

Category	Baseline (Configured)			
		1 A – Customer (Configured)	Approval	
	1 R – Customer (Review)	Acceptance	X	
	1 I – Other (Information Only)			
Not Baseline (Unconfigured)	2 A – Customer (Not Configured)	Approval		
	2 R – Customer (Review)	Acceptance		
	2 I – Other (Information Only)			

Classification	Confidential	
	Proprietary	
	Non-Proprietary	X

Project No.: 2020-043

DDL No.: ES

WP: 5

MS: FR

EXECUTIVE SUMMARY

Magnetic Powder as Propellant in Electrostatic Thrusters

MPEP

Prepared: 15-02-2022	Approved PM: 17-02-2022
Name: Nembo Buldrini	Name: Laura Bettiol
Replaces Issue: --	
Released:	

Customer Approval/ Customer Acceptance	
Name: Eduard Bosch Borràs	
Organization: ESA	Date:
Signature:	

 FOTEC Research Subsidiary of — FH Wiener Neustadt —	EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

DOCUMENT CHANGE LOG

Iss.-Rev.	Date	Pages Affected	Reason for Change
01-00	17-02-2022	All	First release

DISTRIBUTION LIST

Internal

Name	Acronym	Copies	Purpose		
			<i>Approval</i>	<i>Acceptance</i>	<i>Info</i>
Laura Bettiol	LBe	1	X		
Bernhard Seifert	BSe	1			X

External

Name	Organization	Acronym	Copies	Purpose		
				<i>Approval</i>	<i>Acceptance</i>	<i>Info</i>
Eduard Bosch Borràs	ESA	EBo	1		X	
Leopold Summerer	ESA	LSu	1			X
Gian Lorenzo Casini	ESA	GCa	1			X
Moritz Fontaine	ESA	MFo	1			X

	EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

CONTENTS

1. SCOPE OF THE DOCUMENT.....	4
1.1. Applicable Documents.....	4
1.2. Reference Documents.....	4
1.3. Acronyms and Abbreviations.....	4
2. BACKGROUND AND OBJECTIVES	5
2.1. Background and working principle.....	5
2.2. Objectives of the project	6
3. MAIN ACHIEVEMENTS AND FINDINGS.....	6
3.1. Main results of tests in air.....	6
3.2. Main results of thruster parameter tests in small vacuum chamber.....	7
3.3. Main results of performance tests on thrust balance.....	9
3.4. Results summary	11

 FOTEC Research Subsidiary of – FH Wiener Neustadt –	EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

1. SCOPE OF THE DOCUMENT

This document is the Executive Summary of the MPEP project, performed under ESA contract no. 4000133242/20/NL/GLC (OSIP Open Channel Studies Evaluation Session 2020-02) by FOTEC Forschungs- und Technologietransfer GmbH, Austria.

The output of the MPEP project consists of the following technical reports:

- TN-1 Design Report
- TN-2 Propellant Characterization Report
- TN-3 Manufacturing Report
- TN-4-A and TN-4B Test Plan
- TN-5 Test Analysis and Roadmap

A compendium of the above technical reports is also available in the form of a Final Report (Doc. no. FTC2022-012-01-00). The Final Presentation will be held on February 24th, 2022, via telecon because of the Covid-19 pandemic, with ESA and FOTEC representatives.

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-TECSF-SOW-018347	Statement of Work – “OSIP Open Channel Studies Evaluation Session 2020-02 - Magnetic Powder as Propellant in Electrostatic Thrusters”	1.1	14.04.2020

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:

- [RD-1] Trottenberg, T., Kersten, H., & Neumann, H. (2008). Feasibility of electrostatic microparticle propulsion. *New Journal of Physics*, 10(6), 063012. <https://doi.org/10.1088/1367-2630/10/6/063012>
- [RD-2] Seifert, B., Reissner, A., Buldrini, N., Hörbe, T., Plesescu, F., Bilit, A., & Bosch Borrás, E. (2015). Verification of the FOTEC mu-N Thrust Balance at the ESA Propulsion Lab. Presented at the Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan.

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
MS	MileStone
RD	Reference Document
TBC	To Be Confirmed
TBD	To Be Defined
WP	Work Package

	EXECUTIVE SUMMARY	Doc. No.	FTC2022-013-01-00
	Contract no. 4000133242/20/NL/GLC 2020-043	Iss.-Rev.	01-00
		Date	17-02-2022

2. BACKGROUND AND OBJECTIVES

2.1. Background and working principle

The concept of electrostatic micro-particle propulsion was explored in previous studies by Trottenberg et al. (2008) [RD-1]. Advantages of such a propulsion concept would be, for example, high density propellant storage and the possibility to use propellant materials available in space, e.g. asteroid regolith (In-Situ Resource Utilisation). One of the particle acceleration methods proposed involves the use of sharp needles to electrically charge and accelerate small particles (100 nm – 1 μm). Trottenberg shows that specific impulses comparable to that of cold gas thrusters could be obtainable with sub-micron sized particles and acceleration voltages of 20 kV, while accelerating voltages of 200 kV should bring the exhaust speed in the realm of chemical propulsion systems.

The novelty of the approach proposed in this project consists of the use of a magnetic field to shape the propellant itself - for example, iron powder - into sharp spikes. Considering the schematic in Figure 2-1, a spike generation device provides a magnetic field to form the spikes. If the voltage applied between the spikes and an extractor electrode is high enough, particles are detaching from the tip of the spikes, because the magnetic force, which tends to keep the particles together, is there overcome by the pulling force produced by the electric field. As soon as the particle is detached from the bulk, the electric field will act on the electric charge of the particle, causing it to accelerate towards the extractor electrode. The acceleration is proportional to the charge retained by the particle: for this reason, it is convenient to have the propellant arranged into spikes, as the tips of the spikes would allow to transfer high charge amount to the particles due to the local high electric field density.

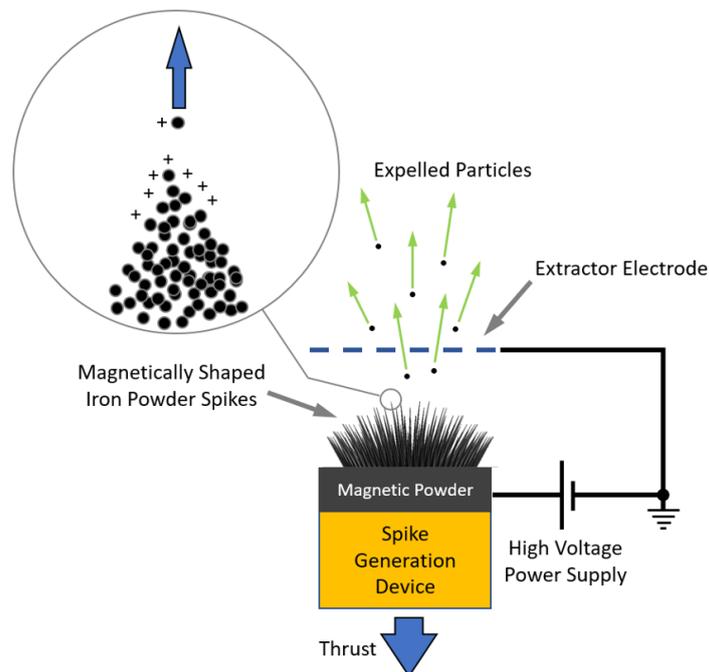


Figure 2-1. Thruster working principle

Once the particles fly past the extractor electrode, the electric field becomes negligible, and the particles are expelled at the speed acquired during the acceleration phase. The spike generation device acts on the propellant with vibrations and varying magnetic fields, so that new spikes are continuously being formed, thus leading to a continuous flow of particles being emitted, which generates a thrust in the opposite direction.

	EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

2.2. Project objectives

The main objectives of this project were to develop a thruster prototype based on magnetic powder electrostatic propulsion and to test it in vacuum with direct thrust measurements. The aim was to check the robustness of the concept and to measure and calculate important performance parameters such as thrust and specific impulse, to allow a comparison with other thruster technologies.

3. MAIN ACHIEVEMENTS AND FINDINGS

This project demonstrated for the first time the feasibility of electrostatic propulsion based on powder emission.

After selecting the most promising magnetic powders, the thruster prototype was designed, manufactured and tested. During the testing phase, several tests were done in three different campaigns:

1. In air, with the aim to understand the behavior of the spike generation devices and identify the most promising set of parameters for further testing in the vacuum chamber.
2. With the thruster in a small vacuum chamber, with high voltage applied to the emitter, in order to quantify the influence of the various parameters on the electrostatic emission of particles.
3. With the thruster in a larger vacuum chamber, to record the thrust produced by operating the thruster prototype on FOTEC's thrust balance [RD-2], and to calculate important figures like power to thrust ratio and specific impulse, at different operating points.

3.1. Main results of tests in air

The goal of this test campaign was to study the dynamic production of spikes delivered by the spike generation device, and to find the combinations of parameters which resulted in the most effective spike generation in terms of spike distribution, spike dimensions and ability to recreate new spikes when others get damaged.

The tests have been carried out without the extractor electrode, and without applying any voltage to the propellant. During these tests, it was observed how the spike generation process varied depending on the type and amount of propellant, and on the settings of the spike generation device.

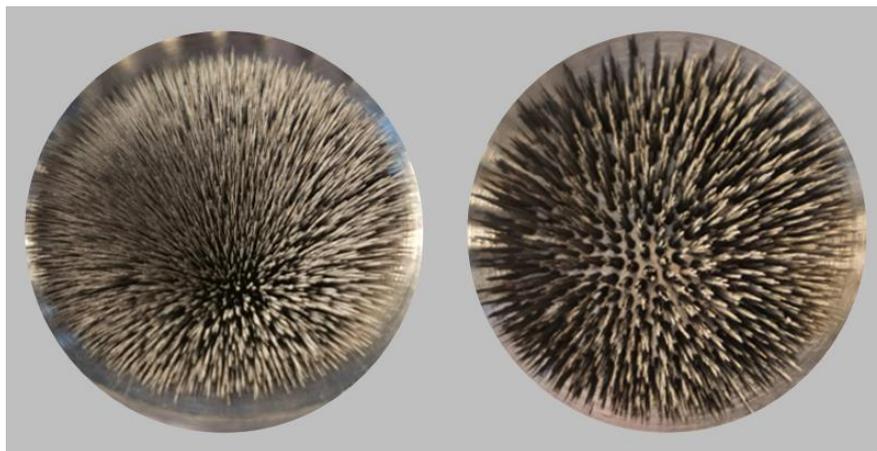


Figure 3-1. Spike patterns with different magnetic field strength acting on the powder

Figure 3-1, for example, shows the different spike patterns which arise upon the application of different magnetic field strengths on the magnetic powder. A higher magnetic field applied to the lump of propellant (left) causes the generation of finely subdivided sharp spikes, whereas a lower magnetic field strength (right) causes the spikes to collect into a smaller number of “tufts” with an overall lower sharpness.

	EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

On the other hand, an even higher magnetic field, especially when associated to a large amount of propellant, causes the disappearance of spikes starting from the border, as they are merging into structures similar to petals (Figure 3-2).



Figure 3-2. Spike pattern with high magnetic field and large amount of propellant

Different propellants also behaved differently upon the action of the magnetic field: an important finding was that the propellants with smaller particle size were the most difficult to reshape into spikes, due to the tendency of the powder to form agglomerates.

The thruster has been operated both in vertical mode (pointing upwards) and in horizontal mode (with the thruster axis parallel to ground), to check the influence of the gravity force on the spike generation process, which resulted negligible for most of the spike generation device settings. This was an important test result, as the thruster had to be operated in horizontal mode during the campaign on the thrust balance.

The test campaign resulted in the identification of the best spike generation device settings and best performing propellant types to be used in the following test campaigns.

3.2. Main results of thruster parameter tests in small vacuum chamber

The tests carried out in the small vacuum chamber gave the first demonstration of the possibility to emit iron powder electrostatically from the spikes created using a magnetic field, and to regulate such emission both acting on the voltage between the propellant and the extractor, and on the settings of the spike generation device.

The thruster prototype was coupled with a small collector (Figure 3-3), which collected the emitted powder and enabled the reading of the beam current.

The recorded collector currents were in the order of tens to hundreds of nA: this is a much lower value when compared to ion thrusters, but it makes sense in that the charge to mass ratio of macroscopic particles is order of magnitudes lower than the charge to mass ratio of ions.

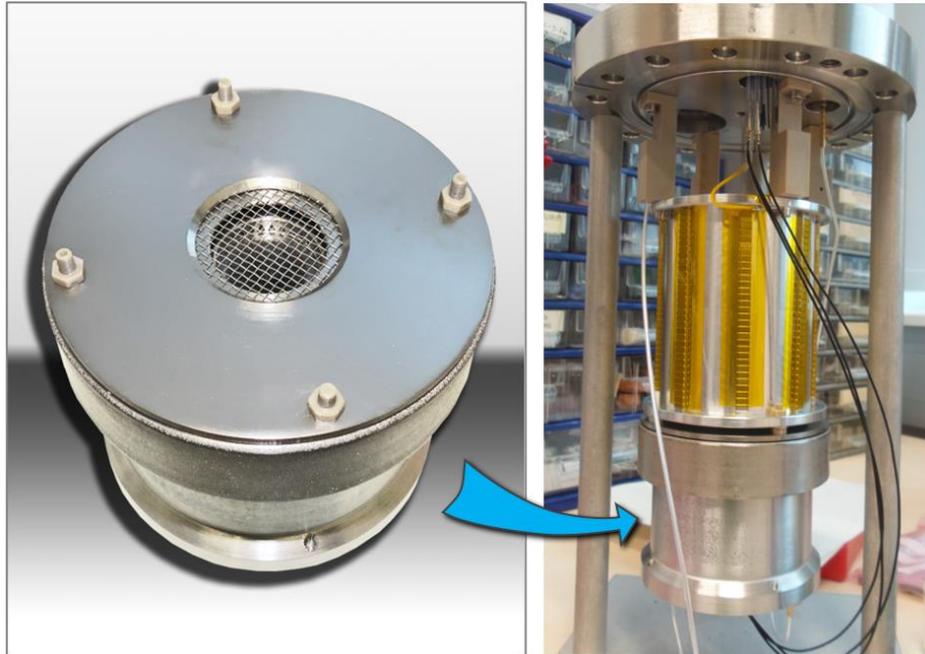


Figure 3-3. Left: Thruster prototype – extractor and extractor grid are recognizable on the top. Right: The Thruster assembled with the small collector and mounted on the vacuum chamber flange

Small magnets suitably distributed on the surface of the collector prevented the powder from falling back onto the thruster. Moreover, the freezing of the powder on the point of impact on the collector allowed to get an estimation of the beam divergence (Figure 3-4).



Figure 3-4. The deposition pattern on the collector when using the extractor with a grid (left) and without a grid (right)

Figure 3-5 shows the collector and the extractor current resulting from voltage sweeps at increasing peak voltages. The “Emitter Voltage” corresponds to the voltage applied to the propellant. It is interesting to point out that the gridded extractor allowed higher collector currents (which would translate in higher thrusts) for the same voltages, at the expenses of an increased extractor current (higher power losses).

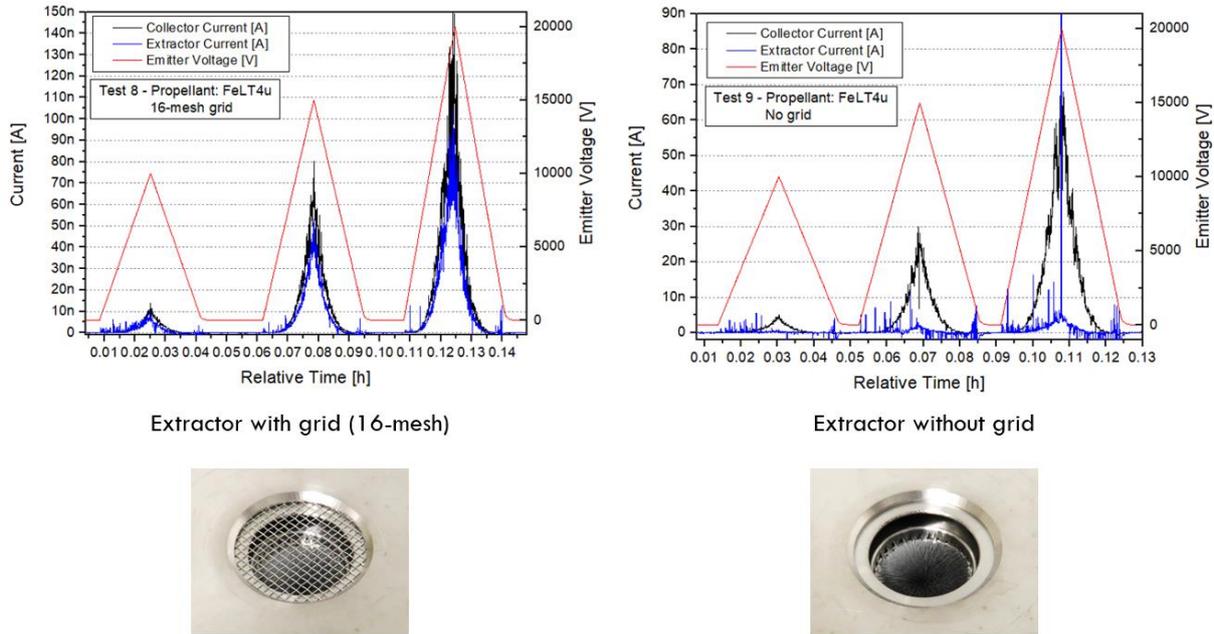


Figure 3-5. Collector and extractor current when using the extractor with a grid (left) and without a grid (right)

One test was carried out with negative voltage applied to the propellant, showing an amount of negative current reaching the collector comparable with the one recorded in the tests at positive voltage. Emitting negative particles is an interesting feat in that it could make the need for a neutralizer optional for this type of thruster: when the propellant voltage is regularly switched between positive and negative, the total emitted charge could be kept close to zero.

The ability of the spike generation device to regulate the particle emission was proven: sweeps of the device power, while keeping the emitter voltage constant, showed an increase of the collector current proportional to the device power.

Finally, the test campaign revealed that the thruster is robust with respect to the applied high voltage and with respect to contamination of internal surfaces. No sustained sparking nor strong contamination was observed for the duration of the entire campaign.

3.3. Main results of performance tests on thrust balance

The thrust measurements were carried out using the FOTEC μ N Thrust Balance. This is a horizontal force-feedback control device for measuring the thrust generated by a propulsion system, with a thrust range of 100 mN and a precision of 2 μ N.

The complete setup, comprising the balance, the thruster prototype, and the collector, is arranged in the vacuum chamber as shown in Figure 3-6.

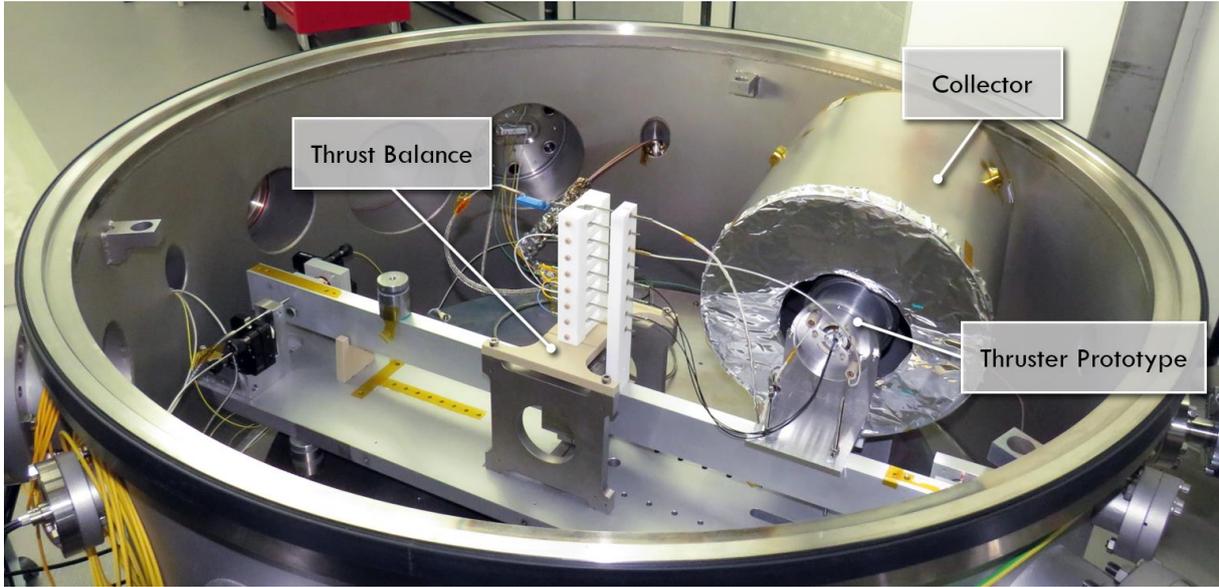


Figure 3-6. Thruster mounted on thrust balance for performance testing

A direct measurement of the thrust produced by the prototype enabled the direct calculation of the average speed of the emitted particles, by dividing the thrust integral over time (total impulse) by the expelled mass. The specific impulse results then from the multiplication of the exhaust speed by the standard gravity.

Using the average speed and the voltage, other interesting figures can be estimated, like the charge to mass ratio of the emitted particles, and their size.

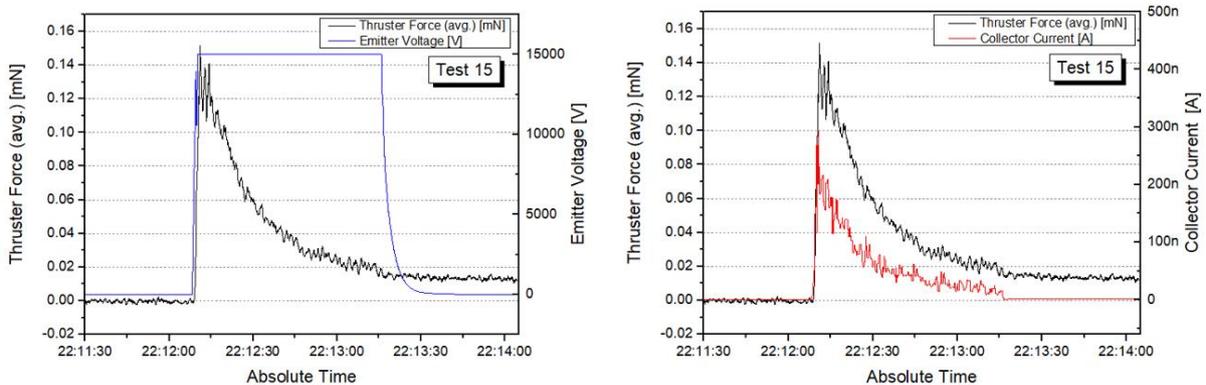


Figure 3-7. Typical thrust plot and associated thruster voltage and current

Figure 3-7 shows the typical thrust and collector current curve in relation to the applied voltage. The current and the thrust decay with time, even if the applied voltage is fixed: this is due to the depletion of propellant, which is loaded in limited amount at the top of the thruster. Future developments will include the design of a reservoir to increase the amount of propellant available, to allow longer stable thrust production.

The peak thrust measured during this campaign was 0.5 mN at 20 kV, using the extractor with the grid. While the use of the grid was useful to reach high thrust levels, the thrust to power ratio resulted lower than the one obtained with the non-gridded extractor: this comes to no surprise as a non-negligible fraction of current (and thus of power) is lost on the grid. Also, as expected, the thrust to power ratio decreases with the applied voltage; however, the overall thrust to power ratio was exceptionally high

	<p style="text-align: center;">EXECUTIVE SUMMARY Contract no. 4000133242/20/NL/GLC 2020-043</p>	Doc. No.	FTC2022-013-01-00
		Iss.-Rev.	01-00
		Date	17-02-2022

for an electric thruster, with values up to 3 orders of magnitude higher than values typical of ion thrusters. This is a direct consequence of the larger particle size, which results in a lower charge to mass ratio, and thus a lower current required.

The lower charge to mass ratio, on the other hand, translates in a lower particle final speed, which has been calculated from the measurements to be in the range between 15 and 30 m/s (depending on the accelerating voltage).

A key discovery of the research was that, in order to account for the actually measured charge to mass ratio, the average radius of the emitted particles has to be much larger – in every test – than the radius of the single particles which constitute the propellant. This means that most of the particles are emitted as agglomerates, with diameters ranging from 10 to 25 times the diameter of the single particles (depending on the propellant type). As, following relevant equations, the particle speed is inversely proportional to their radius, being able to emit single particles would translate in an improvement factor between 10 and 25 times.

Another important insight of the investigation, confirmed both theoretically and experimentally, was that the specific impulse does not show the dependency on the square root of the voltage typical for ion thrusters; instead, the increase is at least linear. This is explained by the fact that the voltage, in addition to be responsible of the particle acceleration, influences also the charge acquired by the particle, while in the ion thruster the charge does not depend on the voltage. This means that the type of engine here described can be scaled up more easily acting on the voltage to achieve higher values of specific impulse.

3.4. Results summary

The results demonstrate that the novel proposed method for electrostatic particle acceleration enables an easily throtttable thrust, with continuous and controlled ejection of electrostatically charged particles. The peak thrust was measured to be 0.5 mN applying the maximum tested voltage of 20 kV. The maximum thrust to power ratio was 50 mN/W, which is 3 orders of magnitude lower than more conventional ion thrusters.

However, the measured exhaust speed is much lower than expected, indicating that the particles are emitted in large agglomerates. It is expected that, using different powders and operating the thruster at higher voltages, the emitted particle size can be reduced and the specific impulse improved.