Performance Mapping and Qualification of the IFM Nano Thruster FM for in Orbit Demonstration

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Abstract: The Aerospace Department at FOTEC has been developing the mN-FEEP technology under ESA research contracts for the last decades with the purpose to create a highly controllable and efficient propulsion technology for future science missions. The mN-FEEP thrusters use a crown of sharpened porous Tungsten needles which are wetted with liquid Indium. This crown is raised to a high positive potential to emit and accelerate In^+ ions. This thruster technology has undergone extensive testing in recent years, including performance mapping of more than hundred emitters and lifetime testing up to more than 13.000 h. Based on this technology, the IFM Nano thruster has been developed as a commercial product for small satellites. This integrated ion propulsion system fits into a volume of less than a single unit CubeSat. In 2017, the first flight model has been manufactured to be flown on an in-orbit demonstration mission, supported by the ESA IOD program ATLAS. This paper presents the results from the extensive test campaigns on proto-flight model level, including efficiency mapping of all subsystems and the validation of the neutralization strategy. The results show that the IFM Nano thruster design is fully functional and provide an outlook on the performance to be expected during in-orbit operation.

Nomenclature

FEEP	=	Field Emission Electric Propulsion
IFM	=	Indium FEEP Multiemitter
mN-FEEP	=	FEEP with around 1 mN of thrust
LMIS	=	Liquid Metal Ion Source
IOD	=	In - Orbit Demonstration

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I.Introduction

THIS paper presents a review on the qualification and acceptance test campaigns of the IFM Nano thruster. The core of the propulsion system is a liquid metal ion source (LMIS) using a porous Tungsten crown which is supplied with Indium as propellant. The crown emitter consists of multiple sharpened porous needles and is raised to high potential so that the electric field at the tips is strong enough to trigger field emission of ions. The Aerospace Engineering Department at FOTEC has provided ion sources for more than 25 years for numerous space missions, such as the well-known ROSETTA mission conducted by ESA or NASA's Magnetospheric Multiscale Mission [1]. Using this ion source technology, FOTEC has developed a Field Emission Electric Propulsion (FEEP) system.

Based on a similar working principle, there are three major types of LMIS: the solid needle, the capillary and the porous emitter. Each of them have their distinct pros and cons. What they have in common, is that the propellant is fed to the tip by exploiting capillary forces which makes an active feeding mechanism dispensable. While the solid needle, whose surface is wetted with Indium, can be manufactured relatively easy, the thing film can tear which prevents the emission site from being replenished with Indium. In addition, the Indium has a large exposed surface that can form oxide layers which can also affect proper emission. Though the capillary emitter type handles the Indium inside, it is more complicated to manufacture and has a lower mass efficiency due to its comparatively large tip. A design that combines the advantages of solid and capillary emitters is the porous Tungsten emitter which can be infiltrates the propellant. Initially developed in Japan [2], FOTEC has further investigated this technology and developed a highly efficient process to produce a circular array of 28 such needle emitters [3] which forms the core of the Indium FEEP Multi-emitter (IFM) technology.

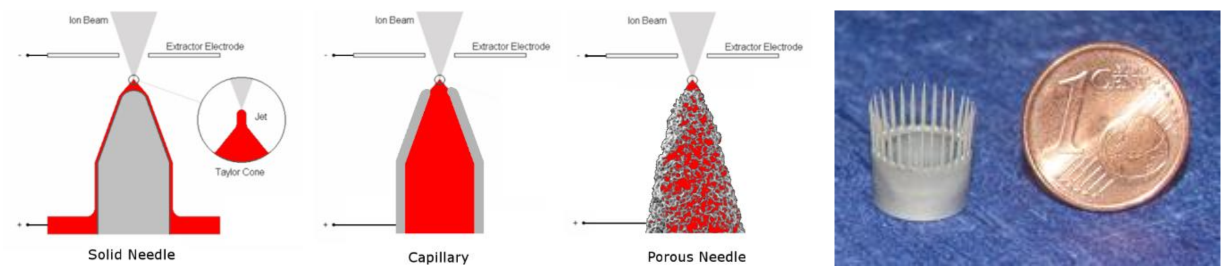

Figure 1: Different types of liquid metal ion sources (left) and the porous crown emitter (right).

More than 10 years of development efforts have resulted in a highly efficient ion source, which builds the foundation for the current success of the IFM thruster family. The most recent development is the IFM Nano thruster [4] , which features a porous crown emitter, all required power and control electronics and a thermionic neutralizer for charge compensation in less than one CubeSat unit of volume (Figure 2, left). If higher thrust levels or an increased total impulse are required, several of these thrusters can be clustered (Figure 2, right).

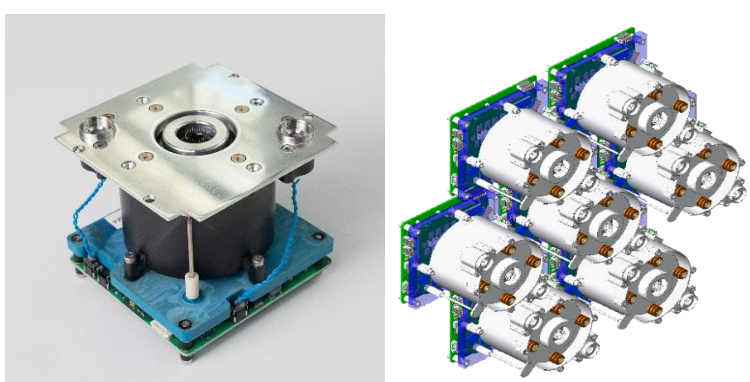

Figure 2: The IFM Nano thruster (left) and a cluster of individual thruster modules (right).

To meet the market demand for such a propulsion system, the spin-off company ENPULSION was founded. This company is focused on the commercialization and industrialization of the IFM technology and is ramping up facilities to produce hundreds of thruster modules per year.

The following section will cover the efficiency and power consumption of all sub-systems of the fully integrated thruster module. Chapters III and IV cover the results from recent test campaigns to validate operational characteristics regarding thrust generation and beam neutralization. These results are then concluded by the final section about the total system performance of the IFM Nano thruster.

II. Sub-system Overview

A major part of the IFM Nano thruster development was the design of an integrated power supply unit. For proper operation of the FEEP porous crown emitter it has to provide several controllable outputs [5]:

- Positive DC high voltage generation for the FEEP emitter: 0 to 10 kV, 0 to 4 mA
- Negative DC high voltage generation for the extractor electrode: 0 to -10 kV, 0 to -500 µA
- Positive DC low voltage generation for the propellant heater: 0 to 15 W
- AC low voltage generation for each of the two neutralizers: 0 to 5 W
- Negative high voltage biasing of both neutralizers: fixed to -200 V

The power supply is mostly based on COTS components to reduce development and production costs.

In order to map the power consumption and electrical efficiency of the listed sub-systems (see also Figure 3), these were operated separately while the entire thruster telemetry was read out via the RS-485 digital communication interface and logged during the test.

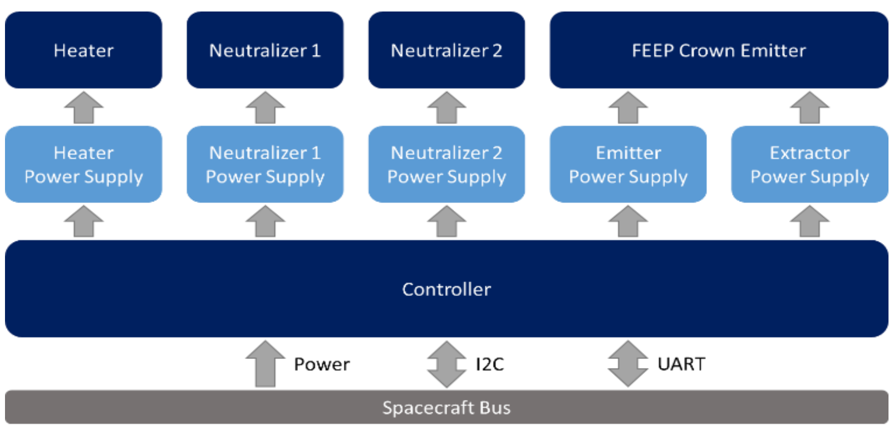

Figure 3: Sub-system overview of the IFM Nano thruster.

For ion emission, the Indium propellant must be kept considerably above its melting point of 156.6°C. Otherwise, there is a danger of preventing propellant feeding to the emission site which may lead to de-wetting of the needle tips and thus permanently damaging the emitter. Thus, the reservoir is kept at 170°C nominal operating temperature which is achieved by a powered ceramic heater disc attached to the bottom of the reservoir. The disc is enclosed by a ceramic insulator to prevent spark-overs to the emitter which is operated at high voltage. To keep the required reservoir temperature, the disc needs to be powered with 3 to 4 W.

To start field emission at the tips of the needles, a sufficiently strong electric field is required. The emitter electrode (porous crown) is therefore biased to a high positive potential of several kV. A ring-shaped electrode around the emitter, called the extractor, is biased negatively to further increase the generated electrostatic field. Since a fraction of the emitted ions is impacting on the extractor electrode and due to electric losses during high voltage generation, a certain power is required to maintain the electric potential (**Fehler! Verweisquelle konnte nicht gefunden werden.**, left). The electric losses of the emitter sub-system depend on the output voltage and power and range from 0 to 5 W (**Fehler! Verweisquelle konnte nicht gefunden werden.**, right).

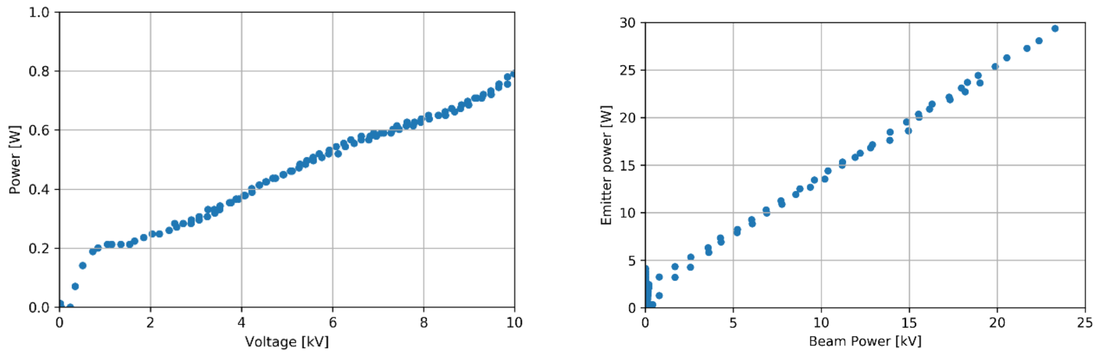

Figure 4: Extractor (left) and Emitter (right) power required to bias the high voltage electrodes

The neutralizer is biased and heated by two separate sections of the PPU. It starts emission at a heating power between 2.5 and 4 W, whereas the emitted current strongly depends on the cathode temperature and thus the heating power. The bias voltage of -200 V is required to repel the emitted electrons and to overcome the negative electrostatic field generated by the extractor electrode. The power consumption of the bias voltage supply is less than 1 W. The total system power of the neutralizer sub-system is typically 5 W.

III.Thruster floating test

The IFM Nano thruster emits positive ions at a high energy which would lead to an immediate charging of the spacecraft to negative voltage which would stop ion emission. In order to prevent this, the neutralizer cathode emits electrons that compensate the positive ion current. For validation of this concept, a setup was built where the thruster was kept at a floating voltage with respect to the chamber ground. To protect the module from high voltage charge-up, anti-parallel Zener diodes were used to limit the voltage difference to ground to ±240 V. During electron emission the thruster potential is limited by the electron bias voltage minus a certain energy penalty that the electrons lose due to inelastic interactions. The ions however, ejected at high kinetic energy levels of several keV, would charge up the thruster highly negative triggering the breakdown of the protection diodes. This consequently limits the thruster potential.

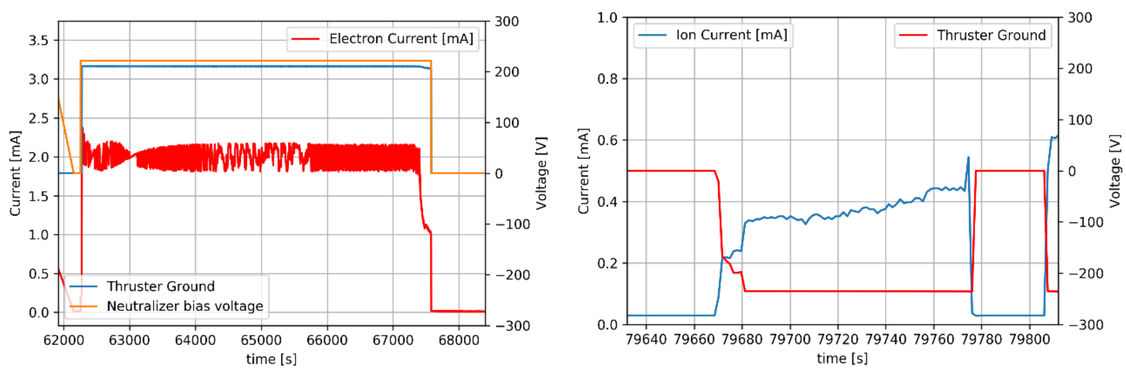

Figure 5: Thruster ground potential during electron emission (left) and ion emission (right).

When emitter and neutralizer are operated at the same time, the thruster potential shows fluctuations but remains between 0 and -100 V. This proved the concept of neutralizing the thruster with thermionic cathodes however the origin of the measured fluctuations still remain unclear, and will require further investigation.

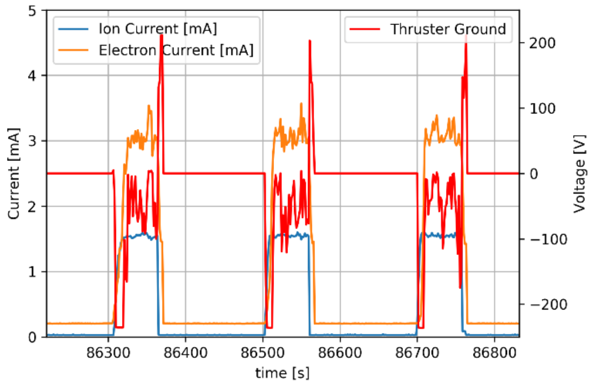

Figure 6: Thruster potential during operation with emitter and neutralizer for an ion current of 1.5 mA.

IV.Performance on System level

While the previous chapters have described the functionality and performance of the thrusters sub-systems, this chapter will focus on the overall system performance during nominal operation. This means that all sub-systems are operated in parallel. The heater maintains the reservoir at 170 °C, the extractor electrode is kept at a bias voltage between 2 and 10 kV, the neutralizer emits electrons and the crown emits an ion beam current of several mA. The herein presented tests were performed at FOTEC's high vacuum facilities at ambient pressure below 10^{-5} mbar. During all tests, the thruster was only connected to a supply voltage of 12 V and via the RS-485 digital communication interface to the computer. The propulsion module was thermally connected to the vacuum chamber. All tests were performed with the same hardware configuration as delivered for the first in-orbit demonstration mission.

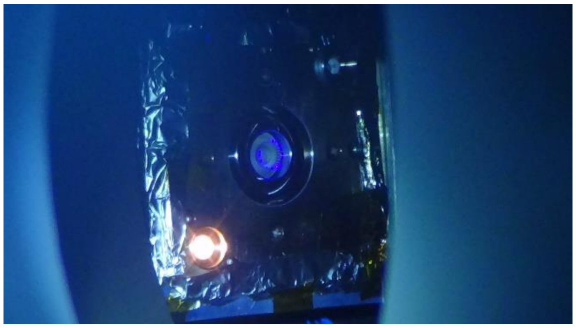

Figure 7: Picture taken during the IFM Nano thruster IOD acceptance test.

The thrust of a FEEP emitter can be calculated from the emitted ion current I and emitter voltage V and results in

$$F = I\sqrt{\frac{2Vm}{e}}\,f,$$

where m is the ion mass, e the elementary charge and f the thrust coefficient which was here assumed to be 0.85 [6]. A crucial characteristic of a field emission thruster is the emitted current as a function of the applied discharge voltage between emitter and extractor. To asses this, a so called "emitter characterization" is performed. This procedure consists of current sweeps ranging from 0 to 3 mA at various extractor voltages as shown in Figure 8. The theoretical background for the current-voltage characteristic was developed by Mair [7].

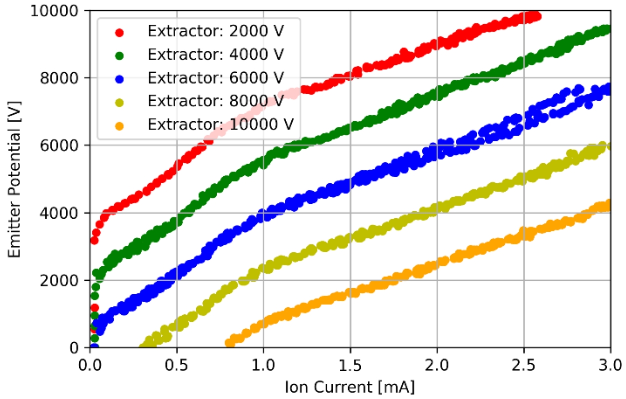

Figure 8: Emitter characterization.

To show that the thruster can operate under nominal conditions over the required thrust range, a test sequence was performed where thrust was commanded in steps of 50 µN up to the maximal thrust level of 350 µN. In the automatic mode, that was used, the firmware of the PPU automatically adjusts all necessary parameters to achieve the commanded thrust. The neutralizer current is controlled to remain above the emitter current to create a surplus of electrons for beam neutralization. The test was performed successfully without any failures. As the supply power was continuously monitored, the required system power at different thrust levels can be evaluated. At max. thrust of 350 µN the IFM Nano thruster drew 40 W. This corresponds to a power-to-thrust ratio of around 115 W/mN.

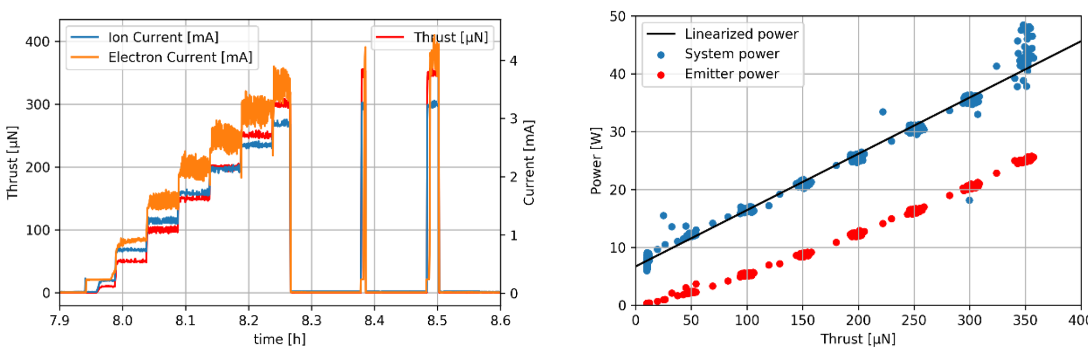

Figure 9: Thrust steps during the acceptance test to obtain the power-to-thrust relationship.

The power-to-thrust relationship was found to follow an almost linear relationship. To obtain an empirical expression for the power P, a linear regression was computed. Using $P = P_0 + C * T$, P_0 and C were found to be 6.69 and 0.097 respectively, with the thrust T in µN (Figure 9, right). Using an empirical model for the mass efficiency [8], the specific impulse can be calculated over the thrust range. With the specific impulse and the power-to-thrust ratio, also a total efficiency combining all sub-system efficiencies can be defined as $\frac{g\, I_{sp}}{2\, PTR}$. AT Figure 10 shows that the specific impulse remains between 3500 and 4000 s and the efficiency approaches to 15 % at higher thrust levels.

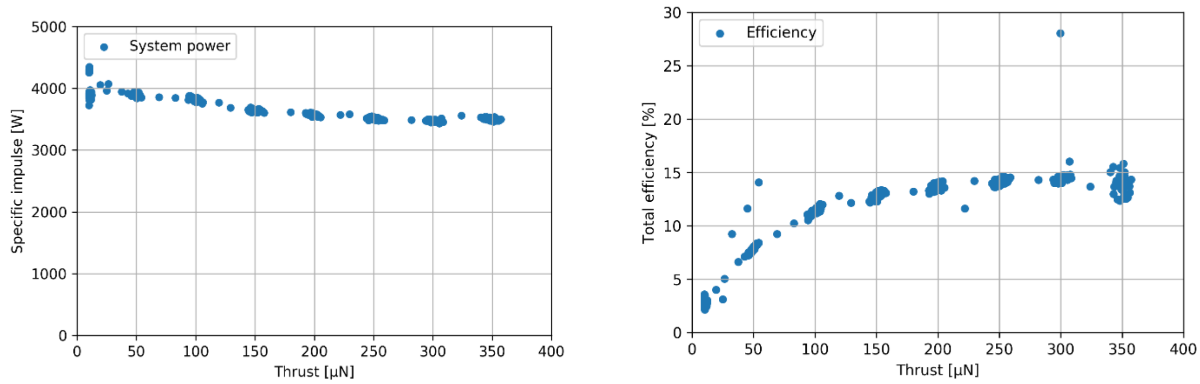

Figure 10: Specific impulse and total efficiency over the thrust range.

V.Conclusion & Outlook

This paper reports for the first time the results of a fully integration test of a FEEP thruster soon to be flown in orbit with all sub-system in operation under nominal performance. The tests verified the design and confirmed the expected efficiencies. The system power at 300 µN was found to be 35W. A significant finding was the result of the floating test, that validated the beam neutralization concept to prevent spacecraft charging. While the IFM Nano thruster uses the heritage of 25 years of emitter research and has reached a maturity that allows the first technology demonstration in space, the system has not yet been subjected to any optimization on mechanical and electrical level. Thus, the design leaves room for further improvements of the system regarding efficiencies and thruster performance. FOTEC continues to extend its product line-up with developments including an up-scaling of the PPU towards 60 W emitter power to achieve thrust levels of up to 700 µN with the same thruster design. In addition, a unit that allows purely electrostatic thrust vectoring without any moving parts will be manufactured in the next years. The production and commercialization of these developments via the spin-off company ENPULSION has the potential to leverage FEEP propulsion into becoming a disruptive technology for the small satellite propulsion market.

Acknowledgments

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