Executive Summary:

Space is a very harsh environment: temperatures are extreme on both sides, distances are measured in terms of millions of kilometres, and vacuum make things even worse.

To successfully explore space, there are some basic 'building blocks' that are needed as a minimum:

1. An effective, reliable and cost-effective way to access Space from Earth (which means a launch system);
2. A robust spacecraft;
3. A shielding system from cosmic rays and solar flares;
4. A power generation system;
5. An efficient and reliable propulsion system.

HiPER project was aimed to give a boost to points 4. & 5. above.

A choice was made to focus exclusively on Electric Propulsion (EP) systems, and on related high power generation, either because of the know-how and expertise of the participating partners, and for the intrinsic advantages of EP technology with respect to the traditional, well known, chemical propulsion (namely, rocket engines).

For the latter aspect, it is useful to address state of the art Specific Impulse capabilities, which are at least an order of magnitude higher for EP systems than for chemical propulsion, and the related overall efficiency. On the other side, chemical do perform better –at least for now- in terms of thrust and of reliability, and do require less electric power than EP.

HiPER aimed to advance knowledge and technology one step further with respect to the original state of the art, either for the selected EP systems and for the related power generation systems.

As a starting point, a study has been conducted on a set of missions that could be operated with high power EP systems. Although space science and exploration will be the main driving force behind the technological development of EP and high power generation systems, novel techniques and methodologies will equally benefit commercial and utilitarian space missions, thus generating a very significant impact on Europe’s capabilities to access and exploit space.

HiPER not only addressed technologies, but also attempted to consider major technological efforts in the framework of social and political scenarios, both internal to Europe and with respect to non-European partners. In this respect, there have been discussions and meetings with NASA and large US companies to share HiPER results and harmonise future roadmaps.

A number of results have been obtained in the project's timeframe, including the definition of a set of exploration and transportation scenarios; the design, prototyping and initial test of a high power (20 kW) Hall Effect Thruster, the design of a multi-gridded Ion Engine and the development of a high current cathode, the design, prototyping and initial test of two 100 kW class Magneto-Plasma-Dynamic Thrusters; the design, prototyping and initial test of an inflatable solar array with Fresnel lens concentration system, and the feasibility study for a 200 kW nuclear reactor power generation system in space.

Project Context and Objectives:

HiPER project was conceived to depict a roadmap for future space exploration and transportation, which could benefit from technological advancements in Electric Propulsion (EP) technologies and from the related advancements in power generation in space.

Rationale for such ambitious goals rely on the intrinsic efficiency of electric propulsion on one side (orders of magnitude better than the 'classical' rocket engines) and on its proven heritage since the late 60s of the past century in a number of scientific and commercial missions, and on the fact that high power EP needs high power generators onboard, on the other side.

To achieve the goal an interdisciplinary team of 20 partners (8 SMEs, 3 large companies, 3 universities, 4 research centres and 2 government bodies), from 6 EU countries, has been formed, grouping most of the specialists in EP and in power generation in space.

The whole HiPER project has been divided into five main technical Work Packages, each of them fully dedicated to a different topic. The first two technical WPs are respectively devoted to mission analysis and to electric power generation. The other three WPs are instead focused on three different electric propulsion concepts (Hall thruster, Ion engine and Magneto plasma dynamic thruster).

Here follows a brief summary of each WP, describing the target activities and the main objectives.

Mission Analysis, Propulsion System Requirements and Recommendations work package

The main goal of this work package was the definition of future scenarios for European space transportation and exploration, and of ensuing possible missions objectives. The reference scenarios has been built by taking into account technical as well as political challenges, and the parallel evolution of non-European trends. Definition of requirements for power generation and electric propulsion systems, based on the above mentioned scenarios, have been produced as input for the other WPs. Medium term scenarios as well as more futuristic, long term scenarios have been produced and presented to various EU and international players.

In-space Power Generation work package

The goal was to design a power generation subsystem (i.e., power generation and power control unit) capable of providing power levels ranging from tens of kW to thousands of kW.

Either Solar Arrays technologies and Nuclear Reactors were studied. Both solutions have been considered and thoroughly investigated. A prototype of an advanced solar array based on concentration has been manufactured and assembled, whereas the nuclear reactor option has been preliminarily assessed and seized in terms of mass, volumes, thermal control systems and shielding from radiations.

High Power work package Hall Thruster Development work package

Within this workpackage the design, manufacturing and development of a HET prototype working at a power level of 20kW has been faced. A very preliminary experimental campaign aimed at measuring the thruster performance and to validate technological solutions envisaged during the thruster's development has been conducted at the end of the workpackage activities. It has to be noted that the produced prototype is the most powerful HET produced in Europe.

High Power Gridded Ion Engine Development work package

This part of the project was aimed at investigating novel concepts for thruster grid choice in order to design gridded ion engines (GIEs) efficiently operating at higher power levels.

The very novel approach of dual stage, multiple grids engine has been analytically investigated, and grids number and distance optimised for future development. At the same time, design, development and experimental campaign on high current hollow cathodes to be used as neutralizers for this class of thrusters has been conducted.

Magneto-plasma-dynamic Thruster Development work package

Within this work package the design, manufacturing and test of two prototypes of MPDTs, one operating with an externally applied magnetic field and one operating with the sole self-induce magnetic field, has been conducted.

Both thrusters have been successfully operated during preliminary tests in vacuum chambers; in parallel the first European multi-channel Hollow Cathode has been developed and successfully tested for more than 100 hours.

Considering the potential impact of the electric propulsion in a near-mid future term, the work carried out along the three years of HiPER program has a significant strategic importance. For the first time a large group of private companies, enterprises, research centres and Universities has been put together to actively discuss about the necessary steps to be taken in order to define a roadmap for the future development and exploitation of high power electric propulsion. And the effort could have hardly be more successful, resulting in a fruitful cooperation among all the involved partners, who worked together under a common objective.

An extensive theoretical and experimental research has been performed on all the principal open issues in the field of electric space propulsion, with special attention for power generation systems, mission analysis and for all the existing types of thruster assembly. The main results of this joint effort will be recalled in the following sections of the present document.

A lively dissemination activity has been carried out in parallel to technical activities, participating at international conferences and producing several high quality papers dealing with the diverse topics investigated along the last three years within the HiPER framework.

Project Results:

Scientific and technological results will be presented grouped by relevant work package.

Mission Analysis and High Power Electric Propulsion Requirements and Recommendations

Introduction and major benefits of Electric Propulsion

In HiPER programme, the analysis of possible mission scenarios is an essential prerequisite to carry out an effective roadmapping and long term technology planning study. Building a credible and motivated long term reference scenarios is however a task which is very complex and implies considerations much beyond the purely technical aspects. Political, economic and social constraints all influenced the evolution of space policies over many decades and many of these elements may undergo unpredictable changes.

Electric Propulsion can play a very important role in future space exploration programmes by enabling more affordable and sustainable space-to-space missions.

Modern EP technologies enable mass saving, launch flexibility, long interplanetary journeys and faster missions with no gravity assist constraints. This also opens the way to transferring large payloads through the solar system more affordably than in the past. Besides, larger payloads can be transported by increasing the operational power level of the propulsion systems.

From the economical point of view, high power EP applications will have a significant reduction on the overall cost of access to space by improving the near Earth orbit transfer and maintenance cost effectiveness of institutional and commercial spacecraft.

With respect to long term sustainability, high power electric propulsion will provide the only sustainable means of transportation in the near-Earth region and across the solar system capable of allowing effective exploitation of space resources and environment.

Target Mission Scenarios

Selected scenarios try to harmonize the long term plans by the main space agencies, with the 'sensitivity' and prediction capability of experienced space executives, and with the visionary inputs by small companies which are at the leading edge of space propulsion innovation. HiPER Mission Analysis team was devoted to define some near and long term mission and transportation scenarios which could specially benefit from high power EP.

The HiPER list of target classes of missions includes:

Orbit transfer in the Earth-Moon system: lessons learned from ISS in terms of routine module assembly and refuelling are directly applicable to the design, development, operations and management of future exploration missions. Larger payloads could be shipped by means of high power EP from LEO to GEO, EML1 and LLO at expense of longer transfer times with respect to conventional propulsion systems.

Robotic Mars Sample Return (MSR): considered as a key mission by all space agencies and a priority for Europe, MSR can represent an important milestone on an international roadmap leading to a human mission to Mars. It can also represent a very good candidate to exploit the benefit of EP (in combination with conventional propulsion) within a reasonable time-scale. In addition to the high scientific value deriving by the analysis of the samples (composition, assessment of evidence of prebiotic processes/past life, analysis of geological processes, etc..), it is recognized that MSR also would have a big impact on the public opinion, just the way it happened when Apollo samples returned from the Moon.

NEOs exploration, exploitation and risk mitigation: after some scientific/sample return missions to NEOs to search for new resources, the exploitation of NEOs can potentially lead to commercial utilization of new resources either on Earth and in-space. The capability to deflect threatening Earth-crossing asteroids can be also developed and thus contribute to increase mankind safety.

Mars and its moons (Deimos and Phobos) fly-bys and science: Mars and its moons fly-bys with crew and cargo missions to coordinate with or control robots on Mars surface.

Outer solar system and beyond robotic exploration and science: scientific/robotic missions to outer planets of the solar system. In particular, missions to Jupiter's and Saturn's moons to search for evidence of life.

Mission analysis

Different strategies have been adopted to analyze the mission profiles previously described, since, even if we are always considering low-thrust transfers, different targets requires different maneuvers (depending on the characteristics of the celestial bodies involved).

For what concern missions taking place within the Moon-Earth system, a Circular Restricted Three Body Model (CR3BP) approach has been used to study the problem. This is the basic model to study the motion under more than a single gravity field and is based on the assumption that the moving body (m3) has a mass so small that it cannot influence the motion of the two massive bodies (the primaries, m1 and m2) exerting the gravitational influence. It can be shown that, under these assumptions, there are five positions of equilibrium in space, the Lagrangian libration points Li, where the gravitational fields of the primaries combined with their centrifugal force are in balance.

For Mars Sample Return, the whole analysis has been divided in several parts. Initially there is an Earth-escape phase, where the spacecraft spirals out of earth sphere of influence; then there is the interplanetary travel between Earth and Mars sphere of influence, followed by a Mars-capture phase. After a certain time of stay, the spacecraft starts its travel back, again divided in three phases: Mars-escape, Mars-to-Earth interplanetary transfer, Earth re-entry. Two different analyses have been carried out for interplanetary phases, once with the goal of minimizing the fuel consumption, then with the goal of minimizing the transfer time.

The mining scenario instead calls for a mission which travels forth and back between Earth and the target asteroid. Starting in a Lagrangian point of the Earth-Moon system (either L1 or L2) the spacecraft travels interplanetary to the asteroid where it is orbit the small body. After some stay time to load the mining material, either raw or processed, the spacecraft returns to the Earth. This mission consists of two interplanetary trajectories. Other maneuvers like capturing at asteroid are neglected for the activities presented in this document. In fact, the target asteroid can be very small and the delta-v for the orbit

insertion is likely to be negligible. Besides, another assumption for this kind of mission is that the spacecraft is powered by a nuclear reactor. Thus, constant power is available for the electric propulsion system independent of the distance from the Sun.

Full details about the results of mission analyses performed in the HiPER framework can be found in project's deliverables from WP2.

EP Subsystem Main Requirements and Key Recommendations

In parallel to the mission scenarios definition phase, a preliminary definition of requirements for power generation and electric propulsion has been carried out, in order to provide a solid basis for the assumptions used in the preliminary mission analysis.

Preliminary requirements are set for each voltage level used to accelerate ions. This choice is also related to the potential concepts and configurations of Power management and distribution.

As the high power Solar Electric Propulsion (SEP) is considered a technology available in the near/medium-term, only the high power HET and GIE technologies have been considered as possible developments in this timeframe. Therefore in SEP case, only requirements for medium and high voltage levels are drafted.

On the other hand, in Nuclear Electric Propulsion (NEP) case also the high power MPDT technology has been taken into account as possible development in the long-term.

In-Space high power generation

Solar Power Generation - introduction

Solar Power Generation is one of the two available options (together with nuclear power) to generate a high amount of electric power in space. Solar arrays are commonly used on present spacecrafts, although up to now with power levels much lower than the ones addressed in HiPER project (the maximum power level ever provided in space is around 100kW on the ISS, while here some 250kW are required for the most ambitious target missions). Along these three years of intense activity, several topics have been investigated with the purpose of making a step forward in solar power generation technology: light concentration (up to 10 times the nominal flux) system design, inflatable substrate and flexible electrical network structural design, prototyping and verification; The solar cell trades started from the very latest achievements in crystalline solar cells. Based on that, a component suitable for light concentration has been identified. This component has been integrated on top of a flexible structure in combination with the concentrating lenses and with an innovative 'smart" deployment mechanic based, also, on Shape Memory Alloys (SMA) performances. Power management and Distribution (PMAD) is a critical aspect of the whole system design which can undermine all the other technical advances. A direct drive approach has been selected as the most suitable solution and an architecture based on solar DC voltage level of about 300V and a current level of about 800 A has been extensively simulated.

Solar Power Generation – Power Management and Distribution (PMAD)

As stated above, the first requisite is that the power system has to deliver a total power of 250 kW and this power is generated by a solar array (SA). Literature reports two main power system configurations: the first is referred to as direct drive where the SA is directly connected to the thrusters, that is without any equipment that performs some sort of power conditioning, the second is based on a power processing unit (PPU) that manages the power generated by the SA and delivers it to the thrusters through a power bus. These two architectures are quite similar since, in both cases, power must be in some ways conditioned before being delivered to the 'core' of the thrusters, the only difference is given by the specific 'logic location' of the subsystems devoted to power handling. In the first case, power management is a subunit of the thrusters, in the second case, power conditioning is performed at the main bus level, by a specific equipment. In the present study an 'intermediate' approach, called Almost Direct Drive Architecture (ADDA), is also presented. Such architecture is, possibly, the best trade off in terms of performance vs. weight and compactness of realisation.

The proposed system is based on the assumptions reported hereafter:

- total power required by the thrusters is 250 kW
- the SA is composed of P sections (with, e.g., P=10);
- the open voltage of each wing in the SA generator is approximately 200V;
- there are P power subsystems working in parallel, each transferring 250/P kW to the main bus;
- when considering architectures with regulated main bus, the bus is at 300V.
- the subsystems are 'star' connected to the 'cold' node of the main bus;
- there are T thrusters (with, e.g., T=10), each rating 250/T kW all connected to the 'cold' node;

In some power system architectures here considered there can be a battery connected to the main bus through a battery discharge regulator (BDR). The battery delivers energy during possible fast power fluctuations introduced by the thrusters. Battery discharge has very strict time limits due to the high power levels involved. Note that the battery plays a fundamental role, since if it were absent and the power absorbed by the thrusters were to become larger than that delivered by the SA, the PPU would immediately shut down. The battery introduces a delay in the shut-down of the PPU or, better said, it allows to quickly reducing the power absorbed by the thrusters without introducing PPU instability or even causing an unwanted total shut-down of the PPU.

The use of a Maximum Power Point Tracker is essential for the mission due to the need of maximizing the efficiency in different illumination conditions. Furthermore, given the extremely large dimensions of the Solar Array, a fractioning of the total solar array power over several wings is a desirable feature.

As already anticipated, the result of the trade-off analysis is the so called 'Almost Direct Drive Architecture' (ADDA). As for the other architectures the total power absorbed by the thruster is partitioned among wings and sections of solar array generator (SA). We considered a SA and its P sections. At first we assume that a single SA section is connected to a thruster of equivalent power (for example 25 kW).

All P sections but 1 are connected in parallel (diodes are properly inserted), the P-1 sections are directly connected to the load. We firstly assume that the thruster works is a 'constant resistance' condition, that is its equivalent resistance and it is kept constant independently from the electrical operating point of the of the P-1 sections of SA. This means that power absorbed by the thruster can be increased by simply increasing the voltage of the direct drive bus. In the sequel the load resistance is varied, so that motor on/off situations and power fluctuations/variations are simulated.

Solar Power Generation – Solar Cells with Light Concentrators

As anticipated at the beginning of this section, the likeliest evolution of the space borne solar cell assemblies is towards thinner and lighter structures, capable to be used in combination with solar generator systems having a reduced volume at launch, combined with outstanding electrical performances. III-V compounds based triple junction solar cells are the baseline building blocks for the majority of the nowadays applications and so they are also the starting point for the present trade off.

The solar cells which have been be used in the frame of bread boarding activity of HiPER are multi-junction (e.g. Ge/GaAs/InGaP lattice matched solar cells); their peak in efficiency is designed to be reached at concentrating factors of decades (e.g. 30X) but they will be also suitable to work at levels around 6 to 8 times the AM0 intensity.

The light concentrator is a Fresnel lens. A lens with an axial symmetry will focus sunlight onto a straight line, centered over the active area underneath. A deployable sustain will position the lens over the solar cell line. Each lens operates coupled to a string of 10 solar cells, and it is realized by using space grade silicone or an optical grade plastic (e.g. polycarbonate). The Fresnel lens is comprised of precisely formed ridges which refract the light from a 10 cm aperture down to a strip of light focused in the middle of a 1 cm wide solar cell, to leave margin for pointing error.

Lens positioning will follow the deployment of the panel/substrate, so that the subsystem lens-sustaining structure will initially be packed. SMA materials are dedicated to the realization of the deployment mechanism which intrinsically includes degrees of freedom. The shape memory property is the characteristic of some materials of getting their shape back when thermally treated. Two are the crystallographic states of these materials: martensitic and austenitic. The structure will be given the deployed configuration shape using a thermal treatment; then be folded into the stowed configuration, before reaching the operative deployed configuration at a given temperature. The SMA adopted in the frame of HiPER solar panel will be an alloy of Nickel and Titanium.

Solar Power Generation – Solar Array Architecture and Prototyping

The design of the solar array module is as follows:

- an inflatable structure has been thought to tension the membranes which sustain the solar cells and his architecture allows to deploy a huge surface
- the substrate is composed by a set of modules all equal to each other
- each module is made by a layer of kapton (50 µm)
- each module is rigidized by a sustaining frame
- the modules are joint by passive hinges
- the deployment relies both on passive hinges and SMA
- printed circuit lines are used to connect electrical items

To demonstrate the functionality of the deployment structure, a breadboard has been built. It is made of three modules each equipped with dummy lens and a set of electrically representative items.

Nuclear Power Generation - introduction

In Work Package 3.2 HiPER team investigated nuclear fission electrical power generation for the exploration of the outer solar system. Mission analysis identified a range of applications from one way journeys to Uranus, return missions to the Jovian and Saturn planetary systems and multiple, shorter infrastructure, or manned, delivery. The nuclear 'space tug' concept was seen as the best fit for these applications.

The objective was to 'develop a roadmap for the longer term provision of nuclear power sources for space electric propulsion supported by critical risk simulation and modelling'. The technical starting point was a Rolls Royce Nuclear Technologies for Space Applications survey and an Acta Shield Design Study which provided the baselines for modelling and simulation. The three main pillars of the investigation were the core reactor, the shield and the power conversion system. However the potential to achieve the individual capabilities had also to be consistent with a viable, overall system architecture as well as each other. The 'space tug' had to be compatible with an Ariane 5 ECA launch. The main constraints are the fairing dimensions and the lift (20 tons to Low Earth Orbit (LEO), 10 tons to Geosynchronous Transfer Orbit (GTO) and 6 tons to a 10000 km circular orbit). Reactor operation only above 800km was taken as a safety constraint but requires a large battery for an in orbit cold start.

Analysis of previous studies showed specific mass to be the principal design driver and a specific mass of 25kg/kWe was thought the best that could be achieved with current and emerging technology. In principle this constrained the power generating capability to 200 kWe which became the target for a concept design.

Initial investigation showed Brayton cycle power conversion to have the most competitive specific mass for the 200 kWe power range. No clear advantage was found between the relative merits of direct cycle, gas cooled, epithermal and indirect cycle liquid metal cooled fast reactor based systems. Consequently the Roadmap identifies the technical development required to realise the concept designs for both technologies developed during the Study.

Nuclear Power Generation – Study Architecture

The study was in three stages. A comprehensive survey was made of previous projects and studies to establish realistic design targets. Achievable performance was then investigated through the modelling and simulation of reactor core, shield and power conversion design options. The results provided the basis for a fission nuclear power generator Concept design together with a Roadmap for the technical developments required for its implementation. In practice Concept Designs were developed for both Direct and Indirect Cycle Brayton over a performance range dependent upon achievable levels of technical development.

Nuclear Power Generation – Reactor Core Physics

The findings of the reactor modelling and simulation are reported in Rolls Royce HiPER Nuclear Power Generator Modelling and Simulation Details. Both Indirect liquid metal cooled and Direct gas cooled reactors could generate 200 kWe over the 10 year lifetime or longer if required. Fuel composition and reactivity control are compatible with water immersion safety requirements.

The more compact liquid metal Indirect Brayton cycle reactor was 25% of the mass of the Direct Brayton cycle (476 compared to 2017 kg) before consideration of the mass of a heat exchanger to transfer the thermal energy from the liquid metal to the Brayton cycle operating gas. The Direct Cycle core physics is dominated by the inlet/exit gas flow paths, which occupy about 35% of the fuelled region volume in the design which was analysed.

Risk analysis indicated scope for technical development to target a higher gas pressure, accepting increased core resistance. The gas flow areas could then be halved, with a 30% reduction in the number of fuel bed annuli, to give a 10% reduction in core size.

Neutron and gamma escape fluxes from the core were calculated at all exterior surfaces. Both showed radial distributions. Activation of the coolant gas was also calculated for the direct design and does not pose problems.

Both reactor designs considered in the risk analysis exhibited quite large excess reactivities with the control media ‘withdrawn’. These were left in the Concept Design to provide margin for loss of reactivity arising from the implementation of engineering features and realistic materials. These margins could be 'trimmed' in future iterations of the designs, to reduce the fuel loading and/or fuel enrichment.

Nuclear Power Generation – Radiation Shielding

The shield modelling and simulation was based on a simple spacecraft configuration using US Government MCNP-MCNPX code. For the Direct cycle the neutron and gamma flux radiated from the reactor is seen to decrease as one moves from the centreline thus allowing a corresponding reduction in shield thickness toward the outer edges. The Indirect cycle had a similar distribution with higher radiation intensity.

Shielding requirements were based on the US SP100 Project criteria (respectively, 1.6 mRad/s and 31700 n/cm2s) which assumes a 22.5 metre boom between the spacecraft and the payload. A 14°

(shadow) layered shielding Concept Design (tungsten for gamma and a combination of Beryllium (Be), Lithium Hydride (LiH) and Boron Carbide (B4C) for neutron shielding) was shaped to match the flux distribution profile. The materials are selected and arranged to optimise performance for radiation shielding, structural and thermal resilience. Coolant pipes can be routed round the shield and control rod penetration leakage would be minimized in detailed design.

The final modelling results gave an end of life gamma dose or neutron flux generally lower by a factor of two to four than the requirement apart from the gamma dose at payload entrance for the Direct cycle reactor, where the margin is only of about 20%. Control rod design minimizing the distance between reactor core and shield gave a 50% mass saving.

Nuclear Power Generation – Power Conversion

The power conversion options investigation showed the Brayton Cycle to be more efficient than a thermionic or thermoelectric design, with cycle efficiencies of 17% to 19% compared with 5% for the latter. Specifically the indirect cycle was the more efficient as a result of a reheat loop but it is a mechanically more complex.

The closed loop Brayton Cycle has radial turbines and compressors and a Helium and Xenon operating gas. Efficiency is increased by a Recuperator and by minimising the pressure drop over the system, especially in the radiator. In the Indirect Cycle a lithium liquid metal coolant is heated by the core which in turn heats the operating gas in a heat exchanger. For the Direct cycle the operating gas is heated as it flows through the reactor core.

For the Direct cycle the lowest radiator mass was achieved with a two-staged compressor and free power turbine arrangement. This optimised of component efficiencies with an appropriate alternator speed for generating 200kWe between two ‘pods’. For 1100°K reactor core outlet temperature a ‘fixed’ radiator for such a cycle would have a total weight of 3.5 tonnes assuming the use of tubes of 0.5mm wall thickness for reasons of manufacturability.

Modelling and simulation showed the Indirect cycle to be more efficient than the Direct cycle, with an 11% lower radiator mass. The optimum turbo-machinery configuration was a two-shaft compressor with a reheat loop driving a free power turbine. The reheat loop increases the temperature of the fluid entering the free power turbine and consequently the temperature of the fluid at the radiator inlet. The heat exchanger for the indirect cycle was not thoroughly investigated as it was not seen as being the main limiting component of the power conversion unit. However, it is anticipated that any heat exchanger design will also be limited by the creep behaviour and the materials employed to achieve a ten year mission life and this will constrain the maximum temperature of the operating gas.

The modelling and simulation identified two critical mass design drivers which would cause a 200 kWe system to exceed the Ariane 5 ECA lift and fairing volume capability: radiator size and turbine inlet (determined by core outlet) temperature. The radiator size is governed by its inlet and outlet temperatures according to a quartic relationship; therefore the higher the operating temperatures of the cycle the smaller the radiator required as a heat sink. The maximum inlet temperature to the turbine is governed by the creep life for the materials in the turbo-machinery design. Today’s most advanced single-crystal super-alloys 10 year creep life is limited to 1100 K optimal 1500 K) giving significant radiator area and mass.

Technical developments to raise turbine inlet temperature are:

- Turbine Inlet Design. Realise the benefit of the turbine rotor experiencing a lower stagnation temperature (~80-200 K) because of its rotation.
- Turbine Blade Cooling. Bleed cooler coolant gas from the compressor onto the turbine rotor can keep turbine blades up to 200 K below the inlet gas temperature.
- Refractory Metal Alloys. High temperature refractory metal alloys such as Niobium which is not susceptible to oxidation operating in with a closed xenon/helium cycle.
- Ceramic Materials. Ceramic materials have the thermal and creep properties for operation up to 1500 K but need to develop resilience to stress fracture.

Singly or in combination these enhancements open the way to core outlet temperatures in the range 1200/100 K (moderate risk) to 1500 K (high risk).

High Power Hall Effect Thruster

A Hall Effect Thruster (HET), also called Stationary Plasma Thruster or Closed Electron Drift Thruster, is an advanced propulsion device that uses an electric discharge to ionize and accelerate a propellant gas. The basic concept of a Hall Effect Thruster was suggested in the early 60s almost simultaneously in the former USSR and in the USA. However, it is only in 1972, that the first demonstration was given in flight by the soviet satellite Meteor. Since the time of pioneer works, several hundreds of spacecrafts have flown with Hall thrusters, which represent a significant heritage in terms of science and technology.

The recent success of the SMART-1 lunar orbiter mission of the European Space Agency demonstrates the possibility to employ Hall Effect Thrusters (HET) as the main propulsion means for an interplanetary journey. The plasma engine onboard the SMART-1 space probe was the 1.5 kW-class PPS®1350-G thruster developed and manufactured by Snecma. The thruster allowed the probe to cover more than 100 millions km consuming only 82 kg of propellant, xenon gas in that case. In spite of a long trip time (16 months to reach the Moon) due to a weak thrust level of 70 mN constrained by the available power, the ESA mission brings to light advantages of electric propulsion over chemical propulsion: low propellant consumption and high spacecraft velocity due to a long burn time.

Currently, 1-2 kW-class HET are employed for station keeping and attitude control of geostationary communication satellites. Nevertheless, ambitious robotic missions like exploration of outer planets of the solar system and far-off comets as well as transfer of cargo vehicle to support crewed missions require very high power electric propulsion systems.

The development of high-power Hall thrusters and of any large-scale device represents certain design and technological challenges. One can mention several requirements like an azimuthally homogeneous magnetic field and gas distribution in the thruster channel, the design of high current cathode, the manufacturing of the discharge channel made of a ceramic, the thermal management of the thruster, the modeling of the plasma discharge with regard to plasma wall interaction and electron transport. All these features that are generally inherent to any size of Hall thrusters may be strongly amplified while occurring in a large design. When considering the testing of high power HETs, a main technical consideration is what level of vacuum is needed within the ground test facility to adequately simulate the environment in which the thruster would operate in space. The ability of a test facility to sustain a given vacuum pressure is related to its pumping speed.

The goal of the HiPER WP4 was to progress in the field of high power Hall Effect Thruster for exploration missions. Six partners from the industry and scientific organizations gathered to address the different technological challenges related to high power HETs: Alta (Italy), IPPLM (Poland), CNRS (France), Tecnalia (Spain), Onera (France) and Snecma, Safran Group (France). Our approach was split into three main steps:

1. Assessments of the main technological options for the development of high power HETs:

The manufacturing of a high power HET prototype needs to consider with specific justifications the material and thrusters pieces interacting with the high energetic plasma flow in the thrusters. A first innovation to be met is the manufacturing of a ceramic discharge chamber of large diameter (about 300 mm). The major limitation was due to the manufacturing process. An alternative approach was developed by the brazing ceramic sectors of the discharge chamber.

Another addressed issue was the interaction of the plasma with the discharge chamber. It is well known that the ion and electron flows of the plasma will interact strongly with the ceramic discharge channel and will affect the thruster performances. The material characteristics of the ceramic are then to be quantified and especially the erosion rate due to energetic ions and the emission yield of secondary electrons, which are critical ceramic properties. Several ceramic samples were studied and their secondary electron emission (SEE) and erosion yields were measured. The influence of ion impinging energy in the 200eV to 800eV range was investigated. These measurements have been compared to predictive simulations. SiO2 that is almost an ideal sample (mirror polished, no grains) leads to simulations very consistent with measurements. In opposition, it was concluded that BN erosion can be influenced by grain detachment effects and roughness effects. Alumina erosion was lower than expected. When considering the SEE yield, it has been shown that materials exposed to electron bombardment evolve so that the SEE rate and in particular the first crossover energy change when the material is exposed to electron dose of few mC/cm^2. This change was attributed to surface and/or near surface composition change induced by the electron irradiation. In addition, the amount of implanted charge also influences the electron emission yield, so that in a HET, the SEE depends on the wall equilibrium potential. The first crossover energy is a key parameter in a number of HET simulation models. This parameter is usually extracted from measurements performed on pristine samples that are hopped to be free from charges. The obtained results highlight that the SEE measured on channel material that has not endured the specific HET environment could be very different from that of the same material under HET working. To be somewhat more representative, the SEE must be measured on materials that have been aged under both ion and electron irradiation.

Finally, the 'Mission Analysis' HiPER working group specified requirements for the propulsion and based on these studies, the technological target was a cluster of 20 kW HETs.

2. Preliminary design of a high power HET laboratory model:

Following the previous studies, it was proposed to manufacture a 20 kW Hall thruster. Several topics were considered for the design of a high power HET: the thruster architecture, its thermal optimization, the design of the electromagnet, the implementation of a cathode delivering up to 70 A and the modeling of the plasma in the discharge channel. We summarize hereafter the main retained options for the design of the 20 kW thruster and the main conclusions issued by the different studies. A monolithic HET architecture was proposed for the 20 kW thruster. In order to offer more thermal margin, a splitting of the neutral injection and anode was proposed. The thermal simulations of the thruster concluded to high enough thermal margins and no high thermal loads, leading to a potential overheating of thruster parts. The magnetic field of the HET was generated by coils and a ferromagnetic circuit. In order to produce a azimuthally homogeneous field, 8 coils were implemented in the external circuit and a single annular for the internal circuit. The magnetic field of the thruster was also measured and a very good agreement with the computations was concluded. Concerning the cathode, alternative technologies were studied like RF cathodes. Nevertheless, due to costs and time limitation, it was decided to implement a state-of-the art hollow cathode. Finally, 1D and 2D modeling of the plasma in the discharge channel of the 20 kW thruster were carried out; see an example of 2D plasma density field hereafter. A description of the plasma topology, dynamic behavior of the discharge and a prediction of the thruster were given. Finally, the design of the 20 kW laboratory model (identified as PPS-20k ML) to be manufactured was set and the drawings to the thruster released.

3. Manufacturing, assembly and testing of a 20kW HET laboratory model:

Following the two previous steps, the last year of this activities was devoted to the manufacturing of a 20 kW laboratory model and its testing in a vacuum facility in order to validate the technological choices made in the HiPER project.

The PPS-20k ML thruster was tested in a cryogenically pumped cylindrical vacuum chamber called Pivoine. This test facility is located in the ICARE laboratory of the CNRS, located in Orléans, France.

As this test facility was designed for the testing of low power HETs, an upgrading of the Pivoine facility was realized before firing the PPS-20k ML. The xenon feed system and the electrical hardware were modified in order to perform high power tests. Another important modification of the Pivoine test facility was the design and the manufacturing of a new test balance.

This balance was designed and manufactured during year 2011. In July 2011, the PPS-20k ML thruster was integrated in the Pivoine test facility. After ignition of the thruster, preliminary test were realized in order to check the behavior of the new thrust balance and cathode and to validate the test facility upgrading. The thruster was then tested at high power by increasing progressively from 5 to 23.5 kW. The 20 kW thruster could be operated very successfully and reached the expected performance, in accordance with the specified specifications. The engine was successfully operated from 2.6 kW to 23.5 kW with a discharge voltage ranging from 100 V to 500 V. The maximum performance was obtained at 500 V, with the following parameters: a thrust of 1050 mN, an Isp of 2700s, a total power of 22.4 kW and a total thruster efficiency of 60%. In the 5 kW to 22 kW range of total power, the total thruster efficiency was quasi-constant and equal to 60% with a 68% peak at 300 V and 5 kW. The cathode-to-ground voltage was about -16 V. Neither thermal limitations nor discharge instabilities were observed during the test campaign.

Following the PPS-20k ML characterization campaign, the following operating point is proposed for our 20kW HET thruster with regard to the HiPER requirements:

PPS-20k ML Operating Point	Measured Performances		Proposed HiPER Point
Thrust	1000 mN	1050 mN	1020 mN
Isp	2400 s	2700 s	2500 s
Discharge voltage	400 V	500 V	450 V
Xenon total mass flow rate	43 mg/s	41 mg/s	42 mg/s
Total electrical power	19.3 kW	22.4 kW	20.5 kW
Total thruster efficiency	60 %	60 %	60 %

As was previously mentioned, the PPS-20k ML HET is a dismountable thruster. Neither complete parametric studies nor magnetic optimizations could be performed during this first test campaign. Consequently, possible improvements of the thruster performance deserve future test campaigns.

Concerning future implementation of high power Hall thruster, it is important to notice that propellant selection is also of critical importance. Xenon was selected as the propellant during our test campaign because it is the only propellant under utilization in the current and near term missions employing Hall thruster propulsion. While typical magnitudes of propellant mass required for projected telecommunication satellites with 1 to 5 kW Hall thrusters does not exceed 100 kg, hundred–kW space missions would require tons of propellant. Availability of xenon supply, therefore, becomes one of the major concerns. Potential alternative fuels for Hall thruster must then be addressed in order to reach economical implementation of high power propulsion.

In conclusion, thanks to the HiPER project, the successful implementation of high power Hall thruster was demonstrated following the design, manufacturing and testing of a 20 kW laboratory model. Evaluation of high power Hall thrusters with alternative propellants is suggested in the future in order to offer an economical access to in-space propulsion.

High Power Gridded Ion Engine

During the course of the WP5 of the HiPER study a novel type of gridded ion engine (GIE) called the Dual Stage Gridded Ion Engine (DS3G) has been studied.

The study focused on both the DS3G thruster concept and on the discharge hollow cathode needed for the most demanding HiPER mission requirements.

DS3G thruster

A DS3G is a gridded ion engine where instead of using a single ion optics stage to extract and accelerate an ion beam, two stages are used to separate the extraction and acceleration process. The main effect of this separation is the fact that, unlike conventional GIEs, the thrust density of this novel thruster (up to 12N/m2 at an Isp f 10,000s have been simulated) can be increased while also increasing the Isp up to values that are several time higher than those currently produced by conventional GIEs. This results in a compact thruster that can process tens of kW of power producing high efficiencies.

To realize a separate acceleration and extraction stage an extra grid must be used hence resulting in a 3-gridded ion engine.

The first aspect of a DS3G that has been analyzed is it applicability and the operating conditions under which its thrust density is in excess of those produced by conventional GIE.

Using analytical model available in the literature and numerical simulations performed with the FFX code, the trend of the thrust density provided by a DS3G in comparison to that provided by a conventional GIE has been derived as a function of the ratio between the voltage drop applied to the acceleration stage to that applied to the extraction stage.

As it can be seen the DS3G offers performances in excess of those of the GIE only if a value of higher than 0.6 is used. Assuming that the DS3G is obtained adding an extra grid to a GIE able to deliver an Isp of 4,500s this means that the DS3G will provide an increase in thrust density only for specific impulse level in excess of 6,200s. Numerical simulation showed that at 10,000s the DS3G was able to successfully extract the same beamlet current as a GIE working at 4,500s delivering slightly more than twice the thrust density.

To deliver high specific impulse levels, high voltages must be employed on the thruster screen grid. The presence of such high voltages produces concern regarding the thruster lifetime since the charge exchange ions (CEX) created within the thrust ion optics can impact on the grid with high energies hence producing high erosion rate and consequently short grid lifetime(and thruster lifetime since the lifetime is dictated by grid erosion).

To address these concerns, a 20cm ion optics for a DS3G with the characteristics reported in Table 2 has been simulated with the FFX code and the results compared to the one obtained from the simulation of a conventional GIE (RefGIE) having the first and second grids identical to the DS3G, with the same potential difference applied between these grids, and working at the same total beam current level. For both the DS3G and the RefGIE molybdenum was used as the material for all the grids.

The DS3G was found to be able to deliver lower beam divergences (about 40% less) than the RefGIE and a much higher thrust density. The DS3G also suffered from lower erosion rates than the RefGIE and consequently was able to provide a longer lifetime. The DS3G lifetime was found to be about 45,000 hours whereas the one of the RefGIE 37,000 h.

DS3G Discharge hollow cathode

Besides analytical and modelling work on the DS3G thruster, a hollow cathode able to deliver the discharge current needed by a DS3G has also been designed and tested. The cathode design has been carried out for the highest current case between those obtained elaborating the mission requirements from WP2.

A cathode able to deliver a current of 180A has been designed and tested. The design has been carried out taking into account that for the NEP mission to Jupiter a lifetime of 17,000 hours must be delivered. The main cathode dimensions determined in DL5.2 are reported below

Mission Class	NEP Missions to Jupiter
HC Discharge current	187.9 A
Cathode Radius	5 mm
Orifice Radius	4 mm
Orifice length	8 mm
Insert thickness	1.5 mm

The cathode has then been built by QinetiQ according to the specifications above whereas the rest of the experimental setup has been built at the University of Southampton.

The cathode insert has been equipped with five thermocouples to monitor the temperature profile. The cathode has also initially been manufacture with a smaller 3 mm diameter orifice.

The main goal of the experimental campaign was to gather more information about the functioning of the cathode and the influence of the orifice size over the cathode insert temperature distribution.

The cathode was tested with three different orifice sizes (3, 5 and 8 mm), at various current levels (ranging from 25 to 180 A) and with various Xenon mass flow rates for a total of 130 h of which 30 were at the 180A discharge current level.

The maximum current of 180A was achieved with a 8mm orifice diameter using 10 sccm of Xenon. The insert temperature distribution at 180A had an average value of 1380 °C and showed a strong peak at the insert downstream end of 1460 °C.

After the test, the cathode was visually inspected and some of the parts of the experimental setup were analyzed using EDX spectroscopy. The cathode did not show major signs of wear and the EDX spectroscopy found deposition of copper (coming from the anode support structure) on the external surface of the keeper and of tantalum and barium (coming respectively from the orifice plate and from the insert low work function compounds) on the inner surface.

The lifetime of the cathode has then been extrapolated using the measured insert temperature profiles, by applying three different life time criteria.

According to the first criterion the cathode will able to deliver up to 20,000 h at 180A assuming the worst case for which all the insert is at the peak temperature of 1480 °C whereas according to the other two criterion the lifetime at 180A will be 15,000 and 3,000 hours, respectively. At the 150A, the cathode lifetime will be in excess of the required 17,000 h according to all three criteria.

Considering the different answers coming from the lifetime evaluation criteria a modification of the cathode design has been proposed to assure that the cathode will be able of deliver the required lifetime.

The numerical investigation of the dual stage ion engine showed that it is able to provide higher thrust densities, lower jet divergences and longer lifetimes (in excess of 100,000 hours if graphite grids are employed) than conventional gridded ion engines.

This makes the DS3G the best candidate for the high specific impulse missions studied in HiPER and for all future high specific impulse missions. Future work will focus on building a DS3G prototype to verify the numerical predictions.

For what concerns the hollow cathode experimental campaign the test will be considered successful mainly considering the limitation in time and budget and the recent efforts performed by other institutions to build a long lifetime cathode able of providing 250A using LaB6 insert in conjunction with water cooled anode.

Moreover the cathode was tested in diode mode and this test setup has been found to lead to higher insert temperatures than those relative to cathode operation inside a discharge chamber.

The development of such high current cathode is not only relevant to DS3G but also important for the future development of high power HETs studied in HiPER given their need for a long lifetime and high current neutralizer cathode.

Further work should include long term testing (with temperature measurements) with a cathode modified according to the design recommendations herein and the development of a full numerical model of the cathode plasma flow and a thermal model.

High Power MagnetoPlasmaDynamic Thruster

Magnetoplasmadynamic (MPD) thrusters have long held the promise of high exhaust velocity (c) at MW power levels. The combination of high c and high power in a compact device is especially beneficial for demanding missions such as the human exploration of other planets, which will require lightweight, high power density propulsion to be feasible. Nevertheless, despite more than 50 years of studies, MPD thruster have somehow failed to meet researchers' expectations entailing a slow but constant decline of interest in such a technology. At present, MPD thruster research is still at a fundamental rather than a development level. Research goals include increasing in thrust efficiency and operative lifetime. In particular applied-field MPD thrusters appear to be more amenable to near-term applications since they retain a satisfactory thrust efficiency (25%-30%) even at power levels in the range 100-200 kW. Nevertheless, the ability to fully realize the transportation and economic benefits deriving from application of high power EP is strongly dependent upon the development of suitable electrical power sources. At present, these are essentially based on photo-voltaic solar arrays, although some early attempts at small radio-isotope and fission-reactor EP missions to the outer planets are under study. These new trends will allow MPD thrusters to be re-considered as viable propulsive option in the near future.

In this context, the efforts undertaken by Alta and IRS during were aimed at recovering and broadening the past knowledge concerning MPDT technology as well as at paving the way for an advanced European MPD thruster to be developed and test in future programs.

Taking advantage of their different backgrounds, Alta focussed on a pulsed, quasi-steady device whereas IRS developed a steady-state MPD thruster. Both of them operated at about 100 kW using argon propellant. At the same time, Alta developed and tested high power cathodes to assess the effectiveness of the multichannel technology as a viable options for future EP devices.

Activities at Alta

Alta MPD thruster was designed taking into account the most promising design options from the past experiences and findings. A coaxial configuration with a central multichannel hollow cathode and a flared anode was finally selected.

Measurements were obtained for a variety of currents, mass flow rates and magnetic field strengths in a power range between 20 and 250 kW. Tests were carried out in Alta's IV-10 vacuum facility. With a volume of about 200 m3, IV-10 allowed for a current-pulse duration up to 1 s maintaining a back pressure lower than 3.10-4 mbar as well as for the minimization of the environmental interaction with the plume. Although the shot duration was still too short to achieve steady-state thermal conditions, it allows for direct, time resolved thrust measurements. To this purpose a new single-axis thrust stand was designed to improve the full scale and the frequency response of the existing thrust stands commonly employed for high power devices. A maximum thrust efficiency of about 30% was obtained at 200 kW for an applied field of 120 mT and a mass flow rate of 60 mg/s. At 100 kW, for the same mass flow rate and magnetic field, the thruster reached a thrust efficiency slightly higher than 20% and a specific impulse of about 2500 s.

These results appear very promising since the thruster performance parameters (specific impulse, thrust efficiency and power-to-thrust ratio) are among the highest ever measured for argon-fed MPD thruster in the power range investigated. Besides, the experimental set up has proven to be reliable and adequate to perform long-lasting (500 ms), quasi-steady pulses allowing for a time-resolved, highly accurate, thrust measurements.

To assess the cathode erosion process during steady-state operations, a reduced-scale multichannel hollow cathode was tested for 100 hours. The cathode wall temperature along the axis was measured by using an optical pyrometer since temperatures well in excess of 2000°C are needed to sustain a stable, diffuse, discharge. In this condition, the material evaporation is the main erosion mechanism. It was found that the start-up phase is characterized by localized arc attachment on the cathode surface where the temperatures at the arc root are often higher than the tungsten melting point (about 3400°C) leading to erosion rates as much as 3-4 orders of magnitude higher than that seen in steady-state operation (~ 1 ng/C) even for extended operation (the ratio between the steady state time over the transient time was about 120).

The McHc assembly (rods pattern and their location with respect to the exit section) was found to highly influences the erosion rate. Unfortunately the reproducibility of the McHc manufacturing is questionable and remarkable steps in this direction are still to be taken.

Activities at IRS – Stuttgart

At IRS a steady-state, AF-MPD thruster, called ZT-1, was design and successfully tested at 6 kW. The data gathered during the experimental test campaign on the ZT-1 allowed for the identification of a guideline towards the design of a 100 kW, steady-state device, named SX-3.

Moreover, the Alta's hollow cathode was also tested at IRS to include spectroscopic analysis. Unfortunately, the test carried out at IRS appeared to be problematic since the hollow cathode was already depleted due to the hours of operations at Alta. Nevertheless, the metallographic analysis undertaken at IRS revealed interesting behaviors of the tungsten under continuous thermal stress. These findings will allow for an improved design procedure in future activities.

European AF-MPD Thruster

if MPD thrusters are to have a role in future electric propulsion missions, completely radiative-cooled versions must be developed with lifetime requirements not lower than 2000-3000 hours. In this context, the main output of the program is the design of a steady-state, gas-fed, applied field MPD thruster conceived to include the most promising design options and material selections suggested so far by the main research institutes with the aim of performance and lifetime enhancement.

The thruster consists in a central lanthanum hexaboride cathode and a concentric conical anode. Argon propellant is injected through an orifice obtained in a De-Laval nozzle which is part of the gas feeding system. The overall cathode length from the orifice to the insert was defined by the need of heat rejection. The thruster overall dimensions are 190 mm diameter and 420 mm length and the estimated total mass is about 25 kg without solenoid, cables and bolts. The thruster is completely dismountable allowing for separate electrodes removal and quick inspections. Sealing between the anode and the housing is accomplished by using graphite gaskets whereas the recovery of the clearances due to the thermal expansion is achieved by using a commercial compression spring. The present design suggests the use of a lanthanum hexaboride emitter cathode. The major reason for using LaB6 cathodes is the robustness, high current density and long life exhibited by these emitters during the long years of qualified space operations in SPT Hall thrusters as well as ion thrusters.

As regards the technology road map, two development paths were identified. Since the major technical obstacle for ground testing of MPD thrusters is the inability of the state-of-the-art vacuum systems to handle the tremendous pumping speeds required for these high power devices, two different paths must be foreseen according to the future availability of testing facilities for steady-state operations.

Path A will allow for a full-scale lifetest opening the possibility of investigating all the relevant technological and scientifically issues at once. By contrary, path B focuses on the investigation of the most critical sub-components, i.e. cathode and magnet. Separate lifetime tests are suggested in order to assess the most probable EOL scenarios at de-rated power conditions.

Potential Impact:

HiPER project has shown that the adoption of high power electric propulsion systems could represent a turning point for enabling a whole new class of missions, which otherwise would be impractical.

A roadmap is here sketched, considering the current development status of thrusters and power generation technologies and taking into account all the open issues that have to be tackled in the next years, in order to pave the way for a successful and widespread usage of high power electric propulsion in space.

For what concerns the thrusters, a substantial amount of work has been carried out in the last three years with the aim of assessing and improving the existing electric propulsion technologies that are considered suitable for being used at high power levels (>20kW).

Among them, Hall thrusters technology is presently the most mature one. Such thrusters have already proven their effectiveness in several space missions, although they have always been designed to operate at lower power levels w.r.t. ones considered in HiPER framework (say <2kW). However, Hall thrusters are more easily scalable to higher power levels than other propulsion devices and they improve their efficiency in a non-negligible way when the operating power level goes up. A 20kW prototype has been designed, manufactured and tested in HiPER program, showing an excellent performance. If used in cluster configuration of two, four or eight units, it is possible to reach total power levels comparable to the ones assumed for the previously mentioned space missions (with the notable advantage of having multiple thruster units onboard, which mitigates the risks connected to a malfunction of one of them).

High power gridded ion engines also have a high level of maturity and, like Hall thrusters, at lower power levels GIEs have been widely employed in many space missions. In HiPER project the main task was to focus the attention on a couple of key issues: the cathode development and the definition of an optimal thruster configuration for high power operation (so called DS3G, Dual Stage 3 Grids). The main strengths of gridded ion engines are the very high specific impulse (a feature that can specially suits the needs of some class of missions) and their extremely long lifetime (which is estimated to be of the order of one hundred thousand hours according to the simulations and the experiments carried out up to now; even if this prediction turned out to be excessively optimistic, the lifetime is expected to be fully satisfying anyway).

The last kind of electric thruster suitable for high power operation is the Magneto-plasma-dynamic thruster. An intensive experimental activity has been carried out on MPD thrusters under HiPER project, in order to assess their performance and to make a step forward in understanding the intrinsic problems (linked to plasma discharge stability) that have always plagued this class of thrusters, severely limiting their efficiency. MPD thrusters are expected to the be the most effective devices when operating at very high power levels, i.e. greater than 100 kW (up to a few MW). Actually, they are the only electric propulsion thrusters capable of processing so much power in a compact size, this resulting in a much higher thrust density (N per m2 of exhaust section area) with respect to Hall thrusters and gridded ion engines. For this reason, going on with a thorough investigation of their behavior is crucial to further improve their performance and to enable their use for real missions. Of course, considering their current Technology Readiness Level and the required power level for a single thruster unit, MPD thrusters will probably play a significant role for space exploration only in the mid-long term.

On the side of the power generation technologies, two are the viable options that have been investigated: solar power and nuclear power.

Obtaining the necessary power from solar arrays, is the most consolidated solution for present spacecraft. Solar energy is readily available in space and the technology to convert it into electric energy is mature and reliable. In the short term, solar power is the preferred choice. Of course there are two main drawbacks. First, if plenty of power is necessary (say hundreds of kW) the size of the solar panels grows larger and larger and handling them becomes truly challenging. Second, if the target mission is heading towards the outer planets, solar energy decreases fast with the increasing distance from the sun. Using solar energy beyond Mars, especially for feeding high power devices, is not advisable. Under HiPER program, newly designed solar cells equipped with light concentrators have been developed and assembled in an array as a prototype technology demonstrator. It has been shown that, relying on this technology, it is possible to unfold a group of flexible solar arrays capable of providing a power of 250kW around the Earth with a power density of 300W per square meter and with a specific power of about 150W per Kg.

As stated above, if even higher power levels are required for a mission or if the spacecraft is operating far from the Sun (further than the Earth), solar energy is not a satisfying solution. In such cases, the other option comes into play: nuclear power generation. By using nuclear power generators it is possible to generate a large amount of power which can continuously feed all the electric systems. The concept of 'space tug' has been chosen as winning candidate for future missions entailing a nuclear power generation system. Here, two the most challenging problems are heat dissipation and radiation shielding (in case of manned missions) and both of them have been addressed and deeply examined along HiPER project. With a constant effort devoted to their further development, space nuclear generators are expected to be fully mature in about then years, then making possible a whole new set of space missions (such as the ones requiring a large amount of power very far from the sun).

Main dissemination activities

Besides presentation of scientific outcomes in relevant scientific congresses, conferences and symposia, resulting in 24 publications that will be presented later, HiPER project has been publicised with the public website and in seven conferences/meetings, part of which also open to general public. The website has been publicized with links via the professional social network 'Linkedin', and the general public social network 'Facebook', by using either personal pages and the ones of the Coordinator, Alta SpA.

Interdependency with other technology areas

Along the three years of HiPER program, several interdependencies of space related activities with other technology areas have been found. Some relevant example is mentioned hereafter:

- Electronics: a technology area closely related to spacecraft systems, especially for what concerns the thuster power control unit and, in case of thruster arrays, the switch control unit.
- Nuclear technology: nuclear power generation was one of the main topics of the program. The study was principally aimed at assessing its capabilities and at developing a new concept of reactor that can be suitable for long range space missions. Of course there are plenty of specific issues connected to such technology which would require a dedicated effort to be tackled.
- Solar cell technology: solar power was the other source of electric energy considered in HiPER. Studying solar power generation means studying the architecture of solar cells (semiconductor materials) as well as their electric connections and the deployment mechanism of a full solar array.
- Ceramic material technology: in order to manufacture the insulator for the Hall effect thruster a special study has been carried out on the most suitable ceramic materials, investigating their properties and their machinability.

Potential benefits to terrestrial needs

In spite of the nature of HiPER project, which is almost totally devoted to space related issues, some potential benefits to terrestrial needs deriving from this activity can be clearly indentified.

Near Earth Objects (NEO) Mining:

The international Space community is more and more recognizing that a Space Exploration programme just based on material transported from Earth would be neither affordable nor sustainable. The cost to extract everything from the Earth’s gravity well exceeds the world economic capability. Therefore, after an initial phase to build up space infrastructures with material sent up from Earth, it is mandatory to start using Space resources. Besides, there may be a future market for asteroid-derived material (such as nickel-iron grains or semi-conductors like silicon and germanium). Due to diminishing terrestrial resources, a future terrestrial market for precious metals (platinum group metals and gold) may exist, requiring delivery of asteroid material to the surface of the Earth.

NEO Hazard Mitigation:

We know now that there is the theoretical possibility to mitigate this threat by deviating the trajectory of dangerous NEOs. To implement such a capability it is a matter of developing the adequate technologies. The possibly devastating hazard posed to Earth if hit by a high-energy asteroid or comet is now well recognized by scientists and policy makers. Missions based on high power electric propulsion turned out to be an effective option to hook a dangerous near-Earth object and slightly deviate its orbit in order to avoid any risk of collision with our planet.

Nuclear Power Generators:

Space nuclear generators and space nuclear electric propulsion systems are not items that can be developed and implemented within the budgetary frame of European Space Agency. The required investment is so huge that only the whole of Europe can afford it. Very fortunately, such an investment would be a real one in favour of generations to come. Once compact, efficient, safe nuclear generators will be available, deployed in space, and tested in very harsh operating conditions, the same generators would be available for Earth applications. Their availability will allow having compact, safe, clean, and competitive power plants nearby the communities using their generated energy. Just for this reason a number of positive fall-outs may be achieved. By dwarfing to a minimum level the use of lengthy high voltage electrical lines: investments and running costs of power distribution would be radically decreased; heavy energy losses through the grid would be minimized; esthetical and physical countryside pollution nearly totally eliminated, as well as the need for high power high voltage gigantic transformers.

Strategic plans and follow on activities

HiPER represented the first joint effort of a large group of specialized partners aimed at defining the future development of electric space propulsion. Plenty of work has been done in the past three years, plenty of work is still there to be completed in the next years to come. HiPER experience allowed us to set the best direction where to move in the process of making high power electric propulsion a winning option for future space missions. However, every single topic can be (and has to be) further expanded, investigated, verified through experimental campaigns, in order to realize items that have the necessary technology readiness level (TRL) to fly onboard a real spacecraft.

The nuclear power generator concept devised under HiPER project has to be physically realized in practice and to be extensively tested, before reaching a level of maturity that can make it ready for a mission. In parallel, a long work of persuasion has to be carried out to underline the intriguing new opportunities offered by a nuclear power generator and to explain that there are almost no risks connected to the launch of such a payload into space (because the reactor would be activated only when in orbit and before the activation it does not emit radiations). This is more politics than engineering, but it is vital as well for the future development of this technology.

The newly conceived solar power generator, which employs solar concentrators (Fresnel lenses) to enhance the flux impinging on a single cell, is already at an advanced development status. A prototype of a complete solar array has been realized in laboratory, using a special inflatable structure to support the solar cells and the lenses. The unfolding procedure of the array has been simulated with success, using an engineering model of the solar panel where dummy cells have been integrated. The next step is to move on towards the space qualification of the whole assembly.

MPD thrusters are probably the devices that are more distant, in terms of development, from the TRL necessary to fly. They require a huge amount of power (although this is not a drawback, because they are supposed to work effectively only at a very high power level and, in theory, to top all the other devices in that power range) and their efficiency is still too low to be competitive with an array of Hall thrusters or Gridded Ion Engines. Understanding the dynamic of the plasma inside such thrusters is the key to shed light on their behavior and to improve their performance.

Gridded Ion Engines are already commonly used in space and the next steps in their future development concern the realization and test of the concept of 'Dual Stage, Three Grids' thruster, theoretically investigated in the HiPER framework. Such configuration is expected to be most beneficial for high power operation of this class of thrusters, increasing both performance and lifetime.

Hall thruster is probably the most mature technology when ‘high power operation’ comes into play. They proved to be easily scalable to higher power levels than usual (where for ‘usual’ we mean around 1-2 kW) and a full model of a 20kW Hall thruster has been manufactured, assembled and fired during HiPER program. Results where impressive, with the thruster that immediately operated with a pretty high efficiency (around 60%) and notable performance in terms of thrust and specific impulse (>1N, around 2500s). The thruster is not yet space-qualified and other tests have to be carried out to reach this objective (such as endurance tests to check that the performance do not degenerate after a prolonged firing time).

List of Websites:

HiPER public website can be found at: http://www.alta-space.com/hiper

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