QUALIFICATION STATUS OF THE FIELD-EMISSION ELECTRIC PROPULSION (FEEP) SYSTEMS NANO R³ AND MICRO R³

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ABSTRACT:

Field-emission electric propulsion (FEEPs) as part of the electrostatic propulsion family are low-thrust, high-I_{sp} 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 Q1 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.

1. 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 thrust would be of need like LISA Pathfinder [4] or NGGM [5], but the fully integrated design 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. Resultingly, 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.

2. QUALIFICATION OUTLINE AND DUTs

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

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] or are tested as part of the qualification, e.g., neutralizer lifetime (standalone) and firmware validation.

2.1. NANO R³

The NANO R³ (Figure 1) is a 98.0 x 99.0 x 95.3 mm sized electric propulsion system including:

- Emitter and extractor for ion emission and acceleration based on field emission
- Neutralizers for charge balance
- 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

Figure 1: ENPULSION NANO R³

The NANO R³ weighs about 1.3 kg ‘wet’ and 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.

2.2. 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. Similar to the NANO R³, the MICRO R³ contains:

- 4 emitters with extractor ring
- Neutralizers for charge balance
- 4 reservoirs with indium propellant and heaters
- High-voltage and low-voltage electronics (in the PPU section)

Figure 2: ENPULSION MICRO R³ (stacked)

Resultingly, the ‘wet’ mass is about 3.9 kg including the PPU with 100 W needed for the nominal thrust of 1 mN. The MICRO R³ PPU requires 28 V input voltage and can be addressed by both RS422 and RS485.

3. QUALIFICATION STATUS – NANO R³

3.1. Qualification Models

Complete qualification models of the NANO R³ including electronics and neutralizers were built with flight-like hardware and EEE parts’ quality (Figure 3). The resulting units were inspected and acceptance-tested prior to their respective test campaigns.

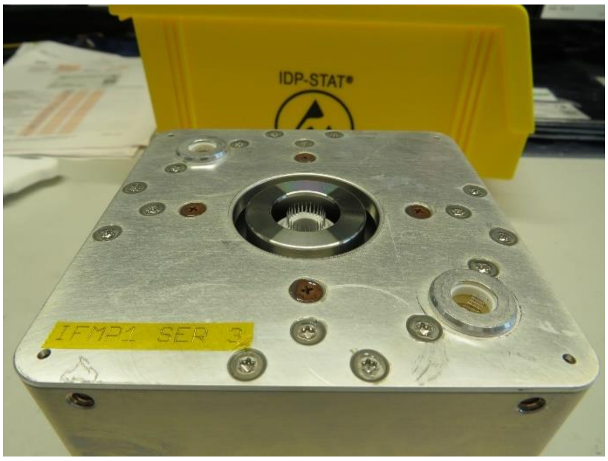

Figure 3: Qualification Model NANO R³

3.2. Thrust performance (indirect)

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
- 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

Figure 4: NANO R³ QM installed in performance test chamber at ENPULSION

3.3. Thrust performance (direct)

Thrust performance was directly evaluated with the QM on the thrust stand of FOTEC (Figure 5) that had been specifically upgraded to fulfil the testing needs [8]. Different operational setpoints were measured together with their telemetry readout to show a good fit between direct measurement signal and indirect telemetry (see Figure 6), which is explained in detail in [8].

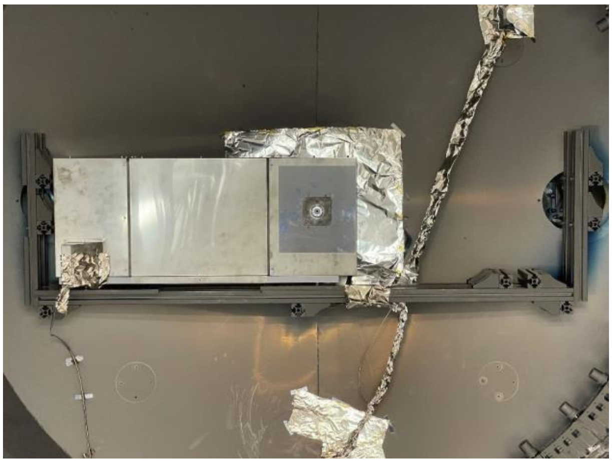

Figure 5: NANO R³ QM on thrust stand at FOTEC

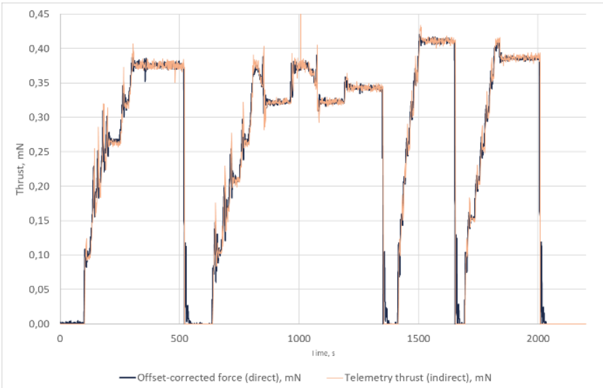

Figure 6: Comparison between directly measured thrust and thrust based on telemetry readback

3.4. 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)
- 24.8 g_{RMS} random vibration

The test sequence was conducted at the vibration facility of FOTEC and is shown in Figure 7.

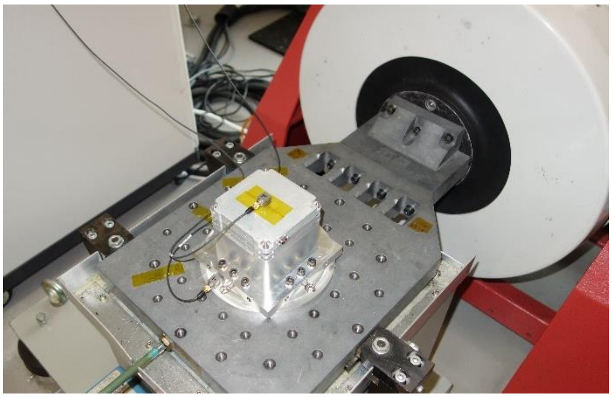

Figure 7: NANO R³ QM mounted on FOTEC shaker

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 8 shows exemplarily the resulting resonance sweep in-plane results indicating that no significant shift has happened.

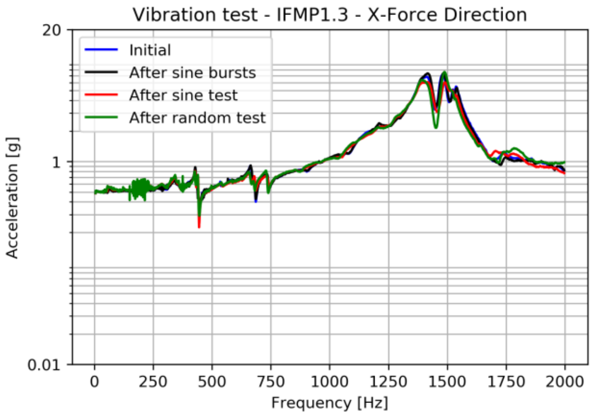

Figure 8: Resonance sweep results for vibration qualification of the NANO R³ QM

3.5. Shock

The QM was further exposed to shocks in all 3 axes by means of a pendulum hammer table at FOTEC (Figure 9) accompanied by resonance sweeps on the adjacent shaker (Figure 7) as well as electric ground test checks of the QM prior and posterior to the shock campaign.

Figure 9: Shock table with installed NANO R³ QM

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 (Figure 10). Ground test showed no loss in functionality or performance degradation across the shock test.

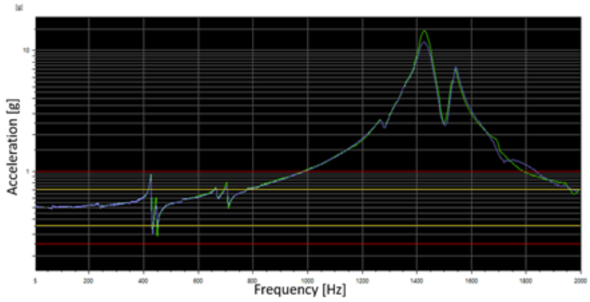

Figure 10: Resonance sweep results for X-axis (in-plane)

3.6. Thermal vacuum (TVAC)

The qualification model was installed into a vacuum facility at ENPULSION capable to control the TRP temperature at the thermal interface of the thruster between the cold (-30 °C) and hot (+45 °C) cases (Figure 11). A total of 7 ON-Cycles (Figure 12) 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

Figure 11: QM installed in TVAC chamber at ENPULSION

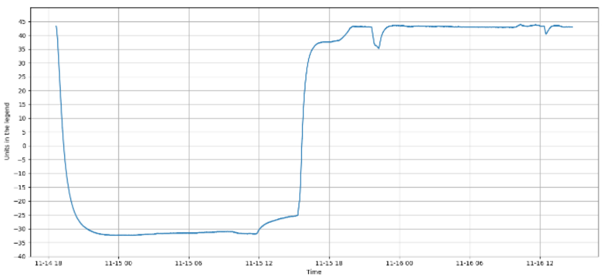

Figure 12: TRP temperature profile for one cycle; jumps in temperature related to change in operational status of thruster

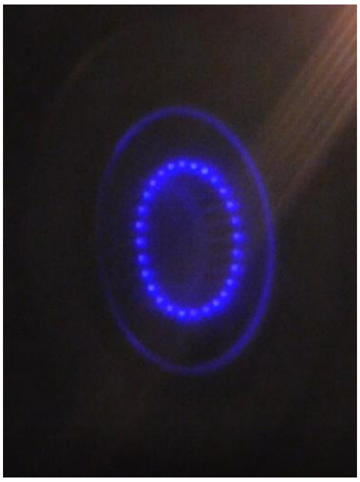

Figure 13: Emitter crown in firing operation; neutralizer operation indicated by light rays in top right corner

3.7. Endurance

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 1000 hr mark at time of writing.

3.8. TID

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 received a total dose of 307 Gy, 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.

3.9. EMC

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 on a PPU integrated in a dummy thruster specifically designed to enable high voltages for the operational load cases in ambient environment (Figure 14).

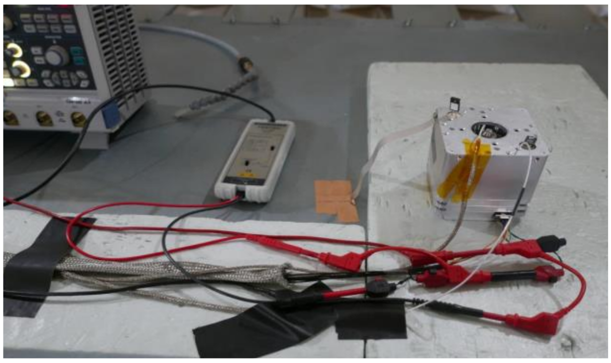

Figure 14: EMC test setup

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.

3.10. SEE

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.

4. QUALIFICATION STATUS – MICRO R³

4.1. Qualification Models

Similar to the NANO R³, complete qualification models of the MICRO R³ including stacked PPU boxes and neutralizers were built with flight-like hardware and EEE parts' quality (Figure 15). Inspections and acceptance testing was done equal to eventual FM production.

Figure 15: Qualification Model MICRO R³

4.2. Thrust performance (indirect)

The MICRO R³ QM was installed in the vacuum facility at ENPULSION and operated (Figure 16) to demonstrate successfully:

- Commissioning of all subsections
- Nominal thrust of 1 mN (indirectly based on telemetry readback)
- Repeatability for different thrust points
- Thrust vector offset within requirements
- Thrust steps
- Neutralization (evaluated by collector measurements)
- Power draws at different operational modes and points
- Commandability of various operational setpoints via embedded firmware

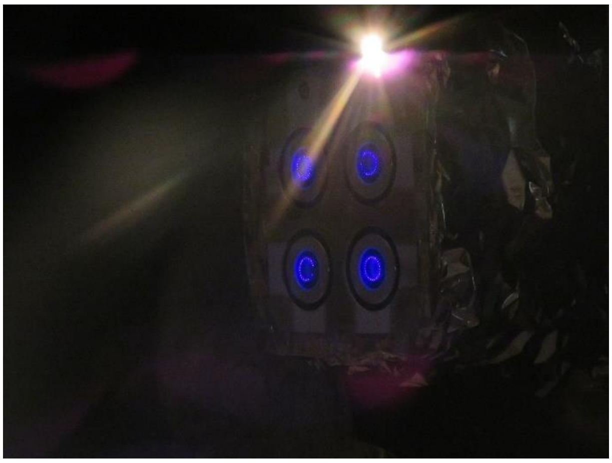

Figure 16: MICRO R³ QM in nominal operation

4.3. Vibration

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 17)

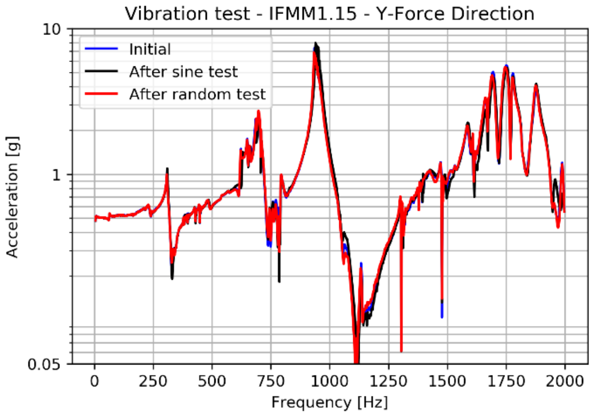

Figure 17: Resonance sweep comparisons across the vibration qualification campaign

4.4. EMC

Similar to the NANO R³ in Section 3.9, a PPU stack with a specifically designed MICRO R³ thruster head to allow for high-voltage loads in ambient environment was qualified at Seibersdorf Laboratories in Q1 2022 with the same series of tests according to ECSS standard. Equally, the overall test campaign proved successful with a minor violation at less than 500 kHz for the conducted emission part at full operational load.

4.5. Outlook

Further tests as listed in Section 2 are still pending at time of writing and are planned throughout 2022. Derisking tests on flight-similar engineering models for shock and direct thrust measurements were conducted to refine test setup and procedure prior to actual qualification.

5. CONCLUSION

Qualification of two FEEP propulsion systems – the NANO R³ and the MICRO R³ - is ongoing and advancing successfully.
Resultingly, flight model production at ENPULSION is ramping up to serve commercial market demands.

6. ACKNOWLEDGEMENTS

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