Category					
Category	Baseline (Configured)	1 **A** –	Customer (**C**onfigured)	Approval	
		1 **R** –	Customer (**R**eview)	Acceptance	X
		1 **I** –	Other (**I**nformation Only)		
	Not Baseline (Unconfigured)	2 **A** –	Customer (Not Configured)	Approval	
		2 **R** –	Customer (**R**eview)	Acceptance	
		2 **I** –	Other (Information Only)		

Classification		
Classification	**Confidential**	
	Proprietary	
	Non-Proprietary	
	Public	X

Project No.: 2021-029
DDL No.: ES
WP: *7*
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EXECUTIVE SUMMARY

Magnetically Shaped Spike Arrays for Field Emission Devices

MAGNIFIED

Prepared: 16-10-2023	Approved QA: 16-10-2023	Approved PM: 16-10-2023
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Replaces Issue:	FTC2023-102-01-00, released on 21-09-2023	
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Customer Approval/ Customer Acceptance	
Name: Eduard Bosch Borràs	
Organization: ESA	Date:
Signature:	

DOCUMENT CHANGE LOG

Iss.-Rev.	Date	Pages Affected	Reason for Change
01-00	21-09-2023	All	Initial release
01-01	16-10-2023	All	Removed copyright notice and changed classification

DISTRIBUTION LIST

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CONTENTS

1. SCOPE OF THE DOCUMENT

This document is the Executive Summary of the MAGNIFIED project, performed under ESA contract no. 4000136206/21/NL/GLC/ov (OSIP Discovery Ideas Open Channel ETD Activities Evaluation Session 2021-05) by FOTEC Forschungs- und Technologietransfer GmbH, Austria.

A compendium of the technical reports is available in the form of a Final Report (Doc. no. FTC2023-101-01-00). The Final Presentation was held on September 27th, 2023 at ESTEC.

1.1. Applicable Documents

Unless specified otherwise, the following documents in their latest revision shall be considered as integral part of this document.

Ref.	Document Number	Title	Issue/ Rev.	Date
[AD-01]	ESA-TEC-SOW-023044	Statement of Work – "Discovery Ideas Open Channel ETD Activities Evaluation 2021-05 – EXPRO"	1.3	15-06-2021

Table 1-1. Applicable Documents

1.2. Reference Documents

The following documents are referenced in the scope of this document and shall be considered as informational only:

None

1.3. Acronyms and Abbreviations

In the scope of this document, the following abbreviated terms are defined and used:

AD	Applicable Document
DDL	Deliverable Documents List
EDX	Energy Dispersive X-Ray
EGaIn	Eutectic Gallium-Indium alloy
FEEP	Field Emission Electric Propulsion
LMIT	Liquid Metal Ion Thruster
MS	MileStone
RD	Reference Document
TBC	To Be Confirmed
TBD	To Be Defined
WP	Work Package

2. BACKGROUND AND OBJECTIVES

2.1. Background

Liquid metal ion thrusters (LMITs) are a type of electric propulsion system used for spacecraft. They work by ionizing and accelerating metal ions to generate thrust. The metal is typically either gallium or indium, which is heated into a liquid state and fed to the emitter.

When a strong electric field is applied between the emitter and an extractor electrode, it pulls positively charged ions from the liquid metal surface at the tip of the needles. These ions are then accelerated by the electric field to extremely high velocities. The accelerated ion beam generates thrust according to Newton's third law of motion (Figure 2-1).

LMITs produce very low thrust levels ranging from micro- to milli-newtons, but have exceptionally high specific impulses of 3,000 to 8,000 seconds. This makes them ideal for long duration station-keeping and attitude control maneuvers.

The porous tungsten emitter is a critical component that largely determines the thruster performance and lifetime. However, manufacturing new emitters is challenging and expensive and this restricts the ability to iteratively test and optimize different emitter designs.

Further research into optimized emitter fabrication methods could help accelerate prototyping and testing of new emitter designs, and reduce the overall expenses.

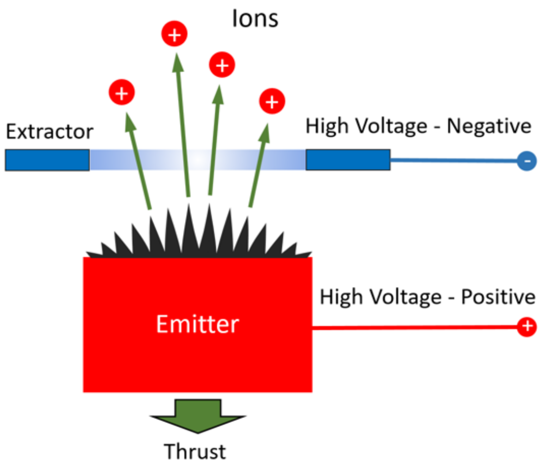

Figure 2-1. Liquid Metal Ion Thruster working principle

2.2. Project Objectives

Here we propose a novel method of producing dense arrays of needle-like structures using magnetically shaped metal powder. Upon the application of a magnetic field, ferromagnetic powders are subjected to instabilities which give rise to the formation of typical arrays of spikes.

The project objectives were to manufacture a variety of emitters using the proposed novel method and to test them in a working ion thruster prototype, with the main aim to assess their performance and durability.

3. MAIN ACHIEVEMENTS AND FINDINGS

3.1. Emitter Manufacturing Results

About 40 emitters were manufactured using magnetically shaped metal powder, 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.

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 metal powder and magnetic fields, the emitter went through the next steps of sintering and wetting.

Figure 3-1 shows an example of emitter needle tips after sintering (left) and after wetting (right).

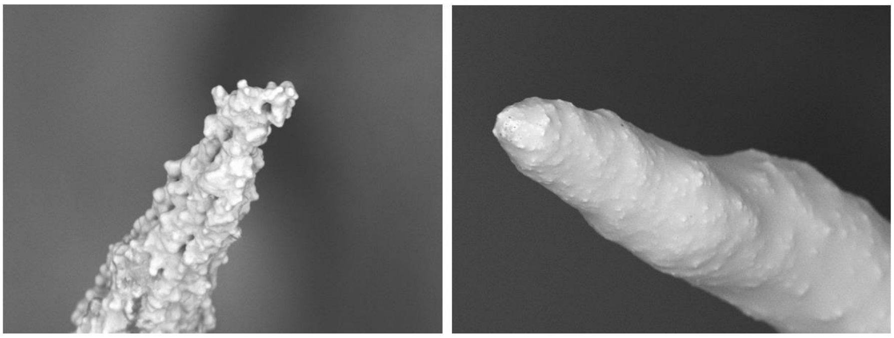

Figure 3-1. The tip of an emitter after sintering (left) and after wetting (right)

3.2. Thruster Prototype

The thruster prototype was designed to be a flexible testbed for evaluating the novel emitter. It has a simple, yet flexible design to allow testing different extractor and emitter designs. 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. The main design challenges were high voltage insulation and preventing propellant contamination of the insulators. This cylindrical thruster attaches to a vacuum flange mechanical interface for testing (Figure 3-2). Overall, the prototype enables investigation of the new emitter behavior and performance in a functional thruster.

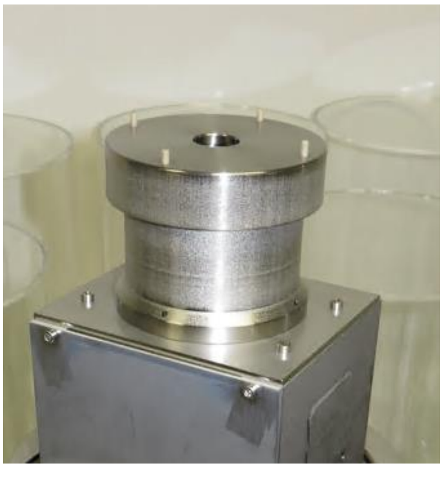

Figure 3-2. The assembled thruster prototype

3.3. Main Results of Performance Testing

A total of 21 performance tests were conducted on 19 different emitters, with 2 emitters tested twice.

The test was conducted in the LIFET 3 vacuum chamber at FOTEC premises (Figure 3-3 and Figure 3-4). High-voltage power supplies were employed to deliver the requisite power to the thruster, and a collector in the vacuum chamber was used to measure the emitted ionic current.

The test protocol consisted in voltage/current characterizations to probe the operation of the emitters at different power levels, and a 2-hour constant current phase, which allowed to observe the stability of the emission and to calculate the emitter mass efficiency.

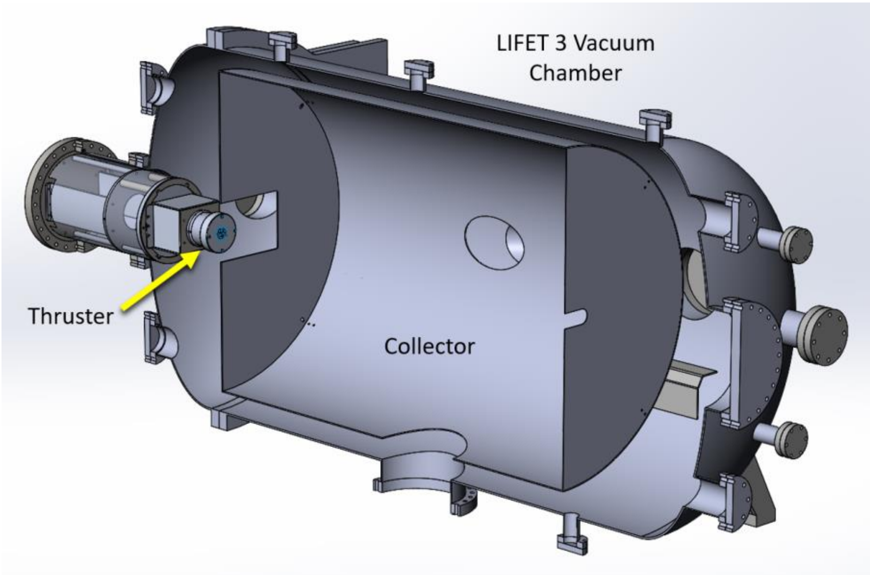

Figure 3-3. A 3D rendering of the thruster mounted on the LIFET3 vacuum chamber

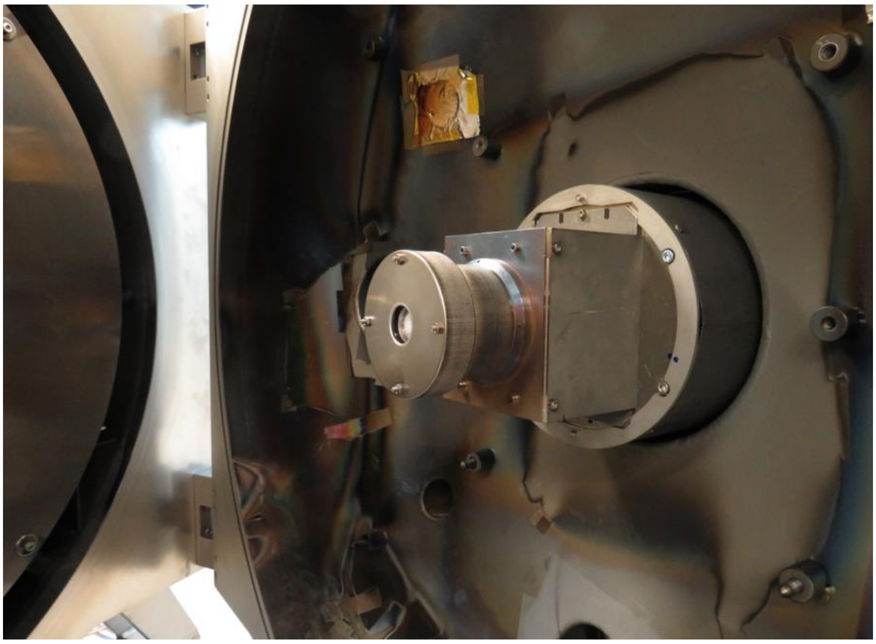

Figure 3-4. The thruster mounted on the vacuum chamber

Figure 3-5 shows the visual characteristics of emitters with different emission points distribution.

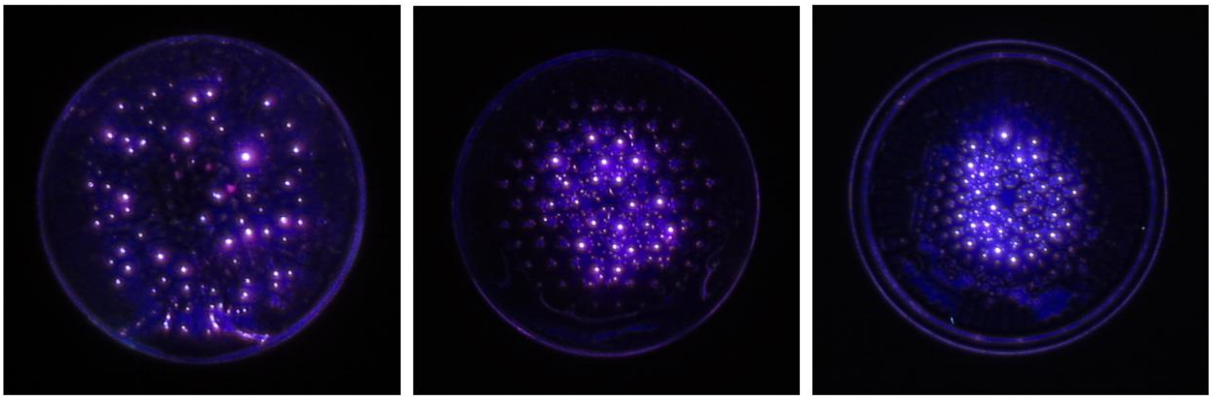

Figure 3-5. Visual characteristics of different firing emitters

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 to 400 µN was maintained during the constant current phase.

The measured power-to-thrust of the new thrusters 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.

The mass efficiency of the new thrusters was up to 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. To increase the mass efficiency to levels competitive with state-of-the-art FEEP thrusters, future work should focus on optimizing these parameters.

3.4. Main Results of Durability Testing

The purpose of the durability testing campaign was to evaluate the evolution of the emitter performance and possible related needle degradation over an extended period (100 hours).

While this notion has been extensively tested on tungsten-based crown emitters, the durability of other metal substrates has never been tested. It needs to be emphasized that the testing conditions were made even more challenging due to the utilization of EGaIn as the propellant, which is constituted by 75.5% of gallium: gallium is notably corrosive to many metals, especially at high temperatures.

The test setup was identical to the one used in the performance testing campaign.

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. 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 modifying the propellant tank, the last two emitters underwent complete 100-hour tests without interruption.

The main issue encountered during the tests was the accumulation of contaminants on the tip of the needles, which resulted in an increasing impedance over the course of the test. While initial concerns were that these contaminants resulted from the metal substrate dissolution into the propellant, EDX analysis showed that the main source of contamination was oxides, most probably gallium oxides, which are produced during the wetting procedure and are concentrating on the tip during the emission process. Figure 3-6 shows two tips from the same emitter, where the tip on the left was firing and the one on the right did not. Notice the different appearance of the tip, where the left one is smooth, thus indicating the presence of fresh propellant, while the right one is covered by rough concretions.

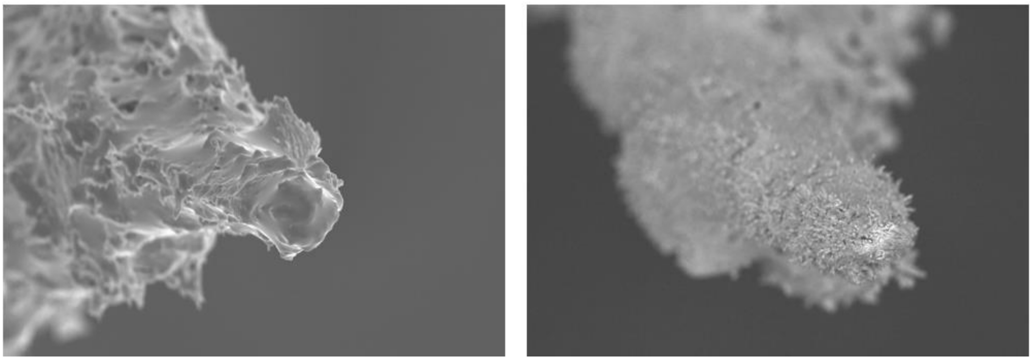

Figure 3-6. SEM Analysis of emitter tips after firing. At the end of the test, the tip of the left fired, while the one on right did not

3.5. Results Summary

- About 40 emitters have been successfully manufactured using magnetically shaped metal spikes, with different needle densities and array shapes
- A thruster prototype has been developed to allow the testing of the newly conceived emitters
- A performance testing campaign has assessed the operation of 19 emitters, revealing the potential and the limitations of the new emitters, and showing a performance envelope in part comparable with the state-of-the-art FEEP emitters
- A durability testing campaign involving four chosen emitters that had previously undergone performance testing, showed that the new emitters can operate for over 100 hours without experiencing significant degradation of the metal substrate
- The technology in its current state can already enable rapid prototyping of FEEP emitters, in particular high density needle arrays, though further refinements would expand its applicability for space missions. Specific improvements needed include reducing electron bombardment and oxide contamination, as well as increasing mass efficiency.