

# The VOLTA thruster: development and ground demonstration of a novel CubeSat- scale air-breathing electric propulsion system

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**Abstract:** air-breathing electric propulsion represents a potential enabling technology for long-duration missions in Very Low Earth Orbit. The VOLTA thruster, developed by Celeste, introduces novel design solutions aimed at system miniaturization and efficient operation under low chamber pressures, making it particularly suited for air-breathing applications.

This work presents the development and testing of the VOLTA thruster across two design iterations, Development Models 1 (DM1) and 2 (DM2). Experimental campaigns demonstrate stable operation over a broad range of pressure and mass flow conditions representative of VLEO environments. In particular, the system has been successfully operated with Ar, N<sub>2</sub>, and N<sub>2</sub>/O<sub>2</sub> mixtures at neutral particle densities down to 10<sup>17</sup> m<sup>-3</sup> and flow rates between 0.01 and 1 SCCM, achieving comparatively dense plasmas, as measured via Langmuir probes.

The DM2 features a 2U envelope, CubeSat interfaces, a passive diffuse intake and dry neutralizers. Ongoing tests are exploring the operation of the thruster with atmospheric propellant in both pipe-fed and air-breathing configuration, where the injected gas is allowed to flow back through the intake ducts rather than going through the thruster, as in the real operative scenario. Thrust levels estimated from the extracted current are comparable to the expected drag of full CubeSat platforms, showing great promise for the complete drag compensation of innovative CubeSat platforms with improved payload performance.

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## I. 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<sup>1,2</sup>. 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<sup>3</sup>. Additionally, the reduced altitude allows for enhanced payload performance<sup>4,5</sup>, potentially minimizing satellite platform size. Operating in the upper atmosphere further reduces exposure to radiation<sup>6</sup>. Atmospheric drag at these altitudes also facilitates automatic re-entry and disposal, mitigating the challenge of space debris<sup>7</sup>. 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<sup>8,9</sup> and SLATS<sup>10</sup>.

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<sup>11</sup>. 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<sup>12,13</sup>. 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<sup>13-24</sup>.

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<sup>25</sup>.

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<sup>13</sup> even proposing a minimum neutral particle density required for operation at  $10^{18} \text{ m}^{-3}$ .
- *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 history and two experimental campaigns performed on the first (DM1) and second (DM2) development models of Celeste's VOLTA technology 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 on the DM1 in a vacuum chamber with pipe-fed argon and nitrogen mass flow rates and pressure levels representative of VLEO flight. The second thruster iteration, the DM2, features fully representative rarefied intake, neutralizers, and CubeSat interfaces and has been tested in both pipe-fed and air-breathing configurations with Argon and N<sub>2</sub>/O<sub>2</sub> mixtures, showing great promise for operation as a CubeSat-scale air-breathing electric thruster

In the following, Section II provides an overview of the VOLTA technology while Section III provides the details of the performed test campaigns and core results. Finally, Section IV summarizes the conclusions and the way forward.

## II. The VOLTA thruster



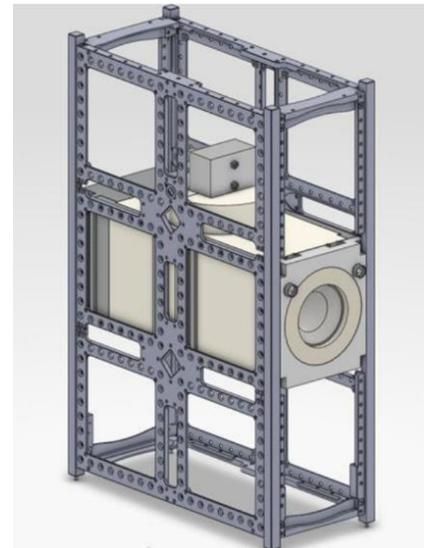
**Figure 1. (left) VOLTA Development Model 1 (DM1). (right) VOLTA Development Model 2 (DM2) isometric view and rear passive intake**

The VOLTA thruster is a miniaturized electrostatic plasma device developed by Celeste featuring novel technological solutions for the effective ionization of rarefied gases. Figure 1(left) depicts the first prototype of the VOLTA technology, denominated 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, which currently serves as the interface with the laboratory transmission line).
- 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. As it will be described in section IIIA, this setup allowed to test the operating envelope of the device through modulating the mass flow and estimating the chamber pressure through DSMC simulations.



**Figure 2. VOLTA DM2 integrated in a 6U CubeSat structure.**



In the framework of the ESA project MISTRAL<sup>27</sup>, a second iteration of the device was developed. As depicted in Figure 1(right) and Figure 2, the VOLTA DM2 features a 2U CubeSat envelope and mechanical interfaces compatible with standard CubeSat structures. From a functional perspective, the DM2 was updated with (i) a CubeSat-compatible passive intake designed and integrated with the system under the conservative assumption of fully diffuse gas-surface interaction; (ii) an improved ionization chamber and ion optics design optimized for air-plasma operation; (iii) a set of oxidation resistant dry neutralizers, introduced in the assembly to ensure plume neutralization during space operation.

The DM2 is compatible with both pipe-fed (through a GSE adapter) and air-breathing operation and represents the first fully functional Cubesat-scale air-breathing electric propulsion thruster. As described in section IIIB, the device is currently undergoing an extensive test campaign to demonstrate the full system functionality and to gauge the performance envelope in real VLEO air-breathing mission scenarios.

### III. Validation tests

#### A. DM1 tests – proof of concept

In September 2024, the VOLTA DM1 was tested in the LiVTF-2 vacuum facility at Aerospazio Tecnologie to validate the operating principle 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.

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 into 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. Only argon was used in this phase due to constraints imposed by the test facility.

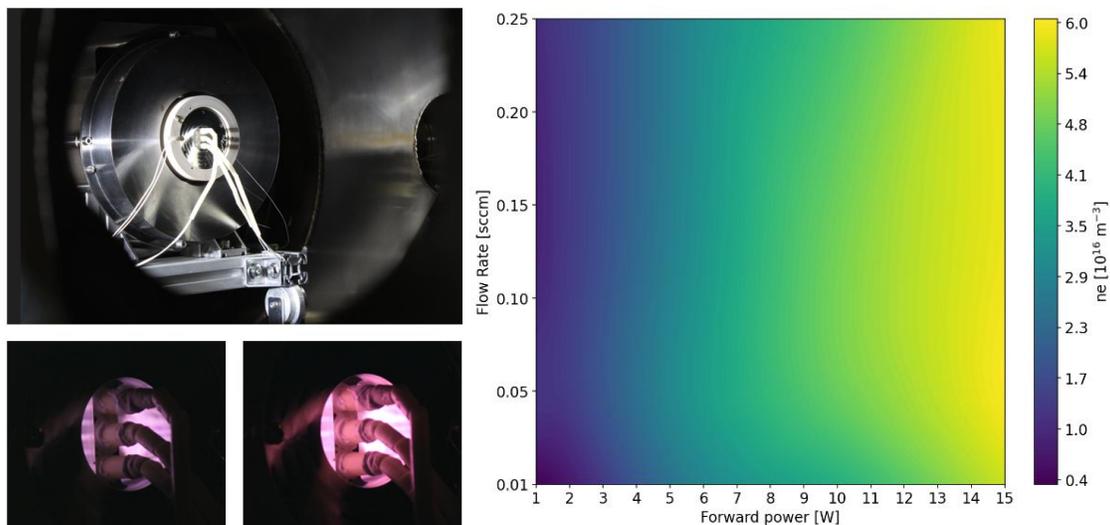


Figure 3. (left) VOLTA DM1 (including surrounding GSE coil) with Langmuir plate installed, Langmuir plate during operation with argon and nitrogen. Plasma density measured by the central Langmuir probe in phase 1 of the VOLTA DM1 test versus nitrogen mass flow rate and forward power at the MW interface.

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  $10^{16} - 10^{17} \text{ m}^{-3}$  range, which is compatible with passively compressed high VLEO ( $> 300\text{km}$ )<sup>26,28</sup> atmospheric properties and almost two orders of magnitude lower than what is typically set as the minimum density for EP thrusters' operation<sup>13</sup>.

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, see Figure 3(left). This setup allowed for the investigation of the core plasma properties of the generated  $\text{N}_2$  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<sup>29</sup>.

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. Ref. 30) 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 test.

Figure 3(right) 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  $\text{N}_2$  operating conditions. As shown in the figure, significant plasma density ( $> 5 \times 10^{16} \text{ m}^{-3}$ ) 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 gases. 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.

In phase 2 of the test, the VOLTA DM1 was characterized with the accelerating grids and argon propellant as shown in Figure 4. 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.

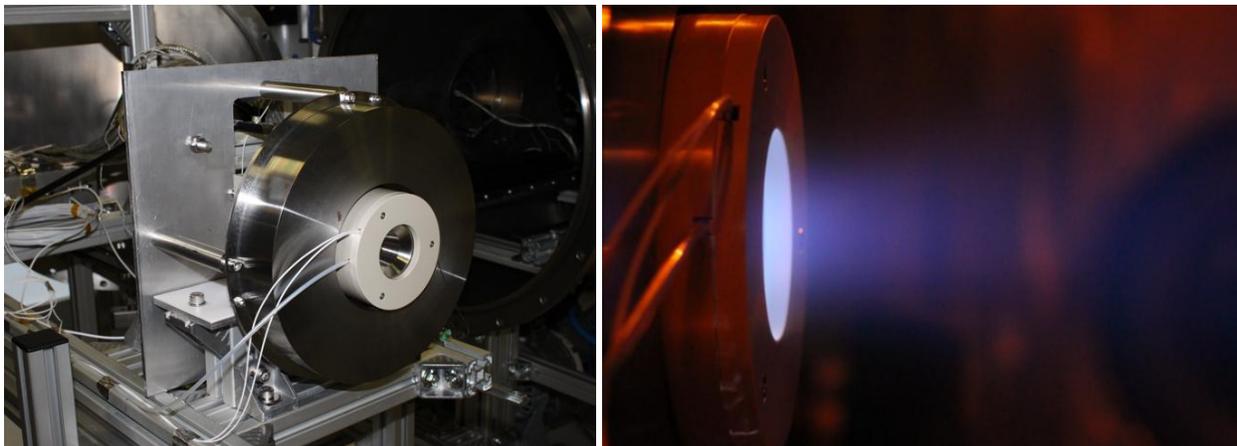


Figure 4. (left) VOLTA DM1 with ion optics installed in the vacuum chamber (including surrounding GSE coil). (right) Side view of the VOLTA DM1 phase 2 test, including argon ions acceleration through the ion optics.

## B. DM2 tests – functional demonstration

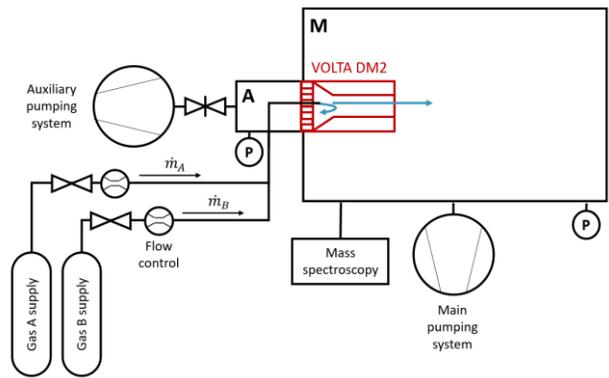
Based on the successful proof of concept on the DM1, the VOLTA DM2 has been developed and is currently undergoing extensive testing in the BREATHE Vacuum Facility, Figure 5(left). This novel vacuum chamber, installed at the Institute of Mechanical Intelligence of the Sant'Anna School of Advanced Studies, features two vessels with



independent pumping systems and is specifically designed for on-ground testing of air-breathing electric propulsion systems<sup>31</sup>.

The DM2 test is divided in two phases:

- **Pipe-fed:** where the intake honeycomb is substituted with a GSE adapter for pipe-feeding argon and an 80%N<sub>2</sub>/20%O<sub>2</sub> air mixture, exploring the full operating envelope of the thruster.
- **Air-breathing:** where the full system, including intake honeycomb, is integrated and the required mass flow rate of 80%N<sub>2</sub>/20%O<sub>2</sub> air mixture is injected downstream of the honeycomb ducts but is allowed to escape back from the intake rather than going through the thruster. By injecting the mass flow rate expected to reach the intake in orbit, this test strategy allows us to simulate accurately the operating conditions expected during real ABEP operation, see Figure 5(right). This includes, most importantly, representative levels of neutral pressure in the discharge chamber for representative levels of mass flow rate, which are a critical feature for the ignition and operation of electric propulsion thrusters.

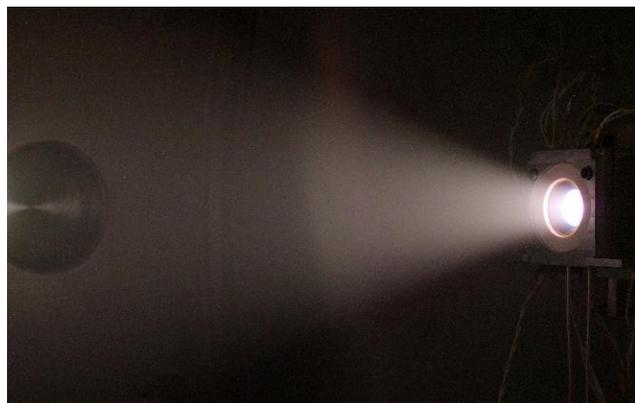


**Figure 5. (left) BREATHE Vacuum Facility at the Sant’Anna School of Advanced Studies. (right) Schematic representation of the DM2 ABEP test in the BREATHE Vacuum Facility.**

The DM2 was tested over a wide range of input conditions, see Figure 6, with mass flow rates of Ar and 80%N<sub>2</sub>/20%O<sub>2</sub> air mixture ranging from 0.01 to 1 sccm, with voltages up to 5000V and forward microwave power up to 13 W, with the operating envelope at higher power and voltage levels still to be explored.

The thruster has routinely confirmed its flexibility in operating over multiple orders of magnitudes of the input parameters, also achieving thermal steady state, including operation at nominal conditions of the dry filament neutralizer. Thus far, the DM2 thruster has cumulated several tens of hours of firing with atmospheric mixtures, with no sign of degradation.

Due to the absence of a thrust balance during the test, the thrust could only be estimated from the extracted current, with corresponding strong uncertainties on the composition of the plume with air propellant. Nevertheless, this preliminary estimate places the generated thrust with air propellant in the range of 20 to 200  $\mu$ N, achieving specific impulses greater than 10,000 s, with higher thrust levels achievable by extending the characterization to higher power levels. 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<sup>26</sup>, where the expected atmospheric pressure (following passive intake compression) and mass flow conditions fall in the range of the tested VOLTA operating envelope.



**Figure 6. VOLTA DM2 firing with 1 sccm of 80%N<sub>2</sub>/20%O<sub>2</sub> air mixture, 5 W of forward power, and 3000 V of acceleration voltage.**



## IV. Conclusion

Air-breathing electric propulsion represents an enabling technology for sustained missions in Very Low Earth Orbits. Nevertheless, achieving sufficient gas ionization in electric thrusters with the required very rarefied atmospheric mixtures is a challenge, as well as performing representative on-ground testing of air-breathing thruster prototypes.

This work has presented the history, status, and ongoing test campaigns of the VOLTA thruster, developed by Celeste. This CubeSat-scale novel air-breathing electric propulsion system is specifically designed for operation with very low-density propellant and has undergone two design iterations. Following the DM1 successful proof of concept, the DM2 now features a fully integrated ABEP thruster with a 2U envelope, CubeSat interfaces, a passive diffuse intake and dry neutralizers. The thruster is undergoing extensive testing in the BREATHE vacuum facility of the Sant'Anna School in the framework of the ESA MISTRAL project. The test is exploring the operation of the thruster in both pipe-fed and air-breathing configuration, where the injected gas is allowed to flow back through the intake ducts rather than going through the thruster, as in the real operative scenario.

Preliminary results confirm the capabilities of the VOLTA thruster of operating stably with the atmospheric propellant mass flows and pressures expected during VLEO flight. The estimated thrust levels indicate strong potential for enabling full drag compensation of CubeSat platforms operating in the 250–300 km VLEO regime.

Upon completion of the planned test campaigns, the next iteration of the VOLTA thruster will include an integrated Power Processing Unit, with the goal of moving towards a CubeSat scale in-orbit demonstration of the technology.

## Acknowledgments

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