

30 kW-Class Hall Thruster: a Key Building Block for Propulsion Needs of Future Space Transportation and Exploration

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P. Rossetti¹, C. Casaregola¹ and M. Andrenucci²
Alta S.p.A., Pisa, 56121, Italy

Abstract: A significant heritage on Geostationary platforms for orbit maintenance and the sustained capability of Electric Propulsion (EP) orbit raising, orbit topping and interplanetary transfers have demonstrated that EP has achieved a sufficient heritage to claim a high level of maturity. What is needed next is to increase the operational power level of EP systems to allow large payloads to be transported in a more affordable way. Due to this new interest in high power, Alta is developing a 30 kW-Class Hall Thruster as enabling technology for future space exploration and transportation activities. An approach to develop such a thruster based on previous experience and the implications of such a development effort with regard to technological issues are discussed.

I. Introduction

A significant heritage on Geostationary platforms for orbit maintenance and the sustained capability of Electric Propulsion (EP) orbit raising, orbit topping and interplanetary transfers, the good agreement between flight data and ground data, long duration and total impulse capability, have demonstrated that EP has achieved a sufficient heritage to claim a high level of maturity. Moreover, based on such a significant flight experience, lots of lessons were learned¹⁻⁶.

What is needed next is to increase the operational power level of the EP systems thus allowing large payloads to be transported in a more affordable way. In fact, as primary spacecraft propulsion, high power EP systems have been shown to be enabling for a number of mission classes.

Since their first appearance in the western electric propulsion community in the early 90's, the Hall thrusters gained a center stage position due to their peculiar performance: relatively high thrust, high efficiency, specific impulse (Isp) nearly optimum for a large variety of missions and high reliability. For these reasons, Hall effect thrusters (HETs) became a viable alternative to the Gridded Ion Engines (GIEs) for replacement of traditional chemical propulsion on-board of many commercial and scientific missions. In particular, for orbit raising and orbit topping missions, HETs provide the best thrust to power ratio among the EP devices to achieve reasonable trip times as well as significant mass-and cost-savings compared to typical chemical systems. However at present, due to the lack of an adequate on-board spacecraft power, the opportunity for these devices to be considered for such missions never arises.

Due to the present growing trend in spacecraft on-board available power and to a renewed interest in high power Electric Propulsion, Alta is developing a 30-kW Hall thruster as enabling technology for future space exploration and transportation.

¹ Project Manager, p.rossetti@alta-space.com, c.casaregola@alta-space.com.

² CEO; Professor, Department of Aerospace Engineering, University of Pisa; m.andrenucci@alta-space.com.

II. Mission Scenarios for potential High Power HET Applications

During last decades, lots of study⁷⁻⁹ were aimed at demonstrating the potential benefits deriving from high power EP systems. In fact, apart from enabling mass saving, launch flexibility, long interplanetary journeys and faster missions with no gravity assist constraints, high power EP technologies will also open the way to transferring large payloads through the solar system. Therefore, by increasing the operational power level, Electric Propulsion could play a very important role for future space exploration and transportation programmes, enabling more affordable and sustainable space-to-space missions.

Under the HiPER programme¹⁰ (“High Power Electric propulsion: a Roadmap for the future”), a 3-year collaborative 7th Framework Programme study partly funded by the European Union, the Mission Analysis team (Alta, Astos Solutions, CNES, Domaine de Beauregard, KopooS Consulting and Space Enterprise Partnerships) has been mainly devoted to select, simulate and optimize the most promising near-term and long-term mission and transportation scenarios which could benefit from the increase of the operational power level of EP systems.

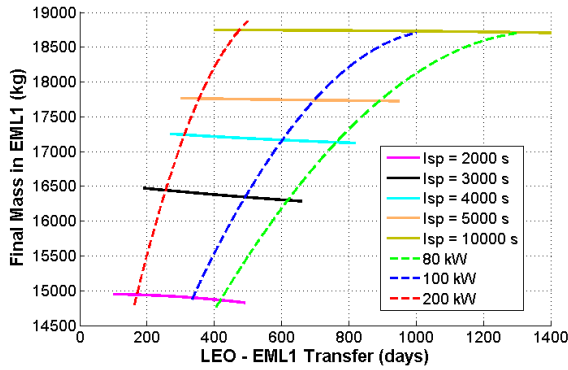


Figure 1. Transfer time vs. final mass for a LEO – EML1 transfer

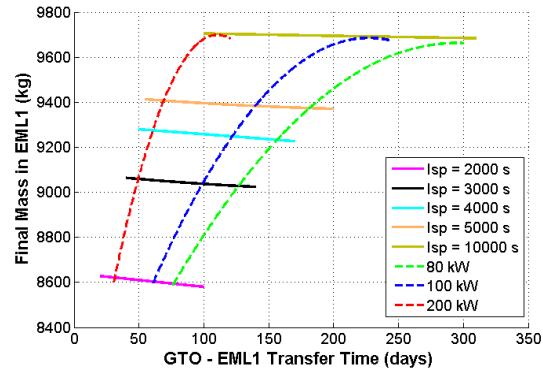


Figure 2. Transfer time vs. final mass for a GTO – EML1 transfer

In Fig. 1 and Fig. 2 preliminary results obtained combining Electric Propulsion with the Circular Restricted Three-Body model are shown.

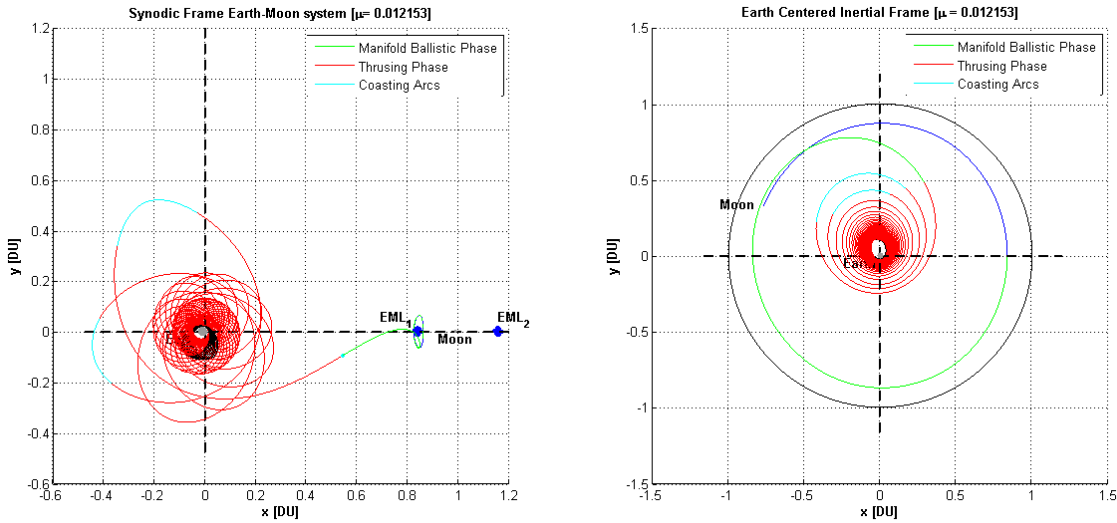


Figure 3. GTO-to-Halo minimum mass transfer in the Earth-Moon rotating frame (left) and in the geocentric inertial one.

For various on-board power levels ranging from 80 to 200 kW and for various specific impulses (Isp) ranging from 2000 s up to 10000 s, simulations of transfers from Low Earth Orbit (LEO) to Earth-Moon Lagrangian point L1 (EML1) and from Geostationary transfer orbit (GTO) to Earth-Moon Lagrangian point L1 (EML1) were performed. An initial mass of 20 tons in LEO and 10 tons in GTO respectively were assumed as compatible with Ariane V ECA

launcher. Results generally show that, at expense of longer transfer times with respect to chemical propulsion, larger payloads can be transported

A complete GTO to EML1 Halo orbit transfer is shown in Fig. 3 in both the synodic and the geocentric inertial frame. In particular, the simulation refers to the 100 kW on-board available power for thrusters. High power HETs are assumed with an $I_{sp} = 2500$ s. Total transfer time takes about 91 days with a propellant mass fraction of about 10% (1023 kg).

Moreover, Alta is proposing the design of a EP-based flexible architecture as stepping stone for future space exploration. Main strategic objective of such an architecture is to improve servicing capabilities beyond LEO by means of testing innovative technologies such as a 30 kW-class HET¹¹ (Fig.4). The proposed architecture is composed of a modular and re-usable service module and inflatable modules. This configuration has been shown capable of delivering a significant payload in the Cislunar space and of performing various mission classes compliant with the flexible path for exploration.

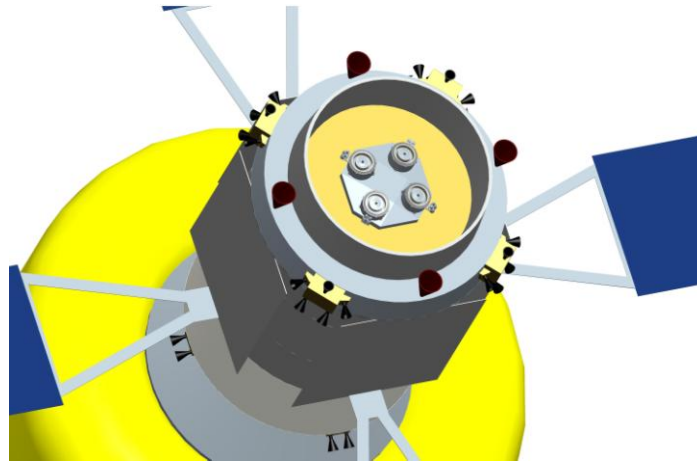


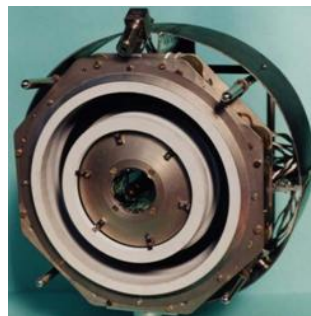
Figure 4. Detail of the high power HETs mounted on the proposed architecture

In addition to Earth-Moon system missions and to reusable space tugs, high power HETs can also allow Mars Sample Return (MSR) missions¹² by assuming a single launch and with an overall transfer time of about 3- 3.5 years.

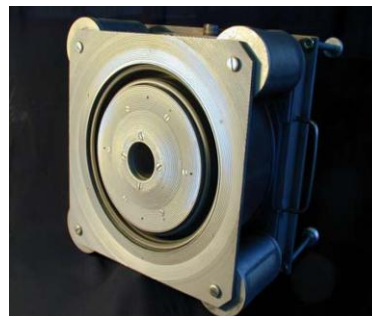
Therefore, based on mission analysis results and scenarios investigated, a significant need for high power Hall thrusters is demonstrated. In addition, the quite easy scalability of the HET performance for different power levels, and the growing availability of on-board power is pushing the research and the industrial efforts towards the development of ever higher power Hall thrusters for the next generation spacecrafts.

III. High Power Hall Thrusters Review

As regards high power Hall thrusters, these efforts, which were for the most part conducted in what was then the Soviet Union, have resulted in successful operational deployment of these devices for stationkeeping purposes on Soviet and later Russian spacecraft.



(a) 25 kW SPT 290 (EDB Fakel)



(b) 25 kW TM-50 (TsNIIMaSh)

Figure 5. Russian High Power Hall Thrusters

The early engines operated at 0.6 kW and later at 1.35 kW. Then research and development activities also focused on higher power levels. The high power Hall thrusters laboratory models and engineering models developed in Russia - former Soviet Union - have demonstrated power level up to 50 kW. Among the high power devices, it is worth mentioning the 10 kW SPT-200 and the 25 kW SPT 290 by EDB Fakel (Fig. 5-a), the 15 kW D-150, the 25 kW TM-50 (Fig. 5-b) and the 150 kW bismuth thrusters D-5 (D-160) by TsNIIMaSh. The SPT 290 was tested at a power level up to 30 kW and a specific impulse up to 3000 s, whereas the TM-50 was tested up to 50 kW and at a specific impulse up to 7000 s.

Since the end of the cold war this technology became available to the rest of the world and development and design of high power Hall thrusters also initiated in western countries.

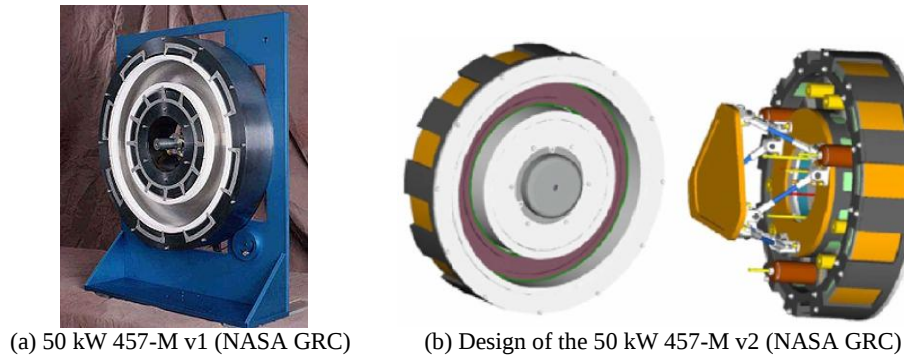


Figure 6. US High Power Hall Thrusters

Development activities on high power Hall thrusters capable of providing both high thrust and high specific impulse were also supported by United States. Research and development tasks on Hall thrusters were carried out at NASA Glenn Research Center¹³⁻¹⁴ (GRC) leading to some laboratory models of high power devices. The NASA 50 kW 457-M version 1 (v1) (Fig. 6-a) was designed and fabricated to nominally operate at 50 kW and 100 A. At nominal conditions, it demonstrated an efficiency of 63%, a thrust of 2.3 N and a total specific impulse > 2500 s. Development activities advanced the Technology Readiness Level (TRL) on this thrusters from TRL 3 to TRL 4/5.

A couple of years later, the reliability of the first version of the laboratory model NASA-457M Hall thruster was improved to provide an evolutionary path to a flight type device by addressing thermal, mechanical and structural issues. The critical features of the first version were incorporated into a NASA-457M version 2 (v2) (Fig. 6-b). With respect to the first version, the geometry of the channel diameter, width and depth were not changed. However, the design of the magnetic circuit was modified to improve the thrusters performance and reduce its mass by 18%. Also the mechanical and thermal design were improved for the second version of NASA 457-M and a representative spacecraft mounting interface was designed.



Figure 7. 50 kW NASA 400M (NASA GRC)

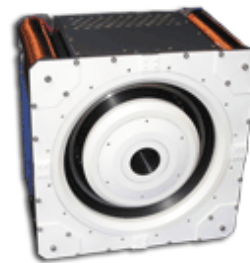


Figure 8. 20 kW BHT-20k (Busek)

As regards high power, high specific impulse Hall thrusters, NASA also developed an evolution of the NASA 457-M v1 improving the design of electrical isolation and of the thermal design. These activities lead to the manufacture of the NASA 400-M laboratory model (Fig. 7) tested with xenon up to 47 kW and at a specific impulse up to 2760 s. With respect to the NASA 457M v1, thrust efficiency was improved. Moreover, this device was also tested using krypton propellant up to 64 kW and at a voltage level up to 1100 Volts obtaining a maximum specific impulse of 4700 s. In US, research and development activities were also carried out at Busek where an engineering model of the

20 kW BHT-20k Hall thruster (Fig. 8) was manufactured and tested. It was able to provide 1 N thrust at a specific impulse of about 2700 s¹⁵. Nevertheless, high power HET activities in US were carried out until 2004, then they underwent a slowdown in interest and no advances were made. Also in other countries, activities on high power HET underwent a stagnation period in which the statement ‘high power HET’ was often associated to power levels of 5–10 kW.

Conceived as one of the enabling technologies in recent debates¹⁶, the interest in high power Electric Propulsion has been renewed. Since 2008, under the European HiPER programme coordinated by Alta¹⁰, the Hall Thruster team (Snecma, Alta, CNRS, IPPLM, Onera and Tecnalía) has been working on the design of the 20 kW prototype (Fig. 9) able to provide 1 N thrust at an Isp of 2500s¹⁷ (Table 1). Assembly phase of the high power HET prototype has been recently performed and testing activities are in progress in Onera Pivoine facility at a reduced power level of 10 kW. Results of test campaign will be available at the end of this summer.

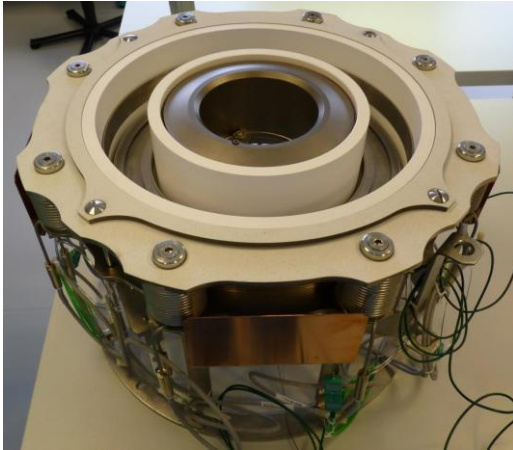


Figure 9. HET prototype “PPS-20k ML”

Table 1. “PPS-20k ML” main specification

Power (kW)	20
Thrust (N)	1
Specific Impulse (S)	2500
Discharge Current (A)	40
Discharge Voltage (V)	500
Xenon mass flow rate (mg/s)	~41
External Diameter (mm)	320
Height (mm)	~110
Mass (kg)	~25

IV. High Power Hall Thrusters development at Alta

Among the EP systems concepts studied and developed at Alta, an important place is for Hall thrusters. Alta’s heritage in Hall thrusters development dates back to 90s, and from then on Alta has been developing Hall thruster systems targeted for various mission classes. As regards high power devices, since 2006 research and development activities were carried out on a 11 kW Multi-channel Hall thruster (Mc-HT) (Fig. 10) able to provide about 0.6 N thrust with an Isp of 1600 s.



(a) Design of the 11 kW Multi-channel Hall Thruster Mc-HT (Alta)

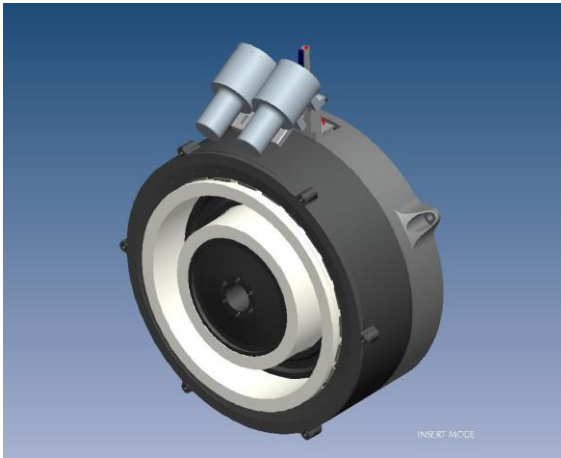


(b) Anode discharge chambers for the 11 kW Mc-HT (Alta)

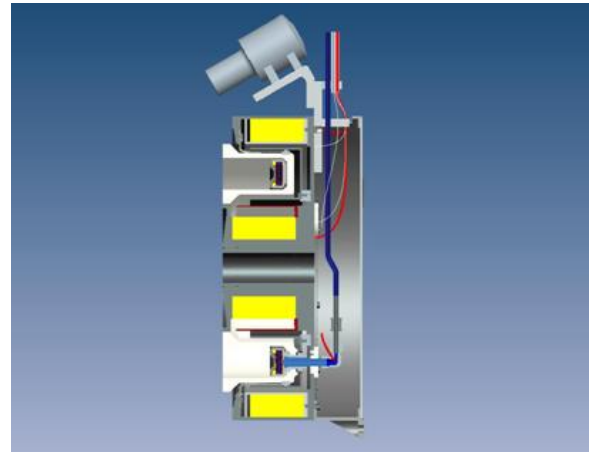
Figure 10. 11 kW Mc-HT (Alta)

Besides, preliminary design activities of a 25 KW Hall thruster were initiated¹⁸. Both the high specific impulse and high thrust configurations were studied. In the high specific impulse configuration, the thruster is able to provide up

to 0.9 N thrust with an Isp of 3400 s, whereas in the high thrust configuration, 1.5 N thrust is obtainable with an Isp of 1700 s.



(a) 30 kW Hall Thruster HT-30 CAD model (Alta)



(b) Section view of 30 kW Hall Thruster HT-30 CAD model (Alta)

Figure 11. 30 kW HT-30 (Alta)

The preliminary design of the Alta HT-30 kW is shown in Fig. 11. Moreover, based on analytical scaling methods developed at Alta¹⁹⁻²⁰ and coupled with statistical database of existing Hall thrusters, main nominal performance objectives of the HT-30 are shown in Table 2.

Significant design and technology challenges shall be considered in the development of a high power Hall thruster. Indeed, some issues that are generally inherent to any size of Hall thrusters may be strongly amplified while occurring in a large design. Scaling laws usually show an increase of HET efficiency for higher power levels, however this effect does not compensate exactly the increase in the input power and thus the total heat load on the thruster wall usually increases for the high power devices. Therefore a correct thermal design is fundamental to decrease the heating of the ceramic discharge chamber particularly critical with respect to thermal stresses and cracking but also to decrease the thermal load on the magnetic circuit, to avoid its saturation and overheating and to reduce the heat load towards spacecraft's surfaces and components.

Table 2. Alta HT-30 nominal performance objectives

Thruster characteristics	Value
Discharge Power	30 kW
Specific impulse	2500 s
Thrust	1.55 N
Discharge voltage	500 V
Discharge current	60 A
Xenon mass flow rate	~65 mg/s
Overall efficiency	0.6

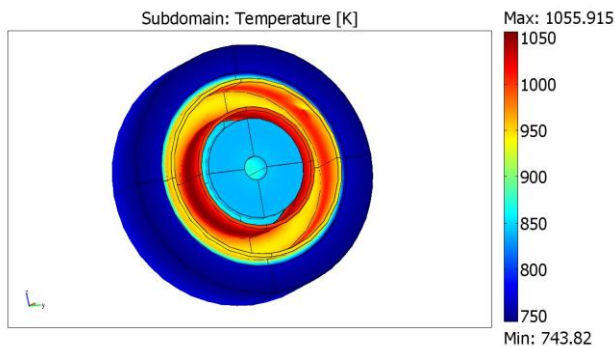


Figure 12. HT-30 thermal analysis

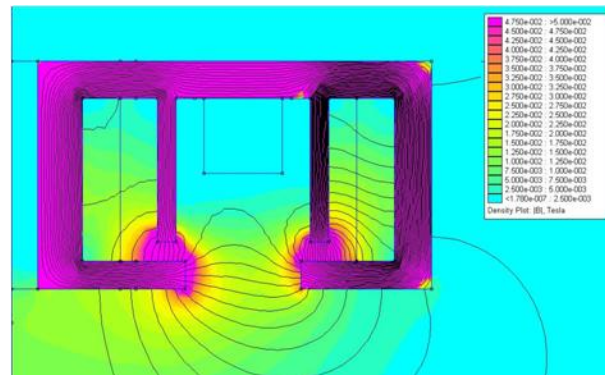


Figure 13. HT-30 magnet field simulation

Thermal loads simulations for the HT-30 were carried out (Fig. 12) and results show that thruster operation at 25 kW is compatible with the ultimate temperatures of all materials. Taking into account its stage of development, the FEM model simplification and the uncertainty on loads and boundary conditions, the safety margin seems appropriate. In particular, including in the design a thermal shield – not optimized for the moment - to prevent overheating of the internal coil and a skirt of aluminum with an external diameter of 1 m, the thruster seems capable of operating in the hot case. As regards the cold case, thruster minimum temperature in geostationary orbit was assessed and the start-up transient provided indications on the temperature rate starting from the cold case. These results represent a valuable reference for both ground-testing on thruster ignition capability from temperatures several tens of degrees under zero and for thermo-elastic analysis.

Another fundamental aspect to be addressed in the design of the HT-30 is the optimization of the magnetic field topology. In fact, although larger dimensions reduce the risk of the magnetic saturation of the materials, an optimized design of the magnetic field topology has beneficial effects on the resultant electric field, which in turn governs the ion/electron losses to the thruster walls and the angle of divergence of the plume (beam focusing). This has a strong impact on the thermal design of the thruster, on its lifetime and on the contamination requirements for spacecraft integration. Magnetic simulation already performed (Fig. 13) provided preliminary dimensioning of the magnetic circuit - geometry and coils current - however further magnetic simulations aiming at optimizing the magnetic field profile and magnetic circuit performance coupled with an extensive experimental characterization will be performed.

Besides, a quasi-static and a modal analysis were carried out and results show that even if at this stage of development, the thruster is potentially able to survive the load of launch environment. The ceramic chamber is potentially critical. Bonding layer effects, neglected in the present analysis, could lead to stress relaxation. Also, as thruster mass is about 50 kg, the design of the spacecraft interface shall require great care.



Figure 14. Alta IV10 Space Simulator

Finally, Alta's IV-10 space simulator (Fig. 14) is fully available for industry and agencies development programmes, as well as for Alta's own EP undertakings. It is currently the largest European facility for EP testing in terms of diameter, internal volume - 6 m in diameter and 10 m in length - and pumping speed (>300.000 l/s on xenon). Its characteristics were tailored to reduce the effects of background pressure, contamination and electromagnetic effects due to chamber walls on thruster performance. The facility is lined with LN2 cooled shrouds in order to improve the pumping speed and perform thermal vacuum tests and the thousands hours of endurance test campaigns confirmed its top level performance in terms of ultimate vacuum level ($2e-9$ mbar) and of operating vacuum ($< 3e-6$ mbar @ 3.6 mg/s of xenon). Its architecture, specifically designed for testing high power thrusters, is therefore suitable for the HT-30 test campaign. It also allows for a high degree of flexibility and expandability to comply with the most stringent requirements possibly demanded by development, qualification and acceptance test from thruster to sub-system, up to spacecraft level.

V. Conclusion

During last decades, a number of previous works have been demonstrating the potential benefits deriving from high power EP systems for various mission classes. Due to the present growing trend in spacecraft on-board available power and to a renewed interest in high power Electric Propulsion, Alta is developing a 30-kW Hall thruster as enabling technology for future space exploration and transportation activities.

Early research and development activities underway at Alta and perspectives for future work to address the technological issues related to such high power EP device are presented in this study.

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