European Interparliamentary Space Conference (EISC)

European Space Agency

Space for Sustainability Award

2025 Edition

Space-Rated Plasma Actuation

ESA's sustainability strategy promotes safer, greener, and more efficient space access. Current systems face challenges in thermal loads, flow separation, and high emissions. Plasma actuators—solid-state devices that control airflow via electromagnetic forces—offer a compact, low-power solution with no moving parts. Ariane-class case studies show payload gains of 250 kg to GTO. Plasma actuation can reduce up to 26 t CO_2, 10 t H_2O, 330 kg black carbon, and 70% NO_x per launch. The technology aligns with SDG 12 (Responsible Consumption) and SDG 13 (Climate Action), and is developed in accordance with ESA's Ecodesign Loop and ECSS standards for reuse, environmental performance, and end-of-life recyclability. This project proposes the development and commercialisation of space-rated plasma actuators, which is the current pursuit of Fusion Dynamics Corporation, a spin-up to the space sector within the ESA UK BIC programme.

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1. Background

ESA is deeply committed to the sustainable development of the space sector, recognizing its indispensable role in Europe's future. ESA's sustainability commitment is structured around three core pillars: Space Safety, Applications, and Enabling & Support, all aimed at ensuring accessible space and fostering future technologies [1]. Plasma actuators directly align with these pillars by enhancing safety during ascent and re-entry, enabling more efficient and environmentally friendly space applications, and fostering the development of innovative technologies for future space access.

Europe's commitment to global sustainability frameworks is evident in the alignment of the EU's climate strategy and Green Deal with the UN 2030 Agenda and its Sustainable Development Goals (SDGs) [2]. Technologies that enhance the sustainability of space activities, such as those reducing the environmental footprint of space missions (e.g., lower emissions, less debris), directly contribute to SDGs related to climate action (SDG 13) and responsible consumption and production (SDG 12). Plasma actuators, by reducing fuel consumption and enabling lighter spacecraft, directly contribute to these environmental SDGs.

A sustainable space sector yields profound societal, economic, and environmental benefits for Europe. Space technologies are fundamental for economic growth, scientific advancement, national security, and societal resilience [3]. Investment in space programs supports Europe's broader transition towards a "Green Economy" and strengthens its competitive edge [4]. Cleaner, more efficient space access, facilitated by plasma actuators, not only generates direct economic benefits but also contributes to environmental goals by reducing the carbon footprint of launch and re-entry activities. Societally, advancements that enhance space safety, such as safer re-entry procedures and reduced communication blackout periods, directly contribute to societal resilience by protecting critical infrastructure and human life.

2. Project Idea Description

Plasma actuators are innovative, solid-state electronic devices with no moving mechanical parts. This design, shown in Fig. 1, represents a significant departure from conventional aerospace control surfaces, offering higher reliability, lower maintenance, and extended operational life. The core operational mechanism involves generating localized, cold plasma jets by applying a high-voltage alternating current across two thin electrodes separated by a dielectric insulating material [5]. This plasma directly interacts with the surrounding airflow, transferring momentum and heat via electromagnetic forces, enabling precise, real-time control over aerodynamic characteristics. Plasma actuation benefits from a fast response time, low mass, cost, and power due to its compact and integrated design, efficiently converting electrical energy directly into kinetic and thermal energy without mechanical intermediaries.

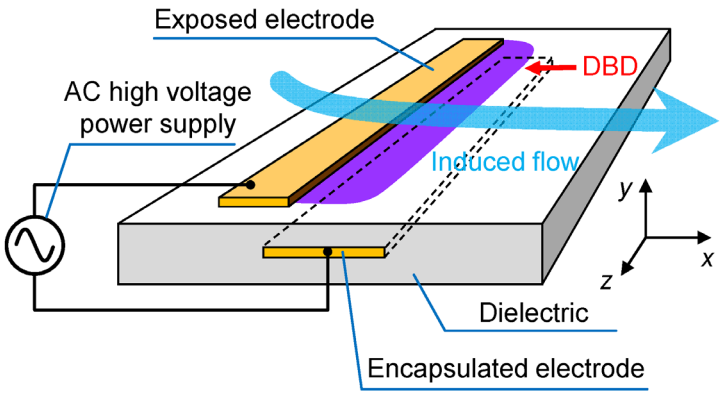

Fig.1: Schematic of a Dielectric Barrier Discharge Plasma Actuator [24]

2.1. Aeroheating and Re-entry Control

Conventional re-entry vehicles face significant challenges related to aeroheating and re-entry control, primarily due to their reliance on mechanical control surfaces. These traditional systems lead to localized heating, high mechanical and thermal stress concentrations, and substantial weight penalties, often accounting for 10-15% of the vehicle's total mass. Their mechanical complexity introduces numerous points of failure, increasing structural risks and maintenance requirements. Plasma actuators offer a transformative solution to these challenges by interacting with the surrounding air flow without moving mechanical parts.

Their core mechanism involves manipulating shockwaves, with research demonstrating shockwave displacement of up to 25% of the undisturbed distance [5, 6]. This displacement significantly increases the shock stand-off distance, the gap between the vehicle's surface and the bow shockwave. By increasing this distance, plasma actuators effectively reduce convective heat flux by 11-18% [5, 7]. This reduction in heat transfer is crucial as it allows for the use of lighter and thinner Thermal Protection Systems (TPS), which typically constitute a significant portion of a re-entry vehicle's mass. A 50% reduction in boundary layer thickness at supersonic speeds further contributes to lowering heating loads [5]. The combined impact of reduced convective heat flux and boundary layer thinning can cut ablative TPS mass by 6-9% [5]. This mass saving directly translates into a reduced launch mass, leading to decreased fuel consumption and a significant reduction in CO2 emissions per launch. The environmental benefits also extend to resource efficiency, as less ablative TPS material is consumed. Such efficiencies can result in savings ranging from £5-20 million per launch.

2.2. Challenges in Traditional Rocket Nozzles and Environmental Impact

Traditional rocket nozzles, particularly those designed for optimal performance in the vacuum of space, face challenges during launch through the lower atmosphere due to flow separation at low altitudes. Nozzles designed for vacuum-optimal expansion overexpand in the denser lower atmosphere, causing the exhaust plume to separate from the nozzle walls. This results in unsteady forces and structural risks, compromising vehicle stability. To mitigate this, conventional designs often use lower expansion ratios, which inherently reduce engine efficiency in vacuum by up to 15% [5]. This trade-off ensures stability at low altitudes at the cost of suboptimal performance and reduced efficiency during the majority of flight, leading to increased fuel consumption and limited payload capacity. Plasma actuators offer a transformative solution by enabling active control of flow separation, allowing for 20-25% higher expansion ratios without incurring risks at low altitudes. This capability maintains optimal flow attachment throughout ascent, significantly boosting vacuum-specific impulse by up to 15% [5].

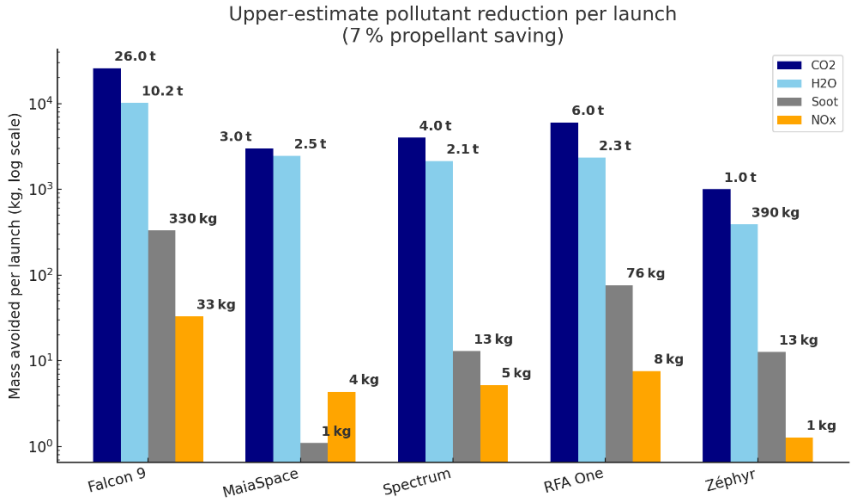

Fig 2: Reduction per launch for CO_2, H_2O, black carbon (soot) and NO_x across five reference vehicles in logarithmic scale

The enhanced vacuum-specific impulse leads to a 5-7% reduction in fuel consumption for first-stage engines. The power requirements for these actuators are remarkably low, typically less than 1% of a turbopump's output, making them a highly efficient addition to launch systems. The direct reduction in fuel consumption translates into significant cuts in CO2 emissions per launch. Figure 2 summarises the upper-bound reduction per launch for CO_2, H_2O, black carbon (soot) and NO_x across five reference launchers. When plasma actuation is used, CO_2 & H_2O are cut by the same fraction as the propellant, giving up to 26 t CO_2 and 10 t H_2O avoided on a Falcon 9-class flight. Moreover, up to 330 kg of black carbon (BC) - the largest non-halogen driver of catalytic ozone loss -) for Falcon 9 and 76 kg for RFDA one is eliminated. NO_x is also reduced in proportion to mass flow, delivering 30–70 % less reactive nitrogen injection into the stratosphere for kerolox stages. The impact of avoided Black Carbon into Ozone-Mass-Deficit (MOD) benefit, is also shown in Fig 3, using the well-established first-order scaling of 50 t of O_3 protected per kilogram of BC not emitted [16].

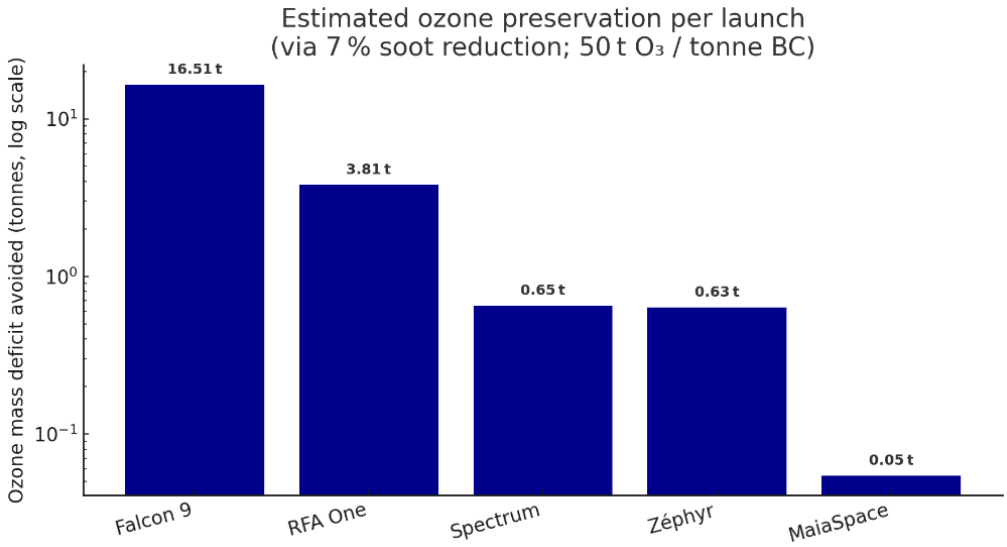

Fig 3 : Expected mass of Ozone preserved per Launch across five reference launch vehicles.

2.3. European Launcher Application Case: Ariane Rocket

Theoretical and computational studies demonstrate a compelling direct impact on launch vehicle performance for the Ariane 5-class launchers [9]. The improved propulsive efficiency, stemming from the ability to utilize higher expansion ratios and boost vacuum-specific impulse, can translate into an additional 250 kg of payload to Geostationary Transfer Orbit (GTO) [9], leading to launching a given payload with fewer missions.

Plasma actuators are adaptable to any bell-shaped nozzle and can be integrated by adding an extension containing the actuators. Developing entirely new rocket engines is capital-intensive and time-consuming. The ability to retrofit existing nozzles or easily adapt the technology to various designs significantly lowers financial and developmental barriers, avoiding costly engine redesigns. This ease of integration means performance and sustainability benefits could be realized faster across the European launcher portfolio, accelerating the transition to more efficient and environmentally friendly operations. A key advantage of plasma actuators is their remarkably low power requirement, ensuring efficiency gains are not offset by significant energy consumption. These systems typically demand less than 1% of a turbopump's output [5]. For instance, in the context of an Ariane 5's Vulcain 2 equivalent engine, the maximum power required for plasma actuators was 450 kW, representing approximately 3% of the turbopump's substantial 14 MW output [9]. This minimal energy demand simplifies integration and ensures a net positive energy balance.

3. Implementation

The commercialization of space-rated plasma actuators requires a structured, phased development plan emphasizing European collaboration and applicability. The initial phase must focus on advanced feasibility studies and the refinement of existing analytical and computational models. Current research indicates challenges related to altitude effects and high Mach number flow physics, particularly concerning the behaviour of Dielectric Barrier Discharge (DBD) plasma actuators in extreme low-pressure and high-temperature environments. Sustaining high space charge density and strong electric fields in supersonic and hypersonic flows remains difficult. At Mach numbers exceeding 5, molecular dissociation begins to occur, and at very high Mach numbers, stagnation point temperatures can reach 12500 K, leading to significant molecular dissociation and ionization [5]. These complex phenomena necessitate advanced theoretical models capable of accurately predicting plasma behaviour, momentum transfer, and thermal interactions across a broad range of reduced electric fields and varying atmospheric compositions.

Following model refinement, a critical step is comprehensive material qualification and prototype development. This phase addresses the severe thermal loads, bonding challenges [10], radiation exposure [11], and vibration environments inherent in space operations [5]. For aerospace applications, actuators must withstand cyclic temperature variations, typically ranging from −50°C to +125°C, with a recommended margin for robust design. Material selection is paramount to prevent plastic deformation due to differing coefficients of thermal expansion between components. Materials like Lexan FR for the dielectric, cold drawn copper for electrodes, and Aluminium 6061-T6 for the spacecraft surface can withstand these thermal stresses without yielding [5, 12].

Prototype development will then integrate these qualified materials into functional DBD actuator units. This includes addressing power requirements for high-Mach number flows, which can be significant, and mitigating potential material degradation under prolonged radiation exposure. The design of a variable power supply to maintain optimal performance across varying altitudes will be necessary. Rigorous ground testing is indispensable to validate the performance and durability of plasma actuator prototypes under simulated space environments. This includes subjecting units to extreme thermal vacuum, vibration, and acoustic tests that replicate or even exceed expected conditions during launch and re-entry. Following successful ground testing, flight qualification will involve in-flight demonstrations and extensive data collection.

3.1. Commercialization Strategy and European Collaboration

The commercialization strategy must address the current market landscape, which is primarily constrained by the absence of commercial suppliers and standardized components for space-rated plasma actuators. This project proposes to bridge this gap by developing and commercializing systems specifically tailored for space applications. European collaboration is fundamental to this endeavour. Leveraging the expertise and resources of entities like ESA, national space agencies, and major industry partners will be critical.

The European Cooperation for Space Standardization (ECSS) provides a framework for coherent, user-friendly standards for European space activities, facilitating the adoption and integration of new technologies like plasma actuators [10, 11, 14]. ESA's role in fostering private investment and commercialization, aiming to position Europe as a commercial space hub, will be instrumental in de-risking market entry and accelerating adoption [4]. Engaging proactively with regulatory bodies to establish clear frameworks for space traffic management, licensing, and environmental standards will also be vital for successful market integration.

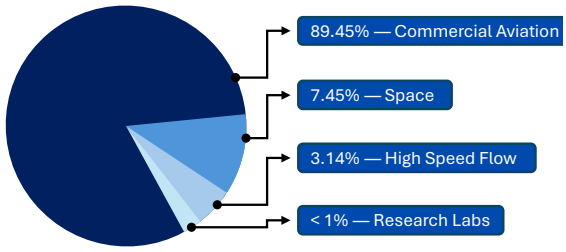

Fig 4.: TAM Market Segmentation

3.1. Ecodesign Integration

To ensure that plasma actuators are matured in a way that is both technically and environmentally sound, the programme will follow the ESA Clean Space “Ecodesign Loop”, which transposes the life-cycle-assessment principles of ISO 14040/44 into the European space-product assurance process. At the outset, a rapid hotspot analysis of the full launcher architecture will quantify the environmental burden of each subsystem so that measurable limits can be embedded in the engineering requirements [19]. During preliminary design, every material and process choice will be screened against the EU REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals, EC 1907/2006) to eliminate chromates, halogenated epoxies and per- and poly-fluoroalkyl substances.

The plasma-actuator assembly itself illustrates how the loop feeds into concrete design decisions. Because the device is solid-state and lubricant-free, it removes several REACH-listed hydrazine derivatives used in traditional flow-control mechanisms. Electrodes produced by cold-spray aluminium or recycled-copper inks on thin ceramic dielectrics can be delaminated and recycled at end-of-life, while the driver electronics are concentrated on a single halogen-free FR-L4 printed-circuit board (PCB) designed for “plug-and-replace” access. Reserving footprints for higher-rated components allows the same actuator strip to be re-flown on reusable first stages, fully aligned with the ECSS (European Cooperation for Space Standardisation) design-for-reuse clauses and the Technology-Readiness-Level (TRL) gate reviews [20]. When the 5–7 % propellant saving demonstrated in the performance analysis is fed back into the system-Life Cycle Assessment, the reduction in propellant consumption outweighs the modest footprint of the actuator hardware by more than one order of magnitude, confirming the ecodesign value of the proposed solution [22].

3.2. Business Development: Scalability, Feasibility, and Market Relevance

The development of space-qualified plasma actuators is positioned as an entrepreneurial solution within the Business Development track, focusing on scalability, feasibility, and market relevance, while integrating ecodesign principles from the outset to minimize environmental impact throughout the product lifecycle. The plasma actuator market is currently emerging, primarily constrained by the lack of commercial suppliers and standardized components. For this reason we incorporated Fusion Dynamics Corporation in May 2025, a limited company in the UK endorsed by the ESA UK BIC incubation programme (www.fusiondynamics.uk), to bridge this significant market gap by developing and commercializing plasma actuators tailored for demanding space applications.

The scalability of plasma actuators is inherent in their modular, solid-state design, allowing for integration into various spacecraft sizes and mission profiles, from small satellites to large launchers. Their low mass and minimal structural impact facilitate widespread adoption without extensive redesigns of existing platforms. The feasibility of this solution is underpinned by established technical viability in scientific literature, with ongoing research addressing current limitations. The proposed phased development plan outlines a clear path to commercial readiness.

From a market relevance perspective, demand for innovative flow control technologies is expected to grow steadily, driven by increasing regulatory pressures and funding initiatives that emphasize experimental reproducibility and advanced solutions. The global total addressable market for plasma actuators across various industries is conservatively estimated to be in the tens of millions of pounds annually, with a projected steady growth of 5-8% in the serviceable addressable market as new applications emerge. By directly contributing to reduced fuel consumption, lower CO2 emissions, and significant cost savings (£5-20 million per launch), this technology offers a compelling value proposition that aligns with Europe's strategic goals for a sustainable and competitive space sector. The Total Addressable Market (TAM) is the full revenue pool available worldwide if every space-sector customer adopted plasma-actuated flow-control devices, and is expected to be as high as £ 14.5 billion in 2025. The Serviceable Obtainable Market (SOM)—the slice realistically capturable in our first 3–5 years of operation—stands at approximately £ 0.44 billion. The segmentation of the TAM is illustrated in Figure 4.

4. Expected Results

The outcomes directly contribute to ESA's sustainability pillars and advance relevant SDGs. From an environmental perspective, the reduction in fuel consumption directly translates into significant CO2 emissions savings per launch. Lighter TPS and reduced fuel consumption contribute to more efficient use of resources, aligning with ESA's "Protect our Planet and Climate" pillar and SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [1]. Moreover, reduced launch mass means fewer resources are needed for the same mission, and improved re-entry control can lead to safer de-orbiting, contributing to the "Zero Debris Technologies" initiative [15].

The quantifiable benefits translate into significant economic savings, estimated at £5-20 million per launch. The development of space-rated plasma actuators addresses a current market gap, fostering the creation of a new, emerging market for advanced flow control technologies. This aligns with ESA's "Boost Growth and Competitiveness" pillar and the broader European goal of strengthening its space industry [4]. Enhanced efficiency and reduced costs bolster the competitiveness of European launchers and space missions in the global market. Improved re-entry control and potential reduction of communication blackout periods enhance the safety of re-entry operations, contributing to ESA's "Space Safety" pillar [1]. Increased payload capacity makes space more accessible for a wider range of scientific, commercial, and societal applications, aligning with ESA's "Applications" pillar [1]. By improving the reliability and safety of space infrastructure, plasma actuators indirectly contribute to societal resilience, as space systems underpin critical services like communication, navigation, and disaster management.

The report highlights two sustainability levers that align with ESA’s Green ESA and Zero-Debris objectives:

- Climate forcing: simultaneous cuts in CO_2, stratospheric H_2O and BC lower both long-lived and short-lived radiative forcing components.
- Ozone stewardship: kerolox vehicles, still prevalent in Europe’s emerging micro-launcher sector, realise tangible O_3 preservation gains (0.6–3.8 kt O_3 per launch) even at small scale.

5. Potential Risks and Mitigation Strategies

The commercialization of space-rated plasma actuators, while promising, is subject to both technical and commercial risks that must be systematically addressed. A primary technical challenge is maintaining a stable plasma discharge in the extremely low-pressure and high-temperature environments encountered during launch and re-entry. The effectiveness of the electrohydrodynamic effect diminishes at very high Mach numbers, and sustaining high space charge density and strong electric fields becomes difficult.

From a material perspective, space environments expose materials to severe thermal cycling, radiation, and vibrations, which can lead to degradation or failure of actuator components, particularly the dielectric material and bonding agents [5, 10, 11]. While plasma actuators are generally low-power compared to mechanical systems, the power requirements for effective flow control at very high Mach numbers or in specific atmospheric conditions can still be substantial and must be managed within spacecraft power budgets. At Mach numbers exceeding 5, the chemical and thermal properties of air are difficult to model and experimentally test. At these speeds, stagnation point temperatures can exceed the melting points of current dielectric materials.

Despite established technical viability, the absence of commercial suppliers and standardized components poses a significant hurdle to market adoption. Challenges include high development costs, limited initial market demand, and competition from established, albeit less efficient, mechanical systems. The evolving regulatory landscape for space activities in Europe, including upcoming EU Space Law, may introduce new licensing requirements, environmental standards, and space traffic management regulations that could impact commercialization efforts.

Mitigation strategies to address technical and commercial challenges in deploying plasma actuators in space environments include both near-term and long-term approaches. Technically, it is advisable to begin with applications in more manageable Mach number regimes, where molecular dissociation and extreme temperatures are less severe. Rigorous material qualification should be implemented, utilizing proven materials such as Lexan FR for dielectrics and cold-drawn copper for electrodes, while employing optimized geometries like ellipsoidal dielectric shapes to reduce stress concentrations [12]. Adaptive power supply systems that modulate electric field strength across varying altitudes and pressures can help maintain stable discharges and ensure reliable performance. Continued investment in fundamental plasma physics research is critical to better understand behaviour in extreme conditions, such as molecular dissociation and ionization, and to eventually expand the operational envelope to higher Mach regimes, potentially through the use of cooling systems or novel high-temperature dielectric materials, while recognizing trade-offs in mass and cost. Commercially, mitigation involves targeted R&D to overcome current actuator limitations, particularly at high velocities and in durability, aiming for systems that are truly space-qualified. Collaboration among ESA, national space agencies, and European industry—under frameworks such as ECSS—can foster shared expertise and standardized approaches [13,14]. Engaging proactively with European regulators will be essential to shape a harmonized framework for safety, security, and sustainability that supports innovation. Finally, forming strategic partnerships with established space companies and commercial launch providers can de-risk market entry, leverage established supply chains, and accelerate adoption of the technology [4].

6. Multidisciplinary Approach

The successful realization and commercialization of space-rated plasma actuators fundamentally necessitates a highly integrated, multidisciplinary approach. This complex endeavour transcends the boundaries of any single engineering or scientific domain, requiring the synergistic integration of diverse expertise:

- **Plasma Physics:** Essential for understanding and optimizing fundamental mechanisms of plasma generation, discharge stability, and momentum transfer in varying atmospheric conditions and flow regimes, particularly at high Mach numbers and low pressures.
- **Fluid Dynamics:** Critical for modelling and predicting interaction between generated plasma and surrounding airflow, including boundary layer modification, shockwave displacement, and flow separation control, as well as assessing aerodynamic performance and heating loads.
- **Materials Science:** Indispensable for selecting, developing, and qualifying advanced dielectric and electrode materials capable of withstanding extreme thermal cycling, radiation, and mechanical stresses encountered in space environments. This includes expertise in bonding and long-term material degradation.
- **Electrical Engineering:** Necessary for designing and optimizing high-voltage power supplies, control electronics, and power management systems required to generate and sustain plasma.
- **Mechanical Design:** Crucial for structural integration of plasma actuators into spacecraft architectures, ensuring robust, lightweight, and aerodynamically optimized designs that can withstand expected vibration and loads.
- **Business Development:** Vital for navigating the emerging market landscape, identifying commercial opportunities, developing viable business models, securing funding, and establishing strategic partnerships.

Ultimately, successful commercialization hinges on a cohesive strategy that integrates technical feasibility with market viability. This holistic approach is the pathway to transform laboratory-proven concepts into reliable, space-qualified systems that deliver tangible benefits for European space sustainability.

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