Qualification status update of the MICRO R³ and NANO R³ FEEP thrusters

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Field-emission electric propulsion (FEEPs) as part of the electrostatic propulsion family are low-thrust, high-Isp subsystems suitable for various mission applications on satellites ranging from Cubesats over constellations to larger satellites and can be easily clustered to fulfil mission requirements. Based on space-proven liquid metal ion source (LMIS) technology, FOTEC developed the IFM Nano Thruster as a standalone FEEP subsystem including propellant management and electronics (PPU) resulting in a first IOD in early 2018. The technology is now being commercialized as ENPULSION NANO thruster by the spin-out company ENPULSION and has resulted in delivery of several hundred thrusters and more than 100 thruster units in orbit (as of Q2 2022). Further R&D efforts at both ENPULSION and FOTEC have resulted in new products: the NANO R³ as an evolutionary step based on the NANO as well as the MICRO R³ based on the same technology for more demanding mission requirements. Both products are now being qualified within an ESA qualification project, and the current status and results are presented herein.

I. Nomenclature

EMC	=	Electromagnetic Compatibility
PPU	=	Power Processing Unit
SEE	=	Single Event Effect
TID	=	Total Ionizing Dose

II. Introduction

Commercially available spacecraft propulsion is in high demand as more and more satellite manufacturers emerge and the realization of constellations for various commercial and scientific aspects result in increasing propulsion requirements. Consequently, the availability of the Enpulsion NANO (formerly: IFM Nano Thruster) to suit those mission needs for propulsion ranging from 3U Cubesats [1] and satellites of 80 kg mass [2] or more has enabled many a mission and commercial success. Starting out as a R&D project at Austrian Research Centers (ARC) and later FOTEC [3], the FEEP was originally intended to support science missions where low but high accuracy thrust would be of

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need like LISA Pathfinder [4] or NGGM [5]. However fully integrated design including PPU, tanks, neutralization and telemetry paired with the easy-to-handle propellant indium has led to a high number of applications in the commercial satellite market [6]. With growing number of thrusters in space and the related feedback from various customers as well as continuous R&D efforts to improve the product portfolio to meet market needs, the Enpulsion NANO was taken as the base for establishing different development branches. For the NANO R³, the electronic design of the NANO was improved to increase radiation hardness, reliability, fault detection capabilities, and quality. As a result the thermal and mechanical design needed adaptations to accommodate for the new electronic design. In parallel, the neutralizer design was enhanced to enable even longer lifetime of the component, and the firmware was upgraded in functionality and quality for space. The resulting unit shares many underlying design principles with the space-proven heritage NANO in particular related to the ion emission and propellant management, but a considerable effort has been put into the design to yield the NANO R³ that is now ready to be formally qualified. In parallel, missions needs for higher thrust and/or higher total impulse could not be adequately met by using several NANOs on the same S/C, and a new product – the MICRO R³ – was designed to include more emission sites and a PPU with higher power throughput to enable higher thrust and, with more propellant included, higher total impulse [7]. Similar to the NANO R³, the electronics design is using architectural principles to result in a more reliable and radiation-tolerant PPU, and the neutralizer design is based on the same concept as for the NANO R³. The thruster is equally ready to be formally qualified.

III. Qualification outline

The qualification efforts are embedded in the framework of an ESA InCubed activity with FOTEC as subcontractor for PPU-related work packages and for tests feasible within FOTEC premises only. The campaign covers the following aspects for both thruster products:

- Thrust Performance (indirect)
- Thrust Performance (direct)
- Vibration (Sine Burst, Sinusoidal, Random)
- Shock
- Thermal Vacuum
- Endurance
- Post endurance performance verification

The endurance portion of the testing does not cover full lifetime of the thruster at this time as the main lifetime limiting factors for FEEP thrusters are propellant depletion and neutralizer burn through.

For both products, additional stand-alone PPU qualification tests are included:

- TID
- EMC (CE, CS, RE, RS, ESD)
- SEE (Proton)

For derisking of product, facility, procedural conduct, subcomponents, etc., several engineering models were tested prior to qualification [6, 7] or are tested as part of the qualification, e.g., neutralizer lifetime (standalone) and firmware validation.

A. NANO R³

The NANO R³ (Figure 1) is a 98.0 x 99.0 x 95.3 mm sized electric propulsion system with 1.3kg wet mass and 210g of propellants. It is a self contained system that only requires power and communication to operate.

Subsystems includes:

- Emitter and extractor for ion emission and acceleration based on field emission
- 2 neutralizers for charge balance, only one is operating at a time
- Reservoir with solid indium propellant
- Reservoir heater to melt indium once in space and to keep at operational temperature (hot standby)
- Potted high-voltage electronics to provide up to 10 kV to both emitter and extractor
- Low-voltage electronics to process power and commands from the S/C and to return telemetry for in-situ performance feedback

The module consumes about 45 W bus power for nominal thrust of 350 μN. The specific impulse (and the resulting total impulse) is a function of the emitter selection during production to fit mission requirements. The PPU is configured to handle either 12 or 28 V, and communication is possible via RS422 or RS485.

Fig. 1 NANO R³ thruster

B. MICRO R³

The MICRO R³ (Figure 2) consists of two subsystems – the thruster head (140 x 120 x 98.6 mm) and the PPU (140 x 120 x 34 mm). The propulsion system can be integrated in a stacked configuration, with the PPU situated directly underneath the thruster head or the PPU box can be integrated separately from the thruster head.

Similarly to the NANO R³ thruster the subsystems consist in:

- 4 emitters with extractor ring, all internally interconnected
- 4 neutralizers for charge balance, only one operating at a time
- 4 reservoirs with indium propellant and heaters, operating in parallel
- Potted high-voltage assembly (in the PPU section) providing up to 12kV.
- Low-voltage electronics to process power and commands from the S/C and to return telemetry for in-situ performance feedback

The total wet mass of the system is 3.9 kg for the stacked configuration with 1.3 kg of propellant. A total system level input power of about 100 W is needed for the nominal thrust of 1 mN. The MICRO R³ PPU takes unregulated 28 V input voltage and can be addressed by both RS422 and RS485.

IV. Qualification Status - NANO R³

A. Thrust performance

The NANO R³ and MICRO R³ thrusters operate on a much larger extractor voltage range than what the 28 needle crown emitter was initially designed for [3, 8]. As a result the divergence of the ion beam is affected with higher divergence at higher extractor voltage (above 8kV) and lower divergence at lower extractor voltages (below 6kV). This in turn affect the thrust for various Isp. The thrust model had to be adjusted to be more accurate over the Isp range of 1500 to 4000s the thrusters be operated at. More details and experimental evidence of that phenomenon can be found in [9] for the NANO R³ . This correction factor leads to a telemetry derived thrust accuracy of about 5% compared to direct thrust measurements. It allows for accurate thrust controlled operation over the full operational map. As a result the performance verification part of the qualification campaign is divided into two parts: one using telemetry derived calculated thrust values and one using direct thrust measurements.

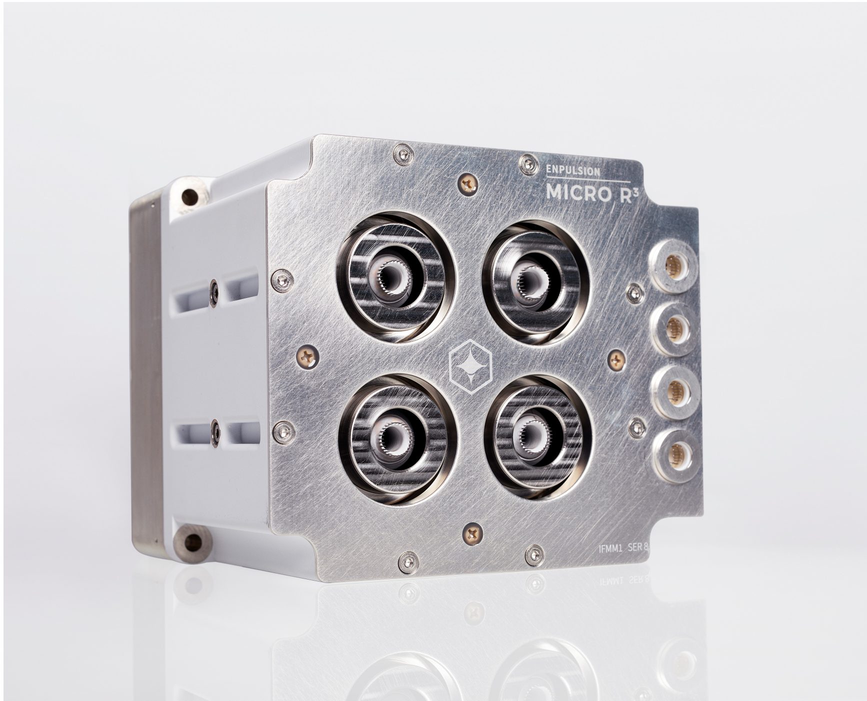

Fig. 2 MICRO R³ thruster

1. Indirect performance verification

As part of the initial reference performance, the thruster QM underwent a series of test scripts to evaluate compliance with performance requirements for the operational range. The following aspects were successfully demonstrated as part of the evaluation:

- Commissioning of all subsections
- Nominal thrust of 350 µN (indirectly based on telemetry readback)
- Repeatability for different thrust points
- Thrust vector offset within requirements (optical method)
- Minimum impulse bits of <25 µNs
- Thrust steps
- Neutralization (evaluated by collector measurements)
- Power draws at different operational modes and points
- Commandability of various operational setpoints via embedded firmware

2. Direct thrust measurements

Thrust performance was directly evaluated with the QM on the thrust stand of FOTEC (Figure 4) that had been specifically upgraded to fulfil the testing needs [9]. Different operational setpoints were measured together with their telemetry readout to show a good fit between direct measurement signal and indirect telemetry, which is explained in detail in [9].

B. Mechanical testing

1. Vibration

The NANO R³ QM was subject to a series of vibration loads in all 3 axes to evaluate robustness to environmental loads:

- 20 g sine bursts
- 25 g sinusoidal vibration (less at low and high frequencies)

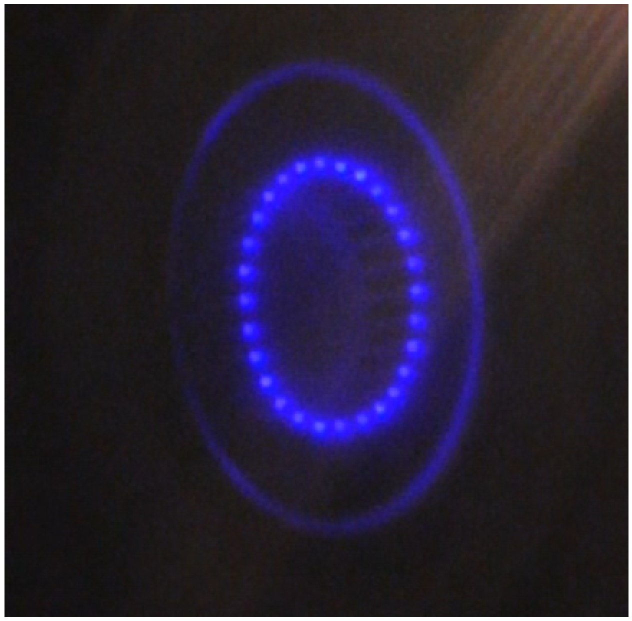

Fig. 3 NANO R³ QM firing with full neutralization

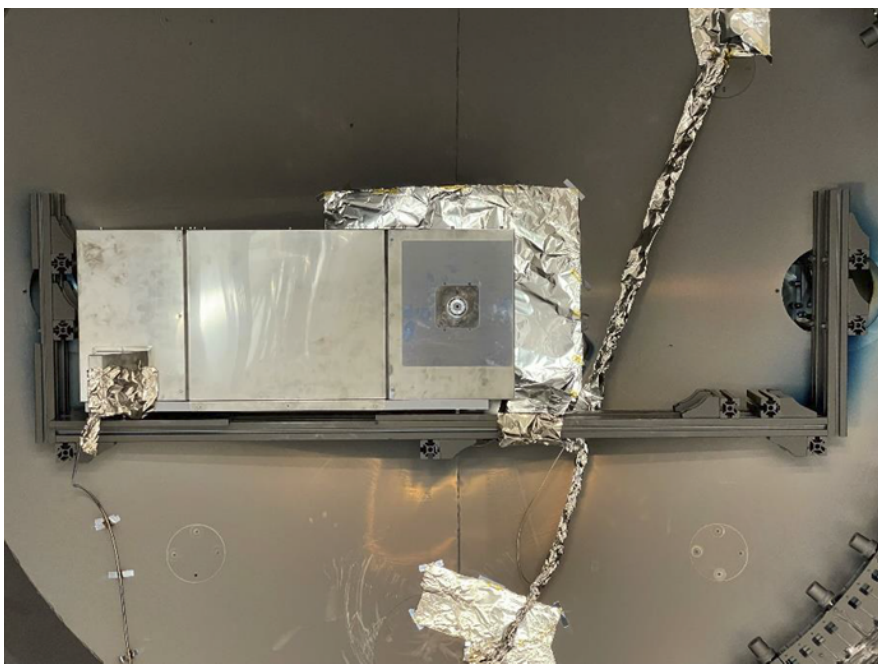

Fig. 4 NANO R³ QM mounted on FOTEC's thrust stand

- 24.8 gRMS random vibration

The test sequence was conducted at the vibration facility of FOTEC and is shown in Figure 5. Each test was followed by a resonance sweep to evaluate frequency and amplitude shifts of the main peaks and evaluate them against the pass/fail criteria. Figure 6 shows the resulting resonance sweep in-plane results as an example showing that no significant shift has happened.

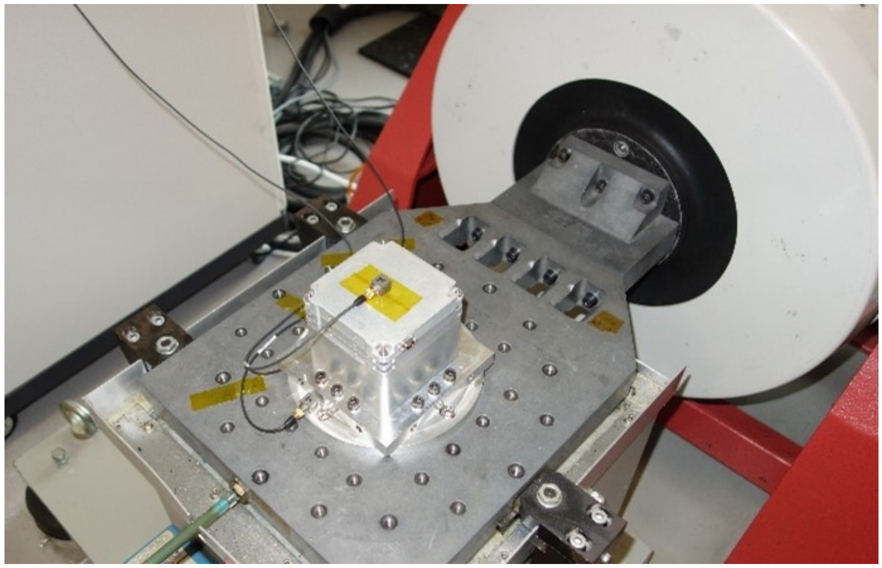

Fig. 5 NANO R³ QM mounted on FOTEC shaker

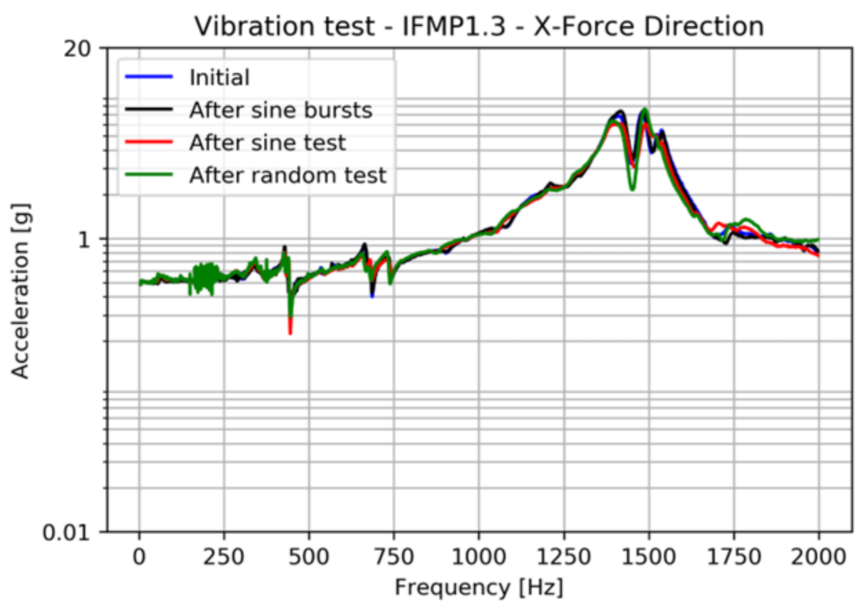

Fig. 6 Resonance sweep results for vibration qualification of the NANO R³ QM

2. Shock

The QM was further exposed to shocks in all 3 axes by means of a pendulum hammer table at FOTEC (Figure 7) accompanied by resonance sweeps on the adjacent shaker (Figure 5) as well as electric ground test checks of the QM prior and posterior to the shock campaign.

The target shocks of 2000 g (from 1000 Hz and higher) were reached as verified by the SRS analysis and resonance sweep indicating again that no significant shift in the major structural modes has occurred. Ground test showed no loss in functionality or performance degradation across the shock test.

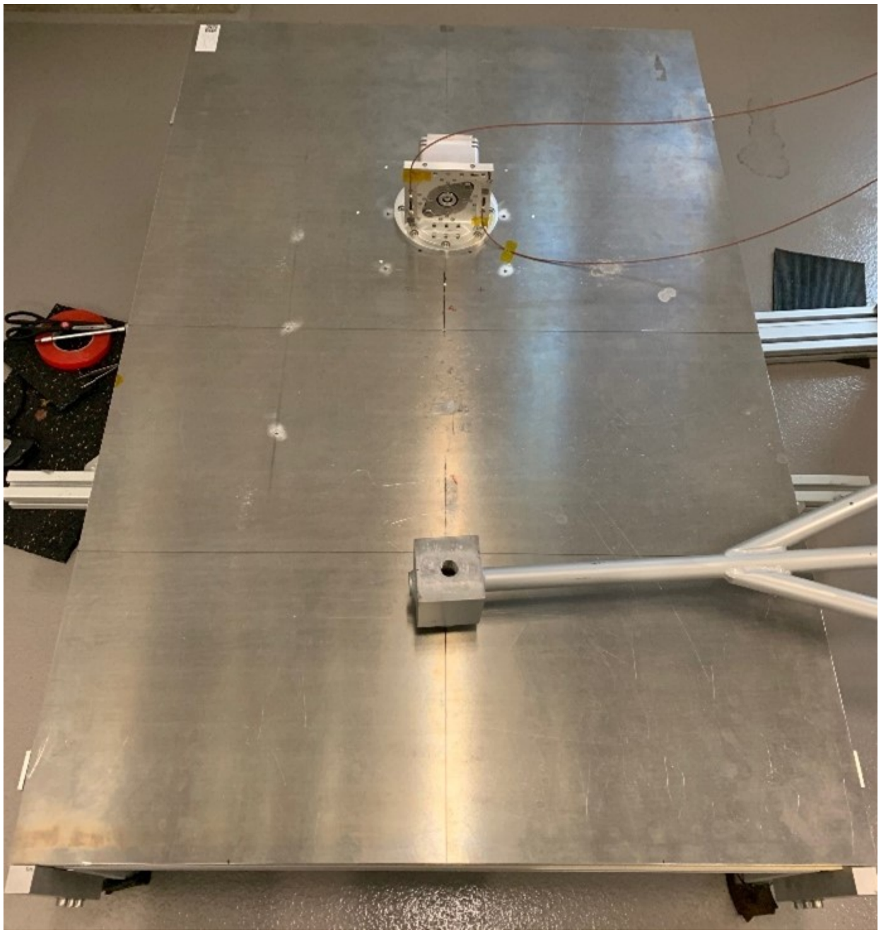

Fig. 7 NANO R³ QM mounted on FOTEC shock table

Fig. 8 NANO R³ thruster mounted in its TVAC test setup

C. Thermal vacuum testing

The qualification model was installed into a vacuum facility at Enpulsion (Figure 8. This setup capable of controlling the temperature at the thermal interface of the thruster between the cold (-30 °C) and hot (+45 °C) cases. Thermal vacuum tests start with solid propellant at the cold limit. Liquefaction of the propellant at the minimum operating temperature is performed. The thruster is then started and kept at this minimum temperature until equilibrium is reached. While still firing the thruster is brought to the maximum operating temperature. Firing is stopped and then resumed from hot standby status. The thruster is then fired until thermal equilibrium is achieved.

This test sequence allow for a demonstration of transition from cold standby to hot standby in cold conditions (the most challenging thermal point) as well as demonstrates thruster start in cold and hot cases.

A total of 7 ON-Cycles was performed comprising successful demonstration and measurements of:

- Cold start and hot start capability
- Nominal operation at 350 µN at both temperature extremes including neutralization
- Power consumption and efficiencies, in-rush currents, emitter characteristics, etc. at both extremes
- Operation at both extremes without exceeding internal limits as observed by on-board sensors and protected by firmware fuses

D. Endurance testing

Endurance testing of several thousand hours is planned for later this year and verification tests on engineering models are conducted to derisk procedure and potential facility effects passing the 1400 hours mark at time of writing.

1. Extractor clogging

One of the challenge of achieving long lifetime with FEEP thruster is deposition of propellant on the extractor electrode. Droplets formed by instabilities on the Taylor cone will deposit on exposed surfaces, slowly building up a layer of Indium. This causes the opening of the extractor to shrink down and can eventually lead to a short circuit between extractor and emitter. The phenomenon can be noticed on 9 where a low mass efficiency emitter was fired at high emission current, leading to high droplet shedding and accelerated clogging.

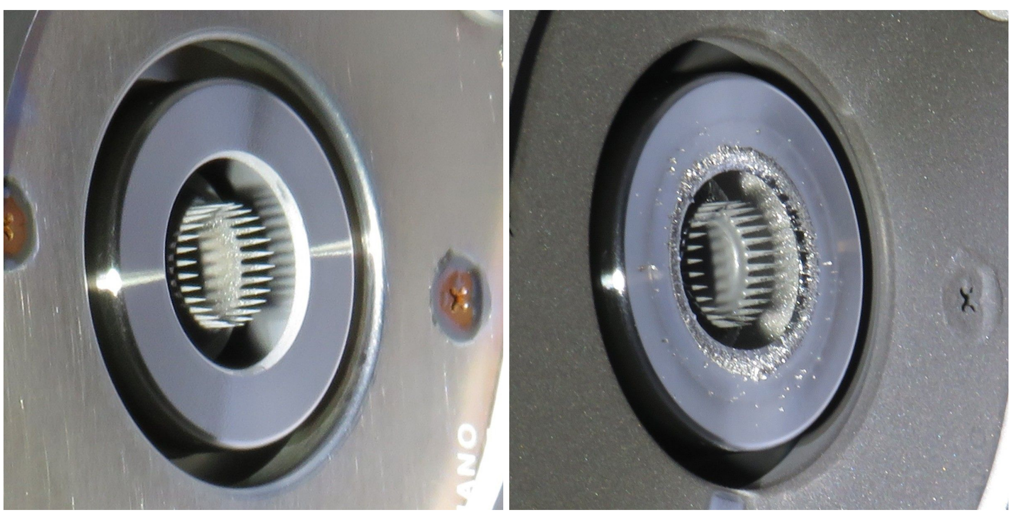

Fig. 9 Thruster after 0h (left) and 500h (right) of operation at high emitter current for a low mass efficiency emitter. Note the closing of the gap between extractor and emitter

These reduced engineering tests as well as the similar tests performed at FOTEC [10, 11] has allowed us to develop a well matching model of the extractor closing velocity. This deposition phenomena depends mainly of the ration of expelled droplets to expelled ions. This so called "mass efficiency" is measured during emitter manufacturing when they are first fired. This flux of droplet is integrated over the view factor from the needles to the extractor edge.

The results have been correlated between multiple different tests and are shown for two of them on figure 10. This model can be used to estimate clogging over a range of operating points.

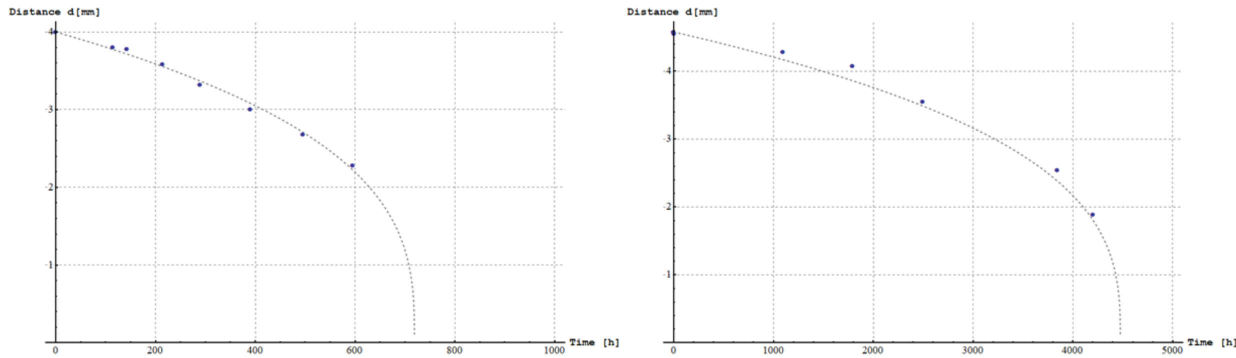

Fig. 10 Distance between emitter and extractor over time. These plots show the match between experiments (dots) and model (dashed line) for a low mass efficiency emitter operated at higher high current (left) and a high mass efficiency emitter operated at low current (right)

These tests also allowed Enpulsion to develop a cleaning procedure where the deposited propellant is melted and pulls away due to capillary action. A couple of cleaning were successfully conducted on flight-like hardware.

2. Other life limiting factors

Careful inspection of the lifetime test thruster revealed no contamination of the high voltage insulator confirming that the protections in place are adequate even for ground testing where chamber sputtering can be an issue.

No other detrimental effects could be observed. No needle electrode erosion could be seen.

Reduced testing was also performed at neutralizer level where it was found that one neutralizer, firing at maximum neutralization current, should last the same amount of time as the propellant when firing at maximum emitter current.

E. Electromagnetic compatibility

EMC qualification based on ECSS-E-ST-20-07C, Rev.1 was conducted in Q4 2021 and Q1 2022 at the ISO17025-accredited EMC test laboratory of Seibersdorf Laboratories. Since EMC testing on an operating electric propulsion thruster is notoriously difficult a dummy thruster was used. A flight quality PPU is integrated in a dummy thruster that can be heated and provides the same grounding scheme as flight thruster (Figure 11). The main discharge is ran through resistive loads. We believe that this is representative of flight conditions as FEEP thrusters do not produce a significant plasma cloud which can have impacts on electromagnetic behavior of the system in flight.

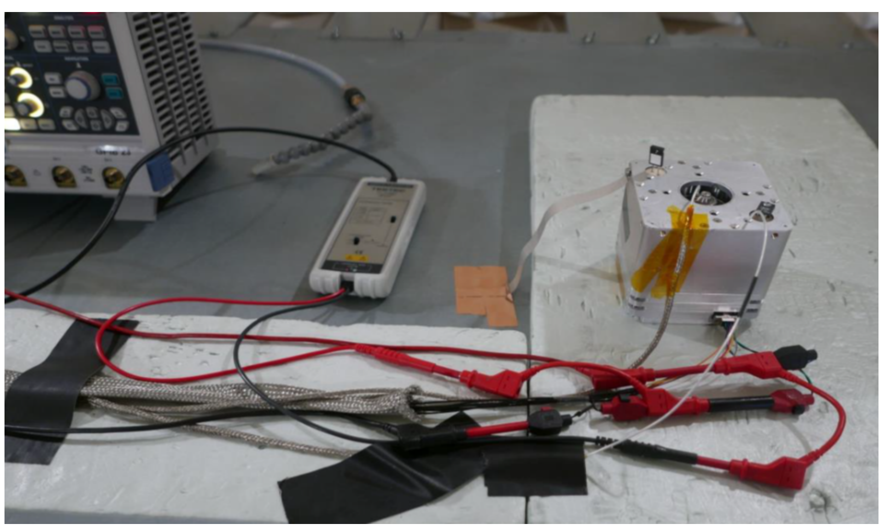

Fig. 11 Test setup for EMC for the NANO R³ thruster. The PPU is mated to a dummy thruster model.

Tests included characterization of conducted and radiation emission as well as susceptibilities to conducted and radiated disturbances and ESD discharges. Overall, the test campaign proved successful where threshold limits were provided in the standard with but a minor violation at 75 kHz and related harmonics for the conducted emission part at full operational load.

F. Radiation testing

1. Total ionizing dose

Irradiation of several PPU DUTs was conducted in Q4 2021 at Seibersdorf Laboratories by means of a Cobalt-60 source to verify radiation tolerance against ionizing radiation (TID) following ESCC 22900. The PPUs were mounted in their frame but did not benefit from any shielding from the housing. The devices received a total dose of 307 Gy (30.7 krad), and all DUTs maintained the operating point until the end. While a drift in some electrical parameters could be observed, general functionality was unaffected by the total radiation dose.

2. Single event effects

Proton beam testing is scheduled for Summer 2022 to evaluate the SEE susceptibility of the PPU. EEE component selection was conducted with available heavy ion test information from customers and national space agencies to increase the overall resilience. Additionally, latch-up protections are implemented in the PPU design to prevent single-event effects to cause detrimental effects on the propulsion system.

V. Qualification Status - MICRO R³

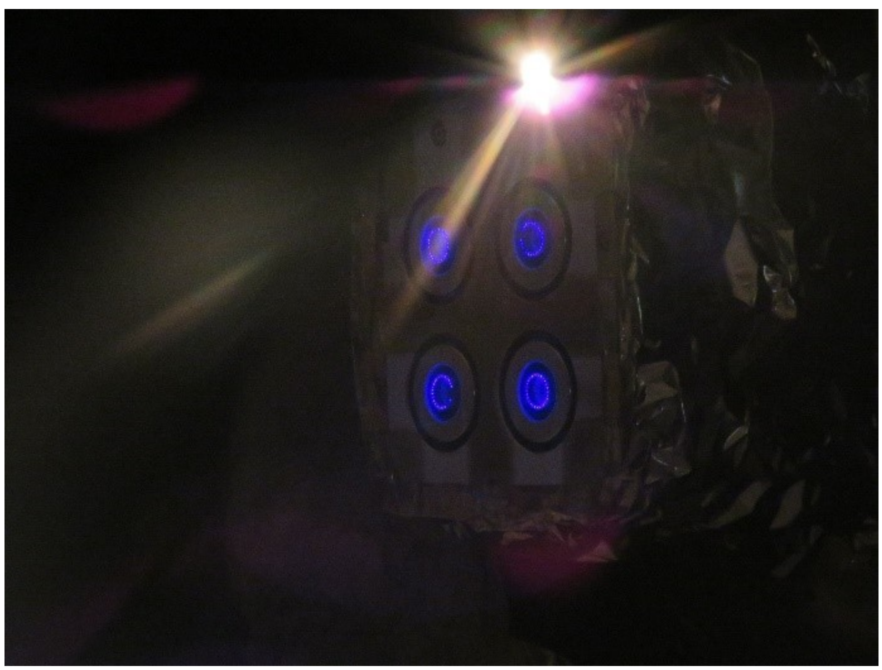

Fig. 12 MICRO R³ firing with full neutralization

A. Mechanical testing

The MICRO R³ thruster had undergone several rounds of mechanical testing on both EM and EQM level prior to QM qualification. The MICRO R³ QM was exposed to a series of mechanical loads on the vibration facility at FOTEC:

- 25 g sinusoidal vibration (less at low frequencies)
- 18.3 g_{RMS} random vibration (out-of-plane)

- 9.5 g_{RMS} random vibration (in plane)

Resonance sweeps before and after each test indicate that no significant shift in amplitude and frequency of the major modes has occurred (figure 13).

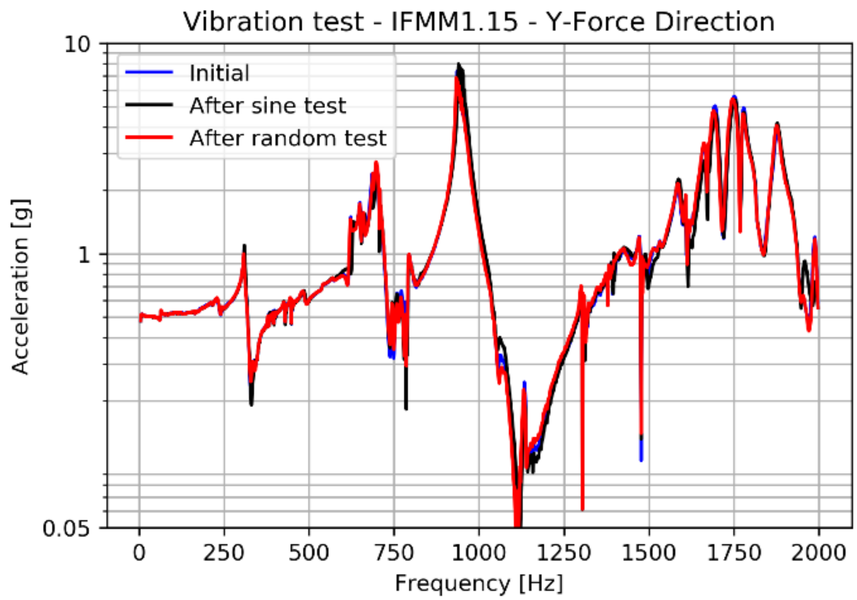

Fig. 13 Result of resonance sweeps for the MICRO R³ QM vibration testing

Shock testing has been performed on engineering model level and is planned in the summer 2022 for the qualification model. The same test profile as the NANO R³ will be used.

B. Thermal vacuum testing

At this time thermal vacuum testing of the MICRO R³ thruster has only been performed on acceptance level (see Figure 14. Typical test sequence follows what has been highlighted in section IV.C.

C. Electromagnetic compatibility

The same principle employed for the Nano and described in section IV.E were used (Figure 15). A dummy thruster was used to ensure that a representative grounding and shielding case was used.

Similarly to the NANO R³ EMC test a minor violation in conducted emissions was measured at 75 kHz at full operational load.

D. Radiation: total ionizing dose and single event effects

Full total ionizing dose (TID) test has not yet been conducted on the MICRO R³ electronics. A similar campaign is planned as the one done with the NANO R³ (see section IV.F). Both powered on and powered off PPU assemblies will be irradiated up to a 30 kRad total dose.

The formal single event upset campaign has not yet been conducted on the MICRO R³ . However some preliminary tests conducted with customers show no destructive events up to LETth of 35 MeV.cm²/mg. Upsets were recovered by either internal protection (hardware and software) or restarting the unit.

E. Thrust performance

While the formal direct thrust measurement of the qualification model has not been performed some preliminary testing was performed to assess the precision of the thrust model and the capacity of the thrust balance.

As with the NANO R³ thruster an additional correction factor was added to include effects of the divergence depending on exact extractor voltage used [9].

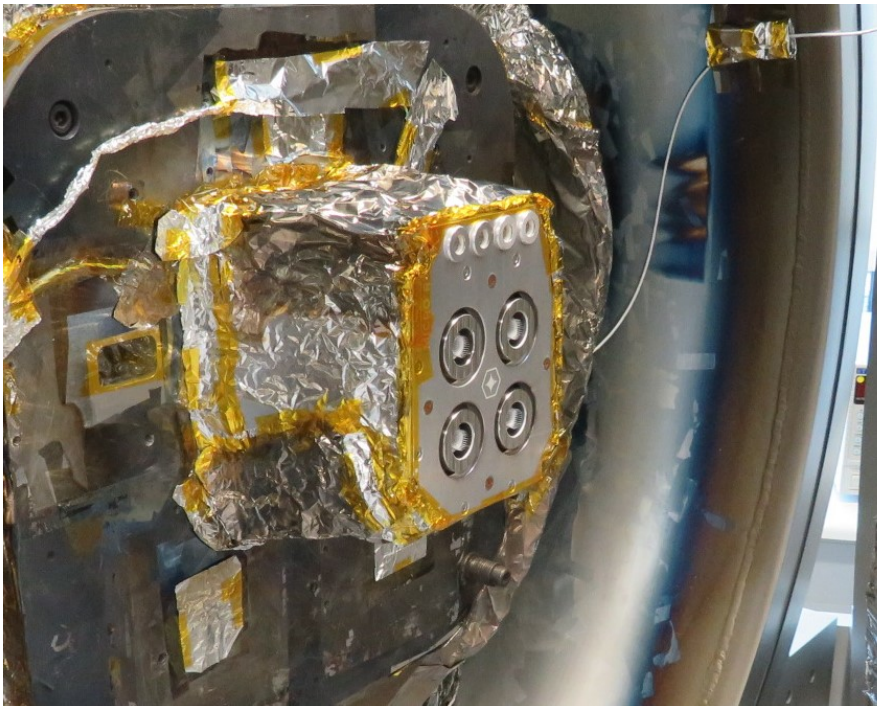

Fig. 14 MICRO R³ TVAC setup

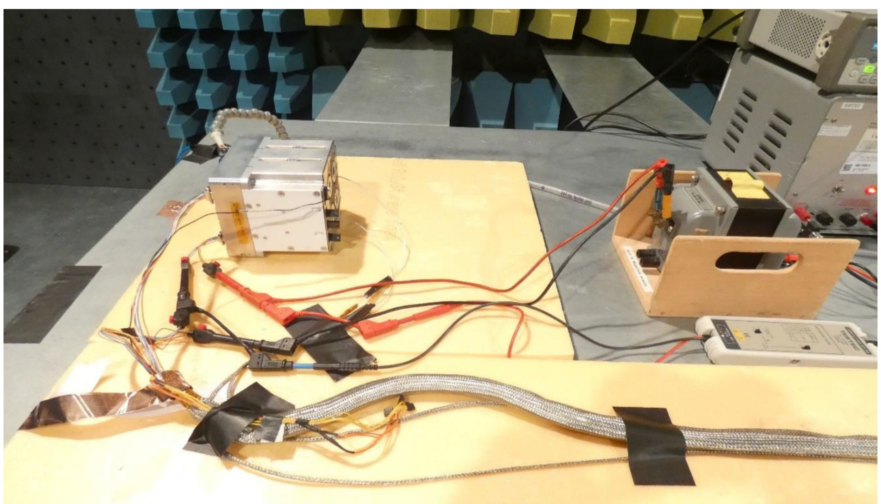

Fig. 15 MICRO R³ test setup for conducted susceptibility EMC test

The model was verified over wide range of thrust values from 0.3 to 1 mN on an engineering thruster. A MICRO R³ was fitted on the same thrust balance as IV.A with an adjusted counterweight. The thruster was operated in thrust control mode and the measure thrust from the balance was recorded synchronized with the telemetry. After ignition the thrust was commanded in steps of 2 minutes until 1.1 mN, whether or not this thrust was reachable at that specific Isp. The thrust was then ramped down.

A typical recording can be seen on figure 16. Due to the higher mass of the system a longer stabilization time is required and the measurement from the thrust stand tends to lag behind the telemetry.

The accuracy of both the controller and the model used to predict the thrust is excellent. As seen on figure 17 all points are within the 5% accuracy target on the envelope tested.

If we include the specific impulse model the operational map coverage see on figure 18 was achieved.

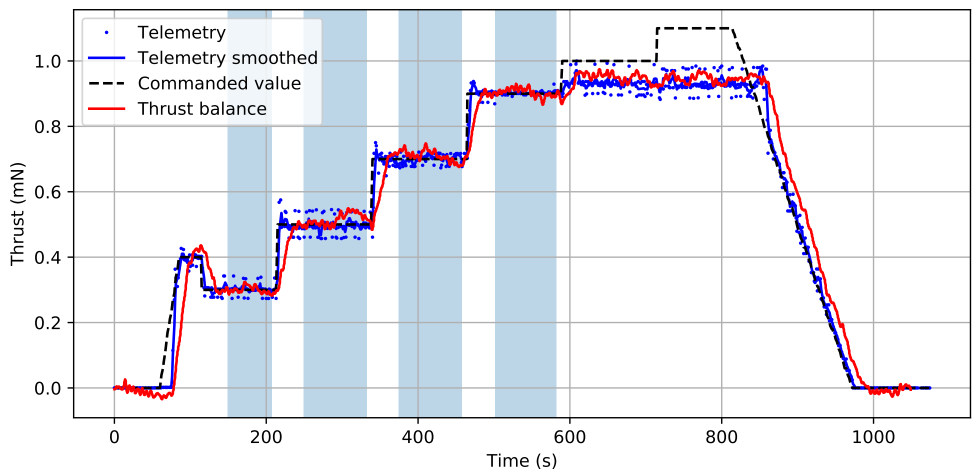

Fig. 16 Typical thrust response for thrust controlled firing at constant extractor voltage. This corresponds to -7 kV extractor voltage (approximately 3700s specific impulse). Highlighted areas show when the thrust balance is stable.

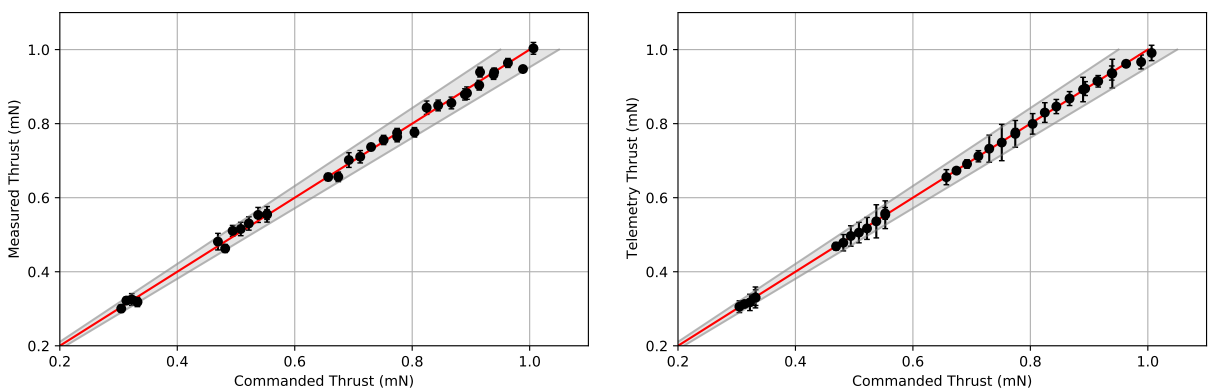

Fig. 17 Comparison of measured thrust (left) and calculated thrust (right) with commanded thrust, red line represents a 1 to 1 ratio, the grey area represents a 5% error envelope.

F. Endurance testing

Endurance testing of the MICRO R³ QM thruster has not been conducted yet and is scheduled for Q3 and Q4 2022. Some preliminary testing on engineering models have shown no degradation.

Since the geometry between extractor and emitter is the same as the NANO R³ , the extractor clogging model explained in IV.D is expected to be applicable. Similarly the same cleaning method should work.

In 2021 a MICRO R³ thruster was operated successfully for 240h hours in low earth orbit on board a customer spacecraft. During that time more than 150 firing arcs were performed.

VI. Outlook

The NANO R³ QM thruster still has to undergo endurance testing as well as final performance measurement. In parallel we are scheduling SEE for the electronics. Even though no erosion can be observed, extension of the endurance testing to full propellant depletion is also currently being considered. The SEE testing of the NANO R³ electronics is also schedule for the end of summer 2022.

The MICRO R³ QM thruster still has to go through shock testing, direct thrust measurement, thermal vacuum testing and endurance firing. However most of those tests have already been conducted on engineering models of the thruster.

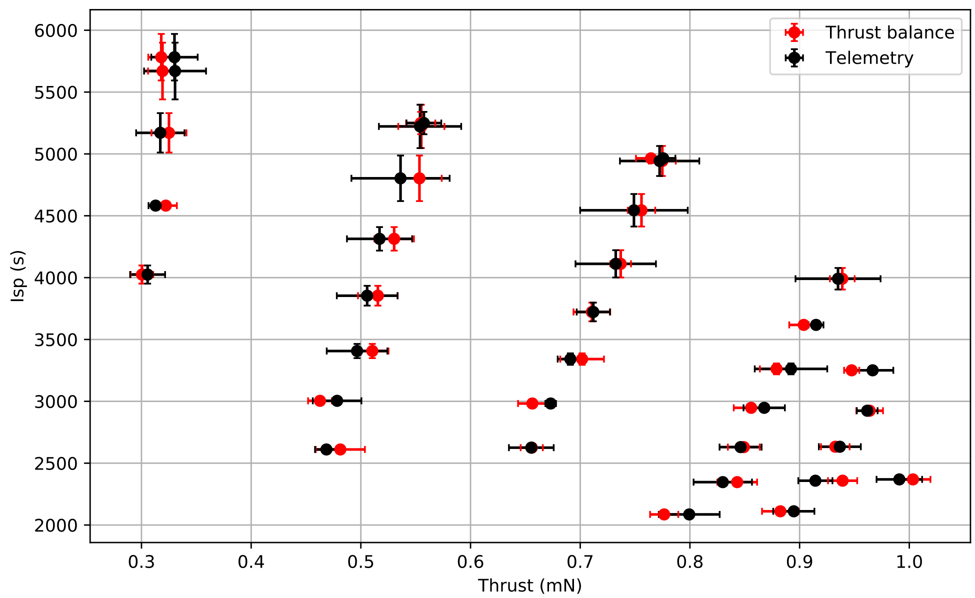

Fig. 18 Operational map showing difference between calculated and measured thrust for various calculated specific impulses. Specific impulse will depend on exact emitter selection.

TID and SEE tests have been postponed due to current EEE component shortage.

VII. Conclusion

Qualification of two FEEP propulsion systems – the NANO R³ and the MICRO R³ - is ongoing and advancing successfully. In parallel, Enpulsion is ramping up flight model production to serve commercial market demands with tens of modules already delivered to customers.

Acknowledgments

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