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ORIGINAL PAPER

Current progress in the development of an ECR plasma source for atmosphere-breathing electric propulsion system

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Abstract

This contribution reports on the experimental demonstration of plasma ignition in an electron-cyclotron-resonance atmosphere-breathing electric propulsion source at pressures representative of very low Earth orbit. Using a MHz-range birdcage resonator in combination with a tailored magnetic field, we achieved sustained plasma discharge at pressures consistent with conditions expected after intake compression at altitudes near 200 km. The scalability of the birdcage resonator with increasing forward power is explored, revealing the potential for future improvement regarding power scaling of the thruster. These findings identify both the feasibility of electrodeless ignition at VLEO pressures, and the engineering limits imposed by resonator heating. We further discuss quantitative links between measured ion currents, estimated thrust, and extraction efficiency. Our results establish critical design insights for scaling ABEP technology toward flight-ready operation.

Keywords Atmosphere-breathing electric propulsion · Very low earth orbit · Electron cyclotron resonance ion source · Electrodeless design

1 Introduction

This contribution summarizes the recent progress in the development of an electron cyclotron resonance (ECR) plasma source intended for atmosphere-breathing electric propulsion (ABEP) systems. The intended operational altitude of ABEP-fitted satellites, approximately 200 km, falls within the very low earth orbit (VLEO) range, imposing several restrictions on the design and development [1]. The residual atmospheric particles at such altitudes exert a substantial aerodynamic drag on the S/C, requiring constant compensating thrust to prevent deorbiting. The theoretical ABEP concept lends itself well to this issue specifically, as it carries no on-board propellant. Instead, propellant is supplied directly from the residual atmosphere around the S/C. Propulsion is typically achieved by extracting ions using high voltage and accelerating them against the direction of flight, thereby generating self-sustaining thrust.

The successful development of the ABEP system is naturally highly sought after by the Earth observation and telecommunication industry. The main benefits lie in the extended mission lifetimes, higher resolution, and reduced latency stemming from operation in lower altitudes. Furthermore, the natural deorbiting of ABEP-fitted satellites due to atmospheric drag at the end of their lifetime reduces the risk of catastrophic collisions by not remaining in orbit as space debris [2].

The main challenge in development comes in the presence of highly reactive atomic oxygen, which is prevalent in VLEO, causing a significant decrease to some components' lifetime [3].

These obstacles combined result in a hostile, extremely low-pressure environment in which plasma ignition and confinement proves challenging. The common factor to many theoretically proposed systems is the presence of a passive

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intake which is intended to aid with the collection of incoming residual atmospheric particles and their subsequent compression [4, 5]. The approach outlined in this contribution was specifically tailored to allow plasma ignition and confinement at pressures in the range of units of mPa which are theoretically attainable at VLEO after compression. The proposed MHz-range driven ion source with resonant behavior described in the later sections has successfully demonstrated such capabilities.

Over the last two decades, multiple approaches to ABEP design have been proposed; however, none have undergone in-orbit testing. The feasibility of a given concept is often ascertained using numerical simulations and rarely tested in VLEO representative laboratory conditions achievable only in a few specialized facilities.

Nevertheless, the feasibility of ABEP was first demonstrated on the ground in three independent programs: Busek's Air-Breathing Hall-Effect Thruster (ABHET), JAXA's Air-Breathing Ion Engine (ABIE) [6], and SITAEL's RAM-EP dual-stage Hall thruster [7]. These end-to-end tests collectively provided the first experimental proofs of the ABEP concept, although none yet achieved full drag compensation [8].

Another notable research is carried out at various universities. Universidad Carlos III de Madrid is one of the leading university groups working on helicon thruster based ABEP, with both experiments and detailed chemistry-aware simulations [9]. National University of Defense Technology in Changsha, China focuses on optical diagnosis of an inductively coupled plasma source ABEP systems [10] while the University of California, Los Angeles (UCLA) develops a miniature RF Gridded Ion Thruster with promising preliminary results [11].

Lately, VLEO has become a frontier of an emerging commercial ecosystem as primes and start-ups including Thales Alenia Space, Redwire, EOI Space, Orbion, Kreios Space, and Deepsat are already positioning for VLEO platforms and constellations. Most notably, Kreios and Redwire have recently secured funding to demonstrate their VLEO technologies in orbit [12].

Furthermore, the radiofrequency (RF) approach to plasma generation has become more widely adopted as of late, as both the NewOrbit company and the Institute of Space Systems (IRS) of the University of Stuttgart report successful ignition and operation of their respective designs. NewOrbit has reported favorable results using an RF gridded ion engine and an air-breathing RF cathode, driven by two RF generators: one operating at 1–5 MHz for the thruster and another at 3–11 MHz for the cathode [13]. The latter utilizes an RF helicon-based plasma thruster (IPT), with a vacuum-model prototype resonating around 4–5 MHz and designed to be compatible with future flight applications [14]. This approach is especially relevant to the work described herein, since the plasma is excited using the birdcage resonator. It marks the first mention of the utilization of the birdcage resonator in an ABEP concept in the literature. However, the birdcage resonator has already been applied in fundamental and fusion plasma research at Federal Polytechnic School of Lausanne (EPFL) [15, 16].

In contrast to helicon and RF gridded ion ABEP thrusters, which target higher thrust levels at tens to hundreds of watts, the present work prioritizes robust electrodeless ignition at VLEO-representative pressures using a single MHz-range resonator, accepting lower current levels at this development stage.

This paper presents two core contributions. Firstly, an experimental demonstration of plasma ignition at 10 mPa using a MHz-range birdcage resonator coupled with an external magnetic field. Secondly, an identification of thermal detuning effects as a limiting factor for resonator scalability beyond 10 W of forward power, with implications for high-power ABEP operation.

The next section describes the design of our plasma source, detailing the current version of the breadboard model and the design of the birdcage resonator. The last section presents the latest results, including a breakthrough in low-pressure ignition and new insights into the power scaling of the resonator.

2 Experimental

Taking the aforementioned obstacles posed by the VLEO environment into account, a project aiming to design and develop a low-pressure ionizer for ABEP systems was launched in 2023. The simulation-driven approach to design gave rise to the current version of the laboratory breadboard model.

2.1 Test facility and experimental setup

All experiments were conducted using plasma ignited in a discharge chamber evacuated using a two-stage pumping system consisting of a turbomolecular pump (Pfeiffer Vacuum TMH 261 P) backed by a dry scroll pump (Edwards NXDS10i), achieving a base pressure on the order of 10^{-4} Pa prior to gas injection. The pressure inside the chamber was measured using a wide-range gauge (Inficon Gemini MPG500) with error ±30% of reading across the whole range and controlled via the gas inflow regulated by an electronic needle valve (Pfeiffer Vacuum EVR 116).

Gas is injected at flow rates calibrated to achieve chamber pressures down to 10 mPa. The gas was supplied from a premixed bottle containing synthetic air, composed of a mixture of pure nitrogen and oxygen in an 80:20 ratio. This is consistent with expected gas composition and pressure in VLEO after passive compression, as indicated by Direct Simulation Monte Carlo (DSMC) simulations described below in further detail [17]. No additional verification of gas composition was required beyond the certified bottle mixture; we therefore assume that the N_2/O_2 ratio remains constant over the range of operating pressures.

The overall arrangement of the vacuum system, gas supply, plasma source, RF generator, and diagnostics is summarized in Fig. 1.

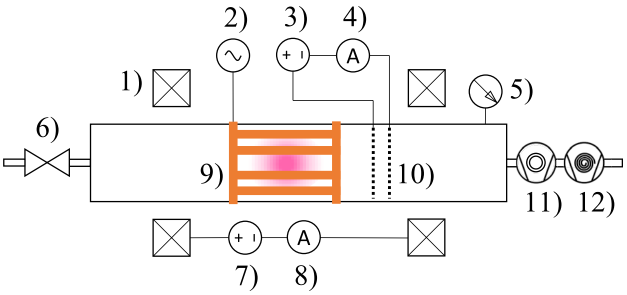


Fig. 1 Block diagram of the test facility: 1 DC coils, 2 RF source, 3 HV source, 4 milliammeter—extracted current measurement, 5 vacuum gauge, 6 electronic needle valve, 7 DC power source, 8 ammeter–DC coils current measurement, 9 birdcage resonator, 10 extraction grids, 11 turbomolecular pump, 12 scroll pump

2.2 Plasma source design

The plasma source follows a modular design, consisting of a cylindrical glass discharge channel enveloped by the birdcage resonator driven by MHz-range frequency, as depicted in Fig. 2. This frequency corresponds to the electron cyclotron frequency from the externally applied magnetic field via a pair of Helmholtz coils, ensuring resonant electron heating. Although conventional ECR ion sources operate at GHz frequencies, the principle of energy transfer is identical: resonant coupling occurs when the driving frequency matches the electron cyclotron frequency, regardless of the absolute scale. This justifies the continued use of the term ECR in this context.

Apart from participating in heating, the Helmholtz coils provide magnetic confinement during laboratory testing, ensuring low charged species losses to walls. Permanent magnet arrays are intended for flight designs. Using permanent magnets decreases the mass and volume of the device and alleviates the stress from in-orbit energy limitations imposed by solar panels' efficiency.

The resonator approach was chosen due to the aforementioned abundance of reactive atomic oxygen in VLEO. Its design offers a substantial advantage over similar systems reliant on conventional electrodes, which are prone to oxygen poisoning. The resonator is typically labelled "electrodeless", but the complete device is not, since the existing

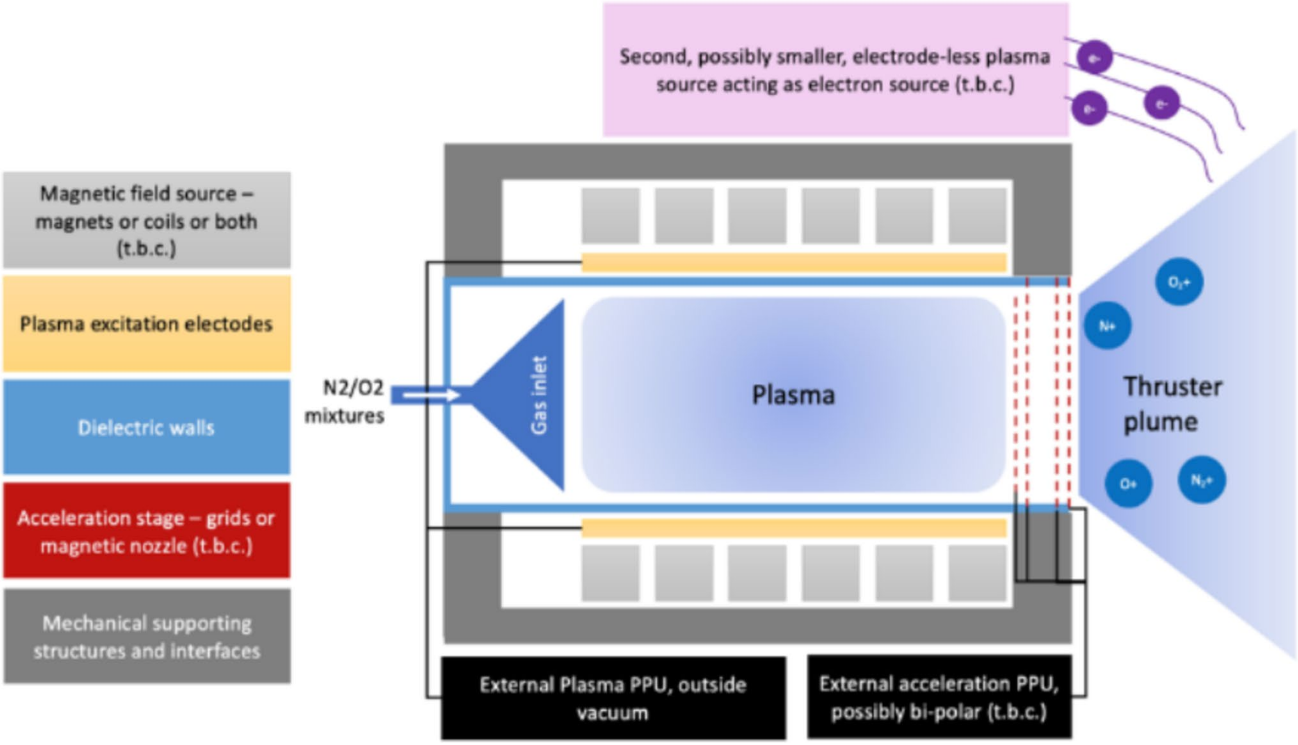


Fig. 2 Schematic diagram of the ion source prototype

ion-extraction approach relies on electrode grids similar to those in a conventional gridded ion engine. In the contemporary model, the grids are biased to a constant acceleration voltage, enabling extraction and extracted ion current measurements. The usage of alternative means of extraction, such as a magnetic nozzle, is also being considered and is the subject of future measurements. Due to the power and pressure restrictions imposed by the VLEO environment, we identify the resonator as the most crucial component of the current design, as it is directly responsible for plasma ignition and power matching. The following section describes the birdcage resonator in more detail, discussing its development and integration into the current breadboard design.

2.3 Resonator

The concept of a birdcage resonator was already presented at the 1st VLEO symposium [18] several years ago. However, the design and manufacturing procedure has changed since then. Most importantly, the resonator is fabricated from the flexible Printed Circuit Board (PCB) material, allowing us to employ a precise and tested procedure for its fabrication. The new design is capable of withstanding higher temperatures, with solder being the most temperature-sensitive part. One of the current versions involves lead-free soldering resistant to temperatures above 200 °C. This opens the doors to further scaling of the resonator to higher powers up to 100 W as seen in the experiments shown in the later chapter.

The improved fabrication procedure (etching the resonator from one single piece of flexible PCB), allows for precise resonance frequency control, routinely achieving a discrepancy below 3%, compared to Finite Element Method-based simulations. Various designs of the birdcage resonator have been tested, with broad range of resonance frequencies from units to hundreds of MHz. Figure 3 below displays an example of a performance of such a resonator. As the performance indicator, the S_{11} on the input of tuned and matched resonator is shown. The S_{11} parameters are recorded using a Vector Network Analyzer (Copper Mountain Technologies TR1300/1). The example resonator is designed to have a resonance frequency of 13.56 MHz of the fundamental mode ($k = 1$; with required field distribution). The real resonance frequency of the fabricated sample is 13.61 MHz, representing a difference of 0.4%. However, the performance of this particular resonator did not show to be competitive compared to other resonators operating on higher frequencies.

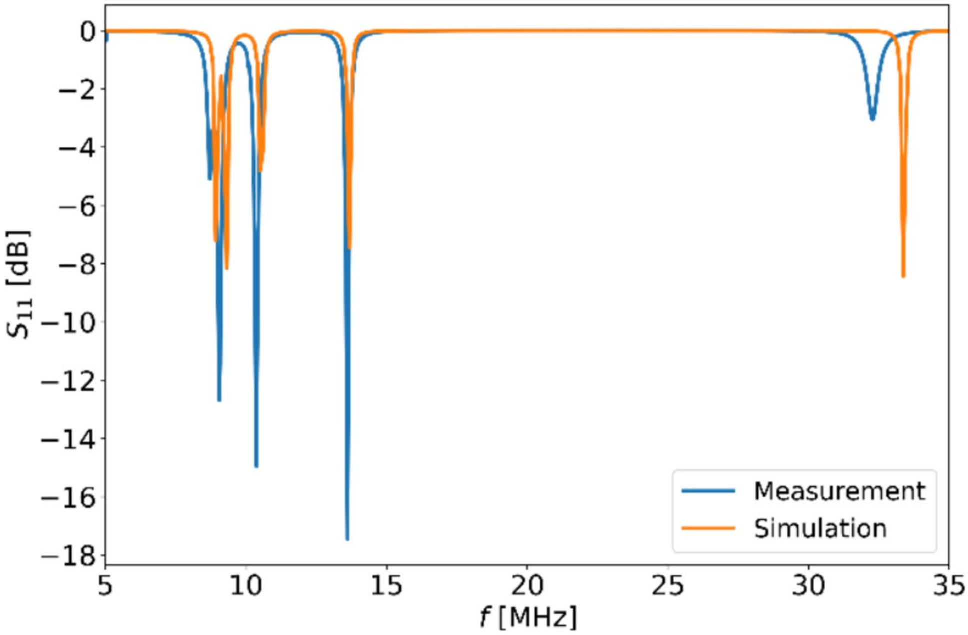
2.4 Diagnostics

The methodology of ion source performance estimation is currently restricted to extracted current measurements with the aim to conduct thrust balance measurements in the immediate future. If we assume the extracted ion beam is axially focused and dominated by singly charged ions, we can estimate thrust T, thrust-to-power ratio T/P, and extraction efficiency η from the ion current.

$$T \approx \frac{I_{\mathrm{ext}}}{q_{\mathrm{e}}} m_{\mathrm{i}} v_{\mathrm{i}}, \tag{1}$$

where q_{e} is the elementary charge, m_{i} represents the ion mass and the exhaust velocity v_{i} is denoted as follows:

Fig. 3 Performance of the novel birdcage resonator (simulation vs. measurement comparison)



$$v_i = \sqrt{\frac{2q_e V}{m_i}}, \tag{2}$$

with V representing extraction voltage applied between grids. The extraction efficiency may be estimated as the ratio of beam electrical power and forward power:

$$\eta = \frac{I_{ext} V}{P_{fwd}}. \tag{3}$$

The authors of this contribution are aware of the limitations imposed by such estimations. The ion beam divergence, presence of multiply charged species, and grid ion optics effects are not considered. To reflect this, a detailed model of ion optics is currently in development.

On the other hand, the measured I_{ext} values are supported by an independent Global Plasma Model (GPM). It predicts the performance of the device based on input parameters such as pressure, forward power and magnetic field strength – see in greater detail in [19].

The expressions (1) and (3) provide a convenient way to benchmark the performance from the limited diagnostics currently available. However, they should be regarded as upper bounds rather than exact performance values until thrust balance measurements become available.

3 Results

3.1 Simulation predictions for VLEO operation

Before describing the laboratory experiments and achieved results, we briefly summarize the DSMC and global plasma modelling used to define the target operating envelope for the ABEP source.

DSMC simulations (Fig. 4) with parabolic intake indicate compression ratios up to 50, leading to internal chamber pressures in the 5–10 mPa range for ambient pressure values near 0.1 mPa [17]. The drag force affecting the satellite was estimated at approximately 1 mN. It must be noted that the simulated geometry was smaller and lighter than conventional satellites, omitting solar panel arrays and payload mass, meaning the reported drag force value must be understood as a lower bound. The simulations were conducted using the dsmcFoam + solver, an open-source extension of the OpenFOAM software framework. OpenFOAM was originally developed by OpenCFD Ltd. and is now maintained by the OpenFOAM Foundation and other contributors.

Although the compression ratio between the mean pressure in the ionization chamber and the ambient pressure has reached only 50 during simulation, many recent advancements in intake design record triple or higher compression ratios [20]. It is therefore reasonable to assume that the pressure in the ionization chamber might reach the order of 10^{-2} Pa, provided a suitable intake is employed. A separate study performed with an older version of the GPM mentioned above has also reached the conclusion that the potential ABEP system may operate only if the internal pressure in the thruster exceeds approximately 5 mPa [21]. These limits obtained from two separate numerical simulations were put to test in laboratory conditions using the latest version of the breadboard model.

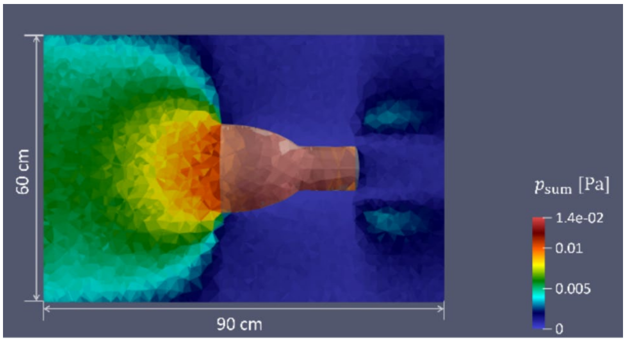


Fig. 4 Total gas pressure at 175 km of altitude–parabolic configuration [17]

3.2 Experimental ignition at VLEO pressures

As of the latter half of 2024, the current laboratory breadboard model is capable of plasma ignition using N_2/O_2 mixture and successful plasma confinement at pressures as low as (10 ± 3) mPa which are theoretically achievable in VLEO.

3.3 Performance estimates based on ion current

Using the scaling relations of Tisaev et al. [22] the required thrust-to-power ratio for a representative 0.03 m^2 VLEO platform orbiting at ca. 175 km is approximately 23 μ N/W, which we adopt as a reference for comparison. Rest of the target values stem from recent requirements imposed by ESA. The full comparison is presented in Table 1.

The parameters were estimated using extracted current values $I_{ext} = (2.5 \pm 0.1)$ mA measured at 10 W of forward power P_{fwd} (approximately 2 W of reflected power P_{ref}) via Eqs. (1–3) and should be interpreted as upper-bound performance estimates pending direct thrust measurements.

Due to limitations of the previous versions of the laboratory device, only 10 W of power used to be achievable. However, the current power scaling allows for up to 100 W of forward power, potentially enabling us to reach the target values summarized in Table 1. Since the prototype has been optimized for low power levels (1–10 W of forward power), a power scaling investigation is conducted to analyze how resonator performance varies at higher power levels.

Table 1 Evaluation of the current prototype: comparison of estimated/measured and target values

Quantity	Target value	Estimated/measured value	Status
Operating pressure	≤ 10 mPa	(10 ± 3) mPa	Demonstrated successful plasma ignition and confinement at target pressure
Thrust-to-power ratio	$> 23\,\mu$ N/W	$(6 \pm 0.24)\,\mu$ N/W	Improvement by factor 4–5 needed (achievable by optimizing the extraction setup)
Total thrust	2.5 mN	N/A	Estimated drag from DSMC simulations, possible to reach at higher powers (500 W) provided power scaling and efficiency is maintained
Extraction efficiency	25%	(20 ± 0.8) %	Goal almost reached for 1000 V acceleration voltage

3.4 Resonator power scaling and thermal detuning

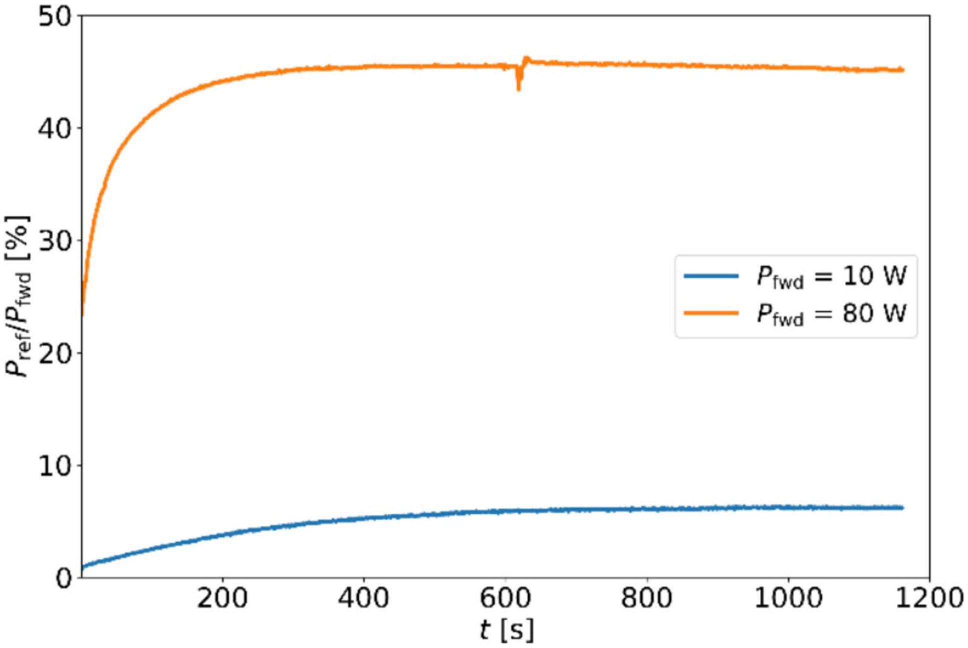
The modular design of the laboratory device supports scalability in dimensions and forward power, currently promising an increase in efficiency with an increase in the respective parameters. To examine the scalability of the birdcage resonator concept, the plasma source is operated at different RF power levels in the range of 10 to 100 W. At these power levels, the heat effects start to play a significant role. The initial tests have been carried out without an applied magnetic field and with atmospheric pressure inside the discharge channel, i.e., under conditions where plasma is not ignited. In the presence of plasma (representing the load), the peak impedance of the resonator is substantially reduced [23]. Without plasma, no energy is dissipated into the discharge, and consequently higher resonant currents flow through the birdcage resonator. This results in increased ohmic losses and, therefore, elevated temperatures. Such a condition represents the worst-case scenario for the thermal resistance of the resonator, which can occur either in the absence of plasma or immediately prior to plasma ignition.

Especially at higher RF powers, we observe an increase in the reflected power. Figure 5 shows a ratio of reflected and forward power for two different levels of forward powers (10 W and 80 W) and its change in time while keeping the same driving frequency. At lower forward power, the ratio is slowly reaching the stable value of approx. 5%. On the contrary, using higher forward power results in a sharp increase in the relative reflected power, stabilizing the ratio at 45%, meaning the resonator is no longer attuned correctly in respect to the original driving frequency.

This behavior is assumed to be predominantly caused by thermal effects. Considering the capacitor stability of ± 30 ppm/°C [24] and a maximum operating temperature of 200 °C, the total capacitance change can be estimated at approximately ±0.5% which leads to a shift in the resonance frequency.

Therefore, a follow-up experiment is conducted using a heat gun to heat up the whole discharge channel with the birdcage resonator. S_{11} is then recorded while the resonator cools down. During this time period, we observe a shift in the frequency corresponding to the minimum of reflected

Fig. 5 Comparison of reflected to forward power ratio development over time for two different forward powers



power. Before the experiment (and when the resonator is cooled down), we can achieve a fine impedance matching with $S_{11} = -33.8$dB at the driving frequency. Conversely, S_{11} rises to − 6.4 dB at the same frequency, when the resonator is heated up.

For future operations with high RF powers, specific measures need to be considered. The driving frequency may be set to reach satisfactory reflection for both cold and hot states (as we can see in Fig. 6, there is such a region, where S_{11} holds below − 10 dB). Additionally, the frequency of operation may also be changed after the start-up of the source. A different approach to the manufacturing process might provide a solution by utilizing higher temperature-resistant materials or replacing components that are highly sensitive to heat variations.

4 Discussion

The presented findings identify both the feasibility of electrodeless ignition at VLEO representative pressures and the engineering limits imposed by resonator heating.

Compared to helicon and cathode-based ABEP prototypes, our ECR approach occupies a distinct design niche. Helicon thrusters rely on inductive coupling to produce high-density plasmas but require high stability RF chains and are susceptible to wall interactions. RF ion engines benefit from well-established grid extraction but at the cost of additional subsystems such as dedicated cathodes and multiple RF drivers. In contrast, the MHz-range birdcage resonator provides electrodeless ignition at VLEO-representative pressures with a comparatively simple RF architecture. Its present limitations are linked not to ignition but to efficient ion extraction and thermal stability at higher powers. By experimentally identifying these bottlenecks, the current work complements numerical studies and extends the landscape of viable ABEP architectures.

Performance scaling remains constrained. Extracted currents are an order of magnitude below mission requirements, and resonator detuning limits efficient power transfer at higher RF levels. Addressing these two challenges: efficient ion extraction and thermal stability, will be central to maturing the concept.

5 Conclusion and outlook

This paper presents the recent developments in the project aiming to design and develop a low-pressure ionizer for ABEP systems.

The demonstrated repeatable plasma ignition and sustained operation at 10 mPa provides direct experimental validation that ABEP systems can operate in VLEO-representative conditions. DSMC and GPM models establish feasibility ranges for intake compression and ignition thresholds. Experimental results confirm ignition within predicted pressure ranges.

However, a preliminary assessment of the extraction performance based on extracted ion current has yet to reach the target values necessary for achieving feasible drag compensation. To meet this goal, the resonator must maintain (or exceed) the reported extraction efficiency while operating on higher powers. The resonator power scaling study shows that the shift of the optimal frequency for ignition due to thermal

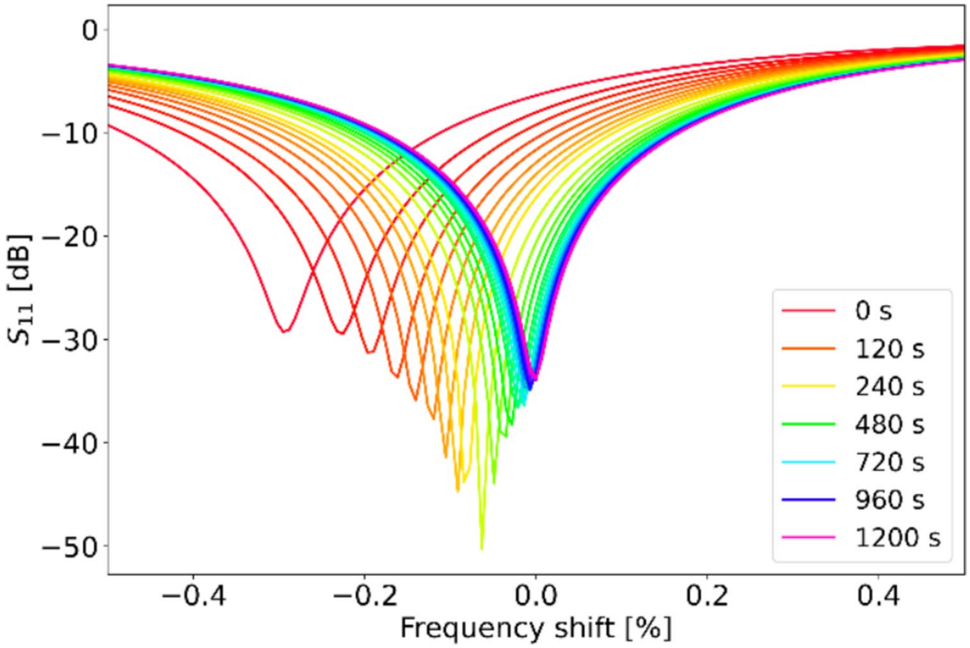


Fig. 6 Shift in the frequency corresponding to the minimum of reflected power during the cooling of the resonator. The room temperature resonance

effects must be considered when optimizing the device for high power operation.

In future work, we will conduct extracted ion current measurements across various power levels to determine whether favorable scaling and efficiency are maintained throughout the high-power range. Additionally, direct thrust measurements are underway to validate or challenge our estimated performance claims.

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Author contributions M. Š., K. M., and K. J. jointly wrote the main manuscript text and played leading roles in the experimental efforts and numerical simulations. P. D. and A. O. provided valuable feedback on both the project development and the manuscript. J. S., L. H., and M. N. contributed primarily to the technical aspects of the project, particularly through the design and servicing of experimental devices. All authors reviewed and approved the final manuscript; frequency is taken as 0.0% reference.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare that there are no competing interests.

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