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Electron Cyclotron Resonance Thruster Technology: A Pathway to Efficient Spacecraft Propulsion

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Abstract

Electron Cyclotron Resonance (ECR) thrusters are emerging as a promising technology for efficient spacecraft propulsion, utilizing the phenomenon of electron cyclotron resonance to generate thrust. This comprehensive review synthesizes key advancements, design strategies, and ongoing challenges within the field. ECR thrusters operate by heating electrons in a magnetized plasma using microwave energy, leading to high ionization rates and favorable thrust-to-power ratios. Unlike traditional propulsion systems, ECR thrusters offer significant advantages, including higher specific impulse and reduced fuel consumption, making them ideal for long-duration space missions.The paper delves into various critical aspects of ECR thruster design, such as antenna configurations, gas injection methods, and magnetic field optimization, highlighting how these factors influence overall performance. It also discusses the latest experimental findings and theoretical models that have addressed issues like efficiency, lifetime, and power transfer. Furthermore, the review explores future directions, emphasizing the need for advancements in materials and automated impedance matching to enhance reliability and thrust generation capabilities.Through this analysis, the paper aims to present a holistic understanding of ECR thrusters, underscoring their potential to become a competitive and sustainable option for future space exploration.

Keywords: Electron Cyclotron Resonance (ECR) Thruster, Plasma Propulsion, Electric Propulsion Technology, Microwave Plasma Acceleration, Magnetic Field Configuration in Thrusters, Ion Acceleration

Introduction

Electron Cyclotron Resonance (ECR) plasma thrusters, first introduced in the 1960s, utilize electric and magnetic fields to accelerate plasma, providing thrust for spacecraft. Unlike traditional thrusters, ECR thrusters are gridless and require only one power supply, making them potentially disruptive in the field of space propulsion[4,10,14]. Recent advancements have focused on addressing past experimental limitations, improving measurement accuracy, and optimizing various thruster parameters. Plasma physics encompasses a diverse range of phenomena observed in ionized gases, with applications spanning natural phenomena, fusion research, and industrial processes[22,30,35]. Despite this diversity, the essence of plasma can be described as the collective behaviour of charged and neutral particles under the influence of electric, magnetic, and electromagnetic interactions. Within the industrial plasma community, the plasma thruster community focuses on developing electric plasma thrusters for space propulsion, aiming to efficiently produce thrust through ion acceleration using electrical power[5,10,30] is shown in figure 1.

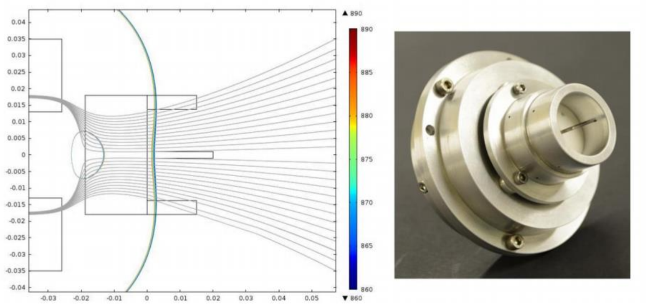


Figure 1 : ECRA thruster geometry, picture of a 30W ECRA thruster,

Design and Optimization of ECR Thrusters

The design of an ECR thruster involves several critical components, including the discharge chamber, microwave antenna, permanent magnets, and ceramic backplate. Key areas of optimization include is shown in figure 2:[15,8,11] It is immersed in a static and divergent magnetic field that is created by an annular permanent magnet. All the necessary power for ionization of the gas and heating of the electrons is provided by the absorption of the microwave. Hot electrons expand in the magnetic nozzle. They create a charge separation electric field accelerating ions. Also, the static magnetic field in this region is less divergent than in the rest of the plasma volume, that we will term *the magnetic nozzle*. It extends from the upper $z = z0$ limit of the interaction region towards increasing z, until the plasma is no longer influenced by the magnetic field. In the magnetic nozzle, no electromagnetic field is present, and the plasma is considered collisionless. Although the $z = z0$ plane limiting the regions is not perfectly well defined, we may have $z0 \cong 1 - 2$ cm. It may not correspond exactly to the plasma volume inside the coupling structure. Unless otherwise specified the origin of z is taken at the interface between the backplate and the plasma. The 20 mm length of the outer conductor of the coupling structure is the result of an experimental parametric optimization ([24], section VI – 3.3). The existence of an optimum length may be interpreted a compromise between increasing plasma losses and increasing neutral gas confinement, when the length of the outer conductor is increased. The electromagnetic field is likely absorbed before the $z = 2$ cm.

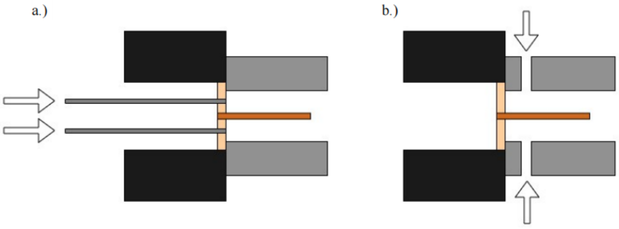


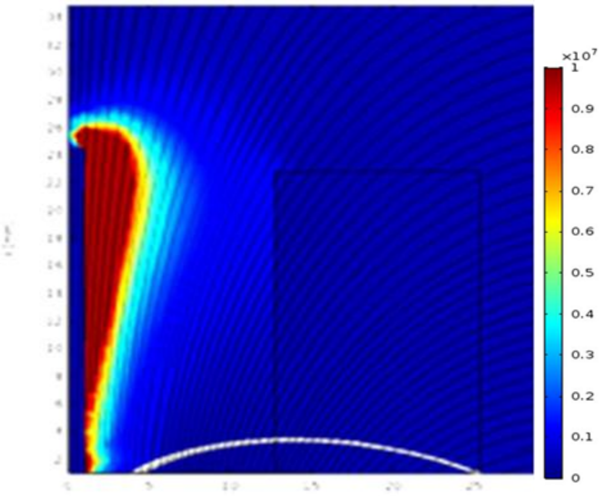
Figure 2:Injection type a)radial b)axial

Antenna Design

Antenna configurations (straight rod, ring, and helical) significantly impact thruster performance. The helical antenna, producing right-hand [5,34,31] has shown in figure 2 promise in efficiently heating electrons. Straight rod: Monopole antenna producing linearly polarized waves, commonly used in previous coaxial ECR thruster testing[9,17,20,3,1]. Straight rod with ring: Improved performance can be observed in micro ECR ion thruster study. Simulation tools like COMSOL RF module help visualize electric field patterns, aiding in the assessment of antenna effectiveness. Quality antenna resonates at desired frequency, matching microwave circuit impedance, verifiable with vector network analyzer (VNA)[7,19,27]. Plasma ignition may alter antenna impedance, affecting transmitted and reflected power to the plasma. The length of antenna has little affect on the performance of the thruster. Antenna lengths adjusted for resonance at 2.45 GHz, confirmed with nano VNA for impedance matching, reducing reflected power and enhancing microwave plasma coupling[23].

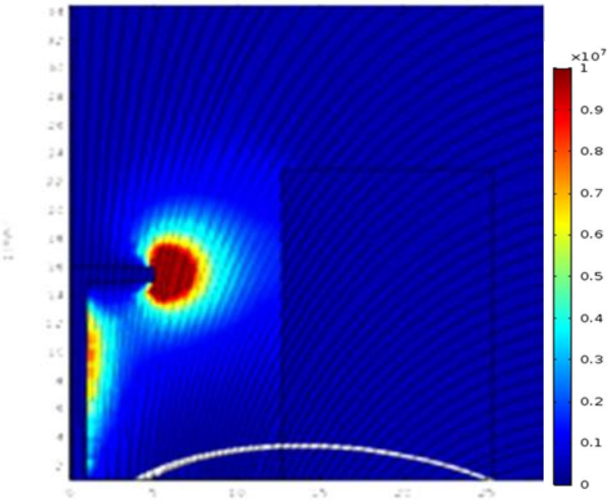
Each antenna design simulated to visualize electric field patterns for effectiveness assessment, following Koizumi and Kuninaka's method for generating perpendicular electric and magnetic field lines[32]is shown in figure 3. Alignment of high electric field intensity regions with ECR region crucial for electron energy gain.

a)



b)

Ring



c) Helical

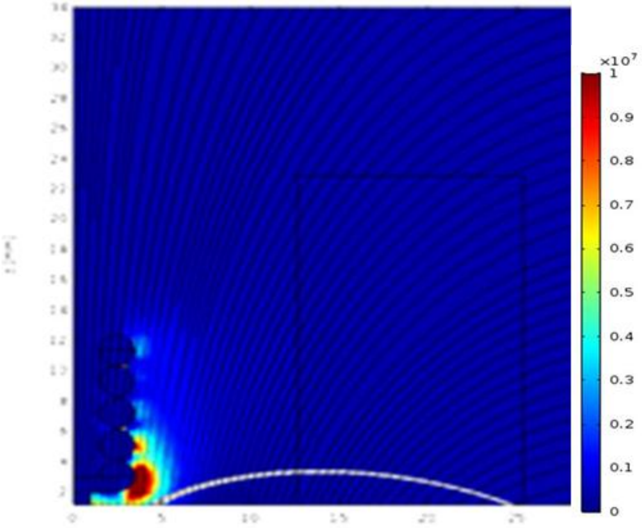


Figure 3:ECR effective heating regions and ECR region(white area) of a).monopole, b) ring, c) helical

Gas Injection

Effective gas injection is crucial for plasma generation. Two primary schemes are radial and axial injection[2,16]. Axial injection, which offers uniform gas distribution, has been found to be more effective than radial injection. Proper gas flow management is essential for successful plasma ignition and sustained thruster operation[25]. Axial injection offers uniform distribution by injecting gas behind or through backplate, with backplate design influencing distribution via cut patterns[29]. Plasma ignition requires gas "puff"; nominal flow rates insufficient, requiring higher flow for ignition. Ignition achieved through downstream valve temporarily closed to build pressure, enabling large gas puff into source chamber; failure to follow procedure leads to unsuccessful ignition attempts[13].

Magnetic Field Structure

The magnetic field in an ECR thruster is formed by permanent magnets, creating a magnetic nozzle for plasma acceleration and an ECR region for plasma generation[6]. Optimizing the magnetic field strength and configuration is essential for balancing plasma containment and detachment, maximizing thruster performance. However, excessive magnetic field strength may hinder plasma detachment from field lines, leading to return of charged particles and no neThe key role of the magnetic field in the acceleration process was clearly demonstrated through separate thrust balance measurement of the force imparted one hand on the magnet (“magnetic thrust”) and on the other hand on the coupling structure (“pressure thrust)[18]. Balancing plasma confinement and detachment crucial for optimal thruster performance, depending on desired ECR region placement. Axial position of ECR region adjustable by moving permanent magnets within thruster casings, altering magnetic field strength in source chamber[21]. WECR thruster design accommodates axial movement of permanent magnets for optimal ECR zone placement, maximizing performance. COMSOL simulations validate ECR region location under varying magnet positions, inner diameters, and number of magnets[24]. Magnetic field profile formed by two neodymium permanent magnets in thruster body, showing axially decreasing strength, facilitating plasma expansion and radial gas injection. Magnetic field measurements made with Lakeshore gauss meter corroborate COMSOL simulations, confirming strong field within chamber and desired ECR region location[12].

ECR Source Region

The primary focus of this thruster is optimizing the Electron Cyclotron Resonance (ECR) region for enhanced performance[33]. It operates in TEM mode within the coaxial line and quasi-TEM mode in the source chamber. Alignment of high field strength areas with ECR coupling zones is crucial for efficient electron heating[28]. Electrons passing through the ECR region gain energy suitable for ionizing gas. Strategies for improving single particle energy absorption in ECR sources involve minimizing magnetic field gradients and enhancing plasma coupling[26]. Adjustments in magnetic field configuration, like adding permanent magnets, can achieve this optimization. Simulation suggests that using two neodymium permanent magnets of specific dimensions can effectively minimize the axial magnetic field gradient. Thrust is dominated by the contribution of ion momentum that are accelerated through a mechanism sometimes called “charged separation coupling” [15]. This mechanism is analogous to that of a sheath and can be outlined as follows. Steady state charge conservation applied to a control volume containing the thruster implies equality of ion and electron flux exiting the volume (this volume is taken sufficiently large that no fluxes exist towards the inside). Yet, the electron flux exiting the interaction region to the right is considerably higher than the ion flux because electrons are considerably lighter than ions and have a comparable or higher parallel kinetic energy. Hence the establishment of an electric field accelerating ions. This electric field is often termed “ambipolar electric field” because no net current is drawn from the thruster. However, the plasma is not, a priori, locally ambipolar. Indeed, simulations suggest that local electric current play an important role in the nozzle dynamics Various methods were employed to enhance microwave plasma coupling. Antenna design, discussed in section 2.3, was utilized to evaluate different magnetic field configurations[22]. COMSOL simulations were conducted for each antenna design to assess their effectiveness. Simulations were effective in determining potential performance improvements with selected antennas. Effective antenna configurations create numerous E x B points, with the electric field component perpendicular to the magnetic field gradient serving as the design index[24]. Effective antenna designs position higher intensity regions within the Electron Cyclotron Resonance (ECR) zone. Different antenna configurations were depicted in Figure 6, showing effective heating regions alongside the ECR zone. The straight rod or monopole exhibited effective heating along its length due to a large perpendicular electric field component[25]. The ring antenna, while altering the heating pattern, allowed for a higher intensity region at a greater radial distance compared to the straight rod. The helical antenna showed the poorest performance overall due to its lack of flat surfaces, as per the antenna design method. However, this method did not consider the effect of Right-Hand Circularly Polarized (RHCP) waves on effectively heating electrons[26].

Performance Evaluation

Performance metrics for ECR thrusters include thrust, specific impulse, efficiency, and lifetime. Recent experiments have demonstrated significant improvements in these areas:

Efficiency

Optimization efforts have led to reported efficiencies, achieved through careful adjustments in antenna design, gas injection, and magnetic field configuration.Monopole antenna had higher efficiency (around

3.2%) compared to helical antenna (around 0.5%)[30]. Increasing microwave power didn't always improve efficiency due to losses to radial walls. Insulating walls could improve performance in future designs. Ways to improve efficiency without changing gas flow or microwave power include increasing total ion current and ion energies. Altering magnetic field could increase ion energy and total ion current without changing flow rate or microwave power. Improvements in these areas could significantly enhance thruster performance

Lifetime

Material selection and design modifications have addressed erosion issues, with graphite-based coaxial coupling structures proving effective. Estimated lifetimes now range from one to a few thousand hours, making ECR thrusters more viable for long-term missions[23].

Specific Impulse

The thruster achieved specific impulses up to approximately 2900 seconds under certain operating conditions, such as at 2.5 SCCM (Standard Cubic Centimeters per Minute) and 250 W of power. While this particular study didn't directly investigate the effects of background pressure, it did record pressure measurements during testing of the WECR thruster. All FC and RPA measurements were conducted with background pressure around 1e-5 Torr, the efficiency dropped to around 2%.It's suggested that if lower pressures were achievable, measured ion energies would be in the range of 200-300 eV. The overall conclusion is that background pressure significantly affects the performance of magnetic nozzle thrusters like ECR thrusters. Facilities capable of operating at pressures below 1e-5 Torr are preferred for optimal performance.[6.18]

Transmitted and Reflected Power

During testing of the WECR thruster, both transmitted and reflected power were observed and recorded across various power levels and flow rates to analyze behaviour. Variations in transmitted and reflected power were noted for different antenna configurations[8,10,34] The monopole antenna showed relatively constant reflected power levels with minimal variation across all operating conditions, while the helical antenna exhibited substantial fluctuations in reflected power. A double stub tuner was employed for impedance matching. An automatically adjusted system, akin to impedance matching circuits for waveguides, could optimize power absorption and minimize reflection Erosion from sputtering was observed on the antenna after testing. Copper, the material used for the antenna, has a higher sputtering yield for noble gas ions[27]. To reduce erosion, alternative materials with lower sputtering yields, such as refractory metals, or coatings with low sputtering yields can be used.

Impedance Matching

Impedance matching ensures that the source's impedance matches the load's impedance for maximum power transfer. In the WECR thruster, the microwave generator serves as the source, and the plasma acts as the load[28].

Optimizing Power Transfer: The primary purpose of the WECR thruster is to utilize microwave power to ionize and energize the plasma, which generates thrust. If the impedance of the microwave circuit doesn't align with that of the plasma, a significant portion of the power may reflect back to the source, leads to inefficiency[29].

Maximizing Absorbed Power, Minimizing Reflected Power:Impedance matching aims to maximize the power absorbed by the plasma while minimizing the power reflected back to the source. Adjusting the microwave circuit's impedance to match that of the plasma ensures that the maximum amount of power is utilized for plasma generation[30]. This optimization enhances the efficiency of the thruster and improves its thrust generation capabilities. Fluctuations in reflected power, especially noticeable with the helical antenna configuration, indicate poor impedance matching. Poor matching leads to variations in reflected power over time. These fluctuations signify suboptimal power transfer, potentially causing inconsistency in thrust generation[31].

Manual Adjustment vs. Automatic System: The current method involves manually adjusting a double stub tuner before each plasma diagnostic experiment to match impedances. While effective, this process is time-consuming and may not adapt to changing plasma conditions in real-time[32]. The suggestion is to implement an automatically adjusted system, similar to those in waveguide impedance matching circuits, for continuous adjustment of circuit impedance to plasma impedance during thruster operation. This automated system would optimize power transfer, leading to improved thruster performance and more reliable thrust generation[33].

Thruster Electromagnetic Emission

Justified calculation of deposited microwave power using a specific equation. Verification that no power is radiated in the tank by the coaxial structure[34]. Analytical calculation and COMSOL simulation of power radiated by the thruster's open end without plasma, yielding a value below 1%. Experimental measurements conducted to ensure plasma presence doesn't enable radiation. Measurements performed with a small loop antenna placed inside the vacuum tank and connected to a spectrum analyzer. Three measurement cases: with microwave power but no plasma, with both microwave power and plasma, and without plasma or microwave power for ambient electromagnetic signal response[25,1]. No significant signal observed between 30 kHz and 3 GHz when the thruster was operational with plasma, except for the microwave generator signal. Conclusion that the radiated power fraction in the presence of plasma is of order -40 dB justifying the neglect of radiation in the power deposition calculation[35].

Conclusion

ECR thrusters represent a significant advancement in electric propulsion technology. Continued research and development efforts are essential to further improve their performance and reliability. With their unique advantages and recent progress, ECR thrusters have the potential to become a competitive propulsion option for future space missions.

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