Development status and way forward of SITAEL's 20kW class Hall thruster, the HT20k

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Abstract: Very high-power electric propulsion systems represent a promising solution for highly demanding future exploration and commercial missions. In the framework of multiple development programmes, SITAEL is strongly engaged in the development a long-life 20kW class Hall thruster unit, the HT20k-TU, composed of the HT20k thruster and HC60 cathode. After multiple design iterations and test campaigns, the thruster unit has now reached the engineering model stage. The present paper reports and gives a summary of all the performed development activities as part of past and ongoing programmes. Moreover, the mission scenarios investigated for very high-power Hall thruster propulsion systems are introduced, together with the main system-level trade-offs. Finally, the paper presents the future development activities and way forward to increase the maturity level of SITAEL's HT20k-TU.

I.Introduction

The recent developments in high-power Hall thruster systems are enabling a wide set of mission scenarios which will further extend the breath of human activities in space. Thanks to the optimal combination of performance, lifetime and reliability, this in-space propulsion technology is increasing the sustainability and affordability of space

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missions across the Solar System. These technological advantages, coupled with the increasing availability of power on board of satellite platforms, are encouraging several spacecraft manufacturers to focus on the implementation of high-power Hall thruster systems for both scientific and commercial applications.

In addition, during the last decade, significant heritage has been gathered as a result of several successful missions that implemented high-power electric propulsion[1,3], incrementing the stakeholders confidence in this technology. Since the nineties, the efforts of multiple research groups and the industry led to the development, manufacturing and testing of several very high-power thruster prototypes, with nominal power levels above 10 kW. However, After the demonstration of high-power operation, a number of factors have limited the possibility of reaching the qualified status with a few notable exceptions such as Aerojet Rocketdyne's AEPS (currently undergoing the qualification process)[4,5].

Some of the key factors that affect the development of this class of thrusters are the availability of test facilities able to support the extended operation of very high-power thrusters in a representative environment, and the high costs of sustaining a complete qualification test campaign. Nevertheless, considering the great performance benefits of very-high-power Hall thrusters, the perspective of market demands for this class of propulsion systems, and the void of efforts in Europe, SITAEL initiated the development of its own very high-power thrusters in 2015 with a Technological Research Project (TRP), funded by ESA. The activities associated with this project led to the design, manufacturing and testing of a new 20kW-class thruster, the HT20k, and a high current cathode, the HC60. This development model (called DM1) was tested in several characterisation campaigns in 2017.

The experience gained on this first development project was then employed for the design of a second development model (DM2) under two main projects: the H2020 CHEOPS, funded by the European commission, and an ESA/GSTP project. One of the key improvements of the DM2 was the implementation of magnetic shielding of the channel walls, which allows to considerably extend the lifetime of the thruster by significantly reducing the erosion of the ceramic channel. The activities on very-high-power Hall thruster is being followed within the framework of an ESA pre-development programme, currently in the phase of manufacturing of an engineering model (EM1).

The engineering model of the HT20k is representative of the flight model in form, fit and function. Thus, particular emphasis is placed on the thermomechanical robustness of the design as well as the maturation of all relevant interfaces.

This paper is aimed at presenting an overview of the activities followed in the past years on design, development and maturation of the SITAEL's HT20k. In addition, we will proceed to establish the outline of the near-term development plans and efforts, and to highlight the system-level aspects regarding the implementation of the thrusters of this power class. In this respect, in section II, a summary of the development activities is given with a particular focus on the technological improvement steps on the HT20k thruster unit. Section III provides an overview of the activities concerning the analysis of high-power electric propulsion systems. These activities, performed as part of the thruster development projects, supported the design of the thruster by providing additional information, such as requirements and constrains on both thruster operations and propulsion subsystem architecture. Finally, the planned future activities are outlined in section IV.

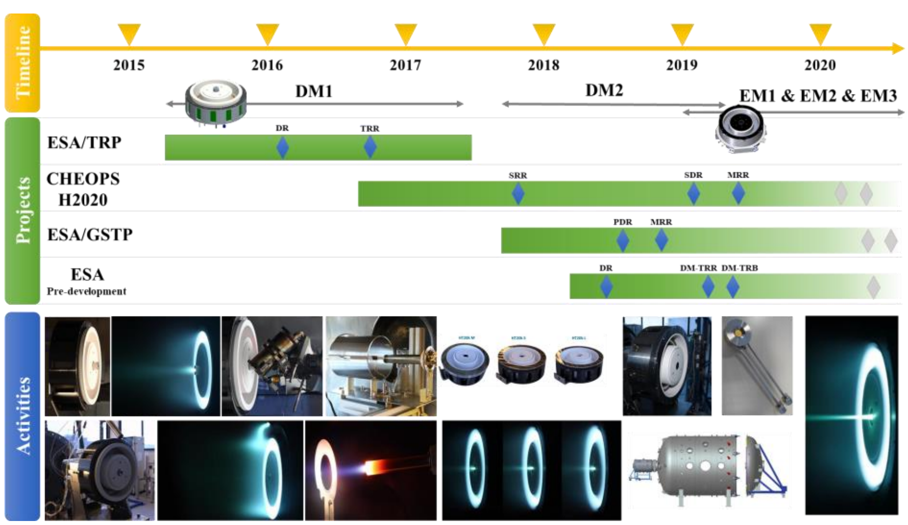

Figure 1. HT20k development history, including timeline main project and main milestones.

II.HT20k development activities

Figure 1 presents a schematic overview of the activities carried out in the past years for the development of the HT20k thruster unit and of the on-going programme. In April 2015, SITAEL began the activities on a 20-kW class thruster in the framework of a Technological Research Project (TRP) founded by ESA. After the conclusion of the TRP activities, design modifications and new technological solutions were devised focusing on the increase of thruster performance, reliability, thermomechanical robustness and lifetime. These activities have been performed in the frame of three different programmes: the EU's H2020 Consortium for Hall Effect Orbital Propulsion System (CHEOPS) programme, an ESA/GSTP project and a dedicated pre-development ESA programme.

Figure 2: (left) SITAEL's IV10 space simulator. (right) HT20k-TU DM1, at 800 V and 20 kW of discharge power.

A. First activities: ESA/TRP development programme

The main objective of this activity concerned the design, manufacture and experimental characterization of a development model (DM) of a 20-kW-class Hall thruster with the objective of providing a preliminary understanding of both operation and performance in this class of power.

After the design phase, the so-called DM1 was manufactured and successively tested in two consecutives experimental campaigns[6]. These were carried out in SITAEL's IV10 Space Simulator (see Figure 2), one of the largest vacuum facilities in the world, suitable for high-vacuum the testing of high-power thrusters.

During the first experimental campaign the thruster was operated over a wide range of voltage levels (from 300 V up to 1000 V) and discharge powers (between 10 kW and 20 kW). The main goal of the campaign was to find the optimal magnetic induction peak that minimizes the amplitude of the discharge current oscillations.

The thruster coupled with a centrally mounted cathode, called HC60, was successfully operated with stable conditions over all the range of selected power levels, reaching at 20kW and 800V over 3000s of total specific impulse. The highest anodic specific impulse equal to 3851s was reached at a discharge voltage level of 1000V with 10 kW of discharge power.

After this preliminary characterization, the thruster was continuously fired for 30-hours at 20 kW and 400V, for the characterization of its thermal behaviour. After an initial thermal transient of 4 hours, the steady-state temperature of about 400 °C was reached at the back-plate of the thruster, as shown in Figure 3.

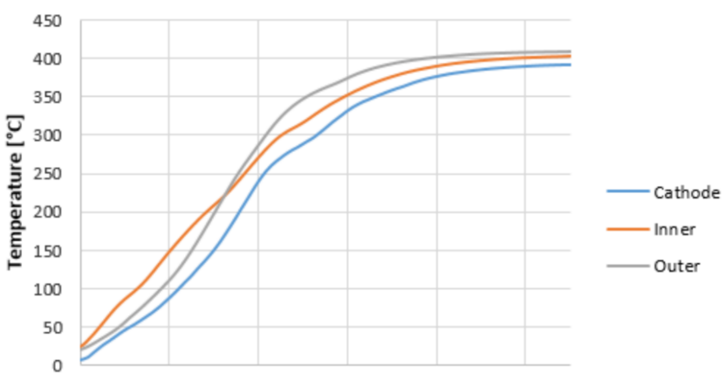

Figure 3: Thermal transient of the HT20k DM1 at 400V of discharge voltage and 20kW of discharge power.

The second characterization campaign focused instead on the assessment of thruster operation at low-voltage levels and different relative positions of the electrodes. Two spacers were placed, respectively, between the anode and the ceramic channel and between the cathode holding assembly and the thruster back flange. As a result, a shorter discharge channel was obtained, and the central cathode was moved backward. On the top of the centrally positioned HC60, an externally mounted cathode was added in order to study the influence of the cathode position on thruster operation. The thruster was operated between 250V and 400V at fixed magnetic induction peak with both cathode configurations. This second characterization campaign allowed to compare the results obtained with the first campaign and, to assess the behaviour and the performance of the thruster in different configurations. (see Fig.4)

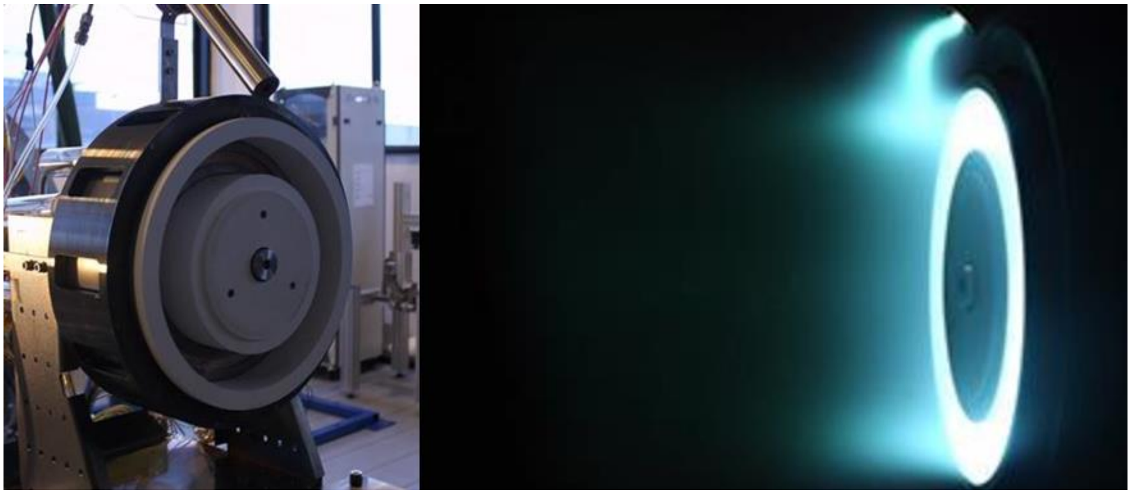

Figure 4: HT20k-TU DM1 mounted on the thrust stand for the second campaign (left) and firing at 300 V and 15 kW with external cathode.

These two characterization campaigns were followed by a wear test of 150 hrs with xenon as propellant in May 2017. This test was the first performed in Europe at such high-power level and represented a fundamental milestone in the development of high-power Hall thrusters. The main outcome was the assessment of the thruster performance and the channel erosion. In particular, the maximum erosion rate detected of the outer walls was ~8 µm/h while a maximum of ~5 µm/h for the inner walls[6].
The ESA/TRP project successfully ended in June 2017, with 250 hours accumulated through the characterization campaigns and the wear test performed.

B. CHEOPS H2020
Among the objectives of the Consortium for Hall Effect Orbital Propulsion System (CHEOPS), a major target is to demonstrate the technical feasibility of a complete high-power HT system for exploration and space transportation scenarios. Trade-off activities between different system architectures were performed throughout the programme (a summary of these activities is reported in Sec. III. The propulsion system SRR was successfully completed in the first semester of 2018. The selected system design is based on a single branch constituted by the thruster unit (TU), a flow management system (FMS) and a direct-drive power control unit (PCU). The single branch is developed as a building block and, based on each specific mission scenario, multiple branches can be used to compose the required EPS.
In order to meet the challenges associated with very high-power levels, innovative engineering models of the subsystems composing the EPS are currently being designed in the framework of the CHEOPS project. The main TU innovations include the implementation of the magnetic shielding approach, to limit the erosion of channel walls and increase thruster lifetime. Due to the selection of a direct-drive configuration, specific attention was devoted to assessing the thruster-plume interactions and different grounding solutions.

C. ESA/GSTP programme
The ESA/GSTP project aims at the development of a 20kW-class Hall thruster with extended capabilities, the HT20k XC, to be offered to the space transportation and exploration market. The main objective of this project is to design a new engineering model of the thruster unit, able to operate at high-voltage and high specific impulse.
In order to improve thruster and cathode performance and reliability, this program envisaged several activities for the assessment of innovative technological solutions to be included in the new design of both units. After the identification of critical components of both the thruster and the cathode, the verification of new technical solutions for each component was performed considering both analyses and tests.

The identified critical components of the thruster were the anode-gas distribution assembly, the electrical isolation of the feeding line and the evolution of the magnetic poles' erosion. The anode-gas distribution shall provide an azimuthally uniform propellant flow inside the thruster channel. A test bench dedicated to the assessment of propellant uniformity was setup and different anode configurations were tested with both xenon and krypton. In parallel, a detailed investigation on COTS breakers was performed in order to find a component capable to withstand to high temperatures without failure. This investigation led to the custom design of a breaker to provide electrical isolation between the propellant feed line and the anode.
Finally, the preservation of the magnetic field topology is fundamental for magnetic shield configuration. Even if no major degradations of either performance of discharge stability were identified during the tests performed, we investigated different strategies to prevent the erosion of thruster surfaces, adapting the magnetic configuration and analysing the effectiveness of surface depositions or pole covers.
The cathode went through the same review of critical components. The major criticalities were found on sizing both the cathode emitter and the tube orifice, due to the required high current level (up to 60A) and cathode lifetime. A second criticality was identified in the robustness of heater with respect to cycling. For the fulfilment of the cathode lifetime and cycling requirements, the cathode ignition voltage shall be minimized in order to reduce the stresses on the emitter. With the aim to improve the heating process and its reliability, different heater configurations were investigated. Cyclical ignitions and thermal tests were performed for different orifice dimensions in stand-alone configurations. Finally, the presence of energetic ions in the cathode plume could cause erosion of the keeper, which is directly exposed to it. The selection of keeper material was supported by analyses and testing.

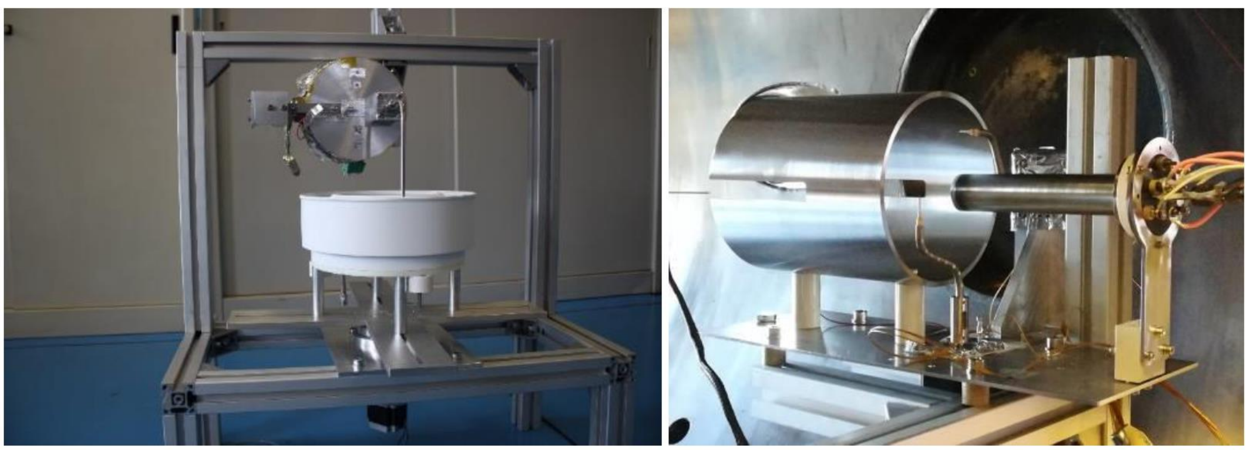

Figure 5: Dedicated test setup to study the uniformity of the gas distribution (left), HC60 before the characterization test(right).

In the frame of the ESA/GSTP programme, Politecnico di Torino is carrying out the analysis on possible mission scenarios and system architectures in order to define the thruster requirements and assess its future applications. This support activities are now focused in the near/medium term scenarios based on the adoption of the HT20k in servicing missions for the telecommunication market. Advance transportation platforms (e.g. space tug) are envisaged thanks to the adoption of the HT20k. The preliminary results showed the interest in increasing the thruster lifetime in order to extend the mission duration avoiding complex fail-safe architectures of the propulsion subsystem (e.g. redundant thrusters)[7-8]. Moreover, the comparison of different subsystem architectures is currently undergoing. The main interest is to provide the assessment of these design options in terms of mission budgets with respect to the mission requirements and constrains.
The manufacturing, assembling and integration of the thruster units are currently ongoing and two consecutive wear tests will take place in the final phase of the programme.

D. ESA pre-development programme

The ESA pre-development programme consists of a series of activities aimed at the optimization of the thruster design for high-thrust operation. The main objective of this project is to develop a thruster prototype able to operate between 225 and 440 V, with a thrust level of 1.3 N and an efficiency of above 60%, for a total impulse of up to 100 MNs. These challenging performance levels allow to fulfil the future mission requirements derived from the envisaged mission scenarios for operation in Cislunar environment.

Based on the experience gained from the development of the unshielded HT20k (DM1) and the SITAEL's 5 kW-class magnetically-shielded HT5k LL thruster, a new version of the thruster, the DM2 was designed and manufactured. This model implements the magnetic shielding configuration and features a flexible magnetic circuit, enabling the assessment of the effect of different channel geometries on the performance of magnetically-shielded Hall thrusters which was a main goal of the DM2 characterization campaign.
The data recorded during several tests were used to improve the existing theoretical scaling models of Hall thrusters by adapting them for shielded thrusters. Therefore, to achieve these objectives, the HT20k DM2 consists of three different configurations. These configurations, named as HT20k S, HT20k M and HT20k L, are mainly different in terms of discharge channel dimensions and have also minor differences in the of magnetic and poles, in order to maintain the same magnetic field topology inside the channel for all configurations. In particular, the channel width is largest for the HT20k L, followed by the HT20k M and HT20k S. The HT20k M has the same channel dimensions as that of the HT20k DM1.

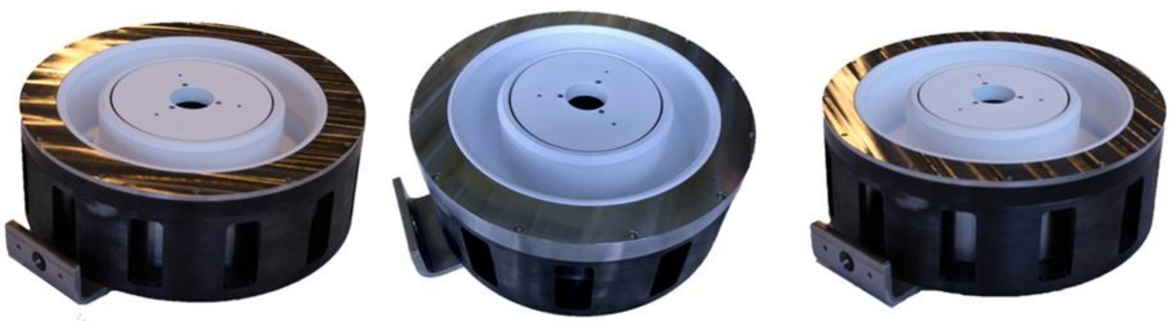

Figure 6: HT20k DM2 and its configurations during the pre-assembly verification; (left) HT20k S, (middle) HT20k M, (right) HT20k L.

In late 2018, the three configurations of the DM2 were tested in a first characterization campaign. Of particular interest regarding this campaign was the assessment of the stability domain of the M, L and S configurations and verifying the effectiveness of the magnetic shielding of the channel walls in all configurations. Moreover, the tests were aimed at identifying an optimal value of the channel aspect ratio. Based on the results of this extensive campaign, the scaling laws were updated to be better applicable to shielded thrusters. The updated laws were implemented for the conceptual design of the engineering model of the thruster. During all tests, SITAEL's HC60 hollow cathode, mounted in the central position, was operated with a mass flow fraction in the range of 6 % to 8% of the anode mass flow rate. The cathode axial position was re-adjusted with respect to the DM1 so as to place the keeper exit plane at the same level of the inner pole. The characterization campaign was performed at constant anode mass flow rates, whereas the discharge voltage was varied between 250V and 500V. Similar to the case of the DM1, the magnetic field optimization was also carried out on all three configurations.

1. IV10 facility upgrades

After the first characterization campaign of the HT20k DM2, a series of upgrades of the IV10 facilities were implemented with the aim of improving the pumping speed and diagnostics capabilities, additionally, increasing the duty-cycle fraction and reducing the operational costs.
The upgrade activities on the vacuum chamber were mainly performed in the first quarter of 2019, within the framework of the ESA pre-development project.
As first step, three cryo-panels and cold heads were added to the facility, bringing to the number of panels and cold heads available to eight. This upgrade allows reducing the background pressure during the thruster firing even in case of maximum flow-rate operation. Furthermore, increasing the number of panels allows longer periods of continuous firing before the need to chamber maintenance. At this status of development, the IV10 vacuum chamber is estimated to be able to sustain 500 hours of continuous firing for the HT20k tests. This estimate will be verified during the planned wear test of the HT20k EM thruster.

Another fundamental improvement of the IV10 is the implementation of an Auxiliary Chamber (AC). On the one hand, it will increase the duty cycle of the chamber, allowing a rapid access to both the thruster and the diagnostics while maintaining the vacuum pressure level in the main chamber. On the other hand, the thruster can be kept under vacuum condition during the main chamber deactivation and ventilation for maintenance reasons. The two chambers will be axially coupled to the each other and detached by means of an ISO DN 1000 gate valve. In order to facilitate the handling of the thruster, the AC will be equipped with a motorized trolley which facilitates displacing the thruster setup outside the AC. The AC, the gate valve and its pumping system are already procured and are currently under the acceptance activities. However, the trolley system will be available in the last quarter of 2019.

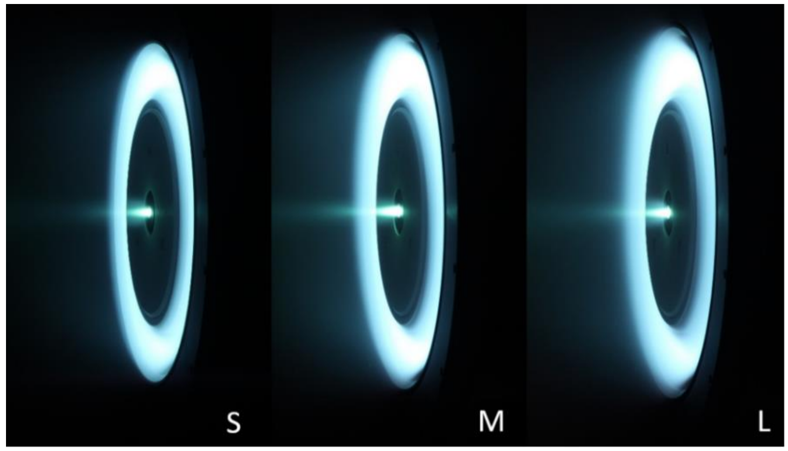

Figure 7: HT20k DM2 firing at 300V and 25mg/s to the anode, from the S to the L configuration, first characterization campaign.

Another part of the upgrade activities on IV10 was related to the design and manufacturing of a xenon recovery system. This system allows to significantly reduce the testing cost, in particular, during long-endurance test campaign. The xenon recovery system is composed by a primary pumping system connected to a dedicated xenon recovery chamber which will be mounted at the base of the IV10 facility.

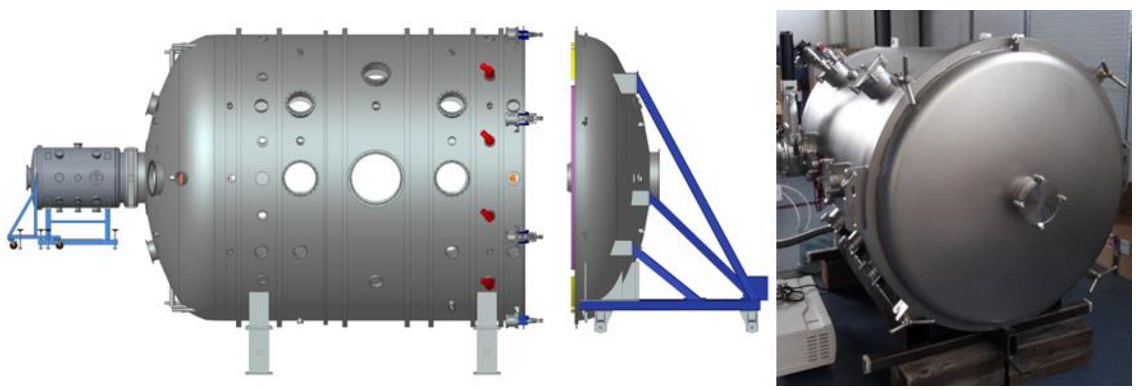

Figure 8: IV10 rendering with the auxiliary chamber (left), auxiliary chamber during acceptance.

All the upgrading activities were performed in parallel with the process of equipping the chamber with new diagnostics. Of particular interest for the magnetically shielded thruster tests, two Quartz Crystal Microbalance (QCM) were installed. The QCM is a transducer measuring the deposition rate of small layers of material on the surface of a quartz crystal resonator. As the material is deposited on the surface of the resonator, its frequency changes. The frequency is thus measured by the dedicated oscillator and the electronic module.
Measuring the deposition rate of the chamber back-sputtered material is an important task since it might be comparable with the erosion rate of thruster walls, thus, resulting in the misunderstanding of the wear progression of the thruster. Moreover, a Retarding Potential Analyzer (RPA) and an ExB (Wien) filter were designed in-house to study the thruster plume more in depth. The implementation of the new diagnostics inside the chamber is currently ongoing.
In addition to chamber diagnostics, the SITAEL's Advanced EP Diagnostic (AED) system was updated to extend its detection capabilities, increasing its field of view and accuracy. Moreover, the upgrades were also related to improving of the positioning system and increasing the degrees of freedom of the probe. At the conclusion of the procurement phase, currently ongoing, and the assembly phase, the new AED will allow the monitoring both the channel and poles erosion.

Figure 9: QCM sensor during acceptance.

2. Magnetically shielded HT20k Engineering Model

The characterizations carried out on the HT20k DM1 and DM2, coupled to the experiences gathered specifically on magnetic shielding through the SITAEL's projects on 5 kW-class thrusters, provided valuable heritage and understanding of the design and operation of magnetically-shielded high-power Hall thrusters. Building up on this expertise, the engineering model (EM) of the shielded HT20k thruster has been designed and is currently in the final assembly phase. Figure 10 shows a CAD model rendering of the design of the EM thruster unit, consisting of HT20k thruster and the HC60 hollow cathode.

The channel of the new thruster was scaled using the insights gained on the HT20k and HT5k LL[9,10] test activities. Furthermore, several modifications were incorporated to address the thermal and structural challenges of the new design and to mitigate possible risks in these areas. Graphite covers are used to mitigate the erosion of the thruster poles, which represents a criticality of the magnetically shielded topology[11].

The contact among different components is improved by implementation of appropriate gaskets. Dedicated thermal paths and radiators are included to facilitate the dissipation of the heat generated inside the thruster unit and the plasma heat loads deposited on various thruster surfaces. The new thruster is now in manufacturing and assembly phase.

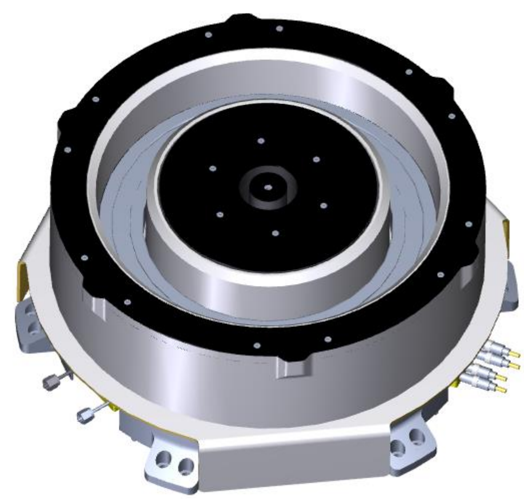

Figure 10: CAD rendering of the HT20k EM.

III. High-power transversal support activities

As a part of the programmes described in the previous section, several support activities were carried out to investigate the possible future adoption of the HT20k. These studies focused on the advantages in the adoption of this thruster for new mission scenarios and in the adoption of alternative subsystem architectures. From all the analyses, a set of requirements and constrains, which tailored the design of the thruster, were derived.

According to a stakeholder analysis, performed taking into account the international exploration roadmaps[12,13] as well as the strategic decision of the major space companies, three main groups of potential customers in short-medium

period were identified: (i) space agencies and other government/institutional customers, (ii) large system integrators and (iii) satellite operators. Each of them addresses quite distinguished application scenarios where the HT20k could provide significant advantages. The near-term applications are mainly found in the possibility to introduce new space-to-space transportation capabilities. In particular, applications such as electric orbit raising (EOR), station-keeping and disposal operations are of particular interest in near Earth orbits (up to GEO) for telecommunication platforms. In the context of transportation scenarios, high-power electric thrusters are envisaged to provide transferring capabilities for either de-orbital or disposal to graveyard orbits. The possibility to operate the thruster at high values of specific impulse allows to strongly reduce the propellant necessary for these phases. Furthermore, the augmented performance nowadays available allow foreseeing the near/mid-term adoption of these technology in advance space transportation systems for the transferring of large cargo payloads.
The stakeholder identified different specific applications ranging from the cargo transferring to resupply purposes of space infrastructures (e.g. space stations) for servicing missions of satellites already in operation. The most promising scenarios envisaged the introduction of a new class of service platforms characterized by both strong operation versatility and a high level of reusability, such as the space tug. This trend is supported by the continuous improvement in the reliability of critical components, allowing for multiple operations and extended mission durations.
The main interest concerns the satellite lifetime extension through refuelling operations, station keeping manoeuvres as well as orbital relocation. Furthermore, the in-orbit assembly of large systems could be also considered in the far future. Last application, nowadays of particular interest, is the active debris removal of large objects in order to mitigate the possible collision risks.

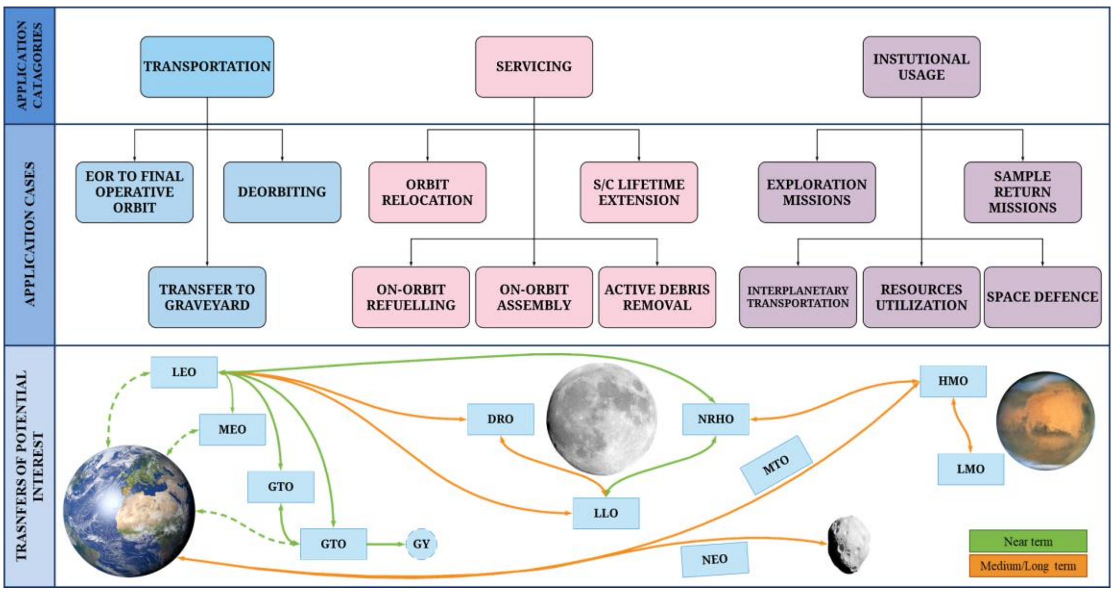

Figure 11: Applications and targets for future high-power missions.

Another important group of applications considering institutional stakeholder (e.g. Space Agencies, International government groups) considers several scenarios in support to the human activities across the Solar System, for sample returning, exploration and transportation missions. The advance goals of these scenarios, planned in a long-term period, allow to consider pioneering technologies, in particular for what concern innovative system architectures as well as power sources. For example, the nuclear power is one of the advance technologies which will enable reaching distant targets in the outer Solar System. In addition to new scientific goals, their adoption will allow to open new economic opportunities such as the commercial exploitation of near-Earth objects.
In the framework of the activities of H2020 CHEOPS project, alternative architectures were investigated in order to reduce the system complexity and decrease the system budgets as well as the mission costs[14]. As a consequence, three architecture alternatives were compared with respect a reference based on a monolithic EPS, adopting a common PPU and operating with xenon. The alternatives investigated are:

1. Monolithic vs cluster EPS architecture: this subsystem can be based on a single EPS string, based on a high-power thruster, or multiple lower powerful EPS strings. The clustering approach improves the overall system

reliability but introduces several complexities in system integration, validation and operation due to the high number of components. In addition, the overall performances of the propulsion subsystem are typically lower than the ones achievable by a monolithic thruster. As a matter of fact, to produce the same level of thrust, the cluster solution requires higher power levels with respect to the monolithic solution. This implies lower thrust-to-power ratios. Additionally, since powerful thrusters are intrinsically more efficient, the difference in the overall efficiency becomes more relevant when comparing a cluster of 5 kW thrusters with a single 20kW device. Despite these advantages, a monolithic system can achieve higher performance reducing, at the same time, the subsystem complexity and the mass budget.

2. Kr vs Xe propellant operation: the adoption of different propellant could bring several benefits in terms of costs. Krypton has physical properties close to those of xenon and a similar non-corrosive nature. The price of krypton is up to eighteen times lower than of xenon [Latest quotation 01/2019]. However, due to its lower atomic mass with respect to xenon, the specific impulse for operation with krypton at the same voltage and power level is higher, whereas the thrust is lower. SITAEL has already accomplished extensive experimental characterization of Hall thruster performance and behavior with krypton. It was used during the test campaigns with two Hall thrusters of different power levels, 5kW-class and 20kW-class. In particular, a dedicated series of tests have been performed under the ESA ARTES 5.1 programme to characterize the performance and erosion of the SITAEL's HT5k thruster[15]. The operation with krypton showed a reduction in thrust and efficiency in parallel to an increase in specific impulse. Another consequence of krypton lower atomic mass is reflected in terms of increased beam divergence. The beam divergence efficiency when operated with Kr was reported to be 8% lower than with Xe[16]. Furthermore, due to the lower first ionization potential and higher ionization rate already at lower electron energies, Xe provides lower ionization cost and higher propellant utilization efficiency. At the same mass flow rate the propellant utilization for Xe was reported to be 5-10% better than for Kr[17]. As a result, the thrust-to-power ratio is typically lower for krypton. From the point of view of the plasma-wall interactions, compared to xenon, the krypton ions are accelerated to higher velocities in the same potential drop and, at the typical ion energies of HTs, the sputtering yield of the wall material increases for lighter particles. Hence, the erosion problem exacerbates with krypton. Moreover, in SITAEL, the HC20 and HC60 cathodes, originally developed for Xe, were tested also with Kr. The cathodes proved to be completely compatible with Kr but operated with higher power consumption, due to the higher ionization energy of Kr[17].

3. Direct Drive vs traditional PPU architecture: instead of feeding the thruster through a Power Processing Unit (PPU), a Direct Drive Unit (DDU) can be used. This has direct and indirect effects at system and subsystem level. The conventional solution for EP systems is to use a power-processing unit (PPU) to modulate the energy produced onboard to meet the requirements necessary for Hall thruster operation in terms of current and voltage. Although PPUs have been successfully used in several space missions, one of the main drawbacks is their relatively large size and mass. Apart from introducing an efficiency loss, the high power PPUs produce a significant amount of heat, therefore, increasing the workload of the spacecraft thermal control subsystem. Another solution to deliver power to the thruster is to directly transfer the energy generated by solar arrays to it. This approach, which is called "Direct Drive (DD)", allows to greatly simplify the PPU, removing all power converters and implementing a simplified filter unit on the anode power line. However, to benefit from the positive aspects of the direct drive approach, it is necessary to develop platforms with high bus voltages in the range of 300 up to 500V, requiring high-voltage solar arrays and power bus.

For the characterization of the advantages gained in the adoption of these alternative architectures a reference mission was introduced. In particular, among the mission scenarios previously introduced, the transfer of a telecommunication satellite from a Low Earth Orbit (LEO) up to the Geostationary orbit (GEO) by means of a space tug resulted of particular interest for near-term adoption of the HT20k. More details on this analysis can be found in Ref.14. The mission design was performed through a simulation software, MAGNETO, developed by Politecnico di Torino in the framework of the ESA/GSTP activities (see Ref.18). It allows to size a platform adopting electric propulsion with respect to mission requirements and constrains defined in the preliminary phase of the mission analysis. Moreover, MAGNETO is able to optimize the system budgets minimizing the wet mass.
Taking into account the results obtained as output, the EPS architecture alternatives have been compared using an Analytical Hierarchy Process (AHP) during the post processing phase. A set of Figures of Merit (FoM) were introduced in order to evaluate each architecture with representative parameters. A detailed description of the procedure can be found in Ref.14. The AHP is based on trade-off weight exploited to represent the influence of each

FoM. The main results obtained in terms of mass and power budget, transfer times and propellant costs, are shown in Figure 12 and Figure 13.

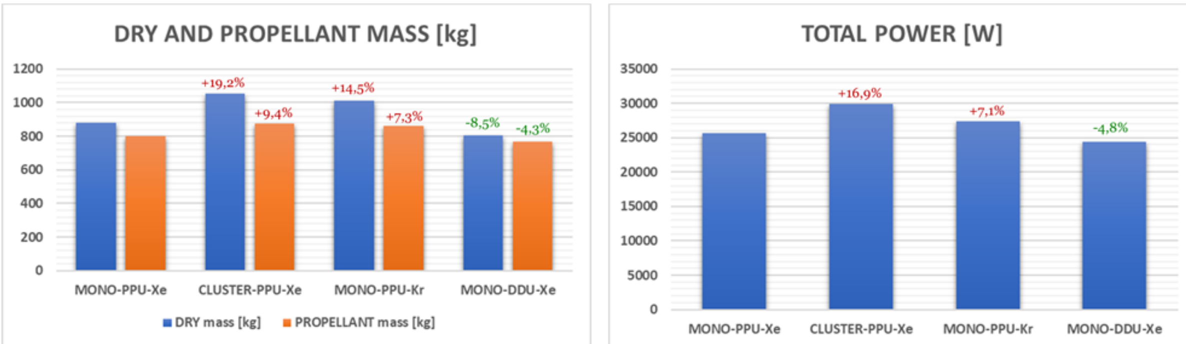

Figure 12: (left) dry and propellant budget, (right) power budget for the four investigated alternative architectures.

Figure 12 (left) shows the mass budgets of the platform. Due to the higher number of components, the dry mass of the tug adopting a cluster architecture is higher than the monolithic configuration. Same consideration can be done for the architecture base on krypton, due to the higher tankage fraction necessary to store the propellant in supercritical condition. On the contrary, the dry mass of the space tug adopting a direct drive architecture is lower owing to the simplification of the PPU as well as the mass save on the power and thermal control subsystem. For all the cases, the wet mass is slightly lower than the dry mass. This result is caused by the fact that the tug has to perform a round trip to return in its initial parking orbit in LEO. Overall, the propellant necessary for the round trip is less than 30% of the total wet mass of the spacecraft. Same trends are followed by the power budget (see Figure 12 (right)). While the cluster and the krypton architectures result having a higher total power, the greater efficiency values achievable by the direct drive allows to reduce the total power to be generated.

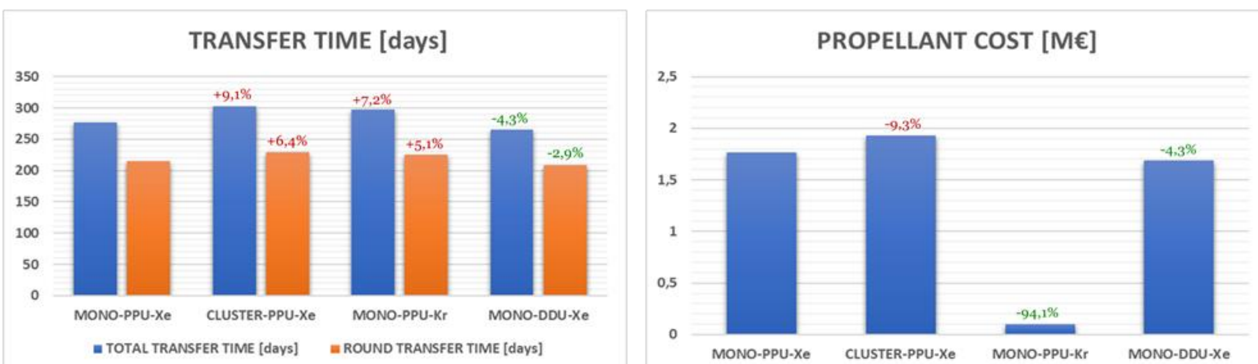

Figure 13: (left) total and round transfer time, (right) propellant cost estimation for the four investigated alternative architectures.

Through the trajectory propagation routine of MAGNETO, it is possible the evaluation of the transfer time necessary for a designed platform. In Figure 13 (left), the blue bars represent the total transfer time for a round trip (up to GEO and back to LEO). The orange bars instead report the round transfer times. These values are directly affected by the mass of the telecommunication satellite, transferred during the round transfer. Therefore, they are of particular interest for the customers, mainly because they represent the time-to-market of the satellite, necessary after the launch, to have revenue from its operation. Due to the higher wet masses, the system based on the clustering approach as well as the krypton architecture have a total transfer time respectively of 9% and 7% greater than the baseline configuration. The reduction of wet mass for the DD configuration allows instead to reduce the total transfer time of around 4%, while a reduction of 3% is obtained for the round trip, where the dry mass has a greater impact.
Another fundamental parameter, for the evaluation of the different architectures, is the propellant costs. In this case, fig XX shows the significant reduction of the cost adopting krypton as propellant. Furthermore, a reduction of around 4% is obtained also for the Direct Drive approach because the propellant saved during the transfer because the lower wet mass.

IV.Way forward: next SITAEL's activities on HT20k

The activities planned for the development of the HT20k comprise the assembly of a first engineering model of the thruster unit before the end of 2019, followed by the assembly of a second TU-EM at the beginning of 2020 and by test campaigns aimed at verifying the compliance of the new design with the requirements of on-going programmes. The test campaigns are presently scheduled for the end of 2019 and during the whole 2020. More in details, the characterization of the first HC60 EM will be performed in stand-alone configuration, followed by a cycling test dedicated to investigate the robustness of the heater design and the resistance of the main cathode components, as well as the repeatability and reliability of the ignition procedure.

In the definition of the new thruster design, a specific attention was dedicated on the thermal design and on the heat dissipation, with the objective to improve the thruster performance, reducing the thermal stresses and minimizing the heat conducted through the thruster mechanical interface. Moreover, dedicated structural analyses supported the mechanical design of the thruster, driving the selection of several technological solution to improve the thruster robustness against shock and vibrations. In order to validate the thermal and structural design of the TU-EM, the first model will be subjected to random vibration and thermal-vacuum tests representative of qualification conditions.

The following phase of the thruster unit testing will comprise the characterization of the thruster performance at different operating conditions, from high-thrust to high-specific impulse operations. For the TU-EM characterization, the diagnostic system will be improved with newly developed ExB and RPA probes, which will be installed in the IV10 vacuum facility.

To validate and improve the performed system trade-off, the impact of the propellant choice will be assessed through specific investigations of thruster performance with both xenon and krypton propellants. In particular, in the framework of the ESA pre-development programme, the thruster unit will be characterized with xenon propellant at high-thrust conditions, whereas in both the CHEOPS programme and the ESA GSTP programme a dedicated comparison between the two propellant will be performed, with a specific focus on high-specific impulse operations. Thanks to the concurrent development of a flow management system (AST) and of a direct-drive power control unit (SITAEL), the CHEOPS programme will offer an ideal framework to perform coupling tests between the main elements of the propulsion subsystem. Testing of the thruster in direct-drive mode, with krypton propellant, will support the assessment of critical architectural alternatives that may represent a key enabling factor for the adoption of high-power propulsion on future missions. The final phase of the TU-EM testing will be focused on the assessment of the thruster lifetimes and operation stability through multiple endurance tests. A 500-hour firing test will be performed on the TU-EM1 with krypton propellant. The erosion of thruster critical surfaces, i.e. the discharge channel and pole covers, will be monitored at regular time interval using the AED system.

After the completion of this first long-duration test, in the framework of the ESA pre-development programme, the TU-EM2 will perform a second firing test with xenon for a duration of 350 hours, at high-thrust condition. This test will allow to verify the stability of the operations with xenon, as well as the thruster erosion. Moreover, the test will permit to verify the effectiveness of the xenon recovery system that will be installed in the IV10 facility, and to define specific testing procedure, both for cold heads regeneration and xenon recovery, to be implemented during the future qualification of the thruster.

Last, in the framework of the ESA GSTP programme, the TU-EM3 will perform a long duration test of more than 2250 hours, which represents a fundamental step toward the design definition of the thruster qualification model. This test will be divided in two subsequent phases, the first performed with xenon for a minimum duration of 250 hours, and the second with krypton for the remaining firing time. Relying on experimental observations on the erosion with krypton[19] and through a conservative selection of the operating condition, the second part of the test campaign will represent an accelerated wear test, which will allow to validate the main design choices of the thruster unit.

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