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INPPS Flagship: Cluster of Electric Thrusters

Frank Jansen [a]*, Tim Brandt [b], Athanasios Dafnis [c], Emmanouil Detsis [d], Simona Ferraris [e], James AP Findlay [f], Ikkoh Funaki [g], Richard Granjon [h], Jan Thimo Grundmann [a], Gerhard Grunwald [i], Lamartine Nogueira Frutuoso Guimaraes [j], Martin Hillebrandt [k], Anatoly S. Koroteev [l], Jim C. Kuijper [m], Francois Lassoudiere [n], Alexander S. Lovtsov [l], Volker Maiwald [a], Frederic Masson [o], Michel Muszynski [n], Stephane Oriol [o], Martin Richter [k], Lars Schanz [a], Alexander V. Semenkin [l], Alexander E. Solodukhin [l], Tim Tinsley [f], Maria Cristina Tosi [e], Jean-Claude Worms [p]

[a] *DLR Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany, frank.jansen@dlr.de, jan.grundmann@dlr.de, volker.maiwald@dlr.de, lars.schanz@dlr.de*
[b] *Czech Technical University Institute of Experimental and Applied Physics, Husova 240/5, 110 00 Prague 1, Czech Republic, tim.brandt@utef.cvut.cz*
[c] *RWTH University, Wüllnerstraße 7, 52062 Aachen, Germany, dafnis@sla.rwth-aachen.de*
[d] *European Science Foundation, 1, quai Lezay-Marnésia, BP 90015 67080 Strasbourg, France, edetsis@esf.org*
[e] *Thales Alenia Space Italia, Strada Antica di Collegno 253, 10146 Torino, Italy, simona.ferraris@thalesaleniaspace.com, mariacristina.tosi@thalesaleniaspace.com*
[f] *National Nuclear Laboratory, Havelock Rd, Workington CA14 3YQ Sellafield, United Kingdom, james.ap.findlay@nnl.co.uk, tim.tinsley@nnl.co.uk*
[g] *JAXA/ISAS, Tokyo, Japan, funaki.ikkoh@jaxa.jp*
[h] *Sagem Defence and Security, France, richard.granjon@safrangroup.com*
[I] *DLR Institute of Robotics and Mechatronics, Münchener Str. 20, 82234 Oberpfaffenhofen-Weßling, Germany, Gerhard.Grunwald@dlr.de*
[j] *Instituto de Estudos Avancados, San Jose dos Campos, Brazil, guimarae@ieav.cta.br*
[k] *DLR Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany, martin.hillebrandt@dlr.de, martin.richter@dlr.de*
[l] *Keldysh Research Centre, Onezhskaya 8, 125438 Moscow, Russian Federation, kerc@elnet.msk.ru, lovtsov@kerc.msk.ru, semenkin@kerc.msk.ru, solodukhin@kerc.msk.ru*
[m] *NUCLIC – Nuclear Innovation Consultancy, Iepenlaan 129, 1741TD Schagen, The Netherlands, kuijper@nuclic.nl*
[n] *Airbus Safran Launchers, France, francois.lassoudiere@airbusafran-launchers.com, michel.muszynski@airbusafran-launchers.com*
[o] *Centre National d'Etudes Spatiales CNES, rue Jacques Hillairet 52, 75612 Paris, France, frederic.masson@cnes.fr, stephane.oriol@cnes.fr*
[p] *c/o COSPAR, 500 rue Jean-François Breton, 34093 Montpellier Cedex 5, France, doc42jc@bbox.fr*
* Corresponding Author

Abstract

This paper describes the results of the European-Russian DEMOCRITOS and MEGAHIT projects related to the electric thrusters on board the International Nuclear Power and Propulsion System (INPPS) flagship. INPPS flagship is a high power space transportation hybrid tug (power supply primary by nuclear power, by auxiliary solar power ring and chemical propulsion due to subsystems transport for assembly at high Earth orbit above 800 km) for Mars, Europa, Moon and asteroid exploration flights.

In dependence from the actual exploration mission, mission phases, trajectory, and preferred international high power electric thrusters (about 20 - 50 kW) with different specific impulse, the results will be discussed in detail - also as a function of the transportable payload mass. Because of the 1 MWe nuclear reactor (successful ground based test confirmed by Russia in 2018) as the power supply for INPPS a cluster of about 15 or more electric thrusters were studied in the DEMOCRITOS project for MARS and EUROPA INPPS flagships. Issues related to power processing units for the electric thrusters were identified and will be discussed. In addition, low power (kW) electric thrusters for an INPPS flagship co-flying small inspection satellite are sketched too.

Insofar the presentation is directly highlighting aspects of disruptive electric propulsion subsystems, within the INPPS space system and applied to visionary Mars (including non-human and human) and Europa exploration and space transport tug flights.

Keywords: 1) DEMOCRITOS and MEGAHIT projects, 2) Nuclear Power Source (NPS), 3) INPPS flagship to Mars and Europa, 4) INPPS flagship high power electric thrusters, 5) cluster of high power electric thruster, 6) low power electric thrusters for INPPS co-flying satellite

Acronyms/Abbreviations

Artificial Intelligence (AI)
Third US human space flight program (Apollo)
Berlin Nuclear Research Reactor (BER II)
Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems (DEMOCRITOS)
Disruptive technologies for space Power and Propulsion (DiPOP)
Electric Propulsion (EP)
Electric Propulsion System (EPS)
Electric Thruster (ET)
Hall Effect Thruster (HET)
intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS)
International Nuclear Power and Propulsion System (INPPS)
International Space Station (ISS)
Ion Thruster (IT)
In Orbit Verification (IOV)
Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions (MEGAHIT)
Nuclear Electric Propulsion (NEP)
Nuclear Power and Propulsion System (NPPS)
Nuclear Power Source (NPS)
Power Management and Distribution (PMAD)
Propellant Management System (PMS)
Power and Processing Unit (PPU)
Radiofrequency Ion Thruster (RIT)
Specific Impulse (I_{sp})
Thrusters with Closed Electron Drift (TCED)
Transport and Power Module (TPM)
Technology Readiness Level (TRL)
Xenon Propulsion System (XPS)

1. Introduction

INPPS flagship is targeted to be a high power (megawatt class) space transportation tug for Mars, Europa, Moon and asteroid exploration flights [1]. In principle – after final Europa moon exploration (see in [2] – the flagship can explore more outer celestial bodies from Saturn to Kuiper belt objects out to the heliospheric boundary and beyond cruising into the local interstellar medium. Thus, the nominal operational lifetime is considered to be ten years (with the capability to operate on full power for 5 years) and work on internationally, drastically improved electrical propulsion systems is intended. The INPPS architecture is given in the Fig. 1.

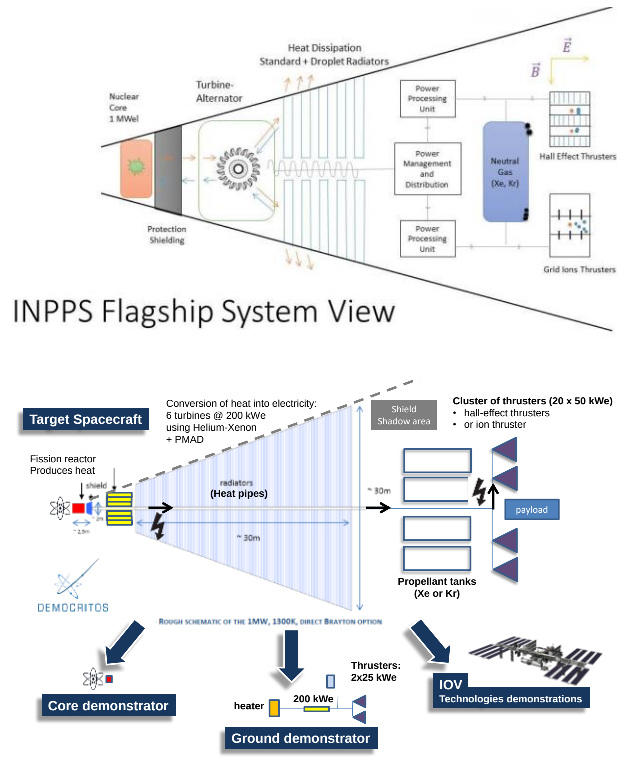


Fig. 1. Top: INPPS as a space system with its sub-systems. Bottom: INPPS flagship principle scheme, characteristics of sub-systems and DEMOCRITOS demonstrator characteristics. Courtesy of CNES / European-Russian DEMOCRITOS project [1] and [3].

2. DEMOCRITOS Project and Progress Beyond

The subchapter 2.1 sketches all nuclear and non-nuclear sub-systems as well as the commonalities and differences between MARS- and EUROPA-INPPS. In subchapter 2.2., all electric propulsion related objectives of INPPS flagship will be described in detail.

2.1 MARS- & EUROPA INPPS Flagship: commonalities and differences

The INPPS flagship reactor (developed and successful ground-tested in Russia [4]) and the U.S.-developed SP-100 [5] and KRUSTY [6] reactors are research reactors according to IAEA. All three NPS developed for use in space systems and for celestial body surfaces have thermal / electrical power at least by a factor of three and up to an order of magnitude smaller than Earth ground based research reactors (Fig. 2).

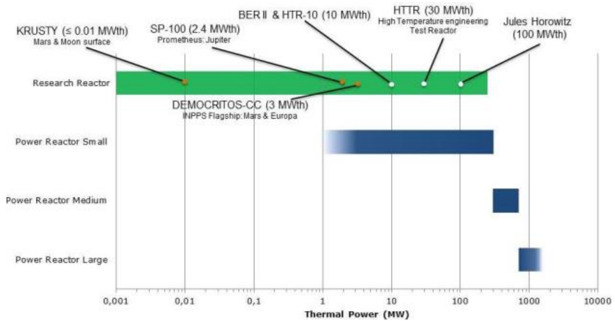


Fig. 2. Orange dots – all three NPS for space applications are kW to MW small research reactors. White dots – Berlin megacity BER II plus three Earth research reactors are also small from thermal power point of view, but with higher power than the space reactors (between a factor of about three to more than one order of magnitude). Medium and large power ranges for power production reactors are also displayed.

The physical character of the Russian MW reactor for INPPS flagship was studied in DEMOCRITOS core concept. The main characteristics are a uranium core with reactor outlet temperatures of 1300 K. It is a He-Xe gas cooled and self-shielded reactor of several meters in size and tons in mass. The reactor ground based tests favour heat emission in the order of 2.5 to 3 MW – via standard plus droplet radiators (see under [7] to [12]). This MW class reactor will be used for both, the MARS- and EUROPA-INPPS flagship core sub-system. Because of project progress for all INPPS flagship subsystems it sounds logical, that Russia may prepare soon a statement about NPS in space.

MARS- and EUROPA-INPPS flagships will have similar high power conversion sub-systems, developed by CNES in the DEMOCRITOS consortium. Moreover, the main truss and deployable boom are the same (see Fig. 3).

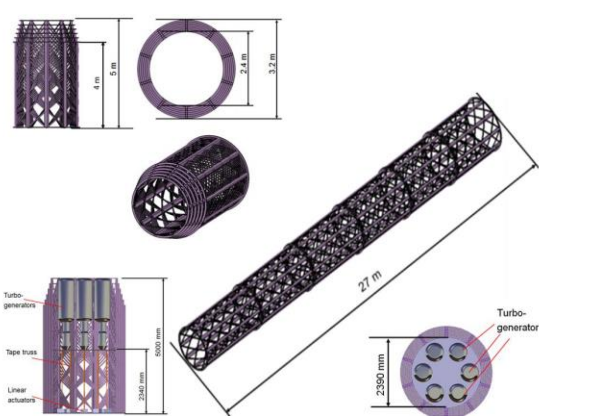


Fig. 3. DLR developed stowed telescopic grid structure / ring, plus turbo generators in rocket fairing. The telescopic grid structure in deployed state (3 m in diameter, 27 m in length). Similar booms were also considered in the U.S. Prometheus Jupiter nuclear spacecraft and Russian TPM / NPPS for radiator mounting.

According to the principle scheme in figure 1, the INPPS flagship's radiators are designed to accomplish the relevant specification requests (see Fig. 4):

- R1 is the main radiator: it consists of high temperature heat pipes (standard radiator) and droplet radiator part.
- R2 may be necessary to reject the heat, which may comes from electric converted power. This radiator could be made of heaters.
- R3 may be necessary to reject at very high temperature after core shut-down.

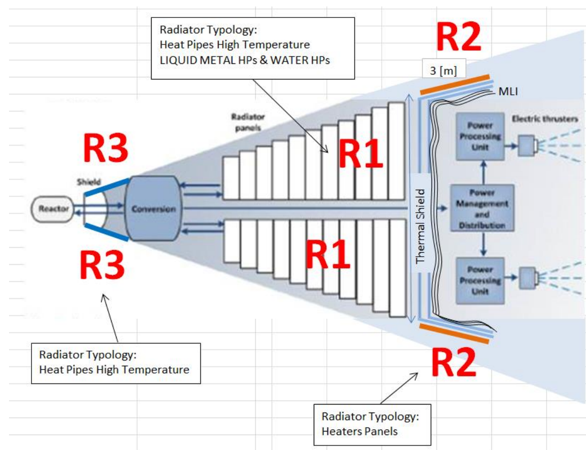


Fig. 4 DEMOCRITOS radiator demands. Due to successful MW reactor tests in Russia, R1 will consist of standard plus droplet radiators in a re-designed INPPS flagship (2020).

The MARS- and EUROPA-INPPS will be equipped with iBOSS common building blocks (15 – 20 blocks currently expected) for instance for the non-nuclear subsystems, deployable boom, electric thruster tanks, PPU, core avionics, PMS, GNC, payload, secondary solar power photovoltaic cells, and others. iBOSS [13] with AI also levels up the human flagship preparation and flight safety.

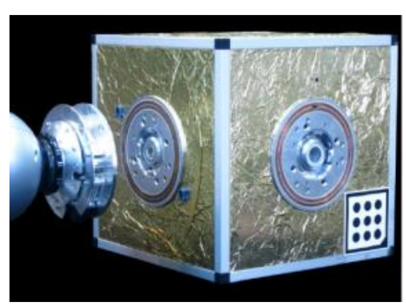


Fig. 5. INPPS autonomous robotic assembly will start in high Earth orbit with iBOSS sub-systems mounting

of non-nuclear INPPS parts. First starts the rear end construction, continued via boom mounting – the last iBOSS equipped subsystems - and finally ends with the physically non-critical core. This to be monitored procedure displays directly the successful realization of the launch and assembly for the flagship. This order of assembly using iBOSS – including AI – sustains the safety of a significant space project with a public 'visibility' potentially comparable to Apollo or the ISS.

The area of two radiator wings is insufficient to dissipate the heat of MW class reactors while still maintaining a compact spacecraft design. Therefore, NASA included for the PROMETHEUS Jupiter spacecraft design, and Russia for the TPM / NPPS, a four-wing radiator structure. In the DEMOCRITOS project, the four wing structure was not only included for the radiators, but partially also for the shielding subsystem. However, the main, visible differences of MARS- and EUROPA-INPPS flagship are the shielding and radiator wing structures (see in Fig. 6). This resulted from the original concurrent engineering (CE) ([14]],[15]) study of two different flagships, with the first flying the non-human Jupiter / Europa mission and the second the human Mars mission. The four propeller-like shielding wings directly protect the four radiator wings. Shielding mass is only applied on lines of sight between the reactor core and spacecraft elements, thus creating an envelope geometry of the shield consisting of all relevant lines of sight.

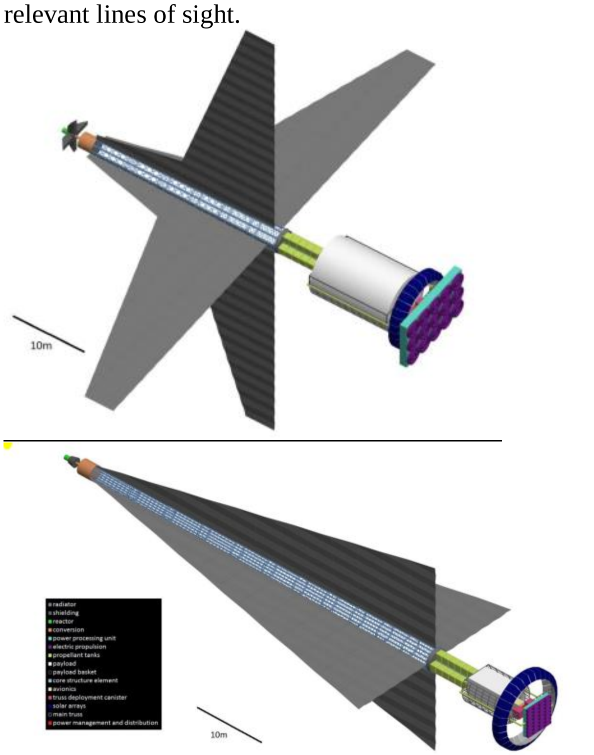
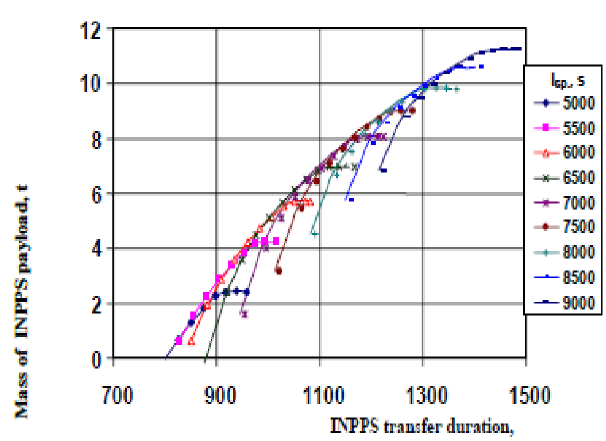


Fig. 6. Top – propeller wide wing EUROPA-INPPS. Below – arrow wing MARS-INPPS. The colour code for all sub-systems listed in the black box is the same in both designed structures (details are given in [2] and [3]).

INPPS is planned to be equipped with particle and electromagnetic radiation detectors. Based on possible residual core radiation spectra and natural radioactivity in space, the MEDIPIX / TIMEPIX semiconductor chip sensors are the preferred solution. About 20 – 50 will be mounted on the flagship surface. [2] These CERN elementary physics developed and space qualified detectors are able to measure x- and gamma-rays, neutrons, nuclei, protons and electrons in keV to MeV energy ranges. Therefore, flagship real time monitoring and scientific data measurements during flights are combined because the various types and sources of radiation remain discernible by this technology.

On both flagships, auxiliary power supply systems are implemented which provide in the order of 10 kW at Jupiter and Mars, respectively. The photovoltaic generators use radiation-resistant CIGS thin-film photovoltaic cells supported on a very large deployable membrane structure ([16], [17], [18]) The ring geometry chosen is strengthening the space system safety because it is efficient in most likely spacecraft orientations which in turn are governed by the thrust vector of the main propulsion system during most of the flight time. This amount of power is necessary for all sub-systems to operate during the assembly phase of the flagship and - also at Mars and Jupiter locations - in case of technical issues with the reactor sub-system. While the reactor is operating, the auxiliary photovoltaic power can add to available propulsion power or reduce the load to be supplied by the reactor sub-system, and it is instantly available without effects of thermal or other inertia.

The payload baskets of both flagships have different size cylindrical volumes. The payload mass is a function of the specific impulse available in the used INPPS ET's (Fig 7).



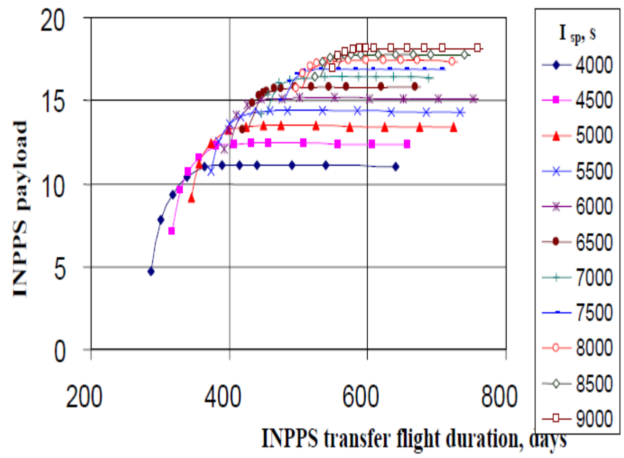


Fig. 7 Top - EUROPA-INPPS payload mass between 1 t to 11 t. The mass is displayed as a function of Earth-Jupiter/Europa transfer flight duration (in days) with the electric thruster specific impulse as a parameter. The minimal flight time to Jupiter is not much more than about 2 years. Isp was considered from 5000 s to 9000 s. Bottom - MARS-INPPS payload mass between 5 t to 18 t. The minimal flight time to Mars is about ten months. The mass is displayed as a function of Earth-Mars transfer flight duration with the specific impulse as a parameter from 4000 s to 9000 s.

2.2 INPPS Flagship electric thrusters

During the MEGAHIT project activity EP technologies from France, Germany, Russia and USA were studied (see in [1]]. In the DEMOCRITOS project and subsequent activities the MEGAHIT favoured ET as well as Japanese ET candidates are included as potential INPPS flagship EP sub-systems. These studied ET are described in this subsection.

In the frames of the MEGAHIT and DEMOCRITOS projects, and under extended considerations, TCED French PPS20k (Snecma), German RITs (ArianeGroup), Russian IT-500, U.S. NASA GRC electric thrusters were considered (see Fig. 8 and Table 1). However, for INPPS EP system design other high power TCED (SPT-290, VHITAL-160, NASA 457M) or IT (NEXIS, HIPEP, RF IT-450) could be also considered for the Earth outward acceleration, the interplanetary cruise and the Mars respectively Europa deceleration phases. The world-wide selection of high TRL ET systems also underlines the internationality of the flagship space tug.

Fig. 8. Left PPS20k, middle IT-500 and right RIT2X-HS photos.

There are at least two 25 kWe-class electrical thrusters in Europe and in Russia which are under development and could be available in 2023 for testing on the ground demonstrator. These are the PPS20k from Snecma (HET), the ArianeGroup RIT2X-HS and the IT-500 from KeRC (GIT). Long duration tests of these thrusters plus cluster tests significantly contribute to their INPPS qualification, and help to demonstrate their good functioning in cluster. Therefore, both thrusters belong to the DEMOCRITOS ground demonstrator design concept.

The RIT-2X system is under qualification at ArianeGroup for telecommunication platform and scientific missions [19]. This engine can be adapted easily to the needs of DEMOCRITOS. The only change considers the ion optics system and the gas insulator. An enlarged version will be capable to process 50kW power and deliver 1N thrust.

Table 1. PPS20k, RIT2X-HS and IT-500 parameters (operating on xenon).

Type of thruster	**PPS20k**	**RIT2X-HS**	**IT-500**
Power [kW]	20-35	20	20-35
Thrust [N]	1 (design)	>0.4	0.4 – 0.75
I_{sp} [s]	2500	>7900	7000
Main voltage [V]	300-700	>4500	4500

1. Ion thrusters are a mature technology. They have already been flown and are in preparation on several exploration missions (see examples in Fig. 9).

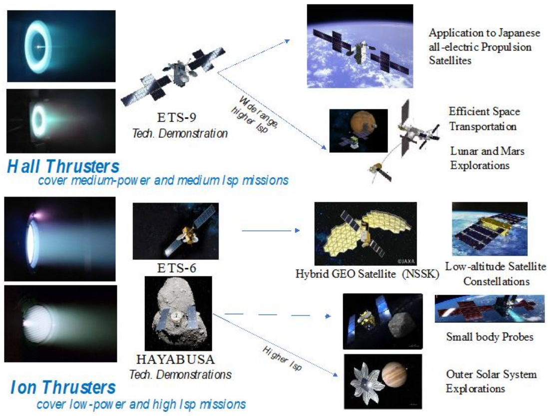


Fig. 9. JAXA's electric propulsion missions benefited from both ion and Hall thrusters. This Hall thruster line-up of 2 kW to 6 kW is added to JAXA's ion thrusters line-up. A variety of missions which follow the flight demonstration on-board ETS-9 are expected, and payload benefit and thus mission strength is tremendously expanded. With these improved HET and IT, JAXA would like to further enrich the future exploration missions according to DEMOCRITOS project objectives.

Ion thrusters have been tested in laboratories up to 30 kW - 40 kW (IT-500, HiPEP). Ion engines offer the best specific impulse but low thrust densities, it can become problematic when considering power levels above 50 kW because the grids diameter becomes very large. That is why the technology readiness level for power above 50 kW can be considered as low.

2. Thrusters with closed electron drift also known as Hall effect thrusters are also mature and have already been flown on exploration missions (SMART-1). The Japan Aerospace Agency (JAXA) is working on the Engineering Test Satellite 9 (ETS-9) program (read in [20] and [21]) with higher power HET (Fig. 10).

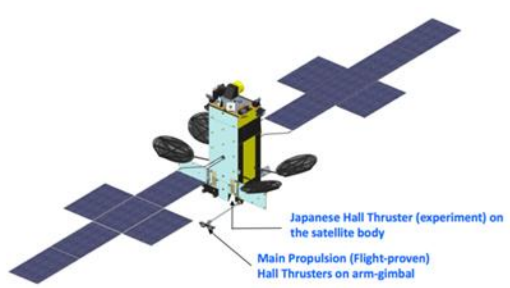


Fig. 10. ETS-9 satellite and its Hall Thrusters as XPS. This newly designed 5-ton class GEO satellite is going to demonstrate key technologies to enable high power (25 kW) HET. The illustration displays four main thrusters on arm gimbals, whereas the Japanese Hall thruster is located on the bottom of the satellite body.

A Japanese Hall thruster may also be used for INPPS flagship maneuver (Fig. 11).

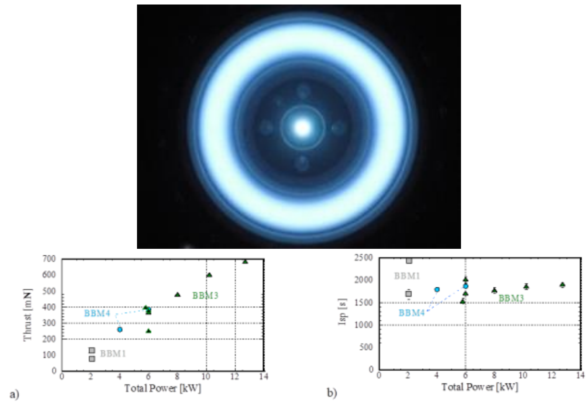


Fig. 11. Above: 6 kW Japanese Xenon HET (Breadboard model (BBM) testing at JAXA.). Below a) to b): thrust and Isp as a function of power for three BBM. BBM4 obtained 393 mN and 1,940s at the beginning of life test [22], and as a result of preliminary life test [22], it is found that Isp and thrust efficiency decreased from 1940 s and 62.9% to reach the constant values of about 1,900s and 60%, respectively. During accumulated operation from 1,012 to 4,048 hours, nearly constant performance continued [23].

This flight opportunity for the Japanese Hall thruster enables not only more efficient all-electric propulsion satellites but also paves the way to near-future high-power space transportation and exploration mission contributions by JAXA: Fig. 11 b) shows BBM3's operation is available either in wide Isp range or in wide power range up to 10 kW, that will be suitable for exploration or transportation of a large vehicle like INPPS.

Ground demonstrators have been tested up to 72 kW (50 kW nominal power NASA 457M) with xenon in the U.S. and 150 kW with bismuth in Russia. In Europe, TCED PPS-20K has been tested up to 23 kW. TCED offer a lower specific impulse compared to ion engine but a much better thrust density which makes them good candidates for INPPS flagship flights.

3. MPD thrusters are probably the best technology for very high power levels but there is a lack of operational flight experience at high power. MPD thrusters have been tested to power levels of several hundreds of kW and even 1 MW in Europe, Russia and USA. A Lithium Lorentz Force Accelerator was tested by Russia at 500 kW during 500 hours. One of the main challenges is the cathode, which sees extremely high thermal loads, currently strongly limiting operation lifetime potential.

Insofar, leading ET candidates are high power IT and TCED for the INPPS electric thruster sub-system: building of an ion thruster with a power rating of 50 kW is possible at the existing technology level at specific impulse of 3000 s to 8000 s and higher (for Kr). TCED application is justified in the specific impulse range of 2000 s to 4000 s (up to 5000 s for Ar). Available technologies allows to make TCED with power level up to dozens kW. Increasing specific impulse may have negative effect on the operation stability and lifetime of TCED.

Concerning EP propellant, xenon, krypton, argon and iodine are considered as possible options. Each propellant has its advantages and drawbacks. Xenon TCED and IT have demonstrated the best operation efficiency. In case of krypton and argon utilization, thrusters' efficiency is reduced in ~5 % and ~10 % -15 % correspondingly. There are not enough experimental data for iodine efficiency up to now, however it should be close that for xenon. Krypton is chosen for INPPS as a reference propellant, because it seems the best compromise on cost and performance.

The logic of determination of requirements to the EP system is given below. Space mission parameters mainly determine high level requirements to EP (see Fig. 12).

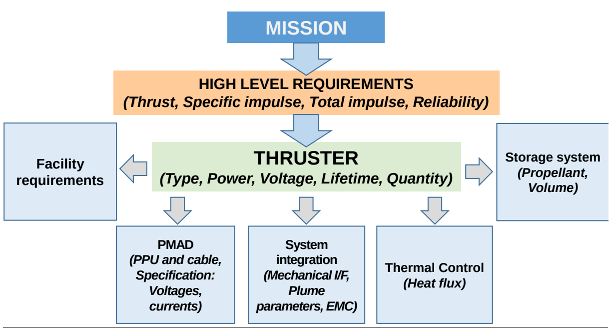


Fig. 12. Requirements to EP system.

The constraints - to INPPS EP sub-system and from the rest of the INPPS sub-systems to EP - are the following:

A) The non-nuclear EP sub-system of INPPS will be mounted in iBOSS building blocks. These are: to some extend, the ET itself and the entire PPU.
B) On the basis of high level requirements parameters of thrusters and preferable type will be defined from:
   – voltage level,
   – power,
   – lifetime and
   – quantity.
C) Facility requirements for propulsion system qualification (according to DEMOCRITOS ground demonstrator concept, presently are preferred existing and extending facilities at CNES, DLR, and KeRC).
D) Electrical Interface Requirements to be defined for PMAD:
   – voltage and current level (main and additional power sources) and
   – integrating PPU with AC/DC for decreasing mass ratio is preferable.
E) Thermal I/F
   – heat flux, requirements for radiators (standard and droplet) and cooling systems (if needed).
F) Interface with On Board Data Handling system integration:
   – mechanical I/F,
   – plume parameters and
   – EMC.
G) Propellant storage system:
   – type of propellant and
   – volume (within iBOSS building block – which includes also standardized fluid interfaces).

There are two potential ways towards the creation of high power EP systems: the development and usage of single highest power thrusters and the use of several, simultaneously operating relatively low power thrusters, i.e. thruster clusters. Insofar, the DEMOCRITOS ground demonstrator concept realization of long duration ET (alone) plus ET cluster tests (including mechanical vibrations tests) are very important before 2025 space qualification of INPPS.

The possibility of single thruster (TCED or IT) power increase is theoretically not limited. Power increases could be simply provided by the thruster size growing, however there are a set of technical questions to be solved, such as: availability of special design materials of appropriate size for the thruster parts manufacturing, testing facilities capabilities to run the high power thruster fire tests. Only these reasons determine the upper power limit to about 100 kW for a single TCED or IT.

Therefore, the most rational way to create EPS of megawatt power level is to use several simultaneously operating thrusters integrated into a cluster unit. A cluster - an integrated system, consisting of several, at-a-time operating thrusters, aimed at executing a common space flight task – enables application of new schemes of EP systems in which, e.g., functions of feeding and control for every thruster can be integrated in one device for all, and one common cathode-neutralizer can serve for operation of several thrusters.

There are no factors limiting the number of thrusters operating with one common cathode from the physical point of view. However, while considering EPS transient modes and operation algorithm such factors appear. Since the number (from *0* to *max*) of operating thrusters has to be changed during mission depending on mission program, thus possibility of operating of any intermediate number of EPS thrusters should be provided.

The number of thrusters in the propulsion system should be defined using reliability of the system and taking into account reliability of each unit. In addition to above mentioned reasons, it should be noted that development and qualification of a 100 kW thruster is much more expensive than the same procedure for a 50 kW thruster.

Taking into account all above mentioned options, a reasonable structure of 1 MW INPPS is to use 20-24 thrusters of 40-50 kW power combined in several thruster modules. Under study is also the importance of usage of only one type of EP thruster for certain reference spacecraft missions of INPPS flagship, because the space operation of mixed EPS will complicate the whole spacecraft design significantly. For example, the MEGAHIT recommendation for EP thruster type choice was following:

– for an optimal specific impulse range of 2500 s to 4000 s TCED application is preferred while
– for a specific impulse range of 4000 s to 8000 s IT is preferred.

Of course, thruster lifetime and total impulse requirements should be also taken into account when choosing EP type.

Other MEGAHIT requirements to the INPPS high-power EP subsystems were as follows:

– specific mass of 40 kW - 50 kW thruster is 1kg / kW - 2 kg/kW, thrust and specific impulse regulation (multi-mode ability),
– cathodes with discharge currents up to hundreds amperes and with possibility to regulate current values in wide range,
– PPU specific mass < 1.8 kg/kW, efficiency > 95% at the maximum flight allowable operating temperature of 60 °C,
– propellant storage system (like iBOSS) with a low tankage fraction and reduced propellant residuals,
– PMS with precise control of the propellant flow rate and
– low mass thruster gimbal (if applied).

For minimization of the mass of the cabling and the equipment, providing required voltages for operation of EP, it is proposed to consider application of the ‘direct-drive’ concept, according to which the spacecraft power supply system is generating a voltage of a required magnitude and the EP is powered directly and the need for high power DC to DC discharge converters is eliminated. In that case, turbo-alternators output voltage as well as PMAD system main voltage should match the electric propulsion thrusters’ main operating voltage value.

As it was mentioned above, there are practical limitations for high power EPS complete cycle of ground testing. The main technical problem is to simulate the environment in which the EPS would operate in space. Possibilities of existing facilities allow providing needed level of vacuum for only single high power thruster testing. Modernization of existing facilities or building a new one for EP cluster qualification is seems to be the most expensive part and are available with the DEMOCRITOS ground concept. Therefore, it is most likely that type, power and propellant of EP thruster will be defined not only by mission requirements but also by parameters of facility needed for qualification of EP system.

For example in the frames of the DEMOCRITOS project a decision was made to plan testing of an EP cluster based on two 25 kW thrusters, since it allows to use existing test bench for ground demonstration (see Fig. 13).

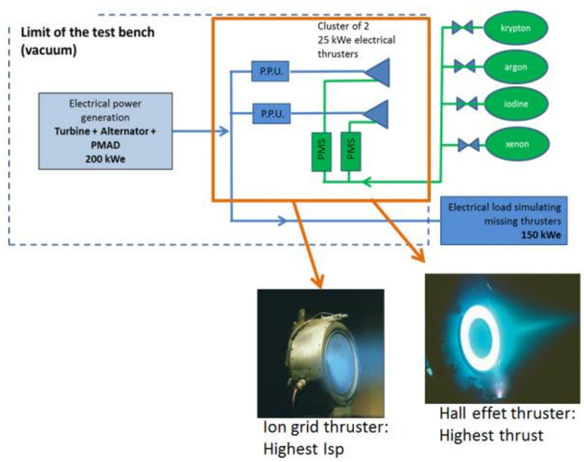


Fig. 13. DEMOCRITOS ground demonstration plan for EP.

According to the DEMOCRITOS test plan the ground demonstrator also included a 200 kW electric power generation part (turbine, alternator and PMAD). The rest of the electrical power (150 kW) should be sent to a thruster simulator. For the first test campaign, two types of clusters were considered: TCED PPS20k and IT-500. It was foreseen that each thruster should have its own PPU and its own PMS. In addition, thrusters should have been tested with different propellants (reference is krypton).

One of the possible solutions of the high power EP cluster ground testing problem is to use flight demo missions or to create a dedicated space platform to provide flight testing of newly developed high power EP key components.

3. Realizable Conclusions and Outlook

Up to now, the maximum power level of flight qualified EP thrusters is 5 kW. The main challenges of megawatt EP realization are following:

- high power thrusters (a minimum power of 50 kW per thrusters should be considered to limit the number of needed thrusters for a 1 MWe system),
- operation in cluster with common cathode(s),
- lifetime tests and reliability demonstration,
- testing of the thrusters (availability of facilities capable of fitting the thruster clusters and simulating a representative environment),
- capability to manage the thrust profile (main mode, stand-by mode, intermediate modes) possibly in "direct drive" and
- availability of a power processing unit capable of operating at this power level..

Taking into account all above mentioned requirements as well as TRL the most likely candidates for the high power EP realization are thrusters with closed electron drift and grid ion thrusters. Magnetoplasmadynamic thrusters are considered as an alternative option. However up to this time there is not enough published information for complete evaluation of data on thrust, mass, dimensional, and especially, lifetime that MPD would have in the case of their development up to engineering or qualification model level.

The critical technologies for both preferred thruster types (IT and TCED) are as follows:

1. for IT:
- the clustering of thrusters including interaction between them (including plume simulation / test),
- the high voltage cables and sockets (up to 5000 V),
- the carbon ion optics (is for instance being developed in the U.S.), and
- EMC.
2. for TCED:
- the lifetime limit under high voltage modes,
- the clustering of thrusters including interaction,
- high voltage cables and sockets (up to 1000 V) and
- EMC.
3. for EP system:
- the long term propellant storage (e.g. krypton, argon),
- the thruster feed system, and
- mounting and testing within iBOSS.

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