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IFM Nano Thruster electric space propulsion: from first Cubesat demonstration to the first 100 thrusters produced

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ABSTRACT

Following the successful In-Orbit-Demonstration of the first IFM Nano Thruster, a high rate production facility has been established at ENPULSION, which has delivered 2 thruster per week since opening in 2018. This paper gives a brief overview on the passively fed, metal propellant based technology which enables simple integration and manufacturing procedures. The thrusters IFM Nano Thruster and the IFM Micro Thruster are described, before a discussion of the underlying high rate production philosophy is given. The paper further details the specific implementation of the high rate approach by discussing the ENPULSION manufacturing flow.

INTRODUCTION

Having evolved into a viable market, the majority of Micro- and Smallsat business cases are based on constellations[1,2,3,4]. Rate of production, as well as streamlined integration, are becoming key drivers for success and result in flow down requirements for all subsystems. Traditionally, this has proven to be a demanding task for the propulsion subsystem, due to complexity of most propulsion subsystems themselves[5,6], which often drives the complexity of integration, as well as strong dependability of the propulsion design on mission requirements. Especially the latter has led to one-a-kind implementation, and therefore complex implementations, long lead- and cycle times, and therefore increased cost.

In this paper, the modular propulsion approach based on passively fed thruster building blocks is discussed, which enables introduction of standardized propulsion modules that adapt to mission requirements by possibility to clustering, and whose inert nature during integration allows for simplified integration.

IFM FEEP PROPULSION

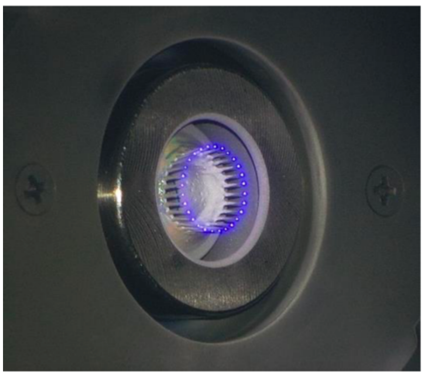

Figure 1 Closeup of IFM emitter during ion emission

The FEEP technology

Field Emission Electric Propulsion (FEEP) is based on extraction and ionization of propellant from a liquid metal, a process that can occur at field strengths in the order of 1Vnm^{-1}. To achieve the necessary local field strength, the liquid metal is usually suspended over a sharp emitter structure in needle form. Different configurations for passive propellant transport by capillary forces have been investigated, including capillary geometries, externally wetted needles and porous needle-like structures. Electrostatic stressing of the liquid metal above a certain threshold causes the metal to deform into a Taylor cone[7], further increasing the local field strength at the apex of the cone, where particle extraction is eventually achieved. In a FEEP device, the electrostatic potential is applied between the metal emitter and a counter electrode called extractor, which is designed to maximize transparency for emitted ions. In such a geometry, ions are then accelerated by the same electric field used for extraction and ionization, making this process highly efficient.

Field Emission Electric Propulsion (FEEP) has evolved[8,9,10,11] from a long heritage of liquid metal ion sources developed for over 25 years at the FOTEC (former Austrian Institute of Technology) and have gained considerable space heritage[12].

An intrinsic advantage of this technology is the unpressurized, solid propellant during integration and launch, which is only liquified once in space, greatly simplifying integration and launch procedures as well as negating typical propellant confinement issues.

The IFM Nano Thruster

The IFM Nano Thruster, shown in Figure 2, features one IFM crown emitter and has been successfully demonstrated in orbit following a launch in early 2018 including independent thrust verification by change of

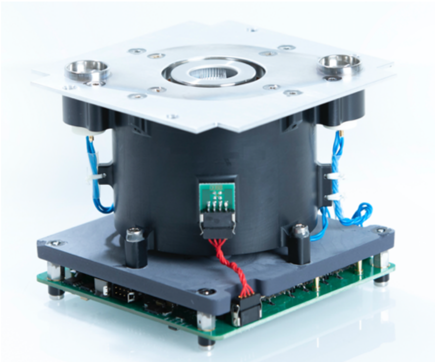

Figure 2 IFM Nano Thruster

orbital parameters[13,14]. The thruster has been developed by FOTEC based on heritage of the proprietary IFM emitter crown[15] and has been successfully introduced into the commercial market by ENPULSION. The thruster features two cold redundant neutralizers and a propellant reservoir of approximately 230g of indium. Depending on the specific impulse chosen by the user, the thruster can deliver total impulses in the range of 5000-10000Ns. At a total power input of 40W, the thruster has a nominal thrust of 350µN.

At time of writing, >15 IFM Nano Thrusters have been launched since the first In-Orbit-Demonstration, and several constellations are currently integrating the IFM Nano Thruster, leading to a fast cadence in flight thruster delivery over the last year, averaging to 2 flight thrusters per week.

The IFM Micro Thruster

The IFM Micro Thruster, shown in Figure 3, is a scaled version of the IFM Nano Thruster, elevating power, thrust and total impulse levels to meet more stringent mission requirements of larger spacecraft. Within an envelope of 10x12x14cm, the thruster carries 1.3kg of propellant, allowing >50kNs of total impulse. At a power draw of 100W, the thruster can deliver over 1.5mN.

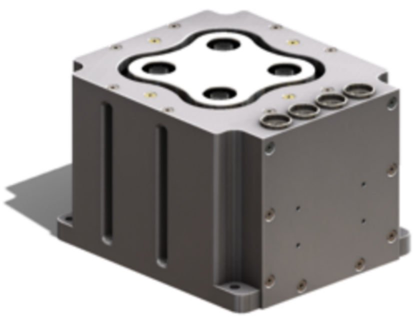

Figure 3 IFM Micro Thruster

The thruster design philosophy is to maximize heritage of the IFM Nano Thruster and heritage IFM emitter technology, and increasing thrust level is therefore achieved by clustering of heritage emitters, rather redesigning the core technology itself. In addition, the thruster is designed according to heritage design standards to fulfill the more demanding quality requirements of higher performing space missions.

Modularity and clustering is an intrinsic philosophy of this thruster, not only on emitter level, but also on system level, as multiple thrusters can be easily clustered together to adapt to specific mission requirements.

HIGH RATE PRODUCTION MINDSET

Scaling

To comply with constellation production rate and implementation requirements, ENPULSION has introduced a modular, universal building-block based propulsion technology which is designed for high rate production. This IFM thruster technology has been successfully industrialized and is currently delivered to customers at rates between 2 to 5 flight propulsion systems per week.

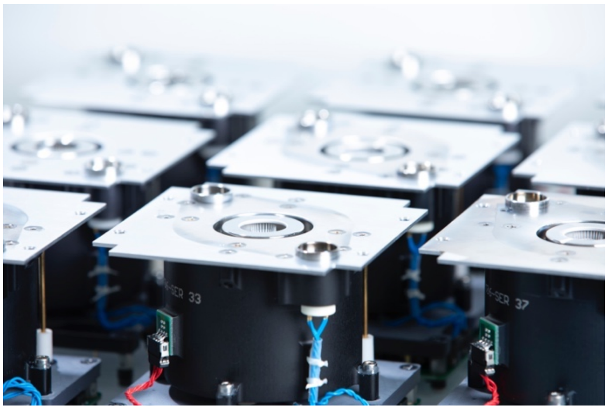

Figure 4 ENPULSION delivers already 2 flight units per week, with capacity up to 5 thrusters per week

Based on a product designed for high rate production, ENPULSION has implemented an adaptable production line, that enables different scalability steps. Based on a heritage laboratory process of thruster production, a first scalability step has already been performed by introduction of batch processes, increasing production capability from 1 per week to 5 per week. Introduction of statistical evaluation of ongoing production processes, optimized selection at early production steps and semi-automatization can allow scalability to 2 emitters per day. Increasing batch sizes by scaling production equipment at the existing production facility to 6 emitters per day. The possibility for multiplication of such a model fabrication line by direct multiplication of facilities and corresponding scaling of support processes makes this concept adaptable to megaconstellation production rates.

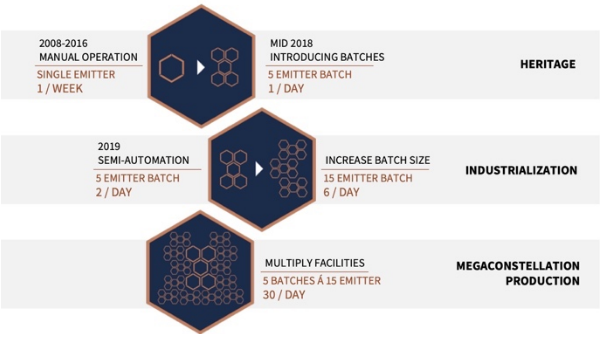

Figure 5: Scalability of production line

Quality in high rate production

There has been a general perception within the so-called New Space Community that increasing production rates to constellation requirements together with cost pressure necessarily leads to a tradeoff against heritage product assurance standards (eg ECSS), given the time and effort significant traditional implementation in heritage space hardware providers. In contrast, ENPULSION has been successful in implementation of heritage quality processes within the current high rate production rate, based on an agile implementation of traditional product assurance (PA) processes. With focus on optimization of PA process execution, the additional implementation effort is compensated by the large number of systems produced. The definition and design of the agile implementation of heritage PA processes has been guided and complimented by directly dialogue with space heritage providers to find optimized implementation complying with both stringent requirements and series production mindset. Optimization of mandatory inspection point (MIP) loops allow implementation with minimum delay by designing the production and testing flow adaptable so that flagged hardware can be taken out of flow and reintroduced after customer decision.

This is complimented with choice of proper tools, both digital and measurement systems, which are both optimized for high throughput, short cycle times and digital implementation. An example for such implementation is a automatized incoming inspection tool that enables parallelized inspection of up to 100 parts, fast measurement cycle times compatible with the production flow and automatized non-conformance reporting implementation for optimized feedback loop to suppliers, and enabling 100% inspection at current production rates.

Lean manufacturing in the space industry

To accomplish high throughput production without trading cost versus quality, a lean manufacturing approach has been introduced into the ENPULSION manufacturing philosophy. In this approach, the five classical steps of lean manufacturing are expanded by a dedicated engineering to scale step, that highlights the importance of incorporating scalability into early product development. Key **value** for the customer is generated by a modular, **high performance propulsion**

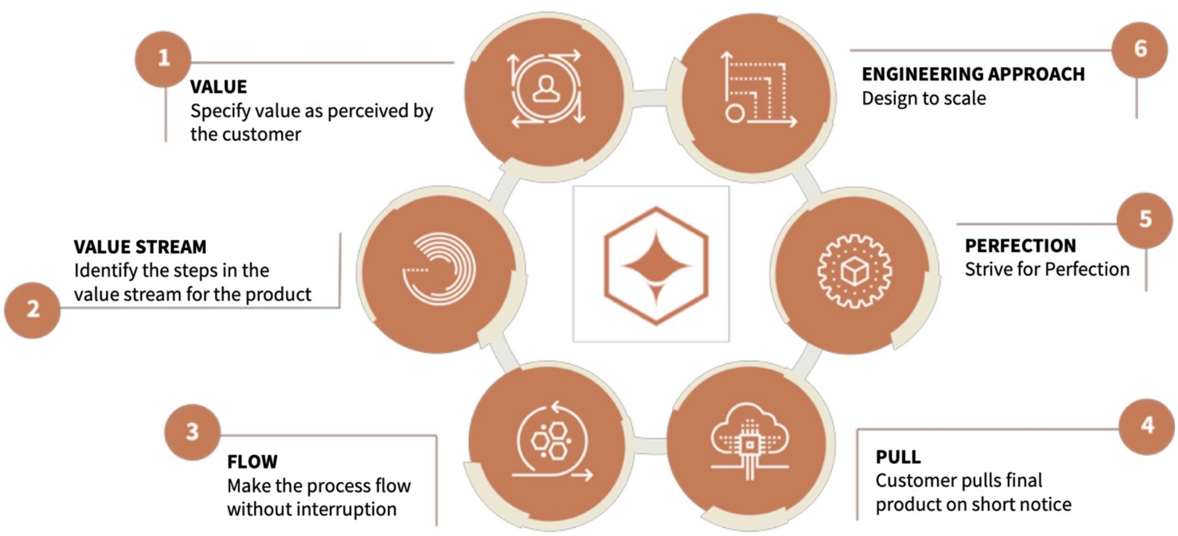

Figure 6 6 steps of lean manufacturing at ENPULSION high rate space propulsion production

technology that combines high capability (large total impulse and high impulse density), high adaptiveness (throttling in specific impulse and thrust), modularity (used as standalone thruster or in clusters enabled by bus design) , as well as attractive price point, both in direct cost (fixed low price offer) and reduced integration cost enabled by solid, inert propellant and fast delivery cycles of two months or lower.

This value generation is succeeded by **value stream** analysis, analyzing required production steps and flow for design throughputs with according buffers, including the identification of bottlenecks and impact. Based on this, the production line is optimized for uninterrupted **flow**, adjusting bottleneck process steps and culminating in the finalized production layout. The resulting ENPULSION production line is a pull based manufacturing line, in which subassemblies are produced independent of customer projects up to late assembly stages, enabling shortened customer cycles.

By placing orders, **customers pull** requested thrusters in suitable configuration from the pool of preassembled and stored thruster parts, triggering the final assembly and acceptance test flow. This manufacturing line design allows total thruster cycle times including standardized acceptance testing within two weeks, generating unmatched short delivery cycles.

Within the entire manufacturing process, the agile implementation of heritage quality processes based on inspection point principles that are seamlessly into incorporated in the production flow as well as tools to continuous improvement result in high quality of delivered products as well as continuous improvement of the production line satisfying the teams **strive for perfection**.

These classic steps of lean manufacturing are based on a complying **engineering approach** philosophy, which introduces the mindset of large-scale production into the early stages of product development and design stages. ENPULSION thruster products are designed in a modularity manner both on thruster and subsystem levels, and scaling between thruster products is accomplished by a philosophy of multiplication of core components and processes. This not only allows to maintain heritage of key components on a technological basis, but is also in-line with the batch based production line design.

Continuous improvement

Engineering processes at ENPULSION are designed in accordance to this lean manufacturing philosophy, linking the key areas with corresponding focal points as depicted in Figure 7. In the interaction between processes and technology, the focus is laid on continuous improvement. The interaction between people and processes is focused on short development cycles, whereas the interface between people and technology is dominated by a focus on quality.

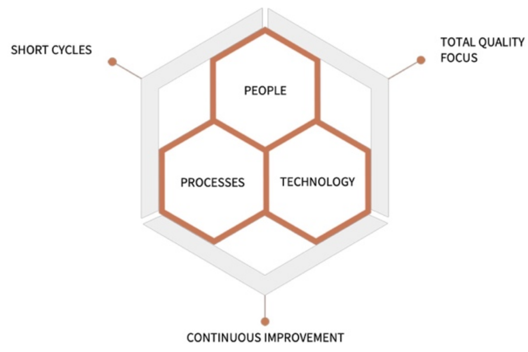

Figure 7 Implementation of lean manufacturing principles

Implementation in the ENPULSION manufacturing flow

Based on these principles, the manufacturing process and scalability for IFM thrusters at ENPULSION can be discussed. In step 1, automatized incoming inspection optimized for design throughput, short non-conformance reporting with direct link to suppliers enables compliance with high heritage quality processes, 100% part inspection and engineering feedback, while allowing the required high throughput. In step 2, emitters, which are the core component of the IFM technology, are manufactured from incoming parts. These complex manufacturing steps are performed in parallel batches , including aligned inspection plans, to achieve nominal throughput. The same scaling principle applies to step 3, in which the propellant is loaded into the emitter in a complex vacuum process. The semi-finished emitters are then scheduled to undergo a first characterization testing in vacuum facilities in step 4, in which average process times, such as evacuation of production chambers, are decreased by testing in batches and automatized test scripts. Steps 2 to 4 strongly benefit from the design to scalability approach of the IFM technology, which results in significant share of subassemblies across different thruster technologies. In a further step, emitters are characterized using topology scanning methods and gathered data is used to establish performance predictive models assisting emitter selection for early identification of unsuited emitters. Selected emitters are stored together with all other preassemblies ready for final thruster assembly which is initiated by customer pull in the requested configuration. The streamlined design of

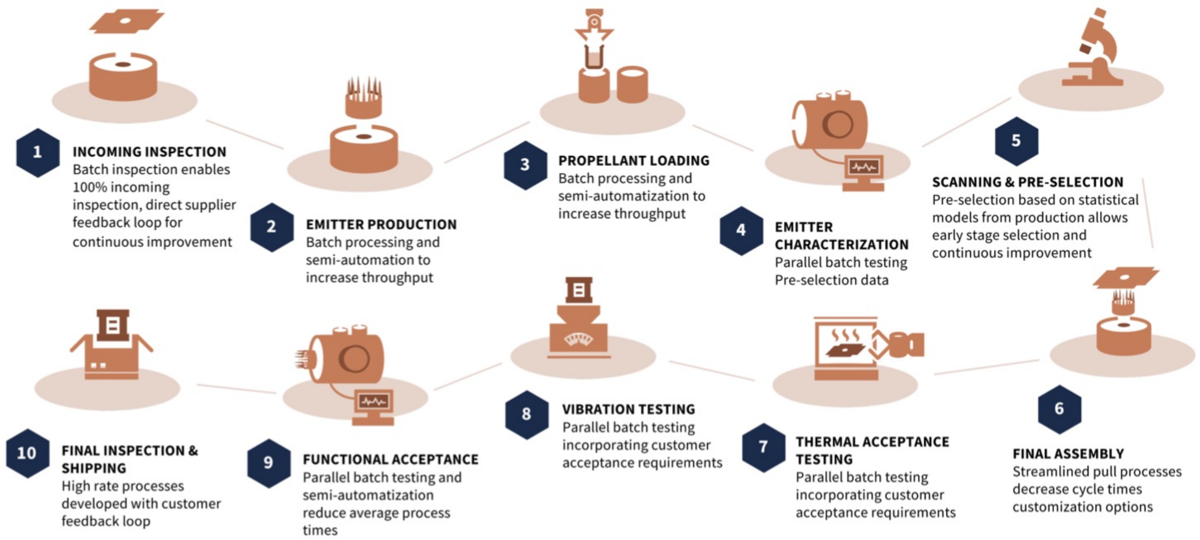

Figure 8 Manufacturing flow at ENPULSION

the thruster allows short assembly times within hours, enabled by the Kanban based manufacturing flow. After final assembly, thrusters are undergoing acceptance testing in step 7, which can incorporate customer provided mission realistic test levels, and is performed in batches. In a next step 8, the thrusters are undergoing vibration testing, which is again conducted in parallel to increase throughput, followed by final functional firing testing in vacuum facilities in final step 9. Throughout steps 7-9, thrusters are assigned to customers, and non-conformance reporting using agile processes and rapid decision cycles are in place, with a replace philosophy in case of major non-conformances. Processes to re-introducing thrusters that have been removed from the production line back into the engineering value chain are in place. Step 10 is a streamlined final inspection, packaging and shipping step, in which a standardized process together with close cooperation with logistics partner allow a maximum on flexibility as well as minimum process times. Shipping specifications and packaging has been developed with significant input from customers to align with respective receiving and incoming inspection processes.

CONCLUSION

ENPULSION has successfully introduced a high rate production of a high performance electric propulsion technology. Based on value stream analysis, a scalable production line design has been implemented that scales to mega constellation production rates. Lean manufacturing philosophy allows to implement a product lifecycle philosophy that combines New Space agility with heritage quality processes, while providing high customer value in terms of product performance, cost reduction and short cycle times.

It can be assumed that this example is largely representative for the industrialization of any other propulsion technology that is planned to be made available for large constellations. The presented case is however benefitting from the fact the used FEEP propulsion system is lacking any fluid, pressurized or toxic propellants and the evaluation of added complexity to handle and store such potentially hazardous propellants and tanks in integrated gas-based propulsion systems are therefore not included in the above discussion.

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