The IFM Nano Thruster - Introducing very high Δv Capabilities for Nanosats and Cubesats

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Abstract: Over the last decade, FOTEC has developed an electric propulsion thruster that can provide a continuous thrust range from 1µN to 1mN to be used for scientific formation flight missions. The core of this thruster is the 1cm porous tungsten crown emitter that can produce 1mN of thrust at a specific impulse of 5000 to 6000s. By removing the focus electrodes from this mN-FEEP thruster, it can be accommodated in a Volume of 10x10x6 cm or 0.6U Cubesat including all power electronics, without miniaturization of the thruster itself. This avoidance of miniaturization allows to directly translate all the heritage from the mN-FEEP thruster developments to this new application. The new IFM Nano Thruster is able to provide more than 5000 Ns of total impulse with 1kg wet mass and 1dm³ volume including thruster, propellant and power electronics. The thruster can be clustered easily and such a cluster of 7 thruster modules has been sold to a commercial customer for an on orbit demonstration in 2017,

I. Introduction

For several years, FOTEC has developed the mN-FEEP thruster to be used in future ESA missions [1]. This thruster can provide highly accurate thrust ranging from 1µN to above 1mN [2]. It will allow large satellites to control their position with an unprecedented accuracy enabling e.g. formation flight of scientific satellites [3]. In order to emit Ions at an Isp of up to 5000s at a dynamic thrust range from 1µN to 1mN, a so called crown emitter is used, that has been developed for the ESA NGGM mission [4]–[7]. This emitter was initially developed to enable fixed formation flight missions and therefore combines high throttablility with extreme accuracy.

As the need of a propulsion system for micro- and nano-satellites became an urgent matter, it has been realized, that the thrust level provided by this mN-FEEP thruster already allows to significantly increase the mission range of such satellites. The high Isp on the other hand allows for very high delta v manoeuvres at a high propellant mass utilization efficiency.

Keeping the emitter as it has been developed for the NGGM mission, the housing of the thruster has been re-designed in order to fit into a CubeSat structure. In parallel, a PPU has been developed and integrated into the thruster module. The result of this redesign is the new IFM Nano thruster family with the particular advantage that no miniaturization of the thruster itself was necessary. It can therefore build on an extensive development history that has started long before the present application has emerged. The result is a highly performant compact thruster module, that includes the whole subsystem from the thruster and PPU to the propellant and neutralizer in 1dm³ and less than 1kg.

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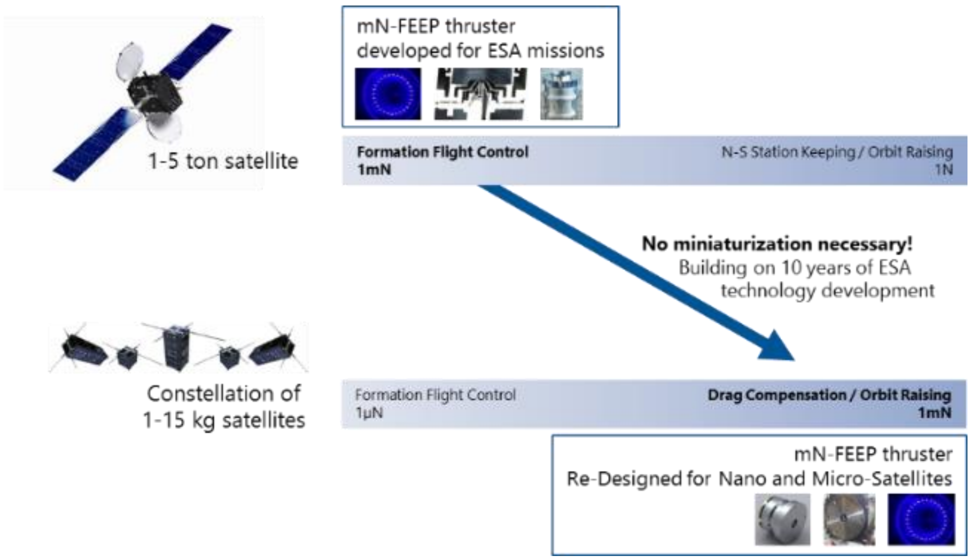


Figure 1 Evolution of the IFM Nano thruster from the mN-FEEP thruster developed for ESA

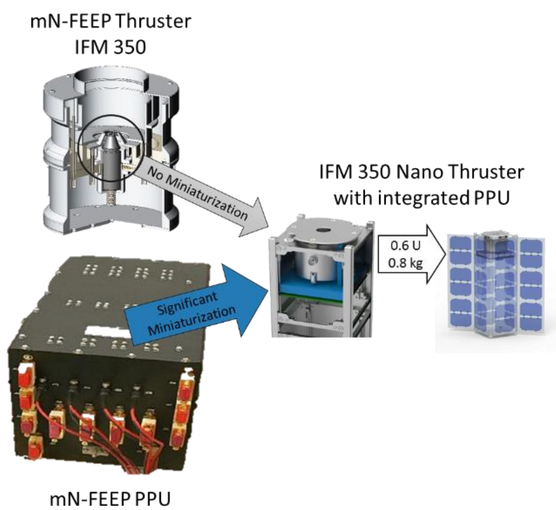


Figure 2 Development of the IFM Nano thruster from existing technology

II. Emitter Technology

The core of the mN-FEEP thruster is the porous tungsten crown emitter. It has been developed for the ESA NGGM Mission and tested extensively[2], [4]–[7]. This so-called porous tungsten crown emitter employs 28 needles for field emission and is thus termed multi-FEEP emitter.

Following the optimization of its manufacturing process, the performance of a large number of emitter has been tested extensively. In an ongoing lifetime test, it has been demonstrated that the performance of the thruster (e.g. mass efficiency, ISp) does not degrade over 10.000 h.

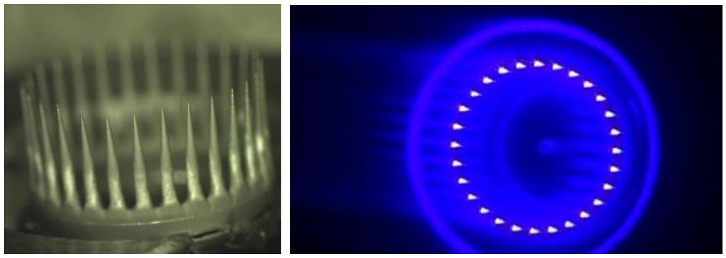


Figure 3 Porous tungsten crown emitter, capable of generating thrust from µN to mN. The crown has a diameter of 10mm.

III. Thruster Design Concept

Figure 4 shows the modular design concept of the IFM Nano Thruster. Each module includes the emitter itself, the propellant with its heater, all high voltage electronics, the power processing unit and a two redundant neutralizers. As the thruster uses Indium as propellant, the propellant is solid at room temperature. Only in orbit, the propellant is heated above its melting point and becomes liquid. Avoiding any liquid and reactive propellants as well as pressurized tanks during integration and launch significantly simplifies all corresponding procedures. Electrical interfaces between the IFM Nano thruster module and the spacecraft are reduced to a low voltage (12V) power line and a digital control line.

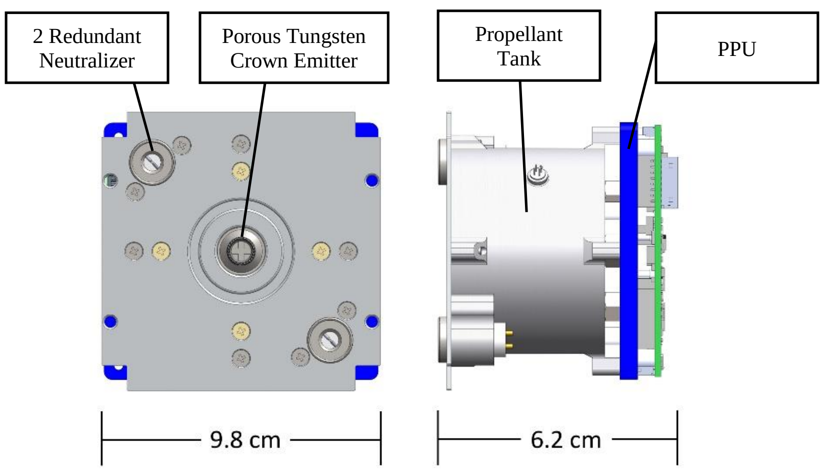


Figure 4 Highly integrated design concept of the IFM Nano thruster family

IV. Power Electronics

For proper operation of the FEEP emitter in the IFM Nano thruster, the integrated power supply has to provide several controllable outputs:

- High voltage for the FEEP emitter: up to 10 kV, up to 3 mA
- High voltage for the extractor electrode: up to -10 kV, up to -300 µA
- Low voltage for the propellant heater: up to 5 W
- Low voltage for the neutralizers: two times up to 3 W

The common input voltage to the FEEP power supply is 12 V which has to be provided by the spacecraft power sourcing unit (PSU). The given voltage and current figures are maximum values which are only reached at maximum thrust levels. For lower thrust requirements or at lower Isp levels, these figures are lower.

The conversion efficiency is crucial for long-term operation since no active cooling means like heat pipes or levers can be implemented in the small size of the module. A Prototype power supply has been developed with a maximum total deliverable power of 40 W, at the final average efficiency of 85%, the total heat losses are therefore below 6 W. At the current development stage, the focus is laid on optimizations regarding reliability and efficiency.

In order to keep the input-to-output ratio of both high voltage sections for the emitter and extractor as low as possible, a highly efficient PWM (Pulse Width Modulation) controlled, fixed frequency, full-bridge topology was chosen. The bridge voltage is 12 V and the optimum switching frequency in the present configuration is around 40 kHz. Commercial CCFL (cold cathode fluorescent lamp) small-size transformers are being utilized to generate output voltages of up to 1300 V, a Villard circuit based diode-capacitor multiplier is then utilized to generate the desired output voltage of up to 10 kV for the emitter and up to -10 kV for the extractor respectively. In Figure 5 the PCB of the power supply is shown, whereas the voltage multiplier is embedded into a separately potted container (not visible in the picture).

Both, the emitter and the extractor can be individually operated in current- or voltage control mode. For nominal operation the extractor is put at a fixed potential and the emitter is current controlled to achieve the required thrust. The generated thrust is internally estimated and a feed-back loop controls the power supplies to maintain the commanded thrust.

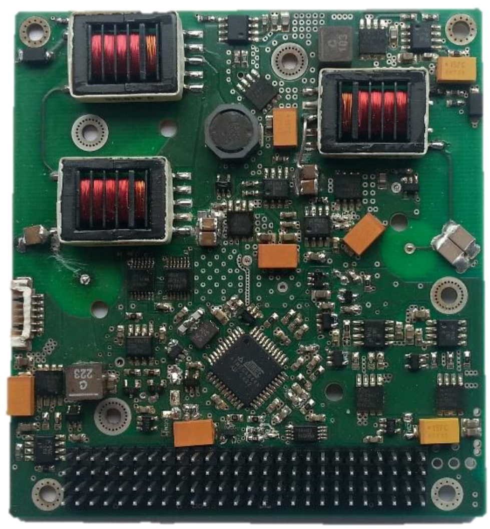


Figure 5 Prototype of FEEP power suitable for standard CubeSat bus.

The heater power supply, used to melt the propellant, uses a half-bridge topology with attached LC-filtering to maintain highest efficiency. The heater itself is either a resistance wire or an encapsulated high-temperature resistor. During hot-standby the heater has to keep the propellant liquid, that the thruster can be enabled without additional delay. If the heater is disabled, the propellant reservoir cools down to ambient temperature and it takes up to 30 minutes to heat up the reservoir again before the thruster itself can be re-enabled.

Since ions are expelled at a total current of up to 3 mA, the FEEP thruster needs means to balance spacecraft charging. This is achieved by the use of redundant electron sources acting as neutralizers. Such an electron source consists of a Tantalum disc which is heated up to 2200 K and the electrons are automatically expelled when the spacecraft is negatively charged. The power supply is able to measure this charge balancing current and it can automatically disable the heating of the neutralizers if the spacecraft is neutral again.

The power supply can be interfaced via I2C (3.3 V) or UART (3.3 V). In addition to the 12 V power supply, it requires 3.3 V supply for the digital control and communication circuitry.

V. Prototype Testing

Two generations of prototypes of the IFM Nano thruster have been manufactured and tested. Integration in an ISIS CubeSat structure has been demonstrated and the performance of the module has been evaluated by direct thrust measurements. These measurements have been conducted on a µN thrust balance that has been developed at FOTEC and verified at the ESA Propulsion Laboratory in 2014 [8]. For more details see IEPC2015-258

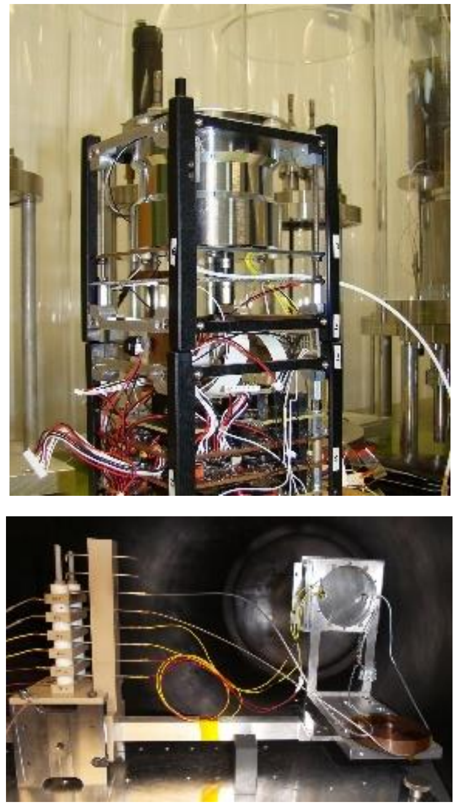


Figure 6 top: IFM Nano thruster integrated in an ISIS Cubesat Structure, bottom: IFM Nano thruster on the FOTEC µN thrust balance

Tests verified, that the IFM Nano is a very flexible thruster, which can operate at an Isp range of 2000s to 5000s. At any given thrust point, higher Isp operation will increase the total impulse while it will also increase the power demand. The thruster can be operated along the full dynamic range throughout a mission. That means, that high Isp and low Isp maneuvers can be included in a mission planning, as well as high thrust orbit maneuver and low thrust precision control maneuvers for formation flight.

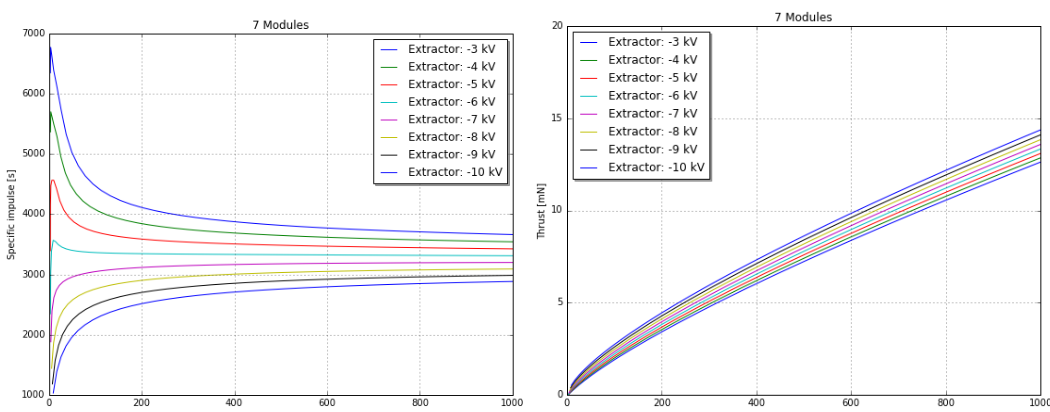
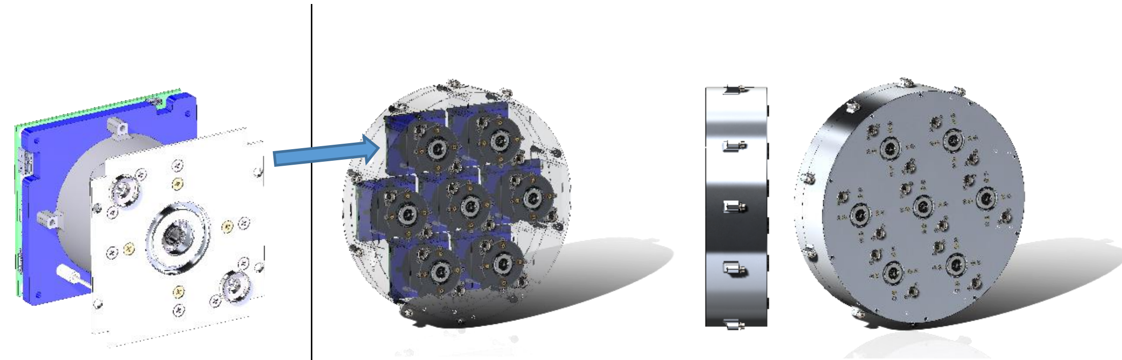


Figure 7 Performance figures of the IFM Nano Thruster

VI. Applications

The power demand of the IFM Nano thruster family starts around 9W for 120µN. It has already been demonstrated, that this can be reduced to 5W, if propellant heating and thruster firing are not operated continuously, but alternating at a frequency of 0.01Hz or higher. Nevertheless, the main advantage of the Indium FEEP technology in general lies in the very high achievable specific impulse, as well as the usage of liquid indium as a propellant. By using capillary forces to feed the propellant to the emitter, it is not necessary to accommodate any propellant feeding system. Also, the propellant is solid and inert during launch, which allows for very lightweight propellant tank designs. Making use of these advantages, allows to achieve a thruster that can provide at least 5000Ns total impulse with one individual module. In micro-satellites, several modules can be clustered as well, as shown in Figure 8.



IFM Nano Thruster
for Cubesats

Cluster of 7 IFM Nano Thruster
to fit inside a 15 inch separation mechanism of a 200W Spacecraft.

Figure 8 Example configurations of the IFM Nano thruster module.

Figure 9 shows two sample configurations of the IFM Nano thruster. Note, that the full range of each of the parameters can be exploited independent of the others. It is for example possible to configure the module with a large tank size providing >5000Ns total impulse even for a CubeSat with <10W power.

	Full Range	**Individual Module**		**7 Modules**	
		High Thrust Operation	High Isp Operation	High Thrust Operation	High Isp Operation
Thrust	1 µN – 1 mN	340 µN	220 µN	2.4 mN	1.5 mN
ISP	2000 - 4500 s	3000 s	4500 s	3000 s	4500 s
Tank Sizes	10 - 250 g	250 g		1750 g	
Total Impulse**	up to 10,000 Ns	3680 Ns	5520 Ns	25 760 Ns	38 640 Ns
Power Demand	2.5 - 80 W	32 W (28 W**)		224 W (196 W**)	
Outside Dimension	0.6 - 1 dm³	10 x 10 x 10 cm		∅30 x 10 cm	
Dry mass		700g			
System Efficiency		85%	*** For pulsed mode with extended duty cycle		
Demonstrated lifetime of the emitter		8700 h			

Figure 9 Sample Configurations of the IFM Nano Thruster. Note, that the tank size and therefore total impulse can be chosen independently of the available power.

A large number of mission studies has been conducted in order to evaluate the potential of the new thruster. The following list gives a brief overview of mission scenarios that could benefit from this technology.

Orbit life extension:

The high total impulse and high delta v allows for highly efficient drag compensation, especially in low altitude orbits that utilize increased resolution for earth remote sensing such as imaging applications. This results in the possibility to extend the mission duration of CubeSats to several years. For example, the lifetime of a 3U Cubesat in 350km Orbit could be extended to more than 5 years, potentially reducing significantly the maintenance cost of constellations.

Orbit raising:

The possibility of having a high delta v budget available on a small satellites allows for significant orbit manoeuvres. A variety of use cases can be studied, starting from CubeSats reaching MTO from GTO. A 15kg satellite with 20W available power could for example perform a 200m/s orbit manoeuvre within 8 weeks commissioning phase. A 70kg satellite with 120W available power could perform a 1000m/s orbit maneuver (either orbit raising or inclination change) within 4 month.

Formation flying and constellation control:

When developing the mN-FEEP thruster for ESA, the main focus was on enabling formation flight. The thruster therefore is especially suitable for e.g. controlling inter-satellite distances in the orbital plane. The reason for this lies in the extreme precision in the thrust throtability.

Highly efficient deorbiting:

In situations where passive deorbiting is not sufficient, the IFM Nano thruster could efficiently deorbit a small satellite from a higher orbit to comply with international Space-Debris Regulations or perform an EOL maneuver putting it in a graveyard orbit.

VII. Conclusion

Using the heritage from the development of the mN-FEEP thruster for ESA missions, a new thruster family has been designed and tested. The IFM Nano thruster uses the emitter technology without the need for miniaturization, while a completely new power supply had to be developed in order to provide a thruster of less than 1cm2 volume and 1kg mass. This envelope includes the whole subsystem (propellant system, thruster and PPU). A first commercial sale will demonstrate the thruster in orbit in 2017.

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