Plasma-RF coupling in electrodeless plasma thrusters for in-Space propulsion

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***Abstract*—Electrodeless plasma thrusters (EPTs) are a novel technology in which a plasma is generated and heated by radiofrequency fields. The plasma then expands quasineutrally in a magnetic nozzle, without the need of a neutralizer. We present the recent developments of two EPT prototypes at UC3M: a helicon plasma thruster (HPT, operating in the tens of MHz, around 500 W) and an electron-cyclotron resonance thruster (ECRT, GHz range, 80–300 W). We describe the hardware employed for RF generation, amplification, and matching in each case, the mechanisms for propagation and absorption of the electromagnetic waves in the plasma in these devices, the laboratory experiments, and their results. We also report on the latest modeling efforts to solve the plasma-wave interaction problem numerically.**

***Index Terms*—Electric propulsion, microwave generators, wave-plasma interaction, experimental prototype characterization, frequency-domain electromagnetic modeling**

I. Introduction

Space plasma thrusters (also known as electric propulsion devices) are characterized by a very low expenditure of propellant compared to chemical rockets, which has made them predominant in multiple propulsive applications (e.g., orbit maintenance and control, interplanetary flight, orbit raising, end-of-life deorbiting) [1], [2]. Mature technologies include gridded ion thrusters and Hall effect thrusters. Those devices require several controlled, vacuum-rated voltage sources (typically in the range 100–2000 V) to operate, controlled current sources (up to several amperes), and an external neutralizer device to generate a current-free plasma jet. The electric requirements make their power processing units (PPUs) complex, while the neutralizer (and the presence of naked electrodes) limits the range of propellants they may use and becomes a lifetime-limiting component.

Electrodeless plasma thrusters (EPTs), such as the helicon plasma thruster (HPT) [3]–[5], and the electron-cyclotron plasma thruster (ECRT) [6]–[10] are an alternative technology under development, characterized by the absence of neutralizer or electrodes. Radiofrequency (RF) fields are generated by the PPU and coupled to the plasma with a waveguide/inductor/antenna [11]. A steady-state, applied magnetic field is created with coils or permanent magnets to enable the propagation and absorption of the RF fields into the plasma, to shield the walls of the ionization chamber, and to establish an external magnetic nozzle, where the plasma expands to generate magnetic thrust [12], [13]. Although EPTs can handle virtually any propellant by design (which incidentally makes them attractive for very-low Earth orbit, air-breathing propulsion applications) and, although some devices have already flown [14], overall they still feature low performance and are subject of continued research. Main hurdles to overcome are the limited understanding of the physics of the plasma-wave interaction [15], [16], and the oscillations, instabilities, and turbulence that may exist within and without the plasma source, giving rise to anomalous cross-field transport [17]–[19]. Sections II and III present the RF hardware and experimental developments of these two technologies at UC3M.

Understanding the propagation and absorption of the electromagnetic fields inside the plasma is of paramount importance to understand the operation of these devices and to determine avenues for optimization. A frequency-domain finite-element (FE) model that treats the plasma as a linear gyrotropic medium through a cold plasma dielectric tensor formulation has been established [15], [20]–[22]. Section IV summarizes latest efforts on this camp.

II. Helicon Plasma Thruster

The latest HPT prototype at UC3M was developed jointly with SENER Aerospace [4], [23]. It operates nominally at 13.56 MHZ, up to 450 W, and with 5–20 sccm of Xe as propellant (although it has been successfully operated with Kr, Ar, and air). It uses a helical antenna/inductor to couple with a ± 1 azimuthal whistler mode in the plasma inside the cylindrical source, and power is absorbed either collisionally/resonantly [22], or by a parametric decay instability [19]. Figure 1(a) displays the prototype under operation. At the current stage of development, power is generated with an ad-hoc DC/DC + RF power generator operating on the air side of the experiment. Power is sent into the vacuum chamber with an N-Type coaxial feedthrough, and reaches a vacuum-side, custom-made matching network located right behind the thruster unit. An FGPA controller of the full system tunes, among other parameters, the operational frequency. This device has demonstrated 1–6 mN thrust.

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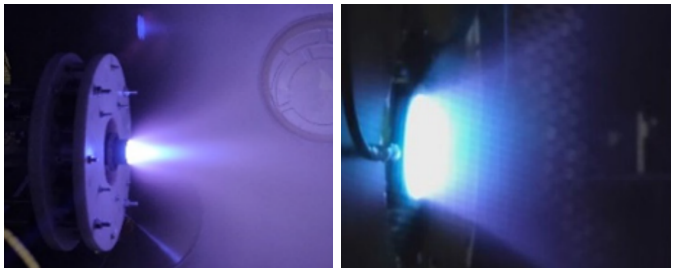

Fig. 1. HPT and waveguide-ECRT prototypes operating in the vacuum chamber at UC3M. From [9], [23].

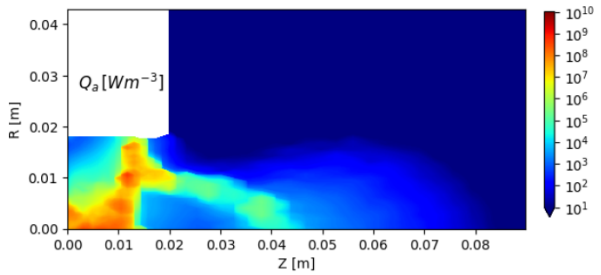

Fig. 2. Simulation results for the wavefields in a waveguide ECRT: power absorption density in the meridian plane of the source and near plume [16].

III. Electron-cyclotron Plasma Thruster

In ECRTs, power at a few GHz is delivered either with a coaxial termination or using waveguides. It is absorbed by the plasma resonantly at the ECR region. A waveguide-ECRT was developed at UC3M that runs at 5.8 GHz, 80–300 W, 2570 G, and 1–40 sccm (Xe) [9], [10]. The prototype under operation is shown in figure 1(b). A 5.8 GHz Magnetron generator, along with a stub tuner (used as a matching network) are located on the air side. A waveguide feedthrough brings the power into the vacuum chamber, which is then guided into the thruster with an additional piece of flexible waveguide. A DC block positioned right upstream the thruster, realized with a small gap between two waveguide pieces, is used to let the thruster body float electrically with respect to ground. Our Waveguide-ECRT has demonstrated up to 3 μN of thrust at 260 W and 8 sccm Xe.

IV. Plasma-wave modeling

A frequency-domain model including a collisional, cold plasma dielectric tensor has been implemented using 2D (radial-axial) mixed Nédélec-Lagrange elements [22] and an azimuthal Fourier mode expansion. The code resolves the amplitudes and phases of the electromagnetic field components in the plasma and the surrounding vacuum for each azimuthal mode, and then computes the absorbed power density as the work of the electric field.

This full-wave code has been used successfully on the HPT [22] and the ECRT [16] (see e.g. figure 2), either alone or in combination with the HYPHEN plasma transport code [24]. Main results in those works include an understanding of where most of the wave power is absorbed, the interplay with the plasma parameters, an the effect on the propulsive performances.

V. Conclusion

Vacuum power electronics for EPTs have quite different requirements from those of other plasma thrusters. While they eliminate the need to generate and control precise voltages and currents, a miniaturized, efficient RF generator is crucial for their operation. This key piece of electronics is still pending development for our HPT and ECRT prototypes.

Overall, we identify the two main specifications for this component, valid for both HPT and ECRT technologies: (1) it needs to be 'throttleable' in power level, and (2) it must be able to deal with input impedance changes that occur during startup, warm-up, and when varying the operating point (mass flow rate, power, applied $\boldsymbol{B}$ field). Impedance matching is critical in both types of device, but even more so in HPTs. Models of the plasma-wave propagation and absorption (ideally coupled with plasma transport models) are needed to understand how and where power is absorbed by the plasma, elucidate simple laws for the power reflected back to the generator in terms of the plasma properties, and find optimal designs.

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