The IFM Micro FEEP thruster: a modular design for smallsat propulsion

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The IFM Micro 100 Thruster is the next evolution in ENPULSION’s indium fed field effect electric propulsion system line. Building upon the technological heritage of FOTEC’s emitter and the flight experience of the IFM Nano Thruster the IFM Micro 100 Thruster is built has a 100 W all in one propulsion module. Taking advantage of the flexibility of the FEEP technology it can provide between 0.05 and 1.5 mN of thrust at specific impulses of 1500 to 4500 s. The module contains 1.3 kg of indium which results in a total impulse of available of up to 50 kN.s. The design of the IFM Micro 100 Thruster is presented. Initial results from engineering model present good agreement between expected emitter behavior and measured one. With its unprecedented impulse density the IFM Micro 100 Thruster enable various missions at minimal integration cost.

Nomenclature

e = Electron charge
\eta = Mass efficiency
f = Beam thrust efficiency
I_c = Critical current
I_{em} = Emitter current
I_{sp} = Specific impulse
M_i = Mass of the ion
T = Thrust
V_{em} = Emitter voltage

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I. Introduction

Electric propulsion systems are real mission enabler for small (≤ 300 kg) satellites. They allow for attitude control, orbit change, drag compensation and end of life management in small and lightweight packages especially adapted to those smaller spacecraft. However those small satellites are often severely power limited. Available power range from a few tens of watts in cubesats to a few hundred watts in larger smallsat. Historically very few mature electric propulsion systems have existed in that power range and today multiple different technology compete in that space.

II. FEEP

A. Physical principle

FEEPs are ion emitters based on field enhancement at the tip of very sharp needles. The needle, coated with some liquid metal, is polarized to high voltage relative to an extractor electrode. The large electric field enhanced by the needle sharpness is enough to ionize the metal propellant and accelerate the ions to high speed. The ions created are mono-charged.

The emission current is dependent on the electric field strength and thus the potential difference between the two electrodes. However the ion velocity far from the thruster is only dependent on the ion emitter potential. This means that the thrust and Isp depend mainly on the emitter electrical parameters. They are expressed as:

\[ T = \sqrt{2 \cdot \frac{M_i \cdot V_{em}}{e} \cdot f \cdot I_{em}} \]  
\[ I_{sp} = \sqrt{2 \cdot \frac{e \cdot V_{em}}{M_i} \cdot f \cdot \eta(I_{em})} \]  

With \( V_{em} \) and \( I_{em} \) respectively the emitter potential (with respect to the spacecraft’s chassis ground) and current. \( M_i \) is the ion mass and \( e \) the elementary charge. The factor \( f \) covers ion optics effects such as beam divergence and ion colliding with the extractor electrode. It has been measured experimentally to be more or less constant over typical operation range.\(^2\) Finally \( \eta(I_{em}) \) is the so-called mass efficiency of the emitter.

This mass efficiency accounts for the fact that at higher current, the fluid Taylor cone at the tip of the needle is oscillating and tends to shed propellant droplets. Those droplets have a very poor charge to mass ratio and are ejected at a slow speed. This represents propellant not used to produce thrust and thus lower the effective specific impulse.

This propellant utilization efficiency at high current can be approximated with the following model for single needles:\(^3\)

\[ \eta = \begin{cases} 
1 & \text{for } I_{em} \leq I_c \\
\left( \frac{I_{em}}{I_c} \right)^{\alpha} & \text{for } I_{em} \geq I_c 
\end{cases} \]  

With the critical current \( I_c \) and the fitting exponent \( \alpha \) being dependent on the propellant used as well as the needle geometry. \( \alpha \) is negative to account for the fact that the ratio of droplets to ion increase with the current.

Considering these behaviors and the fact that critical current is in the order of 100µA and the impedance of each needle several tens of megaohms,\(^1\) it is apparent that in order to reach large thrust values at reasonable Isp, a number of needles needs to be fired simultaneously. The emission current can then be divided between different needles which keeps the efficiency high.
B. Scaling to higher power

1. IFM Nano Thruster

The IFM Nano thruster was developed by FOTEC as part of a ESA funded project to reach unprecedented level of thrust density for a FEEP. Previous FEEP thrusters paired each emitters with its own extractor electrode. However a high voltage insulation gap of several millimeters is required between each those two electrodes to ensure that insulation is maintained up to tens of kilovolts. This means that the density of emission site is very low (around 1.5 to 2 needles per cm$^3$). The basic principle of the IFM Nano Thruster emitter is to group the emission sites. The simplest geometry that achieve an homogeneous electric field is to distribute the needles evenly on a circle. The IFM Nano Thruster is based around this 28 needle “crown” which achieves a 6 time increase in packing density over single needle emitters.

![Performance map for a 28 needle crown emitter in the IFM Nano Thruster. The color map represents the beam power, the blue lines the emitter voltage and the red line the emitter current.](image)

Figure 1. Performance map for a 28 needle crown emitter in the IFM Nano Thruster. The color map represents the beam power, the blue lines the emitter voltage and the red line the emitter current.

From the model highlighted in section A an expected performance map can be established for given set of electrical parameters for such a 28 needle crown emitter.13 The result is an emitter operational map as presented in Figure 1. Those do not include system level losses.

No plasma stability concerns exist during operation. As a result the operating envelope is large compared to most other electric propulsion systems and is only limited by electronics and power processing unit (PPU) capabilities. Figure 2 highlights the various limits encountered in the current IFM Micro Thruster. FEEP emitters do not suffer from life limiting effects dependent on operating points. Operations for more than 10,000 hours have shown no significant degradation of the emitter.8 This means that no limitation in lifetime is observed if the thruster is operated in any of the points in the operating envelope and that operator are able to change operation points at will without concerns for thruster lifetime.

The various limits on the operating envelope are explained below.

1. **Emitter low voltage limit:** During operation if the emitter voltage is too low (typically below 2 kV) the beam is not focused anymore and divergence increase significantly. Operation below that voltage are not allowed
2. **Extractor low voltage limit:** In order to obtain the desired current for a given emitter voltage the extractor voltage has to be adjusted. At low Isp (ie low emitter voltage) the extractor potential reaches its limit of -10 kV in the current IFM Nano Thruster PPU. The exact position of this limit depends on the emitter impedance.

3. **Emitter current limit:** For practical reasons the emitter has a maximal allowable output current which constrain operation in the high thrust, low Isp range.

4. **Emitter power limit:** Maximum power delivered by the PPU for the emitter section.

5. **Emitter high voltage limit:** In order to reach high specific impulse the emitter voltage must be increased. Depending on emitter impedance, the high Isp operation can be limited by the voltage range of the emitter power supply.

6. **Extractor high voltage limit:** At high Isp the emitter voltage is high. In order to limit the emitter current the extractor voltage must be reduced. However the extractor is always kept below -2 kV in order to shield the emitter needles from electron bombardment from the neutralizer or environmental plasma sources. The exact position of this limit depends on the emitter impedance.

The ion emission system does not work in isolation and various efficiency factors and parasitic losses have to be considered at the system level. In the IFM Nano Thruster power is dissipated in the high voltage transformers, the neutralization system, the propellant temperature management system and the on board control system.

The resulting propulsion system is an extremely compact low power module. More than 5 kN.s are available in an “all-in-one” system including power processing unit (PPU), neutralization and control system. For an input power of up to 40 W the IFM Nano Thruster delivers more than 350 \( \mu N \) at 3000 s of specific impulse. By varying the electrode potential the thrust, input power, thrust and Isp can be adjusted to better fit the mission requirements.

The IFM Nano Thruster has flown on various spacecraft.\(^3,4\) As of summer 2019 over 100 flight units have been delivered to customers and 25 are operating in space.\(^10\)

### Figure 2. Envelope limits for a one crown 28 needle emitter

### III. IFM Micro Thruster design

#### A. Design goals

1 While the IFM Nano Thruster can be clustered to reach higher thrust values, Enpulsion identified a need for higher power, compact and easy to integrate propulsion module able to provide significantly more total impulse and reach higher thrust to power ratio.

The goal was to design a 100 W module that would be panel mounted with the minimal possible footprint containing at least 1.3 kg of propellant. Parts and manufacturing processes are shared as much as possible with the IFM Nano Thruster.
B. Thruster performances

1. Emitter operating envelope

In order to achieve higher efficiency and reasonable specific impulse at the higher thrust to power operating points, more emissions sites are needed. With more needles the discharge current per needle is lower and the needle operate at higher mass efficiency. The simplest solution is to re-use the same crown emitter as the IFM Nano Thruster and developed by FOTEC as part of the mN FEEP project for the past decade.\textsuperscript{12,13} Several hundreds of those have already been produced by Enpulsion. An assembly of 4 crown emitters is chosen and connected in parallel.

The resulting emitter operating envelope can be see in figure 4. As compared to a single crown (figure 1.) the 0.4 mN at 3000 s operating point can be reached with only about 16 W of beam power instead of 25 W. The emitter power has to be restricted to 70 W in order to account for inefficiencies and parasitic losses at the system level. With that maximum power a thrust of 1.7 mN can be reached at 1700 s of specific impulse. Any higher thrust would result in even lower specific impulses. At this point the emission current is 0.25 mA.

With 4 crowns in parallel the impedance is four times lower which helps with operation at lower emitter voltage and high power. This effect, coupled with an extended extractor voltage range helps remove the
extractor low voltage limit (labeled “3” on figure 2). High specific impulse operation points are also possible with up to 4800 s Isp for 0.95 mN of thrust. The emitter high voltage limit (labeled “5” on figure 2) is also not a concern with this lower impedance.

2. Experimental results on engineering model test campaigns

![Figure 5](image1.png)

**Figure 5.** Expected (dashed) and measured IV characteristics on the IFM Micro EM Thruster.

A functionally equivalent engineering model (EM) was designed and built by FOTEC. It underwent several test campaigns during the winter of 2018/2019. A first test was realized at FOTEC’s facility for electrical characterization of the thruster. Current sweeps at different extractor voltages were performed. Those sweeps, presented in figure 5, were used to verify the high voltage design and simultaneous operation of 4 emitters.

Another test campaign was conducted with a customer at an external facility. This test campaign included direct thrust measurements to verify that the performance model developed and validated for one emitter\(^2\) was accurate with 4 emitters. Good agreement was derived but regrettably the data cannot be reproduced here due to confidentiality agreements.

However from the points tested at FOTEC a first validated envelope can be derived. The tested points can be seen on figure 6. The high thrust, low Isp region was not reachable due to limitations of the extractor power supply used. However emitter power up to 80 W were successfully achieved.

![Figure 6](image2.png)

**Figure 6.** Experimentally tested operation points during FOTEC’s test campaign.

3. Impedance matching and induced moments

All the emitters do not exactly have the same behavior. Their onset voltage and impedance depend on the exact needle geometry. Even in a series, process controlled production a certain variance is expected
in needle sharpness. Moreover it is not rare that not all 28 needles fire. This is mitigated by meticulous quality screening and testing as well as minimum performance requirements for each emitters delivered to a customer.\textsuperscript{10}

One of the main questions during the IFM Micro development was the behavior of multiple emitters firing in parallel. The current was not expected to distribute evenly between the crowns which could lead to thrust offset, crown not firing and premature tank depletion.

During the manufacturing of the engineering model (EM) of the IFM Micro Thruster impedance matching was test. Out of a batch of 30 emitters, 4 different groups were formed. From their individual measured impedance the impedance of the total thruster was first predicted and then measured. Figure 7 shows 4 emitters firing at the same time on the IFM Micro EM Thruster. The predicted and measured impedance at different extractor voltage can be found on figure 5. The match between the two is excellent and as given us great confidence in the ability to predict thruster performance from individual emitter characteristics. Since every emitter is test fired individually before integration to a thruster, easy screening can be implemented.

The thrust of each of the emitter being slightly different will impart torque to the spacecraft around the nominal center of thrust of the module. Luckily this thrust can be quantified from individual performance data. This includes onset voltage characterization, impedance sweeps and thrust angle offset calculations, all performed during initial emitter firing.

The resulting forces are assessed at the geometric center of the emitters which is also the reference origin point of the thruster coordinate system. The exact torques depends on the operating point but is maximal at the maximum thrust. The results obtained at this point are given in table 1 for the IFM Micro EM Thruster. On this thruster the impedance mismatch is only responsible for a maximum torque of 1.8 mN.mm in the panel plane.

Even without dividing impedance matching the maximum worst case torque in the panel plane is less than 10 mN.mm (equivalent to a center of thrust offset of 6 mm). By placing high thrust emitters on diagonals and dividing the emitter production in 2 impedance group the torque can be limited to less than 5 mN.mm. Such a torque could easily be compensated with on board attitude control systems as it is comparable to gravity gradient induced torques in LEO, or solar pressure induced torques on meter scale sized spacecraft.\textsuperscript{14}

![Figure 7. 4 emitters firing in parallel in the IFM Micro EM Thruster.](image)

<table>
<thead>
<tr>
<th>Thrust emitter 1, 2, 3, 4 (mN)</th>
<th>(0.40, 0.43, 0.45, 0.43)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total thrust (mN)</td>
<td>1.70</td>
</tr>
<tr>
<td>Thrust vector offset (°)</td>
<td>3.3</td>
</tr>
<tr>
<td>Thrust component (Tx, Ty, Tz mN)</td>
<td>(0.03, 0.09, 1.70)</td>
</tr>
<tr>
<td>Moments (Mx, My, Mz mN.mm)</td>
<td>(-1.48, 1.09, 0.33)</td>
</tr>
</tbody>
</table>

### 4. System level performance

From the physical characteristics highlighted above the system performance can be calculated. This includes PPU efficiency considerations, neutralization power and steady state power required for propellant heating. The resulting operation map can be found in figure 8.

Accounting for system level losses the thruster can operate between 30 and 100 W with thrust levels from 0.2 to 1.7 mN and a specific impulse range of 1500 to 6000 s.
C. Thruster design

1. Mechanical design

With the desire to keep as many common parts between the IFM Nano and IFM Micro Thrusters, a lot of the subsystems were carried over. This includes the full propellant temperature measurement and heating system, the neutralizer holding mechanism as well as some of the high voltage insulation pieces. Approximately a quarter of the parts were reused.

One of the challenges of FEEP design is to mechanically secure the high voltage parts during launch while still providing adequate high voltage insulation and minimal thermal transfer. Fast iteration both through prototypes and simulation has allowed us to find a satisfying solution that meets the vibration and shock requirements for small satellites launches. Figure 9 highlights some of the modeling efforts that went into the design of the thruster. The resulting thruster has a maximum random vibration design value of more than 15 g_{rms}.

The basic concept of the IFM Micro Thruster is to have a self-contained module that includes tanks, thruster and neutralizer and that can easily be integrated with the spacecraft. The lack of bulky high pressure tanks means that no complex fluidics is required between an internal tank and outside thruster. The IFM Micro Thruster is designed as a panel mounted module which only requires 4 bolts and an electrical line to be connected. The goal is to offer a “15 minutes integration” capability to the spacecraft manufacturer.

Moreover with its rectangular shape it is easy to cluster in order to reach higher thrust, larger total impulse, and higher redundancy. A cluster of IFM Micro Thrusters also enable differential thrust capabilities and thrust vector control with no moving parts.

2. Thermal model

One of the advantages of using indium as a propellant is that it is a solid, non-toxic and chemically inert block of metal at launch. However once in orbit the propellant has to be liquefied in a heating phase that lasts...
1 to 2 hours depending on available power. Indium melting temperature is 156.6°C. Once at temperature the thruster is in a “hot standby” mode and can be fired at a moment notice (startup time less than 5 seconds). While there are not limits on the number of times the propellant can be solidified and liquefied, an attractive option for spacecraft operator is to keep the thruster in hot standby for extended periods of time. This provides greater operational flexibility for a small energy cost. However in order to enable this kind of operation particular care needs to be taken to ensure that minimal heat is required to keep the propellant hot.

The heating system consist of 4 individual heaters with a 1 failure tolerant architecture. Insulation is ensured by a double wall heat shield system that minimizes radiative transfer to the thruster housing.

On small spacecraft with limited heat rejection capabilities it is also important to minimize heat transfer from the propulsion module. Heating from the propulsion module can limit steady state operation as it triggers internal protection on the spacecraft. The IFM Micro housing is designed to be its own radiator by using white thermal paint which ensures that incoming solar radiation and internal heating is not transmitted to the panel and the rest of the spacecraft. Thermal simulations predict that adiabatic operation is expected for interface temperature of 40°C and less than 10 W rejected to the spacecraft for 0°C panel temperature.

In a cold standby or OFF mode the IFM Micro behaves as a radiator with high emissivity ($\geq 0.8$) and low absorbtivity ($\leq 0.2$).

### D. Power processing unit

Contrary to the IFM Nano Thruster the power processing unit (PPU) of the IFM Micro Thruster is not included in the propulsion module. This configuration allows for more flexibility in terms of PPU offer and integration.

Two main PPU will be offered for the IFM Micro Thruster. The first option is called “COTS+” and is based on the flight heritage of the IFM Nano Thruster PPU. This lower cost and smaller option is built with flight proven COTS components. Lot control and component radiation testing allow for certification of each individual unit to a given total ionizing dose (TID) radiation level at the component level. This PPU is also built to occupy the same footprint as the IFM Micro Thruster and has the option to be stacked between the thruster and the spacecraft panel, adding less than 50 nm to the thruster height and less than 1 kg of mass.

The other option is a high reliability option being developed by a legacy spacecraft electronic manufacturer. This PPU is dedicated to missions in more challenging environments where the radiation hardness cannot be compromised. With a design objective of more than 25 kRad at the component level, it is able to handle longer mission and higher orbits.
E. IFM Micro 100 Thruster overview

The resulting thruster is an extremely compact module. The high density of Indium (1.5× iodine, 4.5× high pressure xenon, 12× high pressure krypton) as well as large Isp range makes for one of the largest impulse density of any low power propulsion system. This is especially important in small satellites where volume is often a limiting factor. It also simplifies integration to the spacecraft as system engineers do not need to worry about tank integration. The thruster can be shipped fully fueled without any restrictions due to high pressure vessels.

The IFM Micro Thruster also features a 4 time cold redundant neutralization system which allow for extended lifetime even if the thruster is fired exclusively at high Isp.

<table>
<thead>
<tr>
<th>System power</th>
<th>30 to 100 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>0.1 to 1.6 mN</td>
</tr>
<tr>
<td>Specific impulse</td>
<td>1500 to 5000 s</td>
</tr>
<tr>
<td>Propellant mass</td>
<td>1.3 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>120×140×96 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>1.9 kg (dry) - 3.2 kg (wet)</td>
</tr>
</tbody>
</table>

IV. IFM Micro capabilities

The IFM Micro Thruster can enable high delta-V missions and new opportunities for small satellites. Its wide operating envelope allow for operating points optimized to mission requirements.

A. Case 1: 50 kg deployed from ISS to 1000 km and back

One of the advantage of the indium propellant is that is has no handling restrictions or safety concerns. This means that a spacecraft propelled with a IFM thruster can be deployed from the International Space Station (ISS) without requiring special waivers for its propulsion module.

In this scenario we assume a 50 kg wet mass spacecraft deployed from ISS at 420 km altitude powered by one IFM Micro Thruster and with a final orbit of 1000 km in the same plane. This mission also includes an End Of Life (EoL) maneuver aimed at bringing its mean altitude to less than 500 km to comply with space debris mitigation directives.

The delta-V cost of low thrust maneuvers is higher than with impulsive Hohmann transfers. An analytical model is used to compute the required delta-V for such a mission. This model assumes continuous firing in the optimal pointing vector at all time. While this strategy is simple it is far from the most efficient, perigee lowering to 250 km for faster reentry after the propulsive phase is also possible for similar delta-V cost but slightly longer active decommissioning time. The results are presented in table 3.
**Table 3. Case 1 example mission**

<table>
<thead>
<tr>
<th>Spacecraft wet mass</th>
<th>50 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion</td>
<td>1 IFM Micro Thruster</td>
</tr>
<tr>
<td>Orbit raising</td>
<td>Circular 420 km 51° to circular 1000 km 51°</td>
</tr>
<tr>
<td>Delta-V</td>
<td>308 m/s</td>
</tr>
<tr>
<td>Operation point</td>
<td>High thrust 1.6 mN 1900 s</td>
</tr>
<tr>
<td>Propellant consumed</td>
<td>0.83 kg</td>
</tr>
<tr>
<td>Maneuver duration</td>
<td>3.6 months</td>
</tr>
<tr>
<td>End of life</td>
<td>Circular 1000 km 51° to circular 500 km 51°</td>
</tr>
<tr>
<td>Delta-V</td>
<td>263 m/s</td>
</tr>
<tr>
<td>Operation point</td>
<td>High Isp 1 mN 4500 s</td>
</tr>
<tr>
<td>Propellant consumed</td>
<td>0.3 kg</td>
</tr>
<tr>
<td>Maneuver duration</td>
<td>5.1 months</td>
</tr>
</tbody>
</table>

**B. Case 2: 200 kg spacecraft deorbit from SSO**

Another interesting use case is deorbiting of more massive satellites in LEO. As regulations on debris mitigation become more strict, active deorbit will be expected for most commercial satellites. Taking for example a 200 kg spacecraft in Sun-Synchronous Orbit (SSO) at 575 km altitude with a 5 m² cross section. As simulated with GMAT¹ a single IFM Micro Thruster could deorbit it in approximately 160 days and less than 1 kg of propellant while operating at a moderate specific impulse of 2000 s. This leaves 300 g of propellant (up to 90 m/s) for stationkeeping, collision avoidance or any other maneuvers. The thruster can also simply be left in a cold unpowered state. Since it uses no pressurized tank or any other type of stored mechanical energy the risk of leaks or micro-impact related explosion is non-existent.

<table>
<thead>
<tr>
<th>Spacecraft wet mass</th>
<th>200 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion</td>
<td>1 IFM Micro Thruster</td>
</tr>
<tr>
<td>In orbit operations</td>
<td>Stationkeeping and debris avoidance</td>
</tr>
<tr>
<td>Delta-V</td>
<td>90 m/s</td>
</tr>
<tr>
<td>Operation point</td>
<td>High Isp 1 mN 4500 s</td>
</tr>
<tr>
<td>Propellant consumed</td>
<td>0.31 kg</td>
</tr>
<tr>
<td>End of life deorbit</td>
<td>Circular SSO 575 km 97.7° to reentry</td>
</tr>
<tr>
<td>Delta-V</td>
<td>93 m/s</td>
</tr>
<tr>
<td>Operation point</td>
<td>High thrust 1.5 mN 2000 s</td>
</tr>
<tr>
<td>Propellant consumed</td>
<td>0.95 kg</td>
</tr>
<tr>
<td>Maneuver duration</td>
<td>5.2 months</td>
</tr>
</tbody>
</table>

**Table 4. Case 2: deorbit from SSO**

**V. Conclusion**

Building from the qualified manufacturing process of the IFM Nano Thruster, the IFM Micro was designed as the most powerful FEEP thruster system built up to date.

A first engineering model has been tested up to 80 W of beam power and has demonstrated the architecture and performance expected from the design phase.

The thruster is entering qualification at the fall of 2019 with a first flight models deliveries schedule for the first half of 2020.
References


7 NIST. NIST Standard Reference Database Number 69, 2019.


