HT5k Thruster Unit Development History, Status and Way Forward

IEPC-2019- 878

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

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Abstract: Since 2013 SITAEL has been developing its 5kW class Hall thruster unit, the HT5k-TU, composed of the HT5k thruster and the HC20 hollow cathode. Through several supporting projects, the thruster unit has undergone three design iterations and is now in the Engineering Model definition phase. During the thruster unit evolution, multiple test campaigns were performed including characterization tests, magnetic field topology optimization for life extension, tests with alternative propellants, assessment of direct drive operation, very low background pressure test, thermal cycling and endurance test, cumulating more than 700hrs of firing on the HT5k-TU thruster family. Extensive performance optimization tests showed competitive performance and demonstrated stable and efficient thruster operation in the 3 kW to 7 kW discharge power range, achieving anodic efficiencies up to 60%. Moreover, the successful implementation of magnetic shielding of the channel walls eliminates the failure mode linked with channel erosion and implies close-to-zero variation of the performance throughout life, making the HT5k-TU an ideal candidate for demanding high power commercial and scientific mission scenarios. Recently, the HT5k-TU was selected to embark on a qualification and flight campaign for the Ital-GovSatCom programme, aimed at the development of an Italian national GEO satellite. This paper presents the development history of the HT5k-TU, including an overview of all tests performed and how they have guided the thruster unit design. Moreover, the roadmap to achieve qualification of the thruster unit is presented and discussed.

I.Introduction

The interest towards the application of Hall thrusters for a wide variety of space mission scenarios has raised in the past years. Thanks to their versatility of operation, high efficiencies and power-to-thrust ratios, Hall thrusters can be considered as one of the most promising options for in-space electric propulsion.

From a commercial perspective, thrusters of power levels neighboring 5 kW are particularly interesting due to their employment in the electric orbit raising and station keeping phases of telecommunication GEO satellites. Moreover, several emerging mission scenarios may considerably benefit from an electric propulsion system capable of highly-efficient operation at power levels ranging from 3 to 7 kW, including navigation satellites, LEO-to-Cislunar

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Space tugs, in-orbit servicing, and advanced launchers provided with an all-electric upper stage for satellite constellation deployment and payload injection to lunar and cislunar orbits. Finally, with the maturity level this technology has reached, exploration and scientific missions, such as Mars Sample Return, are currently considering high power electric propulsion as the main propulsion system, exploiting the high specific impulses these thrusters can provide to reduce the required propellant mass to achieve the mission objectives.

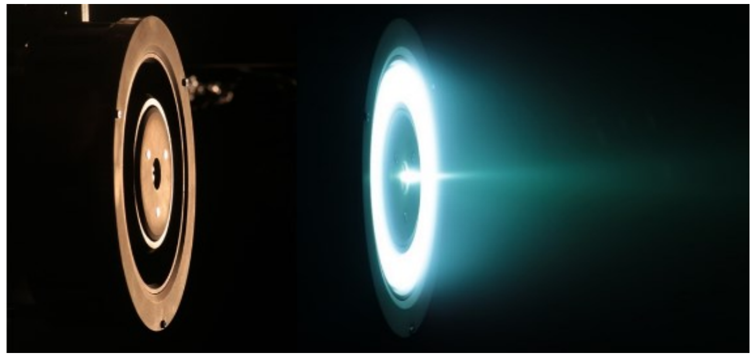


Figure 1. HT5k-TU on the thrust stand (left) and firing (right).

Foreshadowing the increase in interest for this class of thrusters, SITAEL has been developing its 5 kW thruster unit, the HT5k-TU, since 2013. Since then, going through multiple test campaigns and design iterations, SITAEL has cumulated significant heritage on the design and operation of low-erosion 5 kW-class thrusters. SITAEL's HT5k-TU is a high-power Hall thruster unit designed to operate in the 3 to 7 kW range (see Figure 1). The HT5k-TU can be operated in a wide range of operating conditions that span from the High Thrust Mode, suitable for orbit insertion, raising or repositioning, to the High Specific Impulse Mode, typically used for station-keeping applications. The HT5k-TU is composed of two main elements: the HT5k Hall thruster and the HC20 Hollow cathode. Recognized as a critical component of the thruster unit, the cathode has been developed in parallel to the thruster since its inception. Table 1 reports the specifications of the HT5k Thruster unit, as well as the flow down to the HC20 cathode.

HT5K TU Specifications	
Mass flow rate (including cathode)	9 – 24 mg/s
Discharge power range	2500 – 7500 W
Thrust	120 – 410 mN
Specific Impulse (total)	up to 2300 s
Voltage Range	250 – 500 V
Mass	10.5 kg
Lifetime (estimated)	> 15 MNs

HC20 Specifications	
Current Emission	8 – 25 A
Keeper Current	≤ 4 A
Heater Current	≤ 12 A
Heater Power	< 140 W (during ignition)
Mass Flow Rate	0.5 – 2 mg/s
Ignition Voltage	< 200 V
Number of Cycles (estimated)	> 10000

Table 1. (Left) HT5k-TU and HC20 DM3; (right) design specifications for the HT5k-TU and the HC20.

Today, the design of the HT5k-TU Engineering Model is in its final phases and the thruster unit has reached a level of maturity sufficient to embark on a qualification campaign targeting flight in the early 2020s. In fact, the HT5k-TU was selected as the main propulsion unit for the Ital-GovSatCom programme, aimed at the development of an Italian national GEO satellite platform. As part of these activities, the thruster unit will undergo full qualification in parallel with the SITAEL-developed 5 kW PPU.

This paper presents the history of the HT5k-TU development, the current status and the roadmap to qualification. Specifically, Section II describes the various design iterations that the thruster unit has gone through, summarizing the various test campaigns performed and highlighting the main results. Finally, Section III presents the way forward and discusses the scheduled steps to achieve qualification.

II.HT5k Development and Test History

In 2013, SITAEL decided to internally fund a development programme to produce a 5 kW-class Hall thruster unit in order to tackle the emerging market of high power electric propulsion. This effort led to the production of the first development model (DM1) of the HT5k thruster and HC20 cathode. Since then, the HT5k TU has undergone two additional design iterations (DM2 and DM3) as part of several national and international projects, cumulating more than 700 hours of firing with xenon and more than 700 hours of firing with alternative propellants. In particular, the thruster unit has been extensively characterized:

- over a very wide range of operating conditions (250-600 V, 2.5-7.5 kW), to optimize its performance and stability from low to high voltage and power levels,
- with long duration firings (up to 250 hours of continuous firing) to demonstrate the low erosion rates and the thermal steady-state behavior,
- under multiple levels of background pressure down to 7E-6 mbar (Xe), to study the effects of high vacuum on performance and stability,
- with different magnetic field configurations to maximize performance and lifetime,
- with multiple cathode positions to evaluate the effect of internal vs external configurations,
- with alternative propellants (krypton, Xe/Kr mixtures and N_2/O_2 mixtures),
- in direct-drive mode, coupled with a solar-array simulator.

A summary of the various development projects that supported the development of the HT5k-TU is provided in Table 2, together with a summary of the main tests performed.

Programme	**Test Facility**	**Model**	**Objective**	**Performed Tests**	**Ref.**
High Power Hall Thruster Development (internal)	IV10	DM1	Develop and test the first iteration of the HT5k-TU.	• Magnetic optimization. • Performance Characterization test.	1, 2
Identification, Evaluation and Testing of Alternative Propellants for Electric Propulsion Systems (ESA ARTES 5.1 4000113792/15/NL/NR)	IV10	DM1	Evaluate thruster performance and lifetime with Kr and Xe/Kr blends.	• Performance Characterization test. with Kr and Xe/Kr blends. • 500 hours endurance test with 75%Kr/25%Xe blend. • 150 hours endurance test with Kr.	3-6
Low Erosion Long Life Hall Effect Thruster (ESA TRP 4000113279/14/NL/KML)	IV4 & IV10	DM2 & DM3	Investigate the effect on performance and erosion of the magnetic field topology and optimize the design of a long-life thruster.	• Performance characterization of three different magnetic topologies. • 250 hours endurance test. • Krypton test of magnetically shielded thruster.	7-12
Assessment Of Key Aerothermodynamics Elements For A RAM-EP Concept (ESA TRP 4000113278/14/NL/SW)	IV4	DM1	Evaluate thruster behavior when fed with atmospheric propellant (ancillary objective of the project).	Characterization of the HT5k-TU with N_2/O_2 mixtures as propellant.	13-15
Experimental Investigation of a Direct-Drive Hall Effect Thruster System (ESA TRP 4000117884/16/NL/PS)	IV10	DM3	Demonstrate and optimize the operation of Hall thrusters in Direct drive mode.	• Coupling test with a solar array simulator. • Performance characterization in direct drive mode.	16

Programme	Test Facility	Model	Objective	Performed Tests	Ref.
Assessment of Critical Technologies (internal)	IV4 & IV10	DM3	Evaluate the effectiveness of multiple design improvements in terms of performance and lifetime. De-risk tests on critical elements of the TU.	Performance characterization to verify design upgrades of thruster and cathode critical components. • External vs central cathode position, • 4 different anode design solutions, • 3 different cathode designs, • Low erosion magnetic poles, • Upgraded geometry Magnetic Screen, • Upgraded geometry Ceramic Channel, • Custom anode voltage break.	17
VEnUS (VEGA development programme)	IV10 (upgraded)	DM3	Investigate the use of a 5kW HT on an electric upper stage for the VEGA launcher.	• Reference performance Test (4.4kW and 5.3kW 300V). • Very low background pressure test • Wear Test. • Thermal Cycling Test.	-

Table 2. Summary of projects and test activities on the HT5k-TU family.

Figure 2 presents the entire development history of the HT5k-TU thruster family where all the relevant projects are highlighted against the development timeline and a very brief summary of the related activities.

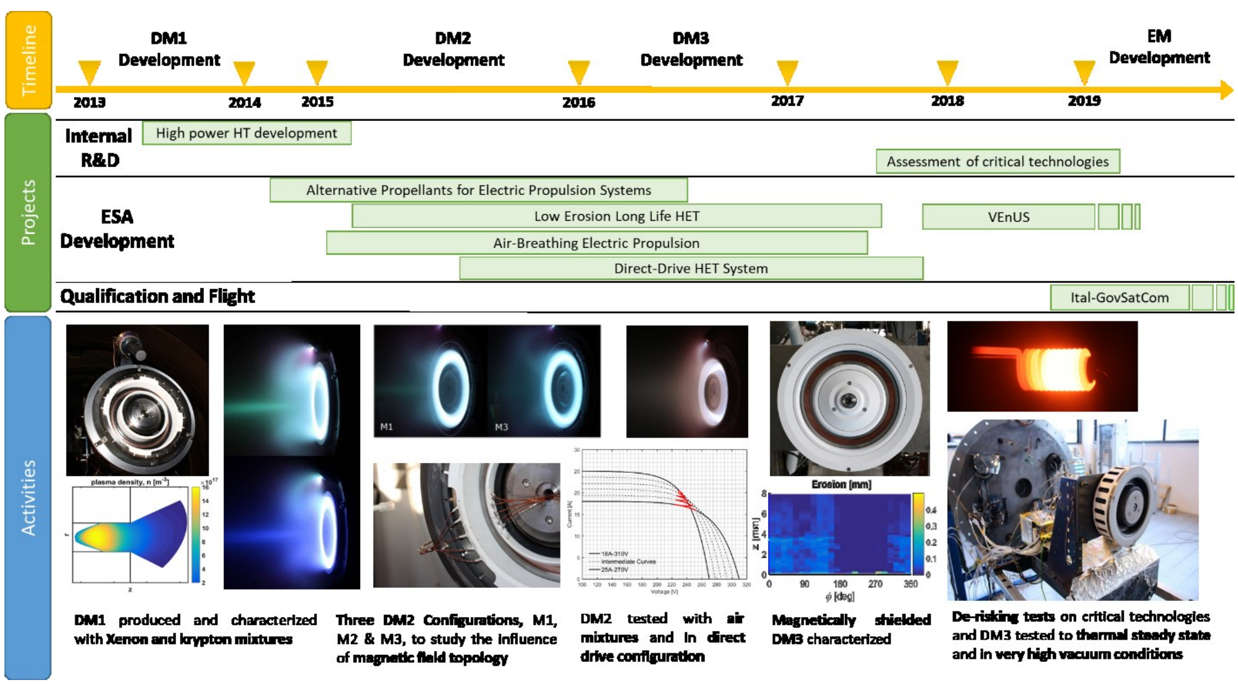
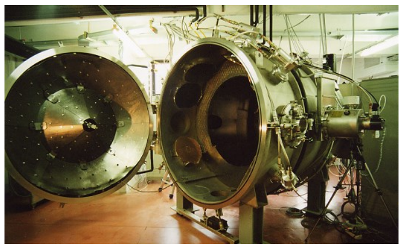


Figure 2. HT5k-TU Development history, including timeline, supporting projects and main activities.

All tests on the HT5k-TU described in the present paper where performed in SITAEL's two largest vacuum facilities, IV4 and IV10, according to Table 2. Both chambers are equipped with an extensive set of diagnostics, including an in-house-developed thrust balance and a moving set of faraday probes to investigate the plume properties and divergence angle. Additionally, fast moving Langmuir probes can be installed and used in both chambers to investigate the plasma properties inside the thruster. An in-house-developed Advanced Electric propulsion Diagnostic (AED) tool[8] is installed in IV10, capable of precise estimation of the erosion progression of the channel walls. The IV10 chamber also features multiple quartz crystal microbalances (QCM) to measure the back-sputter deposition rate. Finally, an ExB probe and a retarding potential analyzer (RPA), while not used for past tests, are currently being installed in the IV10 chamber. It is worth noting that the IV10 Vacuum facility is the largest vacuum chamber in Europe for electric propulsion testing and it ensures a high fidelity of the ground tests with the behavior of the thruster in orbit. The most relevant properties of the two vacuum chambers are presented in Table 3, observing that the pumping capabilities and diagnostic systems of IV10 were upgraded in February 2018.

IV4 vacuum facility



IV10 vacuum facility

	IV4 vacuum facility	IV10 vacuum facility: **Pre-upgrade**	IV10 vacuum facility: **Post-upgrade (Feb. 2019)**
Free diameter	1900 mm	5740 mm	
Free length	2500 mm	6000 mm	
Total leak rate	<10^{-4} mbar-l/s (GHe)	<10^{-4} mbar l/s (GHe)	
Pumping speed	45000 l/s (Xe)	320000 l/s (Xe)	**450.000 l/s (Xe)**
Ultimate pressure	$5 \cdot 10^{-7}$ mbar	$5 \cdot 10^{-7}$ mbar	
Operating pressure with 5kW TU firing	~ $1 \cdot 10^{-4}$ mbar (Xe)	~ $1 \cdot 10^{-5}$ mbar (Xe)	**~ $7 \cdot 10^{-6}$ mbar (Xe)**
Thrust balance	✓	✓	
Plume scanning (Faraday probes rack)	✓ (180° x 160°)	✓(180° x 180°)	
Channel Erosion diagnostics (AED)		✓	
Back sputter rate measurement (QCM)			✓
Optional: fast moving Langmuir probe	✓	✓	

Table 3. Main properties of SITAEL's vacuum facilities for high power testing, IV4 and IV10.

In the following, each design iteration of the TU is extensively discussed, and the results of the various test campaigns presented.

A. HT5k-TU Development Model 1

The first design iteration of the HT5k-TU (DM1) consisted of a classical SPT-like Hall thruster based on the scaling methodology developed in SITAEL in previous years[18] and building on the heritage gathered on thrusters of lower power levels. In this first iteration, the magnetic field topology was predominantly radial at the channel exit and the ceramic channel did not include any chamfer.

The TU featured the HC20 DM1 hollow cathode positioned externally with respect to the ceramic channel, held by a separate mechanical interface. The electromotive force needed to generate the quasi-radial magnetic field was provided by a set of four coils: two main coils (internal and external) and two trim coils to refine the topology in the near-anode and exit regions (see Figure 3).

In 2014, as part of an internal development project, a wide experimental investigation of the performance of SITAEL's HT5k-TU operating with xenon was performed in the IV10 vacuum facility. The thruster unit was characterized at discharge voltages from 250 V up to 600 V for anode mass flow rates between 5 mg/s and 20 mg/s. A fixed cathode mass flow rate of 1 mg/s was used for all points tested.

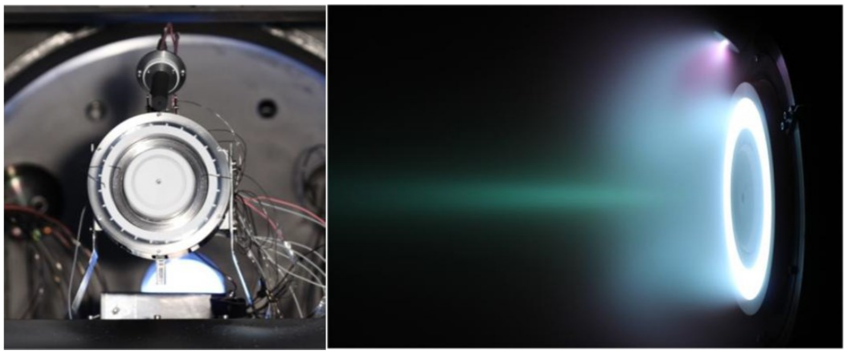


Figure 3. The HT5k thruster on the thrust stand (left) and during operation with xenon (right).

The magnetic field was optimized by means of all four available magnetic coils. During the optimization of the magnetic field, no notable effect on the thruster performance due to the activation of the behind-anode trim coil was observed. Whereas effect from the outer trim coil was significant and allowed to increase thruster performance up to 10% depending on the operational regime. Only one optimized configuration of the magnetic field topology was applied for all studied operation points. Figure 4 presents the thruster performance obtained during the test campaign. The maximum value of thrust of 396 mN was demonstrated at a power level of 7245 W with Vd=350 V and AMFR=20 mg/s, whereas highest specific impulse was obtained at a power level of 5850 W with Vd=600 V and AMFR=10 mg/s.

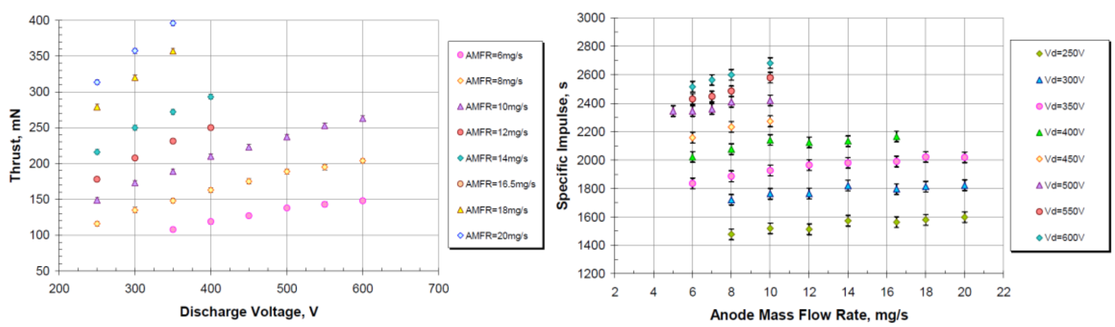


Figure 4. HT5k-TU DM1 characterization test results.

The test campaign also included the measurements of the plume divergence angle on every point tested and the evaluation of the thermal transient and steady state condition through the employment of multiple thermocouples and an IR camera. Ref. 1 gives more details on the results.

Following the first characterization campaign, the HT5k-TU DM1 was used to investigate the effect on performance and lifetime of the use of alternative propellants, specifically krypton and various xenon/krypton mixtures (see Figure 5), as part of the ESA ARTES 5.1 "*Identification, Evaluation and Testing of Alternative Propellants for Electric Propulsion Systems*" project[3].

The thruster was operated with pure krypton and three different xenon/krypton mixtures with 75%, 50% and 25% of krypton in a wide range of discharge voltages (250-600 V) and powers (2-7 kW). The discharge was stable within the entire operating envelope covered during the test. In addition, thanks to the two auxiliary coils, the magnetic field of the thruster was optimized during the test for different conditions of discharge voltage, mass flow rate and type of propellant. The thruster was capable of reaching high thrust efficiencies even with

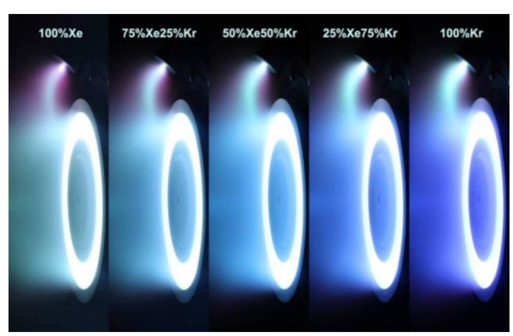


Figure 5. Near field plume region of the HT5k-TU operating with different mixtures.

pure krypton as propellant. In this case, for most of the investigated points, the anodic thrust efficiency was in the range 40%-50%. For high voltage operation points (up to 600 V), thrust efficiency has reached values slightly higher than 50%. Values of the anodic specific impulse higher than 2000 s were found for most of tested operating points with maximum values close to 3000 s (see Figure 6).
In general, with the transition from pure xenon to pure krypton, the maximum of the thrust efficiency shifted towards higher power levels. For pure xenon, the maximum was found near the 4000-4500 W power range, whereas for pure krypton, and for all mixtures, the thrust efficiency grows for power levels higher than 6500 W. Plume measurements indicated that beam divergence calculated for 95% of registered ion current density was in a range of 35-37 degrees for pure xenon and 38-42 degrees for pure krypton. As expected, values of beam divergence for xenon/krypton mixtures depends on the amount of krypton in the mixture: the higher the percentage of krypton in the mixture, the higher the beam divergence.

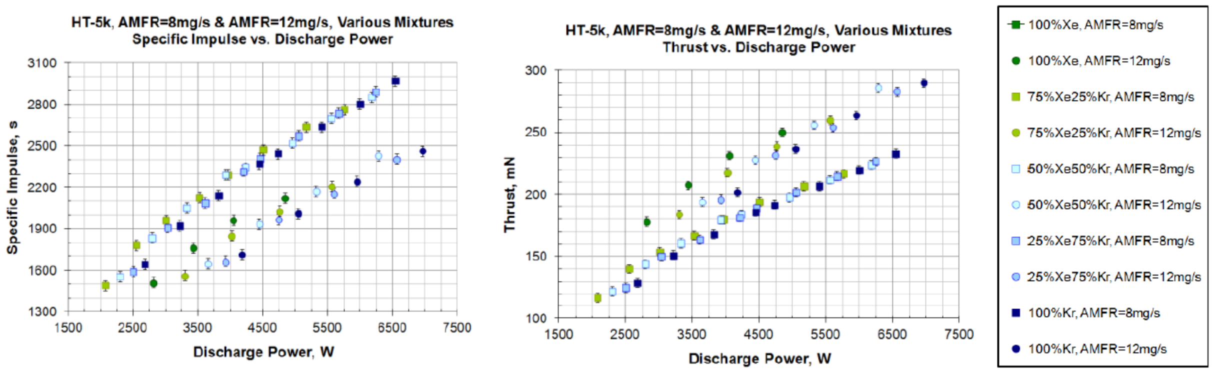


Figure 6. Specific impulse (left) and thrust (right) as functions of discharge power for various mixtures at different mass flow rates.

Following the performance characterization, a second test campaign was performed, focusing on the investigation of the effect of the adoption of alternative propellants on the erosion and lifetime of Hall thrusters[4,6].

The test campaign was composed of two phases: first, the thruster operated for 33 hours with pure xenon at 4.5 kW of discharge power and a discharge voltage of 350 V, whereas in the second phase the thruster operated for 500 hours with a mixture of 25% of xenon and 75% of krypton in the same operating point (4.5 kW/350 V). The thruster performance remained stable during the whole test. The measurements performed in the two test phases allowed to characterize the progression of wall erosion and, in particular, the effect of the selected alternative propellant on the thruster lifetime. The wall profiles, measured at different azimuthal positions by means of the AED system, allowed for the assessment of the channel walls erosion and the identification of its angular variation. Erosion measurements were performed at the beginning of the test campaign, after the 33 firing hours with xenon and at regular intervals during the 500 hours firing with the alternative propellant. In particular, the thruster was switched off every 30-50 hours to perform performance and erosion measurements (see Figure 7).

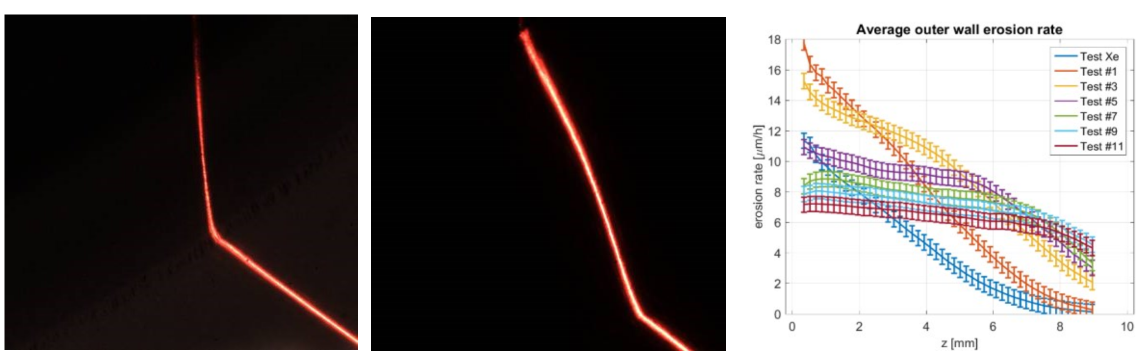


Figure 7. Outer channel wall profile at the beginning of the tests (left) and at the end of the campaign (middle). Average erosion rate measurement at multiple points of the endurance test (right).

The comparison between the erosion rates measured during phase 1, i.e. for pure xenon, and at the beginning of phase 2, after approximately 30 hours of operation with the Xe/Kr mixture, shows a significant increase of the wall erosion. In order to highlight the effect of the propellant, we compared the total impulse I_{tot} of the two operating conditions. Given the thruster configuration and considering the thruster lifetime to be inversely proportional to the erosion rate at BOL, the ratio between the total impulses, with xenon and with the mixture, results

$$\frac{I_{tot}^{Xe}}{I_{tot}^{Mix}} \approx 1.82\,.$$

An additional mini-endurance test of 150hrs was then performed with pure krypton as propellant, highlighting an analogous trend. The reduction of total impulse for standard thruster configurations when the thruster operates with krypton, or with Xe/Kr mixtures, thus represents a fundamental factor for the development of EP systems based on such alternative propellants.

The full test campaign and discussion can be found in refs. 3-6, while a set of analyses concerning the system level implications of adopting alternative propellants based on the measured data is presented in ref. 5.

The behavior of high-power Hall thrusters with alternative propellants was further investigated as part of the "*Assessment of Key Aerothermodynamics Elements For A RAM-EP Concept"* project. The results successfully demonstrated, for the first time worldwide, the operation of an air-breathing electric propulsion thruster in a representative environment. In the framework of this project, the HT5k-TU DM1 was used as a Particle Flow Generator (PFG) to recreate the low-density high-speed atmospheric flow that the RAM-EP thruster was expected to encounter during operation. In the process the DM1 was, therefore, characterized with a $1.27N_2 + O_2$ mixture as propellant for the thruster (the cathode was operated with xenon for material compatibility issues). Specifically, the following activities were performed during the PFG preliminary test:

1) Verification of the operation with Xe for very low input mass flow rates;
2) Xe to N_2-O_2 mixture transition investigation;
3) Magnetic characterization;
4) Voltage sweep characterization;
5) Mass flow rate sweep characterization:
6) Final operating point investigation for RAM-EP concept validation.

The test campaign was successfully completed and the thruster reliably ignited with the selected nitrogen/oxygen mixture. Figure 8 shows a picture of the DM1 firing with the $1.27N_2 + O_2$ mixture and reports the performance measured for the operating point identified as the most suited for the PFG. An exhaustive discussion on the tests is outside of the scope of the present paper and can be found in ref. 13-15.

HT5k-TU DM1 Operating as PFG	
Discharge Voltage	300 V
Anodic Mass Flow Rate	5 mg/s
Discharge Current	8 A
Discharge Power	2.4 kW
Thrust	65 mN

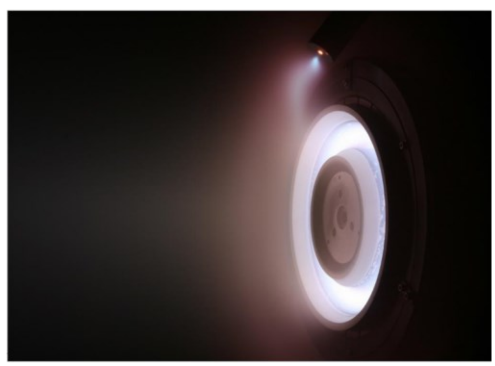


Figure 8. HT5k-TU DM1 operating with atmospheric propellant, measured performance (left) and thruster firing (right).

Ultimately, the first development model of the HT5k-TU has demonstrated SITAEL's capabilities in producing a highly competitive 5kW class Hall thruster system with standard magnetic topologies and has allowed gaining significant insight in the design and operation of these thrusters with alternative propellants such as Kr/Xe mixtures and N_2/O_2 mixtures.

B. HT5k-TU Development Model 2

One of the main lifetime limiting factors in standard Hall thruster technology is the erosion of the channel walls due to sputtering from high-energy ions. In fact, the analysis of Hall thruster qualification campaigns and endurance tests has shown a substantial degradation of the ceramic channel walls. However, after an initial phase of high erosion rate, the wear process progressively reaches a saturation condition[19,20]. This prompted the analysis of non-standard magnetic field configurations aimed at drastically increasing the thruster lifetime. The concept of magnetic shielding, discussed in refs. 21 and 22, is a promising approach to overcome the limitations of traditional thruster configurations, without significantly reducing the thruster performance.

The ESA project "*Low-Erosion Long-Life Hall-Effect Thruster*" (LLHET), was specifically aimed at investigating the effect of different magnetic field topologies and channel geometries on the performance and erosion of Hall thruster to ultimately design, build and test, an optimized thruster model.

The activities started with the implementation and validation of a series of design modifications on the former, unshielded 5kW-class Hall thruster (the DM1) to create a flexible thruster model capable of achieving full-magnetic shielding capabilities (the DM2). As an output of the project, an optimized magnetically shielded HT5k thruster (the DM3) was realized, tested and validated (see section C). The HT5k-TU DM2 is, therefore, equipped with a flexible magnetic circuit and a chamfered channel. This thruster allows the characterization of a continuous spectrum of magnetic field configurations, ranging from standard topologies to completely magnetically shielded ones. In the framework of the LLHET project, three configurations of the magnetic field were identified (see Figure 9). The main difference between the three configurations is in the position of the radial magnetic field peak with respect to the channel exit. To distinguish each configuration, we considered the magnetic line tangent to the channel chamfer, the so-called grazing line, and the one corresponding to the peak of B_r on the centerline and we introduced the parameter $\kappa = \lambda_{grz}/\lambda_{peak}$. This parameter represents the fraction of the magnetic flux bounded by channel walls and enclosed between the anode and the magnetic field peak. Standard magnetic field configurations are characterized by $\kappa = 1$, whereas magnetically shielded configurations have κ close to zero.

The first thruster configuration, named M1, presents the same magnetic field topology of the HT5k-DM1, with the only difference of the chamfered channel, which simulates conditions close to the end-of-life of the thruster, $\kappa \cong 0.8$. In the second configuration, the M2, the magnetic peak is moved further out of the channel, with $\kappa = 0.5$, in order to test intermediate conditions. Finally, the M3 implements full magnetic shielding and, consequently, has $\kappa = 0$.

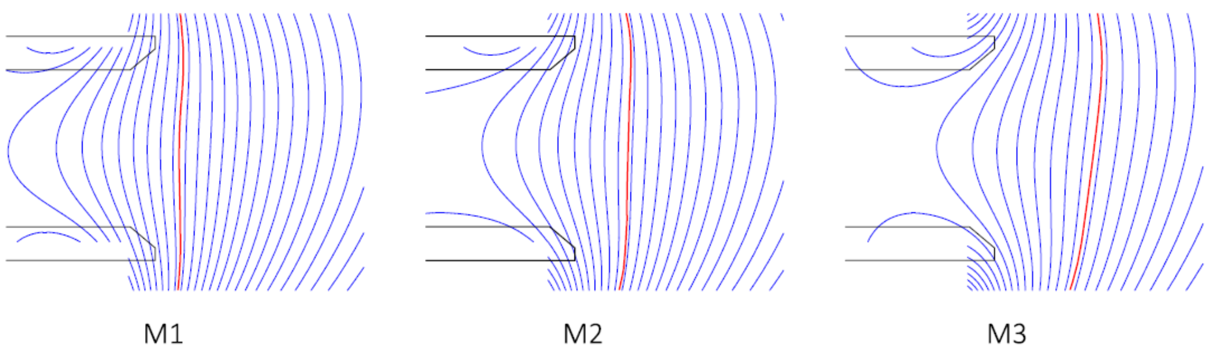


Figure 9. Investigated configurations of the HT5k DM2 thruster (The red line indicates the magnetic field line corresponding to the peak of the magnetic field on the channel centerline*).*

The M1, M2 and M3 DM2 variants were designed and the relevant components procured and assembled. For each configuration, a mapping of the magnetic field in the channel and near plume was performed to ensure that the final outcome was compliant with the designed magnetic field[11].

In parallel to the thruster development, a quasi-2D numerical model of the plasma behavior inside Hall thrusters with non-standard magnetic field topologies was developed in order to help gather insight on the influence of the selected configurations on the thruster behavior. The results for the plasma density in the M1 and M3 configurations are presented in Figure 10 and all the details concerning the model formalism can be found in ref. 12.

Figure 10 also presents a comparison of the plume shape of the M1 and M3 configurations highlighting the effectiveness of magnetic shielding in detaching the high density, high temperature plasma region from the ceramic walls, minimizing the erosion rate.

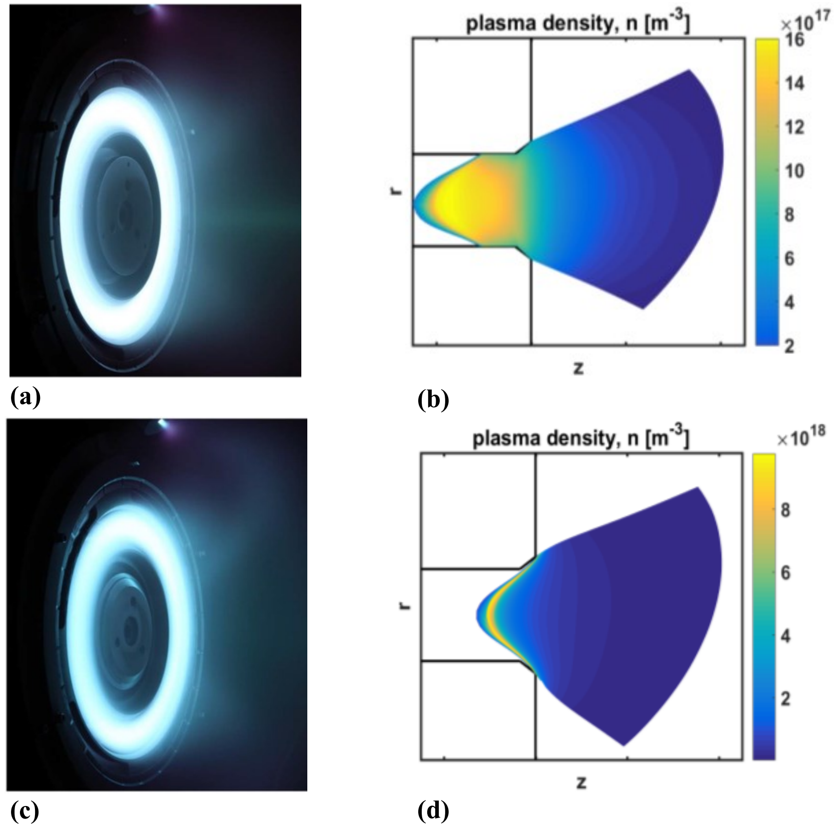


Figure 10. (a) DM2-M1 firing and (b) model prediction for plasma density distribution; (a) DM2-M3 firing and (b) model prediction for plasma density distribution.

The three configurations (M1, 2 and 3) were tested in relevant operating points in SITAEL's IV4 vacuum facility, employing an extensive set of diagnostic tools. The performance results presented in this paper cover 300 V of applied voltage and 4.5 kW of discharge power. For each configuration, the magnetic field peak value along the channel centerline was kept constant.

Table 4 reports the performance results obtained for the three configurations, comparing the measurements with the model's predictions.

	Mass flow rate [mg/s]	***Discharge Power [W]***	***Thrust [mN]***	***Specific impulse [s]***	***Thrust efficiency [%]***	***Plume divergence [deg]***
DM1	15.0 ± 0.1	4425 ± 33	263 ± 5 (269)	1790 ± 50 (1826)	0.52 ± 2.5 (0.54)	*37±0.1*
DM2-M1	14.1 ± 0.1	4400 ± 33	255 ± 5 (259)	1840 ± 50 (1871)	0.52 ± 2.5 (0.54)	*46±0.1*
DM2-M2	13.3 ± 0.1	4550 ± 33	237 ± 5 (251)	1830 ± 50 (1820)	0.47 ± 2.5 (0.49)	*55±0.1*
DM2-M3	*13.9 ± 0.1*	*4525 ± 33*	*257 ± 5 (260)*	*1870 ± 50 (1924)*	*0.52 ± 2.5 (0.55)*	*46±0.1*

Table 4 Performance of all thruster configurations. For all configurations, the applied voltage is 300 V. Simulation results are reported in brackets.

The comparison shows that no significant degradation of the performance can be observed in the M3 configuration, whereas a clear degradation of the performance was assessed, both numerically and from the experiments, in the M2 configuration. It can be noticed that using a shielded configuration (M3) implies an increase of the plume divergence. However, this increase seems comparable with that of the thruster end-of-life condition (M1).

In order to assess the influence of the magnetic topology on the near-wall plasma conditions and erosion, the ceramic channel was equipped with a set of 16 Langmuir probes embedded in the ceramic and flush with the walls. The probes were distributed on the internal and external walls at different azimuthal and axial locations (see Figure 11).

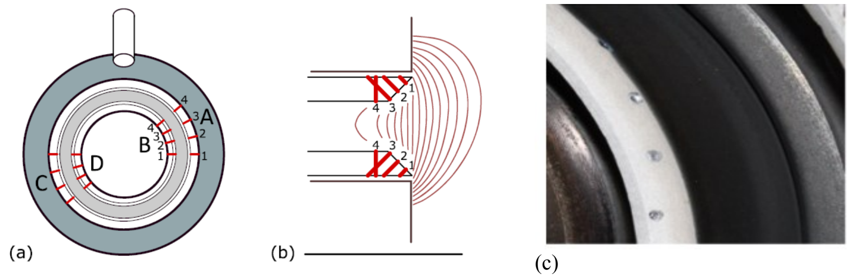


Figure 11. Distribution of the langmuir probes: (a) azimuthal distribution; (b) axial distribution; (c) photo of the manufactured.

The near wall plasma properties are shown for the M1 and M3 configurations in Figure 12, averaged with respect to the two azimuthal probe sets, both for the inner and outer walls. In agreement with the magnetic shielding approach, the translation of the magnetic field peak outside of the channel corresponds to a decrease of the electron temperature near the walls. In particular, the electron temperature of the HT5k-M3 configuration is below 10 eV at the walls. Such low temperatures, in a region where instead the plasma potential is high and close to the applied voltage, imply low ion energies in the near wall region and, consequently, low sputtering. The effectiveness of magnetic shielding in minimizing the erosion is also corroborated by the fact that after the test the M3 channel was covered in back sputter from the chamber.

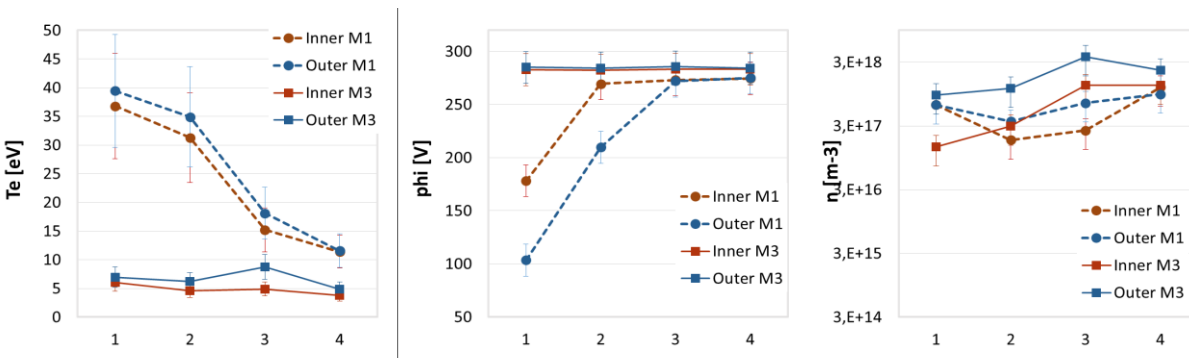


Figure 12. Plasma properties obtained from wall probe measurements for M1 and M3 configurations.

Moreover, a triple Langmuir probe was mounted on a fast-moving articulated arm (see Figure 13) to measure the electron temperature, plasma potential and density along the channel centerline. The arm rapidly inserts and extracts the probe from the thruster. Since a triple Langmuir probe requires neither any voltage sweep, nor switching, it allowed for the assessment of the plasma properties within short times, of the order of the probe response time. Three tungsten-rhenium wires (75% W and 25% Re) with a diameter of 0.178 mm were installed inside a 1/8-inch alumina tube. The electrodes were separated by a distance of ~2 mm in order to avoid any interaction and a length of 2 mm allowed having an adequate spatial resolution.

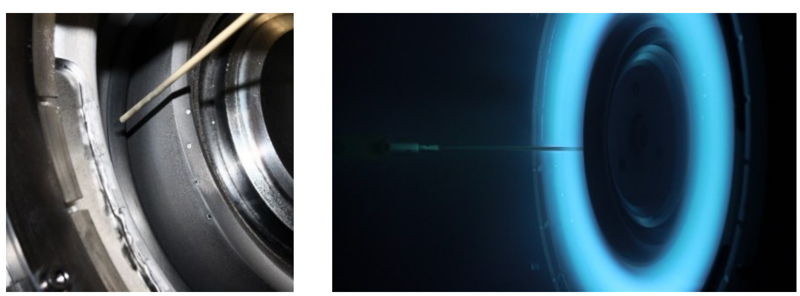


Figure 13. (left) triple probe in the M3 channel; (right) triple probe rapidly inserting in the channel during operation.

An extract of the data gathered with the fast triple Langmuir probe and processed with a Bayesian analysis for the configurations M1 and M3 is illustrated in Figure 14. On the horizontal axis it is reported the axial position of the probe with respect to the channel exit section, whereas the color map corresponds to the probability that a given value represents the measured plasma property and the red line represents the parameter value with the highest probability.

Due to the relatively low voltage applied between the electrodes of the triple Langmuir probe, a limit imposed by the setup, we obtained an accurate description of the plasma flow only in the regions with electronic temperatures below ~15 eV. It is however possible to assess, from the comparison of figures, that higher electron temperatures are measured in the M3 configuration. Moreover, in this configuration the region of high temperature extends outside the channel for a longer fraction of the probe trajectory.

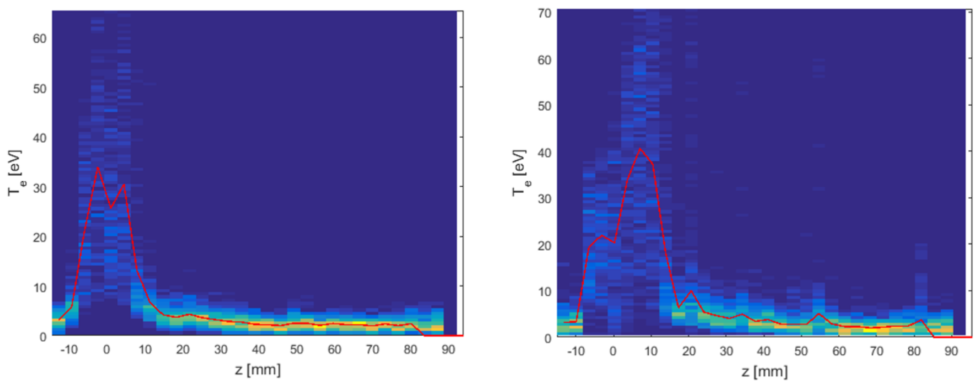


Figure 14. Electron temperature measurement with triple probe along the channel axis for the M1 (left) and M3 (right).

A full description of the tests performed and the gathered results for the test campaign of the three configurations of the HT5k-DM2 can be found in refs. 7-12.

Finally, the M3 was tested with krypton as propellant to understand the effectiveness of magnetic shielding when propellants different from xenon are employed (9). The performance evaluation shows that while performance can be maintained with xenon as propellant, in the case of krypton, low power operation shows that the shielded configuration presents a wider efficiency gap.

Wall probes measurements confirm that magnetic shielding is an effective way of reducing the erosion of the ceramic channel, as electronic temperatures are reduced and the plasma potential close to the wall remains constant and equal to the anodic value. However, magnetic shielding is less effective when krypton propellant is used as higher temperatures are achieved close to the channel exit. Krypton plasma showed a higher temperature peak, while density is lower than in xenon case. As expected, a larger ionization region was observed for krypton.

The DM2 allowed an unprecedented insight into the plasma behavior in Hall thrusters and the influence on performance and lifetime of non-standard magnetic field topologies. In turn, this heritage has guided the design of the magnetically-shielded DM3.

C. . HT5k-TU Development Model 3

In the frame of the ESA contract "*Long Life Low Erosion Hall Effect Thruster*", a new magnetically shielded Hall thruster unit, called HT5k-TU DM3, was designed and manufactured in 2016. Improvements were made by reducing the number of mechanical parts and independent coils with respect to the former HT5k development model. Moreover, the design was modified to allow for a centrally-mounted cathode[8].

Figure 15. HT5k-TU DM3 on the thrust stand.

From the beginning of the year 2017, the HT5k DM3 was extensively characterized in the IV10 vacuum chamber, with the HC20 hollow cathode[23], mounted externally with respect to the thruster. Afterwards, a 250-hour wear test at 300 V and 5 kW showed a significant reduction of the channel erosion with respect to the HT5k-TU DM1. Indeed, almost no variation in the channel inner wall profile was observed using the in-house erosion diagnostic (AED) system. On the outer wall, however, an azimuthal asymmetry in erosion was visible. This erosion asymmetry was most likely due to the external cathode position. However, the average erosion rate over the 250-hour wear test was less than 1 μm/hr, which is approximately an order of magnitude lower than that of the HT5k DM1, see Figure 16.

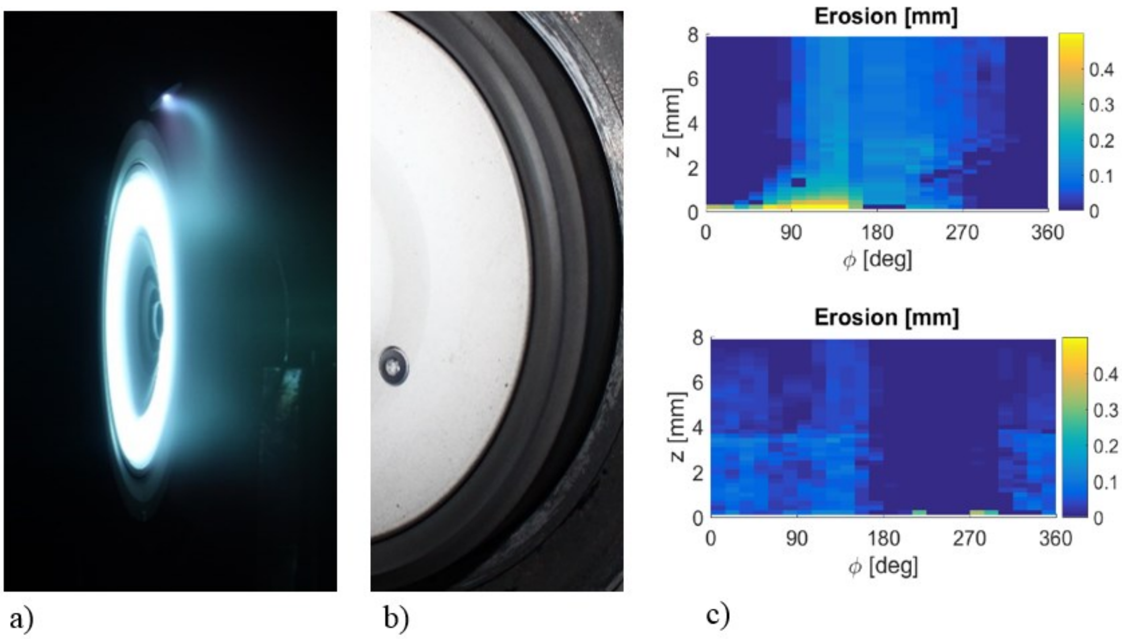


Figure 16. HT5k DM3 firing during the 250 hours wear test (a); detail of the ceramic channel after the 250 hours wear test (b); outer (top) and inner (bottom) channel measured erosion during the 250 hours wear test (c).

As Figure 17 shows, almost no variation in thruster performance during the endurance test at nominal operating point of 300 V and 5 kW was observed. After the wear test, the HT5k-TU underwent another characterization. In particular, it was found that the thruster performances at 300 V remained almost identical to those before the 250 hours firing. It is worth mentioning that, with the HC20 cathode mounted externally, the HT5k DM3 produced the same level of thrust with respect to the unshielded HT5k DM1 in the power range of 3 kW to 4 kW and at 300 V of discharge voltage. At 400 V, same levels of thrust were measured from 4 kW to 5 kW of discharge power. In these regions, the efficiency remained equal or greater with respect to the unshielded HT5k thruster[17]. Thus, the HT5k-TU DM3 showed that the implementation of the magnetic shielding effectively reduces the erosion of the channel without notably affecting the performance.

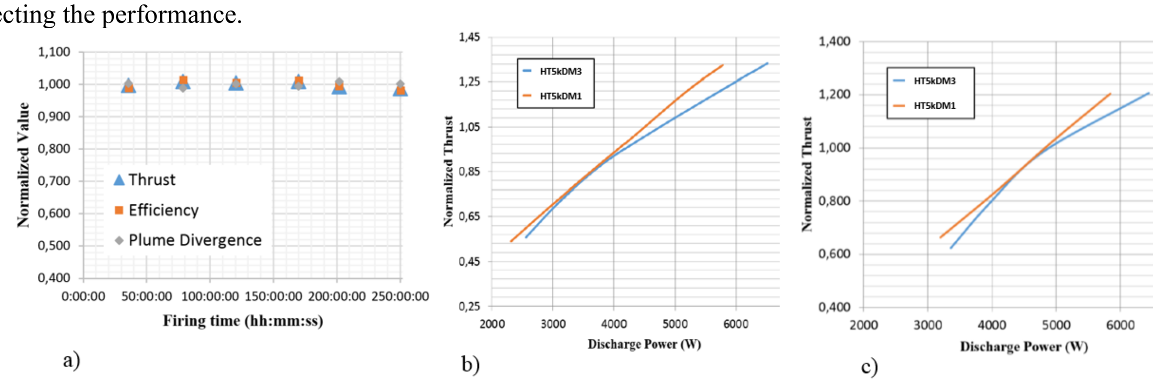
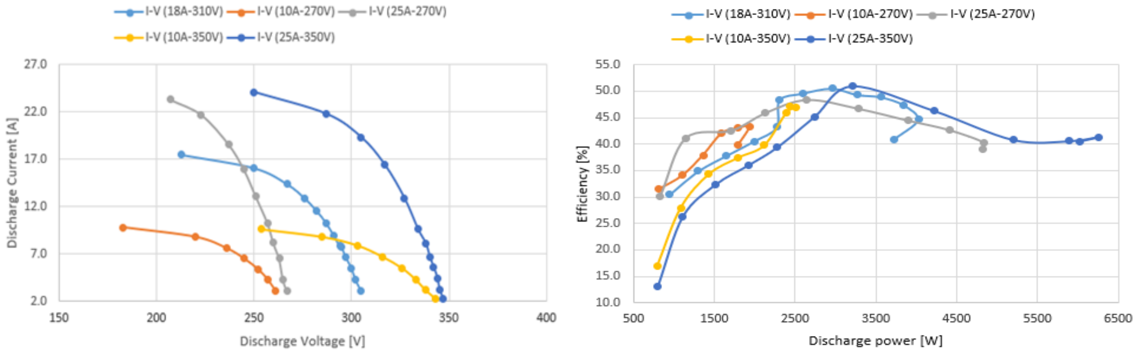


Figure 17. variations in thrust, anodic efficiency and plume divergence vs. hours of operation during the endurance test (a); HT5k DM3 vs HT5k DM1 normalized thrust at 300V (b) and 400V (c).

In October 2017 and within the framework of the ESA-funded *Experimental Investigation of a Direct-Drive Hall Effect Thruster System* programme, the HT5k-TU DM3 was connected to a solar array simulator (SAS) and tested at different operating conditions, see Figure 18. These activities were performed to verify the applicability of the Direct-Drive approach to the HT5k-TU, see refs. 16. Overall, no major deviations, neither regarding start-up transients nor regarding thruster stability, were found. In addition, three different control laws were implemented and were proven to be effective in controlling the thruster behavior with respect to representative variations in SAS characteristics.



a) b)

Figure 18. Set of the I-V curves implemented in the SAS (a) and thruster efficiency vs. discharge power for the tested operating points along the five characteristic curves (b).

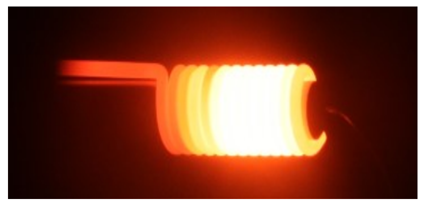


Figure 19. HC20 DM3 heater during thermal cycling.

The HT5k-TU DM3 was then developed as part of an internal development programme in order to investigate and optimize the most critical design and technological solutions in the thruster unit. First, an extensive thruster characterization for three different cathode technological solutions was performed throughout 2018. The main results were the definition of the optimal cathode emitter and orifice geometries, a significant thermo-mechanical improvement of the heater/keeper/emitter assembly design and the final selection of a central cathode as design baseline for the thruster. Several characterizations and cycling tests were performed on the HC20 cathode heater (see Figure 19). Figure 20 shows some of the significant experimental results obtained in these campaigns. In particular, it was shown that the use of a central cathode increases the total thruster efficiently by up to 5% with respect to an externally mounted cathode. More information can be found in ref. 24.

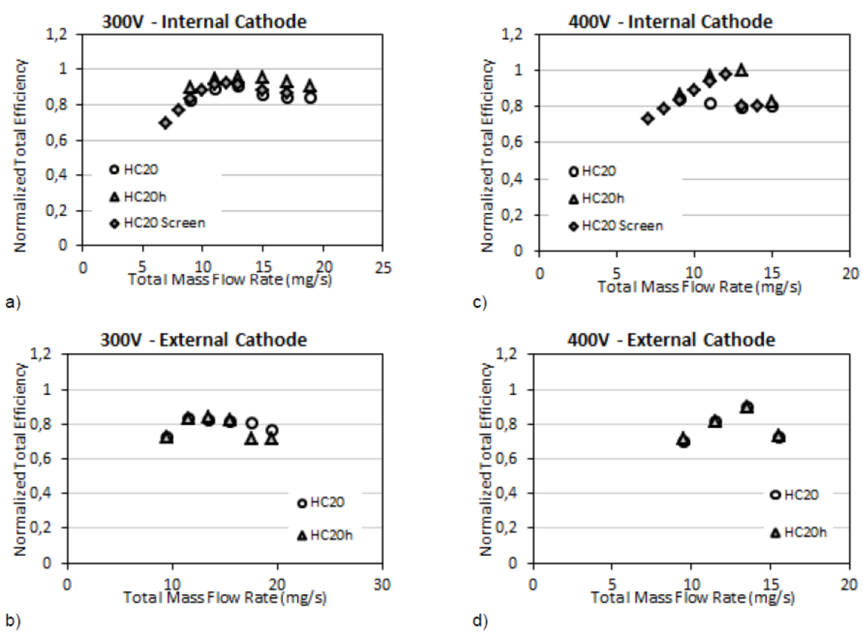
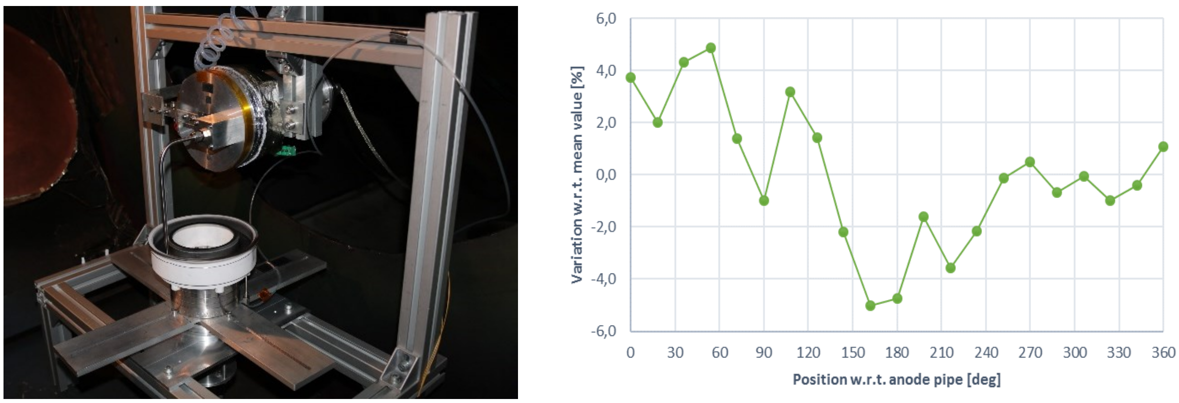


Figure 20. HT5k-TU DM3 normalized total efficiency at 300V with internal cathode (a), external cathode (b) and at 400V with internal cathode (c) and external cathode (d). Different markers identify different technological solutions in the HC20.

In parallel, the HT5k thruster development focused on increasing the robustness of the design of the most critical components. In particular, several anode design solutions and means of improving the electrical insulation of the anode propellant feeding line were extensively investigated.

Concerning the anode, it is well known how the azimuthal uniformity of the injected neutral flow has a direct consequence on the thruster performance and stability envelope. As Figure 21 shows, a dedicated test setup was realized and tested in IV4 vacuum facility to verify the propellant distribution uniformity of each of the designed and realized anode solutions. The setup comprised a rotating stage and a Pitot tube, allowing measuring the total pressure of the injected neutral flow at several angular positions. For an injected mass flow rate of 15 mg/s, the selected anode design showed a percentage pressure variation with respect to its mean value of less than ± 5%.

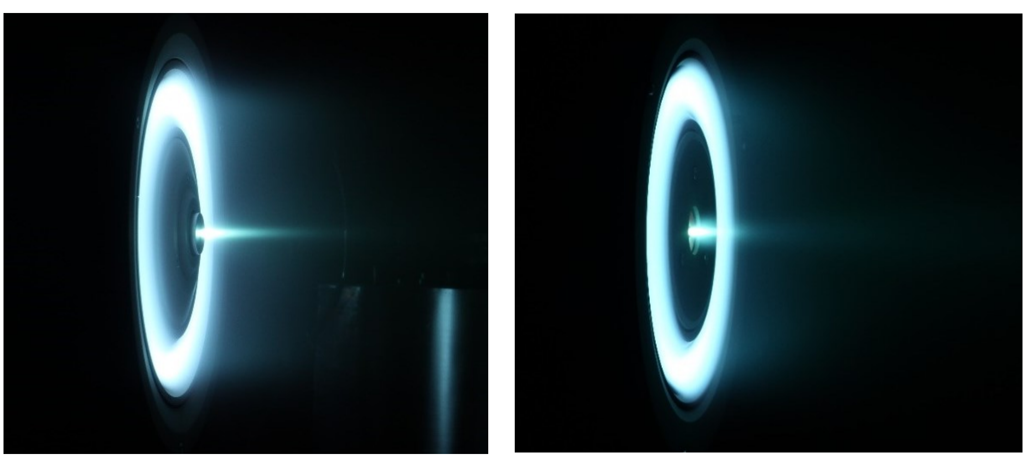


a) b)

Figure 21. Anode flow distribution test setup (a) and injected flow total pressure variation vs azimuthal position of the selected anode design operating at 15 mg/s (b).

Concerning the insulation of the anode fluidic line, the breakdown behavior of several COTS voltage breaks was characterized. The collected data were used to design a custom voltage breaker, in which the critical metal-ceramic welding process are avoided while maintaining the voltage isolation characteristics and extremely low leakage rates.

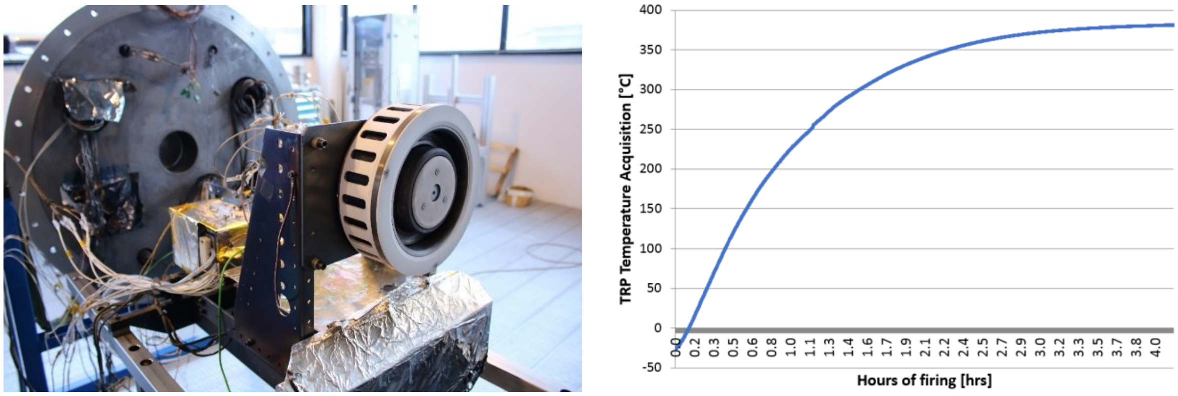
After the successful verification of all the critical components by means of extensive thruster characterizations, the HT5k DM3 magnetic circuit was modified to obtain a more refined magnetic field topology, with the specific objective of reducing the pole erosion, identified as a critical phenomenon in magnetically/shielded thrusters. In particular, the following thruster components were substituted: inner and outer poles, magnetic screens and ceramic channel. The implemented magnetic circuit modifications were verified during a characterization campaign performed in January 2019, see Figure 22.



a) b)

Figure 22. HT5k DM3 before (a) and after (b) the magnetic circuit upgrade.

The last upgrade implemented on the HT5k-TU DM3 concerned the optimization of the thruster thermal behavior, by the use of a high emissivity surface treatment on the thruster body. The final version of the HT5k-TU DM3 was tested from May to June 2019 to verify the performance and thermomechanical robustness of the thruster when operated at high temperatures. The test took place in the upgraded IV10 facility, achieving pressures of the order of 7E-6 mbar (Xe) while firing a 4.4 kW of discharge power.



a) b)

Figure 23. HT5k-TU DM3 test setup before chamber closure (a) and thermal transient at 5.3 kW of discharge power and initial TRP temperature below -30°C.

Within the framework of this test, the thruster was fired for continuous durations up to 30 hours at discharge power levels of 4.4 kW and 5.3 kW, successfully achieving the thermal steady-state conditions. To evaluate the robustness of the critical components design, the thruster was ignited in cold condition, fired for 4 hours and cooled down up to TRP temperatures lower than -30°C. The process was repeated 5 times at 4.4 kW of discharge power and 5 times at 5.3 kW of discharge power, thermally cycling the thruster and cathode to representative conditions. The test was successfully completed. The temperature at the thruster TRP was always below 395° C (Figure 23) and no performance or component degradation was observed.

More than 124 hours of firing were cumulated throughout the test. A direct comparison of the HT5k TU ceramic channel before and after the test campaign is provided in Figure 24, which shows how the ceramic channel was covered by graphite, back sputtered from the chamber walls. This is a typically reported phenomenon for magnetically-shielded Hall thruster, meaning that the average graphite deposition rate is greater than the average ceramic channel erosion rate. During the test, two QCMs (Quartz Crystal Microbalance) positioned near the thruster measured an average graphite deposition rate of 2.35 µm/khrs.

a) b)

Figure 24. Detail of the HT5k DM3 ceramic channel before (a) and after (b) the test campaign.

III.Way Forward to TU Qualification

Over the last few years, SITAEL significantly advanced the design of its HT5k thruster unit, gaining broad experience in the development of high-power, magnetically shielded Hall thrusters. At its most mature stage of development, the HT5k-TU DM3 showed competitive performance and demonstrated stable and efficient operation in the 3 kW to 7 kW discharge power range, achieving anodic efficiencies up to 60%. Figure 25 shows the performance map plotted by fitting all the experimental data obtained from the HT5k-TU DM3 configuration.

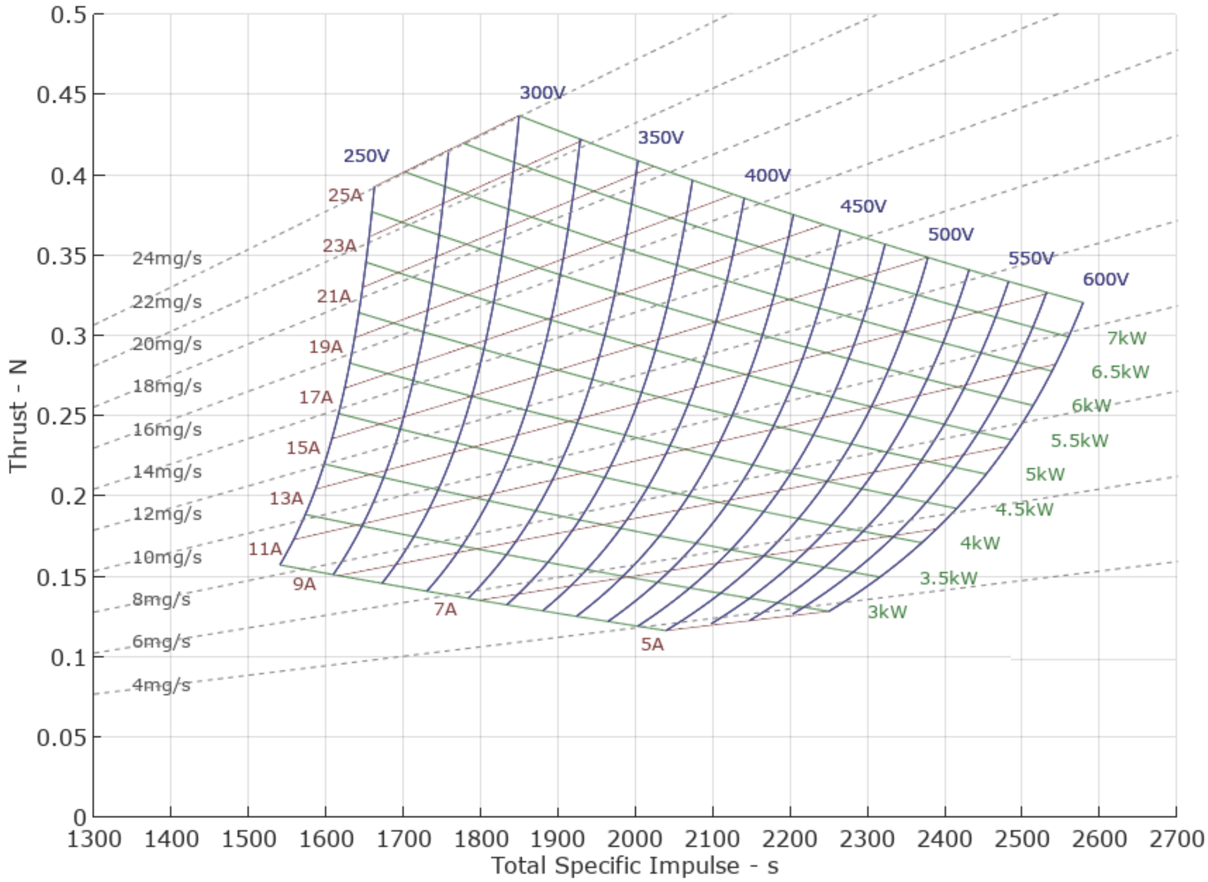


Figure 25. HT5k TU DM3 Performance Map.

All these results have shaped the current version of the HT5k thruster unit: the first HT5k-TU Engineering Model is currently in the design finalization phase, with the objective of realizing the first EM prototype and moving to EM tests in 2020. In particular, the main advances of the HT5k-TU EM design with respect to HT5k-TU DM3 will concern the optimization of the magnetic circuit and of the thruster interfaces. An internally developed multi-objective optimization tool is aiding the design of the magnetic circuit[25], resulting into the best fit to customer requirements in terms of thruster mass and power dissipated by the electromagnets. The implementation of a light thermal radiator will ensure a safe thermal regime at operation up to 7 kW of discharge power, while a titanium mechanical support will be added to withstand the prescribed environmental loads and to allocate all the thruster interfaces relevant to platform integration. Moreover, all the thruster interfaces (mechanical, fluidic and electrical) are being redefined to be compliant with the industry requirements and applicable standards while maintaining simplicity and robustness to environmental loads.

The HT5k-TU will be qualified throughout 2021-2022 as part of Ital-GovSatCom, an awarded national programme led by an alliance between Thales Alenia Space Italy and Telespazio with the goal of designing, realizing and putting into service an innovative platform for GEO applications. In this context, SITAEL is responsible of developing the entire propulsion system.

The necessary information to advance towards an EQM model will be acquired by performance and wear tests in the 3 kW to 7 kW discharge power range and in the 300 V to 450 V discharge voltage range, through sine and random environmental tests representative of the targeted space mission scenarios, and by coupling tests with an elegant breadboard model of SITAEL's 5 kW dual-mode PPU, currently under PDR stage in the framework of the ESA GSTP project "*Dual Mode 5kW PPU*", as well as with space-qualified flow control units from other European companies. SITAEL intends to fully exploit the synergies resulting from the parallel in-house development of TU, PPU and PMA, considerably increasing the design confidence and harmonization of the main propulsion subsystem components. In addition, a de-risking cycling test on the HC20 EM cathode in stand-alone configuration is scheduled to verify its capability of withstanding thousands of cycles without failures or observable component degradation before moving to EQM models realization.

After the EM phase, the qualification models will go through a qualification plan according to the customer requirements, complying with all the applicable standards. The current schedule, foresees to achieve full qualification for the orbit rising phase by the end of 2021, completing the full lifetime demonstration in 2022, in parallel to the production of the flight models.

Bringing to fruition the extensive developments of the past years, the qualification of SITAEL's HT5k-TU represents a milestone of paramount importance. It will bring to the market a highly efficient, long-lifetime 5 kW thruster unit designed to tackle the emerging mission scenarios of the 2020 decade, including, but not limited to, orbit rising and station keeping for large telecommunication platforms and navigation satellites, space tug platforms, in-orbit servicing, advanced launchers electric upper stages and high total impulse scientific and exploration missions.

Acknowledgments

The authors wish to express their gratitude to Daniela Pedrini and Giulia Becatti, for their support and guidance in the HC20 development; to Manuel Martin Saravia for his valuable assistance in data postprocessing; to Angela Rossodivita for managing most of the projects described in this paper to completion; and to Ugo Cesari, Cosimo Ducci, Alexey Arkhipov, Nicola Giusti, Carlo Tellini, Luca Pieri and Massimo D'Urso, for their valuable assistance in preparing and performing the experimental campaigns and test setups. Part of the development work described in this paper has been funded by the European Space Agency in the framework of multiple projects. The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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