Electrodeless Plasma Thruster research within the ERC-ZARATHUSTRA project

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Abstract

The objectives and activities of the ERC-Starting Grant ZARATHUSTRA, aimed at understanding electrodeless plasma thruster physics and exploring novel thruster designs, are described. A selection of achievements of the project is reviewed, and the last results and ongoing activities are presented. In particular, efforts on kinetic-electromagnetic modeling, magnetic arch modeling and testing, data-driven analysis of azimuthal plasma fluctuations, and RF heating and transport studies are discussed. The contribution ends with an outline of the proposed future development of electrodeless thruster technologies.

1 Introduction

Electrodeless plasma thrusters[1, 2] (EPTs) include several new plasma thruster concepts, wherein plasma generation and acceleration are carried out without any electrodes or neutralizers immersed in the plasma. This key difference with respect to other plasma thruster technologies (e.g. Hall effect thrusters, gridded ion engines) eliminates a critical element in thruster design, which can limit lifetime and the choice of possible propellants that can be used. As such, EPTs offer a greater system simplicity, promise several advantages in up- and down-scaling, and the possibility of addressing new and upcoming propulsive needs. In particular, the ability of EPTs to operate with virtually any gas as propellant makes them ideally suited to tackle complex missions requiring in-situ resource utilization (e.g. refueling in Mars from atmospheric gases) and for very-low Earth orbit air-breathing propulsion. For these reasons and due to their potential impact, EPTs have spurred a huge interest in the propulsion research community, and were labeled as a disruptive technology by the European Commission Strategic Research Cluster on EP[1].

The basic EPT design consists of a cylindrical ionization vessel into which propellant is injected. An electromagnetic (EM) field coupling system (sometimes called antenna) delivers EM power to ionize and heat the propellant into a plasma. An axial magnetic field is applied inside the source with a triple function: (1) enable the propagation and absorption of a selected electromagnetic wave mode in the plasma; (2) reduce plasma losses to the lateral walls of the vessel and protecting them from erosion (magnetically shielding); (3) generate a diverging magnetic topology outside of the thruster called magnetic nozzle (MN), which converts thermal plasma energy into directed kinetic energy contactlessly to produce magnetic thrust. Prominent

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examples of EPTs under development are the helicon plasma thruster[3, 4, 5, 6, 7] (HPT) and the electron-cyclotron resonance thruster (ECRT) [8, 9, 10, 11]. Both concepts exploit the propagation of right-hand polarized waves in overdense plasmas and a MN; they differ mainly on the operational frequencies, and the targeted absorption mechanism.

Nevertheless, EPTs have not yet demonstrated competitive performance and have several standing issues, which prevent them from complementing established technologies: Best self-reported data indicates that HPT prototypes have only recently approached 20-30% of thrust efficiency[12], and the best ECRT results have claimed 40% or greater[8]. While these values are promising and exciting, and some devices have even been tested in-flight [13], the physics that govern EPT efficiency are still not clear, and to be commercially competitive, a better understanding of the physics to guide design and attain a higher performance is necessary.

Regarding the missing physical understanding, we can identify two major areas that require further work: wave-plasma interaction, and plasma transport. The use of EM waves to heat the plasma is key for the performance of the device, since ionization rates, thrust, and specific impulse in EPTs scale with the thermal energy of electrons[14]. The wave must typically traverse several parametric wave regimes in a small domain before being absorbed, which depend on the applied frequency, magnetic field[15, 16, 17, 18]. Propagation of the EM fields is intimately coupled with plasma generation, the kinetics of electrons, and the transport of the plasma species, and cannot be successfully approached without considering all three aspects. Absorption can occur through resonant and collisional mechanisms, but may also involve the nonlinear decay of the pump wave into other modes prior to absorption.

State of the art models use cold plasma models that neglect all kinetic and transport aspects [19]. Recent advances have coupled this type of model with the plasma transport through a heating term in the electron energy equation[15, 16, 17, 18]. However, this still misses the couplings that might exist at the momentum equation level, and any nonlinear interactions. To date, there is still no satisfactory theory of EM fields-kinetic interaction in EPTs. A thorough understanding of the wave-plasma problem is still needed.

The transport of particles perpendicular to the magnetic lines dictates the plasma losses to the walls and their erosion, and it is thus central to the efficiency and durability of the device. Experimental evidence shows classical models lousily underpredict the data, underestimating losses in EPTs by a factor of 10 to 100[7]. This anomalous transport, present in many other partially-magnetized $E \times B$ plasma devices[20], remains an unexplained phenomenon in all EP devices, and even more so, in EPTs, where the problem is further complicated by the presence of the high-amplitude EM fields used for heating. Oscillations and near-wall conductivity need to be investigated as potential causes of anomalous transport.

Last but not least, there is a wide design space for EPT geometry that has not been explored, which may offer advantages over the single cylindrical source. Indeed, the single MN imparts a large divergence angle to the plasma jet[21], and the standard cylindrical design brings a sizable magnetic dipole to the satellite platform, which is usually undesired for simple attitude control. New, ground-breaking EPT thruster configurations may overcome these limitations.

This conference paper begins with an introduction to the ongoing ERC-Starting Grant project ZARATHUSTRA, which aims to unravel the physics of electrodeless plasma thrusters and revolutionize their design, in section 2. Section 3 reviews some of the accomplishments of the project so far and presents the latest results. Finally, section 4 gathers conclusions and offers and outlook on the continuation of the development of EPT science and technology beyond the ZARATHUSTRA project.

2 ZARATHUSTRA project overview

Project ZARATHUSTRA is a 5-year ERC Starting Grant project, which begun on 2021 with the following overarching goal: *To unravel the physical underpinnings of electrodeless plasma thrusters and revolutionize their design.* The project logo is depicted in figure 1, and the project

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website[2].

Figure 1: Logo of the ERC-Starting Grant Zarathustra project

The project has three specific objectives:

1. Reveal the underlying physics of EM plasma heating in EPTs.
2. Identify the likely causes of anomalous particle, momentum, and energy transport in EPTs and plasma losses.
3. Establish a first laboratory-scale proof of concept of a new magnetic topology, termed "magnetic arch" (MA), for plasma acceleration, and determine its feasibility, study its physics and operation, and identify potential advantages and issues.

The MA concept consists of collocating two EPT sources side by side, but with opposing magnetic polarities. This will cause their independent MNs to connect and merge into a novel, partially-closed, arched topology. Studying the MA configuration for plasma acceleration is relevant, as this is the natural choice to cluster pairs of EPTs to increase total thrust and cancel their respective magnetic dipoles. See figure 2 for an artist impression of the concept.

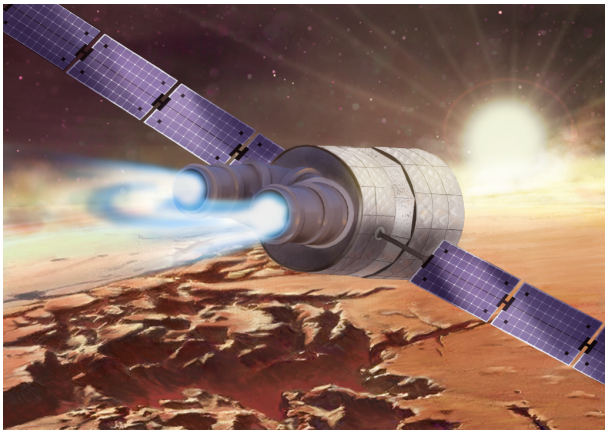


Figure 2: Artist's impression of the magnetic arch (MA) plasma acceleration concept

The proposed methodology to accomplish the objectives of the project combines (1) novel modeling and numerical simulation techniques, (2) state-of-the-art experimental measurements, (3) advanced data analysis techniques and (4) thruster bread-board prototype development. The four aspects of this multidisciplinary approach walk hand in hand, complementing, reinforcing, and validating each other.

2.1 Modeling and simulation

The ability to model the plasma in an EPT retaining three-dimensional geometries, kinetic effects, plasma-wall interactions, electromagnetic fields, and collisional processes is deemed indispensable to answer the research questions on the complex mechanisms involved in heating and thermalization of the electrons, as well as to elucidate the role of the possible causes of anomalous transport.

[2]ERC-Starting Grant ZARATHUSTRA website: https://erc-zarathustra.uc3m.es.

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In plasma physics and EP, the Particle-in-Cell (PIC) method with Monte-Carlo collisions has been very successful in the simulation of the kinetics of the different species. So far, only electrostatic PIC algorithms of low dimensionality have been used to successfully model instabilities of HETs[22, 23], in particular, to identify the growth of electron-cyclotron drift instabilities in the thruster channel. To mitigate the high computational cost, PIC codes typically reduce the size of the thruster artificially , or modify physical parameters like the permittivity of free space ε_0 and the mass ratio of ions/electrons. No major 3D PIC simulations of EP devices still exist, although there are some exceptions[24]. Low-dimensionality finite difference direct-Vlasov models have also been used in EP so far[25, 26]. The study of EPTs with PIC methods has so far been essentially limited to hybrid models, where electrons are treated as a fluid to lower the computational cost[15, 16, 17, 18].

The ZARATHUSTRA project proposes a multilayered modeling strategy, with two levels differing in complexity and physical detail. This is doubly advantageous, since:

- The lower-complexity models can be used independently to understand the fundamental physics, perform faster parametric analyses, and guide the design of new thruster configurations.
- The higher-complexity models can use base-flow information from the lower complexity models. Moreover, results from the higher-complexity models will also be used to refine the hypothesis of the lower-complexity ones.

The lower-level rung of this modeling strategy is composed of two codes to be developed:

- A multi-fluid code to compute the base, steady state flow of the magnetized plasma inside and outside the thruster. Ions, neutrals, and electrons will each be treated as a fluid species, and the interactions among them (i.e. collisions) will be taken into account. The code will also solve the steady-state plasma-induced electric and magnetic field to study the acceleration and detachment process in a MA[27, 28].
- A full-wave, frequency-domain, finite-element (FE) code to solve the fast electromagnetic fields with a dielectric tensor description of the plasma. World-class FE libraries and advanced techniques to tame numerical instabilities[29] will be used.

The higher-level rung has one advanced code:

- A versatile Electromagneic-kinetic code based that will explore, for the first time in EP, the innovative time-implicit PIC scheme[30, 31, 32].

In addition, the project will benefit from the use of existing codes at UC3M, such as HYPHEN and EP2PLUS (hybrid PIC/fluid codes) and PICASO (explicit full-PIC, electrostatic code).

2.2 State-of-the-art experimental measurements

Measuring the time evolution of the plasma and EM field properties at high sampling frequency and at multiple locations is essential to tackle the objectives of the project. Experimental data will also be used to validate models and simulations.

Various plasma sources will be used in ZARATHUSTRA:

- Two canonical cylindrical EPT plasma sources, with highly-controllable, near-axial magnetic field and operating in the MHz range and the GHz range respectively. The first one is an HPT-type source, and the second one is a waveguide ECRT-type source.
- A pair of coaxial ECRT-type sources, used together to generate a MA external topology for plasma acceleration

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- A novel MA-EPT prototype, with a U-shaped geometry[33], as discussed in the section 2.4.

Different EM radiation systems (waveguide, antennas), input powers, applied magnetic field strengths, propellant types, and mass flow rates will be thus tested in the project. The ability to study two different plasma sources is fundamental to discriminate what aspects of the problem at hand (heating, anomalous transport) are transversal to all EPT geometries and what are specific to a particular configuration.

A unique set of three groups of plasma diagnostic systems will be developed and used to characterize EPTs with an unprecedent level of detail. The multiplicity of diagnostic system in each group allows exploiting their complementarity and performing their cross-calibration by comparison. They also avoid the risks associated with the use a single measurement technique:

- Plasma plume probes: the quasi-steady-state features of the plasma flow in the plasma plume in the MN and the MA will be investigated with Simple Langmuir probes, Faraday cups, RPAs, and similar probes. The probes will be positioned with a robotic arm to scan the plume region.

- Fast diagnostics: In order to sample the plasma property fluctuations in the plume, fast double Langmuir probes will be developed that can reliably reach 1–4 MHz [34]. This range covers an important part of the spectrum where many of the plasma oscillations are expected[35]. The possibility of using wall probes to measure inside the plasma source with minimal perturbation will be explored for the first time in EPTs. Additionally, electromagnetic radiation sensors (i.e., dipole and loop antennas) with sensitivities in the GHz range will be developed and used to pick up the wave field signatures inside and outside the vacuum chamber during thruster operation.

- Thermal diagnostics: wall-mounted thermistors and thermocouples will allow to estimate the total energy flux to the thruster walls by measuring their temperature history. This information is essential to evaluate the perpendicular energy transport and quantify anomalous transport. It can also help determine potential thermal problems that may affect EPT scaling to high power.

2.3 Advanced analysis techniques

The vast amounts of data generated by the simulations and experiments need to be processed in order to become valuable information and obtain physical insights. ZARATHUSTRA will make use of advanced linear and nonlinear data analysis techniques to squeeze the most from the available data. A major advantage of these data-driven analyses is that they prevent researcher biases by operating directly on the raw data, without additional assumptions. However, experience teaches us that they need to be complemented by expert knowledge to be of any real use.

Some phenomena in EP thrusters have an underlying linear nature. The spectrogram, based on the standard Fourier transform or on wavelet analysis, can reveal the existence of unstable modes as regions of the spectrum with high power. Likewise, correlations can be used to infer whether there is a connection between the time series of different variables in the plasma. ZARATHUSTRA will apply linear techniques to obtain a first assessment of the operation of EPTs and guide further analysis.

The physics of EPT plasmas are highly nonlinear, and thus linear techniques are inadequate to capture all the complexities of the underlying dynamics, which can be chaotic, exhibit intermittence, and global relationships among the different variables. This project will apply nonlinear time series techniques[36] to explore the nonlinearities in the fluctuations that could be behind anomalous transport. In EP, these techniques have only recently begun to attract attention and yield results[37]; however, EPTs have still not been analyzed in this way.

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In other, more mature fields of plasma physics, such as magnetically-confined nuclear fusion, turbulence and instabilities are known to produce continuous power spectra across many physical scales, and to develop direct and inverse power cascades[38]. Bispectral techniques will be used to aid identify the existence of nonlinear couplings.

2.4 Breadboard MA prototype development

In order to prove or disprove the MA concept for plasma acceleration, and assess its advantages and specific problems, a laboratory breadboard proof of concept in the 500 W range operating on xenon as propellant will be designed, built and tested.

As a first step, the MA concept will be preliminary designed and investigated using the fluid and wave codes of section 2.1. This will set the basic understanding of its operation and the differences with respect to conventional MNs. Moreover, it will allow a quick estimation of its performance and the identification of optimal designs.

Next, a prototype consisting of two coaxial ECRT sources will be designed and built, to assess the plasma acceleration and thrust generation mechanisms in this new magnetic configuration, as well as the role of the plasma-induced magnetic field in the detachment of plasma jet from the closed magnetic field lines downstream (i.e., whether it enables the plasma to stretch and carry the magnetic field lines to infinity, in resemblance with the solar protuberances of similar geometry). The breadboard prototype will be built with flexibility and modularity in mind to allow for modifications; the modeling and test campaigns will provide useful information to update and improve the design. As part of these activities, a roadmap for the continued development of the MA concept will be conceived.

Lastly, an attempt will be made to design and operate a U-shaped EPT discharge chamber [33], to explore the viability of joining the two sources and govern them under a single mass flow and MW unit. Attention will be put in the design of its EM circuit, in charge of generating, transmitting, and coupling the EM power with the plasma.

3 Latest results

This section presents a selection of the project achievements and the latest, ongoing activities. For a complete account of the project outputs, including publications, conferences, and datasets, the reader is referred to the project website[3]. Other recent advances in the project are covered in other contributions to this conference; see, in particular, [39, 40].

3.1 Kinetic-electromagnetic modeling of a magnetic nozzle with waves

As part of the modeling activities of the project, several concepts were explored to enable the simulation of plasma kinetics together with the electromagnetic fields in reasonable computational times. The selected option is based on the novel time-implicit particle-in-cell technique[30], combined with the Darwin approximation to Maxwell's electromagnetic equations. The initial work was carried out by P. Jiménez during a research visit to Los Alamos National Laboratory, hosted by L. Chacón. A first 1D electrostatic version and a study of a paraxial MN was presented in [31]. Estimates showed that this approach offers a 30x faster computational time than other state of the art codes.

The latest iteration of the code is a 1D electromagnetic model. Using this approach, the propagation of a right-hand polarized wave into the MN of a HPT, and its ultimate absorption around the ECR surface that exists downstream, was investigated. The kinetic-electromagnetic code allowed the inspection of the moments of the electron velocity distribution function, in particular its temperature and heat flux components, as well as the Poynting vector, shedding light on the heating mechanism present in this device[32]. For illlustration purposes, figure 3

[3]ERC-Starting Grant ZARATHUSTRA results website: https://erc-zarathustra.uc3m.es/results.

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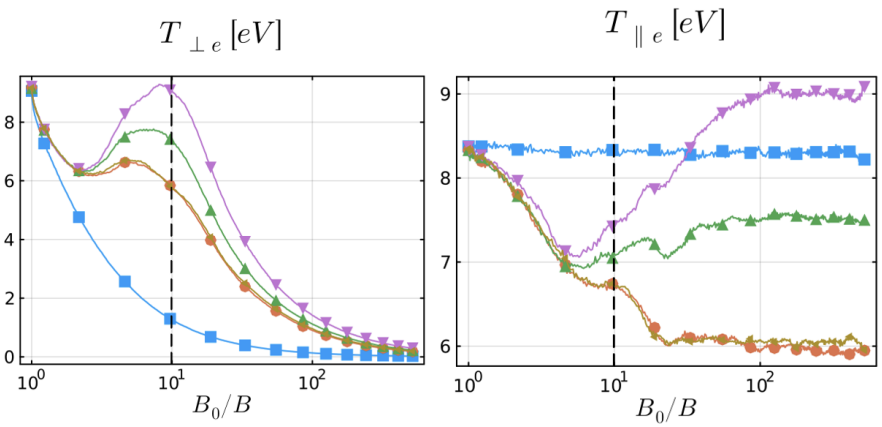


Figure 3: Perpendicular and parallel electron temperature evolution along a paraxial MN subject to a right-hand polarized wave traveling downstream, for various incident power levels. The dashed line indicates the location where ECR conditions are met.

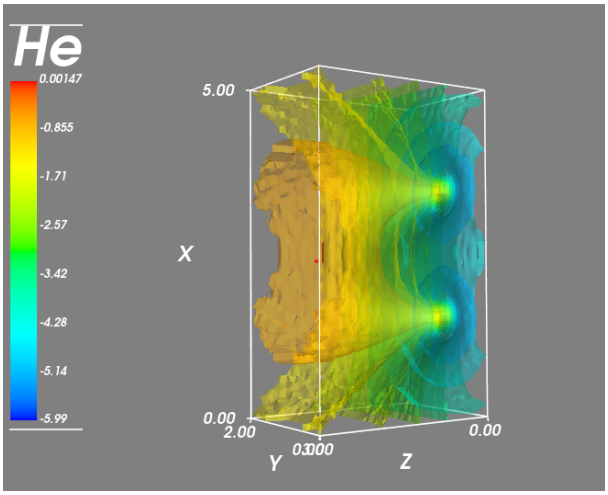


Figure 4: 3D fluid simulation of the thermalized potential in a magnetic arch.

depicts the evolution along the MN of the perpendicular and parallel electron temperatures, under varying wave power levels. Incidentally, a rise in the electron temperature around the ECR region has been observed experimentally in recent HPT measurements[18], similar to the one observed in the simulations.

3.2 Plasma acceleration in a magnetic arch

The multi-fluid code developed in the project has been used to investigate the expansion of a plasma in a 2D-planar MA topology, to understand the key physics of the expansion[27]. Key findings include evidence that it is possible to extract a plasma jet from this closed-line magnetic configuration. Results hinted at the possibility that the beam divergence could be lower than that of a MN, thanks to the shape of the MA magnetic field. However, they also showed that the ion energy would be lower than in a comparable MN, as the central part of the arch acts as a barrier for electrons, which set up an adverse electrostatic potential that partially decelerates ions. Currently M. Cortés-Hernán is exploring the 3D aspects of the MA plasma expansion with an extension of this multi-fluid code, see figure 4.

In addition, it was also shown that the plasma-induced magnetic field (generated by the electric plasma currents) tends to stretch and open the arch. This lowers the potential barrier described above, resulting in an overall rise of the produced thrust at moderate β values. The

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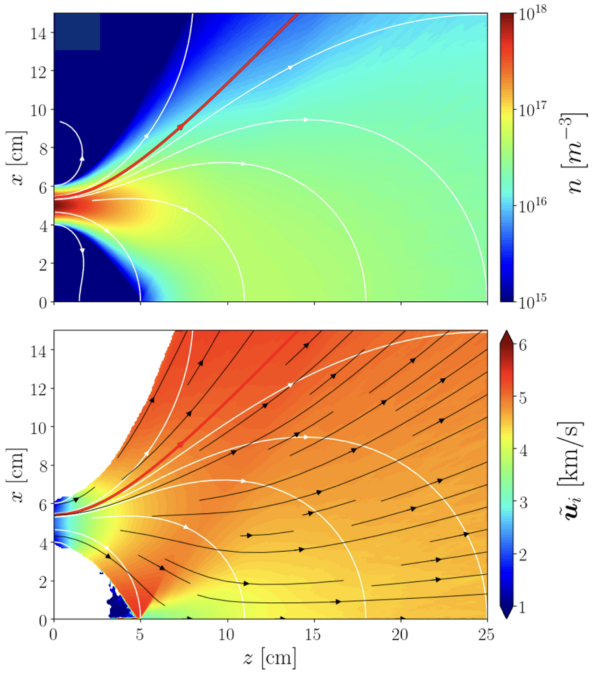


Figure 5: Hybrid PIC/fluid simulation of a planar magnetic arch plasma expansion. Electron density and ion velocity in the upper half of the plane (bottom is the symmetry line). White lines are magnetic lines, the red line is the magnetic separatrix, black lines are ion streamlines. Adapted from [28].

PhD thesis of D. García-Lahuerta enabled these developments.

The same problem was later simulated also with the hybrid PIC/fluid EP2PLUS code, including collisions[28], a work carried out by M. Guaita. This allowed to address consistently the interaction region between the two beamlets (coming from each of the plasma sources), revealing that the expansion does not feature a strong shockwave, and otherwise confirming previous findings. This work also studied the electron current solutions under various Hall parameter values, and the demagnetization effect as the Hall parameter goes to zero. Figure 5 illustrates some of the key modeling results.

A MA prototype consisting on a cluster of two basic coaxial-ECRT sources was designed, built, and tested in C. Boyé's thesis[41], see figure 6. The ion current and energy was measured with a Faraday cup and an RPA, finding results in qualitative agreement with the model. A comparison with the flow in the MN of a single ECRT source revealed a lower divergence angle in the plane of measurement, yet a lower ion energy as expected. A second test campaign took place in the laboratory of S. Mazouffre (CNRS), where the ion velocity distribution function was characterized via 2D LIF[42].

Recently, S. Huot has characterized the MA magnetic field in 3D, and the plasma properties in the horizontal and vertical planes using electrostatic probes, in the framework of his MSc thesis. The magnetic field shows small to medium asymmetries between the two sources, and small ones in the MA region. Figure 7 presents early results from this study, revealing a the map of the plasma density and a high electron temperature in the central part of the arch (in particular, in the magnetic tube that joins the two ECRT core elements). Results also shown an electrostatic potential that is non-monotonic in the axial direction, along the thruster centerline. Interestingly, measurements also show the deflection of the plasma jet sideways in the vertical plane. A plausible explanation for this is that $E \times B$ drifts in the central part of the arch cause the nearly-trapped electrons in this regions to slowly drift preferentially in one direction; indeed, switching the polarities of the two sources simultaneously reverses the direction of the drift, as can be observed in figure 6. Further analysis is necessary to establish a model of this

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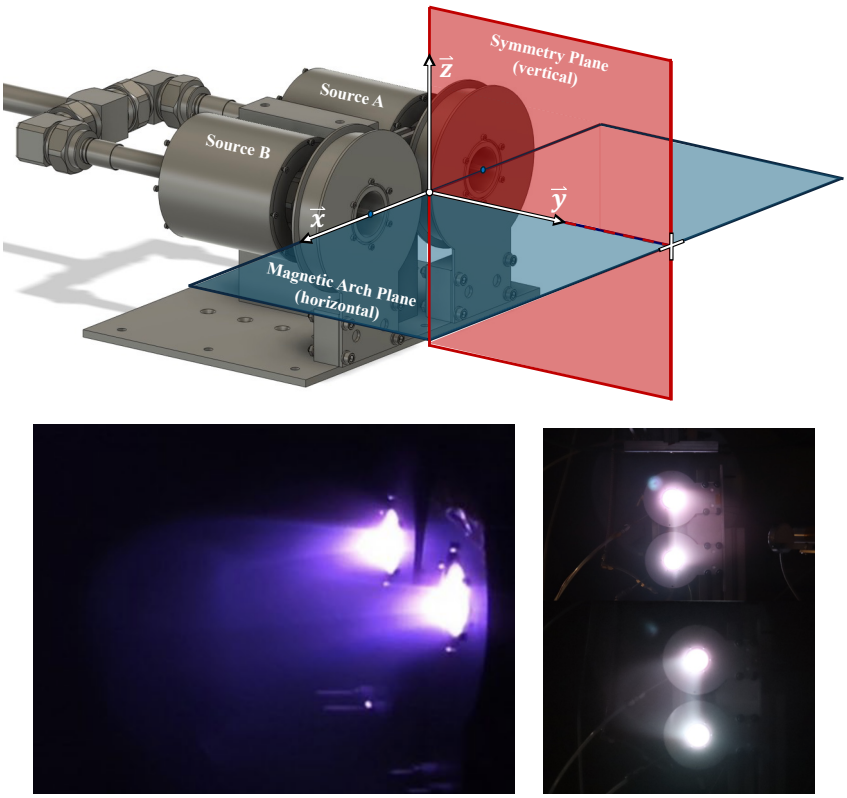


Figure 6: (Top): Sketch of the setup. (Bottom left): Photograph of the two ECRT sources operating with opposing magnetic polarities, forming a magnetic arch. Adapted from [41]. (Bottom right): Front-view photographs of the arch, with the B field pointing from top to bottom (upper photo) and from bottom to top (lower photo), obtained in recent experiments by S. Huot.

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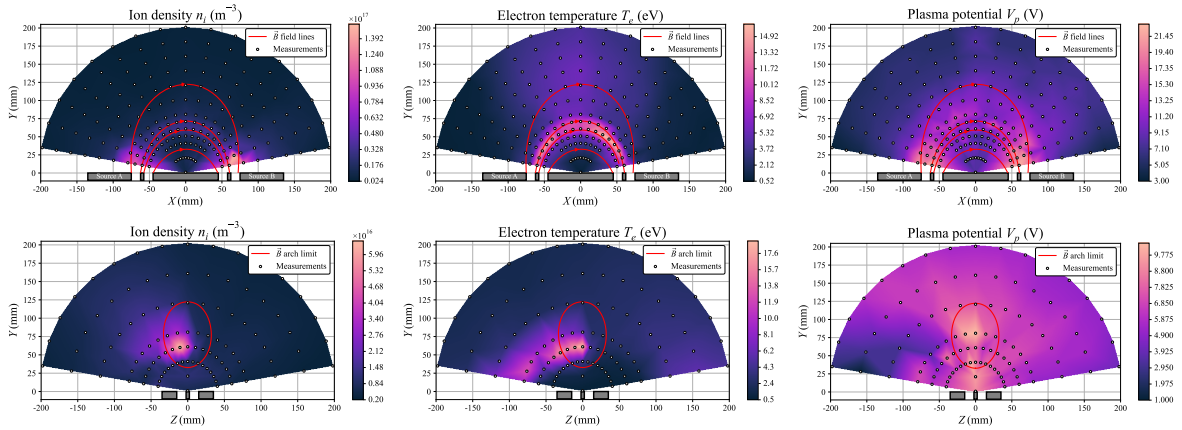


Figure 7: Langmuir probe measurements of ion density, electron temperature, and plasma potential in the horizontal and vertical planes of the MA. The red lines indicate magnetic lines in the top row, and the intersection of the main magnetic tube with the vertical plane in the second row.

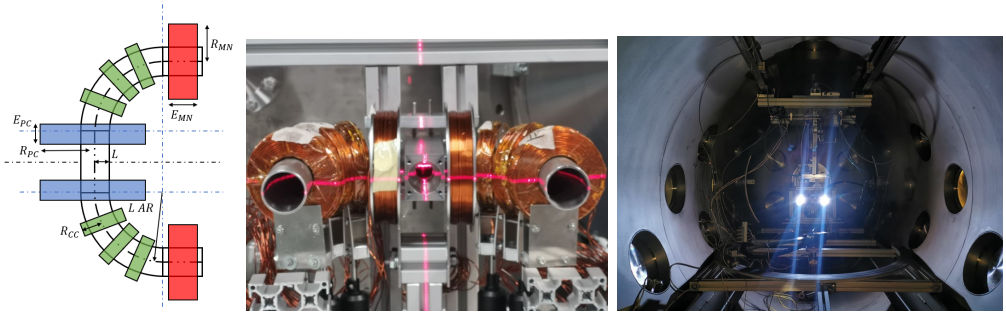


Figure 8: Sketch and photographs of the geometry of the U-shaped prototype.

behavior, and devise means to mitigate (or exploit) this sideways drift.

Finally, a U-shaped thruster prototype was built and tested by C. Boyé, based on the initial concept described in [33]. The device consisted of metallic walls and a set of coils distributed along its curve to generate the applied magnetic field. A central injector and a central coaxial antenna operating at 2.45 provided the gas and power for the operation. While the device was ignited successfully in the 100–500 W and 10s of Xe sccm range, it was evidenced that the performance was sub-par compared to the two independent ECRT sources. Several hypotheses exist as to this. First, it seems likely that such device may require a higher magnetic field to magnetized ions, and help those ions generated in the middle of the device to reach the exits without colliding with the walls. Displacing the power deposition nearer to the exits may help in this regard. Second, metallic walls may result in an enhanced plasma loss inside the device, as electric currents can close through the walls. A dielectric ionization chamber could mitigate this problem.

For this reason, progress on the characterization of the external MA for plasma acceleration will continue with the two independent sources. This has the added benefit that the relative distance and orientation of each source can be easily modified, without redesigning the whole setup.

3.3 Data-driven analysis of plasma fluctuations in EPTs

Experimental work by D. Maddaloni, where the floating potential fluctuations in the plume of an HPT were measured with multiple fast Langmuir probes, helped obtain some of the first evidence of azimuthal oscillations in EPTs[43], complementing those of other groups [44, 45].

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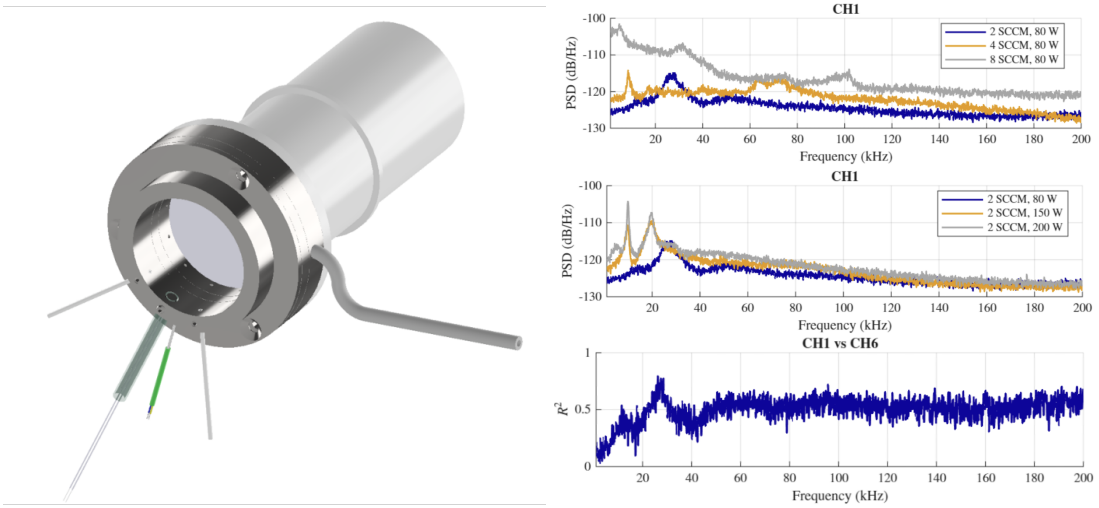


Figure 9: Waveguide ECRT setup, modified to host two wall probes, a thermocouple, and a thermoresistor. Preliminary power spectral densities at one wall probe for various operating regimes, and the coherence squared among the two probes for R^2 at 80 W, 2 sccm, are shown.

The dispersion relation of the oscillations was reconstructed using the cross-spectral power density between two probes and circular statistics. Moreover, a bicoherence analysis showed a relevant correlation between the phase of the < 200 kHz spectrum and the pump wave at 13.56 MHz. Similar measurements were also conducted in a coaxial ECRT device at ONERA facilities [46]. Currently, E. Lettera is exploring the use of two wall probes to sample the azimuthal oscillations directly in the source of a waveguide ECRT, in the framework of his MSc thesis. Distinct spectral features with good correlation among the two probes are found in the < 200 kHz range. In addition, a thermocouple and a thermoresistor, embedded into the device's walls, are being used to recover the thermal history of the thruster under operation, to estimate thermal losses to walls from analysis. Figure 9 illustrates the setup and preliminary data of the fluctuations at various operating points and the coherence squared R^2 at 80 W, 2 sccm.

The work of B. Bayón-Buján explored the use of these higher-order spectral techniques and sparse regression (SINDy) to identify nonlinear couplings among modes and establish reduced order models in an $E \times B$ discharge simulation[47].

3.4 RF heating and plasma transport in the plasma source

Various simulations and experiments have been conducted to better understand the key problems of heating and transport in EPTs. P. Jiménez studied wave-plasma propagation and absorption in the context of HPTs[17], identifying the power deposition that takes place in the plume when the ECR condition is met (this occurs similarly to ECRTs, but the location of the ECR surface is farther downstream, outside of the source). The study continued with the assessment of the self-consistent plasma transport under the action of the wave using hybrid PIC/fluid simulations[18].

The full-wave code employed in these studies employs a cold plasma dielectric tensor model and is based in edge finite elements. The latest iteration of this code has been optimized in the Julia programming language and is being used to understand 2d and 3d features of the wave-plasma interaction problem by H. Bergerioux[40].

3.5 First international EPT workshop in Madrid

The first International Workshop on Electrodeless Plasma Thrusters took place in Madrid July 3-4 at UC3M, organized and partially sponsored by the ZARATHUSTRA project. The work-

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shop brought together 40+ experts across Europe, America, and Asia to share and discuss the latest advances on Electrodeless Plasma Thrusters, and the roadmap for the continued development of these technologies. The workshop was opened with a keynote from ESA. All information can be found in the workshop website[4].

4 Conclusions and outlook

Electrodeless plasma thrusters are a novel family of electric propulsion concepts, characterized by the contactless generation and acceleration of a plasma (with electromagnetic waves and magnetic nozzles, respectively). This characteristic enables them to operate with virtually any gas, an essential quality for future ambitions missions requiring in-situ resource utilization for refuelling and very-low Earth orbit (VLEO) air breathing missions.

The ERC-Starting Grant ZARATHUSTRA project has aided understand the basic physics underlying their operation and performance, and has explored novel magnetic topologies for their plasma acceleration (the magnetic arch). The magnetic arch forms naturally when clustering EPTs with opposing polarities to cancel their magnetic dipole, and therefore is essential for high-power missions relying on EPTs. The ongoing activities (wave and plasma transport simulations, magnetic arch characterization, and fluctuation and thermal history measurements) are expected to further our knowledge on these key areas of EPT physics.

One of the key findings of the project is related to the causes of the poor efficiency of EPTs. Available evidence attributes this to anomalous transport, brought about by the azimuthal oscillations present in the plasma, which are also known to exist in other $E \times B$ plasma discharges like Hall effect thruster. These oscillations are generated by instabilities and may involve nonlinear power-transfer couplings across modes. Notwithstanding this, EPTs feature additional complexity due to the presence of high-amplitude RF fields, which may interact with and further complicate the oscillations in the plasma.

The outlook for the future of EPTs is that careful design of the internal and external magnetic field is needed to optimize their performance, in order to mitigate losses passively. Nevertheless, it seems likely that higher efficiencies may only be attainable by introducing active control over the proximal causes of anomalous transport, i.e., the fluctuations responsible for it. This is by no means an easy task, and requires major breakthroughs in the understanding of cause-effect relations among fluctuations and transport, as well as assessing the observability and controllability of fluctuations by simple sensors and actuators that can be embedded in the thruster design without a major increase in their complexity. Collaboration among research institutions and companies developing the EPT technologies is essential to address this challenge.

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