SITAEL's Magnetically Shielded 20 kW Hall Thruster Tests

IEPC-2019-879

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: Within the framework of three development programmes, SITAEL is currently developing a 20kW class Hall Thruster. The activities focused on increasing the performance and lifetime of the thruster by implementing a magnetically shielded topology. Several IV10 chamber upgrades have been implemented at the beginning of 2019, resulting in lower pressure levels in the facility. Thanks to this, it was possible to test three different channel geometries at different chamber background pressures. This paper presents a summary of the results of the latest tests on the magnetically shielded version of the thrusters.

I.Introduction

In the past years, the rise of in-space power generation capabilities and the advances in other supporting elements of electric propulsion architectures has resulted in an increased interest among the spacecraft manufacturers and operators towards high power Hall thrusters. Such systems allow for the realization of a spectrum of space missions from near-Earth satellite servicing and space-tug to deep-space exploration and transportation.
A few numbers of facilities today are compatible with the stringent testing requirements of this category of Electric Propulsion (EP) systems. In addition, the high cost of any test campaign, as well as the time and costs related with the facility operations, significantly affects the development of very high-power thrusters.

Nevertheless, considering the great performance benefits of high-power Hall thrusters, the perspective of market demands for this class of propulsion systems, and the void of efforts in Europe, SITAEL initiated developing a very high-power Hall thruster in 2015, within the framework of a Technology Research Project (TRP) funded by ESA. The project comprised the development of a 20kW-class Hall, and of a high-current hollow cathode (the HC60). As a result, the HT20k DM1 thruster unit was manufactured and went under several characterization campaigns through 2016 and 2017 in SITAEL's IV10 vacuum facility, one of the largest vacuum facilities for electric propulsion testing in the world (Figure 1).

During the first campaign on the DM1, the thruster was characterized from 300 V to 1000 V of discharge voltage and from 10 kW to 20 kW of discharge power. The thruster, coupled with the HC60 cathode mounted in central position, was able to achieve stable operations at different power levels, demonstrating more than 3000 s of total specific impulse at 20 kW and 800 V. A maximum anodic specific impulse of 3851 s was reached at 1000 V of discharge voltage and 10 kW of discharge power.

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The thermal transient throughout a 30- hour long continuous firing at 20 kW and 400V was then recorded, indicating a steady-state temperature of about 400 °C at the back of the thruster after 4 hours of operation.
A second characterization campaign was then carried out, focusing on low-voltage operation (250-450 V) with different relative position of the electrodes (see Ref.1 for further details). In addition, a new prototype of the HC60 hollow cathode was manufactured and mounted externally to the thruster. In this configuration, the thruster underwent a dedicated characterization test to assess the influence of the cathode position on the thruster performance.
In May 2017, for the first time in Europe for this class of power, the HT20k DM1 went through a wear test of 150 hours with xenon propellant. This test allowed assessing the evolution of the thruster performance and channel erosion, showing maximum erosion rates on the outer and inner walls of, respectively, ~8 μm/h and ~5 μm/h. At the end of the campaign (May 2017), the HT20k DM1 cumulated a total of 250 hours of firing.
After the conclusion of the TRP activities, several design modifications and new technological solutions were devised, focusing on the increase of thruster performance, reliability, thermomechanical robustness and lifetime.
In 2018, a second design iteration of the thruster unit, the HT20k DM2, was developed and used to perform several investigations of various technological and design issues pertaining to thrusters of this power level. One of the main features of the HT20k DM2 was the implementation of magnetic shielding of the ceramic channel in order to increase the lifetime of the thruster.

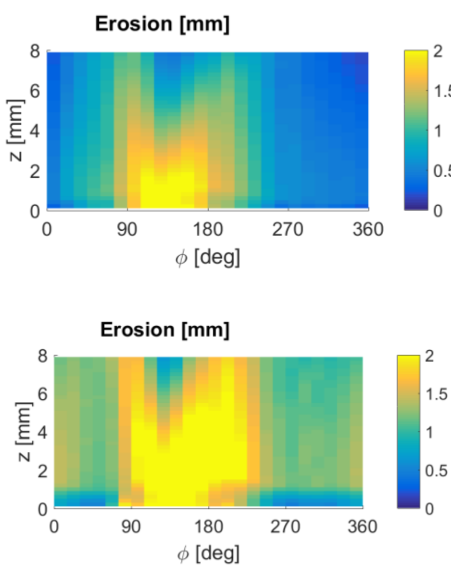

Figure 3 Erosion of the inner (top) and outer (bottom) ceramic for the HT20k DM1 after 150 hours at 300 V and 15 kW with external cathode.

Figure 1 SITAEL's IV10 Large Space Simulator.

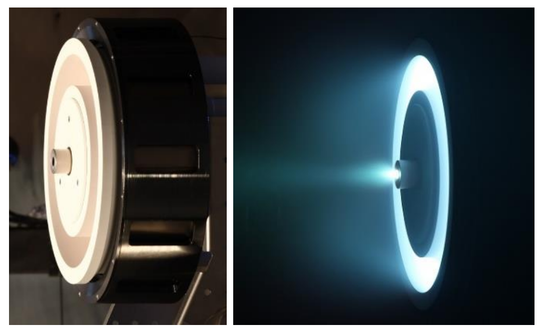

Figure 2 HT20k DM1 before the first test (left), and firing at 400 V 20 kW (right).

The most recent development activities (2018-to date) have been performed in the frame of three different programmes: EU's H2020 Consortium for Hall Effect Orbital Propulsion System (CHEOPS) programme, an ESA/GSTP programme and a dedicated pre-development ESA programme. A detailed description of the onging programmes can be found in Ref.2.
This paper focuses on the tests of the HT20k DM2, giving a summary of the test which have been performed in the past two years, in particular on the pre-development ESA programme.
In section II, the results of the first characterization of the HT20k DM2 during the year 2018 are provided. Section III focuses on SITAEL's IV10 upgrades. Last, Section IV summarizes the results of the HT20k DM2 characterization after the chamber upgrades, providing a preliminary comparison of the HT20k DM2 thruster performance before and after the upgrade of the pumping system.

II. HT20k DM2, first experimental campaign

As previous stated, the HT20k DM2 was designed and manufactured at the beginning of 2018. In order to have a better insight in the scaling of high power magnetically shielded Hall thrusters, the HT20k DM2 can be arranged in three configurations, labeled respectively HT20k M, HT20k S and HT20k L (see Figure 4). Each configuration has a discharge channel of different width (L>M>S) and a different set of magnetic screens and poles to have the same shielded topology of the channel. The main coils and the backplate of the magnetic circuit are the same of the HT20k DM1. It is important to highlight that the HT20k M retains the same channel dimensions of the unshielded version (DM1) and the mean channel diameter is always kept the same. This first DM2 characterization took place in the end of 2018 and was aimed at studying the stability domain of the thruster and the effectiveness of the magnetically shielded topology. Furthermore, the test had the objective of defining the best channel aspect ratio for the design of the engineering model (see Ref. 2 and 3) and defining scaling laws for magnetically shielded Hall thrusters of this power level.

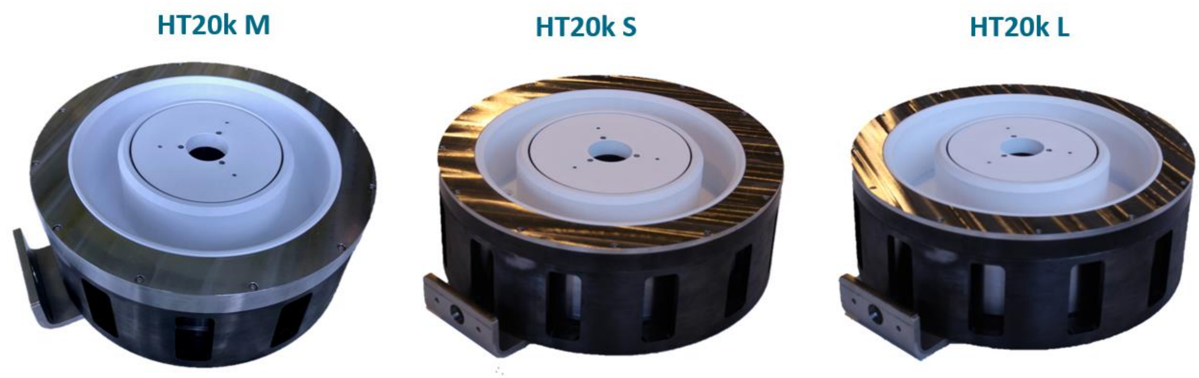

Figure 4 HT20k DM2 and its configurations, respectively HT20k M, HT20k S and HT20k L.

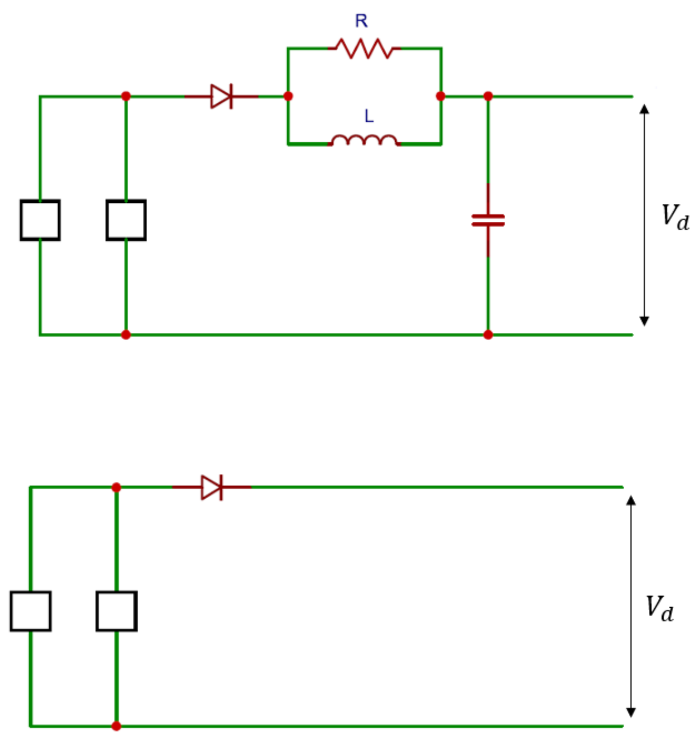

Figure 4 Simplified scheme of the anode line, with the filter unit (top), without the filter unit (bottom).

SITAEL's HC60 hollow cathode[4] with graphite keeper was used. During all the first campaign, the cathode mass flow rate was always 6-8% of the anode mass flow. The cathode, mounted in the central position was pulled backwards with respect to the HT20k DM1 tests [1], to have the keeper tip at the same level of the inner pole cover (as shown in Figure 6).
The characterization was performed at fixed values of anode mass flow rate, from 250V to 500V of discharge voltage. For each operative point, magnetic field peak optimization was carried out, in order to minimize discharge current and maximize thrust.
The same test setup of the HT20k DM1 characterization campaigns was used, with two Regatron TC.P.20.500.400.S power supplies. Each power supply is capable of providing up to 50A and 500 V between the anode and the cathode.
In particular, the power supply units were mounted in parallel in order to provide the required discharge current compatible with high power low voltages points. In addition, no dedicated filter unit in the anode line was implemented (as shown in Figure 5, bottom). The IV10 pumping system was the same used for previous HT20k DM1 and HT5k LL characterizations with 5 cryogenic panels [1, 5, 6]. Two separate laboratory mass flow controllers were used (the Bronkhorst F-201CV-500-

AAD-88V for the anode and the Bronkhorst F-201C-FAC-88-V for the cathode the same of the characterization on the DM1).
After any chamber closing, the thruster was fired for at least 5 hours at a selected ignition point to properly outgas. Once the outgassing phase was finished, before any characterization test, the thruster was fired for at least 1.5 hours in order to heat up all the components.

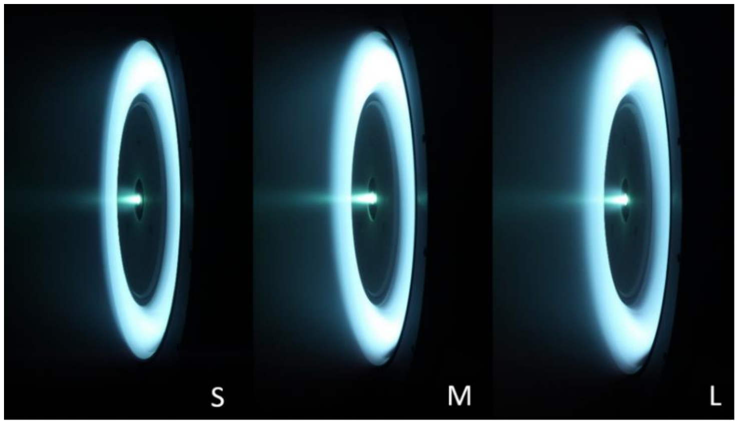

Figure 6 HT20k DM2 firing at 300V and 25mg/s to the anode, from the S to the L configuration, first characterization campaign.

The effectiveness of the magnetically shielded topology was visually verified by noticing the graphite back-puttering deposition on the ceramic channel. Another indication is the detachment of the plasma from the ceramic walls (Figure 7). The same behavior was also observed with the HT20k L and HT20k S.
Even if several points were characterized, without a proper filtering of the discharge current, the power supply was not able to manage current peaks relative to anode mass flow rates larger than 35-40 mg/s. The latter resulted in the impossibility of characterizing the points at low voltage and high-power levels (e.g. 300V, 20kW), which had been possible with the unshielded version (HT20k DM1).
In particular, at 300 V, the maximum characterized power levels were about 15kW of discharge power.
A performance comparison between the M configuration and DM1, since they have the same channel dimensions, is provided in Ref.7.
The comparison of the three configurations (at the optimum magnetic field peak) in terms of thrust and specific impulse at various voltage levels is summarized in Figure 8. The M configuration performed consistently better than the other two. On the other hand, especially at higher discharge voltages, the L configuration had the worst performance levels. The maximum anodic efficiency was obtained (depending on the voltage and configuration) in the 25-30 mg/s range.

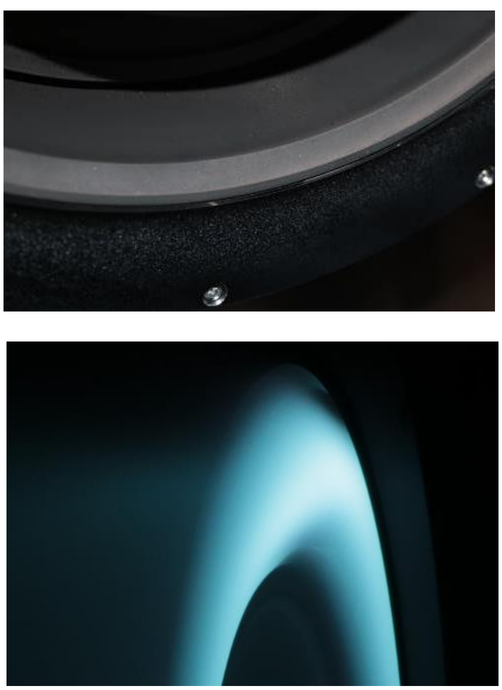

Figure 7 Graphite deposition on the ceramic channel after the characterization test (top), and detail of the plasma detachment from the channel walls.

III. IV10 facility upgrades

After the first characterization campaign on the HT20k DM2, the IV10 facility underwent a series of planned upgrades in order to enhance its pumping capabilities and diagnostic systems. The first series of upgrades were implemented during the first two months of 2019 (see Table1). Three cryo-panels, coupled with their new cold heads, were added to the existing pumping system, allowing for a significant reduction of the background pressure.

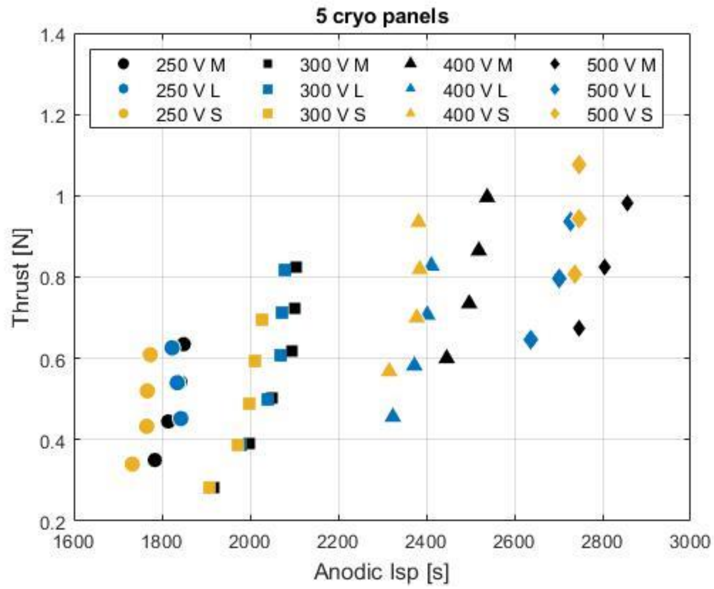

Figure 8 HT20k DM2 performace comparison in terms of thrust vs anodic Isp at various dicharge voltages, first experimental campaign (2018, 5 cryo-panels).

The increased pumping surface would allow for longer time of continuous firing prior to chamber opening, estimated to be about 500 hours (for the a HT20k like thruster). These intervals will be verified during the foreseen wear tests on the engineering model (see Ref.2).
In order to quantify the carbon back-sputtering deposition rate (which may be compatible with erosion of the channel, especially in high power magnetically shielded Hall Thrusters), two Quartz Crystal Microbalance (QCM) sensors were installed in the chamber, one at the side and the other one at back of the thruster.
Other planned upgrades consist of a Xenon recovery system, new probes and diagnostics, and an auxiliary chamber (AC). Further details can be found in [2, 3, 7].

IV10 vacuum facility

	Pre-upgrade	**Post-upgrade (Mar. 2019)**
Free diameter	5740 mm	
Free length	6000 mm	
Total leak rate	<10^{-4} mbar l/s (GHe)	
Pumping speed	~300.000 l/s (Xe)	~450.000 l/s (Xe)
Ultimate pressure	5·10^{-7} mbar (Xe	5·10^{-7} mbar (Xe)
Operating pressure with 20kW TU firing	up to ~6·10^{-5} mbar (Xe)	up to ~3·10^{-5} mbar (Xe)

Table 1 IV10 vacum facility features before and after the upgrades implemented at the beginning of 2019 .

IV. HT20k DM 2 second campaign

The second campaign on the HT20k DM2 was carried out from March to May 2019. A dedicated filter unit was also designed, manufactured and integrated in the test setup according to the scheme of Figure 5. The same commercial power supply units of the first campaign were used. This campaign aimed at evaluating the performance

at various operating regimes at fixed power levels from 15 to 22.5 kW, at 300 to 450V (according to the Table 2) at 3 magnetic field peaks, from the lowest (labeled B0) to an intermediate (B1) and highest value (labeled B2).
The characterization was carried out using 7 of the 8 available cryo-panels. It must be said that, during all the characterization at fixed power levels, the cathode mass flow was always kept at 1/15 of the anode mass flow.

	300 V	375 V	450 V
15 kW	X	X	X
17.5 kW	X	X	X
20 kW	X	X	X
22.5 kW	X	X	X

Table 2 HT20k DM2 characterization matrix, fixed power levels.

Thanks to the use of a dedicated filter unit, it was possible to characterize all the planned points from low to high magnetic field peaks. The filter allowed to have stable operation even at low magnetic fields peaks, at high mass flow rates (e.g. 300V 20kW, B0, and 300V 22.5kW, B0) and/or high discharge voltages. After the characterization of the M configuration, the HT20k DM2 underwent a thermal steady state test, firing the thruster at 300 V and 20 kW of discharge power. After 4 hours of firing, the temperatures values at the back of the thruster ranges from 320 to 360 degrees Celsius, suggesting that the thermal load to the thruster structure was lower with respect to the unshielded HT20k DM1 (see Ref.1 for comparison).
The graphs from Figure.9 to Figure 11 summarize the thruster M, L and S configurations performance data. At B0 of magnetic field peak intensity, the M and S configuration performed better than the L at 300 V and 450 V of discharge voltage. No substantial difference was noticed at 375 V.

At B1 of magnetic field peak, at the same power level, the S configuration produced larger thrust levels at 300 V and 375 V of discharge voltage. At 450 V, on the other hand, the M produced more thrust with respect to the S. The same behavior was noticed at B2.
To sum up**,** the M and the S configuration showed larger values of efficiency. In particular, the M configuration performed consistently better for B0 300 V, B1 450 V, and B2 450 V. The S configuration, on the other hand, performed better at 300 V B2.

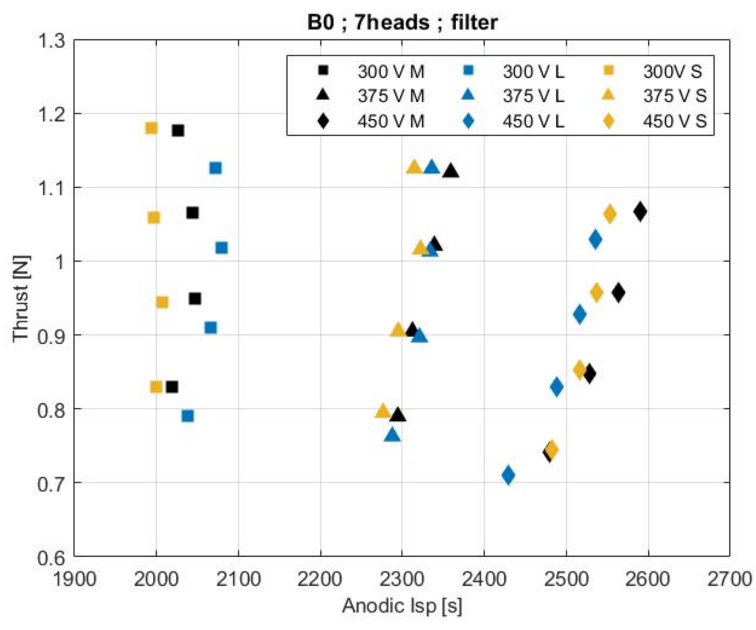

Figure 9 HT20k DM2 M, L and S performance data comparison, B0 of magnetic field peak (7 cryo-panels, with filter).

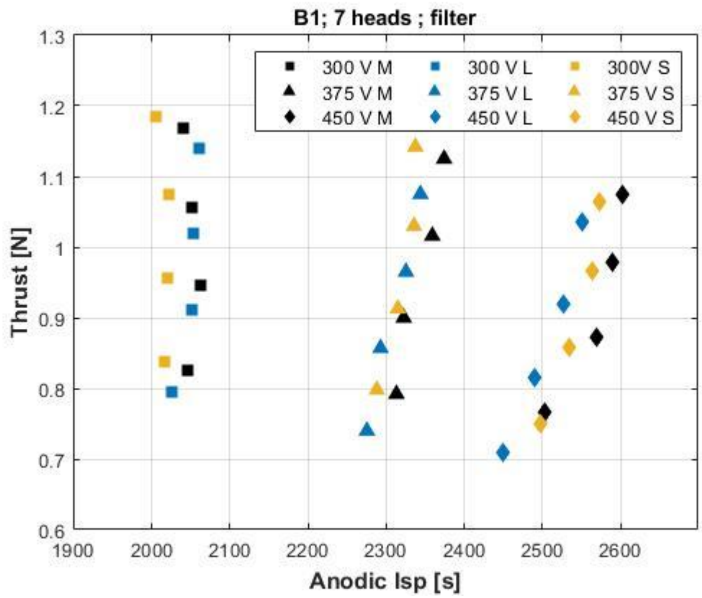

Figure 10 HT20k DM2 M, L and S performance data comparison, B1 of magnetic field peak (7 cryo-panels, with filter)

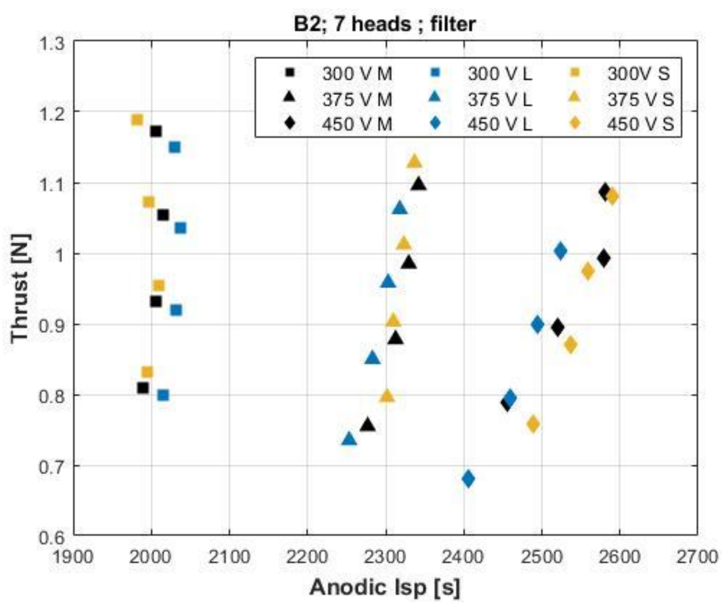

Figure 11 HT20k DM2 M, L and S performance data comparison, B2 of magnetic field peak (7 cryo-panels, with filter)

Preliminary results of the average back-sputtered deposition rate showed that, for each configuration, the average deposition rate was about 4 µm/kh and 8 µm/kh, respectively for the back and side QCM sensor. During the fire at 300V and 20kW of discharge power, the deposition rates were about 6 µm/kh and 13 µm/kh.

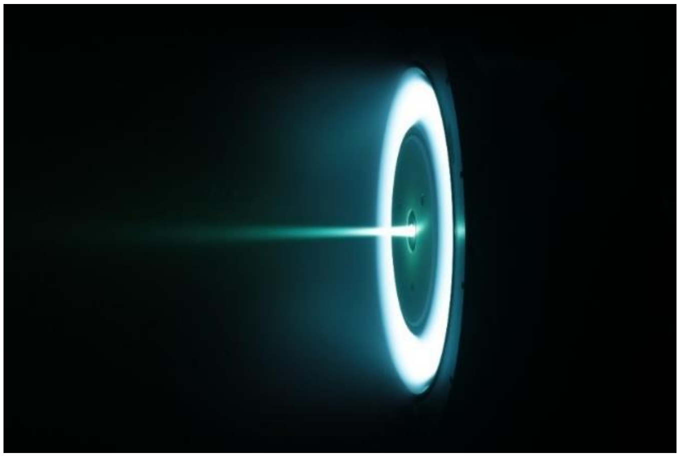

Figure 12 HT20k M firing at 450V and 22.5kW of discharge power, B2 of magnetic field peak.

A. HT20k DM2 before and after the facility upgrade

After the characterization described above, each configuration underwent a test to compare its performance before and after the facility upgrade, in particular with 5 and 7 cold heads. The same setup of the first characterization was used, with no filter unit on the anode line. The same point of the first characterization were repeated, using the magnetic field peaks and cathode mass flow. In this paper only the performance comparison of the M configuration is presented.

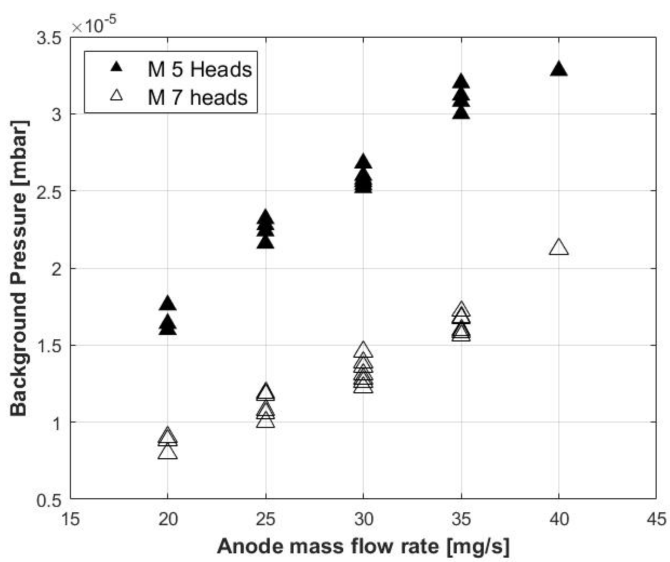

Figure 13 HT20k M pressure comparison between 5 and 7 cryo-heads (left), HT20k S pressure levels with 7 and 8 cryo-heads (right).

It must be highlighted that, with anode flow rate levels lesser than 20mg/s, the background pressure is lower than $1 \cdot 10^{-5}$ mbar. As for the M, the operation with 7 cryo-heads resulted in significant lower values of the pressure (Figure.13).

The performance comparison of the M configuration is shown in Figure 14 and Figure 15. The filled marks refer to operation before the upgrade. As it can be seen, regardless of the discharge voltage, lower pressure levels resulted in lower values of specific impulse, due to lower collected current and measured thrust. Consequently, the efficiency was always lower (Figure 15). However, it must be said that no magnetic field optimization was carried out.

The maximum pumping capability was then used during the testing the S configuration. As shown in Figure 16, the maximum measured pressure was about $3 \cdot 10^{-5}$ mbar with anode mass flow rates levels of about 60mg/s.

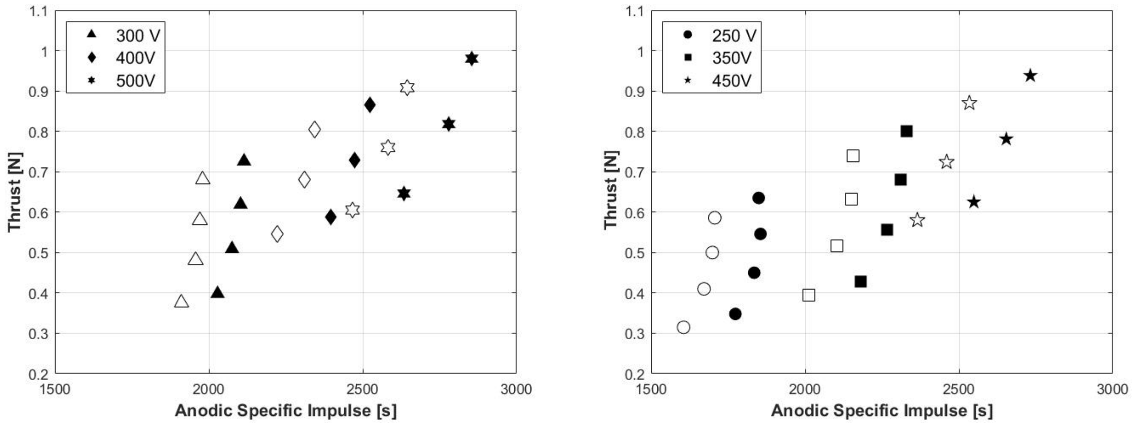

Figure 14 HT20k M performance map comparison between 5 and 7 cryo-heads, filled marks refers to operations before the facility upgrade, no filter used.

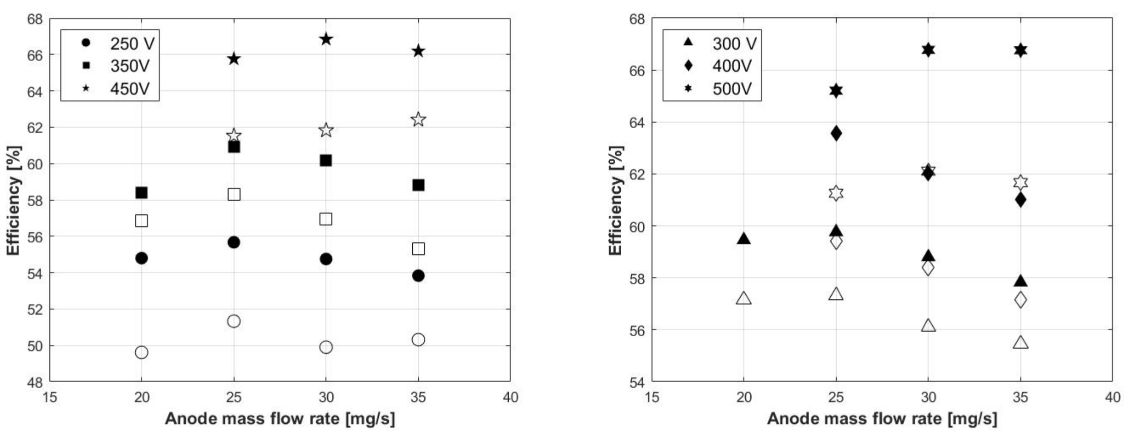

Figure 15 HT20k M, anodic efficiency comparison between 5 and 7 cryo-heads, filled marks refers to operations before the facility upgrade, no filter used.

V.Conclusion

This paper presents a summary the status of test activities in progress on SITAEL's HT20k Hall propulsion system. A magnetically-shielded development model of the thruster labelled HT20k DM2 was designed and manufactured. After a first experimental campaign in the second half of the 2018, the pumping system of IV10 vacuum facility was upgraded and a filter unit was designed and manufactured. Thanks to the filter, it was possible to have stable operation of the thruster up to 22.5kW of discharge power, from 300 to 450V of discharge voltage. The back-sputtered deposition rate measured by two QCM sensors was in the order of 4-13 µm/kh, depending on the sensor position.

During a dedicated thermal steady state test at 300 V and 20kW of discharge, the order to characterize the thruster performance for different geometric configurations (M, L and S). After a preliminary temperature at the back of the thruster ranged from 320 to 360 degrees Celsius.

An extra characterization at fixed anode mass flow rates highlighted that, for the M configuration, lower performance levels were recorded after the facility upgrade, highlighting the fact that the neutral ingestion may have an important role in the acceleration process of high power magnetically shielded hall thrusters.

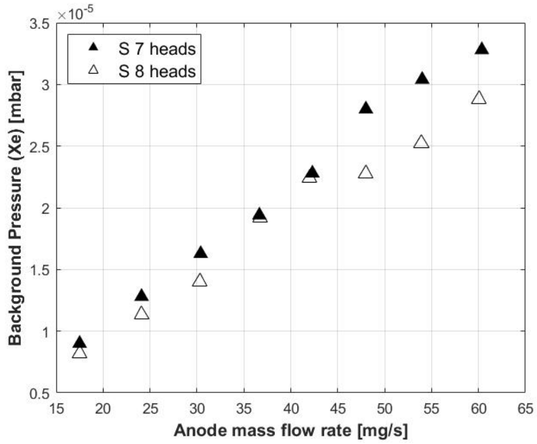

Figure 16 HT20k S, background pressure comparison between 7 and 8 cryo-heads.

Results of the other two configurations at different background pressures and further measurements will be presented in future works.

In addition to this, it must be highlighted that a new HT20k engineering model was designed and manufactured implementing the lesson learned from the experimental campaigns on SITAEL's HT5k LL [6,8] and HT20k Hall Thrusters. The new EM will be extensively characterized in the frame of the on-going development programmes [2, 3, 7].

Activities aimed at upgrading the existing facilities are currently ongoing with the objective to reduce time and costs associated to high-power EP development and qualification. Last, the foreseen environmental and wear tests will strongly contribute to the qualification of the thruster unit.

Acknowledgments

The authors wish to express their gratitude to Ugo Cesari, Nicola Giusti, Luca Pieri, and Carlo Tellini for their valuable assistance in preparing and performing the experimental campaign, Luciano Milaneschi for supervising the upgrades of IV10 vacuum facility and Raffaella Lorenzoni for the procurement of the thruster and cathode components. A special acknowledgement to Giulia Becatti, for the fruitful discussions about high current hollow cathodes. The work described in this paper has been funded by the European Union under H2020 Programme CHEOPS-GA 730135 and E3P ExPeRT Programme, Contract 4000123396.

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