CONCEPT DEVELOPMENT OF A CATHODELESS INDUCTIVELY-COUPLED GRIDDED ION ENGINE FOR VERY LOW EARTH ORBIT ATMOSPHERE-BREATHING PROPULSION

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ABSTRACT:

Atmosphere-breathing electric propulsion (ABEP) is a key enabling technology for sustained operations in very low Earth orbit (VLEO), where continuous drag compensation is required. System-level constraints imposed by limited mass flow, variable atmospheric composition, and power–drag coupling severely restrict the range of viable propulsion technologies. Previous assessments have identified gridded ion engines (GIEs) as the only class capable of meeting the required exhaust velocity and efficiency under realistic intake conditions; however, their reliance on external neutralisation represents a critical limitation for ABEP systems.

This paper presents the concept development of a cathodeless, inductively coupled, gridded ion engine based on beam-switching operation, enabling the simultaneous extraction of positive and negative charge carriers without a dedicated neutraliser. A design methodology linking VLEO environmental conditions to thruster requirements is outlined, followed by the development of a representative thruster architecture and a downscaled demonstrator. Performance is assessed through modelling, which indicates the feasibility of drag compensation under relevant VLEO conditions.

1. Introduction

Very Low Earth Orbit (VLEO), typically defined as altitudes below 250 km, offers significant advantages for Earth observation, telecommunications, and scientific missions due to reduced latency, improved spatial resolution, and enhanced signal strength. However, operation in this regime is fundamentally limited by strong atmospheric drag, which requires continuous compensation to maintain orbital altitude. Atmosphere-breathing electric propulsion (ABEP) has emerged as a promising solution, as it enables the use of residual atmospheric particles as propellant, eliminating the need for onboard storage and, in principle, allowing indefinite mission lifetimes[1].

Despite its conceptual attractiveness, ABEP imposes a set of tightly coupled system-level constraints. The available mass flow is strictly limited by atmospheric density and intake collection efficiency, while the achievable thrust is directly linked to the exhaust velocity and the propulsion system's mass utilisation efficiency. At the same time, the available electrical power is constrained by spacecraft geometry, which itself contributes to drag. These interdependencies significantly restrict the range of viable propulsion technologies as well as generally viable solutions of this task. Previous studies have shown that only electrostatic thrusters, particularly gridded ion engines (GIEs), can achieve the combination of high exhaust velocity and efficiency required for drag compensation under VLEO conditions [2].

A critical limitation of conventional GIEs in the context of ABEP is the requirement for external neutralisation. Classical hollow cathodes rely on dedicated propellant supply and stable operating conditions, both of which are incompatible with the low-density, variable, and reactive atmospheric environment encountered in VLEO [3]. Moreover, diverting a fraction of the collected atmospheric flow for neutralisation directly reduces the mass available for thrust generation, thereby increasing the minimum required exhaust velocity and further constraining system feasibility.

To address this limitation, alternative neutralisation concepts must be considered. Among these, beam-switching approaches, widely used in industrial applications [4-7], offer a pathway to extract both positive and negative charge carriers in a time-resolved manner, enabling quasi-neutral plume formation without a dedicated cathode. While similar concepts have recently been explored in space propulsion, their application to atmosphere-breathing systems and operation with molecular, reactive propellants remains largely unaddressed [8,9].

This paper presents the concept development of a cathodeless inductively coupled gridded ion engine for ABEP applications in VLEO. The proposed approach combines a radio-frequency (RF) inductive discharge with a low-frequency beam-switching extraction system, aiming to mitigate plasma instabilities and avoid undesired capacitive effects associated with high-frequency grid excitation. A design methodology is introduced that links environmental constraints to thruster requirements and guides the development of the thruster architecture. To enable experimental validation within realistic facility limitations, a downscaling strategy is applied, and a representative demonstrator is designed. The performance of the proposed concept is assessed through modelling, and its feasibility for drag compensation under VLEO conditions is discussed.

2. System Level Constraints for ABEP in VLEO

The feasibility of ABEP systems is fundamentally governed by the properties of the orbital environment. In VLEO, typically between 160 and 250 km altitude, the residual atmosphere is characterised by low particle densities, strong variability driven by solar activity, and a compositional shift from predominantly molecular nitrogen to increasing fractions of atomic oxygen as altitude decreases. As a result, both the available propellant mass flow and the drag imposed on the spacecraft are directly determined by orbital conditions (for set satellite geometry) and cannot be independently controlled [2].

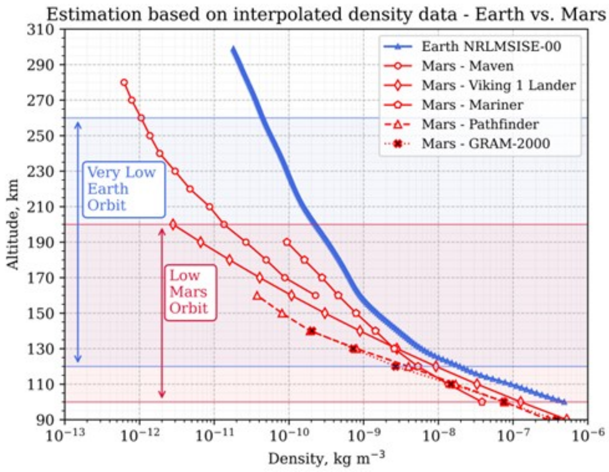

Figure 1. Atmosphere density for very low orbits of Earth and Mars.

For a given intake area, the collectable mass flow rate scales with atmospheric density and orbital velocity, while the aerodynamic drag scales with the same parameters and the spacecraft drag coefficient. Consequently, each collected particle contributes simultaneously to both thrust potential and drag generation. This intrinsic coupling imposes a fundamental requirement on the propulsion system: the exhaust velocity must be sufficiently high to compensate for drag under all expected operating conditions. First-order analyses show that this requirement is largely independent of the absolute mass flow rate and is instead governed by intake efficiency and spacecraft drag characteristics.

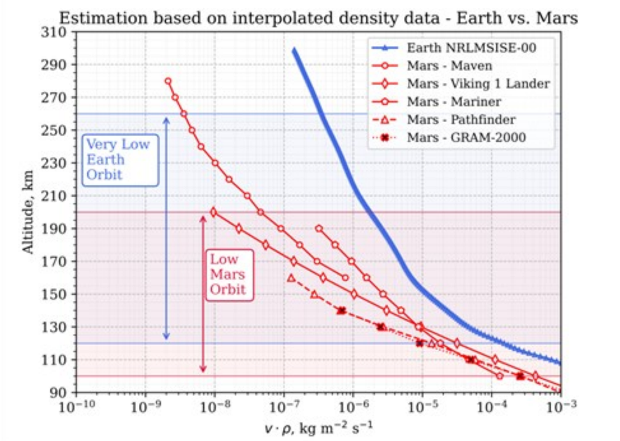

Figure 2. Mass flow rate available per frontal cross-section area of intake for Earth and Mars in very low orbits.

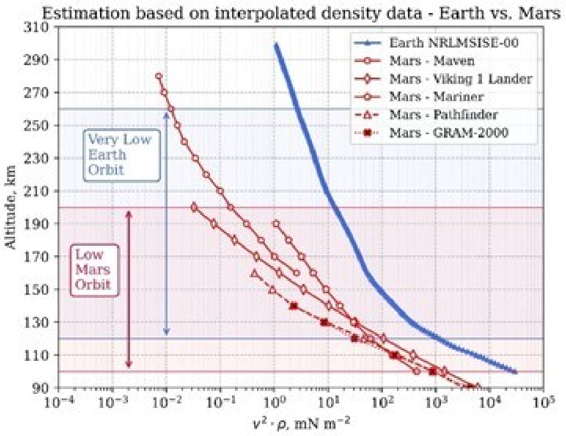

Figure 3. Drag generated per frontal surface area of satellite for Earth and Mars in very low orbits.

The use of atmospheric propellants introduces further constraints. Molecular species such as N_2 and O_2 could be dissociated prior to or during ionisation, leading to additional energy losses and resulting in a lighter propellant species. The probability of dissociation of molecular species is strongly dependent on electron temperature and plasma conditions, favouring propulsion concepts that can operate efficiently at relatively low electron temperatures. Furthermore, the wide variation in atmospheric composition across the VLEO altitude range introduces additional complexity, as plasma chemistry and ionisation efficiency depend sensitively on the local gas mixture.

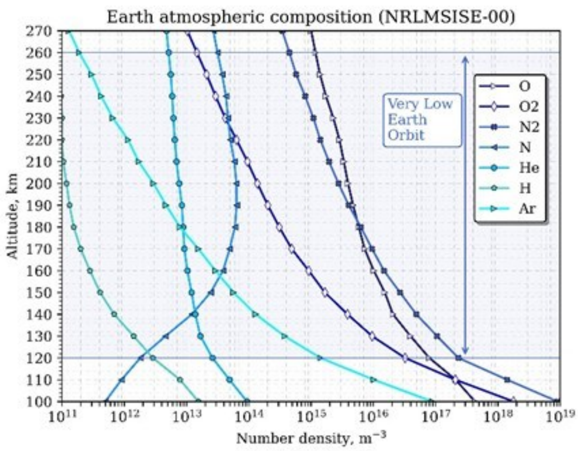

Figure 4. Atmospheric composition for very low orbits of Earth.

It is important to note that the parameters presented in Figs. 1–4 represent average conditions at a given orbital altitude. In reality, the VLEO environment exhibits significant temporal and spatial variability, even at constant altitude. Atmospheric density can vary by a factor of 5–10 due to solar activity, geomagnetic conditions, and diurnal effects. Similarly, neutral temperature may range from approximately 700 K to over 2000 K across the solar cycle, while the relative composition of species, such as the O/N_2 ratio, changes with altitude and solar conditions.

These variations directly affect the available mass flow rate, aerodynamic drag, and the thermodynamic and plasma conditions at the intake and within the thruster. As a consequence, the propulsion system must be capable of stable operation over a wide range of mass flow rates, propellant compositions, and inlet conditions. In addition, the required thrust level must adapt dynamically to compensate for drag variations while maintaining a desired orbital altitude.

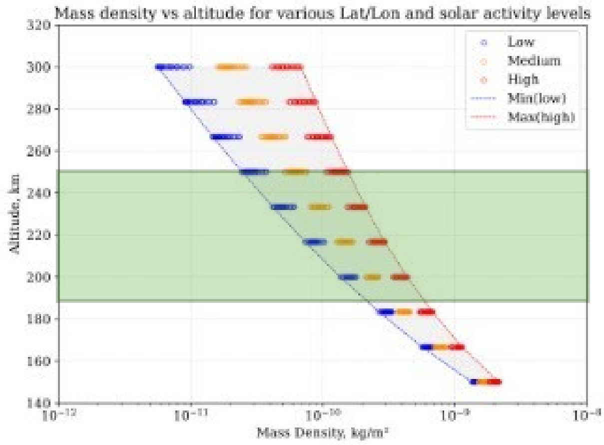

Figure 5. Atmosphere density variation for very low orbits of Earth at different solar activity levels.

In practical terms, this implies that the propulsion system cannot be optimised for a single operating point, but must instead sustain performance across a continuously shifting operating envelope. These constraints further narrow the range of viable propulsion technologies and strongly favour concepts with robust performance under varying plasma and flow conditions.

In addition to exhaust velocity, the propulsion system's overall electrical efficiency and thrust-to-power ratio must meet strict constraints imposed by the spacecraft's power budget. In VLEO, the available electrical power is typically limited by solar array size, which itself contributes to drag. This creates a strong interdependency between propulsion efficiency, available power, and spacecraft geometry. Increasing power to achieve higher thrust often leads to larger solar arrays, which in turn increase drag, reducing the net system benefit. As a result, only propulsion concepts capable of simultaneously achieving high exhaust velocity and high electrical efficiency can be considered viable.

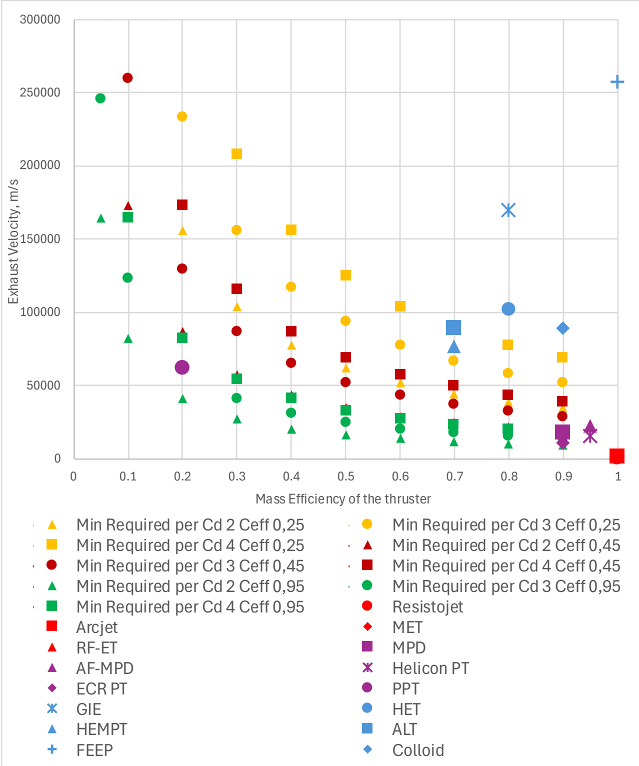

Figure 6. The maximum theoretical performance (exhaust velocity vs thruster mass efficiency) achievable for each technology, plotted against the minimum required exhaust velocity per incoming particle for Earth.

When these constraints are evaluated across the main classes of electric propulsion technologies, a clear trend emerges. Electrothermal systems are limited by achievable temperature and, therefore, exhaust velocity, making them unsuitable for VLEO drag compensation. Electromagnetic thrusters, while capable of achieving relatively high exhaust velocities, generally suffer from low efficiency at the power levels relevant to small spacecraft and exhibit unfavourable scaling with atmospheric propellants. Inductively and capacitively coupled plasma thrusters offer operational flexibility but are typically limited by dissociation losses and comparatively low effective exhaust velocities under realistic conditions, particularly when operating with molecular atmospheric propellants.

Electrostatic thrusters, and in particular GIEs, provide the most favourable combination of high exhaust velocity and electrical efficiency. Their performance is primarily determined by the applied acceleration potential, allowing direct control of ion energy largely independent of plasma temperature. This makes them well-suited for operation with low-density atmospheric flows and reactive propellants. However, their applicability to ABEP is critically constrained by the requirement for charge neutralisation, which becomes a dominant design challenge in the absence of a dedicated propellant supply.

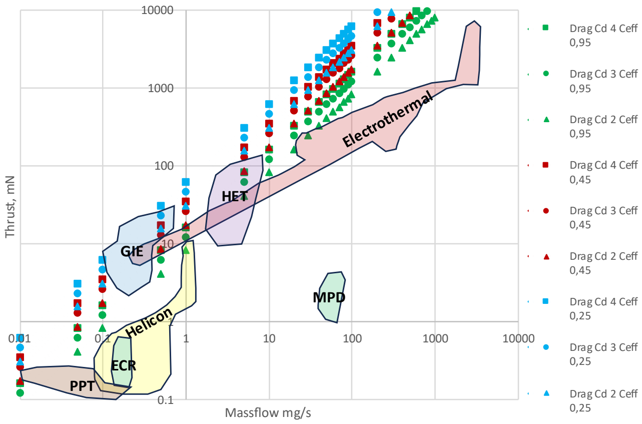

Figure 7. Experimentally declared performance of different EP groups plotted against the minimum required thrust per thruster mass flow for Earth.

These system-level considerations indicate that while GIEs represent the most promising propulsion technology for ABEP in VLEO, their conventional architecture must be fundamentally adapted to enable cathodeless operation under highly variable atmospheric conditions.

3. Cathodeless Operation and Beam-Switching Concept

As identified in the previous section, electrostatic propulsion, and in particular GIEs, provides the most favourable combination of exhaust velocity and electrical efficiency for ABEP in VLEO. However, the applicability of conventional GIE architectures is fundamentally constrained by the requirement for external neutralisation. The use of hollow cathodes or alternative electron sources introduces additional system complexity, requires a dedicated propellant supply, and reduces the effective mass available for thrust generation. These limitations are particularly critical in ABEP systems, where the available mass flow is limited and directly coupled to drag.

To overcome this constraint, a cathodeless operation principle must be established, enabling quasi-neutral plume formation without an external electron emitter. One possible approach is based on beam-switching concepts, in which the extraction system alternates between regimes that favour the acceleration of positive and negative charge carriers. In such a configuration, charge neutrality is achieved in a time-averaged sense, eliminating the need for continuous external neutralisation.

Beam-switching approaches have been widely applied in industrial ion-source applications, where alternating extraction of ions and electrons (or negative ions) is used to control surface interactions [4-7]. More recently, related concepts have been explored in the context of space propulsion; however, their application to low-density, reactive atmospheric propellants and ABEP-specific constraints remains largely unexplored [8, 9].

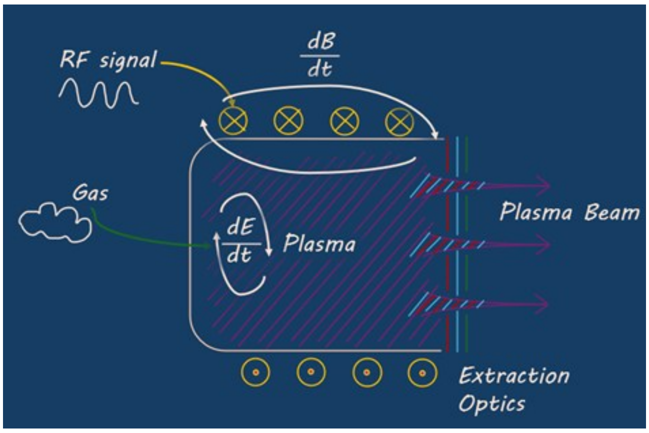

Figure 8. Scheme of a cathodeless electric propulsion thruster concept.

In this work, a cathodeless concept based on a radio-frequency (RF) inductively coupled plasma source combined with a gridded extraction system is proposed. The use of inductive RF coupling enables plasma generation without internal electrodes, significantly reducing erosion in reactive environments and ensuring compatibility with atmospheric propellants such as nitrogen and oxygen. In addition, RF discharges are characterised by relatively low electron temperatures compared to other electric propulsion technologies, which is advantageous for minimising dissociation losses in molecular propellants and improving overall energy efficiency.

The proposed beam-switching operation is implemented at comparatively low frequencies, in contrast to approaches relying on high-frequency excitation of the grid system. This choice is motivated by the need to avoid parasitic capacitive coupling effects, uncontrolled sheath dynamics, and additional power losses typically associated with high-frequency operation in capacitive regimes [10]. By separating plasma generation (inductive RF) from particle acceleration (electrostatic), the concept preserves the main advantage of GIEs: independent control, thereby optimising ionisation and acceleration stages of the thruster.

From a system perspective, this approach enables the use of a single incoming atmospheric flow to generate both thrust-producing ions and the charge carriers required for plume neutralisation. As a result, no fraction of the collected mass flow needs to be diverted to a dedicated neutraliser, potentially improving overall system efficiency and simplifying integration with the intake and propellant supply system.

The combination of inductively coupled plasma generation and beam-switching extraction, therefore, represents a promising pathway towards cathodeless electrostatic propulsion for ABEP applications. However, it also introduces new challenges, including the need to maintain stable plasma conditions across switching cycles, ensure efficient extraction of both charge-carrier species, and manage potential asymmetries in grid loading and erosion. These aspects are addressed through the design methodology and modelling approach presented in the following sections.

4. Thruster Design Methodology

The design of a cathodeless gridded ion engine for ABEP must directly reflect the system-level constraints identified in Section 2 while implementing the cathodeless concept described in Section 3. In this work, a structured design methodology is adopted that links environmental conditions and mission requirements to the selection of thruster architecture and key design parameters.

4.1. Design Drivers

The primary design drivers are defined by the VLEO environment and ABEP system constraints. The available propellant is limited to low-density atmospheric flow composed primarily of molecular nitrogen and oxygen, with significant variability in composition and thermodynamic state. As a result, the thruster must operate efficiently at low, variable mass flow rates while maintaining stable performance across a broad operating envelope.

A key requirement is the ability to generate sufficiently high exhaust velocity to compensate for aerodynamic drag under all expected conditions. This must be achieved while preserving high electrical efficiency, due to the strong coupling between propulsion power and spacecraft drag. In addition, operation with molecular propellants imposes constraints on plasma conditions, favouring regimes with relatively low electron temperature to minimise dissociation losses and associated energy penalties.

Finally, the cathodeless operation concept imposes additional requirements on the extraction system, which must enable effective, time-resolved acceleration of both positive and negative charge carriers while maintaining overall beam stability and efficiency.

4.2. Quantitative Design Targets

Based on the system-level analysis and environmental constraints described in Section 2, a representative operational envelope for ABEP applications in VLEO was defined. To ensure feasible drag compensation while maintaining operational flexibility, an altitude range of approximately 190-250 km was selected. Within this range, atmospheric variability is comparably low, allowing for controlled operation and recovery from transient density increases without immediate risk of orbital decay.

For typical spacecraft configurations, the required thrust level ranges from a few milli-Newtons up to approximately 30 mN, depending on spacecraft size, drag coefficient, and orbital conditions. The corresponding available mass flow rates span from approximately 0.05 to 0.7 mg/s for realistic intake efficiencies, and up to ~1.75 mg/s under idealised conditions.

To compensate for drag in this regime, an exhaust velocity of about 60 km/s is required. This corresponds to effective specific impulse values of approximately 6000 s. Accounting for realistic mass utilisation efficiencies of 50–60% for the ion engines, the characteristic ion velocities must exceed 100 km/s. These requirements place the propulsion system firmly within the operational domain of electrostatic acceleration.

The overall system efficiency is constrained by both plasma generation and the cathodeless beam-switching operation. While beam-switching reduces the effective thrust due to alternating extraction phases, the high efficiency of RF gridded ion engines enables operation at approximately 50% overall efficiency, which remains compatible with ABEP system requirements.

In addition to performance targets, lifetime considerations are critical for sustained VLEO operation. Previous developments of RF gridded ion engines have demonstrated operational lifetimes on the order of 60,000 hours with reactive propellants, indicating that the required lifetime targets (>20,000 hours) are achievable with appropriate material selection and operating conditions [11].

These quantitative targets define the design space for the cathodeless gridded ion engine and guide the subsequent development of the thruster architecture and its scaling for experimental validation.

4.3. Architecture selection

Based on these drivers, a gridded ion engine architecture with inductively coupled RF plasma generation is selected. This configuration enables independent optimisation of ionisation and acceleration processes, which is essential for achieving high exhaust velocity while maintaining efficient plasma production at low densities.

The use of inductive RF coupling allows plasma generation without internal electrodes, significantly improving compatibility with reactive atmospheric species and reducing erosion-related lifetime limitations. This is particularly important in ABEP applications, where exposure to atomic oxygen and other reactive constituents is unavoidable.

For particle acceleration, a multi-grid electrostatic extraction system is employed. This approach provides direct control over ion energy through the applied potential difference, largely decoupled from plasma temperature, and is therefore well suited for achieving the high exhaust velocities required for drag compensation.

The thruster design must also accommodate an interface with the intake to enable future adaptation to ABEP configuration. At the same time, for stand-alone characterisation in early TRL stages, an alternative feed-system strategy is required.
The TransMIT approach in this regard is to employ frontal gas injection. This distinctive feature has been widely used in our previous designs and is therefore well validated.
Furthermore, TransMIT's overall strategy for ABEP implementation is to support dual propellant supply modes:

- residual atmospheric propellant, supplied through a rear intake directly coupled to the thruster, and
- a conventional propellant feed delivered through the frontal inlet.

This configuration enables robust characterisation during initial in-orbit demonstrations while also providing a means of risk mitigation for broader commercial deployment. In particular, it offers operational flexibility in case of insufficient atmospheric propellant or unexpected in-orbit perturbations.

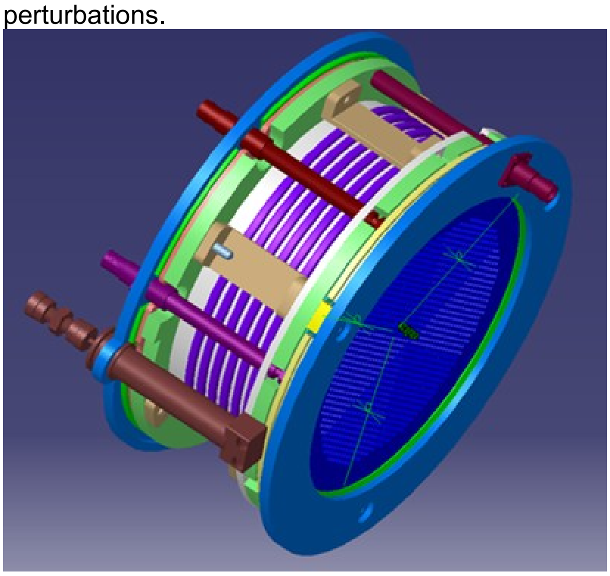

Figure 9. Cathodeless electric propulsion thruster-16 prototype general view.

The overall thruster configuration builds upon established gridded ion thruster concepts and incorporates modifications to enable cathodeless operation via beam switching. In addition, the design is informed by prior developments of double-sided ion thruster configurations, which provide a useful reference for managing plasma symmetry and extraction efficiency in systems with modified boundary conditions [13].

4.4. Key Design Adaptations

To ensure compatibility with ABEP-specific constraints, several key adaptations to conventional gridded ion engine design are implemented.

The discharge chamber geometry is defined by scaling considerations that balance plasma density, residence time, and power-coupling efficiency. Particular attention is given to achieving stable plasma operation over a wide range of mass flow rates and inlet conditions, as required by the variability of the VLEO environment.

The ion optics system is optimised using numerical tools to ensure efficient extraction and acceleration of charged particles while minimising losses and mitigating potential erosion mechanisms. Parameters such as aperture geometry, grid spacing, and alignment are determined through simulation-driven optimisation rather than fixed empirical scaling to account for the specific requirements of operating with atmospheric propellants.

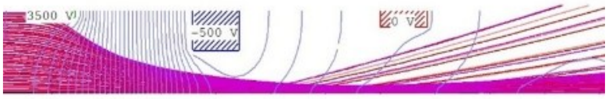

Figure 10. Example of performed simulation of the extraction optic for N2, O2, N, NO and O species.

Material selection is guided by the need for compatibility with reactive species, thermal stability, and long operational lifetime. Materials commonly used in gridded ion thrusters, such as ceramics and refractory metals, are selected due to their demonstrated resistance to erosion and degradation in harsh environments, including exposure to atomic oxygen.

Finally, the integration of beam-switching operation imposes additional constraints on both plasma generation and extraction subsystems. The design must ensure stable transitions between operating phases, maintain efficient utilisation of the available mass flow, and avoid excessive parasitic losses associated with switching dynamics.

Through this methodology, the resulting thruster design is not optimised for a single operating point, but rather for robust performance across the wide range of conditions inherent to ABEP operation in VLEO.

5. Scaling Strategy and experimental approach

5.1. Facility Constraints and Representativeness

Experimental validation of ABEP thrusters is fundamentally constrained by the ability to reproduce representative background pressure conditions. For the targeted VLEO altitude range of 190–250 km, the effective in-orbit pressure lies in the order of 10^{-7}–10^{-6} mbar. Achieving comparable dynamic pressure levels on the ground during thruster operation is challenging and requires very high pumping speeds, particularly when operating at atmospheric propellant mass flows of 0.05–0.7 mg/s.

Only a limited number of vacuum facilities in Europe can simultaneously support the required pumping speed (>mid 10^4– mid 10^5 L/s), beam power (kW-class), and an appropriate background composition. In addition to their limited availability, such facilities involve high operational costs and limited flexibility for iterative low-TRL development. These constraints make full-scale experimental validation impractical within early-stage development programmes.

5.2. Impact of Background Pressure on Performance

Facility background pressure is known to influence electric propulsion performance. While gridded ion engines are generally less sensitive to this effect than open-discharge thrusters, TransMIT's experimental results with atmospheric propellant mixtures show that measurable deviations still occur.

In particular, the operation of a gridded ion engine *RAM-RIT22/16* with CO_2-based mixtures showed a reduction in discharge power of up to 30% as background pressure increased to ~10^{-4} mbar. This effect is attributed to the increased neutral density in the discharge chamber, which reduces the ionisation energy required to sustain the plasma. As a result, higher facility pressure can artificially improve the apparent thruster efficiency, leading to a non-representative performance assessment.

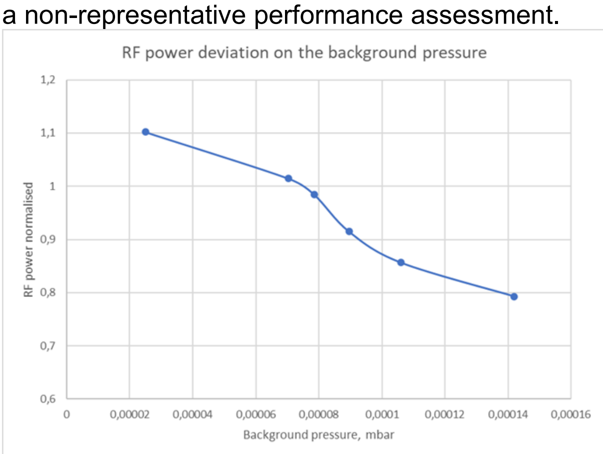

Figure 11. Experimentally derived power variation of the RAM-RIT22/16 operating with a carbon dioxide/oxygen/nitrogen mixture.

These findings highlight the necessity of maintaining low and well-characterised background pressure conditions when evaluating ABEP thruster performance.

5.3. Rationale for Downscaling

To overcome these limitations, a downscaled thruster approach is adopted. By reducing the characteristic mass flow range to approximately 0.01–0.06 mg/s, the required pumping speed decreases by nearly an order of magnitude, enabling operation in a wider range of research-grade vacuum facilities while maintaining representative pressure conditions.

In addition to improving facility compatibility, downscaling offers several practical advantages:

- increased availability of suitable test infrastructure,
- reduced operational costs,
- improved flexibility for iterative testing and design refinement,

and the possibility to systematically investigate performance sensitivity to background pressure.

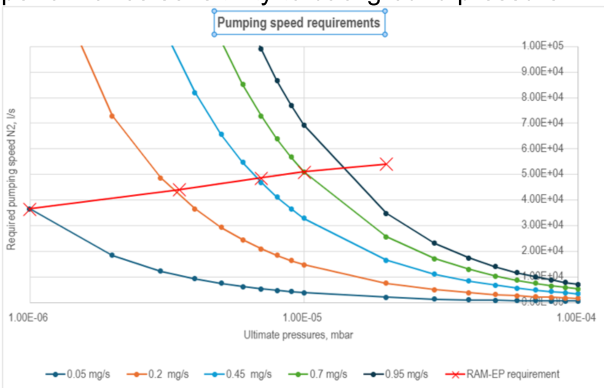

Figure 12. Pumping speed required per achieved facility pressures for constant flows of oxygen-nitrogen mixture, together with the required pumping speed curve for the nominal thruster size.

5.4. Similarity and Scalability Considerations

The applicability of downscaled testing depends on the preservation of key physical processes that govern thruster operation. For RF gridded ion engines, well-established scaling relationships enable consistent adaptation of discharge and geometric parameters across different sizes. In particular, discharge pressure and RF coupling characteristics can be adjusted to maintain similar plasma conditions, whereas ion-optics performance primarily depends on propellant type and ion energy rather than on absolute scale.

It is recognised that smaller thrusters typically operate at higher discharge pressures and exhibit slightly lower efficiency than larger thrusters. However, this effect yields conservative performance estimates, which is advantageous in early development stages, where minimum performance thresholds must be demonstrated.

Additional analysis confirms that similar neutral-density distributions can be achieved between nominal and downscaled air-intake configurations when geometric similarity and gas-surface interaction characteristics are preserved [14]. This supports the validity of extrapolating experimental results from the downscaled demonstrator to the full-scale system.

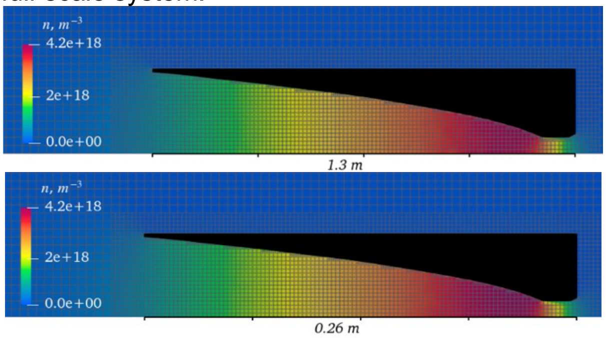

Figure 13. The exemplary simulation results for nominal and downscaled size intakes, neutral density distribution [14]

Overall, the adopted scaling strategy provides a technically sound and programmatically efficient pathway for experimental validation of the cathodeless gridded ion engine concept under representative conditions.

6. Downscaled Thruster Implementation (CEPT3.5)

Based on the scaling strategy outlined in Section 5, a downscaled cathodeless gridded ion engine demonstrator, referred to as CEPT3.5, has been defined. The design is derived from the well-established RIT3.5 radio-frequency ion thruster, which has demonstrated reliable operation in laboratory conditions and is under qualification for multiple small- and cube- sat missions [15-17].

The selection of the RIT3.5 architecture as a baseline enables the reuse of proven design solutions for plasma generation, structural configuration, and subsystem integration, while focusing development efforts on the modifications required for atmosphere-breathing operation and cathodeless beam generation.
Nominal configuration of this thruster does as well utilise the frontal gas injection, which makes it a perfect candidate for employment of the dual propellant supply strategy of TransMIT.

The CEPT3.5 thruster is designed to operate within a mass flow range of approximately 0.005–0.03 mg/s, corresponding to the expected intake performance for a representative small-scale ABEP platform with a characteristic cross-section of ~0.2 m. Within this regime, the required thrust range is approximately 0.1–1 mN, consistent with drag-compensation requirements at altitudes of 190–250 km.

Figure 14. General View of CEPT3.5

To meet these performance targets, the thruster is designed to achieve effective specific impulse values exceeding 5500 s, with corresponding ion exhaust velocities in the range of around hundred km/s. As in the nominal system, overall efficiency is influenced by the beam-switching operation required for cathodeless functionality. Based on prior experimental experience with RF ion thrusters, the expected efficiency remains within a range compatible with ABEP feasibility constraints.

The primary design modifications relative to the heritage RIT3.5 configuration include adapting the discharge chamber geometry to accommodate lower and variable mass flow rates, as well as re-optimising the ion optics system for operation with atmospheric propellant mixtures. The latter has been supported by numerical simulations, which confirm stable beam extraction and efficient acceleration under the modified operating conditions.

In addition, the thruster is designed to operate in conjunction with a representative intake interface, with particular attention given to the resulting neutral density distribution within the discharge chamber. This aspect is critical to ABEP operation and has been considered in defining the inlet configuration and operating envelope.

The CEPT3.5 demonstrator is currently in manufacturing and will be used to experimentally validate the cathodeless gridded ion engine concept under controlled laboratory conditions. The test campaign will focus on characterising performance as a function of background pressure, propellant composition, and operating parameters, providing the necessary data for extrapolation to nominal-scale systems.

Through this approach, CEPT3.5 serves as a key intermediate step toward developing a full-scale cathodeless ABEP thruster, enabling validation of the underlying physical principles and supporting the maturation of the technology to higher readiness levels.

7. Conclusion

This work has presented the concept development of a cathodeless inductively coupled gridded ion engine for atmosphere-breathing electric propulsion in Very Low Earth Orbit.

A system-level analysis of the VLEO environment has shown that the feasibility of ABEP is governed by a combination of high exhaust velocity requirements, strict efficiency constraints, and significant variability in atmospheric conditions. Among the main classes of electric propulsion technologies, gridded ion engines have been identified as the only viable candidates capable of simultaneously meeting these requirements. However, their conventional reliance on cathodes represents a critical limitation for atmosphere-breathing operation.

To address this challenge, a cathodeless concept based on beam switching has been proposed, enabling charge-neutral operation without the need for an external electron source. The resulting architecture combines the advantages of RF plasma generation with electrostatic acceleration, providing a pathway toward efficient operation with reactive atmospheric propellants.

Given the limitations of ground-based testing at representative pressure conditions, a downscaled experimental approach has been adopted. The analysis has shown that downscaling enables operation within accessible vacuum facilities while preserving the key physical processes governing thruster performance. This approach allows systematic investigation of performance dependencies and provides a reliable basis for extrapolation to full-scale systems.

A downscaled demonstrator, CEPT3.5, has been defined based on the RIT3.5 heritage thruster and adapted for atmosphere-breathing and cathodeless operation. The demonstrator is currently under development and will be used to experimentally validate the proposed concept.

The results presented in this work establish a consistent framework linking environmental constraints, propulsion requirements, and thruster design. They confirm the feasibility of cathodeless gridded ion engines for ABEP applications and define a clear pathway toward experimental validation and further technology maturation.

8. Acknowledgements

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