
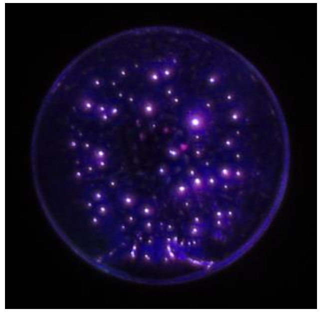
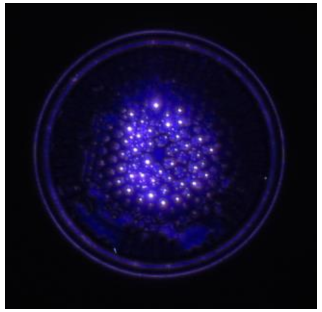

Project MAGNIFIED – Final Presentation

ESTEC – Noordwijk, Netherlands
27 September 2023

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Summary

- Background and Motivation
- Proposed Idea and Objectives
- Emitter Manufacturing
- Thruster Prototype Development
- Performance Testing
- Durability Testing
- Conclusions and Outlook

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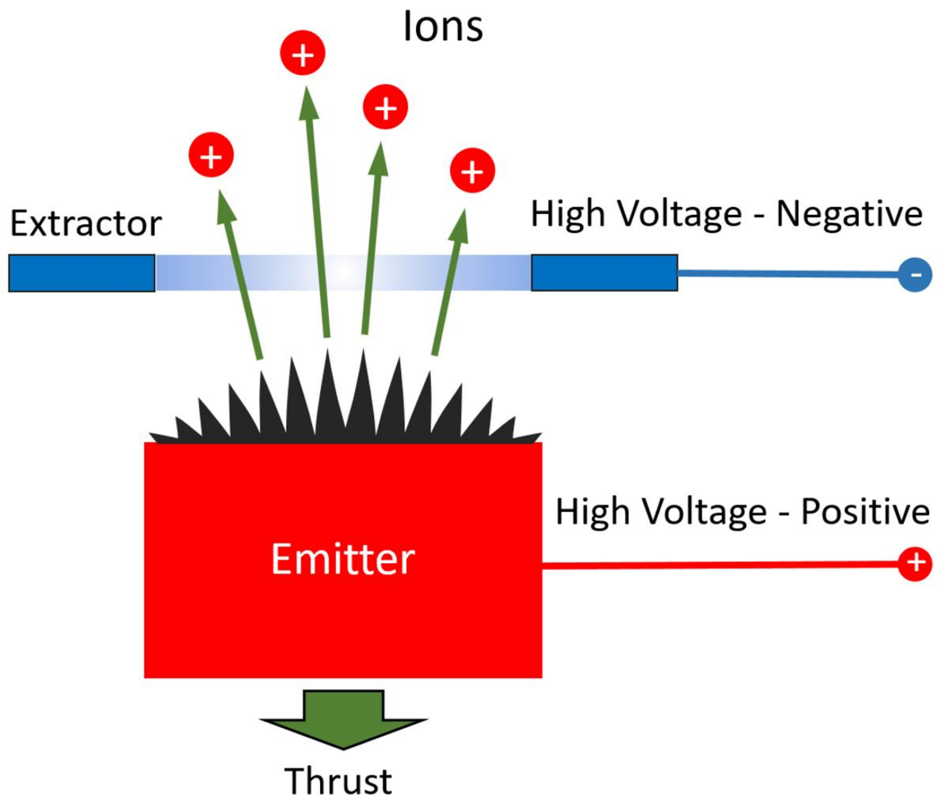
Background and Motivation

- Field Emission Electric Propulsion (FEEP) is a type of propulsion for spacecraft where a liquid propellant is ionized and accelerated in one step to produce thrust
- The device which allows this process is the **emitter**, which is constituted by a multitude of very sharp needles
- The state-of-the-art emitter for FEEP based on liquid metal is made of porous tungsten
- Manufacturing new porous tungsten emitters is presently challenging and expensive, limiting the ability to test and optimize new designs
- Research into optimized fabrication methods could accelerate prototyping, testing, and development of new emitters.



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Proposed Idea and Project Objectives

- Use magnetic fields to shape magnetic metal powders into an array of spikes/needles constituting the emitter
- Design and manufacture a variety of emitters with this novel method
- Design and manufacture a thruster prototype for testing the manufactured emitters
- Assess the performance and the durability of the newly conceived emitters.

Example of magnetically shaped array of spikes

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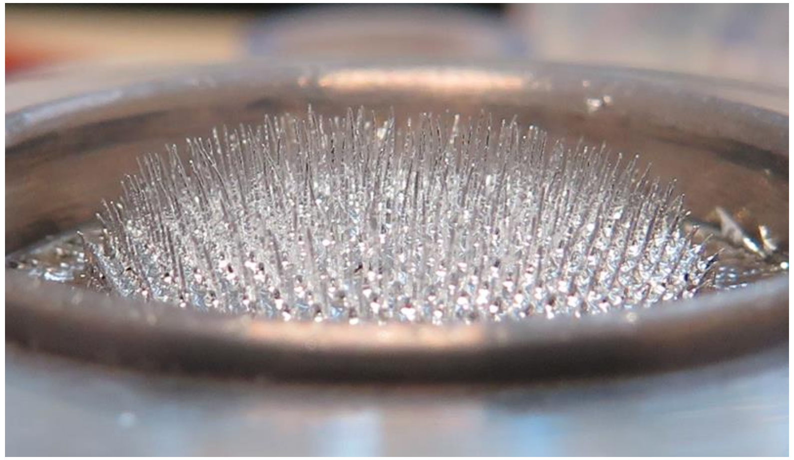
Emitter Manufacturing

- The process started with the manufacturing of titanium and stainless-steel **bases,** which were then used as support structures for the creation of the spikes
- After the creation of the spikes using iron powder and magnetic fields, the emitter went through the next steps of sintering and wetting
- **36 emitters have been manufactured,** with different needle array densities and shapes
- Of these, **28 have been wetted with the propellant,** consisting in a eutectic alloy of gallium and indium, which is liquid at ambient temperature



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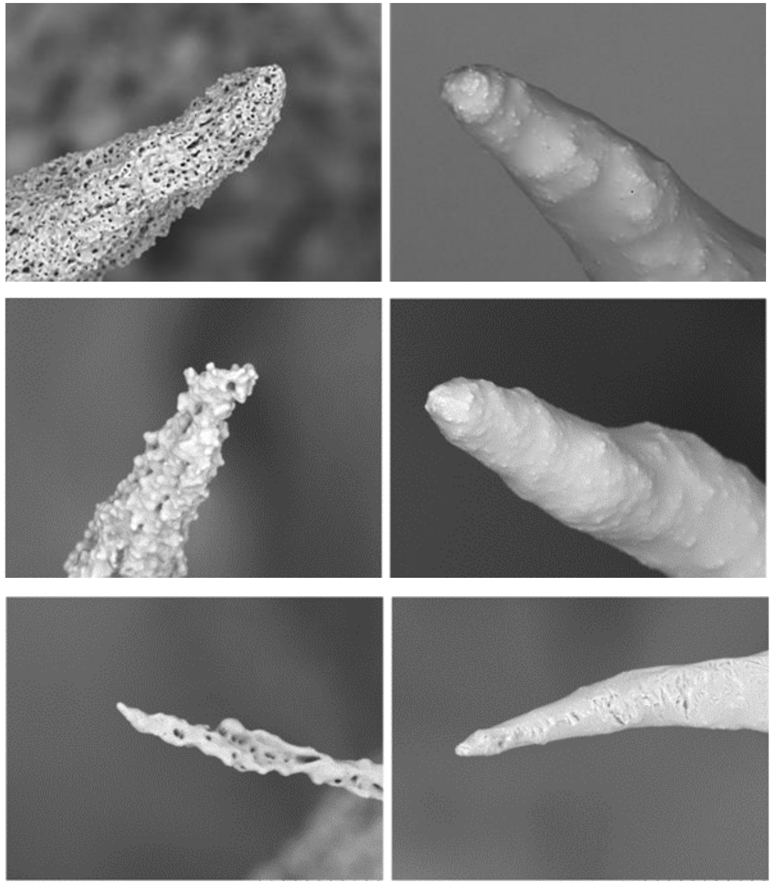
Emitter Manufacturing

- Measured tip radii ranging from **1.5 to 25 µm**
- Most of the emitters were fabricated as **2D arrays** of spikes, that is, spikes distributed over a two-dimensional surface
- The 2D arrays could be roughly grouped into three categories depending on the **density of the spikes**: low, high, and medium density, corresponding respectively to approximately 50, 100 and 200 spikes per square centimeter
- The exception was a crown-like emitter, constituted by 40 spikes arranged on a closed circular path (1D array).



Tips before (left) and after (right) wetting

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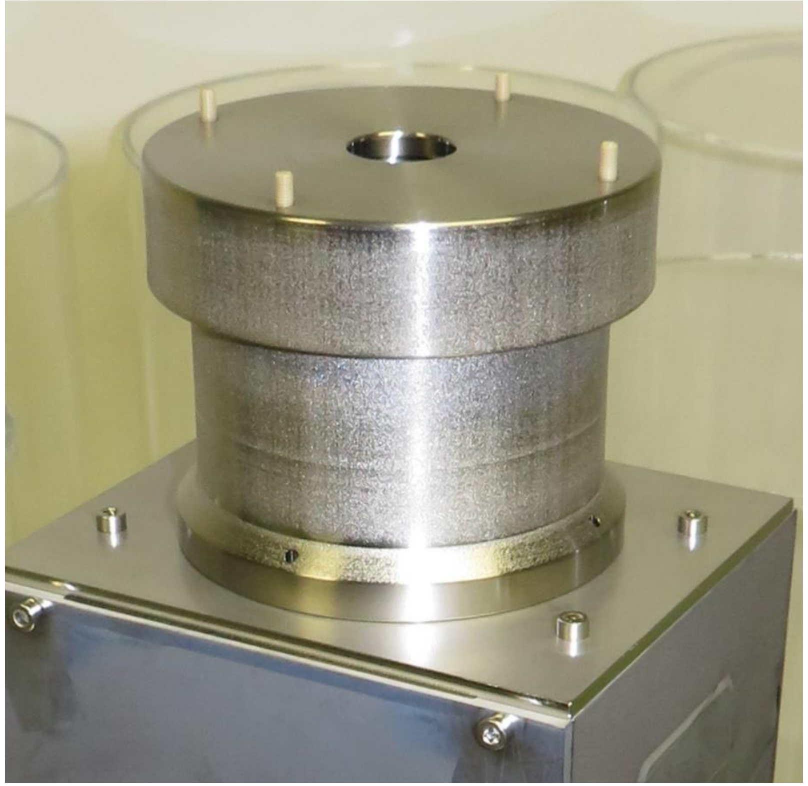
Thruster Prototype

- The thruster prototype was designed to be a **simple and flexible testbed** for evaluating the novel emitter
- Since the emitters use liquid metal propellant, **no heating** or thermal control is needed
- The thruster is **compact,** with a diameter of 86 mm and height of 70 mm
- Main design challenges were **high voltage insulation** in such a small volume and preventing propellant contamination of the insulators
- It can withstand peak emitter and extractor voltages of **20 kV.**



The thruster module (cylindrical) attached to the mechanical interface to the vacuum flange

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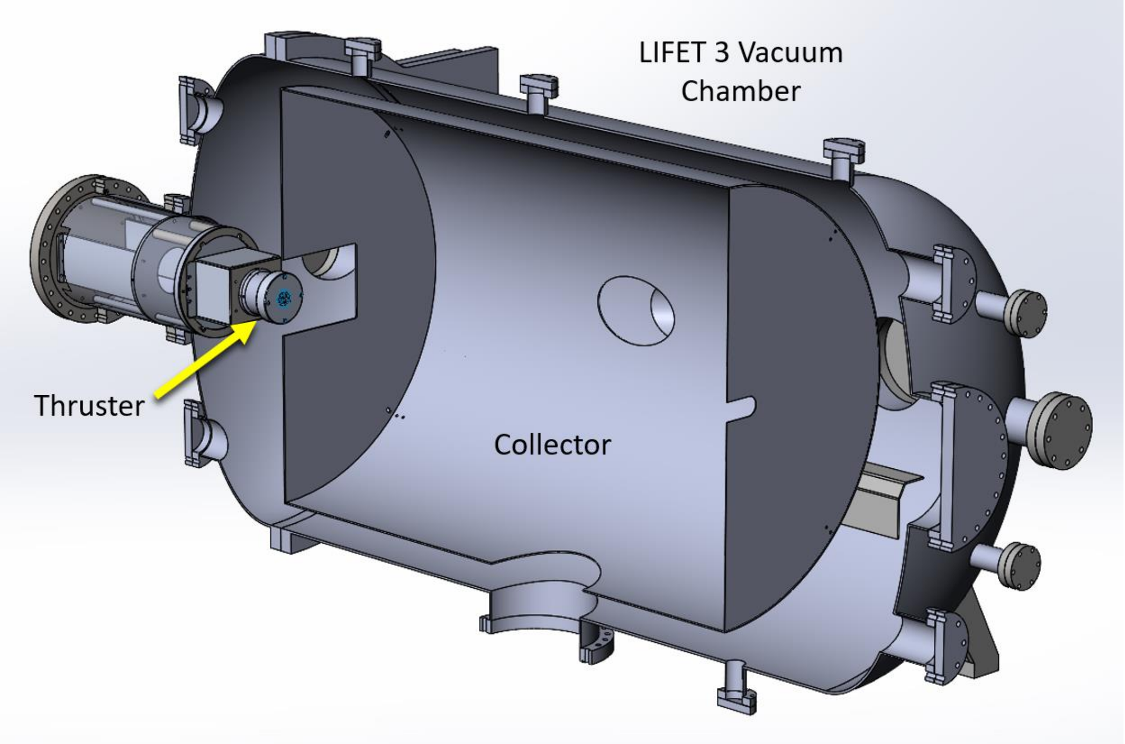
Performance Testing – Setup

- The test campaign was conducted in the **LIFET 3 vacuum chamber** at FOTEC premises
- Vacuum system with roughing pump + turbo pump, **ultimate pressure 10^{-7} mbar**
- A **collector** in the vacuum chamber was used to measure the emitted ionic current
- The pressure in the chamber was measured using a PKR251 Pfeiffer vacuum gauge (5×10^{-9} mbar)
- Viewports located at the side and at the back of the chamber allowed to **observe and take pictures of the operating thruster**



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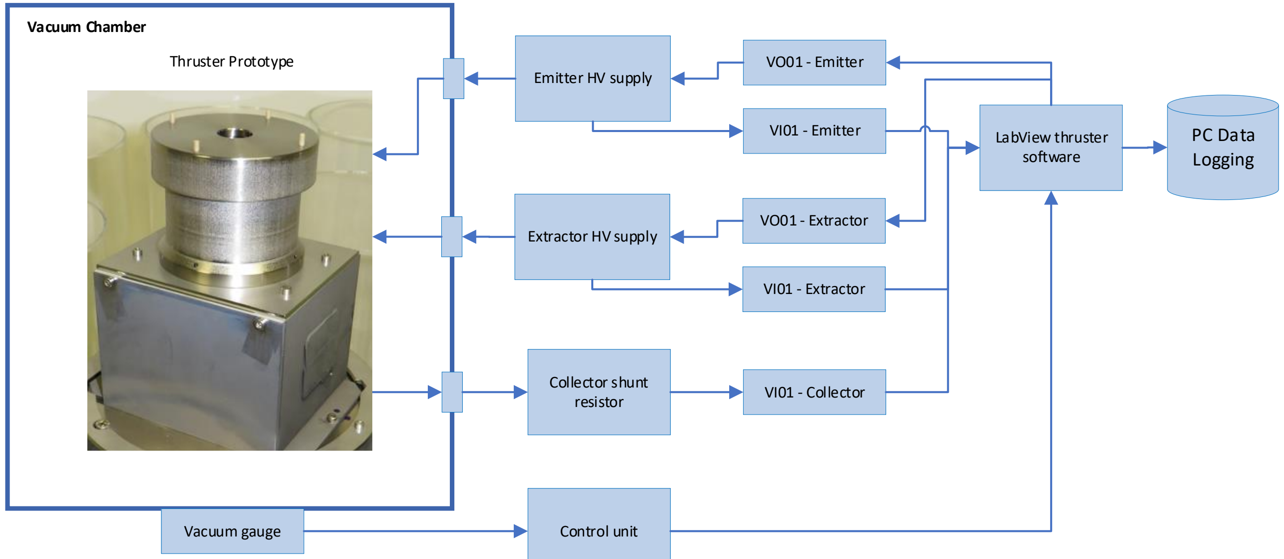
Performance Testing – Setup

- The **power to emitter** was provided by a Matsusada AU-100R22-LCF (0-100 kV / 0-22 mA, limited to 20 kV/20 mA)
- The **power to extractor** was provided by a Heinzinger PNC 20000-10 (0-20 kV / 0-10 mA)
- All the data from the power supplies, the collector and the vacuum gauge was **monitored and recorded by a Labview-based software**



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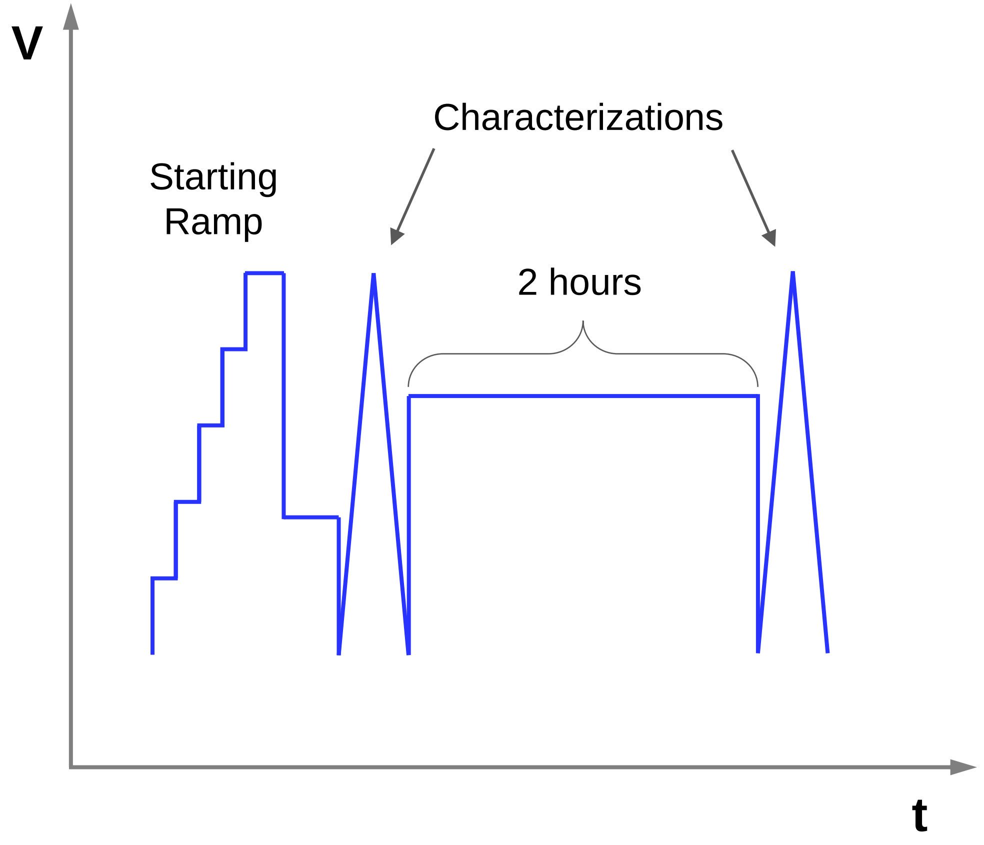
Performance Testing – Test Protocol

- Emitter (+tank) weighted and assembled into the thruster
- Truster mounted in the vacuum chamber
- Vacuum pumps started. Pressure level for starting the ion emission: < 10^{-6} mbar
- The test protocol consisted in:
  - A startup voltage ramp (0-20 kV, 8mA current limit)
  - Voltage/current characterizations to probe the operation of the emitters at different power levels
  - 2-hour constant current phase, which allowed to observe the stability of the emission and to calculate the emitter mass efficiency
- Thruster dismounted, emitter weighted + SEM pictures



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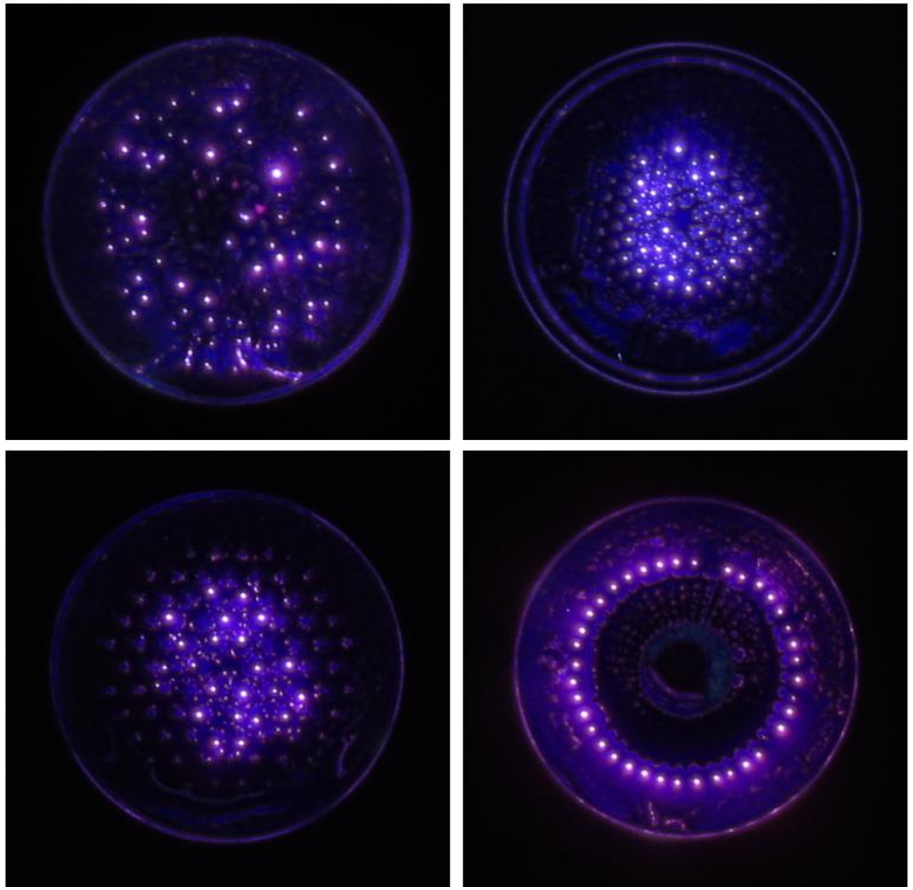
Performance Testing – Result Overview

- A total of **21 performance tests were conducted on 19 different emitters**, with 2 emitters tested twice.
- **Over 100 firing needles** were achieved on some of the emitters, proving the feasibility of firing high density arrays with a **single extractor**
- **Peak thrust reached 2 mN**, while **50-400 µN** was maintained during the constant current phase
- Firing currents as high as **20 mA** were obtained
- The measured **power-to-thrust of the new emitters ranged from 70 to 200 W/mN**, while the **specific impulse was between 400 and 4600 seconds.** The top end of these performance metrics is **comparable with existing FEEP thrusters.**



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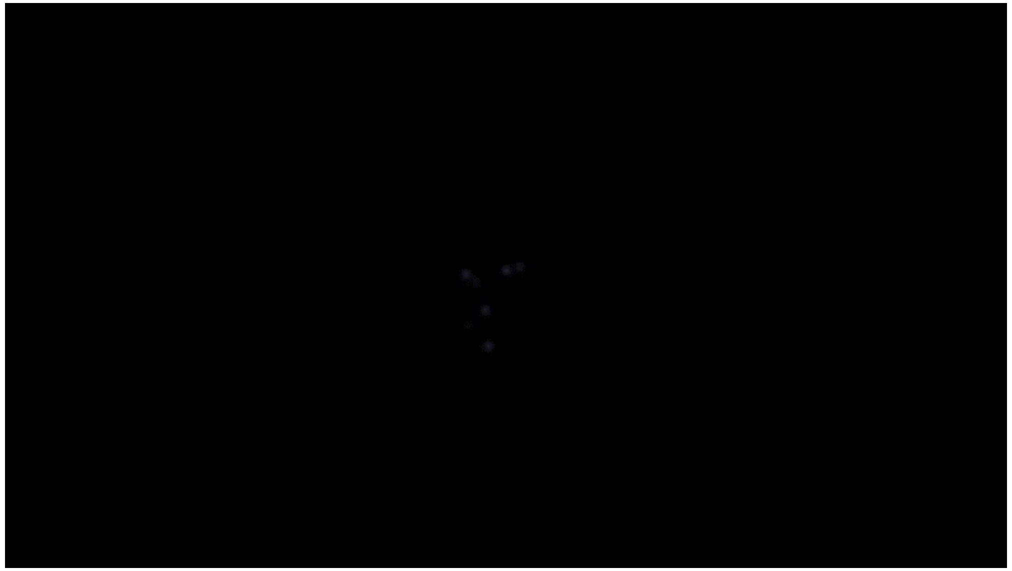
Firing videos



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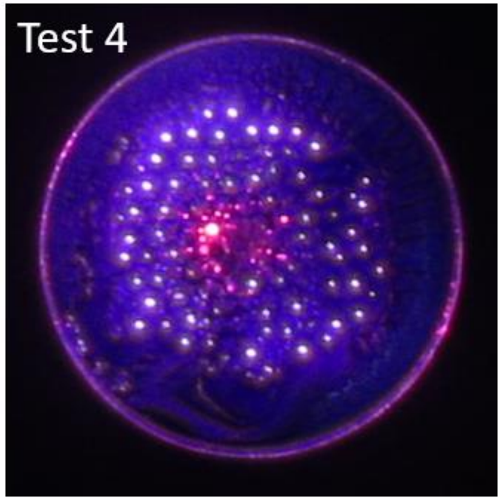
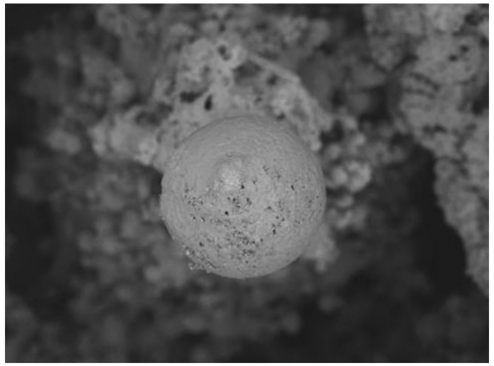
Performance Testing – Electron Bombardment

- A limiting factor encountered early on during the performance test campaign, was a **localized overheating of the emitter,** causing irreversible damage of some needles
- We identified **electron bombardment,** caused by electrons generated from the ion beam impinging on the extractor, as the source of this overheating
- The identification of this issue allowed us to take steps to mitigate it, at the cost of sacrificing the thrust and the count of firing needles
- It must be stressed that, on the other hand, **high emission current per se was NOT a limiting factor** (the crown-like emitter fired at 20 mA without issues on the needles).



Emitter 19 (Test 4) firing at high current



SEM image of a molten tip

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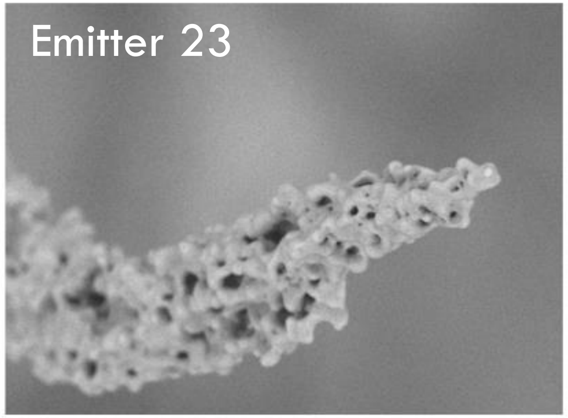
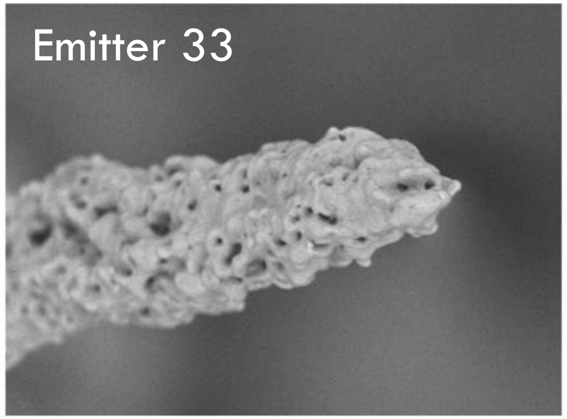
Performance Testing – Mass Efficiency

- The **mass efficiency of the new emitters was between 2 and 27%,** which is lower than the best performing FEEP emitters currently available
- As expected, emitters with **sharper tips and lower current per tip exhibited higher mass efficiency**
- The characteristics of **wetting** are believed to influence the mass efficiency too: rich wetting (thick propellant layer) → more droplets emission → lower mass efficiency



20% Mass Efficiency



8% Mass Efficiency

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Performance Testing – Impedance

- Arrays with **higher needle density showed higher impedance** and onset voltage
- The high impedance of the 2D arrays was also due to the **larger distance between the needles and the extractor,** compared to the crown-like emitter
- An **increase in impedance** was observed during some of the performance tests. This behaviour could be attributed to three factors:
  - Accumulation of **contaminants,** primarily gallium and indium oxides, on the needle tips
  - Tip degradation caused by **electron bombardment over-heating**
  - Progressive **de-wetting** of the liquid metal from the tips of the needles (unstable wetting, propellant depletion).

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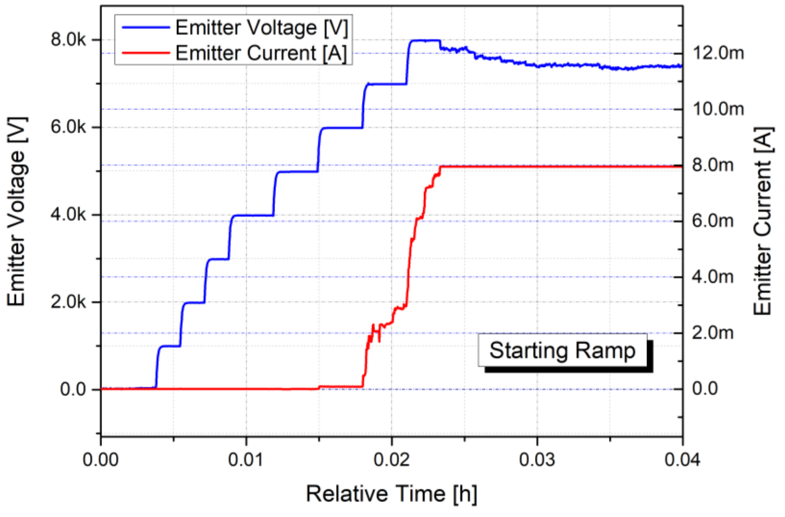
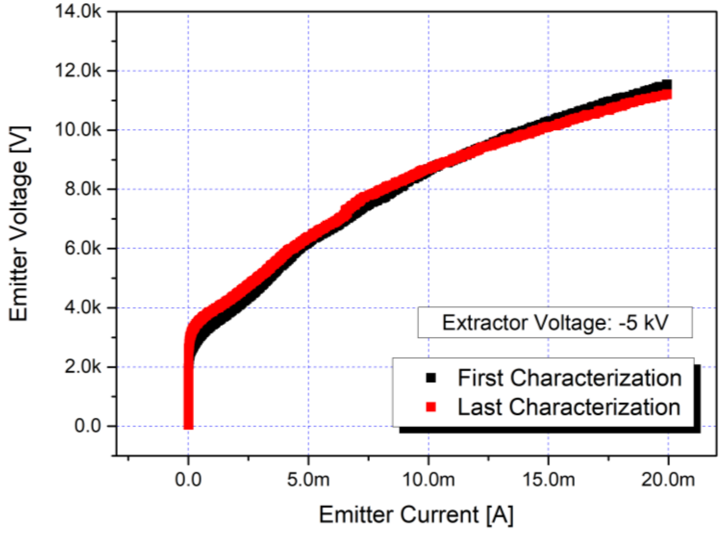
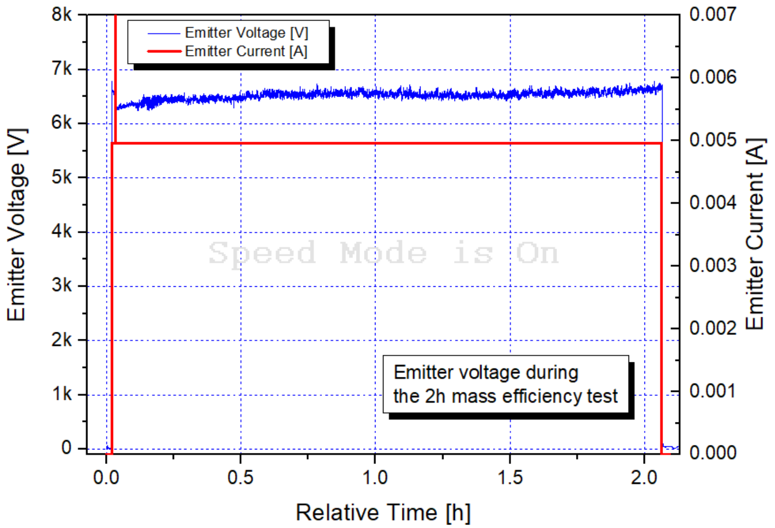
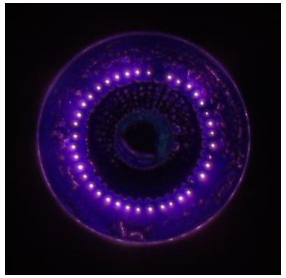
Performance Testing – Performance Graphs (Test 1 – Emitter 20)









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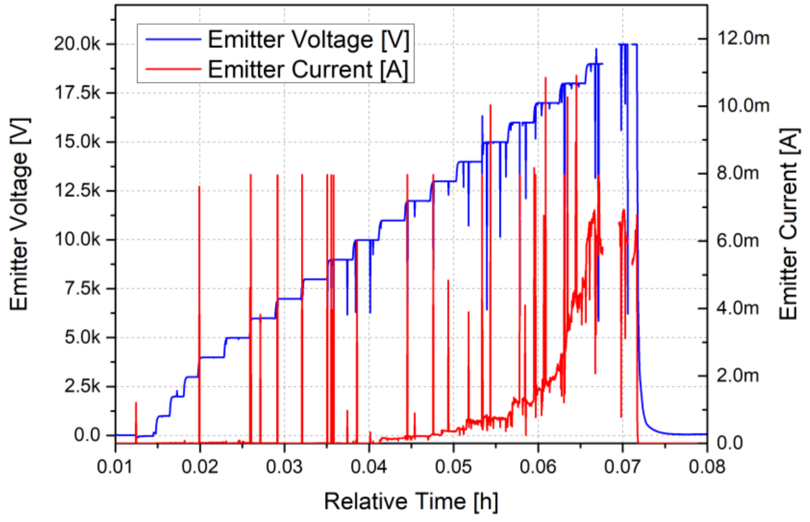
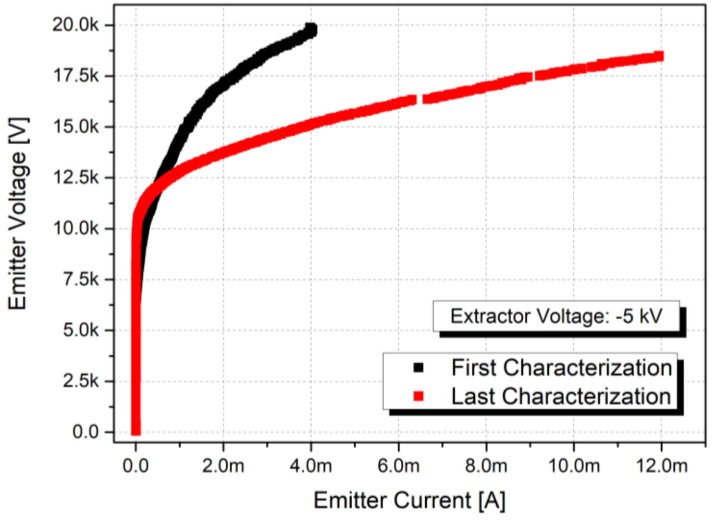
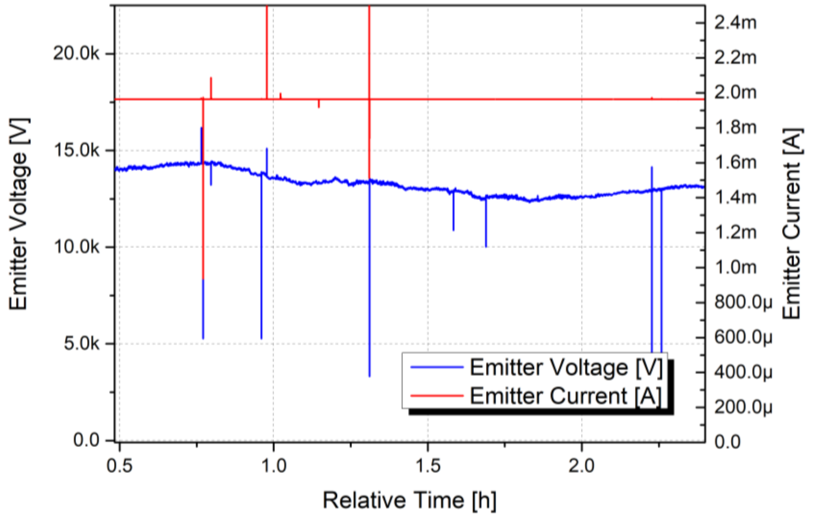
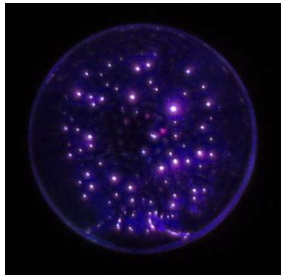
Performance Testing – Performance Graphs (Test 7 – Emitter 28)









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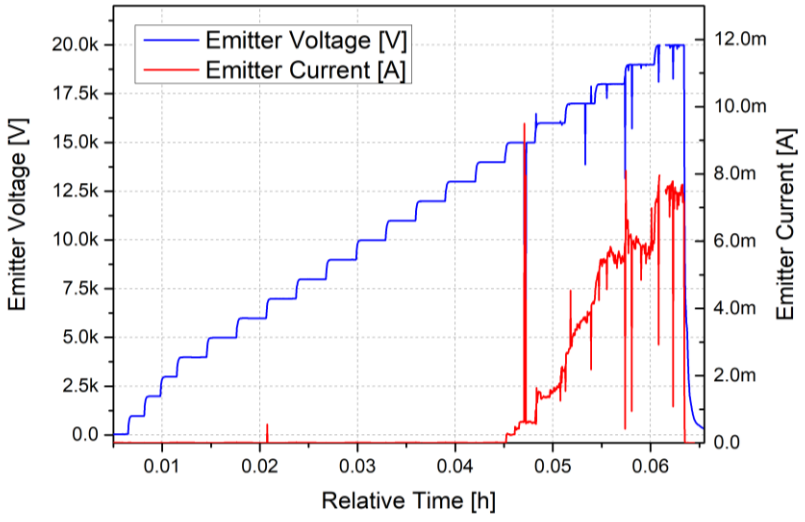
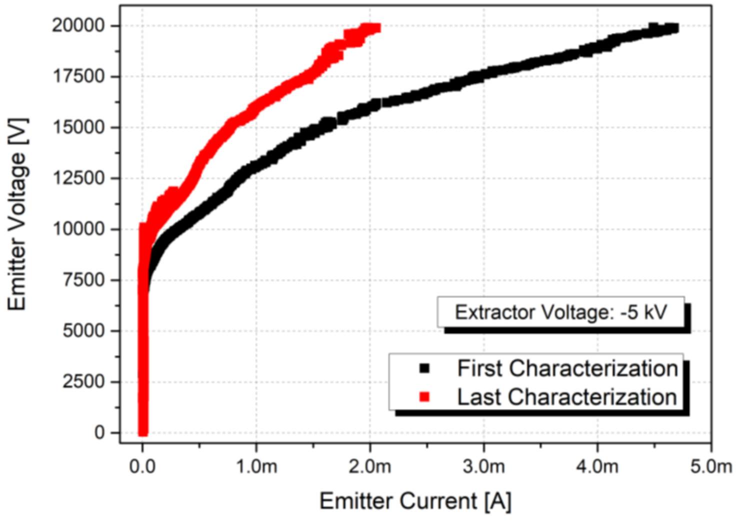
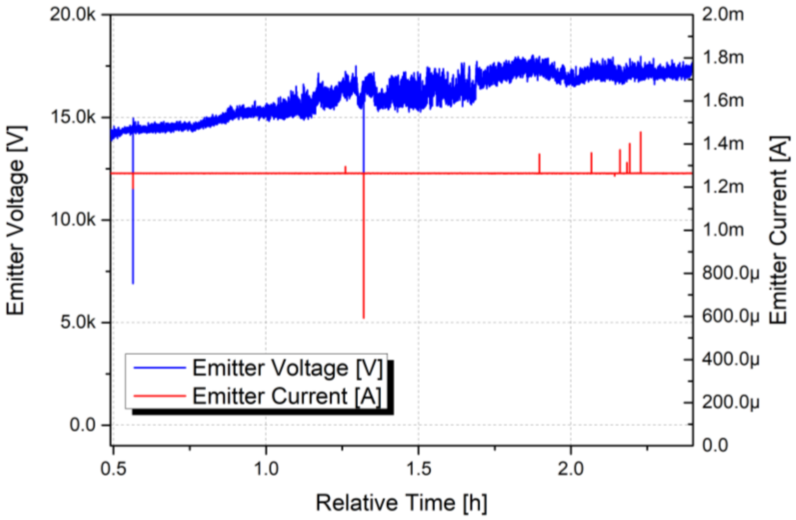
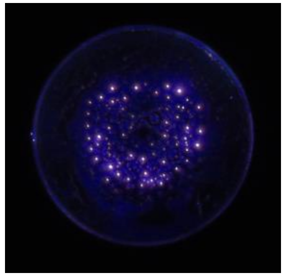
Performance Testing – Performance Graphs (Test 16 – Emitter 32)









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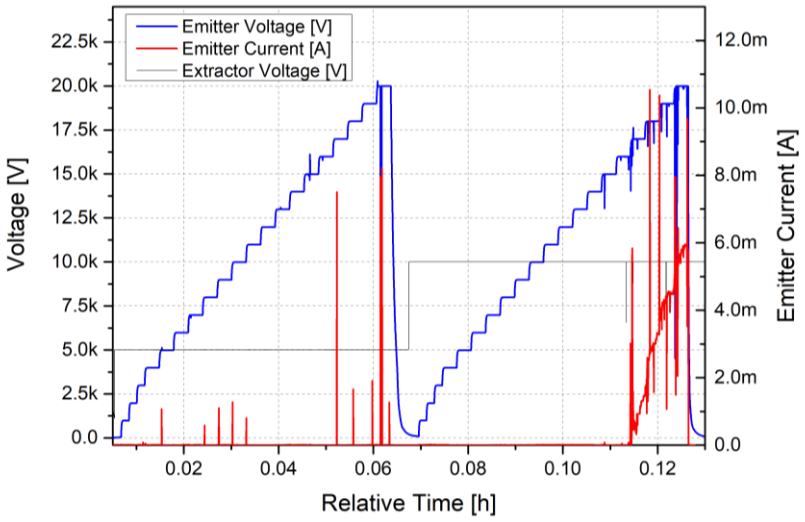
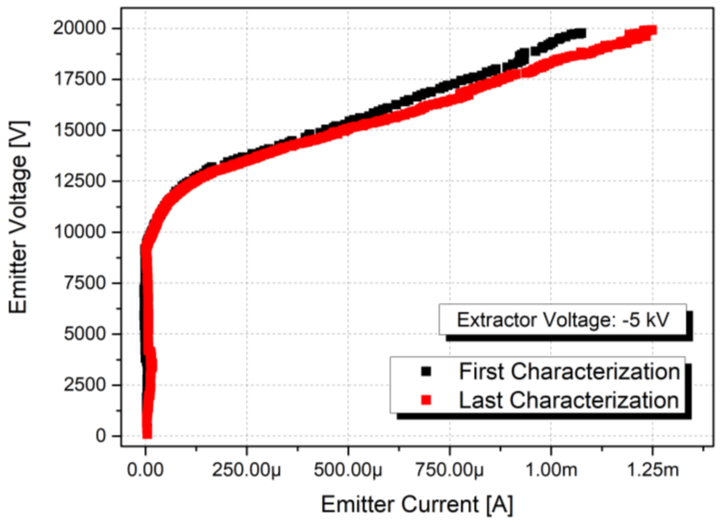
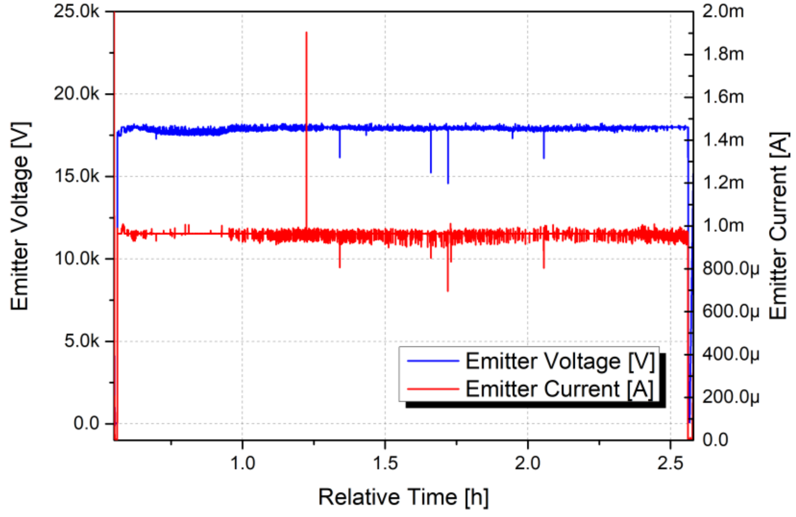
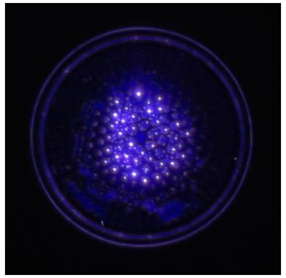
Performance Testing – Performance Graphs (Test 19 – Emitter 33)









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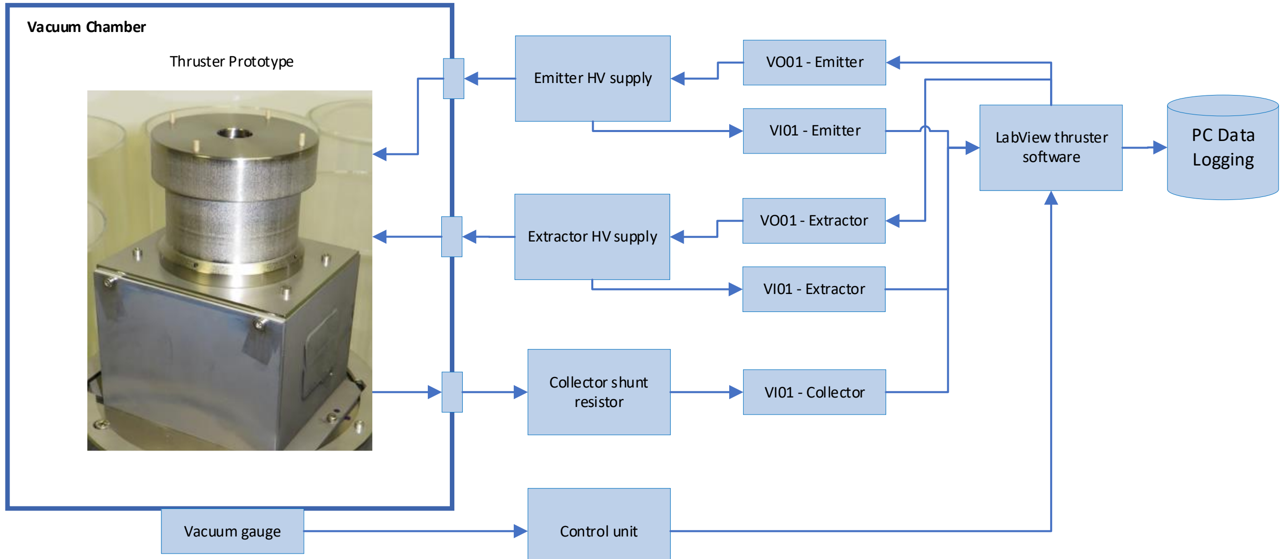
Durability Testing

- The purpose of the durability test was to evaluate the **evolution of the emitter performance and possible related needle degradation over an extended period** (100 hours)
- Test setup identical to the one used in the performance testing campaign
- The base testing protocol was the same as the one used in the performance test, with the constant current phase extended to 100 hours (50x).



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Durability Testing – Result Overview

- The tests have been conducted on **four emitters**, which were selected among the best performing ones from the performance testing campaign
- **All four emitters reached at least 100 hours** of cumulative firing with various degrees of performance degradation
- The first two emitters were tested across three segments totaling 100+ hours, due to propellant feeding issues from the tank, which required test interruption to refill the emitter
- After **modification of the propellant tank,** the last two emitters underwent complete 100-hour tests without interruption (the last emitter operated for 190 hours).

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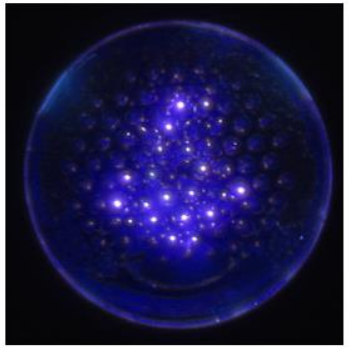
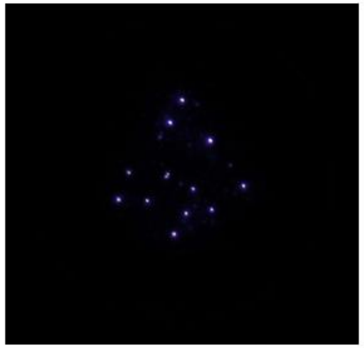
Durability Testing – Firing Pictures (Test 1 – Emitter 23)

Test 1 – 1st Part

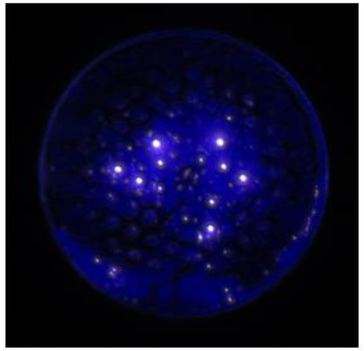


Peak

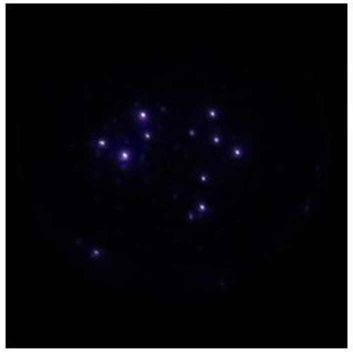


Nominal

Test 1 – 3rd Part



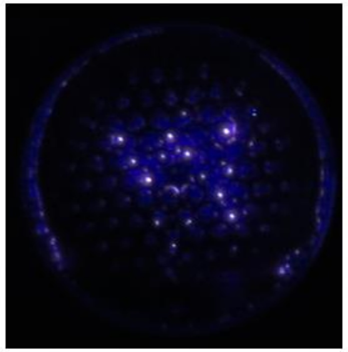
Peak



Nominal

Note: 2nd Part was aborted due to propellant electrostatic spilling, and consequent emitter-extractor shortcut

Test 1 – 4th Part



Peak

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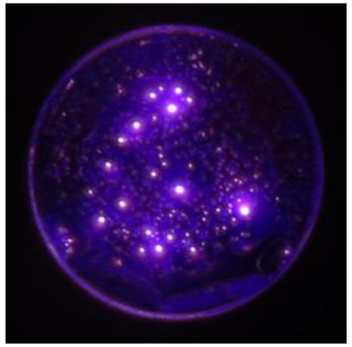
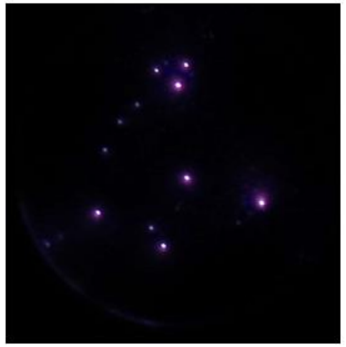
Durability Testing – Firing Pictures (Test 2 – Emitter 28)

Test 2 – 1st Part



Peak



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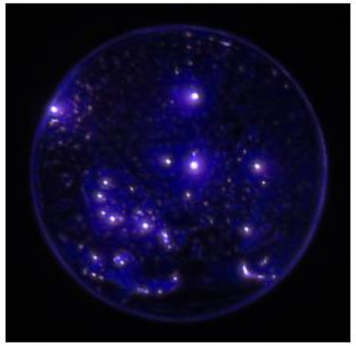
Test 2 – 2nd Part



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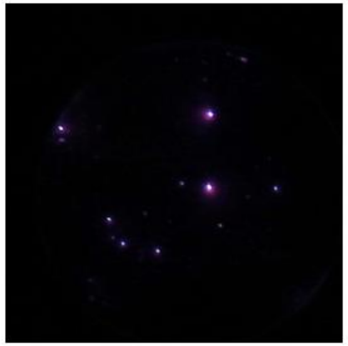

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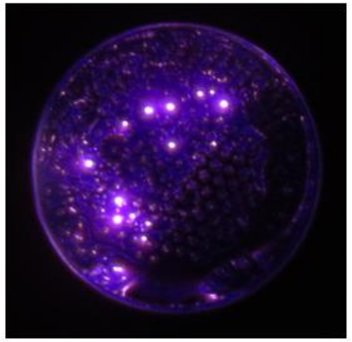
Test 2 – 3rd Part



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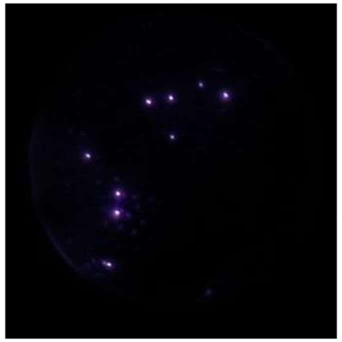

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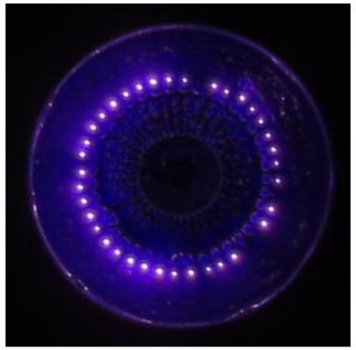
Durability Testing – Firing Pictures (Test 3 – Emitter 20)

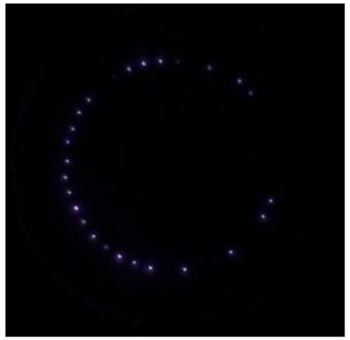
Test 3 – 0h


Peak


Nominal

Test 3 – 48h


Peak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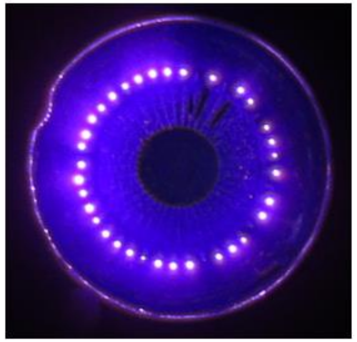
Test 3 – 100h


Peak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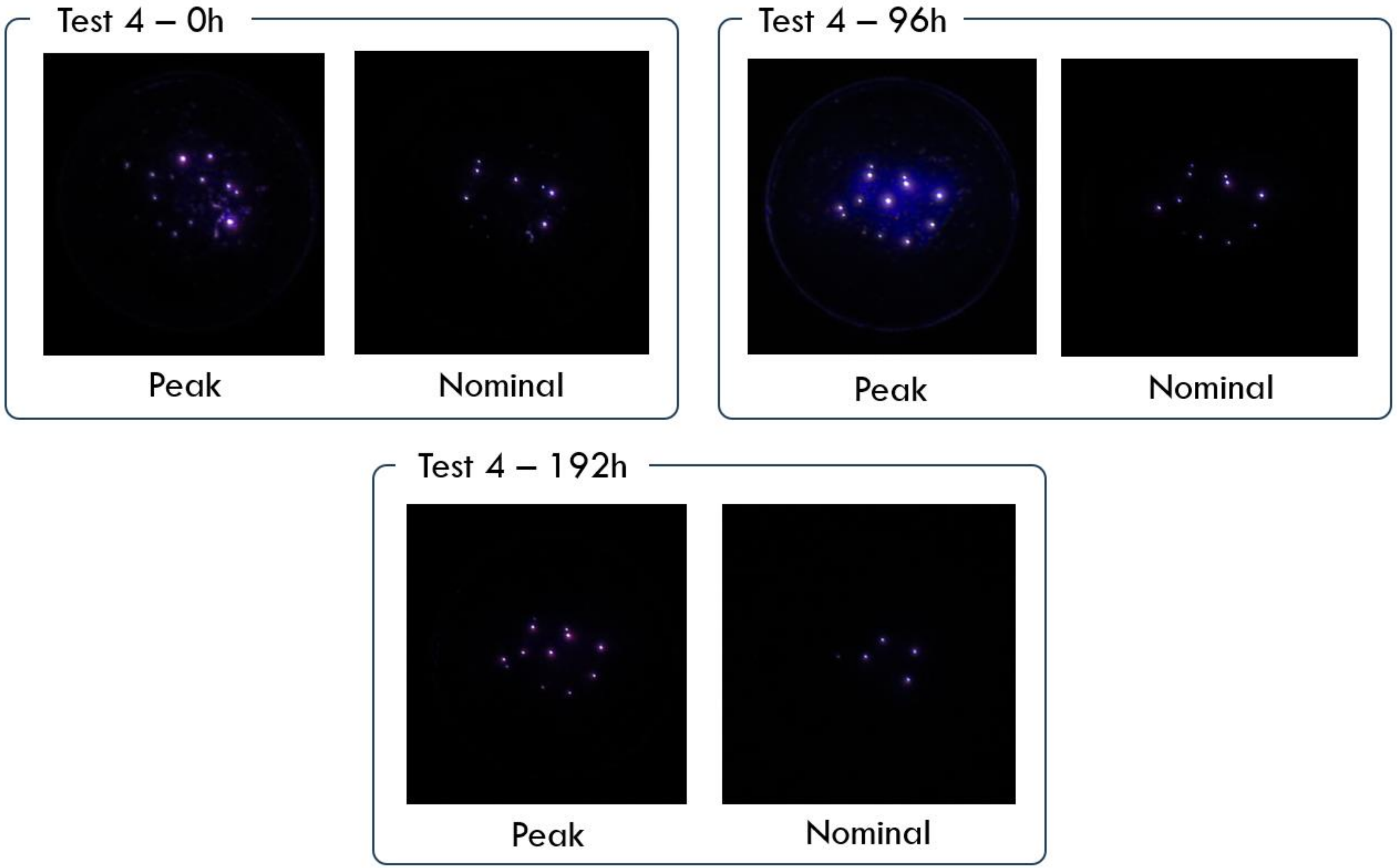
Durability Testing – Firing Pictures (Test 4 – Emitter 27)



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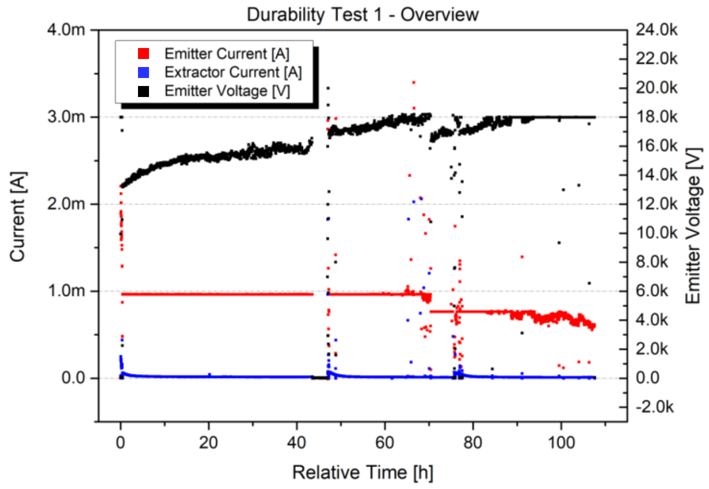
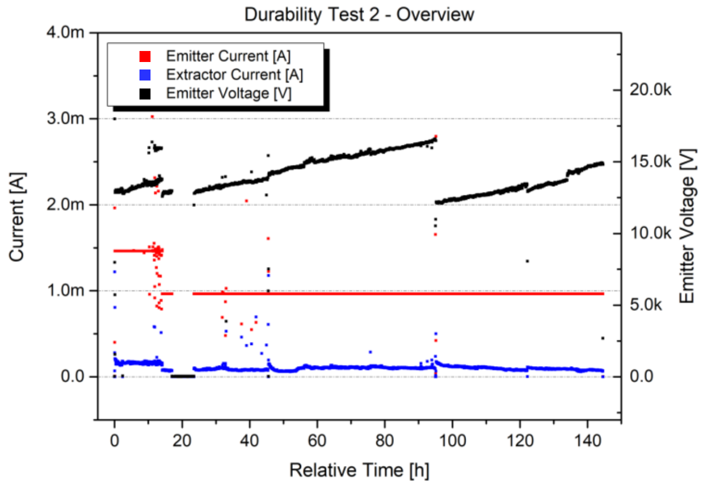
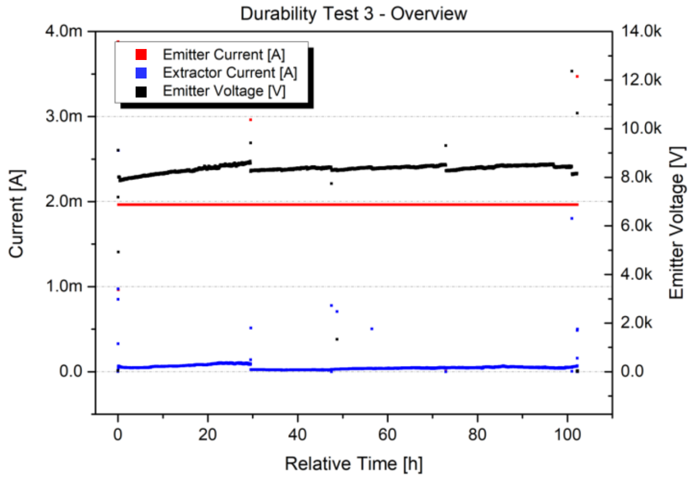
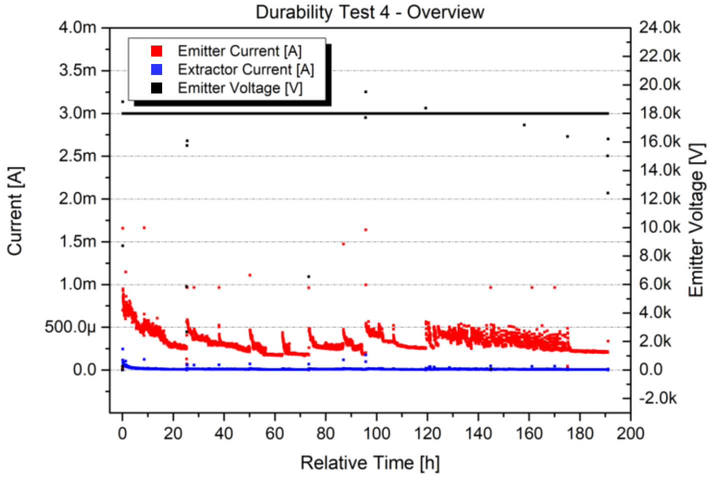
Durability Testing – Test Graphs









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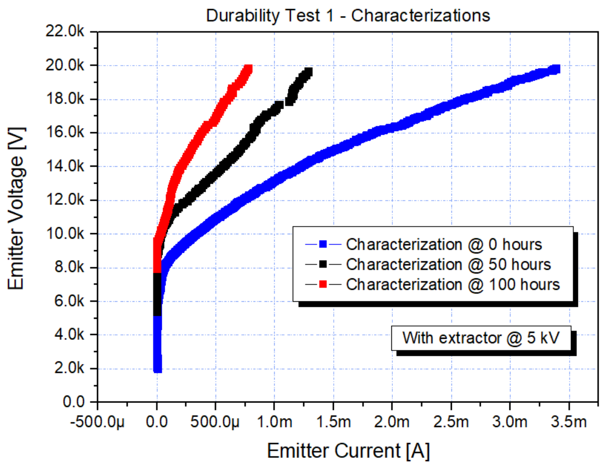
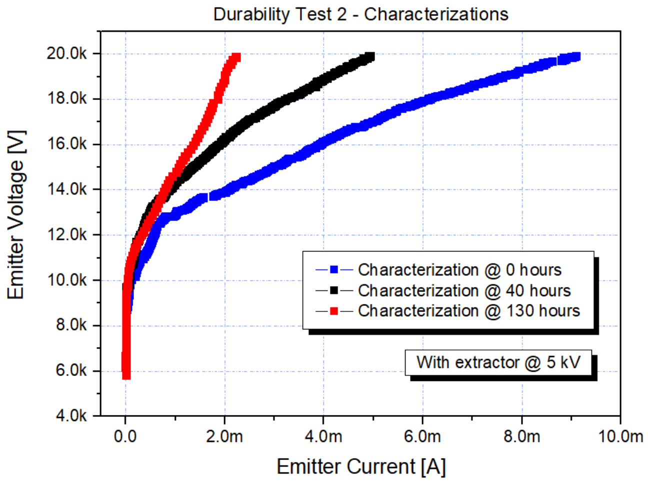
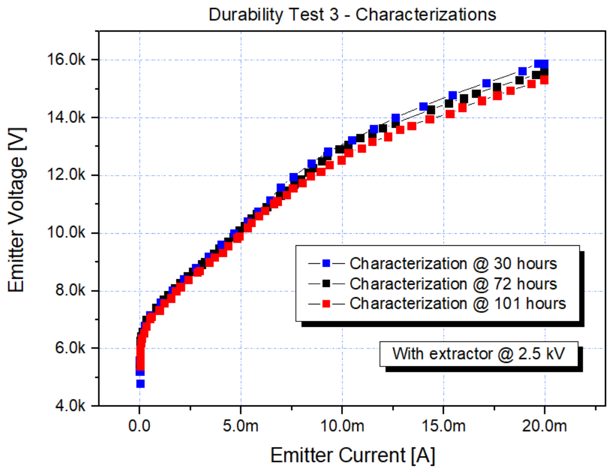
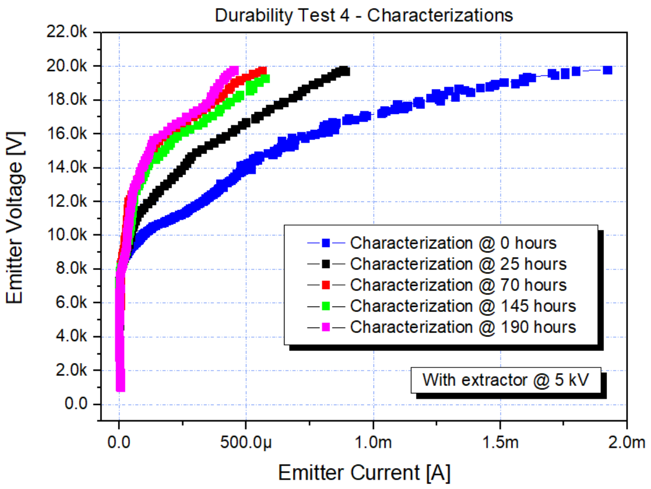
Durability Testing – Test Graphs









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Durability Testing – Results Table

Test #	Emitter #	Total Firing Time [h]	Avg. Mass Efficiency [%]	Thrust [µN]	Power/Thrust [W/µN]	Avg. Emitter / Extractor Voltage [kV]	Avg. Specific Impulse (f-factor: 0.8-0.9) [s]	Max Number of Firing Needles	Peak Emitter Current [mA]	Nominal Emitter Current [mA]
1	23	103	34.6	130 – 140 – 100	0.12 – 0.12 – 0.13	16.6 / - 5.0	5600-6300	20 – 13 – 14	7	1 – 0.8 – 0.8
2	28	138	5.7	140 – 115 – 110	0.12 – 0.13 – 0.12	13.9 / - 5.0	850-950	22 – 13 – 13	9	1.5 – 1 – 1
3	20	102	11.0	190	0.09	8.4 / - 2.5	1250-1400	38	20	2
4	27	190	24	45	0.13	18.0 / - 5.0	4080-4590	13	2.5	0.35

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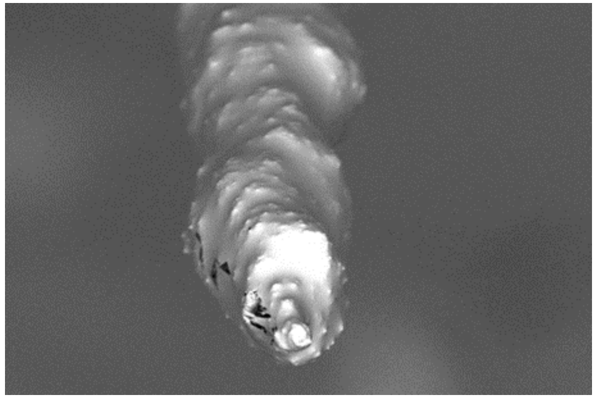
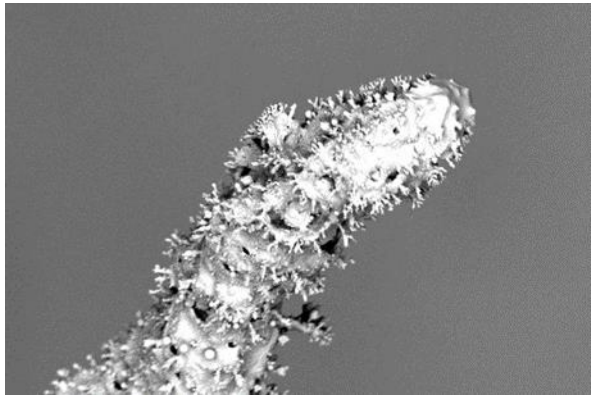
Durability Testing – SEM and EDX Analysis (Test 1)

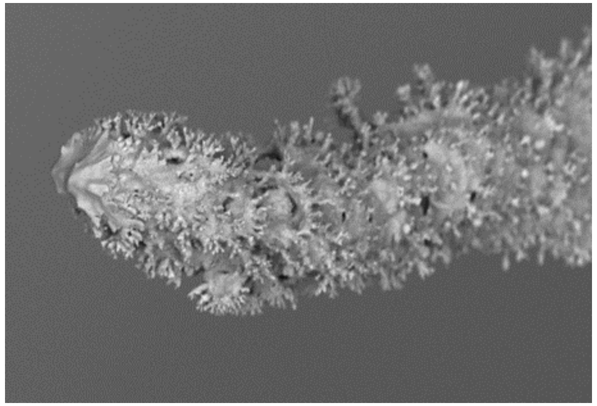
Before 1st part



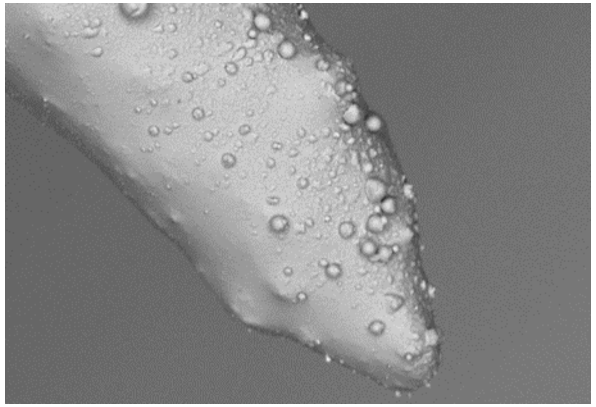
After 1st part



After 3rd part



After 4th part



NOTE: The tips may not be the same!

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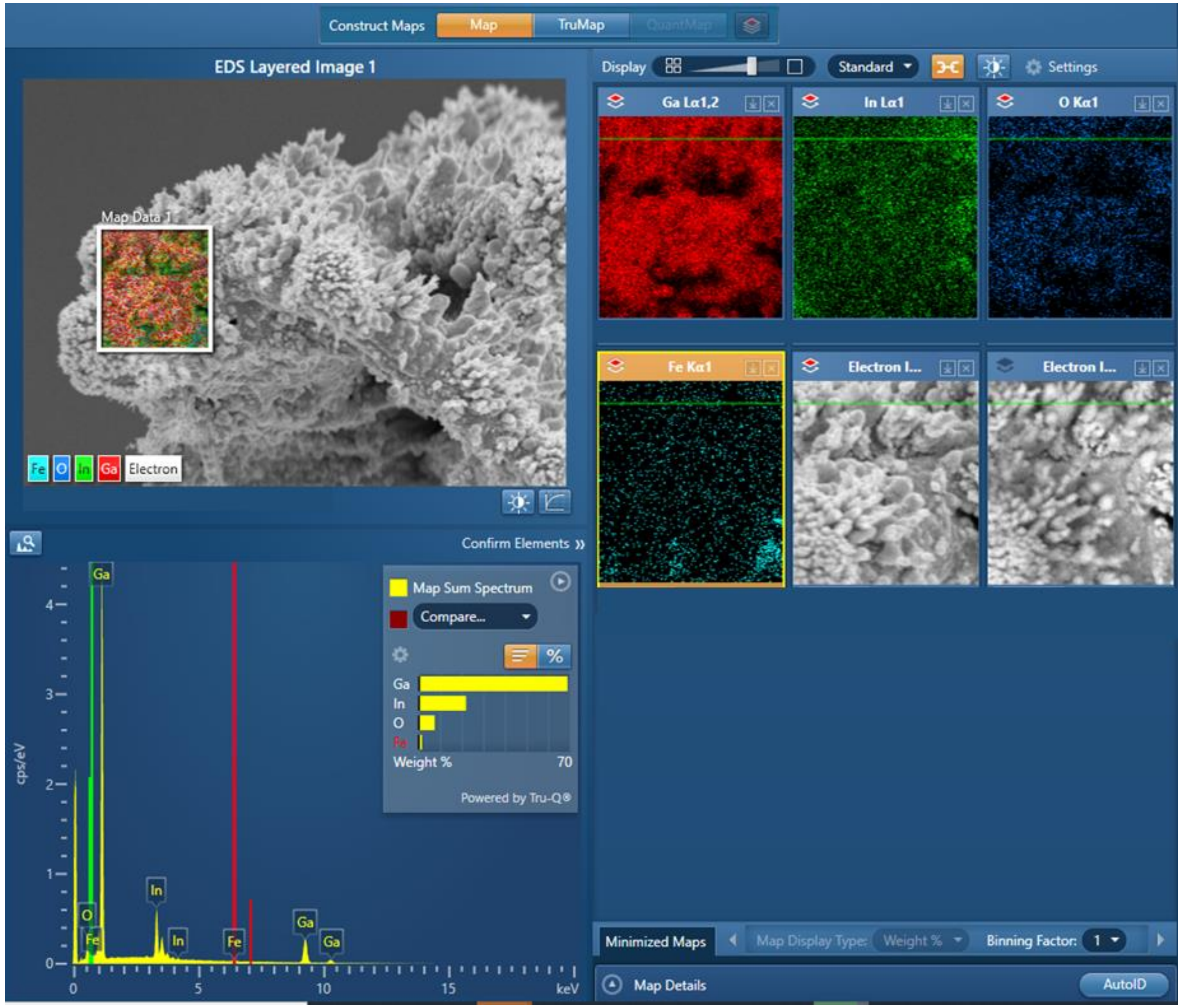
Durability Testing – SEM and EDX Analysis (Test 1)

- Metallic elements proportions compatible with EGaIn
- The presence of **oxygen** indicates the formation of oxides of one or both elements constituting the propellant
- It is believed that these concretions are one of the main causes of the increase in impedance of the emitters



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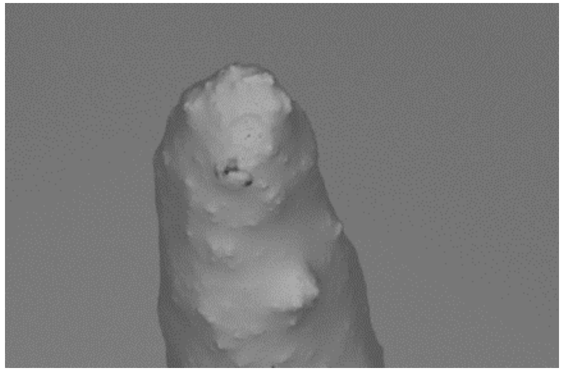
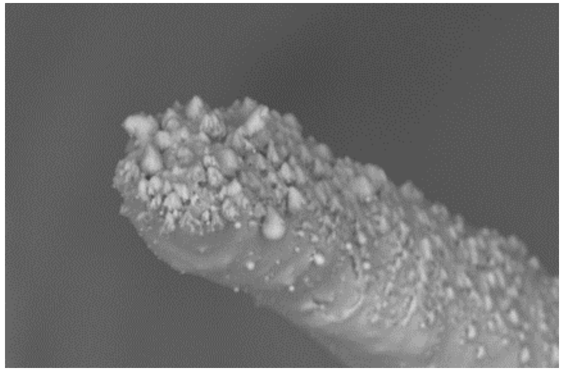
Durability Testing – SEM and EDX Analysis (Test 2)

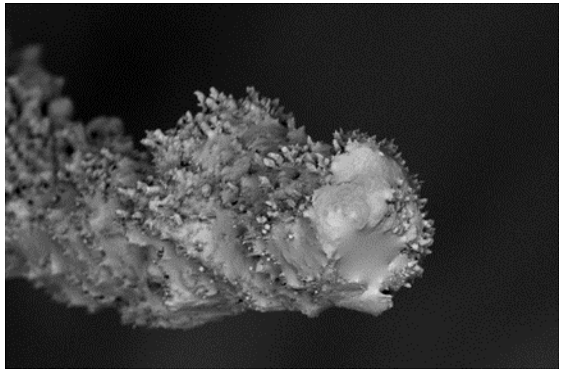
Before 1st part



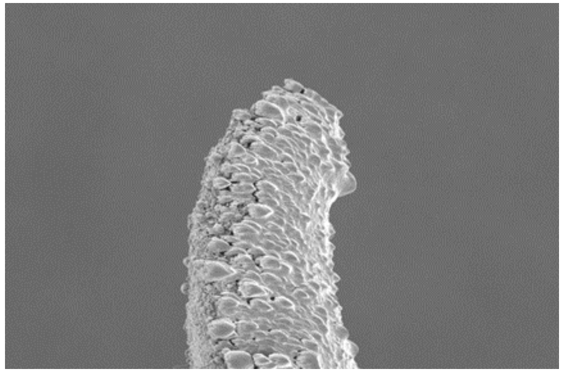
After 1st part



After 3rd part



After 3rd part



NOTE: The tips may not be the same

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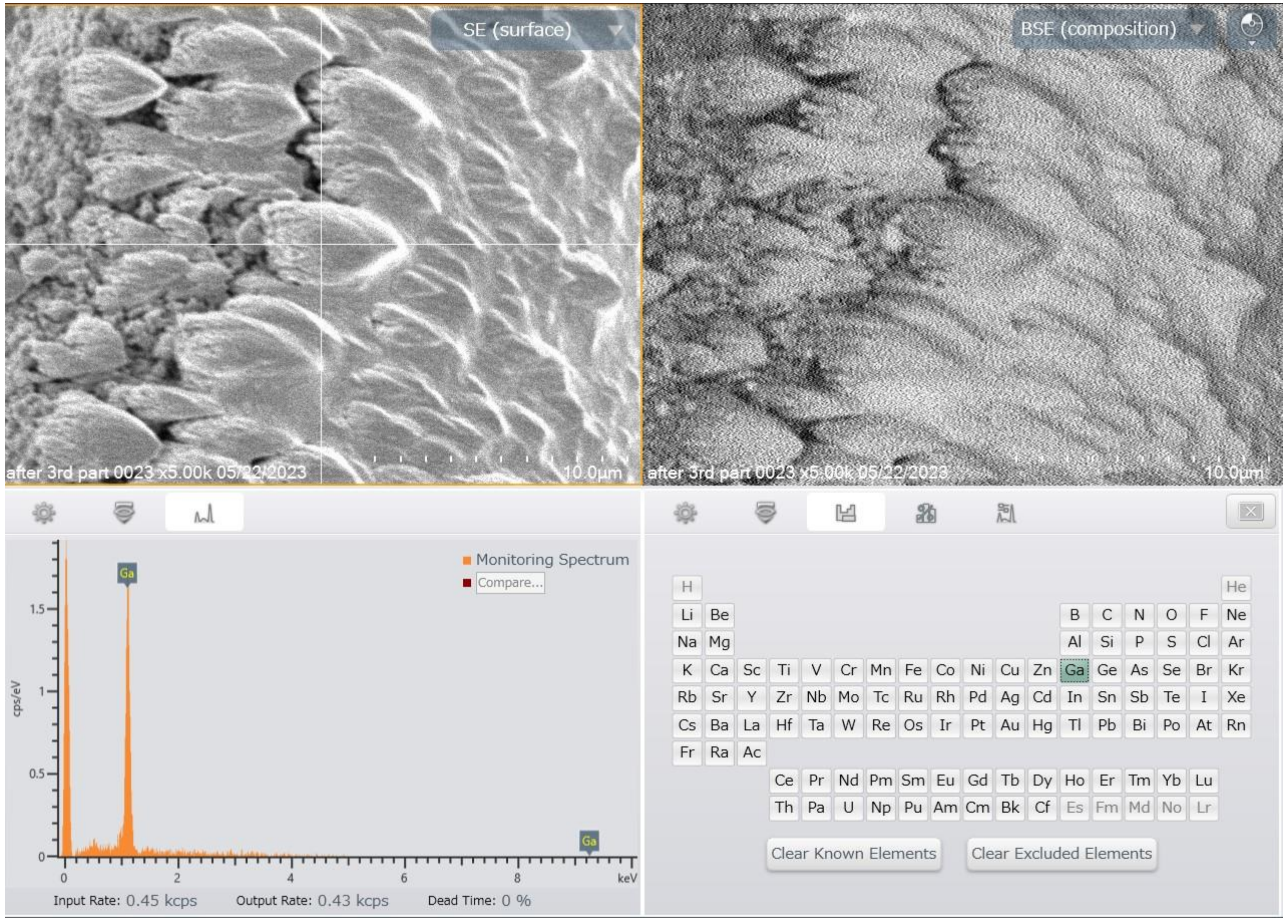
Durability Testing – SEM and EDX Analysis (Test 2)



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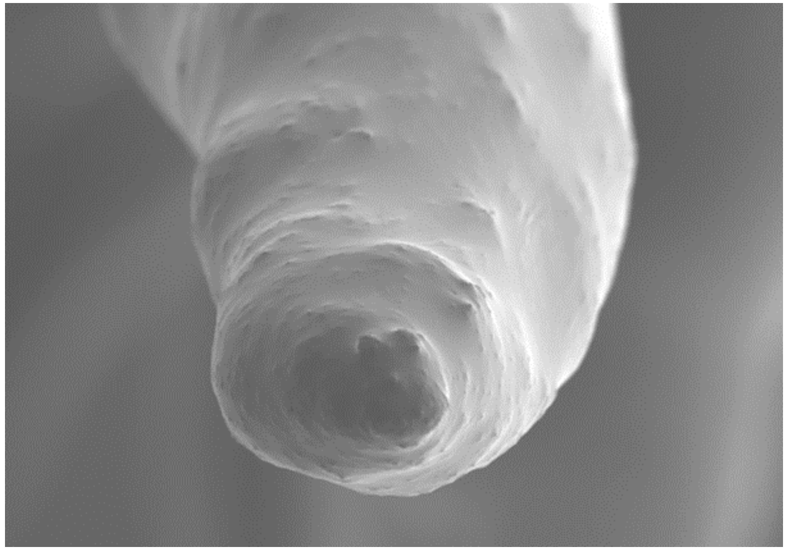
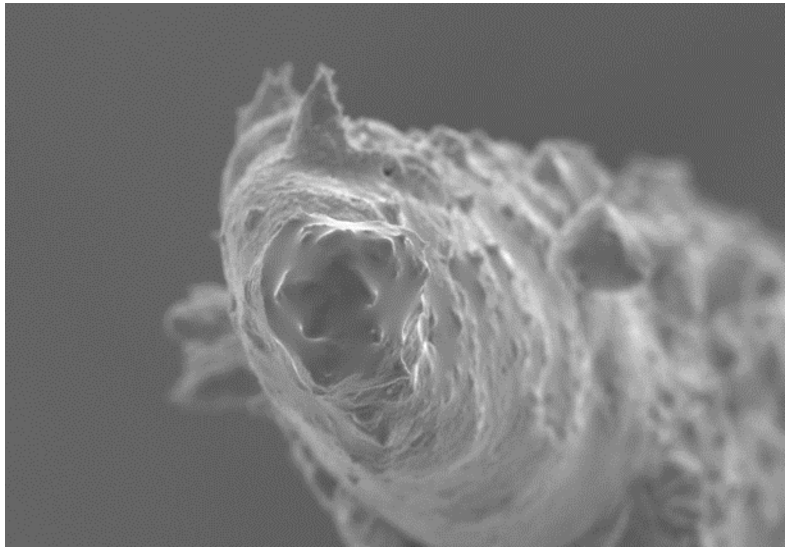
Durability Testing – SEM and EDX Analysis (Test 3)





Before Test NOTE: The tips may not be the same! After Test

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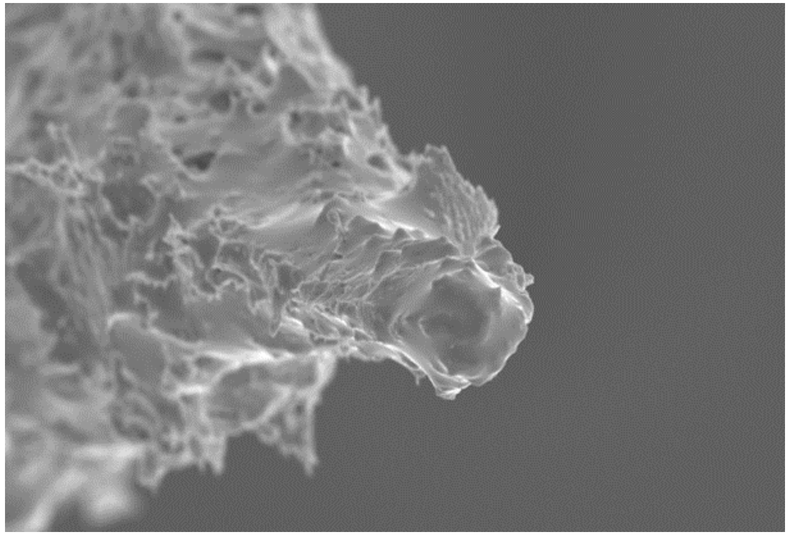
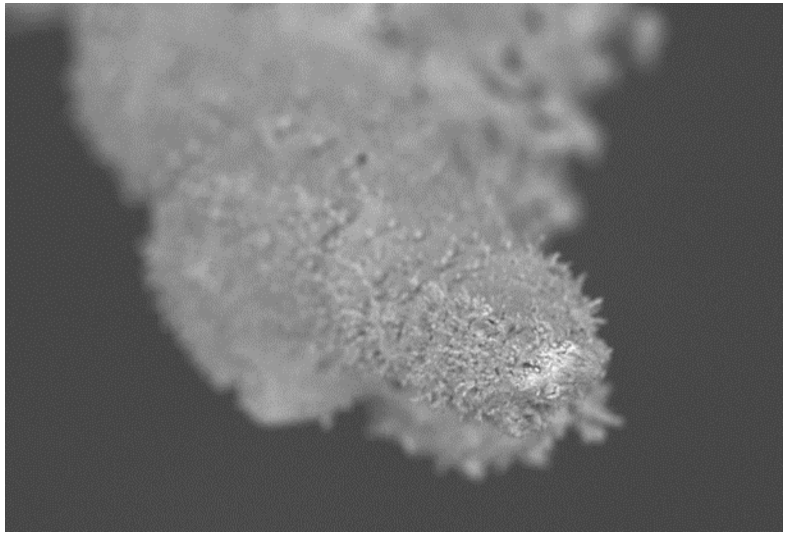
Durability Testing – SEM and EDX Analysis (Test 3)



After Test – Firing Tip



After Test – Non-Firing Tip

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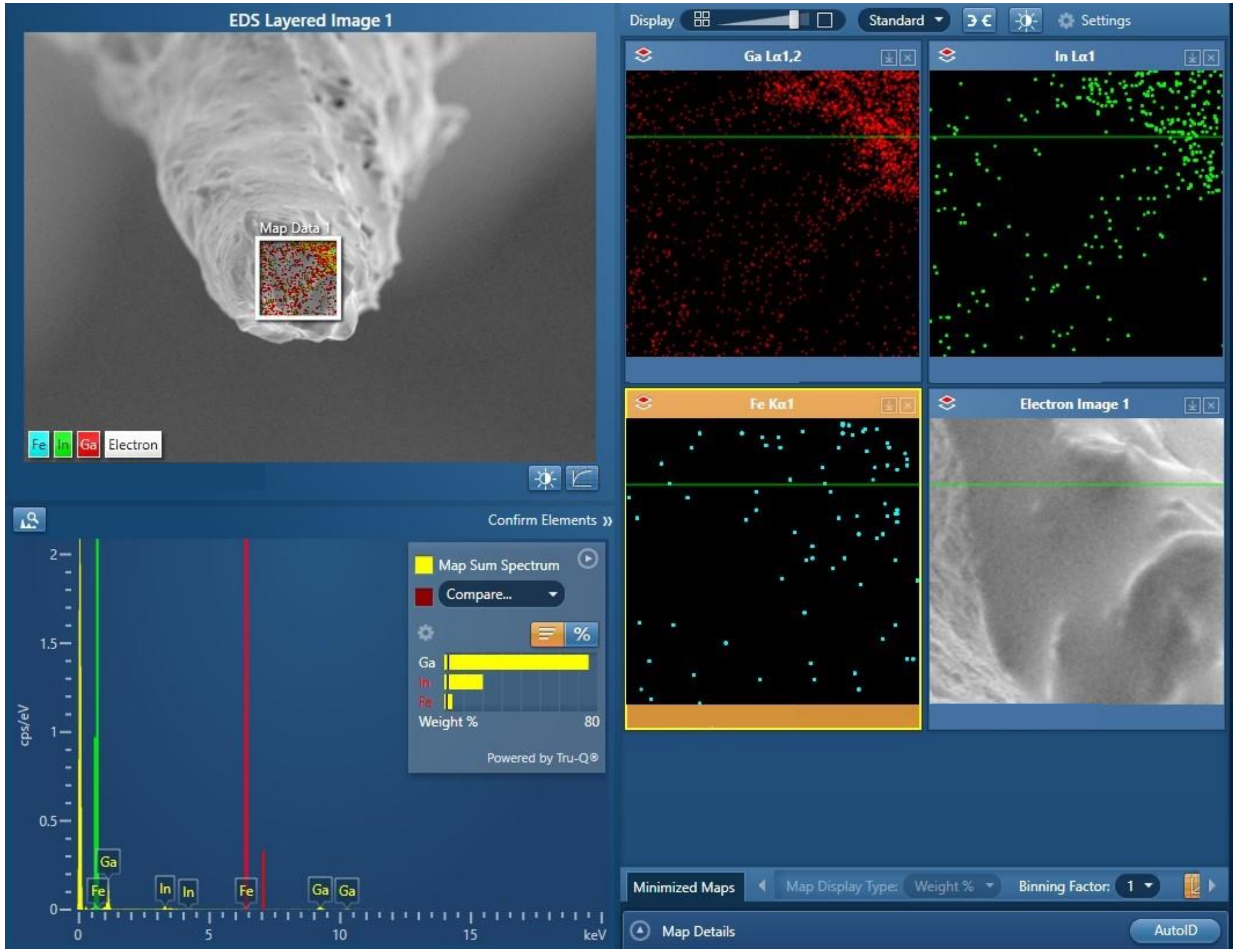
Durability Testing – SEM and EDX Analysis (Test 3)

- EDX confirms the presence of fresh propellant
- The detected small amounts of iron could be either completely exposed or covered by a thin layer of propellant, which, due to the low thickness, can be penetrated by the analyzing electron beam



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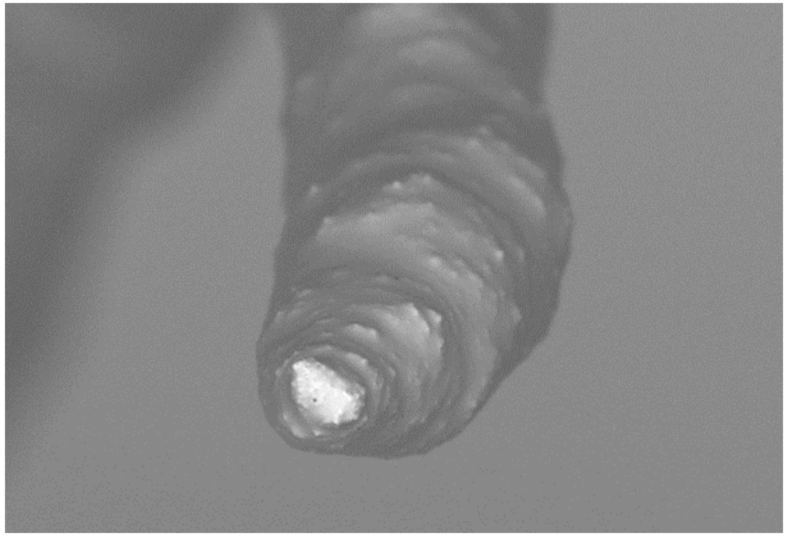
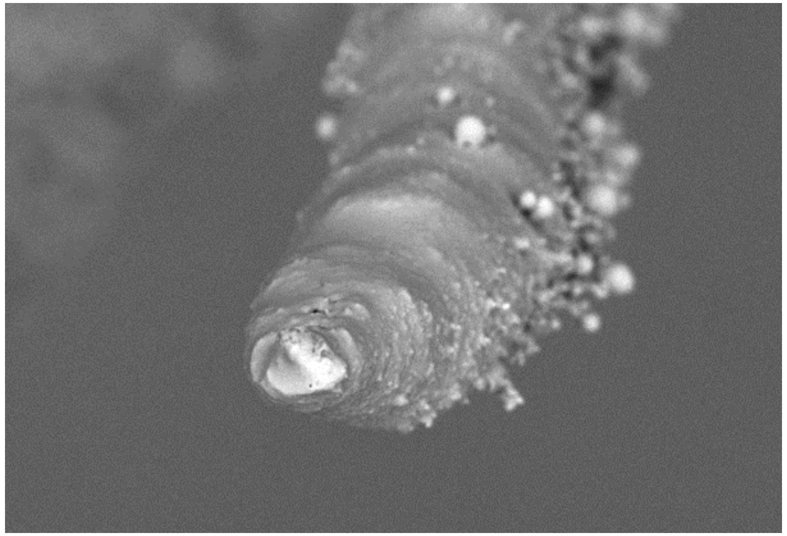
Durability Testing – SEM and EDX Analysis (Test 4)


Before Test


After Test

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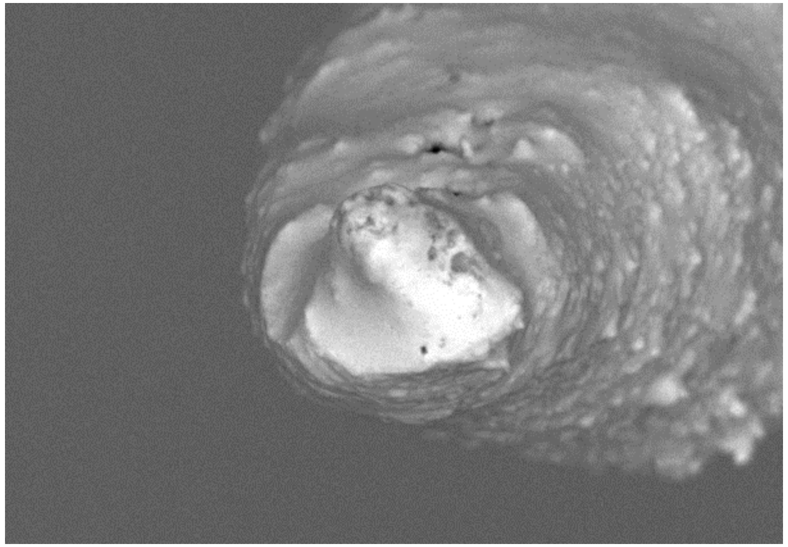
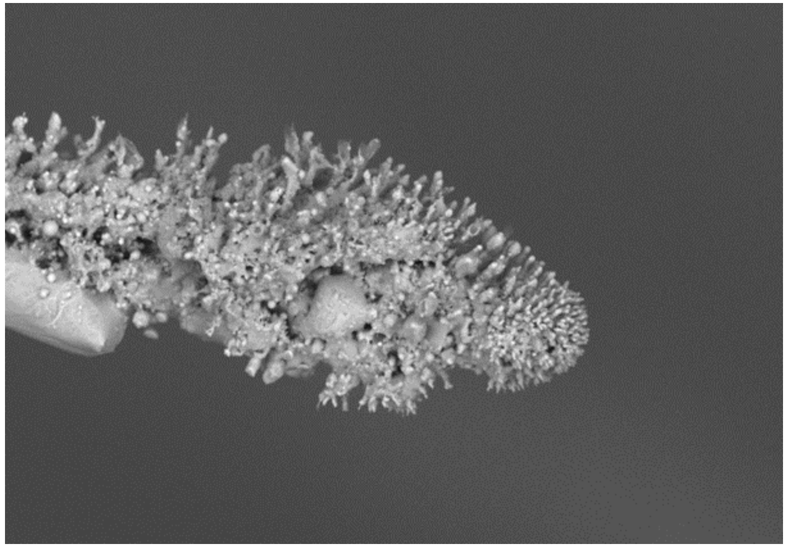
Durability Testing – SEM and EDX Analysis (Test 4)


After Test – Firing Tip


After Test – Non-firing Tip

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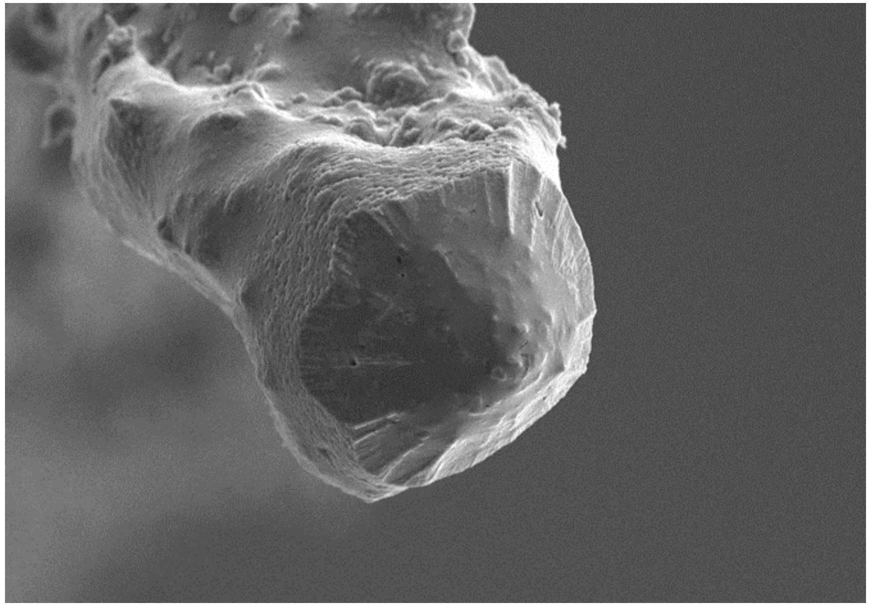
Durability Testing – SEM and EDX Analysis (Test 4)



Firing tip with interesting signs of erosion

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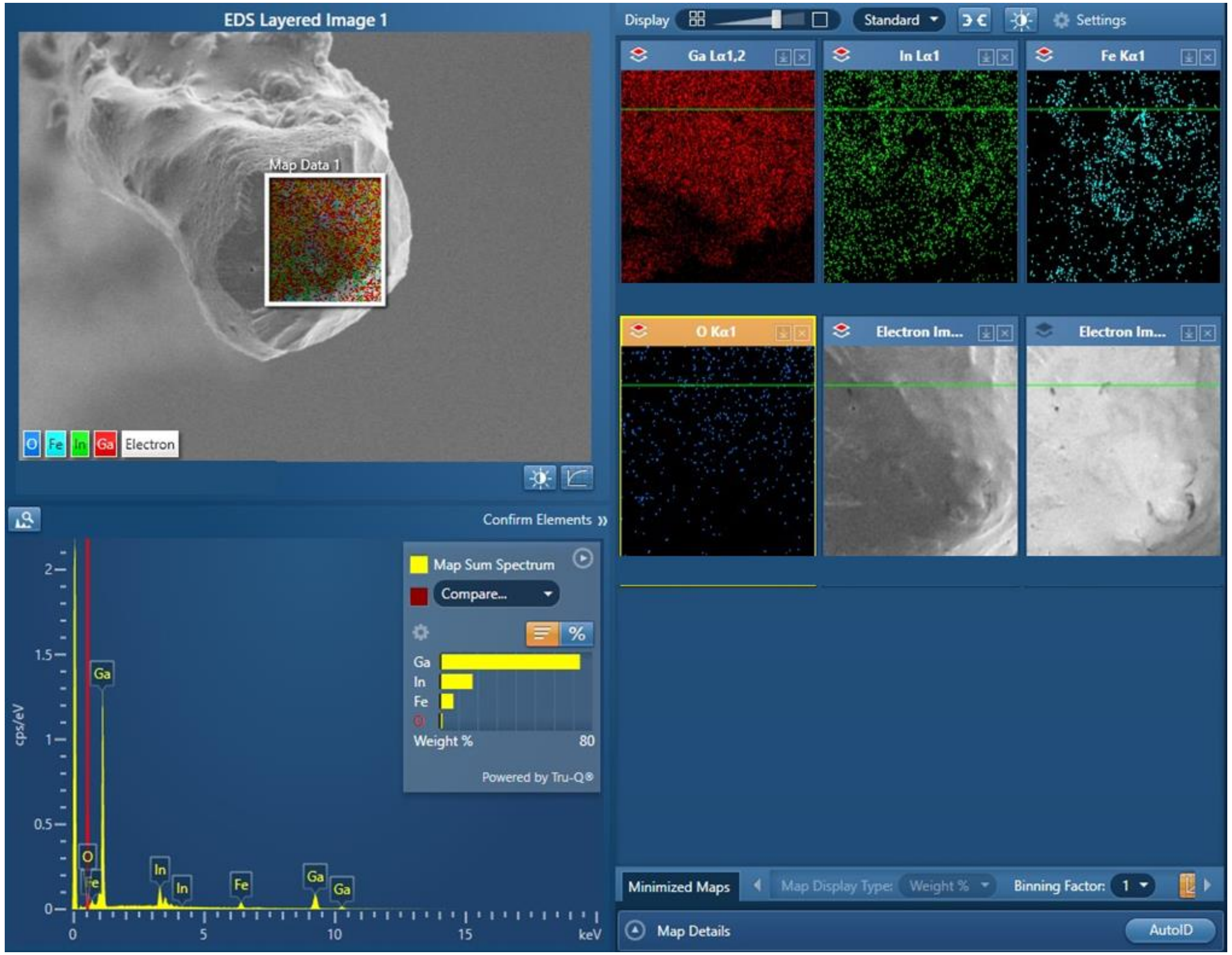
Durability Testing – SEM and EDX Analysis (Test 4)

- The material covering the tip is mostly gallium-indium
- One possible explanation for the shape, is that this tip was previously covered by a thick layer of gallium and indium oxides, then it started firing, eroding away the oxides sideways by ion beam erosion.



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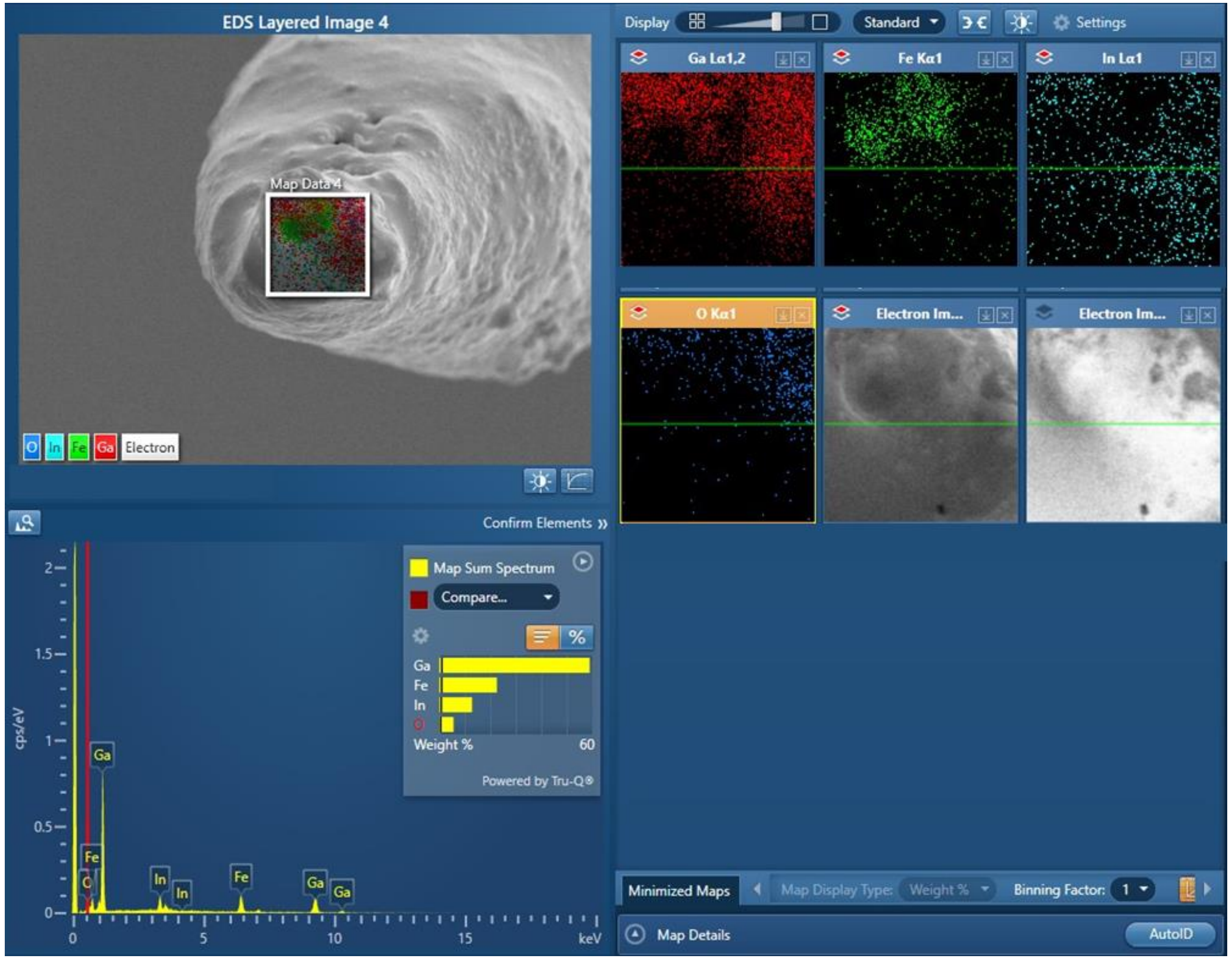
Durability Testing – SEM and EDX Analysis (Test 4)

- Iron seems separated from the other elements, indicating exposure of the underlying substrate and not a diffusion process



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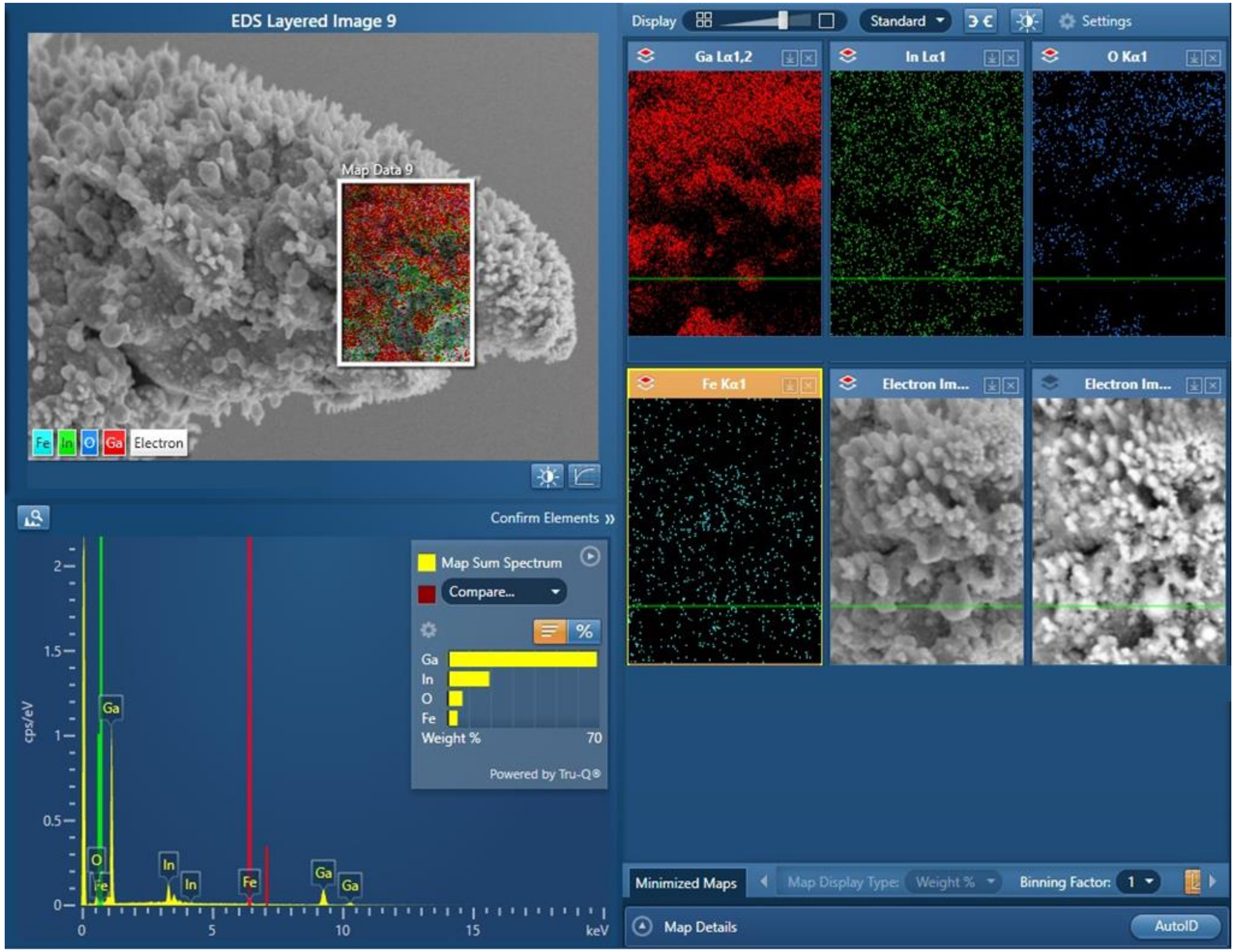
Durability Testing – SEM and EDX Analysis (Test 4)

- Metallic elements proportions compatible with EGaIn
- The presence of **oxygen** indicates the formation of oxides of one or both elements constituting the propellant
- It is believed that these concretions are one of the main causes of the increase in impedance of the emitters



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Main Achievements – Emitter Manufacturing and Wetting

- Successful manufacturing of **36 emitters** using the new process
- Different types of arrays and needle densities using the same process (no difference in costs)
- Successful wetting of **28 emitters** with EGaIn

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Main Achievements – Thruster

- Functioning thruster module
    - Capable of operating at elevated voltages (up to 30kV emitter-to-extractor voltage)
    - Total cumulative time of operation > 500 hours

- Newly designed functioning propellant tank

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Main Achievements – Emitter Testing

- Successfully demonstrated emitter firing in both 1-D and 2-D needle arrays
- Achieved firing from more than 100 needle tips; however, encountered issues at high currents due to the effects of electron bombardment
- High firing current per needle was not a limiting effect
- Durability tests conducted on 4 emitters, for at least 100 hours (max 190 hours), revealed little to no erosion of the iron tips, provided heavy electron bombardment was avoided. Oxide accumulation issue.

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Conclusions

- Demonstrated **manufacturing, sintering, wetting and firing** of FEEP emitters using a new method based on magnetic shaping of iron powder
- Demonstrated **performances comparable in part with state-of-the-art FEEP emitters**
- Demonstrated **no major signs of needle erosion in tests spanning up to 190 hours** of total cumulative firing time

Outlook

- Elimination or reduction of the electron bombardment issue
- Improvement of mass efficiency
- Use of pure indium as propellant (to reduce oxide formation and potential erosion)
- Evaluation of the technology for rapid and inexpensive FEEP emitter prototyping
- Evaluation of implementation into present (de-orbiting?) and future mission typologies

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THANK YOU for your attention!

Questions?

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Performance Testing – Result Overview

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Test #	Emitter #	Emitter brief description	Electron Bombardment Power during M_{eff} test [W]	Max Needles firing	Needles firing during M_{eff} test	Emitter Current during M_{eff} test [mA]	Emitter Voltage during M_{eff} test [kV]	Thrust during M_{eff} test [µN]	Power/Thrust during M_{eff} test [W/µN]	Specific Impulse during M_{eff} test (f/factor 0.8) [s]	M_{eff} [%]	Note
1	20	crown-like, SS	4 ~ 5	38	27	5	6.5	400	0.07	500	5	
2	06	medium spike density, SS	N/A	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Test interrupted after the second characterization post-outgassing phase, due to a discharge between emitter and ground
3	15	medium spike density, SS	~ 1	20	10	1	18	150	0.13	900	5	
4	19	medium spike density, SS	N/A	>100	20-30	N/A	N/A	N/A	N/A	N/A	N/A	Emitter/Extractor shortcut before M_{eff} test
5	18	high spike density, SS	4	>100	8	~ 0.8	19	46	0.20	400	2	Mass efficiency test part done with extractor at -7.5kV, because current too low at -5kV. Emitter heavily damaged by electron bombardment
6	02	high spike density , flat bottom, Ti	0.5 ~ 1	26	7	0.6	17	75	0.12	3300	20	
7	28	medium spike density, Ti	~ 7	>100	20-30	2	13.5	200	0.13	2200	15	
8	21	high spike density, Ti	11-25 (avg.: 16)	40	2->30	2.5	18 -> 13.5	200	0.17	720	4.8	
9	12	high spike density, dome shaped bottom, Ti	N/A	60	10-15	N/A	N/A	N/A	N/A	N/A	N/A	Only last characterizations recorded
10	04	high spike density, flat bottom, Ti	~ 1	30	6	0.4	18	50	0.12	4600	27	
11	26	medium spike density, dome shaped bottom, Ti	~ 1	30	10	0.8	18	110	0.13	1500	9	
12	10	medium spike density, flat bottom, SS..	~ 5	4	2	0.8 -> 0.3	18	70	0.17	2000	12	Partial mass efficiency test (about 1h). Test not completed due to high emitter and extractor voltages, low emitter current and low number of firing needles
13	27	medium spike density, flat bottom, Ti.	1 ~ 2	20	15-20	1.5	16.5	200	0.12	3000	19	
14	WP01	Emitter with wetted powder	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Very low current. Test interrupted after startup.
15	23	Low spike density, SS	~ 1	20	10-15	1	12	120	0.11	2700	20	
16	32	medium spike density, SS	~ 3	50	10-15	1.3	14.5 -> 17.7	160	0.13	2700	17	
17	20	crown-like, SS	1.5	38	13	2.5	5.5	190	0.07	700	8	
18	25	high spike density, dome shaped bottom, SS.	3.5	~ 40	10	1.4	12.3	150	0.12	500	3.6	First attempt resulted in discharge between emitter and extractor, due to a droplet. After removal of the droplet, second attempt successful.
19	33	medium spike density, SS	~ 1	40	10-15	1	18	135	0.13	1400	8	
20	32	medium spike density, SS	~ 4	30	12	1.3	14.5 -> 16.2	150	0.13	1700	11	Broken after second test during handling.
21	35	high spike density, SS	N/A	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Extractor voltage has to be increased to -20kV to reach ignition. Test stopped because too high voltages needed (and the high extractor voltage lead to high extractor current).