Magnetically Shielded HT100 Experimental Campaign

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Abstract: **Electric propulsion, with its low propellant mass and high efficiency with respect to traditional chemical propulsion systems, represents one of the most advanced technologies currently adopted for large geostationary telecoms as well as Low-Earth-Orbit applications and space exploration. Among the different electric propulsion systems, Hall Effect Thrusters (HETs) are easily scalable and provide an optimal trade-off between specific impulse and thrust. In this context, an efficient, long-life, low-power HET is an attractive choice for a wide range of missions requiring specific impulses as high as 1500 s and thrust-to-power ratios in excess of 50 mN/kW. However, poor lifetime and low thrust efficiency are primary areas of concern for small-scale (<5 cm dia.) HETs operating at low-power (<300 W). As a matter of fact, together with the degradation of the cathode, the erosion of the thruster ceramic walls due to plasma energetic particles represents the main limiting factor of the HET lifetime. The progressive wear of the ceramic walls deteriorates the thruster performance and eventually expose the magnetic circuit to the flux of plasma particles, leading to possible thruster failures. Many experimental and numerical investigations have highlighted the role played by the magnetic field in the erosion process, showing that a so-called "magnetically shielded" configuration can significantly reduce the wall damage and extend the life of the thruster. In the present work, a preliminary characterization of a magnetically shielded low power HET (MSHT100) will be presented and the experimental results will be compared with the ones obtained with a conventional Hall thruster (HT100) operating at the same power level.**

Nomenclature

BOL	=	Beginning Of Life
EOL	=	End Of Life
HET	=	Hall Effect Thruster
LEO	=	Low Earth Orbit
PMA	=	Propellant Management Assembly
PPU	=	Power Processing Unit
VLEO	=	Very Low Earth Orbit

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I.Introduction

Efficient, long-life and low-power Hall effect thrusters (HETs) are very attractive for a wide range of missions, including drag compensation for Very Low Earth Orbits (VLEO) observation satellites (300 to 400 km in altitude), final orbit insertion for small-sats launched as piggyback, and small-sats end-of life disposal. Their high specific impulse and their capability to be turned on and off for thousands of times at different operating points, make these thrusters very appealing both for their flexibility and for the remarkable propellant mass savings that they bring. In the last few years, SITAEL has devoted significant efforts in designing the low power HET, named HT100, and developing the accompanying electronics (Power Processing Units) and propellant feeding systems[1]. To serve increasingly ambitious missions, the primary challenges for HETs at small scale such as the HT100 are connected to their limited lifetime. A novel version of the thruster, named MSHT100 (Magnetically Shielded HT100) is under development in order to overcome the lifetime limitation of the traditional HT100.

II.Magnetically Shielded HT100

Since the magnetic field influences the plasma properties inside the channel, the topology of the magnetic field can affect the erosion rate of the walls that is one of the main constraints on the HETs lifetime (Fig. 1). Currently, SITAEL activities are devoted to design and test a new version of HT100, named MSHT100 (Magnetically Shielded HT100), again based on permanent magnets, but with a new magnetic field topology that limits the walls erosion and increases the thruster lifetime. The result is a thruster with improved lifetime performance (a total impulse three times greater than HT100), although with a mass slightly greater than HT100 (about 640 g vs 450 g). MSHT100 is a device capable of providing thrust levels in the 4-15 mN range, total specific impulses up to 1300 s (coupled with HC1 cathode[2] operated at 1 mg/s Xe) and with an expected total impulse exceeding 200 kNs. Therefore, MSHT100 is capable of attaining a much longer lifetime by means of a special magnetic field topology which protects the ceramic channel from erosion phenomena. Deep investigation of such magnetic field topology started in the U.S. a few years ago[3,4,5,6] on mid- to high-power Hall thrusters and is here applied for the first time to a very-low power HET equipped with permanent magnets.

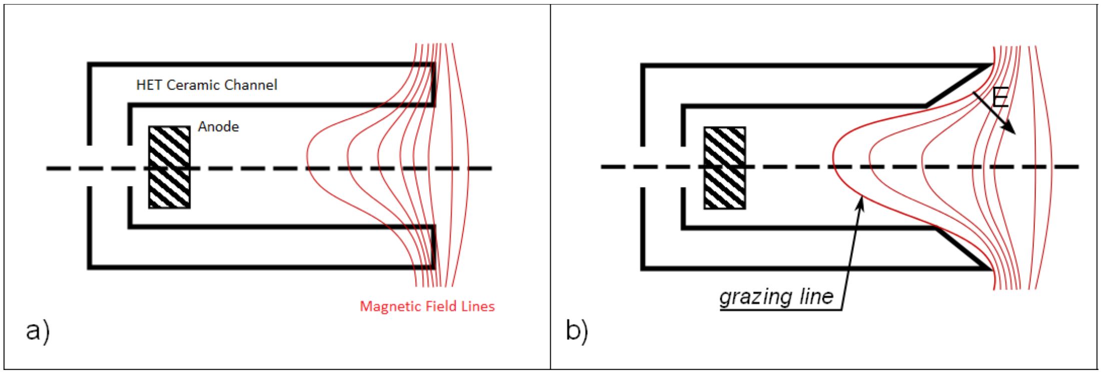

Figure 1. Magnetic field topologies for a standard HET (a) and for a magnetically shielded HET (b).

The MSHT100 is designed to operate with unaltered performance for 6000 hours, cumulating a total impulse of about 200 kNs, assuming to lower the erosion of at least a factor three. This thruster works well with the very same subsystems (PPU, PMA) already adopted for the traditional version of HT100, and its improved lifetime allows it for serving much more ambitious mission scenarios like the ones envisaged for the large small-sat constellations to be deployed in LEO for granting worldwide fast internet access.

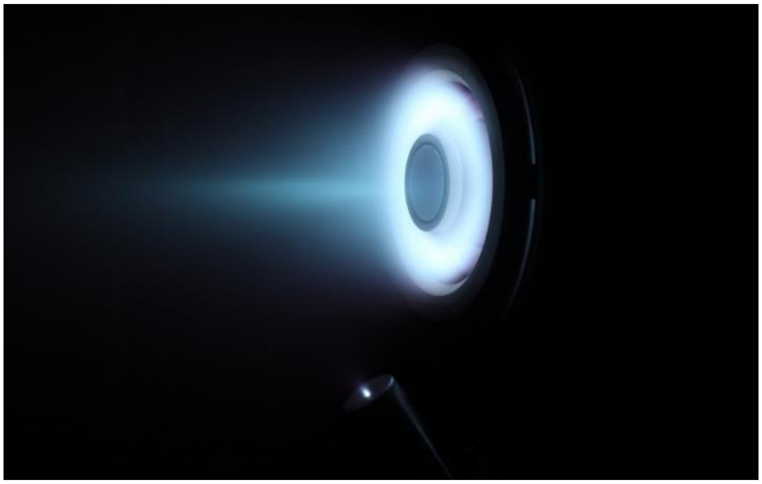

Figure 2. Magnetically shielded HT100 firing at SITAEL premises.

MSHT100 has been tested (coupled with SITAEL HC1 hollow cathode) for the first time in October 2016 at SITAEL premises in Pisa (Fig. 2), performing a full thruster characterization and a short endurance test (350 hours) to validate the design effectiveness in preventing the thruster wall erosion.

III.Test Setup and Target Objectives

A. Vacuum Chamber

MSHT100 thruster has been tested in SITAEL IV-4 vacuum chamber (Fig. 3). MSHT100 was installed on a balance to measure its thrust at different operating points, whereas a rack of seven Faraday probes was used to scan the plasma beam at a distance of 1 m from the thruster. The IV4 facility consists of two different bodies made of AISI 316L stainless steel with low magnetic relative permeability (μ_r<1.06). The main chamber has a diameter of 2 m and a length of 3.2 m, whereas the small chamber is a 1 m-diameter, 1 m-length service chamber. The two bodies are connected through a 1 m-diameter gate valve. The small chamber was used to accommodate the thruster setup, its electrical and gas-feeding systems, whereas the main chamber allowed for a free expansion of the plasma plume and it is directly connected to the main pumping system. A bi-conical, water cooled, Grafoil-lined target is installed in order to dump the beam energy down. The chamber pumping system is capable of maintaining a back pressure in the range of 10^{-5} Pa (ultimate pressure) by using a primary stage located in the main chamber and a secondary stage located in the small chamber. The combined pumping speed of the system is approximately 1.3×10^5 l/s for xenon. The pressure level within the chamber is continuously monitored by three Leybold-Inficom IT90 Pirani/Bayard-Alpert sensors and recorded via LabVIEW.

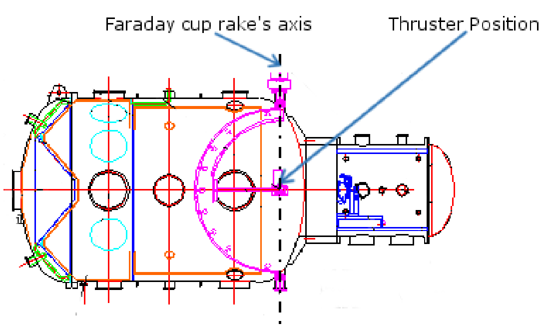

Figure 3. SITAEL IV4 vacuum test facility.

B. Diagnostics

Sitael's thrust stand characteristics are summarized in Table 1. During the test, the thrust has been measured at the shutdown of the thruster to avoid any eventual thermal drift affecting the measure. The thrust balance calibration was performed before the experimental campaign with a calibrated load cell. During the test, the calibration has been verified using an electromagnet installed on the thrust stand. This device is capable to apply a known force in two opposite directions, the applied force is directly measured by the balance.

Thrust Balance Characteristics	Value
Max. thruster weight	2 kg
Full scale	100 mN
Accuracy	0.5 mN
Resolution	0.1 mN

Table 1: Sitael thrust balance, main parameters

During the experimental campaign several beam scans were performed to investigate the ion current density distributions of the MSHT100. Sitael beam diagnostic system is equipped with seven Faraday probes installed on a semicircular rake (0°, ±15°, ±30°, ±60°) able to scan an angle of 160°(±80° with respect to the thruster axis). The thruster is positioned with its channel exit section on the rake axis.

C. HC1 Hollow Cathode

HC1 was designed to provide a discharge current in the 0.3 - 1 A range[2]. The cathode operates in steady-state conditions at mass flow rates between 0.08 and 0.5 mg/s of xenon. The expected cathode lifetime, estimated on the basis of the theoretical model, is higher than 10^4 hours. The cathode mass, without cables, is about 30 grams. The cathode assembly includes a heater, used during the ignition phase to ease the discharge initiation by increasing the emitter temperature to thermionic emission values. The use of a heater allows for starting the cathode with low applied voltages between the keeper and the cathode tube. HC1 operated with xenon for more than 550 hours and cumulated more than 350 ignitions, both with and without the use of an in-house-made heater. In the case of a heaterless ignition, keeper voltages as high as 800 V were required to start the discharge, whereas a heater power of about 45 W allowed for ignitions with keeper voltages as low as 45 - 50 V. HC1 operated with MSHT100 during a 350-hour endurance test on xenon, with a keeper current of 0.5 A.

IV.Test Results

A. Thruster Performance

The following figures report the measured performance, showing specific impulses (Fig. 4) and thrust levels (Fig. 5) very much in line with the ones provided by the traditional HT100.

At the same power levels, MSHT100 shows a lower thrust with respect to HT100 at BOL when the operating power is higher than 200 W, whereas the performance is substantially the same at the lower limit of the power gamut. The measured reduction in thrust is always below 15%, with the advantage of an increased lifetime of the device (the expected cumulated total impulse at the EOL is over twice the value of HT100). Besides, by preventing erosion phenomena, the performance of MSHT100 does not deteriorate in time as the shape of the ceramic channel where the plasma ionization/acceleration takes place does not change from BOL to EOL.

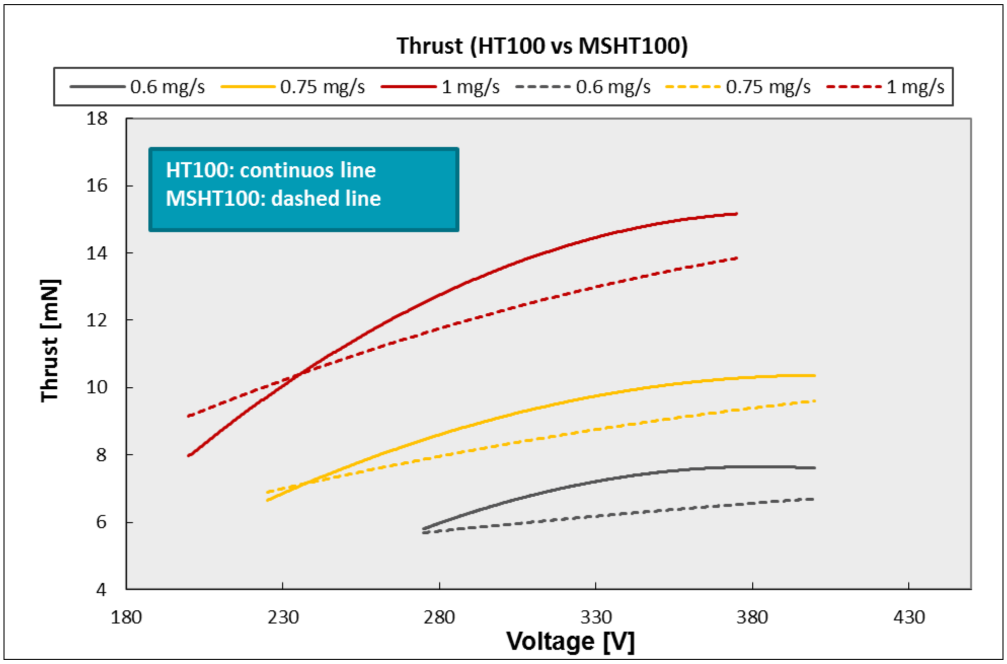

Figure 4. Comparison of thrust-voltage curves for HT100 and MSHT100, at different Xe mass flow rates.

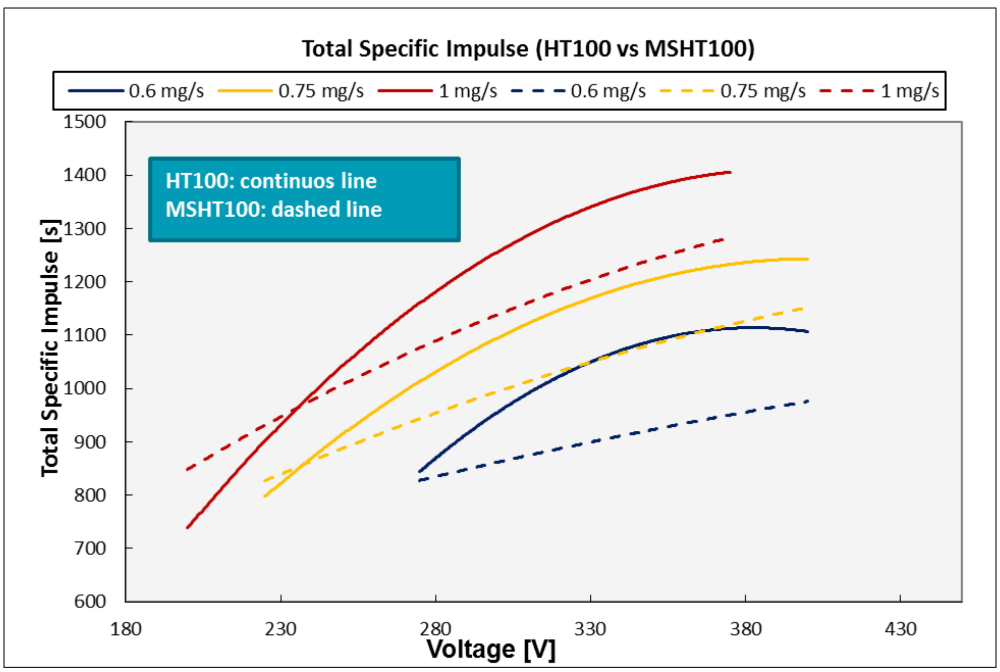

Figure 5. Comparison of total specific impulse-voltage curves for HT100 and MSHT100, at different Xe mass flow rates.

B. Thruster Lifetime Extension

The first developed model of the magnetically-shielded thruster included a region of the channel left unprotected, as red-marked in Fig. 6, since the primary aim was to assess the effectiveness of the magnetic shielding technique on the thruster ceramic walls by comparing what happens in protected and unprotected areas.

As a matter of fact, after 350 hours of operation, the channel surface that was completely shielded by the magnetic field did not show any evidence of erosion, as can be seen in Fig. 7 by looking at the sharp edge of the channel, but also by the color of the surface, which is totally black due to graphite back-sputtering coming from the vacuum chamber walls. A black surface means that the hot plasma beam was not in contact with it, otherwise the erosion would have swept away the graphite deposition and the surface would have looked white as the tip of the internal channel wall (which in this experiment, as already mentioned, was left intentionally unprotected to appreciate the difference between shielded and unshielded areas). The unprotected area, as said, was very important to verify the magnetic shielding concept. Its function was fundamental to identify exactly the necessary characteristics of the magnetic field topology to achieve the protection of the channel.

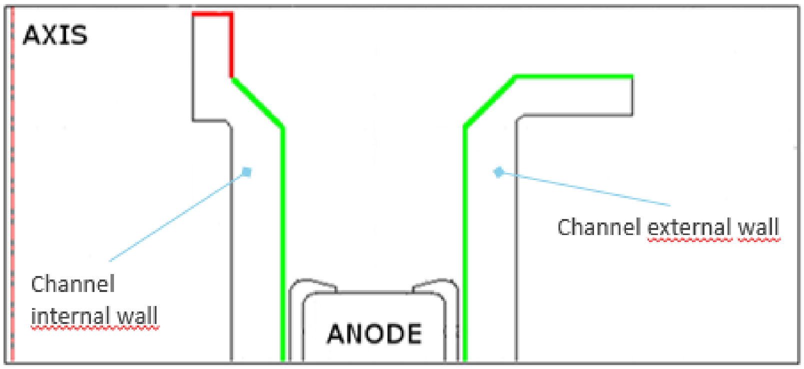

Figure 6. MSHT100 ceramic walls: the magnetically shielded areas are marked with a green line, whereas the red lines identify the unprotected areas.

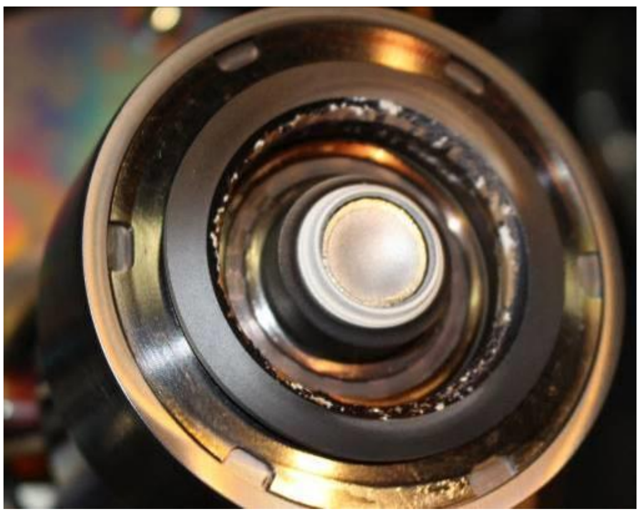

Figure 7. MSHT100: post-test inspection after 350 hours of operation.

A reliable lifetime prediction is difficult at this stage, as the erosion seems to be almost completely prevented and, if this proves to be confirmed over a longer firing period, the next life-limiting mechanism for the thruster has still to be identified. Presently, the HC1 cathode is assumed to be the life-limiting component, given the expected lifetime of about 3000 hours. In that case, the lifetime of the propulsion device can be extended to reach the target level by using multiple cathodes (6000 hours, total impulse of 200 kNs).

C. Performance with Krypton Propellant

Traditionally, xenon has always been the propellant of choice for electrostatic propulsion applications due to the optimal compromise between performance and ease of handling it can provide. Although xenon has several technical advantages as a propellant, namely low ionization energy, high atomic mass and easy storage and flow metering, its high price suffers of a remarkable fluctuation. Krypton represents a promising alternative due to its moderate cost, its handling properties and the small performance reduction that its use as a propellant implies. The main effect of krypton on the thruster performance, with respect to xenon, is a reduction of the thruster efficiency and an increase of the specific impulse values. Moreover, krypton is up to ten times cheaper than xenon. As a main drawback, considering a typical storage condition at a pressure of 150 bar and a temperature of 40 °C, the xenon density value is about 1.80 kg/dm^3, whereas for krypton is 0.61 kg/dm^3. To obtain storage density above 1 kg/dm^3, krypton shall be stored at pressure higher than 250 bar (or maintained at a very low temperature). A preliminary test of the MSHT100 coupled with HC1 fed with krypton has been carried out. Only one-single operative point has been verified, with the thruster that exhibits stable performances.

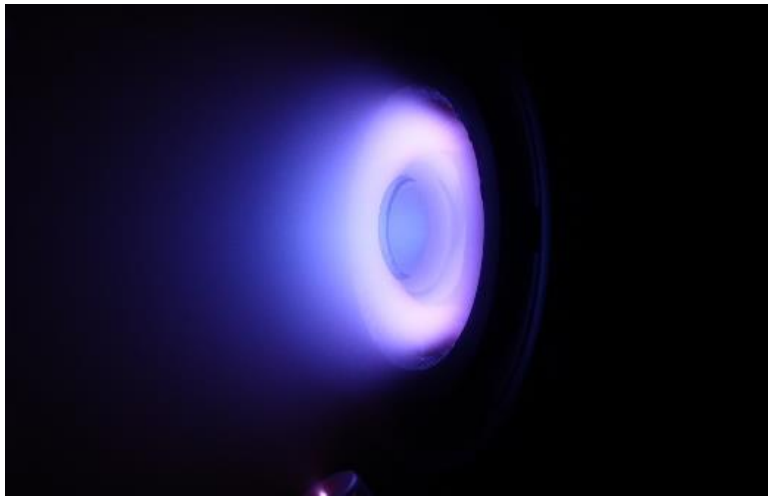

Figure 8. MSHT100 firing with krypton.

V.Future Work and Conclusions

A new version of HT100, named MSHT100 was developed in the last months at Sitael in order to increase substantially the lifetime of the thruster. The total impulse, already demonstrated by test for the HT100 of 75 kNs has now been increased up to at least 200 kNs. As a matter of fact, the new design seems to be capable to prevent completely the erosion of the ceramic channel and the new life limiting factor could be identified in the cathode lifetime (estimated around 3000 h, 6000 h with two cathodes). The experimental campaign carried out on this model has verified the magnetic shielding technology, giving precious information about the necessary magnetic field topology. In the next redesign a complete ceramic channel protection will be implemented.

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