Space Missions potentially benefit or enabled by the prospective use of Helicon Plasma Thrusters

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M. Ruiz[1], I. Urdampilleta[2] and J.M. del Cura[3]
SENER Ingeniería y Sistemas, Tres Cantos, Madrid, Spain

E. Ahedo[4]
Universidad Carlos III de Madrid, Madrid, Spain

J. Navarro-Cavallé[5]
Universidad Politécnica de Madrid, Madrid, Spain

Abstract: The concept of using helicon sources as a thruster (Helicon Plasma Thruster or HPT) dates only from a decade ago and was envisaged as a robust, scalable, reliable and (mainly) long-life device, because of its electrode-less and simple design. Although these expected capabilities are still to be fully verified, the available data and understanding still sustain the HPT as a potentially durable, throttlable and high thrust device, with intermediate specific impulse and competitive thrust efficiency. In order to better understand the potential benefits or enabling capabilities of HPTs, a definition of the possible constrains and requirements of different Space missions are to be defined. The study presented herein started with a mission survey from which different missions scenarios were evaluated. The most interesting cases resulting from preliminary analyses were subject to detailed mission analyses from where propulsive requirements were derived. These been set, different escalations of HPT are proposed and traded against existing Electric Propulsion technologies. The results are analyzed, focusing on the interest and prospective enabling capabilities of HPT for specific missions.

I. Introduction

HELICON Plasma Sources (HPS) have been known for more than 40 years and are of interest for plasma research and industrial applications because they produce relatively high plasma densities (up to 10^{20} m^{-3}) when compared to other Radio Frequency (RF) sources. The Helicon Plasma Thruster (HPT) is essentially a modified HPS that generates and heats plasma via RF emissions inside a magnetized cylindrical chamber and accelerates it supersonically in an external divergent magnetic nozzle, producing thrust. At the present, the HPT concept is being researched intensively[1-7].

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[1] Project Manager, Aerospace Division, mercedes.ruiz@sener.es.

[2] Project Engineer, Aerospace Division, igone.urdampileta@sener.es.

[3] Project Manager, Aerospace Division, jm.delcura@sener.es.

[4] Professor, Equipo de Propulsión Espacial y Plasmas, UC3M, eduardo.ahedo@uc3m.es.

[5] PhD Candidate, Equipo de Propulsión Espacial y Plasmas, UPM, jaume.navarro@upm.es.

Helicon Plasma Thrusters have been envisaged as a robust, scalable, compatible with a wide range of propellants, and (mainly) long-life device, because of its electrode-less and simple design[1,3,4]. Although these expected HPT capabilities are still to be fully verified, the available data and understanding still sustain the HPT as a potentially durable, throttlable and high thrust device, with intermediate specific impulse and competitive thrust efficiency.

The work presented in this paper explores in more detail the results of the analyses of those missions with demanding performance and functional requirements that could be potentially enabled or highly benefit from HPT development and use. The study departs from the acknowledgment of Electric Propulsion (EP) as an enabling and/or beneficial technology over Chemical Propulsion (CP) for different Space missions and deepens in the potential added value of HPTs over other existing EP thrusters.

II. Survey and analysis of candidate missions

A. Criteria followed for Space missions classification

In the frame of current study, mission survey and analyses were performed in order to identify the possible mission exploitation of the technology and the HPT comparative Mission-System performance with respect to other Electric Propulsion (EP) technologies.

The survey was done studying different missions classified as for their application field (Earth Observation, GEO platforms, human/robotic exploration, etc…) and the platform's onboard and available power for the propulsion system (low, intermediate and high power missions).

Power thresholds defined for this study were established as follows:

- Low power missions: Platforms where available/required power is less than 2.5 kW. The number of electric thrusters onboard may vary between 1 and 3 thrusters. The upper limit for individual thruster power consumption would be between 0.5 kW and 1 kW. Missions in this range are, mainly, Earth Observation missions in LEO, University small satellites and precision Formation Flying (FF) missions.
- Intermediate power missions: Platforms where available/required power is between 2.5 kW and 30 kW. The number of electric thrusters onboard may vary between 1 and 8 thrusters. The upper limit for individual thruster power consumption would be around 10 kW. Missions in this range are typical telecommunications satellites, some robotic exploration and Science platforms.
- High power missions: Platforms where available/required power is greater than 30 kW. The platform may equip as many thrusters as can be fed by the power source to accomplish the mission profile. Spacecrafts (SCs) equipping this amount of power have been mainly proposed for Human exploration of the Solar System, although some scientific and exploration missions might be enabled by high power availability (e.g. Mars Sample Return missions).

For each of the possible application fields, several mission scenarios (listed in Table 1) were analyzed to identify constrains and propulsive requirements that could be demanded from a prospective HPT system, for instance: Earth Observation (EO) in very low orbits, Formation Flying in low altitudes, orbit rise, inclination change and End-of-Life (EoL) deorbiting, LEO active space debris removal mission using the Ion Beam Shepherd concept (IBS), orbit transfer to GEO and orbit topping, the All Electric Spacecraft (AES) in GEO, Solar Electric Propulsion (SEP) exploration/science to the Moon, inner planets exploration/science mission, SEP for Earth-Moon cargo transfer mission, Mars sample return mission using SEP, mission to Outer Solar System using NEP and human exploration of Mars.

While evaluating the results of these mission analyses, special care was taken to characterize the main figures of merit that describe main propulsive performances requirements: mission total impulse, thrust level, specific impulse (I_{sp}) and thruster input power. In addition to these, some functional constrains were investigated, such as: maneuvering needs, thrust vector orientation need and throttlability.

Following the previously described mission classification criteria, three different possible HPT escalations were specified: Low Power HPT (LPHPT), Intermediate Power HPT (IPHPT) and High Power HPT (HPHPT). The requirements specification process for these escalations is reviewed in following paragraphs.

Table 1. Studied mission scenarios.

Mission Scenario	Description
Low power mission scenarios	
1	Small spacecraft with high delta-V requirement
2	CubeSats, pico-satellites with orbit maintenance requirements
3	Equipping high power SAR instrument for EO mission
4	Formation Flying in low altitudes
5	Orbit rise, inclination change and EoL deorbiting
6	Precise formation flying constellation in L2
Intermediate power mission scenarios	
7	LEO active space debris removal mission using IBS
8	GEO orbit Station Keeping
9	Orbit transfer to GEO and orbit topping
10	The All Electric Spacecraft (AES) in GEO
11	Solar Electric Propulsion exploration/science to the Moon
12	Inner planets exploration/science mission
High power mission scenarios	
13	SEP for Earth-Moon cargo transfer mission
14	Mars sample return mission using SEP
15	Mission to Outer Solar System using NEP
16	Human exploration of Mars

B. Summary of low power missions analysis

A clear and basic result of the preliminary analysis of low power missions was that propulsive requirements for mission scenarios 4 and 6 (formation flying in LEO and precise formation flying respectively) differ from the other low power considered scenarios. This means that at least two or three different low power escalations of HPT should be available to cope with all the low power mission scenarios propulsive requirements.

The scenarios where small satellites down to pico-satellites were studied, showed that, even if EP could be of interest for some specific applications, simple chemical propulsion systems perform appropriately and cover mission constrains and requirements.

While the eventual development of HPT technology could possibly enable orbiting in the 150 km to 250 km range, due to the HPT absence of electrodes and potential longer actuation lifetime, this application would be really meant to be for an air-breathing system and still needs to solve other important issues such as the collection of propellant from the atmosphere. For other applications such as precision Formation Flying, there are already available different micro-thrusters solutions dedicatedly developed in the last years.

In view of the performed mission analysis and survey and the prospective advantages of HPT concept over other existing EP thrusters, it was considered that most interesting mission scenarios for a low power escalation of HPT are 3 and 5 (drag compensation for EO in LEO in the 300 km range and orbit changes in the LEO-MEO region).

However, even for those two missions, some of the main propulsive parameters differ too much for a single thruster to comply with all of them. Some previous studies[8-9] have shown that the benefits of EP for orbit changes and deorbiting in the LEO-MEO region was mainly interesting if the thrusters were to be used for other mission's functionalities.

The requirements derived for a Low Power Helicon Plasma Thruster were based on those for a mission scenario like 3, but with some enhanced requirements in terms of lifetime and thrust levels, so that the same thruster could be used not only for atmospheric drag compensation and orbit maintenance, but also to perform some orbit changes within acceptable durations and propellant consumptions. Having a thruster compliant with those requirements would increase very LEO missions lifetime and make them more flexible, in a sense that some orbit changes and final deorbiting could be performed with the same thruster used for atmospheric drag compensation.

C. Summary of intermediate power missions analysis

Taking into account the preliminary mission analyses performed on the studied intermediate power missions, it was seen that two different thrusters could cope with the described scenarios needs. One would be an intermediate-high power thruster maximizing the specific impulse (e.g. Active Debris Removal with IBS or exploration missions), while the other would work with less power providing intermediate levels of specific impulse and thrust (e.g. application to North-South station-keeping). In all the cases, the total impulse requirement is high, close to existing technologies limits, and a thruster that could still perform well once those limits are trespassed could be advantageous. This could be the case of an Intermediate Power Helicon Plasma Thruster according to its prospective advantages.

For the specification exercise, and in order to look for a thruster than could enhance or enable some Space missions in the intermediate power range, it was proposed to specify a single intermediate power escalation of a HPT that could serve for most of the mission scenarios under study. Such a thruster could be optimized for the scenario number 10 (All Electric Spacecraft) for a large platform of several tones, and still serve appropriately in the other mission scenarios. For this scenario, it would be very interesting to reduce the estimated transfer times to GEO. If an EP device with sufficiently high thrust is used, the total transfer time for a large platform could be acceptable (below 10 months) while taking advantage of EP higher I_{sp} when compared to CP. This approach could also introduce some advantages on platform design solutions.

Such a thruster shall be throttlable, providing a high level of thrust for orbit transfer maneuvers where time constrains exist, and still provide good specific impulse levels in order to save propellant for less time demanding maneuvers. Throttlability is therefore required. Considering the available power for a large GEO communications platform when the payload is off (i.e, during transfer), higher levels of thrust could be attained in order to reduce transfer times. High power-to-thrust ration would be consequently required. Still, it would be interesting to use the same transfer thruster for station keeping maneuvers if the thruster performs appropriately during a large operation lifetime and the thrust can be steered appropriately.

D. Summary of high power missions analysis

When compared to low or intermediate power missions, the high power mission scenarios that were studied are much more demanding in terms of thrust level and even two level of magnitude higher regarding overall mission total impulse. On the other hand, specific impulse requirements are not differing order of magnitudes from low and intermediate power missions' values. The power requirements to feed the thrusters in an efficient way are much more challenging and would require high efficiency power supplies, based on advance solar power technologies or even nuclear power sources.

Among the mission scenarios in the table, the scenario number 16 (Human exploration of Mars) is the most different and demanding one for most of the propulsive performance parameters. Moreover, it would most possibly require a set of very specific thrusters for its accomplishment. Scenario number 13 (SEP for Earth-Moon cargo transfer mission) is also very demanding in terms of power when compared to the other two mission scenarios (Mars Sample Return with SEP and exploration of outer planets with NEP).

This kind of missions would represent major challenges not only for the propulsion subsystem, but also for most of the subsystems and units to be onboard and associated with the propulsion subsystem. This is especially relevant in this case for those technologies related to the power generation, supply, control, storage and distribution.

For the purpose of deriving requirements for a High Power Helicon Plasma Thruster that could serve to some of these scenarios and maybe to some other exploration missions classified in the intermediate power range (e.g. exploration of inner Solar System planets), a representative case in the range of $1 \cdot 10^8$ N·s total impulse will be specified.

III. Requirements analysis and preliminary trades

E. Low Power Helicon Plasma Thruster

Several Low Power Mission scenarios were analyzed as described in previous paragraphs, most importantly: Earth Observation with high power instrument in very low Earth Orbits, Earth Observation in orbits below 250 km, Formation Flying missions, orbit rising, inclination change, and EoL deorbiting.

It is expected that the missions where a LPHPT could be of interests are those where the thruster is used to compensate atmospheric drag and/or allows for orbit reconfiguration. A thruster that fits within these missions could possibly also serve for deorbiting considering a wider thrust range. In addition to this, a low power escalation of the HPT could serve as an attitude control thruster for higher power missions and larger platforms.

In order to have a versatile unit, a small thruster providing a little bit more thrust and with longer lifetime than those currently available was specified. A summary of the derived requirements is provided for the mini-HPT application to the mentioned missions:

- With a target $2\cdot10^6$ N·s total impulse requirement, the thruster should be able to operate at least for 20,000 hours accumulated lifetime (considering a mean 30 mN thrust).
- Throttlability would not be strictly required, but interesting if available.
- It should provide relatively low thrust (1-50 mN) or thrust levels in this range. An intermediate range of 30 mN could be considered for this trade-off. Higher thrust would benefit the HPT use for orbit changes and EoL deorbiting. Lower thrust levels would make the thruster more efficient for drag compensation purposes in low orbits. Thrusts closer to the 1 mN value could possibly also be used for formation flying missions.
- Attainable I_{sp} levels should be within an interval of a minimum of 500 s and as high as possible (up to 3,000 s). The higher the I_{sp}, the lower the propellant mass consumption. However, the optimum I_{sp} could differ from one mission to another.
- Input power levels should fit within the hundreds of Watts range, always below the 1 kW. Higher power levels would be required for some specific missions. For this study, 500 W could be an intermediate reference power level.

In order to identify possible benefits or enabling capabilities of HPT for such applications, fully-developed, improved versions of existing LPHPTs prototypes[4,6,10,11,3,12] must be traded off against well-developed EP technologies, such as small ion and Hall thrusters. There are other EP technologies that can be operated marginally in this power range but their main operational ranges pertain better to either the very low power range (such as pulsed plasma thrusters and electrospray thrusters) or the mid-power range (such as flight-qualified arcjets).

F. Intermediate Power Helicon Plasma Thruster

As summarized in previous paragraphs, different intermediate power missions were analyzed, including Ion Beam Shepherd active debris removal mission, different configurations for GEO platforms and exploration missions to the Moon and Inner Solar System bodies.

From the analyses of these missions, it was concluded that the most interesting application field of an Intermediate Power HPT would be for GEO communication satellites that need to raise and top their orbit and perform station keeping maneuvers once in the corresponding GEO slot. In this case, and considering the use of the same thruster for different functionalities, there is a need for throttlability that allows reasonable transfer times (below 10 months) while minimizing the station-keeping propellant consumption once in GEO (maneuvers for 10-15 years). This is of special interest for large platforms (of several tones and high power payloads).

There are other characteristics such as thrust vector steering and long operation lifetime that are required for a thruster to accomplish such a mission, as discussed below. A thruster of these characteristics would also fit for other applications such as interplanetary science and exploration missions, being a versatile escalation of a HPT.

A summary of the derived specifications is provided for the IPHPT application to the mentioned mission:

- With a target $20\cdot10^6$ N·s total impulse requirement, the thruster should be able to operate at least for 15,000 hours accumulated lifetime (considering a mean 400 mN thrust).
- Throttlability would be required, as wider as possible, in order to prioritize thrust over I_{sp} when the orbit raising maneuvers are performed and I_{sp} over thrust when performing station keeping. Orbit transfer duration is critical, and for large platforms, high thrust levels would be required.
- It should be capable of coping with thrust levels in the range of the hundreds of mN. If the thruster is to be optimized for a large platform (of several tones) and a mission with GTO-GEO or LEO-GEO transfer time of less than one year, then the thrust range required for the whole mission would be between 200 mN and 800 mN, the top value to be used during transfer. Higher thrust levels would reduce travel time.
- Depending on the mission profile, the optimum specific impulse may vary, in this case, I_{sp} level should be within an interval of a minimum of 1,000 s and up to 2,500 s. For certain applications, the top figure could be

higher. For the defined mission, I_{sp} in the order of 1,000 s during orbit transfer could be considered. Even if this value could be a little bit low for and EP thruster, there would be anyway a significant gain in the propellant mass savings when compared to the use of chemical propulsion.

- Input power levels should fit within the kilowatts range or even close to the 10 kW. For the defined mission, the limits of available power are mostly related to the power the platform provides to the payload, which is available for the propulsion system for orbit transfer and topping. For such a GEO mission, the power for propulsion should be considered to be between 2,500 W for SK and 10,000 W for orbit transfer and topping.

Nominally, no HPT prototype has been designed for this power range, but it can be assumed that the mHTX[12] can be scaled up and the HPHT[1] can be scaled down. An IPHPT evolved from any of these must be compared with ion and Hall thrusters again, and the arcjet technology can be added too.

G. High Power Helicon Plasma Thruster

The studied high power mission scenarios are very different one from each other, as discussed in previous paragraphs. The concepts that were analyzed are as varied as: Human exploration of Mars, Mars Sample Return Mission, cargo mission to the Moon and Outer Solar System planets exploration making use of Nuclear Electric Propulsion.

Due to its interest and as a first step for more complex exploration missions, the baseline requirements for a High Power HPT escalation were derived for a Mars Sample Return (MSR) Mission concept. This would specify a high power HPT with enhanced total impulse requirements, which could also serve, when duly organized in clusters and with appropriate modifications to the power generation and supply subsystem, for missions of larger scope.

A summary of the derived specifications is provided for the HPHPT application to the mentioned missions:

- The total impulse for such a MSR mission would be in the order of $1 \cdot 10^8$ N·s. For an average 1.5 N thrust, this would represent around 18,500 hours of accumulated thruster firing. This figure would (sometimes greatly) increase for any other high power mission differing from the MSR.
- Throttlability would be required, in order to function in different thrust modes.
- For the MSR mission, less that 1.5 N would be enough in these defined conditions to accommodate a 2,000 kg payload mass. Trades between trip time, on-board installed power and payload mass should be considered when defining a specific MSR mission. As thrust increases, trip time decreases, but the power required to accomplish the mission would demand for higher power subsystem mass, impacting on the payload mass accommodation. Thrust levels in this range could also serve for Earth-Moon cargo mission, but for other high power missions such as human exploration or NEP to outer solar System, higher thrust levels or thrusters clusters are required.
- Attainable I_{sp} level should be within an interval of a minimum of 3,000 s and up to 6,000 s. According to the analysis performed, for the same input power of approximately 50 kW, an I_{sp} of 2,500 s would allow for a 830 kg payload mass, while for 4,000 s, this mass would be increased to the mentioned 2,000 kg value. As in the previous case, these values would also be acceptable for thrusters for cargo missions in the Earth environment, but required I_{sp} would drastically increase for human exploration missions.
- Input power levels should fit within the tenths of kW range. In this high power mission's case, it is to be noted that the power increase impacts notably the mass associated to the power subsystem and the overall allowable mass for payload accommodation.

Leaving aside VASIMR-HPSO[13], the only HPT prototype in the high power range is the HPHT[1]. There is no other EP technology space-qualified within this power range. Moreover, the discussion of laboratory prototypes requires distinguishing the, say, 20-100 kW range, with increasing interest for near and mid-term applications, and the long-term or nuclear-power-based over-100 kW range. For the first range, up-scaled designs of ion and Hall thrusters are being tested more or less intensely. Above 50-100 kW, the present consensus on using ion and Hall thrusters is to implement a cluster of devices. Other options in the hundreds-of-kilowatt range are the magnetoplasmadynamic thruster (MPDT), and the applied-field MPDT (AFMPDT).

IV. Conclusion

From the analyses, requirements derivation and trades, several preliminary conclusions can be extracted at this point related to the potential benefits or enabling capabilities of HPT over other EP technologies for some specific missions.

In the low and intermediate power ranges, existing EP technologies such as ion and Hall thrusters are well developed and some of them have extensive Space heritage. Beyond potential improvements in particular missions, an optimistic forecast would see the HPT as an enabling technology for very-low-orbit air-breathing drag compensation, GEO all-electric-spacecraft with a large thrust-to-power ratio (say, above 100 mN/kW) in orbit rising, and/or missions with high needs of thrust steering.

Looking at the high power case, there is still no EP technology with Space heritage, and few EP thrusters have been developed beyond the 10 kW threshold. The missions requiring high power EP also pose high total impulse requirements, where the HPT could eventually result to be competitive. Moreover, although no severe technological constraints are expected for ion and Hall thrusters at high power, they become too bulky at tens of kW, either using single units or a cluster of them. In this power range, the HPT offers typically a thrust density one order of magnitude higher than Hall and ion thrusters, and is more compact.

As a result of this preliminary analysis, it can be concluded that the potential benefits offered by different escalations of HPT could benefit and/or enable some of the studied missions, in particular:

- Missions enhanced by larger thruster operation lifetime and capability.
- Dual-mode missions (like a "quick" GEO rising followed by a propellant-efficient SK) where it is required large throttlability, with the high thrust-to-power mode extending into the sub-1,000 s range of I_{sp}.
- Missions where chemical and electric thrusters are implemented and sharing the same propellant is needed.
- High power missions with large thruster operation time, since there is no EP technology fully developed in the high power range.

Although several HPT prototypes exist and have been tested, there are still many uncertainties about their eventual performances and capabilities. Here, detailed models and simulation tools become essential for the HPT performance prediction and design characterization. Development and testing of prototypes are important for the validation of these tools, and to allow for a better understanding of the real potential and competitiveness of this technology.

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