

Magnetic Powder Electrostatic Propulsion - MPEP

Final Presentation

Overview



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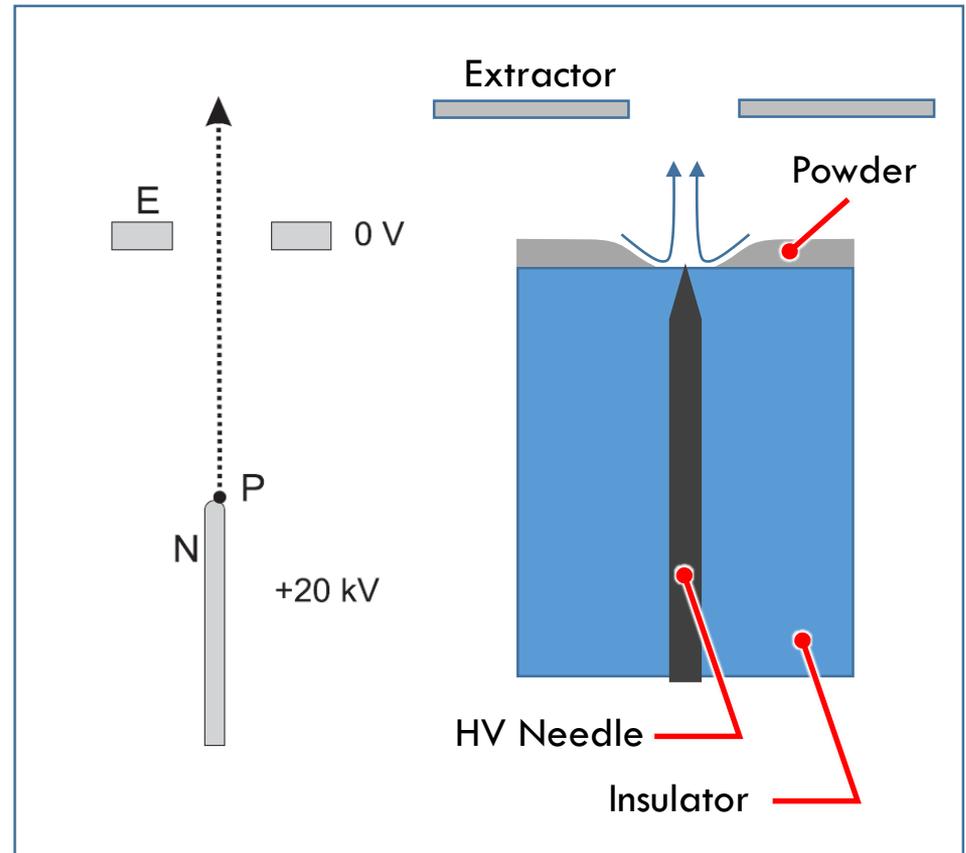
Summary

- Background and working principle
- Prototype development
- Propellant characterization
- Testing in air
- Electrostatic emission testing in vacuum
- Performance testing on the thrust balance
- Conclusions and outlook

Overview

Background

- Particle propulsion – Why?
 - High thrust, low electric power
 - High density (low volume) propellant storage
 - In situ resources utilization
- Trottenberg's scheme
 - Contact charging
 - Charging electrodes embedded in dielectric
 - Difficult continuous emission
 - No measurements produced

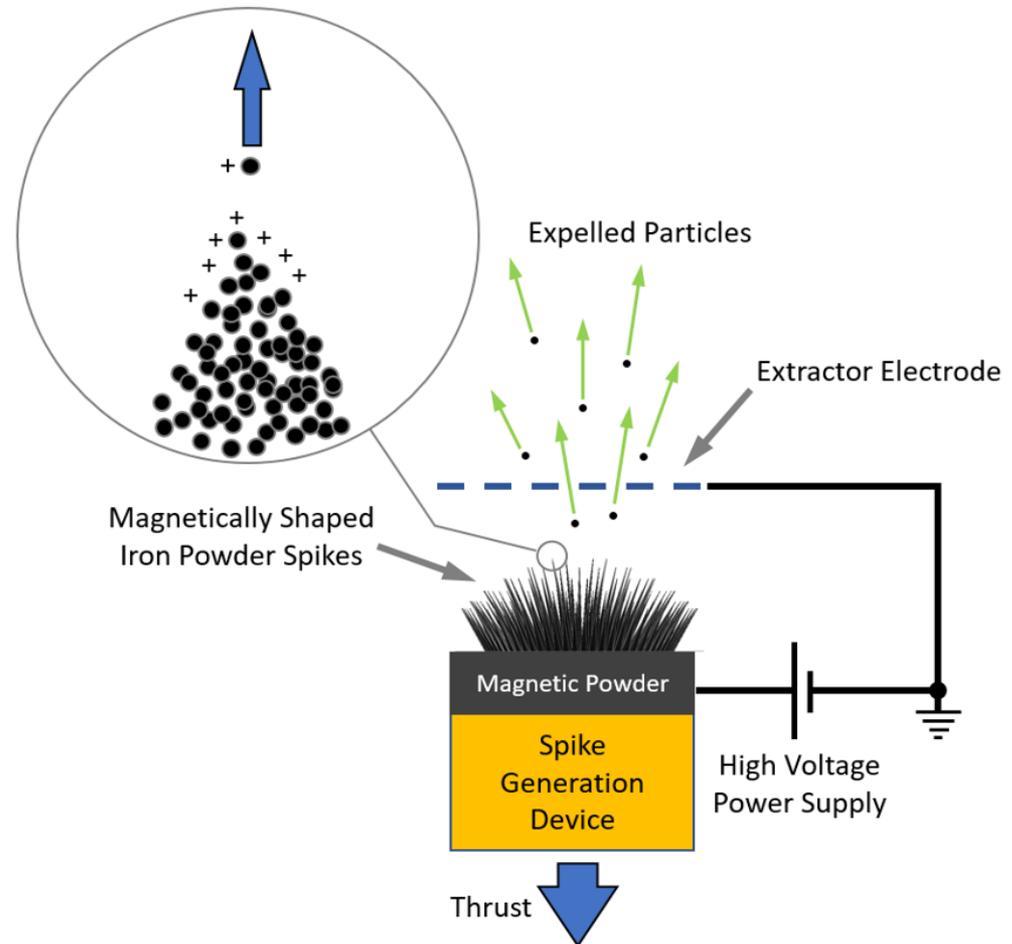


Trottenberg's Scheme
(Trottenberg 2007, 2010)

Overview

Working Principle

- Magnetic powder is shaped into an array of spikes by a magnetic field
- A voltage is applied between the powder and an extractor electrode
- Electrically charged particles detach from the tips by the action of the electric field
- The charged particles are accelerated by the electric field
- Past the extractor, the particles will be expelled at the speed acquired during the acceleration phase
- New spikes are continuously being generated by the spike generation device
- The continuous flow of particles being emitted generates a thrust in the opposite direction.



Prototype Development



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The Thruster Prototype

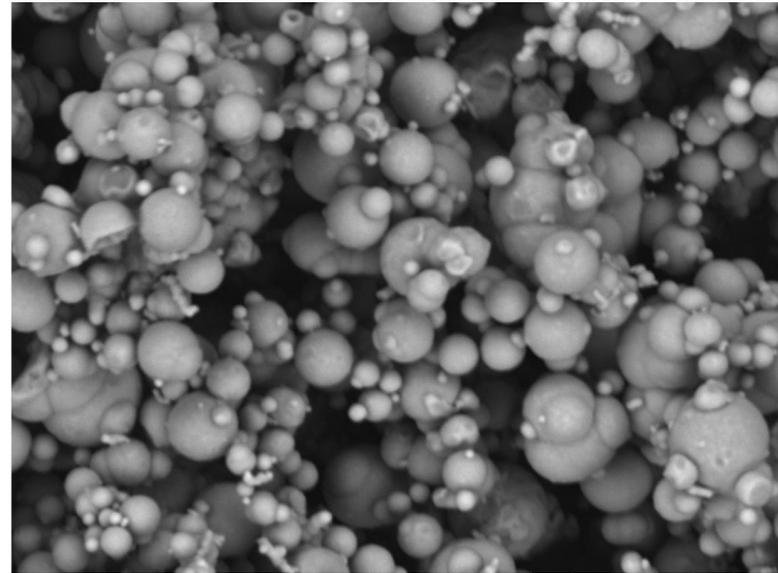
- The thruster prototype has been manufactured following the general guidelines used in our **FEEP design**, as far as it regards the distance between the electrodes and electrical insulation measures
- The module has been designed to withstand voltages in excess of 20 kV
- The metallic parts – excluding some small parts – are made from **non-magnetic material** (aluminium or titanium), to avoid interference with the magnetic field generated by the spike generation device
- The thruster is very **compact**, with a diameter of 86 mm and a height of about 70 mm



Propellant Characterization

Propellant Identification

- Two viable propellant **materials** have been identified: **Iron and Magnetite** (Fe_3O_4) powders
- Other possibilities exist, like **nickel, cobalt and rare earths**, but not considered due to potential toxicity, especially in powder form, and no clear advantage over iron compounds
- Four propellant sorts have been characterized
- Three candidates, one constituted by a blend, have been selected



Iron10u_0006

2021.03.07 12:13 D2,6 x5,0k 20 um

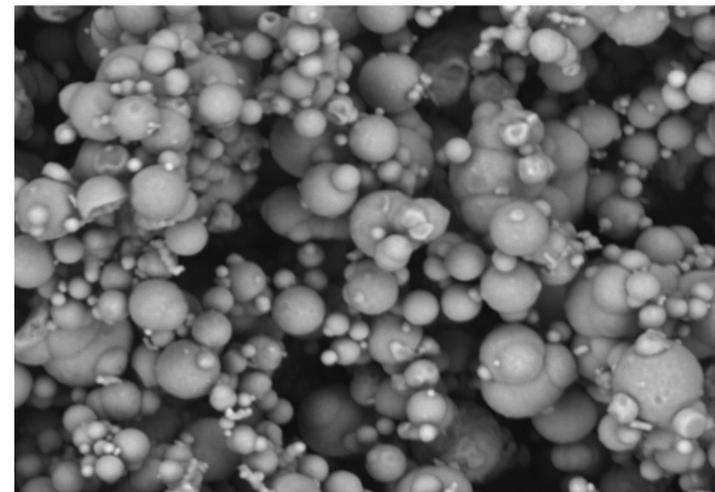
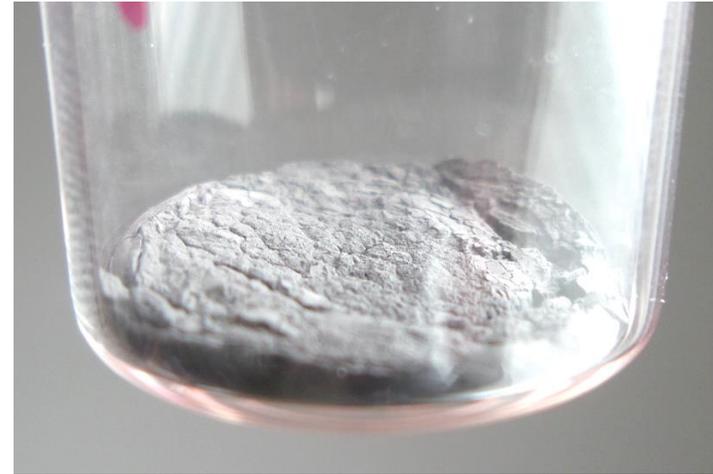


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Propellant Characterization

Iron Powder, Spherical, < 10 μm

- Supplier: Alpha Aesar
- SEM analysis confirms particle shape and dimensions given by the supplier
- Good flowability
- Good behaviour upon application of a magnetic field: spikes with high sharpness and slenderness, homogeneous shape and spatial distribution
- Working denomination: **FeLT10u**



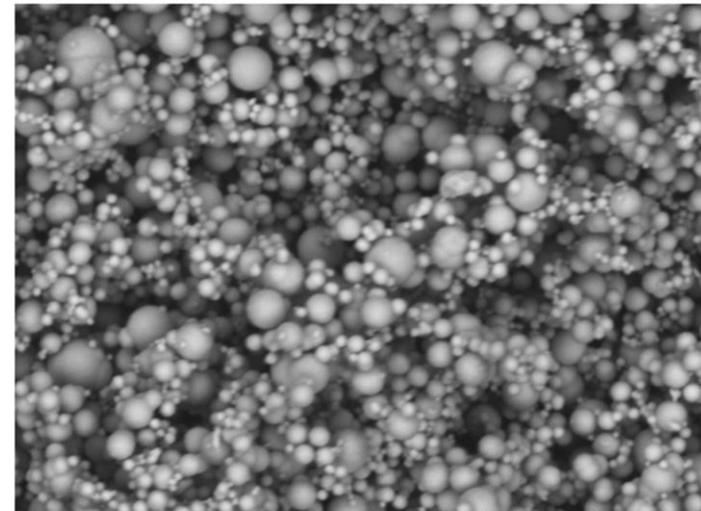
Iron10u_0006

2021.03.07 12:13 D2,6 x5,0k 20 um

Propellant Characterization

Iron Powder, Spherical, 1-3 μm

- Supplier: Alpha Aesar
- SEM analysis confirms particle shape, but doesn't strictly confirm dimensions given by the supplier
- Poor flowability
- Good behaviour upon application of a magnetic field: spikes with high sharpness and slenderness, homogeneous shape and spatial distribution (but requires more stirring compared to FeLT10u)
- Working denomination: **FeLT4u**



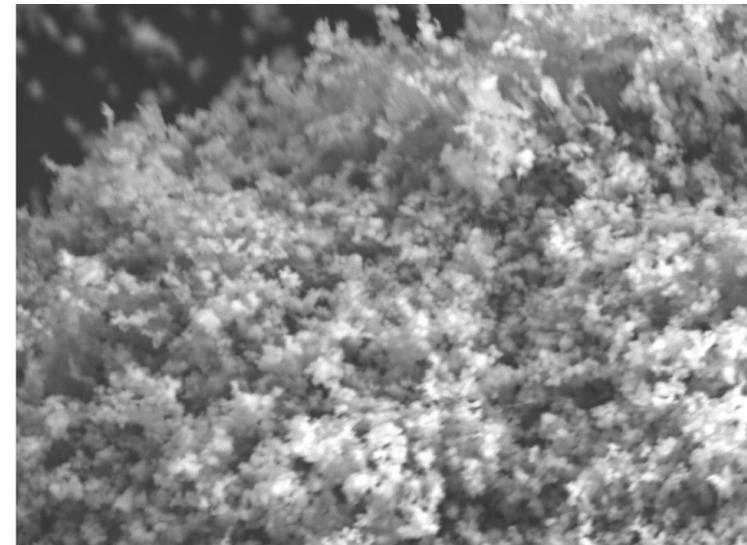
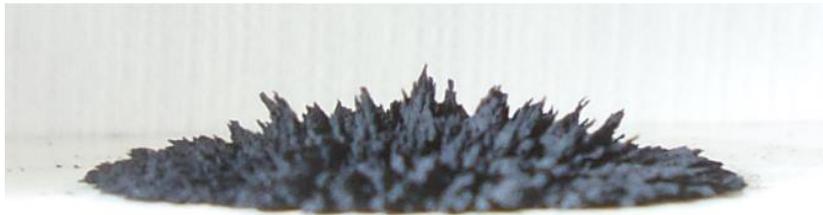
Iron1-3u_0002

2021.03.07 12:24 D5,0 x5,0k 20 μm

Propellant Characterization

Magnetite (Fe_3O_4) Powder –
Particle size: $< 5 \mu\text{m}$

- Supplier: Sigma Aldrich
- SEM analysis is difficult due to the small particle dimension, but the observation doesn't match with the description given by the supplier
- Bad flowability
- Poor behaviour upon application of a magnetic field
- Working denomination: **Fe3O4LT1u**



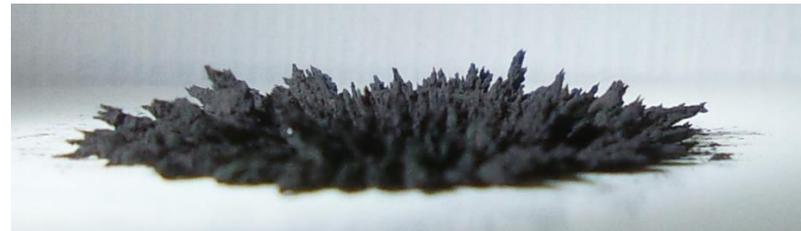
Fe3O4 <5um

2021.03.19 14:28 D1,9 x5,0k 20 um

Propellant Characterization

Magnetite (Fe_3O_4) Powder –
Particle size: 50-100 nm

- Supplier: Sigma Aldrich
- Bad flowability
- Very poor behaviour upon application of a magnetic field
- Not selected



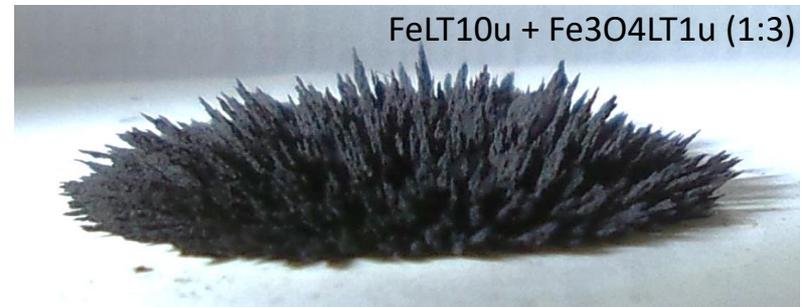
Propellant Characterization



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Blends

- Blending **FeLT10u** with **Fe3O4LT1u** results in an omogeneous compound with interesting characteristics
- Flowability and behaviour with magnetic field depends on the amount of Fe powder
- Blends could be used to *tune* the propellant for specific lsp ranges
- Blends are also interesting with regards to in-situ resource utilization, where a perfect material refinement might not be possible



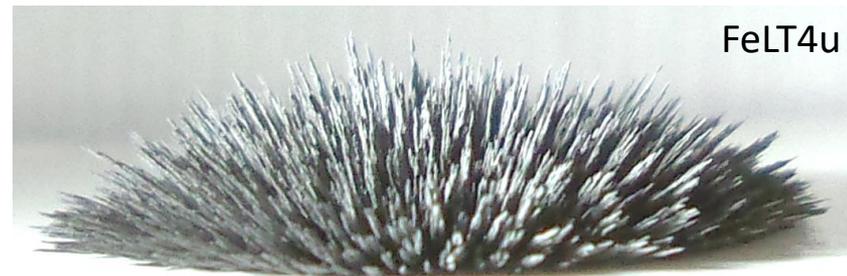
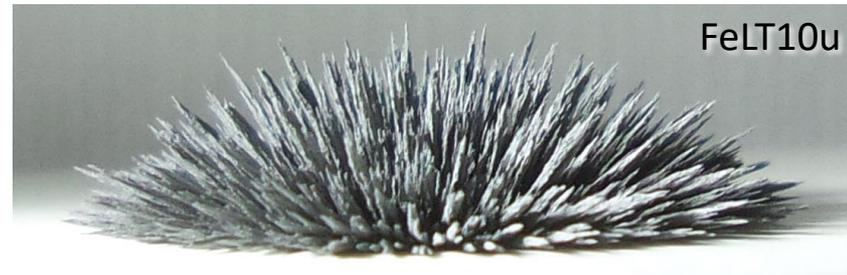
Propellant Characterization



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Selected Propellants

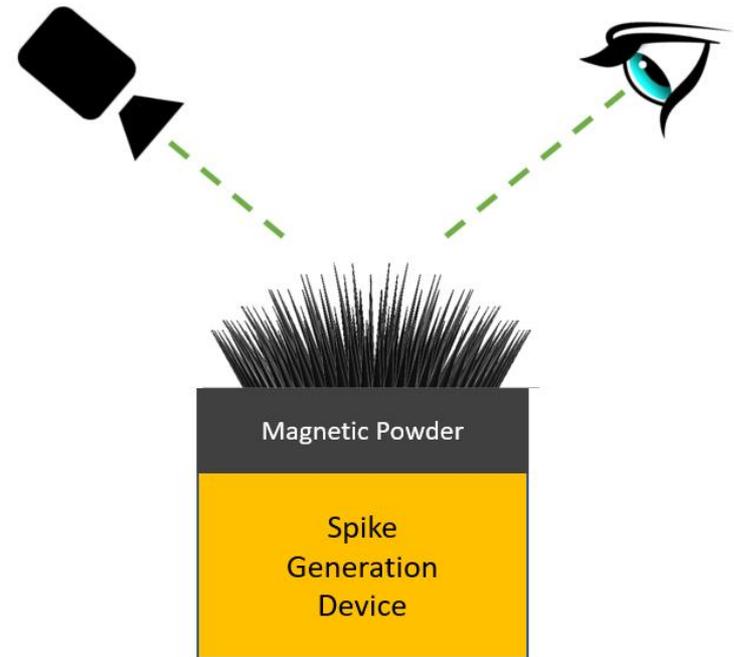
- FeLT10u
- FeLT4u
- FeLT10u + Fe₃O₄LT1u (1:1 in volume)



Spike Generation Device (SGD) Testing in Air

Test Setting and Objectives

- The goal of this test was to study the formation dynamics of the spikes, finding the combination(s) of parameters which resulted in the most effective spike generation
- Two spike generation device (SGD) types have been tested (Type 1: moving magnet, and Type 2: varying magnetic field)
- During operation, the following aspects have been observed:
 - Spike distribution (height, spacing)
 - Spike shape dynamics
 - Behavior following spike damaging
- Some runs were performed with the thruster axis parallel to the ground, to observe the effect of the gravity force

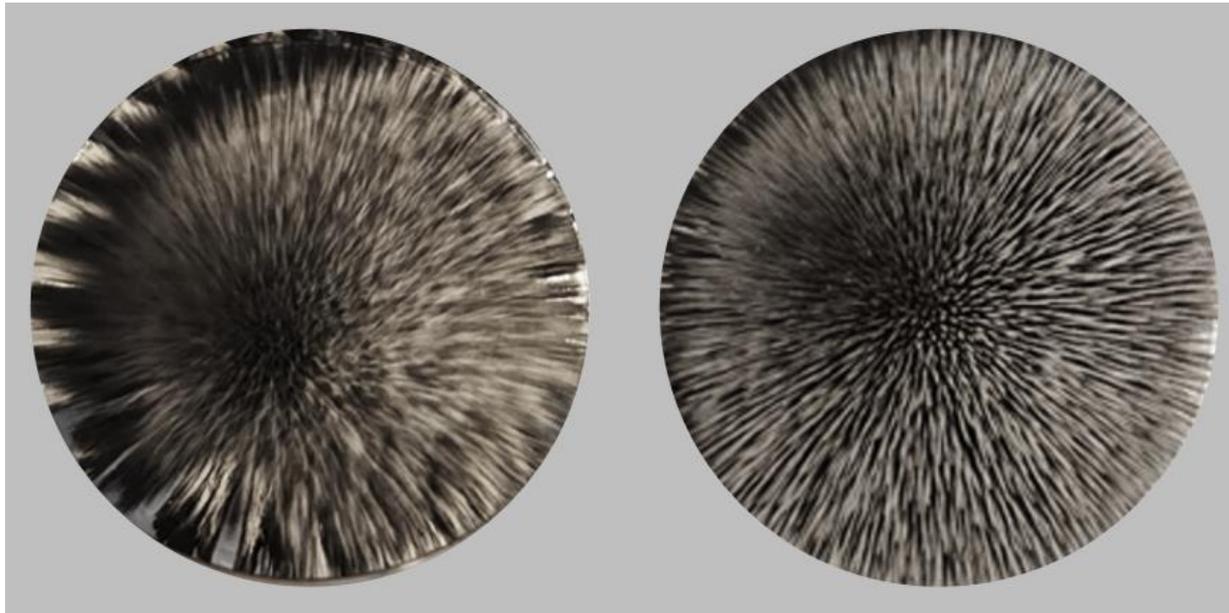


Spike Generation Device (SGD) Testing in Air

Spike distribution vs. SGD distance from the propellant



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3.5mm distance

6mm distance

200mg FeLT10u

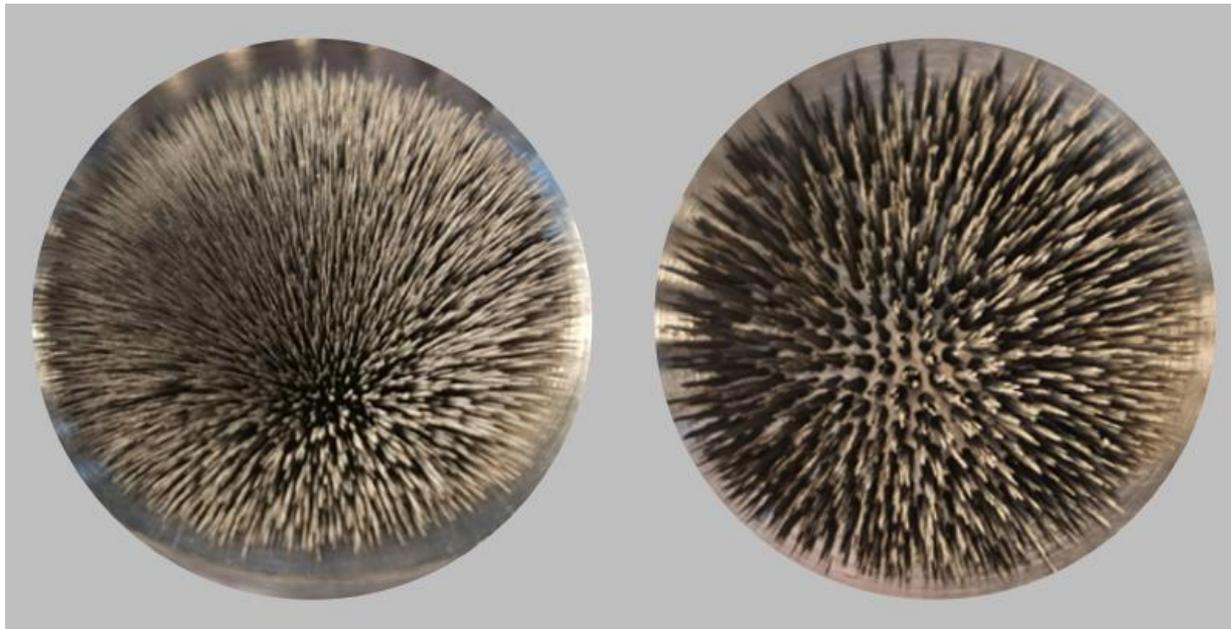
SGD 1

Spike Generation Device (SGD) Testing in Air

Spike distribution vs. propellant amount



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3.5mm distance

6mm distance

100mg FeLT4u

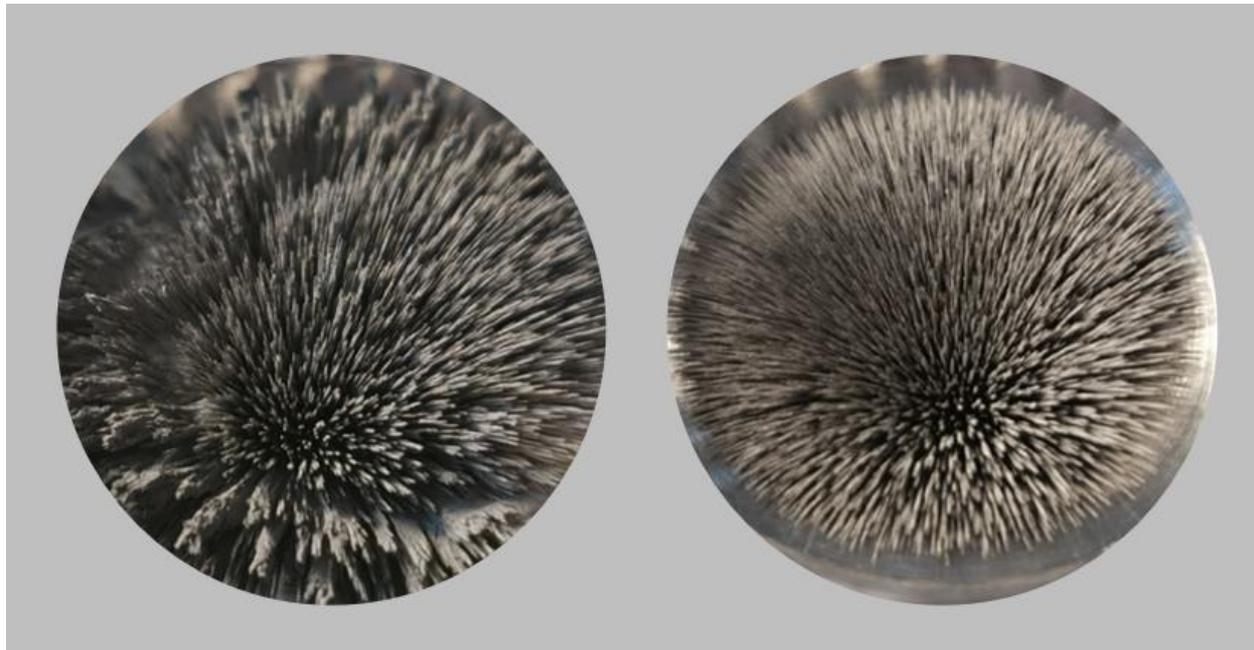
SGD 1

Spike Generation Device (SGD) Testing in Air

Spike distribution vs. propellant amount



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350 mg

FeLT4u

100 mg

Spike Generation Device (SGD) Testing in Air

Media Highlights



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Spike Generation Device (SGD) Testing in Air



Results - Summary

- The propellant type FeLT10u presented the best performance in terms of spike formation in both SGD types
- SGDs performed well, with one (moving magnet) performing better in terms of spike formation on all types of propellants
- Lower amounts of propellants displayed in general best spike generation behavior
- Operation of the thruster with the axis parallel to ground showed a drift of the propellant when using the SGD Type 2 device and the largest distance between the SGD and the propellant. All the other tested configurations did not show signs of propellant drift.

Electrostatic Emission Testing in Vacuum

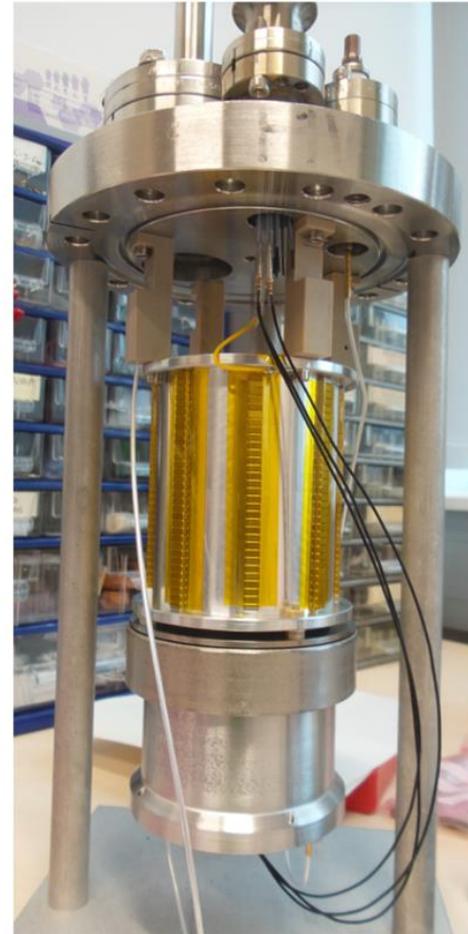
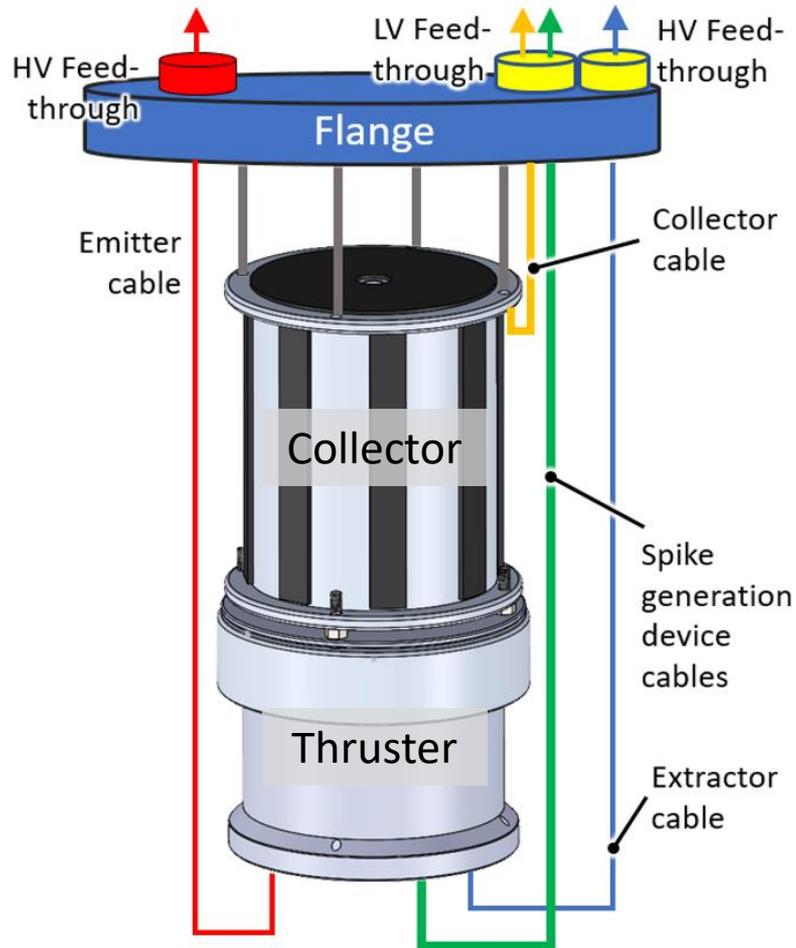
Test Setting and Objectives

- The objectives of this test campaign were to proof the thruster robustness (especially with regards to high voltage) and to gather information on its capabilities in terms of electrostatic powder ejection when different parameters are varied
- To do that, the thruster has been operated in a small vacuum chamber, with a small collector to gather the emitted powder and measure the current produced by the flow of charged particles
- The following figures were evaluated:
 - Propellant consumption
 - Collector current vs. emitter voltage
 - Extractor current losses
 - Beam divergence (in terms of rough density distribution of the powder deposited on the collector surface)
- The varying parameters were:
 - Propellant type and amount
 - SGD type and settings
 - Extractor distance and grid type

Electrostatic Emission Testing in Vacuum



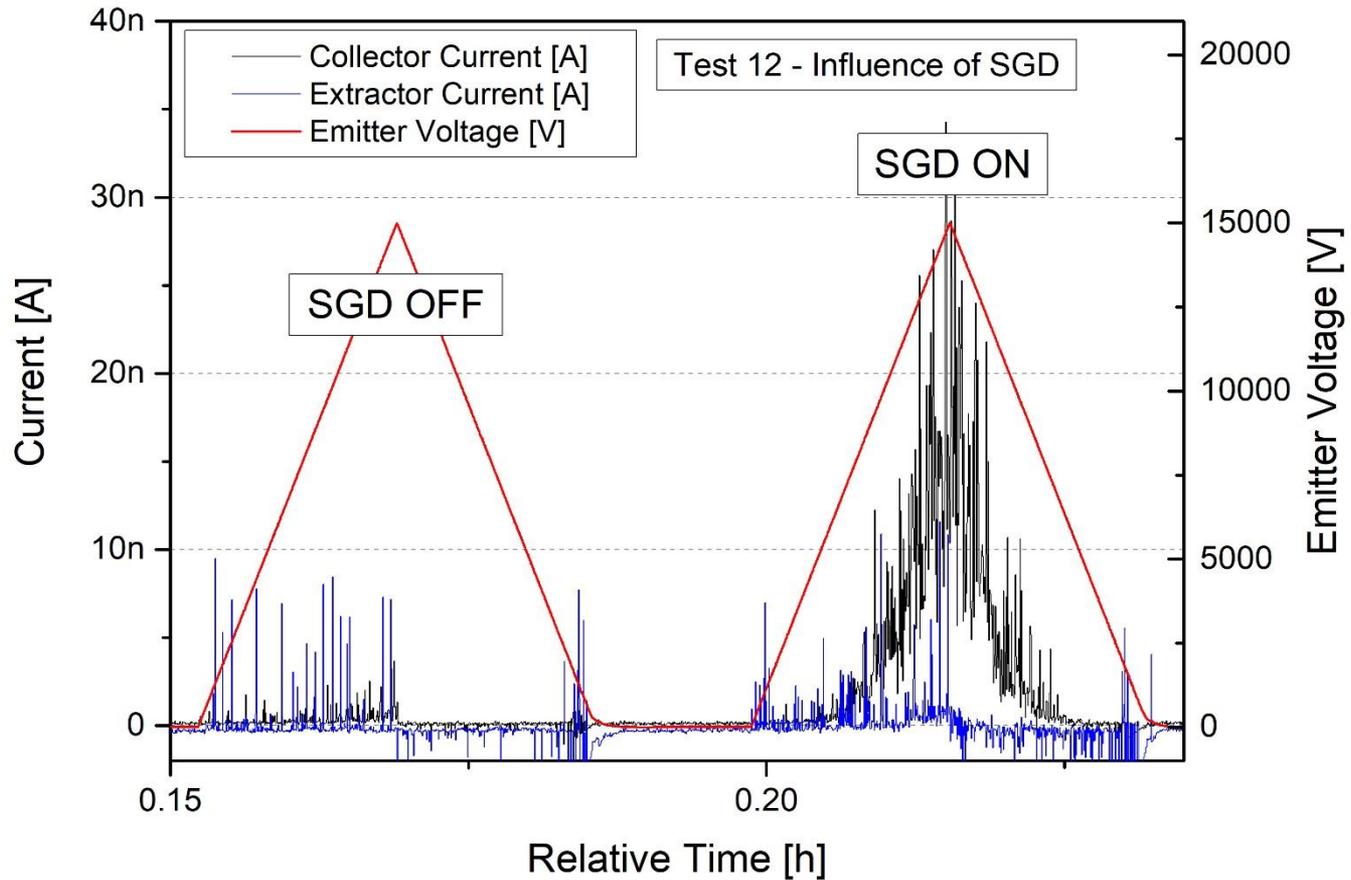
Test Setup



Electrostatic Emission Testing in Vacuum



Voltage sweeps with SGD OFF and SGD ON

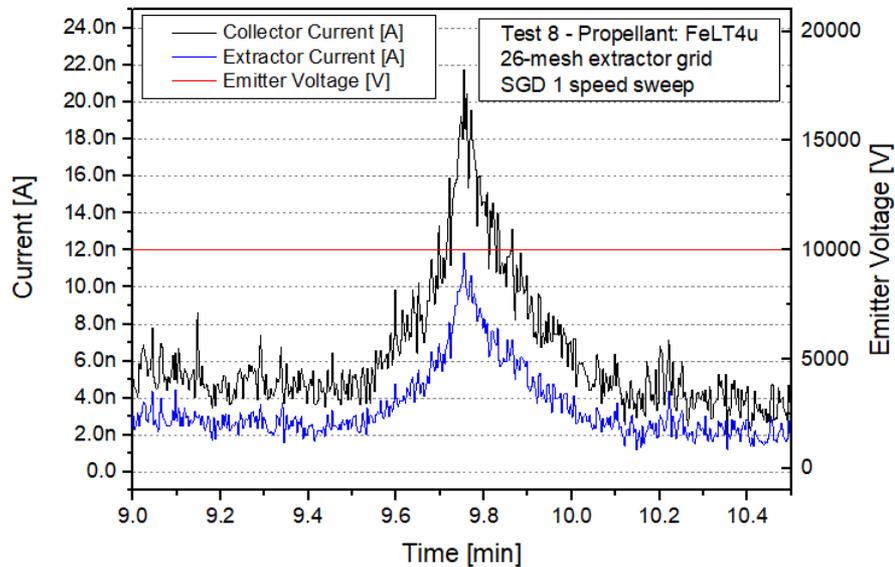


Electrostatic Emission Testing in Vacuum

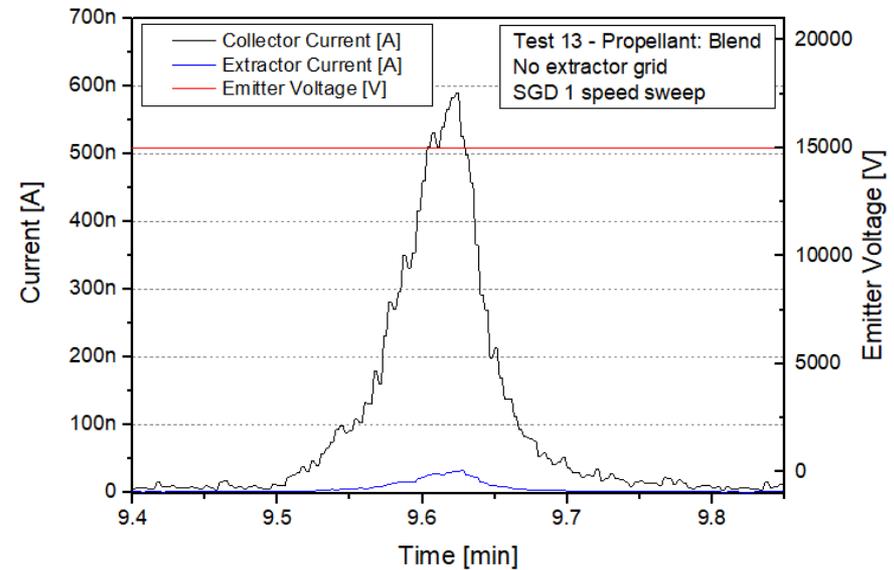


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Emission current vs. SGD speed setting



Sweep ~40-200-40 Hz
Constant emitter voltage: 10kV
Propellant: FeLT4u



Sweep ~40-200-40 Hz
Constant emitter voltage: 15kV
Propellant: Blend

Electrostatic Emission Testing in Vacuum

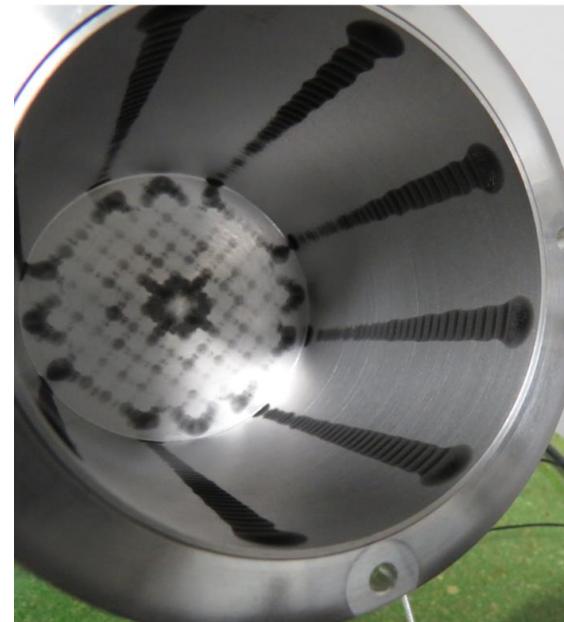
Deposition pattern on the collector – Extractor influence on beam divergence



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Extractor with 16-mesh grid



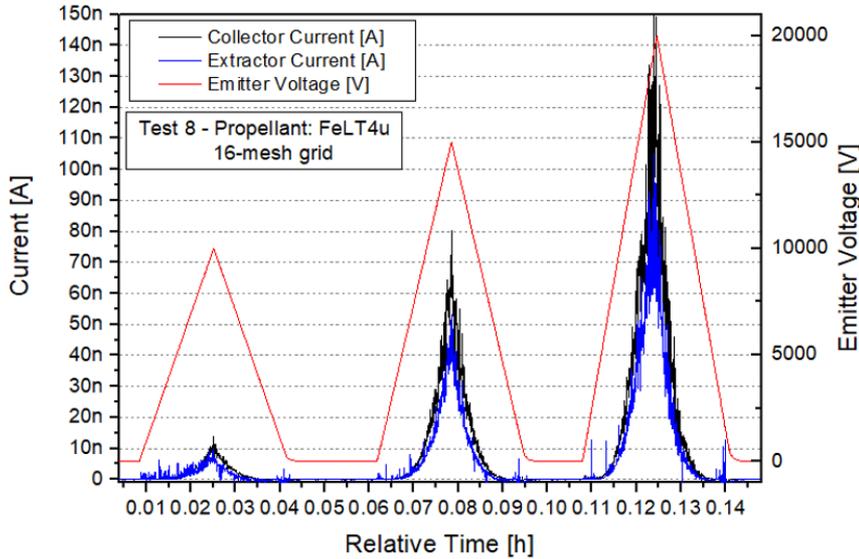
Extractor without grid



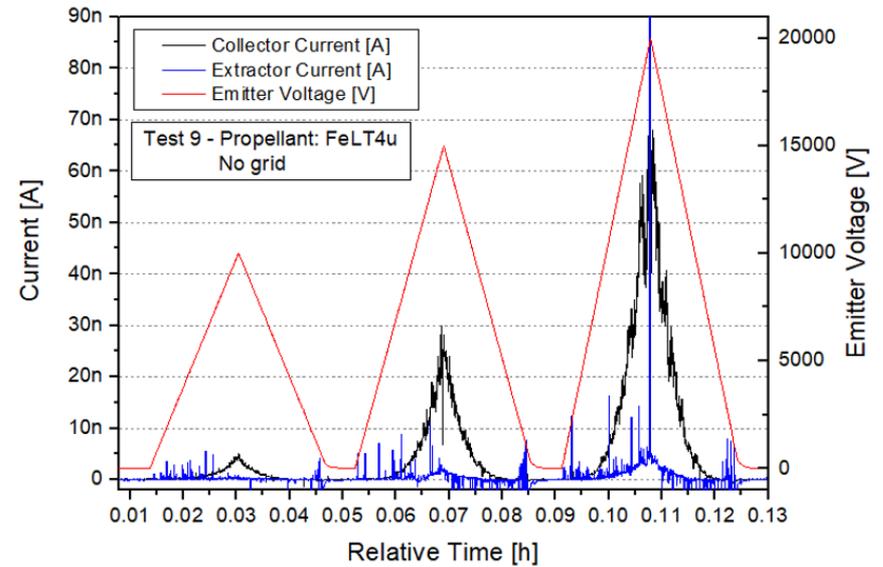
Electrostatic Emission Testing in Vacuum



Extractor configuration (grid, no grid) vs. collector and extractor current



Extractor with grid (16-mesh)



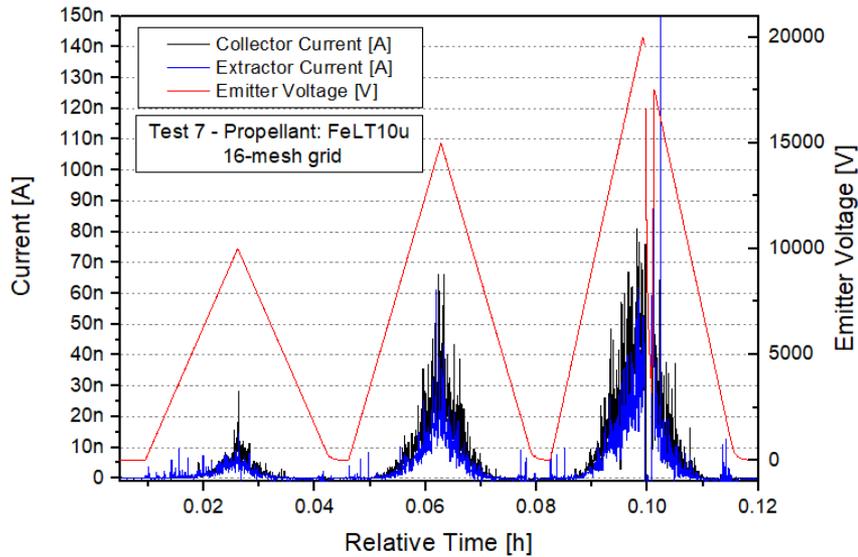
Extractor without grid



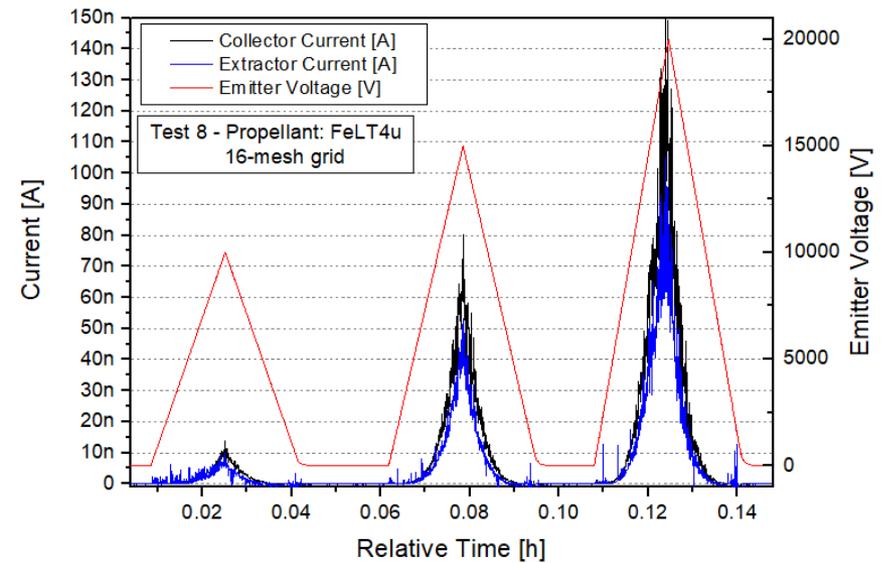
Electrostatic Emission Testing in Vacuum



Propellant type influence on the emitted current



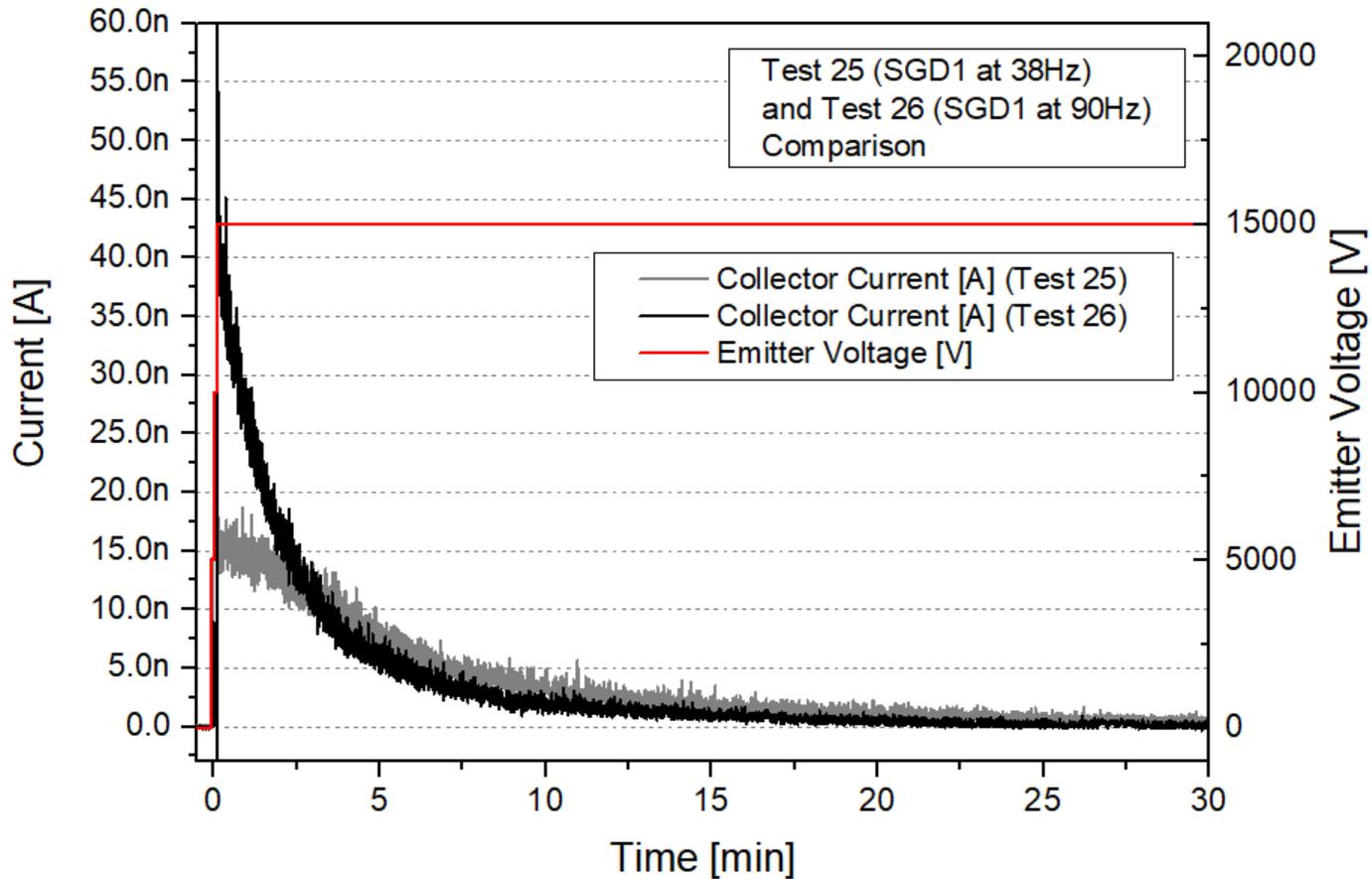
Typical current plots from
FeLT10u emission



Typical current plots from
FeLT4u emission

Electrostatic Emission Testing in Vacuum

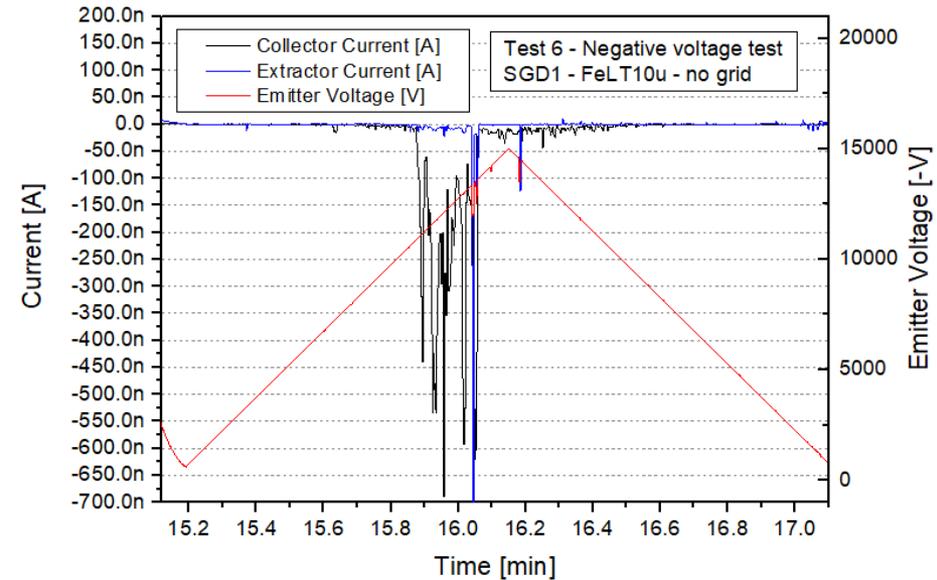
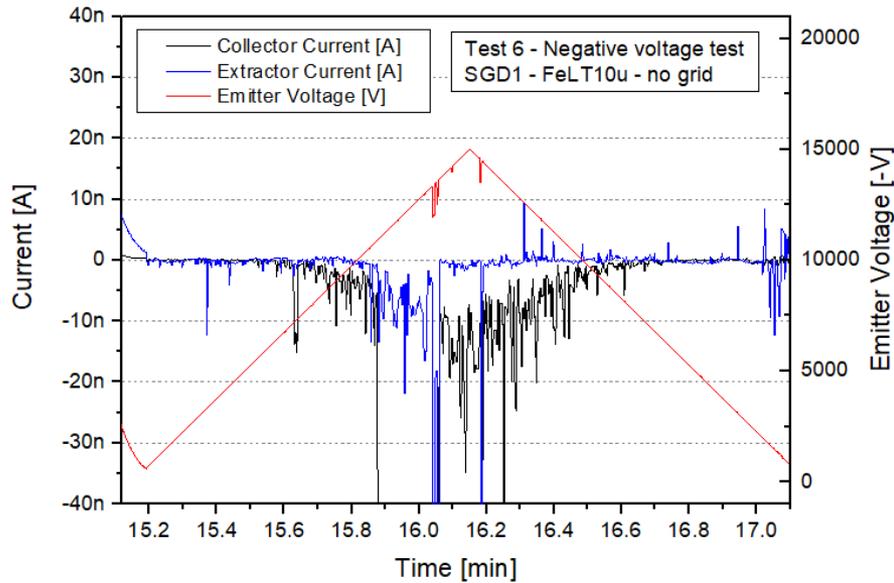
Propellant consumption at different SGD speed settings



Electrostatic Emission Testing in Vacuum



Emission at negative emitter voltage



Anomalous high current emission (possible electron emission from the iron spike tips?)

Electrostatic Emission Testing in Vacuum



Results - Summary

The test campaign demonstrated the following facts:

- Electrostatic acceleration of iron powder from magnetically shaped spikes
- Need for the SGD in order to produce the particle emission
- Possibility to regulate the emission acting both on the SGD settings and on the applied emitter voltage
- Emission of negatively charged particles (no need for a neutralizer?)

Parameters influence on the emission:

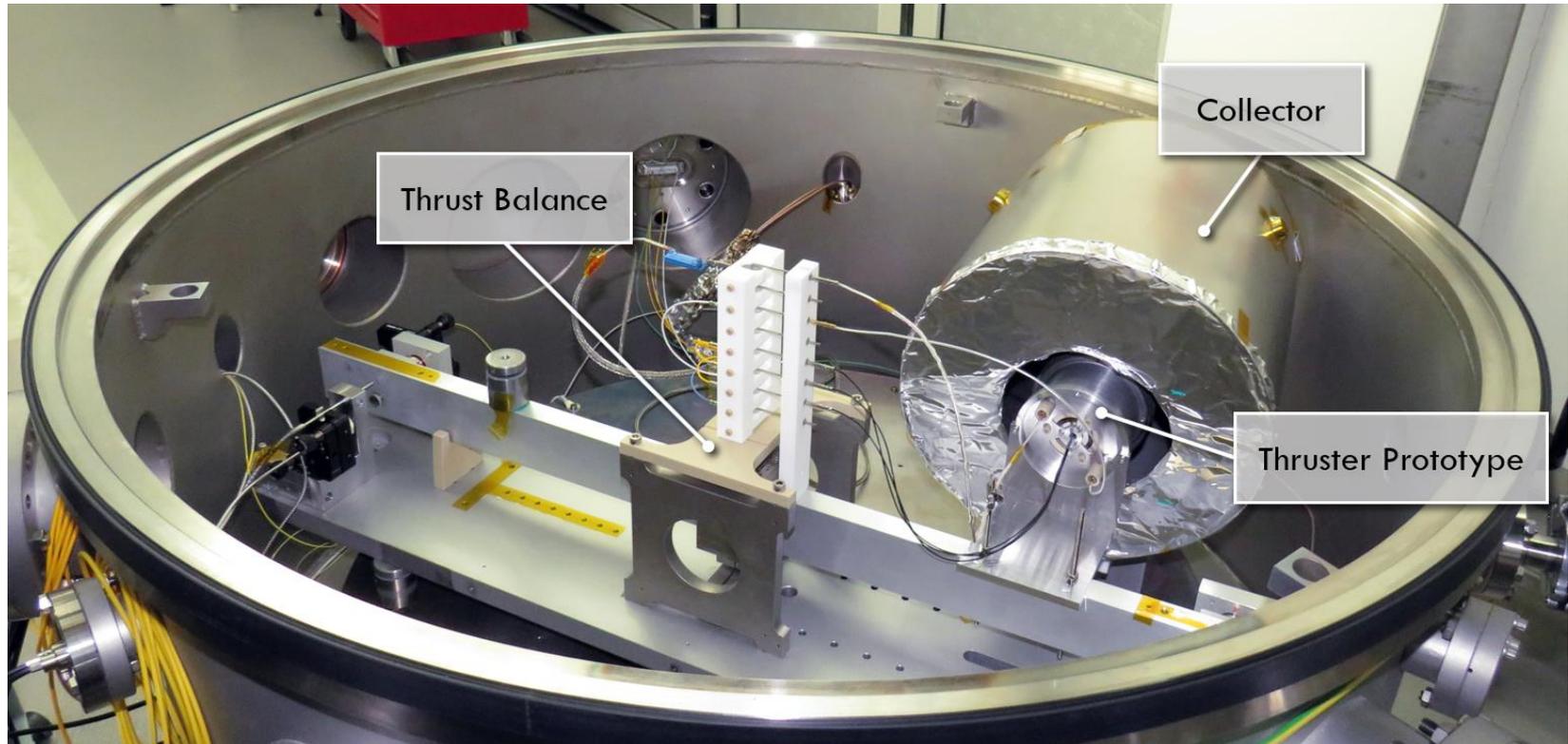
- SGD
 - Type 1 gave the best performance in terms of emission duration and throttability
- Extractor
 - The tested extractor distances resulted in minor result differences
 - The presence of the grid implied large extractor currents and influenced the emitted current. Signs of higher beam divergence when no grid is used.

Performance Testing on the Thrust Balance

Test Setup



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Performance Testing on the Thrust Balance

Measurements and Derived Figures

Measurements:

- Emitter voltage
- Collector current
- Extractor current
- Thrust
- Emitted powder mass

Calculated Figures:

- Thrust to power ratio
- Specific impulse
- Charge to mass ratio of the emitted particles
- Emitted particle average size

Performance Testing on the Thrust Balance



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Test Campaigns

Thrust at different voltage levels:

- Short runs at different voltages within the same test
- Map thrust vs. voltage and current
- Thrust performance change due to varying parameters:
 - Extractor Type
 - Propellant Type
- Total Tests: 4

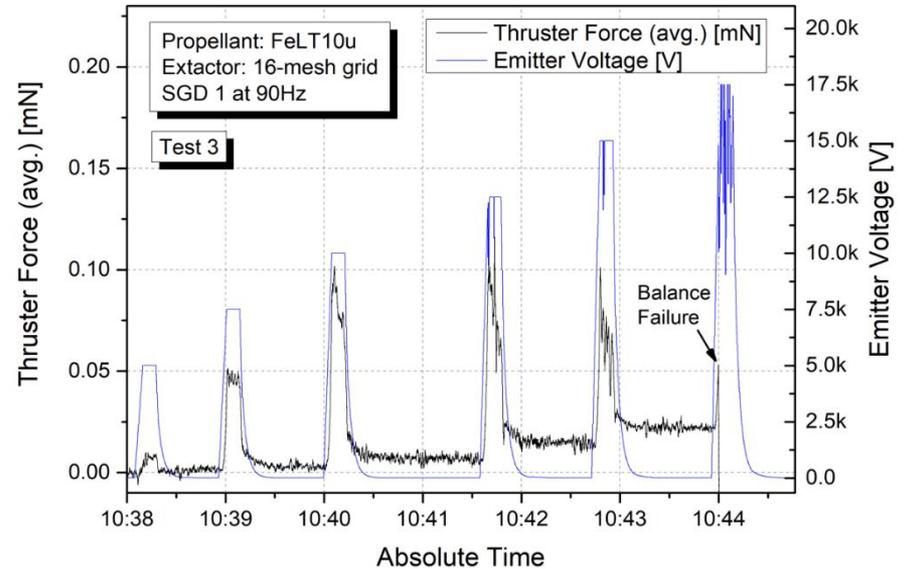
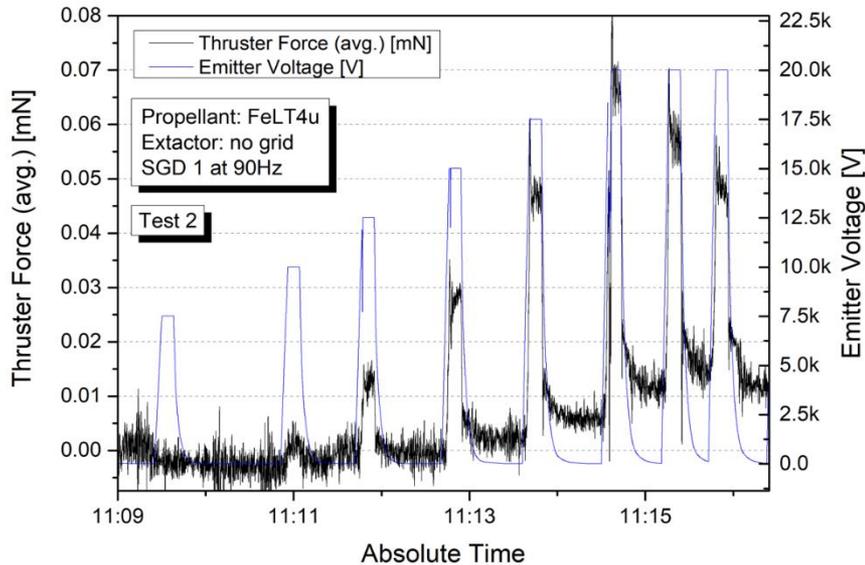
Static voltage tests:

- Operation at fixed voltage within the same test
- Map I_{sp} at different voltages
- Charge to mass ratio of the emitted particles
- Total Tests: 12

Performance Testing on the Thrust Balance



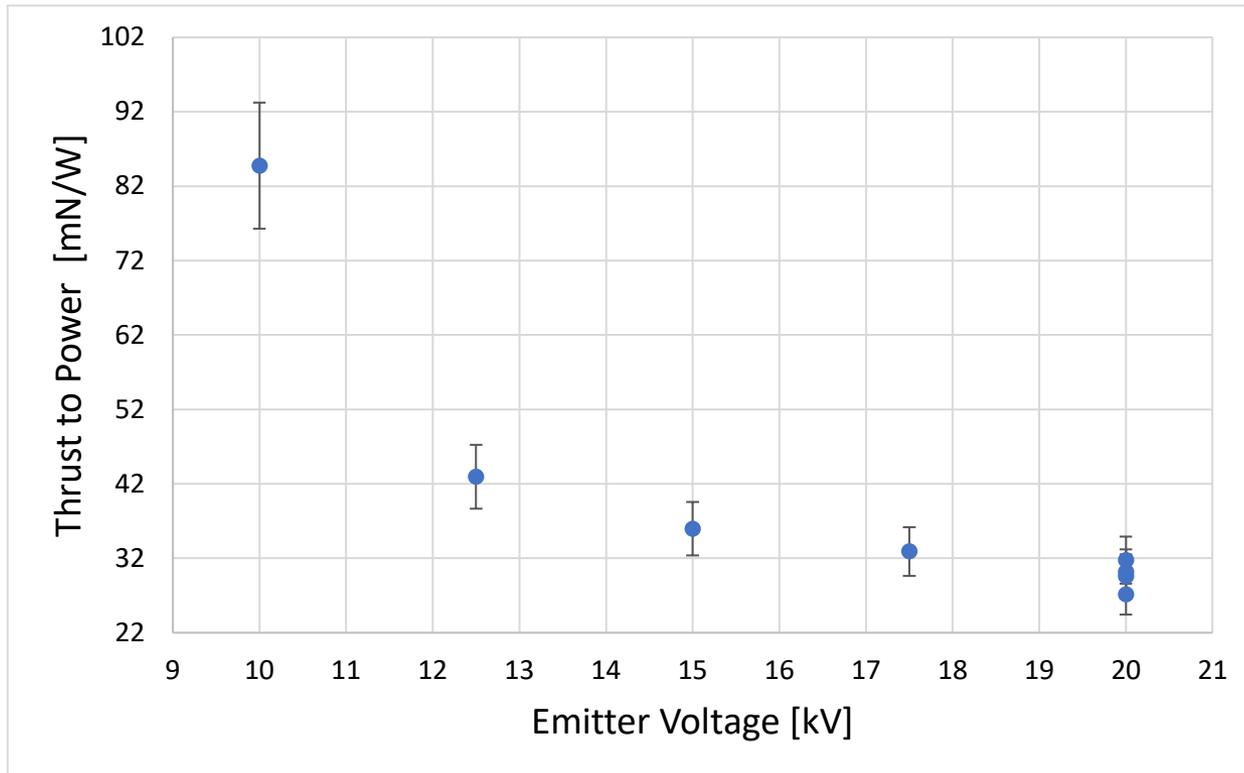
Test Results – Thrust Profiles



Performance Testing on the Thrust Balance



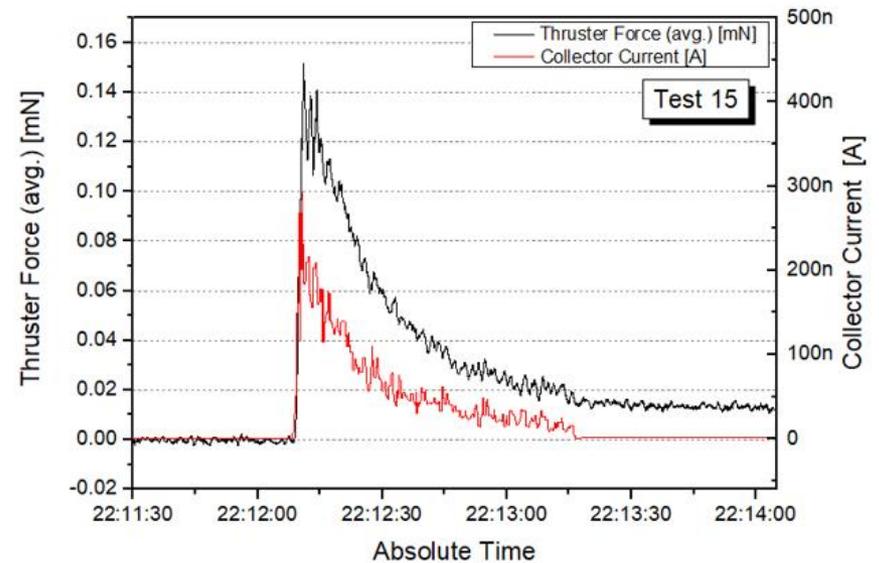
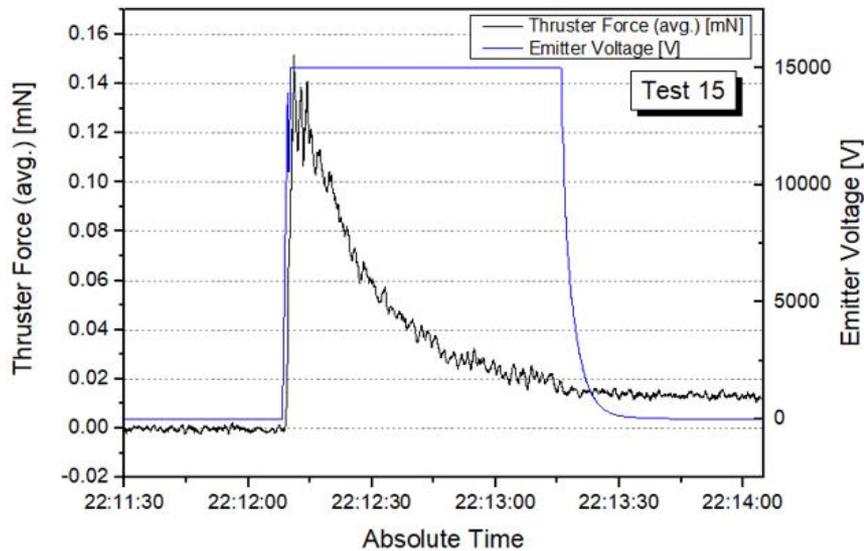
Test Results – Thrust to Power Ratio (from Test 2)



Performance Testing on the Thrust Balance

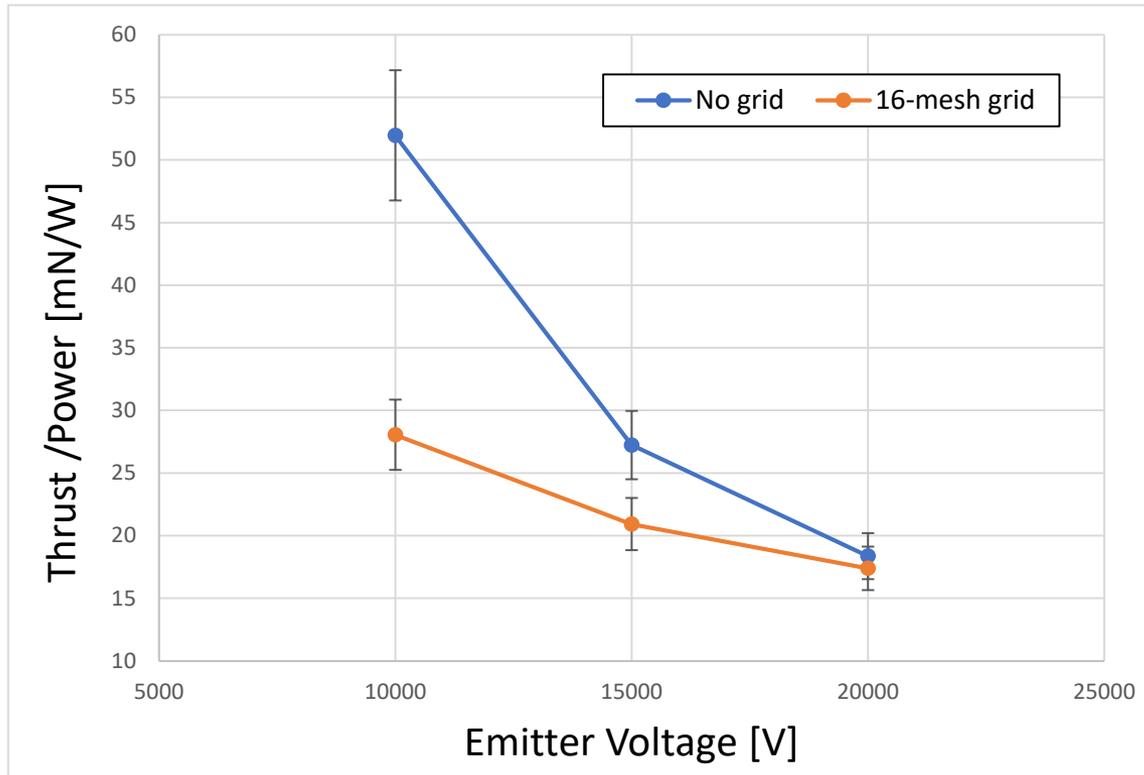


Test Results – Tests at fixed voltage – Typical Thrust and Current Profile



Performance Testing on the Thrust Balance

Test Results – Tests at fixed voltage – Thrust to Power Ratio vs. Emitter Voltage

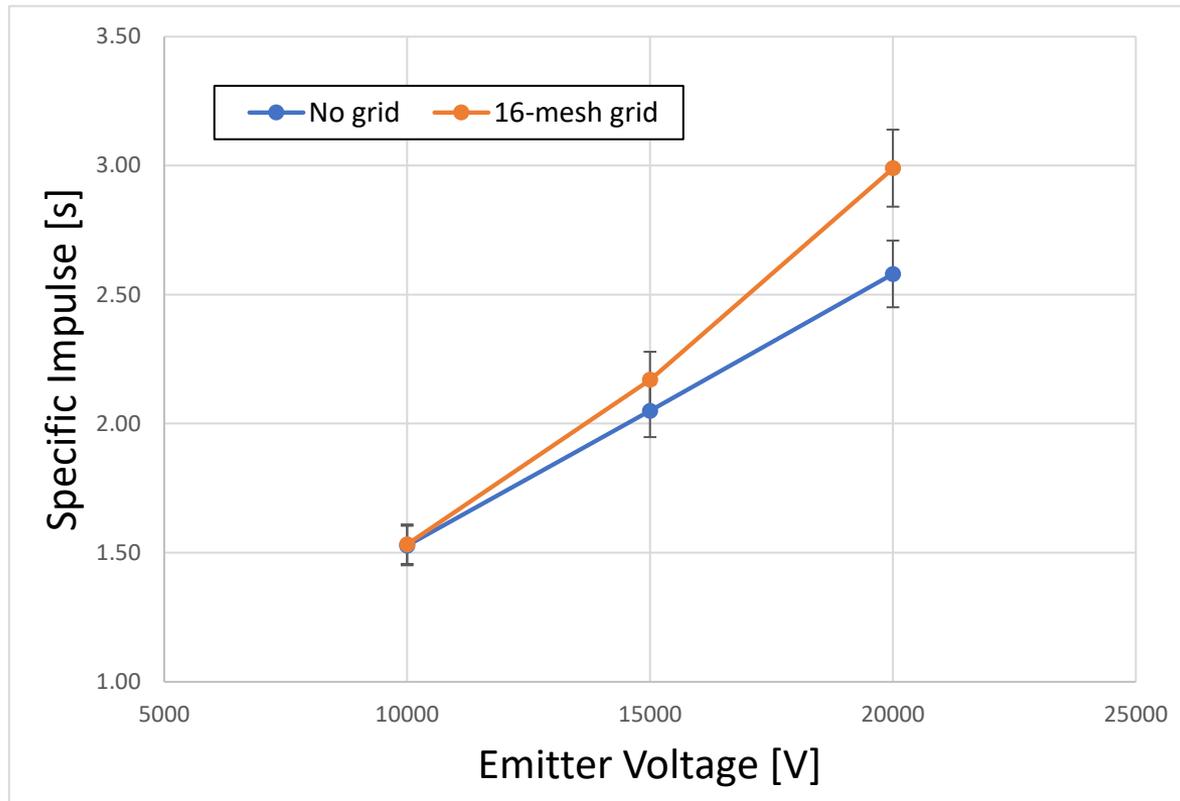


Performance Testing on the Thrust Balance

Test Results – Tests at fixed voltage – Specific Impulse



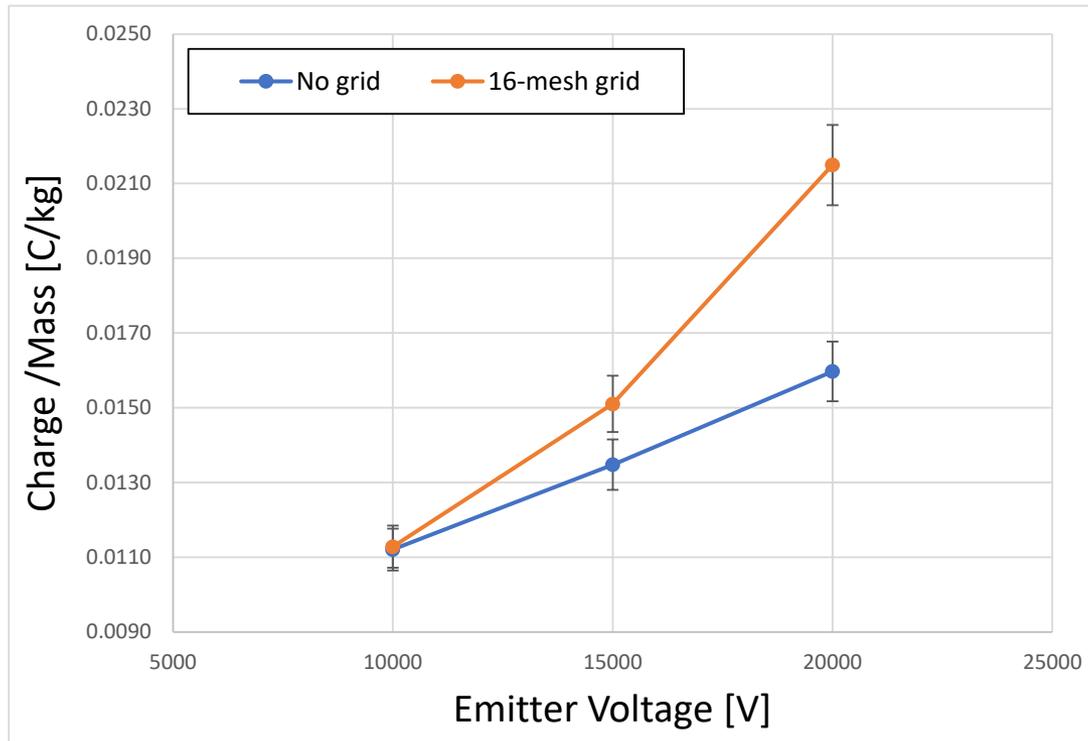
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Performance Testing on the Thrust Balance



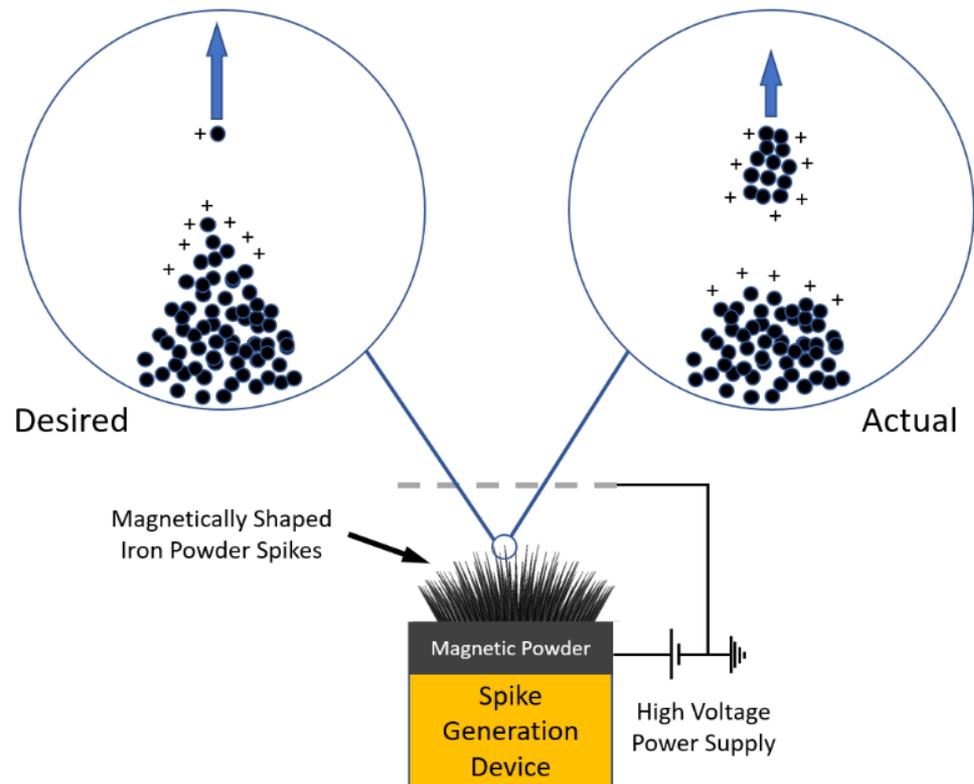
Test Results – Tests at fixed voltage – Charge to Mass Ratio



Performance Testing on the Thrust Balance

Test Results – A note on the emission process

- The actual emitted particle diameter seems to be roughly an order of magnitude larger than the single powder particles
- Tendency of the particles to clump together (adhesion, residual magnetism)
- Slightly worse I_{sp} with finer powders (whereas the contrary would be expected if no clumping occurred)
- An improvement factor of 10 to 25 (depending on the propellant) on the specific impulse could be expected when the particles were emitted singularly
- As a note of caution, the emitted particle diameter is inferred using a simplified theoretical approach





Performance Testing on the Thrust Balance

Results – Summary

- Peak Thrust: 0.5 mN at 20 kV (extractor: 16-mesh grid). Power: 30 mW
- Specific Impulse: 1.5 to 3 s (10 to 20 kV)
- Thrust to power ratio: 50 to 20 mN/W (10 to 20 kV, no grid), 20 to 17 mN/W (10 to 20 kV, 16-mesh grid)
- Estimated average emitted particle diameter: about 100 μm

Conclusions and Outlook



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Conclusions

- A novel approach to electrostatic particle propulsion has been proposed, based on the arrangement of the propellant into spike arrays using B-fields
- The approach has been implemented on a thruster prototype
- It has been demonstrated that the prototype is able to emit a continuous flow of charged particles, controllable both acting on the spike generation device and on the voltage applied to the propellant
- Controllable thrust has been measured
- Data analysis indicates that the propellant is emitted in agglomerates, leading to a non-ideal particle final velocity

Conclusions and Outlook



Outlook

- Further development should mainly address the issues with the particle emission process, with the aim to increase the charge to mass ratio
- A tank with a suitable feeding system should be implemented in order to produce a longer lasting stable thrust
- A corollary activity could be a refinement from the theoretical side, adopting derivations already present in the literature in order to better estimate the emitted particle diameter

Delivered and to be submitted

WP	Document Title	Document No.	Iss.-Rev.	Status
2	Prototype design (presentation)*	-	-	Accepted
2	Design report	FTC2021-029-01-00	01-00	Accepted
2	Propellant characterization report	FTC2021-030-01-00	01-00	Accepted
3	Manufacturing report	FTC2021-059-01-00	01-00	Accepted
4	Test plan TN-4A	FTC2021-064-01-00	01-00	Accepted
4	Test plan TN-4B	FTC2021-109-01-00	01-00	Accepted
5	Test analysis and roadmap	FTC2022-006-02-02	02-02	Submitted
5	Final report	FTC2022-012-01-00	01-00	Submitted
5	Final presentation	-		To be submitted
5	Executive summary	FTC2022-013-01-00	01-00	Submitted
	Technology achievement summary	-		Submitted
	Final presentation recording ~3min	-		Submitted
	Website article			Not required
	Photographic documentation	-		Submitted
	Contract Closure Documentation			In preparation
	Technical Data Package			In preparation

*The “prototype design (presentation)” was attached to the MoM of the PDR meeting (Doc. Nr.: FTC2021-033-01-00).