Development and Testing of a Miniature Helicon Plasma Thruster

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Abstract: a joint effort between the Center for Space Studies and Activities "CISAS – G. Colombo" of the University of Padua, Italy, and T4i, an Italian SME active in the field of space propulsion, is aimed at the development of a miniature plasma propulsion module, suitable for integration in small platforms down to Nanosatellite scale and versatile enough to cover different applications, such as Nano/Micro/Mini/Small satellites orbit maintenance (drag compensation), station keeping, orbital parameter changes and deorbiting. The module is centered around a a Mini Helicon Thruster (MHT) currently being developed by T4i and CISAS as a development of the technology developed at CISAS in the past years[1, 5]; the MHT is capable of operation in a wide thrust level range and of covering different needs in a same mission thanks to its high total impulse. In the paper we report i) the results thus far achieved during the test campaign performed on the MHT, ii) the overall design of the related MHT propulsion module, iii) some examples of mission profiles made possible by the module.

Nomenclature

HPT = helicon plasma thruster
MHT = Mini Helicon Thruster
Isp = specific impulse
RF = radio frequency
PPU = power processing unit
PCU = power control unit

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I. Introduction

Helicon Plasma Thrusters[1,2] (HPTs) are electromagnetic Radio-Frequency (RF) plasma generation and acceleration systems, which descend from high-density industrial plasma sources. HPTs have encountered widespread interest in the research community, thanks to a number of key features such as (i) a very simple structure (Figure 1), based on few elements (a dielectric discharge chamber in which plasma is generated, an RF antenna for propellant ionization and a magneto-static field which confines and accelerates the plasma), (ii) the lack of neutralization cathodes and other electrodes immersed in the plasma, granting a potential advantage in terms of lifetime and (iii) the capability of efficient operation with different propellants, both mono-atomic and molecular.

The Center for Space Studies and Activities (CISAS) of the University of Padua, Italy, is active since 2007 in the development of such innovative thrusters through both EU and national research initiatives, developing an innovative, high efficiency plasma source based on helicon technology[3-10]. This know-how is currently being exploited in a joint effort between CISAS and T4i, an Italian SME active in the field of space propulsion, in order to develop a Mini Helicon Thruster (MHT) propulsion module. The system is to be integrated in a spacecraft and is versatile enough to cover different applications, such as Nano/Micro/Mini/Small satellites orbit maintenance (drag compensation), station keeping, orbital parameter changes and deorbiting. The MHT can operate in a wide thrust level range and thanks to its high total impulse it can cover different needs in a same mission.

The MHT propulsion module is a self-contained system based on a compact, low power RF thruster, being designed in order to fit within an 1U cubesat envelope featuring the “tuna-can” additional volume, excluding the propellant tank.

At present MHT prototype has been developed by T4i and CISAS. The thruster has a mass of 0.4 kg, a diameter of 60 mm and a length of 120 mm and is being subject to an extensive characterization and optimization campaign, operating in a wide range of input power (10-60 W) and mass flow rate (0.01-0.15 mg/s) with different propellant gases (Xe, Ar, Air, to cite a few).

The tests are being carried out within CISAS’s electric propulsion facility, extensively described in other works[1,6], which is equipped with a dedicated thrust balance[10,11,7], specifically designed in order to test RF plasma thrusters, and a Faraday probe[1,6], mounted on a Cartesian robot, which is employed to map the ion current within the plasma plume ejected from the thruster.

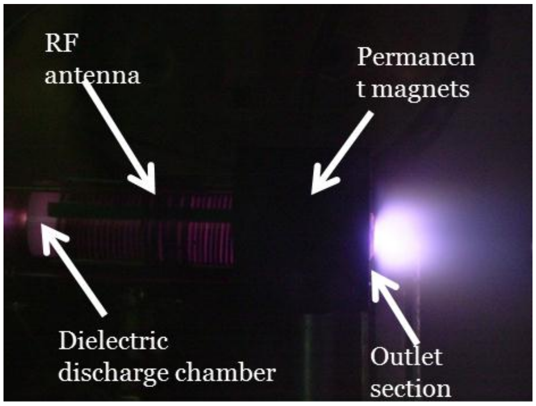


Figure 1. Helicon plasma thruster laboratory model employed during project HPH.Com.

II. Helicon technology developments at CISAS – T4i

The Center for Space Studies and Activities (CISAS) of the Universityof Padua is active in the development of this technology since project Helicon Plasma Hydrazine Combined Micro HPH.COM[3,11], funded by the European Commission in the frame of the 7th Framework Program between 2008 and 2012, aiming at the development of a 50 W – 1 mN Helicon Plasma Thruster specifically tailored for small platform. The project was coordinated by CISAS and involved 12 other institutions among France, Spain, Italy, Holland, Denmark Ukraine and Russia. Multiple thruster configurations were tested in different operating regimes, employing both electromagnets and permanent magnets for magneto-static field generation. Thruster and plasma source performance were monitored in several research facilities belonging to HPH.Com partners, such as CISAS, KhAI and ONERA, by means of a wide array of diagnostics[4] such as optical spectrometers, a microwave interferometer[12], a Retarding Potential Analyzer, Faraday current probes and a thrust balance. One important result of this research project has been the development of an innovative antenna for plasma generation, which has been recently patented (Patent NO. WO2016113707 A1) by D.

Pavarin, A. Selmo, M.Manente and F. Trezzolani). Performances extrapolated through thrust measurements at 20W has been 1.4 mN at 50 W of Power, with 1350 of Isp[13]. The know-how developed during HPH is being further developed at CISAS within the frame of project SAPERE-STRONG, funded by the Italian Ministry for University and Research (MIUR) and coordinated by Thales Alenia Space Italia (TASI), aiming at the development of a kW-level thruster working on Argon and CO2 was initiated. The program was focused on the development of a 1kW motor for space-tug capable of working with CO2 and Xenon. Several numerical and experimental activities have been carried out in this frame leading to a dedicated test-bed. In the same frame a counter balanced thrust balance was also developed to allow in-house thrust characterization[6].

Along with STRONG, another development of HPH.Com technology is being carried out by T4i S.r.l., an Italian SME born as aspin-off of Padua University, which started a strong development effort in order to miniaturize the system making it more attractive to micro platforms down to multi-U systems.

Figure 2. The HPH.Com thruster firing inside CISAS vacuum chamber. The tip of a Faraday probe immersed in the plume is visible on the right of the picture.

Figure 3. The STRONG prototype firing on CISAS's thrust stand during characterization tests.

III. The Mini Helicon Thruster

A. General description

The Mini Helicon Thruster (MHT) is a recent development of the helicon plasma thruster technology developed in Padua. The thruster was developed employing a numerical-experimental approach, combining dedicated simulation codes developed at CISAS[8,9,14,15] – T4i with characterization and optimization tests carried out on thruster laboratory models. The result of this process is a thruster which shares the same operational range of the HPH.Com thruster, although condensed in a much more compact system (Figure 4): the latter was characterized by an envelope of approximately ϕ124 x 157 mm and a mass of around 1.6 kg, while the MHT fits within a ϕ55 x 120 mm cylinder and weights between 0.3-0.4 kg, depending on its configuration.

Figure 4. The MHT, held in hand by T4i personnel. The discharge chamber, RF antenna and magnets are enclosed within an EM shield structure. The small scale of the device can readily be appreciated.

The thruster features the same basic elements of HPH.Com, namely a dielectric discharge chamber, an RF antenna for plasma ionization and a magnetic system based on SmCo permanent magnets, encased in Peek housings; these elements are housed within an aluminum "cage" structure, which provides structural support as well as an electric ground reference. An outer metal shell can be installed in order to create a Faraday cage and possibly, if high magnetic permeability materials are employed, also a magnetic shield, in order to protect the external environment from EM and magneto-static interference produced by the thruster. As a further development with respect to

HPH.Com the discharge chamber was made of Boron Nitride, due to its superior thermal and dielectric properties with respect to the less performing pyrex glass employed in the previous system.

The MHT model was designed to allow for an extensive re-configurability, in order to meet the need of cross-checking the predictions of numerical codes and of investigating the optimal thruster configuration; this is possible thanks to interchangeable discharge chambers and outlet diaphragms of different size, variable magnets configurations and different RF antennas.

B. MHT performance

The current MHT layout is the result of an intense experimental characterization campaign (Figure 5), mainly focused at verifying the performance scaling of the thruster as a function of several factors, in order to investigate the optimal configuration of the system and, secondarily, to collect data useful for codes validation. The key parameters involved in the analysis are:

1. the geometry of the discharge chamber, in terms of diameter, length and outlet section area;
2. the position, shape and strength of the magneto-static field;
3. the type of propellant;
4. the RF frequency.

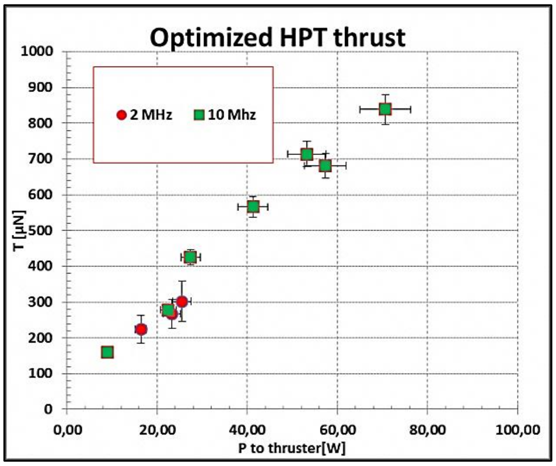
The key instruments in the monitoring of the performance were i) the thrust balance, ii) a Faraday probe for ion current investigation and iii) RF probes for vector voltage and current measurement, employed to monitor the power coupling and the impedance matching between the thruster and the RF amplifier powering it.

The propulsive performance, in particular, was cross-checked between the results achieved with the balance[10] and those estimated with Faraday probe measurements: the latter are obtained by integrating the total ion current emitted by the thruster, the average ion kinetic energy and the focusing effect of the probe bias on the incoming ion flux. Balance and Faraday probe results substantially agree, although within a relatively wide 30-35% margin, which is mainly due to the uncertainties associated with ion energy and focusing factor estimation[7].

Unfortunately we cannot provide quantitative detail on the tested MHT configurations due to NDA restrictions.

The performance resulting from the experimental optimization process is reported in Figure 6 and Figure 7: the MHT, when operating with xenon propellant, is capable of stable operation in the 10-70 W power range and can achieve a thrust and a specific impulse up to 0.82 mN and 850 s respectively. Most tests were carried out at around 10 MHz due to the available RF power generation system, but additional tests carried out later at a lower frequency (around 2 MHz) have confirmed the performance scaling with power. This last fact is an advantage since operation at low frequency leads to increased efficiency of the RF power generation systems, since it minimizes parasitic power losses due to skin and proximity effect in the conductors and allows for a more efficient operation of the semiconductor devices (MOSFETs, transistors) found in RF power amplifiers.

Figure 5. MHT testing with Xe (left) and Ar (right) propellants. The thruster is mounted in the thrust balance, while the Faraday probe is being employed for current measurements within the plume.



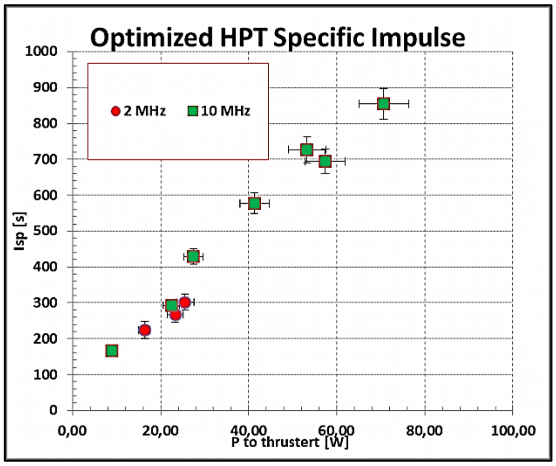
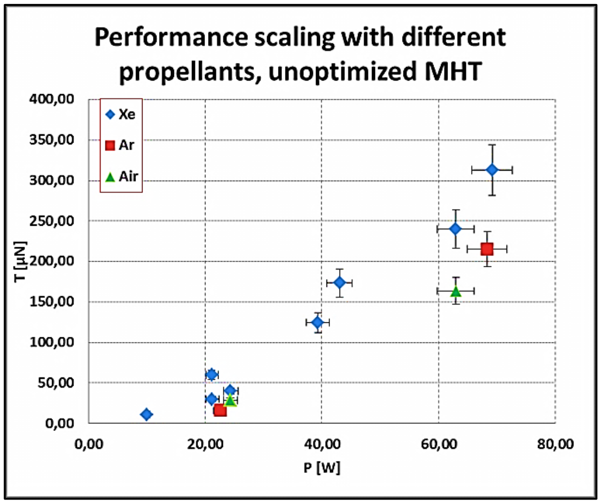


Figure 6. MHT thrust scaling, 10-7 kg/s Xe flow for two different RF frequencies.

Figure 7. MHT Isp scaling with power, 10-7 kg/s Xe flow for two different RF frequencies..

The tests have evidenced that, as expected, Xe represents the optimal choice for the propellant, although the MHT is capable of operating with other gases as well: Kr, Ar, Ne, N_2, air, only to cite a few, were investigated, although the overall performance drops with respect to Xe. Operation with Iodine propellant, which is attractive since it is storable in solid form, is expected to be possible, although not yet tested.

An example of thrust and Isp scaling with different propellants is reported in Figure 8 and Figure 9, which show the results achieved when operating with xenon, air and argon propellants with an intermediate (i.e. still not optimized) MHT configuration: in particular the Isp drops considerably with air and Ar with respect to Xe, while the corresponding reduction in thrust is proportionally smaller.



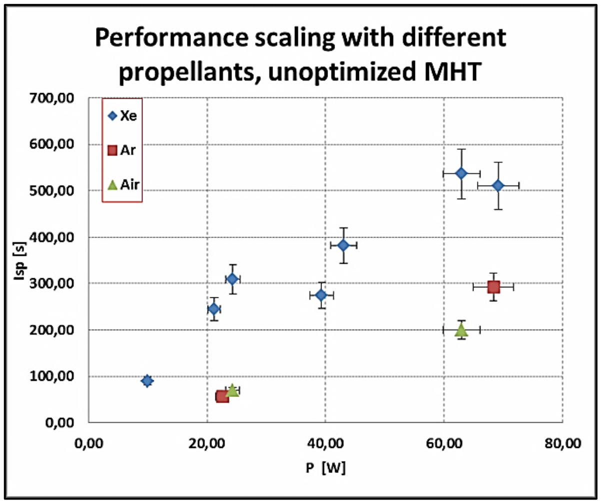


Figure 8. uno-ptimized MHT thrust scaling with different propellants.

Figure 9. un-optimized MHT Isp scaling with different propellants.

At present the MHT is being developed from a laboratory model into a flight system. In order to assist this process the tests are still ongoing, with the objective of further improving the results and verifying eventual issues related to the design modifications required by this process.

IV. MHT propulsion module

The MHT will be at the heart of a dedicated propulsion module, which is currently being developed at the University of Padua-T4i.

A. General description

The propulsion system associated with the MHT is intended to provide to system integrators a propulsion package easy to be integrated into the platform with standard interfaces. The target is to develop a box (Figure 10) of about 100 x 100 x 100 mm, with the additional “tuna can “ volume, having inside the motor, the Power Processing and Power Control Units (PPU and PCU respectively), and the low pressure fluidic section, and a separate box of different size depending on the total impulse required, with the tank and the high pressure fluidic system.

The system was designed after a detailed evaluation of the manufacturing / assembly and acceptance process and was tailored specifically to drastically reduce recurring costs and infrastructure while fully exploiting the performance of the MHT.

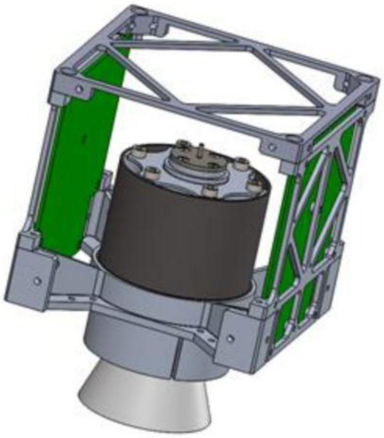


Figure 10. Draft CAD of the MHT module, evidencing its 1-U cubesat envelope, with the additional “tuna can” volume housing the frontal part of the thruster, which protrudes from the module itself. The green boards housed on the lateral surfaces of the module represent the PPU and PCU layout.

B. Data and power interface

The MHT propulsion module is designed to have the minimum impact with the hosted bus. The PCU interfaces with the bus (the choice of the specific connectors is to be agreed upon with the system integrator and/or manufacturer) , receiving command signals and DC power from it and relaying back diagnostics data on the status of the MHT system. The PCU also controls to the other sub-systems of the module.

The PCU will receive all the analog signals from diagnostic sensors (conditioned by the PCU and part of the PPU) and also provides the correct activation and deactivation system of the thruster.

The PCU will interact with the satellite with different protocols which be implemented depending on the customer needs (CAN bus, I2C, LVDS, or other).

C. The PPU

The PPU concept is based on a modular, highly reconfigurable architecture, developed at CISAS-T4i and tailored to achieve both low development cost and low recurring cost to target the mini/MICRO-satellite market. The main concept is to develop a system which is based on a complex circuital architecture but using simple and non-critic elementary (low-cost) components. This will may lead to a device less optimized respect to existing system from the mass budget point of view but able to provide a viable option for low cost satellite which at the moment cannot afford the cost of an electric propulsion platform.

The system is sub-divided into two main sections, namely i) the driver section and ii) the power section.

The driver section is devoted to the command of the high power MOSFETS mounted on the power stage and employs a fully analog circuitry; this section is capable of efficient operation in the 20 kHz - 2 MHz frequency range and can operate both in PWM mode (for output power regulation) and in variable-frequency mode (in order to adapt to the load).

The power section contains the active elements (MOSFETS), arranged in a push-pull configuration and connected to an output transformer whose role is to adapt the output power signal to the load constituted by the thruster itself. An additional diagnostic section, devoted to output voltage and current measurement, can be inserted between the transformer and the thruster in order to monitor the power coupling and impedance matching. The power stage will also host part of the conditioning circuit for diagnostic systems.

Both the driver and the power section can be fed with DC power at 20-30 V DC from the bus.

The PPU will be stacked up to four boards, which are planned to be placed on the lateral surfaces of the propulsive module.

It is worth noting that this PPU concept is highly flexible and may be employed also to power RF ion thrusters (RIT) or, with the addition of a final AC/DC converter, even conventional ion and hall effect thrusters, thanks to the broad operating frequency range available.

D. Fluidic System

The MHT module, in its current configuration, is intended for fixed-point operation in order to reduce complexity and costs. A mechanical pressure regulator maintains the specified pressure level upstream a calibrated orifice, which is designed to provide the desired mass flow rate. The mass flow is monitored by a combined pressure/temperature measurement downstream the orifice itself. In alternative this function can be performed by a mass flow detector.

The xenon propellant will be stored in supercritical state with a pressure up to 150 bar. The size of the tank depends on the selected mission profile and will have to be agreed upon with the system integrator.

E. Thermal Interfaces

The MHT propulsion system will employ a passive thermal control system; the module itself will be thermally insulated from the rest of the bus and will employ its free surface for heat radiation. Prolonged operation at high power may require the bus to provide a radiator, to which waste heat will be conveyed by dedicated thermal links.

F. Spacecraft-Plasma Interaction

According to the performed SPIS simulations, the surface charging is not expected to generate dangerous voltage drops. As a worst case scenario the voltage drop between the thruster exit plane and spacecraft ground does not exceed 300 V, not enough to ignite electric arcs. According to simulations, the plasma impingement on the spacecraft is expected to be negligible.

V. Example Mission Profiles

The achieved performance allows the MHT to target platforms mainly in the range 6-80 kg, capable of providing up to 30-70 W to the thruster, for missions where high total impulse is required. Examples of such applications are Cube Sat dispenser satellites, drag-compensation for LEO Earth Observation, long term station keeping and deep space missions. A pair of quantitative examples of the expected MHT module performance for practical missions are reported in Table 1 and Table 2: the first one is relative to a lunar mission scenario with an 8 kg dry mass satellite, capable of providing 60 W to the MHT module, while the latter refers to possible earth orbit maneuvers for the same type of spacecraft. The high total impulse of the system allows to performing highly demanding maneuvers with a relatively low propellant budget.

Dv [m/s]	Propellant mass [kg]	Transf. time [days]	Description	Mission phase
3900	5,97	691	Smart 1 orbit injection	Lunar orbit injection
4500	7,23	836	Intermediate orbit start	
6950	13,62	1575	Starting orbit 600 km LEO	
28,24	0,03	3,75	Orbit raising from 700 km to 800 km	Maneuvers in lunar orbit, starting from 700 km height
194,3	0,23	26,0	5° inclination changing	
94,72	0,11	12,6	Eccentricity change from 0 to 0.1	
42,73	0,05	5,68	Orbit raising from 100 km to	Maneuvers in lunar orbit, starting from

			200 km	100 km height
223,7	0,26	30,1	5° Inclination changing	
109,0	0,13	14,6	Eccentricity change from 0 to 0.1	

Table 1. Expected MHT module performance for a moon mission, hypothesizing an S/C with a dry mass of 8 kg and an available MHT module power of 60 W.

Dv [m/s]	**Propellant mass [kg]**	**Transf. time [days]**
Circular orbit raising from 500 km to 1000 km	0.20	31
Circular orbit lowering from 500 km to 200 km	0.13	20
Inclination change from i=63° to i=89° at 500 km	5.81	900
Inclination change from i=10° to equatorial at 500 km	1.82	276
Eccentricity change from circular to e=0.2 at 500 km	0.83	127
Drag compensation for one year at 300 km for CubeSat	0.060	10
Max orbit raising from 500km with a ≈1 kg of propellant: 3250 km	0.973	147

Table 2. Expected MHT module performance for an earth mission, hypothesizing an S/C with a dry mass of 8 kg and an available MHT module power of 60 W.

VI.Conclusion

An innovative MHT is undergoing development at T4i / University of Padua, achieving a performance level enabling it to consititute a viable competitive, low cost propulsion option for small platforms and so fully exploit their huge potential. The system has been specifically developed for platforms in the range 6-70 kg having power available from 30 W to 70 W, even if the system can still operate at 10 W with reduced Isp.

An entire propulsion module is currently being designed around the MHT, in order to be easily integrated and operated on small satellites.

At present the remaining challenge is to fully develop the MHT and its propulsion module into a flight system, through a development roadmap based on the “model philosophy” (EM, QM, FM). This roadmap has already been outlined and has the final goal of achieving TRL8 by the end of Q4/2018.

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