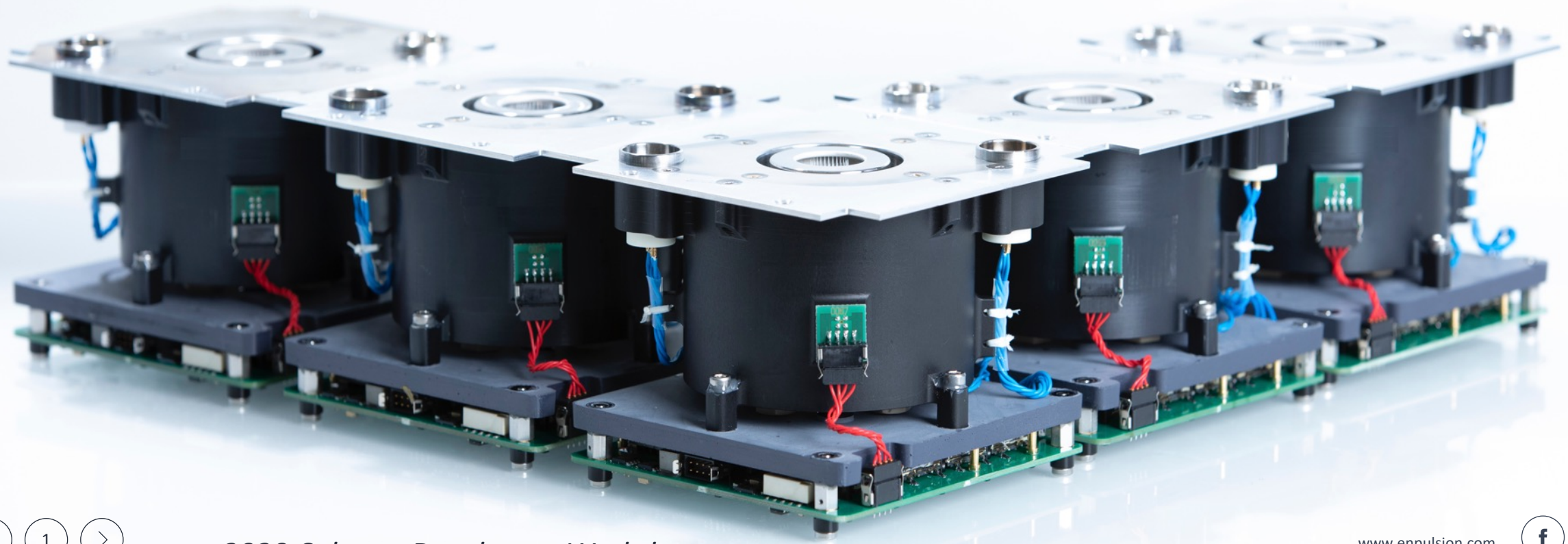
Electric propulsion as a standardized building block for CubeSats

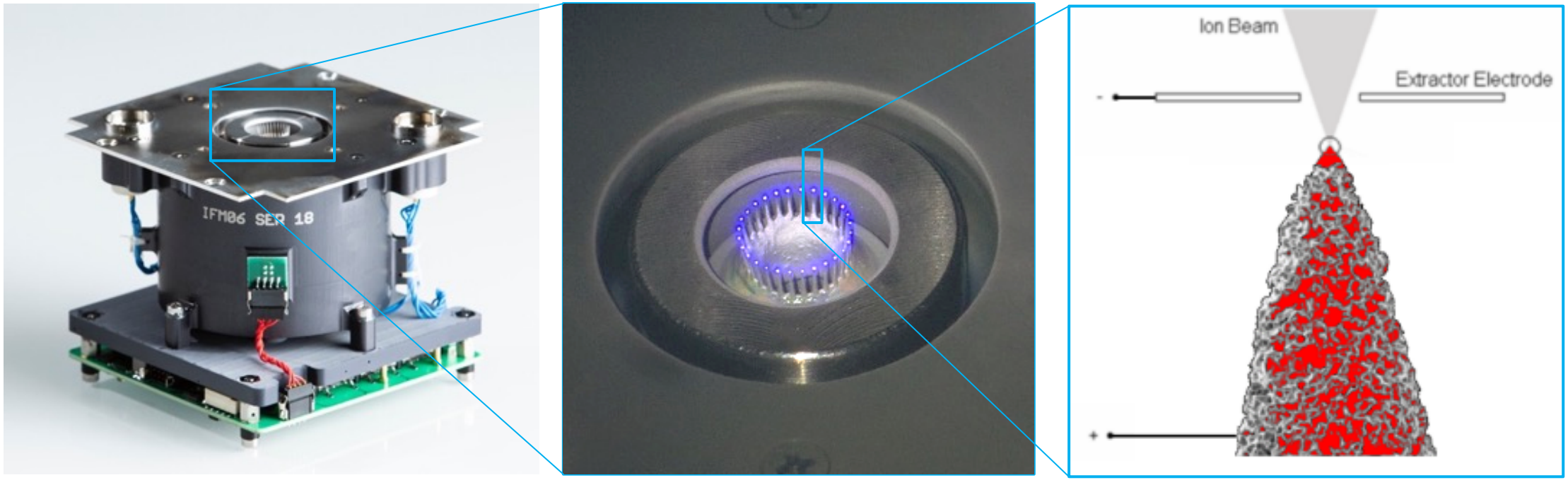
David Krejci and Alexander Reissner ENPULSION



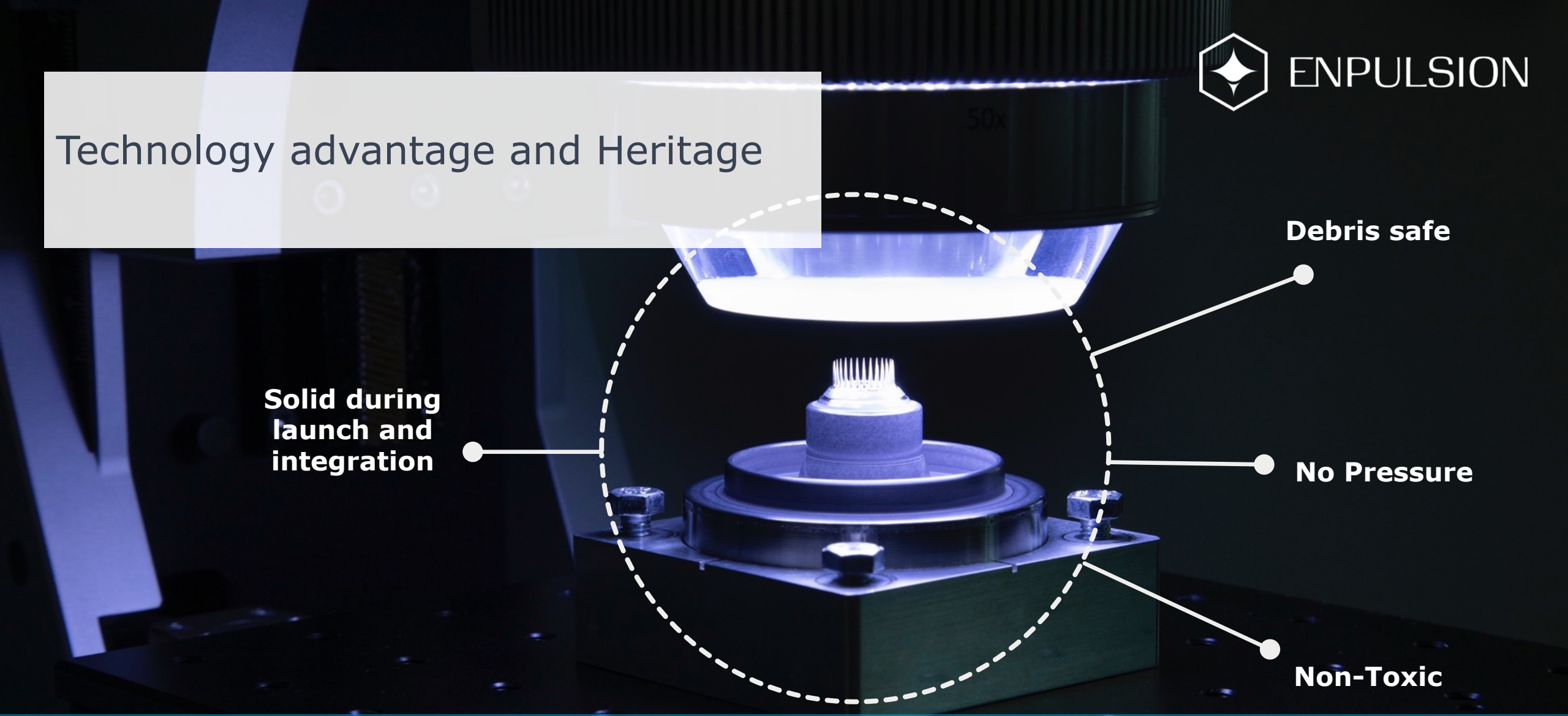
FEEP Technology

Electrostatic ion emission and acceleration from a Taylor cone

Operation at different Thrust and Specific impulse setpoints



Technology advantage and Heritage



Ion emitter validated in ongoing lifetime test, surpassed 30,000h of operation (>4x the lifetime of the IFM Nano Thruster emitter)

Heritage in science missions

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>25 years of flight heritage in LMIS

The FEEP technology was developed at AIT (now FOTEC) for > 25 years for scientific missions, support through ESA

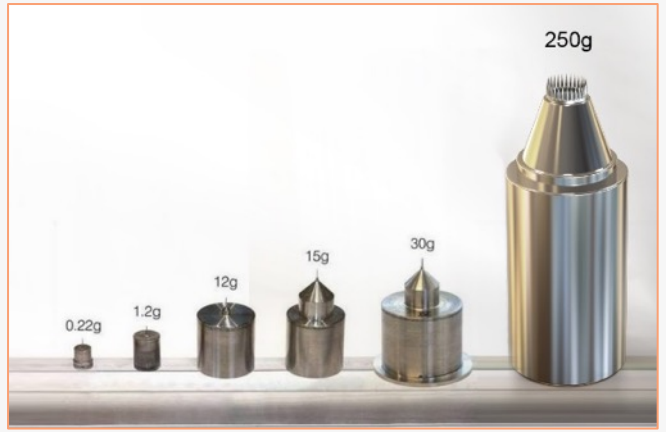
The IFM Thruster technology was developed by Fotec based on this heritage

FOTEC Research Subsidiary of — FH Wiener Neustadt —

AIT/FOTEC Liquid Indium emitter flight missions

Experiment	Function	Spacecraft	No. of LMIS	Operation Time
LOGION	Test of LMIS in µ-Gravity	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	Ariane 5 Launch Failure 1996 Still operational after Crash
ASPOC-II	S/C Potential Control	CLUSTER-II	32	6516 (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 successfully in 2015

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY → FOTEC Research Subsidiary of — FH Wiener Neustadt —



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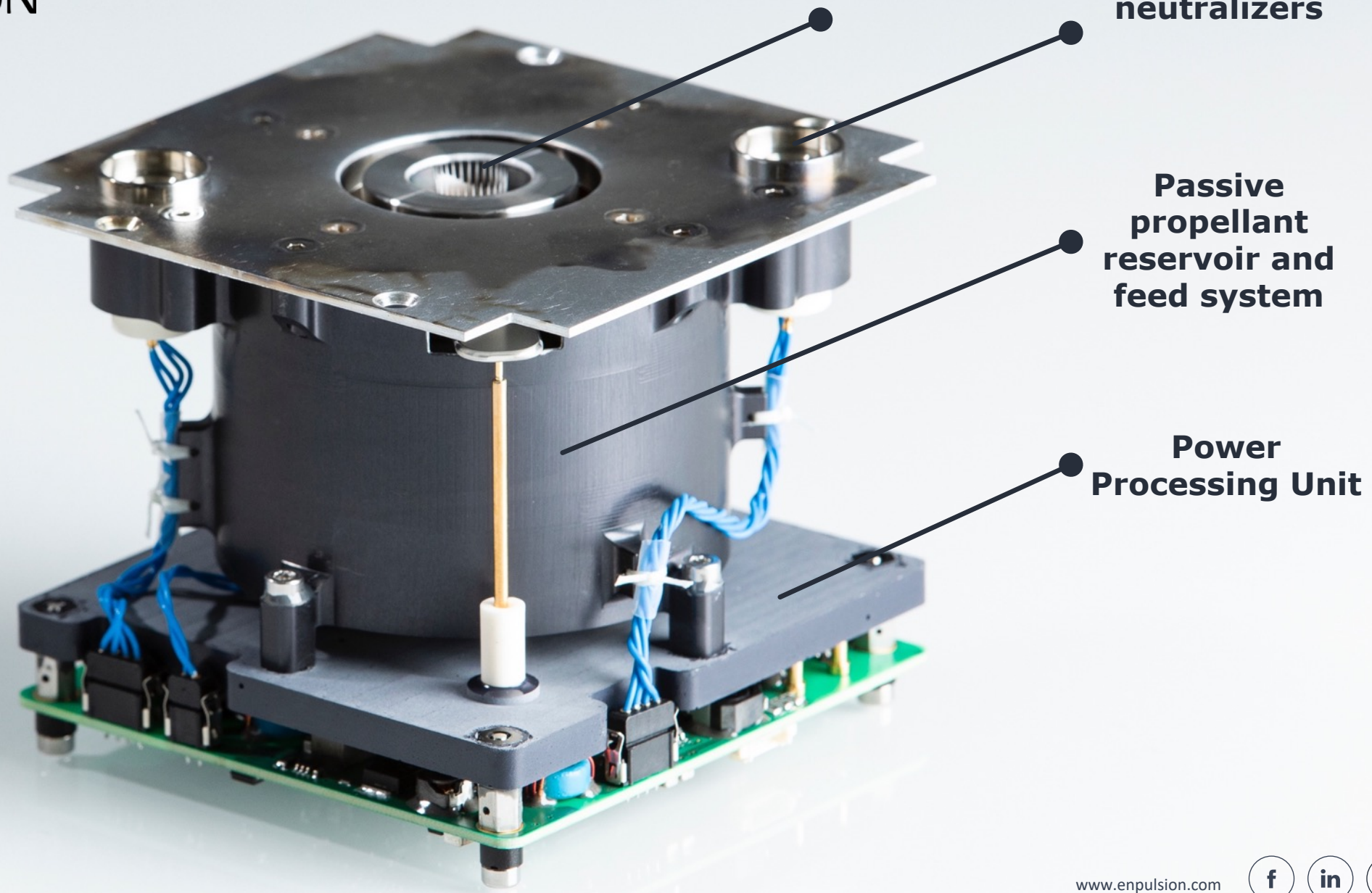
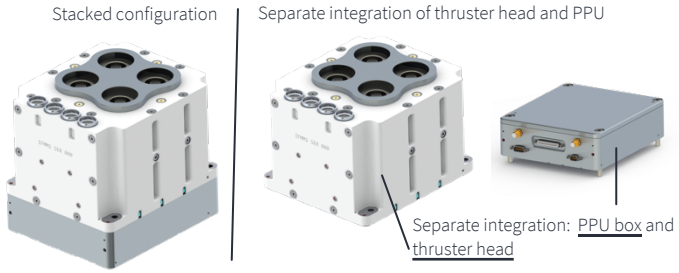

Porous crown emitter
Cold redundant neutralizers
Passive propellant reservoir and feed system
Power Processing Unit

Products

IFM Nano Thruster

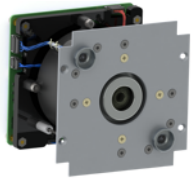


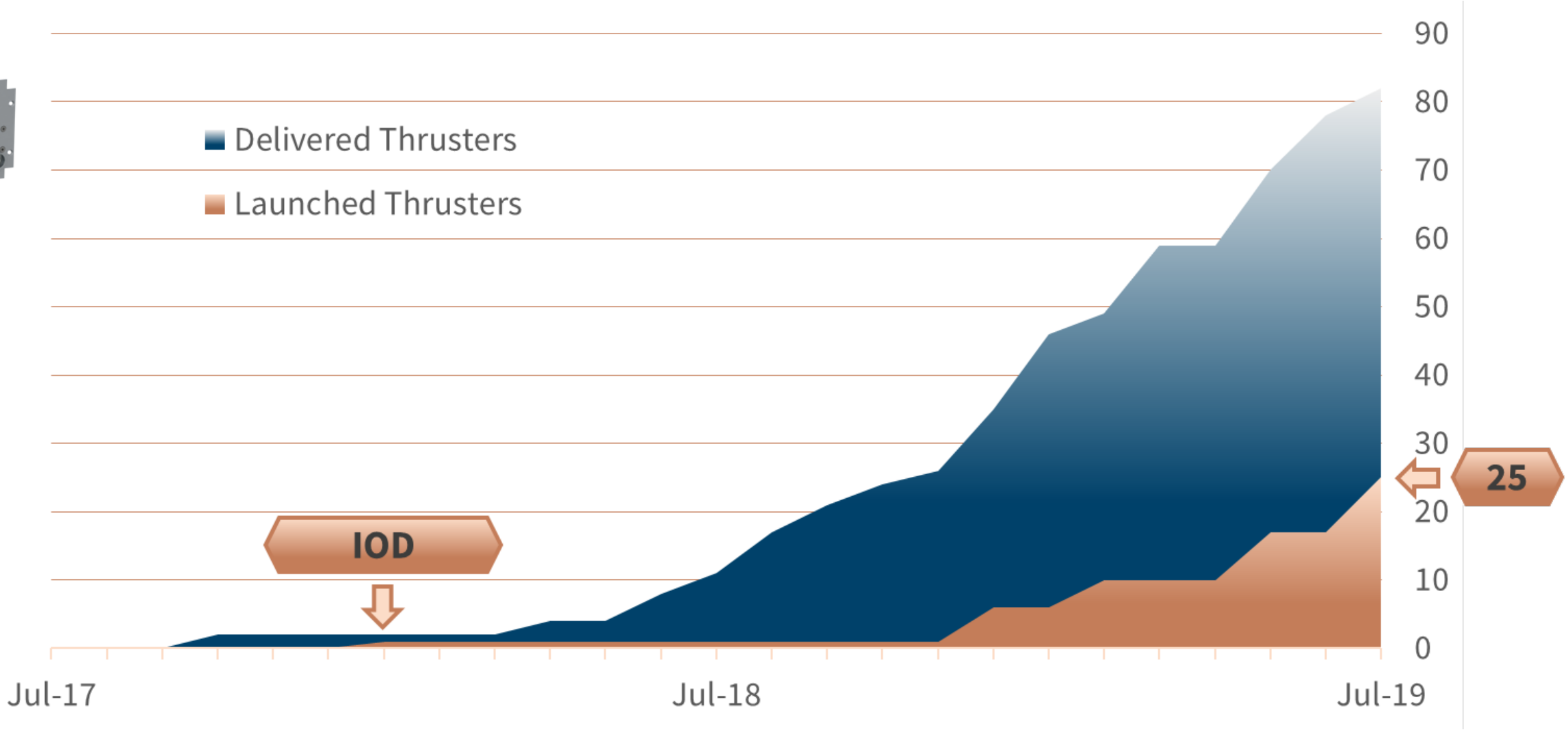
IFM Micro Thruster

	IFM Nano Thruster	IFM Micro Thruster
Dimensions	100 x 100 x 82.5 mm^3 (<1U)	140 x 120 x 98.6 mm (thruster) 140 x 120 x 34.0 mm (PPU)
Mass (dry / wet)	0.67 / 0.9 kg (incl. PPU)	2.6 / 3.9 kg (incl PPU)
Total input power to PPU @ nominal thrust	40 W incl. neutralizer	100 W incl. neutralizer
Thrust range (Nominal thrust)	10-400 µN (350 µN)	75 – 1,450 µN (1,000 µN)
Specific impulse	2,000 – 6,000 s	1,500 – 6,000 s
Total impulse	> 5 kNs	> 50 kNs
Command interface	RS422 / RS485	RS485
Input voltage	12 V / 28 V / Others	28 V / Others
STATUS	28 in space	First FM delivery Q2 2020

IFM Nano Thruster Numbers

ENPULSION





Lottery of the 100th thruster

Serial number 100 given away for free in ballot

Winner chosen at IEPC in Vienna

- President of Electric Rocket Propulsion Society drew winner in public raffle
- Winner will receive thruster with serial number 100 for free to include in their CubeSat mission

IFM Nano Thruster Status update

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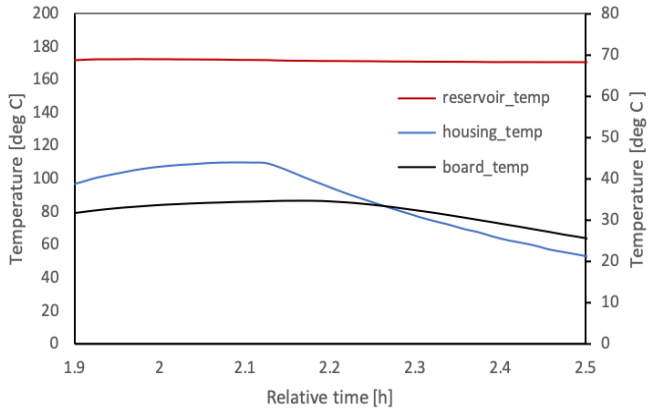
In-orbit data analysis

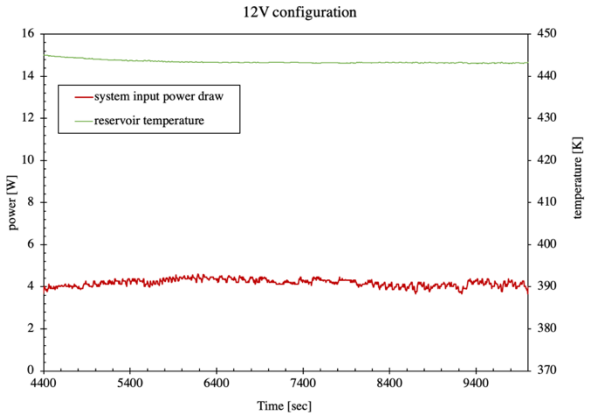
Serial Production ongoing
Flight unit delivery at constant rate since 2018
Multiple constellation contracts ongoing

- Learning from advanced number of units in orbit
- Close cooperation with customers to optimize individual missions
- Introducing advanced testing into Acceptance testing

Thruster capability to control propellant temperature in changing thermal environment entering eclipse



Hot-standby power draw of thruster in 500km LEO orbit



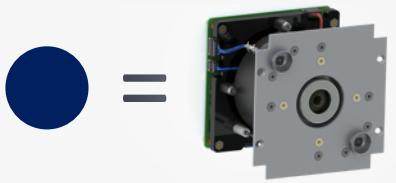
100 thrusters: acceptance data

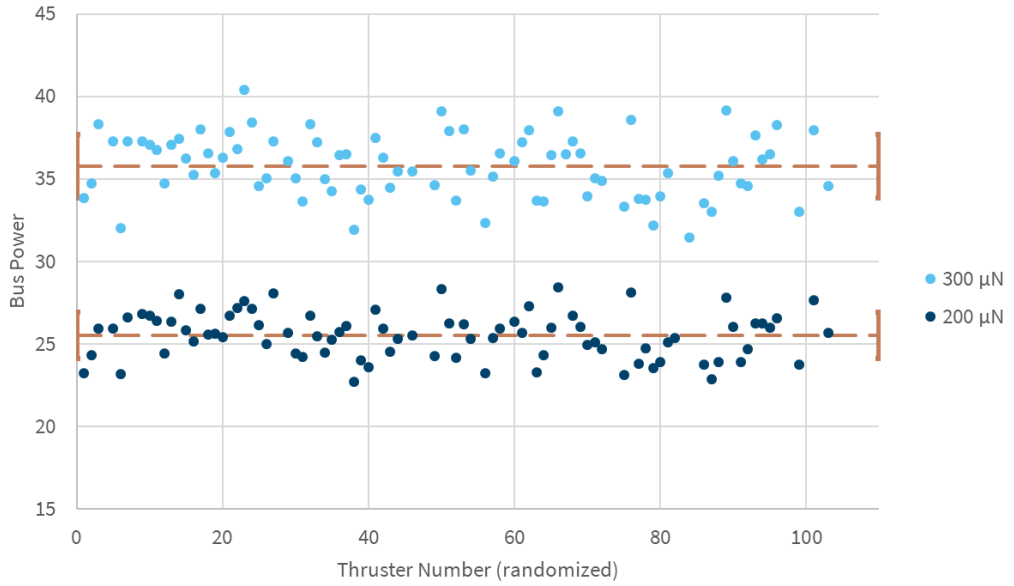
ENPULSION

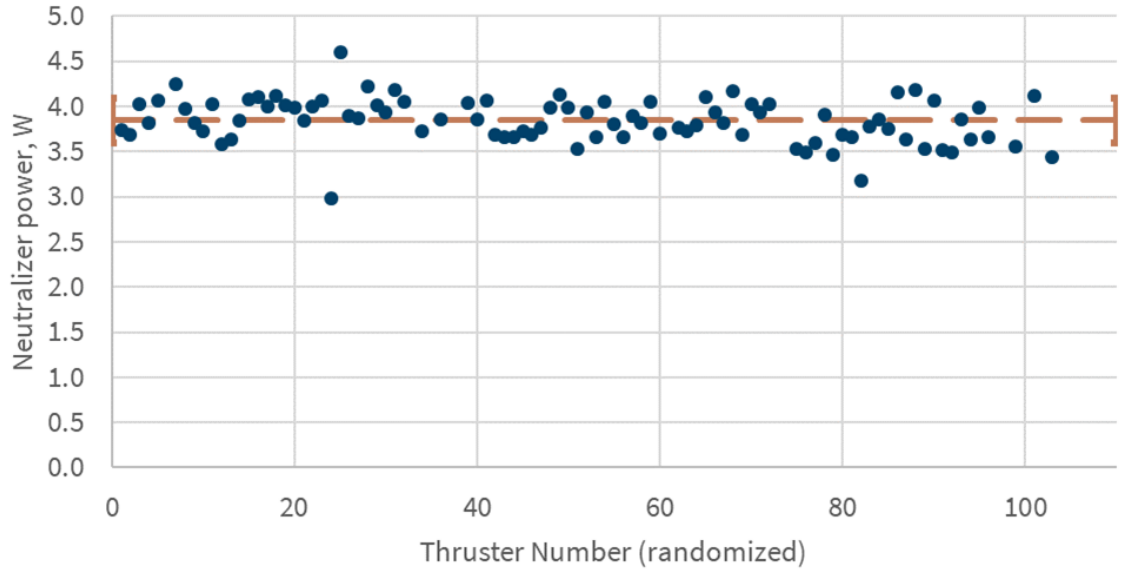
Acceptance data statistics

Large number of thrusters allows to leverage statistical tools

Each data point represents a flight model







IFM Micro 100 Thruster Status

ENPULSION

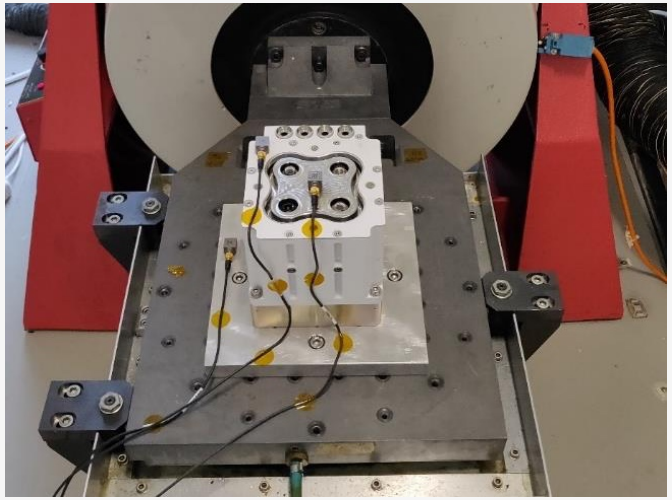
Qualification started

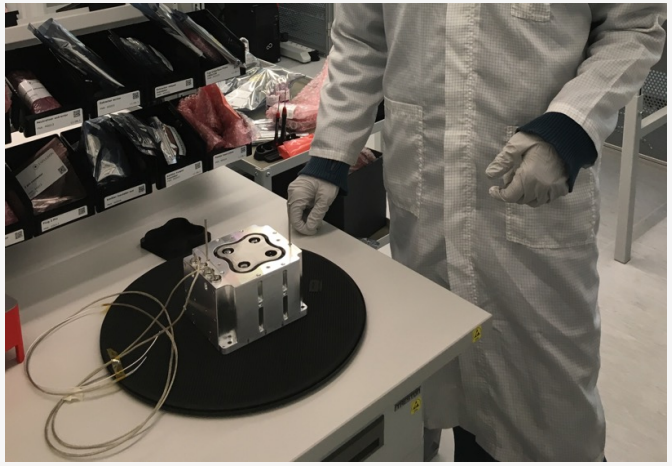
Qualification models built

COTS+ PPU in stacked configuration

Design verified:
- Vibration testing
- Shock testing
- Thermal design during heat-up and hot standby
- High voltage insulation
- Functional coupling testing with COTS+ PPU
- Beam diagnostics

First flight module delivery to customer
in Q2 2020





IFM Nano Thruster Flight Heritage

Independent orbit verification

3U Cubesat
SSO orbit

Thrust calculated by PPU (based on emission current and potentials) compared to GPS data provided by spacecraft operator

Independent orbit change verified within uncertainties of measurement

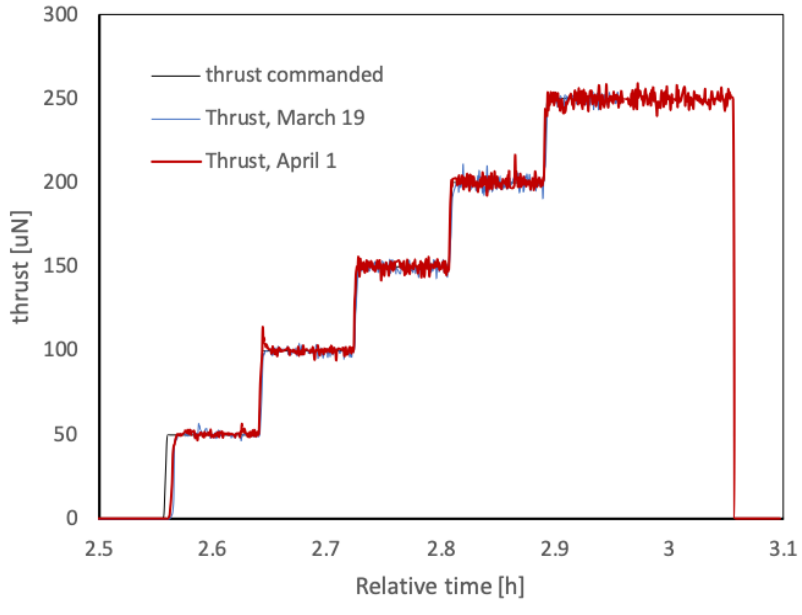
Table 1. Change in average spacecraft semi-major axis due to thrust maneuver, measured from GPS data and calculated from propulsion telemetry

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

From: Krejci et al: *Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit*, 4S symposium, 56, Sorrento, IT, 2018.

1 year after comissioning

- Thrust steps with controlled transients
- Reproducability of thrust profiles
- High Isp operation



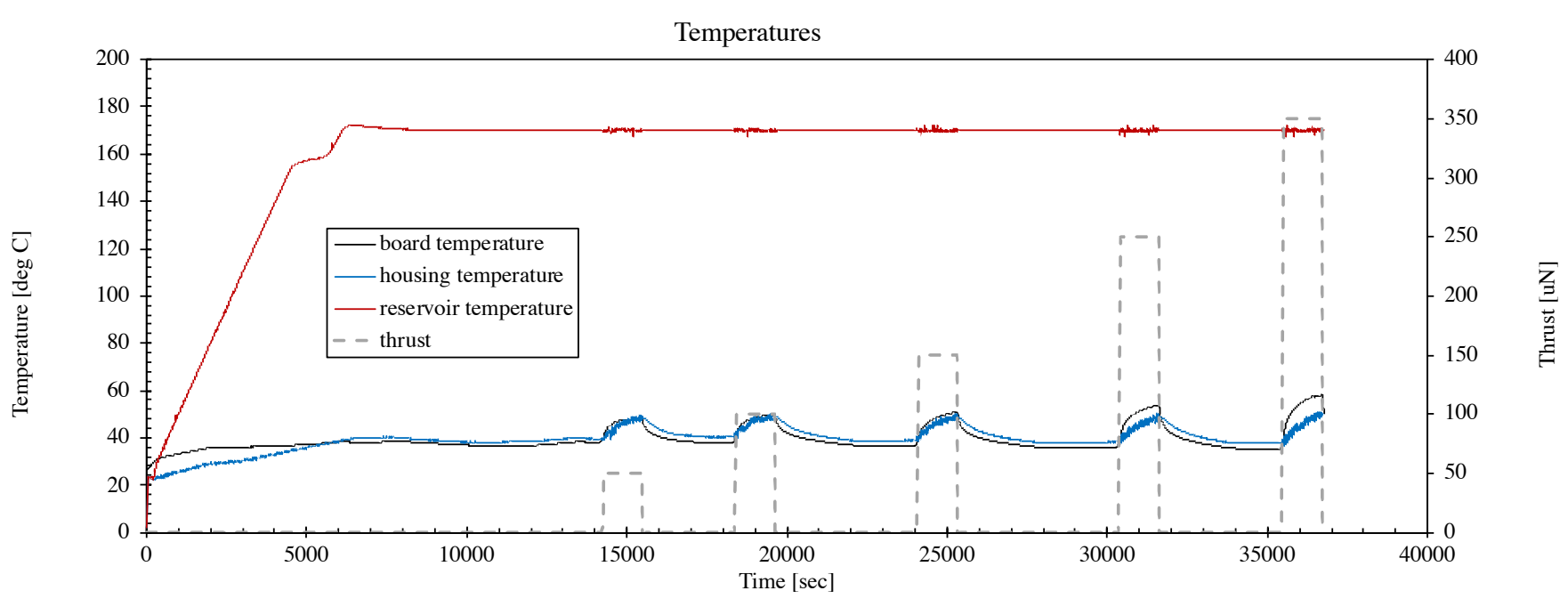
Different thrust levels, remaining in hot-standby mode

Smallsat launched in 2018

Carrying 4 IFM Nano Thruster

Thermal data of IFM06.03

- Propellant liquification
- Hot-Standby
- Firing sequences with increasing thrust levels



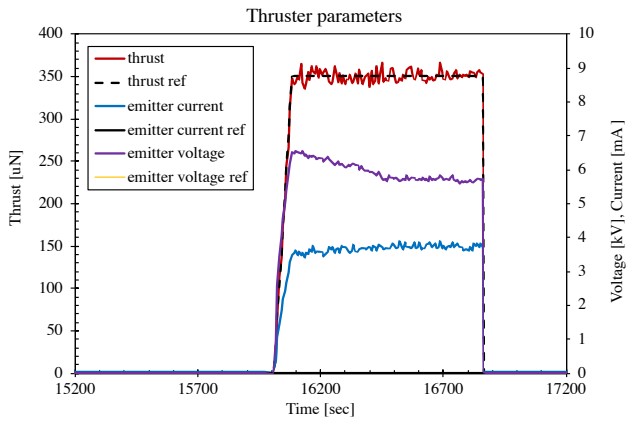
From: Krejci, Reissner, Schönherr, Seifert, Saleem, Alejos: Recent flight data from IFM Nano Thruster in a low earth orbit, IEPC-2019-A724, 36th International Electric Propulsion Conference, Vienna, Austria, Spt 2019

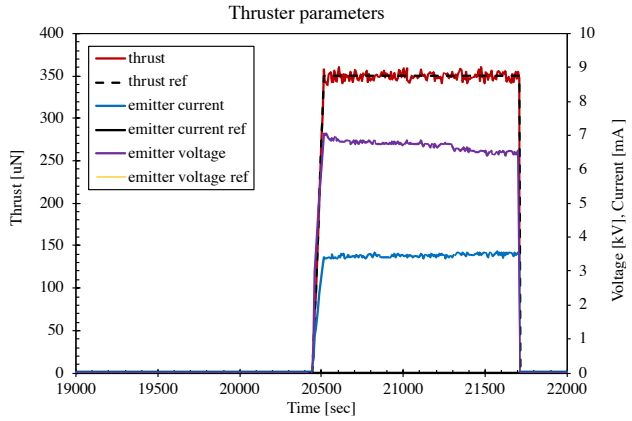
Nominal operation point confirmation

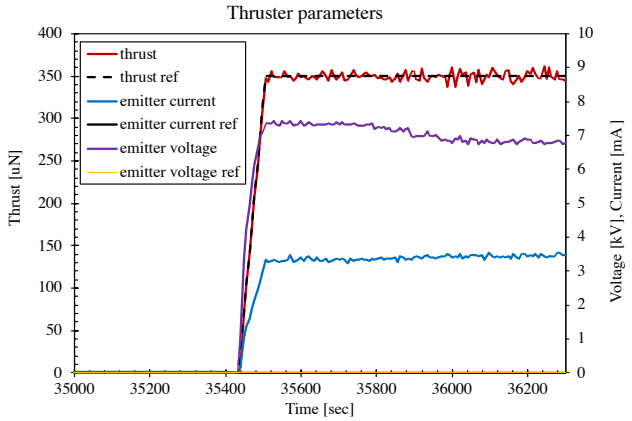
Smallsat launched in 2018

Carrying 4 IFM Nano Thruster

Firing with increasing thrust levels: 150µN, 250µN, 350µN







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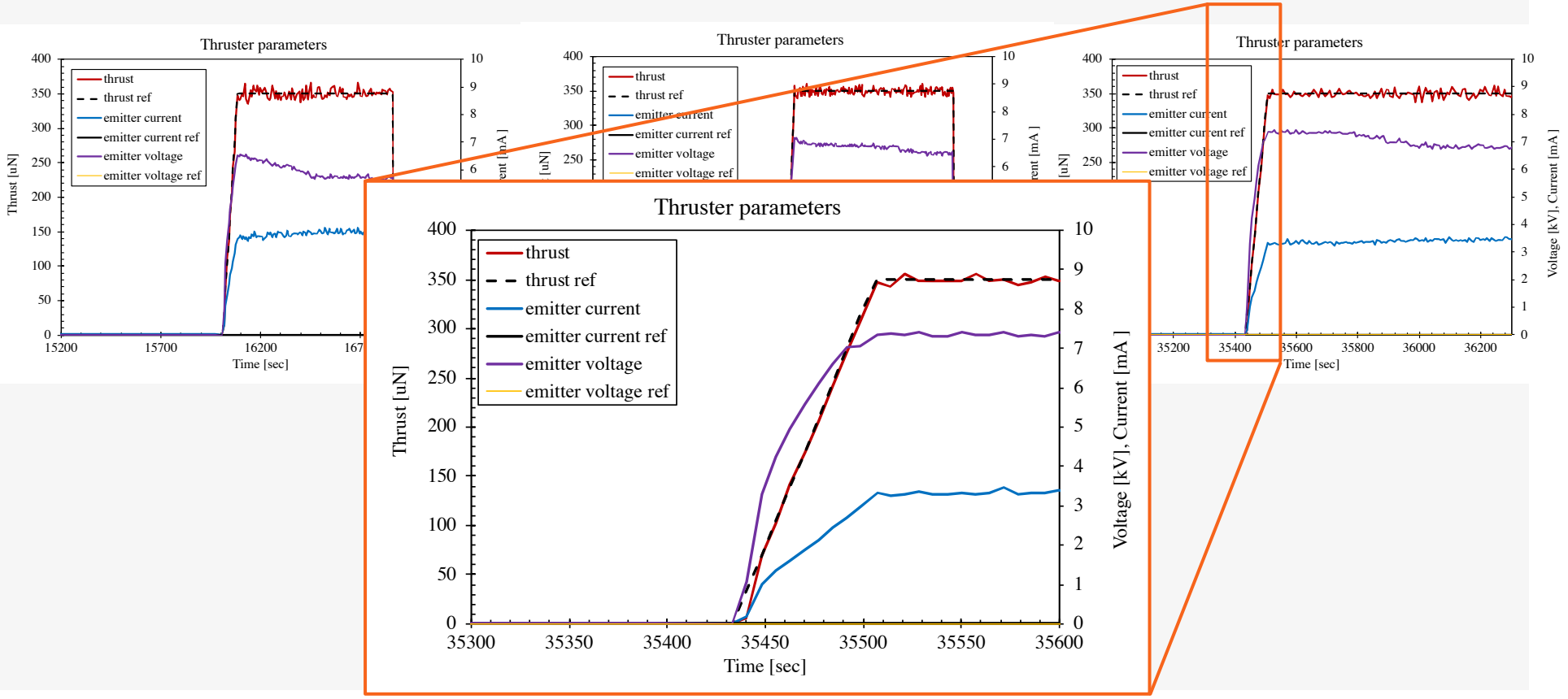

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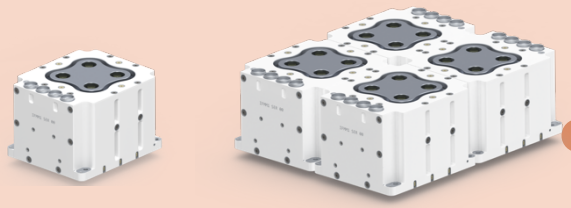
Manufacturing line

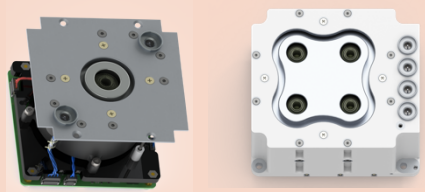
Scalability

Product

Modularity
Building larger systems



Scalability in product design
Core component



Production

Scaling production by batch processing
Modular core components

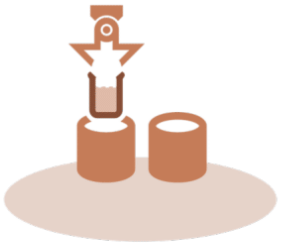
Scaling production by performing
Semi-automatization based on statistical data from series production

Scaling by multiplication
Model factory

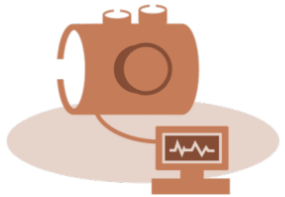
ENPULSION Production Line

1 **INCOMING INSPECTION**
Batch inspection enables 100% incoming inspection, direct supplier feedback loop for continuous improvement

2 **EMITTER PRODUCTION**
Batch processing and semi-automation to increase throughput



3 **PROPELLANT LOADING**
Batch processing and semi-automatization to increase throughput



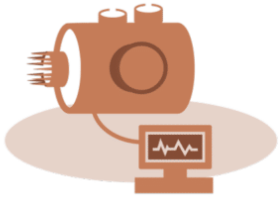
4 **EMITTER CHARACTERIZATION**
Parallel batch testing
Pre-selection data

5 **SCANNING & PRE-SELECTION**
Pre-selection based on statistical models from production allows early stage selection and continuous improvement

6 **FINAL ASSEMBLY**
Streamlined pull processes decrease cycle times customization options

7 **THERMAL ACCEPTANCE TESTING**
Parallel batch testing incorporating customer acceptance requirements

8 **VIBRATION TESTING**
Parallel batch testing incorporating customer acceptance requirements



9 **FUNCTIONAL ACCEPTANCE**
Parallel batch testing and semi-automatization reduce average process times

10 **FINAL INSPECTION & SHIPPING**
High rate processes developed with customer feedback loop

Manufacturing line

ENPULSION

Audited manufacturing line

Currently delivering >2 IFM Nano Thruster per week to customers
Current scaling to the IFM Micro Thruster (4 emitters per unit) ongoing
Clean rooms:
- ISO class 6: assembly
- ISO class 8: thruster vacuum testing and environmental testing (including vibration)

Kanban based
Audited by multiple space integrators

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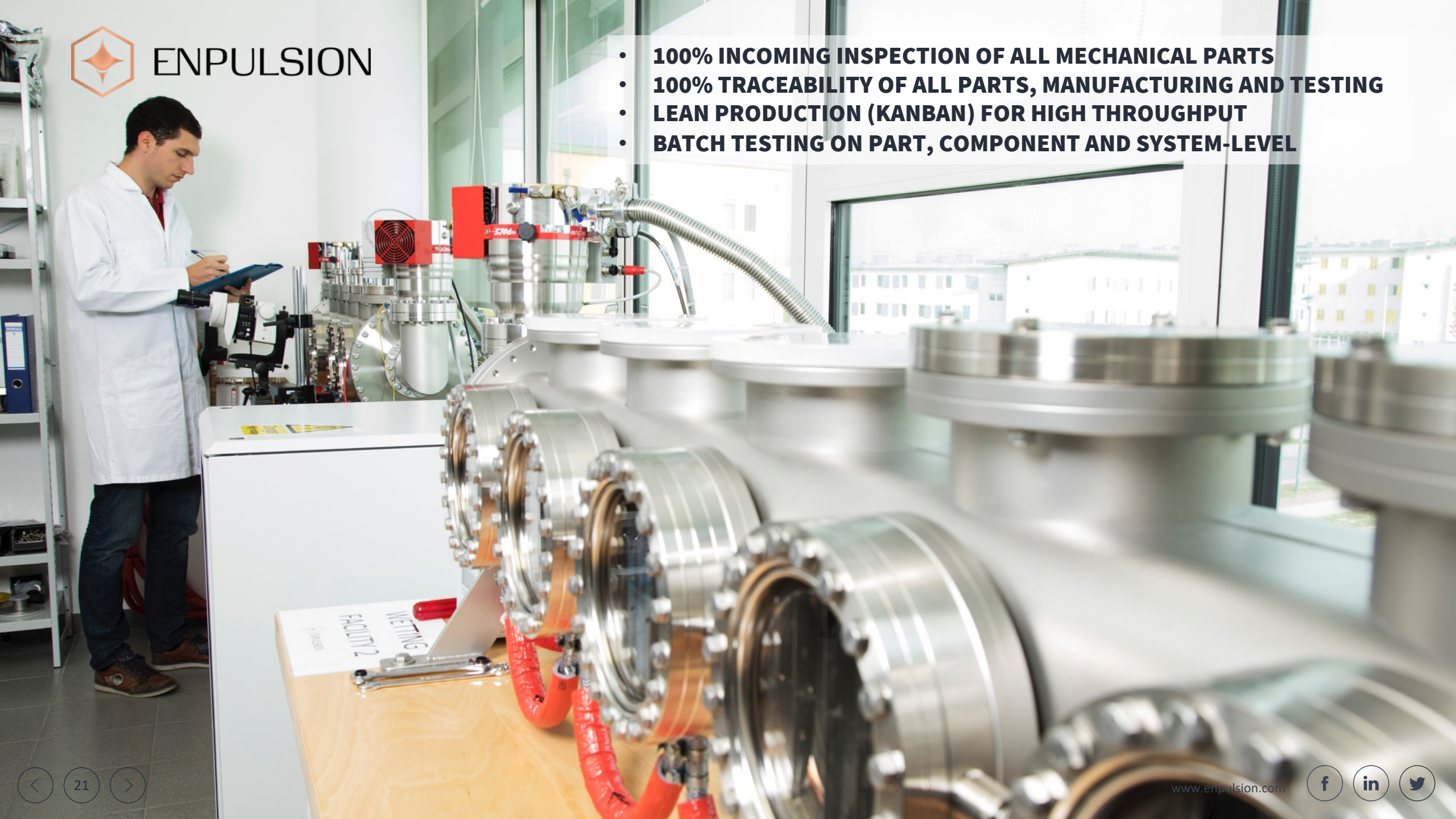
- 100% INCOMING INSPECTION OF ALL MECHANICAL PARTS
- 100% TRACEABILITY OF ALL PARTS, MANUFACTURING AND TESTING
- LEAN PRODUCTION (KANBAN) FOR HIGH THROUGHPUT
- BATCH TESTING ON PART, COMPONENT AND SYSTEM-LEVEL



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- **100% outgoing testing**
- **Emitters are characterized (firing and geometry based) before thruster assembly**
- **Each emitter is fired 2x**

Conclusion

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High rate	Multiple thrusters per week shipped to customers, enabled by standardization and batch testing
In-orbit data	Double digit number of thrusters in space now, firing tests presented show good controllability of thrust. Data is used to improve propulsion system and optimize missions together with customers
Introducing the IFM Micro 100 Thruster	IFM Micro 100 Thruster becoming available, with first customer deliveries in Q2 2020. Design verified by testing.


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SPACECRAFT TECHNOLOGY