Electric Propulsion activities at ESA

Jose Antonio Gonzalez del Amo
Head of the Electric Propulsion Section
European Space Agency, ESA

University of Bilbao, 6 March 2023

Funded by the European Union

Overview

Funded by the European Union

1. Introduction
2. Mission Applications
    - Telecommunications
    - Scientific Missions: Earth Observation & Space Science
    - Exploration
    - Cubesats
3. EP Capabilities in Europe
4. EU H2020 PSA: EPIC *(Electric Propulsion Innovation & Competitiveness)*
5. ESA Capabilities
    - ESA Technology Programmes for Technology Developments
    - ESA Propulsion Lab
3. Conclusions

Introduction:
Electric Propulsion

Funded by the European Union

- In general, Electric Propulsion (EP) encompasses any propulsion technology in which electricity is used to produce thrust.
- Electrical energy is used to ionize the propellant (gas, liquid, solid) and accelerate the resulting ions/plasma to very high exhaust velocities (10-40km/s)
- Electric Propulsion is very fuel efficient, but much lower thrust levels achievable than for chemical propulsion.
- Depending on the process used to accelerate the propellant, electric propulsion thrusters fall into three main categories.

- **Electrothermal**
  - **Resistojets***
  - **Arcjets***

- **Electrostatic**
  - **Gridded Ion Engines (GIE)***
  - Colloid
  - Field Emission Electric Propulsion (FEEP)

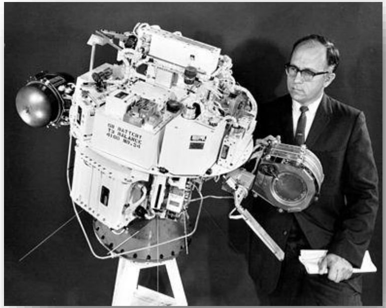
- **Electromagnetic**
  - **Hall Effect Thruster (HET)***
  - **High Efficiency Multistage Plasma Thruster (HEMPT)***
  - Pulsed Plasma Thrusters
  - Magneto Plasma Dynamic Thrusters

***Applicable for GEO satellite propulsion**

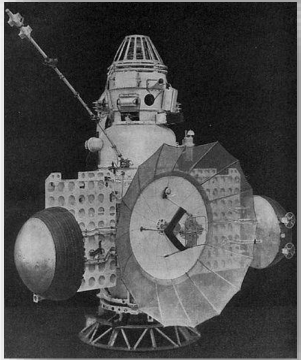
Funded by the European Union

Introduction:
History of Electric Propulsion

- First uses of electric propulsion in space in early 1960’s:



SERT-1 (US)
July 1964
Ion Thruster



ZOND-2 (Soviet Union)
Nov 1964
Pulsed Plasma Thruster

Increasing number of EP systems flown late-1970’s onwards (resistojets, arcjets, ion thrusters, hall effect thrusters).

- Station-Keeping (NSSK, EWSK)
- Orbit Raising

ARTEMIS (ESA)

- De-orbiting

GOCE (ESA)

- Drag-compensation

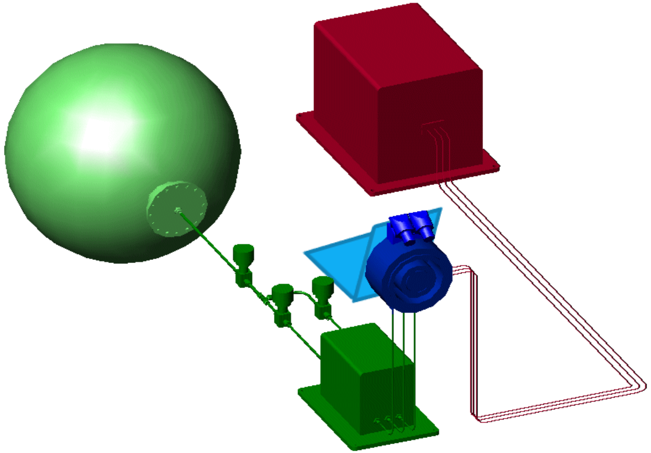
BepiColombo (ESA)

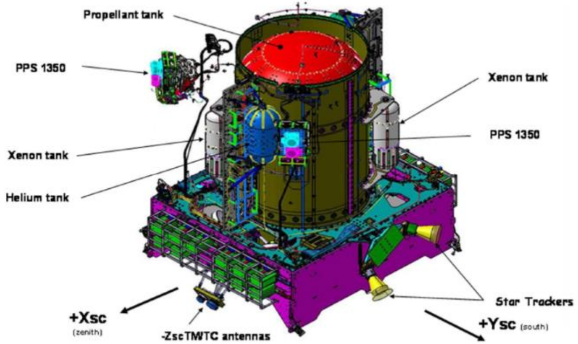
- Interplanetary transfer

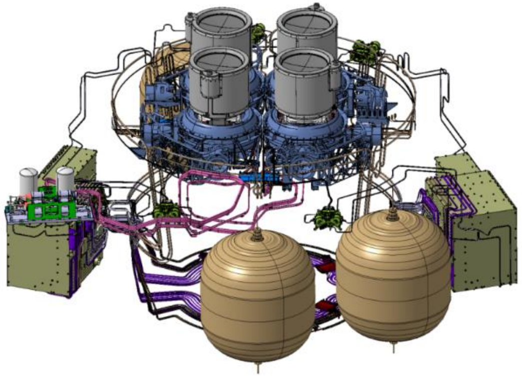
Introduction:
Electric Propulsion Systems

Funded by the European Union

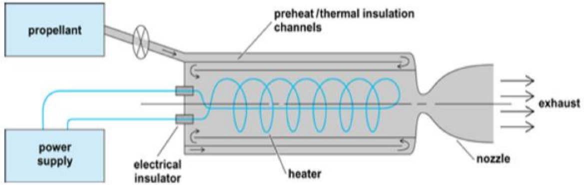
- Propellant Storage
- Fluidic Control
- Power Conditioning
- Pointing Mechanism
- Thruster

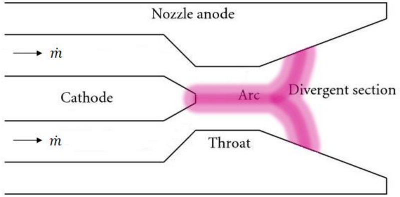


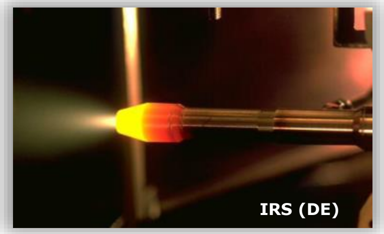




Electrothermal Thrusters: Resistojets / Arcjets



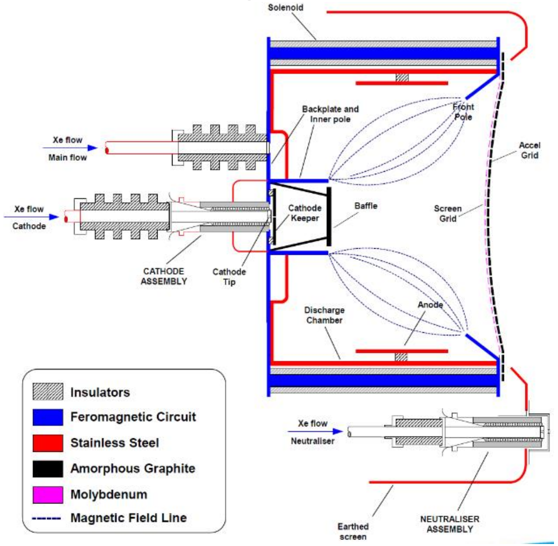


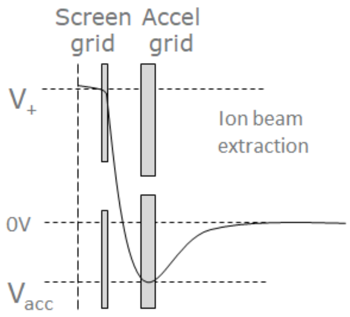


- Resistojets are electrothermal devices in which the propellant is heated by passing through a resistively heated chamber or over a resistively heated element before entering a downstream nozzle.
- The increase in exhaust velocity is due to the thermal heating of the propellant, which limits the specific impulse to low levels (<500 s).
- Resistojets are relatively simple devices and can be used as auxiliary propulsion on satellites.
- The amount of energy added to the flow in a resistojet is limited by the maximum working temperature of the heating element.
- In an Arcjet thruster, an electrical discharge (arc) is generated within the flow between a cathode and anode. This imparts additional energy to the propellant flow, and therefore, higher specific impulse is achievable compared to resistojets.

Electrostatic Thrusters: Gridded Ion Engines (GIE)

- Gridded Ion Engines comprise three main processes:-
  - Generation of a plasma discharge via ionization of propellant by electron bombardment.
  - Extraction of ions and subsequent acceleration to very high velocities across potentials of few kV applied between multi-aperture grids (electrodes).
  - Space-charge neutralization of the ion beam using an external electron source (cathode)





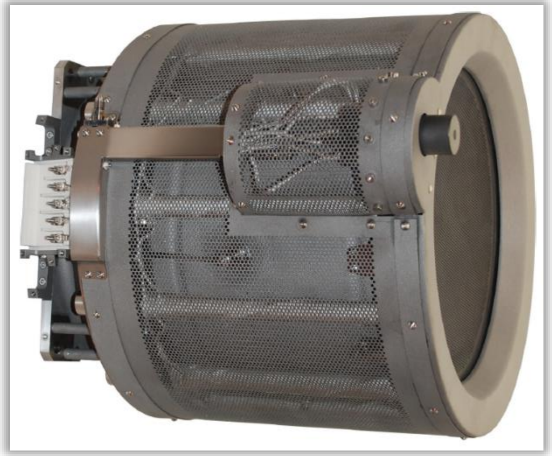
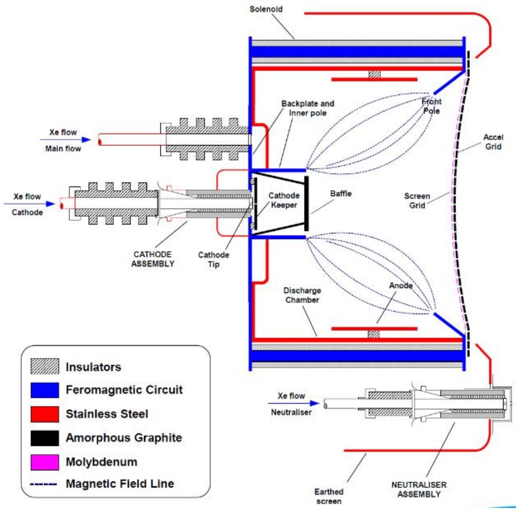


Image: QinetiQ

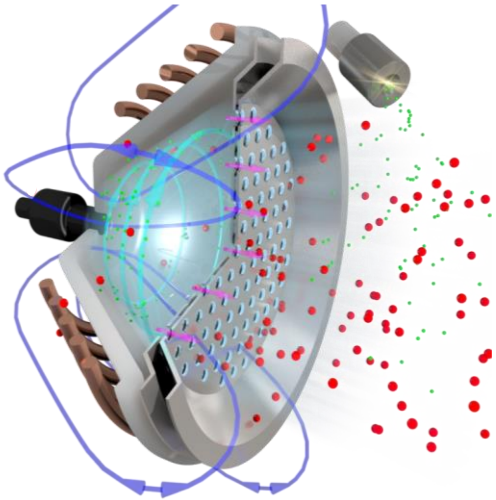
Electrostatic Thrusters: Gridded Ion Engines (GIE)

Funded by the European Union

- The plasma discharge in GIEs can be achieved by a number of methods:
  - Direct electron bombardment, whereby energetic electrons are emitted from an internal cathode inside the discharge chamber to ionize neutral particles. [Kaufman GIEs, e.g. QinetiQ T6 thruster]
  - Power coupling via radio-frequency energy or microwaves to excite electrons within the discharge chamber and maintain a plasma discharge. [Radio-frequency Ion Thruster (RIT), e.g. Ariane Group RIT-10 thruster]



Kaufman thruster



$$B_z = \mu_0 \frac{N}{l} I_{RF} e^{i\omega t}$$

$$E_\theta = -\frac{i\omega r}{2} B_{z0} e^{i\omega t}$$

RIT thruster

Electrostatic Thrusters:
Field Emission Electric Propulsion (FEEP)

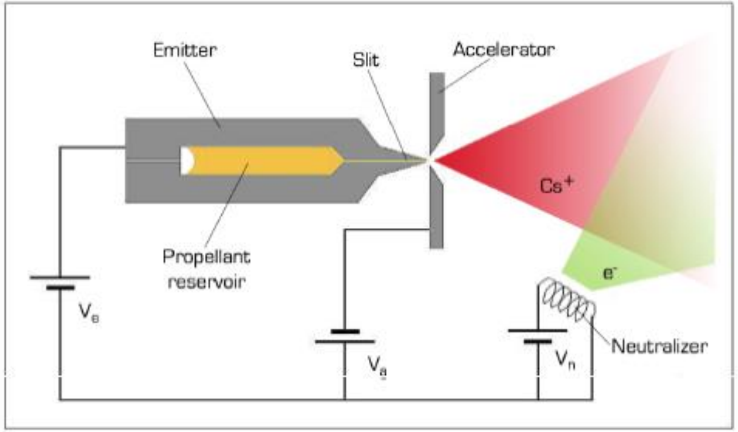
FEEP is an electrostatic type thruster:

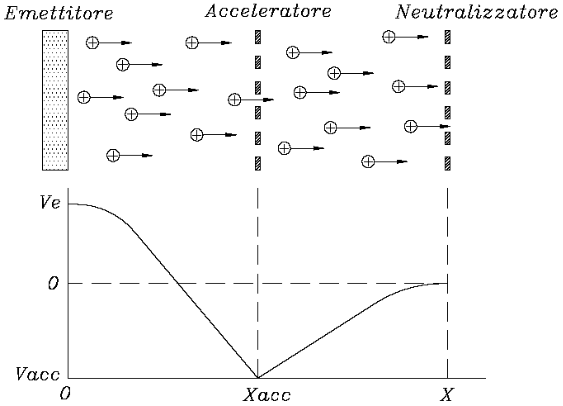
⇒ thrust is generated by ions accelerated by electric fields at high exhaust velocities;

⇒ electrons need to be emitted downstream in the same quantity for charge balancing.

$$qV_e = \frac{1}{2} M v_e^2 \Rightarrow v_e = \sqrt{\frac{2qV_e}{M}}$$

$$\dot{m}_i = \frac{M I_b}{q} \qquad I_b = I_e - I_a$$

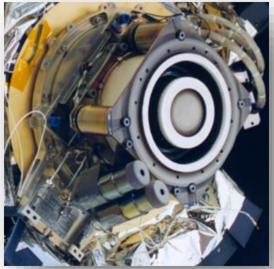


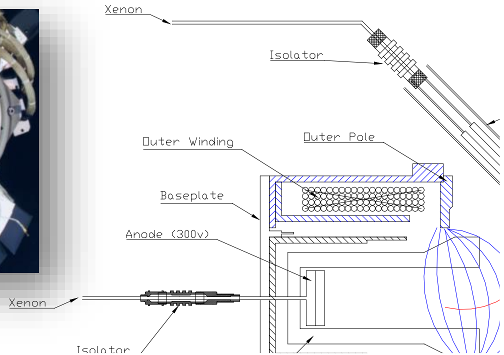


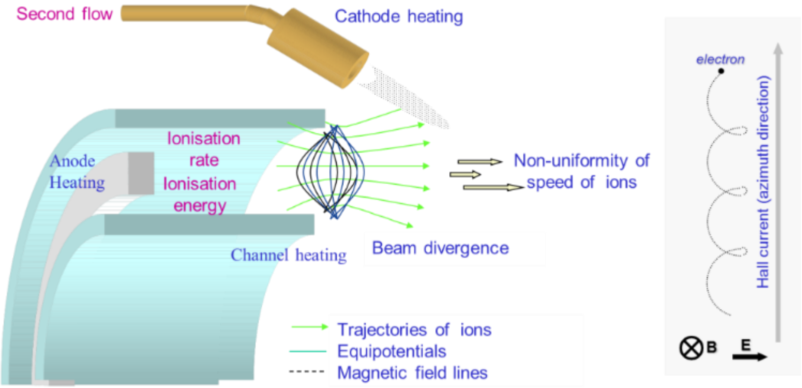
Electromagnetic Thrusters:
Hall Effect Thruster (HET)

Funded by the European Union

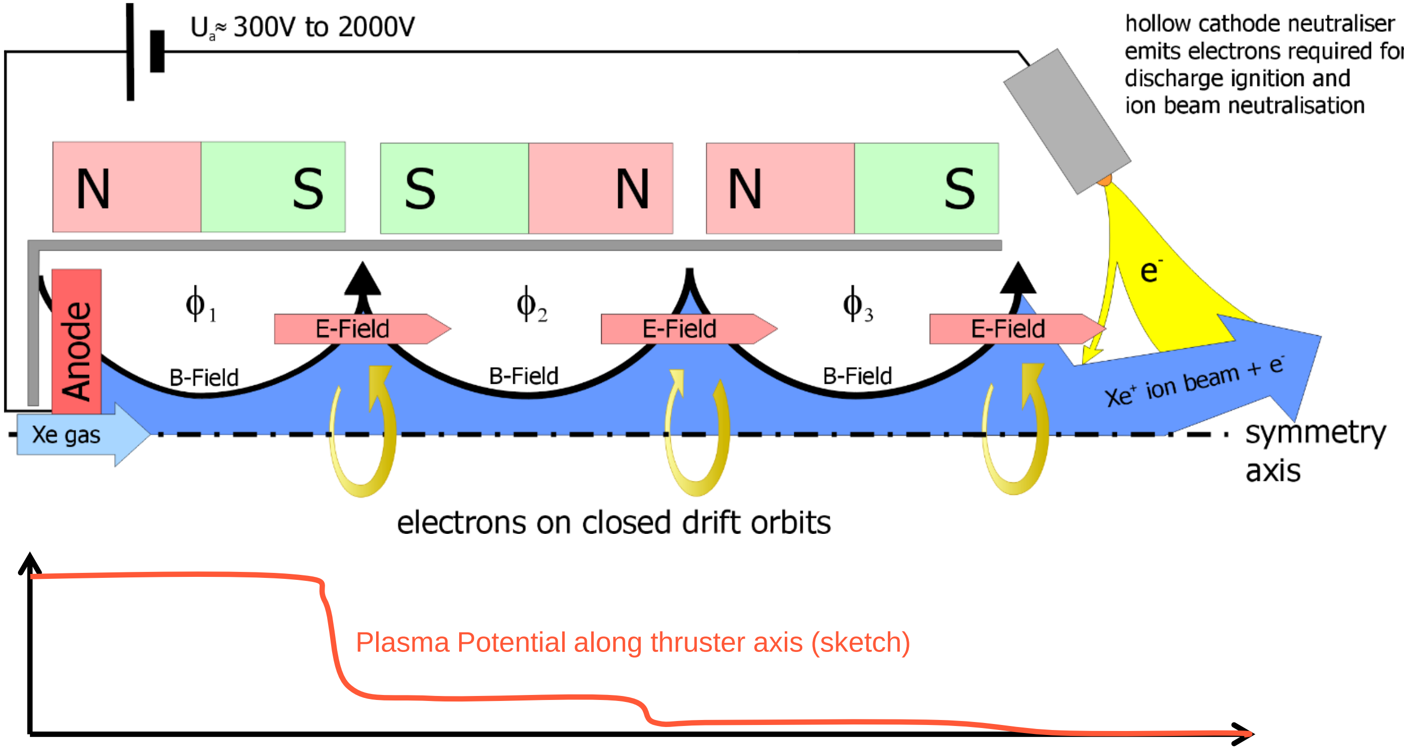
- Neutral gas supplied to hollow cathode and fed through anode at base of discharge chamber.
- Potential difference applied between cathode and anode.
- Electromagnets generate radial magnetic field in discharge channel.
- Electrons are magnetized; follow field lines and enter discharge channel towards anode.
- E x B field causes azimuthal drift of electrons around axis of thruster → circulating hall current.
- As neutrals diffuse into discharge channel, they are ionized by high energy electrons.
- The more massive ions are not magnetized and are accelerated out of the discharge channel by the electric field.
- Equivalent number of electrons emitted by cathode → space charge neutral plasma plume







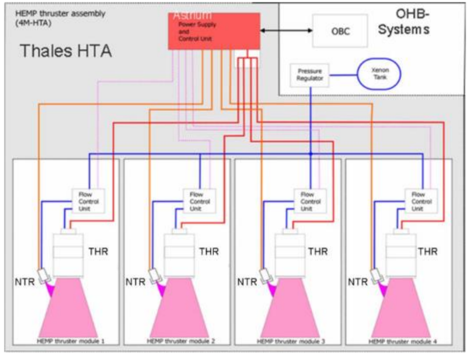
Electromagnetic Thrusters:
High Efficiency Multistage Plasma Thruster (HEMPT)

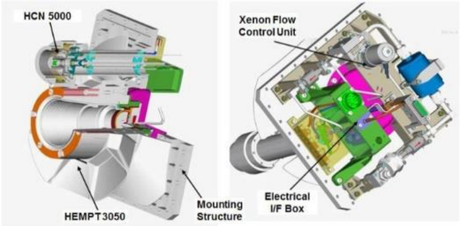


Capabilities in Europe
Thales Electron Devices : HEMPT

Thruster Performances HEMPT 3050 (SGEO):

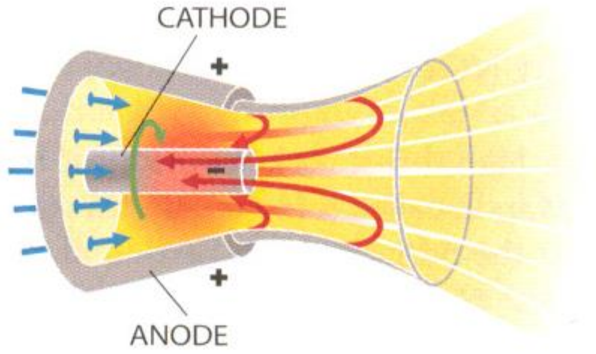
- Average Thrust Level during lifetime : ≥ 44 mN
- Average Thruster Power during lifetime : ≤ 1380 W
- Average Specific Impulse during lifetime : ≥ 2300 s
- Number of Cycles without safety margin : 6500 cycles
- Operational lifetime without safety margin : 4800 h
- Thruster total Impulse without safety margin : 0.76 x10^6 Ns
- Agreed qualification factor of 1.5 to be demonstrated



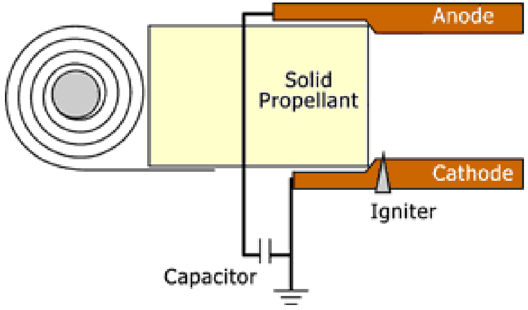


ELECTROMAGNETIC THRUSTERS

Funded by the European Union



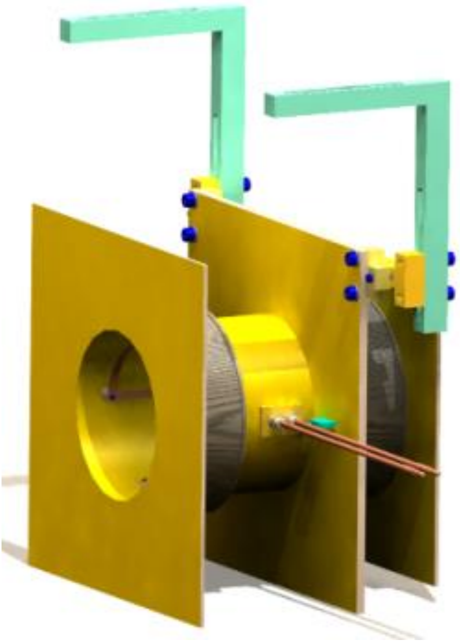
MPD Thrusters

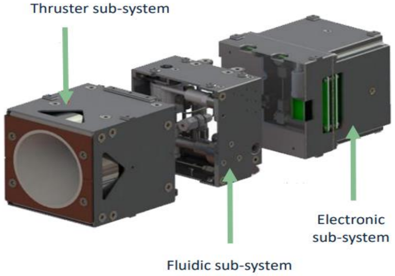


PPT Thrusters

Helicon Antenna Thruster

Funded by the European Union





E-REGULUS
low cost, extended lifetime

Comparison:
Gridded Ion Engine vs Hall Effect Thruster

Funded by the European Union

- Between HETs and GIEs, a wide range of capabilities are available for different applications

Characteristic	Hall Effect Thruster	Gridded Ion Engine	Comment
Specific Power	18W/mN	25-35W/mN	Lower number represents improved Orbit Transfer durations for a given power ceiling
Thruster Efficiency	50%	70%	Higher number tends to reduce thermal interface demands for a given power ceiling
Specific Impulse	1500-2500s	2500-4500s	Higher number represents wet mass saving / higher payload fraction
Operating Voltage	300-400V	1000-2000V	Linked to specific impulse, higher voltages are more challenging for power supply design.
PPU Specific Mass	5kg/kW	10kg/kW	Higher number represents increased EP system dry mass penalty
Plume Divergence	45°	15°	Lower number reduces complications of thruster beam interaction with spacecraft appendages (solar arrays, antennas, deployable radiators etc.)
Throttle Range	2:1	10:1	20:1 demonstrated on GOCE (QinetiQ T5) Higher ratio useful for power limited missions (MP-R)

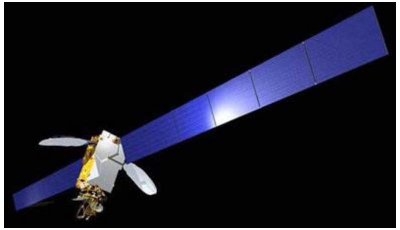
Propellants for EP

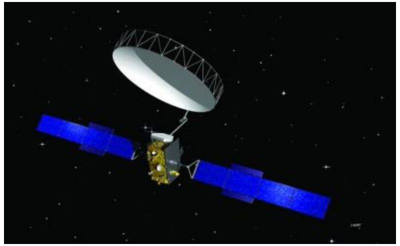
- Heavy metals were used in early years of EP (mercury, cesium).
- Xenon is today the most common propellant for both HETs and GIEs for the following reasons:-
    - Naturally occurring (87ppb in atmosphere) with very low chemical reactivity.
    - Low first ionization potential.
    - High atomic Mass.
    - Gaseous at ambient temperature.
- From a Satellite perspective:-
    - Safe to handle during filling operations
    - No decontamination required
    - Transportable by air
    - Compatible with electron sources
    - Low power consumption to ionize.
    - High thrust efficiency
    - High storage density

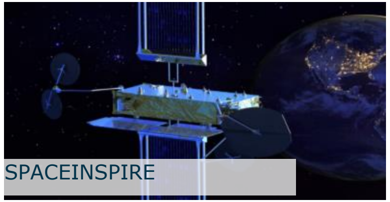
AlphaSat Chemical Fuelling: Hazardous Operation

Funded by the European Union

Commercial Mission Applications:







Funded by the European Union

ESA **Artemis** satellite using 4 ion engines (2 RIT and 2 UK-10) has paved the way for the use of electric propulsion in telecommunication spacecraft.

AIRBUS and Thales with several spacecraft launched (4 **Inmarsat,** 1 **Intelsat and 1 Yasat** satellites, …) and many more satellites in construction has the most important experience in Europe in integration of Electric Propulsion Systems.

AIRBUS and Thales have demonstrated their capability to integrate this technology in GEO satellites. The ESA **Alphasat** spacecraft will use PPS1350 for NSSK operations. Alphabus evolution will also consider Electric propulsion for future missions.

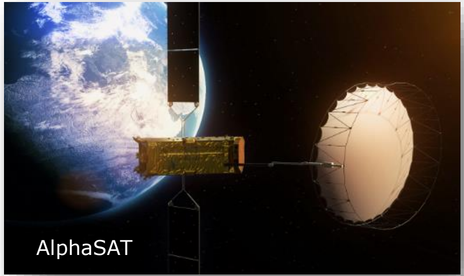
Small GEO satellite has 4 Hall Effect thrusters, SPT-100,

NEOSAT and ELECTRA will have EP for station keeping and ORBIT RAISING manoeuvres. FULL EP SPACECRAFT (PPS5000). AIRBUS and Thales use the HET technology in Eurostar and Spacebus platforms.

SPACE INSPIRE is a new product line for geostationary satellites that will allow customers unprecedented flexibility for video broadcasting and broadband connectivity services by reconfiguring their missions and services instantly in-orbit.This spacecraft will use EP (RIT-22).

Telecommunication Spacecraft:
Operational Station-Keeping

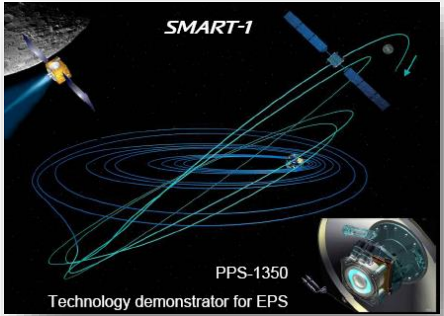
- Since the 1980s EP has been used for station keeping of telecom satellites (US, Russia).
- In 2001, following a launch injection failure, ESA's Artemis mission was saved using its EP station keeping thrusters for partial orbit raising.
- In 2004, Intelsat 10-02 became the first European developed telecom satellite using EP for station keeping.
- Since then several satellites have been built in Europe that feature SPT-100 thrusters for station keeping: Astra-1K, Stentor, Intelsat-10, Yahsat 1A & 1B, Inmarsat-4 F1,F2 & F3, Eutelsat 10A & 36B, Yamal 402 & 601.
- In July 2013, AlphaSat became the first European developed telecom using four SAFRAN (FR) built PPS1350G thrusters for north/south station keeping.

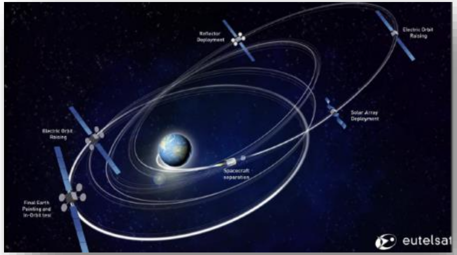

AlphaSAT

Telecommunication Spacecraft:
Orbit Raising

Funded by the European Union

- In Europe, Orbit Raising/Transfer with Electric Propulsion was demonstrated by the SMART-1 lunar probe (5000 hours of almost continuous in-space operation) and by Artemis; worldwide by Deep Space 1, Dawn, Hayabusa.
- On telecom satellites, orbit transfer to GEO was typically consuming chemical propellant that amounted to 40% of the satellite mass and was completed in few days after launch. Using EP, the manoeuvre takes significantly longer (months), but can reduce the propellant consumption by thousands of kilograms, increasing the useful dry mass fraction and reducing the launch cost dramatically.
- Boeing was the first satellite manufacturer to introduce partial EP orbit raising (orbit topping) on their 702HP platform.
- Boeing's announcement in 2012 of sales of 4 of its all-electric small platform (702SP), featuring EP for station keeping and full orbit raising, triggered a revolution in the commercial utilisation of EP.
- In 2015, the Boeing built Eutelsat 115 and ABS 3A became the first all-electric commercial satellite demonstrating Electric Orbit Raising.
- The first European built all-electric satellite was launched in 2017 (Airbus Eurostar E3000 EOR satellite).





Telecommunication Applications:
Future Architectures

Funded by the European Union

- The use of Electric Propulsion in the telecommunication space market is essential to improve the position of the European space sector. The announcement of Boeing in 2012 on the procurement of 4 telecommunication spacecraft (platform 702SP) , offered for only 125 million dollars each including launch, thanks to the use of electric propulsion for both NSSK and orbit raising from GTO to GEO, has been noted by European operators and primes. The launch of the first 2 spacecraft took place on the 1 March 2015.

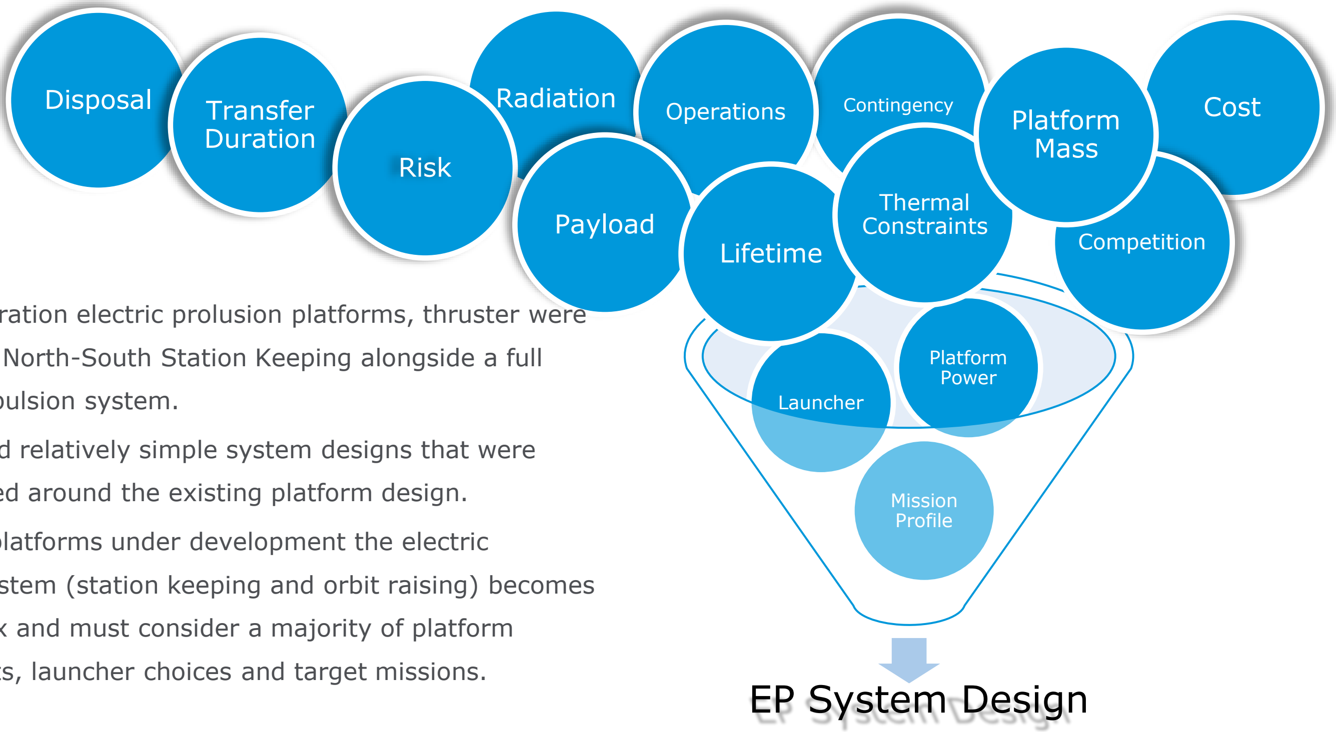
- ESA is now fully involved in the preparation of several telecommunication programmes (**NeoSat, Electra)** that will make use of electric propulsion for all the key maneuvers, paving the way for the commercial use of all-electric platforms by the European primes: Airbus Defence and Space, Thales Alenia Space and OHB Systems.

- Boeing has selected the Falcon 9 for the launch of these spacecraft. Current and future European launchers will need to be capable to optimise their performances, interfaces and operations to offer the best launch options to new all-electric platforms.

- In the short term, the adoption of electric propulsion might offer new opportunities for the heavy lift Ariane 5, that typically offers to launch two spacecraft, one large and one medium. Adding the option of a low mass 702 SP class comsat, Arianespace could accommodate larger primary payloads co-manifested with a single all-electric spacecraft, without exceeding the rocket's total capacity. In the longer term, Ariane 6 will have to be compatible with a new generation of full electric spacecraft

Electric Propulsion Systems
System Trade-off Considerations

Funded by the European Union



- For first generation electric prolusion platforms, thruster were only used for North-South Station Keeping alongside a full chemical propulsion system.
- This permitted relatively simple system designs that were accommodated around the existing platform design.
- For the new platforms under development the electric propulsion system (station keeping and orbit raising) becomes more complex and must consider a majority of platform design aspects, launcher choices and target missions.

Telecommunication Applications:
Existing Platforms

Funded by the European Union

Platform	Prime Contractor	Status	Platform Mass Range (tonnes)	Platform Power Range (kW)	EP Function	EP Thruster	EP Thruster Type
ARTEMIS	Thales Alenia Space- Italy	Flight Proven	3.0	3.0	NSSK (OR during recovery)	2 X UK-10 (T5) 2 X RIT-10	GIE
Eurostar E3000	Airbus Defence & Space	Flight Proven	4.5 – 6.0	9 - 16	NSSK	4 X SPT-100	HET
SpaceBus	Thales Alenia Space	Flight Ready			NSSK	4 X PPS-1350G	HET
AlphaBus	ADS / TAS	Flight Proven	6.0 – 6.5	12 - 18	NSSK	4 X PPS-1350G	HET
AlphaBus Extension	ADS / TAS	Flight Proven	<8.4	12-22	NSSK, Orbit Topping	4 X PPS-1350G 4 X PPS-1350G OPTION T-6	HET/GIE
SGEO	OHB	PFM 2014	3.2	6.5	NSSK, EWSK, Momentum Management	8 X SPT-100 Or 8 X HEMPT	HET/HEMPT
NEOSAT	ADS /TAS	Under development	3-6	15- 25	NSSK, Orbit Raising	4XPPS5000	HET
ELECTRA	OHB	Under Development	3.2	7	NSSK, Orbit Raising	4XPPS5000	HET

With the exception of ESA's ARTEMIS platform, all European commercial platforms utilize Hall Effect Thrusters.

Telecommunication Applications:
Full-EP platforms for EOR & STK

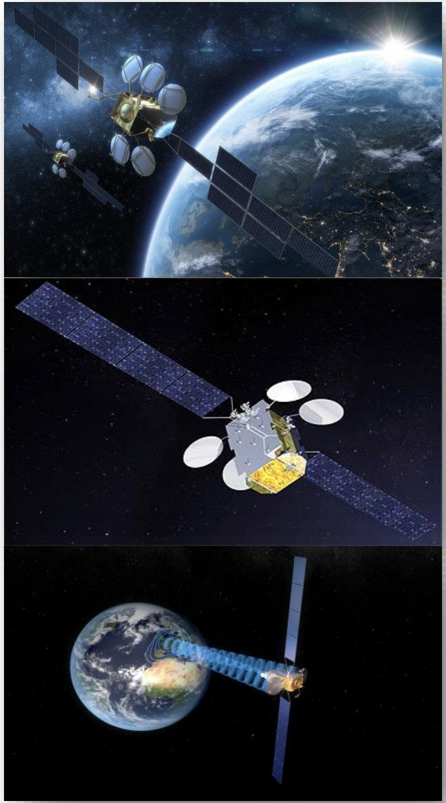
Funded by the European Union

All of the 3 main European LSIs are at present developing all-electric commercial satellites (via ESA programmes: NEOSAT and Electra).

HET-based subsystems are currently the preferred choice by European LSIs for full-EP telecomm platforms

However other architectures selected by non-European Primes (for example, Boeing 702SP platform used US XIPS engine (GIE); Boeing have also recently selected SAFRAN (FR) PPS5000 for a commercial program and are developing a RIT-2X subsystem jointly with ArianeGroup (DE)).

- NEOSAT (ARTES-14) → successful sales of Eurostar NEO and Spacebus NEO
- Electra (ARTES-33) → targeting small-GEO platforms
- Space Inspire Platform (Novacom II programme)

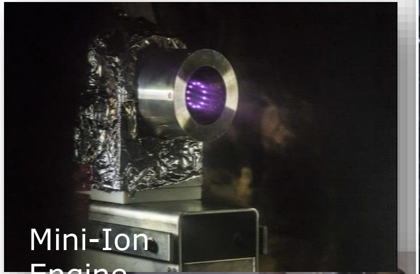


Constellations

Starlink (SpaceX): up to 12,000 spacecraft (possible up to 42,000) using low power HET (Krypton, Argon)

OneWeb: > 700 spacecraft

Others: (Telesat, LeoSat, ICEYE etc.)

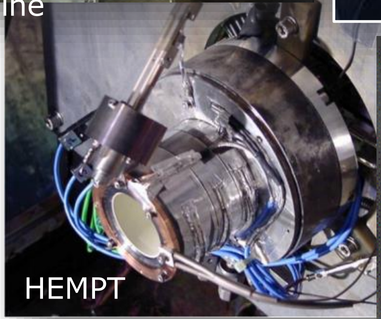


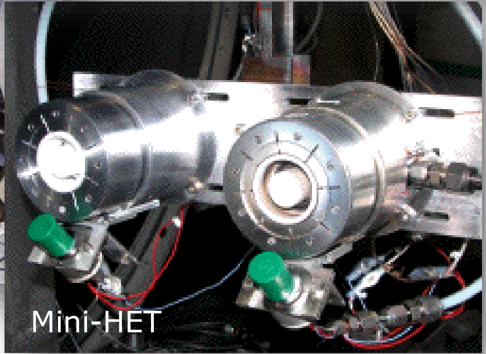
Constellations will use propulsion to perform:

- orbit acquisition, maintenance and de-orbiting from low earth orbit (around 600 -1000km)

Satellites

- ~ 200 kg-500kg with power for propulsion ~ 200 - 1000 W
- Mini-HET, HEMPT, FEEP are interesting options
- Spacecraft cost ~ 500 000 – 1 M $
- Propulsion system (thruster ~25 000 $ and electronics ~50 000 $)





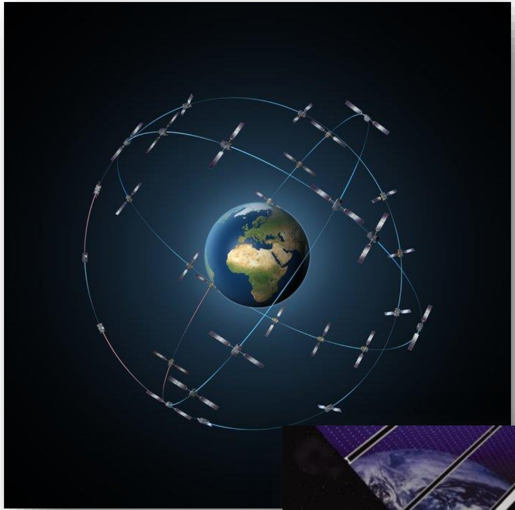
IFM AR3
ENPULSION FEEP

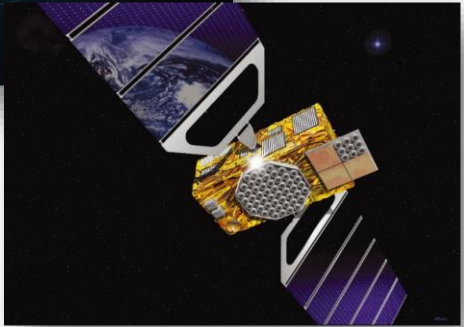
<u>**Critical**</u> – end-of-life disposal strategy

Navigation Applications:
Galileo 2nd Generation (G2G)

Funded by the European Union

- ESA & EU are preparing the future replacement of the GALILEO constellation and is targeting the possibility to increase the Galileo Payload capability without impacting the launch costs (even possibly reducing them).
- The increase in payload capability could be achieved by changing the launch injection strategy and by using Electric Propulsion to transfer the satellite from the injection orbit to the target operational orbit.
- The use of Electric Propulsion might allow to use small launchers such as VEGA or place more spacecraft in the current SOYUZ and Ariane 5, 6 launchers.
- GIE and HET subsystems are currently considered for the transfer by the selected Primes of the Phase A/B1 studies.





Commercial Applications:
Telecoms & Nav, future trends

Funded by the European Union

2023-...

Further Minimizing Transponder to Orbit costs

- Further Mass Saving
  Further Mass Reduction
- Further Minimizing of Time to Orbit (mission scenarios)

2018-2023

Commercial Exploitation

2013-2017

Development for Commercial Exploitation

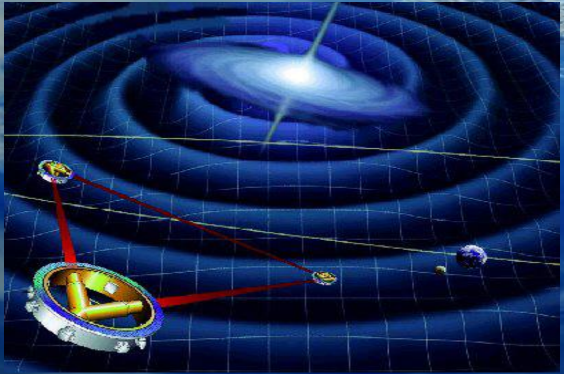
- Xenon market evolution and availability
- LEOP(Launch early Operation) costs
- Electric propulsion driven recurring and non-recurring prices for Design to Cost options
- Industrialization and production chain
- 5KW and low poer Propulsion Systems

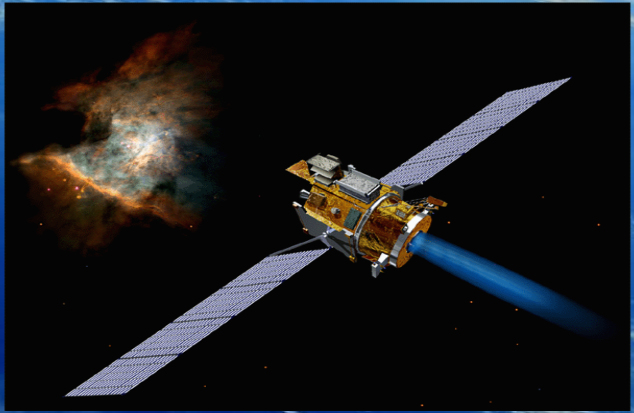
Scientific Mission Applications:

Scientific Spacecraft

Interplanetary Missions

- More scientific payload
- Shorter trip time
- Reduced launch window limitations





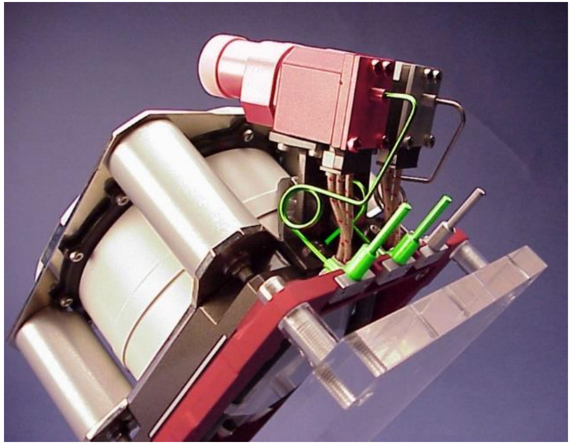
High Precision Pointing Missions

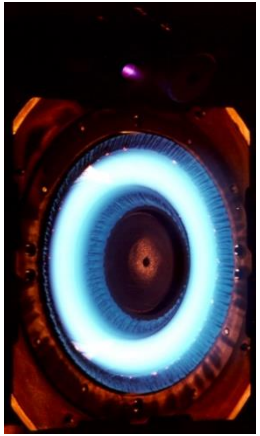
- Space interferometry
- Sintetic aperture observatories
- Formation flying

Funded by the European Union

EPIC

Funded by the European Union

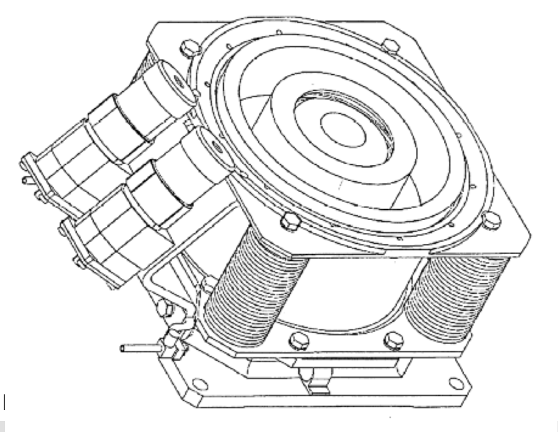




On SMART-1, Electric Propulsion was used as Primary propulsion system.

The thruster selected for this mission is the

PPS-1350 (SNECMA - F).



The PPS-1350 thruster was a derivative of the qualified Russian SPT-100, with increased performance in terms of thrust and specific impulse.

The PPS-1350 has been qualified for a 15 years mission for the NSSK of a large GEO Telecom. An EP diagnostic package (EPDP) was flown to assess the spacecraft thruster interaction

Earth Observation:
GOCE (the 'Ferrari' of space missions)

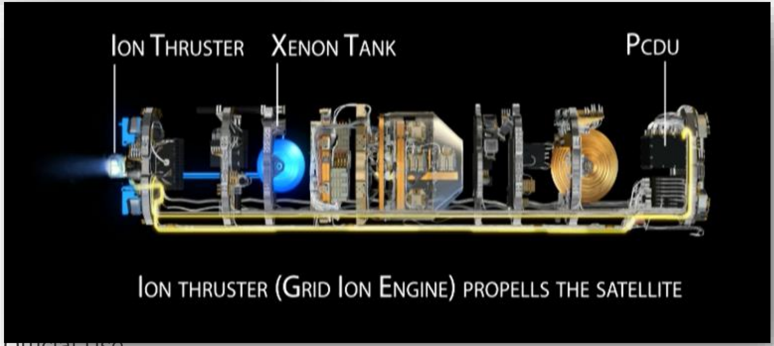
Funded by the European Union

Electric Propulsion was enabling for ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission.

GOCE utilised the QinetiQ T5 GIE.

After nearly tripling its planned lifetime, GOCE completed its mission in October 2013.

The mission came to a natural end when it ran out of fuel and the satellite began its descent towards Earth from a height of about 224 km.



Air-breathing electric propulsion

In 2007, a high level CDF study at ESTEC proof the feasibility of compensating the drag of a spacecraft operating at altitude as low as 180 Km using the ram-EP concept.

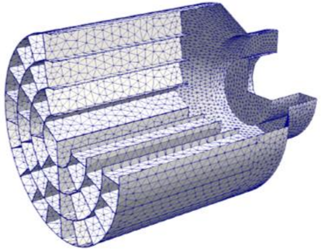
In 2010, TRP contract about two test campaigns were carried out on two engines: SNECMA PPS 1350 (Hall effect engine) aka HET and RIT-10 (Ion Engine) aka RIT.

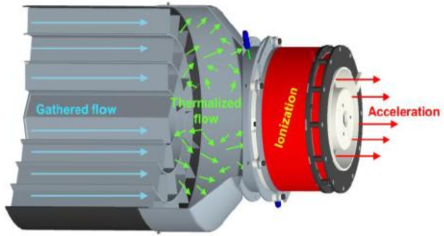
In 2015, TRP with SITAEL and QuiteScience: concept engine measuring net thrust in a ground facility .

In 2019, GSTP with VKI, the design of the collection took place.

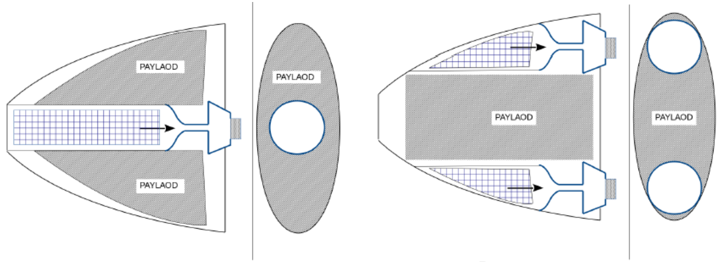
In 2021, GSTP with SITAEL for the phase B1 of a demonstrator (RED).

In 2023 an ARTES activity will be placed.





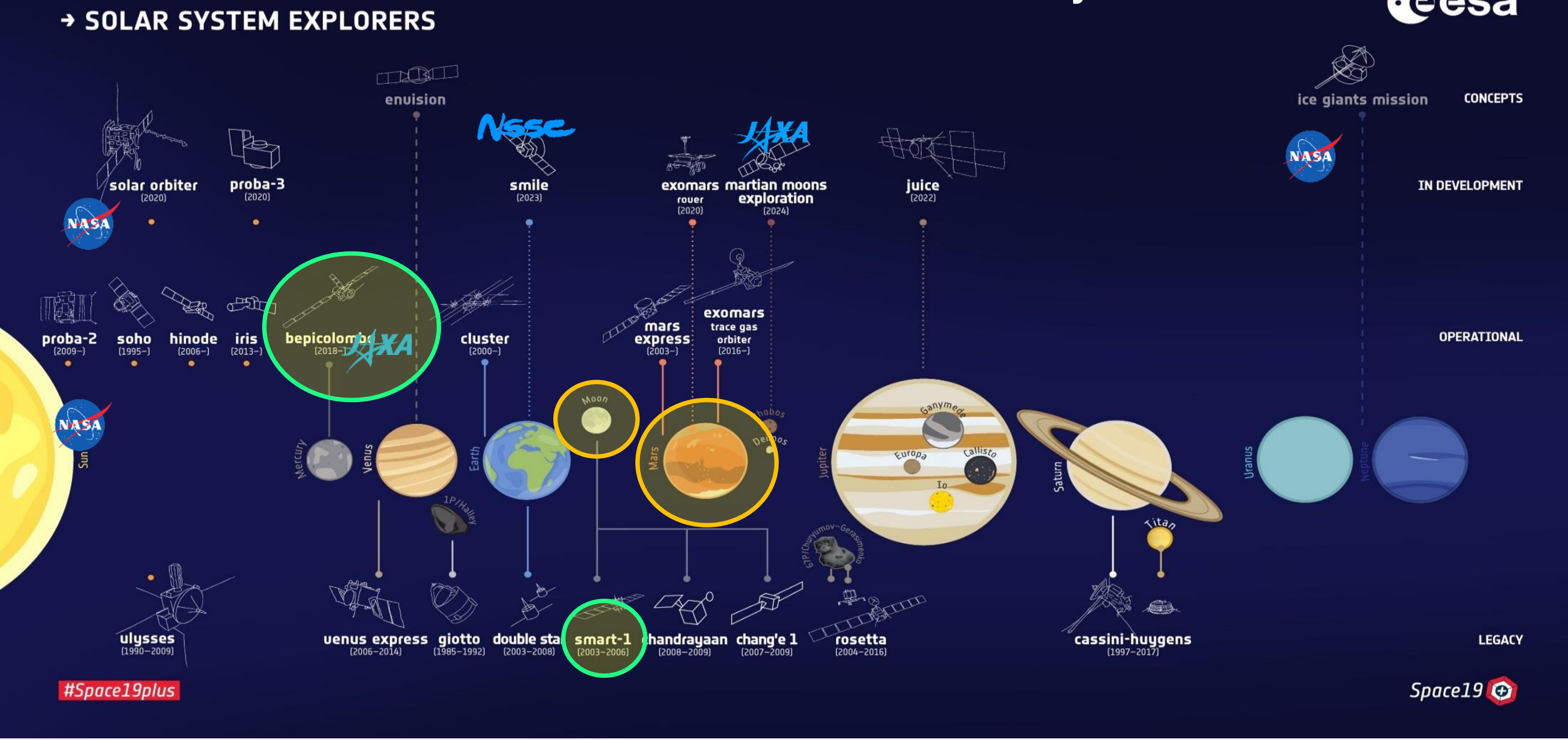
RAM-EP Assembly[1]



(a) Central engine. (b) Side engines.

Figure 2.8: Rear intake-collector configuration.

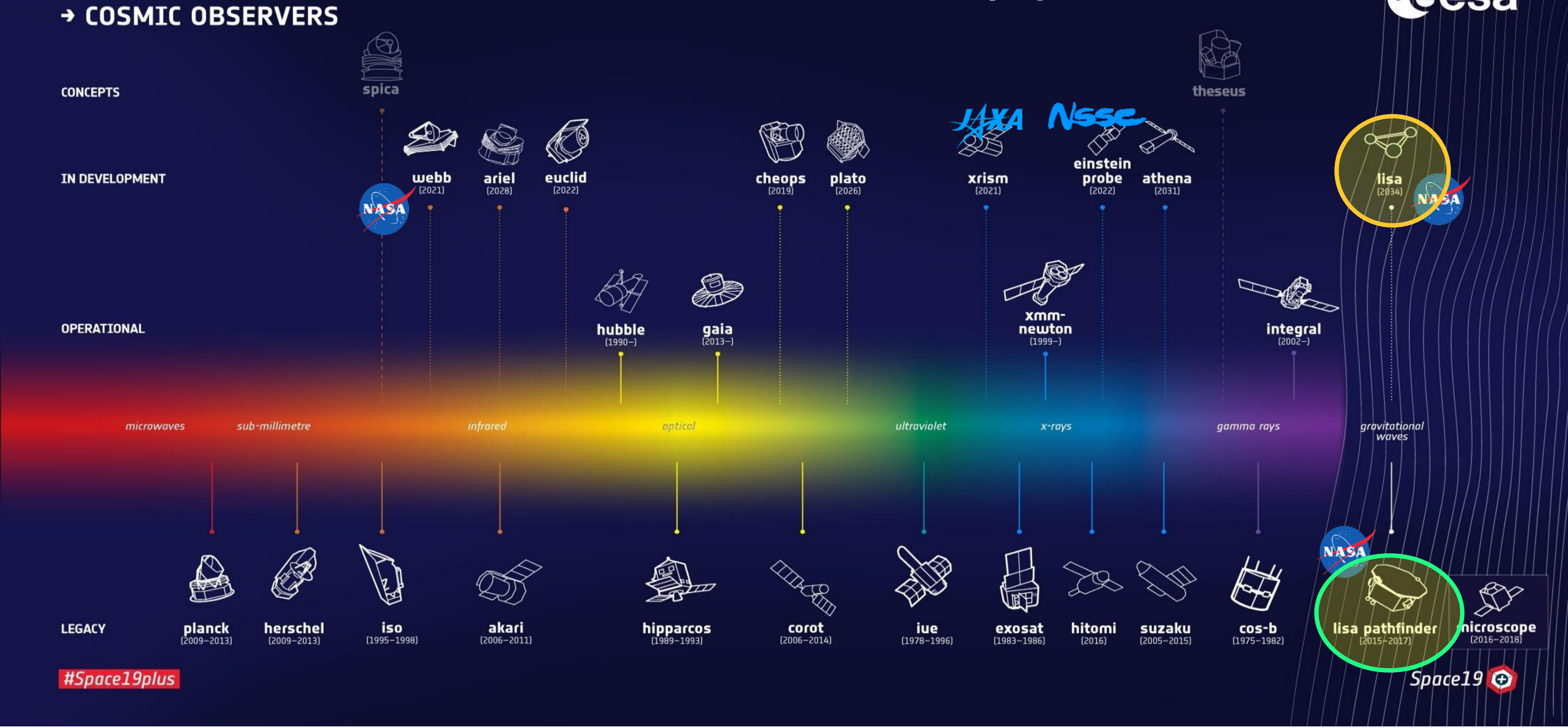
The ESA Science Fleet in the Solar System



ESA UNCLASSIFIED - For Official Use

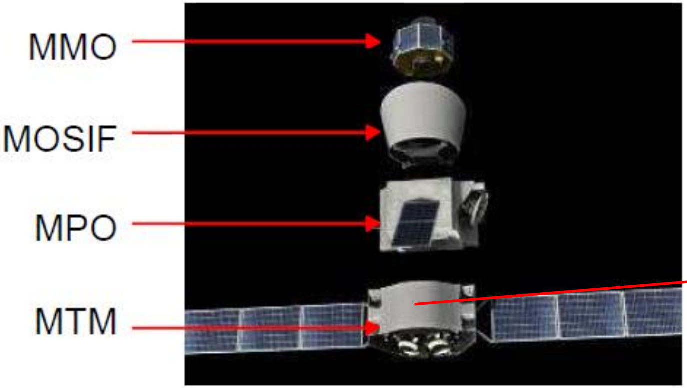
European Space Agency

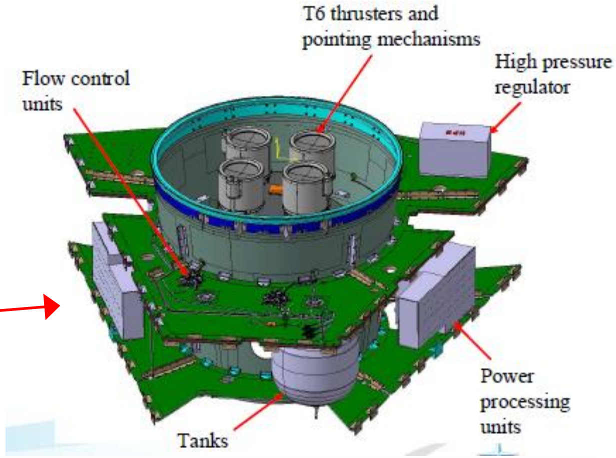
The ESA Science Fleet for Astrophysics

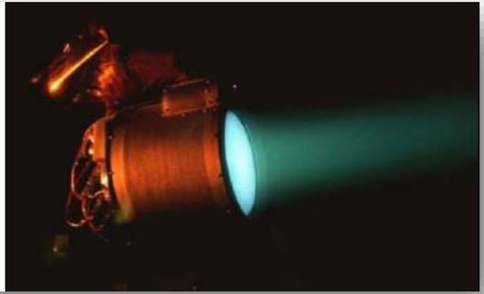


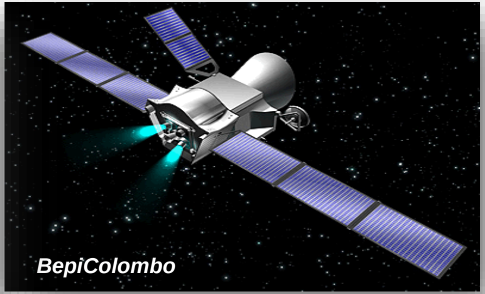
Science Missions: BepiColombo

Funded by the European Union





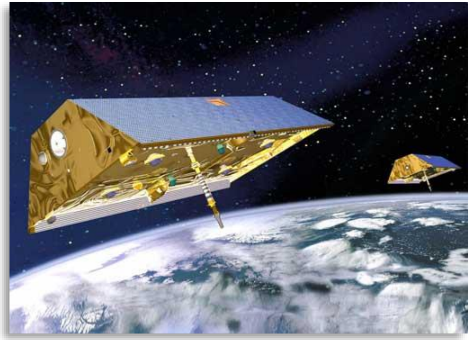


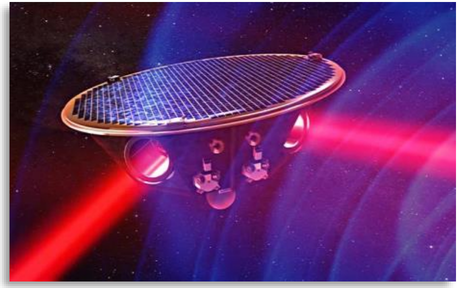


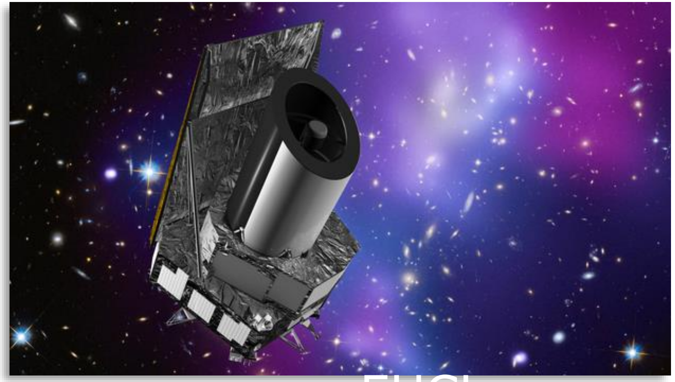
Science and Earth Observation

Required on-going & future developments

- Mini-ion engines system and micro-field emission thrusters are in development to satisfy the needs of future gravity missions and other science missions such as NGGM and Euclid.
- Mini-hall thrusters system are in development to satisfy the needs of future mini/micro-satellites to perform SK and disposal maneuvers.
- Large Ion Engines and Hall Effect Thrusters must be developed to meet the needs of future asteroid or planetary exploration missions. Cargo missions to Mars will also make a good use of these systems.





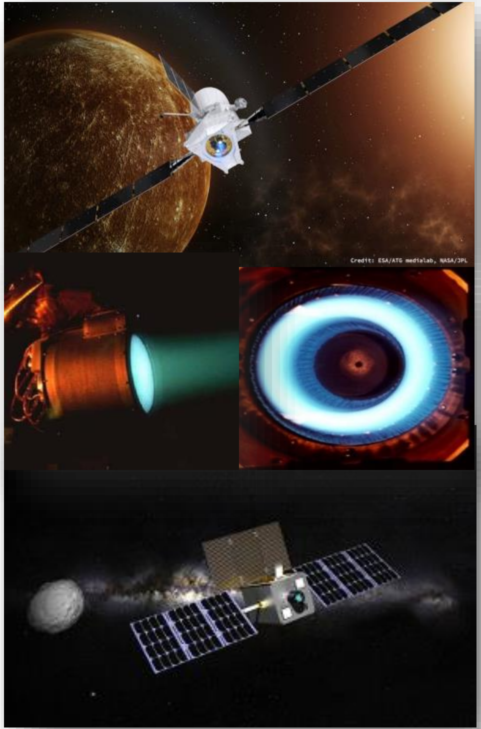


Funded by the European Union

Scientific Missions: Future Applications

Where are we today?

- Electric propulsion has taken Europe to the Moon (SMART-1) and has allowed us to measure the Earth's gravitational field with unprecedented accuracy (GOCE).
- Electric propulsion is taking us to the planet Mercury (BepiColombo) and could allow us to investigate gravitational waves (LISA).



Future applications and development needs

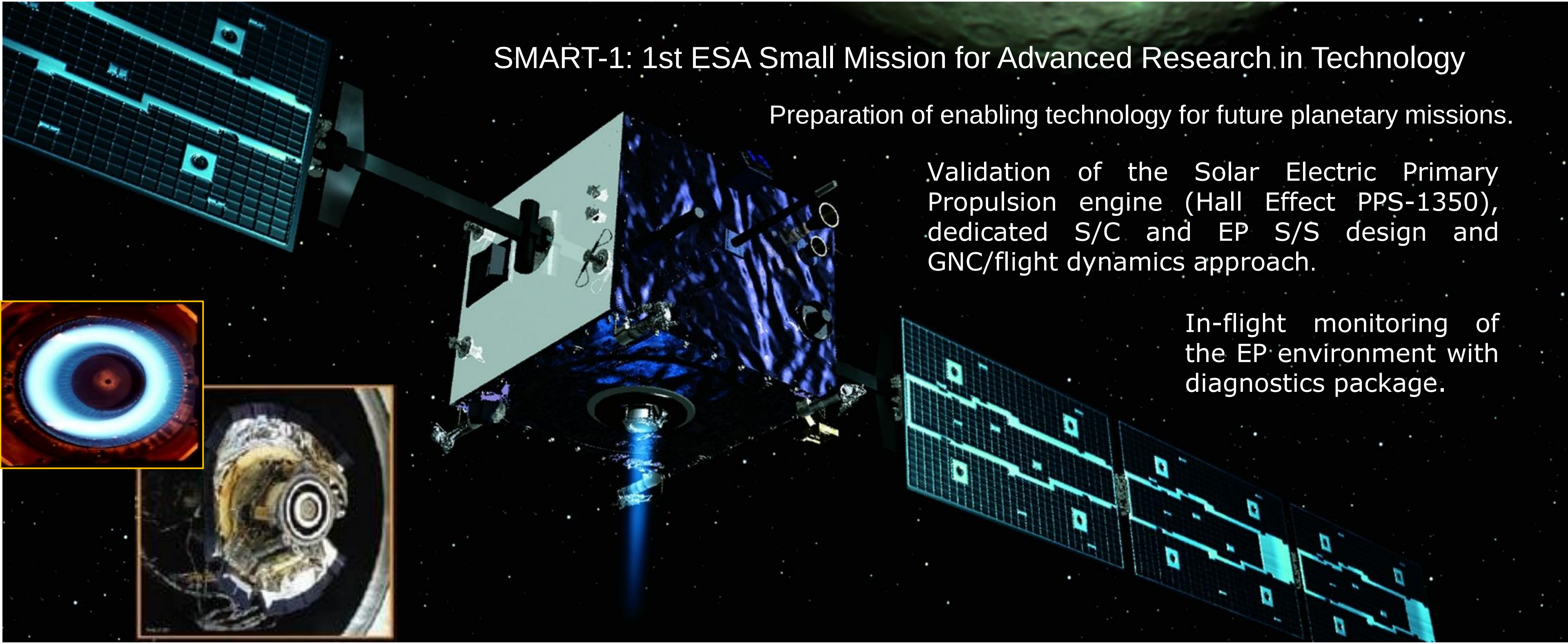
- Electric Micro-Propulsion for drag compensation and precision formation control: miniature GIE subsystems and FEEP subsystems are in development in Europe to satisfy the needs of future gravity missions and other science missions (NGGM, applicable also for LISA).
- Low power / miniature EP subsystems for small satellite planetary missions and LEO constellations: miniature HET subsystems are in development to satisfy the needs of future mini/micro-satellites to perform SK and disposal maneuvers, miniature GIE subsystems for NEO target missions (M-ARGO).
- High Power (~ 15-20 kW) GIE and HET in Europe would be beneficial for future asteroid or planetary science missions.
- RAM-EP for future EO and exploration applications

Funded by the European Union

Exploration Mission Applications:

Exploration:
Lunar: SMART-1

Funded by the European Union



SMART-1: 1st ESA Small Mission for Advanced Research in Technology

Preparation of enabling technology for future planetary missions.

Validation of the Solar Electric Primary Propulsion engine (Hall Effect PPS-1350), dedicated S/C and EP S/S design and GNC/flight dynamics approach.

In-flight monitoring of the EP environment with diagnostics package.

Exploration:
Lunar: SMART-1

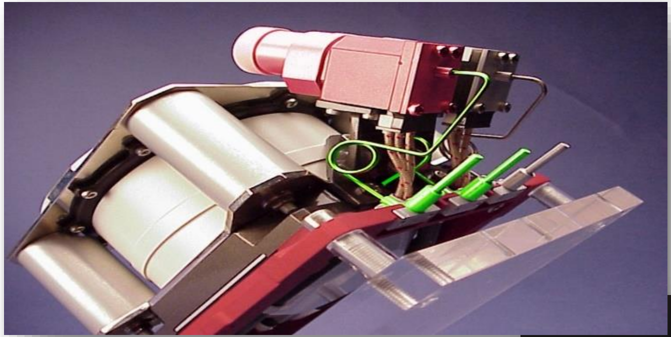
Funded by the European Union

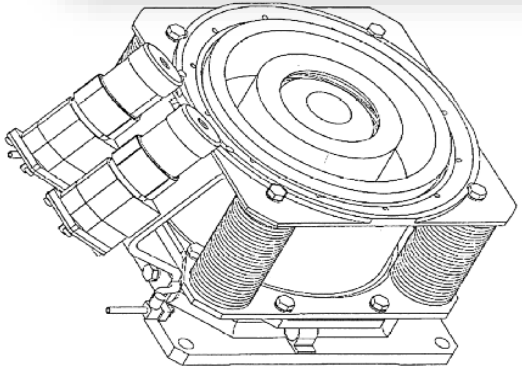
The SMART-1 mission utilised the SAFRAN PPS-1350 HET

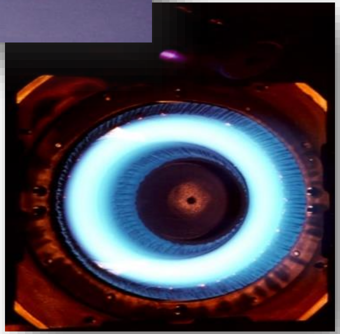
The PPS-1350 thruster is a derivative of the qualified Russian SPT-100, with increased performance in terms of thrust and specific impulse.

The PPS-1350 has also been qualified for a 15 year mission for the NSSK of a large GEO Telecom.

An EP diagnostic package (EPDP) was flown on SMART-1 to assess the spacecraft thruster interaction.





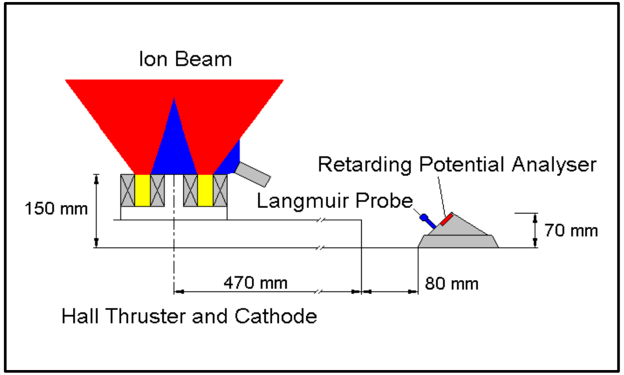


Exploration:
Lunar: SMART-1

Funded by the European Union

Goal for the technology experiment (EPDP) in SMART-1:

"understanding the local environment of a spacecraft using Hall Effect Thrusters (erosion, deposition, torque perturbations, thermal and electric behaviour)"



Working Approach:

- Flight measurements with the EPDP and SPEDE
- Ground laboratory measurements for correlation
- Models based on physical principles and mechanisms

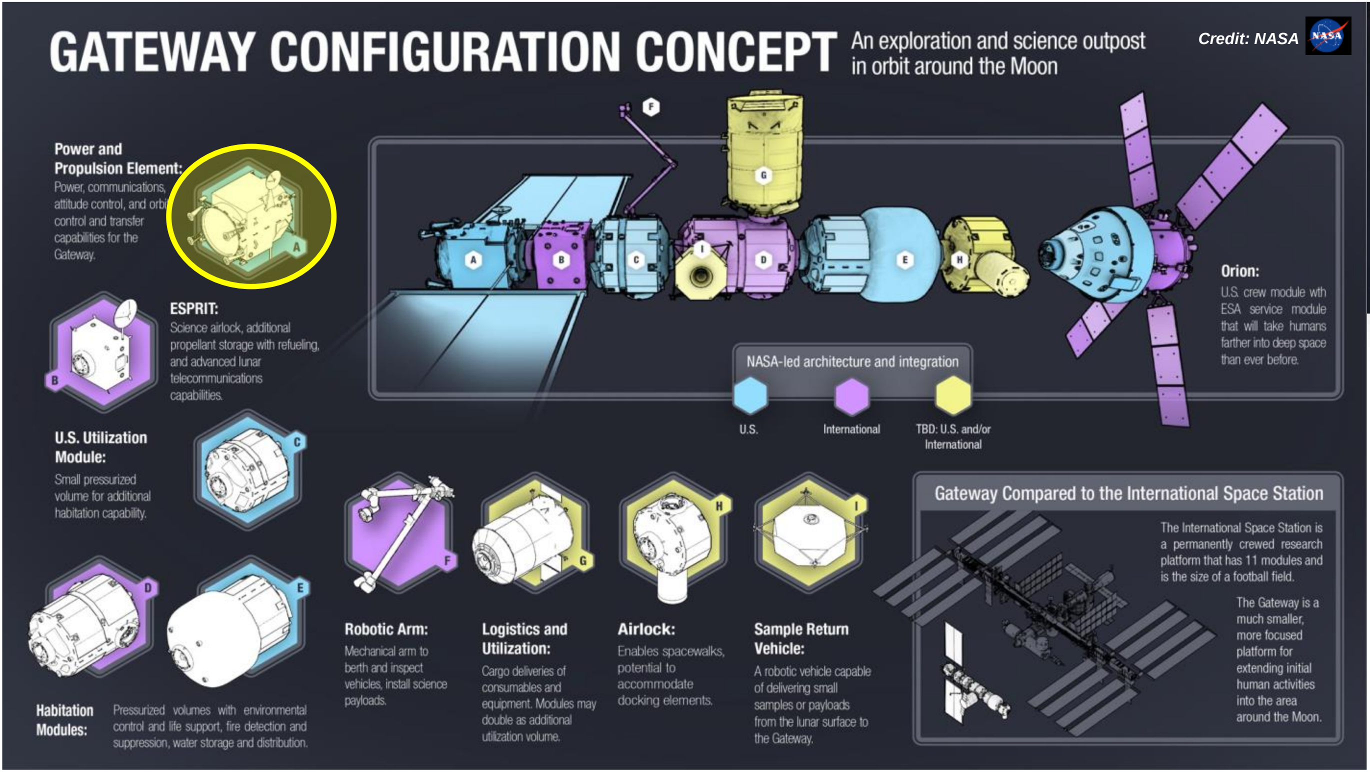
LP Sensor	**Plasma density** **Plasma & floating potential** **Electron temperature** **Ion current density**
RPA Sensor	**Ion Energy Spectrum** **Ion current density**
QCM Sensor	**Mass deposition (contamination aspects)**
SC Sensor	**Open, short, load circuit effective resistance**

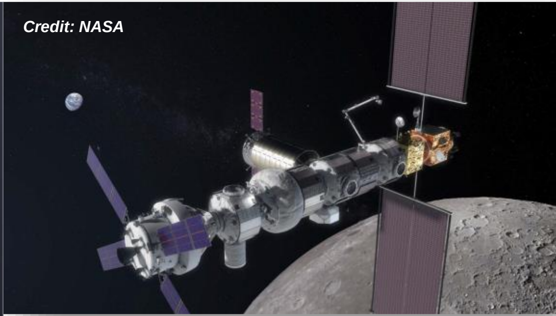
EPDP: Plasma Diagnostic Package instrument

Summary of estimated parameters (derived quantities)

Exploration:
Lunar Gateway (as part of NASA ARTEMIS program)

Funded by the European Union



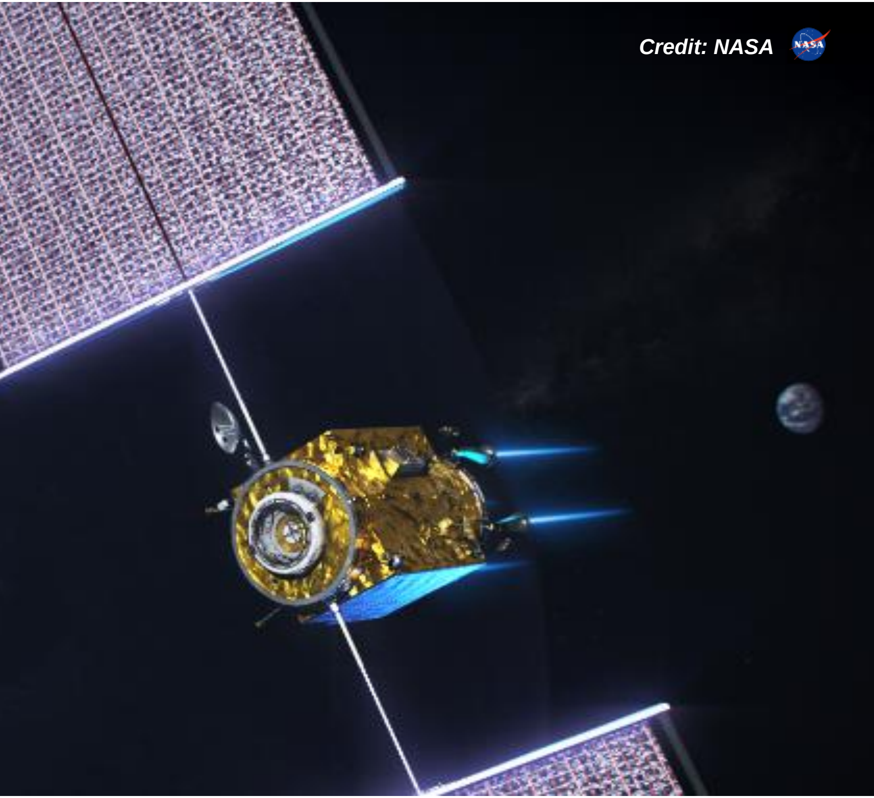


NASA's new ARTEMIS lunar exploration programme aims at establishing a sustainable presence at the moon.

First element to be launched in Phase I of NASA's ARTEMIS program will be the Power & Propulsion Element (PPE) module.

Exploration:
Lunar Gateway (as part of NASA ARTEMIS program)

Funded by the European Union



Power and Propulsion Element
First module in lunar orbit for Gateway
19

Key Characteristics:
- 2022 launch on partner-provided commercial launch vehicle
- Up to one year joint commercial/NASA on-orbit flight demonstration
- 15 year on-orbit operational life after launch vehicle separation
- 50 kW class spacecraft with 40 kW class EP system

Core Functions for Gateway:
- Power transfer to other Gateway elements
- Transport of Gateway to multiple cislunar orbits
- Attitude control and orbit maintenance for Gateway stack
- Communications with Earth, visiting vehicles, and initial communications support for lunar surface systems
- Accommodations for payloads

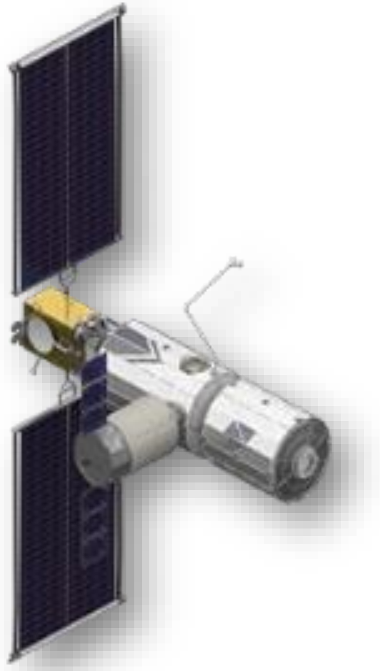
Exploration:
Perspective for Cis-lunar Infrastruture

Funded by the European Union

- Prior to the acceleration of NASA's ARTEMIS programme, as a potential ESA contribution to the PPE module ESA was considering to provide:
  - A 15-20 kW HET string (thruster, thrust vector control, Power Processing Unit) in addition to the (NASA) AEPS to be embarked.

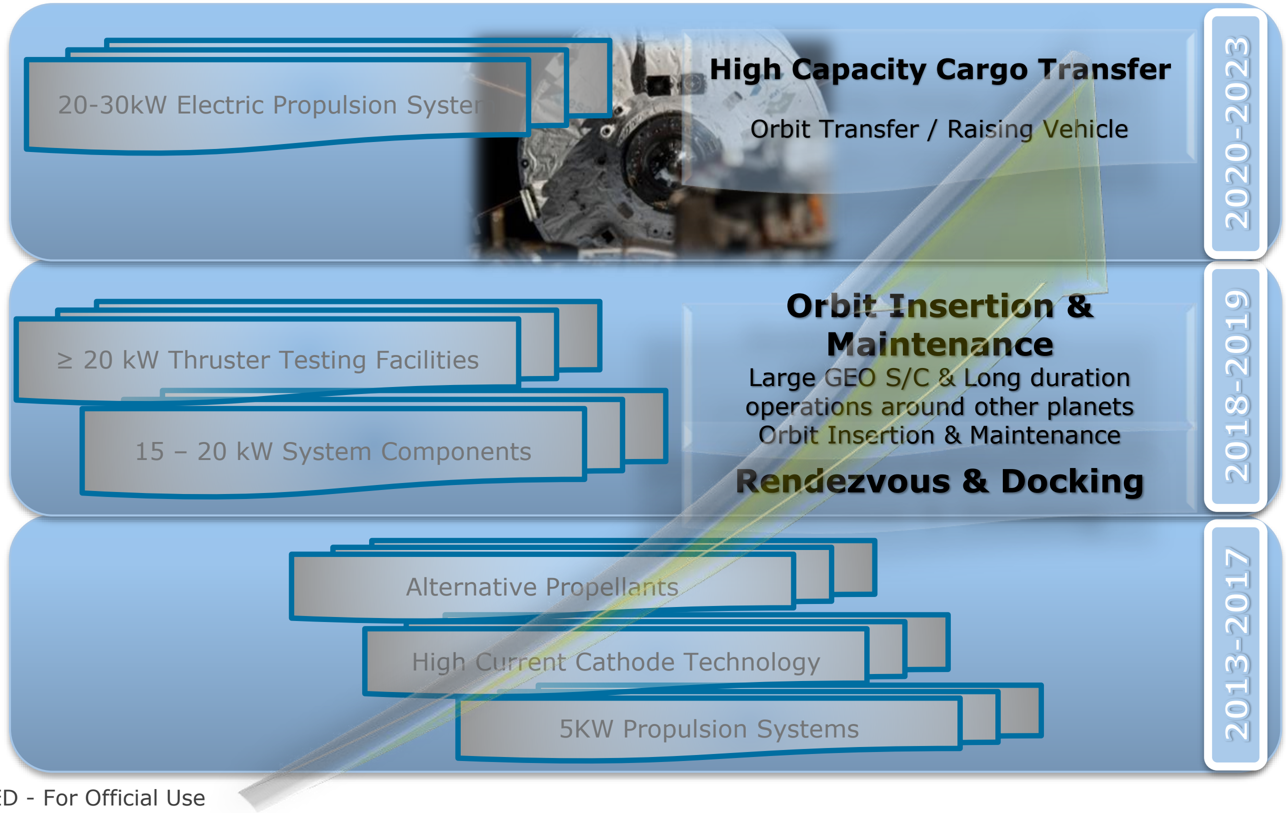
- The business case for a SEP system (class 40-60 kW) is not demonstrated yet, but could use the same thruster.

- High power SEP is becoming more and more interesting for various applications:
  - Large satellite transfer to GEO
  - Interplanetary missions
  - Cis-lunar Phase 2 (sustained lunar exploration) and Mars transfer
  - Spacecraft servicing



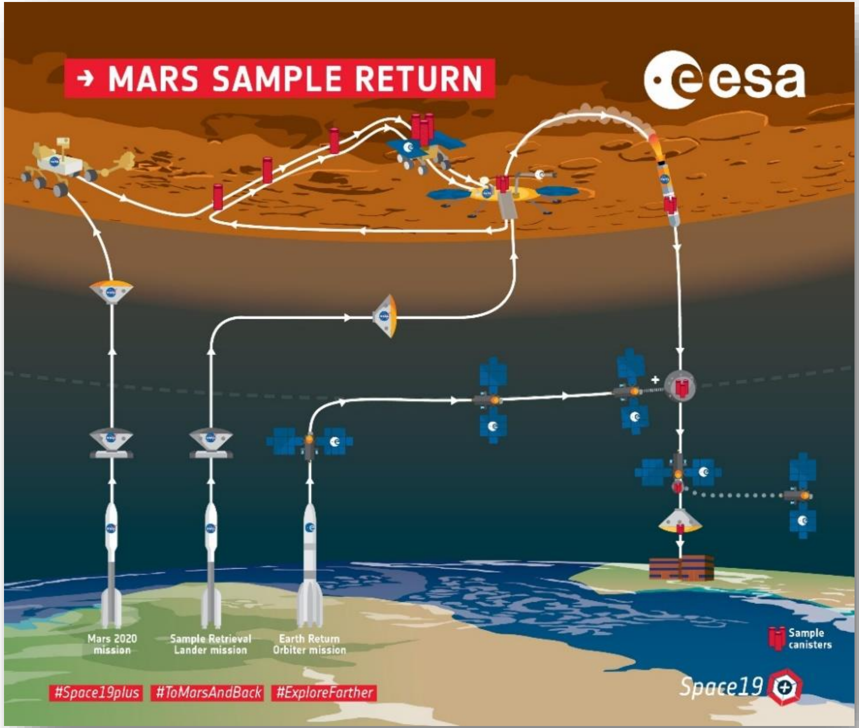
Exploration:
Future Applications – Space Tugs

Funded by the European Union



Exploration:
Potential Near-Term Future Applications – Mars Sample Return

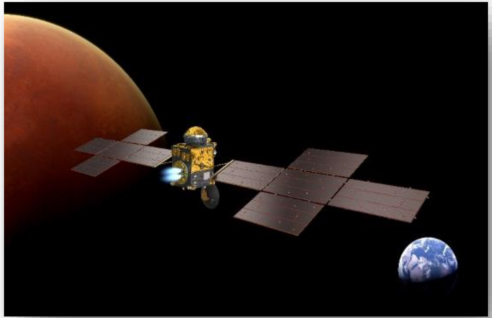
Funded by the European Union

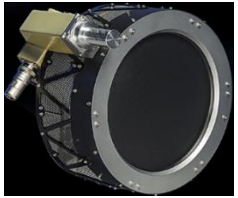


Mars Sample Return would represent a cornerstone in the exploration of the Solar System. The MSR overall architecture is based on three different missions as an international effort.

ESA is leading industrial studies for the Earth Return Orbiter (ERO) mission.

Solar Electric Propulsion (SEP) is considered for cruise phases (transfers) and orbit lowering/raising at Mars. RIT-22 is the EP technology.





Exploration:
Potential Far-Term Future Applications – RAM-EP

Martian Atmosphere Breathing Hall Effect Thruster (MABHET) by Busek & NASA : Extremely Long Mission Capabilities

Funded by the European Union

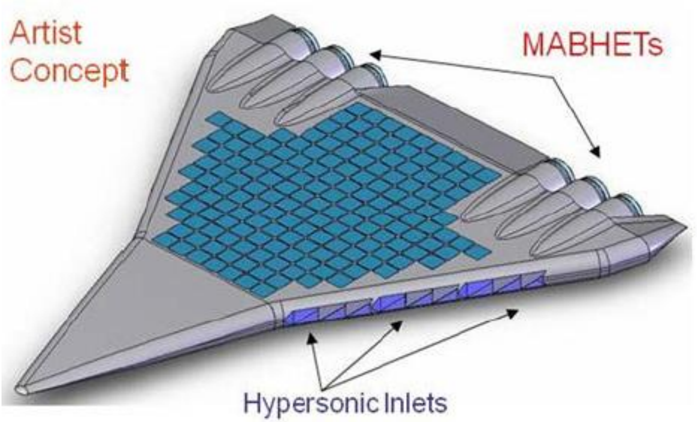
Concept studies by Busek / NASA Glenn:

(K. Hohman, V. Hruby, H. Kamhawi)

Solar Electric Power Orbiting Spacecraft that ingests Mars Atmosphere, ionizes a fraction of that gas and accelerates the ions to high velocity.

Mars atmosphere is thin and composed mainly of CO_2.

- The altitudes of interest are 120-180km due to drag and power requirements.
- The orbital velocity is around 3.4km/s.
- Solar Flux is about 584 W/m2 (Earth ~1350 W/m2) .



Exploration:
Potential Far-Term Future Applications – RAM-EP

Funded by the European Union

RAM-EP / Air-Breathing Electric Propulsion: History of ESA studies and developments

The RAM-EP concept was first studied in ESA with respect to Earth Observation applications.

In 2007, a high-level ESA CDF feasibility study concluded that to compensate the drag of a spacecraft operating at altitudes lower than 180 km in Earth's atmosphere, a RAM-EP concept could be a feasible solution.

In 2010, under ESA TRP contract, two test campaigns were carried out - one on a SAFRAN PPS1350 Hall Effect Thruster and one on a RIT-10 gridded ion engine - for performance characterization using atmospheric-representative propellant:

- HET and RIT technologies are compatible with N2/O2 mixtures, which is of interest for RAM-EP applications in LEO (200-250 km).
- Thruster lifetime is strongly affected by corrosion/erosion phenomena. However, with appropriate choice of materials, it is predicted that thruster lifetime could be in the 1000-10,000 hours range.

Exploration:
Potential Far-Term Future Applications – RAM-EP

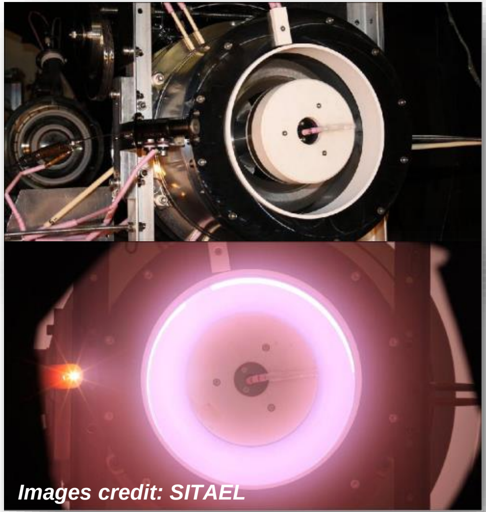
Funded by the European Union

RAM-EP / Air-Breathing Electric Propulsion: History of ESA studies and developments

Industrial efforts carried out by SITAEL with support of QuinteScience and coordinated by ESA demonstrated experimentally the feasibility of such a concept in a ground facility.

The breadboard system tested in a vacuum chamber, comprised:

a) a particle flow generator,
b) a particle collector system,
c) a HET thruster (to generate the required thrust) and
d) a measurement system to characterize the flow and to obtain the forces.


Images credit: SITAEL

Interplanetary Human Missions, MARS

Land a crew of humans on Mars and return them safely, ensuring planetary protection for both, Earth and Mars,

Demonstrate human capabilities needed to support human presence on Mars,

Perform exploration and expand scientific knowledge taking maximum advantage of human presence including sample selection,

Assess suitability of planet for long term presence

Use of Electric Propulsion Systems for cargo

Required Knowledge

Funded by the European Union

Existence of life forms on Mars

Radiation Environment

Effects of Radiation on Humans

Medical and Physiological Aspects

Psychological Reactions

Martian Soil Properties

Martian Atmosphere Properties

Required Capabilities

Funded by the European Union

- *Assembly in Orbit*
- *Advanced Interplanetary Propulsion*
- *Light-weight Habitats*
- *Life Support Systems*
- *Aerocapture/Aerobraking*
- *Descent and Landing*
- *Space Infrastructure (Telecom, Navigation)*

Funded by the European Union

Cubesats Applications:

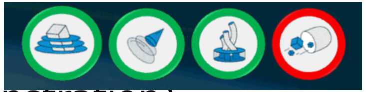
ESA's view on Cubesat propulsion

Funded by the European Union

- Cubesats originally intended for educational purposes and technology demonstrations but increasingly becoming attractive to **institutional and commercial users** for applications spanning from Earth Observation to Telecommunication, Information and even Exploration.
- **Propulsion capabilities are becoming crucial to enable mobility and enhance utilisation potential of CubeSats**
- Propulsion needed for insertion, station keeping, repositioning, **collision avoidance, deorbiting** but also for interplanetary transfers.
- Today, 100s of Cubesats are launched every year. Market forecast:
- +50 CubeSat propulsion subsystems (EP or CP) under development in Europe, mainly by SME. Only few flight ready.
- **+80 CubeSat propulsion subsystems in space**, from few suppliers and with limited return of experience: IOD missions with limited operation time and limited access to flight data.
- With a wide range of missions there is **no propulsion technology that fits all** and a portfolio of commercially ready technologies needed.
- Future **regulations on debris mitigation** may impose mandatory implementation of qualified and, perhaps, **independently certified propulsion** for CubeSats (e.g. for deorbiting/CAMs).
- Several announced (ESA) IOD missions to demonstrate propulsion capabilities but IOD is not (always) sufficient to demonstrate high technology readiness => **on ground qualification still required!**
- There are no official standards specific to CubeSat propulsion => necessity to tailor existing propulsion ECSS OR to create **dedicated ECSS** and **engineering guidelines** for Cubesat propulsion, particularly addressing **requirements for verification**, including life test.

ESA's view on Cubesat propulsion

- Strategic for cubesat propulsion:
  - **Cost reduction** while insuring performance, **reliability and safety**
  - **Increased reliability through ground testing** (including life demonstration)
  - Increased production rate
  - Availability of reliable microfabrication techniques, controlled manufacturing and cleanliness
  - Access to flight data from performed IODs to extract lessons learned.
  - Limit dependence on components subjected to export control restrictions.
  - Availability of test facilities, test methodologies, test equipment (e.g. to accurately measure static thrust down to µN level but also transients, noise, response time and MIB) and plume diagnostics:



- An **independent Test Center for End-to-End testing of Cubesats with propulsion** would offer a **unique capability** in Europe that will provide European industry with an opportunity to place **innovative**, **low-cost, enabling** propulsion technologies in the market with **reduced life cycle, increased maturity and reliability.**

Cubesat mission needs

Funded by the European Union

- The availability of propulsion may enable a wide range of future missions where specific capabilities are required:
    - new Earth Observation missions including constellations,
    - Telecommunication & Information missions in LEO including mega constellations,
    - In-orbit servicing and space debris monitoring,
    - Navigation constellations,
    - missions for astronomy and astrophysics and to study space weather
    - deep-space exploration.
- At present, the CubeSats available in the market that can host propulsion subsystems have a 3U (~5kg), 6U (~12kg), 12U (~20kg) and 16U (~30kg) form factor configuration.
- Cubesats require propulsion for insertion, repositioning, drag compensation, collision avoidance, disposal, precision pointing, formation flying, proximity operations, deep-space transfers.

RACE in close proximity

Eutelsat ELO constellation

Kineis constellation

ESA Technology Cubesat IOD missions with Electric Propulsion

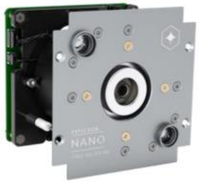
Funded by the European Union

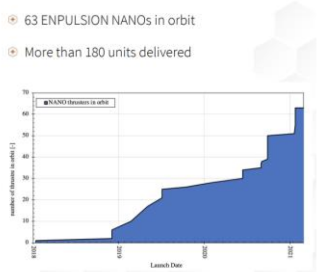
- Main objectives for propulsion on ESA Cubesat IOD mission: **demonstrate high DV and 6 DoF.**
- ESA IOD Missions:
  - M-ARGO (Miniaturised Asteroid Remote Geophysical Observer): first stand-alone deep space 12U-XL Cubesat demonstrating an hybrid xenon-fed system made of cold gas thrusters and a RIT 3.5 gridded ion engine from Mars Space (UK) for1-3 years low-thrust interplanetary transfer and 6 months close proximity operation at a Near Earth Object (NEO)
  - GOMX-5: 12U Cubesat from GomSpace (DK) demonstrating the iodine-fed NPT30 electric propulsion system from ThrustMe (FR) for large orbit transfer (delta-V > 280m/s).
  - VMMO (Volatile & Mineralogy Mapping Orbiter: Lunar orbiter, planning to use FEEP for delta-V of 240-670 m/s depending on launch option.
  - E-Inspector, planning to use an electric propulsion system to reach and inspect a large debris.

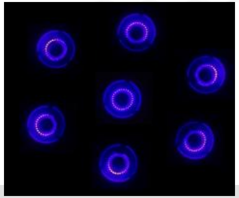
TDE – Innovative Propulsion for Cubesats & Microsats (Enpulsion)

Funded by the European Union

- Project also named **Enpulsion Nano AR3**
- **Contractor:** Enpulsion (A)
- **Objective:** to design, manufacture and test the IFM AR3 indium FEEP electric subsystem with segmented extractor at breadboard level (target TRL: 3/4).
    - Building on the flight heritage of the Enpulsion Nano (60+ in space), the Nano AR3 expands controllability towards active thrust vector control without moving parts.
    - Three-segmented extractor allows electrical field shaping, differential emission throttling, precise thrust vectoring.
- **STATUS:**
    - Subsystem requirement and design review successfully completed.
    - Manufacturing of all parts of the subsystem ongoing.
    - Testing at ESA propulsion Laboratory September 2022 (performance characterisation and endurance test)





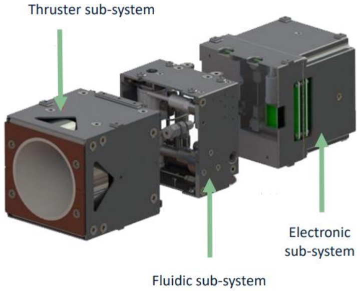


TDE – Innovative Propulsion for Cubesats & Microsats (T4i)

Funded by the European Union

- **Contractor:** T4i (I) with Opencosmos, Tyvak Int. (I) and University of Surrey (UK)
- **Objective:** to design, manufacture and test the E-REGULUS electric propulsion system at breadboard level (target TRL: 3/4).
    - E-REGULUS is an enhanced version (150W) of the 50W REGULUS system (IOD ongoing) using xenon instead of iodine as propellant.
    - Based on helicon plasma technology, it is a magnetically enhanced RF plasma thruster composed of a discharge chamber, an antenna and a magnetic field generator.
    - It does not use electrodes and does not require a neutraliser, thus allowing cost reductions and extended lifetime.

Thrust	0.25 – 0.65 mN (0.55 mN @ 50 W)
Specific Impulse	Up to 650 s (550 s @ 50 W)
Total Impulse	3000-11000 Ns (up to allowed tank size)
Required power	30 – 60 W (50 W nominal)
Mass flow	0.1 mg/s
Propellant	Solid Iodine (I2)
Volume	93.8 x 95.0 x 151.0 mm @ 3000 Ns 93.8 x 95.0 x 200.0 mm @ 11000 Ns
Weight	2.5 kg @ 3000 Ns
Electrical interfaces	CAN BUS, i2C with CSP protocol

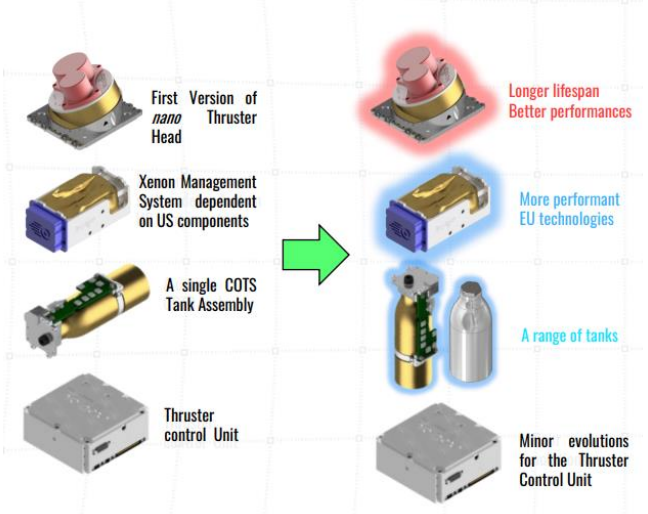


Thrust	From 0.4 (modulable)
Specific Impulse	From 500 s
Total Impulse	From 1500 Ns (up to allowed tank size)
Required power	50 – 150 W (150 W nominal)
Mass flow	0.2 mg/s
Propellant	Xenon (Xe)
Volume	93.0 x 96.0 x 245.7 (single-box configuration, without tank)
Weight	Less than 4 kg
Electrical interfaces	CAN BUS, i2C with CSP protocol

TDE – Innovative Propulsion for Cubesats & Microsats (Exotrail)

Funded by the European Union

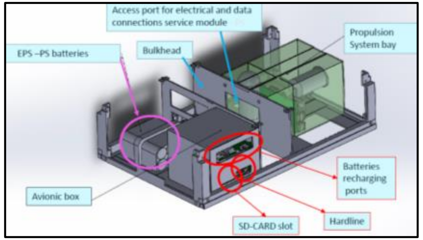
- Project also named **Springboard**.
- **Contractor:** Exotrail (FR)
- **Objective:** to design, manufacture and test of the ExoMG™-nano-L system at Breadboard level (target TRL: 3/4).
  - This is an electric propulsion system based on Hall Effect Thruster technology operating with Xenon and targeting longer lifespan (up to 5kNs), use of EU technologies and new tanks than the current flight ready version.
- **STATUS:**
  - Subsystem requirement and design review ongoing.
  - Testing at ESA propulsion Laboratory took place in Q1 2022 (performance characterisation and endurance test)

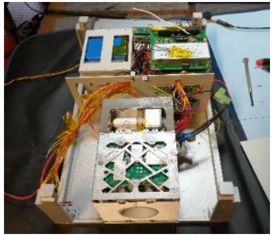


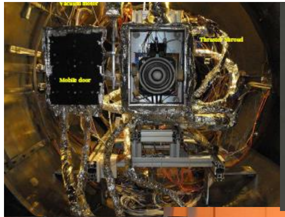
ESA plan to upgrade the ESA Propulsion Laboratory (EPL)

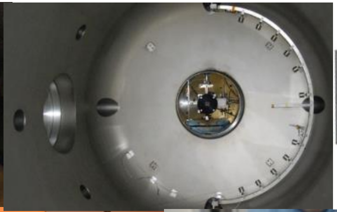
Funded by the European Union

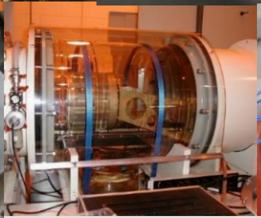
- The ESA Propulsion Laboratory (EPL) located at ESTEC has already capability to test Electric Propulsion and cold gas systems for Cubesats:
  - 7 vacuum test facilities, plume diagnostics, thrust balances,..
  - **Cubesat Propulsion Test Platform** was commissioned in Q4 2021.
- ESA/EPL has submitted an internal plan to become the **ESA Test Center for Cubesats Propulsion** to support the development of innovative CubeSat propulsion in Europe and provide functional/ performance/ environmental test of CubeSats with firing propulsion (**End-to-End testing**).
- The plan foresees **incremental upgrades** starting with the upgrade of one existing facility to a **TVT test facility** by Q1 2022 to enable performance verification of electric and chemical propulsion subsystems in relevant thermal environment.

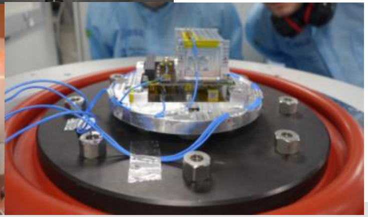












EP Future Developments

Funded by the European Union

- **HALL EFFECT THRUSTER:** Extension of lifetime via magnetic confinement and double operation point (higher thrust during orbit raising and higher specific impulse during NSSK). TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. Power levels around 5 kW or higher. System activities, cost reduction and industrial production issues should be assessed.

- **ION ENGINE:** Reduction of the power to thrust ratio via the cusp design . TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. Power levels around 5 kW or higher. System activities, cost reduction and industrial production issues should be assessed.

- **HEMPT:** High power HEMPT with high lifetime (Germany and Italy) and different operation points to adapt the thruster output t the power of the solar array of the spacecraft. TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. Power levels around 5 kW or higher. System activities, cost reduction and industrial production issues should be assessed.

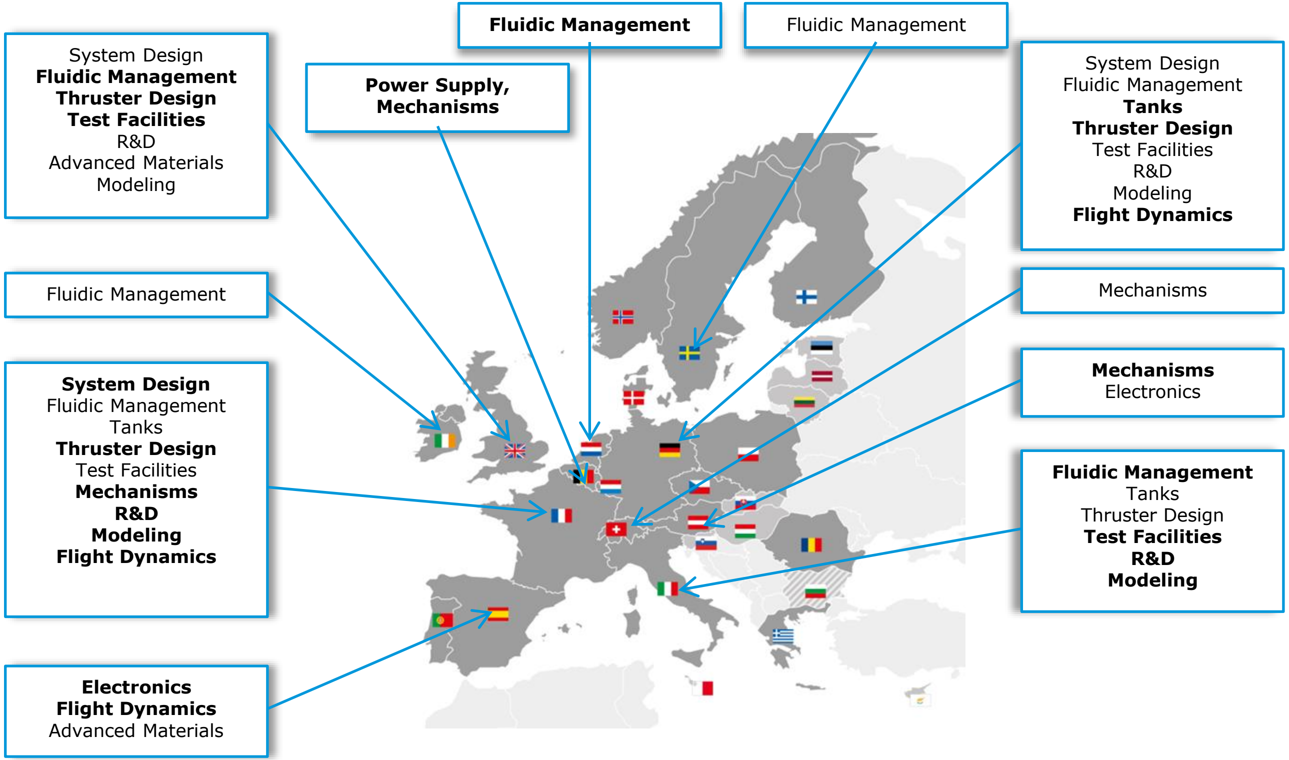
- **Mini-ion engines, FEEPs and mini-Hall effect thrusters, mini Helicon Antenna Thrusters** for science and Earth observation missions and **Cubesats**. Thrust levels from micro-Newtons to some milli-Newtons. Lifetime will be a special issue to be assessed.

- **Testing facilities:** The utilisation of High power engines will pose challenging requirements on acceptance testing facilities. The standardisation of testing methods will also be required to reduce cost and risk of EP developments.

- **New High Power Electric Propulsion** Concepts evaluation (Helicon Antenna Thruster, Electron Cyclotron Resonance thruster, MPD, E-Imapct thruster, etc.).

EP Capabilities in Europe

Funded by the European Union



EPIC: H2020 SRC for Electric Propulsion

Funded by the European Union

- Electric propulsion has been identified by European actors as a Strategic Technology for improving the European competitiveness in different space areas.
- **The European Commission (EC)** set up the "In-space Electrical Propulsion and Station-Keeping" Strategic Research Cluster (SRC) in Horizon 2020 with the goal of enabling major advances in Electric Propulsion for in-space operations and transportation, in order to contribute to the leadership of European capabilities in electric propulsion at global level within the 2020-2030 timeframe.
- The SRCs is implemented through a system of grants consisting of:

1) "Programme Support Activity" (**PSA**): The main role of this PSA is to elaborate a roadmap and implementation plan for the whole SRC and provide advice to the EC on the calls for operational grants.

2) Operational grants for R&D.

EPIC: Programme Support Activity

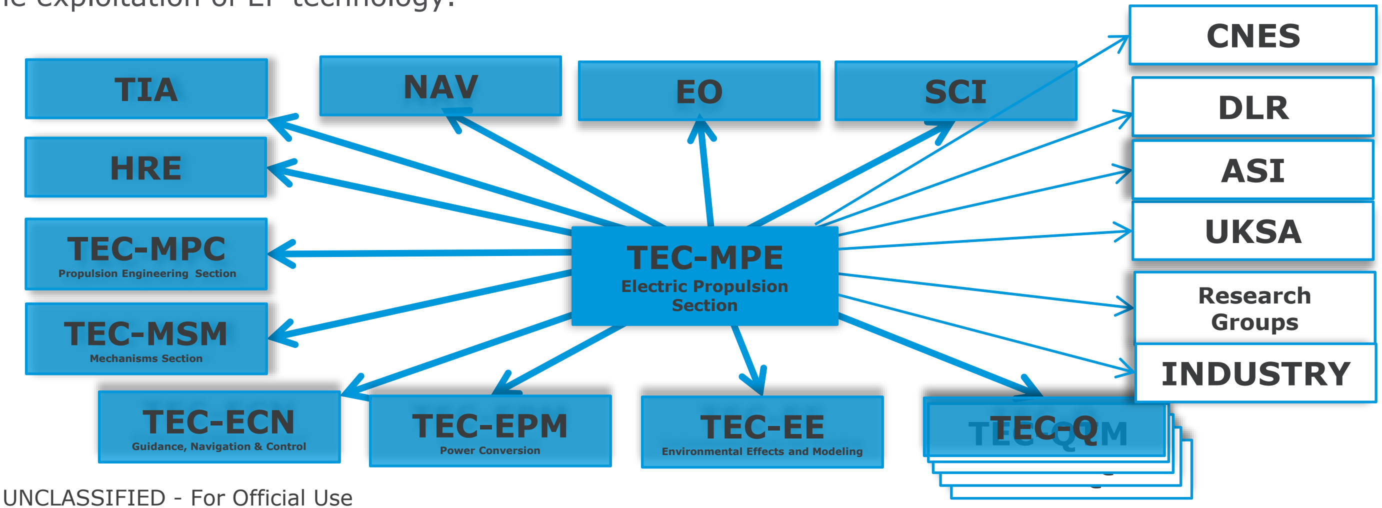
Funded by the European Union

- The European Commission (EC) has funded, as part of the Horizon 2020 Space Work Programme 2014, a Programme Support Activity (PSA) for the implementation of the **Strategic Research Clusters (SRC) on "In-Space electrical propulsion and station keeping"**.
- The "**Electric Propulsion Innovation & Competitiveness**" **(EPIC)** project is the PSA for the Electric Propulsion SRC funded as response to the H2020 Space COMPET-3-2014 topic.
- It was initiated in October 2014 and has a duration of **5 years + extension**, during which it is meant to support the European Commission on the definition and successful implementation of the SRC in Horizon 2020, in order to achieve the objectives set for it and subsequently for Europe on this increasingly relevant technology area at worldwide level. The activities have been extended until 2023.
- **The EPIC PSA aims at providing advice to the EC preparing Roadmaps, drafting call texts and assessing results of the SRC operational grants.**
- The R&D work will come in the SRC as a part of future Calls made by the EC, open to all EU Member States and H2020 participants, and will be selected and supported through the normal Horizon 2020 grant procedures
- **EPIC PSA Partners: EPIC – ESA (coordinator), ASI, BELSPO, CDTI, CNES, DLR, UKSA, Eurospace, S4S**

Electric Propulsion activities in ESA

Funded by the European Union

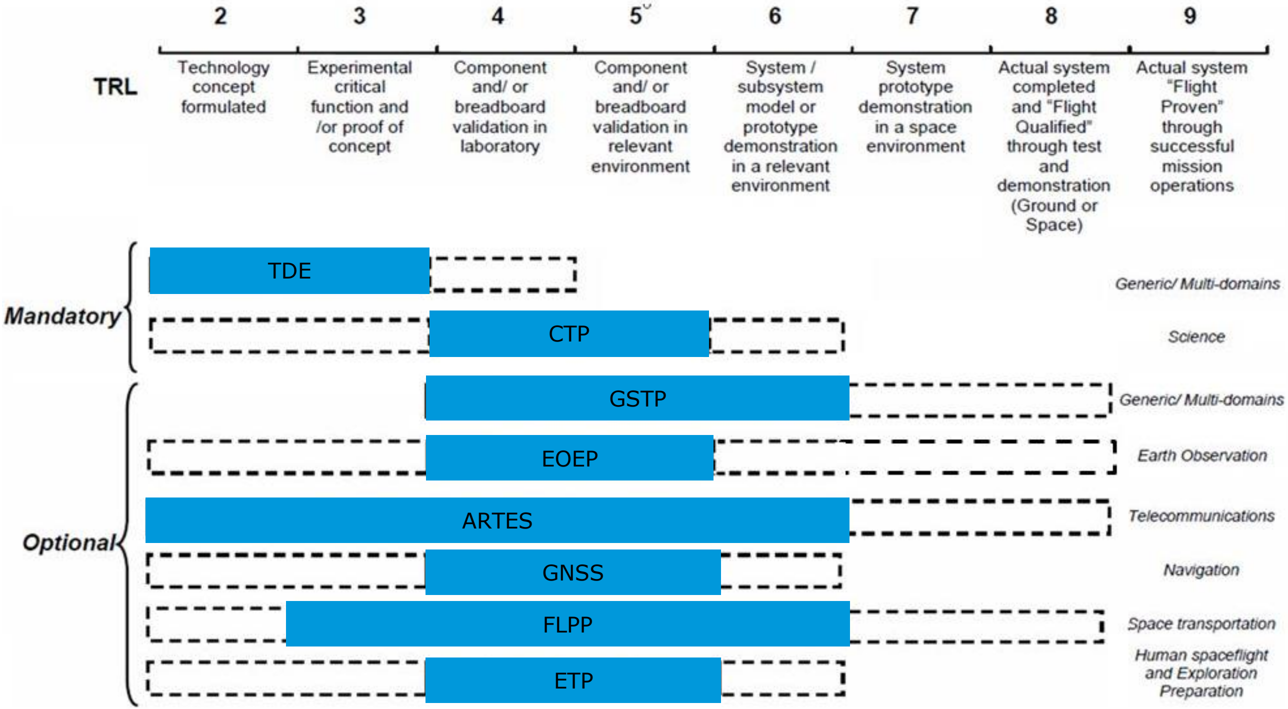
- The Electric Propulsion Section at ESA (TEC-MPE) coordinates all ESA activities in the field of electric propulsion.
- TEC-MPE is part of ESA's Directorate of Technical & Quality Management (D-TEC), which is the directorate providing engineering support to ESA's Application Directorates: Telecoms & Integrated Applications (TIA), Navigation (NAV), Earth Observation (EO), Science (SCI) and Human & Robotic Exploration (HRE).
- TEC-MPE interfaces with the many disciplines that are needed to support the development of technologies, right through to implementation of **flight ready systems**.
- The function of TEC-MPE, is entirely dependent on excellent working relationships with all European entities involved in the exploitation of EP technology.



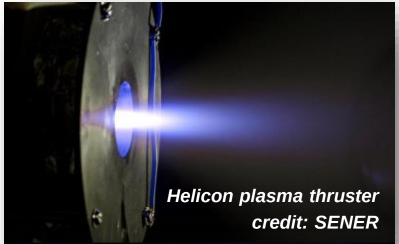
Indication of regular interactions between specialist disciplines, customers & suppliers involving TEC-MPE.

Electric Propulsion activities in ESA:
ESA Technology Programmes

Funded by the European Union



EP development activities supported via a range of ESA programmes.



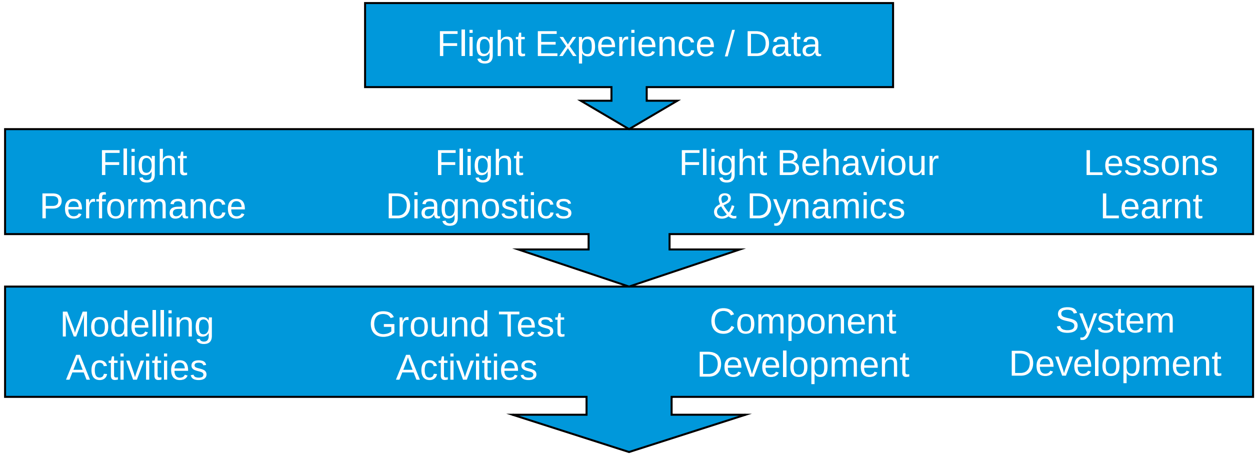
Helicon plasma thruster credit: SENER

HT20K HET credit: SITAEL

Electric Propulsion activities in ESA:
Return of Experience from Flight Programs

Funded by the European Union

- Coordinated by TEC-MPE, dedicated activities are implemented to ensure maximum return of experience from Flight Programs, both institutional and commercial.



Verification of current designs

Securing confidence in technology

Next Generation of EP Systems / Applications

Electric Propulsion activities in ESA:
The ESA Propulsion Laboratory

Funded by the European Union

- The ESA Propulsion Laboratory (EPL) is located in ESTEC, The Netherlands.
- It provides test services to the Propulsion and Aerothermodynamics division of the European Space Agency, which is responsible for the technical support to ESA projects and the R&D activities in the areas of chemical propulsion, electric and advanced propulsion, and aerothermodynamics.


CORONA


Micro Newton


Small Plasma Facility


FEEP


GIGANT


ELECTRON


GALILEO

Electric Propulsion activities in ESA:
The ESA Propulsion Laboratory

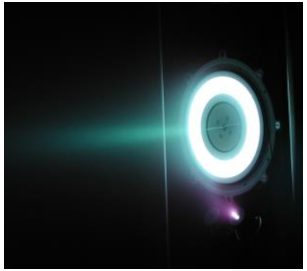
Funded by the European Union

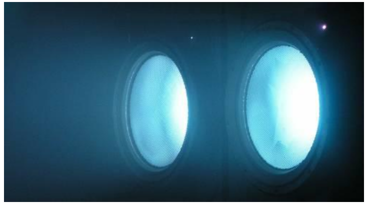
- EPL today provides independent assessment on EP thrusters & propulsion components performances.
- Tests are mainly focussed on low power EP propulsion and cold-gas system.
- Future improvements are aiming at enabling measurement of thrust and thrust noise in µN regime for science and earth observation application (NGO, Euclid, NGGM) and at characterising mid-high power thrusters for science, navigation and telecommunication applications (>2kW).
- Planning and execution of performance characterization of electric thrusters (HET, GIE, FEEP, Resistojets), cold gas thrusters & propulsion components.
- Design, manufacturing and validation of diagnostics (thrust balances, data acquisition systems, beam probes) in collaboration with European industries/research centers.
    - ISO 17025 certification of thrust, mass flow and electrical power:
    - Force: 1 µN – 500 mN
    - Mass flow: 1 µg/s – 300 mg/s
    - Power: 1 mW – 2 kW

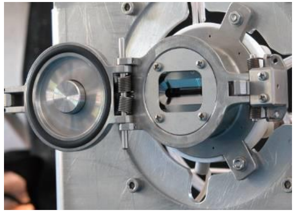
Important and last Technology Developments

Funded by the European Union

- **Thrusters**
  - **Higher and lower power versions of current engines (HETs, Ion Engines)**
  - **HEMPT engine**
  - **MEMS, Helicon Antenna Thrusters, In-Porous milliNewton thrusters, Micro-PPTs, FEEPs, etc.**
  - **Mini-ion engines, mini-Hall Effect thrusters**
- **Components (emphasis on cost reduction)**
  - **Xenon storage, regulation and flow control systems**
  - **Cathodes and neutraliser**
- **Electric Propulsion in-flight Diagnostic Packages**
- **Verification Tools and techniques**
  - **Advanced plume characterisation tools and models**
  - **Electric Propulsion EMI validation facilities**
  - **EP system design and performance verification models**
- **EP Implementation Support**
  - **Assessment of Flight data from missions in-orbit**
  - **Optimisation of systems configurations**





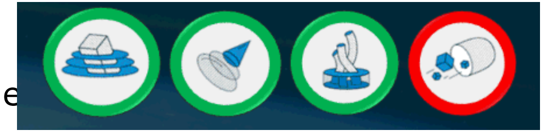


ESA Technology Strategy

Funded by the European Union

- **ESA responsibility:**
  - make sure that the **right technology** will be available at the **right maturity** at the **right time** for future missions.

- **ESA technology targets**:
  - 30% improvement of development time by 2023,
  - one order of magnitude improvement in cost efficiency with every gene



  - 30% faster development and adoption of innovative propulsion technologies,
  - inverting Europe's contribution to space debris by 2030.

- **Propulsion technology strategy:**
  - Develop in-space propulsion:
    - to enable new, emerging applications
    - to enhance the creation of new markets
    - to enhance reliability and competitiveness of European propulsion products.
  - Develop testing and diagnostic tools to enhance the capability for independent forecast and validation of the performances of European propulsion technologies.

Electric Propulsion activities in ESA:
ESA Strategy on EP

Funded by the European Union

- *Consolidation of the current European products (Hall Effect Thrusters, Gridded Ion Engines, field emission thrusters, HEMPT, MPD, etc.). In this process the qualification of the European products is one of the main activities together with the European autonomy in components. ESA aims to have full European systems where not only the thruster is European but also the other elements as well, such as pressure regulators, power processing units, neutralizers, etc.*
- *Utilization of heritage flight data (Artemis, Smart-1, GOCE, Inmarsat 4F, Intelsat 10, Astra 1K, Alphabus, BepiColombo etc.) to validate the models that will be used by spacecraft providers in the future.*
- *Standardization of engineering processes and testing facilities employed in the design, manufacturing and qualification of electric propulsion systems.*

Conclusion

Funded by the European Union

- Exploitation of Electric Propulsion in Europe has reached the end of the beginning, with mission success demonstrated for Telecom, Science and Earth Observation programmes.
- **High power EP (5kW) medium term applications**: telecommunication will be able to make an immediate use of these technologies or on obit control and full or partial transfer. **Ion Engines, Hall Effect thrusters and HEMPT**.
- Later, Navigation, Science (interplanetary missions) and Exploration (the Moon, Asteroids and Mars) will require such systems.
- In order to improve European access, it is important to retain a capability to deliver alternative 5 Kw technologies The power for these engines is around **5kW**. **New propellants, Krypton, Argon, Iodine,…**
- ESA is also developing micro thrusters such as **mini-ion engines, FEEPs, mini-Halls**, etc. with capability to fulfil stringent Science and Earth Observation requirements (LISA, NGGM, Euclid, microsatellites etc.). Airbus, ALTA, FOTEC, ENPULSION, etc. are busy with these developments where lifetime will have to be assessed.
- The Next evolution of the current engines developed today for high power (5kW) will have to provide higher LIFETIME, lower power to thrust ratio, higher specific impulses and be more efficient. These are the main challenges. **10 and 20 kW engines** will have to be developed.
- **Constellations of satellites** will make use of EP systems at very low prices due among several reasons to the large quantities. Low power engines for **constellations**.
- **Cubesats are a new market for Electric Propulsion.**
- ESA, Space Agencies and Industry have participated to the **EPIC** activity within the European Community Horizon 2020 programme. ESA has been the coordinator of this programme.