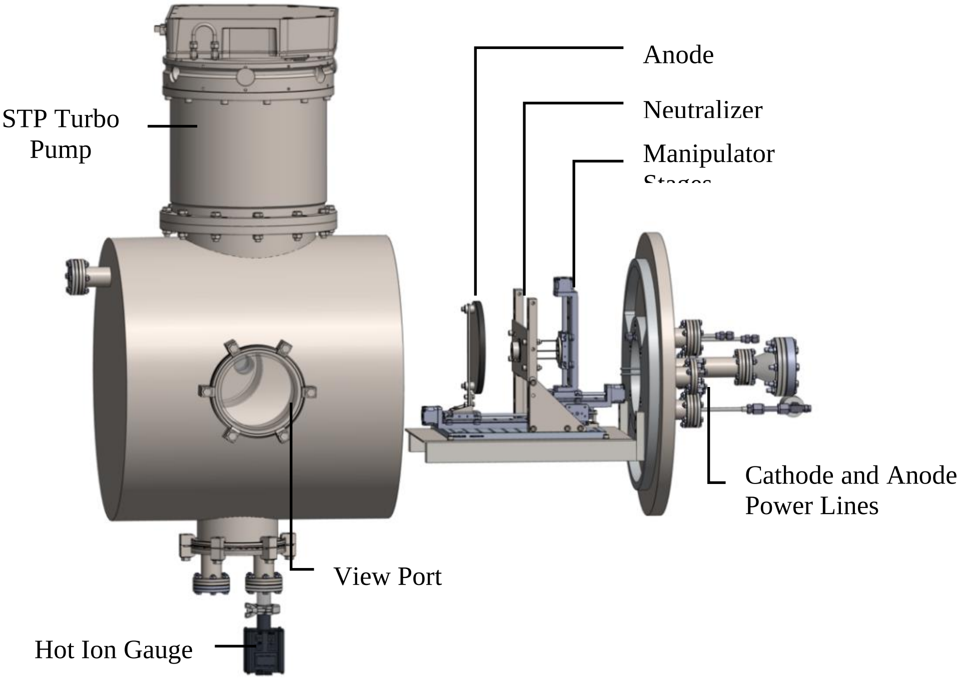

Figure 16 Miniature Neutralizer configuration integrated into the MSL-VC3 test facility.

V. RIT 3.5 Applications and Possible System Concepts

As mentioned above, Mars Space are currently optimizing the RIT 3.5 to suit multiple applications for CubeSat and earth observation application such as M-ARGO and NGGM. The following sections give a brief overview of a possible configuration for multiple RIT 3.5 with a single hollow cathode neutralizer and also a ‘stand-alone’ RIT 3.5 configuration with a local ‘dry’ neutralizer.

A. Multiple RIT 3.5 with Hollow Cathode Neutralizer

The RIT3.5 based EP system architecture is still under consideration, and further engagement with primes and the various sub-system suppliers are needed to settle on a recommended EP system solution. Figure 17 shows a simplified architecture of a concept showing 2 x RIT 3.5 with a single hollow cathode neutralizer.

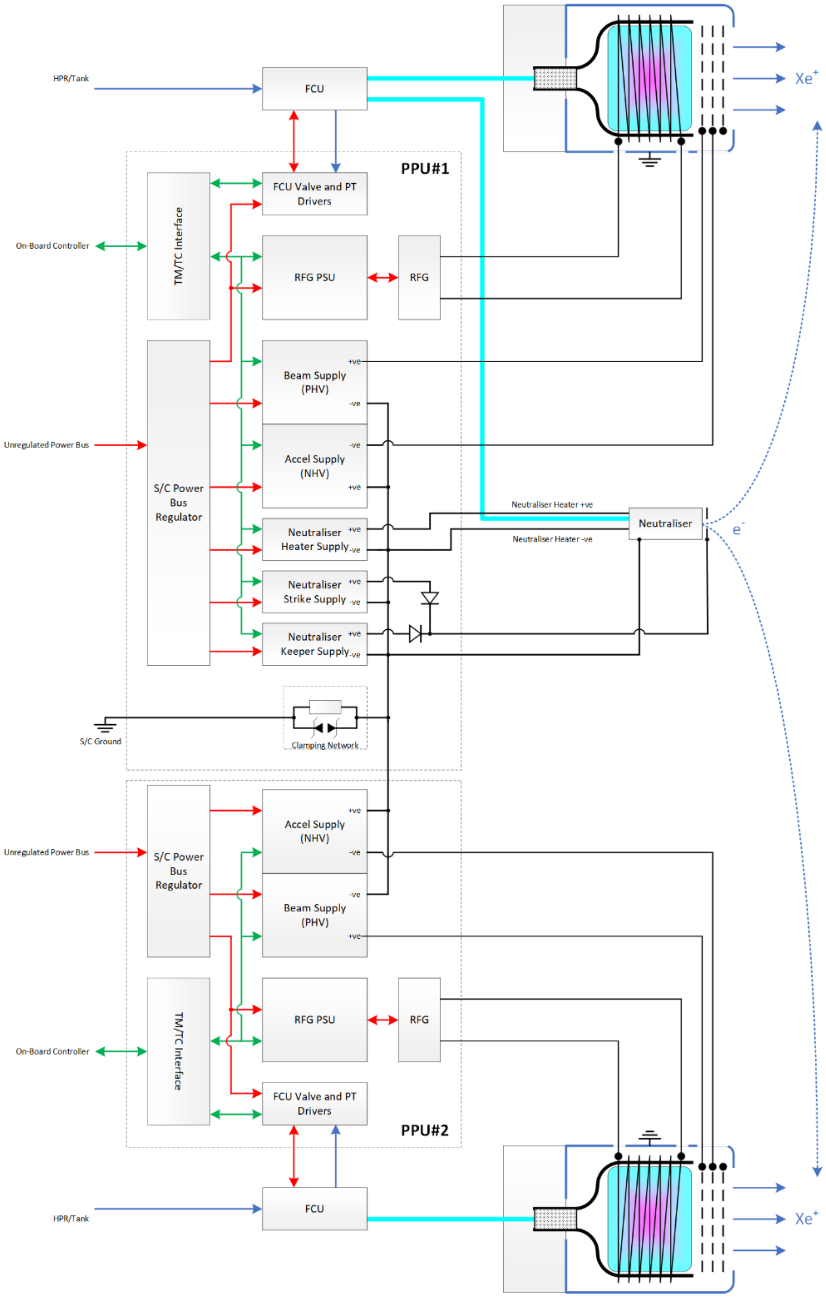

Figure 17 Multiple RIT 3.5 with single Hollow Cathode Neutralizer (concept)

The separation of the thrusters from each other and from the neutralizer is still TBD at this stage, so MSL have planned to carry out a performance/sensitivity analysis to assess the coupling of the neutralizers. MSL will determine how much the neutralizer coupling potential (NCP) will be influenced by the position of the device with respect to the thruster(s) and how this may impact the overall performance of the EP system, i.e. power, thrust (due to NCP) and impacts on thruster lifetime. Another objective of the twin engine test is to assess the potential effects of asymmetric neutralizer coupling between two operating thrusters by varying the location of the neutralizer and the extraction currents from each thruster. Assessment will need to be made in both steady-state and dynamic mode with different relative positions of the neutralizer during the test activities.

Mars Space plan to characterize a number of different positional options by the way of in-situ MGSE (vacuum compatible mechanisms) to adjust the radial and axial positions of the neutralizer with respect to the operating thrusters. The absolute positions are currently TBD; however, the foreseen configurations are shown in Figure 18 (provided for illustrative purposes only).

Note the following position representation: -

- RNOM = Nominal Radial Neutralizer Position
- R+1 (R+2 etc) = Neutralizer Radial Position +1 (etc) with respect to nominal (co-planar with grids)
- A+1 (A+2 etc) = Neutralizer +ve Axial Position +1 (etc) with respect to nominal
- A-1 (A-2 etc) = Neutralizer -ve Axial Position -1 (etc) with respect to nominal

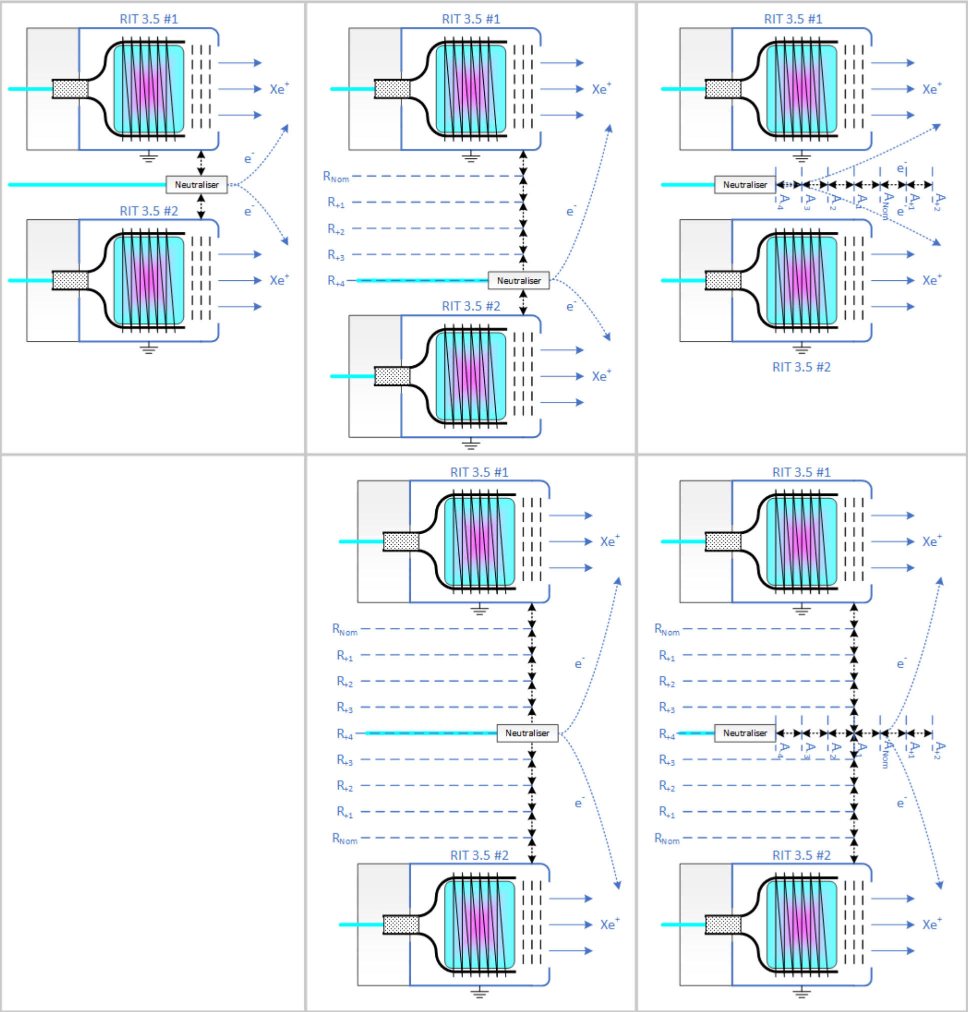

Figure 18 Multiple RIT 3.5/Hollow Cathode Neutralizer Radial/Axial Positions Characterization Concept

B. Single RIT 3.5 with local 'dry' Neutralizer

This technology development project is focused on bringing the dry neutralizer to TRL 6, to address future CubeSat applications and explore the potential use as a backup solution for NGGM. The dry neutralizer technology (currently TRL2/3) will include the addition of a neutralizer mounting structure given that the neutralizer is not currently part of the thruster.

Two power supplies are needed for this technology, one for the heater and one for the extraction electrode. The power demand and number of units required to meet the emission current demand and lifetime is dependent on the selected mission profiles, it is however anticipated that (at least) a single dedicated dry neutralizer would be required per RIT3.5 thruster, although this technology is also suitable for a stand-alone application.

As before, the dry Neutralizer will require careful consideration on the precise axial/radial position with respect to the thruster, especially in light of restrictions on the spacecraft accommodation, which form parts of MSL's neutralization concept strategy.

VI. Mars Space UK Vacuum Test Facilities

The following section provides a short overview of Mars Spaces' vacuum chamber capability.

A. Existing Mars Space Vacuum Test Chambers

Mars Space have been operating small vacuum chambers for many years, supporting the development of small cathodes and ion thruster technology. More recently, MSL successfully characterized a large prototype ring cusp discharge chamber in VC1, which eventually fed into the design and optimization of the GIESEPP T7 ring cusp thruster (a collaboration between Mars Space and QinetiQ).

Table 1 Existing Mars Space Vacuum Chambers

Facility Name	Location	Pumping Speed (l/s)	Dimensions (m x m Ø)
MSL VC1	Mars Space UK	2,200 (Xe)	1.5 x 0.6
MSL VC2		4,500 (Xe)	1.5 x 0.6
MSL VC3		2,200 (Xe)	0.52 x 0.52

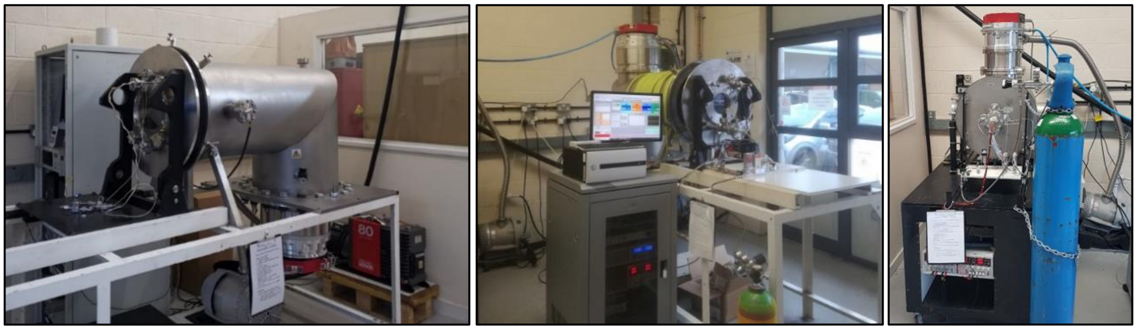

Figure 19 MSL VC1 (Left), MSL VC2 (Centre) & MSL VC3 (Right)

B. Newly acquired Mars Space Test Chambers

Within the last year, Mars Space has purchased the Vacuum chambers previously developed by QinetiQ Farnborough, that were utilized for successful programs such as GOCE [10][11] and BepiColombo [7][8][9], along with many other electric propulsion activities. The engineers/scientists existing and new to Mars Space have many years' experience in operating these vacuum chambers for development, qualification, acceptance and complex system coupling tests [6], and were involved in the original layout/design, including the diagnostics, which remain with the chambers.

Table 2 provides a performance overview of the chambers, detailing the pumping speed, dimensions and ultimate pressure when last tested.

Table 2 New Mars Space Vacuum Chambers

Facility Name	Location	Pumping Speed (l/s)	Dimensions (m x m Ø)	Ultimate pressure (mbar)
LEEP 1	Mars Space UK	50,000 (Xe)	5m x 2m	9.0 x 10^{-7} mbar
LEEP 2		100,000 (Xe)	(4m x 3.8m) + (5m x 2.6m)	5.0 x 10^{-7} mbar
LEEP 3		200,000 (Xe)	7.2m x 3.3m	5.0 x 10^{-7} mbar
IVOR		TBC	1.7m x 0.9m	6.0 x 10^{-7} mbar
Leybold		TBC	1.8m x 0.6m	TBC

In the summer 2021, Mars Space relocated all of the large vacuum chambers from QinetiQ Farnborough into its new laboratory in Southampton (~15,000 sq ft), see Figure 20. Mars Space is currently underway in the re-commissioning activities to swiftly bring the vacuum chambers back online.

Figure 20 LEEP1/2 and 3 located in Mars Spaces' new facility

VII. Conclusion

Mars Space have identified a detailed program of work to identify the industrialization of the RIT 3.5 along with the sub-assembly units to fulfill both the cubesat and earth observation missions such as M-ARGO and NGGM. The activities are ongoing, and Mars Space are developing the required neutralization concepts to suit the various applications as well as stand-alone configurations.

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