ENPULSION

FINAL PRESENTATION – NANO AR^3

TDE CONTRACT 4000130766/20/NL/RA

14.03.2023

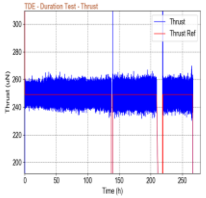
AGENDA

ENPULSION

Company Introduction

Technology / Previous Work

Work Packages and Objectives



Results and Outcome

Outlook

ENPULSION AT A GLANCE

Industrial Pioneer
ENPULSION is the first company worldwide that has established an ISO 9001 certification for the serial production of in-space propulsion systems

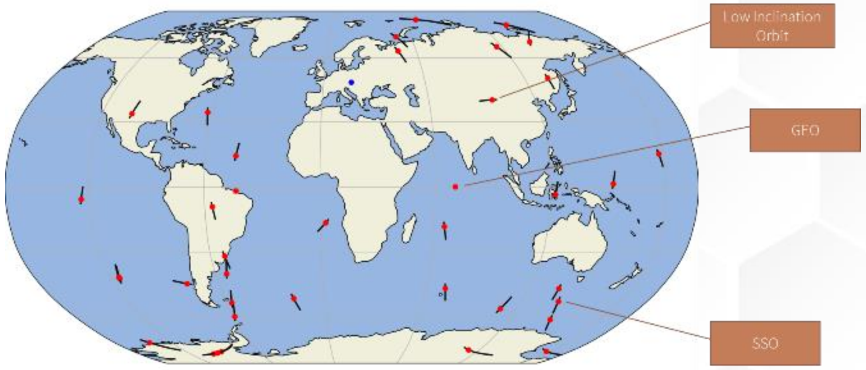
Technology Excellence
ENPULSION has exclusively licensed 30 years of academic research

Reliable Solution
ENPULSION has close to 200 products in space and accumulated more than 60 years of flight heritage

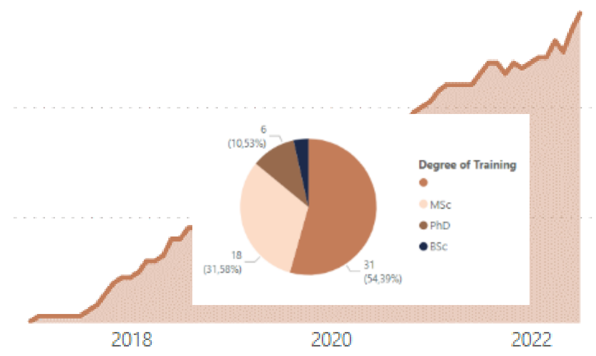
Global Market Leader
ENPULSION has established a new industry standard for small satellite propulsion and delivered propulsion solutions to more than 40 global customers

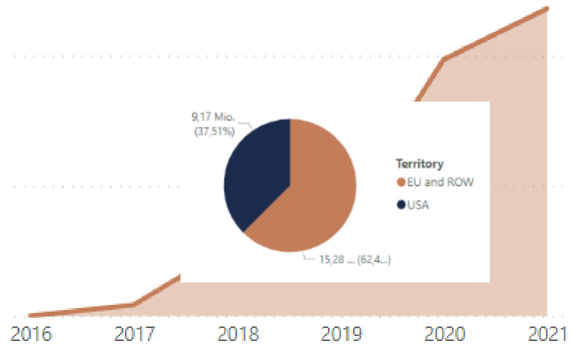
Employees
ENPULSION hired experienced leaders and a diverse international team which has repeatedly proven its ability to continue its growth trajectory through external crises

INDUSTRY STANDARD MARKET LEADER

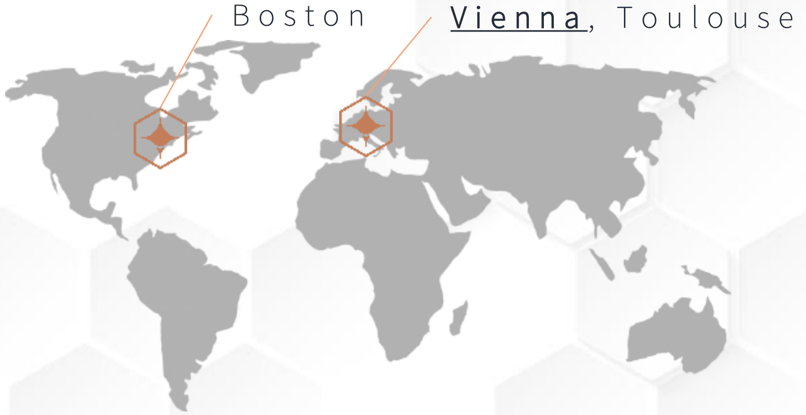


SUSTAINABLE GROWTH

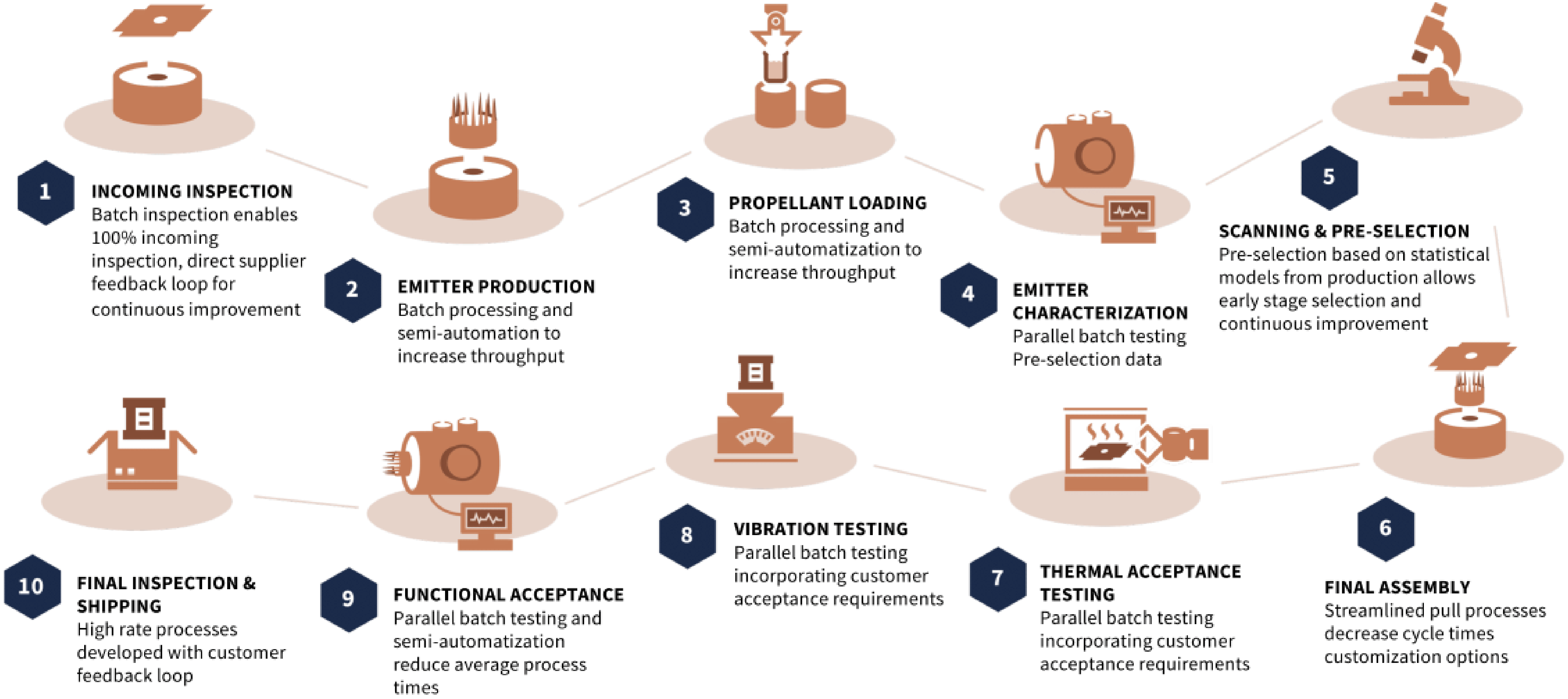




GLOBAL FOOTPRINT



ENPULSION Production Line



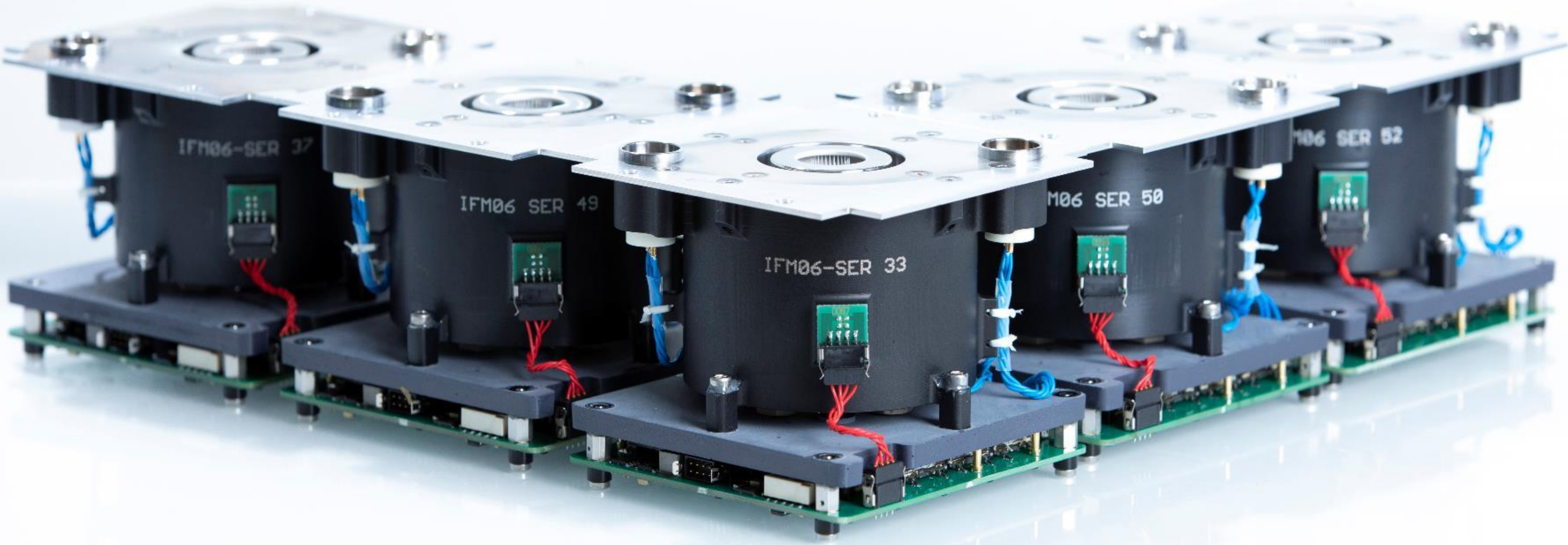
ENPULSION

A RELIABLE PARTNER

200 THRUSTERS IN SPACE

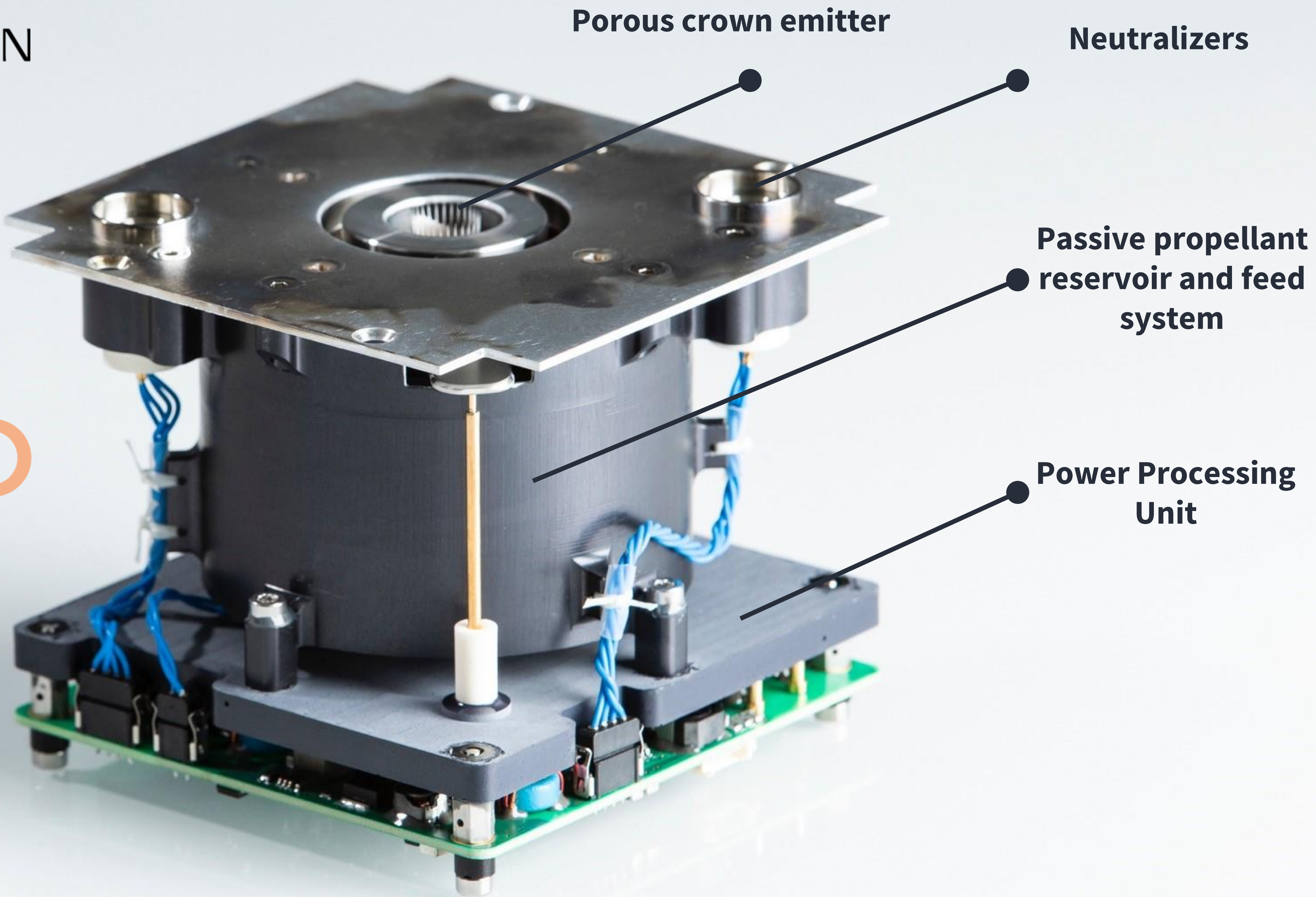
300+ THRUSTERS DELIVERED WORLDWIDE

60 ACCUMULATED YEARS OF ON-ORBIT OPERATIONS



ENPULSION

ENPULSION
NANO



ENPULSION

AGENDA

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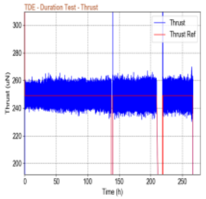
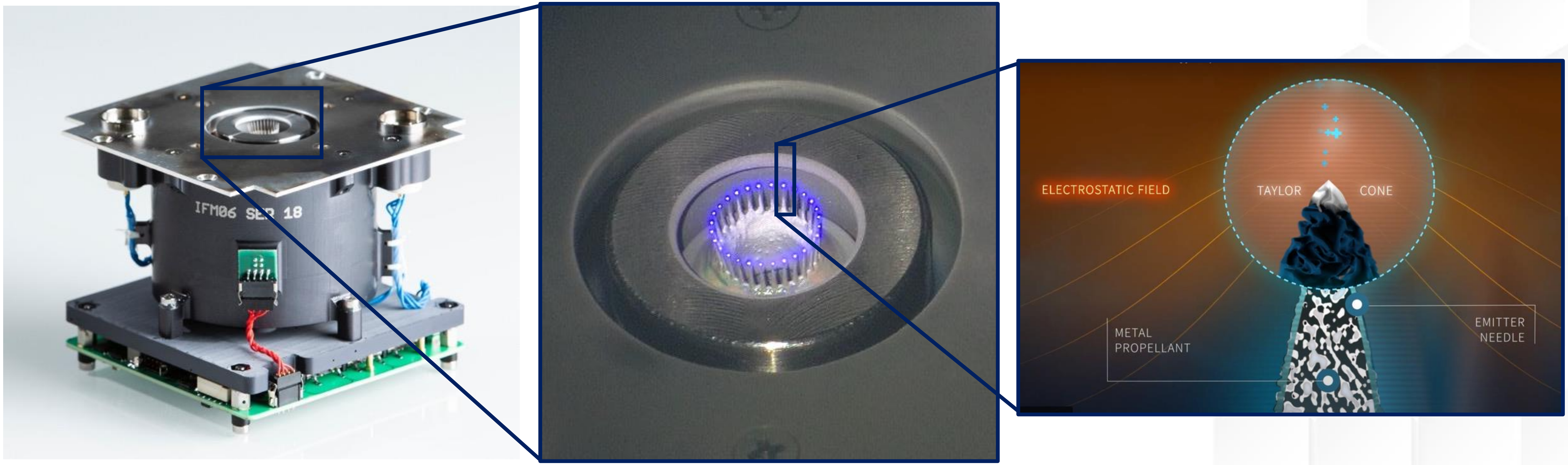


Results and Outcome

Outlook

FEEP TECHNOLOGY – HOW IT WORKS

Emitter based on Liquid Metal Ion Source (Indium)

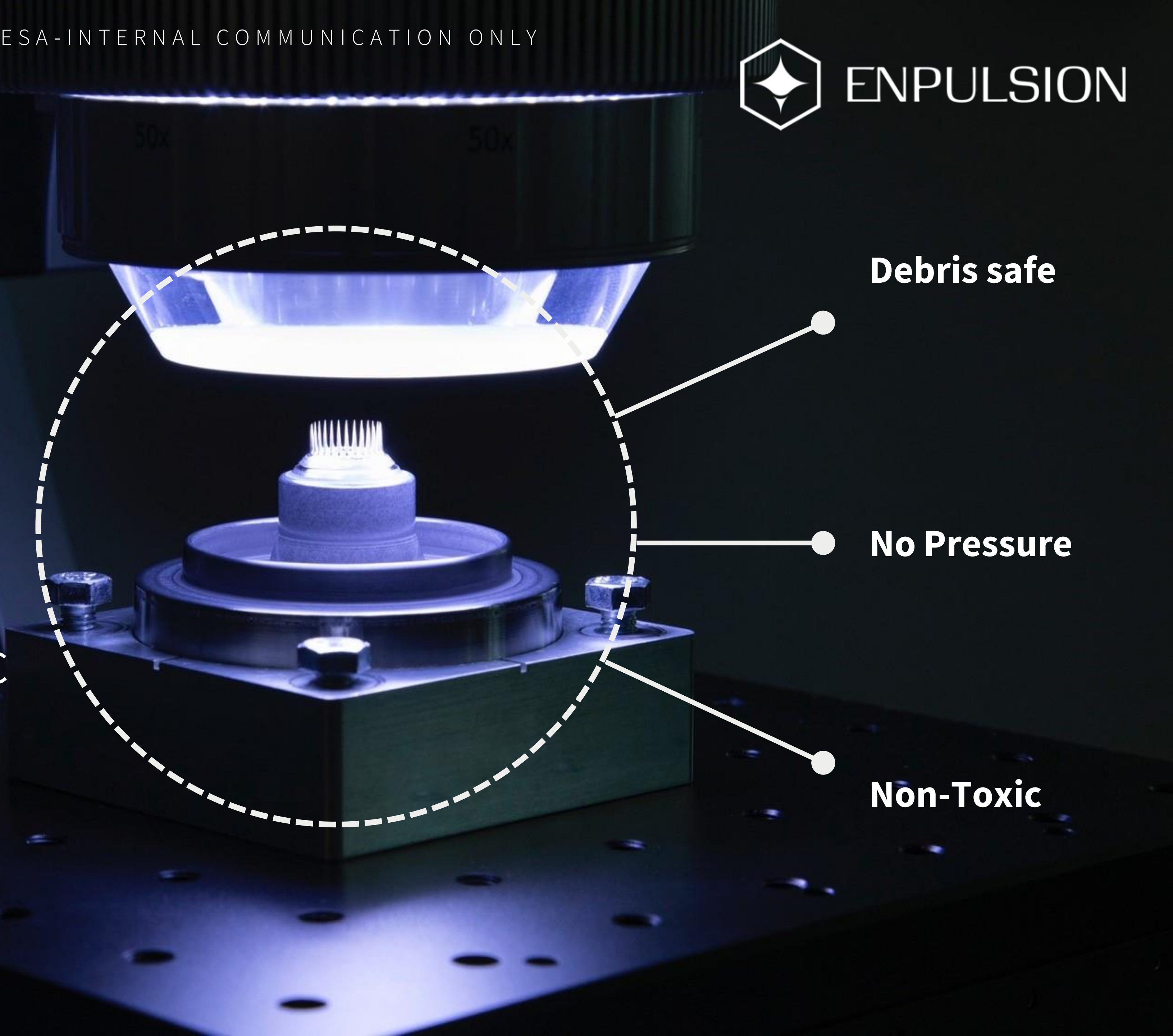


ENPULSION

Indium FEEP ion emitter

Building on 30 Years of Development at FOTEC

FOTEC
Research Subsidiary of
— FH Wiener Neustadt —



Debris safe

No Pressure

Non-Toxic

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ENPULSION NANO

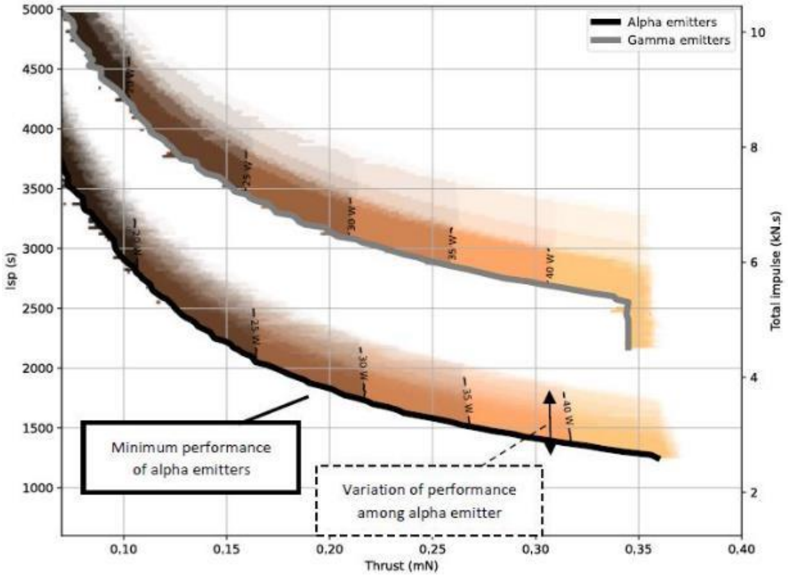
FLIGHT HERITAGE

The ENPULSION NANO has been developed and extensively tested in cooperation with the European Space Agency. First thrusters have been successfully demonstrated in orbit.

FLIGHT HERITAGE More than 150 propulsion units have been launched on various spacecraft by early 2023.

MATURE TECHNOLOGY The ENPULSION NANO is a mature technology, developed under ESA contracts for 15 years. In this time more than 100 emitter had been tested and an ongoing lifetime test has demonstrated more than 30,000 h of firing without degradation of the emitter performance.

SAFE AND INERT SYSTEM The ENPULSION NANO contains no moving parts and the propellant is in its solid state at room temperature. Avoiding any liquid and reactive propellants as well as pressurized tanks significantly simplifies handling, integration and launch procedures.



DYNAMIC THRUST RANGE[1]	10 TO 350 µN
NOMINAL THRUST	330 µN
SPECIFIC IMPULSE	1,500 TO 5,000 s
PROPELLANT MASS	220 g ± 5%
TOTAL IMPULSE[2]	> 5,000Ns
POWER AT NOMINAL THRUST	40 W INCL. NEUTRALIZER
OUTSIDE DIMENSIONS	100.0* x 100.0* x 82.5 mm
MASS (DRY / WET)	680 / 900 g
TOTAL SYSTEM POWER	8 – 40 W
HOT STANDBY POWER[3]	3-5 W
COMMAND INTERFACE	RS422/RS485
SUPPLY VOLTAGE	12 V, 28 V, OTHER VOLTAGES UPON REQUEST

*) can be customized

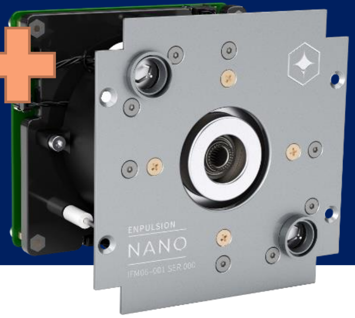
Development Roadmap

More thrust

ENPULSION
MICRO R^3

ESA-EOP InCubed

Better electronics



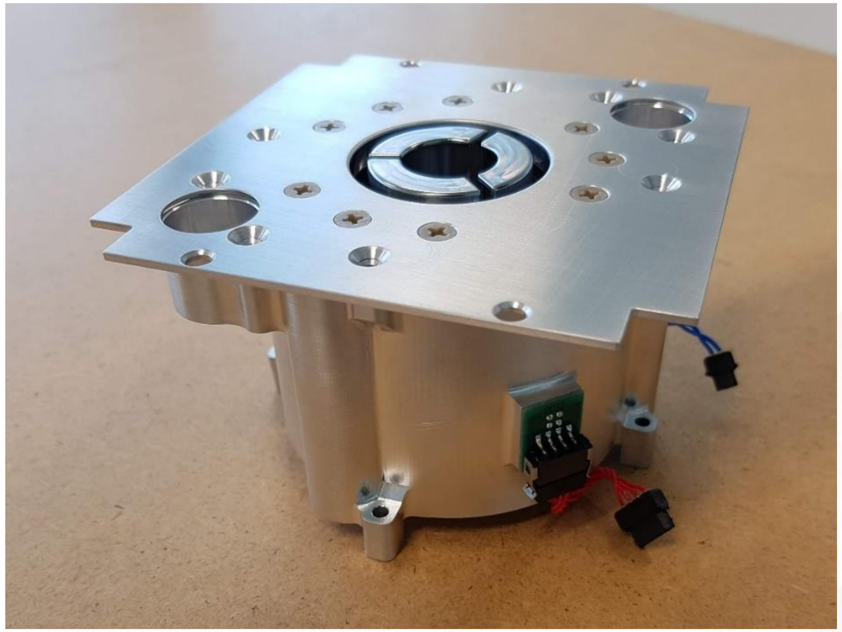
ENPULSION
NANO R^3

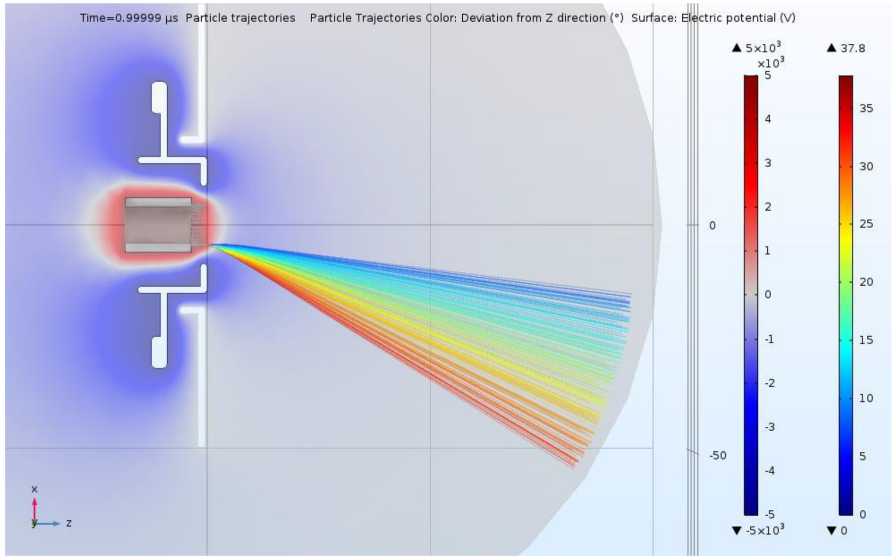
Qualifi-
cation

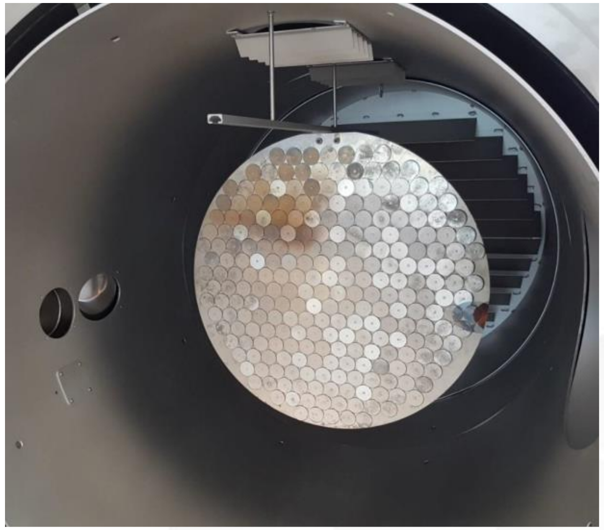
Idea for thrust vector control

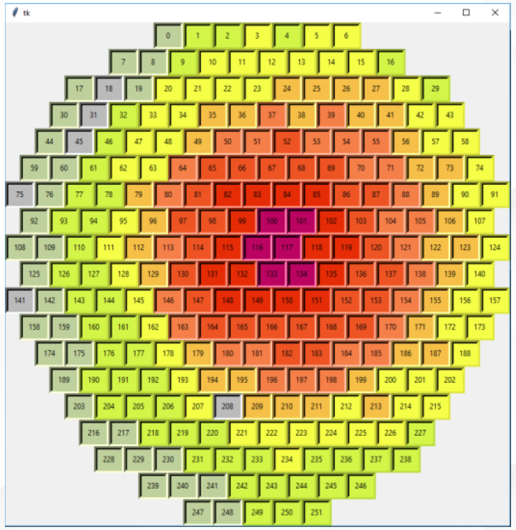
Master Thesis work at FHWN (Jan 2019)

- Ejected ion beam is accelerated by extractor potential
- Asymmetric extractor potential will lead to steered beam
- Preliminary tests to evaluate feasibility





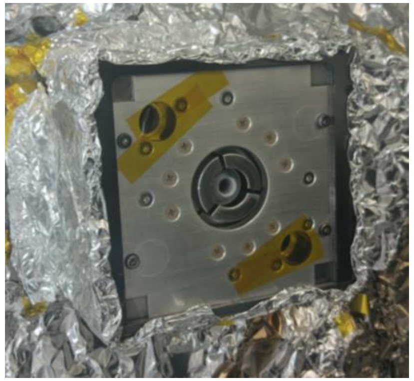


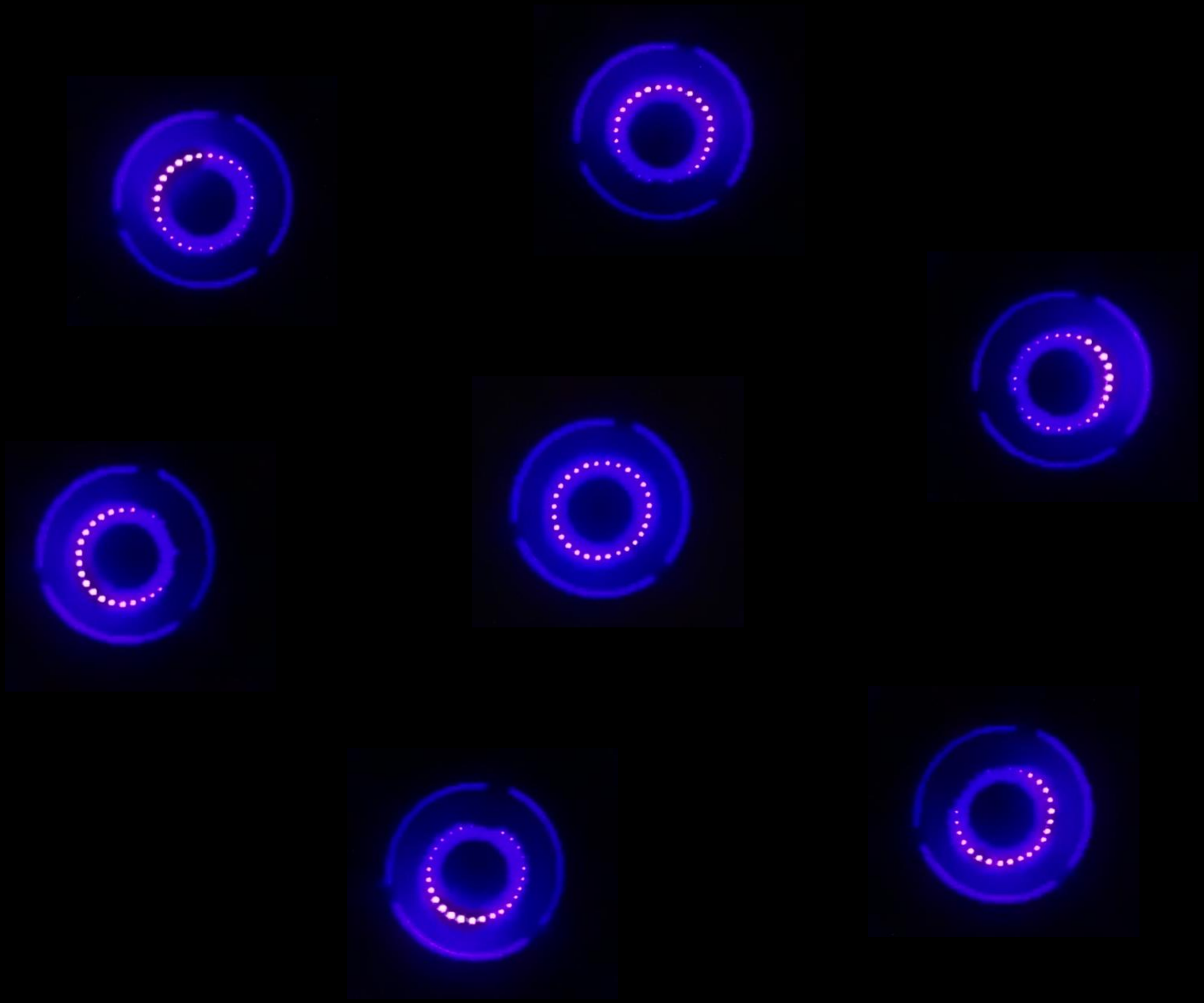


BBM Testing

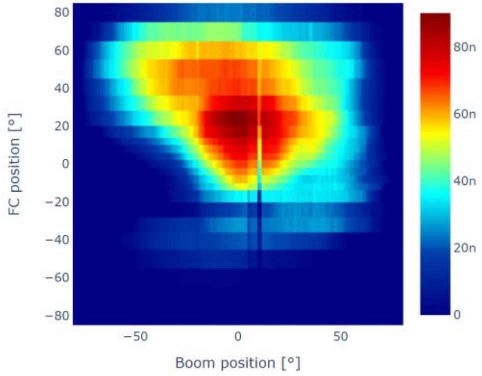
Testing at FOTEC (Lifet-4)

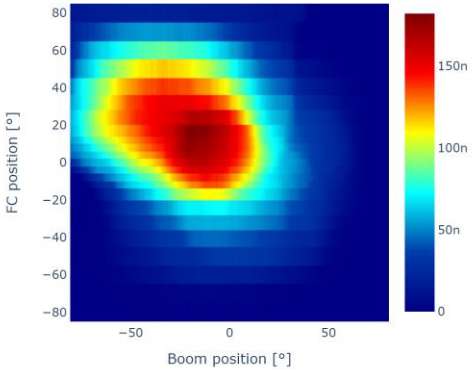
- Thruster Head functionality test successfully performed.
- Extensive test campaign with diagnostic boom to determine thrust vector capability.
  - 23 Faraday-Cups
  - -80 deg to +80 deg scan
  - Over 150 operation points analyzed

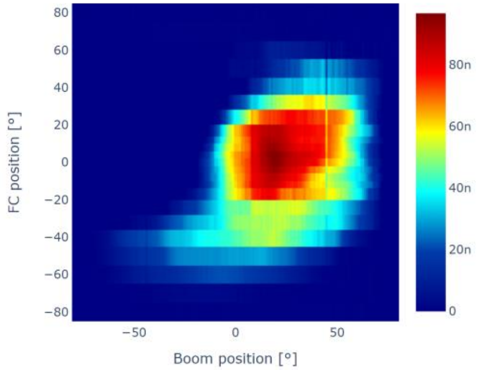


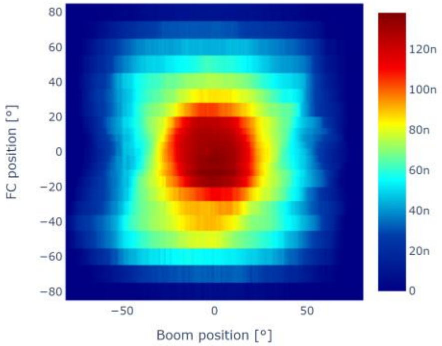


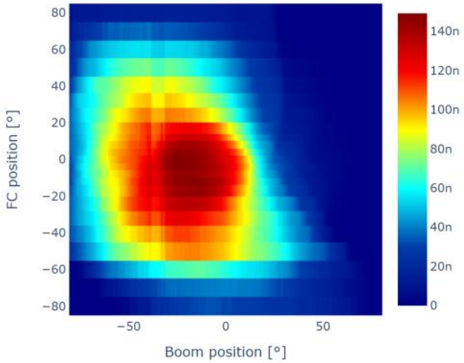
BBM Testing

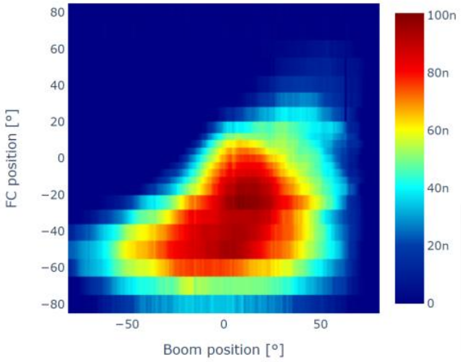

FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
80n 60n 40n 20n 0

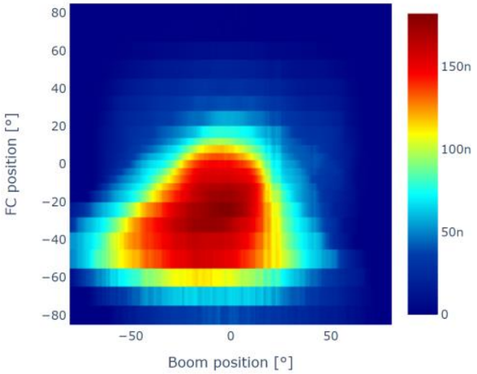

FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
150n 100n 50n 0


FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
80n 60n 40n 20n 0

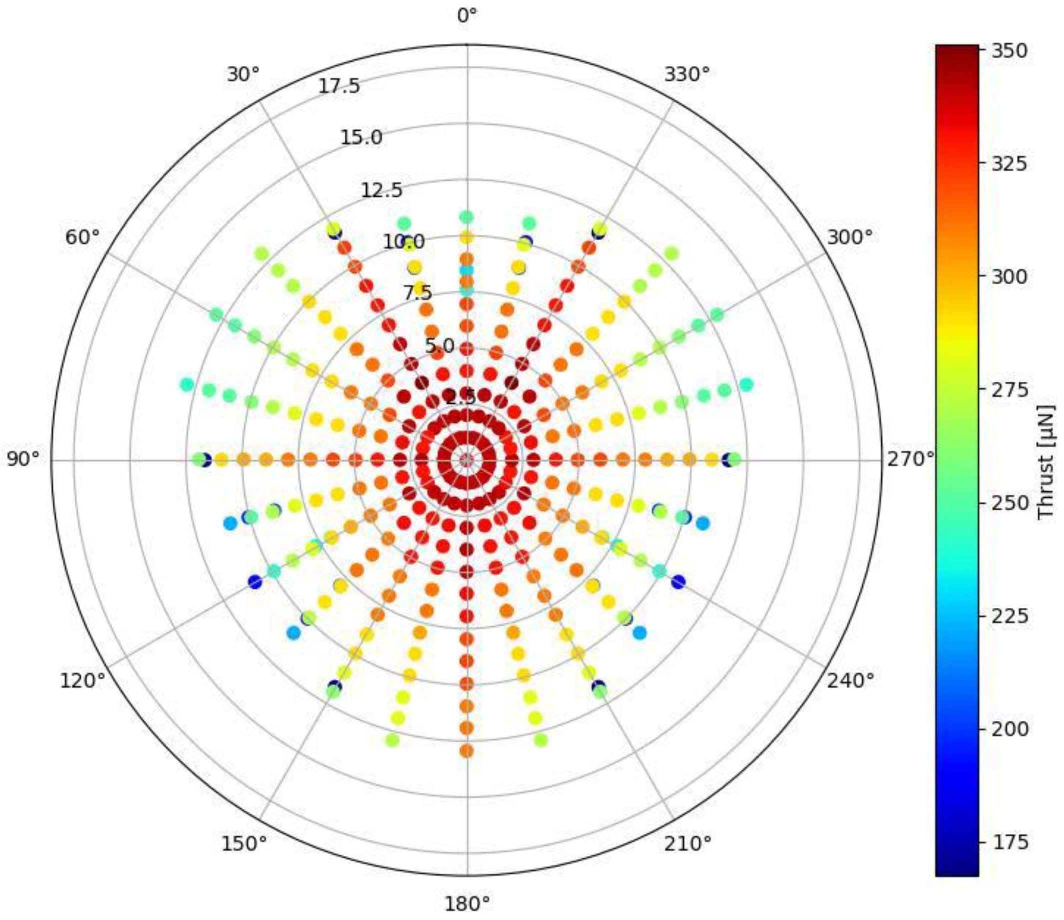

FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
120n 100n 80n 60n 40n 20n 0


FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
140n 120n 100n 80n 60n 40n 20n 0


FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
100n 80n 60n 40n 20n 0

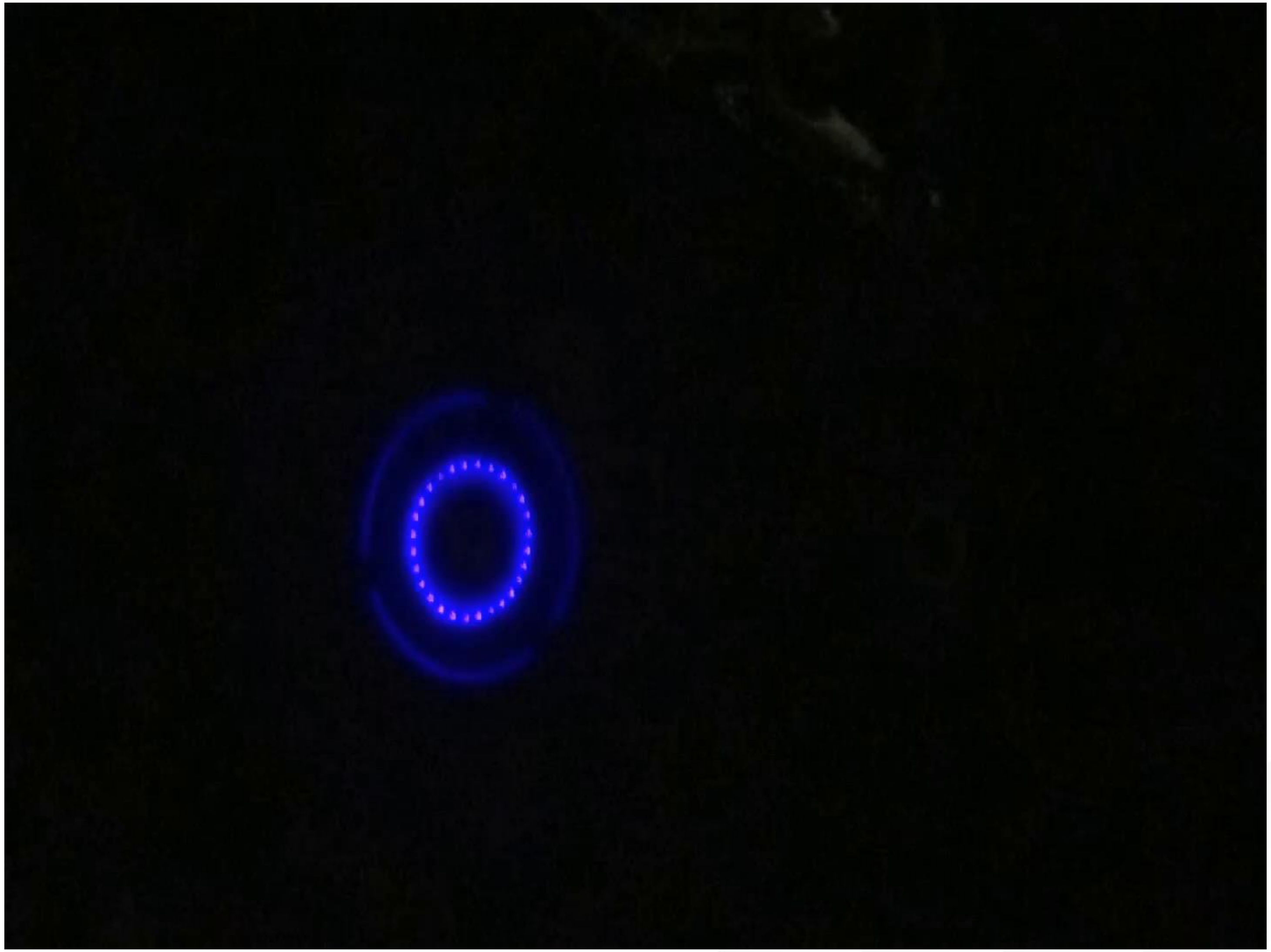

FC position [°]
80 60 40 20 0 −20 −40 −60 −80
−50 0 50
Boom position [°]
150n 100n 50n 0

Modeling of resulting thrust magnitude



Show and Tell

Breadboard Model Test at FOTEC

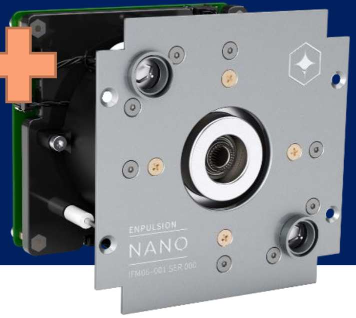


Development Roadmap

More thrust

ENPULSION
MICRO R³

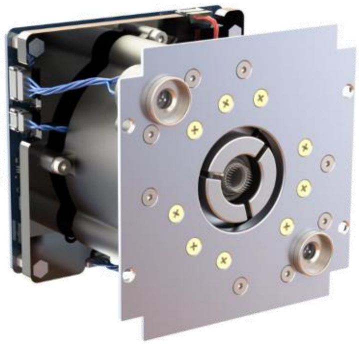
ESA-EOP InCubed



ENPULSION
NANO R³

Better electronics

Thrust vector control



Qualifi-cation

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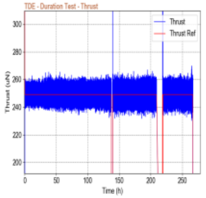


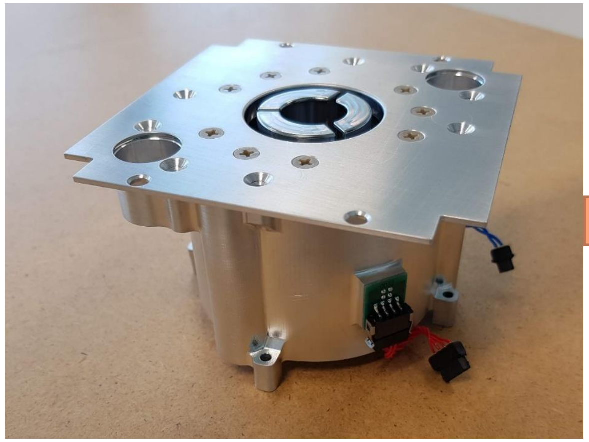
Results and Outcome

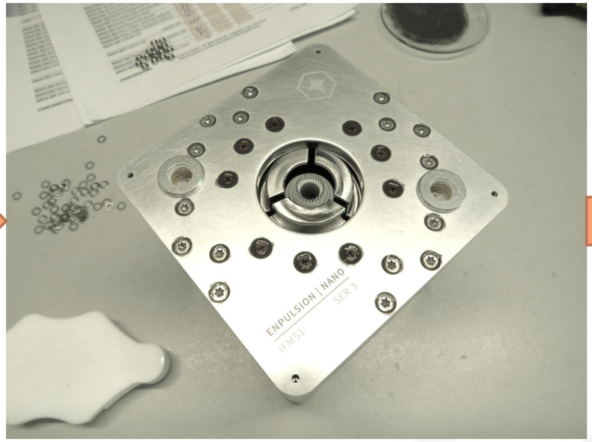
Outlook

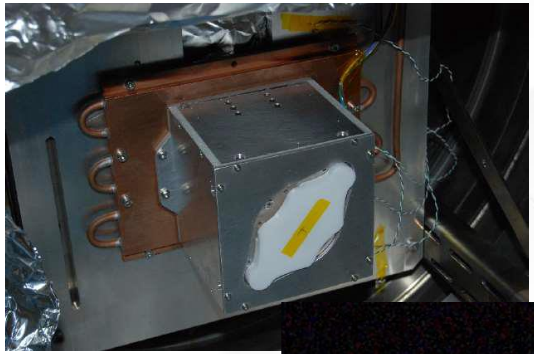
Objectives

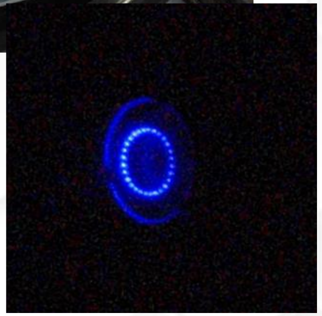
Based on ESA-TRP-TECMPE-SOW-015295

- **Task 1:** Propulsion System Specification and Design
- **Task 2:** Propulsion System MAI
- **Task 3:** Propulsion System Testing
- **Task 4:** Further Development Road-mapping

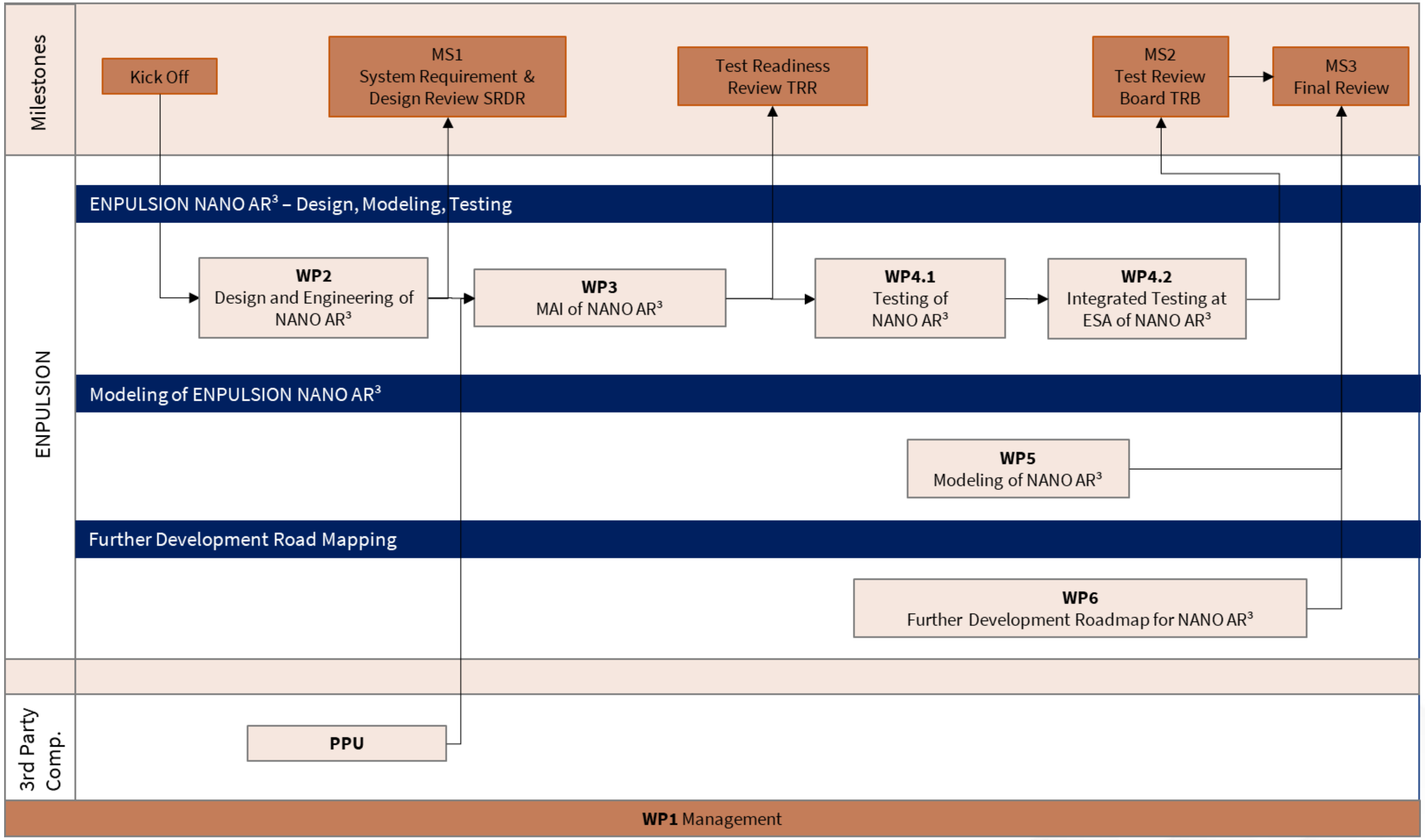








Work Package Breakdown

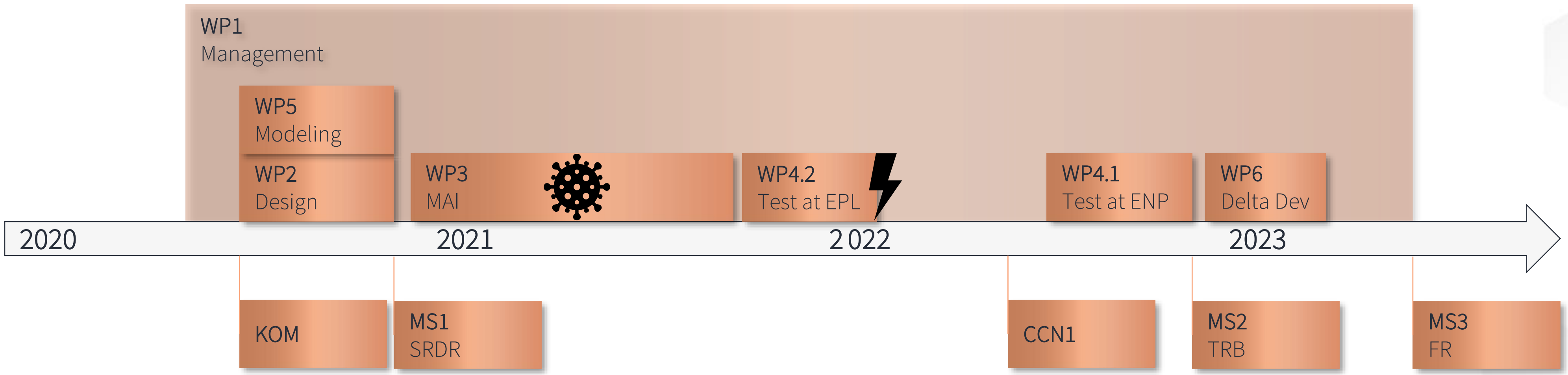


WP	Task
1	-
2	1
3	2
4.1	3
4.2	3
5	1
6	4

Work Package Description

- **WP2** - Definition of system requirements, thruster configuration, related design definition documentation, test planning, supplier definition
- **WP3** - Parts procurement, assembly and acceptance testing of device under test (DUT)
- **WP4.1** - Various verification test activities at ENPULSION/FOTEC to evaluate EM status
  - Faraday cup measurements
  - Environmental verification
- **WP4.2** - Various verification test activities at ESA-ESTEC to demonstrate TVC
  - Faraday cup measurements
  - Endurance firing
- **WP5** - Structural and thermal modelling supporting the design definition and verification
- **WP6** - Definition of subsequent development and verification activities

Schedule


WP1
Management
WP5
Modeling
WP2
Design
WP3
MAI
WP4.2
Test at EPL
WP4.1
Test at ENP
WP6
Delta Dev
2020
2021
2 022
2023
KOM
MS1
SRDR
CCN1
MS2
TRB
MS3
FR

Work Package Description (incl. CCN1)

- **WP2** - Definition of system requirements, thruster configuration, related design definition documentation, test planning, supplier definition
- **WP3** - Parts procurement, assembly and acceptance testing of device under test (DUT)
- **WP4.1** - Various verification test activities at ENPULSION/FOTEC to evaluate EM status
  - ~~Faraday cup measurements~~
  - ~~Environmental verification~~ + Endurance firing
- **WP4.2** - Various verification test activities at ESA-ESTEC to demonstrate TVC
  - Faraday cup measurements
  - Endurance firing*
- **WP5** - Structural and thermal modelling supporting the design definition ~~and verification~~
- **WP6** - Definition of subsequent development and verification activities

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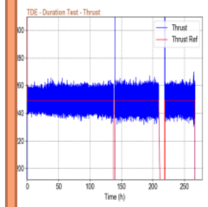


Results and Outcome

Outlook

ENPULSION NANO R³ ESA-EOP InCubed

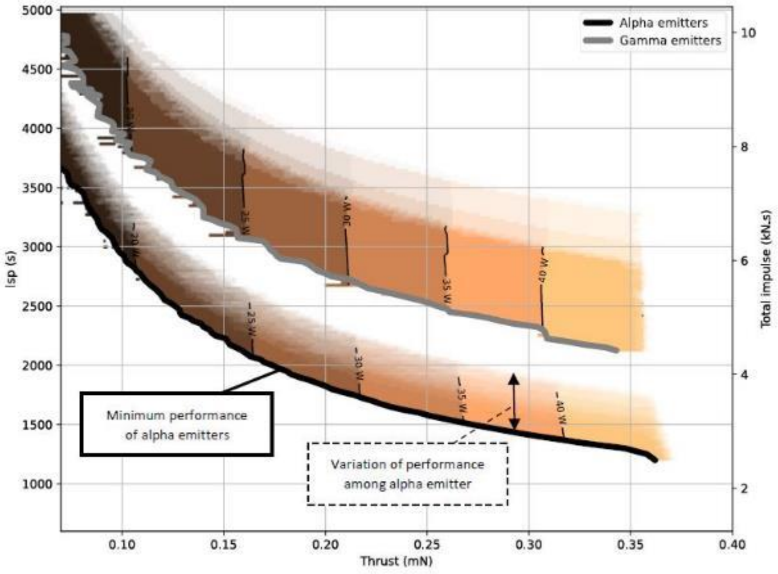
ENPULSION

ROBUST

The ENPULSION NANO R³ is an updated version of the space proven ENPULSION NANO. It leverages the proven design and offers increased radiation protection as well as electronic reliability.

RAD-TOLERANT ELECTRONICS All EEE components of the ENPULSION NANO R³ are procured in lot-controlled batches. Selected sets of these batches are subjected to radiation testing, so that each thruster delivered to a customer can be traced back to a fully representative qualification model using components from the same batch. EEE components were selected and integrated to be more tolerant to TID and SEE.

PROTECTIVE CASING The thruster is assembled into a protective casing that shields the electronics from the hazardous space radiation environment, facilitates handling during integration, and allows side mounting.



DYNAMIC THRUST RANGE [1]	10 TO 350 µN
NOMINAL THRUST	350 µN
SPECIFIC IMPULSE	1,500 TO 5,000 s
PROPELLANT MASS	220 g
TOTAL IMPULSE[2]	MORE THAN 4,000 Ns
POWER AT NOMINAL THRUST	45 W INCL. NEUTRALIZER
OUTSIDE DIMENSIONS	98.0 x 99.0 x 95.3 mm
MASS (DRY / WET)	<1180 / <1400 g
TOTAL SYSTEM POWER	15 – 45 W
HOT STANDBY POWER[3]	4 - 7 W
COMMAND INTERFACE	RS422 / RS485
SUPPLY VOLTAGE	12 V, 28 V, OTHER VOLTAGES UPON REQUEST

Development Roadmap

More thrust

ENPULSION
MICRO R³

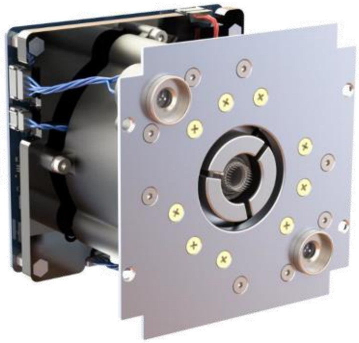
ESA-EOP InCubed

Better electronics

ENPULSION
NANO R³

Qualifi-
cation

Thrust vector control

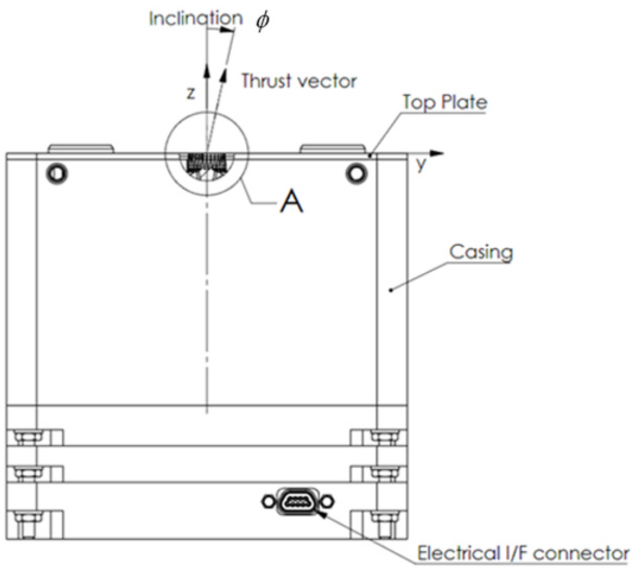


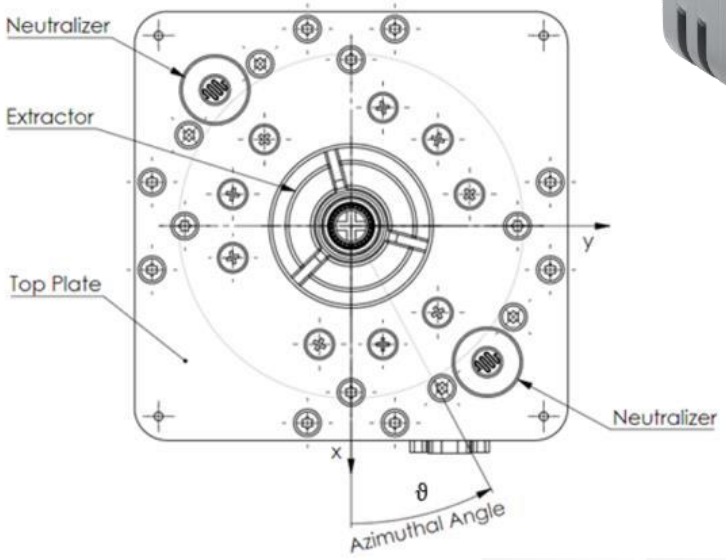
ENPULSION NANO AR³

VERSATILE

Building on the flight heritage of the ENPULSION NANO, the ENPULSION NANO AR³ expands controllability towards active thrust vector control, without moving parts.

ACTIVE THRUST VECTOR CONTROL The ENPULSION NANO AR³ allows to control actively its resulting thrust vector – without any moving parts. It can therefore steer, correct for CoG mismatch, or enable advanced missions requiring thrust pointing.





Differences between the NANO R^3 and NANO AR^3

- Design deltas between NANO R^3 and NANO AR^3

Aspect	Design Delta	Covered by TDE?
Emitter	None	No
Extractor	Segmentation, HV Clearance, new structural concept	Yes
Neutralizer	Same as NANO R^3	No
PPU	Additional extractor sections on HV board, additional transformers on LV board, adjusted control electronics, new mechanical and thermal layout	No
Mathematical model	New analytical equations to derive angles from electric parameters to derive control functions	Partially
Firmware	Many similarities to NANO R^3, extended register map and fuse register, more control functions, overlying PID loops for new mathematical functions	Partially
Environmental resilience	Similar or same to NANO R^3	Partially

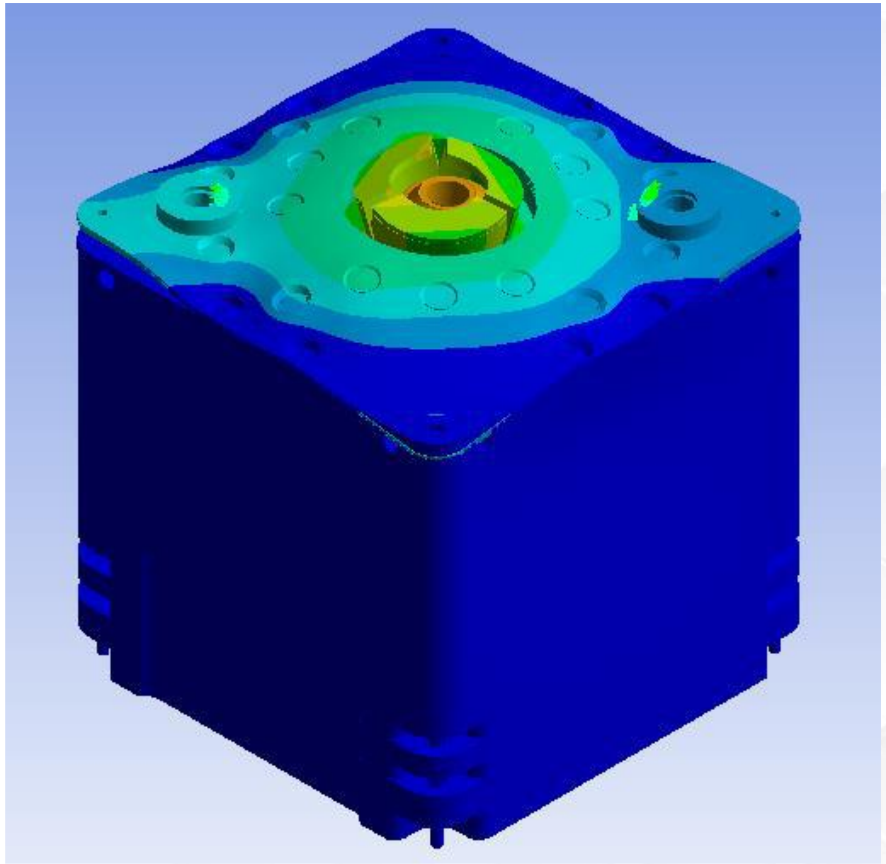
Structural Modeling

WP2&5 / Task 1

- MSC Patran & ANSYS
- Only random vibration loads considered (no shock)
- Intended qualification profile

Frequency	ASD (g^2/Hz)
20	0.026
50	0.16
800	0.16
2000	0.026

- Assumptions for unknown material data and modeling factors included (no structural correlation yet)
- Resulting MOS > ECSS-required MOS



Thermal Modeling

WP2&5 / Task 1

- MSC Patran & ANSYS
- Heat losses derived from heritage values and early testing
- Load case for design
  - Thruster operating at max power
  - Mechanical and thermal I/F at max temperature
  - Incident solar flux onto external surfaces
- Assumptions for material data, conduct conductances, etc. included (prior thermal correlation)
- Components checked against thermal derating and/or absolute rated values → margin > 0

System Requirements and Design Review

SP-01

TN-01

TP-01

SP-02

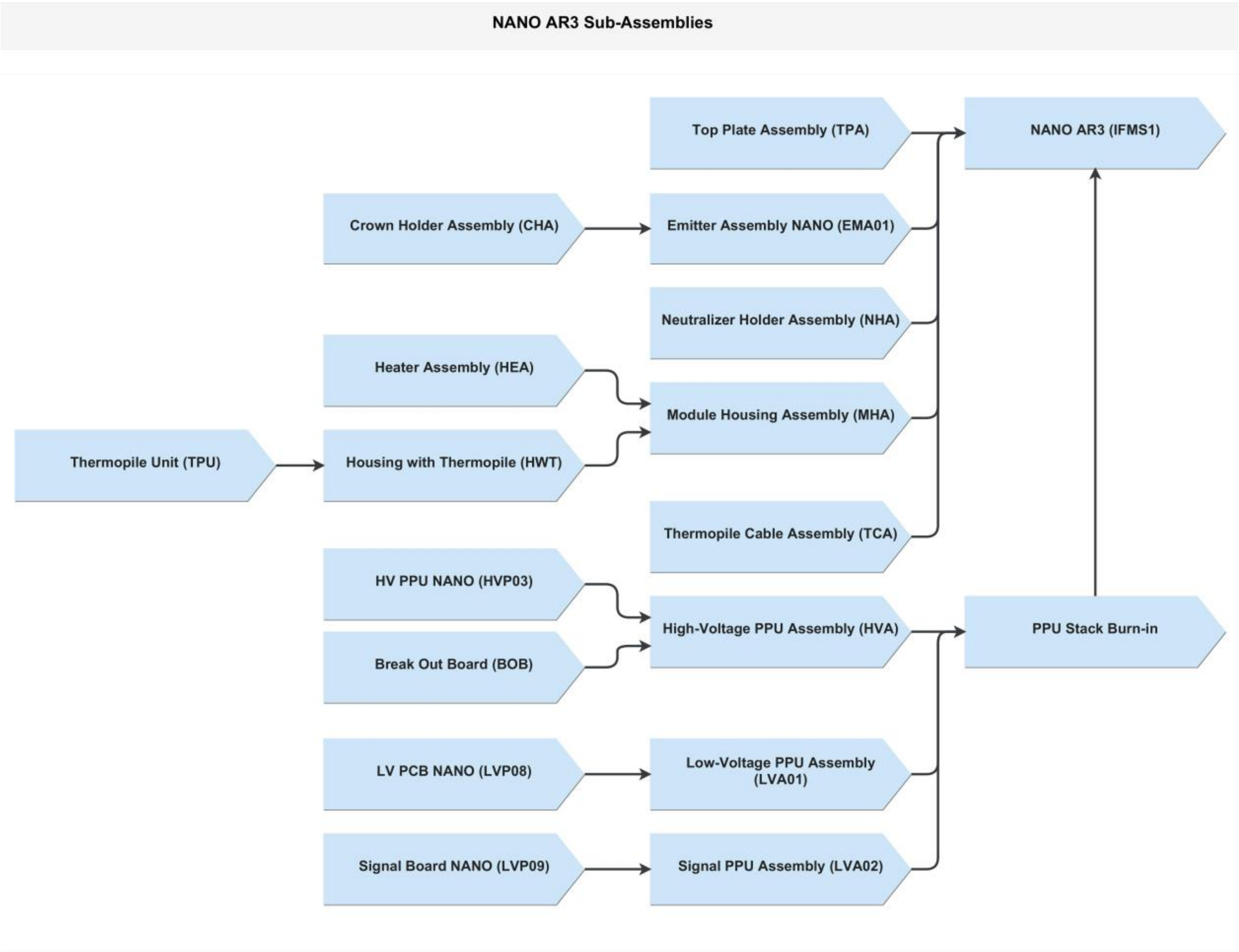
- ENP2019-099.A IFM Nano Thruster SE - ICD Volume I - Mechanical, Electrical, and Thermal Interfaces
- ENP2019-099.A IFM Nano Thruster SE - ICD Volume II - Communication Interface
- ENP2020-020.A IFM Nano Thruster SE - Design Definition File
- ENP2020-029.B Generic Development Plan + Annex
- ENP2020-077.A IFM Nano Thruster SE - Technical Requirements Specification
- ENP2020-079.A IFM Nano Thruster SE - Product Tree
- ENP2020-080.A IFM Nano Thruster SE - Function Tree
- ENP2020-081.A IFM Nano Thruster SE - Specification Tree
- ENP2020-082.A IFM Nano Thruster SE - Technical Budgets
- ENP2020-083.A IFM Nano Thruster SE - Design Justification File
- ENP2020-084.A IFM Nano Thruster SE - Risk Assessment Report
- ENP2020-086.A IFM Nano Thruster SE - Test Plan
- ENP2020-087.A IFM Nano Thruster SE - Critical Item List
- ENP2020-088.A IFM Nano Thruster SE - FMECA
- ENP2020-089.A IFM Nano Thruster SE - VCD
- ENP2020-090.A IFM Nano Thruster SE - DML
- ENP2020-091.A IFM Nano Thruster SE - DPL
- ENP2020-092.A IFM Nano Thruster SE - DMPL
- ENP2020-097.A PPU Requirements COTS+
- ENP2020-098.A IFM Nano Thruster SE - Main Suppliers List
- ENP2020-099.A IFM Nano Thruster SE - Target Price

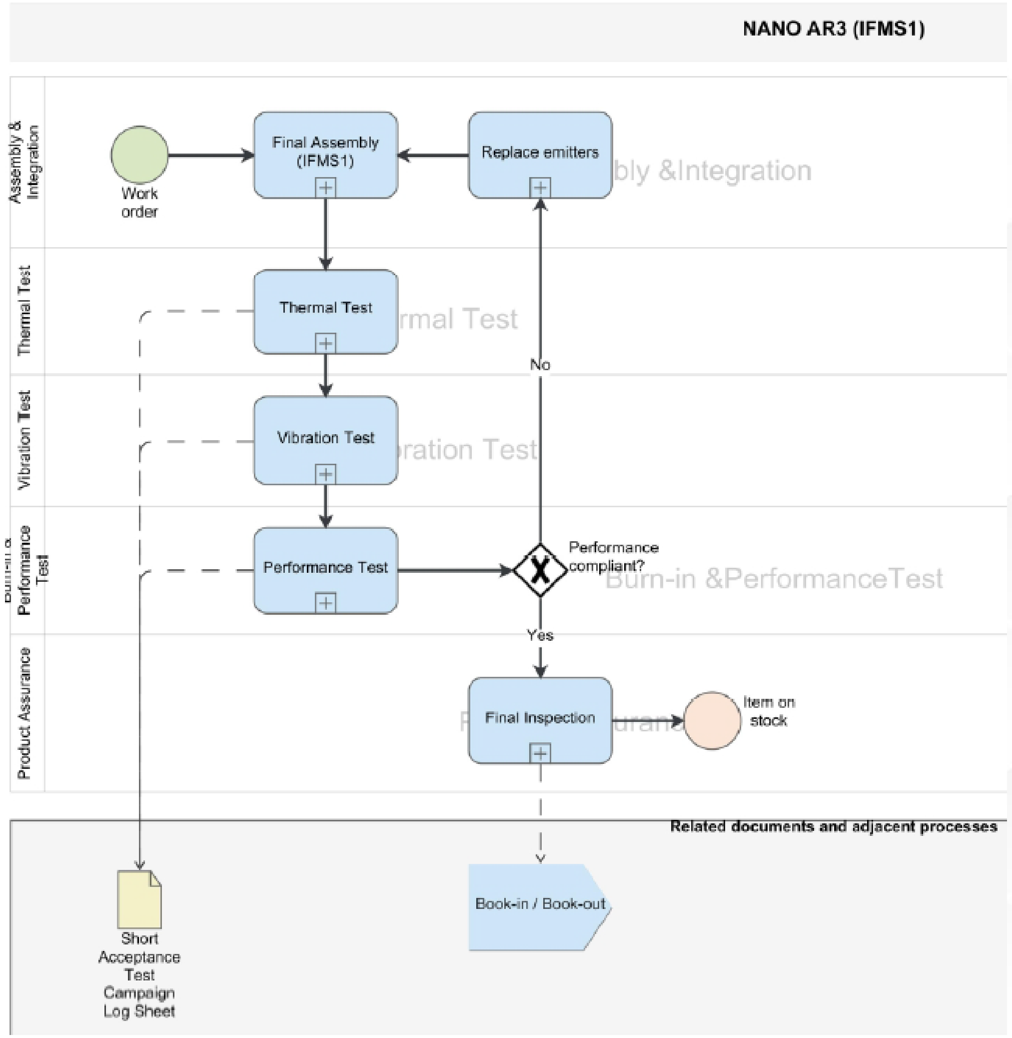
103 RIDs

- Documents updated based on feedback
- SRDR passed with a thruster design

MAI

WP3 / Task 2

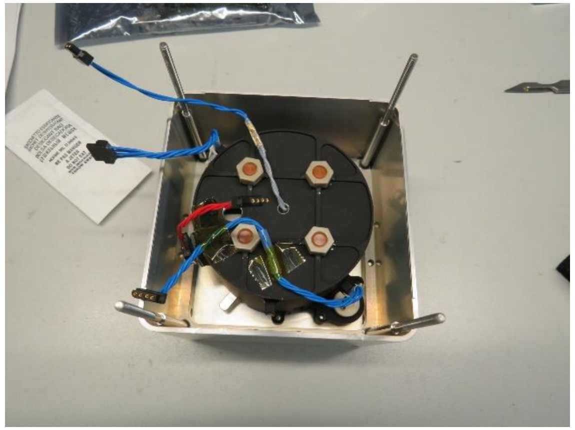


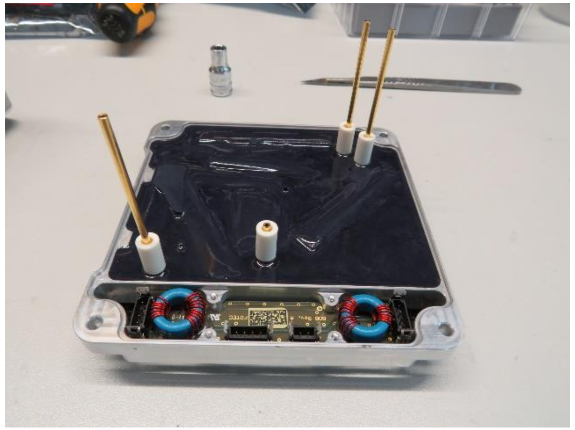


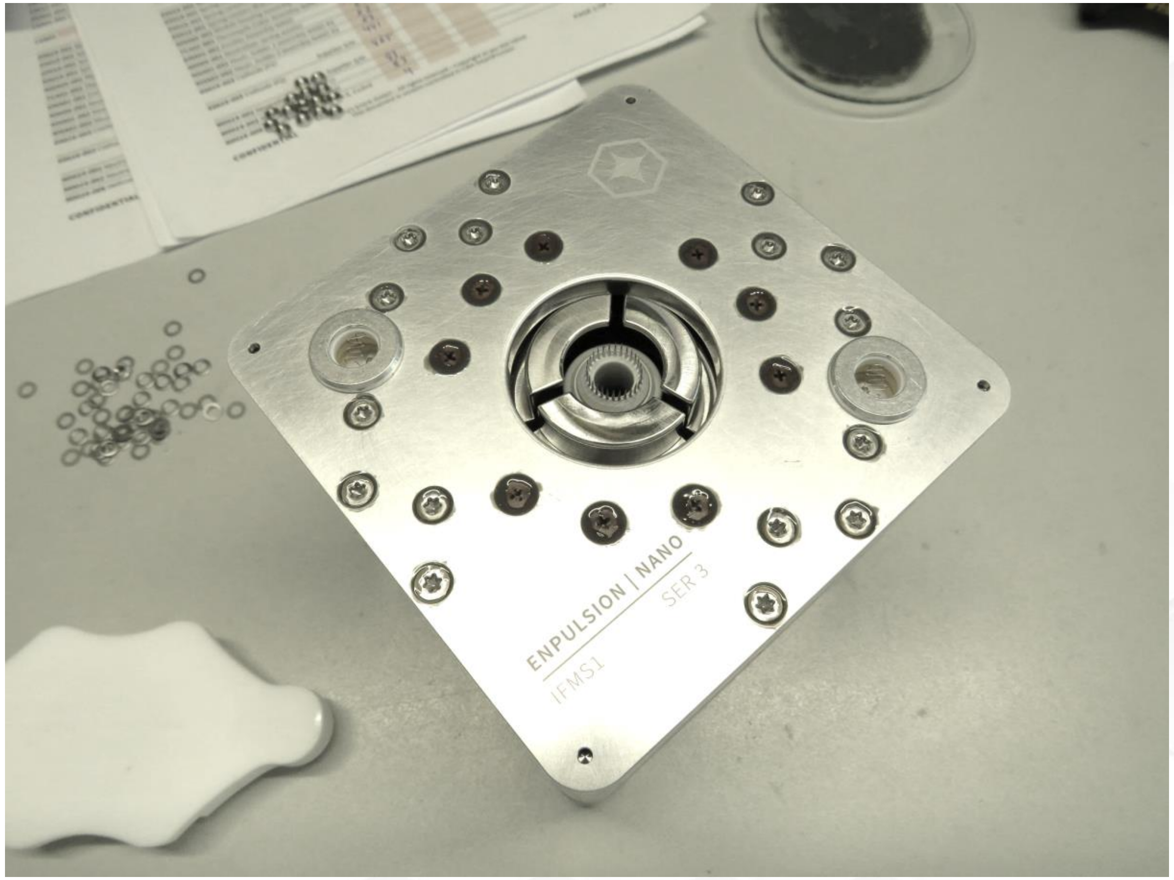
MAI

WP3 / Task 2

Assembly of ENPULSION NANO AR³ - SER 3







Testing at EPL

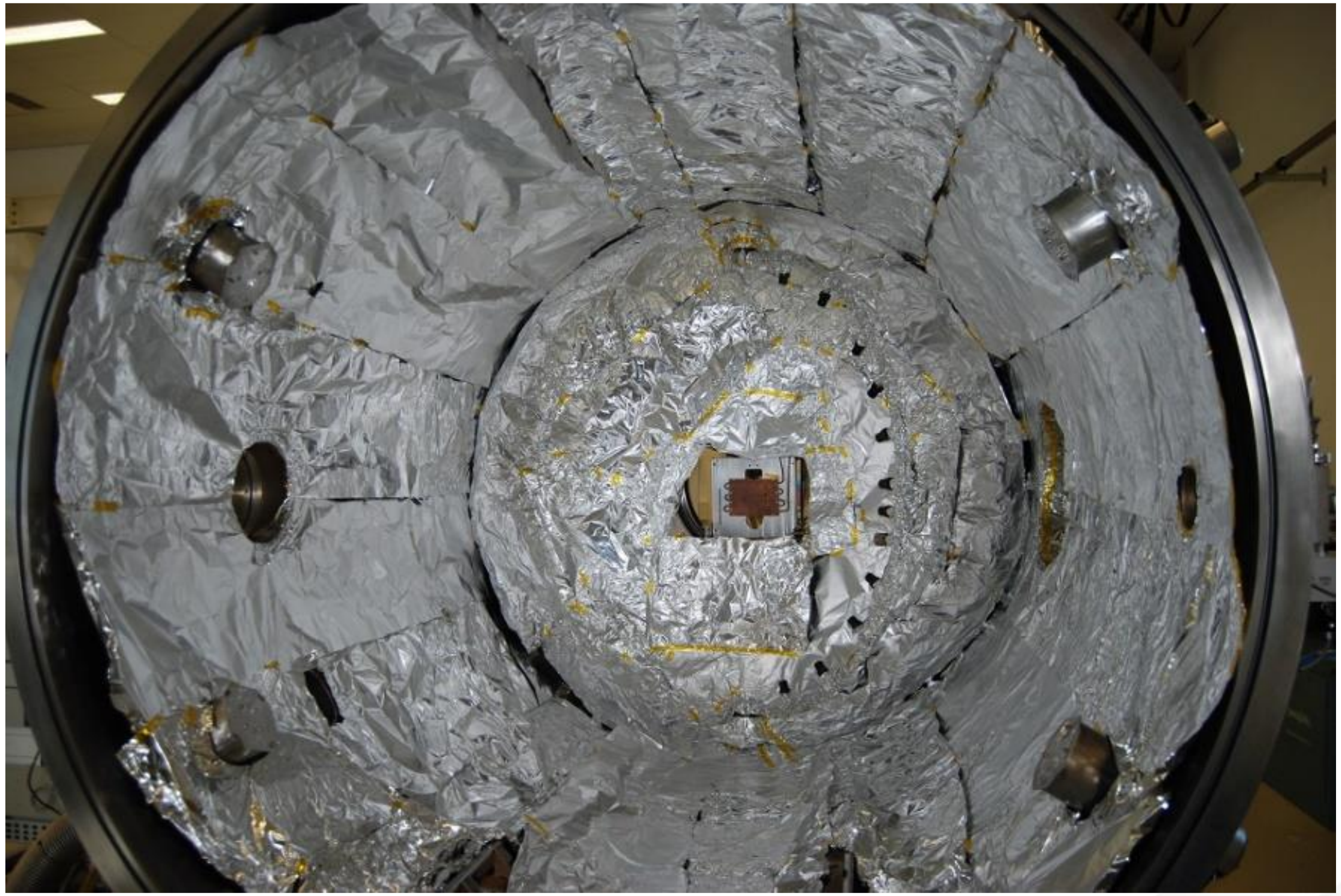
WP4.2 / Task 3

- 2 main objectives
  - Independent verification of thrust vector control
    - Faraday cup measurements on rotating boom in EPL (SPF – Small Plasma Facility)
    - Secondary objective to compare probe designs
  - Endurance firing at an operational point using TVC
    - Thrust performance can be sustained over the course of an extended period of firing
    - Neutralizer is functional at nominal operating conditions over the course of an extended period of firing
    - PPU is functional at nominal operation conditions over the course of an extended period of firing
    - Thrust vector is stable over course of long-duration operation
    - Specific impulse is matching prediction
    - Predictions by mathematical performance model are within acceptable proximity

Testing at EPL

WP4.2 / Task 3

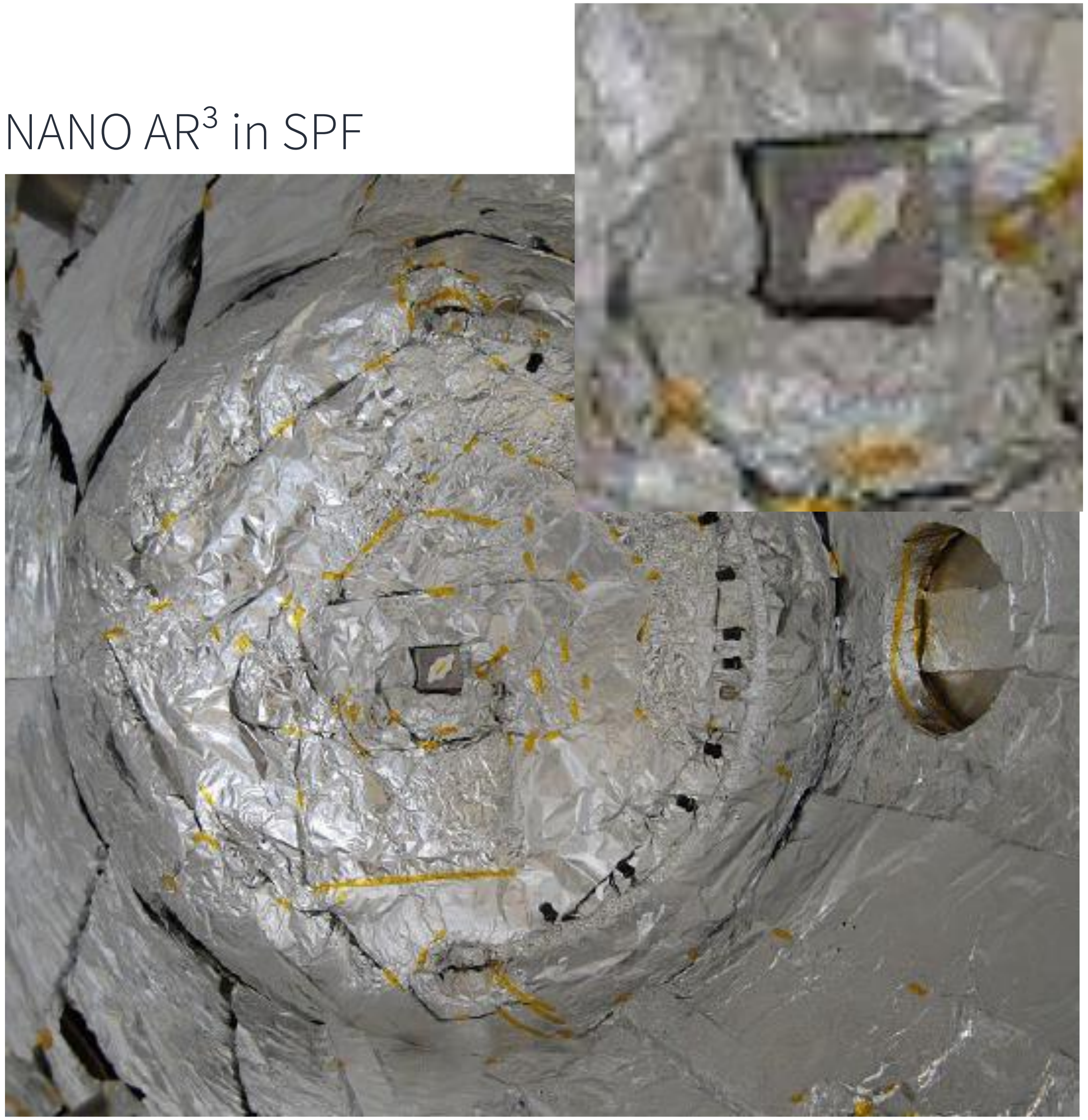
- Preparation of SPF for indium propellant (11 FOTEC probes + 1 EPL probe)

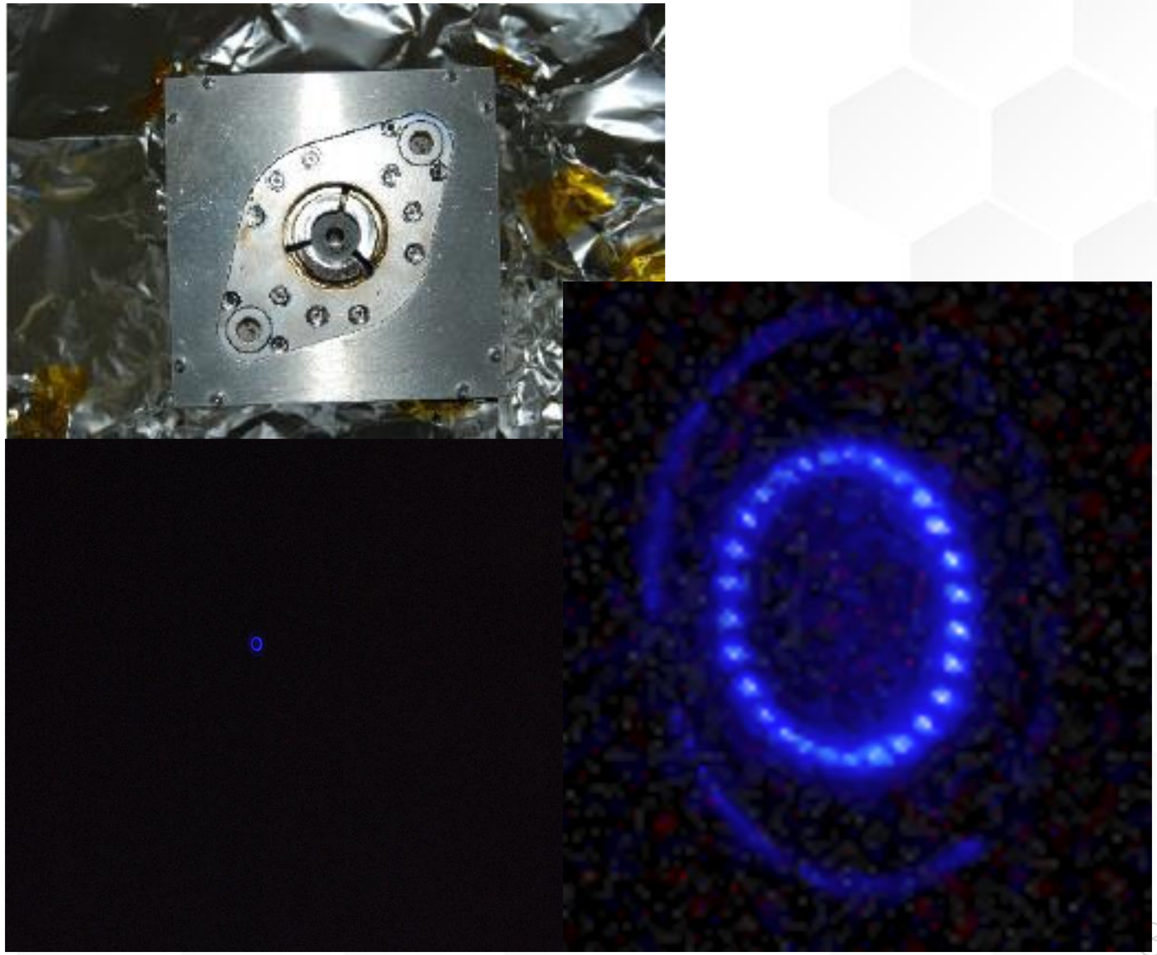


Testing at EPL

WP4.2 / Task 3

- NANO AR^3 in SPF



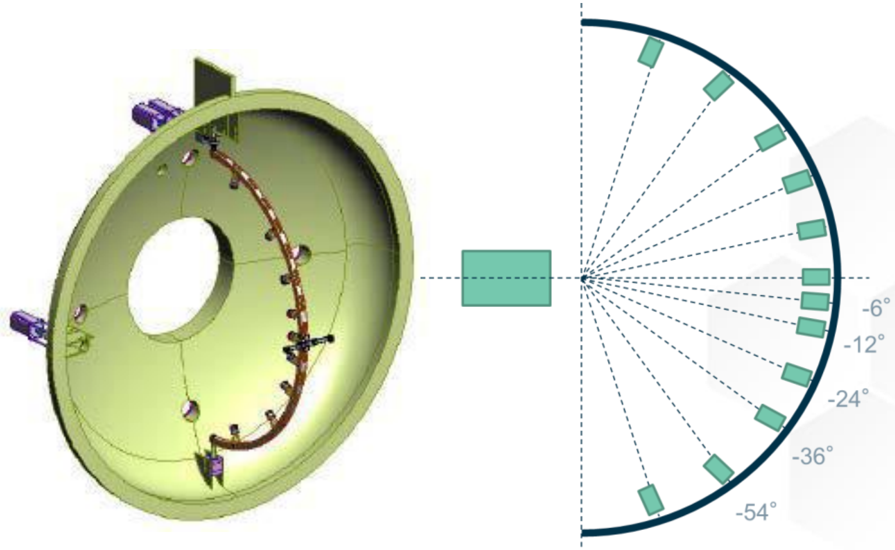


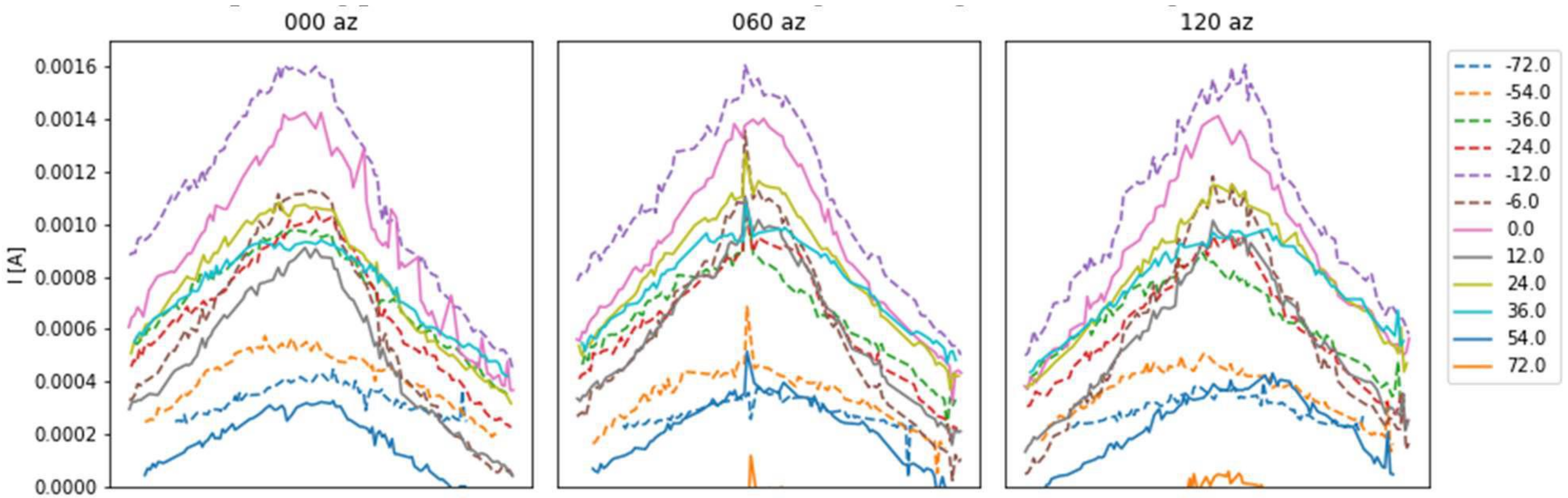
Testing at EPL

WP4.2 / Task 3

- Measurement at different thrust levels and inclinations

Test	Thrust, µN	Inclination, °	Azimuth, °
1	350	5	0-300 (by 60)
2	300	10	0-300 (by 60)
3	250	12.5	0-300 (by 60)



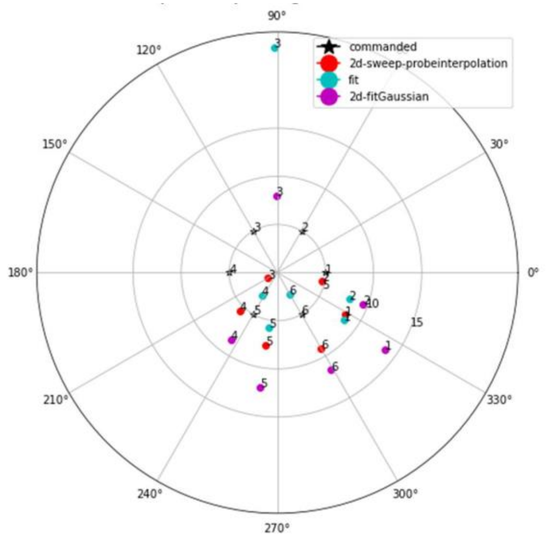


M. Eizinger (ESA-YGT), "ENPULSION NANO AR³ FEEP thrust vectoring capability", Space Propulsion Conference, Estoril, 2022

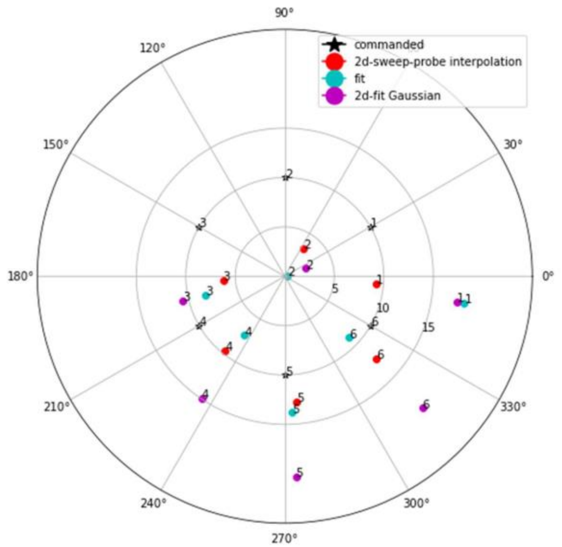
Testing at EPL

WP4.2 / Task 3

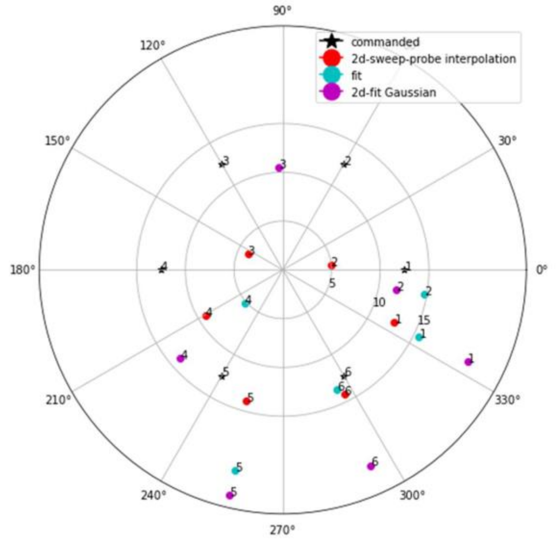
- Measurement at different thrust levels and inclinations



Test 1



Test 2



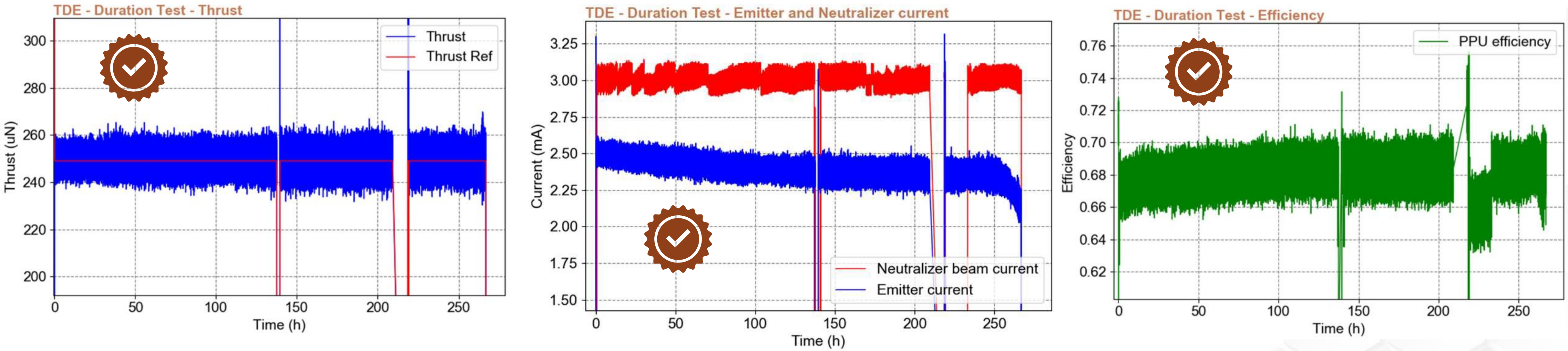
Test 3

- Qualitative verification of thrust vector control (up to 14 °)
- Quantitative verification of thrust vector control
- Comparison of probes

Testing at EPL

WP4.2 / Task 3

- Endurance firing – 250 µN, 10° inclination, 220° azimuth



- Thermal losses observed to be higher than anticipated → lower-power setpoint chosen for extended firing to not overheat electronics (reflected in PPU efficiency)
- NCR at 250+ h terminated endurance firing prematurely

Testing at EPL

WP4.2 / Task 3

- Endurance firing
  - Thrust vector stability (within known accuracy limitations of diagnostic setup)

Time, h	Inclination, °	Incl delta to BOL, °	Azimuthal Angle, °	Azimuthal delta to BOL, °
0	9.7	-	-141.7	-
137.5	11.1	1.4	-138.7	3
207	8.6	-1.1	-124.6	17.1

  - Specific impulse and mathematical model correctness could not or only partially be assessed

Testing at ENP

WP4.1 / Task 3

- Continuation of test campaign not completely feasible due to NCR
- Rework of thruster to resume operativeness
  - Replacement of emitter and some related components
  - Replacement of low-voltage board for critical design update
  - Upgrade of firmware to latest development build
  - Addition of thermal mitigation hardware
- Preparation of setup to reduce thermal load on thruster
- As delta development was deemed necessary to overcome the PPU/Thermal challenge, benefit from environmental campaign and continued modeling descoped by CCN1, and additional endurance campaign of 250 h at ENPULSION added to investigate NANO AR^3-specific design aspects (as certain verification aspects are covered similarly by NANO R^3 qualification)

Testing at ENP

WP4.1 / Task 3

- Preparation of reworked NANO AR[3] in Miranda

Testing at ENP

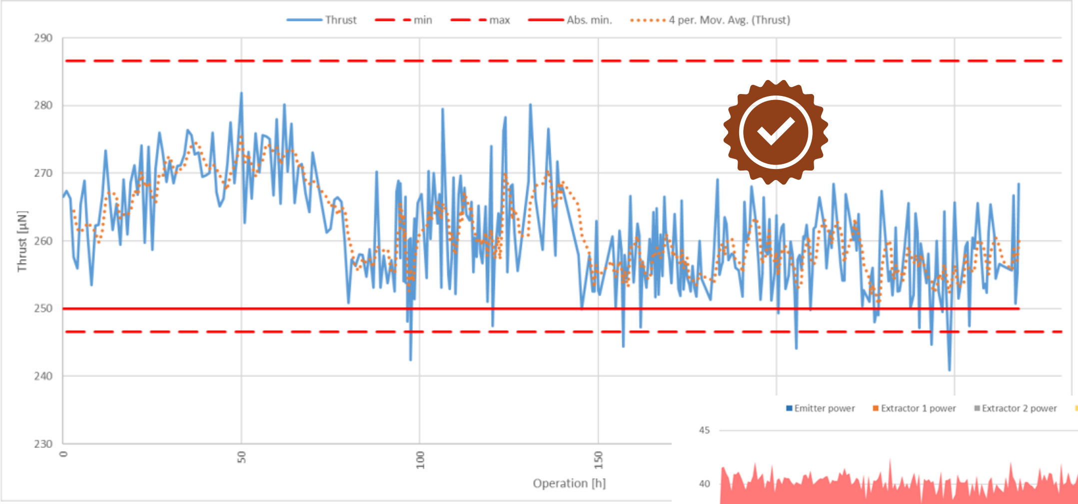
WP4.1 / Task 3

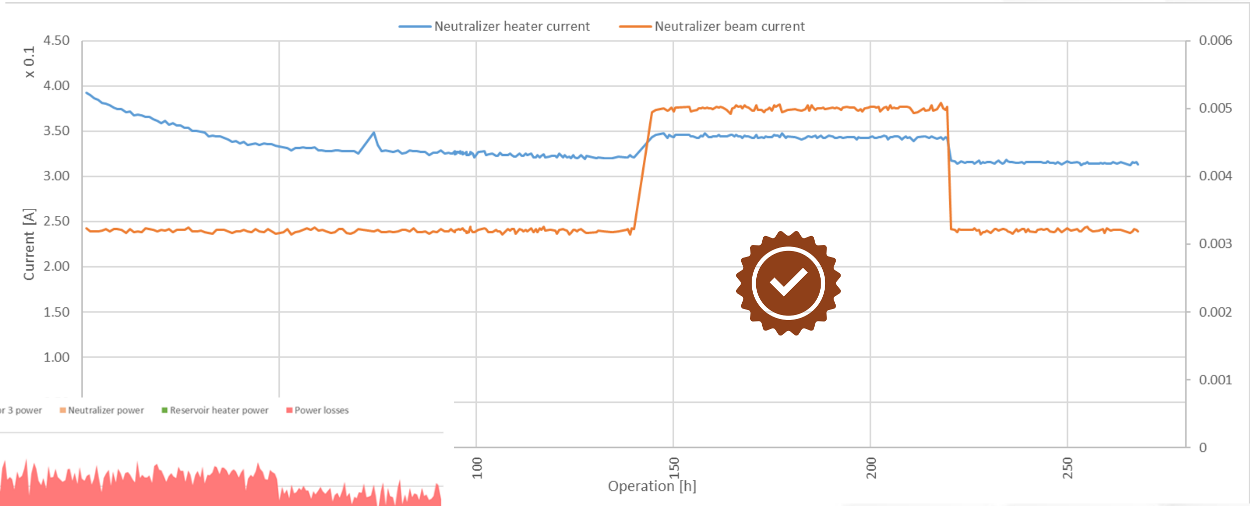
- Endurance firing at an operational point using TVC
  - Thrust performance can be sustained over the course of an extended period of firing
  - Neutralizer is functional at nominal operating conditions over the course of an extended period of firing
  - PPU is functional at nominal operation conditions over the course of an extended period of firing
  - Thrust vector is stable over course of long-duration operation (w/o Farady cups, only optical assessment)
  - Specific impulse is matching prediction
  - Predictions by mathematical performance model are within acceptable proximity
  - Indium deposition is not affecting operation

Testing at ENP

WP4.1 / Task 3

Endurance firing – 250 µN, 10° inclination, 150° azimuth

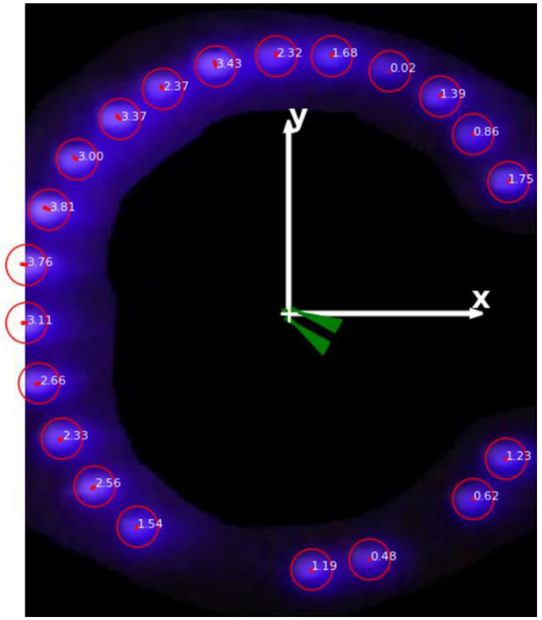




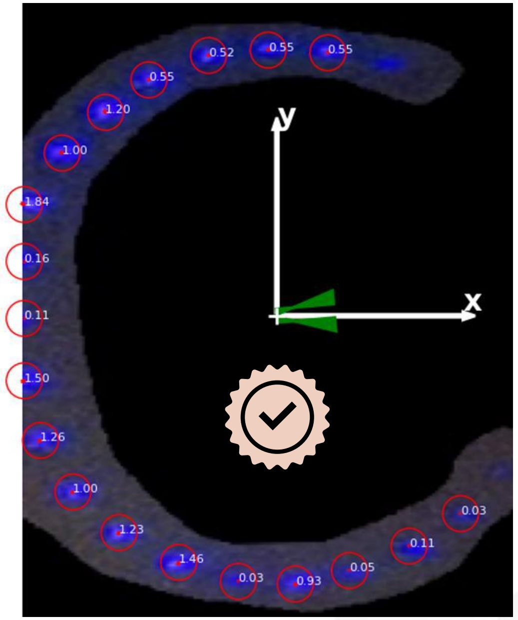
Testing at ENP

WP4.1 / Task 3

- Endurance firing
  - Thrust vector stability assessment affected by quality of images and accuracy of optical evaluation
  - Due to FW development status, no fully automatic TVC was possible to compensate potential drifts



0 h (BOL)

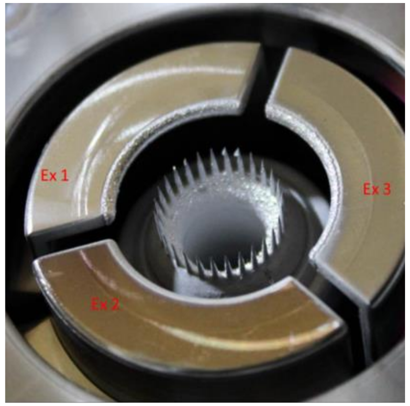


250 h

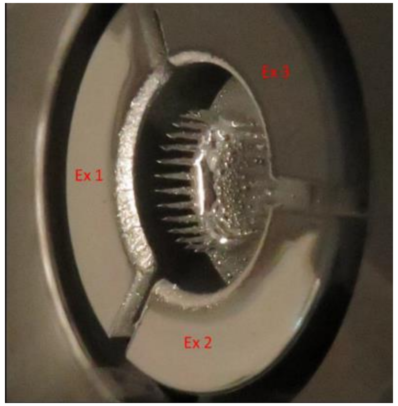
Testing at ENP

WP4.1 / Task 3

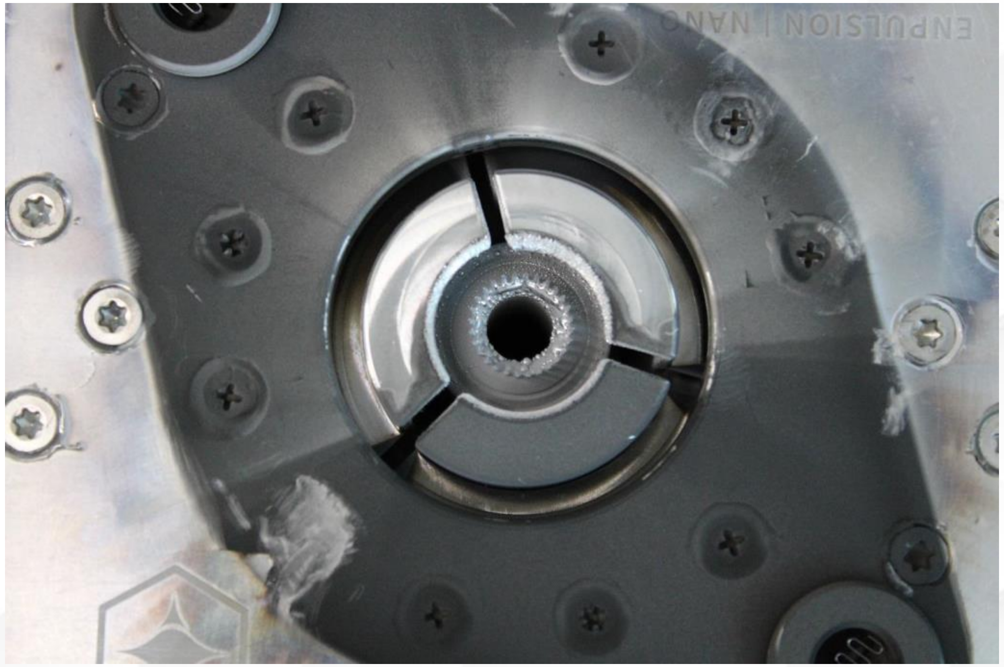
- Endurance firing
  - Specific impulse derived from electric parameters slightly less than objective (1800 vs 2000 s), but improved FW with direct feedback and improved control loops could have compensated
  - Mathematical model off by 28% (objective: 25%) with potential facility effects
  - Indium deposition between extractor segments



0 h (BOL)



250 h



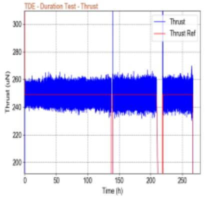
ENPULSION

AGENDA

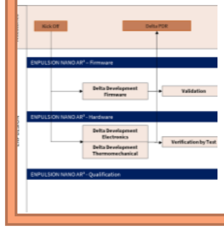
Company Introduction

Technology / Previous Work

Work Packages and Objectives



Results and Outcome



Outlook

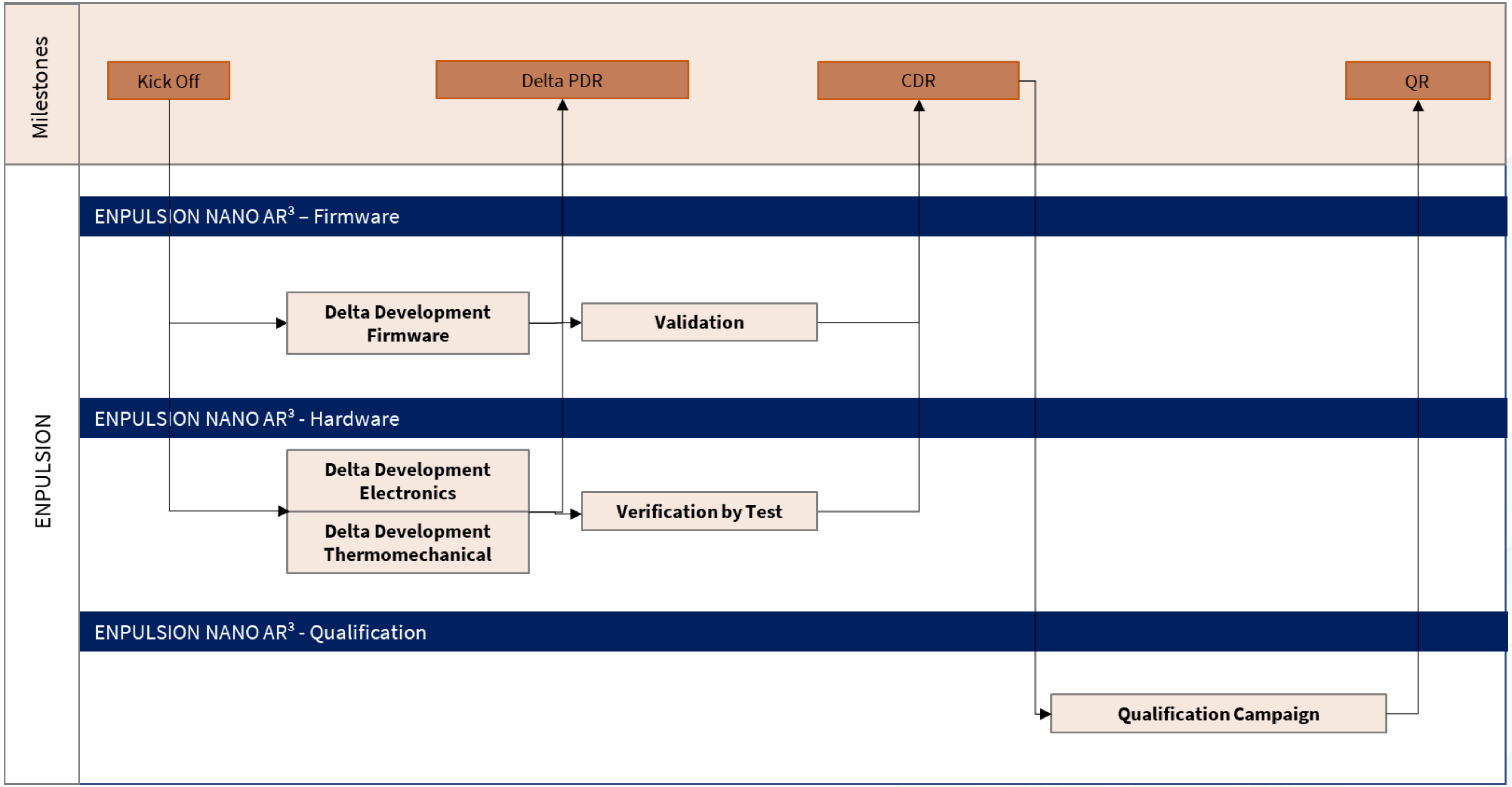
DDVP

WP6 / Task 4

- Lessons learned and anticipated changes from testing activities within and parallel to this TDE activity
  - PPU
    - Higher losses than anticipated for additional HV rails → strong negative impact on thermal situation
    - Design of HV board leads to intensive manufacturing effort and risk of component damage
    - Thermal mitigation on electronics side to be investigated (either by component iteration and/or PCB adaptation)
  - Thermal
    - Enhanced thermal mitigation necessary to direct heat losses away from critical components
    - Impact also on mechanical side
  - FW
    - Additional routines challenging microcontroller's computational limitations due to code base in C++ based on NANO
    - Improvement of quality level to DAL C done for NANO R^3 development, which needs to be adapted to the NANO AR^3

Further Development Roadmapping

WP6 / Task 4



ENPULSION

WE ARE LOOKING FORWARD TO
DRIVING YOUR ADVANCE

ENPULSION

FULLY INTEGRATED PROPULSION SYSTEMS






	ENPULSION NANO	ENPULSION NANO R^3	ENPULSION NANO AR^3	ENPULSION NANO IR^3	ENPULSION MICRO R^3	ENPULSION NEO
	FLIGHT HERITAGE	ROBUST	VERSATILE	POWERFUL	DURABLE	DURABLE AND POWERFUL
DYNAMIC THRUST RANGE	10 µN TO 350 µN	10 µN TO 350 µN	10 µN TO 0.35 mN	10 µN TO 500 µN	300 µN - 1 mN	5 - 21 mN
NOMINAL THRUST	330 µN	350 µN	350 µN	500 µN	1 mN	20 mN
SPECIFIC IMPULSE	1,500 TO 5,000 s	1,500 TO 5,000 s	2,000 TO 6,000 s	1,500 TO 4,000 s	1,500 - 4,500 s	1,500 TO 4,000 s
PROPELLANT MASS	220 g ± 5%	220 g	220 g	220 g	1.3 kg	20 kg
TOTAL IMPULSE	MORE THAN 5,000 Ns	MORE THAN 4,000 Ns	MORE THAN 5,000 Ns	MORE THAN 4,000 Ns	MORE THAN 30,000 Ns	MORE THAN 300,000 Ns
TOTAL SYSTEM POWER	8 – 40 W	8 – 40 W	8 – 40 W	8 – 45 W	30 - 120 W	50 – 800 W
POWER AT NOMINAL THRUST (incl. Heating and Neutralizer)	40 W	45 W	40 W	45 W	105 W	1000 W
OUTSIDE DIMENSIONS	Fully Integrated System: 100.0* x 100.0* x 82.5 mm *can be customized*	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Thruster head: 140 x 120 x 98.6 mm PPU box: 140 x 120 x 34.0 mm	Thruster incl. Propellant: 265 x 195 x 180 mm (TBC) PPU: 250 x 200 x 100 mm (TBC)
MASS (DRY / WET) including PPU	680 / 900 g	< 1180 / < 1400 g	< 1230 / < 1450 g	<1200 / < 1420 g	2.6 kg / 3.9 kg	11 / 32 kg (TBC)
HEAT-UP POWER	4 – 10 W	4 – 10 W	4 – 10 W	4 – 10 W	20 – 40 W	TBD
HOT STANDBY POWER	3-5 W	4-7 W	3.5 W	3.5 W	10 - 15 W	TBD
SUPPLY VOLTAGE	12 V ± 1 V or 28 V ± 2 V *other upon request*	12 V ± 1 V or 28 V ± 2 V *other upon request*	12 V ± 1 V or 28 V ± 2 V *other upon request*	12 V ± 1 V or 28 V ± 2 V *other upon request*	28 V ± 2 V	26 to 33.6V (TBC)
COMMAND INTERFACE	RS422 or RS485	RS422 or RS485	RS422 or RS485	RS422 or RS485	RS422 or RS485	TBD

ADVANTAGES OF INDIUM AS PROPELLANT

ENPULSION

COMPACT, SAFE, READILY AVAILABLE

	INDIUM	IODINE	XENON	KRYPTON
	SOLID		SUPERCRITICAL FLUID	
DENSITY (IN FLIGHT TANK)	7.3 G/CM³	4.9 G/CM³	1.6 G/CM³	0.6 G/CM³
PRESSURE	0 BAR	< 1 BAR	> 100 BAR	> 100 BAR
TOXICITY*	NONE	0.1 PPM PER 8H	NONE	NONE
LAUNCH WAIVER REQUIREMENTS	NONE	VARYING	PRESSURE VESSEL	PRESURE VESSEL
PRICE OF PROPELLANT	$$	$$	$$$$	$$
AVAILABILITY	~1000 TONS/YEAR	UNLIMITED	~10 TONS/YEAR	~100 TONS/YEAR