# Advancing Space Propulsion: Development of a State-of-the-Art Electric Thruster Testing Facility in the United Arab Emirates

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**Abstract:** **Testing of electric propulsion thrusters requires specialized facilities that can accommodate high vacuum and high-power systems. This paper provides an overview of the development of a new facility in the United Arab Emirates to test electric propulsion thrusters. The facility, located at the Technology Innovation Institute (TII), Abu Dhabi, is currently being designed to support the development and testing of a wide range of electric propulsion thrusters. The central components of the facility are three vacuum chambers with an integrated thrust measurement test stand, augmented by state-of-the-art clean rooms and comprehensive mechanical and electronics workshops. Best in class diagnostics will be implemented in the test vacuum facility to full characterize engine performance. The new TII facility will be a valuable resource for the space community, enabling researchers and engineers to study and optimize the performance of these critical technologies. In addition, the facility will supplement other existing UAE testing facilities (Mechanical, TVT, EMC). Therefore, future space projects can benefit from a full testing cycle to verify spacecraft functionality and performance. The TII SEP facility will support research and development efforts aimed at improving the efficiency, reliability, and performance of electric propulsion thrusters, helping to advance the state of the art in space propulsion systems.**

## I. Introduction

IN In recent years, the paradigm of model-based systems engineering (MBSE) has become increasingly prevalent, emphasizing the use of simulation tools for design, analysis, and optimization across various engineering disciplines. However, within the realm of spacecraft electric propulsion, particularly concerning Hall effect thrusters, the transition to simulation driven approaches has been constrained by the inherent complexities of these systems. While simulation plays a crucial role in understanding and predicting the behavior of Hall effect thrusters, most improvements are still found through extensive experimentation. The intricate interplay between plasma dynamics, electromagnetic fields, and thruster geometry presents significant challenges in developing comprehensive computational models that can reliably replicate real-world performance. Consequently, reliance on experimental validation and testing persists as a fundamental aspect of advancing our understanding and capability in spacecraft electric propulsion. Despite ongoing efforts to enhance simulation techniques and computational models, the empirical validation of these simulations through rigorous experimentation remains indispensable for ensuring the reliability and effectiveness of Hall effect thrusters in space missions.

Several factors, discussed below, contribute to the difficulty in accurately modeling Hall effect thrusters. The behavior of the plasma inside the thruster chamber is highly complex and nonlinear. Plasma instabilities, ionization

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and recombination processes, charge exchange collisions, and plasma-wall interactions, are challenging to model accurately due to their dependence on numerous parameters, including magnetic field strength, propellant properties, and operating conditions[2]. Hall effect thrusters rely on the interaction between electric and magnetic fields to accelerate ions. Modeling these electromagnetic fields accurately requires complex numerical simulations, which can be computationally intensive and prone to numerical errors, especially near the thruster walls where boundary effects are significant [8]. Modeling different geometries, magnetic field configurations, and electrode layouts is challenging, as small variations in geometry or operating conditions can have significant effects on performance and efficiency [14].

Many physical processes occurring within Hall effect thrusters, such as electron transport, ionization, and plasma-wall interactions, involve inherent uncertainties and simplifications in modeling assumptions. These uncertainties can propagate throughout the simulation, leading to discrepancies between modeled and observed behavior[3]. Experimental data can help validate modeling assumptions and improve understanding of processes and key variables. In the field of electric propulsion, testing and experimentation plays an equivalently important part as modeling. In summary, while significant progress has been made in modeling Hall effect thrusters [16] for spacecraft electric propulsion, the complexity of plasma dynamics, electromagnetic fields, thruster design, and limited experimental data, present ongoing challenges. Researchers continue to work towards improving the accuracy and reliability of computational models to better understand and optimize the performance of Hall effect thrusters. Despite progress in computation modeling methods and improvement in calculation speeds, empirical validation through testing still provides indispensable insights into the behavior and capabilities of these propulsion systems under real-world conditions. The value and importance of testing and experimentation can be summarized by:

**Validation of Performance Metrics:** Testing allows for the direct measurement and validation of performance metrics such as thrust, specific impulse, and efficiency. This validation ensures that the propulsion system meets the specified requirements for the intended mission.[10]

**Verification of Computational Models:** Testing provides experimental data required to validate and verify computational models used in the design and analysis of electric propulsion systems. Comparison of experimental results with model predictions helps ensure the accuracy and reliability of simulations.[7]

**Identification of Operational Limits:** Testing helps identify operational limits and failure modes of electric propulsion systems. By subjecting the system to various operating conditions and stress tests, engineers can assess system limits and identify potential failure modes.[5]

**Optimization of System Design:** Through testing, engineers can iterate on the design of electric propulsion systems to optimize performance and efficiency. Testing different configurations and components allows for the identification of design improvements that enhance overall system performance.[9]

**Risk Mitigation**: Testing helps mitigate the risks associated with deploying electric propulsion systems in space. By conducting comprehensive testing on the ground, engineers can identify and address potential issues before they pose a risk to the success of a space mission.[13]

Testing spacecraft electric propulsion systems is essential for verifying performance, validating computational models, identifying operational limits, optimizing design, and mitigating risks for space missions. These factors collectively contribute to the overall success and reliability of electric propulsion systems in space exploration.

## II. Key Driving Requirements

Important stakeholders in the UAE, such as government agencies, industry and research institutions, recognize the importance of developing electric propulsion systems for spacecraft. This interest is driven by the strategic initiative to assert the UAE's leadership in space exploration and promote the country to a prominent position in the global space industry. By investing in the development of electric propulsion technology, the UAE aims to improve its capabilities in designing, manufacturing, and operating spacecraft that can carry out missions for Earth Observation in LEO, enable new ways to reach the Moon and explore the Solar System beyond. Based on the above strategic statements, we have established the following requirements:

**LEO satellites:** The facility shall be capable of designing and developing electric propulsion systems for satellites up to 250kg in weight to enable new methods of Earth Observation (EO) constellation control.

**Lunar exploration:** The technology shall enable capability to reach and explore the Moon

**Solar System exploration:** The facility shall be capable of conducting research, development and testing of engines to enable interplanetary transfers

**State-of-the-art facility:** The facility shall be capable of measuring key parameters of the propulsion system: thrust levels, Specific Impulse, properties of the exhaust plume, provide estimates for lifetime and reliability of the electric propulsion system.

## III. Laboratory Design

The Propulsion and Space Center (PSRC) of the Technology Innovation Institute (TII) is currently building a new facility to feature a cutting-edge laboratory dedicated to development of spacecraft electric propulsion (SEP) technology. The PSRC facility occupies a 4000m$^2$ space dedicated to labs, office and all other needs. The SEP laboratory will occupy 500m$^2$, which will allow ample space to conduct state-of-the-art research and experiments in electric propulsion technology.

The laboratory is equipped with advanced infrastructure, including vacuum chambers, power supply units, diagnostic tools, and computational resources, to facilitate comprehensive studies on SEP systems. Moreover, the facility shall feature environmental controls to ensure optimal experimental conditions. Precise ISO level of the lab cleanliness is still under consideration as a trade-off exists between space part qualification requirements and total cost of the facility. To ensure quality of research and products as well as safety in the lab, ECSS (European Cooperation for Space Standardization) standards will be used to guide our activities.

The lab layout is straightforward. All the noisy equipment (turbomolecular pumps, cryogenic stations, water chillers etc) will be installed in a separate room with soundproofing. A monorail crane beam will help to place equipment and service or replace it when necessary. The main testing room will have 3 vacuum chambers (known as VC1, VC2 and VC3, description below), as well as test preparation workbenches. The chambers will be situated in a clean room with one transparent wall, to allow visitors to observe preparations and testing. Right next to the testing facility is a 42m$^2$ full-scale electronics lab. This will allow servicing of the PPU (Power Processing Unit) as well as implementing simple electronics tests. A mechanical workshop will be situated next to the Electronics lab. This layout will allow all the necessary adjustments to the propulsion system to be performed in the vicinity of the testing stands, therefore optimizing workflow.

## IV.Equipment Requirements

### A. Vacuum chambers

**VC1:** The chamber will be used to conduct short term testing of high thrust engines (≥100mN), or long term testing of smaller (e.g. 15-30mN) engines. VC1 shall allow continuous uninterrupted testing (> 1000hours) of an electric propulsion thruster of up to 150 mN maximum thrust. This chamber will be capable of testing more powerful thrusters (albeit for a short time) destined for interplanetary missions.

**VC2:** The VC2 chamber will be the main workhorse for the experiments to be conducted in the lab. Currently, the specification calls for accommodation of a thruster with a maximum power of 2kW and maximum thrust level up to 85mN. The construction of the chamber shall allow uninterrupted testing of more than 1000 hours at the 85mN thrust level. This chamber shall satisfy requirements for thrusters intended for Earth Observation (EO) missions and will allow experiments for lunar transfers.

**VC3:** The VC3 chamber will be used for testing and developing thruster sub-assemblies such as cathodes. The chamber shall also be configurable as a SEP thruster environmental test facility for thermal vacuum testing of SEP components (such as hollow cathodes or PPUs).

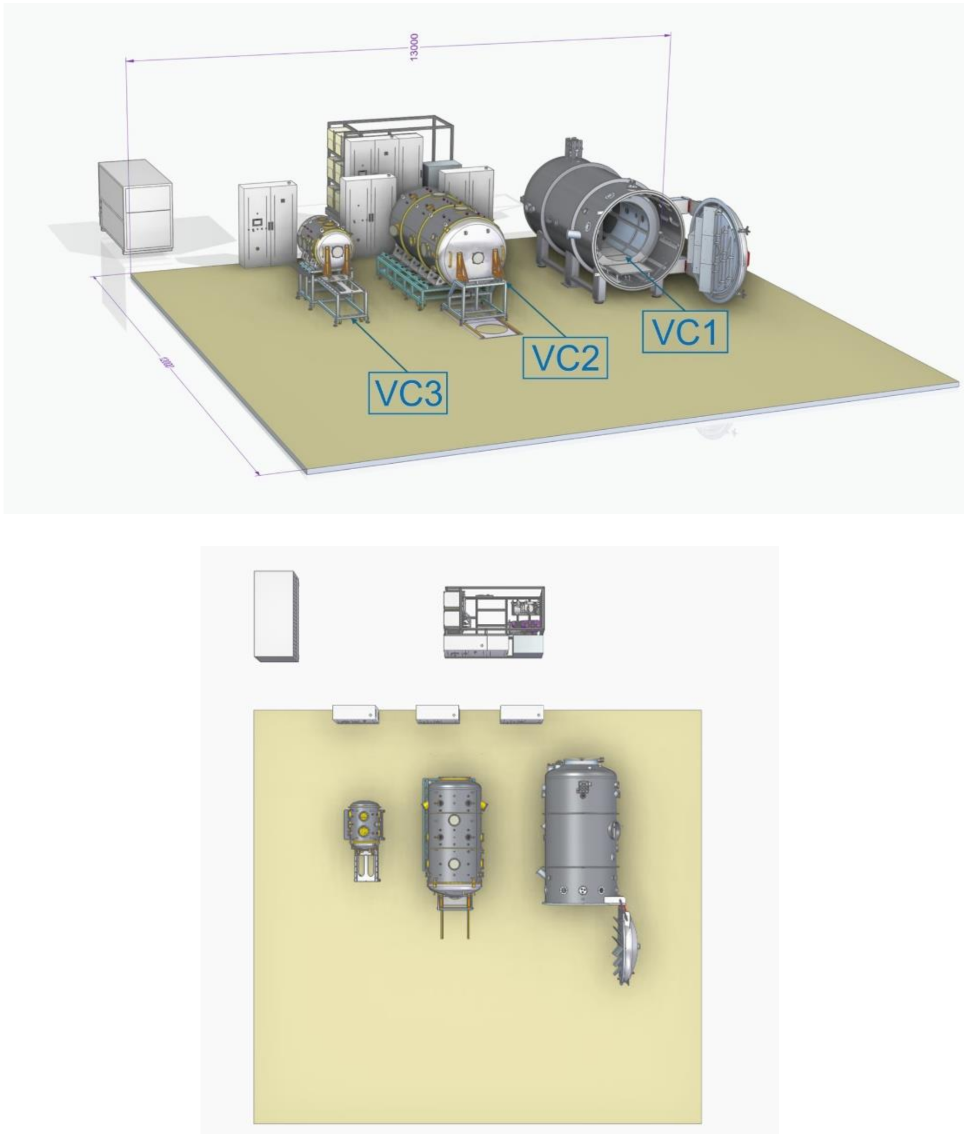


**Figure 1. Conceptional drawings of vacuum facilities and test stand area.**

### B. Vacuum facility diagnostics

The laboratory will be equipped with a comprehensive suite of instrumentation and equipment dedicated to characterizing spacecraft electric propulsion thrusters. This includes state-of-the-art thrust balances capable of accurately measuring the thrust output of thrusters under various operating conditions. Additionally, the lab will feature advanced diagnostic tools such as Faraday cups, Retarding Potential Analyzers (RPAs), mass spectrometers and Langmuir probes, enabling detailed analysis of the propellant ionization process, the resulting plasma properties and characterization of the thruster beam. The facilities will also incorporate optical grade windows to enable thruster plasma remote characterization via high-resolution optical and spectroscopic diagnostic systems. Furthermore, the laboratory will house sophisticated data acquisition systems capable of capturing and analyzing performance data in real-time, facilitating precise measurement and evaluation of thruster efficiency metrics such as specific impulse and thrust-to-power ratio. The following equipment is currently planned:

**Thrust Measurement Stand:** Thrust measurement serves as a fundamental indicator of the propulsion system's performance, providing essential feedback for validating theoretical models and optimizing operational parameters. A pendulum-based system will be implemented with a relatively long measurement shoulder to enhance measurement precision. Direct thrust measurement of the engine's developed thrust is crucial to the evaluation of Hall effect thrusters since highly controlled and precise thrust is necessary for satellite positioning, attitude control, de-orbiting, target pointing, and relative maneuvers in formation flying. Moreover, future mission requirements call for increasingly fine thrust resolution and low thrust noise figures, which will need to be reflected in the design of thrust balances used to characterize these engines. VC1 and VC2 (described above) will be specifically designed to accommodate high precision thrust measurement stands.

**Thruster Plume Measurement:** Ion density measurements in the thruster plume provide insights into the behavior of the plasma generated within the thruster, offering data on the distribution and concentration of ions in the exhaust plume. Accurate quantification of ion density profiles will provide information on: thruster efficiency and stability, identification of potential instabilities or anomalies, and refinement of the thruster design to maximize performance and reliability. These measurements will also aid in computational model validation of electric propulsion systems under study.

**High Resolution 3D Scanner:** With scanning accuracy of less than 0.005 mm, this device will provide critical information on thruster lifetime by quantifying erosion following endurance testing.

### C. Supporting equipment

In addition to specialized instrumentation for characterizing thruster efficiency, the laboratory will be equipped with essential Ground Support Equipment (GSE) to facilitate comprehensive testing and evaluation of propulsion systems. These supporting devices include Electrical Ground Support Equipment (EGSE) which comprise of high-performance power supplies capable of delivering precise and stable electrical power to the thrusters and cathodes, ensuring reliable operation and accurate performance measurement. Test control systems will enable researchers to automate, monitor and store data of experimental procedures, providing precise control over test parameters and ensuring reproducibility of results. Furthermore, the laboratory will feature Fluidic Ground Support Equipment (FGSE) designed to safely store and accurately supply the requisite propellants, such as Xenon, Krypton or Argon gas, to the thrusters during testing. The FGSE will incorporate safety features and regulatory compliance measures to mitigate risks associated with handling and storage of propellants. The following equipment is currently planned:

**FGSE:** Initial testing is planned using Xenon as propellant, with Argon and Krypton being candidates for future testing of alternative propellants. The FGSE shall provide storage and exact feeding of gaseous propellant to Hall Effect Thruster anode and cathode neutralizer units.

**EGSE:** The EGSE element includes the design, procurement and assembly of bespoke power supply racks to power and control the thruster (or thruster component) experiments with requisite interlocks and safety features. The EGSE data acquisition system will also control and log the thruster diagnostics. All data will be stored in a central database and visualized during and after the experiment.

**Test stand control system:** The control system is tasked with management and supervision of the facility, performing the following functions: Management, both manual and automatic, of the units (pumps, valves, water cooling, etc.) related to maintenance of required vacuum level in the chamber. Monitoring of all relevant test vacuum chamber parameters. Data logging and download of the data and Plant safety interlocks.

## V. Case Studies

### A. Earth observation satellites

In recent years, spacecraft electric propulsion has emerged as an important technology for the maintenance and optimization of low Earth orbit (LEO) satellite constellations. A compelling case study of its application can be observed in the context of satellite constellation maintenance, where traditional chemical propulsion systems face limitations in fuel efficiency and operational flexibility. By integrating electric propulsion systems into LEO satellites, operators can achieve significant advantages due to the higher total impulse extracted from the same mass of fuel stored onboard. This capability is particularly crucial for large-scale LEO constellations comprising hundreds or thousands of satellites, where precise positioning is essential for optimal coverage and connectivity services. Current projections indicate significant future demand for EO small satellites (mass less than 250kg) employing a thruster of 5 to 30mN class with an specific impulse greater than 2000s.

One notable example of the application of spacecraft electric propulsion in LEO constellation maintenance is SpaceX's Starlink project. Leveraging Hall effect thrusters powered by solar arrays, Starlink satellites utilize electric propulsion for precise orbit adjustments, constellation reconfiguration, and end-of-life disposal maneuvers. The use of electric propulsion technology enables Starlink satellites to maintain optimal orbital positions with minimal propellant consumption, maximizing operational efficiency and extending satellite lifetimes. As a result, spacecraft electric propulsion plays a central role in enabling the scalability, agility, and cost effectiveness of the Starlink project, demonstrating its efficacy in revolutionizing satellite constellation maintenance, and enabling global connectivity solutions.

### B. Solar System exploration

Spacecraft electric propulsion has been used extensively to enable lunar and interplanetary missions by offering propulsion solutions for extended-duration missions with significant delta-v requirements. The SMART 1 mission stands as a pioneering example of spacecraft electric propulsion being employed for interplanetary exploration. Launched by the European Space Agency (ESA) in 2003, SMART 1 [11] utilized a Hall effect thruster for its journey to the Moon. SMART 1's successful arrival at the Moon in 2004 validated the effectiveness of electric propulsion technology for enabling cost-effective and sustainable interplanetary missions.

For interplanetary missions, a notable example is NASA's Dawn [12] spacecraft, which utilized ion propulsion for its mission to study the protoplanet Vesta and the dwarf planet Ceres in the asteroid belt. Equipped with three xenon ion engines, Dawn became the first spacecraft to orbit two extraterrestrial bodies. The Dawn mission demonstrated the feasibility of using electric propulsion for long-duration interplanetary missions, significantly reducing transit times and enabling close-up observations of multiple celestial bodies within a single mission. The Psyche mission [1, 4] represents another example of spacecraft electric propulsion being utilized for interplanetary exploration. Launched in 2022, Psyche is currently on route to its name-sake asteroid. The Emirates Mission to the Asteroids, which targets to visit 6 asteroids on its way to 269 Justitia, will also employ a Hall Effect thruster for some of the trajectory maintenance maneuvers and proximity operations.

## VI. Conclusion

In conclusion, the paradigm of model-based systems engineering (MBSE) underscores the importance of simulation tools for spacecraft electric propulsion system design, analysis, and optimization. However, the intricate nature of Hall effect thrusters, characterized by complex interactions among plasma dynamics, electromagnetic fields, and thruster geometry, poses significant challenges to simulation driven approaches. Despite ongoing advancements, the fidelity and accuracy of simulations remain largely experimental, necessitating empirical validation through rigorous testing. The Technology Innovation Institute's Propulsion and Space Center (TII/PSRC) recognizes the critical role of experimental validation in ensuring the reliability and effectiveness of Hall effect thrusters in space missions, underscoring the need for continued efforts to enhance simulation techniques and computational models.

Testing spacecraft electric propulsion systems is indispensable for verifying performance, validating computational models, and mitigating risks associated with space missions. Through empirical validation, valuable insights are gained into the behavior and capabilities of these propulsion systems under real-world conditions. TII shall invest into development of a state-of-the-art facility that will feature 3 vacuum chambers, dedicated for monitoring processes in thrusters, equipped with supporting measurement systems and other necessary equipment for research and development of SEP thrusters and propulsion systems.

The development of spacecraft electric propulsion systems at the PSRC is driven by key requirements identified by stakeholders in the UAE, including government agencies, industries, and research institutions. These requirements aim to assert the UAE's leadership in space exploration and promote the country to a prominent position in the global space industry. The PSRC's Spacecraft Electric Propulsion lab (SEPLab), equipped with advanced infrastructure and instrumentation, will enable the development of electric propulsion systems for Earth observation satellites, Lunar exploration, and interplanetary missions. Guided by use cases spanning from Earth orbit to the edge of the Solar System, the PSRC is committed to meeting these requirements and advancing electric propulsion technology. The design of the lab will be completed in 2024 and by 2026 construction is expected to be completed with laboratory activities commencing.

The establishment of the PSRC's dedicated laboratory for spacecraft electric propulsion system development represents a significant step towards fostering innovation, enhancing capabilities, and ensuring the reliability and effectiveness of electric propulsion systems for diverse applications in space exploration. Through comprehensive testing, empirical validation, and adherence to rigorous standards, the PSRC aims to contribute to the advancement of electric propulsion technology and enable future space exploration missions. The PSRC's efforts align with the strategic goals of stakeholders in the UAE, positioning the country as a leader in space exploration and advancing the frontiers of science and technology.

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