Development, Production, and Testing of the IFM Nano FEEP Thruster

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With the rising market in small satellite constellations and emerging New Space companies, the demand in propulsion systems for Cubesats and small satellites grew rapidly in recent years. Due to its compact design, its versatile operation, and its plug-and-play character, the IFM Nano Thruster was and is an electric propulsion system advantageously suitable for the needs of a wide variety of space mission applications. The thruster is an indium-consuming field-emission electric propulsion (FEEP) system that is the result of more than 20 years of research on liquid metal ion sources (LMIS), and fits into less than 1U generating 350 µN of nominal thrust at very high specific impulse. With a high demand in number of thrusters, the production rate and testing capability alike had to be set up accordingly. This paper summarizes the transition of the thruster technology towards a product, and the unprecedented challenges associated to mass production of electric propulsion systems. Further, with almost 100 thrusters delivered, a statistical analysis of the production data is presented to demonstrate the resulting quality.

Nomenclature

e	= elementary charge
f	= thrust factor
F	= thrust
I_{em}	= emitter current
I_{sp}	= specific impulse
m	= atom mass
V_{em}	= emitter potential
η_{m}	= mass efficiency

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I. Introduction

Space and how it is used has changed in recent years. While large satellites for telecommunications, navigation, and science are still very common, many new companies and approaches have emerged using much smaller satellites. Cubesats and small satellites today dominate the market by the number with about 1000 cubesats put in orbit already[1]. The majority of those smaller satellites are put in space without propulsion either for technical reasons or to allow for a fast technology demonstration. However, more and more satellite manufacturers see the potential of propulsion, and especially electric propulsion, even on smaller satellites up to 100 kg or higher. With the increasing market presence of electric propulsion systems in the general space sector[2,3], the acceptance and awareness also in the New Space industry has increased steadily. Traditional electric propulsion systems using pressurized gases like Hall effect thrusters, or ion engines, are less scalable to the volumes and power levels available on smaller satellites, due to a steep decrease in thrust performance and a too high mass penalty resulting from the fluid management system and the complex power processing units (PPU). The use of solid propellant instead reduces the system size and allows for more compact designs of propulsion systems. Although the idea ranges back to the very first electric propulsion used in non-ballistic space application with PTFE-based pulsed plasma thrusters[4,5], wide-range application had not been achieved due to the absence of smaller sateillites in the beginning of the space age. With the emerging of the liquid metal ion sources (LMIS), developed at the Austrian Institute of Technology and later at FOTEC, the perfect technology, based on field-emission principles, was found. Combining solid indium propellant with a highly versatile operational envelope intrisic to field-emission-based systems, the IFM Nano Thruster was developed at FOTEC as a next stage of the space-proven LMIS and is commercialized in the FOTEC spinout ENPULSION. With the high demand in a thruster for the small satellite market, a concept had to be found to allow for mass production of the thrusters while maintaining a quality necessary to satisfy the space market. This paper is a summary of the efforts up to the 100th thruster ready for delivery.

II. The IFM Nano Thruster

A. Electrospray and field emission

In the presence of a strong electrostatic field, a conducting fluid will be subject to a force in the field gradient direction. Resultingly, the surface will change its shape until an equilibrium between external field forces and surface tension has been established. If the applied field exceeds a critical threshold - the onset voltage -, the fluid will change shape to a cone-like structure and emit an ionized particle beam from its end. This electrospray effect has been first observed in the late 16th century[6], but only became well understood in the middle of the 20th century by Sir Taylor[7] which resulted in the naming of the Taylor cone. Already in this period, intentions to use this physical principle in propulsion arose[8]. Using a conducting liquid consisting of molten metal (e.g. gallium or indium), ion emission becomes significantly more efficient and less prone to form droplets. An electric propulsion system based on this principle is then called field-emission electric propulsion (FEEP) to distinguish them from other electrospray thrusters like colloid thrusters or ionic liquid ion sources. To allow for the necessary field strength leading to a proper formation of the Taylor cone, a sharp emitter structure is required. The counterelectrode - the exctractor - aids in both ionization and acceleration as a result of the strong electric field that typically exceeds 10 kV. Intrinsic to field emission is the independent controllability of both thrust and specific impulse. This is reflected by their analytical description[9]:

$$F = I_{\mathrm{em}} \cdot \sqrt{2 \cdot V_{\mathrm{em}} \frac{m}{e}} \cdot f \tag{1}$$

$$I_{\mathrm{sp}} = \frac{1}{g} \sqrt{2 \cdot V_{\mathrm{em}} \frac{e}{m}} \cdot f \cdot \eta_{\mathrm{m}} \tag{2}$$

Here, I_{em} refers to the current extracted from the emitter, V_{em} is the positive potential applied to the emitter, m is the mass of the propellant atom, f is a beam divergence factor, and η_{m} the mass efficiency. Since only ions are emitted, this principle can be either use for spacecraft potential control, or can be paired with a neutralizer to complete a quasineutral propulsion system.

B. Technology heritage and development

The origins of the FEEP thruster lie in the technology of liquid metal ion sources (LMIS). The former "Space Propulsion and Advanced Concepts" unit of the Austrian Institute of Technology (AIT), and later the newly founded Department of Aerospace Engineering at FOTEC has a long and successful history in research, development, and flight application of those LMIS for potential control of spacecraft or scientific purposes like mass spectrometry. Table 1 summarizes the flight heritage of these LMIS.

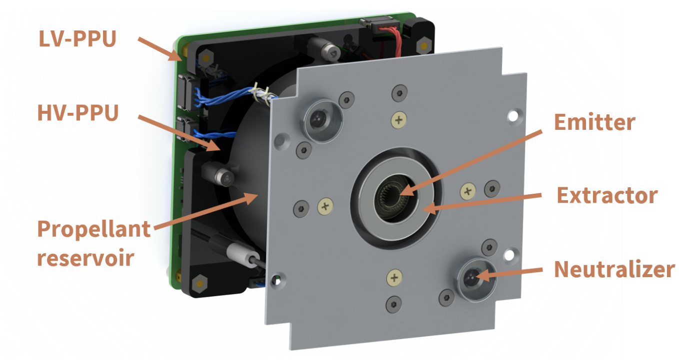
Table 1: Flight heritage of liquid metal ion sources

Experiment	Function	Spacecraft	No. of LMIS	Operation Time
LOGION	IOD of LMIS	MIR	1	24 h (1991)
MIGMAS/A	Mass spectrometer	MIR	1	120 h (1991-94)
EFE-IE	S/C potential control	GEOTAIL	8	600 h (1992-)
PCD	S/C potential control	EQUATOR-S	8	250 h (1998)
ASPOC	S/C potential control	CLUSTER	32	Launch failure
ASPOC-II	S/C potential control	CLUSTER-II	32	6516 h (2000-)
COSIMA	Mass spectrometer	ROSETTA	2	2004-2014
ASPOC/DSP	S/C potential control	DoubleStar	4	8979 h (2004-2007)
MMS ASPOC	S/C potential control	MMS	32	Commissioned in 2015

With adjustment of the electric field configuration and an increase in emission sites, the LMIS became a FEEP[10,11]. Starting from 1997, R&D activities extended towards the development of a FEEP thruster that could provide ultra-precise thrust in the µN-range primarily suitable for scientific missions where attitude control is required to fulfil the payload objectives[12]. With increasing the amount of emission sources to a 28 needle porous emitter crown, the thrust performance increased to a level suitable for space propulsion[13]. With some further development steps especially on the electronics side, this technology eventually resulted in the design definition of the IFM Nano Thruster that is now mass produced and commercialized by ENPULSION.

C. State of the art

The IFM Nano Thruster in its standard configuration is shown in Figure 1a, and in operation in Figure 1b respectively. Within less than 1U of volume, the thruster stack consists of the low-voltage PPU, the potted high-voltage PPU, the indium reservoir, the porous crown emitter, the extractor electrode, and two redundant neutralizers. During operation, the ion current emission from the 28 needles is observed as a characteristic blue dot emission without a plasma plume typical for other electric propulsion sysytems.



(a) Flight configuration

(b) Operation

Figure 1: IFM Nano Thruster

The mechanical design and the geometry follow the Cubesat standard to allow for easy integration, but is of course suitable for non-standard satellites too. Communication, either by RS422 or RS485 protocol, is conducted via one single 8-pin connector that also provides the supply voltage of either 12 or 28 V. A maximum power input into PPU of 40 W can yield a nominal thrust of 350 µN at very high specific impulse of a few 1000 s. As explained in Section A, thrust and specific impulse can be independently controlled. This feature combined with a slight variation in mass efficiency and impedance of the crown emitter resulting from manufacturing, allows for selecting the correct emitters for the requirements of the intended application. Typically, values of 2000-2500 s at maximum thrust and higher than 4000 s at reduced thrust are achieved.

The first in-orbit demonstration of the IFM Nano Thruster successfully took place in early 2018, which not only led to a confirmation of the general operational functionality, but also to an in-orbit verification of the thrust performance [14]. These indirect thrust measurements were then again confirmed by direct thrust measurements at the ESA Propulsion Laboratory (EPL) [15].

The IFM Nano Thruster was developed for low cost, small satellites featuring rapid design and lifecycles. Consequently, the standard version is based on Commercial-off-the-Shelf (COTS) components. While the design of the thruster has been validated through i.a. radiation testing, the usage of COTS components limits the applicability of such results to the individual thrusters.

Therefore, a new COTS+ variant of the PPU is currently being implemented in the production. The IFM Nano Thruster COTS+ is a thruster version introducing a full lot-control and lot-testing component philosophy. For this thruster version, large batches of thruster electronics are procured, selected samples of which are then subjected to verification testing including radiation testing. The remaining sets of electronics, from the same batch as the experimentally qualified units, are then used to build the IFM Nano Thruster COTS+. By following this lot-controlled philosophy, a maximum of applicability of radiation test results onto the flight units can be guaranteed. The IFM Nano Thruster COTS+ is therefore built to a higher quality level, while still delivering identical performance as the space proved IFM Nano Thruster.

In a next step, a thruster with a segmented extractor (SE) will be developed allowing limited steering capability of the direction of the ion beam, and, hence, thrust vector control. With this method, which has been proven in a feasibility study, mechanical components like gimbals are not required to extend the range of applications.

III. Mass production of electric propulsion systems

A. Facility aspects

The challenge to mass produce space hardware of high quality with appropriate testing and documentation infers requirements on the entire production facility. That is, the chain from reception of parts up until the shipment of the thruster and its associated EIDP is strictly controlled and optimized to ensure a timely and high-quality production. As such, a 100% incoming inspection with an appropriate configuration management (permutations of input voltages, communication protocols, and customer-specific parts) and trackable parts guarantees that only to-design parts are going into production with a clear history and traceability. Capabilities for emitter manufacturing, assembly, and acceptance testing were set up to allow for having the entire production chain in house. This permits a proper scheduling of the single production steps of each thruster, a better traceability in terms of performance data as well as cleanliness and contamination control, and a reduction in logistics with external partners. This in turn reduces the time that is required to produce and test a thruster before delivery − a feature well regarded by New Space and heritage integrators alike. Current production rate of two thrusters a week is being upgraded to allow for a higher rate for the IFM Nano Thruster, and to extend the thruster portfolio with the IFM Micro Thruster in short future [16], and with the IFM Nano Thruster SE in mid-term future.

B. Production figures of merit

Resulting from the setup of the mass production line, shipping of the thrusters to their satellite integrators has steadily increased within the last year as can be seen in Figure 2. With a certain time shift, depending on integration and testing time before launch, the thrusters are deployed in orbit with a total of 25 thrusters in space at the time of writing. Flight data for some of the first thrusters are reported in a separate paper [17].

While process optimization and production improvements take place, procedures and product assurance are to guarantee constant quality of the final product. Independent of customer-specific adaptations, however, quality of the crown emitter and the resulting performance do vary as a result of inevitable inaccuracies at process level. Since every thruster is undergoing acceptance testing before delivery, the actual as-built

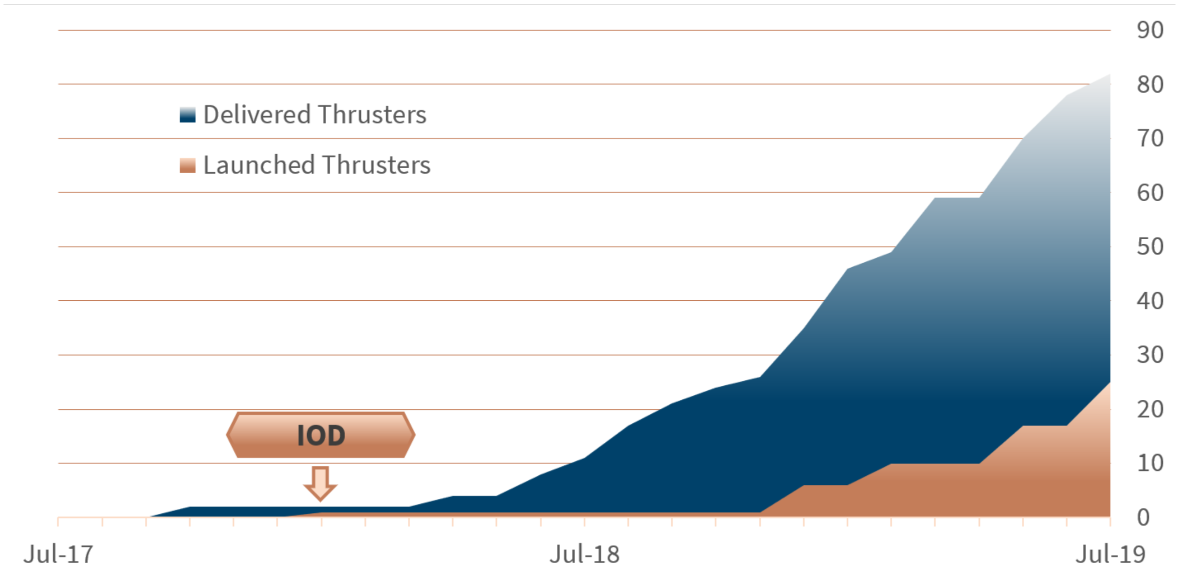


Figure 2: Shipping and in-orbit deployment of IFM Nano Thrusters

performance is known, and communicated to ensure that the application is not influenced negatively. Consequently, it allows for a statistical approach on the thruster production with regards to the core quantities of the performance. For the sake of customer anonymosity, the data presented in the following graphs have been randomized, and as such do not show any temporal tendencies.

One of the more important figures of merit is, of course, the thrust at a given power level. For the IFM Nano Thruster, the maximum emitter power is limited to 25 W, and as such the maximum thrust that can be produced. Since emitter performance is evaluated prior to assembly, the quality of the indiviudal emitters can be matched with the requirements of the application and the emitters then allocated accordingly. That is, for some applications a higher thrust is desired whereas for other applications a higher specific impulse, and a consequently higher total impulse, is desired. Figure 3 shows the nominal thrust measured at 25 W emitter power during performance acceptance testing for delivered thrusters. Resulting from the different emitter categories, the distribution of the nominal thrust is quite large, with an average thrust of slightly higher than 350 µN.

Another aspect is the linearity of the bus power as a function of thrust. For the produced thrusters, these numbers are plotted in Figure 4. Again with keeping in mind the different categories of emitters, the average bus power for 200 and 300 µN is 25, and 35 W respectively. These values include power required for heating the propellant as well as to operate the neutralizer. The scalability of the thrust is demonstrated, and is a constant feature for the thruster independent whether it is made for high thrust or high specific impulse.

For operation of the neutralizer, the power draw is plotted in Figure 5 at nominal operation point during acceptance testing. Since this is only dependent on the the quality of the supplied neutralizer filament, the variation in performance is less prominent. It shows, however, that expected performance of the neutralizer can be well extrapolated and is not prone to process effects.

C. Acceptance testing

Not every space application is the same, and as such requirements for every thruster vary throughout production. This does not only apply to the various configurations of the thrust itself, but also on the amount and levels of acceptance testing requested before shipping. The IFM Nano Thruster undergoes several stages of acceptance testing before cleared for delivery to the customer. Environmental acceptance tests following established standards (ECSS-E-ST-10-03, NASA GSFC-STD-7000A) can and are conducted to standard or custom levels. All of the data are part of the acceptance test reports following a tailored DRD from ECSS-E-ST-10-02C Rev.1 accompanying every thruster as part of the EIDP.

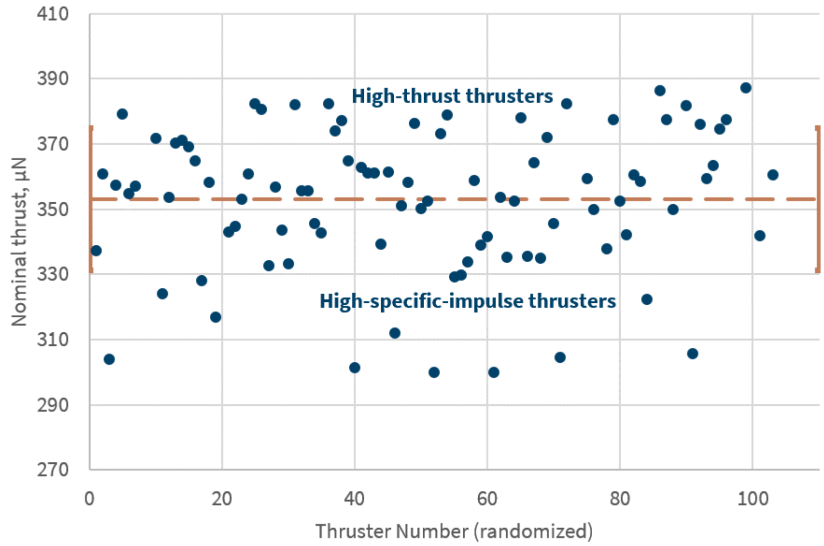


Figure 3: Nominal thrust at 25 W emitter power. Note that emitters are produced to meet customer requirements of having either higher specific impulse or higher thrust.

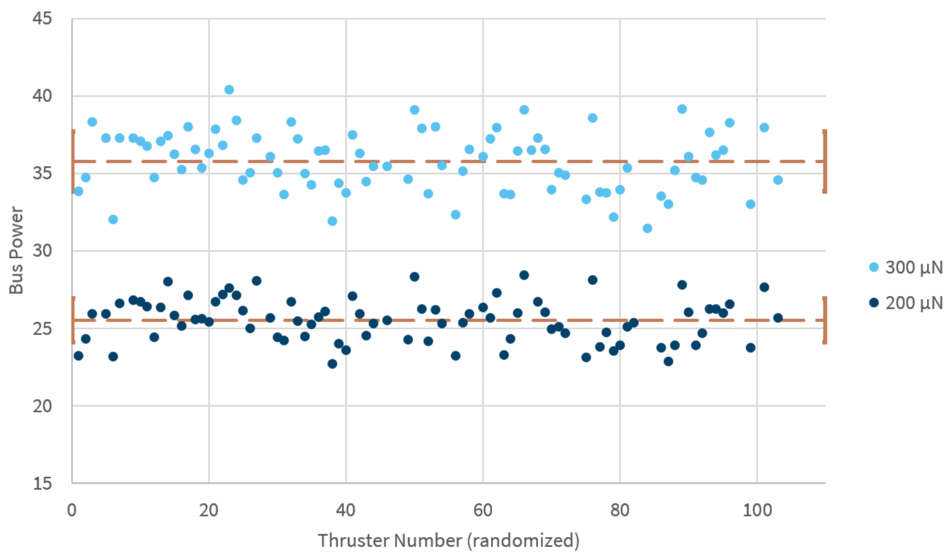


Figure 4: Bus power required to reach thrust steps during acceptance testing

1. Burn-In

Once the emitter has been assembled, it will be subject to a firing test (burn-in test) where emitter-specific performance data are characterized. This includes among others a general verification of functionality, and a characterization of mass efficiency and impedance. Consequently, accepted emitter will be integrated into the rest of the thruster module. It is at this stage where the allocation of emitters depending on their performance and the application requirements will be conducted.

2. Mechanical

Mechanical tests encompass random vibration and sinusoidal excitation with a verification by resonance sweeps before and after the test campaign. Standard test levels for random vibration are defined as per NASA

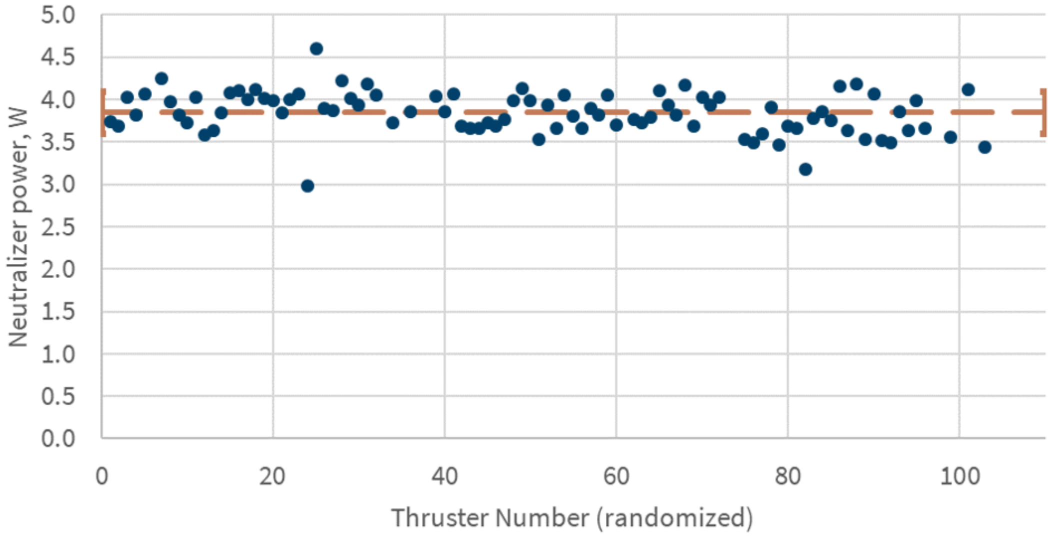


Figure 5: Neutralizer power draw at nominal operation during acceptance testing

GEVS (GSFC-STD-7000A) and are listed in Table 2 and 3 below. Typical test levels for sinusoidal vibration are listed too. Adaptation to customer-specific test levels can be conducted within facility limitations.

Table 2: Typical random vibration test levels during acceptance testing

RANDOM VIBRATION		
	Acceptance	Protoflight
Frequency (Hz)	PSD (g^2/Hz)	PSD (g^2/Hz)
20	0.013	0.026
50	0.08	0.16
800	0.08	0.16
2000	0.013	0.026

Table 3: Typical sinusoidal vibration test levels during acceptance testing

SINUSOIDAL VIBRATION	
Frequency (Hz)	Acceleration (g)
5	1.11
21	19.6
21	20
60	20
60	6
100	6

3. Thermal

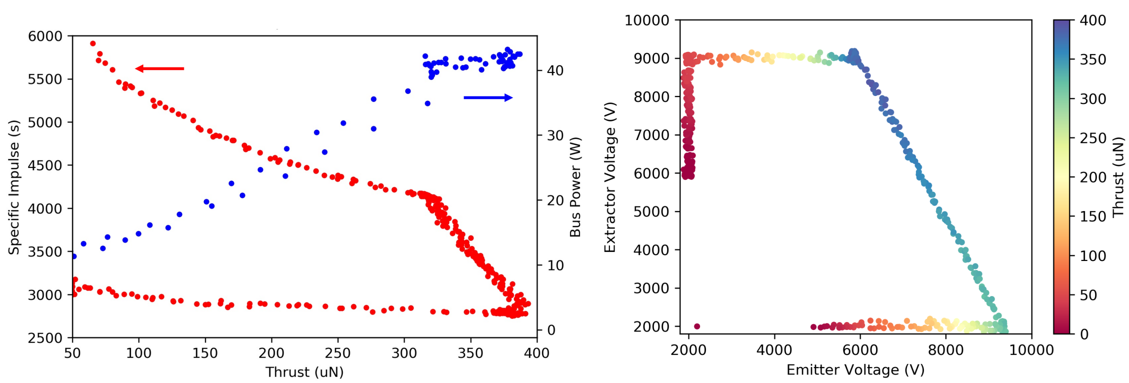
Thermal tests typically encompass non-operational (off-cycle) ambient testing with an application-specific number of cycles.

4. Functional performance

After successful passing of the environmental tests, the thruster module will be subject to a final functional verification and performance test in suitable vacuum chambers (see Figure 6) to ensure that all subsystems including neutralizers are working and performing nominally. Thruster-specific data are collected and analysed including look-up tables for the performance and a thrust vector analysis.

Figure 6: Vacuum chambers for acceptance testing

Exemplary data from acceptance testing are plotted in Figure 7. These data are provided to allow users to evaluate the operational envelope that is available for their mission application, and to allow for trajectory optimization.



(a) Performance envelope[a]

(b) High-voltage envelope

Figure 7: Exemplary performance acceptance test data

If all acceptance criteria have been passed, the thruster is then packaged within the clean room, and sent out to the customer; typically on the same day to reduce the lead time of the thruster.

IV. Development testing

While the IFM Nano Thruster in its current state is suitable for flight application, development testing is still being conducted to characterize further the performance to match with application requirements. These tests also serve to improve the quality of the ongoing production with respect to thrust performance, lifetime, and to generate feedback to suppliers. Exemplarily, the results of a hot cycling test to evaluate potential

[a]Note that the specific impulse is read from telemetry data with a typical mass efficiency taken into account, and is not adjusted to reflect the real mass efficiency of the emitter.

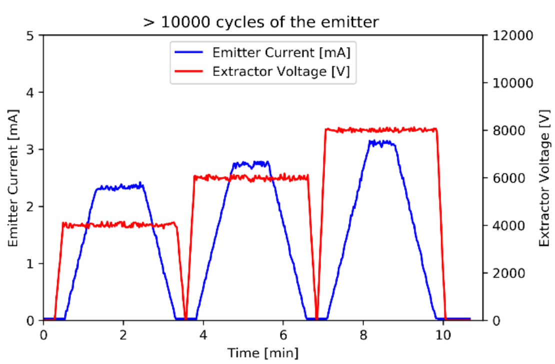
degradation of the emitter and/or the neutralizer with periodic quasi-steady application are presented in the subsequent Section.

A. Hot cycling test

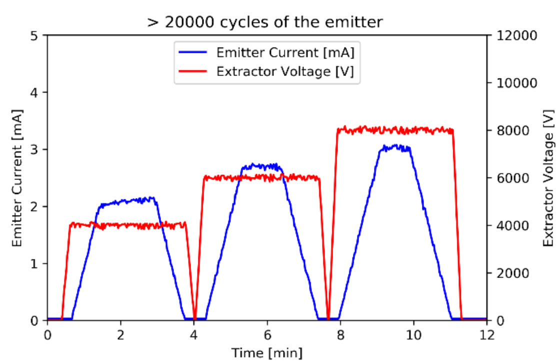
The main objective of the hot cycling tests was to demonstrate the feasibility as well as the reliability of using the thruster under study in a periodic quasi-steady mode. A to-design built EQM thruster was used for this test campaign, and operated in a small vacuum chamber with an ultimate pressure of 10^{-7} mbar. The following test sequence was conducted:

- 10,000 cycles of the emitter (1 mA of emission current)
- I-V characterization to assess any performance changes
- 10,000 cycles of the emitter (1 mA of emission current)
- I-V characterization
- 20,000 cycles of the neutralizer (5 mA of beam emission current)
- I-V characterization

Due to limitations of the cooling system and the size of the vacuum chamber, the emitter could only be operated at an operational point lower than nominal operation. Further, the EQM used featured a suboptimal emitter with less than 28 needles firing, since the operation inside the small vacuum chamber is prone to degrade the emitter resulting from backsputtering. As can be seen in Figure 8, however, the performance of the emitter stayed constant over the course of the cycling test, demonstrating that no degradation occured. Similarly, the 20,000 cycles of the neutralizer had no adverse effect on the emitter performance. Impedance of the emitter increased slightly during the test campaign from 2.6 to 2.9 MΩ, indicating some lifetime effect likely due to backsputtering material on the emitter needles.



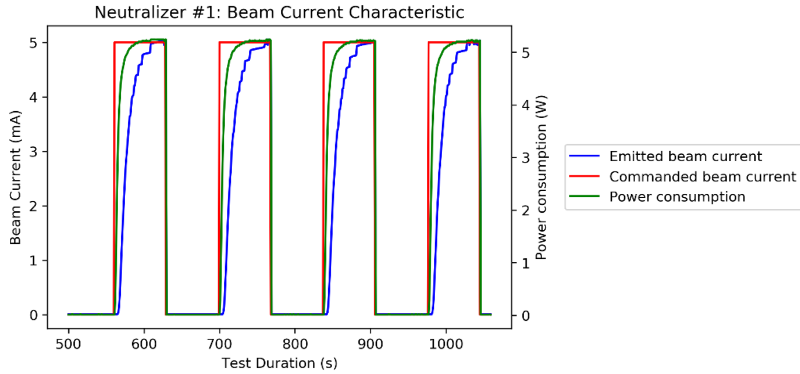
(a) I-V characteristics after 10,000 cycles



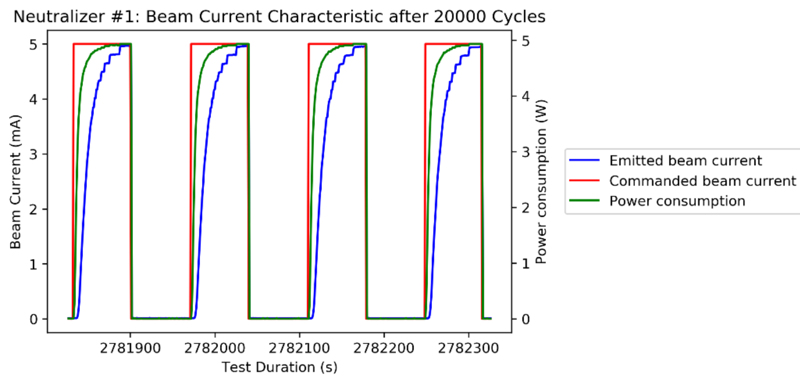
(b) I-V characteristics after 20,000 cycles

Figure 8: Performance results from hot cycling test - emitter

For the neutralizer itself, the power limit was set to 6 W, the current limit to 0.5 A, and a nominal beam current of 5 mA commanded. The intrinsic properties of the neutralizer paired with the control logic of the PPU firmware result in a relatively slow rise time of the beam current. This is done to avoid e.g. an overheating of the neutralizer due to overshooting in the controlled currents. As is shown in Figure 9, the neutralizer is able to operate at same performance level with the same rise time after 20,000 cycles without any obvious degradation. In fact, the power draw at the beginning of the test campaign was higher than towards the later phases, which is likely a result of backsputter material from the emitter cycle test that was removed with additional power during the earlier phase of the neutralizer test.



(a) Neutralizer characteristics at test start



(b) Neutralizer characteristics after 20,000 cycles

Figure 9: Performance results from hot cycling test - neutralizer

V. Conclusion

The IFM Nano Thruster, developed by FOTEC and commercialized by ENPULSION, as the consequential step from the FOTEC heritage on liquid metal ion sources and FEEP technology has become a widely applied propulsion system on small satellites, with now 25 thrusters in space, and a mass production exceeding the 100th thruster at time of publication. With improvements on the PPU part, and the planned option to include thrust vector control, a continuous effort is conducted to respond to the needs of the application market.

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References

[1] Villela, T., Costa, C. A., Brandão, A. M., Bueno, F. T., and Leonardi, R., "Towards the Thousandth Cubesat: A Statistical Overview," *International Journal of Aerospace Engineering*, Vol. 2019, 2019.

[2] Lev, D. R., Myers, R. M., Lemmer, K. M., Kolbeck, J., Keidar, M., Koizumi, H., Liang, H., Yu, D., Schönherr, T., Gonzalez del Amo, J., Choe, W., Albertoni, R., Hoskins, A., Yan, S., Hart, W., Hofer, R. R., Funaki, I., Lovtsov, A., Polzin, K. A., Olshanskii, A., and Duchemin, O. B., "The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years," 35th International Electric Propulsion Conference, Oct. 2017, IEPC-2017-242.

[3] Schönherr, T. and Gonzalez del Amo, J., "Electric Propulsion," *CEAS Quarterly Bulletin*, Vol. 2017, No. 4, 2017, pp. 18–21.

[4] Burton, R. L. and Turchi, P. J., "Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 14, No. 5, Sept.-Oct. 1998, pp. 716–735.

[5] Schönherr, T., *Encyclopedia of Plasma Technology*, Vol. 2, chap. Thrusters: Ablative Pulsed, Plasma Acceleration in, Taylor & Francis, New York, NY, USA, 1st ed., Feb. 2017, pp. 1452–1461.

[6] Gilbert, W. and Dowling, A., *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure*, 1600.

[7] Taylor, G. I., "Disintegration of water drops in an electric field," *Proceedings of the Royal Society of London. Series A, Mathematical, Physical and Engineering Sciences*, Vol. 280, No. 1382, 1964.

[8] Huberman, M. N., Beynon, J. C., Cohen, E., Goldin, D. S., Kidd, P. W., and Zafran, S., "Present Status of Colloid Microthruster Technology," *Journal of Spacecraft and Rockets*, Vol. 5, No. 11, Nov. 1968, pp. 1319–1324.

[9] Vasiljevich, I., Tajmar, M., Grienauer, W., Plesescu, F., Buldrini, N., Gonzalez del Amo, J., Carnicero Dominguez, B., and Betto, M., "Development of an Indium mN-FEEP Thruster," 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2008, AIAA-2008-4534.

[10] Vasiljevich, I., Buldrini, N., Plesescu, F., Tajmar, M., Betto, M., and Gonzalez del Amo, J., "Porous Tungsten Crown Multiemitter Testing Programme Using Three Different Grain Sizes and Sintering Procedures," 32nd International Electric Propulsion Conference, Sept. 2011, IEPC-2011-065.

[11] Tajmar, M., Vasiljevich, I., Plesescu, F., Grienauer, W., Buldrini, N., Betto, M., and Gonzalez del Amo, J., "Development of a Porous Tungsten mN-FEEP Thruster," Space Propulsion 2010, May 2010.

[12] Tajmar, M., "Overview of Indium LMIS for the NASA-MMS Mission and its Suitability for an In-FEEP Thruster on LISA," 32nd International Electric Propulsion Conference, Sept. 2011, IEPC-2011-009.

[13] Vasiljevich, I., Buldrini, N., Plesescu, F., Tajmar, M., Betto, M., and Gonzalez del Amo, J., "Consolidation of milli-Newton FEEP Thruster Technology based on Porous Tungsten Multiemitters," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July-Aug. 2011, AIAA-2011-5592.

[14] Krejci, D., Reissner, A., Seifert, B., Jelem, D., Hörbe, T., Plesescu, F., Friedhoff, P., and Lai, S., "Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit," 4S Symposium, May-June 2018.

[15] Krejci, D., Hugonnaud, V., Schönherr, T., Little, B., Reissner, A., Seifert, B., Koch, Q., Bosch Borras, E., and Gonzalez del Amo, J., "Full Performance Mapping of the IFM Nano Thruster including Direct Thrust Measurements," *Journal of Small Satellites*, Vol. under review, 2019.

[16] Grimaud, L., Krejci, D., Reissner, A., and Seifert, B., "The IFM Micro FEEP Thruster: a Modular Design for Smallsat Propulsion," 36th International Electric Propulsion Conference, Sept. 2019, IEPC-2019-675.

[17] Krejci, D., Reissner, A., Schönherr, T., Seifert, B., Saleem, Z., and Alejos, R., "Recent Flight Data from IFM Nano Thrusters in a Low Earth Orbit," 36th International Electric Propulsion Conference, Sept. 2019, IEPC-2019-724.