The European Prospects on High Power Electric Propulsion Technology for Future In-Space Operations

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Future In-Space Operations (FISO)
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HiPER description and Objectives

- "**Hi**gh **P**ower **E**lectric propulsion: a **R**oadmap for the future" (**HiPER**)
- 19 partners from 6 European Union countries under the coordination of Alta
- Duration: **36** months; started on **October, 2008**
- Approved budget: **5,3 M€**; Approved grant **3,6 M€**
- **Strategic objectives:**

✓ to conceive and substantiate a long term vision for mission-driven Electric Propulsion development considering realistic advances in state-of-the-art of EP related technology.

✓ to perform basic research and proof-of-concept experiments on some of the key technologies identified by such a vision

HiPER Project Logic and Phases

Year 1 | Year 2 | Year 3

Phase 1

Definition and selection of future Exploration and Transportation scenarios

Phase 2

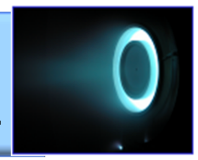
Technical Specifications for EP systems

Technical Specifications for Power Generation

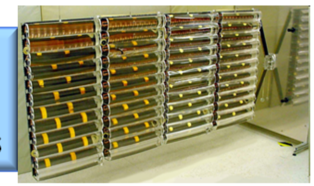
Phase 3

Tier 1

High Power HET design & development

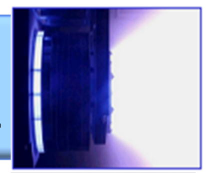


High Power High efficiency Solar arrays & PCUs

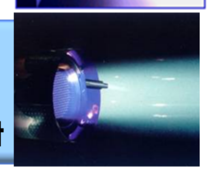


Tier 2

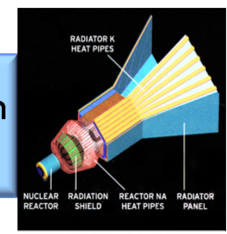
High Power MPDT design & development



High Power GIE design & development



Nuclear power generation preliminary study

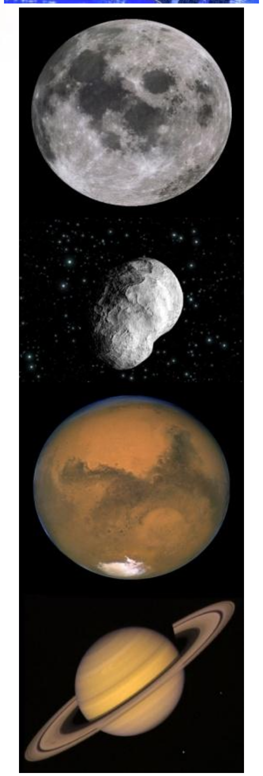


SAIRS Lightweight 100 kWe Power System with AMTEC Energy Conversion for Future NASA Space Exploration Missions, Developed at UNM-ISNPS.

Phase 4

Review of Results and consolidation of scenarios

Mission Analysis: Selected Mission Classes



	2015 – 2020	2025 – 2030 – 2035
LEO	- ISS programme extension - Implementation of ISS capabilities: module assembly, refueling	
EML1/ Moon	- Large payloads shipped from LEO to GEO, EML1 and LLO.	- Large telescopes assembly in EML1 to be shipped to SEL2 - Moon ISRU for missions beyond the Earth-Moon System
NEOs	- Scientific Missions to NEOs	- NEOs Exploration, Exploitation and Risk mitigation
Mars	- Robotic Mars Sample Return	- Crew missions to orbit Mars, Deimos and Phobos
Outer Planets		- Scientific/Robotic missions to the outer planets to search for evidence of life
	Near-Term Scenarios	Long-Term Scenarios

Preliminary Definition of Requirements and Open Issues

- System Requirements:
  - ✓ Power requirements for both SEP (80-200 kW) and NEP (200 - 2000 kW) cases
  - ✓ Propulsion requirements set for three different voltage ranges used to accelerate ions
  - ✓ Parameters assumed are best estimates from the available experience at this stage→ possible error bars to be considered
  - ✓ Necessary review and updates as technical investigations and demonstrations results are available

- Other aspects and open issues:
  - ✓ Power chain voltage level trade-off → optimization of the mass
  - ✓ Propulsion Subsystem redundancy architecture (full vs. partial, acceptable degraded performance levels, active thrust orientation,...)
  - ✓ Propellant choice: Xe limited world production → viable alternatives (Ar, Kr, metal vapors, etc.)…how do they affect test activities?

SEP Transfers in the Earth-Moon System

General Assumptions:

• Initial Orbit: - circular LEO @ 1000 km of altitude → atmospheric drag neglected
- GTO (250 x 35950 km)

•Initial mass: 20 metric tons @ LEO and 10 tons @ GTO (compatible with SoA heavy launchers, e.g. Ariane V ECA)

• Final EML1 Halo orbit

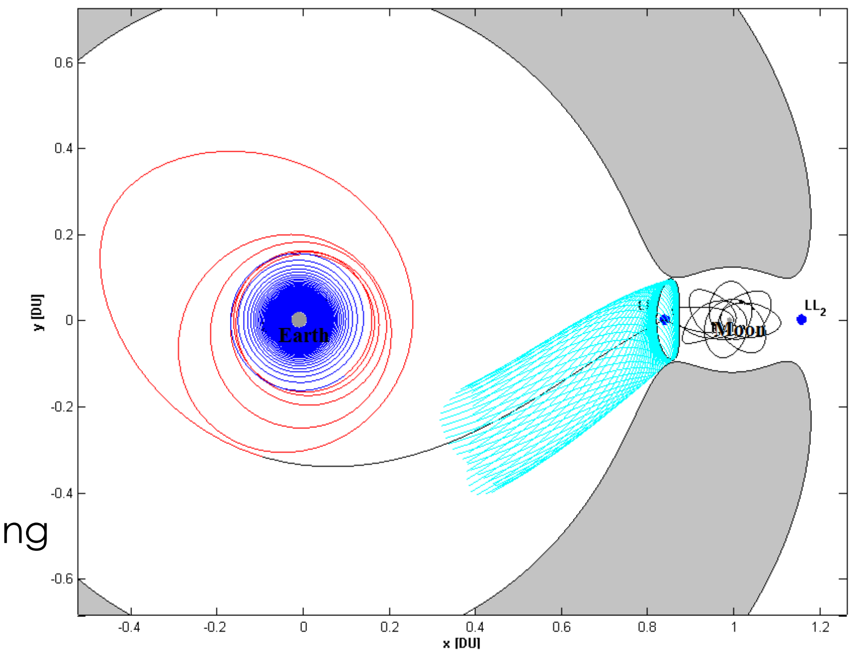
• Three Power levels: 80 kW, 100 kW and 200 kW

• Five Specific Impulse values:

2000 s, 3000 s, 4000 s, 5000 s, 10000 s

• Four/two Phases Transfer:

- Tangential thrust up to 25000 km radius
- Phased Tangential thrust to increase eccentricity
- Elliptic orbit (GTO) to Manifold insertion optimized thrusting
- Manifold ballistic phase



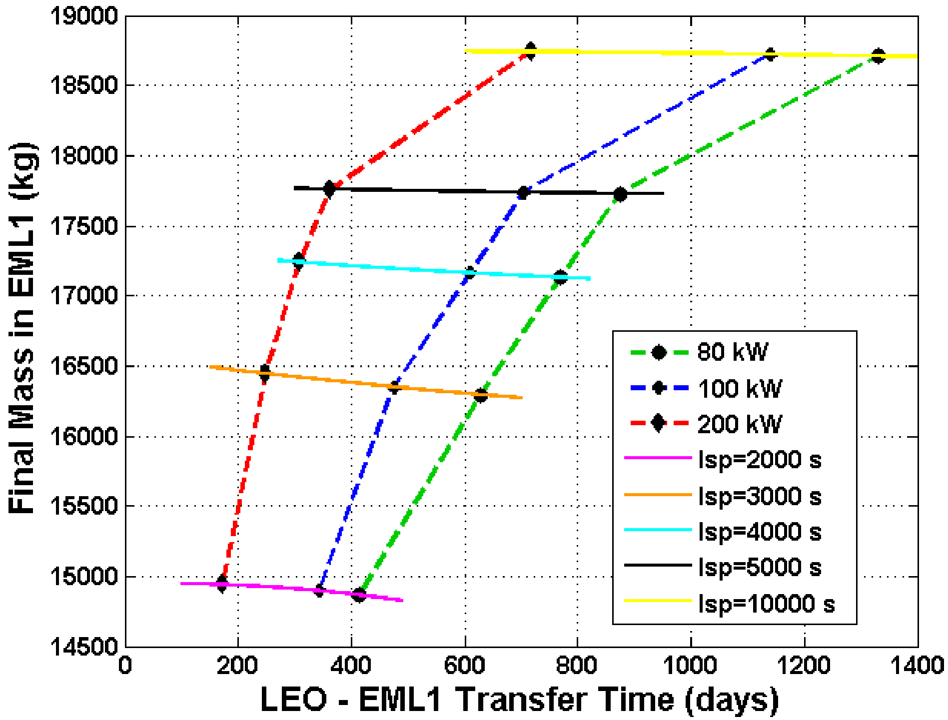
Space Hub in EML1: LEO – EML1 Transfers

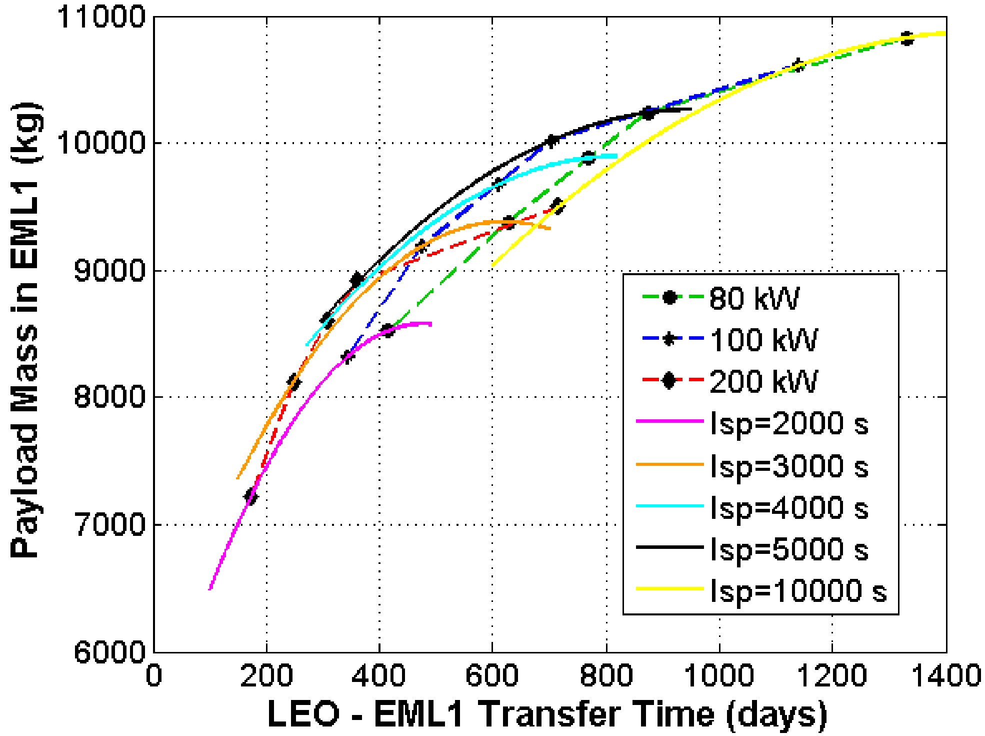
Payload Mass obtained with a preliminary mass breakdown:

✓Solar arrays: 20 kg/kW

✓PPUs & thrusters: 3 kg/kW

✓Tanks & related structures: 20% of propellant mass

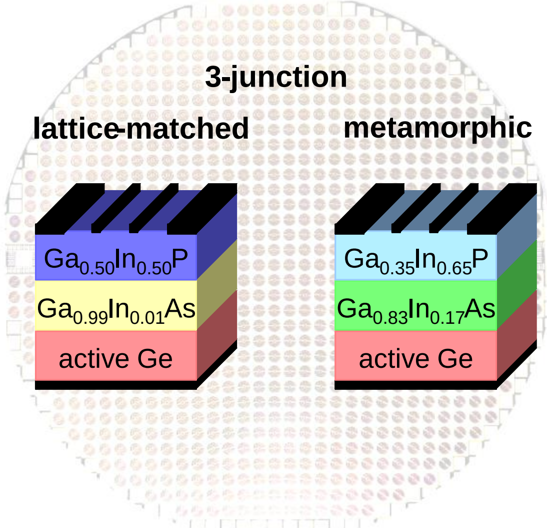




Solar Electric Power (SEP) Generation: PV Cell Design

Objective: Design and Prototyping of a Space Concentrator on a flexible and foldable substrate for high power application (up to 200 kW)

- ✓ Increase specific power → reduce weight
- ✓ Increase stowed power density



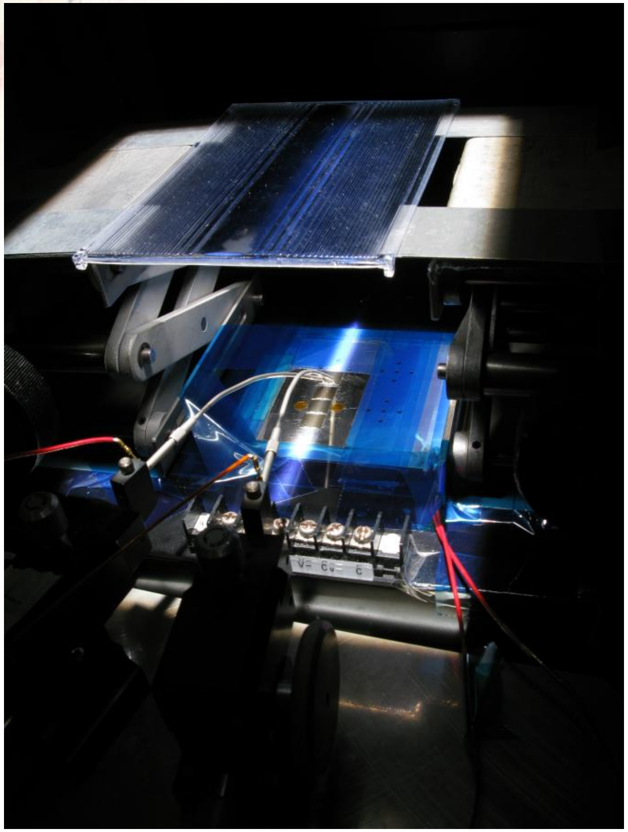
- Multi-junction *Ge/GaAs/InGaP* lattice matched solar cells in HiPER Breadboarding activity

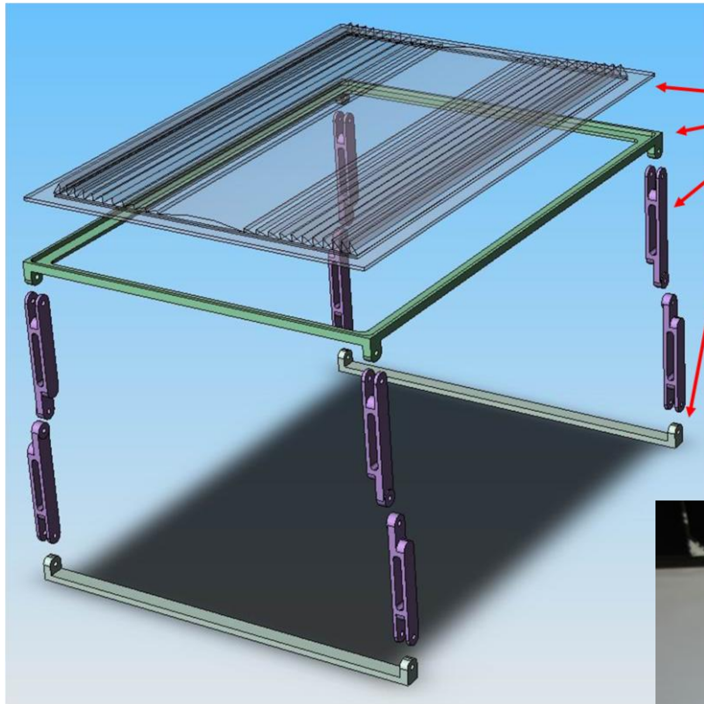
- Coupled cell-lens system (optimum concentration ratio) gives advantages in the performance of solar cells when used in space concentrators:

- ✓ Higher efficiency due to concentration
- ✓ Higher end of life (EOL) performances due to radiation shielding and due to higher current densities in the solar cell
- ✓ Lower price for fixed active area, being shunt defects less significant (thus increasing production yield)

	Power Density @ BOL (W/m^2)	Specific Power @ BOL (W/kg)	Stowed Power Density @ launch (kW/m^3)
SoA rigid panels	**300**	**100**	**10 - 15**
High Power Concentrator Design	**300**	**150**	**20 - 30**

SEP Generation: Optical Design



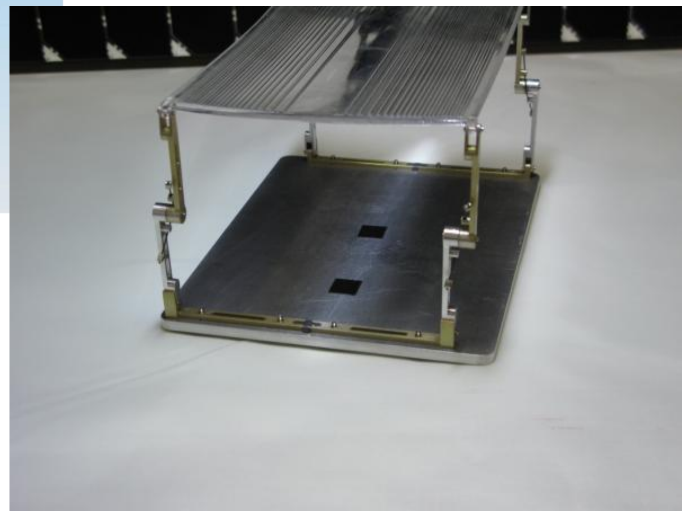


CONCENTRATOR MODULES

Main elements:

- Fresnel lens
- Sustaining frame
- Joints
- Sustain
- Substrate and Hinges

Joints are moved by smart material springs

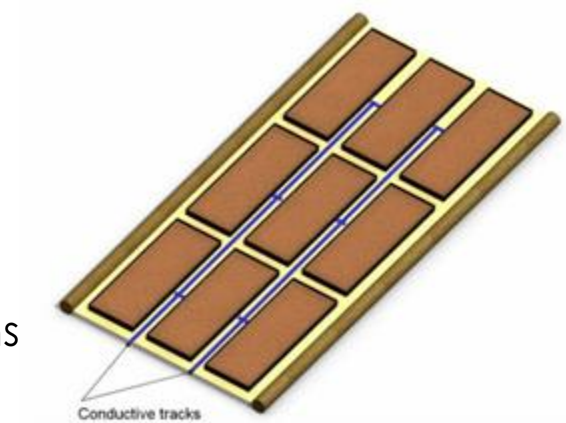


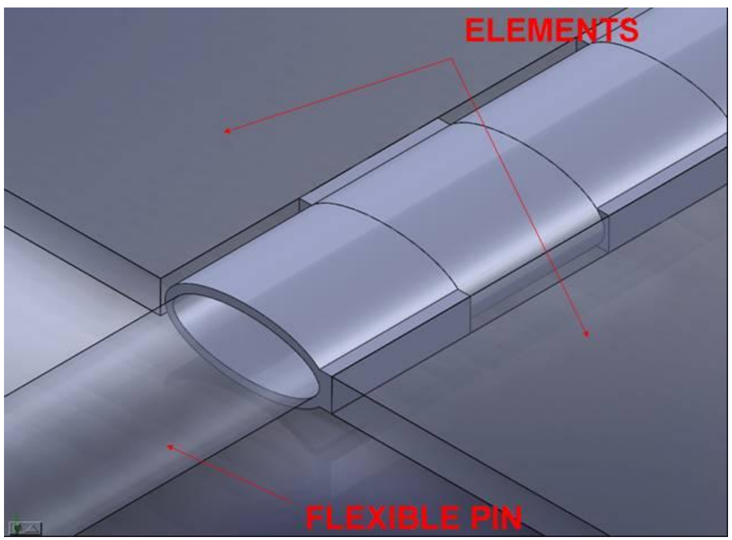
Effective concentration factor better than 5 x

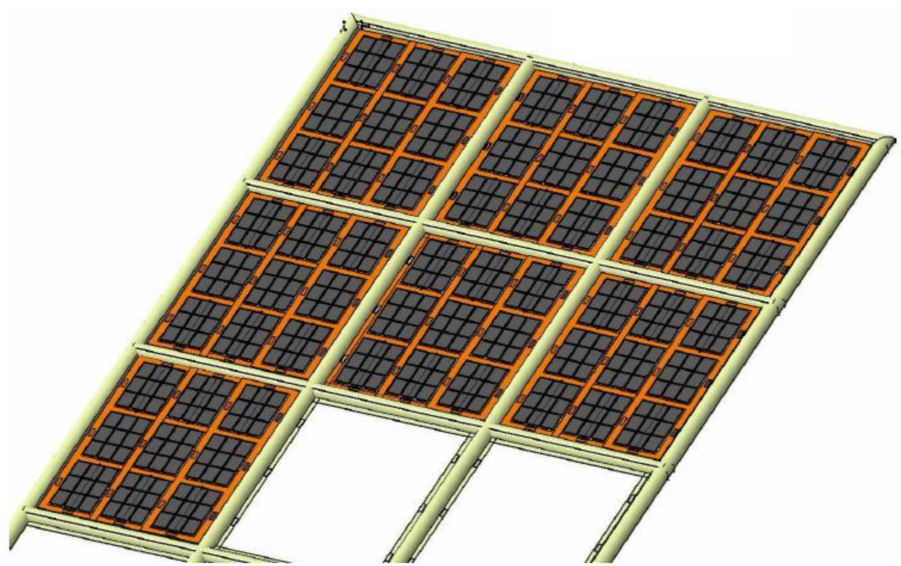
SEP Generation: Substrate Preliminary Design

Shape Memory Alloys (SMA) will also be used to deploy the substrate:

- the substrate is composed by a set of modules
- each module is made by a layer of kapton (50 μm)
- each module is rigidized by an inflatable sustaining frame
- Modules are joint by pins
- the deployment relies both on inflatable structure and SMA
- Copper embedded into the substrate for PVA network connections

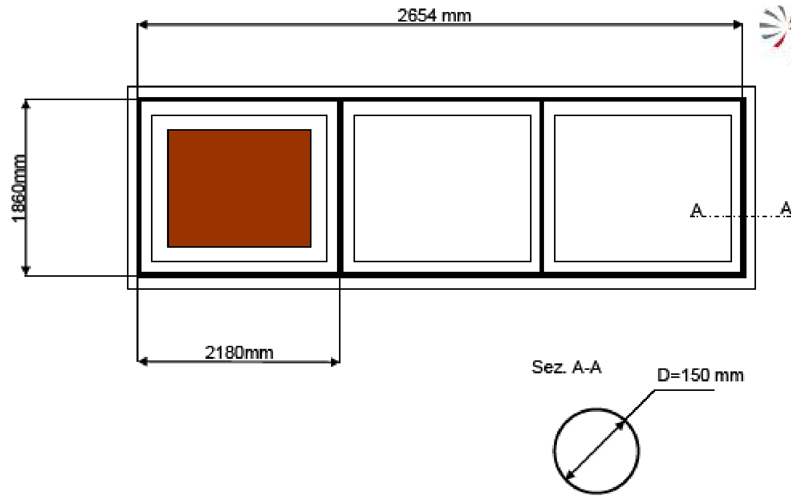


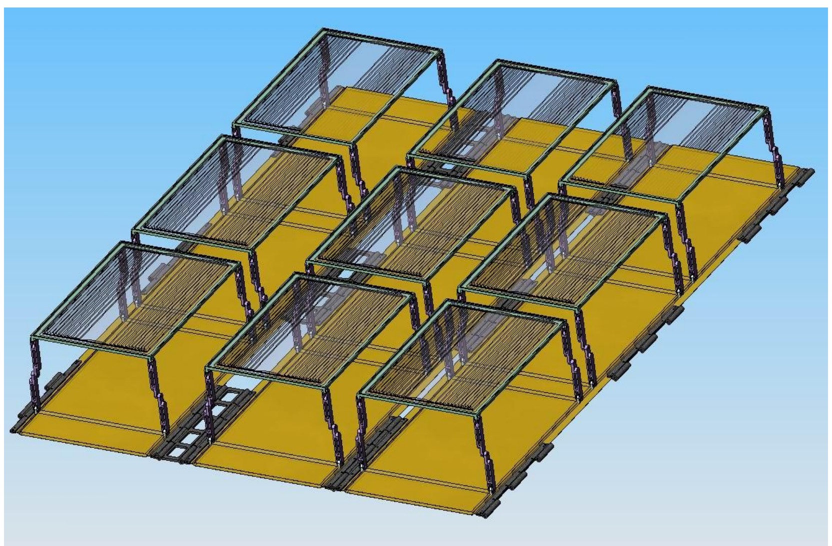




SEP Generation: MAIT Activities

- ✓The breadboard formed by three single elements has been already manufactured
- ✓Integration of PVA network connections, solar cells and optical system will be assembled next month
- ✓Test activities on the breadboard will be performed next July





Nuclear Electric Power (NEP) Generation: Design Constraints

Based on realistic technology improvements in the next 10 - 15 years, the NEP roadmap study was constrained by:

✓Launch mass (Ariane V ECA):

- 20,000 kg to LEO (200*200 km altitude),
- 10,000 kg to GTO (200*36000 km altitude),
- 6500 Kg to Circular orbit (15,000 km altitude)
- 5500 Kg hyperbola V_{inf} 2.3 m/s for earth escape

✓Minimum Launch altitude 800 km

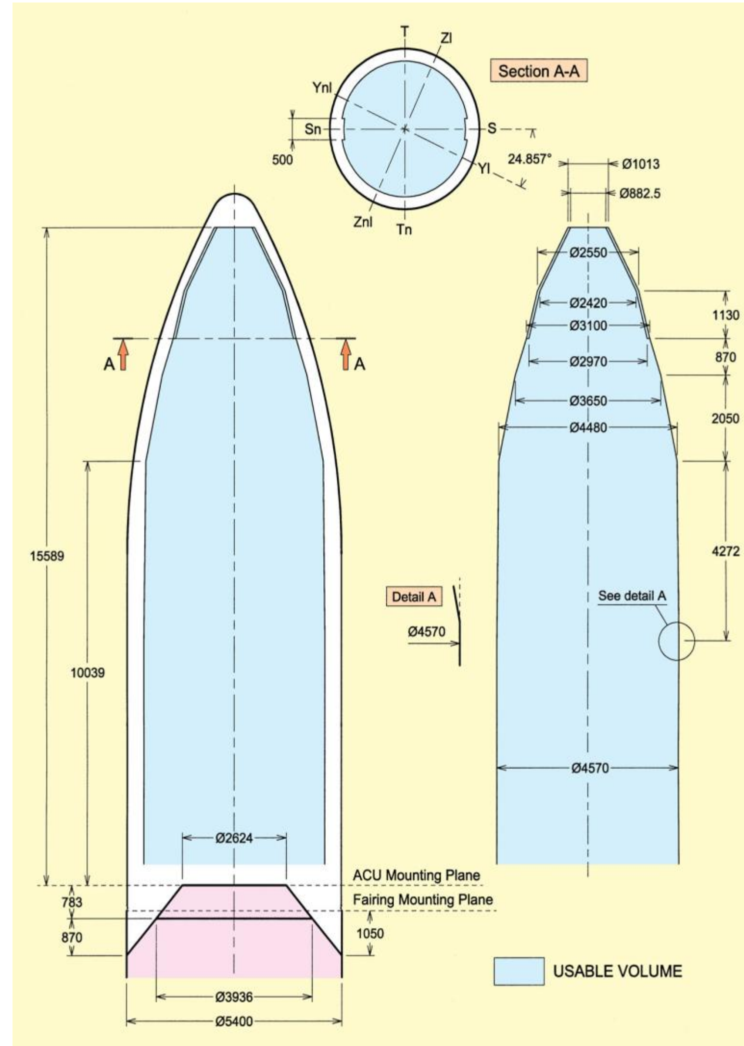
✓Inert launch and survive immersion

✓Launch fairing volume:

- See opposite

✓Thruster technologies 20 KW to 2 MW.

✓Atlas V HL has 10% more capacity.



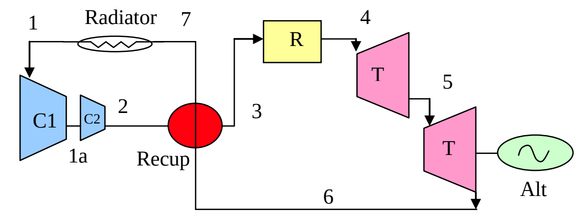
NEP Generation: Concept Design Options

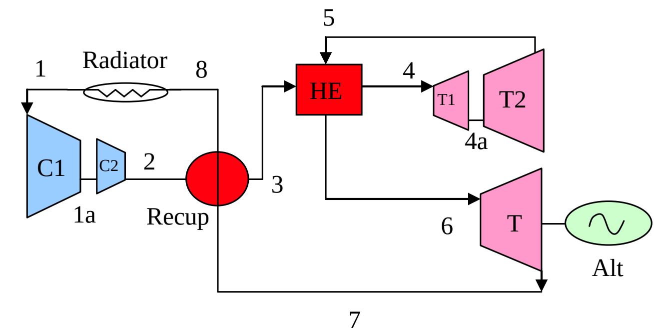
System & Baseline Example	Direct Fixed Radiator	Indirect Deployable Radiator	Direct Fixed Radiator
T hot, K	**1500**	**1200**	**1300**
Power **MWth** **MWe**	1.183 0.200	1.117 0.200	1.183 0.200
η	0.169	0.179	0.169
Reactor Mass (kg)	**1627** *8.13*	**528** *2.64*	**1627** *8.13*
Shield (kg)	**800** *4*	**975** *4.88*	**800** *4*
Reactor Control (kg)	**42.6** *0.21*	**31.1** *0.16*	**42.6** *0.21*
IHX (kg)		**366** *1.83*	
Generation (kg)	**1656** *8.28*	**1612** *8.06*	**1656** *8.28*
Radiator Area (m^2) Mass (kg)	**80.8** **1441** *7.21*	**225** **1798** *8.99*	**143** **2589** *12.99*
Total Mass (KG)	**5566.6**	**5310**	**6714**
Sp. Mass, (kg/kWe)	**27.83**	**26.55**	**33.57**

Nuclear Power Generation Results

➢ HiPER NEP Concept Design:

- Direct Gas or Indirect Liquid Metal Cooled reactor
- Brayton Cycle Power Conversion
- Power: 200 kWe (1 - 1.2 MWth)
- Specific mass: 30-37.5 kg/kW:
  - NEP Generator 28-33.5 kg/kWe,
  - Power Management and Distribution ~ 2-4 kg/kWe,
- Low volume high density fixed or high volume low density deployable radiator.
- Life time: 10 year operations,
- Ariane 5 ECA launch.





SPACE ENTERPRISE PARTNERSHIPS

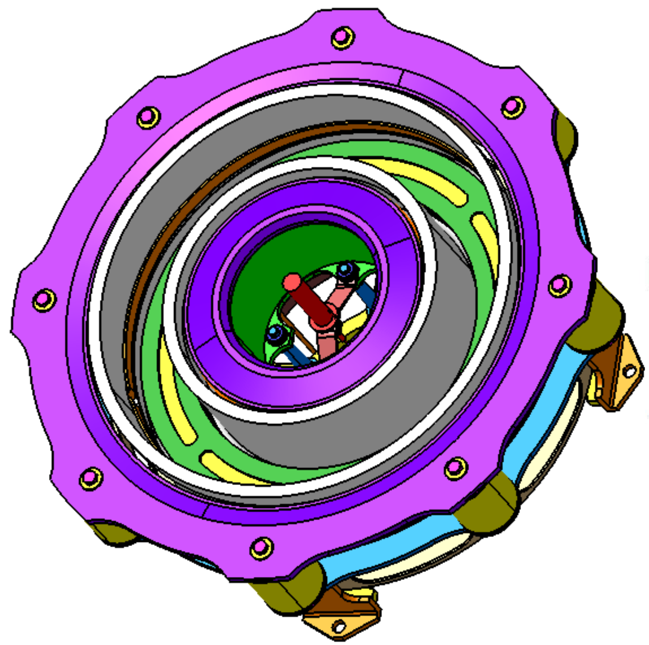
ACTA BEYOND THE RESEARCH

Rolls-Royce

High Power Hall Effect Thruster (HET) Activities

- ✓ Assessment of the material options for the anode and improvement of the ceramic process for increased HET diameter
- ✓ Measurement of ceramic erosion and of secondary electron emission to choose the best anode ceramic.
- ✓ The most important geometrical and functional parameters of a **20 kW-class** HET have been defined
- ✓ Prototype test activities will be performed next July at a power level of 10 kW

HiPER "PPS-20k ML" main specifications	
Power	**20 kW**
Thrust	**1 N**
Specific Impulse	**2,500 s**
Discharge current	**40 A**
Discharge Voltage	**500 V**
Xenon mass flow rate	**~ 41 mg/s**
External Diameter	**320 mm**
Height	**~100 mm**
Mass	**~25 kg**

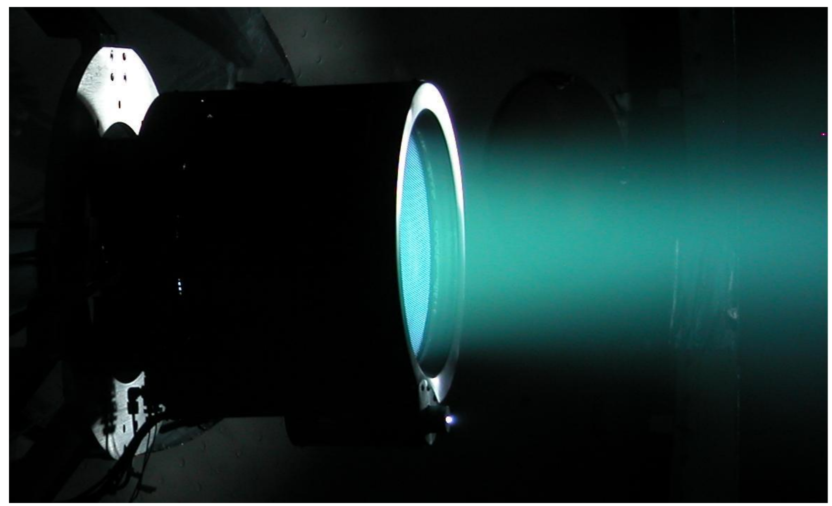


High Power Gridded Ion Engine (GIE) Activities

Based on the mission analysis requirements, high power GIE activities were aimed at:

- ✓ Defining the most important geometrical and functional parameters of a **20 kW-class Double Stage 3 Grids** Ion thruster
- ✓ Designing, manufacturing and testing of a high current Hollow Cathode

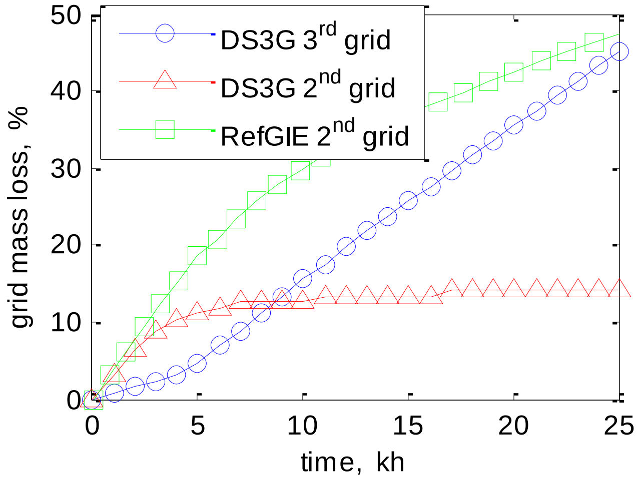
HiPER DS3G GIE main specifications	
Power	**20 kW**
Thrust	**0.45 N**
Specific Impulse	**10,000 s**
External Diameter	**340 mm**
Screen Grid Voltage	**8,120 V**
Extraction Grid Voltage	**6,120 V**
Accelerating Grid Voltage	**-120 V**



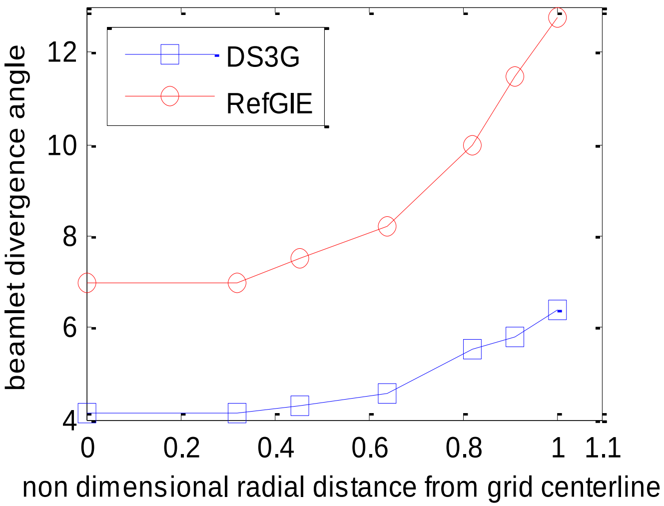
(T6 Courtesy of QinetiQ)

High Power Gridded Ion Engine: Ion Optics Design

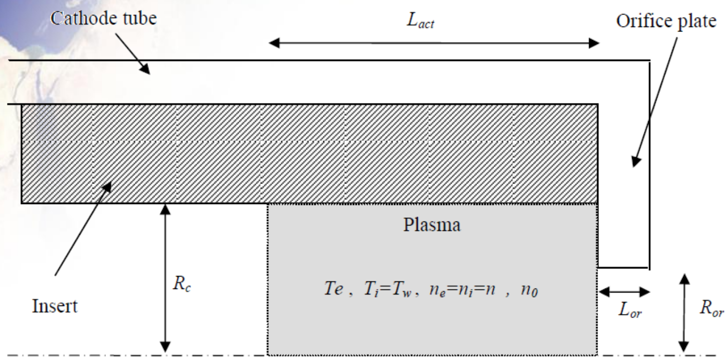
- The ion optics design presented is for a specific impulse of 10,000 s and beam currents in the range 1.5 - 3.5 A
- The predicted RefGIE lifetime will be about 35,000 hours, whereas for the DS3G the lifetime will be about 45,000 hours.

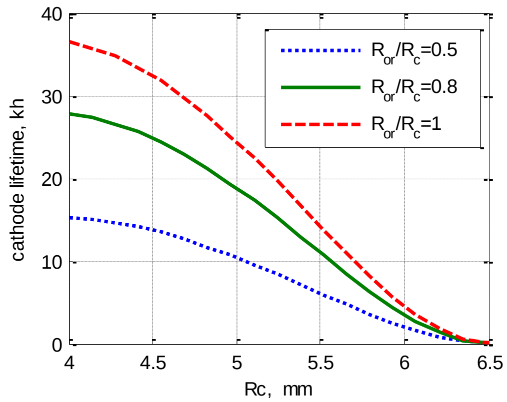


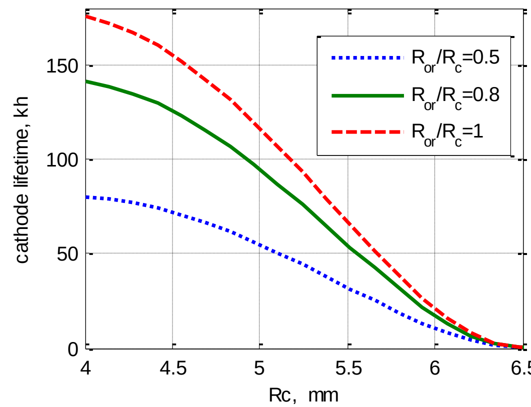
	Aperture radius	Thickness	Voltage
1st grid	1 mm	-	8120 V
2nd grid	0.7 mm	4x the 1st grid	6120 V
3rd grid	0.7 – 1 mm	4x the 1st grid	-250 V
Grid spacing	Center	edge	
1st – 2nd	~0.5 mm	~1 mm	
2nd – 3rd	1.5 mm	1.5 mm	



High Power Gridded Ion Engine: Hollow Cathode Design and Test







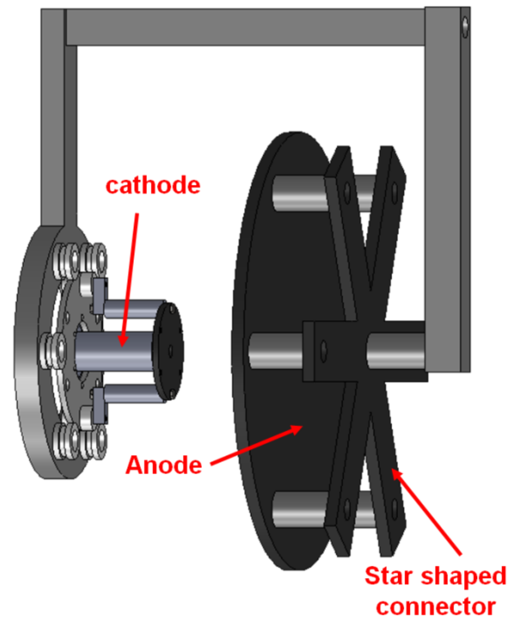
The main objective of the test is to demonstrate the ability of the cathode designed to:

- ✓provide the required current of 186 A
- ✓survive a 500h life test

Secondary objectives of the test are to gain data relative to dependence of the insert temperature on:

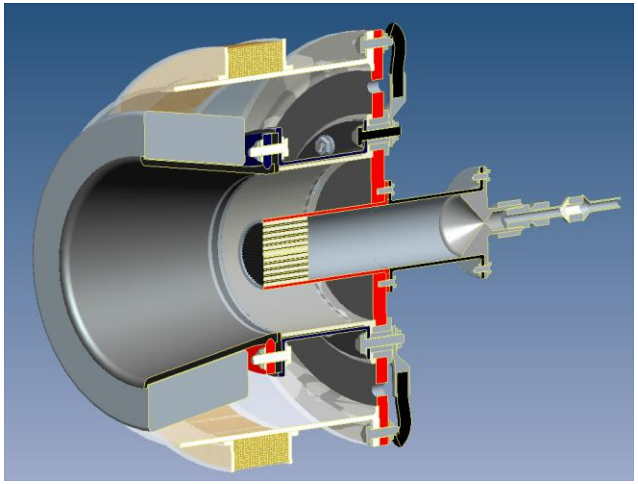
- the orifice radius
- the propellant mass flow rate
- the discharge current
- to investigate the current range in which the cathode can be operated

Test activities will be performed next August



Magneto Plasma Dynamic Thruster (MPDT) Activities

HiPER activities on MPDT aim at design TWO **100 kW-class** Applied-Field MPDT. Activities done:



✓Characterization of plasma instabilities and identification of design solutions for instability control

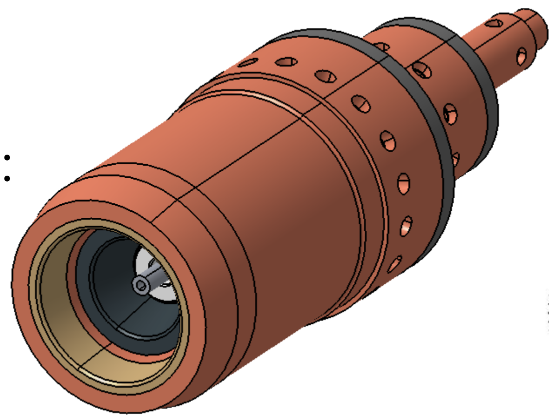
✓Development of high current cathodes

✓Alta Development Model (DM) main specifications:

- **Pulsed quasi-stationary MPDT**
- **Isp=2500 s, T = 2.5 N**
- **Nominal current: 2100 A**

✓University of Stuttgart DM main specifications:

- **Stationary MPDT**
- **Isp=3000 s, T = 3 N**
- **Nominal current: 1000 A**



ALTA

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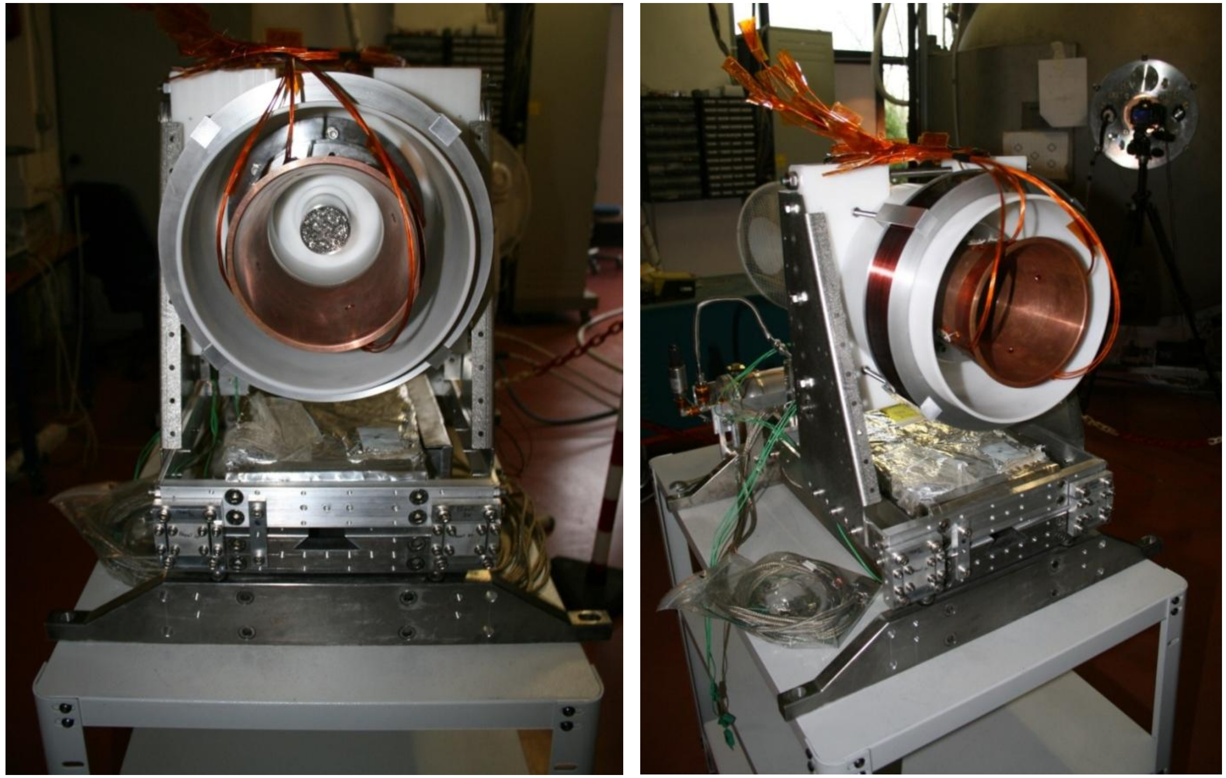
Magneto Plasma Dynamic Thruster (MPDT) Activities

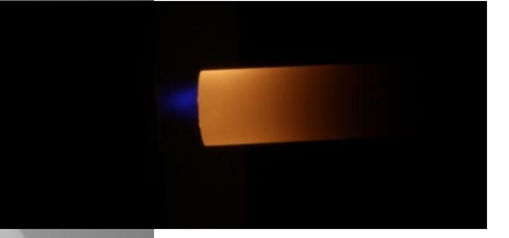
- Preparation of test set-up in Alta Laboratories (0.5 s pulse).
- Thrust balance assembled and calibrated (strain gages, no ballistic method).
- Feeding system (argon, xenon) assembled. To be calibrated.
- Power system based on supercapacitors to be assembled and verified.
- Test activities will start at the end of May.

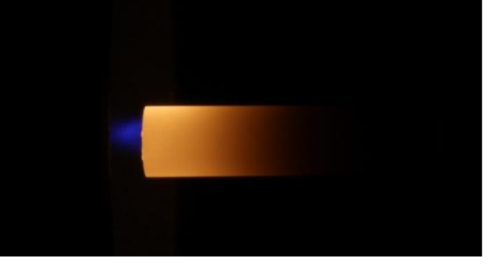


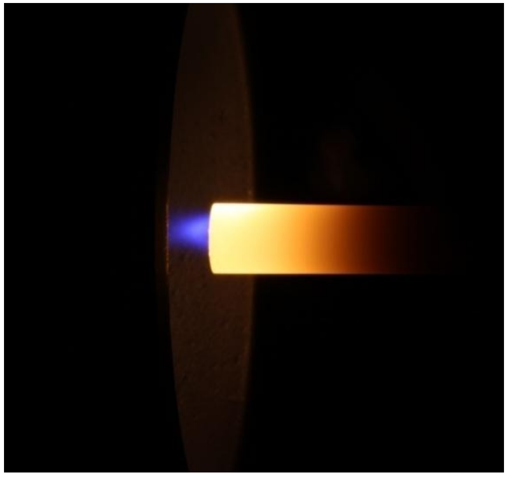
100-kW unsteady MPD thruster on the balance @ Alta lab

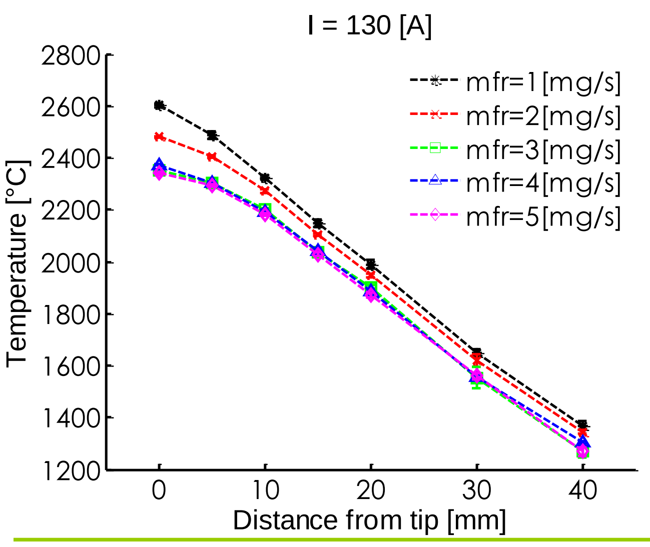
MPDT Activities: High Current Cathode Test Results

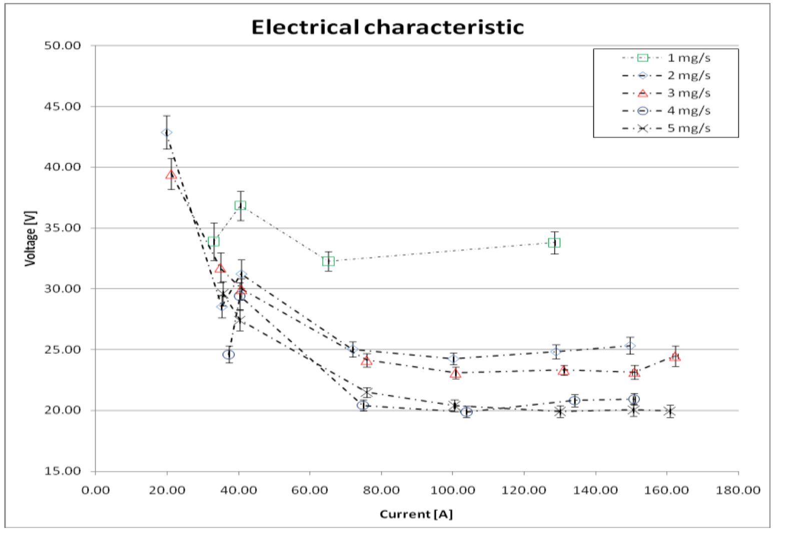
- Experimental activity on a scaled multichannel hollow cathode (first in Europe) completed @ Alta in December 2010.
- Assessment of cathode erosion (main mechanisms and relevant rates)
- Definition of design rules for long-life MPDT cathodes











Conclusions

- HiPER is a project partly funded by the European Union aimed at laying the technical and programmatic foundations for the development of innovative Electric Propulsion technologies and of related power generation systems
- High Power Electric Propulsion could play a very important role in future international space exploration programmes by enabling more affordable and sustainable space-to-space missions
- The first 2 years of HiPER activities have been mainly devoted to:

✓ Select and study mission scenarios which could benefit from high power EP

✓ Define requirements for both solar and nuclear power generation and for high power EP thrusters studied (HET, GIE and MPDT)

✓ Have technological assessment of the new concepts

✓ Define preliminary design specifications of technological activities

✓ Manufacture and assemble test items to be tested in the third year

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Selex Galileo	Italy	Fraunhofer Institute – ISE	Germany
Space Enterprise Partnerships	United Kingdom	Rolls Royce	United Kingdom
Domaine de Beauregard	France	Acta	Italy
Astos Solutions	Germany	IPPLM	Poland
Politecnico di Milano	Italy	Aero Sekur	Italy
CNRS	France		
Onera	France		
Tecnalia	Spain		
KopooS Consulting	France		
Consorzio RFX	Italy		
CNES	France		

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Back Up Charts

Space Hub in EML1: GTO – EML1 Transfers

Payload Mass obtained with a preliminary mass breakdown:

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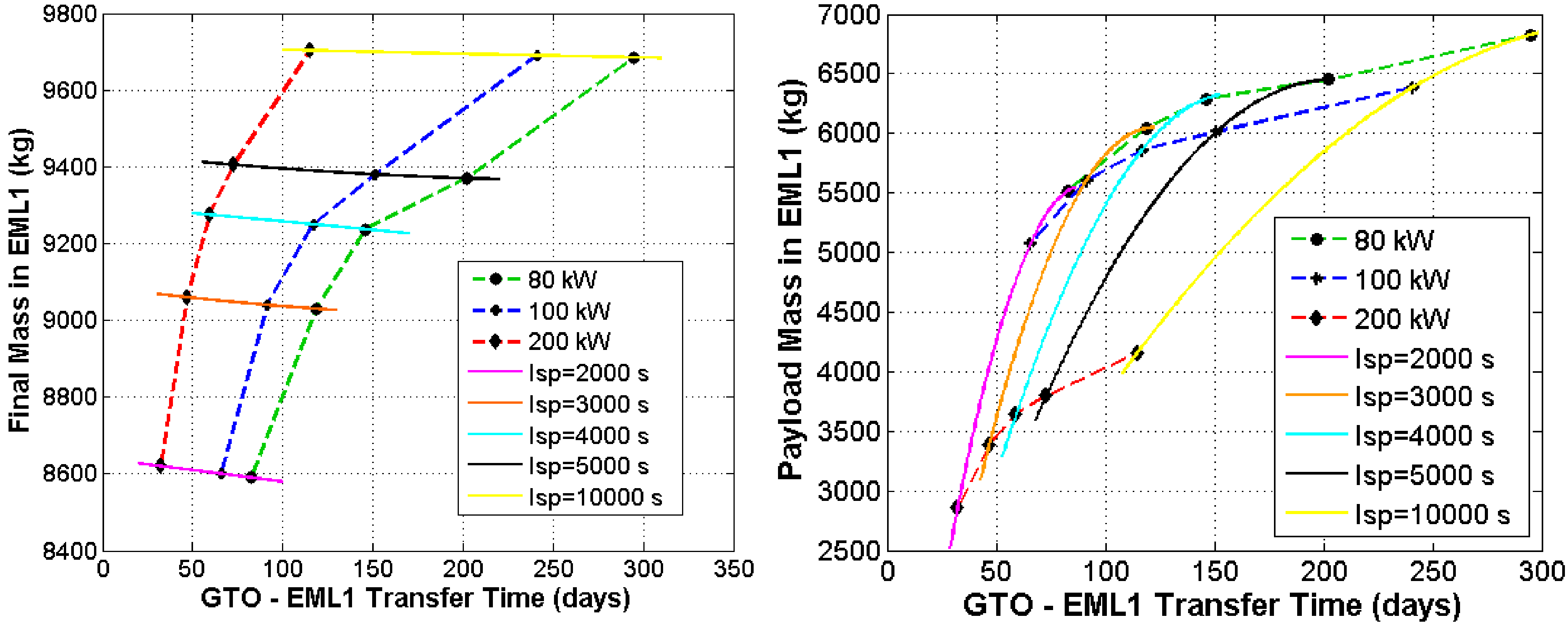
✓Tanks & related structures: 20% of propellant mass



Mars Sample Return Assumptions

- Single launch with Ariane 5 into GTO (250 km x 35950 km)
- Initial total wet mass of Spacecraft is 10,000 kg
- Direct transfer, no fly-bys (more flexibility on launch window)
- Overall transfer time < 6 years (mass of return capsule is 20 kg)
- Same transfer period (~2019/2020 - ~2025) for all cases
- Power level up to 200 kWe (at 1 AU)
- Thrust levels 1.22 N, 1.5 N, 1.75 N, 2.0 N, and 2.44 N
- Isp levels 2500 s and 5000 s

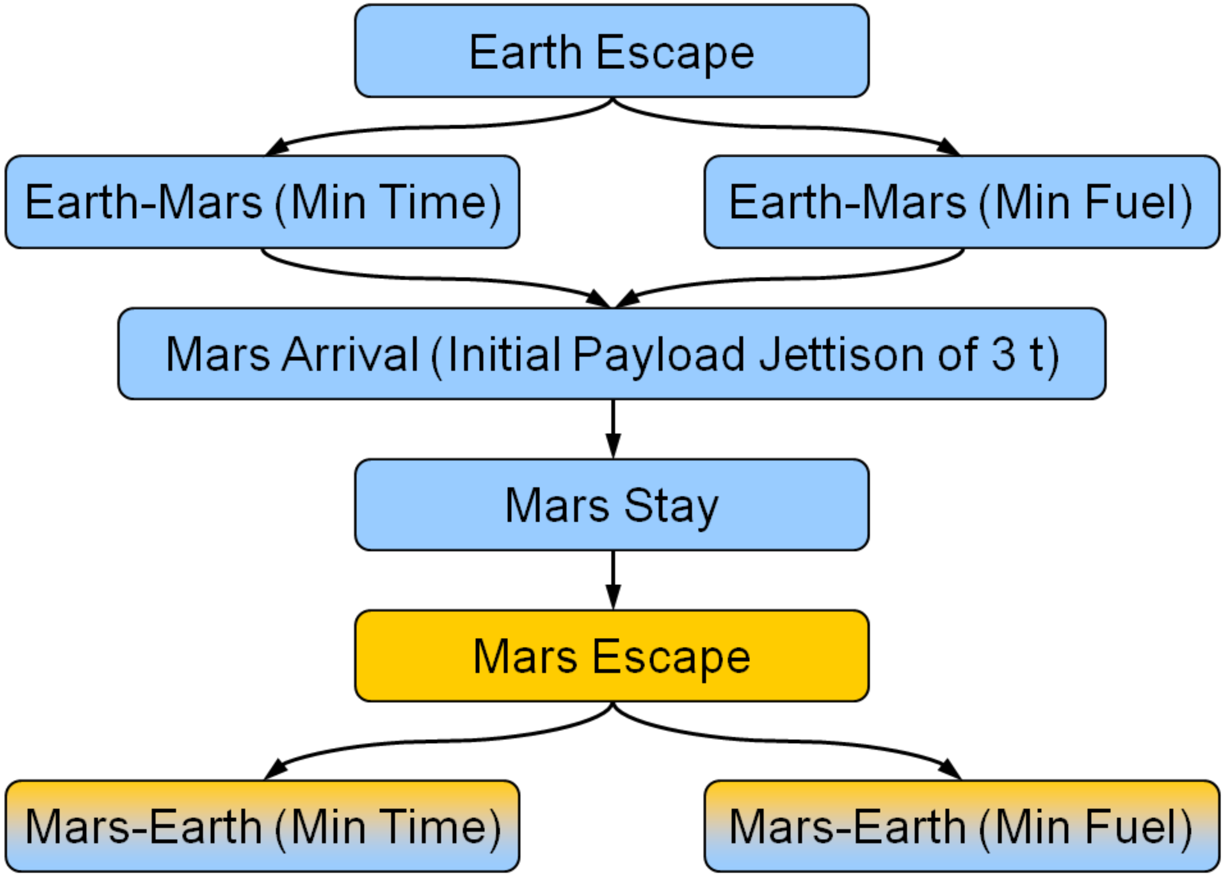
Spacecraft Specific Parameters		
Name	**Unit**	**Value**
Mass Spacecraft Bus	(kg)	1000
Solar Array Specific Power	(We/m2)	300
Solar Array Specific Mass	(kg/kWe)	20
PPU & Thruster Specific Mass	(kg/kWe)	3
Structural Mass Factor	(-)	0.2
System Efficiency @ 2500s	(-)	0.43
System Efficiency @ 5000s	(-)	0.526

ALTA

Mars Sample Return Assumptions

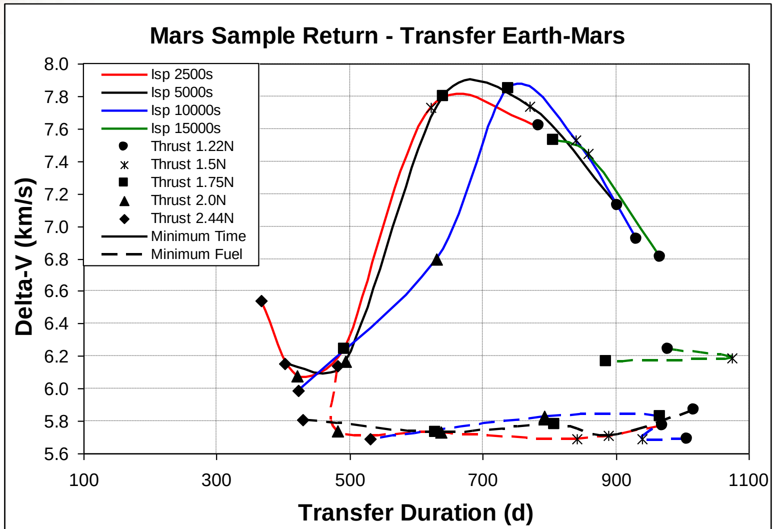
Case	Isp (s)	Thrust (N)	Solar Array Power (kW)	Solar Array Surface (m^2)	Power Subsystem Mass (kg)	PPU and Thruster Mass (kg)
1A	2500	1.22	34.779	116	696	104
1B	2500	1.50	42.762	143	855	128
1C	2500	1.75	49.888	166	998	150
1D	2500	2.00	57.015	190	1 140	171
1E	2500	2.44	69.559	232	1 391	209
2A	5000	1.22	56.864	190	1 137	171
2B	5000	1.50	69.914	233	1 398	210
2C	5000	1.75	81.567	272	1 631	245
2D	5000	2.00	93.219	311	1 864	280
2E	5000	2.44	113.727	379	2 275	341

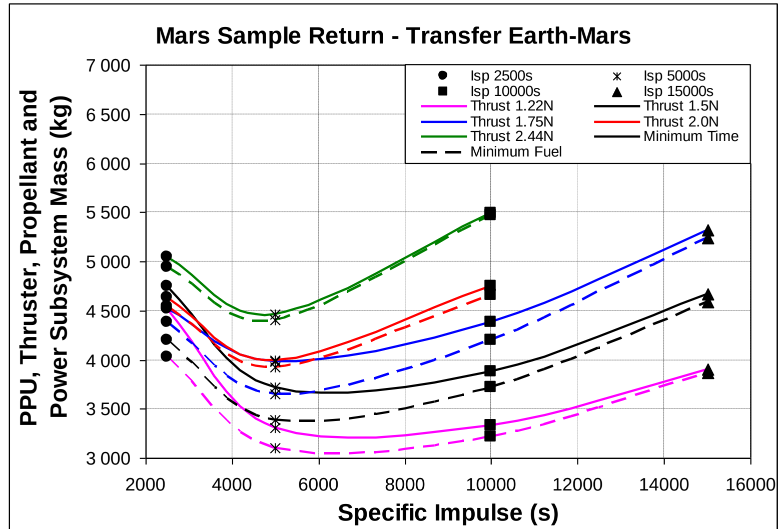
Mars Sample Return Strategy

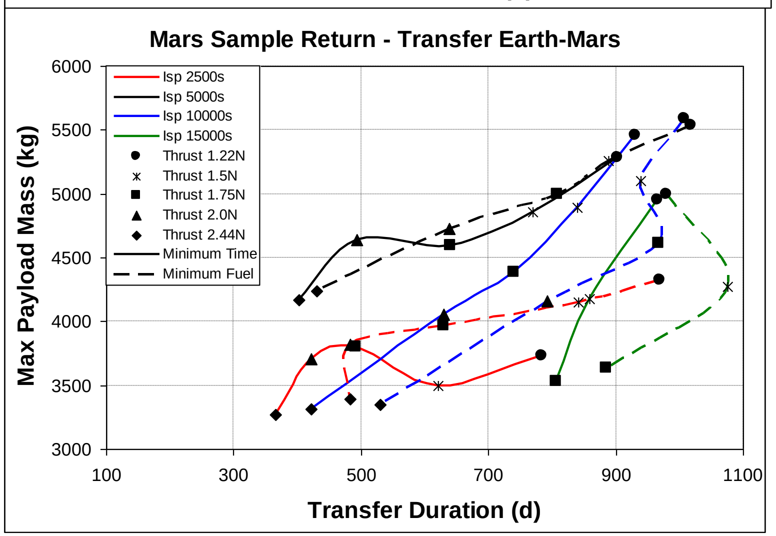


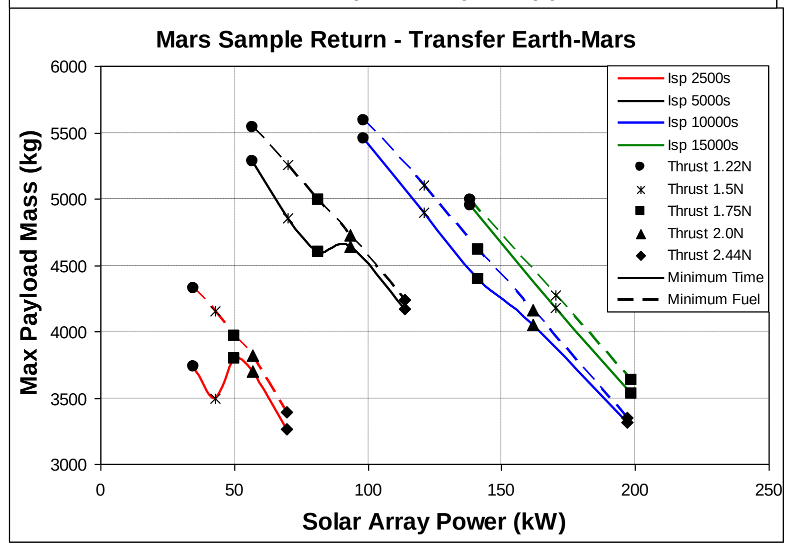
ALTA

Mars Sample Return Results









Mars Sample Return Results