EXECUTIVE SUMMARY REPORT

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DOCUMENT CHANGES DETAILS

Issue	Date	Page	Description of Change	Comment
1.0	26/04/2023	All	New document created	
1.1	08/05/2023	6-8	Updated text	

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1. SCOPE AND PURPOSE

1.1 SCOPE

The Executive Summary Report (ESR) document presents the key aspects and findings of the de-risking phase of the BirdCage Electric Propulsion (BC-EP) system development. It presents the rationale for development of BC-EP propulsion system. Additionally, it briefly outlines the subsequent development activities to be carried out in the subsequent phases foreseen as of now.

1.2 PURPOSE

This document serves a project overview report briefly describing the project and its potential use cases. Additionally, it offers a summary on the finding s of the current contract and insights into the next phases.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1 APPLICABLE DOCUMENTS

In the text the following documents are applicable documents and referred to as [AD #].

[AD 1]	0_BC-EP_WP0_SRS_RR_070622_01	System Requirements Specification

2.2 EXTERNAL REFERENCE DOCUMENTS

In the text the following documents are the external reference documents and referred to as [RD #].

[RD 1] Romano, F., Chan, Y.-A., Herdrich, G., Traub, C., Fasoulas, S., Roberts, P., Smith, K., et al., "RF Helicon-based Inductive Plasma Thruster (IPT) Design for an Atmosphere-Breathing Electric Propulsion system (ABEP)." Acta Astronautica 176: 476-483 (2020).

[RD 2] Kempe, W., Sweers, "Business Plan for VLEO & LEO Enabling Electric Propulsion" Internal Report, Stellar Space Industries, Noordwijk (2020).

[RD 3] Businesswire, LEO Satellite (Small, Cube, Medium, Large Satellites) Markets - Global Forecast to 2026 - ResearchAndMarkets.com.
Available:https://www.businesswire.com/news/home/20220422005302/en/LEO-Satellite-Small-Cube-Medium-Large-Satellites-Markets---Global-Forecast-to-2026---ResearchAndMarkets.com

[RD 4] Euroconsult, "Satellites to be Built and Launched: A complete analysis & 10-year forecast of the satellite manufacturing & launch service markets", Free extract (2022) Available: https://digital-platform.euroconsult-ec.com/product/satellites-to-be-built-launched-new/

[RD 5] Sheetz, M., "Planet prepares to launch another line of imagery satellites to expand data-gathering operations"(2022) Available: https://www.cnbc.com/2022/09/21/planet-prepares-to-launch-hyperspectral-satellites-called-tanager.html

[RD 6] Satellogic, "Satellogic Announces Successful Expansion of Aleph-1 Constellation Following SpaceX Transporter-6 Mission Launch"(2023) Available: https://investors.satellogic.com/news-releases/news-release-details/satellogic-announces-successful-expansion-aleph-1-constellation

[RD 7] Warwick, M., "E-Space plans a constellation of 300,000 LEO satellites" (2022) Available: https://www.telecomtv.com/content/access-evolution/e-space-plans-a-constellation-of-300-000-leo-satellites-45686/

[RD 8] Spacewatch Europe, "NewSpace system house UNIO Enterprise forms to build European satellite constellations" (2022) Available: https://spacewatch.global/2022/09/newspace-system-house-unio-enterprise-forms-to-build-european-satellite-constellations/

[RD 9] Research and Markets, "Global Satellite Electric Propulsion Market Report: Increasing Demand for Large Constellations for Smaller Telecom Satellites in Low Earth Orbit Drives Growth" (2022) Available: https://www.globenewswire.com/news-release/2022/09/15/2516565/0/en/Satellite-Electric-Propulsion-Market-A-Global-and-Regional-Analysis-Focus-on-Mass-Class-Mission-Type-Mission-Application-Component-and-Country-Analysis-and-Forecast-2022-2032.html

3. DEFINITIONS AND ABBREVIATIONS

Abbreviation	Description
BB	BreadBoard
BC-EP	BirdCage Electric Propulsion
COTS	Commercial of-the-shelf
EP	Electric Propulsion
PPU	Power Processing Unit
FCU	Flow Control Unit
TH	Thruster Head

4. PROJECT SUMMARY

The project aims to develop an electrodeless propulsion system based on an advanced RF Helicon Plasma Thruster, as seen in Figure 1 for commercial small-sat platforms. Designed to obtain a thruster efficiency of more than 20%. The BC-EP system's present design also allows for future compatibility with an intake, transforming it into an Atmosphere-Breathing Electric Propulsion (ABEP) system and effectively removing/mitigating the requirement for onboard fuel. It should be noted that though the system is primarily designed for VLEO operations, thus possessing an inherent robustness and reliability, its application extends naturally to other orbits and mission scenarios. Small sats in all orbits require propulsion capabilities to improve performance and lifetime capabilities.

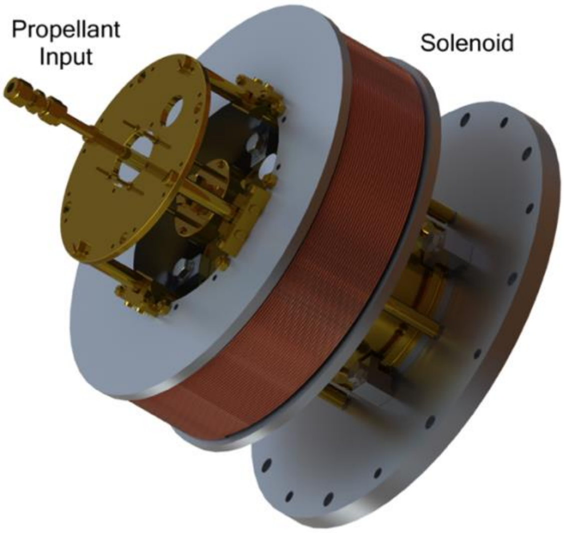

Figure 1: RF Helicon-based Plasma Thruster (IPT) Render [RD1]

The BC-EP is an advanced Helicon Plasma Thruster (HPT). While the conventional HPTs are severely limited by their efficiency, the BC-EP operates at resonance conditions, which enables higher thruster efficiencies by maximizing electrical efficiency and producing an optimized electromagnetic field configuration for plasma acceleration. The novel BC-EP thruster is at the forefront of the state-of-the-art EP development schemes due to its high efficiency, electrodeless nature, and low power needs. The thruster is compatible with any propellant due to its electrodeless design, including propellants with aggressive corrosive properties and varied density and composition. The employment of aggressive/low-grade propellants in EP systems such as Hall-effect and Ion thrusters, on the other hand, causes substantial component degradation over time.

The BC-EP is composed of three key subsystems: Thruster Head (TH), Power Processing Unit (PPU), and Flow Control Unit (FCU). The RF power is fed to an antenna that surrounds a discharge channel where the propellant is injected. Such an antenna emits electromagnetic waves that ionize the propellant while ensuring no direct contact with the plasma. Hence, the ejected plasma is quasi-neutral.

5. RATIONALE FOR BC-EP DEVELOPMENT

Decreasing the orbital altitude of a satellite leads to improved payload performance or similar payload performance at a reduced cost. However, high aerodynamic drag with an atomic oxygen-rich environment that the satellite must actively compensate for directly negates these benefits. As a result, VLEO (Very Low Earth Orbit), ranging in altitude up to 450 km, is a largely unexploited resource despite the fact that the lowest satellite mission costs are realized between 220-260 km [RD2] for a fixed resolution and coverage. Stellar Space Industries (SSI) in collaboration with the Institute of Space Systems, University Stuttgart (IRS) intends to develop a Commercial-off-the-Shelf (COTS) Electric Propulsion system for Smallsats addressing specifically these altitudes. The COTS Electric Propulsion (EP), referred to as Birdcage Electric Propulsion system (BC-EP), is an electrodeless thruster that exhausts a quasi-neutral plasma and is, therefore, able to operate in VLEO and above while mitigating performance degradation. This new method is in direct contrast to existing methods such as the Hall effect and Ion thrusters opening up VLEO orbits for utilization as mission duration can be increased.

Additionally, for satellites operating at other orbits, the BC-EP system offers increased lifetime, minimal degradation in performance over designed life along with accessibility to cheaper and greener propellants. This combination of enhanced performance combined with sustainability makes it a lucrative option for the rapidly growing and evolving 'Newspace' market. Over the last decade, the growth of this sector has exponentially increased leading to a number of start-ups in the field of Earth Observation (EO), Internet of things (IoT) and broadband services. This market segment focuses primarily on LEO and is projected to grow from USD 9.6 billion in 2021 to USD 19.8 billion by 2026, at a CAGR of 15.5 % [RD3]. Another trend that the Newspace market is experiencing is the emergence of satellite constellations and mega-constellations. It is estimated the 24468 Smallsats to be launched before 2031 of which large 69% will be part of a constellation [RD4]. Note that these constellations include Smallsat constellations currently under development such as Planet [RD5], Satellogic [RD6], E-Space [RD7], and the UNIO [RD8] and many more commercial players.

Evidently, these developments have led to strong demand for space propulsion technologies, specifically electric propulsion due to the various advantages it imparts in a mission, such as long lifetime, mass-saving capability, and cost-effectiveness. The global satellite electric propulsion market is estimated to reach $1,027.3 million in 2032 from $522.3 million in 2021, at a growth rate of 4.10% during the forecast period [RD9]. Even though not all Smallsats will be equipped with an EP system, the demand for EP systems will increase as a function of the number of Smallsats launched. SSI aims to be the supplier for the EP systems of the SmallSats of the future. Considering that the proposed BC-EP system is less complex: with no neutralizer and no electrodes in the plasma, the system reliability is expected to be higher than that of competing Hall Effect thrusters and Ion propulsion systems. The consortium will benefit from the proposed work plan as insight will be obtained into the scalability of the BC-EP system, thus allowing for the development of a product family of the low-cost low-power propulsion system for Smallsat applications.

6. MAIN ACHIEVEMENTS OF THE DE-RISKING PHASE

The aim of the de-risking phase of the project was to establish proof-of-concept with breadboard level models. The success of the phase was aimed to be demonstrated by achieving plasma ignition with SSI developed subsystems and IRS lab model. Prior to the test campaign, the team achieved several significant milestones in the design, simulation, and testing of two PPU architectures (See Figure 3), as well as the development of throttleable four valve concepts (See Figure 4). Note that in parallel a new TH has been designed and simulated.

During the testing phase, the team observed instabilities with the lab PPU (CESAR Generator water cooled connected to a dynamic matching network, which were successfully eliminated with SSI's Class E amplifier. As SSI developed four different throttleable valves, a wide range of performance options were considered before selection and integration of one of the systems within the test set up. The ignition test campaign was conducted from 11th -14th April, 2023 at IRS, Stuttgart. The testing campaign was considered completely successful as plasma ignition was obtained with both the SSI FCU and SSI PPU connected to the IRS IPT lab model as seen in **Error! Reference source not found.**.

The successful elimination of instabilities, integration of subsystems, and design of a new TH are all significant achievement that demonstrate the project's team expertise and dedication.

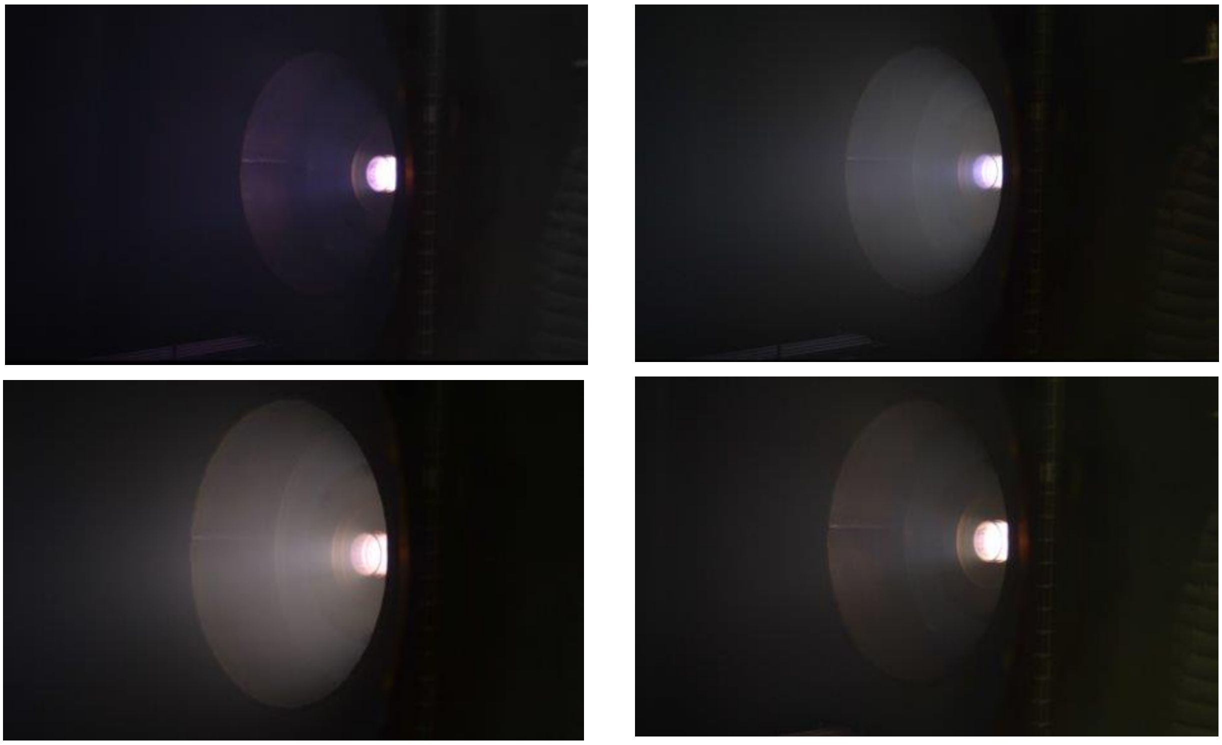

Figure 2: Plasma Ignition Campaign visual results at various power and flow conditions

Figure 3 BreadBoard of PPU used during test campaign.

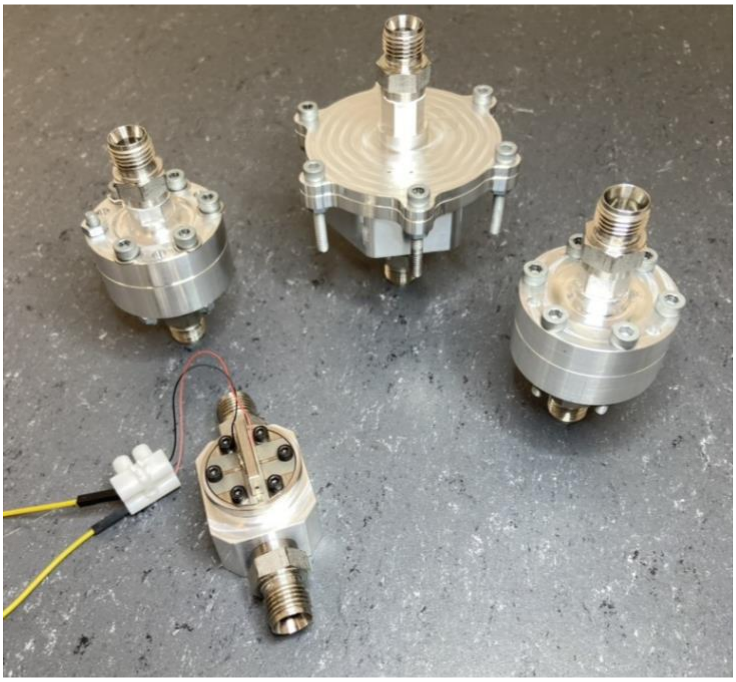

Figure 4 Four scalable fast response throttleable valves BreadBoards.

7. FUTURE DEVELOPMENT ACTIVITIES

Development Stage	Objective & expected outcome	Projected Timeline	Achievements and remarks
Development of BC-EP components and subassemblies	To develop critical processes, components/subassemblies to TRL-4 (component validation in laboratory environment)	KO + 18	BC-EP TRL 4 I_{sp}, thrust and efficiency of TH determined, throttleable PPU and FCU capability determined
Development of Engineering Model BC-EP	To design, manufacture and test a complete EM. Testing shall be "Design verification testing in relevant environment".	KO + 30	BC-EP TRL 5 BC-EP nominal performance verified
Relevant environment demonstration (limited low-cost market)	Launch and relevant "space" environment testing to validate survivability and compatibility.	KO + 34	Subsystems and structural integrity validated
Formal ground qualification	To build and test a complete system that can either go through a formal ground qualification (QM system) of a Proto Flight Model (PFM) for an in-orbit experiment.	KO + 48	BC-EP TRL 6 (Peer reviewed) and initial steps for TRL 7
Flight demonstration (limited low-cost market)	Fly a proto flight model of the complete BC-EP developed	~ 2027	BC-EP TRL 7

8. CONCLUSION

The de-risking phase of the project "Development of the Electrodeless Birdcage Electric Propulsion system (BC-EP)" was initiated in August 2022. The objectives outlined in the phase were successfully achieved and demonstrated. The de-risking phase has gone through the complete process of design, simulation and manufacturing demonstrating not just the functionality of the breadboard but also the commercial viability of the products developed. Additionally, each of the subsystems are designed with scalability and mass production as intrinsic characteristics to allow development of product family along with adaption as per market trends and demand. The follow-on phase will focus on determination and optimization of performance characteristics of every subsystem through iterative design and testing processes.