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HIPATIA: A project for the development of the Helicon Plasma Thruster and its associated technologies to intermediate-high TRLs

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Abstract

HIPATIA (HelIcon PlasmA Thruster for In-Space Applications) is a project recently awarded with an European Commission H2020 grant for the development of the Helicon Plasma Thruster and the technologies associated to it. The goal of the HIPATIA Project is to verify the function and performances of an Electric Propulsion System based on the HPT technology, for its application in non-geostationary satellites constellations and other small spacecraft. The Consortium, led by SENER Aeroespacial, counts with the participation of Universidad Carlos III de Madrid, AIRBUS Defence and Space, the Centre National de la Recherche Scientifique and Advanced Space Technologies. The Partners bring to HIPATIA a solid background in the development, integration and test of Electric Propulsion (EP) Systems. The HPT is a radiofrequency powered plasma propulsion technology that can prospectively offer a good level of performance while eliminating many of the design and manufacturability issues (electrodes, high voltage electronics, and complex fabrication) which have afflicted EP systems to date. Given the relatively simple and robust design of the HPT technology (no grids neither cathodes), HIPATIA has the potential for providing a cost-effective solution for large constellation of small satellites. The impacts associated to having a disruptive thruster in high TRLs would not be achieved unless the complete EP System has proven its integration and operation consistency. HIPATIA will advance the development status of the HPT up to TRL6-7, but it will also face the integration challenges of a complete EP System, constituted by the HPT Thruster Unit (TU), the Radiofrequency and Power Unit (RFGPU) that feeds it with power and the Propellant Flow Control Unit (PFCU) that controls the propellant pressure and mass flow. The System will be integrated and verified against the requirements derived from the market needs. Development activities will be complemented with research and experimental tasks, in order to propose design actions to improve the HPT performances. The paper reviews the market needs for small platforms in-Space propulsion, analysing the needs and requirements imposed to an HPT-based propulsion subsystem. The status of the technologies to be developed and integrated in the HIPATIA Project will be discussed. From this point, the paper explores the Consortium's plans on research and development for taking an HPT-based propulsion subsystem to TRL6 in 2022.
Keywords: Helicon Plasma Thruster, HIPATIA, H2020.

Acronyms/Abbreviations
Breadboard Model (BBM)
Elegant Breadboard (EBB)
Engineering Model (EM)
Electric Propulsion (EP)
Engineering Qualification Model (EQM)
Geosynchronous Orbit (GEO)
Gridded Ion Engine (GIE)
Hall Effect Thruster (HET)
Helicon Plasma Thruster (HPT)
Low Earth Orbit (LEO)
Medium Earth Orbit (MEO)
Propellant Flow Control Unit (PFCU)
Power Processing Unit (PPU)
Radiofrequency and Power Unit (RFGPU)
Technology Readiness Level (TRL)

1. Introduction

Among the different technologies that can improve Space platforms and missions performances, the use of Electric Propulsion (EP) for orbit transfers and attitude control has attracted considerable attention in the last years.

The utilisation of EP introduces important savings in terms of propellant consumption when compared to chemical thrusters. In the last 2-3 decades, EP has been mostly used for secondary propulsion tasks (e.g., station-keeping manoeuvres of GEO platforms). However, in the past few years, the use of EP thrusters for other applications (such as LEO-MEO constellations' satellites and GEO platforms delivery to final orbit) has been proposed and it is currently under implementation by several operators. This new kind of applications enhanced, or even enabled, by the use of improved EP concepts, are key to expand the position of the European Space sector.

To date, electrostatic thrusters such as the Hall Effect Thruster (HET) and the Gridded Ion Engine (GIE) have been the preferred solution when introducing EP in different satellites platforms and missions. They offer high design maturity and reliability, achieved after many years of development, but still present challenges regarding implementation impact and costs.

The Helicon Plasma Thruster (HPT), a technology under development by SENER and UC3M, is a radiofrequency powered plasma propulsion technology that can offer a good level of performance while eliminating many of the design and manufacturability issues - electrodes, high voltage electronics, and complex fabrication - which have afflicted EP systems to date. Given the relatively simple and robust design of the HPT technology (no grids neither cathodes), HIPATIA has the potential for providing a cost-effective solution for large constellation of small satellites (<500 kg, <750W of power for EP).

2. The HIPATIA Project

2.1 Background

SENER and UC3M started to collaborate on the development of the first HPT prototype in 2015. The HPT-05 was firstly ignited in October 2015 at ESA premises, and it was subject in different test campaigns at the UC3M Electric Propulsion Laboratory since spring 2016. It was a 1kW experimental platform providing flexible architecture and operation capabilities, in order to maximise the knowledge obtained from the characterisation tests [1].

The knowledge collected from this first prototype, as well as a review of the market needs at that moment, resulted in the decision to go for a lower power version of the HPT. The HPT-05M was an intermediate model developed to validate different design modifications that are required for the system transition from 1kW to 400W.

In 2018 the evolution to a higher TRL model, the HPT-03 started. The most important change with respect to HPT-05M was the substitution of the coil-based magnetic generator by a permanent magnet set-up. The HPT-05M and HPT-03 were extensively tested in 2018-2019, its performances results been reported in [2].

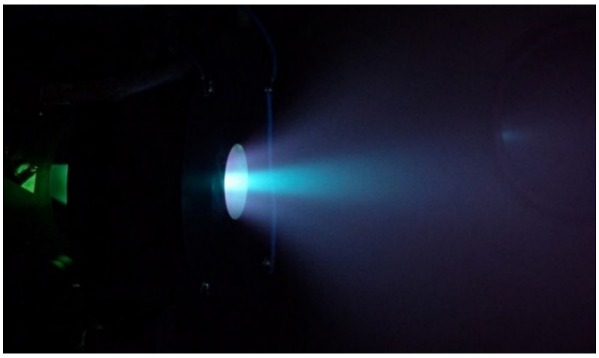

Fig. 1. HPT-05M running at UC3M facility.

At that point, it seemed the HPT could be an interesting technology for the small platforms market. So far, the development had focused in the thruster and the electronics, but a complete propulsion subsystem development was necessary to ensure the impact of the technology in the in-Space propulsion scenario. Therefore, the idea behind HIPATIA is to develop the whole propulsion subsystem to a TRL level that ensures in can be flight-ready in the defined timeframe. For this to be done, several gaps, needs and related activities were identified when preparing the proposal: definition of a use case, development of a deep market survey to derive requirements, improve the propulsive performances, further investigate the plasma physics behind the helicon concept, perform coupling tests… These needs were translated into the following goal and objectives for the HIPATIA Project.

2.2 Goal and objectives

The goal of the HIPATIA Project is to verify the function and performances of an Electric Propulsion System based on the HPT technology, for its application in non-geostationary satellites constellations and other small spacecraft.

To achieve this goal, the HIPATIA Project Team will work focused on the following objectives:

- Advance in the HPT technology development to fit market needs. Assessing the performances of the technology, identifying requirements and analysing the HPT impact in the Space platform.
- Improve the performance of the HPT. Through key research and testing activities during the course of the Project, developing a better understanding of the plasma physics in helicon sources and thrusters.
- Raise the TRL of the HPT and its associated technologies (fluidics and electronics) to TRL6. Detailing the design of the different units that will support the thruster operation, defining interfaces

and performing thorough analyses (mechanical, thermal, EMC…) supported and validated by testing activities.

- Plan the development for higher TRLs and industrialisation. Exploitation of the Project results includes the final assessment of HIPATIA achievements, the roadmapping of additional developments towards full qualification for flight as well as business planning.
- Create and consolidate a collaboration scheme among the Consortium Partners, integrating key players in the value chain.

2.3 The Consortium

The HIPATIA Consortium, led by SENER Aeroespacial, counts with the participation of Universidad Carlos III de Madrid (UC3M), AIRBUS Defence and Space, the Centre National de la Recherche Scientifique (CNRS) and Advanced Space Technologies (AST) GmbH..

The Consortium is complementary (as shown in Table 1) from the perspective of serving the value chain of the Project. The Team covers the design, analysis, manufacturing and testing capabilities required to fulfil the Project objectives.

Table 1. Competences and complementarity within the HIPATIA Consortium.

	SEN	UC3M	ADS	CNRS	AST
Coordination	X				
Systems Engineering	X		X		X
TU	X	X			
RFGPU	X				
PFCU					X
Final User			X		
Testing		X		X	X
Plasma physics		X		X	

3. The Helicon Plasma Thrusters

3.1 The Helicon Plasma Thruster Concept overview

The Helicon Plasma Thruster is a disruptive electromagnetic thruster for in-Space propulsion, which is under research [3] and development [4, 5, 6] in several countries around the World.

The physical elements of a HPT are (Fig.2): a cylindrical dielectric chamber; a gas injection system, usually at the back of the chamber; an external antenna (including a small matching circuitry) wrapped around the chamber and emitting RF waves, typically in the range 1-26MHz; and a magnetic field generator (permanent magnets for HIPATIA) that creates a longitudinal magnetic field, typically in the range 10^2 to 10^3 Gauss. Outside the chamber, the divergent magnetic topology creates a magnetic nozzle that channels the supersonic plasma flow, transforming the plasma internal energy into axially directed one, in a process very similar to the expansion of hot gas in a conventional solid nozzle.

The HPT functional mechanism can be split into the following basic processes. First, the propellant, typically an inert gas, is ionized by exciting it with an electromagnetic RF field. Broadly, this corresponds to an inductively coupled plasma discharge, giving a quasi-neutral plasma where the populations of electrons and ions interact with each other, maintaining a mean neutral electrical charge, which is contained in a dielectric discharge chamber. Simultaneously, an external stationary magnetic field is applied to the plasma discharge with three roles. At the plasma production chamber, the magnetic field enhances the RF-wave propagation and plasma heating, optimally reaching the desired Helicon mode. This mode is characterised by an inherent high plasma density and moderate electron temperature. The second role of the magnetic field is to shield the plasma from the chamber walls with the purpose of reducing thermal loads and erosion, thus, enlarging the lifetime of the thruster. Furthermore, at the external region of the discharge chamber, the close magnetic field typically shapes a divergent nozzle, or magnetic nozzle in the specialised literature.

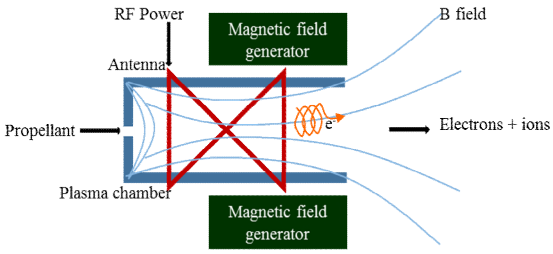

Fig. 2. Conceptual design of the HPT and its main constituents.

This magnetic nozzle is responsible for converting the thermal energy of the plasma within the discharge chamber, mostly carried by the electrons population, into axially directed ion kinetic energy. Electrons, which are fully magnetised (at the 200-2000G range) will expand outwardly following the magnetic field lines. Because ions are heavier than electrons and are just weakly magnetised (at this field ranges), an ambipolar electric field arises within the plasma to keep its quasi-neutral character. This potential drop along the nozzle expansion, which is highly related to the electron temperature at the plasma production source, accelerates the ions downstream, producing thrust.

3.2 HPT-03 reported performances

As explained in the background section, SENER and UC3M have been working together on the development of the HPT concept for five years, having integrated and tested several breadboards to demonstrate the concept and to research its fundamental physics, the HPT-XX family. In parallel to the thruster, SENER has designed its PPU unit, the so-called Radio Frequency Generator and Processing Unit (RFGPU), manufacturing and testing a breadboard model (BBM) that can work with powers up to 1kW. In late 2018, a successful coupling test campaign with both the HPT-03 BBM, operating in the 300-600W range and the RFGPU BBM, marked the consecution of TRL4 for the integrated TU+RFGPU System. The main results achieved in this campaign are depicted in Table 2.

Table 2. HPT-05M performances for Xenon propellant at 450W power at RFGPU output.

$\dot{m}$ [mg/s]	η_u [%]	η_t [%]	T [mN]	I_{sp} [s]
0.5	98-99	7.7-10.5	5.2-6.1	1027-1212
1	70-77	8.5-9.7	7.6-8.2	762-813

In early 2020, it was expected to have the HPT-03 EM ready for test. However, due to the outbreak of COVID-19, the integration of this Engineering Model was delayed. The characterisation tests for the HPT-03 EM have started already in the summer 2020 but they have not concluded yet. Performances will be reported in coming publications.

3.3 The HIPATIA System Concept

The impacts associated to having a disruptive thruster in high TRLs would not be achieved unless the complete EP System has proven its integration and operation consistency. HIPATIA will advance the development status of the HPT up to TRL6-7, but it will also face the integration challenges of a complete EP System.

Propulsion system design around Electric Propulsion thrusters for in-Space propulsion differs quite substantially from that of Chemical Propulsion subsystems. The first ones are much more complex since still implementing propellant management assemblies, they are also required to manage large amounts of power, magnetic fields, etc...

The constituting blocks of the HPT propulsion subsystem are shown in Figure 3, being the Thruster Unit (TU) the principal element of the subsystem. In order for this to operate appropriately, it shall be provided with the required conditioned RF power and propellant, being all of these inputs properly managed by adequate sensing and control means.

In the case of the Helicon Plasma Thruster, in addition to the TU, the EP system also counts on:

- An RFGPU to power and control the whole System. It converts DC power from the spacecraft bus into the required RF power to the thruster antenna. In addition to this, the RFGPU includes an Acquisition and Control Unit (ACU) for System elements control throughout the thruster operational ranges.
- A PFCU to manage the propellant expansion and flow from the tanks to the thruster. In open loop operation the PFCU provides the desired flow to the thruster by ramping up during ignition and provide a constant flow around the optimal operational point as set by the ACU. In closed loop operation with the thruster the truly needed flow is based on the thruster feedback signal.

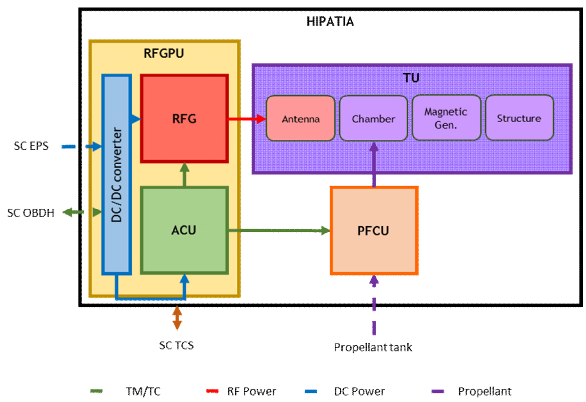

Fig. 3. Block diagram for the HIPATIA System, including the main interfaces with the spacecraft.

Within this System, the main interfaces of the TU are the propellant inlet that interfaces the PFCU, the RF connector interfacing the RFGPU via the bidirectional coupler. Apart from these, the different elements constituting the thruster are mounted on a structure that is the main interface towards the spacecraft, both at structural and thermal levels. The main interfaces of the RFGPU within the HIPATIA System are the RF connector that allows routing the radiofrequency power to the TU through a dedicated harness, the interface with the PFCU that allows telemetry/telecommand for control.

4. The HIPATIA development context

4.1 Market needs

One of the first tasks HIPATIA Consortium has undertaken is the review of the market status and its middle term perspectives. This analysis stands on two different and complementary analyses: the overall satellite market projections and the identification of specific platforms and users needing a simple and prospectively low cost EP system as HIPATIA.

Initial identification of the most suitable market fit for the HPT, considering its current development status, operation range and its performances, has led to target HIPATIA to the small satellites market. The small satellite market size has increased notably in the last years due to the development and deployment of large satellite constellations [7]. These constellations are being operated in the LEO-MEO region and are usually constituted by hundreds of satellites. The size of the platforms usually ranges in the 150-300kg interval. For upcoming constellations, the expected trend is towards platforms ranging higher in mass, probably up to 1000kg. The use of the HIPATIA system in such platforms induces some functional, operational and performance requirements on the HPT. A complete set of specifications have been compiled for the HIPATIA system attending to the small satellites market needs, and they have been flown down to unitary level.

Other markets might be open in the long term to the introduction of HPT for other applications considering the disruptions the technology may achieve. For instance, air-breathing satellites in very low orbits could make use of the HPT when an appropriate intake is developed for air breathing, since the HPT provides a cathodeless solution that can operate in the conditions of those orbits. Scalability of the HPT might open its application to the GEO platforms and the Space-tugs market on the large platforms side, due to its prospective high thrust-to-power-ratio. At the opposite point of the scale, smaller versions of the HPT could be used in CubeSats.

4.2 Development plan

HIPATIA will advance the development status of the HPT up to TRL6-7, but it will also face the integration challenges of a complete EP System, constituted by the Thruster Unit, the Radiofrequency and Power Unit that feeds it with power and the Propellant Flow Control Unit that controls the propellant pressure and mass flow. The start and target TRLs for the HIPATIA system and its units is provided in Table 3.

Table 3. Start and target TRLs for the HIPATIA system and units.

	System	TU	RFGPU	PFCU
Starting TRL	TRL3	TRL5	TRL4	TRL5
Target TRL	TRL6	TRL6	TRL5-6	TRL6

To achieve this development progress, the HIPATIA Project has been organised following three main action lines:

- Technology design and development. Technology development are the central line in HIPATIA, where System activities and Units development lay within. Specification, impact assessment, design, analysis and manufacturing options are addressed in the technology development tasks.
- Research activities. Research activities will provide an insight on the plasma physics necessary to improve the HPT current performances (reported in Table 2 for the HPT-05M). Research activities will rely on the use of available prototypes and facilities to test and investigate different improvement options for the technology, supported by the additional development and use of theoretical models.
- Verification and Test. Apart from those test performed in the course of research (e.g. alternative TU configurations) and technology development (e.g. unitary tests) activities, HIPATIA has allocated an action line devoted to test the integrated System at two different Project stages: at Project start and right before the Project end.

These action lines are developed within a 30 months' timeframe and in four different phases:

- Phase 1. Dealing with the technology assessment, impact and requirements specification, evaluating the HPT technology potential impact on the in-Space propulsion scenario, starting from previous projects and developments' results. Based on this evaluation, and following a market survey and analysis, requirements have been derived.
- Phase 2. Detailed design & analysis activities, structured in four blocks:
    - Research activities supporting the HIPATIA technologies and System developments
    - HIPATIA Units design and analyses activities with eventual delivery of EBBs and/or EMs
    - The tasks related to System level analyses and integration
    - The test activities to be carried out with the EBB/EMs integrated System.
- Phase 3. Working on the Assembly, Integration and Test (AIT) activities. After the CDR review, the research activities will follow in support to technical developments. For the Units, EQMs will be manufactured, assembled and unitary tested, for their later integration in a coupled System configuration. The integrated System will be tested in relevant environment to verify overall functionalities and performances. In addition to this, a second TU EQM will be subject to environmental testing to advance towards TRL6-7.

- Phase 4: Project results assessment. Once the research, design, development and test related tasks have been completed, HIPATIA results will be assessed in order to serve as a basis for the Business Plan, development roadmap and exploitation plan completion.

5. Conclusions

HIPATIA is an ambitious Project developed by a strong Consortium for advancing in the development and verification of a propulsion subsystem based on the Helicon Plasma Thruster technology up to TRL6 by end 2022.

The goal of verifying the function and performance of an integrated HPT based EP System is achieved in two steps, first at EBB-EM level, then at EQM level. The tests at EBB-EM level run parallel and fertilise the analysis and design activities of the EQM Units and System, following a de-risking approach.

The inter-related activities of design - development and verification - testing are also supported by a continuous research activity including modelling and simulation as well as laboratory tests.

When fulfilling the Project's objectives, and including additional development at its conclusion, the HIPATIA Team will be ready to introduce a qualified and prospectively cost-efficient propulsion subsystem in the small satellite market by end 2023.

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