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Development of a Novel CubeSat-scale Air-breathing Electric Propulsion System

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Abstract

In recent years, air-breathing electric propulsion has emerged as a potential enabling technology for long-duration space missions in Very Low Earth Orbit (VLEO). The concept of air-breathing electric propulsion relies on an intake situated in front of the spacecraft to collect residual atmospheric particles, which are then used as propellant in an electric thruster to generate thrust and sustainably counteract satellite drag.

Celeste has developed an innovative plasma source, denominated VOLTA, based on novel technological solutions specifically tailored to enable the miniaturization of the system and to improve its efficiency at low chamber pressures, making it particularly suited for air-breathing operation.

This work presents an overview of the first ground test results of the VOLTA system. The experimental results show how the VOLTA technology is capable of operating in a wide range of pressure and mass flow conditions representative of real VLEO scenarios. Specifically, the system was successfully operated with argon and nitrogen neutral particle densities down to $< 10^{17}$ m^{-3} and mass flow rates in the 0.01-1 SCCM range, which are significantly lower than the typical operating conditions of electric thrusters. Relatively high plasma densities ($n_e > 5e16$ m^{-3}) were measured through Langmuir probes and a thrust comparable to the expected drag of full CubeSat platforms flying in VLEO was estimated from the extracted current. Ultimately, these results show great promise for the complete drag compensation of innovative CubeSat platforms with improved payload performance.

Furthermore, this work discusses the ongoing developments to adapt and verify in representative conditions the VOLTA technology as a CubeSat-scale integrated air-breathing thruster hosted in a 2U form factor, ensuring a rapid and cost-effective avenue for the deployment of the system in the real operative environment.

Key words: air-breathing electric propulsion, Very Low Earth Orbit, CubeSat, Electric Propulsion

1. Introduction

Operating space assets in Very Low Earth Orbit (VLEO), at an altitude below 400 km, offers significant advantages compared to missions at higher altitudes [1][2]. Proximity to Earth's surface enhances communication capabilities by reducing latency and transmission power while maintaining data link performance. For Earth observation, VLEO improves imaging conditions, enabling higher-resolution reconnaissance [3]. Additionally, the reduced altitude allows for enhanced payload performance [4][5], potentially minimizing satellite platform size. Operating in the upper atmosphere further reduces exposure to radiation [6]. Atmospheric drag at these altitudes also facilitates automatic re-entry and disposal, mitigating the challenge of space debris [7]. However, this drag must be compensated by a propulsion system to maintain orbit, directly linking the satellite's operational lifespan to its onboard propellant capacity. This creates stringent design challenges, reducing the commercial and scientific return of candidate VLEO missions. Consequently, satellites do not typically operate in VLEO, with notable exceptions such as GOCE [8][9] and SLATS [10].

The concept of air-breathing electric propulsion (ABEP) represents a potential enabling technology for sustained VLEO flight. The concept of air-breathing electric propulsion relies on an intake placed in front of the spacecraft to gather the same atmospheric particles that generate the drag. Utilizing electric power derived from solar arrays or batteries, an electric thruster then ionizes and accelerates these particles to generate thrust. By leveraging these limited yet renewable resources, it becomes possible to decouple the spacecraft's lifetime from the availability of propellant, enabling extended mission durations at low altitudes.

However, ABEP implementation involves complex trade-offs. The system's feasibility depends on the platform design, mission requirements, and energy transfer efficiency [11]. Below a critical altitude, excessive power is required to process the collected flow, while at higher altitudes, insufficient ionization of rarefied particles hinders thrust generation [12][13]. Several research efforts have examined satellite designs and ABEP feasibility for altitudes below 300 km, focusing on sun-synchronous orbits, spacecraft masses of 100–1000 kg, and on-board power availability in the 0.3–3 kW range [13]-[24].

Various propulsion technologies, including Hall thrusters, Inductive Plasma Thrusters, Helicon thrusters, and Gridded Ion Engines, are under investigation for ABEP applications, both from a numerical and experimental perspective. For a complete review of the literature on the topic refer to Ref. [25]. While these activities have improved the development status of ABEP systems, in all cases relevant performance metrics were either not measured or shown to be insufficient for compensating the drag levels of realistic VLEO mission scenarios. This is largely due to the difficulties in achieving sufficient ionization performance with the expected atomic oxygen/molecular nitrogen mixture as propellant, and with the comparatively low neutral density levels expected in the discharge chamber even after intake compression [25].

Ref. [26] presented a general system level analysis of air-breathing platforms, identifying the core requirements for drag compensation feasibility in terms of a full air-breathing system efficiency, defined as a combination of intake area fraction, intake collection efficiency, and thrust efficiency. This study has highlighted two core features of ABEP flight:

- *The requirement on the ABEP efficiency for full drag compensation becomes lower for higher VLEO altitudes.* Nevertheless, for higher orbits the atmospheric density will be lower, and the electric thruster will need to operate with lower chamber pressures. Notably, the efficiency of traditional electric thrusters is linked with propellant pressure since the propellant ionization efficiency is strongly dependent on the local neutral particle density, with some authors [13] even proposing a minimum neutral particle density required for operation at 10^{18} m^{-3}.
- *Small spacecraft do not imply a stricter requirement* on the atmosphere-breathing performance for concept feasibility and benefit more than larger spacecraft from the adoption of ABEP technology in the trade-off with stored propellant solutions.

Novel high-performance VLEO CubeSat systems thus represent an appealing candidate for the early adoption of air-breathing propulsion, benefiting from a cost-effective and rapid development cycle, while retaining the improved payload performance of very low altitude flight.

These missions can be enabled by a miniaturized air-breathing thruster capable of efficient ionization of the atmospheric flow at pressures and densities much lower than what is typically found in the discharge chamber of EP thrusters, thus capable of operating at relatively higher VLEO altitudes where the drag compensation feasibility requirement becomes achievable.

This work presents the development and the first experimental validation of Celeste's VOLTA plasma source which is a novel CubeSat-scale plasma device specifically designed for the effective ionization and acceleration of very low pressure gases, including atmospheric mixtures. The thruster operating principle has been experimentally verified in a vacuum chamber with argon and nitrogen mass flow rates and pressure levels representative of VLEO flight, showing great promise for operation as a CubeSat-scale air-breathing electric thruster.

In the following, Section 2 provides an overview of the VOLTA technology while Section 3 provides the details of the performed test campaign and core results. Section 4 details the ongoing development activities in the framework of the MISTRAL project and finally Section 5 summarizes the conclusions of this work.

2. The VOLTA Plasma Source

The VOLTA source is a miniaturized electrostatic plasma device developed by Celeste featuring novel technological solutions for the effective ionization of rarefied gases. Figure 1 depicts the first prototype of the VOLTA technology, now denominated VOLTA Development Model 1 (DM1).

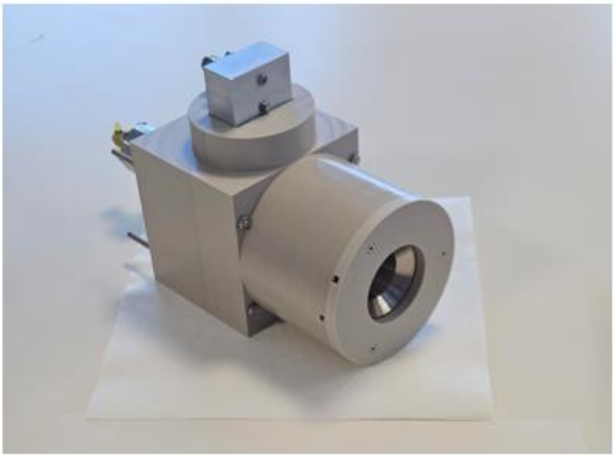

Figure 1. VOLTA Development Model 1 (DM1).

The core features of the VOLTA DM1 thruster are:

- A miniaturized envelope with a length < 150 mm and a frontal envelope < 100×100 mm (excluding the top connector).
- Effective ionization through electron cyclotron resonance (ECR) power deposition in the plasma.
- A novel magnetic field topology to support the ionization process
- An acceleration scheme based on high voltage electrostatic grids to extract and accelerate the ions.
- Oxidation resistant materials to ensure compatibility with aggressive propellant species such as atomic oxygen.

This first prototype features a classical pipe-fed gas injection through a DC breaker in the discharge chamber. While not fully representative of air-breathing particle collection, this setup allowed to test the operating envelope of the device through modulating the mass flow and estimating the chamber pressure through DSMC simulations.

3. VOLTA DM1 Ground Validation

3.1. Test overview

In September 2024, the VOLTA DM1 was tested in the LiVTF-2 vacuum facility at Aerospazio Tecnologie to validate the operating principle and envelope of the system. The vacuum chamber pumping capability was sufficient to maintain the background pressure level below 10^{-6} mbar in all tested operating conditions.

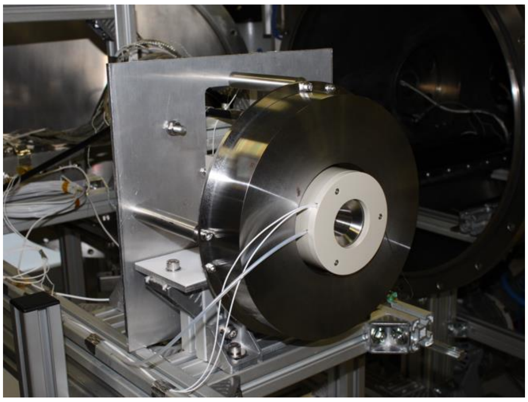

Figure 2. VOLTA DM1 installed in the vacuum chamber (including surrounding GSE).

As shown in Figure 2, the thruster was installed on a mechanical support structure and a large GSE coil was used to alter the magnetic field during testing. In this test, the gas was directly injected in the discharge chamber but by lowering the mass flow it was possible to verify plasma ignition at representative pressure levels.

The test was divided in two phases:

- **Phase 1:** the ion optics were substituted with a plate of similar transparency equipped with three Langmuir probes for the evaluation of the plasma properties of the discharge with pure nitrogen (N_2) and argon (Ar) propellants.
- **Phase 2:** using the ion optics for plasma acceleration to measure the extracted current and estimate the generated thrust. Only argon was used in this phase due to constraints imposed by the test facility.

In both phases, the thruster was operated over a wide range of mass flow rates (0.01 - 1 SCCM) and power levels (0.1 - 25 W), spanning several orders of magnitudes.

Remarkably, plasma ignition was always achieved, in all phases and for every combination of propellant, power, and mass flow rate. To estimate the pressure conditions in the ionization chamber during testing we performed a series of DSMC simulation via OpenFOAM, importing the real thruster geometry. At the lowest set points the neutral density in the discharge chamber was estimated to be in the $10^{16} - 10^{17} m^{-3}$ range, which is compatible with passively compressed high VLEO (> 300km) [26][27] atmospheric properties and almost two orders of magnitude lower than what is typically set as the minimum density for EP thrusters' operation [13].

3.2. Langmuir probe test results

In the first phase of the test the ion optics were substituted with a GSE diagnostic plate featuring three Langmuir probes, flush with the extraction plate, and a set of holes to present a similar transparency to the neutral gas flow as the real set of grids. This setup allowed for the investigation of the core plasma properties of the generated N_2 and Ar plasma and to discern their distribution over the extraction plane. Argon was selected as a simulant to atomic oxygen to evaluate ionization performance due to the similarity in terms of ionization collision cross section and energies [28].

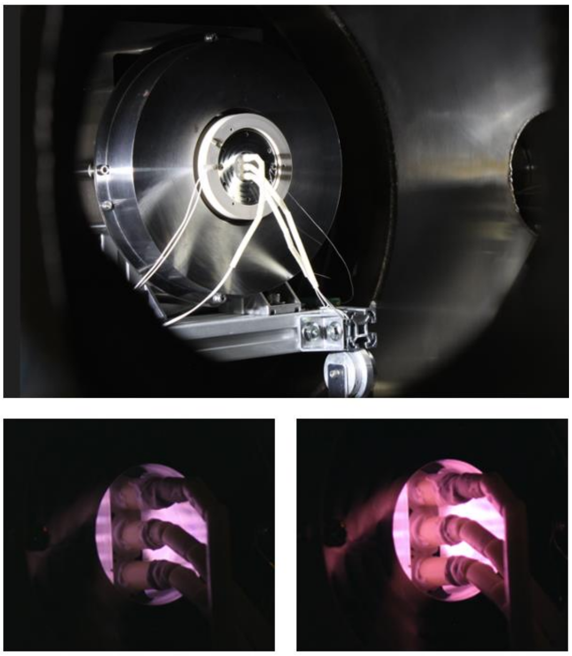

Figure 3. (top) Test item with Langmuir plate installed; Langmuir plate during operation with Argon (bottom left) and nitrogen (bottom right).

The Langmuir probes were biased over a sufficiently large range of voltages to resolve all plasma features, and the resulting I-V curves were processed according to the classical planar probe theory (see e.g. [29]) to extract the plasma density and electron temperature at each operating condition. Only information on the forward MW power at the thruster interface was gathered in this first test. Future efforts will focus on the measurements of the reflected power and on the optimization of the impedance matching of the line when the plasma is generated.

Figure 4 reports the plasma density measured by the central Langmuir probe versus nitrogen mass flow and forward MW power at the thruster interface on a subset of N_2 operating conditions. As shown in the figure, significant plasma density (> 5e16 m^{-3}) was obtained even at very low nitrogen flow rates, down to 0.01 SCCM, and thus neutral densities, highlighting the effectiveness of the system in ionizing very low pressure gasses. The obtained density significantly increases with forward MW power at the interface while it is less sensitive to variations in the mass flow rate, underlying the robustness of the system to variations in upstream conditions. The measured electron temperature ranged between 5 and 10 eV over the investigated operating envelope.

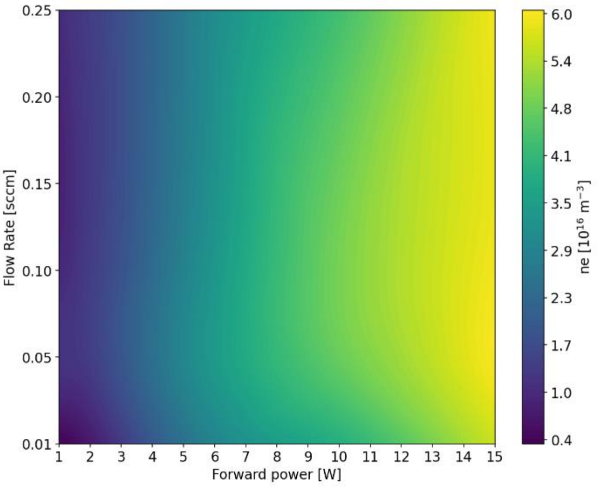

Figure 4. Plasma density measured by the central Langmuir probe in phase 1 of the VOLTA DM1 test versus nitrogen mass flow rate and forward power at the MW interface.

3.3. Firing test results

In phase 2 of the test, the VOLTA DM1 was characterized with the accelerating grids and argon propellant as shown in Figure 5. The accelerating voltage was varied between 250 V and 3000 V for an ion focusing through the grids up to 95% depending on the operating condition. Due to the absence of a thrust balance during the test, the thrust could only be estimated from the extracted current. Assuming the presence of solely singly charged argon ions, this preliminary estimate places the generated thrust in the range of 20 to 115 µN., for 0.01 – 0.1 SCCM of argon, and a specific impulse up to 10.000 s. Although approximate, these results show promise as they are in the expected drag range of full CubeSat platforms flying in the 250-300 km VLEO range [26], where the expected atmospheric pressure (following passive intake compression) and mass flow conditions fall in the range of the tested VOLTA operating envelope.

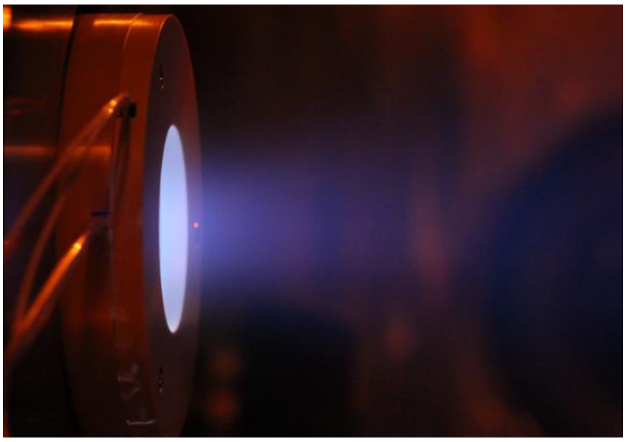

Figure 5. Side view of the VOLTA DM1 phase 2 test, including argon ions acceleration through the ion optics.

4. Towards a CubeSat-scale air-breathing electric propulsion system

Following the test results gathered on the DM1, the development of the VOLTA technology is ongoing in the framework of the MISTRAL project, in collaboration with the Sant’Anna School of Advanced Studies.

MISTRAL (Miniaturized Innovative Space Thruster for operation with Rarefied Air in Low orbit) is an ESA-funded project in the Discovery framework with the core objective of developing and ground testing a CubeSat scale air-breathing thruster.

This is further articulated in three sub-objectives (SOs)

SO1: the derivation of the main propulsion requirements for VLEO nanosatellites,

SO2: the implementation and verification of novel thruster design solutions for very low pressure, high-efficiency air discharges, and

SO3: the assessment of the EP performance envelope at miniaturized scale with air propellant.

The project is leveraging on Celeste's VOLTA miniaturized plasma source design and experimental data on low pressure argon and nitrogen operation to adapt it as a high efficiency full air-breathing electric propulsion system in a 2U CubeSat envelope. This new device iteration, denominated VOLTA DM2, will feature (i) a passive intake for collection and compression of the atmospheric flow; (ii) an optimized functional design implementing the lesson learned from the DM1 tests; (iii) a dry neutralization system; and (iv) a mechanical design and interfaces ready for integration in standard CubeSat structures.

In December 2024 the VOLTA thruster DM2 has successfully completed the project’s Preliminary Design Review milestone and is currently under manufacturing.

In the next step of the MISTRAL project the thruster will be tested in Sant'Anna School's BREATHE vacuum facility (see Figure 6): a two-volumes test chamber specifically designed for the ground validation of ABEP systems in a representative environment. For additional details on the test strategy see Ref. [30]

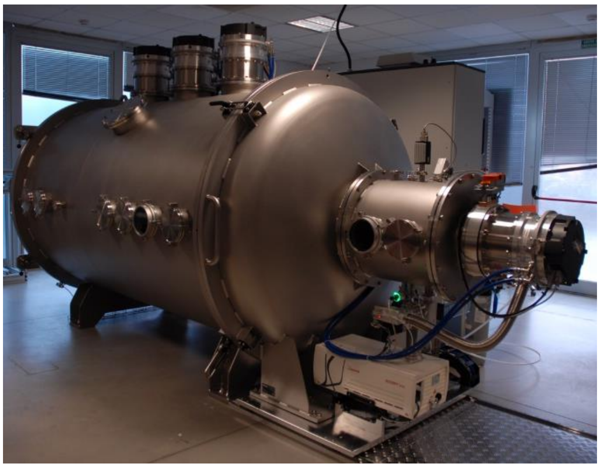

Figure 6. BREATHE Vacuum Facility at the Sant’Anna School of Advanced Studies.

5. Conclusions

This work has presented the first ground test results of a novel plasma device under development in Celeste, denominated VOLTA. This miniaturized electrostatic plasma technology is specifically designed to operate with extremely rarefied gases while maintaining good ionization performance and is uniquely suited for operation as a CubeSat-scale air-breathing electric propulsion system.

The first development model of the VOLTA technology, the DM1, was extensively tested with argon and nitrogen propellants by measuring both the plasma properties in the discharge chamber through Langmuir probes and the acceleration performance through a set of ion optics.

The results confirm the capabilities of the thruster of generating relatively dense plasmas (n_e > 5e16 m^{-3}) even with very low mass flow rates (0.01 – 1 SCCM) and neutral densities (down to n_n < 1e17 m^{-3}), much lower than what is typically found in the discharge chamber of electric propulsion thrusters. These conditions are expected in real ABEP VLEO scenarios following passive intake compression at relatively high VLEO altitudes > 250km, where the ABEP feasibility requirement for drag compensation becomes lower and more easily achieved.

The thruster performance could only be estimated from the extracted current, but this first estimation puts the produced thrust in the expected drag range of full CubeSat platforms flying in the 250-300 km VLEO range.

The VOLTA technology is now undergoing a second design iteration in the framework of the ESA-funded MISTRAL project, in collaboration with the Sant'Anna School of Advanced Studies. The DM2 features the intake collection system and a mechanical design compatible with standard CubeSat structures. The system has completed PDR and is now under manufacturing, to be then verified in the Sant'Anna School vacuum facility in representative conditions for air-breathing operation.

The presented results show great promise towards full air-breathing drag compensation of CubeSat platforms through the utilization of the novel VOLTA technology. The adoption of CubeSats will also ensure a rapid and cost-effective avenue for the following In-orbit experiment of the system and for the early adoption of the validated technology

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