

Article

Development and Testing of a Helicon Plasma Thruster Based on a Magnetically Enhanced Inductively Coupled Plasma Reactor Operating in a Multi-Mode Regime

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Abstract: A disruptive Electric Propulsion system is proposed for next-generation Low-Earth-Orbit (LEO) small satellite constellations, utilizing an RF-powered Helicon Plasma Thruster (HPT). This system is built around a Magnetically Enhanced Inductively Coupled Plasma (MEICP) reactor, which enables acceleration of quasi-neutral plasma through a magnetic nozzle. The MEICP reactor features an innovative design with a multi-dipole magnetic confinement system, generated by neodymium iron boron (NdFeB) permanent magnets, combined with an azimuthally asymmetric half-wavelength right (HWRH) antenna and a variable-section ionization chamber. The plasma reactor is followed by a solenoid-free magnetic nozzle (MN), which facilitates the formation of an ambipolar potential drop, enabling the conversion of electron thermal energy into ion beam energy. This study explores the impact of an inhomogeneous magnetic field on the heating mechanism of the HPT and highlights its multi-mode operation within a pulsed power range of 200 to 500 W of RF. The discharge state, characterized by high-energy electron-excited ions and low-energy excited neutral particles in the plasma plume, was analyzed using optical emission spectroscopy (OES). The experimental testing campaign, conducted under pulsed power excitation, reveals that, as RF input power increases, the MEICP reactor transitions from inductive (H-mode) to wave coupling (W-mode) discharge modes. Spectrograms, electron temperature, and plasma density measurements were obtained for the Helicon Plasma Thruster within its operational envelope. Based on OES data, the ideal specific impulse was estimated to exceed 1000 s, highlighting the significant potential of this technology for future LEO/VLEO space missions.

Keywords: helicon waves; inductive mode; wave-heated mode; space propulsion; half-wavelength right helical antenna; radio-frequency energy



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1. Introduction

The rise of new space business models has created a highly competitive environment for Electric Propulsion (EP) systems, driving the need for advancements in reliability, performance, cost-effectiveness, and flexibility. Specific strategic applications, such as Earth Observation missions in both Low-Earth-Orbit (LEO) and Very Low-Earth-Orbit (VLEO) orbits, demand innovative propulsion technologies capable of delivering high thrust and specific impulses over extended operational periods. These systems must also be compact, lightweight, and efficient in order to address the unique challenges posed by such missions.

Hall Effect Thrusters (HETs) and Gridded Ion Thrusters (GITs) have proven highly successful in the low to medium power range, showcasing their effectiveness across a

variety of space missions, including the BepiColombo mission [1], the Hayabusa 1 and 2 missions [2,3], the SMART-1 mission [4], and the Dawn mission [5].

In HETs and GITs, ions are electrostatically accelerated and expelled alongside an equivalent flux of electrons from neutralizers, ensuring zero net current is released from the system. Under these conditions, the coupling of direct current (DC) electric power with plasma within these thrusters poses significant challenges, particularly regarding the exposure of the electrodes in both the thruster and neutralizer to damaging effects such as ion sputtering and thermal loading [6]. These issues raise concerns regarding the longevity of these thrusters, prompting efforts to extend their operational lifespan through advanced designs. For instance, the 7 kW class NEXT ion thruster has operated for nearly 50,000 h in ground tests [6]. However, as critical components such as ion-acceleration grids and hollow cathode neutralizers remain limiting factors, extending the operational lifetime of both HETs and GITs will pose a major challenge in the near future.

In the context of extending the operational lifetime of EP systems, HETs and GITs face significant challenges, primarily due to critical components such as ion-acceleration grids and hollow cathode neutralizers. The degradation of these components during prolonged operation can significantly limit the lifespan of the thrusters. As mission profiles demand higher performance and longer operational durations, addressing these limitations will be crucial for the future development of reliable and durable propulsion systems. Innovations in materials and design, as well as alternative approaches to neutralization and ion acceleration will be essential in overcoming these challenges.

To address the limitations of existing EP systems—such as reliance on hollow cathode neutralizers, high-voltage acceleration grids, and a restricted selection of propellants—a novel concept is proposed to enhance the performance of LEO/VLEO modern spacecraft. This innovative approach aims to improve efficiency, simplify design, and broaden propellant compatibility, leading to more effective and adaptable propulsion solutions for space applications. Various types of electrodeless plasma thrusters (PTs) have emerged as potential disruptors to current technologies, including the Helicon Double Layer Thruster (HDLT) [7,8], the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [9], the High Power Helicon (HPT) thruster [10,11], the Helicon Hall Thruster (HHT) [12,13], and the Electron Cyclotron Resonance Thruster (ECRT) [14]. These designs collectively represent a significant shift towards robust and high-performance propulsion systems that are suitable for a wide range of space missions. Table 1 highlights the advanced research on RF-powered propulsion technology conducted by different research groups worldwide.

Table 1. Performance metrics of different HPTs with RF powers below 1000 W [15].

Authors	Group	Year	P_{RF} (W)	F (mN)	I_{sp} (s)	$\frac{F}{P_{RF}} \left(\frac{mN}{kW} \right)$	$\eta\%$	Prop
Takahashi et al. [16]	Tohoko	2011	900	3	510	3.3	0.8	Ar
Pottinger et al. [17]	Surrey	2011	650	2.8	286	4.3	0.6	Kr
Takahashi et al. [18]	Tohoko	2011	800	6	816	7.5	3	Ar
Takahashiet et al. [19]	Canberra	2012	800	5	680	6.3	2.1	Ar
Takahashi et al. [20]	Tohoko	2013	1000	11	1559	11	8.4	Ar
Williams et al. [21]	Atlanta	2013	600	6	136	10	0.7	Ar
Harle et al. [22]	Surrey	2013	400	1.1	187	2.8	0.3	Ar
Oshio et al. [23]	Tokyo	2017	1000	6	510	6	1.5	Xe
Siddiqui et al. [24]	Phase Four	2017	100	5	146	50	3.6	Xe
Trezzolani et al. [25]	Padova	2017	150	1.4	714	9.3	3.3	Xe
Siddiqui et al. [26]	Phase Four	2018	440	6.2	1350	14.1	9.3	Xe

Fully electrodeless Electric Thrusters (ETs) have emerged as disruptive propulsion systems, characterized by several advanced features, including high plasma densities, low electron temperatures, extended operational lifetimes, flexible propellant options, scalable power outputs, and a compact, simple design [27]. Helicon Plasma Thrusters (HPTs) based on Magnetically Enhanced Inductively Coupled Plasma (MEICP) reactors show consid-

erable potential in meeting the growing demand for efficient and sustainable propulsion solutions in the space sector. This technology can provide continuous, precise propulsion metrics over prolonged periods, making it ideal for applications such as station keeping, orbit raising, constellation flights, and deep-space exploration. Market segmentation [28,29] reveals a diverse range of customer groups, including satellite manufacturers, space agencies, and private space exploration companies, each with unique requirements. Innovative EP systems that address these specific segments are essential for market participants looking to capitalize on growing opportunities in the rapidly evolving space industry. In the context of “new space business”, HPTs based on multi-mode MEICP reactors offer a novel solution to the challenges associated with LEO/VLEO missions, as illustrated in Figure 1.

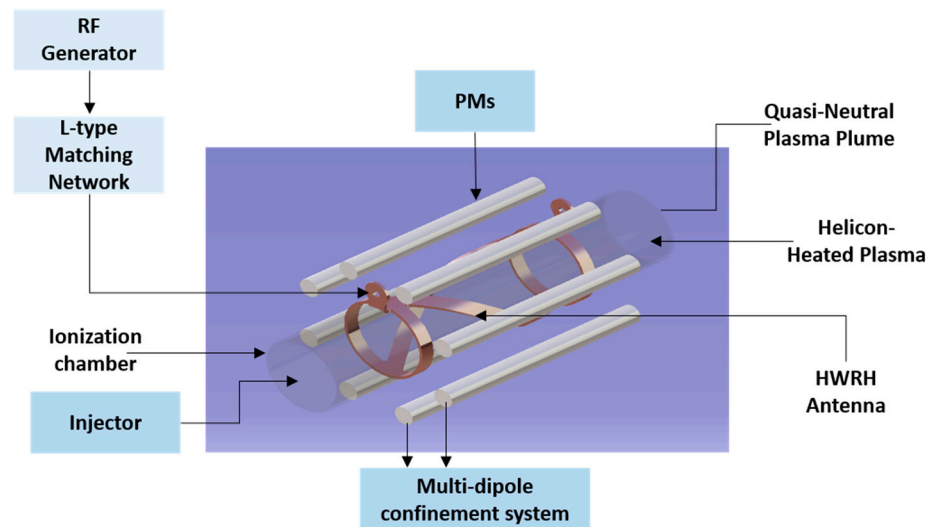


Figure 1. Block diagram of a HPT based on MEICP reactor and inhomogeneous magnetic field.

Its compact form-factor, combined with high specific impulse capabilities, enhances its potential for in-space commercialization and exploration initiatives. Furthermore, the thruster’s extensive thrust throttleability allows for effective adaptation to atmospheric density fluctuations, optimizing propulsion metrics in varying operational environments.

Helicon-heated plasmas offer multiple benefits for space propulsion applications, including the ability to maintain stable high-density plasmas (ranging from 10^{12} to $\div 10^{13} \text{ cm}^{-3}$), high ionization efficiency, operation at low magnetic fields, independent control of ion and electron, energies and low-pressure operation [30].

A Helicon Plasma Thruster based on a compact MEICP reactor operates at frequencies near the hybrid resonance, which lies between the ion and cyclotron frequencies, with low external magnetic fields (50–1200 G) [28]. This capability is sustained across a wide operational range, accommodating different scales, working gasses, and RF antenna designs. The primary challenges associated with wave-heated discharges, particularly in MEICS, involve optimizing plasma generation sources to establish a competitive EP system. Achieving optimal propulsion efficiency requires a comprehensive assessment of key parameters that influence plasma power absorption, such as RF supply power, magnetic field strength, neutral pressure, and antenna configuration. Effective RF power transfer and deposition are essential for generating highly ionized, dense plasmas even in low magnetic field conditions. In addition, it is crucial to ensure that all subsystems and components remain simple, lightweight, and robust. The HPT must also exhibit a wide range of thrust throttleability to adapt to various mission profiles. Finally, extending the operational lifespan in LEO and VLEO environments is of utmost importance.

Due to several inherent challenges, including robustness, RF antenna design, wave coupling efficiency, wave propagation, and wave absorption, MEICP reactors utilizing helicon waves are among the most complex heating systems to miniaturize effectively.

This article presents findings from an experimental testing campaign conducted on a compact HPT breadboard model specifically designed for spacecraft operation in LEO and VLEO environments. The study focuses on operational regimes characterized by low magnetic fields (<400 G) and a moderate power envelope (<600 W) in a pulsed wave mode (PWM) operation.

To address the deep-throttling requirements and multiple thrust vectoring capabilities of a fully electrodeless plasma thruster, this research aims to validate the multi-mode operation of an MEICP reactor complemented by a magnetic nozzle (MN) acceleration scheme.

This paper is structured as follows: Section 2 provides a survey of various power absorption mechanisms present in a HPT, particularly one featuring a compact MEICP reactor. It also discusses a critical element of multi-mode operation, the Helicon to Whistler (H-W) transition, which significantly influences the thruster's overall performance metrics. Section 3 ensures a detailed description of the HPT breadboard architecture and an overview of its design point. Section 4 addresses the test setup and the experimental testing campaign of the HPT in a PWM. Section 5 presents the measurement results obtained from the HPT tests, drawing conclusions based on the data. The results provide critical insights into the thruster's performance, validating its design and highlighting areas for potential improvement.

2. Multi-Mode MEICP Reactors Theoretical Background

The next-generation of LEO solar-powered spacecraft imposes extended control capabilities, including initial orbit and final orbit insertion, phasing, and station keeping, followed by orbit maintenance, re-phasing, and attitude control. A HPT based on MEICP reactors and the MN acceleration scheme is engineered to provide a versatile operational envelope based on MEICP reactors and the MN acceleration scheme for the future commercialization of both LEO and VLEO orbits. This flexibility supports both short pulses and steady-state operation, with magnetic fields that closely replicate the optimal conditions for helicon-wave excitation.

To develop compact EP systems based on a fully electrodeless architecture, it is essential to have a comprehensive understanding of the wave–plasma coupling mechanisms and their synergistic relationships with propulsion metrics and plasma parameters. Low-frequency whistler waves, commonly known as helicon waves, appear within a distinct area of the Clemmow-Mullaly-Allis (CMA) diagram. This particular region is defined by an operational frequency (ω) that lies between the lower hybrid frequency (ω_{LH}) and the electron-cyclotron frequency (ω_{ce}) while remaining much lower than the plasma frequency [31]. The operation of the HPT is analyzed through a self-consistent model that integrates power balance, particle balance, and the structure of the RF field. In the MEICP reactor, power deposition is governed by the RF field structure, which is defined by the excited eigenmode. The operational resonance frequency is such that the eigenmode arises from electron response, irrespective of ions influence. When the helion waves propagate near resonance cone angle ($\theta_{res} = \cos^{-1}(\omega/\omega_{ce})$) [32], plasma density peaks in the MEICP reactor. An RF-driven HPT using a HWRH antenna can generate right-rotating RF fields, causing free electrons to oscillate at a frequency dictated by the static magnetic field.

A global model (GM) of RF-driven HPT, relying exclusively on energy and particle balance, has been proposed to predict the steady-state electron temperature and density as function of the input parameters [33]. Furthermore, this GM is not influenced by the specific plasma excitation methods and has been used in the preliminary design of the MEICP reactor. Nevertheless, the GM cannot foresee certain peculiarities of the helicon-heated plasmas, such as abrupt transitions between different modes, necessitating experimental validation. Using a helicon-pulsed excitation technique, the proposed RF-driven electric thruster exhibits distinct behaviors based on the power levels and density thresholds. The MEICP reactor performs in either Capacitively Coupled Plasma (CCP or, E-mode) or Inductively Coupled Plasma (ICP or H-mode) at low and medium power levels. At high power levels, above 500 W, the plasma reactor may transition to Wave Coupled Plasma

(WCP), known as the helicon mode. One of the distinctive characteristics of argon MEICP source discharges is the mode transition, marked by a significant increase in electron density as RF power or magnetic field strength increases. The W-mode induction occurs in a capacitive E-mode due to the voltage drop across the azimuthally axisymmetric HWRH antenna. When exposed to moderate power, the reactor of the HPT transitions into an inductive H-mode [34,35]. This is distinguished by the generation of an oscillating magnetic field in the antenna, which, in turn, induces the electric field that sustains the discharge. An optimal level of RF input energy is required to satisfy the dispersion relation of the helicon wave. This operating point is associated with a state of resonance when the wavelengths of the HWs match the demands for the cavity modes. At low plasma densities, the MEICP reactor is dominated, but beyond a certain plasma density threshold, the W-mode becomes dominant [11,36]. This transition is often marked by the emergence of a centralized blue core (BC) that is influenced by the antenna geometry, magnetic confinement configuration, and the relative positioning of reactor components.

The specific impulse is proportional to the square root of the internal plasma energy, thus requiring high plasma temperatures. Optimal thrust efficiency, on the other hand, requires effective wave–plasma energy conversion, significant plasma heating, and efficient transformation of internal energy into directed axial energy while minimizing plume divergence [28,29].

From an operational perspective, a compact HPT utilizing an MEICP reactor in the 500 W power class predominantly transfers Radio Frequency (RF) energy via helicon and Trivelpiece–Gould (TG) waves throughout the plasma volume. This energy is subsequently converted into directed axial energy by an MN, enabling efficient thrust generation [6].

Helicon waves, which are low-frequency whistler waves in magnetized plasma, exhibit different characteristics in bounded environments compared to free space. While whistler waves in free space are right-circularly polarized electromagnetic waves, their behavior changes in a radially bounded axial reactor. In such configurations, helicon waves generate short-wavelength electrostatic components, known as TG-modes [37]. Shamrai et al. [38–42] propose that the strong collisional damping of the TG wave plays a critical role in facilitating effective power absorption within the plasma. This damping mechanism enhances wave–plasma interactions, thereby improving energy transfer efficiency in the system.

Between the lower hybrid and electron cyclotron frequencies ($\omega_{LH} < \omega \ll \omega_{ce}$), the wave refractive index may be expressed as follows [43]:

$$N^2 = \frac{k^2 c^2}{\omega^2} = \frac{\omega_p^2}{\omega(\omega_{ce} k_z / k - \omega)}, \quad (1)$$

where ω , ω_{ce} , and ω_p are the excited angular, cyclotron, and electron plasma frequencies, c is the speed of light, and k , k_z , and k_r are the total, longitudinal, and transverse wave numbers, respecting the equality of $k = (k_r^2 + k_z^2)^{1/2}$.

Shamrai et al. and Taranov [41] propose that the dispersion relation for a magnetized inductively coupled plasma can be effectively represented by a biquadratic equation, enabling a comprehensive analysis of the wave propagation characteristics within such plasma environments. This formulation helps to better understand the complex interactions between the plasma and electromagnetic waves under varying conditions [44]:

$$k_r^{2\pm} = k_{\parallel}^2 \frac{1}{2\gamma^2 \alpha^2 \beta^2} \left(1 - 2\gamma\alpha - 2\gamma^2 \alpha^2 \beta^2 \pm \sqrt{1 - 4\alpha} \right), \quad (2)$$

where,

$$\alpha = \frac{\omega_p^2}{\omega_{ce}^2 N^2}, \quad \beta = \frac{\omega \omega_{ce} N^2}{\omega_p^2}, \quad \gamma = 1 + i \left(\frac{\nu}{\omega} \right), \quad (3)$$

with ν being the electron collision frequency between the neutral particles and ions and N_z being the longitudinal refractive index. Equation (2) underlines that there are two values of k_r related to the fast and slow waves branch; k_r^- corresponds to the FWB (helicon) perpendicular wave number and k_r^+ corresponds to the slow waves branch (SWB) Trivelpiece—Gould perpendicular wave number. For helicon waves to propagate in a plasma, the condition for the bracketed term in Equation (2) must be positive, happening when $\beta < 1$ or $\omega_p^2 > \omega\omega_{ce}N_z^2$. Assuming, $N_z = ck_z/\omega$, the parameters α and β can be expressed as follows:

$$\alpha = \frac{\omega_p^2\omega^2}{c^2\omega_{ce}^2k_z^2}, \quad \beta = \frac{\omega\omega_{ce}c^2k_z^2}{\omega_p^2\omega^2}, \quad (4)$$

According to reference [45], α is inversely proportional to the square of the applied magnetic field ($\alpha \propto n_0/(B_0^2k_z^2)$). Helicon waves propagate radially outward from regions of higher plasma density to lower plasma density, with parameters β and α playing critical roles in defining the wave's propagation characteristics. Specifically, for helicon waves, $\beta \sim 1$ indicates that the plasma density is sufficiently high for efficient wave propagation and $\alpha = 1/4$ corresponds to the boundary conditions associated with the lower and higher cutoff frequencies for helicon waves.

In the proposed HPT, radial non-uniformities are influenced by the cusped magnetic field configuration, leading to distinct propagation characteristics for helicon and TG waves within the plasma. These waves propagate in the interior of the plasma when $\alpha < 1/4$ and $\beta > 1$. The SWB (TG waves) propagates in the outer region of the plasma under similar conditions of $\alpha < 1/4$, $\beta > 1$. As the external magnetic field strength increases, a clear separation between the helicon and TG waves becomes apparent. This separation allows for the distinct operational modes of the thruster. Notably, there exists a natural mode confluence at critical magnetic field strengths corresponding to the conditions where to $\alpha = 1/4$ and $\beta \sim 1$ [46].

In high magnetic fields, helicon (H) and TG waves display distinct characteristics, but as the magnetic field strength decreases, their wave patterns converge, allowing for significant mode coupling between the two waves and facilitating energy transfers [45,47]. The helicon waves, also referred to as the fast waves branch (FWB), can propagate within a specific density range, as outlined in the work of Shamrai et.al and Taranov [41].

$$n_{Low} = \frac{m}{4\pi e^2}\omega\omega_{ce}N_z^2 < n < n_{Up} = \frac{m}{16\pi e^2}\omega_{ce}^2N_z^2 \quad (5)$$

n_{Low} represents the cutoff for the helicon wave; at n_{Up} , the fast waves branch (FWB) merges with the SWB, known also as the TG-mode. According to references [40,48], the propagating electromagnetic wave (FBW) transitions into an electrostatic resonance (SWB) when the two waves converge at the condition $\alpha = 1/4$, where $k_r^- = k_r^+$ [35]. Unlike the helicon mode, which demonstrates maximum field strengths along the discharge axis, the electric field associated with the TG-mode is primarily localized near the plasma's radial boundaries. In ultra-compact helicon reactors, the generation of plasma is significantly enhanced through the interaction between the helicon wave and the dissipative TG-mode, which then transfers energy to the plasma electrons, promoting continuous ionization and sustaining the plasma state. The helicon and TG waves operate through distinct channels of RF input, facilitating power deposition in various regions of the plasma column. TG waves experience significant damping, primarily depositing energy in a narrow surface layer of the plasma. This surface power input channel is particularly evident when the plasma source operates outside the anti-resonance regime, thereby enhancing overall power transfer and plasma generation [49,50]. At high magnetic fields, helicon (H) waves penetrate deeply into the plasma due to their low damping, while TG waves experience stronger damping and remain localized near the plasma edge, resulting in distinct propagation characteristics [45,47].

The efficiency of converting helicon waves into TG waves is significantly determined by the plasma's density distribution and collisions rate. In high-density plasma, TG waves dominate power absorption at the plasma boundary, while Helicon waves primarily facilitate heating in the core. This complementary absorption pattern leads to a more balanced energy distribution within the plasma, enhancing overall heating performance. Mode conversion [35,45,51] between helicon and TG waves primarily occurs through two key mechanisms: surface mode conversion at the plasma boundary and bulk mode conversion within the plasma core. Bulk conversion happens near the mode conversion surface, where the properties of helicon and TG waves intersect, significantly influencing plasma behavior, shaping its density profile, and enhancing the efficiency of energy absorption from external sources [39,42].

Effective plasma generation in an MEICP reactor is achieved through volume oscillations that are resonantly excited by antennas configured for an azimuthal mode of $m = +1$. This mode enables optimal coupling of the RF power into the plasma, enhancing the overall plasma density and stability. Considering Ohm's law and the waves expressed in the form of $\sim \exp(i(kz - \omega t + m\theta))$, the magnetic components of the bounded helicon waves B can be represented using Bessel functions [52]. When the wave is confined within a reactor of radius R_r , the boundary conditions for the wave, assuming $k_z \ll 1$, can be derived from the following equation:

$$\frac{\omega \omega_p^2}{\omega_{ce} k_z^2 c^2} \frac{m}{k_r R_r} J_m(k_r R_r) + J'_m(k_r R_r) = 0, \quad (6)$$

where θ is the angle of the helicon wave propagation relative to the magnetic field, J_m and J'_m are the Bessel function and its derivative with respect to argument, and m represents the helicon wave azimuthal mode number. In the case of the $m = +1$ operating mode, the lowest Bessel root is $k_r R_r = 3.83$, imposing that $k_r \ll k_z$, and Equation (5) becomes [44]:

$$\frac{3.83}{R_r} = \frac{\omega}{k_z} \frac{\mu_0 e n_0}{B_0} \propto \frac{\omega}{k_z} \frac{n_0}{B_0} \quad (7)$$

with μ_0 and e being the magnetic permeability of the vacuum and the electric charge.

Equation (7) highlights a linear relationship between the plasma density (n_0) and the external magnetic field (B_0) for a fixed mode, where both the angular frequency ω and the axial wave vector k_z are held constant. This suggests that plasma density is approximately proportional to magnetic field strength ($n_0 \propto B_0$) [43]. As the magnetic field increases, the plasma density tends to rise, indicating that the magnetic field significantly influences the ionization and overall characteristics of the plasma.

This correlation is essential for optimizing plasma conditions in various applications, including EP systems, where precise control over plasma density is crucial for performance.

One peculiar characteristic of the MEICP reactor dedicated to a HPT is the operating mode transition from the inductive (H-mode) to the helicon wave (W) mode [53,54]. Generally, the H-W transition is associated with sharp changes in plasma impedance and a jump in the plasma density. Research by Degeling et al. [55] has demonstrated that, under specific operational conditions, the helicon mode exhibits pronounced ionization effects, particularly near the center of the plasma. This strong ionization is closely linked to the presence of helicon waves, which facilitate enhanced energy transfer and electron heating within the plasma. As a result, the H-W transition not only alters the operational dynamics of the plasma but also plays a crucial role in optimizing the performance of the HPT, ensuring efficient propulsion capabilities. Achieving a significant increase in plasma density—especially following mode transitions—relies heavily on the effective design of RF antennas in a helicon reactor. Various antenna configurations have been proposed to optimize this process, including loop antennas, double saddle coils, Nagoya Type III antennas, spiral antennas, birdcage antennas, and half-helix antennas [56]. As electromagnetic waves are expressed as a combination of the Bessel function, the choice of

antenna geometry plays a critical role in determining the azimuthal mode numbers and the associated electromagnetic field distributions, which are essential for maximizing energy transfer to the plasma. Thus, ongoing research and development in antenna design are crucial for enhancing the performance of helicon plasma systems and achieving the desired operational outcomes.

The geometry of the RF antenna used to excite helicon waves within the MEICP reactor is a critical factor, as it directly influences the azimuthal mode number m . This mode number, which characterizes the spatial variation in the electromagnetic fields within the plasma, affects the efficiency of wave coupling and energy deposition. The azimuthal mode number essentially governs the distribution of the electromagnetic fields around the reactor, thereby impacting the overall performance of the plasma source. The HWRH antenna's helicity is specifically designed to optimally couple with the right-hand circularly polarized ($m = +1$) helicon mode (Figure 2), generating an electrostatic field that rotates in space in synchrony with the $m = +1$ mode as it propagates parallel to B_0 [57].

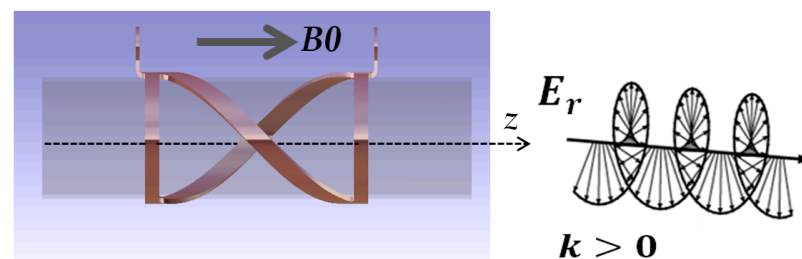


Figure 2. Representation of the electric field pattern of the $m = +1$ azimuthal mode in an MEICP reactor.

3. Development Strategy of a HPT Based on MEIC Plasma Reactor

The most significant figures of merit in EP systems are specific impulse, thrust efficiency, and thrust-to-weight ratio. The first two figures are closely tied to the characteristics of the plasma discharge. Specific impulse (I_{sp}) is directly proportional to the square root of the plasma's internal energy, meaning that achieving a high specific impulse requires a high plasma temperature. A higher internal energy translates to higher exhaust velocities, increasing specific impulse and improving propellant efficiency. Achieving high thrust efficiency involves several key factors. First, efficient wave–plasma energy conversion from the antenna is critical to ensuring that the maximum amount of input energy is transferred to the plasma. Second, efficient plasma heating is essential to raising the plasma's internal energy, which contributes to higher specific impulse and thrust. Finally, the system must effectively convert the internal energy of the plasma into directed axial energy, which propels the spacecraft. Minimizing plume divergence is crucial in this process, as it ensures that most of the energy is directed in the desired direction, maximizing thrust and overall efficiency. Table 2 outlines the HPT requirements.

Table 2. Helicon Plasma Thruster requirements.

Power Class	500 W
Thrust	10 mN
Specific Impulse	>1000 s
Plasma Density	$10^{12} \div 10^{13} \text{ cm}^{-3}$
Propellant Flow Rate	8 – 20 sccm
Operating Frequency	13.56 MHz
Electron Temperature	3 ÷ 5 eV

The proposed HPT is engineered with a multi-stage architecture, as illustrated in Figure 3. This architecture is strategically divided into two interdependent stages that work in synergy: the plasma ionization stage and the plasma acceleration stage.

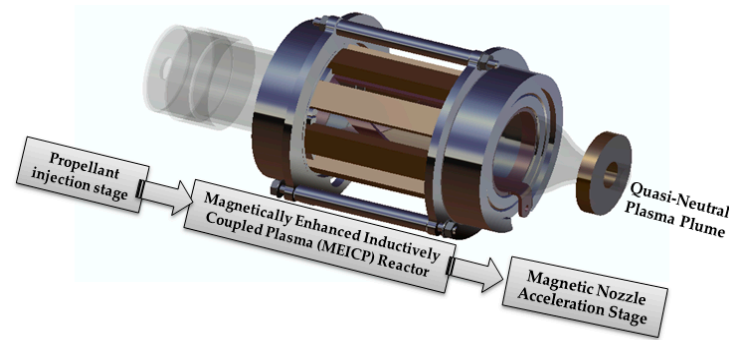


Figure 3. CAD rendering of the Helicon Plasma Thruster Breadboard Model (HPT-BM).

The first stage is represented by a compact MEICP reactor with multi-dipole cusp confinement based on permanent magnets. In this configuration, RF power, operating in the megahertz range, primarily couples with the electrons in the plasma. The energy transferred to the electrons heats them, and this energy is subsequently converted into ion beam energy through electrostatic acceleration. This process occurs via an ambipolar electric field, specifically within a current-free double layer [58,59], where electrons that overcome the potential drop effectively neutralize the accelerated ions [60,61].

The second stage of the HPT is defined by the MN. In this stage, an internal azimuthal electric field current is spontaneously generated within the plasma. This current facilitates electromagnetic plasma acceleration through the Lorentz force, which efficiently directs and accelerates the plasma, contributing to the overall thrust of the system [19,62,63]. The thrust in a HPT is generated progressively within the magnetic nozzle, where the internal plasma energy is converted into axial kinetic energy. This process involves efficient plasma detachment and momentum transferring from the plasma to the spacecraft.

The MEICP reactor is composed of several key elements:

- A cylindrical ionization chamber made from a low thermal expansion material, with a diameter of 30 mm and a length of 150 mm, featuring a convergent nozzle at the outlet with a 10 mm diameter;
- A cooper half-wavelength right helical (HWRH) antenna (Figure 4), measuring 78 mm in length and 1.25 mm in thickness, surrounded the ionization chamber. The material was chosen specifically to minimize its inductive load, thereby reducing power losses;
- A multi-dipole cusp magnetic confinement system composed of eight plate-shaped neodymium iron boron (NdFeB) magnets (PMs) of 38EH grade with gold plating, arranged near the $m = +1$ mode antenna, capable of producing an external magnetic field strength of 800 G. The PMs are radially magnetized;
- A solenoid-free MN represented by a ring-shaped NdFeB PM of 38 EH with gold plating (Ni-Cu-Ni-Au) to extend its Curie point limit;
- A primary structure and positioning system, consisting of a magnetic support, stiffening rods and stiffeners, all fabricated from aluminum.

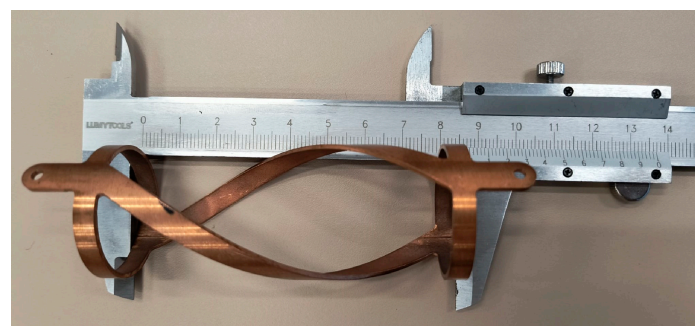


Figure 4. Cooper-based half-wavelength right helical (HWRH) antenna used to excite helicon waves within the MEICP reactor.

The proposed HWRH antenna, presented in Figure 4, is designed to excite the right-hand circularly polarized ($m = +1$) mode of the helicon dispersion relation, thereby ensuring the highest possible density within the MEICP reactor. The currents applied to the HWRH antenna generate an RF magnetic field within the MEICP reactor of the Helicon Plasma Thruster, which induces an RF electric field parallel to the externally applied magnetic field B_0 . This electric field drives electrons along the direction of B_0 , establishing the necessary space charge distribution to mitigate the axial component of the electric field [57]. However, the perpendicular electrostatic field produced by this space charge is not neutralized, as the multi-cusp magnetic field configuration effectively confines electrons in the perpendicular direction. This perpendicular electric field efficiently couples with the helicon wave's space charge field in the perpendicular direction. This perpendicular electric field efficiently couples with the helicon wave's space charge field, enhancing the overall efficiency of the plasma system.

The magnetic system is a critical component of the HPT, serving the following multiple functions: it enables the excitation of helicon waves, minimizes plasma losses to the internal thruster walls, and generates the external MN necessary for supersonic plasma expansion. To develop a competitive cathodeless EP system based on the MEICP reactor, a magnetic field configuration using permanent magnets (PMs) is proposed, optimized for both plasma generation and acceleration. The use of NdFeB permanent magnets with gold plating (Ni-Cu-Ni-Au) results in a simpler and more lightweight thruster unit, capable of generating the required magnetic field in space with limited electric power [64–66], while also extending the operational temperature range due to the higher Curie point. The magnetic confinement system of the MEICP reactor consists of a set of eight PM bars, each measuring 70 mm in length, 10 mm in width, and 5 mm in thickness, with radial inward magnetization. As depicted in Figure 5b, this configuration creates a cusp magnetic confinement structure with a magnetic field intensity of 800 G.

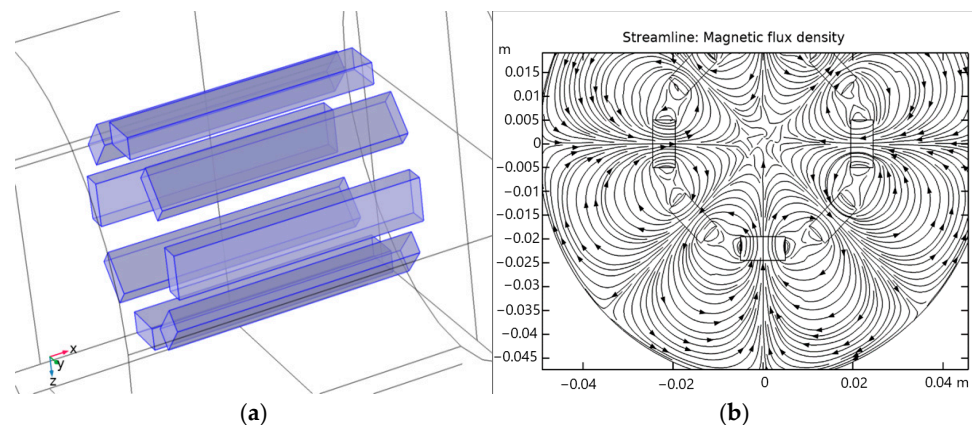


Figure 5. (a) Relative displacement of the PMs within the multi-cusps magnetic confinement system and (b) a cross-section view depicting the magnetic field flux density profile within the MEICP reactor.

The magnetic system along the reactor axis can be adjusted by varying the distance between the two sets of PMs. The multi-cusp magnetic configuration minimizes particle losses to the ionization chamber walls, thereby increasing plasma density and improving plasma uniformity [67,68]. Utilizing a non-uniform magnetic field, such as a converging–diverging magnetic nozzle or a magnetic cusp located near the RF antenna [69], may further enhance thrust performance. In this helicon plasma source, utilizing the non-uniform magnetic field could enable more efficient plasma production.

To enhance thrust performance, it is crucial to maintain higher plasma pressure upstream of the magnetic nozzle. Thereby, the outlet section diameter of the ionization chamber was reduced to 10 mm. A ring-shaped permanent magnet is positioned in the

critical section of the reactor (Figure 6), creating a converging–diverging magnetic field that functions as a magnetic nozzle.

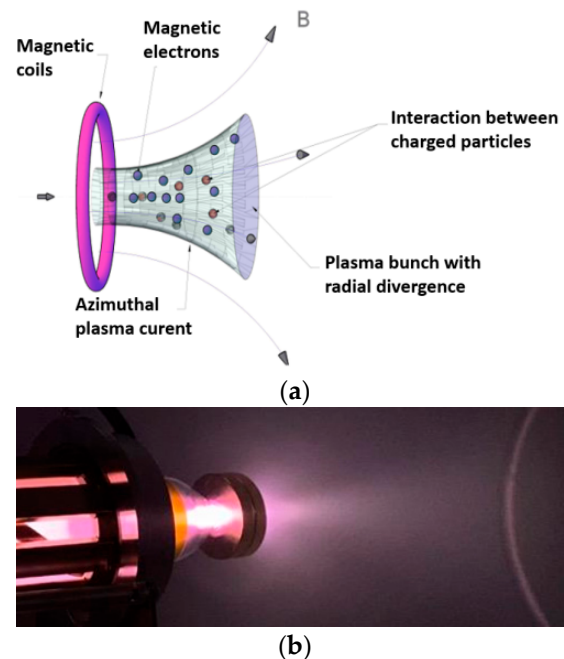


Figure 6. (a) A schematic representation illustrating the conversion of azimuthal momentum into axial momentum within a magnetic nozzle, where B is the applied magnetic field and (b) the formation of the expanding magnetic field downstream of the MEICP reactor.

Increasing the density peak at the helicon source's center [69] directly contributes to improved thrust from the magnetic nozzle. Moreover, achieving a higher magnetic flux density is vital, as it helps confine the elevated plasma pressure and enhance magnetic nozzle acceleration closer to its theoretical potential. Hot electrons expand radially under the magnetic field's confinement, generating an axial ambipolar electric field that accelerates ions. This mechanism facilitates the conversion of internal energy into directed kinetic energy. The interaction between the magnetic field and electron azimuthal currents induces a reaction force on the thruster, which manifests as magnetic thrust. Furthermore, effective plume formation downstream requires adequate detachment from closed magnetic field lines, ensuring proper plasma separation and efficient thrust generation [70,71].

4. Experimental Setup and HPT Test Plan

The proposed HPT, based on a compact MEICP reactor and an MN acceleration scheme, is designed as a modular breadboard platform (Figure 7), allowing for the validation of the influence of key operational parameters. In this study, a fully electrodeless EP system was designed and manufactured, where the transition from the H-mode (ICP) to the W-mode (HWP) was analyzed using OES.

In regard to standard measurement techniques for particle density, energy distribution, and flux, the electric space propulsion community relies on intrusive measurement techniques such as Langmuir probes, Faraday probes, and Retarding Potential Analyzers (RPAs). However, when the inner diameter of the plasma reactor becomes comparable to the size of the probe, these intrusive measurements can disrupt the discharge conditions of the thruster, affecting its acceleration dynamics. In such cases, intrusive probe diagnostics become unsuitable, making non-intrusive methods like OES highly advantageous. The area of particular interest was along the longitudinal axis of the breadboard model, specifically near the downstream region of the magnetic nozzle, where the magnetic field gradients undergo a directional change (electron diamagnetic thrust in the MN).

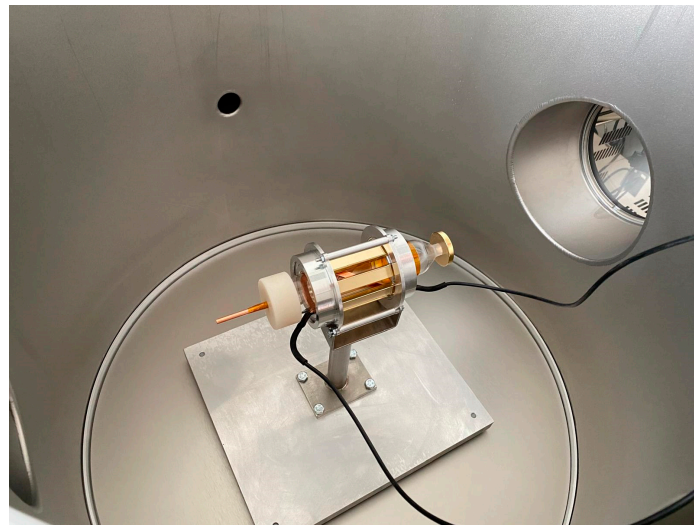


Figure 7. The Helicon Plasma Thruster Breadboard Model during its commissioning procedure.

The experimental HPT system (Figure 8) comprises the thruster unit mounted on the vacuum chamber along with an RF power supply system, propellant delivery system, vacuum infrastructure, and measurement lines.

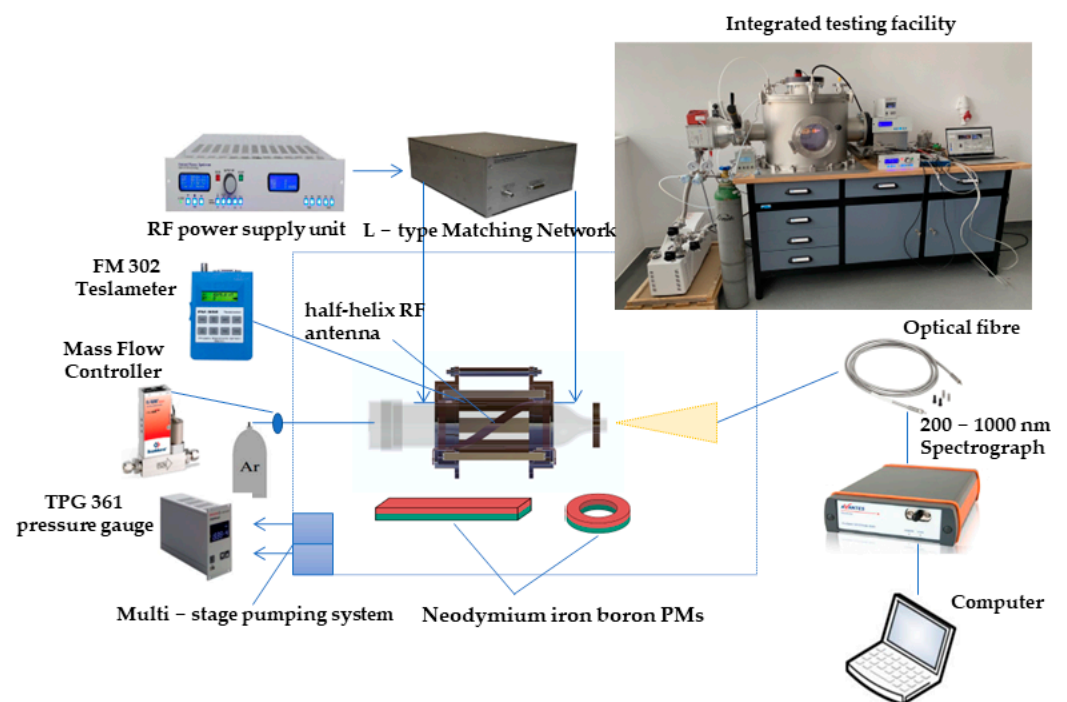


Figure 8. Helicon Plasma Thruster experimental system schematic.

The experiments were conducted in a vacuum facility made of nonmagnetic stainless steel that was 508 mm in diameter and 400 mm in length, equipped with several flanges that provide electrical, gas, and optical feedthroughs. This vacuum infrastructure was designed to simulate the LEO environment, achieving an ultimate vacuum pressure of $2 \cdot 10^{-5}$ mbar. This level of vacuum was attained through the combined operation of a Pfeiffer mechanical pump (ACP 28–40) (Pfeiffer Vacuum GmbH, Asslar, Germany) and a Pfeiffer turbomolecular pump (HiPace 400) (Pfeiffer Vacuum GmbH, Asslar, Germany). Additionally, the chamber pressure was monitored using a TPG 361 Pfeiffer gauge.

To regulate the argon flow rate within the range of 0–15 standard cubic centimeters per minute (sccm) during the discharge, a Bronkhorst mass flow controller (F-201CV-500-

AGD-33-V) (Bronkhorst High-Tech B.V., Ruurlo, The Netherlands) was employed. To ignite the HPT, an RFG600-13 RF power generator (Coaxial Power Systems, Lancashire, UK) was utilized in conjunction with an AMN600 impedance matching unit. The RF generator produces the RF wave responsible for creating the plasma and is designed to ensure optimal power transmission to the plasma by matching the impedance effectively. To match the impedance of the MEICP reactor with the $50\ \Omega$ impedance of the RF generator, an automatic L-type impedance matching network along with an automatic matching network controller (AMNC) were utilized. This setup (Figure 9) also ensures that the reflected power remains below 15% of the forward power. The RF current supplied to the HWRH antenna was set at a fixed frequency of 13.56 MHz, with the RF power system operating externally in radio external control (REC) mode.

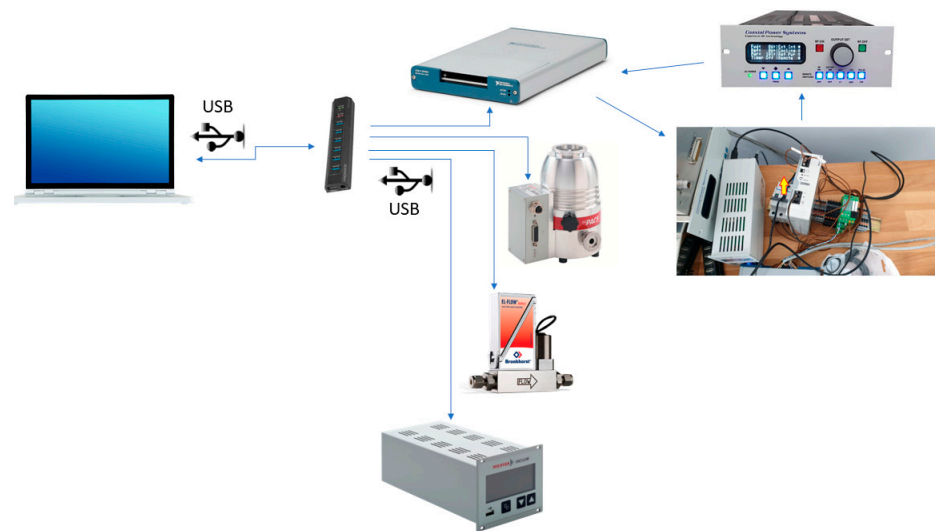


Figure 9. A schematic sketch of the communication connection overseen for the HPT experimental testing campaign.

EP systems operating in low-pressure plasmas require precise control of plasma parameters to optimize throttling capabilities. A promising strategy for controlling ion energies involves a pulsed RF power operation mode [57]. The strategic goal of the proposed experimental testing campaign was to investigate the discharge regimes (H-W mode) and density jumps in a HPT by employing OES. At higher neutral pressures, an MEICP reactor can transition into wave-heated mode (W-mode) even at relatively low RF power levels, specifically below 500 W [36]. To promote the development of the blue core within the plasma column at relatively low RF power and prevent thermal damage to both the antenna and the discharge chamber, a PWM was proposed. A software routine was developed to automatically control the RF power and propellant flow, following the specific pattern shown in Figure 10, to generate pulsed-power-modulated high-density argon plasma within the HPT.

The duty cycle consists of three phases: an Off Timer (toff), during which both RF power and gas flow are either turned off or set to a low value; an On Timer (ton), where both RF power and gas flow are activated or set to a high value simultaneously, and a delay (tdelay) between the activation of the gas flow and the RF power. In the proposed testing program, two key parameters were modulated: the RF input power and the argon mass flow rate.

Starting from the initial parameters listed in Table 3, the optimal ignition sequence was experimentally determined by adjusting the initial values. The initial and optimized PWM ignition sequences are shown in Table 3.

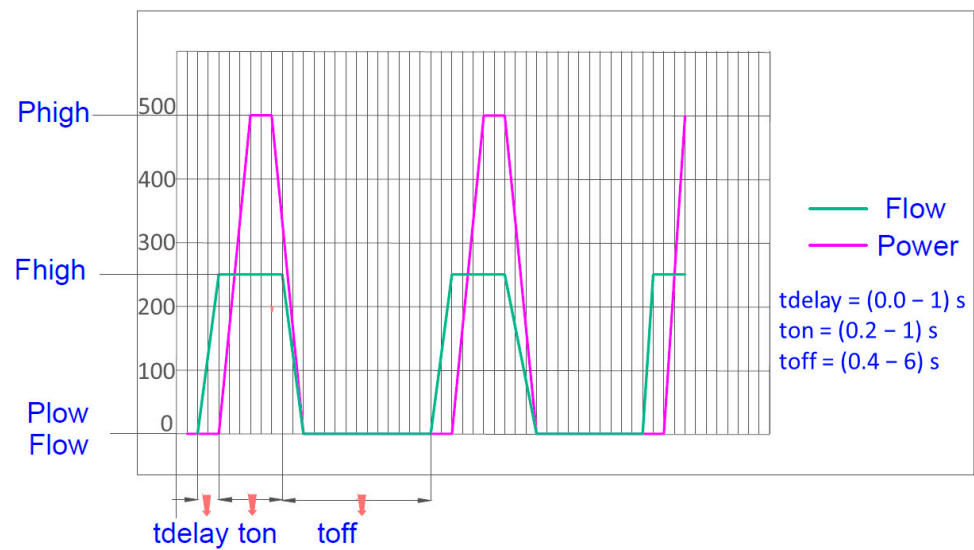


Figure 10. RF envelope-auto ignition of the MECP reactor under a pulsed wave modulation (PWM) regime.

Table 3. Initial and optimized PWM ignition sequences.

State	P _{low} (W)	P _{high} (W)	Flow (sccm)	F _{high} (sccm)	Toff (s)	Tdelay (s)	Ton (s)
Initial	17	150	5	20	6	1	0.2
Optimized	8	500	0	12	0.4	0	1

During the initial phase of the on-time, the electron temperature rapidly rises above steady-state levels. This rapid increase, driven by the application of higher power relative to continuous wave (CW) operation, enhances the confinement of charged particles within the thruster's plasma production stage. Conversely, during the early off-time phase, the electron temperature quickly decreases, reducing Bohm velocity and, consequently, lowering particle losses. This sequence leads to a higher time-averaged power output.

The innovation of the proposed testing program lies in its ability to control the reaction within the MEICP reactor by adjusting the modulation period. This approach enables multi-mode operation, allowing for transitions between inductive (H) mode and wave (W) mode. The pulse mode starts with an ultimate vacuum of $2.4 \cdot 10^{-5}$ mbar. In this approach, gas insertion is synchronized with the RF power, with both being activated and deactivated according to the pulse scheme. This method allows the gas to enter the thruster tube, creating a momentary increase in pressure which, when combined with the RF pulse, ignites the plasma more efficiently and effectively than in continuous mode. The argon propellant flow rates remain constant at 12 sccm for the final testing campaign.

The pulse parameters, including the duration of the RF pulse, the gas flow duration, the delay between gas flow and RF pulses, and the interval between pulses, RF power levels, and gas flow rates, were all adjustable to optimize reflected power and plasma discharge characteristics. The impedance-matching network's capacitance was adjusted by altering the settings on the two capacitors, achieving optimal impedance matching for the plasma discharge. This match was validated by monitoring the RF power supplied to the plasma, as indicated on the RF power supply display. Additionally, the effectiveness of the match was confirmed through visual assessment of the plasma's brightness and stability, observed through a vacuum window port. Table 4 summarizes the operating parameters for the HPT test program.

Table 4. Representative operating parameters envisioned by the HPT test program.

Source Type	MEICP—Helicon Waves Plasma
RF antenna type	Half-wavelength right helical
RF antenna length	78 mm
Ionization chamber length	150 mm
Inner radius	15 mm
RF power	<600 W
Pulse length	1 s between 200 and 500 W
Radio frequency	13.56 MHz
Propellant gas	Argon
Nominal propellant flow rate	12 sccm
Background magnetic field	<800 G
Core magnetic field strength	400 G
The ultimate vacuum	$2.4 \cdot 10^{-5}$ mbar

According to Table 4, the HPT test program envisions the following representative operating parameters:

- RF power level: Adjustable within 250 to 600 W to optimize plasma ignition and stability. Under this power envelope, a H-W mode transition is expected.
- Propellant flow rates: Initially modulated within the range of 6–20 sccm, it was determined that 12 sccm is the optimal value for PWM operation.
- Pulse timing: Includes the duration of RF pulses, gas flow timing, the delay between the initiation of gas flow and RF power, and the interval between successive pulses, all of which are critical for achieving the desired plasma characteristics.
- Reflected Power: Maintained at minimal levels, typically between 30 and 50 W, to ensure efficient energy transfers and minimal losses.
- Modulation period: Variable to control the reactor’s operational mode, facilitating transitions between inductive (H) and wave (W) modes.
- Post-pulse recovery time: The PWM testing sequences ensure a fast post-pulse recovery time.
- Pressure conditions: During operation, a pressure in the range of $3.5 \cdot 10^{-3}$ mbar was maintained.

The spectral intensity of the plasma in the downstream region of the magnetic nozzle was measured using a basic optical emission spectroscopy setup. The collected plasma light was transmitted through an optical fiber (ThorLabs—Liner-to-Linear Bundle model), 2 m long and with a 200 μm core diameter, connected to a spectrometer (AvaSpec—ULS4096CL—EVO, Avantes BV, Apeldoorn, The Netherlands) with a wavelength range of 200 to 1100 nm. OES was involved in capturing the time-resolved optical emission intensities of both argon atomic (Ar I) and argon ion (Ar II) emissions. According to the principles of OES, the Ar I lines are generated through electron collisions with ground-state argon atoms while the Ar II lines are produced by the excitation of ionized argon (Ar^+) in its ground state. To validate the spectral data, the measured wavelengths and excitation energies of the emission lines were systematically cross-referenced with the NIST Atomic Spectra Database lines [72]. This verification ensured that the experimental data met international standards, enhancing the reliability of the results. Emission lines observed in the wavelength range of 700 to 950 nm were identified as low-energy electron-excited neutral argon lines (Ar I), and, conversely, emission lines in the 350 to 500 nm range were attributed to high-energy electron-excited ionic argon lines (Ar II) [73]. The spectral intensity measurements were conducted by applying pulsed RF power, beginning at 200 W and incrementally increasing up to 500 W.

5. Discussions

Visual observation of the plasma reveals that increased RF input power has a significant impact on both the color and intensity of the emitted radiation. The plasma

plume, containing high-energy electron-excited ions and low-energy electron-excited neutral particles, was analyzed using OES within the 400–850 nm wavelength range for argon discharge. For both modes, the argon propellant was fixed at 12 standard cubic centimeters per minute (sccm).

Figures 11–13 illustrate the Helicon Plasma Thruster in operation, with Figure 11 representing the thruster under 200 W RF power in the Inductively Coupled Mode (H-mode) while and Figure 12 highlighting the emission spectrum characteristic of the ICP mode. Figure 13 point out showing the thruster operating at 500 W RF power in the Wave Coupled Mode (W-mode).

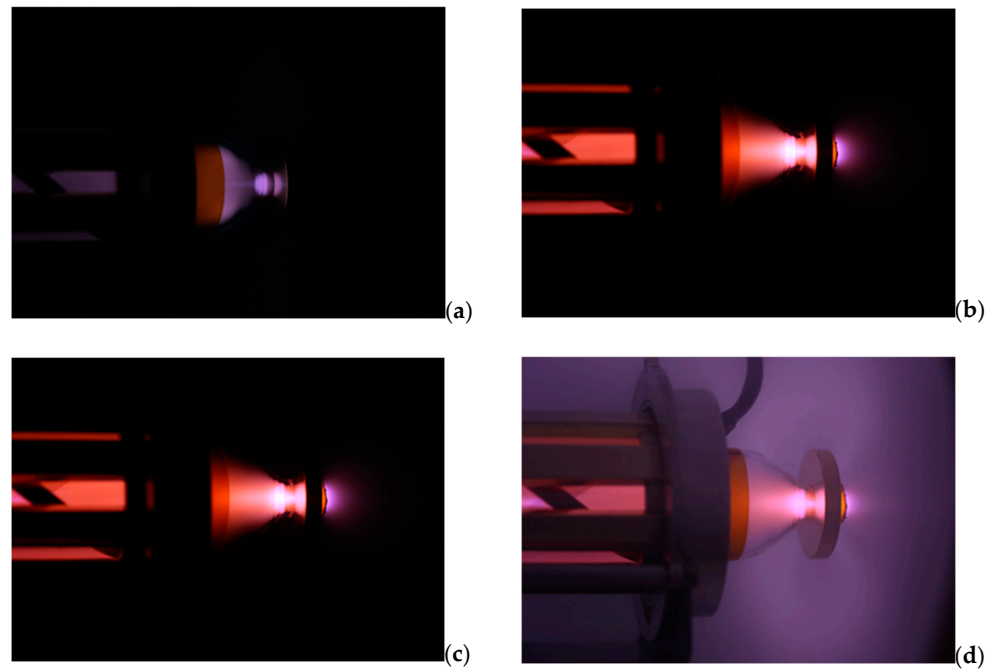


Figure 11. The representative images of the HPT during a testing sequence in Pulse Width Modulation (PWM) mode, operating with a forward power of 200 W (a) 15 ms, (b) 30 ms, (c) 45 ms, and (d) 60 ms after ignition initialization. The sequence features 1 s of RF on-time followed by 0.4 s of RF off-time.

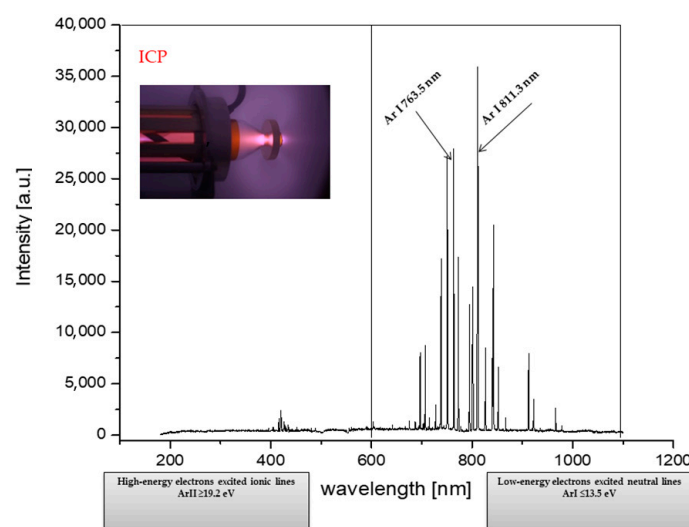


Figure 12. ICP mode emission spectrum of the Helicon Plasma Thruster with a forward power of 300 W and 1 s of RF on-time followed by 0.4 s of RF off-time.

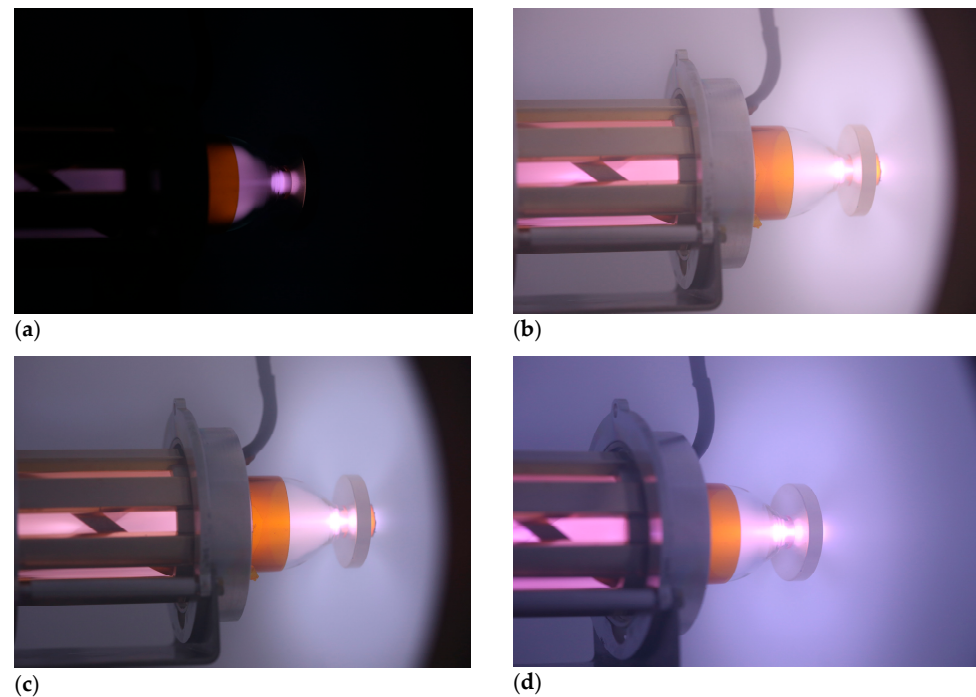


Figure 13. The representative images of the HPT during a testing sequence in Pulse Width Modulation (PWM) mode, operating with a forward power of 500 W (a) 15 ms, (b) 30 ms, (c) 45 ms, and (d) 60 ms after ignition initialization. The sequence features 1 sec of RF on-time followed by 0.4 s of RF off-time.

In H-mode, the argon plasma displays a red–pink color, with its luminosity primarily concentrated near the HWRH antenna. In contrast, during W-mode, the plasma develops a distinct bright core throughout the entire discharge chamber, attributed to intense emission from excited argon ions (ArII). This bright core is well documented in the literature as a hallmark of the transition from H-mode to W-mode [19,64].

Two ignition methods have been identified in the proposed HPT: the E-H mode transition for power levels below 300 W and the E-W mode transition for RF input energy of 400 W or higher.

Figures 12 and 14 show two distinct particle groups that can be observed in the HPT: high-energy electrons excited ionic lines (ArII) and low-energy electrons excited neutral lines (ArI). Figure 14 illustrates a more pronounced rise in the intensity of the high-energy electron-excited ionic population compared to the low-energy electron-excited neutral population as the input power increases from 200 W to 500 W in a pulsed modulated power sequence. The decrease in neutral emission within the MEICP reactor of the HPT can be attributed to an increased ionization fraction of the argon, driven by more efficient electron heating through wave–particle interactions. During H-mode operation, the emission from argon neutral lines becomes more pronounced.

A comparison between the ICP and HW modes of operation (Figure 15) in a Helicon Plasma Thruster was established using twenty emission lines with the highest signal-to-noise ratio (SNR) from a single emission spectrum. The following selected high-energy electron-excited ionic lines should be noted: 415.9 nm, 419.7 nm, 420 nm, 425.9 nm, 425.9 nm, 430 nm, 434.8 nm, 451.3 nm, 461 nm, 480.6 nm, and 488 nm.

In the current RF-powered propulsion technology, the W-mode of operation has been experimentally demonstrated at 500 W, a lower power threshold compared to other experiments that generate BC modes inside a helicon reactor. Takahashi et al. [64] reported BC generation at around 1000 W using argon gas and a double-loop antenna. M.D. West et al. [74] achieved BC at 1100 W with argon as the working gas and a double saddle antenna. Additionally, G. Zhang [75] demonstrated BC using argon and 1500 W RF energy with a Nagoya Type III antenna, while D.D. Blackwell et al. [76] produced BC at 1800 W

using argon and a helical antenna. The direct transition from E-mode to W-mode can be attributed to the optimized RF power modulation and inhomogeneous magnetic field configuration generated by eight plate-shaped samples of neodymium iron boron (NdFeB), while featuring gold plating (Ni-Cu-Ni-Au) leads to a broad range of magnetic field values that are accessible in the near field of the antenna. This PM arrangement enables helicon waves to extend deeper into the plasma column, facilitating the transmission of electromagnetic energy, which is subsequently absorbed via wave resonance. A potential mechanism driving the W-mode operation is the resonant interaction between the fast branch helicon waves and the highly damped electrostatic TG waves. Under these conditions, the ME-ICP reactor in the HPT demonstrates a hybridized behavior (B/E), primarily due to the interaction and mixing of electromagnetic components (helicon waves) with electrostatic components (TG waves). The variations in the wavelengths of 434.8 nm and 480.6 nm in the blue core exhibit remarkable sensitivity, maybe attributed to the non-uniform magnetic field in that specific area. In the discharge process, the reflection of helicon waves by a magnetic field gradient leads to the generation of a standing wave, therefore enabling the deposition of energy. Experimental findings suggest that the existence of a non-uniform magnetic field during the discharge of helicon plasma is beneficial for the absorption of radio frequency power, thereby facilitating the development of a blue core.

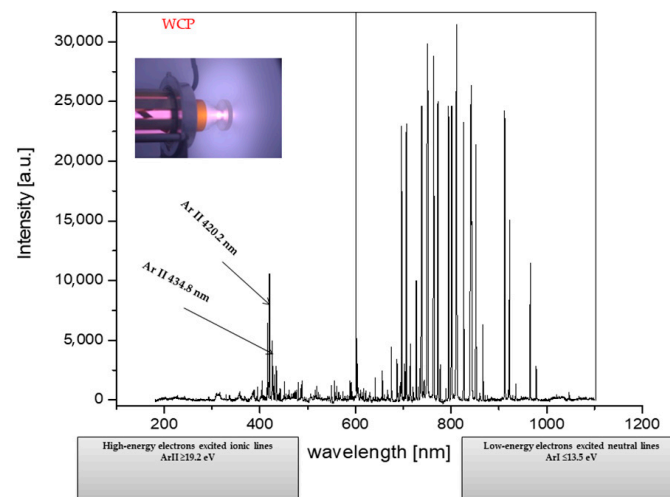


Figure 14. WHP mode emission spectrum of the Helicon Plasma Thruster with a forward power of 500 W and 1 sec of RF on-time followed by 0.4 s of RF off-time.

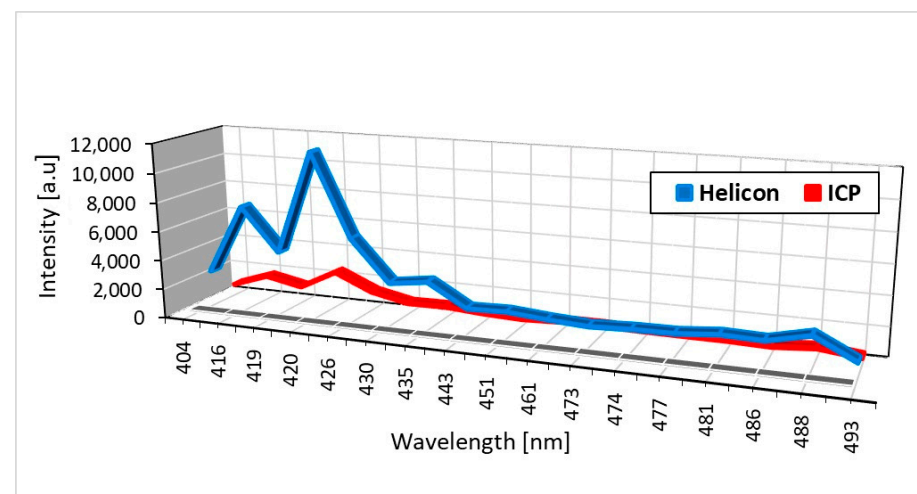


Figure 15. Comparison of the Argon Plasma Spectra for ICP and Helicon modes of operation in 404–493 nm.

The multi mode operation of the MEICP reactor, transitioning from E-mode to H-mode, highlights the high adaptability of this EP technology for complex maneuvers such as orbit insertion, station keeping, orbit maintenance, and attitude control. Pulsing the discharge within a comprehensive testing framework improves the ion-to-neutral influx ratio and enables rapid control of the reactor's operating modes. Regarding acceleration, Figure 13b,c demonstrate a radiant plasma plume in WCP mode, providing evidence for the generation of ionic shock waves when subjected to a pulse wave modulation of 500 W. The plume is highly concentrated and intense, characterized by the visible shock waves pulsating through it, indicating ion acceleration.

The initial calculation of propulsion metrics assumes that the flow of argon ions is comparable to that of a classical sheath with a density reduction of approximately $\exp(-1/2) \sim 0.6$ [77]. Consequently, the plasma density decreases by around 40% [78] as it passes through the critical section of the HPT, defining a supersonic flow regime.

With the increase in RF power, there was a notable rise in the intensity of high-energy electron-excited spectral lines within the 400–500 nm wavelength range. According to the NIST Atomic Spectra Database [72], peaks corresponding to Ar II in this region corroborate the presence of a helicon-wave (HW)-sustained discharge [76,79–82]. Additionally, a collisional-radiative model was used to simulate the intensities of the “red lines”. Spectral lines of argon in helicon plasma are powerful tools for understanding the complex processes occurring in the plasma. This model considers the populations of 21 energy levels, including the ground state (denoted as level 1); the 1s5 and 1s3 metastable levels; the 1s4 and 1s2 resonant levels; the 2p1 to 2p10 levels; and the 2sd3, 3p, and high levels (hl), each grouped into a single level. Additionally, it accounts for the populations of argon excimers (Ar_2^*) and ionized argon species (Ar^+ , Ar^{2+}). The primary processes included in the rate equations are the excitation and de-excitation mechanisms of the electronic states. The spectral lines for which intensities were estimated using the collisional radiative model includes data from Table 5.

Table 5. The argon plasma emission spectra peaks in the wavelength range of 750–950 nm at 500 W, 400 G magnetic field intensity, and 12 sccm propellant flow rate.

Wavelength [nm]	Upper Level	Lower Level
912.2967	2p ₁₀	1s ₅
965.7786	2p ₁₀	1s ₄
811.5311	2p ₉	1s ₅
801.4786	2p ₈	1s ₅
842.4648	2p ₈	1s ₄
978.4503	2p ₈	1s ₂
772.3761	2p ₇	1s ₅
810.3693	2p ₇	1s ₄
866.7944	2p ₇	1s ₃
935.4220	2p ₇	1s ₂
763.5106	2p ₆	1s ₅
800.6157	2p ₆	1s ₄
922.4499	2p ₆	1s ₂
751.4652	2p ₅	1s ₄
714.7042	2p ₄	1s ₅
794.8176	2p ₄	1s ₃
852.1442	2p ₄	1s ₂
706.7218	2p ₃	1s ₅
738.3980	2p ₃	1s ₄
840.8210	2p ₃	1s ₂
696.5431	2p ₂	1s ₅
727.2936	2p ₂	1s ₄
772.4207	2p ₂	1s ₃
826.4522	2p ₂	1s ₂
667.7282	2p ₁	1s ₄
750.3869	2p ₁	1s ₂

Typically, the fitting parameters in such models include electron concentration and electron temperature. However, because the spectral lines are partially absorbed within the plasma (indicating that the plasma is optically thick for these lines), it was necessary to calculate the escape factor. This escape factor, which influences both line intensities and population levels, depends on several variables, such as gas temperature, pressure, path length through the plasma, and particle distribution. Spectral measurements were conducted longitudinally at a distance of 12 cm, a considerable distance that promotes the reabsorption of spectral lines within the plasma. These measurements were taken without the use of collimation optics, meaning that the optical signal was collected from the entire plasma, resulting in a highly averaged signal. These factors made the process of minimizing the chi-square function particularly challenging. The estimated plasma density and electron temperature for the 500 W RF supply power in pulsed mode, using the right helical antenna with a length of 78 mm, were $n_e = 5 \cdot 10^{17} \text{ m}^{-3}$ and $T_e = 5 \text{ eV}$. Considering the resulting electron temperature from the collisional radiative model (CRM), the Bohm velocity of ions (C_s) becomes 3460 m/s. Under the Lieberman et al. [73] approximation for the acceleration coefficient ($\alpha_{\text{accel}} \sim 3.2$), the specific impulse under ideal conditions becomes approximately 1100 s ($I_{\text{spideal}} = \alpha_{\text{accel}} C_s / g_0$). Correspondingly, the ideal thrust force is estimated to be above 3 mN ($T_{\text{ideal}} = M_i \Gamma_i A_i v_i \sim 3.21 \text{ mN}$).

To advance the breakthrough of HPT operation, it is essential to correlate the heating mechanisms in both the Inductively Coupled Mode (normal waves, NW-H mode) and the helicon wave-sustained discharge (W mode).

In Section 2, it was underlined that, in an MEICP reactor, both helicon and TG waves contribute to the plasma heating. At low operating pressures and high-density magnetic field RF discharges, the TG wave is strongly absorbed at the plasma edge ($\sim \text{mm}$). Conversely, due to its low damping characteristics, the helicon wave penetrates deep into the core reactor region, where it is absorbed and drives on-axis plasma heating. As noted in [44,51], the helicon wave absorption may result from parametric decay instability, generating ion acoustic turbulence, that contributes to electron heating. According to [44], this turbulence can arise under the following particular conditions: at relatively high external magnetic fields ($B_0 \sim 1000 \text{ G}$), where the lower hybrid frequency closely matches the pump wave frequency ($\sim 13.56 \text{ MHz}$), or at very low magnetic fields in the range of 20 to 80 G.

In the proposed Helicon Plasma Thruster, the wave frequency exceeds the lower hybrid frequency ($B_0 < 800 \text{ G}$), indicating that parametric instability is unlikely to be the primary driving mechanism for plasma heating in this configuration. The transition from H-mode to W-mode, as seen in the spectrograms, reveals an increased abundance of high-energy electron-excited ionic particles. This observation suggests that power deposition in the MEICP reactor core occurs through helicon wave collisionless processes.

In a collisionless plasma, where the skin depth is $\delta = \omega / \omega_{ce}$, the axial k_z wavenumber can be determined by the axial length of the antenna, as derived from the power spectrum of the HWRH antenna. Given that the parallel and perpendicular components of the wavenumber cannot vary continuously in a bounded system, the plasma density (for a fixed B_0) and the corresponding dispersion relation will not change smoothly. Instead, they must undergo discrete jumps, particularly when the H-W transition occurs. In agreement with Shinohara [56], with a small ionization chamber radius of 30 mm, the $k_r k_z$ is proportional to the ω_p^2 / B_0 ratio, in accordance with the dispersion relation (Equation (7)), because the perpendicular wave number k_r is higher than k_z .

In this configuration, with an azimuthal mode number $m = +1$, the dispersion relation to induce the W-mode is not satisfied before the density jump. Helicon wave conversion into electrostatic electromagnetic waves at the plasma edge, as explained by Shamrai et al. [38–42], aligns with the experimental testing campaign.

According to [76], in W-mode, the plasma density typically ranges between $10^{12} \div 10^{13} \text{ cm}^{-3}$, allowing electromagnetic fields to penetrate deeper into the plasma reactor and exhibit

oscillating profiles. This suggests that low-damped fast helicon waves facilitate efficient wave coupling between the antenna and the plasma.

6. Conclusions

This study examines two operational modes of a HPT equipped with a compact MEICP reactor and a MN acceleration scheme. It demonstrates that, under pulsed power excitation (pulsed wave mode) at moderate RF power levels (below 500 W), the HPT undergoes a transition from inductive mode (H) to helicon wave-sustained discharge (W). This transition is characterized by a rapid increase in argon ion emissions (ArII). In W-mode, atomic line emissions are governed by neutral density and often reach saturation due to neutral depletion. In contrast, ion emissions, which are closely tied to electron density and temperature, show a substantial increase upon transitioning to the wave-heated mode (W). Conversely, in H-mode, atomic line emissions remain predominant.

This scientific work highlights the transition between wave modes (H-W) in a 500 W-class HPT, specifically from the surface mode (involving helicon to TG-mode conversion) to the global heating mode dominated by helicon waves. The TG-mode plays a crucial role in plasma heating prior to the H-W transition. In W-mode, under moderate magnetic field conditions, such as the current case with a 400 G field, the plasma heating through mode conversion diminishes, leading to direct heating by the helicon mode, which becomes the primary mechanism for plasma heating. This transition results from the nonmonotonic relationship between power absorption and plasma density, influenced by reduced power absorption under the anti-resonance condition of the TG wave.

The experimental characterization of a compact HPT-BM resulted in the development of a versatile MEICP source, facilitating rapid transitions between operating modes (H-W), thereby enhancing the thruster's throttleability. From optical emission spectroscopy (OES) data, a collisional radiative model (CRM) estimated the electron density and temperature of the argon plasma, yielding a specific impulse of 1100 s and a thrust of 3.2 mN for a propellant flow of 12 sccm.

To improve the Technology Readiness Level (TRL) of the HPT based on the compact MEICP reactor and MN acceleration scheme, future work will focus on optimizing plasma ionization efficiency, refining RF power-plasma matching, and improving magnetic nozzle acceleration. Additionally, the development of advanced materials and the applications of both intrusive and non-intrusive plasma diagnostic setups will be essential for further enhancing the thruster's performance.

The anticipated performance values of the HPT Breadboard Model have been highlighted. While the system is still in early development and not yet optimized, this testing campaign represents a critical step toward achieving competitive propulsion metrics.

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References

- Steiger, C.; Montagnon, E.; Accomazzo, A.; Ferri, P. BepiColombo Mission to Mercury: First Year of Flight. *Acta Astronaut.* **2020**, *170*, 472–479. [\[CrossRef\]](#)
- Kuninaka, H.; Shimizu, Y.; Kawaguchi, J.; Yoshida, H.; Ueno, H. Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer. *J. Propul. Power* **2007**, *23*, 544–551. [\[CrossRef\]](#)
- Nishiyama, K.; Hosoda, S.; Tsukizaki, R.; Kuninaka, H. In-Flight Operation of the Hayabusa2 Ion Engine System on Its Way to Rendezvous with Asteroid 162173 Ryugu. *Acta Astronaut.* **2020**, *166*, 69–79. [\[CrossRef\]](#)
- Foing, B.H.; Racca, G.D.; Marini, A.; Frew, D.J.; Grieger, B.; Almeida, M.; Foing, A. SMART-1 Mission to the Moon: Status, First Results, and Goals. *Adv. Space Res.* **2006**, *37*, 6–14. [\[CrossRef\]](#)
- Brophy, J. The Dawn Ion Propulsion System. In *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*; Russell, C., Raymond, C., Eds.; Springer: Berlin/Heidelberg, Germany, 2012; pp. 123–145.
- Takahashi, K. Thirty Percent Conversion Efficiency from Radiofrequency Power to Thrust Energy in a Magnetic Nozzle Plasma Thruster. *Sci. Rep.* **2022**, *12*, 18618. [\[CrossRef\]](#)
- Charles, C.; Boswell, R. Directional Power Absorption in Helicon Plasma Sources Excited by a Half-Helix Antenna. *Plasma Sci. Technol.* **2003**, *19*, 105403.
- Charles, C.; Boswell, R.; Alexander, P.; Costa, C.; Sutherland, O.; Pfizner, L.; Franzen, R.; Kingwell, J.; Parfitt, A.; Frigot, P.E.; et al. Operating the Helicon Double Layer Thruster in a Space Simulation Chamber. *IEEE Trans. Plasma Sci.* **2008**, *36*, 1196–1197. [\[CrossRef\]](#)
- Winglee, R.M.; Slough, J.; Ziemba, T.; Goodson, A. Mini-Magnetospheric Plasma Propulsion: Tapping the Energy of the Solar Wind for Spacecraft Propulsion. *J. Geophys. Res. Space Phys.* **2000**, *105*, 21067–21077. [\[CrossRef\]](#)
- Ziemba, T.; Euripides, P.; Slough, J.; Winglee, R.; Giersch, L.; Carscadden, J.; Schnackenberg, T.; Isley, S. Plasma Characteristics of a High Power Helicon Discharge. *Plasma Sources Sci. Technol.* **2006**, *15*, 517–526. [\[CrossRef\]](#)
- Isayama, S.; Shinohara, S.; Hada, T.; Chen, S.H. Spatio-Temporal Behavior of Density Jumps and the Effect of Neutral Depletion in High-Density Helicon Plasma. *Phys. Plasmas* **2019**, *26*, 053504. [\[CrossRef\]](#)
- Boswell, R.W.; Porteous, R.K. Large Volume, High Density RF Inductively Coupled Plasma. *Appl. Phys. Lett.* **1987**, *50*, 1130–1132. [\[CrossRef\]](#)
- Shinohara, S.; Yonekura, K. Discharge Modes and Wave Structures Using Loop Antennae in a Helicon Plasma Source. *Plasma Phys. Control Fusion* **2000**, *42*, 41–49. [\[CrossRef\]](#)
- Han, Y.; Xia, G.; Sun, B.; Zhang, J.; Chen, L.; Lu, C. A Novel Transversal-Feed Electron Cyclotron Resonance Plasma Thruster: Design and Plasma Characteristics Analysis. *Aerospace* **2023**, *10*, 865. [\[CrossRef\]](#)
- Wijnen, M. Diagnostic Methods for the Characterization of a Helicon Plasma Thruster. Doctoral Dissertation, Universidad Carlos III de Madrid, Getafe, Spain, 2023.
- Takahashi, K.; Lafleur, T.; Charles, C.; Alexander, P.; Boswell, R.W.; Perren, M.; Laine, R.; Pottinger, S.; Lappas, V.; Harle, T.; et al. Direct Thrust Measurement of a Permanent Magnet Helicon Double Layer Thruster. *Appl. Phys. Lett.* **2011**, *98*, 141503. [\[CrossRef\]](#)
- Pottinger, S.; Lappas, V.; Charles, C.; Boswell, R. Performance Characterization of a Helicon Double Layer Thruster Using Direct Thrust Measurements. *J. Phys. D Appl. Phys.* **2011**, *44*, 235201. [\[CrossRef\]](#)
- Takahashi, K.; Lafleur, T.; Charles, C.; Alexander, P.; Boswell, R.W. Electron Diamagnetic Effect on Axial Force in an Expanding Plasma: Experiments and Theory. *Phys. Rev. Lett.* **2011**, *107*, 235001. [\[CrossRef\]](#)
- Takahashi, K.; Lafleur, T.; Charles, C.; Alexander, P.; Boswell, R.W. Axial Force Imparted by a Current-Free Magnetically Expanding Plasma. *Phys. Plasmas* **2012**, *19*, 083509. [\[CrossRef\]](#)
- Takahashi, K.; Charles, C.; Boswell, R.W. Approaching the Theoretical Limit of Diamagnetic-Induced Momentum in a Rapidly Diverging Magnetic Nozzle. *Phys. Rev. Lett.* **2013**, *110*, 195003. [\[CrossRef\]](#)
- Williams, L.T.; Walker, M.L.R. Thrust Measurements of a Radio Frequency Plasma Source. *J. Propuls. Power* **2013**, *29*, 520–527. [\[CrossRef\]](#)
- Harle, T.; Pottinger, S.J.; Lappas, V.J. Helicon Double Layer Thruster Operation in a Low Magnetic Field Mode. *Plasma Sources Sci. Technol.* **2013**, *22*, 015015. [\[CrossRef\]](#)
- Oshio, Y.; Shimada, T.; Nishida, H. Experimental Investigation of Thrust Performance on Position Relationship Between RF Antenna and Magnetic Cusp of RF Plasma Thruster. In Proceedings of the 35th International Electric Propulsion Conference, Atlanta, GA, USA, 8–12 October 2017.
- Siddiqui, M.U.; Cretel, C.; Synowiec, J.; Hsu, A.G.; Young, J.A.; Spektor, R. First Performance Measurements of the Phase Four RF Thruster. In Proceedings of the 35th International Electric Propulsion Conference, Atlanta, GA, USA, 8–12 October 2017; IEPC-2017-431.

25. Trezzolani, F.; Manente, M.; Selmo, A.; Melazzi, D.; Magarotto, M.; Moretto, D.; De Carlo, P.; Pessana, M.; Pavarin, D. Development and Test of a High Power RF Plasma Thruster in Project SAPERE-STRONG. In Proceedings of the 35th International Electric Propulsion Conference, Atlanta, GA, USA, 8–12 October 2017; pp. 1–9.
26. Siddiqui, U.; Cretel, C. Updated Performance Measurements and Analysis of the Phase Four RF Thruster. In Proceedings of the 2018 Joint Propulsion Conference, Cincinnati, OH, USA, 9–11 July 2018; p. 4817.
27. Sun, Y.; Zhang, J.; Zhang, Z. Design and Testing of a Mini-RF Plasma Thruster with Permanent Magnets. *J. Electr. Propuls.* **2024**, *3*, 1. [\[CrossRef\]](#)
28. Merino, M.; Navarro, J.; Casado, S.; Ahedo, E. Design and Development of a 1 kW-Class Helicon Antenna Thruster. In Proceedings of the Joint Conference of the 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference, and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan, 4–10 July 2015; IEPC-2015-297/ISTS-2015-b-297.
29. Navarro-Cavalle, J.; Wijnen, M.; Fajardo, P.; Ahedo, E. Experimental Characterization of a 1 kW Helicon Plasma Thruster. *Acta Astronaut.* **2018**, *149*, 69–73. [\[CrossRef\]](#)
30. Popov, O.A. *High Density Plasma Sources: Design, Physics and Performance*, 1st ed.; Materials Science and Process Technology Series; Noyes Publications: Totnes, UK, 1997; ISBN 0815513771.
31. Shinohara, S. *High-Density Helicon Plasma Science: From Basics to Applications*; Springer Series in Plasma Science and Technology; Springer: Berlin/Heidelberg, Germany, 2022; ISBN 978-981-19-2899-4.
32. Chen, F.E. *Introduction to Plasma Physics and Controlled Fusion*, 2nd ed.; Vol. 1: Plasma Physics; Plenum Press: New York, NY, USA, 1984.
33. Lieberman, M.A.; Lichtenberg, A.J. *Principles of Plasma Discharges and Materials Processing*, 2nd ed.; Wiley-Interscience: New York, NY, USA, 2005; ISBN 9780471724254.
34. Xia, Y.; Yang, X.; Chang, L.; Zhou, H.; Zhang, J.H.; Jing, D.; Xu, Q.; Niu, G.J.; Zhou, H.S.; Luo, G.N. Development of a Compact Helicon Plasma Source with Two Sets of Ring Array Permanent Magnets for the Study of a Blue Core Plasma. *Rev. Sci. Instrum.* **2023**, *94*, 125110. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Eom, G.S.; Kim, J.; Choe, W. Wave Mode Conversion and Mode Transition in Very High Radio Frequency Helicon Plasma. *Phys. Plasmas* **2006**, *13*, 073505. [\[CrossRef\]](#)
36. Boswell, R.W.; Vender, D. An Experimental Study of Breakdown in a Pulsed Helicon Plasma. *Plasma Sources Sci. Technol.* **1995**, *4*, 534–540. [\[CrossRef\]](#)
37. Ghosh, S.; Barada, K.K.; Chattopadhyay, P.K.; Ghosh, J.; Bora, D. Localized Electron Heating and Density Peaking in Downstream Helicon Plasma. *Plasma Sources Sci. Technol.* **2015**, *24*, 034011. [\[CrossRef\]](#)
38. Shamrai, K.P.; Shinohara, S. Mode Structure and Dispersion Properties in Helicon Plasma Sources. *Phys. Plasmas* **2001**, *8*, 4659–4669. [\[CrossRef\]](#)
39. Shamrai, K.P.; Taranov, V.B. Helicon Wave Heating and Current Drive in Plasma. *Plasma Phys. Control Fusion* **1994**, *36*, 1719–1736. [\[CrossRef\]](#)
40. Shamrai, K.P.; Taranov, V.B. Volume and Surface RF Power Absorption in a Helicon Plasma Source. *Plasma Sources Sci. Technol.* **1996**, *5*, 474–485. [\[CrossRef\]](#)
41. Shamrai, K.P.; Pavlenko, V.P.; Taranov, V.B. Excitation, Conversion, and Damping of Waves in a Helicon Plasma Source Driven by an $m = 0$ Antenna. *Plasma Phys. Control Fusion* **1997**, *39*, 505–523. [\[CrossRef\]](#)
42. Shamrai, K.P. Stable Modes and Abrupt Density Jumps in a Helicon Plasma Source. *Plasma Sources Sci. Technol.* **1998**, *7*, 499–507. [\[CrossRef\]](#)
43. Virko, V.F.; Kirichenko, G.S.; Shamrai, K.P. Geometrical resonances of helicon waves in an axially bounded plasma. *Plasma Sources Sci. Technol.* **2002**, *11*, 10–26. [\[CrossRef\]](#)
44. Isayama, S.; Shinohara, S.; Hada, T. Review of Helicon High-Density Plasma: Production Mechanism and Plasma/Wave Characteristics. *Plasmacapacitive Inductive Fusion Res.* **2018**, *13*, 1101014. [\[CrossRef\]](#)
45. Chen, F.F.; Arnush, D. Generalized Theory of Helicon Waves. I. Normal Modes. *Phys. Plasmas* **1997**, *4*, 3411–3421. [\[CrossRef\]](#)
46. Barada, K.K.; Chattopadhyay, P.K.; Ghosh, J.; Kumar, S.; Saxena, Y.C. Observation of Low Magnetic Field Density Peaks in Helicon Plasma. *Phys. Caplasmas* **2013**, *20*, 042119. [\[CrossRef\]](#)
47. Arnush, D.; Chen, F.F. Generalized Theory of Helicon Waves. II. Excitation and Absorption. *Phys. Plasmas* **1998**, *5*, 1239–1254. [\[CrossRef\]](#)
48. Stix, T.H. *Waves in Plasmas*; AIP: New York, NY, USA, 1992; p. 339.
49. Chi, K.K.; Sheridan, T.E.; Boswell, R.W. Resonant Cavity Modes of a Bounded Helicon Discharge. *Plasma Sources Sci. Technol.* **1999**, *8*, 421–428. [\[CrossRef\]](#)
50. Guittienne, P.; Jacquier, R.; Pouradier Duteil, B.; Howling, A.A.; Agnello, R.; Furno, I. Helicon Wave Plasma Generated by a Birdcage Antenna: Magnetic Field Measurements and Analysis in the RAID Linear Device. *Plasma Sources Sci. Technol.* **2021**, *30*, 075023. [\[CrossRef\]](#)
51. Krämer, M.; Aliev, Y.M.; Altukhov, A.B.; Gurchenko, A.D.; Gusakov, E.Z.; Niemi, K. Anomalous Helicon Wave Absorption and Parametric Excitation of Electrostatic Fluctuations in a Helicon-Produced Plasma. *Plasma Phys. Control Fusion* **2007**, *49*, S123–S138. [\[CrossRef\]](#)

52. Boswell, R.B. Very Efficient Plasma Generation by Whistler Waves Near the Lower Hybrid Frequency. *Plasma Phys. Control Fusion* **1984**, *26*, 1147–1162. [\[CrossRef\]](#)
53. Ellingboe, A.R.; Boswell, R.W. Capacitive, Inductive, and Helicon-Wave Modes of Operation of a Helicon Plasma Source. *Phys. Plasmas* **1996**, *3*, 2797–2804. [\[CrossRef\]](#)
54. Shinohara, S. Propagating Wave Characteristics for Plasma Production in Plasma Processing Fields. *Jpn. J. Appl. Phys.* **1997**, *36*, 4695–4703. [\[CrossRef\]](#)
55. Degeling, A.W.; Jung, C.O.; Boswell, R.W.; Ellingboe, A.R. Plasma Production from Helicon Waves. *Phys. Plasmas* **1996**, *3*, 2788–2799. [\[CrossRef\]](#)
56. Porte, I.; Yun, S.M.; Arnush, D.; Chen, F.F. Superiority of Half-Wavelength Helicon Antennae. *Plasma Sources Sci. Technol.* **2003**, *12*, 287–293. [\[CrossRef\]](#)
57. Charles, C. A Review of Recent Laboratory Double Layer Experiments. *Plasma Sources Sci. Technol.* **2007**, *16*, R1–R25. [\[CrossRef\]](#)
58. Biloiu, I.A.; Scime, E.E.; Biloiu, C. Ion Beam Acceleration in a Divergent Magnetic Field. *Appl. Phys. Lett.* **2008**, *92*, 191502. [\[CrossRef\]](#)
59. Takahashi, K.; Charles, C.; Boswell, R.W.; Kaneko, T.; Hatakeyama, R. Measurement of the Energy Distribution of Trapped and Free Electrons in a Current-Free Double Layer. *Phys. Plasmas* **2007**, *14*, 114503. [\[CrossRef\]](#)
60. Takahashi, K.; Charles, C.; Boswell, R.W.; Fujiwara, T. Electron Energy Distribution of a Current-Free Double Layer: Druyvesteyn Theory and Experiments. *Phys. Rev. Lett.* **2011**, *107*, 035002. [\[CrossRef\]](#)
61. Ahedo, E.; Merino, M. Two-Dimensional Supersonic Plasma Acceleration in a Magnetic Nozzle. *Phys. Plasmas* **2010**, *17*, 073501. [\[CrossRef\]](#)
62. Fruchtman, A.; Takahashi, K.; Charles, C.; Boswell, R.W. A Magnetic Nozzle Calculation of the Force on a Plasma. *Phys. Plasmas* **2012**, *19*, 033507. [\[CrossRef\]](#)
63. Takahashi, K.; Oguni, K.; Yamada, H.; Fujiwara, T. Ion Acceleration in a Solenoid-Free Plasma Expanded by Permanent Magnets. *Phys. Plasmas* **2008**, *15*, 084501. [\[CrossRef\]](#)
64. Takahashi, K.; Motomura, T.; Ando, A.; Kasashima, Y.; Kikunaga, K.; Uesugi, F.; Hara, S. Transport of a Helicon Plasma by a Convergent Magnetic Field for High Speed and Compact Plasma Etching. *J. Phys. D Appl. Phys.* **2014**, *47*, 425201. [\[CrossRef\]](#)
65. Meier, S.M.; Tsankov, T.V.; Luggenhölscher, D.; Czarnetzki, U. Measurement of Plasma Densities by Dual Frequency Multichannel Boxcar THz Time Domain Spectroscopy. *J. Phys. D Appl. Phys.* **2017**, *50*, 245203. [\[CrossRef\]](#)
66. Ahedo, E.; Merino, M. On Plasma Detachment in Propulsive Magnetic Nozzles. *Phys. Plasmas* **2011**, *18*, 053504. [\[CrossRef\]](#)
67. Tsankov, T.V.; Chabert, P.; Czarnetzki, U. Foundations of Magnetized Radio-Frequency Discharges. *Plasma Sources Sci. Technol.* **2022**, *31*, 084007. [\[CrossRef\]](#)
68. Ito, S.; Nakamura, T.; Nishida, H.; Shinohara, S. Performance of RF Plasma Thruster for Various Magnetic Field Configurations by Permanent Magnets. In Proceedings of the 30th International Symposium on Space Technology and Science, Kobe, Japan, 7–9 July 2015. IEPC-2015-412/ISTS-2015-b-412.
69. Otsuka, S.; Nakagawa, T.; Ishii, H.; Teshigahara, N.; Fujitsuka, H.; Waseda, S.; Ishii, T.; Kuwahara, D.; Shinohara, S. Generation and Acceleration of High-Density Helicon Plasma Using Permanent Magnets for the Completely Electrodeless Propulsion System. *Plasma Fusion Res.* **2014**, *9*, 3406047. [\[CrossRef\]](#)
70. Merino, M.; Ahedo, E. Plasma Detachment in a Propulsive Magnetic Nozzle via Ion Demagnetization. *Plasma Sources Sci. Technol.* **2014**, *23*, 032001. [\[CrossRef\]](#)
71. Wang, C.; Liu, Y.; Sun, M.; Zhang, T.; Xie, J.; Chen, Q.; Zhang, H. Effect of Neutral Pressure on the Blue Core in Ar Helicon Plasma under an Inhomogeneous Magnetic Field. *Plasma Sci. Technol.* **2023**, *25*, 045403. [\[CrossRef\]](#)
72. NIST Atomic Spectra Database (ver. 5.9), [Online]; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2023. Available online: <https://physics.nist.gov/asd> (accessed on 28 July 2024).
73. Lieberman, M.A.; Charles, C. Theory of Formation of a Low-Pressure, Current-Free Double Layer. *Phys. Rev. Lett.* **2006**, *97*, 045003. [\[CrossRef\]](#)
74. West, M.D.; Charles, C.; Boswell, R.W. Mode Transitions in the Helicon Double-Layer Thruster Prototype Operating in Xenon. *IEEE Trans. Plasma Sci.* **2011**, *39*, 2468–2469. [\[CrossRef\]](#)
75. Wang, C.; Liu, Y.; Sun, M.; Zhang, T.; Chen, Q.; Zhang, H. Effect of Inhomogeneous Magnetic Field on Blue Core in Ar Helicon Plasma. *Phys. Plasmas* **2021**, *28*, 123519. [\[CrossRef\]](#)
76. Blackwell, D.D.; Chen, F.F. Two-Dimensional Imaging of a Helicon Discharge. *Plasma Sources Sci. Technol.* **1997**, *6*, 569–576.
77. Chen, F.F. Physical Mechanism of Current-Free Double Layers. *Phys. Plasmas* **2006**, *13*, 034502. [\[CrossRef\]](#)
78. Charles, C.; Boswell, R. Laboratory Evidence of a Supersonic Ion Beam Generated by a Current-Free Helicon Double-Layer. *Phys. Plasmas* **2004**, *11*, 1706. [\[CrossRef\]](#)
79. Thakur, S.C.; Brandt, C.; Cui, L.; Gosselin, J.J.; Tynan, G.R. Formation of the Blue Core in Argon Helicon Plasma. *IEEE Trans. Plasma Sci.* **2015**, *43*, 2754–2761. [\[CrossRef\]](#)
80. Guo, X.M.; Scharer, J.; Mouzouris, Y.; Louis, L. Helicon Experiments and Simulations in Nonuniform Magnetic Field Configurations. *Phys. Plasmas* **1999**, *6*, 3400–3406. [\[CrossRef\]](#)

81. Rayner, J.P.; Cheetham, A.D. Helicon Modes in a Cylindrical Plasma Source. *Plasma Sources Sci. Technol.* **1999**, *8*, 79–86. [[CrossRef](#)]
82. Franck, C.M.; Grulke, O.; Klinger, T. Mode Transitions in Helicon Discharges. *Phys. Plasmas* **2003**, *10*, 323–331. [[CrossRef](#)]

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