The first 100 FEEP propulsion systems in space: A statistical view and lessons learnt of 4 years of ENPULSION

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David Krejci*, Alexander Reissner†
ENPULSION, Wr Neustadt, Lower Austria, 2700, Austria

The in-orbit demonstration of an ENPULSION NANO propulsion system in 2018 marked the first liquid metal field emission electric propulsion system tested in space, and the successful introduction of the ENPULSION NANO. In the four years since then, this propulsion system was successfully industrialized and 136 systems have flown on 61 different spacecraft. In parallel, new propulsion systems based on FEEP technology have been developed, expanding the thrust and power range and introducing new features and lessons learnt from the large space heritage of the ENPULSION NANO. Two of these new propulsion systems have been launched to space so far. This paper present telemetry data of ENPULSION NANOs from several spacecraft, including larger orbital change maneuvers, and discusses applications utilizing ENPULSION NANO systems so far. We then provide an overview of the current onorbit statistics of the ENPULSION propulsion systems. We present aggregated onorbit statistical data of the ENPULSION NANO, discuss challenges encountered and present lessons learnt during onorbit operations, customer AIT support and ground test campaigns conducted at different facilities.

I. Nomenclature

AIT	=	Assembly, Integration and Test
COTS	=	Commercial off-the-shelf
EEE	=	Electronic, Electrical and Electromechanical parts
EP	=	Electric Propulsion
ESPA	=	EELV Secondary Payload Adapter
FDIR	=	Fault Detection, Isolation, and Recovery
FEEP	=	Field emission electric propulsion
HV	=	High Voltage
IOD	=	In Orbit Demonstration
LV	=	Low Voltage
OBC	=	On-Board Computer
PPU	=	Power Processing Unit
SEE	=	Single Event Effect

II. Introduction

After launch in Dec 2018, the first propulsion system based on liquid metal Field Emission Electric Propulsion (FEEP) was successfully demonstrated in orbit in 2019 in an IOD conducted together with FOTEC [1,2,3]. Since then, 135 additional ENPULSION NANO systems (formerly IFM Nano Thruster) were launched. In addition, a higher power and total impulse thruster, the ENPULSION MICRO R^3 has been developed, which was successfully demonstrated in orbit

*CTO, david.krejci@enpuslion.com.
†CEO, alexander.reissner@enpuslion.com.

in 2021. To date, hundreds of flight models have been manufactured, acceptance tested and delivered to 36 customers. Based on lessons learnt during manufacturing, AIT and in-space operation of the ENPULSION NANO, a new generation of propulsion systems with increased resilience has been developed, denoted the ENPULSION NANO R^3 product family. The first propulsion model in AR^3 configuration with thrust vectoring capability was recently launched.

This paper provides an overview of the launch statistics of the ENPULSION systems, as well as selected accumulated operational metrices, including total accumulated onorbit time. We discuss the limitations of the data imposed by visibility of customer data in some instances. Based on this, we derive lessons learnt, best practices and limitation based on AIT, onorbit operations and ground tests over a large number of propulsion systems and different implementations for a standardized electric propulsion system.

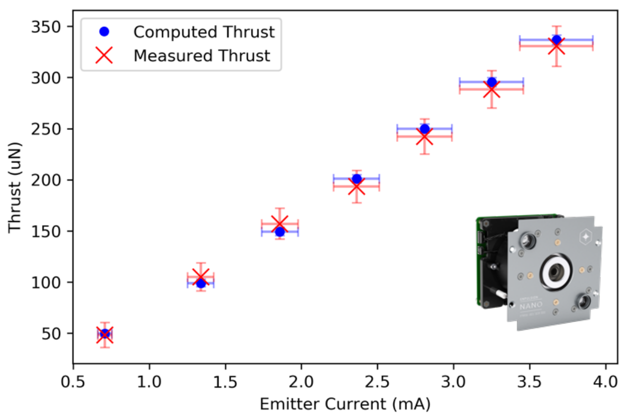
III. Propulsion system development

To date, two propulsion systems based on the proprietary FEEP technology have achieved flight heritage: the ENPULSION NANO, shown in Fig. 1, and the higher power ENPULSION MICRO R^3 (Fig. 2, left hand side) [1, 4, 5]. The ENPULSION NANO AR^3 (Fig. 2, right hand side) [6], a successor of the heritage ENPULSION NANO with added thrust vectoring capability, was recently launched.

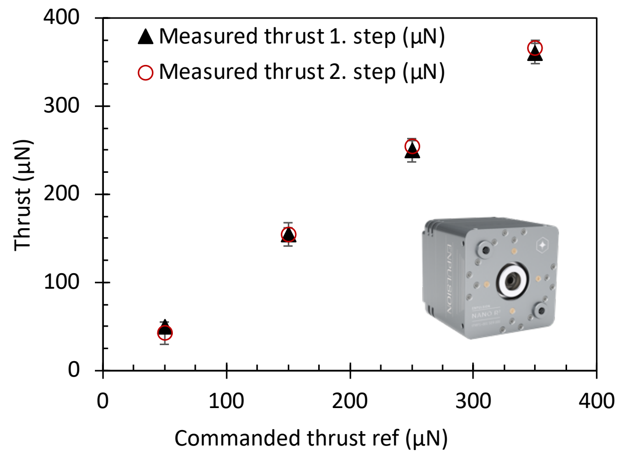
Fig. 1 Heritage system with significant flight heritage: ENPULSION NANO propulsion system

Fig. 2 Next generation R^3 propulsion systems launched to date: ENPULSION MICRO R^3 (left) and ENPULSION NANO AR^3 (right)

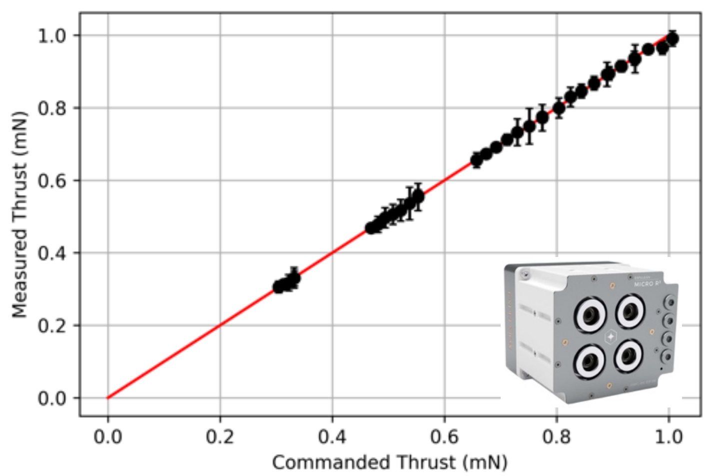
Direct thrust measurements have been performed on the ENPULSION NANO, the ENPULSION NANO R^3 and the ENPUSLION MICRO R^3. Several independent thrust measurement campaigns have been conducted on the ENPULSION NANO, at facilities of two space agencies, two customers and at FOTEC. The ENPULSION NANO R^3 and ENPULSION MICRO R^3 have both been tested on FOTEC's direct thrust measurement facility [8]. Fig. 3 shows sample results of such test campaigns, comparing the directly measured thrust to thrust commanded or computed by telemetry for each of the systems. Results displayed have been acquired at the ESA test facility (ENPULSION NANO) and at FOTEC (ENPULSION NANO R^3 and ENPULSION MICRO R^3).



NANO (thrust measurement at ESA facility) [7]



NANO R^3 (thrust measurement at FOTEC facility) [8]



MICRO R^3 (thrust measurement at FOTEC facility)

Fig. 3 ENPULSION NANO, ENPULSION NANO R^3 and ENPULSION MICRO R^3 direct thrust measurements, facilities and original publication indicated if applicable

IV. On-orbit demonstration of the ENPULSION NANO

The first IOD of the ENPULSION NANO, which also represents the first propulsive operation of a FEEP thruster in space, has been reported in [1, 2]. This IOD was conducted on a 3U Cubesat launched in 2018, and included an independent thrust verification by comparing the s/c altitude change expected from propulsion system telemetry, to the altitude change determined by GPS measurements before and after at 15 min and a 30 min thrusting maneuver. A comparison of expected (from propulsion system telemetry) to observed (GPS) altitude change is given in Table 1, and confirms the good agreement of FEEP thrust models seen in ground test campaigns (Fig. 3). Later, more precise orbit determination methods confirmed the good agreement of thrust model on different spacecraft.

As part of the IOD, the controllability of the propulsion system to perform precise thrust steps, as well as thrust repeatability after several idle days, were verified as discussed in [1, 3].

Table 1 Change in average spacecraft semi-major axis due to thrust maneuver, measured from GPS data and calculated from propulsion telemetry, from [1]

Maneuver parameters	Average change in semi-major axis, m	
	Calculated from thruster telemetry	GPS measurements
Test 1: Iem=2 mA, 15 min	72	70 ± 5
Test 2: Iem=2 mA, 30 min	115	116 ± 5

V. On-orbit operations of the ENPULSION NANO

Va. Propulsion system commissioning

Previous publications [1, 2] presented the early subsystem commissioning efforts conducted during the IOD of the ENPULSION NANO in 2018, and telemetry from commissioning and early stage operation of multiple propulsion systems on a small satellite [3]. This paper presents data from ENPULSION NANO onboard of 4 additional spacecraft (identified here as spacecraft A to D). A typical system temperature behavior showing propellant liquification and thrusting at increasing thrust levels is reproduced in Fig. 4 from [3].

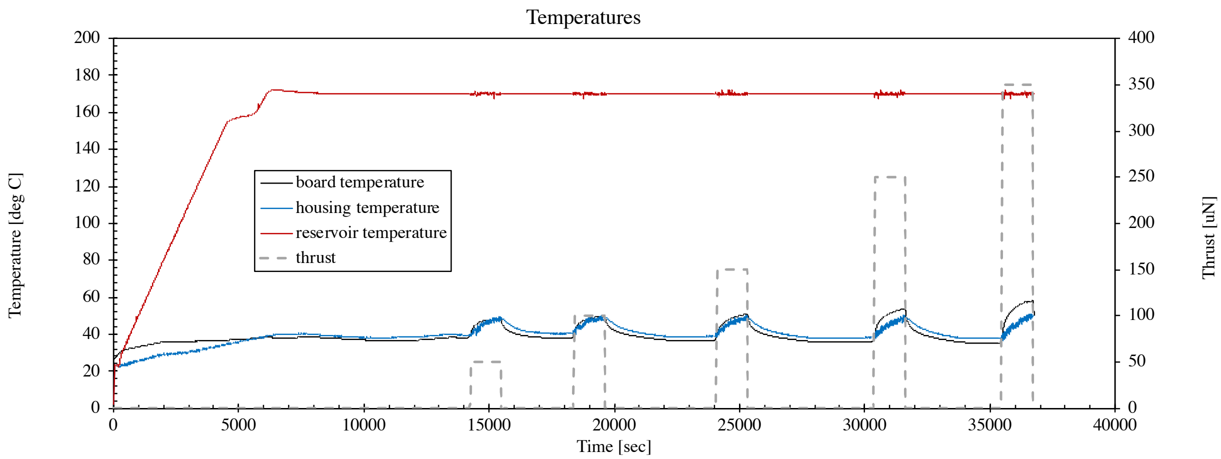


Fig. 4 Thruster temperature telemetry during multiple consecutive firings with different thrust levels [3]

Fig. 5 (left hand side) reproduces a firing plot from these early stage commissioning firings. During this stage, the emitter performance is increasing as ion emission sites are initiated after AIT efforts and prolonged exposure to atmosphere, which can be seen by steadily decreasing emitter impedance when operated in a constant thrust mode. This is clearly visible by the decreasing emitter voltage in conjunction with increasing emitter current require to achieve the commanded thrust set point of 350 µN. The spacecraft carrying this thruster was launched in Dec. 2018.

On the right hand side of Fig. 5, a similar thrusting is shown for a different propulsion system on a different spacecraft for a thruster that had previously completed commissioning and has been thrusting for some time. One can see the constant emitter impedance, reflected in constant emitter voltage and emitter current to achieve the set thrust point of 300 µN in this example. For this particular thruster, the accumulated on-orbit time and thrusting time prior to the shown plot are in the order of 112 days, and 4.7 hours respectively. The spacecraft carrying this propulsion system was launched in Spt. 2020.

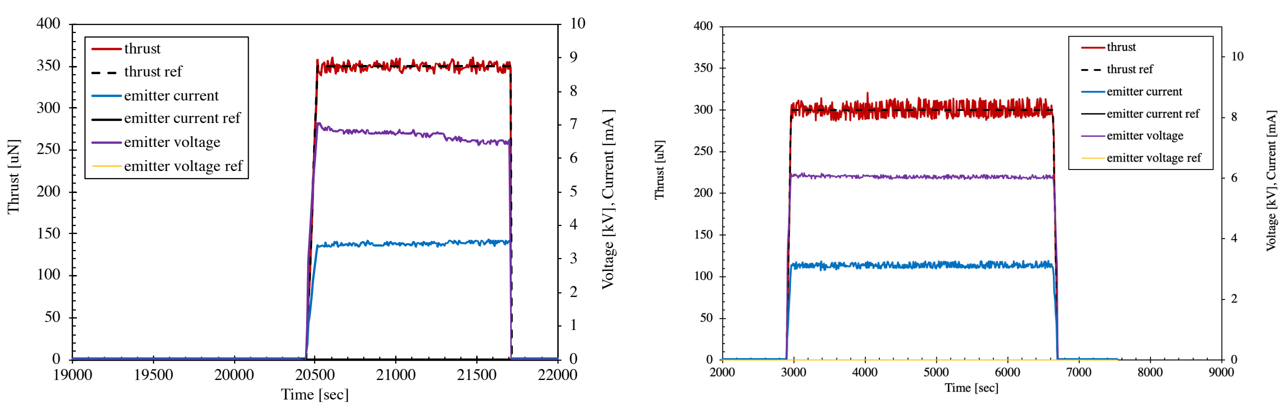


Fig. 5 Left: Propulsion system firing during commissioning [3] (left) and after on-orbit burn in, telemetry shown from a different system and spacecraft A (right)

Fig. 6 shows an early life, 38 h segment of a propulsion system on spacecraft D (launched in June 2021) at constant thrust operation, during which the emitter impedance settles, while the thruster is able to achieve the commanded thrust level throughout.

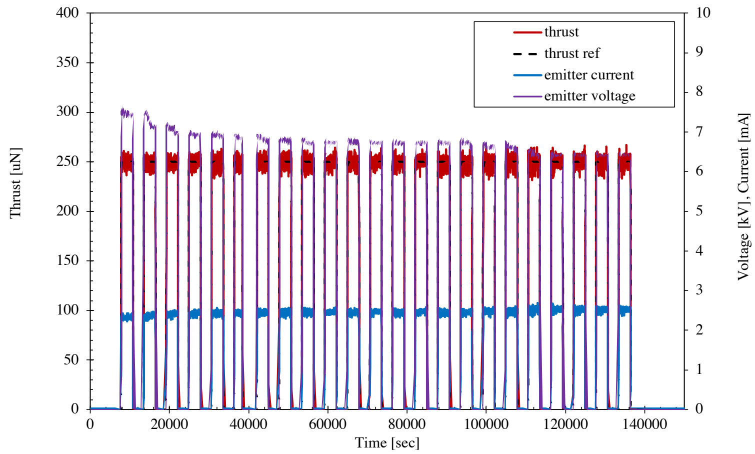


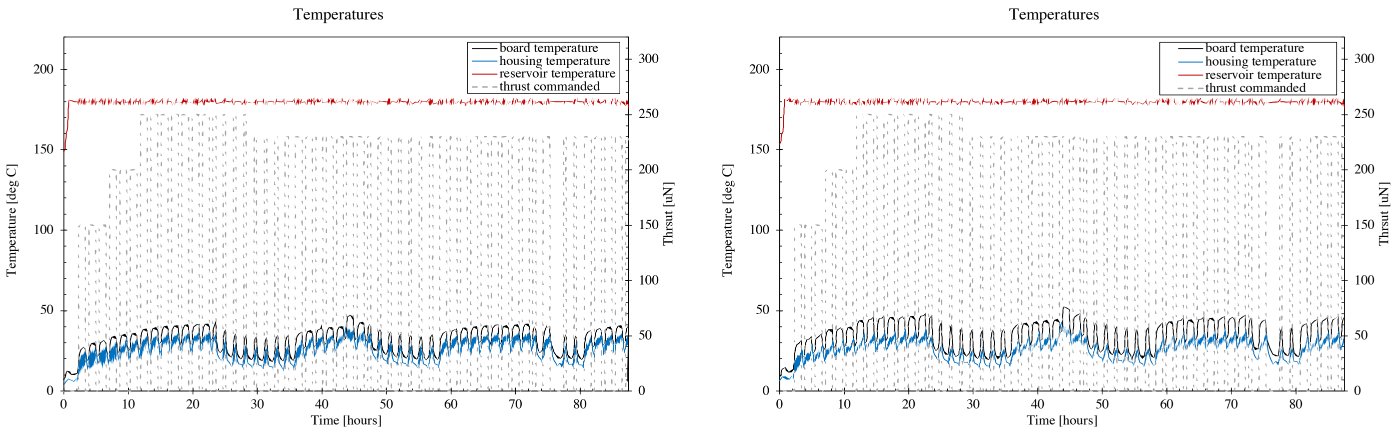
Fig. 6 Settling emitter impedance in the initial hours of operation on a propulsion system on Spacecraft D

Vb. Propulsion system operations

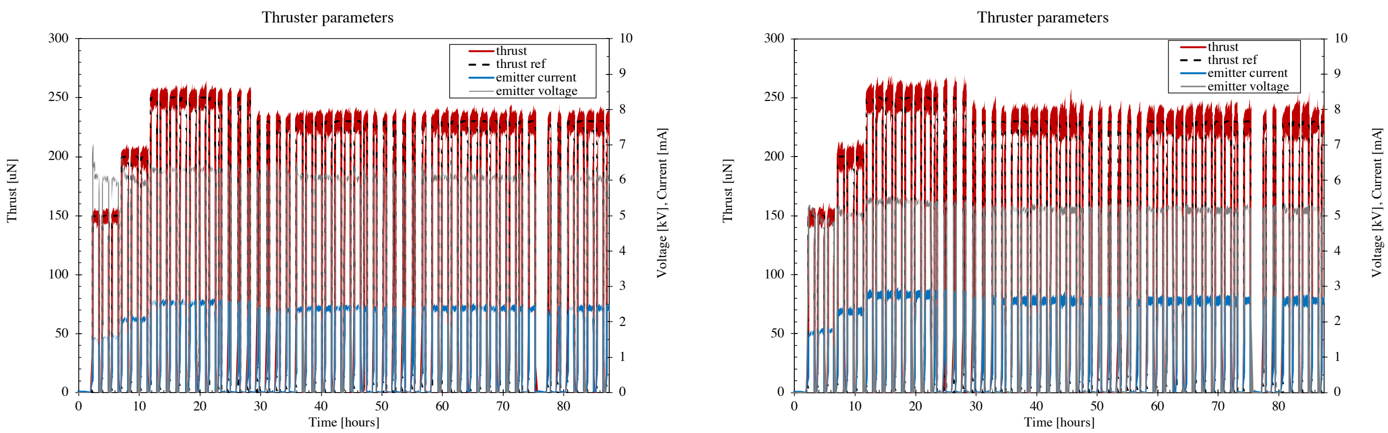
This section presents sample telemetry data from 4 propulsion systems on two different spacecraft that have been operated in parallel in extended orbit change maneuvers.

Fig. 7 shows telemetry segments of two out of four propulsion systems onboard an ESPA class spacecraft that were operated in parallel. During the time segment, which spans approximately 3.5 days, the propulsion systems were operated at different thrust set points and firing durations to optimize system power and thruster duty cycle, allowing to optimize the fully system from a power standpoint and to understand the thermal situation during extended orbit change operation. Fig. 7a shows the system temperatures and commanded thrust setpoints. The response of electronics board temperature to sections of increased power draw during thrusting operations can be seen.

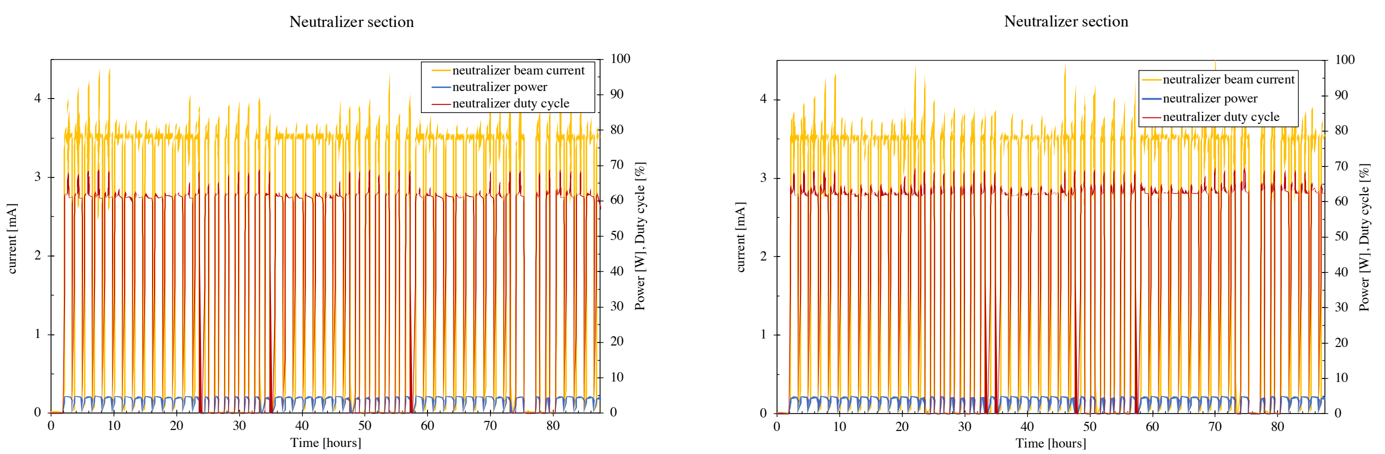
The corresponding propulsive parameters including thrust achieved (calculated by the propulsion system based on the internal thrust model using primarily emitter voltage and current) and measured ion emission current are shown in Fig. 7b, while the main neutralizer parameters are plotted in Fig. 7c.



a) Temperatures and thrust setpoints for two ENPULSION NANOs operated in parallel



b) Achieved thrust and emitter telemetry for two ENPULSION NANOs operated in parallel



c) Neutralizer operation for two ENPULSION NANOs operated in parallel

Fig. 7 Spacecraft B: Two ENPULSION NANOs used in parallel during orbit acquisition maneuver, operated at different thrust and power levels and duty cycles to optimize overall system.

A different orbit change maneuver, using a constant thrust approach on two propulsion systems operated in parallel, is shown in Fig. 8 for a different ESPA class spacecraft. A segment of just over 420 hour total maneuver duration is shown, with a 12 hour detail highlighted for one of the systems, showing the constant thrust operation at specific duty cycle.

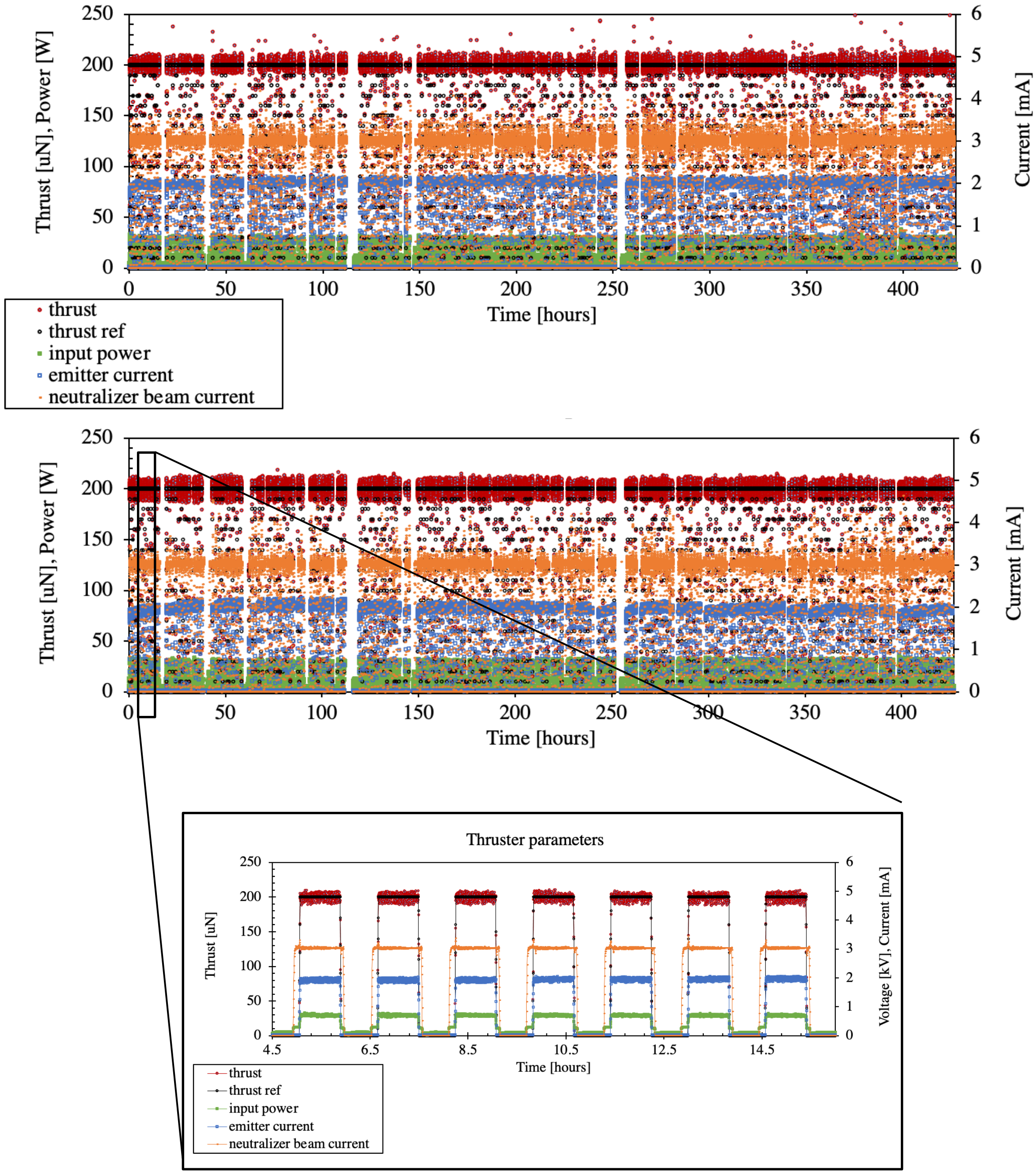


Fig. 8 Spacecraft C: Constant thrust maneuver using two ENPULSION NANOs with firing duty cycle in accordance to orbital cycle

While typically during commissioning propulsion systems are operated in a specific way to only liquify the propellant when thrusting operations are planned, during operational usage we have seen multiple instances that kept the propulsion systems in hot standby for weeks or months in between thrusting operations.

Vc. Propulsion system application

In line with the variety of different missions using ENPULSION systems, the application of the propulsion systems has been varied. Typical applications that use or plan to use the ENPULSION NANO have been:

- bring into target orbit, in conjunction with ride share
- formation and cluster initiation
- maintenance of precise orbits to improve ground track

- constellation rollout
- deorbiting

An example combining some of the above is shown in Fig. 9, plotting the semi-major axis evolution of two spacecraft carrying ENPULSION NANO systems. The data shows the initial natural decay of both spacecraft before commissioning of the propulsion systems, followed by a propulsive transfer to the target orbit. Once reaching the target orbit, in this case a repeat ground track orbit, the propulsion units were frequently used to maintain a precise target orbit, in this example to improve the ground track for an earth observation instrument. The data shows two spacecraft that were launched from a shared launch vehicle, including in-plane separation achieved by staggered orbit acquisition maneuvers.

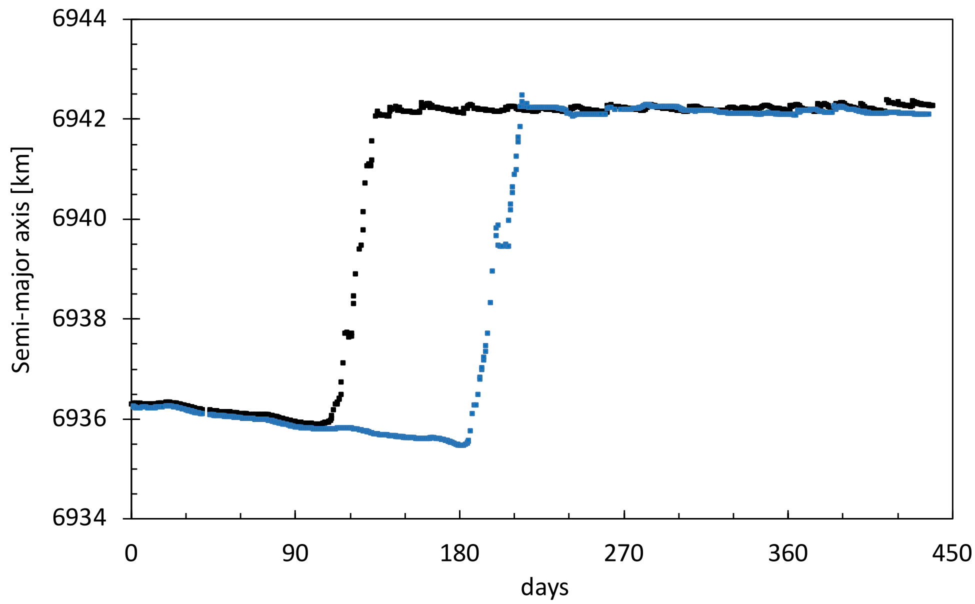


Fig. 9 Spacecraft A & B: Average semi-major axis evolution of two spacecraft using multiple ENPULSION NANO systems for orbit transfer each, arbitrary relative time in days: natural decay before propulsion system usage, followed by orbit acquisition, followed by precise orbit keeping during operational mission. Both spacecraft were launched on the same rideshare, data shows drifting separation. Data taken from [9].

VI. On-orbit statistics

To date, hundreds of propulsion systems have been delivered to customers for integration. All delivered systems have been subjected to at least the standard acceptance test procedure, consisting of emitter characterization firing, vibration and ambient thermal cycling testing, followed by a standardized functional acceptance firing, in which the total system performance and ion emission parameters are determined. In total, 138 propulsion systems have been launched, on a total of 63 different spacecraft.

Table 2 summarizes the number of propulsion systems currently on orbit and the number of spacecraft the proulsion systems are distributed, ranging from 1 propulsion system on a 3U Cubesat, to a cluster of 7 systems on a >100 kg class spacecraft.

Table 2 Summary of ENPULSION propulsion systems in space

Propulsion System	Number of s/c	Number of Thrusters	Thrusters on Cubesats	Thrusters on ESPA class s/c	Different launches
ENPULSION NANO	61	136	22	114	19
ENPULSION NANO AR^3	1	1	1	0	1
ENPULSION MICRO R^3	1	1	0	1	1

Fig. 10 shows the launch evolution of the ENPULSION NANO over four years since the IOD. Popular rideshare launches can be identified by corresponding stepwise increase in number of propulsion systems on-orbit, typically consisting of several spacecraft with one or more propulsion system onboard participating in the same launch.

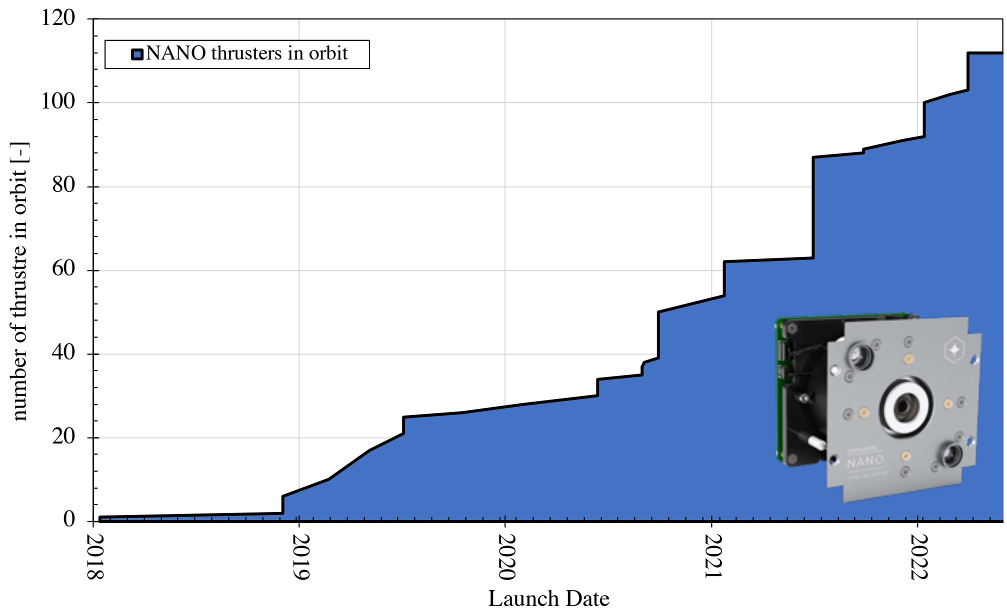


Fig. 10 Launch history of the ENPULSION NANO.

VII. On-orbit telemetry data availability

Given the commercial nature of most of the missions employing ENPULSION propulsion systems today, data availability becomes the premier issue for statistical analysis. Nevertheless, we are able to continuously receive significant amounts of telemetry, creating a valuable basis for statistical analysis of onorbit propulsion performance and behavior.

Fig. 11 shows the data availability of accumulated onorbit telemetry times for the heritage ENPULSION NANO systems currently in space that ENPULSION has received full telemetry on. From Fig. 11 it would appear as if hot standby times scale with accumulated thrusting time. However, from operations support we often see that during mission operations, propulsion systems are frequently kept in hot standby for weeks or even months between thrusting maneuvers, which would make us expect hot standby times accumulating even in times of little thrusting operation. The fact that this is not reproduced in Fig. 11 shows that the data shown does not correspond to the true accumulated onorbit times, but only to the portion that is made available to ENPULSION in the course of review and support, which is often skewed around specific customers and operational constraints (eg. when support is provided during a change of thruster operation). In addition, repetitive thrusting maneuvers and hot standby durations are less frequently reported to ENP to minimize customer effort. Only data where the full telemetry provided to ENP was included in the data shown, while firing and hot standby durations reported by the customer qualitatively without telemetry is not included. This means that the actual accumulated firing time and hot standby times onorbit are likely to be higher, and the data shown in Fig. 11 corresponds to the lower bound of accumulated durations.

With only one ENPULSION MICRO R^3 and ENPULSION NANO AR^3 system each onorbit at time of writing it is not possible to present data without allowing to infer on customer and mission profile.

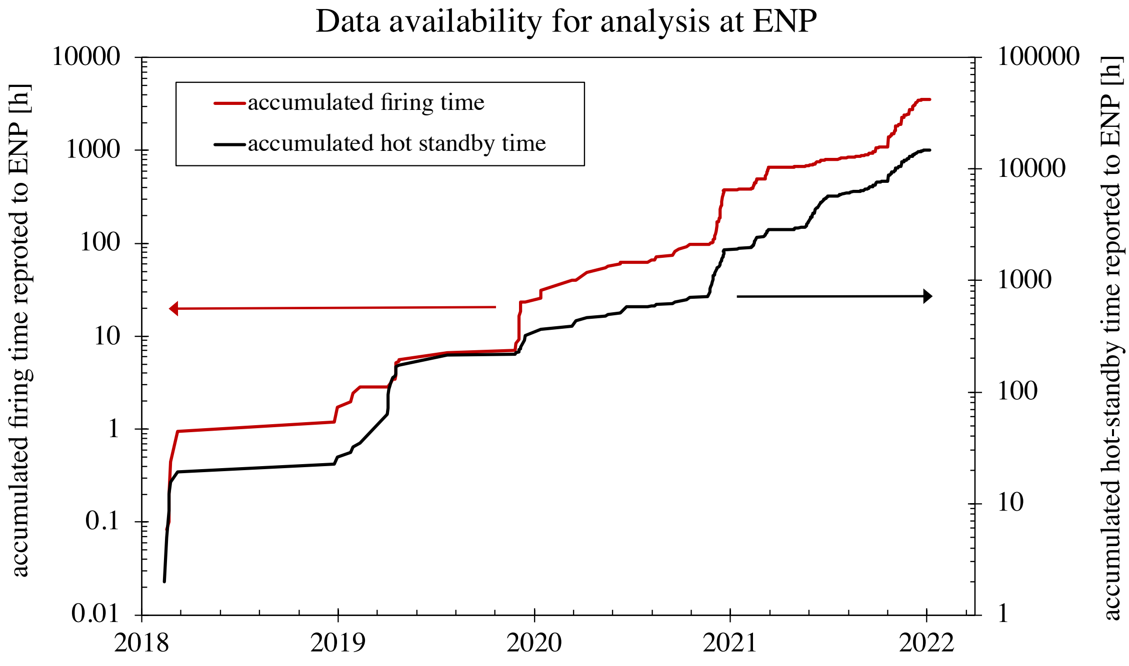


Fig. 11 NANO propulsion sytem data availability for analysis at ENPULSION: Accumulated firing time and hot standby time for which full telemetry was made available to ENPULSION. The scaling of hot standby time with firing time indicates that the data shown is limited by data visibility, and accordingly represents minimum accumulated times, with true on-orbit times likely higher, based on customer communication.

The data underlying the high-level parameters shown in Fig. 11 represents an exhaustive source for analyzing propulsion onorbit performance over a large number of different missions, usages and customers.

Table 3 provides high-level statistical data availability, as well as the longest accumulated firing of a single propulsion system of over 650 hours of thrusting. Note that propulsion systems that are awaiting commissioning, e.g. only used in deorbiting, are not included in this summary.

Table 3 Accumulated On-orbit operation time of all ENPULSION NANO systems, as of Feb 2022

	Accumulated time**
Accumulated orbit life for all operational propulsion systems where ENPULSION has visibility on thrust generation*	58.3 years
Accumulated orbit life for all operational propulsion systems between launch and last telemetry of thrust maneuver made available to ENPULSION	22.0 years
Longest accumulated firing time on a single propulsion system (launched in June 2021)	> 650 hours

*note that this includes time accumulated between the last telemetry was made available to ENP and Feb 2022, assuming that during normal operations, any anomaly would be reported to ENPULSION

**as several customers provide telemetry after commissioning only intermittently to ENP, the two values are considered a lower and upper bound for accumulated times. Also note that propulsion systems not yet commissioned are not appearing in this table.

VIII. Lessons learnt from the ENPULSION NANO propulsion system

Based on the significant heritage and data available on the ENPULSION NANO, several lessons learnt, and issues observed can be derived. This section gives a brief discussion of aspects encountered.

1) **Value of flexibility to change on-orbit command software**
   A significant benefit of the large number of parallel onorbit commissionings and operations is the opportunity to improve operation across different missions. The large amount of data, operation time accumulated and learnings from multiple propulsion systems operated in different architectures and operation modes, allows for continuing learning of system behavior onorbit and improvement of propulsion system operation, including optimized commissioning strategies or identification of new FDIR conditions. This can create significant benefit as learnings can be shared across missions and customers by infusing findings into new revisions of the user manual, without violating mission confidentiality. However, to fully leverage this potential, operators are required to have the flexibility to change their onorbit command sequences and command structures to implement new findings. As this can cause additional implementation and validation efforts, it is observed that operators may tend to neglect or significantly delay implementation of such newer findings. The outcome of such lack of timely implementation of new findings has been observed to range from continuing to perform unnecessary extra tests, to omitting the implementation of a new FDIR condition that was found in another customer mission, which in the worst case, could lead to failure.

2) **Propellant solidification cycling and propulsion system resets**
   When high voltage is applied to the ion emitter after launch for the first time, a thin oxidation layer has to be overcome and therefore voltages to initiate the emission are higher, increasing the likelihood of sparks between the emitter and the extractor. The high voltage sections of the PPUs are designed to be resilient against such sparking events, which occur primarily during the early startup of ion emission from the emitter needles, but internal interferences in the HV and LV sections of the heritage PPU of the ENPULSION NANO have been found to be capable of triggering electronics resets that can cause the propulsion system electronics to reboot into idle state. Since the PPU is also used to control the propellant temperature to maintain the propellant in liquified state during ion emission, such resets can lead to propellant solidification, if not acted upon within several minutes of the reset by the OBC by commanding temperature control mode. It has been found that especially during early thruster life, solidification cycles can bear the risk of thruster degradation, if repeated solidification cycles are performed without properly conditioning the ion emitter by achieving sustained ion emission first. Most customers have been able to implement the recommended FDIR measures to identify such resets and command the propulsion system back to liquefication mode within several minutes. However, relying on an external FDIR implementation is considered a certain risk, especially given the combination of increased occurrence of sparking events at early commissioning, in combination with the higher risk of degradation by repeated solidification cycles which is also amplified during early commissioning stages. Both aspects of the early commissioning stage, during which the thruster-system interaction is typically less well understood, can lead to failure in systems that are unable to successfully detect such events. To refrain from relying on the external FDIR implementation on OBC side, resilience of the PPU against sparking to maintain propellant liquification throughout commissioning, was a design driver on the upgraded propulsion system development of the ENPULSION NANO R^3 series and ENPULSION MICRO R^3.

3) **Volatile contamination during storage, AIT and launch**
   Exposure of the ion emitter to a contaminating material that features more favorable wetting properties on Tungsten than Indium, was found as a root cause for decreased propellant availability at the emission sites, which can ultimately result in a loss of ion emission. Examples of such materials include silicone oils, hydrocarbon lubricants or volatiles of certain epoxies. This effect can be augmented by the fact that the ENPULSION NANO design (contrary to the new R^3 generation design) features large internal venting paths that form, in many cases, the largest venting path of the spacecraft. This leads to a situation in testing and deployment in space, in which a significant proportion of the internal volume of the spacecraft and therefore volatiles from non-space compliant materials, could be vented through the ENPULSION NANO ion emitter. Exhaustive compatibility studies of commonly used materials, including exposing samples during curing, have been investigated based on material lists provided by a range of customers.

4) **OBC commanding forbidden states**
   Instances have been encountered during which forbidden command states, eg forbidden high voltage settings during propulsion system operation in manual mode, or violation of the startup sequence of auxiliaries, such as

the neutralizer prior to ion emission when operated in manual mode, were commanded. In the ENPULSION NANO, commanding such forbidden states can lead to damage, or loss, of the propulsion system. Three main causes leading to these events are highlighted:

a. In an instance observed, an anomaly was caused by sending overlapping command sequences, eg following a trigger of an FDIR while executing a command script, which was remedied by a manual reset of the propulsion system, but without aborting the continuing command script. After manual thruster initialization, the propulsion system therefore received command segments from the OBC from the inadvertently continuing earlier script.
b. Starting from an undefined state due to a previous, not fully executed, or incorrectly finished script: While the ENPULSION NANO preforms a full initialization when power cycled, no initialization of the command registers is performed between thrust maneuvers. This bears the risk of an undefined propulsion system state after a thrust maneuver was commanded, if not properly commanded to initial state. It has been observed that in subsequent activation of subsections of the PPU, the thruster was then effectively commanded to control to the previously setpoints, which can lead to issues in case of time sensitive startup sequences, such as the required start of the neutralizer before ion emitter activation to guarantee neutralization through all stages of the operation.
c. Due to insufficient ground verification of commanding scripts: Errors in commanding sequence scripts sent by the OBC have been encountered, which may have been avoided with increased effort and time spent in ground verification. However, this is amplified by the strong time pressure in a majority of the missions, and the typically stringent facility requirements necessary to perform an EP propulsion end-to-end verification after integration. The latter capability is in many cases beyond the capability of most Smallsat customers, and necessitates assistance by the propulsion provider to assist such joint testing in the propulsion manufacturer facilities.

5) Beam interaction with metallic structures (Baffle/Facility)

Due to the neutral droplets ejected from the FEEP emission site during ion emission that can condense on surfaces that have a direct view path to the emission site, baffles to shield sensitive equipment have been sometimes employed when placing sensitive equipment within the view of the emission site could not be avoided. Such a baffle is however not only blocking the unwanted droplet trajectories, but is also exposed to the high angle portions of the high energy ion plume, which in turn leads to backsputtering of the baffle surface material to the emitter. This leads in turn to a situation in which the ion emitter is exposed to a – usually metal – surface which experiences ion impingement of different energies, depending on distance and angle at which the baffle is introduced into the field of view of the thruster. Similarly, when operating a FEEP in a vacuum chamber, such as in a verification campaign, the chamber walls are hit by high energy ions and can lead to secondary species emission and significant backflow during ground test campaign [10].

Depending on geometry, material choice and operation modes, it has been observed that metal backflow from features implemented by the customer to shield sensitive equipment that would violate the defined plume stayout zones can lead to degradation effects of the ion emitter over extended duration operation. The same degradation mechanism has been reported during ground test campaigns. The degree of such degradation is dependent on the specific materials employed, geometries such as view angle and distance of the obstruction, and operation mode, eg emission current level, of the propulsion system. For example, the presence of metal backflow condensing on the emitter, if soluble in the propellant, can lead to locally changed physical properties of the propellant, if the ratio of backflow to reemitted flow is large, as can be the case when introducing a significantly large metal surface into the stayout zone, which then comes in contact with the ion plume.

The interaction when introducing an obstruction into the ion beam of any EP system is a complex topic and is highly depending on the specific geometry and materials, as well as the system operating parameters, typically requiring dedicated experimental characterization of each specific configuration. During customer integration support, we have performed a significant number of in-depth investigations of specific customer integrations and operation points, as well as material compatibility studies, complemented by establishing significant understanding of the ion beam properties at ENPULSION and FOTEC [11,12,13].

Due to this interaction of the ion emitter with material backflow either from baffle obstructions or facility walls, testing FEEPs in new environments on ground remains a difficult endeavor that typically requires several iterations to minimize facility impact on the ion emitter, a prerequisite to allow testing emitters for extended durations of time.

6) Space environment interaction effects:

Certain aspects of the orbital environment are complex to simulate during ground testing, but remain relevant to the onorbit performance of the propulsion system.

a. ATOX in combination with lower orbits and hot standby facing in Ram direction

We have noticed a potential correlation showing degradation of performance for specific lower orbits in combination with extended hot standby operation, with the spacecraft pointing the propulsion system with liquified propellant in Ram direction, in combination with not performing any thrusting operation (ion emission). During hot standby, the metal propellant is held in liquified state at increased temperature, facilitating oxidation buildup in combination with ATOX in lower earth orbits when facing Ram direction for extended durations. While oxides can be removed to some extent by ion emission when thrusting, oxide buildup during extended idle times when kept in hot standby and facing Ram direction could lead to potential emitter degradation. While this is currently in investigation including onorbit verification, this effect can be mitigated by means of implementing a stayout orientation for lower orbits when propellant is liquified and no thrust maneuvers are performed.

b. Operator negligence of local environment during operation, eg. high geomagnetic activity

While the PPU of the heritage ENPULSION NANO system has been matured through testing, it remains a COTS component based high voltage electronics. Given the lack of EEE part lot control, and therefore limited applicability of radiation testing results across different production lots, usage in orbit commends certain safety precautions, which may include safety precautions like suspension of high voltage operation during significant geomagnetic activity. Two measures have been implemented to remedy such failure case:

- Increase awareness at customers, especially customers with strong focus on Newspace business cases, of potential risk and limitations.
- New generation ENPULSION NANO R^3 and ENPULSION MICRO R^3 propulsion systems that are developed with a focus on PPU resilience, including part lot control.

7) Propellant accumulation on extractor

The accumulation of propellant droplets accumulating at the inward facing circumference of the extractor ring during long duration operation has been previously reported [14, 15]. If not counteracted, this can lead to changes in the electrical field geometry and ultimately establish a physical, and therefore electrical bridge between the emitter and the extractor. So far, this effect has not been encountered in space. As this is a deposition mechanism and not an erosion effect, it is reversible by melting the deposited Indium. This so-called cleaning has recently been verified successfully during an endurance test campaign. Recent tests however have indicated a stronger dependency of the rate of clogging with respect to the emitter mass flow, which can lead to higher clogging rates than previously reported [14, 15]. A model of the clogging process which provides good agreement with experimental data is described in Ref. 17, and a method of removing such propellant accumulation by changing the operational parameters of the thruster before a short can occur has been experimentally verified on ground. This method can be executed after accumulating a certain period of operation to remove and redistribute the propellant at the extractor without additional means required and can be implemented on orbit if telemetry would indicate the need for such a “cleaning” procedure.

IX. Expanding capabilities

Incorporating lessons learnt as described in section VIII, the development of new products and product updates has focused on:

- Improved operations by increasing propulsion system autonomy and resilience in terms of software and resets
- Increased electronics resilience, including EEE part lot control
- Increased agnostic against system integration issues, eg by minimizing satellite internal outgassing impacting sensitive propulsion components
- Improved firmware including fully automatic thruster operation.
- Added capabilities: AR^3 beam steering while maintaining an entirely passive system

A new generation of fully integrated propulsion systems has been developed since 2018 (see Fig. 12). This new generation is using many of the core elements of the heritage product, but features several distinct improvements on the PPU that allow the overall system to meet commercially relevant lifetime requirements in a broad range of applications. This includes a redesign of the PPU targeting increased radiation resilience with the support from agencies, lot-controlled testing and a new firmware that allows full automatic propulsion system operation and recovery. The R^3 design also avoids several failure modes on user-side by protecting sensitive parts from handling-issues during AIT and features extended protection against errors during operations. [16,17].

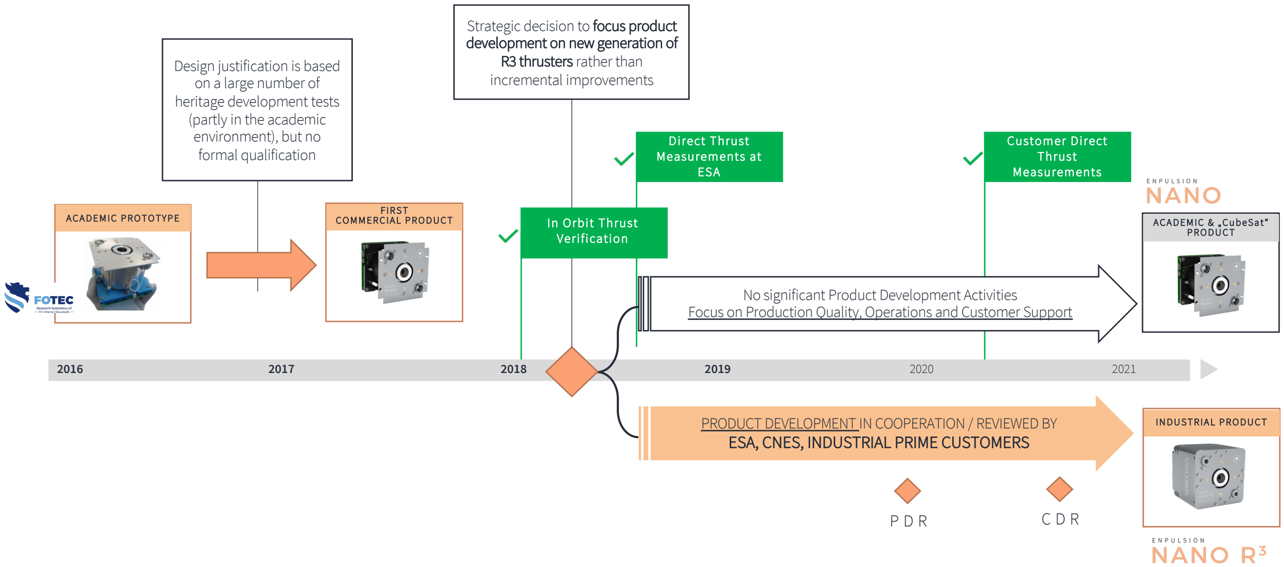
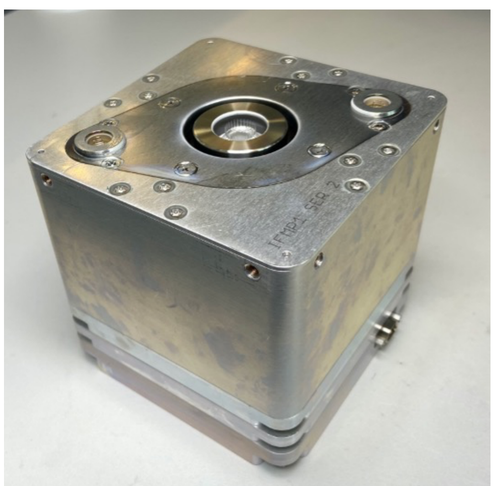


Fig. 12 Development logic of the ENPULSION NANO R³

The new ENPULSION NANO R³ product family (Fig. 13) also includes the addition of new capabilities to the FEEP propulsion systems, such as the thrust vector steering capability of the ENPULSION NANO AR³ system. This propulsion system, which shares the major propulsion system modules with the ENPULSION NANO R³, has the added capability to steer the net emitted ion beam by spatially distributed differential throttling of the ion emission sites. This is accomplished using multiple extractor electrodes, and does not require moving parts [18,19].



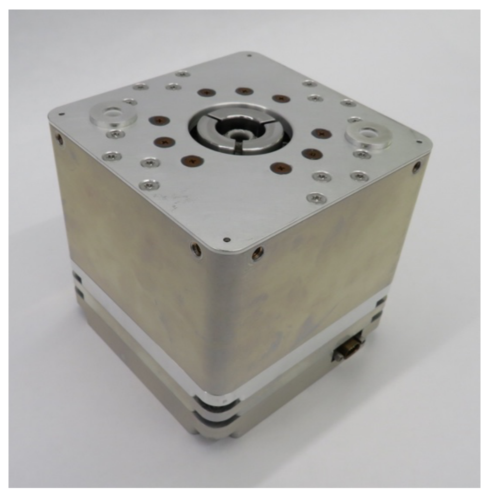


Fig. 13 ENPULSION NANO R³ (left) and ENPULSION NANO AR³ (right)

X. Conclusion

This paper presents the on-orbit statistics of the ENPULSION NANO, ENPULSION NANO AR³ and ENPULSION MICRO R³ propulsion systems, with a total of 138 propulsion systems launched to date on 63 spacecraft. Through the significant number of propulsion systems launched, as well as the standardization of the ENPULSION NANO, we explore the opportunity to gather a statistical view of onorbit data, as well as on integration in a large variety of missions and integrator capabilities. We presented selected flight telemetry from propulsion systems on 4 spacecraft, including two significant propulsive orbit maneuvers, and discuss different applications, including an example of precise orbit keeping during the operational phase of two spacecrafts. We discuss data availability regarding a large number of ENPULSION NANO propulsion systems and based on this present high level statistical ENPULSION NANO data including the data availability regarding total firing and hot standby durations, and report an accumulated firing duration of >650 hours on orbit for an ENPULSION NANO in space. We discuss a variety of lessons learnt based on on-orbit operation, integration, and customer side ground test campaigns, which have been incorporated in the next generation ENPUSLION R^3 propulsion products.

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