Development of a 20 kW Class Hall Thruster for Space Transportation and Exploration

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The Case for High Power Electric Propulsion

The expansion of human presence in space will certainly pose the need to develop very-high-power electric propulsion systems

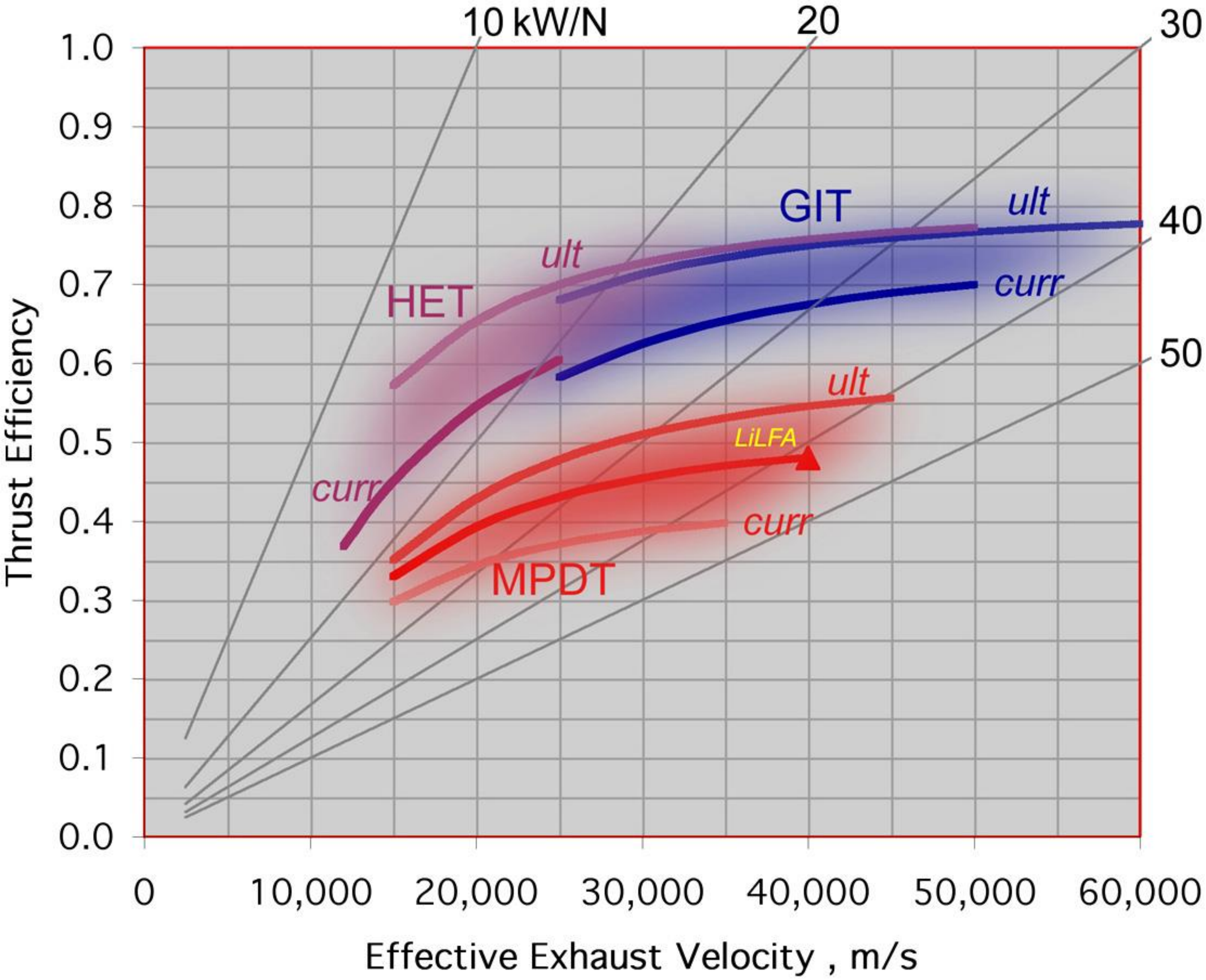
- High power electric propulsion can enable performing deep space observation and sending probes to the edge of the Solar System …
- High Isp propulsion needed for the higher energy missions, with Isp levels of up to 10,000 s and beyond, to minimize launch mass
- High power levels also needed for crewed planetary exploration vehicles, but larger thrust leves required for acceptable trip times
- High power applications to be generally based on nuclear power systems; high performance photovoltaic power generation also applicable for inner solar systems operations
- Higher power propulsion systems obtainable in principle by clustering; but 0.1 to >1 MW single thruster capability needed, so that the number of thrusters per spacecraft remains reasonable.

Propulsion Options

- Among the various electric propulsion concepts proposed in the past decades, only a few types of devices provide, in principle, the ability to process hundreds of kilowatts to megawatts of power at reasonably high efficiencies
  - Ion thrusters
  - Plasma thrusters
    - Hall Effect Thrusters, HEMP Thrusters
    - MPD Thrusters
  - Arcjets
  - Other Concepts
    - VASIMR, Helicon, . . .

- Among the above categories only the first two seem to meet the relevant selection criteria for the intended missions in terms of performance capability, lifetime potential, mid-term TRL, . . .
- Ion thrusters, in particular, appear especially suited for very high Isp , while plasma thrusters allow achieving higher thrust densities

Performance Levels



Potential High Power SEP Applications

Today's scenario already features a plethora of available solutions for in space power generation up to 20 kW and above, but no Hall thruster above 10 kW was flown yet, nor a full qualified solution exists for this class of power. Consequently, there seem to exist ample opportunities for such high power EP systems

Even in the current market condition, a speculation based on trends can be drafted. Market niches that could benefit from a high power Hall thruster in the near future and beyond are basically:

- **Future large GEO SatComs.**
- **Space transportation; space tugs (either in Earth Orbit and within the Solar System);**
- **Servicing**
- **Exploration missions**
- **Science missions**

Potential Applications: Large GEO Platforms

As regards the large geostationary telecom satellites, commercial platforms able to produce 20kW or more of power are already a reality in the space telecommunication market. The American company Space Systems Loral with its high power platform SSL-1300 represents a reference in the market with its extensive flight experience.

Moreover, bus power levels up to 25kW are planned for the near future. Currently large coms satellites in the range of 20-25 kW use a cluster of smaller 5 kW HET thrusters for orbit raising. Once at GEO these smaller thrusters are used for attitude control/station keeping. In this frame, an EOR with a single, higher power, thruster would represent a competitive advantage for all electric satellites in terms of reduced time to orbit.

Therefore, the availability of a large power HET could change the paradigm, leaving the orbit transfer to the higher power thruster and utilising smaller thrusters for attitude control/station keeping, potentially with a subsystem mass advantage and more efficient use of the propellant. The situation would improve as the telecom satellites become more powerful, and larger in scale.

Potential Applications: Space Transportation; Space Tugs; Servicing

This case can be considered as a mix in between coms satellites and servicing. EP based space tugs are inherently suited to be re-usable, and a high power HET would contribute also to re-usability (less time through the van Allen Belt, lower solar array degradation).

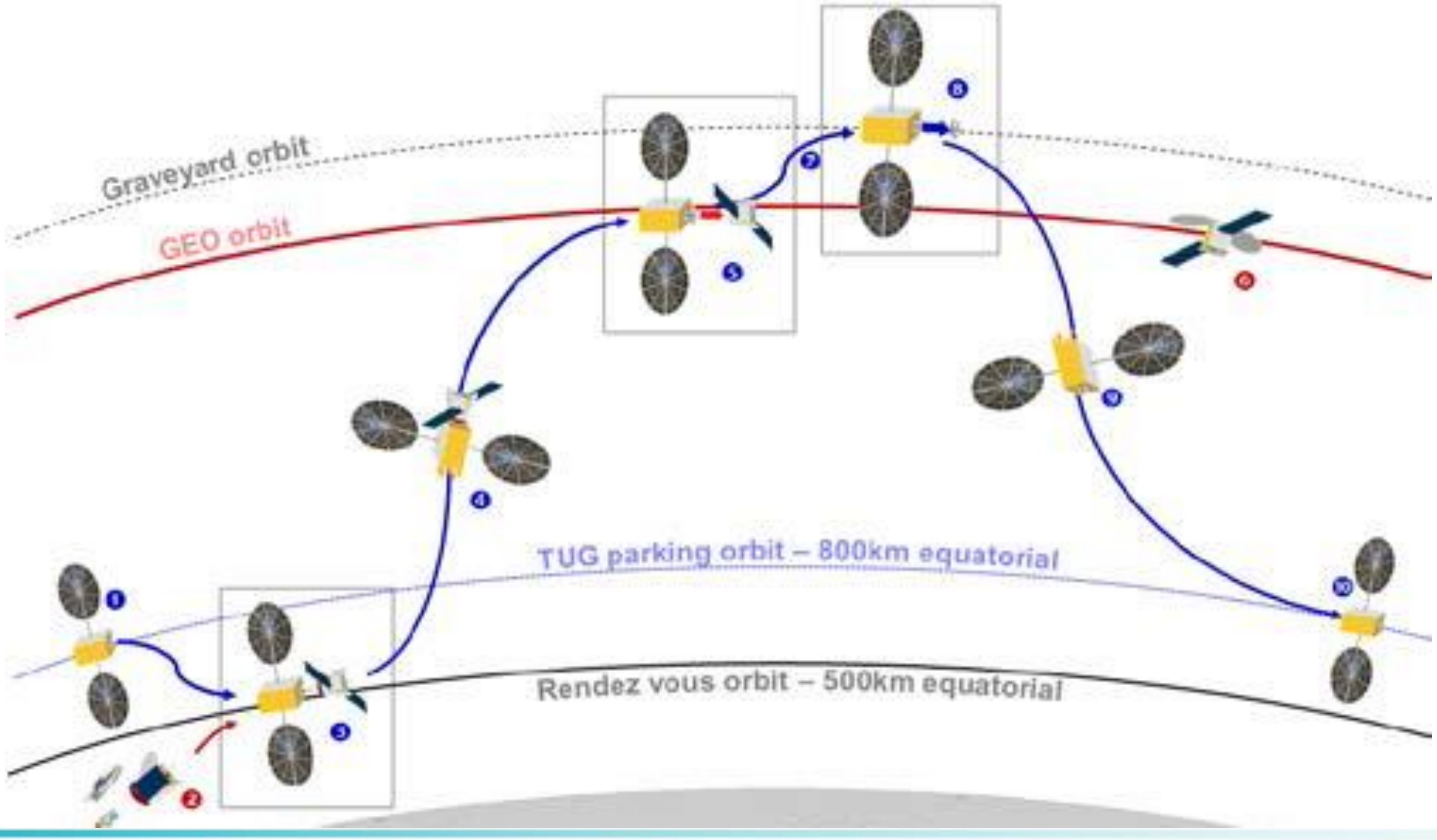
Space Transportation scenarios cover a huge number of possibilities: from space tugs moving up and down different orbits around Earth and lifting satellites up GEO slots, to in orbit maintenance spacecrafts with refuelling, de-orbiting or repositioning tasks, to shuttle tugs commuting between big depots or manned outpost orbiting in Lagrangian points (or NEOs) and Earth orbits.

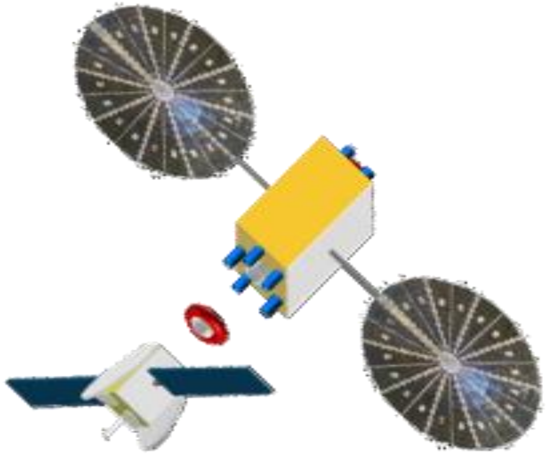
In a farther future ,space transportation may cover also asteroid mining missions.

Also servicing would make a clear case for high power HETs (or EP systems in general), due to their inherent aptness to re-usability, which would allow multiple orbit transfers or transfer of spacecrafts between orbits.

Space Tugs

SEP is a key enabler for a multi-mission transportation platform, especially for space-tug applications to transfer payloads between low Earth orbits and higher





(Source: **AIRBUS** DEFENCE & SPACE)

Potential Applications: Exploration Missions

Deep Space Gateway/Power Propulsion Bus

- Contribution to orbit transfer, including self-delivery of the PPB to Cislunar, excursions from one type of NHRO to another or from NHRO to EML2 and back (all missions foreseen in the DSG mission requirements) and driving tank loading
- Attitude control, in particular roll control for the DSG (the CG is quite off-set in the Y/Z plane from the DSG X-axis)
- Approximately 2.5 t of Xe are envisaged to be used over 15 years, with a max/min of power available for SEP of approximately 40/27 kW (and augmented DSG, beyond the basic configuration, i.e. with the addition of a second habitation module and a crew descent vehicle)

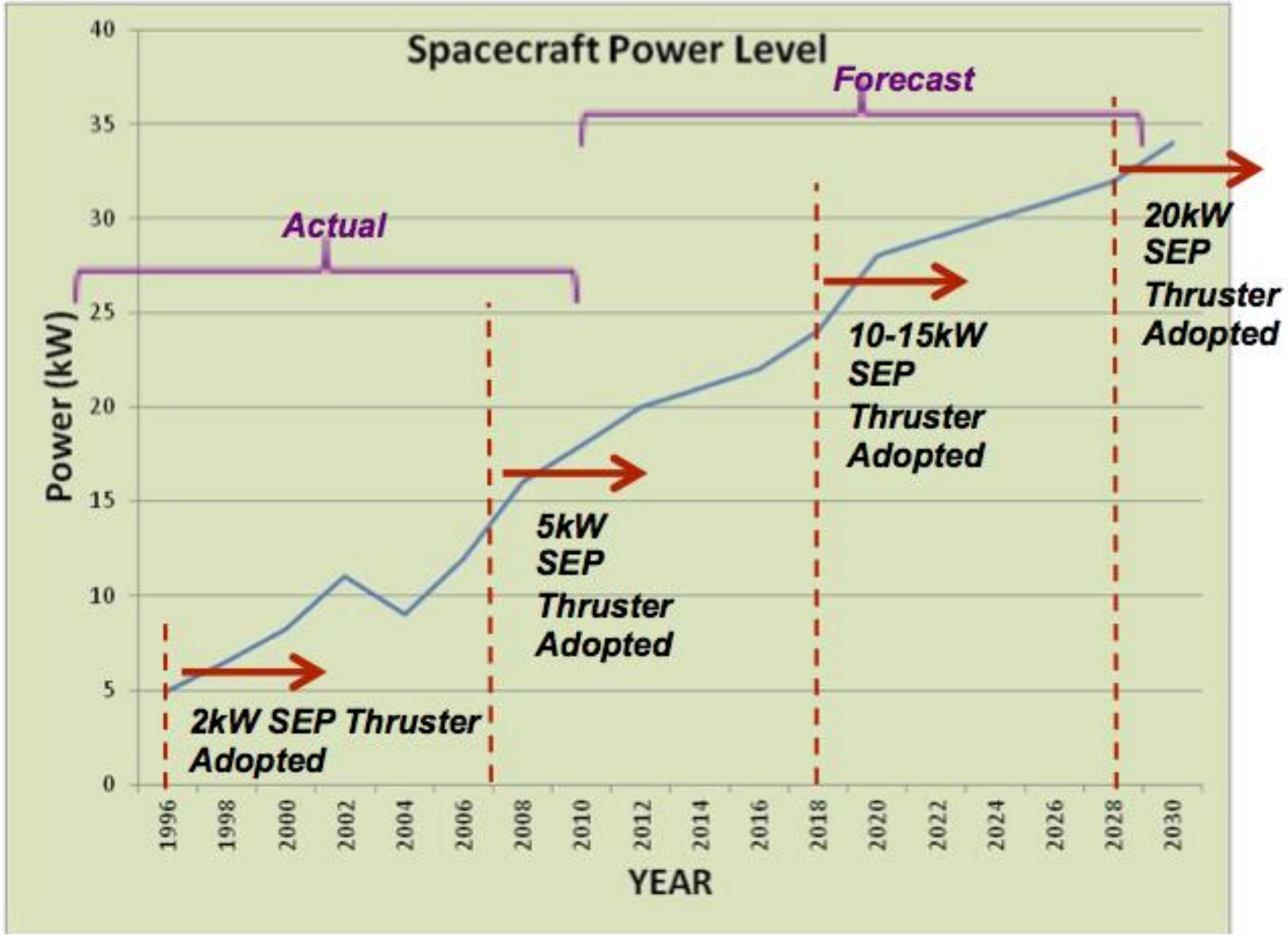
Logistics/module delivery

- Delivery and removal of non-time critical logistics or outfitting elements, in particular during phase

Potential contributions for DSG Phase 2

- Part of the HET thruster cluster for the Deep Space Transporter (150 kW) as European contribution to future Exploration missions, crew/logistics/outfitting missions to Mars

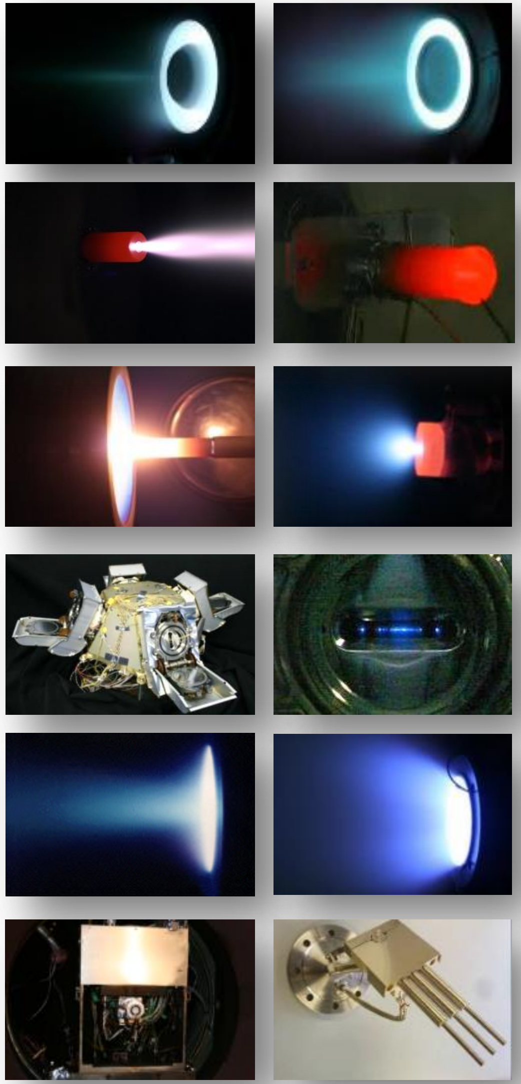
Trend in Power increase



Roger Myers, “Next Generation Electric Propulsion Systems for Satellites”, Presented at the 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan, July 7,2015.

Electric Propulsion at Sitael

A long standing involvement in EP



- **Hall Effect Thrusters**
  - From 100W (12 mN) to 5kW (350 mN)
  - Orbit raising, station keeping, exploration
- **Electrothermal Thrusters (Resistojets, Arcjets)**
  - 50-250mN
  - Station keeping
- **Hollow Cathodes**
  - Low and High Current
- **Field-Emission Electric Propulsion**
  - 150μN
  - Very accurate pointing for Scientific missions
- **Magneto-Plasma-Dynamic Thrusters**
  - 1-150N
  - Future Deep Space Exploration Programmes
- **Diagnostics Equipment**
  - Thrust Measurement Systems
  - QCM, Faraday Cups, RPA, Langmuir Probes
  - Thermography, Telemicroscopy

Electric Propulsion at Sitael

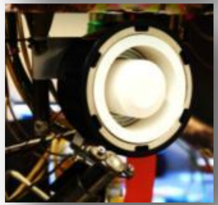
Hall Thruster Technology

Through its Alta component, Sitael’s heritage in Hall Thrusters dates back to the mid 1990s. Hollow Cathodes for low and high currents were also developed in parallel. As of today, the Sitael group can offer a complete HET propulsion subsystem, including thruster, cathode, PPU and fluidic line, completely based on proprietary technology

HT100

Power: 100-350 W
Thrust: 6-18 mN
Efficiency: 40%

Mass: < 450 g
Isp: 1000-1600 s
Permanent magnets



HT400

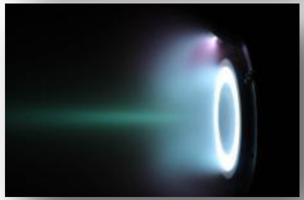
Power: 200-1000 W
Thrust: 20-50 mN
Efficiency: 50%

Mass: < 900 g
Isp: up to 1850 s
Permanent magnets

HT5k

Power: 2,5-7,5 kW
Thrust: 150-350 mN
Efficiency: > 55%

Mass: 12200 g
Isp: 1700-2800 s
Coils



Technology Development Lines

- Lifetime extension
  - Novel magnetic topologies
  - Alternative ceramic wall materials
  - Alternative anode layer solutions (metal walls, wall-less,external discharge)
- Alternative propellants
  - Low purity Xenon,
  - Other gases (Krypton, Argon, Atmospheric), mixtures
  - Iodine
  - Bismuth, Cesium, Mercury
  - Solid
- Alternative configurations and clustering
  - Multi-channel
  - Racetrack
  - Cellular

- Improved cathode technology
- Performance improvement and optimization
  - Novel operating parameter sets (E, B, n)
  - Novel channel aspect ratios (L, b)
  - High thrust operation (High current/mass flow rate)
  - High specific impulse operation (High V)
- Power range extension
  - 5 ➔10 kW short term
  - 10 ➔30 kW medium term
  - 30 ➔ ? kW long term
- Performance modelling and prediction, plasma simulation
- Thruster/system/mission tradeoff studies

High Power Hall Thrusters Overview

- The first prototype of high power Hall Thruster was the Russian Fakel SPT-290, which was operated at 5-to-30 kW of power and was able to produce up to 1.5 N of thrust.
- The first high-power prototype developed in the USA was the NASA T-220, a 10 kW-class HT. This prototype was developed and tested at NASA GRC in 1998. Other American high power Hall thruster prototypes are the Aerojet Rocketdyne XR-12, tested at a power level of 12 kW and the Busek BHT-20k16.
- More recently, NASA GRC and Jet Propulsion Laboratory have been developing a 12.5 kW magnetically shielded Hall thruster, the HERMeS13.
- In Europe, the PPS-20k ML developed by SNECMA demonstrated a maximum thrust of 1050 at 22.4 kW of total power, with an anodic specific impulse of 2700 s.

	Voltage [V]	Discharge Power [kW]	Thrust [N]	Anodic Efficiency	Anodic Specific Impulse [s]	Outer Diameter [mm]
SPT 290	Up to 600	5-30	Up to 1.5	Up to 0.7	Up to ~ 3000	290
NASA 300M	200-600	10-20	Up to 1.13	0.57-0.73	1709-3154	300
NASA 400M	200-600	4-47	0.27-2.1	0.46-0.72	1741-3245	400
NASA 457M	300-650	9-72	0.37-2.9	0.46-0.65	1741-3245	457
BHT-20k	200-500	5-20	Up to ~1	0.51-0.69	1430-2630 ***	
PPS-20k ML	100-500	2.6 – 23.5 ***	Up to 1.05	~0.6 **	Up to 2700	320

* Total Power ** Total Efficiency *** Total Specific Impulse

The TRP Project

- The development of a 20 kW class Hall Thruster, the so called HT20k, was undertaken at SITAEL in the framework of the project "Very High-Power Hall-Effect Thruster for Exploration", a Technology Research Project (TRP) funded by ESA
- This TRP was aimed at performing all necessary preparatory activities in view of developing a 100% European very-high-power Hall-effect thruster capable of high performance levels and lifetime capability. Such preparatory activities included the breadboard design of the thruster and the associated high-current cathode, manufacturing and long-duration testing.
- The thruster unit requirements, as identified by ESA at the time, were:

Thruster Requirements	
Power	20 kW
Thrust	~1 N
Efficiency	> 0.6
Specific Impulse	> **2500** s
Total Impulse	> 30 MNs

Thruster Design

The design of the thruster was based on the extensive experimental and theoretical heritage of SITAEL in the field of HETs.

A broadly validated theoretical scaling methodology was used to size the HT20k (see for instance, M. Andrenucci, F. Battista and P. Piliero, "Hall Thruster Scaling Methodology," IEPC-2005-187)

HET scaling:

- A well known thruster is assumed as reference (e.g. Fakel's SPT 100)
- A set of basic parameters is selected in order to define the thruster geometry.
- Thruster performance and operating characteristics are obtained as a function of the basic parameters through a set of scaling relations describing the behaviour of the scaled-up thruster with respect to the reference thruster.

Thruster Design

- In the traditional design of a Hall thruster the channel dimensions scaled in order to keep the physical processes in the thruster unchanged with respect to the reference thruster
- This implies retaining the same plasma density as in the reference thruster. In this case, therefore, the channel area would scale linearly with the mass flow rate.
- When scaling up to very high power levels the application of this scaling approach leads to very heavy and large devices.
- With the purpose of increasing the thrust to mass ratio of the thruster, we decided to use a design approach different from the traditional one. The HT20k was designed to operates with a higher density than in the reference thruster.
- This increase of the plasma density implies an increase in the wall losses. However, the effect of wall losses in determining thruster performance tends to become less important when increasing thruster discharge power.
- A very compact high power HET could thus be obtained, while maintaining a high thrust efficiency.

Thruster Design

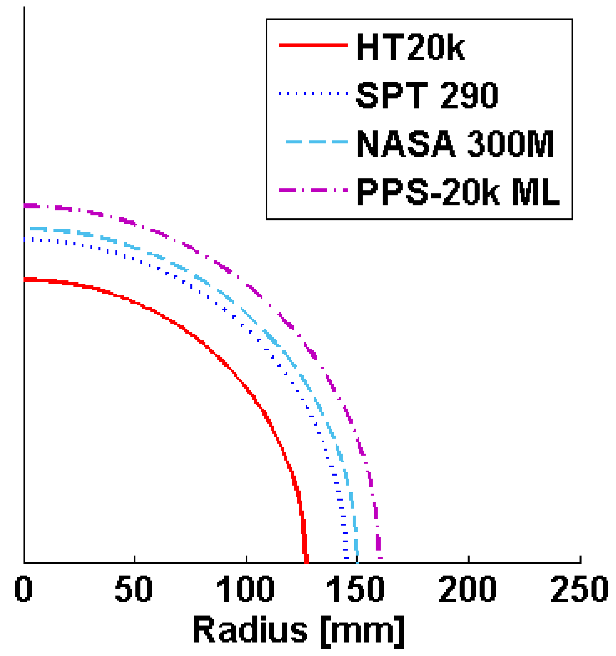
For a fixed discharge power of 20kW, a wide range of thruster configurations were analyzed. For each configuration:

- Thruster performance levels were estimated by means of the scaling methodology,
- Different configurations of the magnetic circuit were investigated,
- The magnetic circuit was optimized in terms of mass and dimensions.

The most compact configuration (outer diameter of 254 mm), compatible with the required performance was then chosen as the final HT20k configuration

The erosion rate was evaluated through scaling relations and included into the model, so as to define the ceramic wall thickness.

Thermal simulations were performed in order to evaluate the overall thermal stresses for the choose design.



Thruster	Outer Diameter [mm]
HT20k	254
SPT 290	290
NASA 300M	300
Snecma PPS–20k ML	320

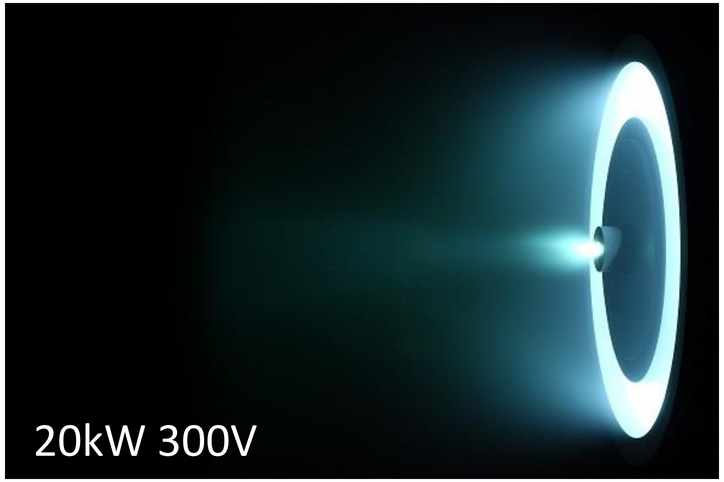
Test Campaigns

The HT20k performance was mapped over a wide range of voltages and power levels in the IV10 facility at Sitael, Pisa, between April 2015 and June 2017.

The first test campaign was carried out from August to October 2016

- **Only centrally mounted cathode**
- **Extensive characterization from 300 to 800V and from 10 to 20kW of discharge power (on Xe)**
- **An operating point at 1kV and 10kW was also tested**
- **Magnetic field peaks ranging from 20 to 30mT**

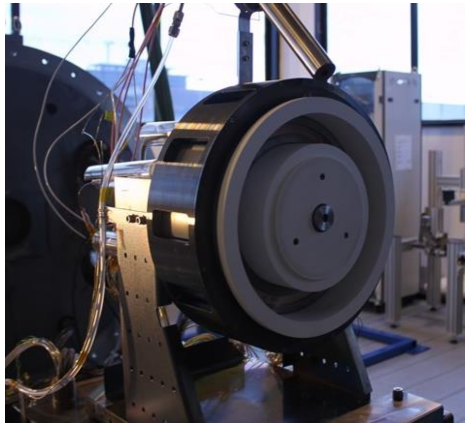
Notwithstanding its mechanical envelope, considerably compact if compared with other thrusters of the same power class, the HT20k exhibited a sustainable thermal behaviour within the required operating parameters

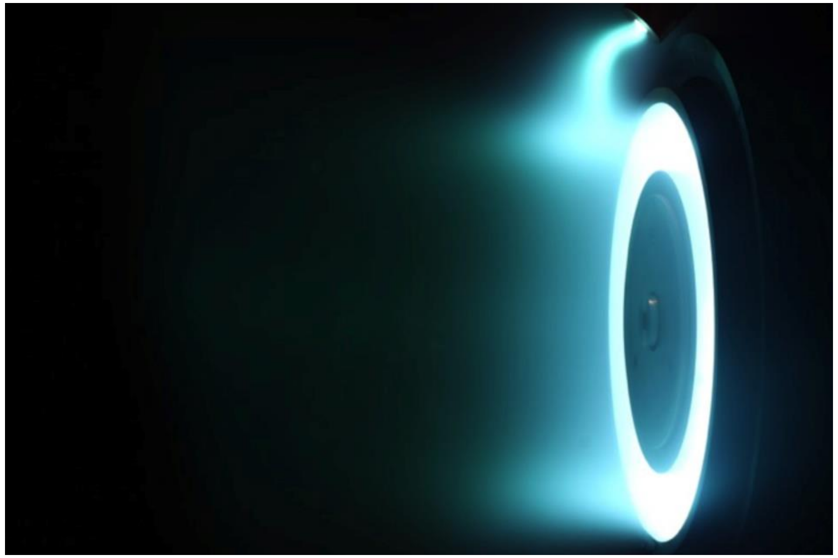


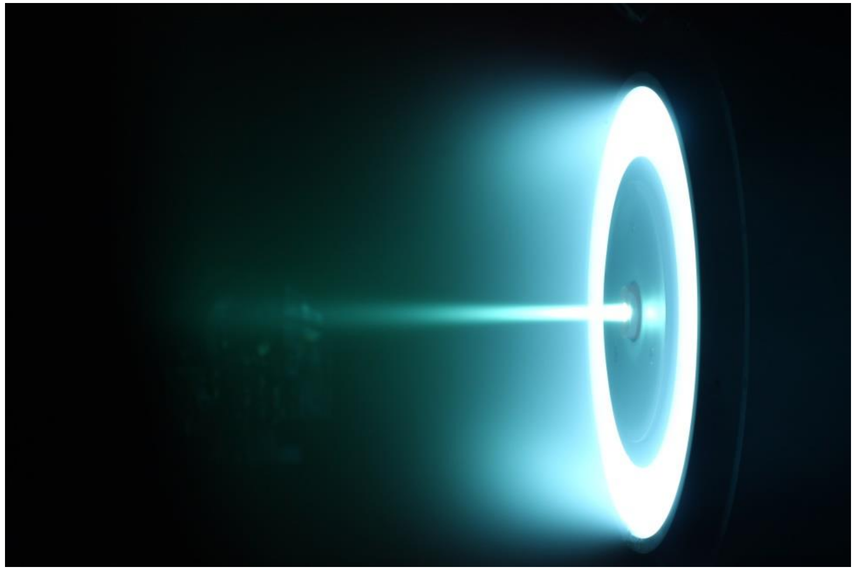
Test Campaigns

The second test campaign was carried out from March to May 2017

- A modified relative position of the electrodes was tested
- Shorter dicharge channel w.r.t. the first campaign
- Both Externally and centrally-mounted cathodes
- Characterization from 250 to 450V with both cathodes
- 150 hours wear test with external cathode





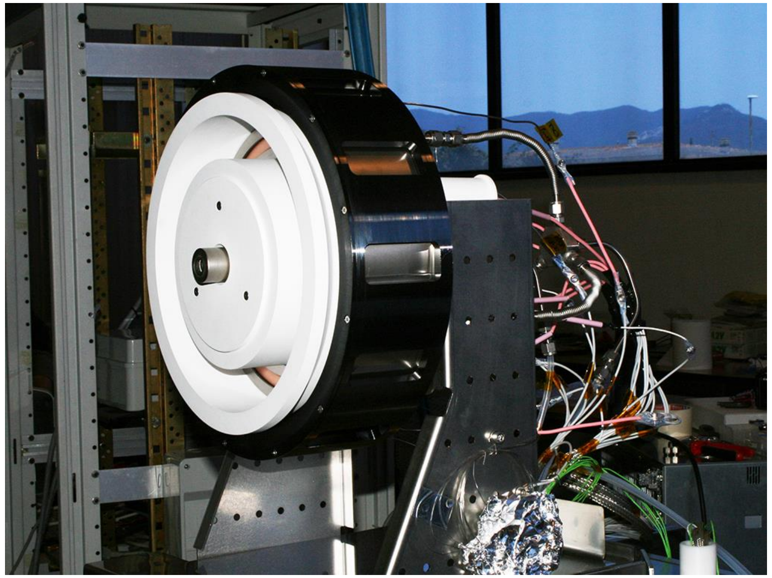


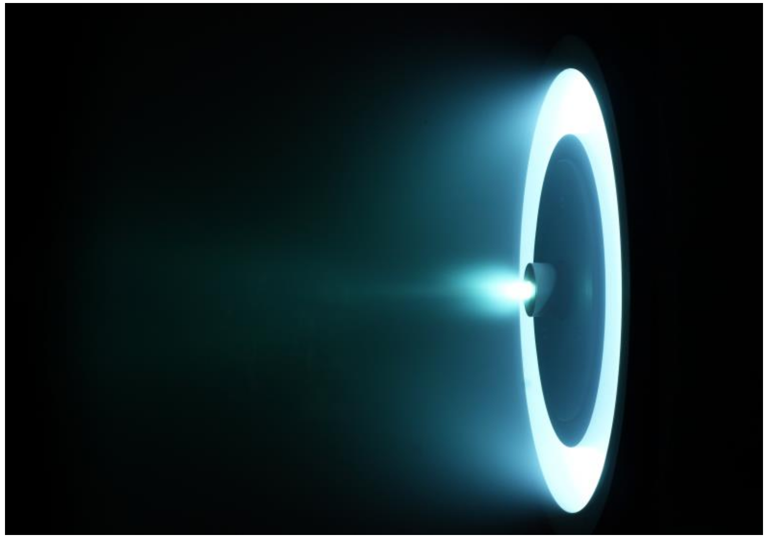
Test Campaigns

The HT20k performance was mapped over a wide range of voltages and power levels in the IV10 facility at Sitael, Pisa, between April 2015 and June 2017.

The thruster performance demonstrated during the TRP test campaigns over several hundred hours of continuous firing, are summarized below:

Thruster operating parameters and performance	
Voltage [V]	300-1000
Power [kW]	10-20
Efficiency	Up to 72%
Thrust [mN]	300-1100
Specific Impulse [s]	2000-3800





More info in: Antonio Piragino, Andrea Leporini, Vittorio Giannetti, Daniela Pedrini, Angela Rossodivita, Tommaso Andreussi, Mariano Andrenucci, "Characterization of a 20kW-Class Hall Effect Thruster," IEPC-2017-381, 35th International Electric Propulsion Conference, Atlanta, USA, October 8 – 12, 2017

Planned Development Activities: the CHEOPS Project

After completion of the TRP project, further development activities of the HT20k are kept running at Sitael in preparation for the activities planned under the H2020 Consortium for Hall Effect Orbital Propulsion System (CHEOPS) programme and of the HT20k XC GSTP programme, that has been just kicked-off (October 2017).

In particular, the CHEOPS project is focussed on the propulsion system as a whole (including thruster, cathode, PPU and Flow Management System). As regards the thruster, the plan includes:

- **Implementation of a magnetically shielded version to increase the thruster lifetime capability;**
- **Upgrading of the cathode, for extended lifetime;**
- **Improvement of the thruster unit (thruster + cathode) architecture;**
- **Optimization of interfaces between thruster PPU and FMS;**
- **Testing (characterization and 500 h endurance).**

Coupling tests between system elements are currently planned for May to October 2018. Tests on the overall propulsion system, including a 500 h endurance, are planned for April to October 2019.

Planned Development Activities: the GSTP Project

The goal of the project to be funded under the ESA GSTP (General Support Technology Programme) scheme is to make available a 20kW-class Hall Thruster with Extended Capabilities (HT20k XC) intended for the Space Transportation market.

In view of a near-future qualification and application to realistic mission scenarios, the basic HT20k design shall be substantially modified and upgraded. An advanced high power thruster unit will be designed, manufactured and tested. The thruster unit will consist of an improved version of the HC60 hollow cathode and of a novel design model of 20 kW class Hall thruster designated HT20k XC.

The HT20k XC will be optimised to operate nominally at high-voltage (600-800 V) and high specific impulse (3000-3500s anodic) and will feature an upgraded magnetic topology in order to ensure lifetime capabilities compatible with longer-term space transportation and space exploration mission requirements. After full characterization on Xenon and Krypton, the thruster will undergo an extended test on Krypton at the nominal operating point, to assess the extended operation behaviour and pave the way for its qualification.

The initial test campaign for the HT20k XC is currently planned for November 2018 to April 2019 in the IV10 test facility.

Planned development activities: DSG/PPE

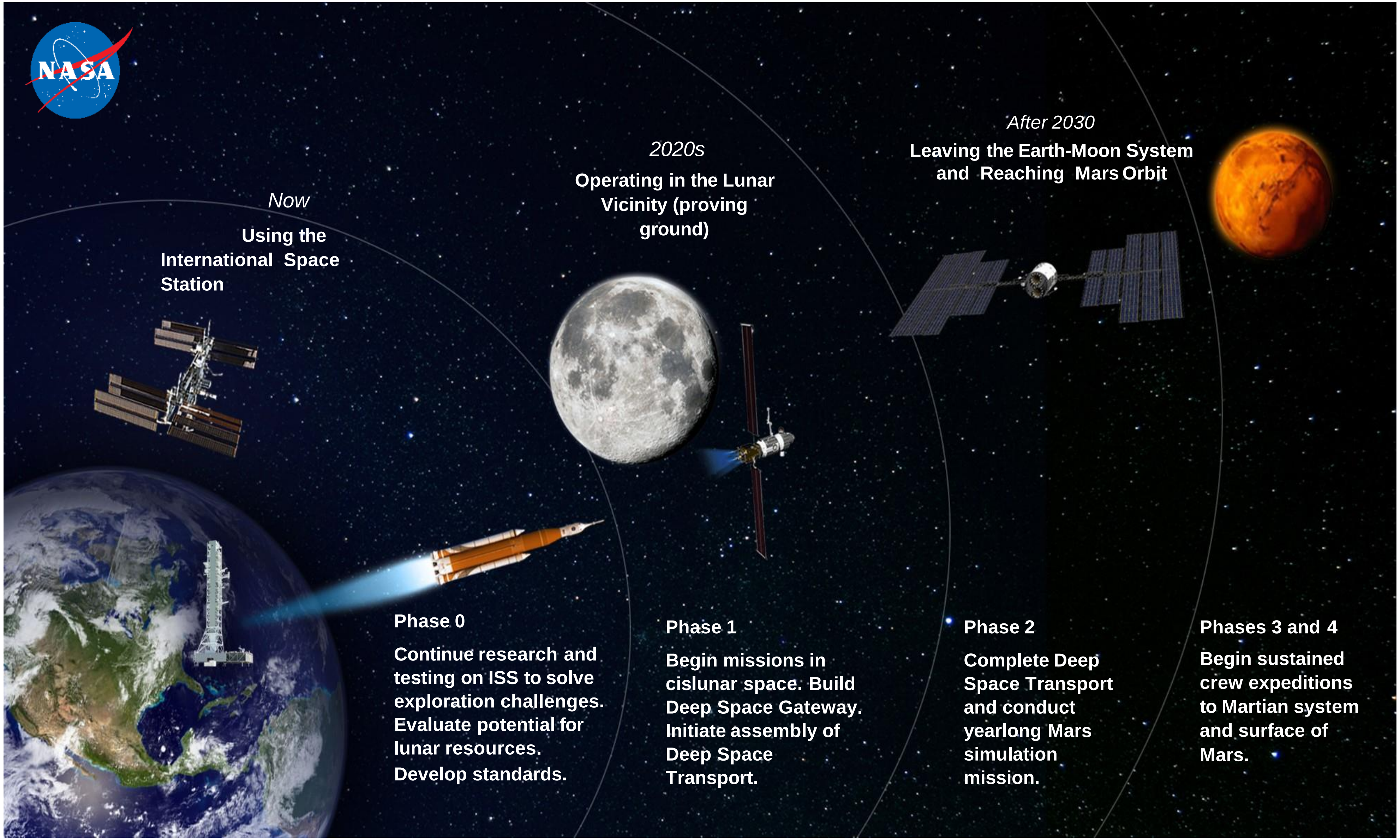
The current model of SITAEL's 20 kW class Hall thruster HT20k is also considered an eligible candidate for the European segment of the envisaged ESA/USA collaboration on the DSG/PPE SEP system, to be made available as a part of the ESA/USA collaboration on the DSG

An ITT for the preparatory phase of a qualification program aiming at making available such a thruster within the relevant time frame was recently launched by ESA

All these programmes are focussed on different features and applications of this class of thruster, as indicated above. Nevertheless, strong synergies are envisaged between these and other potential future programmes on very high power Hall propulsion, that can help collect the financial critical-mass required to raise the system TRL towards flight qualification.

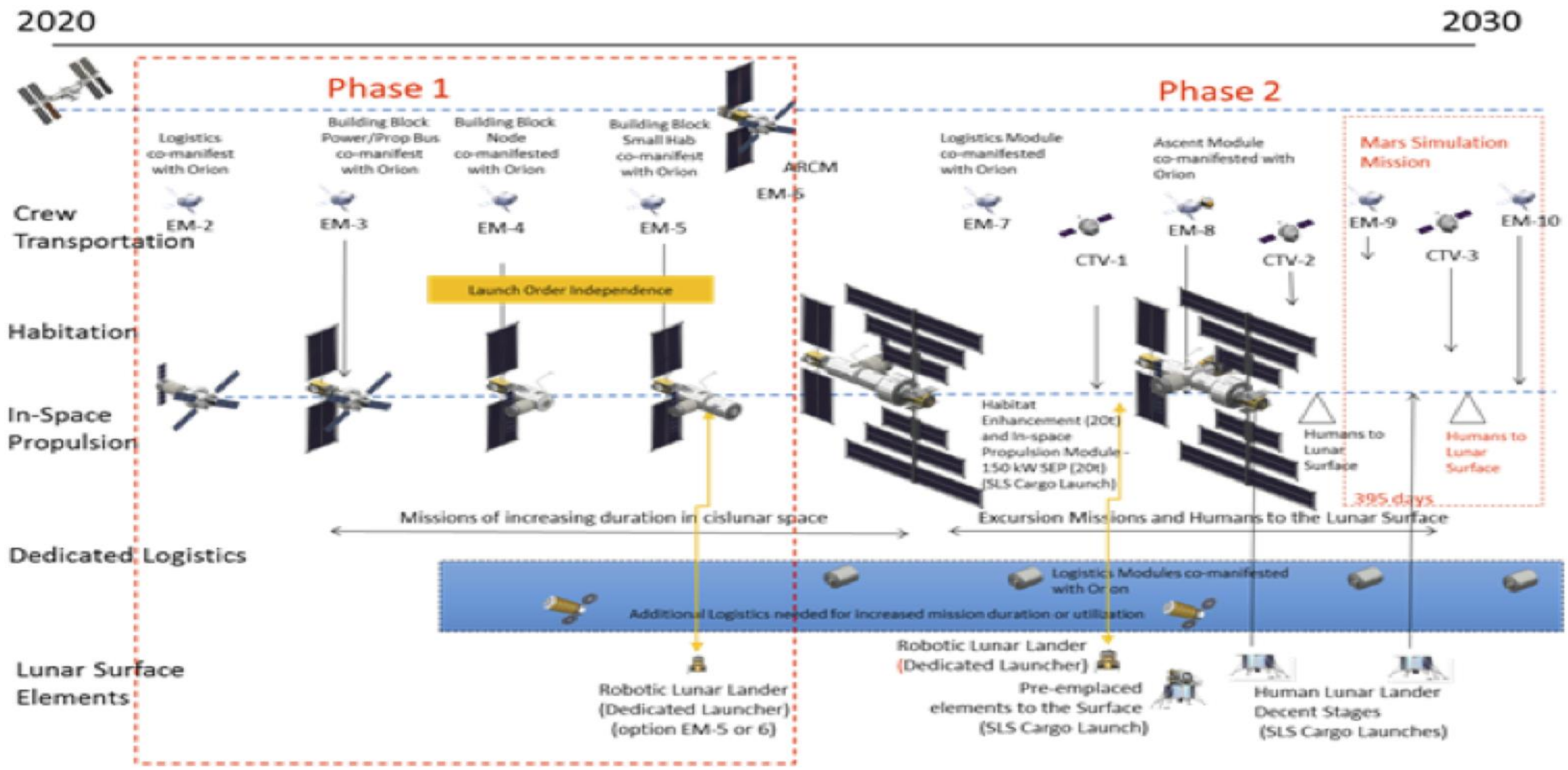
The NASA View

(March 2017)



Cislunar PPE as a Part of the Proving Ground Scenario

NASA's Notional Proving Ground Scenario



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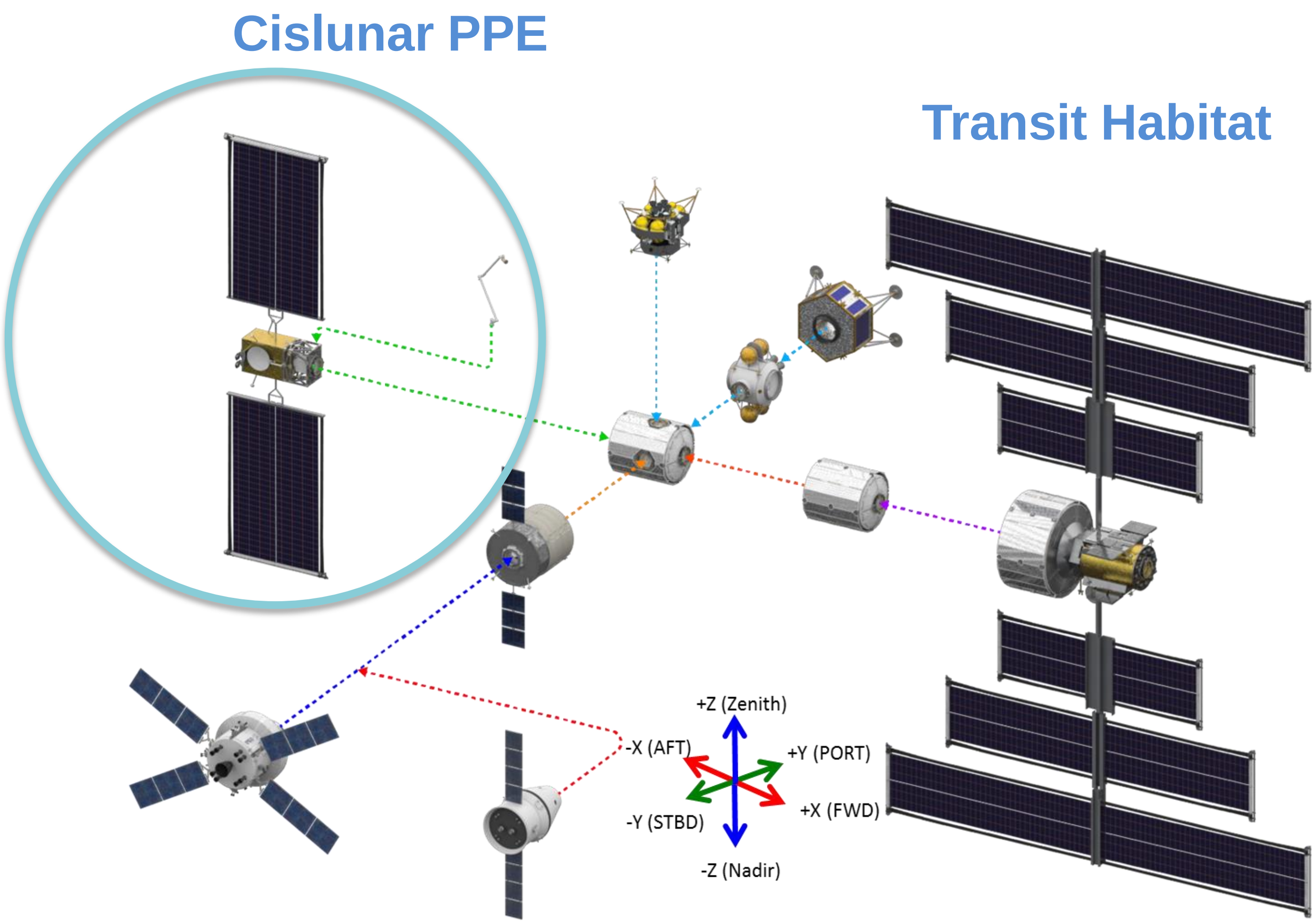


The Proving Ground Scenario (PGHS-15-02), proposed a Cislunar Power and Propulsion Element (PPE) as the initial element for proving-ground operations in the early 2020s.

Cislunar PPE as a Part of the Proving Ground Scenario

Cislunar Power and Propulsion Element Overview

The first permanent element of the Proving Ground is a robotic Cislunar Power and Propulsion Element (PPE) that can provide electrical power and orbit maintenance for the modules that will follow, some of which may not have those capabilities themselves.

This approach:

- substantially reduces the architecture's mass by eliminating the need for every element to be able to fly on its own;
- improves the architecture's resilience by allowing later elements to launch in any order.

The concept proposed is to develop a generic SEP Bus that could support multiple possible mission applications. Mission analysis has demonstrated that a 40kW SEP bus could be effectively utilized for

- technology demonstration increasing the state of the art for SEP systems;
- supporting potential satellite servicing missions;
- use as a power and propulsion bus for human missions in the Cislunar vicinity.

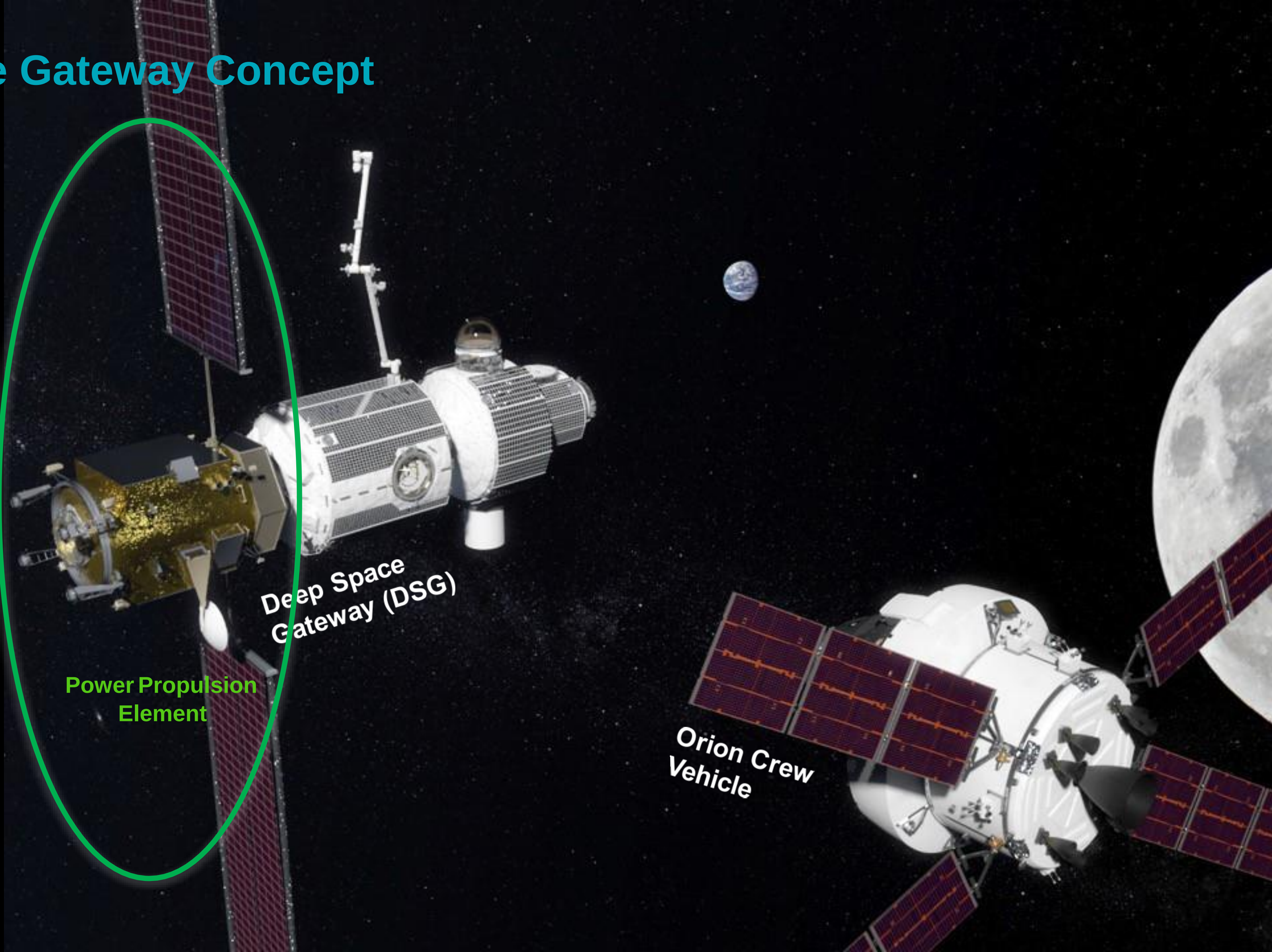
Deep Space Gateway Concept

The PPE SEP system consists of four boom-mounted 12.5 Hall Thrusters powered by two 25 kw-class solar array wings

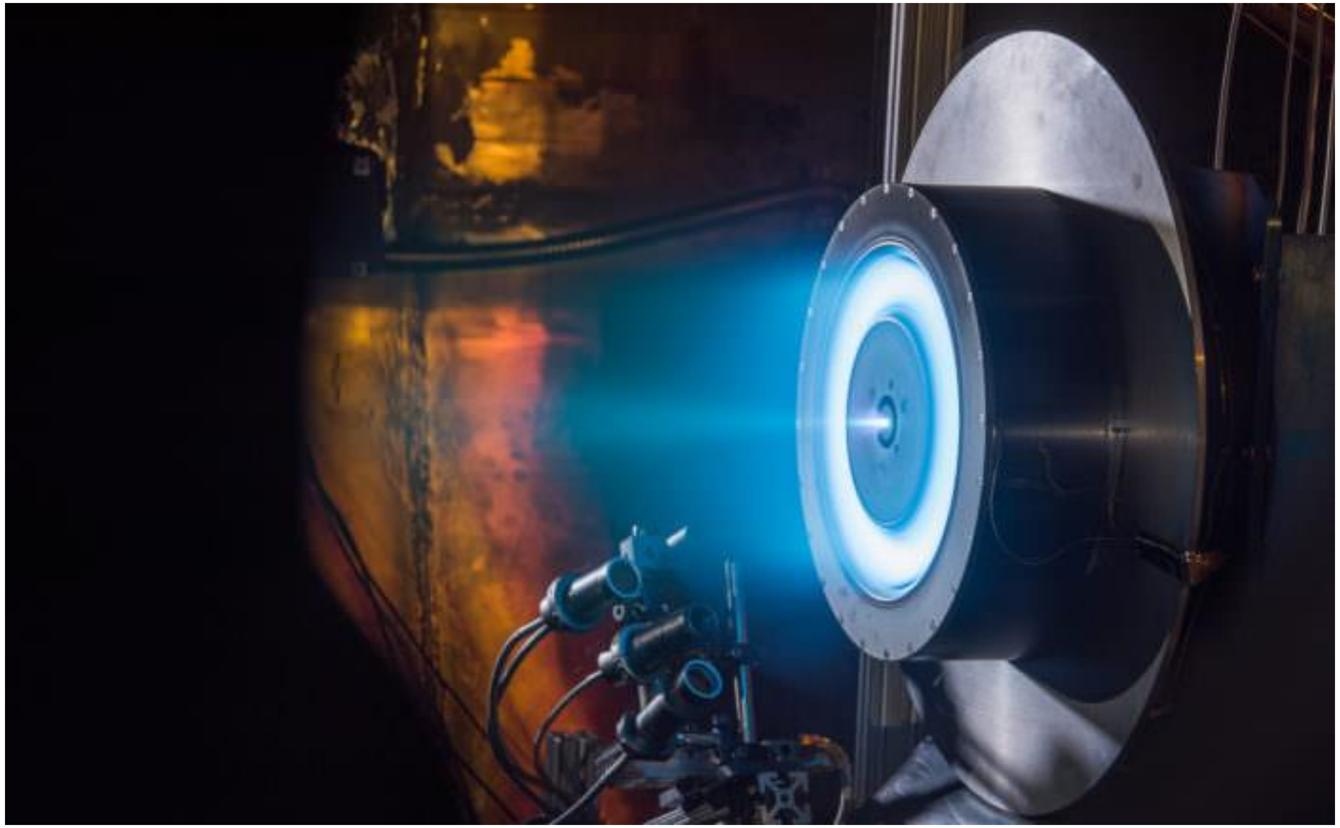
The four 12.5 kW-class Hall thrusters, utilize Xe propellant and produce a nominal Isp of 2600 s at 600 V.

The Power and Propulsion Element is designed to hold 5 t of Xenon propellant in four Composite Overwrap Pressure Vessels (COPVs).

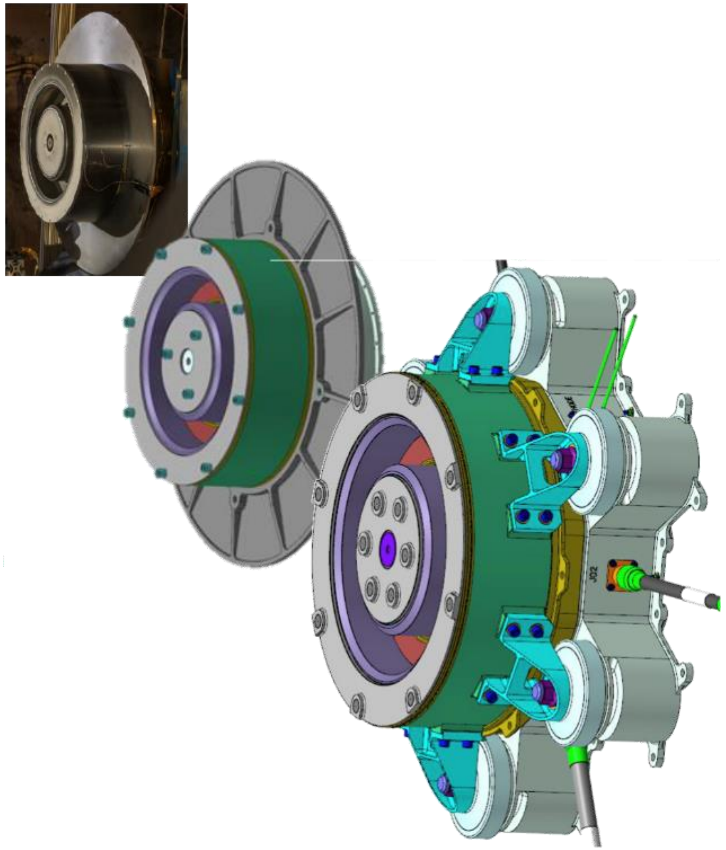
The PPE should have a mass of about 8-9 t, and should capable of generating 40 kW of solar electric Power.



High Power Hall Truster Development in the USA



This prototype 13-kilowatt Hall thruster was tested at NASA's Glenn Research Center in Cleveland and will be used by industry to develop high-power solar electric propulsion into a flight-qualified system.

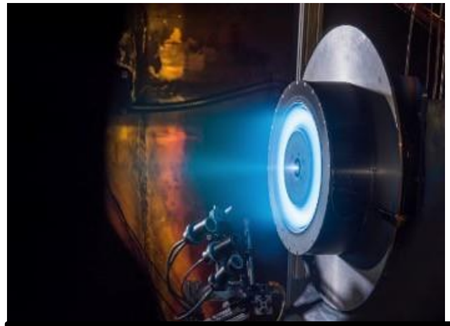


AEPS EDU thruster design improves upon NASA HERMeS development investments.

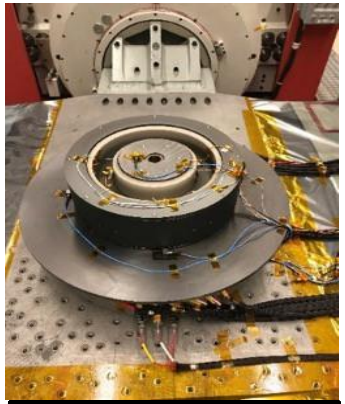
Solar Electric Propulsion Progress at NASA Glenn

Risk Reduction

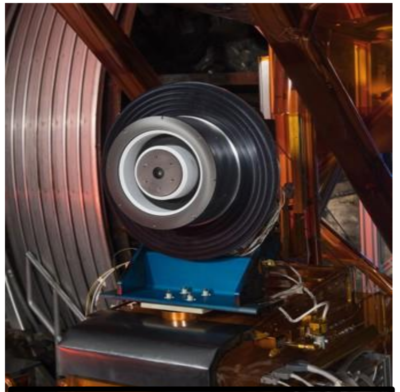
- **Technology Development Unit Thruster (TDU-1) and Power Processing Unit (PPU) Risk Reduction Tests at NASA-Glenn**
  - Confirmed thruster magnetic shielding (enables long-life operation)
  - PPU vacuum tests successfully completed
  - Conducted 12.5 kW thruster integrated tests w/ 300-V & 120-V PPUs
  - 2200 hours of testing completed
- **TDU-2 vibe and thermal balance testing**
  - Successfully completed random vibe, will run thermal test in chamber at JPL after sputter test and graphite chamber risk reduction tests are completed
- **TDU-3 wear testing in Vacuum Facility 5 at NASA-Glenn**
  - Represents flight-like configuration of downstream thruster on Advanced EP System (AEPS)
  - Final short duration risk reduction test segment completed at 600 V, 12.5 kW, 250 G
  - Over all four risk reduction test segments, the thruster was operated for 940 hours and consumed a total of 75 kg of xenon. Long duration 3000 hour wear test to follow.



Demonstrated full performance compatibility between thruster and PPUs



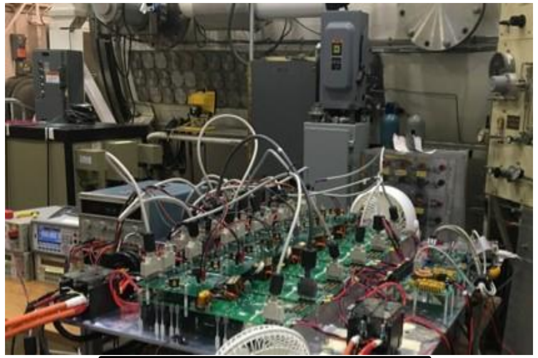
TDU-2 on Vibetable



TDU-3 Test Preparations

AEPS Contract

Early Integrated System Test in Vacuum Facility 6 - successfully conducted a series of hot-fire tests to demonstrate stable operation and characterize performance of Aerojet's PPU discharge module, a key PPU assembly. Test results inform AEPS design leading up to August Preliminary Design Review (PDR).



PPU Test

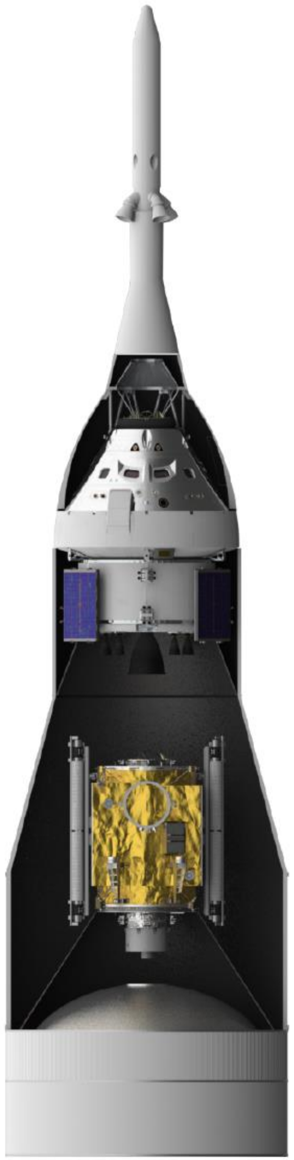
Proposed NASA/ESA Cooperation on the PPE

As a part of the intended NASA/ESA cooperation on Exploration programs ESA has been proposed to add a thruster module of European production to the cluster of four included in the basic PPE configuration.

This thruster would be placed in a pod to be added to the basic PPE configuration. This pod would also accomodate a dedicated power processor and other equipment associated with the thruster s/system, while the main source of power and propellant would be granted by the PPE itself.

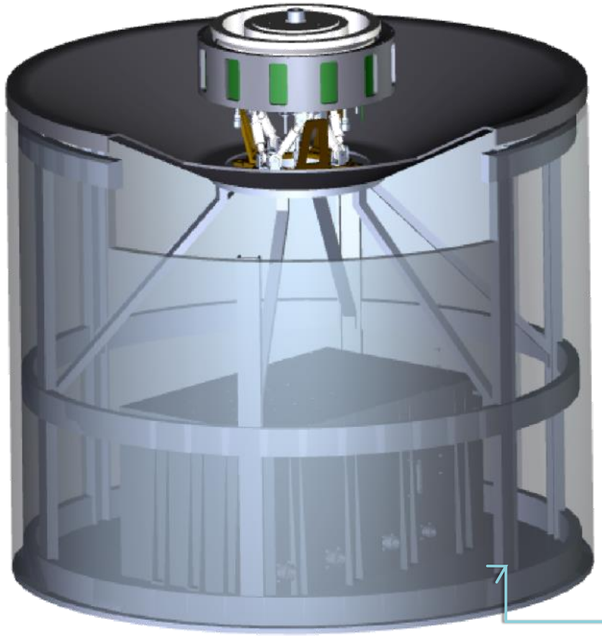
A preliminary conjecture regarding the coupling of the ESA HET Pod with the PPE foresees inserting the pod somewhere in the middle of the four booms supporting the four HET thrusters in the basic configuration.

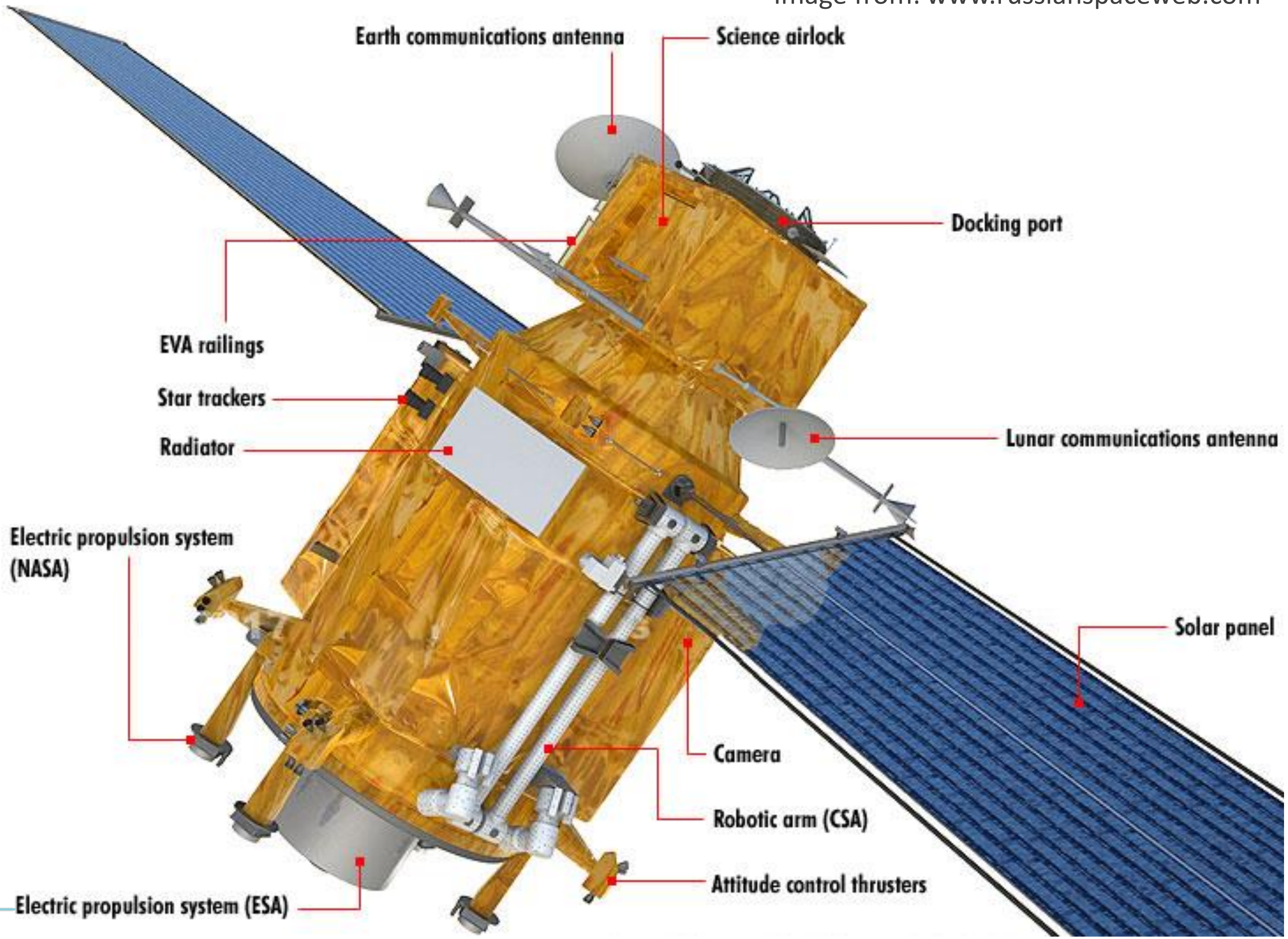
A more specific definition of the intended characteristics, specifications and interfaces of the intended ESA HET Pod are to be discussed between ESA and NASA at a later phase.



A European module for the PPE

Image from: www.russianspaceweb.com





Benefits of an early Demonstration of a 20 kW HET at the DSG

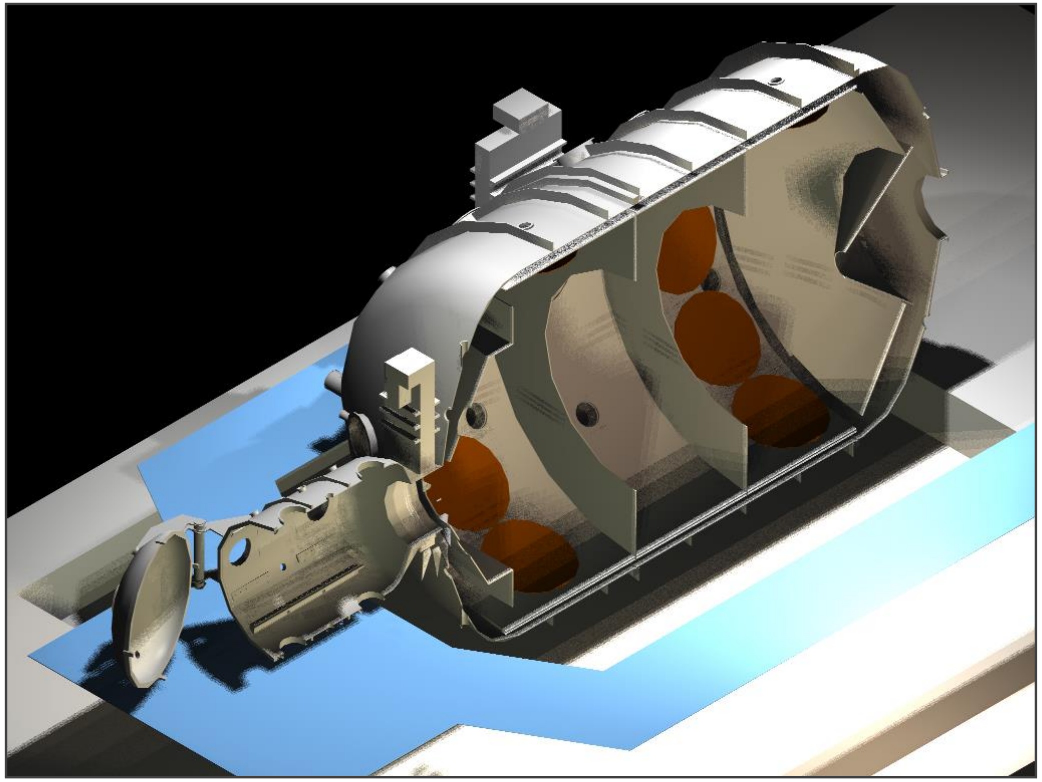
While probably far from coming near the qualification limits (100 MN-s impulse, 40000 hrs of operations, 16000 on/off cycles), an early demonstration on the DSG could provide useful on-orbit information years ahead of any other practical use of a 20 kW HET thruster, such as:

- **Achieve at least 2000 hrs of operations (approx. 800 kg of Xe) and 800 on/off cycles over 15 years (all TBC) – The achievement of such demonstration targets coupled with suitable extrapolation models would represent a strong validation of the thruster capability to eventually reach the intended qualification limits**

- **Identification of thrust effects/impacts due to surrounding thrusters and effects on structures/solar arrays (e.g., QCMs)**

- **Plume observations and visual examinations of thruster conditions via camera or other dedicated tool inspections (through robotic arm)**

Sitael IV-10 Vacuum Facility



Europe's largest spacecraft propulsion test facility: 6 m internal diameter, 12 m length, measured ultimate pressure 10^{-9} mbar, four stage pumping system currently capable of a pumping speed in excess of 300.000 l/s (1,500,000 l/s max) on Xe

CONCLUSIONS

SITAEL has a long standing experience in EP and competence to develop electric thrusters suitable to serve the purposes of future space missions in the domains of robotic on-orbit servicing, space tugging, space transportation, exploration

SITAEL's unique set of testing facilities and diagnostics provide the ideal environment to fully develop in-house all of the related thruster characterization, life-testing, qualification and acceptance activities

Provided that the necessary financial conditions are secured, SITAEL is ready to commit to make a 20 kW-class Hall truster available for flight within a 5 to 6 years timeframe

SITAEL is ready to act with respect to all of the relevant institutional and political authorities to secure the necessary support to this project


Thank you