Sitael Low Power Hall Effect Thrusters for Small Satellites

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Abstract: **Efficient, long-life and low-power Hall thrusters would be attractive for a wide variety of missions ranging from drag compensation in LEO and VLEO to accurate final orbit insertion and spacecraft end-of-life disposal. The primary challenges for Hall thrusters at small scale (<500 W) concern the thruster lifetime and the low thrust efficiency, due to the inherently higher surface-to-volume ratio. In the last few years, Sitael has devoted significant efforts in designing and testing low-power Hall thrusters providing thrust levels in the 4-40 mN range, specific impulses up to 1600s and estimated lifetimes in the order of 2000 hours. Besides, extensive research and development activities have been carried out with the aim of designing and testing low-current hollow cathodes that can be effectively coupled with such thrusters.**

I. Introduction

THIS paper presents Sitael's ongoing activities in the field of low power Hall effect propulsion. Low power electric propulsion (power levels <500W) is now rapidly emerging as a winning option for a number of missions involving mini- and micro- satellites. From Earth Observation platforms to large constellations intended to provide worldwide internet coverage, the possibility of adopting an electric thruster turns out to offer a tremendous improvement in terms of propellant mass reduction. Missions that require a total DV larger than 100 m/s already experience significant benefits thanks to the high specific impulse of electric thrusters. More ambitious missions, requiring a total DV of 200 m/s or more, can be accomplished only with EP, as it would be otherwise impossible to store the necessary propellant onboard. Typical EP tasks are drag-compensation (which is a very demanding task for satellites operating in VLEO), orbit insertion (EP will be then used to bring the satellite into the target orbit, allowing the satellite operator to trade-off the exact choice of a release orbit with a lower launch cost), de-orbiting at the end of mission life. Hall effect technology is well consolidated and time has come to wrap up all the research heritage cumulated in the past years and exploit it to provide flight-ready devices that can quickly respond to the market needs. For a small satellite orbiting close to the Earth the available power is the most limiting factor for the adoption of an electric propulsion system, considering the limited size of the solar arrays and that the satellite can spend up to 30% of its life in eclipse. Power budget can be extremely variable, depending on the satellite architecture and on the mission profile. Thus, it is of primary importance to develop thrusters which are optimized for different power levels. At Sitael Space Division (formerly Alta), this led to the choice of designing three distinct

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thrusters which, all together, cover a broad power spectrum ranging from 70W to 800W. In the following sections the thrusters and cathode units that have been developed are described, together with the main test results and the next planned steps to further advance their Technology Readiness Level and, eventually, achieve their full space-qualification.

II. HT100 Hall Effect Thruster

Sitael's HT100 is the smallest and lowest power-consuming HET ever developed in Europe [1], thanks to its peculiar architecture based on permanent magnets which brought a significant reduction in thruster weight, complexity and size. Extensive test campaigns have been carried out on the thruster, with the aim of improving its Technology Readiness Level (TRL) and successfully go through a full space-qualification process in the near future.

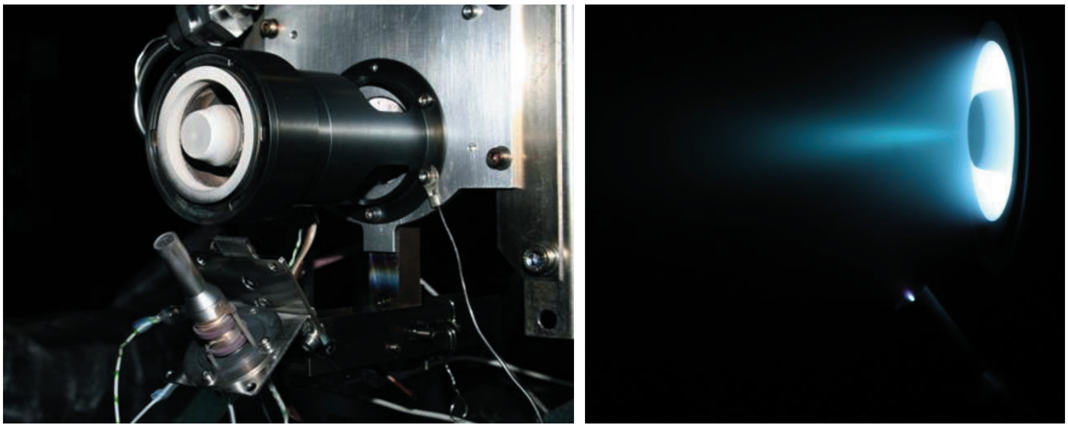


Figure 1: HT100 thruster firing in Sitael's vacuum facility during characterization test

Thruster Performance:
HT100 has a nominal operating power of 175W with an applied voltage of 300V, corresponding to a thrust of 8.5mN and to an anode efficiency close to 35%. The thruster can anyway operate in a broader power range, between 120W and 300W (anodic power), providing a thrust in the 5-16mN interval. Specific impulse is strictly connected to the chosen operating voltage and can be as high as 1450s. In the following pictures HT100 measured thruster performance are reported. The adopted cathode was here Sitael HC3, operated, during the characterization, with a mass flow of 0.1mg/s. In this conditions operating voltages below 250V are unpractical, as the plasma suffers a transition from 'spike mode' to 'diffuse mode' with a consequent reduction of the thruster performance. However a small increase in the cathode mass flow rate up to 0.15mg/s has revealed (in this voltage range) a new transition back to the spike mode with performance increase in terms of efficiency and specific impulse.

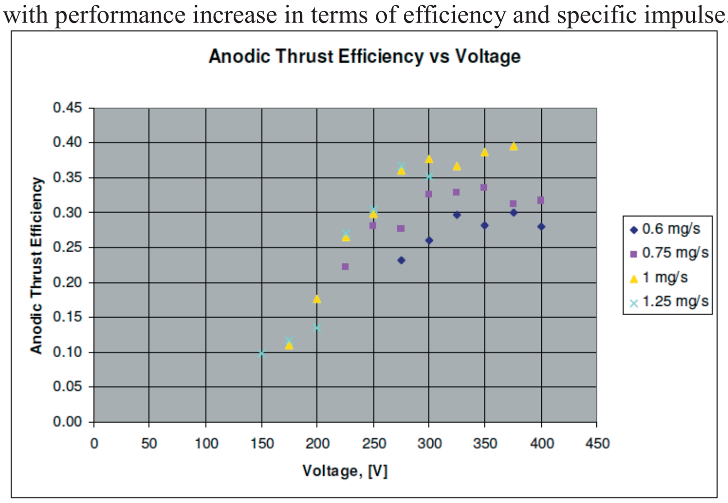


Figure 2: HT100 measured performance, anodic efficiency

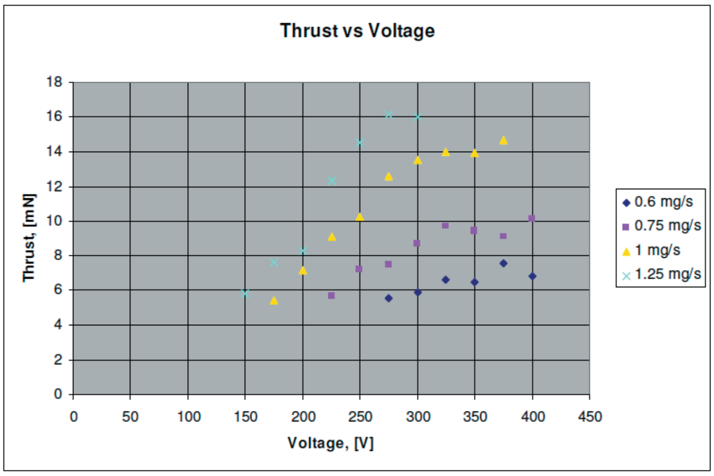


Figure 3: HT100 measured performance, thrust

Thruster Endurance Test:
Presently, HT100 is performing an endurance test in Sitael laboratories, operating at a fixed operating point with a discharge power of about 215W and an applied potential of 300V. The aim of the test is to assess the effective lifetime of the thruster. HT100 has already cumulated 940 hours of firing (corresponding to a total impulse of 34000Ns) without any performance degradation or discharge instability.
The choice to carry on the endurance test at a power level which is 20% higher than the nominal operating power of the thruster (175W), still maintaining the nominal operating voltage, results in an accelerated lifetest. Actually, in terms of insulator erosion, 940 hours of operation at the chosen operating point roughly correspond to nearly 1150 hours at the nominal operating point. [2]
The expected lifetime, predicted with a channel erosion model developed by Sitael [3], is about 1500 hours for a total cumulated impulse exceeding 50000Ns. The thruster end-of-life (EOL) is defined as the time needed for the erosion to completely wear out the insulator in at least one section of the channel. Actually, it makes more sense to monitor the thruster performance and associate the thruster EOL to a significant performance reduction (in terms of total thrust, beam focusing or thrust vector orientation). In the latter case, the thruster can survive beyond the complete erosion of the channel in the terminal section and continue working until the ion impingement on the magnetic circuit does alter the magnetic field topology and leads to an unacceptable performance deterioration.

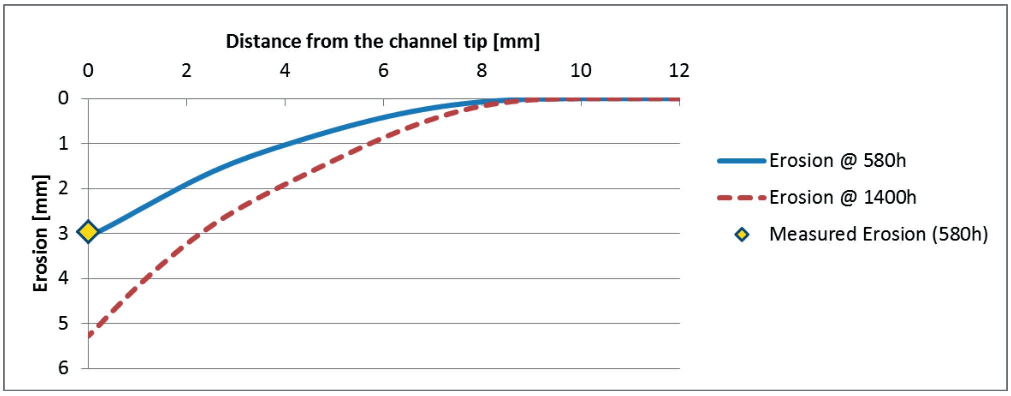


Figure 4: HT100 erosion prediction

Thruster Structural Analysis:
A preliminary structural analysis of the HT100 has been performed in order to verify the hardware compatibility with typical launch loads (static loads, random and sine vibrations). The loads applied to the thruster in this analysis constitute a conservative envelope of the launch loads generated by the existing small launchers.

Quasi-static loads		
Axis	**Limit loads**	
Out of plane	60g	
In plane	60g	
Sine Vibration loads		
Axis	**Frequency[Hz]**	**Qualification**
Out of plane	5-20	15 mm
	20-100	24g
In plane	5-20	9.9 mm
	20-100	16g
Random Vibration loads		
Axis	**Frequency[Hz]**	**Qualification**
Out of plane	20-100	6 dB/octave
	100-400	0.05x(M+20)/(M+1)=0.6875
	400-2000	-3 dB/octave
Overall g_{RMS} 26.14		
In Plane	20-100	6 dB/octave
	100-200	0.05x(M+20)/(M+1)=0.6875
	200-2000	-4 dB/octave
Overall g_{RMS} 17.71		

Table 1: Loads introduced in the structural analysis

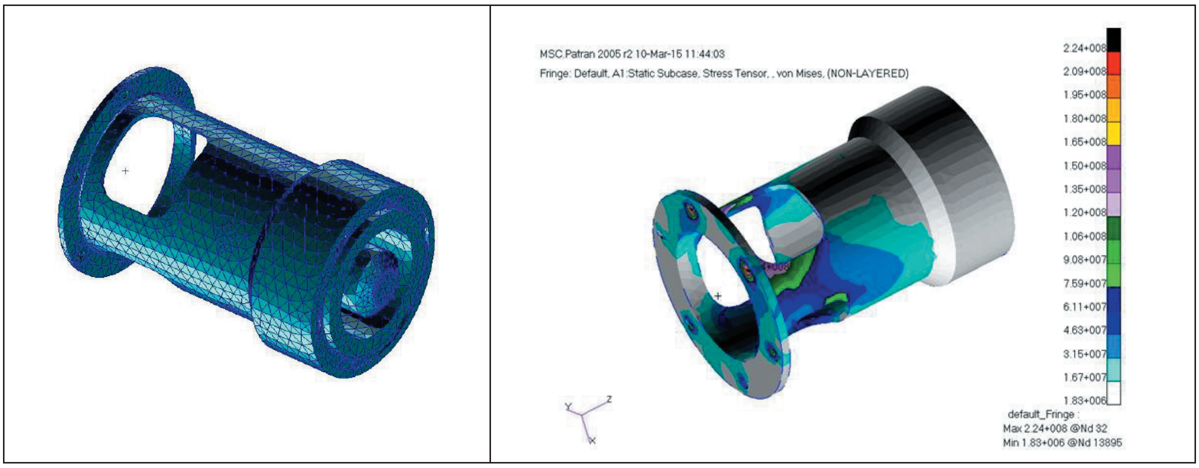


Figure 5: HT100 thruster FEM model(left) and results from random analysis (right)

The results have shown a very good structural response to the applied loads and highlighted the need of minor re-design efforts at I/F level.

III. HT400 and HTX0 Hall Effect Thrusters

Targeting a larger variety of missions, Sitael also developed two other Low Power HETs that operate respectively up to 700W and down to 70W. They both rely on permanent magnets to generate the magnetic field which is necessary to ionize and accelerate the gas flow and their geometric configuration has been derived through the application of appropriate scaling laws.

A. HT400 Thruster

HT400 is a low power Hall effect thruster operating in the range 350W-800W [4]. The magnetic circuit design based on permanent magnets is the result of an extensive work of performance investigation obtained on two previous prototypes: both the models having exactly the same dimensions of the HT400 ceramic channel. One of this, based on coils, has been used to study the effect of magnetic field intensity and topology on the performance. The other one based on permanent magnets has been used to carry out a preliminary characterization of the thruster and to perform an endurance test of about 500h. The present engineering model of HT400 has very interesting performance (comparable with the SPT-70) and optimized design with reduced mass (lower than 1kg) and dimensions and increased lifetime (with respect to the previous models). In addition, from the mechanical point of view, the thruster(together with HT100 and HTX0) is provided with a stiffening structure which connects all the components together and which is capable to sustain all the mechanical loads the thruster can meet during its life(e.g. launch loads).

Figure 6: HT400 Hall Effect Thruster

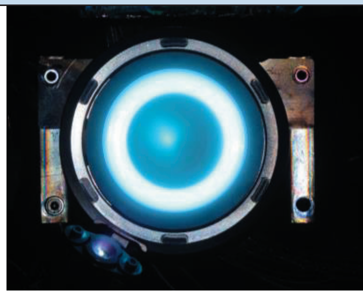
HT400 Thruster Performance		
Thrust, [mN]	20-50	
Power, [W]	350-800	
Specific Impulse, [s]	1100-1800	
Thrust efficiency, [-]	30-50	
Mass, [kg]	0.9	
Predicted Lifetime [h]	4000	

Table 2: HT400 measured performance

B. HT-X0 Thruster

Taking advantage of the solid heritage of Sitael/Alta on low-power HETs, a new 100 W-class HET has been created to address the needs of future power-capped space missions. The HTX0 thruster is designed to work at nominal power of 90W and is expected to operate down to 70W with satisfying performance. The design of the thruster has been obtained scaling down the HT100. The magnetic circuit is still based on permanent magnets and with respect to the HT100 the thermal design has been improved reducing as much as possible the temperature of the most sensitive elements. The objective was to produce a thruster capable to work with a quite high efficiency at very low power (70-100W) and simultaneously to have the possibility to reach higher discharge power (up to 150W) without any thermal issues. The thruster, as in the case of HT100 and HT400, is equipped with a stiffening structure designed to connect together the magnetic circuit, the passive cooling system, the anode system and the thruster support.

The HTX0 thruster is going to be manufactured in the next months and together with the HT100 and the HT400 will be part of the Sitael low power Hall thruster division that covers the whole power range under 1kW.

Figure 7: HTX0 thruster vs HT100

IV. Hollow Cathodes

The hollow cathode is a mature technology employed to produce electrons in HETs, for both ionizing the propellant and neutralizing the accelerated ion beam. A performance improvement is particularly needed in the field of the 100 W-class propulsion for small satellites, where a reduction in power and propellant consumption has a significant impact on the overall thruster performance. As a matter of fact, the cathode flow rate in xenon Hall thrusters tends to be 7–10% of the anode flow rate [5], whereas the cathode power consumption can reach up to 20% of the available power [6]. A hollow cathode is typically made of a refractory metal tube, which houses an insert providing electrons by means of thermionic effect. The tube ends with an orifice plate to increase the internal pressure. The cathode assembly is enclosed by a keeper electrode, whose primary functions are to help the discharge initiation and protect the inner parts from ion bombardment. The standard cathode configuration includes a heater, consisting of a properly insulated wire, which brings the insert temperature to thermionic emission values. The use of a heater allows for a lower voltage applied to the keeper, despite introducing a single-point of failure for the cathode. Among the mostly used inserts, the dispenser barium-based type has a relatively low work function (about 2.1 eV), however it is susceptible to contamination and requires a specific and long activation procedure. As a viable alternative, the lanthanum hexaboride (LaB_6) compound is less sensitive to contaminants and air exposure, and allows for the possibility of heaterless ignitions, at the cost of a slightly higher work function (between 2.4 and 2.7 eV).

Two hollow cathodes have been developed and tested at Sitael for the 100 W-class HETs. A LaB_6 cathode was conceived for the current range 1-3 A and tested with and without a heater. A dispenser cathode was developed for current values lower than 1 A and its ignition relies upon the use of the heater.

A. Hollow Cathode for 1-3A (HC3)

The LaB_6 cathode HC3 is made of a tantalum tube and an orifice plate, enclosed by a titanium-alloy keeper electrode. The heater consists of a W-3Re wire immersed in an alumina potting and placed around the main tube.

The cathode was characterized in diode mode with the keeper and coupled with the HT100, at mass flow rates between 0.08 and 1 mg/s Xe (Figure 8). The heaterless ignition technique consisted in applying voltages up to 950 V to the keeper and a cathode mass flow rate between 1 and 2 mg/s Xe. Supplying the heater with a power of about 50 W, the cathode was successfully started with keeper voltages as low as 300 V and cathode mass flow rates between 0.4 and 0.8 mg/s Xe. The cathode-to-keeper voltage was found in the range 14 - 30 V, for a corresponding power consumption between 15 and 60 W as shown in Figure 9. The estimated cathode lifetime (based on emitter evaporation rate) is in the order of 10000 hours.

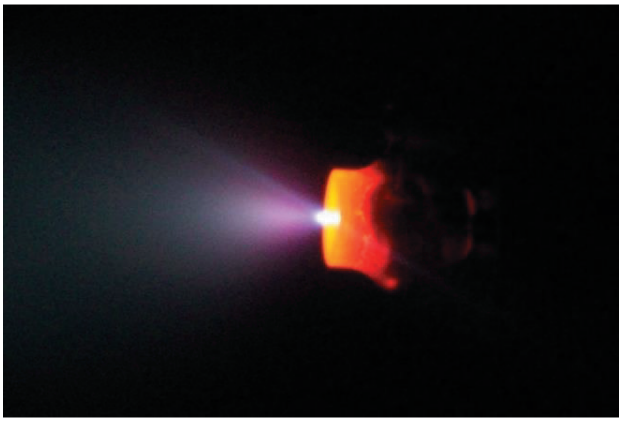


Figure 8: HC3 operated in diode discharge with the keeper.

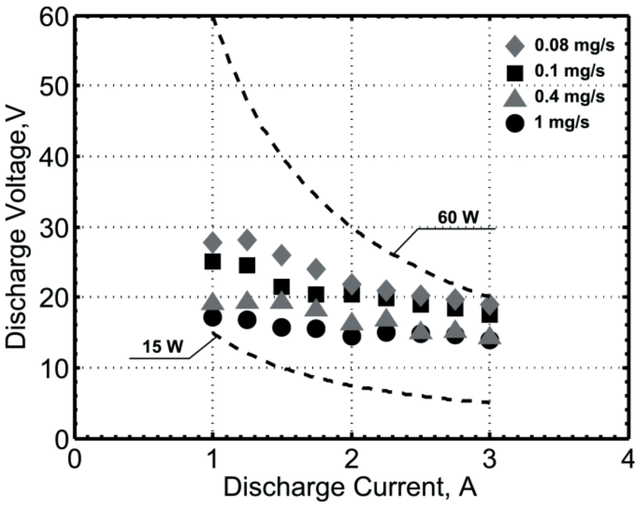


Figure 9: HC3 electrical characteristics at four xenon mass flow rates.

B. Hollow Cathode for less than 1A (HC1)

The HC1 hollow cathode features an S-type emitter, namely a triple mixture of $BaCO_3$, $CaCO_3$ and Al_2O_3 with a molar ratio of 4:1:1. The cathode design is similar to the HC3, with smaller dimensions due to the different emitter material and to the lower current demand (Figure 10). This cathode is expected to operate at discharge voltages in the order of 20 V at mass flow rates as low as 0.05 mg/s Xe, with a conditioning phase requiring 30 W of heater power. The current is drawn from the insert at temperatures up to 300 K lower with respect to LaB_6, thus a surface emitting temperature of about 1500 K is predicted. The lifetime estimated (based on BaO compound depletion) for the HC1 cathode is in the order of 8000 hours.

Figure 10: HC1 cathode.

V. Next Steps and Conclusions

Sitael is actively developing three low power Hall effect thrusters: HT100, which is already at EQM level and is presently under qualification following ESA standards, HT400, which has been extensively tested and is ready to start a full qualification process, and HTX0 which has been recently designed, manufactured and assembled and will be the next one to be tested in our facilities in order to obtain its full characterization. In parallel, two suitable cathodes have also been developed; both cathodes are specifically designed for low current levels (<3A), but they are based on different technologies (heatered vs. heaterless device) so to explore advantages and disadvantages of the two alternative choices and be always ready with the most appropriate solution to respond to given mission needs.

Next steps, in the short term, will be mainly focused on completing all the necessary tests to qualify HT100. Thermal vacuum tests are foreseen within the next two months, immediately followed by shock and vibration tests to complete a typical environmental test campaign. At the same time, a significant effort will be carried out to quickly advance the Technology Readiness Level of the cathode unit: here the target is to have a full characterization of its electrical behavior, a perfectly repeatable ignition process and to achieve a lifetime that is in line with standard mission requirements (especially for the number of on/off cycles, which is often one of the most critical aspects).

From the market standpoint, the three devices under development can effectively provide a sound solution for accomplishing several mission tasks, extending the capabilities of small platforms operating in LEO. Power is often the most important constrain for small satellites and it is thus crucial to develop different devices for different power levels, in order to optimize the thruster size and get the best performance in terms of thrust efficiency. Besides, all thrusters have been designed paying special attention to production costs, as the propulsion system price is certainly a driving factor in this market niche.

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