PhD Aerospace Engineering Doctoral Meeting 2025

Experimental investigation of the physics of Electrodeless Plasma Thrusters for in-space propulsion

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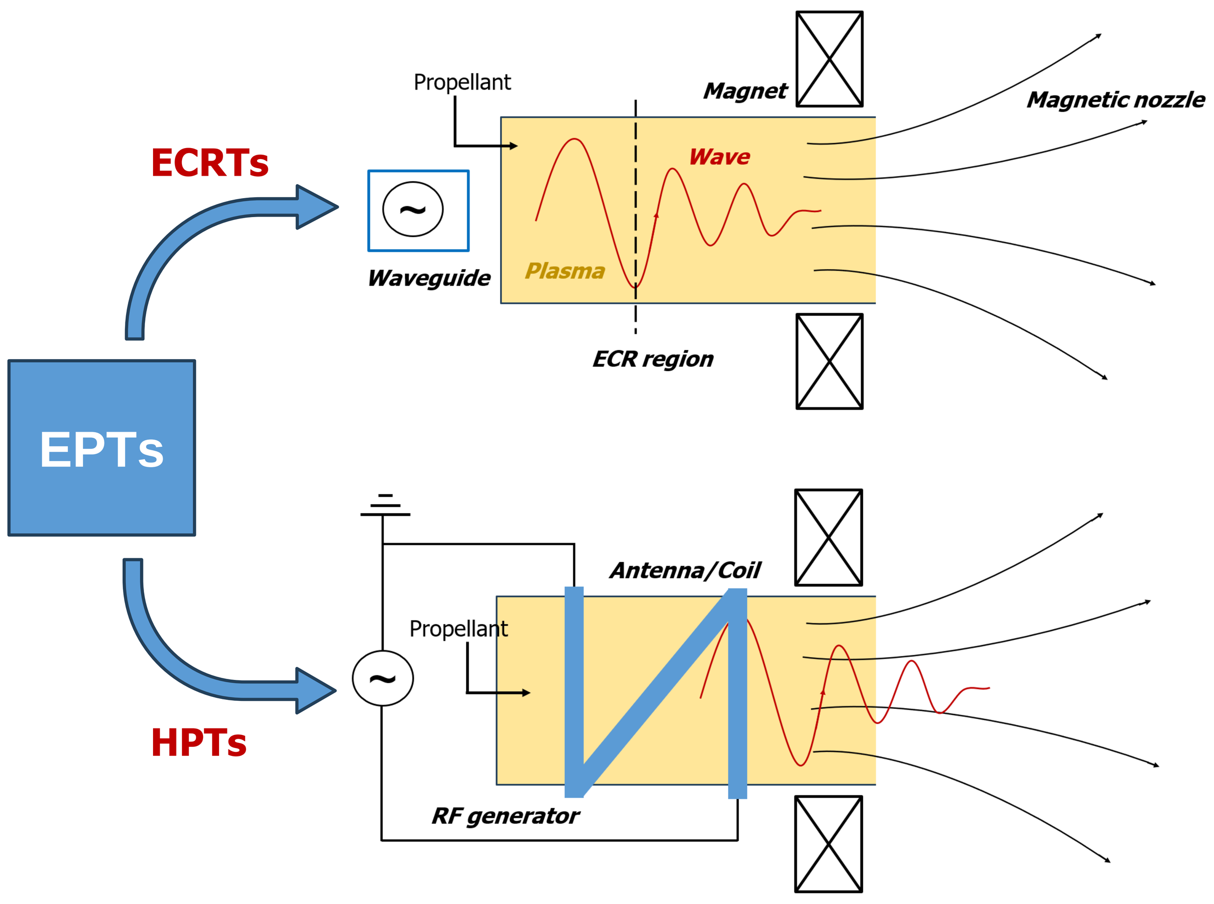
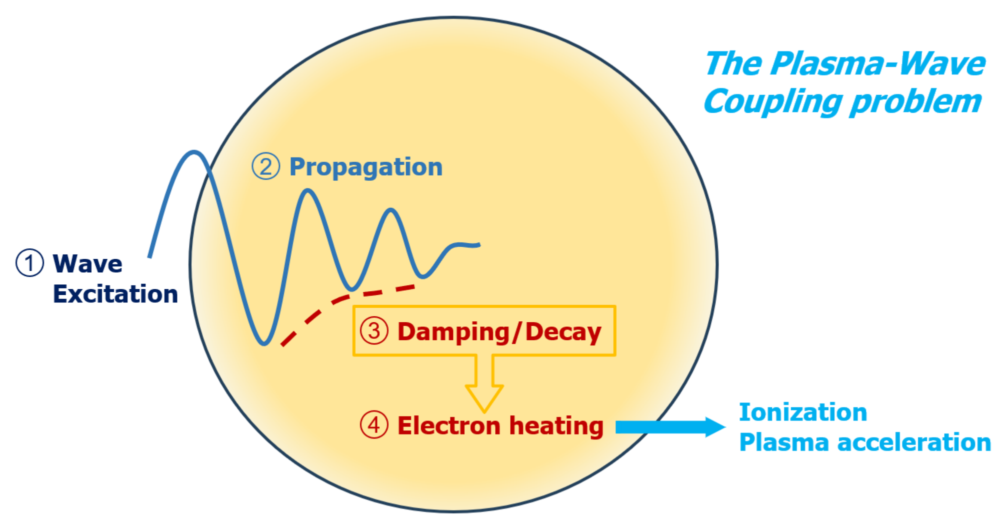
The aim of this Thesis is to improve our understanding of the key processes behind plasma transport and wave coupling in Electrodeless Plasma Thrusters (EPTs). This knowledge will help develop more efficient and reliable EPT systems for practical application in future space missions. The work also focuses on developing and using advanced plasma diagnostics to improve experimental measurements and increase the accuracy in the validation of plasma thruster performance.

Introduction

- Electrodeless Plasma Thrusters (EPTs) are a promising class of electric propulsion devices that generate and accelerate plasma without the use of electrodes, reducing component wear and operation with multiple propellant types, making them attractive for a wide range of space missions, from satellite station-keeping to Very Low Earth Orbit (VLEO) drag compensation [1]
- Two instances of EPTs are exemplified by **Helicon Plasma Thrusters** (HPTs) [2] and **Electron Cyclotron Resonance Thrusters** (ECRTs) [3] which use **radio-frequency** (RF) and **microwave** power, respectively, to ionize the propellant and energize it. This plasma is then accelerated by a diverging magnetic field, forming a Magnetic Nozzle (MN), to produce **thrust**.
- Despite their advantages, the underlying physical mechanisms that govern plasma transport and wave-plasma interactions in EPTs remain only **partially understood**, being the main reason for the low technological readiness level of EPTs [4]. Solving this knowledge gap could allow for the optimization and predictive modeling of EPT performance.



[Plasma Cross-Section]



Thesis objectives

The objectives of this Thesis are

- To clarify the main physical mechanisms governing plasma transport and wave coupling phenomena in EPTs and their MNs
- To advance the implementation of cutting-edge diagnostics, beyond the current state of the art, for the characterization and validation of EPTs.

In order to achieve them, the Thesis will be divided into three main activities:

- **Study of heavy particle distributions** in space and velocity → development of **ExB probe** and **LIF** diagnostics
- **Characterization of wall losses** → use of **thermal tomography, wall probes**, etc.
- **Study of wave propagation and oscillatory phenomena** within the produced plasma

Knowing the particle distribution, wave damping and plasma wall losses, one can fill-in the gaps of particle and energy balances to get a complete picture of the energy pathways from the waveguide/antenna to plasma production and acceleration.

Development of an ExB probe

Design

To characterize the plasma composition in EPT plumes, this Thesis first focused on designing, simulating, manufacturing and testing an ExB probe.

The ExB probe filters ions by velocity using perpendicular electric ($\sim\Delta V_p/d_p$, where d_p is the distance between two parallel plates) and magnetic (B) fields. Ions with velocity $v_i = (\Delta V_p/d_p)/B$ pass through the probe, while others are deflected. By sweeping ΔV_p and measuring the transmitted current, the Ion Velocity Distribution Function (IVDF) can be determined.

Assuming all ions are accelerated by a potential ΔV_{acc} such that $v_i = \sqrt{2Ze\Delta V_{acc}/m_i}$, the ExB probe is able to:

- Identify ions of multiple charge states (Z=1,2,3…)
- Identify the plasma composition in air-breathing thrusters ($m_i = m_{O_2}, m_{N_2}, m_O \dots$)

The probe was designed to be unique in how small and modular it is, to be used in a variety of plasma thrusters with very different ΔV_{acc} and m_i.

Preliminary results

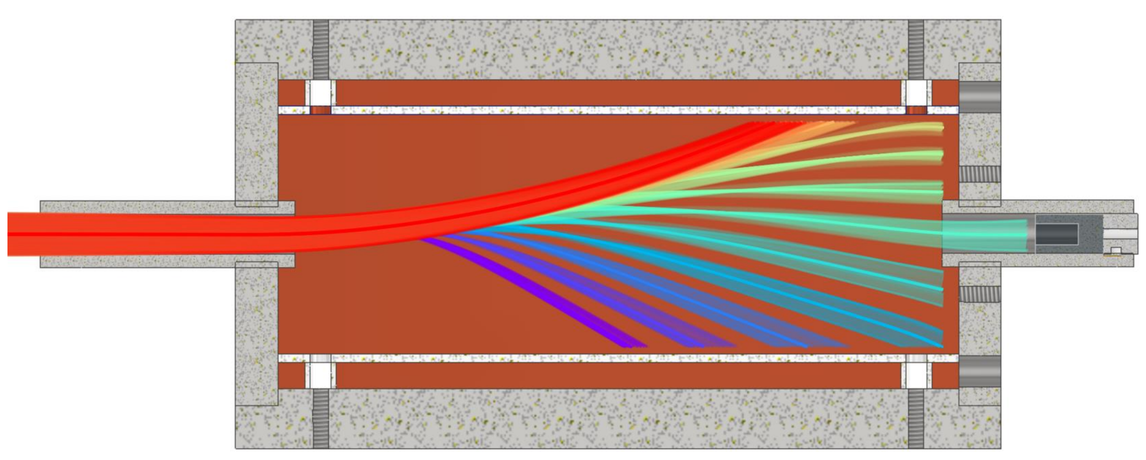
Multiply-charged ions were detected for the first time in the plume of a waveguide ECRT. However, the current trace was significantly affected by the probe's transmittance. Additional issues—including velocity discrepancies with RPA measurements, substantial background current, and unexpected peaks in the low-voltage range—highlight the need for further research to better understand the probe's behavior and address existing gaps in the literature.

Simulation

Inhomogeneous magnetic and electric fields, ion optics effects, the finite size of collimator apertures… all of this can perturb the measured spectra.

By simulating particle trajectories under the imposed fields, one can estimate how well the probe filters (or transmits) each particle velocity, thus determining the probe's "transmittance"

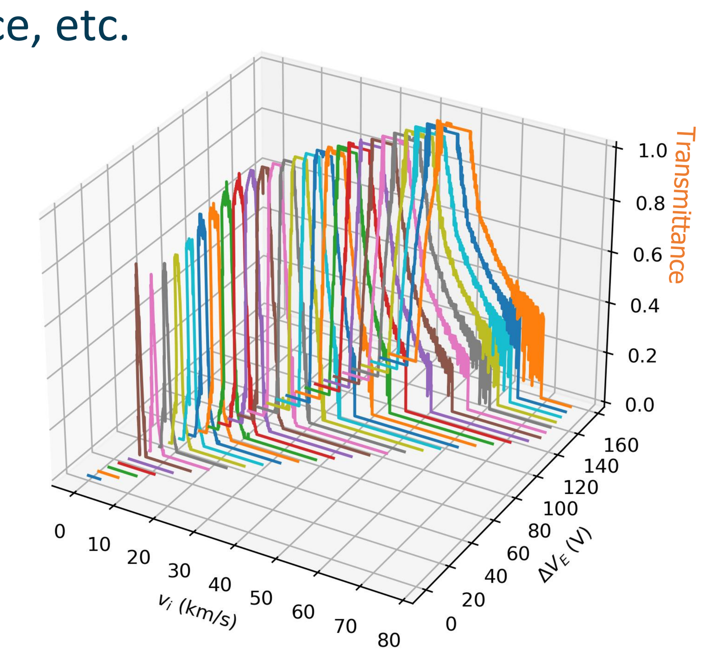
[Top-Down View]



Testing

An extensive testing campaign is being carried out to validate the probe design and its use in ECRTs and HPTs alike, including

- Sweeps of thruster operation points, changing the power and mass flow rate
- Comparison with other diagnostics (RPA, Faraday cup)
- Study of different ExB probe configurations, changing the collimator diameter, inter-electrode distance, etc.



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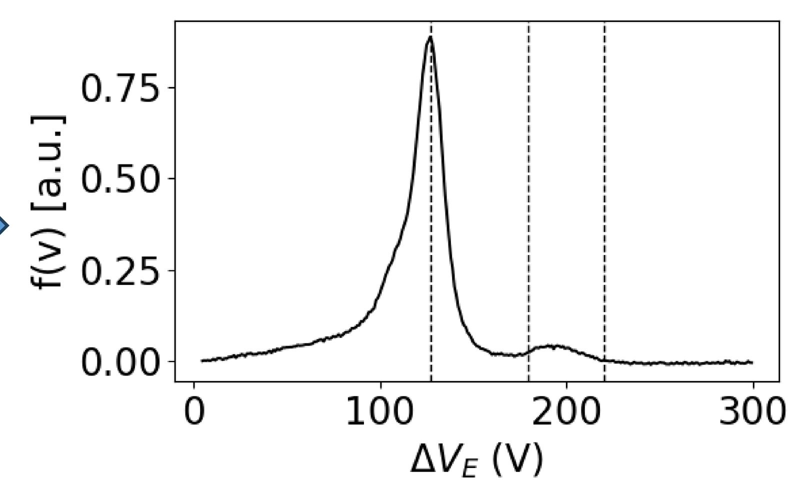

[1] S. Mazouffre, "Electric propulsion for satellites and spacecraft: established technologies and novel approaches". Plasma Sources Science and Technology, 25(3), (2016) 033002.

[2] J. Navarro-Cavallé, M. Wijnen, P. Fajardo, E. Ahedo, "Experimental characterization of a 1 kW Helicon Plasma Thruster", Vacuum 149 (2018), pp. 69-73.

[3] M. R. Inchingolo, M. Merino and J. Navarro-Cavallé, "Plume characterization of a waveguide ECR thruster", J. Appl. Phys. 133, 113304 (2023)

[4] K. Takahashi, "Helicon-type radiofrequency plasma thrusters and magnetic plasma nozzles", Rev. Mod. Plasma Phys., 3(3), (2019)

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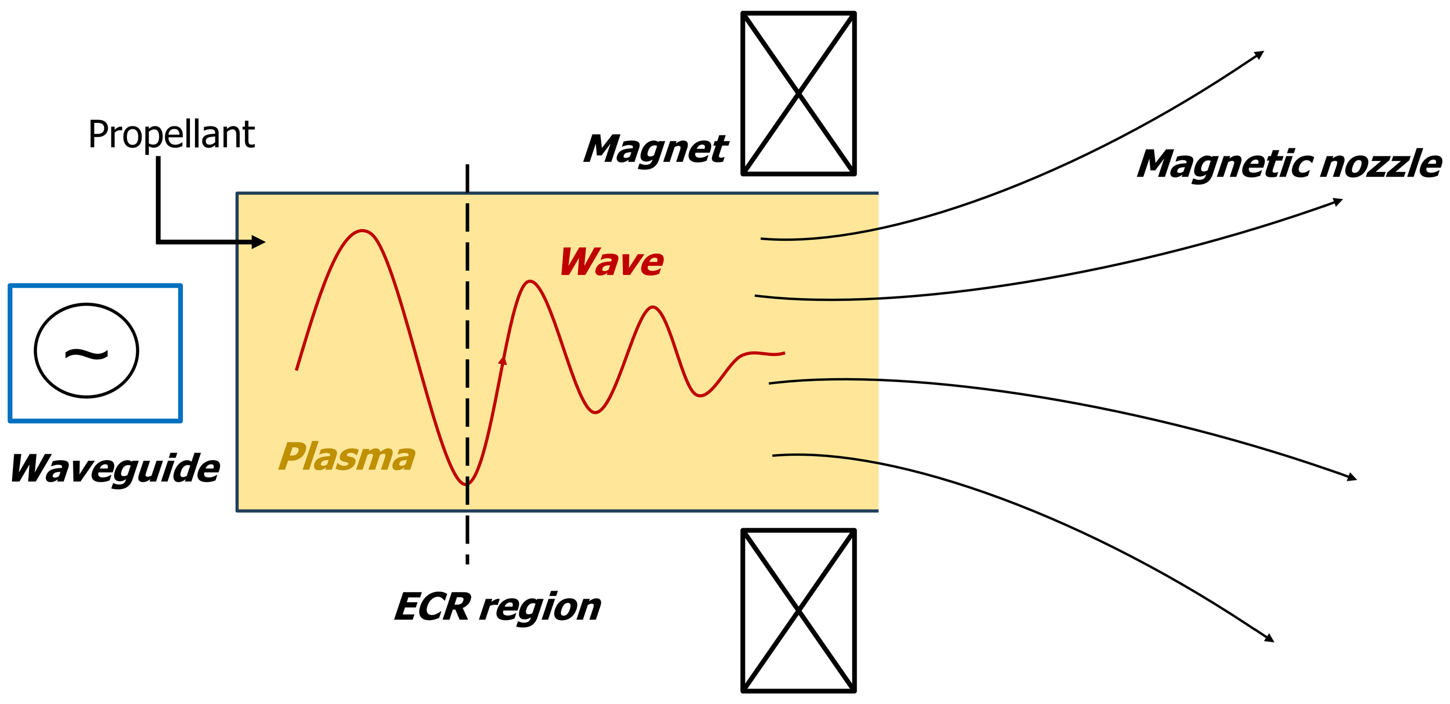

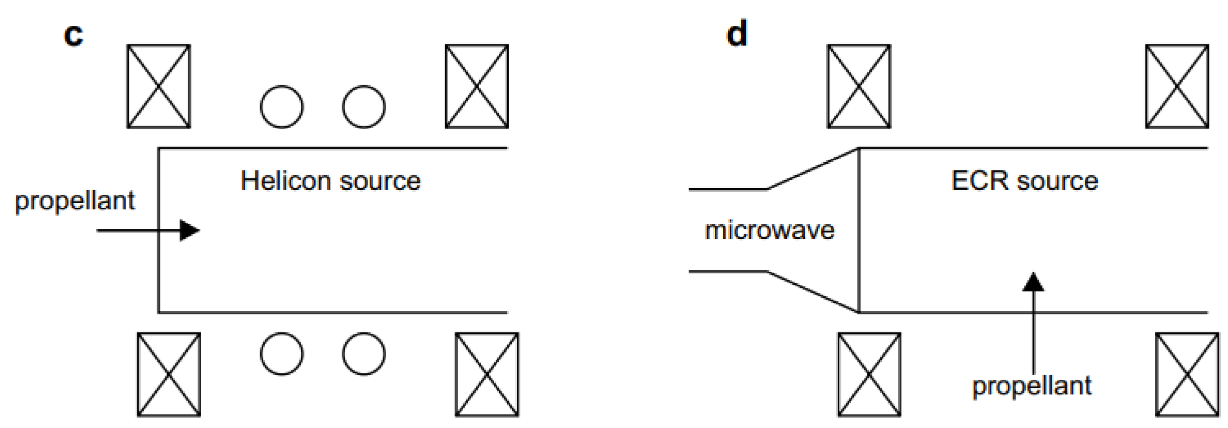

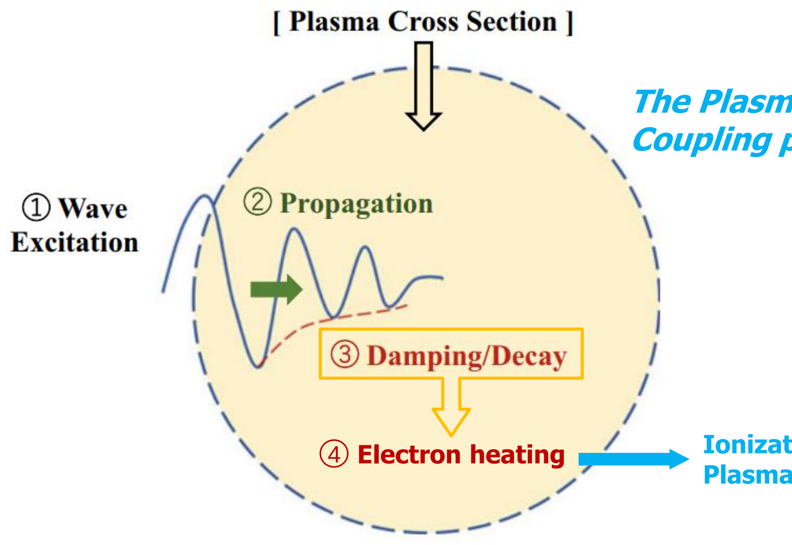

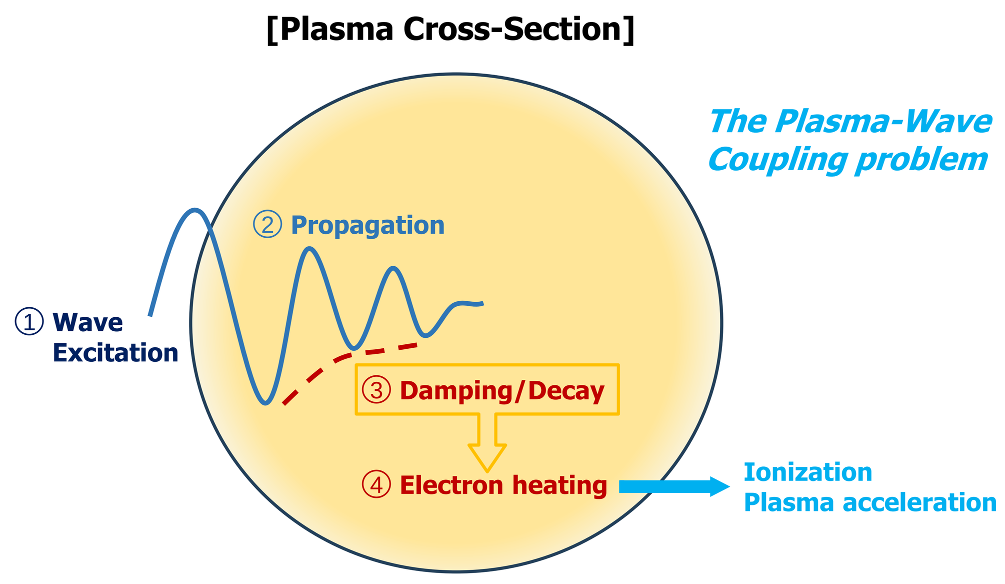

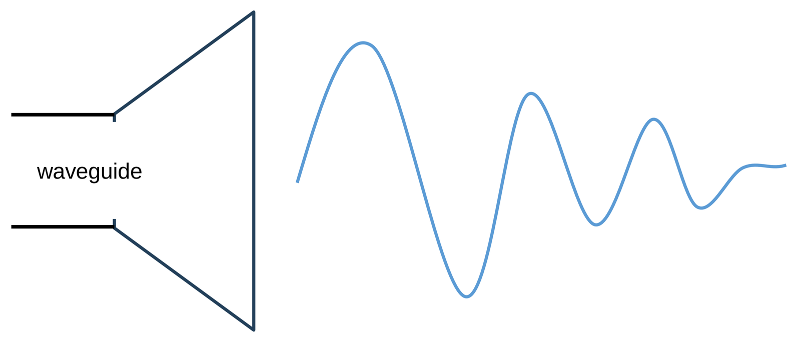

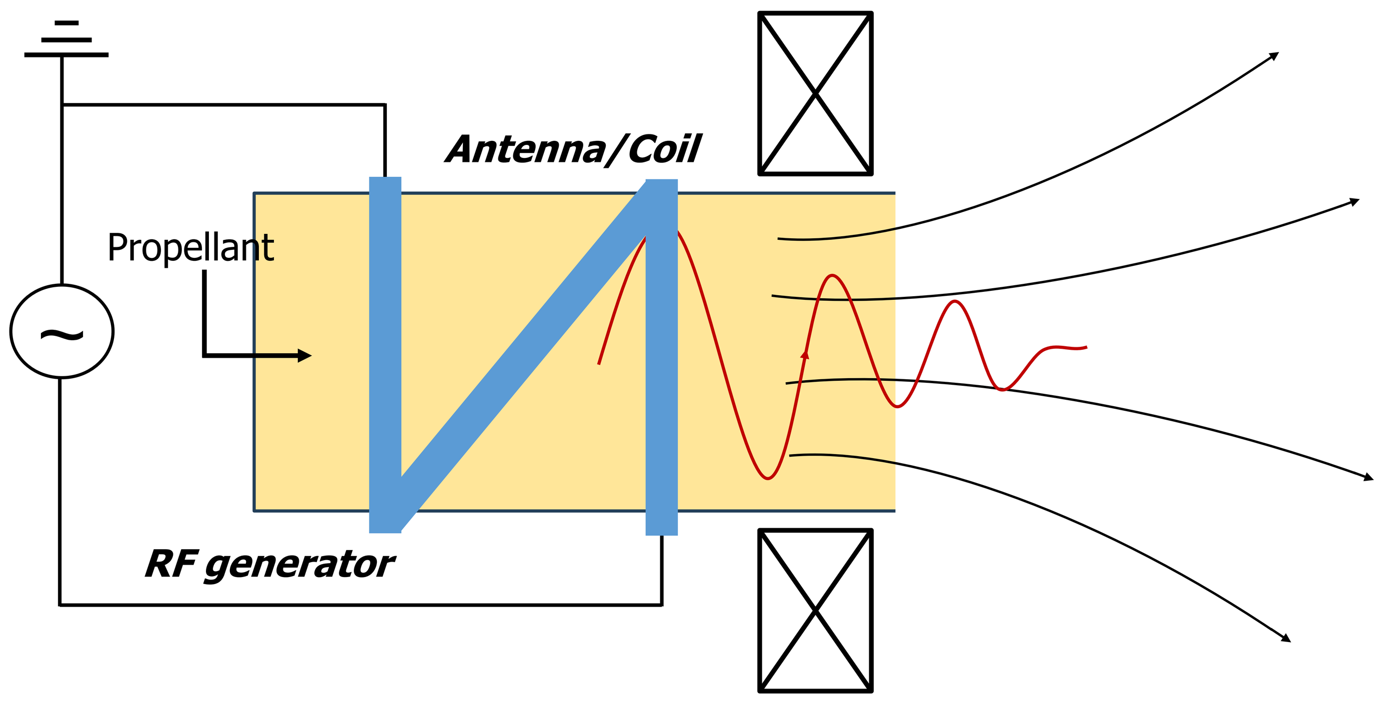

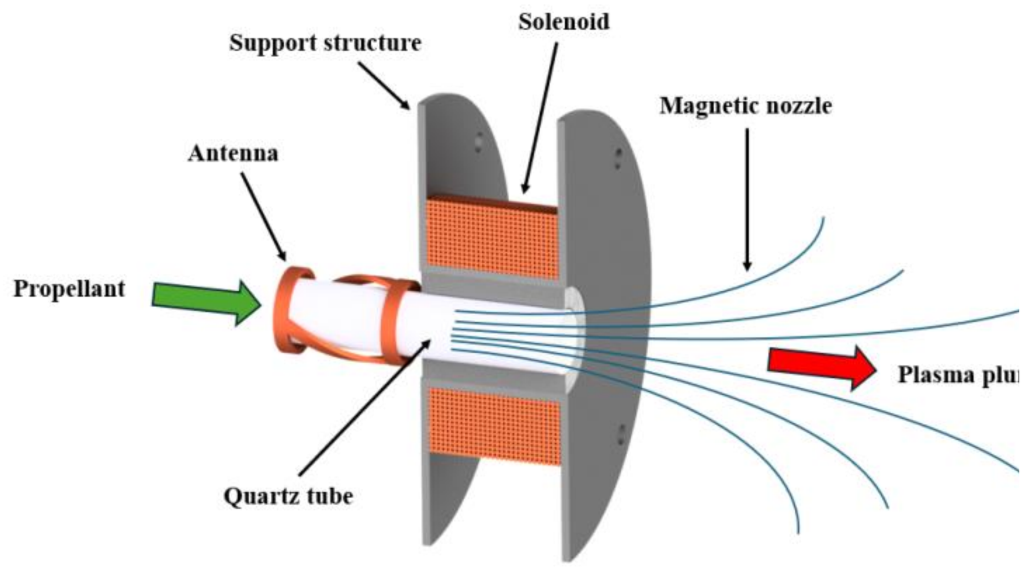

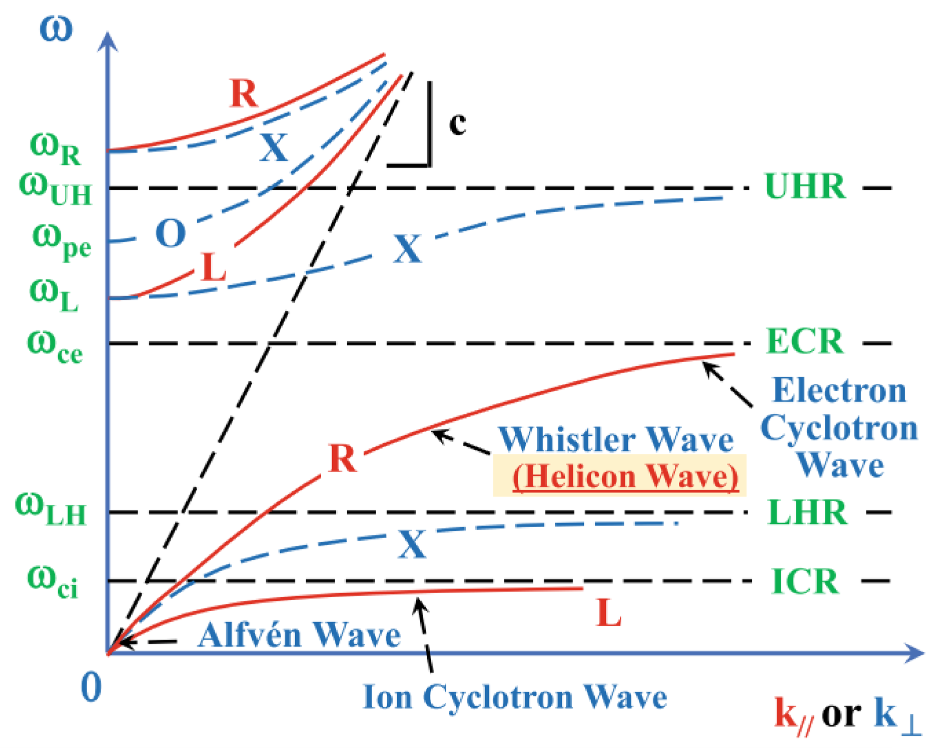

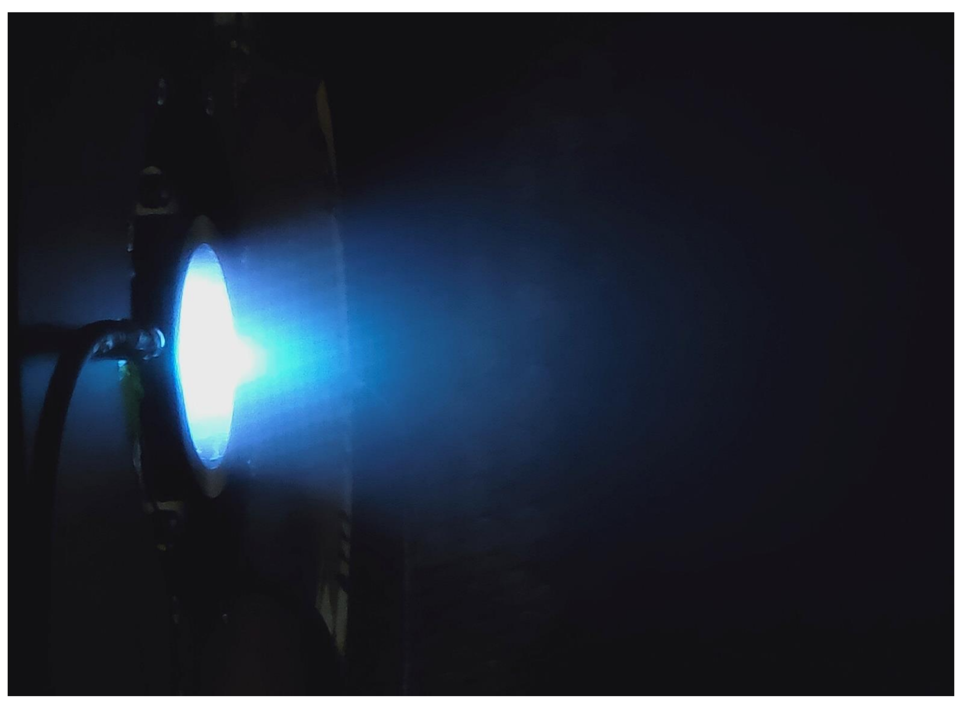

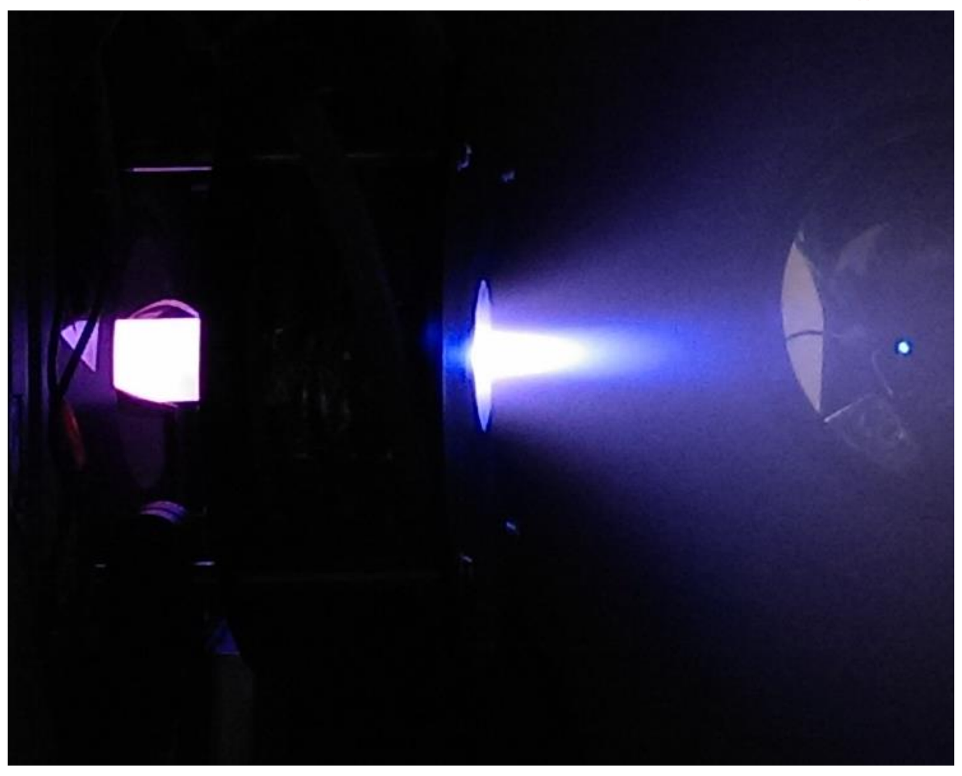

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