

mN-FEEP Thruster Module Design and Preliminary Performance Testing

A.Reissner¹, N. Buldrini², B.Seifert³ and F.Plesescu⁴
FOTEC Forschungs- und Technologietransfer GmbH, Wr. Neustadt, Austria

C. Scharlemann⁵
University of Applied Sciences Wr. Neustadt, Austria

and

J. Gonzales del Amo⁶
ESA-ESTEC, Noordwijk, The Netherlands

Abstract: In the scope of ESAs Basic Technology Research Programme (TRP), FOTEC is currently developing the first FEEP thruster capable of operating from several μN to the mN-Range. The core of the new mN-FEEP thruster is a porous tungsten crown emitter, which has 28 emission sites arranged in a circle of 1cm diameter. After optimizing the manufacturing process of the emitters, the latest development is a new thruster module that has been designed to meet the requirements of ESAs Next Generation Gravity Mission (NGGM). The thruster module has a new electrode concept that includes a focus electrode allowing for a reduced beam divergence. This concept also makes room for a new heating system significantly increasing the heating efficiency of the thruster. The module performance has been investigated by measuring the power consumption of the new module as well as the achieved firing homogeneity using the new focus electrode.

I. Introduction

FOTEC is currently developing the first FEEP thruster capable of operating from several μN to the mN-Range¹. The core of the new mN-FEEP thruster is a porous tungsten crown emitter, which has 28 emission sites arranged in a circle of 1cm diameter². The manufacturing process of the new porous tungsten crown emitter has been investigated and optimized in a previous activity³. The manufacturing from the raw materials to the crown with sharpened needles is defined in a process that consists of automatized steps with clearly defined procedures. Thus, it is now possible to manufacture large batches of emitter (in the order of 100 emitter per batch) where almost all emitter fulfil the requirements for the sharpness of the needles and can be accepted. The few that have to be discarded are due to inhomogeneities in the raw materials and the percentage of those is extremely low, especially compared to all previously used manufacturing processes of Indium FEEP Emitter.

In order to meet the requirements of ESAs Next Generation Gravity Mission (NGGM)⁴⁵, a new thruster module has been designed including several advancements from previous designs. These are in particular the introduction of a focus electrode to reduce the beam divergence as well as the increase in propellant capacity by a factor of ten. The following sections describe the implementation of these advances followed by first test results characterizing the functionality of the new module.

¹ Head of Department, Aerospace Engineering, reissner@fotec.at

² Research Scientist, Aerospace Engineering

³ Research Scientist, Aerospace Engineering

⁴ Lead Technician, Aerospace Engineering

⁵ Head of Department, Aerospace Engineering

⁶ Head of the Electric Propulsion Section

II. Design of a Focus Electrode for the Porous Tungsten Crown Emitter

A. Multi-zone focus

Because of the large initial beam divergence and the stringent requirement for a low final divergence, as well as preclusion of apertures for the ion beam (since they would be eroded by the high energy ions), some portions of the beam are easier to focus than others. An overall solution for all the beam angles is a difficult compromise.

For this reason, a new focus concept which employs several zones of varying potential was conceived. Portions of the beam which require only a small change in their trajectory would be influenced mostly by electrodes with a low positive voltage, whereas the highly divergent beam portions, requiring a large change in direction, would be exposed to high positive voltage electrodes. Naturally, the additional potential levels entail the use of additional power supplies, or voltage dividers and the reduction in size of the focus electrode needs to be commensurated to the added complexity of the electronics.

A division of the focus into a maximum of 4 segments was investigated for the following reasons:

- spatial separation of focus segments required due to high voltages
- diminishing returns for more voltage levels in a switched power supply

Three voltage levels would be related in a straightforward manner to the emitter voltage as:

- $3/3$ of emitter voltage (=equal to emitter voltage)
- $2/3$ of emitter voltage
- $1/3$ of emitter voltage

These three levels are responsible for collimating the lowly divergent to medium divergent beam segments. An additional voltage level which is higher than the emitter voltage is introduced for the highly divergent portions of the beam. By providing a strong repulsive force for the most divergent ions, the necessary space in which the trajectory is changed, can be reduced.

Simulations of such a multi-tiered focus, based on measurements of the initial beam divergence near the individual needle tips⁶ have been conducted. They show that the portions which only exhibit $1/3$ of the emitter voltage do not appreciably affect the ion beam anywhere, so that this level can be omitted for further considerations.

Portions of the focus which have $2/3$ of the emitter voltage have a small effect on the ion beam, but analysis shows that this portion can be replaced with a slightly longer portion of the focus which is biased to $3/3$ of the emitter voltage, so that the $2/3$ part can be foregone as well.

This leaves a multi-zone focus consisting of an electrode with emitter voltage and an electrode which is biased above the emitter. The voltage level above the emitter voltage is not constrained to a multiple of thirds due to power supply considerations, so that the bias can be used to fine-tune the focus behaviour in addition to the focus geometry.

For the considered minimum distances between opposing electrodes of 4 mm, a value of $1.2 \times$ emitter voltage yields the smallest focus electrode that can achieve a beam divergence half angle of 25° . Herein, the 'backplate' of the focus, which is parallel to the plane in which all the needles of the crown emitter lie, serves to guide the most divergent beam portions and rapidly turn them in direction of the thruster axis. The remaining electrode biased to emitter voltage is then used to shape the remaining mid- and low- divergence portions of the beam.

Overall, the approach of using a multi-zone focus to obtain a compact focus electrode for a FEEP emitter is viable. Only two stages are required to obtain a low beam divergence, one at the emitter voltage itself and a second stage slightly above the emitter voltage.

B. Single-piece focus

In order to compare the size of the multi-zone focus with a more traditional approach of using a single stage, which is biased to the emitter voltage itself, additional simulations were performed. The overall geometry of having a rotation-symmetrical L-shaped cross section was kept, but with the backplate having direct contact to the cylindrical section since the parts have identical voltage bias in this configuration (see Figure 1).

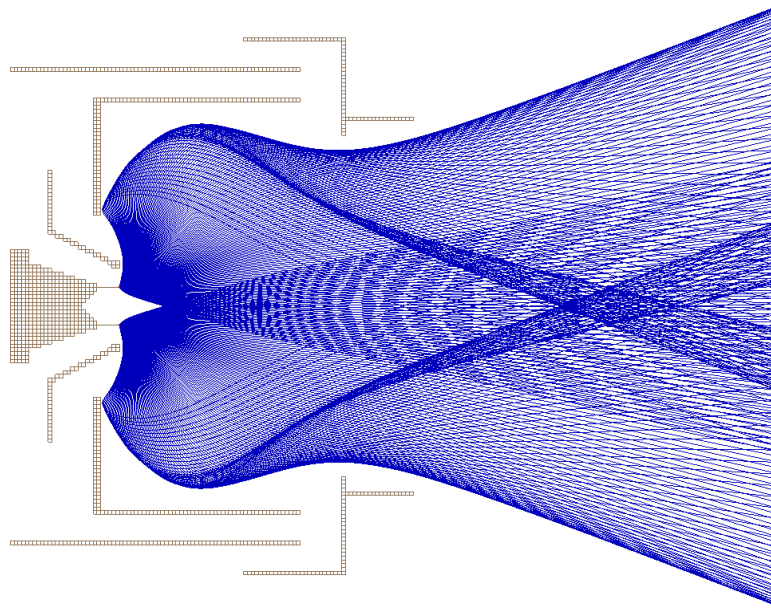


Figure 1 Single-piece focus electrode for a mN-FEEP thruster.

This configuration also does not use a central extraction electrode anymore and only uses the outer extraction electrode to generate the electric field at the needle tips.

Because of the inclusion of a focus, the functions of the extraction electrode and the cover plate are separated into generation of field and repulsion of secondary electrons respectively. The cover plate (shown right-most in Figure 1) has a ring-like structure which extends from the surface. Its function is two-fold; for one, it provides a hard limit for any stray droplets which might be emitted, so that no expelled matter can be found outside of the cone given by the triangle formed by the crown emitter and the edges of this ring on the cover plate. Secondly, it increases the electron repelling effect of the cover plate due to its larger surface.

As shown in Figure 1, the ion beam is collimated to a final half-angle divergence of just 25° , so that the ions are expelled in a clearly preferential direction away from the spacecraft, thus minimizing the risk that part of the propellant returns to the spacecraft.

C. Comparison of Focus Designs

Two types of foci were simulated and analysed; one used a multi-tiered electrode setup whereas the other one is electrically simpler in that it only has a single electrode and a single voltage. While the multi-stage focus results in a smaller focus volume, the added complexity of having several power supplies or divider stages linked to several separated electrodes is not worth the small increase in diameter of the focus. The single stage focus, with its much simpler geometry and electronic connections is merely 10 % larger in diameter and collimates the beam equally well. For this reason, the baseline design for the emitter module has been chosen to be a single stage focus with a voltage equal to the emitter voltage.

III. Redesign of Propellant Tank for 10.000h Operation

The propellant tank used in previous activities is capable of holding up to 26 grams of indium, which enables continuous emission at nominal thrust of 0.35 mN for 1000 hours. A planned lifetime test of the new emitter is composed of 4 tests with 2500 hours each, for a total of 10000 hours with a single crown. A viable approach to achieving this goal would entail interruption of the firing test every 1000 hours in order to refill the indium and re-install the emitter in the vacuum chamber. This, however, exposes the emitter to ambient air up to 9 times during the 10000 hour test and involves the dismounting of the thruster module.

The formation of an oxide layer while the emitter is handled outside the vacuum chamber introduces a potential failure mode or may change the characteristics of the emitter temporarily. Likewise, repeated exposure of the emitter to air is not representative of its operation in continuous and good vacuum conditions in space.

In order to reduce the frequency of removing the emitter from the vacuum chamber, and in order to obtain a propellant tank which is capable of providing a mN-class FEEP thruster with propellant for 10000 hours, a new tank design was made. This has a strong impact on the whole module design, since the size of the emitter determines all structures in its vicinity.

The goals for the new design can be summarized as follows:

- hold enough indium propellant for a firing duration of 10000 hours at a nominal thrust of 0.35 mN
- design inner surfaces of propellant tank so that capillary forces are directed to the crown emitter at all times and for all states of filling
- find solution for a heating concept with increased reliability and decreased complexity

In the following, the approach to meet these goals shall be elaborated in more detail.

A. Size

It is clear that a ten-fold increase in maximum firing duration entails a likewise increase in volume of the tank. The manner in which this increase in volume is achieved, however, is not straightforward due to the environments in which the thruster needs to be operated. For one, the thruster has to operate reliably in a zero-g environment in space. In this environment, the only force affecting the liquid mass of propellant is the capillary force, which is determined by the shape of the internal surfaces. Ideally, the inner surfaces would taper towards the central axis and towards the front of the emitter, where the crown sits. Capillary forces are the topic of the next chapter.

Apart from its operation in space, however, the thruster secondly also has to operate reliably in a terrestrial laboratory, where gravitational pull on the dense liquid plays a major role. Testing is performed with the emitter firing in a horizontal direction, so that gravity pulls the liquid indium downward to the lateral wall of the propellant tank. This means that, when the tank is mostly empty, the liquid has to be pulled up against gravity by adhesive and capillary forces in order to reach the porous crown structure. In this case, providing the inner surface of the tank with a smart geometry which utilizes capillary forces, solves the problem of getting the liquid propellant to the crown. When the tank is full, however, gravity leads to a hydrostatic pressure contribution at the position of the crown (see (Eq. 1) with h as the height between the upper edge of the liquid and the lower edge of the porous crown, ρ as density and g as gravitational acceleration on Earth)

$$p = \rho gh \quad (\text{Eq. 1})$$

The large density of indium of 7.31 g/cm^3 leads to a significant pressure even for small height values (e.g. 5 cm). Due to the horizontal position of the emitter, an overly large pressure at the porous crown might lead to pressure-induced leakage at the porous needle tips, with subsequent problems for loss of isolation between opposing electrodes.

For this reason, the diameter of the tank shall be as small as possible. This means that the largest contribution to the increase in volume has to come from an elongation of the tank, since this dimension does not contribute to hydrostatic pressure in an emitter lying horizontally in a terrestrial laboratory. The outer tank geometry will thus resemble a cylinder with a length that exceeds its diameter as shown in Figure 2.



Figure 2 Orientation of propellant tank during testing in a terrestrial laboratory. The red arrow indicates the maximum contribution to hydrostatic pressure at the bottom of the crown when the tank is filled. In order to keep this pressure low, the tank is long and uses a small diameter.

The overall length of the new tank design is 7 cm and the diameter 3 cm. The tank has a capacity of more than 240 g of indium. Compared to the previously used design with a diameter of 2.2 cm, the pressure-determining height between the upper edge of the tank and the lower edge of the crown in horizontal orientation has increased by a factor of just 1.4 while the overall volume has increased by a factor of 10.

B. Capillary Forces

When an energetically favourable bonding between a liquid and a solid surface forms, the liquid tends to spread over the surface since it can minimize its energy in this manner. After successful wetting, the solid surface is 'attractive' to the liquid and gives rise to capillary forces. These forces depend on the radius of curvature of the solid surface, so that the capillary force in a wide tube is small, but can become large in a sufficiently tight tube; hence, the difference in rising height in tubes of different diameter.

When the radius of curvature of a tube continually decreases, the capillary force points in the direction of the smallest curvature, i.e. the smallest portion of the tube. This effect is utilized in the propellant tank by introducing conically shaped surfaces and tapering cylindrical segments.

C. New Heater Concept

The central extraction electrode, which runs along the central axis of the emitter in all previous modules using the crown emitter, serves to increase the electric field and provide an equal strength of the electric field on the inside and outside of the crown, thus leading to a symmetrical ion beam. If the central extractor is removed, the ignition and operation voltage increases, since the electric field is lower, and the pull from the electric field is now one-sided towards the outer rim, leading to a higher beam divergence.

The focus, however, serves to gather the ions and bend their trajectories to a very low divergence. If the focus is capable of handling the extra beam divergence coming from the removal of the central extractor, it is possible to use the volume reserved for the central extraction electrode and its isolation to install a heater at this position. The advantages of having a heater at this central position over a heater on the outer circumference of the emitter are clear:

- very compact heater
- the entirety of the generated heat remains in the tank
- encapsulated heater is protected against potential contaminants on the outer surface

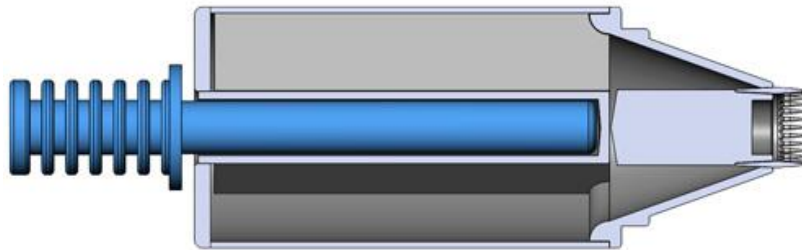


Figure 3 New propellant tank with room for a central heater (blue in the picture) instead of central extraction electrode.

IV. Thruster Module Design

A. General Design Concept

In order to accommodate the new focus concept (with modified extractor and coverplate electrodes) and the new indium tank, a completely new module design has been necessary, although it is based on previous proven concepts wherever possible. In particular, it is based on the 2x2 Burn-In module used for the LISA PF project, which has collected several thousand hours of cumulative operation, with single tests lasting up to about 3000 hours.

Fehler! Verweisquelle konnte nicht gefunden werden. depicts a sectional view of the module, with the denomination of the main components. Here is a short description of the main parts of the module (and constituting materials):

Module Housing (Aluminium). It constitutes the mechanical support for the internal components, provides protection against external contamination and, with its mirrored internal surfaces, acts as a thermal shield

Indium Reservoir (Tantalum)

Base Plate (PEEK: PolyEther Ether Ketone, a high temperature thermoplastic, low outgassing). Made of two parts, it constitutes the fixing support for the emitter assembly, the extractor and the focus electrodes, for the high voltage contacts and for the thermocouple sensor

Electrode Assembly (Aluminium): Extractor, Focus, Cover Plate

Heater (Aluminium Oxide and Nickel Chromium wire). It provides the heat necessary to melt the indium propellant.

The emitter assembly is constituted by the indium reservoir itself, a stainless steel sleeve which holds the reservoir, and two aluminum oxide holders (one on the bottom and another on the top) which are connected to the base plate with PEEK screws. The central heater completes the assembly, and will be described in more detail in section D.

The extractor and the focus electrodes are fixed to the base plate with PEEK screws. The cover plate is fixed to the module housing by means of PEEK screws and spacers, in order to guarantee adequate electrical isolation.

The design of the internal parts has been conceived so that there are no enclosed volumes inside the module, in order to allow proper outgassing of all the inner surfaces. The main outgassing port is the central hole of the cover plate, while the slid between the housing and the cover plate provides an additional outgassing pathway. The outgassing of the parts located on the lower side of the base plate is guaranteed by holes on the bottom of the housing. Every PEEK screw which fastens on a blind threaded hole is provided with a central hole in order to permit the escape of trapped air during evacuation.

As with previous concepts, the new module has been designed in such a way to permit easy access to the emitter, for quick exchange and maintenance. This has been achieved with modular design and the use of spring contacts (Figure 4). The module is in fact composed of two detachable parts: the “cold assembly”, which comprises the electrodes and the upper part of the housing and of the base plate, and the “hot assembly”, which comprises the emitter tank, the heater and the bottom part of the base plate where the spring contacts are fixed.

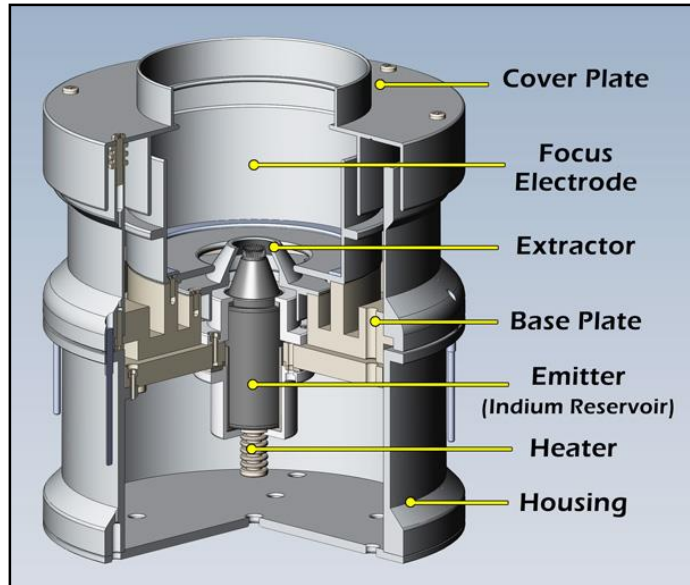


Figure 4 Sectional view of the new emitter module.

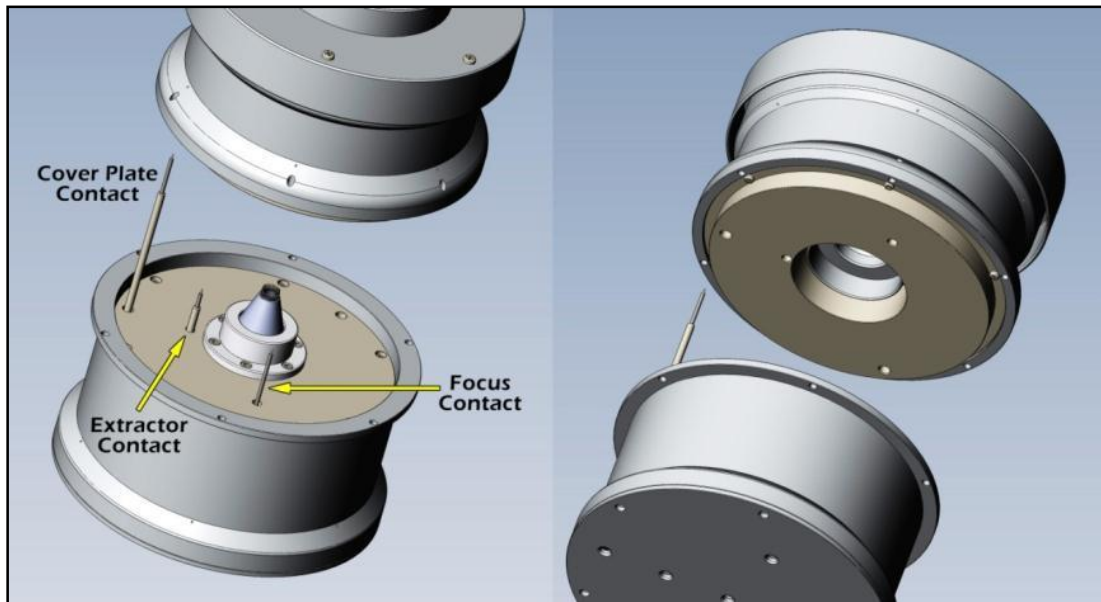


Figure 4 Modular design.

Figure 5 reports the overall dimensions of the complete module. The maximum external diameter, 180mm, allows the mounting of the module on a CF 200 flange for an easy installation on the test chamber.

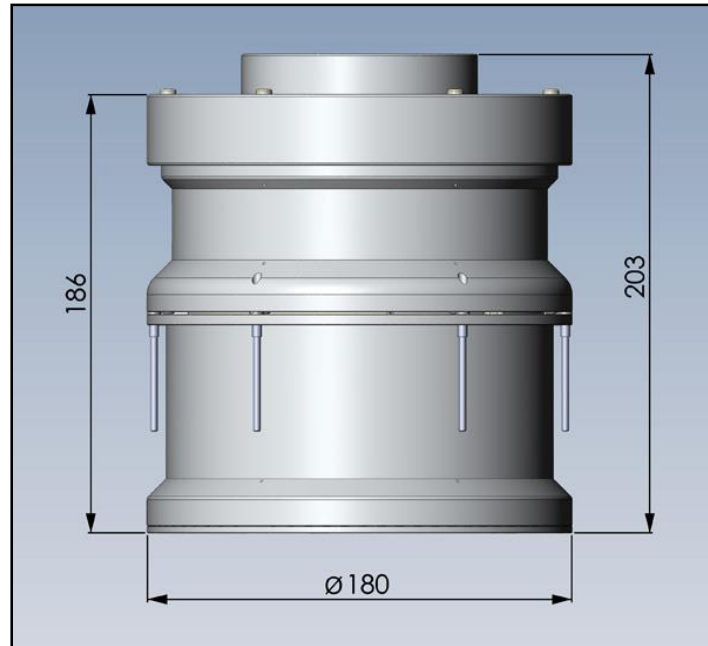


Figure 5 Main dimensions of the new emitter module.

B. High Voltage Supply

One challenge when designing modules for LMIS is the distribution of the high voltage power to the emitter and to the electrodes. Care must be taken in order to avoid any possible electrical discharge between the feeding lines and the parts of the module which are at different electrical potentials. The emitter and the focus electrode share the same voltage through a Y connection embedded in the base plate. The emitter and focus line can withstand a maximum positive voltage of about +20kV. The electrical connection to the electrodes and to the emitter is provided by spring contacts, a technology which has been tested in previous proven designs: they allow easy module disassembly of emitter exchange and maintenance. Particular care has been taken in the high voltage lines so that the diameter of the conductors and the radius of the edges is significantly larger than the one which could trigger corona discharges; the electric field of the only sharp part, the contact point to the electrodes, is suppressed by the vicinity of the metallic surface of the electrodes themselves. Furthermore, all the high voltage lines are embedded in isolating materials.

C. Internal Surface Design

A careful design of the internal surfaces of the module is essential when considering module lifetime. The tips of the crown's needles (emission points) produce a flow of indium droplets distributed over a solid angle of 360 degrees. So every surface which directly sees the emission points will be covered with a layer of indium after long-term operation. If the surface is an isolator, then it will become conductive and will lead to loss of insulation. In addition to direct droplet deposition, secondary deposition will occur: every point of the surfaces directly impinged by the indium droplet flow, in fact, behaves in turn as an emission point, because of the sputtering effect given by the kinetic energy of the impacting droplets. As a consequence, all the surfaces in direct sight of the directly impinged surfaces will receive a certain amount of indium, which will accumulate in time and could lead to a loss of insulation after an operation time in the range of 100 hours (this time can vary in relation to the mass efficiency of the emitter). Figure 6 shows the predicted deposition pattern for indium contamination on the internal surfaces of the module. This kind of prediction comes directly from geometrical considerations, and previous testing activities has repeatedly confirmed the effectiveness of this prediction method. In long duration testing (>~1000h), also third order deposition has to be taken into account, which comes from indium droplets or gas generated by the impacts on surfaces where secondary deposition occurs. A special labyrinth design has been developed in the new model in order to manage the indium droplet flow and to assure that a sufficiently large surface of isolator remains clean over the whole duration of the endurance testing.

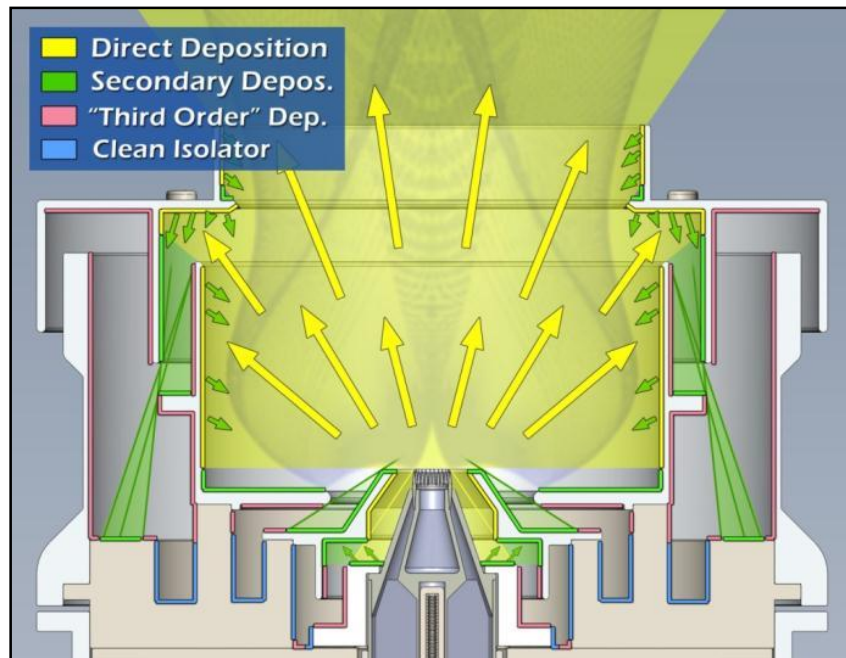


Figure 6 Indium deposition pattern on module internal surfaces

D. Thermal Design

With the decision of removing the central extractor in the new design, it became possible to use the free space in the middle of the reservoir to accommodate the heating source, which permits to melt the propellant and keep it liquid very effectively. The central allocation of the heater improves the thermal design with a reduction of the thermal radiation losses when compared with the previous design, where the heater surrounded the reservoir. The used heating element is inserted inside an aluminum oxide housing, which provides a good electrical isolation from the emitter, while guaranteeing fairly good heat conduction (Figure 7).

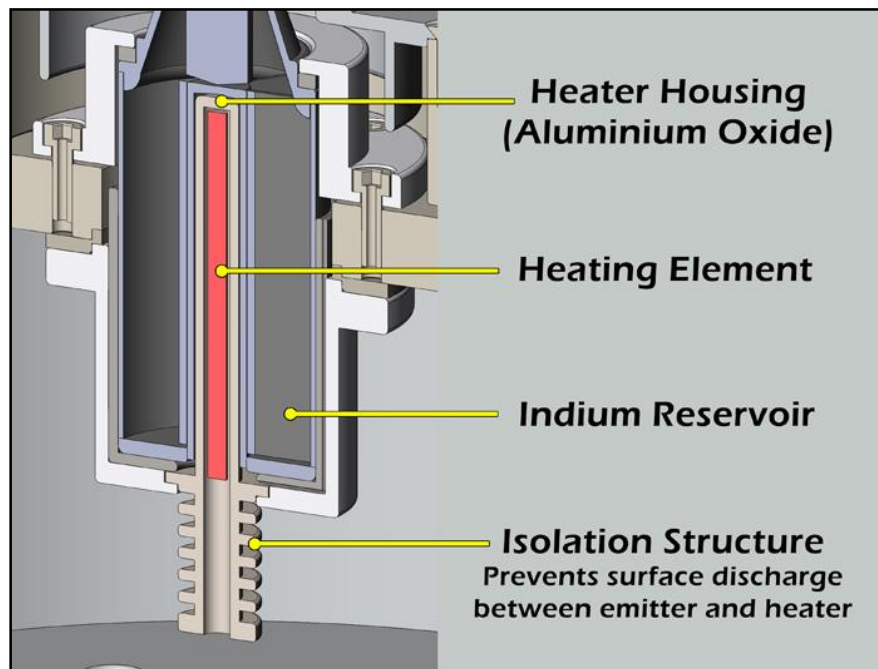


Figure 7 The new heater design

E. Protection against Backflow-Contamination

During long-term operation a significant amount of indium deposition on all outer parts of the module has to be expected. Thus, the housing will be directly connected to a flange via a continuous shield, incorporating all connections to the outside of the chamber. This concept, already used for previous tests with the crown emitter assures that the outer layer of the module is completely grounded and does not suffer from the deposition of a conductive layer.

V. Failure Mode Analysis

Table 1 summarizes the main failure modes anticipated for the new mN-FEEP thruster module. It is important to note, that since there is no experimental experience yet with the new module, the likelihood of each failure is taken from experience with previous Indium FEEP modules. All preventive design measures have been included in the new module and the effect of those measures on the likelihood of a certain failure mode is yet to be tested experimentally.

Table 1 Failure Modes for the mN-FEEP thruster module

Failure Mode	Worst Case Consequences	Likelihood	Severity*	Preventive Measures
Heater wire breaks	Heater failure leads to inability to heat the fuel to its melting temperature. Complete failure of the module	Unlikely	Fatal	Intrinsic redundancy in the heater: two parallel wires per heater or large margins in the heater power
Backflow Contamination, especially with three thrusters next to each other like in NGGM configuration	Sputtered surfaces get conductive and can cause voltage breakthrough between emitter and extractor or ground	Depending on the module design	Fatal	Complete outside coverage of each module by grounded surfaces
	Passive emitters get sputtered by backflow from firing emitters and cannot be reactivated	Very unlikely	Serious	Consideration in operation scheme of the thrusters. Firing of all thrusters at lower currents instead of only one thruster at a time
Indium Leakage through the crown due to higher hydrostatic pressure in the new 250g tank in gravity (during qualification test campaign)	Fuel is lost into the inner parts of the emitter module and creates a shortcut between the emitter and grounded parts	Very unlikely	Fatal	Sealing of the base of the crown emitter by gluing. (Necessity to be determined experimentally)
	Fuel is lost and the lifetime of the thruster is reduced	To be tested	Serious	
High voltage wire to emitter / extractor / focus breaks	The corresponding electrode gets floating, resulting in an uncontrollable overall electrode configuration	Very unlikely	Fatal	Implementing spring contacts for all high voltage electrodes

*Severity is stated with respect to the individual thruster module, holding only one emitter. A complete failure of one module does not affect the other two in the three emitter configuration proposed for NGGM.

VI. Thruster Module Verification

A. High Voltage Capability and Electrode Design

Initial tests have been performed with the module applying up to 25kV potential difference between the emitter/focus and the extractor electrode. The support structure of the electrodes and all insulations were able to withstand this potential difference with no detectable leak currents occurring. A crown emitter was mounted on the new tank and integrated in the module. Despite the major changes in the electrode design (removal of central extractor and introduction of a focus electrode), the crown could be ignited without any problems. The firing homogeneity was reaching 91%.

Figure 10 shows the currents during the initial testing. At the nominal current of 2mA, the emitter voltage was 10kV, only slightly higher than in previous tests (ref xxx!). After 50h, the small amount of propellant that has been put into the tank for preliminary testing has been consumed completely, causing the emitter voltage to raise to the maximum of 20kV.



Figure 8 Assembled Thruster Module

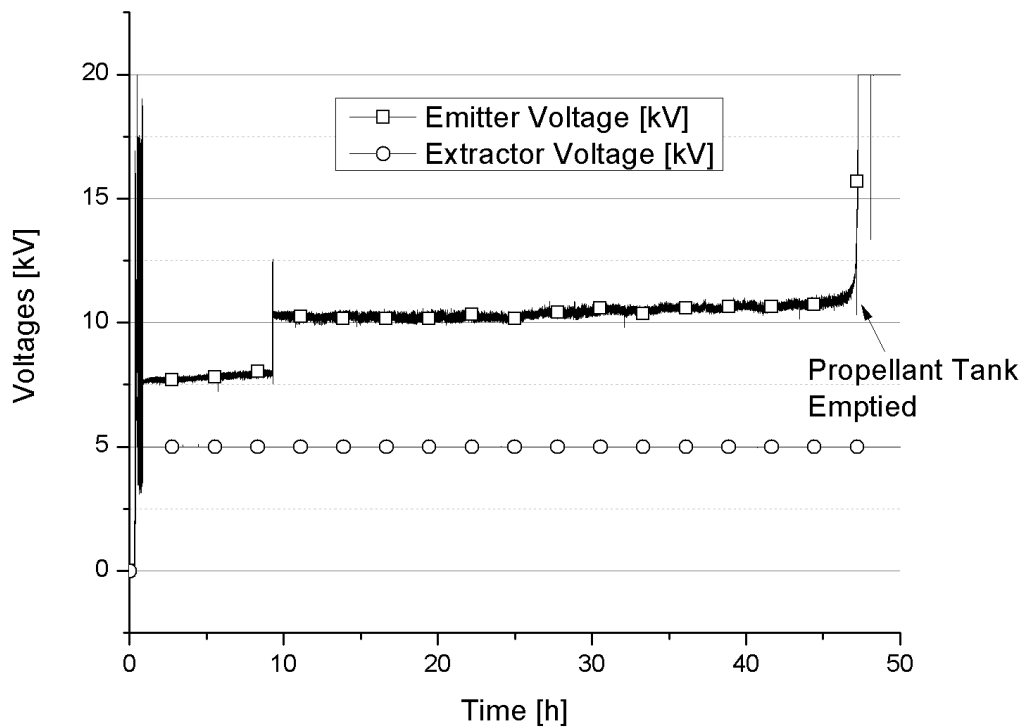


Figure 9 Electrode Voltages during preliminary Testing

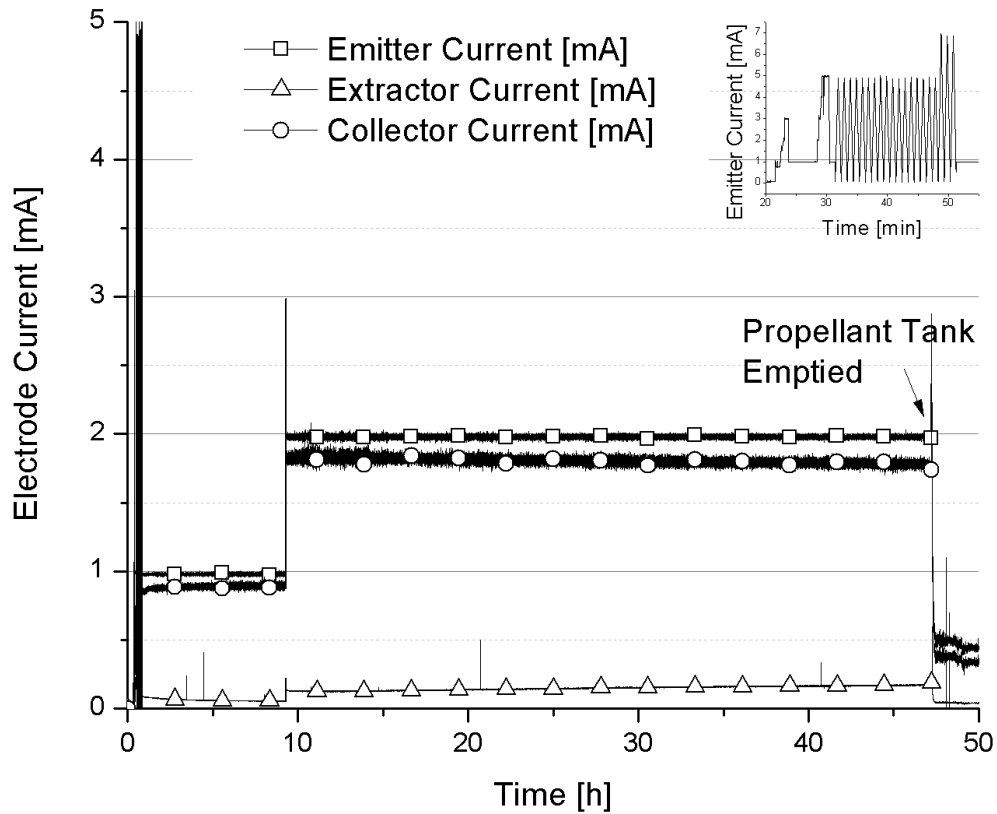


Figure 10 Currents during preliminary testing

During these first tests, the extractor current was always below 10% of the emitter current. This indicates that 90% of the expelled ions are focused to a beam divergence of $<25^\circ$ half angle, as predicted by the simulation. The other 10% are impacting the focus or the extractor. The reasons lie within inhomogeneities in the ion distribution at the emission sites or small discharges between emitter and extractor. Those possible causes will be investigated in more detail, in order to increase the focusing efficiency as much as possible.

B. Heater Power

It is clear, that increasing the propellant tank by a factor of 10 results in a significant increase in the heater power necessary to keep the propellant at the nominal temperature. The main goal of the new internal heater concept was to reduce this increase in heater power as much as possible. Fig. xxx shows the heating of the new 240g tank.

During the initial heating, the heater power reached 14W and stabilized at 12W while firing at 1mA. Switching to the nominal performance point of 2mA reduced the necessary heater power further down to about 10W. Comparing these results to 5W nominal heater power for the 24g tank clearly shown the success of the new heater concept.

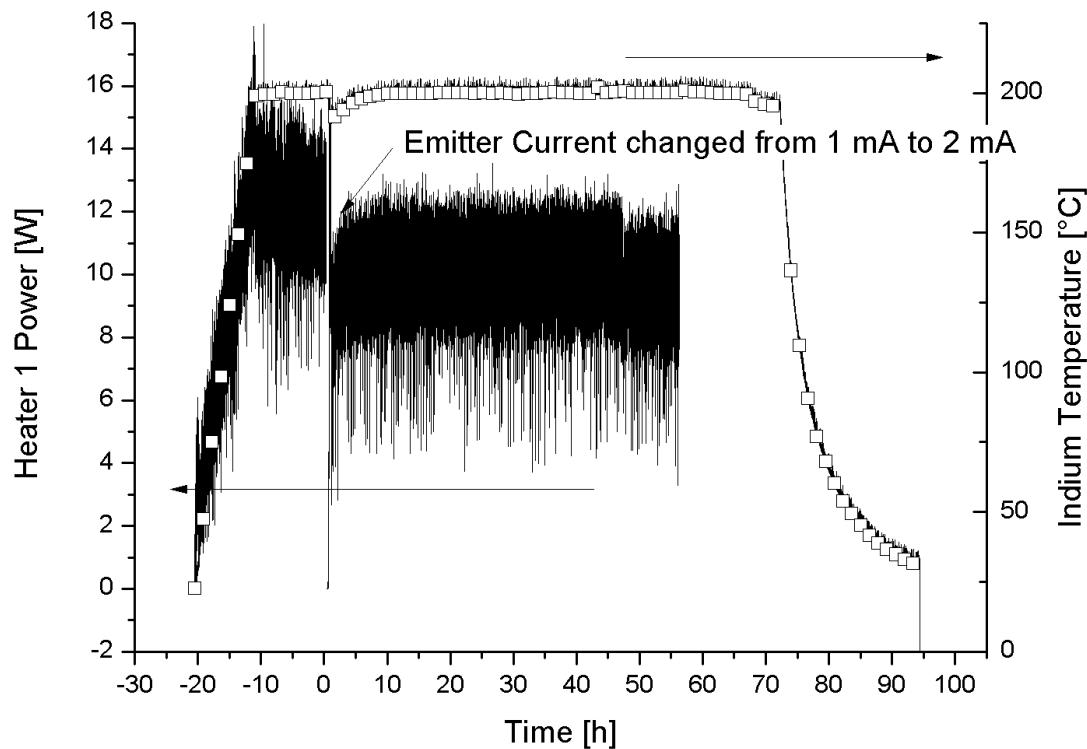


Figure 11 Heater performance during preliminary testing

VII. Conclusion and Outlook

A new mN-FEEP thruster module has been developed for the porous tungsten crown emitter. The module is optimized for long term testing and uses the mission requirements for the ESA Next Generation Gravity Mission NGGM as a baseline. It features a new focus electrode as well as a new highly efficient heater concept. Also, the propellant capacity has been increased by a factor of ten.

Initial testing has verified the function of the focus electrode as well as the efficiency of the heater. While the propellant capacity has increased by a factor of ten, the required heater power has only doubled. The increase in operation voltage, due to the removal of a central electrode and the introduction of the focus, has been smaller than expected.

The module is designed in a way to easily exchange the emitter and thus allow for a statistical evaluation of the performance of a large number of emitters. These investigations are being planned to start in 2014, in order to get a thorough understanding of the performance of the mN-FEEP thruster based on a large statistical database.

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