High Power Electric Propulsion: MARS plus EUROPA – Already Beyond 2025!

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Abstract: It's mid-term realization plus global strategic investments: the results of the European Russian DEMOCRITOS project (Horizon 2020) related to the MW class INPPS (International Nuclear Power and Propulsion System) flagship will be described. INPPS flagship includes high power electric thrusters cluster, supplied electric power by the nuclear reactor (successfully tested in Russia) and a solar power ring. Two INPPS versions were studied – the wide and arrow wing versions. Both versions have a futuristic design with standardized interfaces for several flagship subsystems. Especially the high payload mass of INPPS allows the transport of – for example – up to 12 t to JUPITER moon EUROPA and about 18 t to MARS – as a function of specific impulse of electric thrusters.

INPPS flagship not only allows scientific, but especially commercial and communication payloads as well. This means industrial-scale production of space flight systems for robotic and human space exploration.

International cooperation related to INPPS realization are necessary within an International High Power Space Transportation program to realize the DEMOCRITOS core, ground and space components until 2025.

DEMOCRITOS project included partners from Europe, Russia and a Brazilian guest observer and received several inputs from NASA Cleveland and JAXA Tokyo.

Nomenclature

AI	=	Artificial Intelligence
Apollo	=	Third US human space flight program
DEMOCRITOS	=	Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems
DiPoP	=	Disruptive technologies for space Power and Propulsion
EP	=	Electric Propulsion
HET	=	Hall Effect Thruster
iBOSS	=	intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly
INPPS	=	International Nuclear Power and Propulsion System
IOV	=	In Orbit Verification
ISS	=	International Space Station
IT	=	Ion Thruster
MEGAHIT	=	MEGAwatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long -duration Exploration Missions
MPD	=	Magnetoplasmadynamic
NEP	=	Nuclear Electric Propulsion
NTP	=	Nuclear Thermal Propulsion
NPS	=	Nuclear Power Source
PMAD	=	Power Management and Distribution
PPU	=	Power and Processing Unit PPU
SAA	=	South Atlantic Anomaly
RIT	=	Radio Frequency Ion Thruster
TECD	=	Thrusters with Closed Electron

I. Introduction

THIS paper highlights high power electric propulsion for non-human / human and high mass payload transports. This high power space transportation was studied in the European Commission funded DEMOCRITOS, MEGAHIT and DiPoP projects [1]. The projects members were from Europe and Russia. Brazil was guest observer in DEMOCRITOS and MEGAHIT. Additionally, in DEMOCRITOS project institutes from NASA Cleveland as well as JAXA Tokyo and Airbus Germany contributed with several inputs to the DEMOCRITOS MARS- and EUROPA-INPPS flagship design and subsystem - during the concurrent engineering study. The flagships are foreseen to be equipped with – the successfully ground based tested (2018) - MW class Russian reactor. The space qualification of INPPS is already intended beyond 2025. Non-human MARS-INPPS cruise to Mars and back to Earth plus continuation towards to Jupiter Europa moon allows to test most maximal the space system and subsystems under the longest, most distant, longest delayed communication as well as harsh natural radiation and darkest conditions. This would be the most optimal case, to apply the first INPPS flight experiences for the production of the only second INPPS for human transports to Mars surface. Therefore the resulting MARS- and EUROPA-INPPS flagships will be described in detail.

All UN NPS regulations [2] will be fulfilled by the following five measures

1) first of all, different launchers lift offs all non-nuclear subsystems to high Earth orbit (above 800 km),
2) after complete successful robotic assembly of non-nuclear subsystems, Russian heavy launcher transports - the physical non-critical reactor to high Earth orbit - and robotic assembly and mounting to non-nuclear subsystems will be carried out,
3) it follows the step by step switch on of all subsystems and extensive testing of entire space system before interplanetary departure,
4) by the real time video and charged particle / electromagnetic radiation monitoring on INPPS flagship and
5) the release of co-flying monitoring satellite during INPPS interplanetary cruise will be envisaged.

The INPPS as a high quality, international space system additionally itself contributes to safety by

- secondary kW power supply by solar light via a photovoltaic ring and
- building blocks with standardized interfaces, which are used for many non-nuclear subsystems. Advantages are the maximum and flexible use of subsystems in both flagships plus artificial intelligence applications for subsystem analysis and including faults identifications.

This strategy is also directed towards international cost and finally INPPS flagship operation reductions.

Therefore the resulting MARS- and EUROPA-INPPS flagships from DEMOCRITOS project will be described in the next chapters.

II. European-Russian DEMOCRITOS Project and Progress Beyond

DiPOP was the first strategic orientated EC project for NEP in the 2010th. The deliverables contain the low power (kW) European roadmap, which includes documents related to scientific, technical status, exploration mission targets as well as European space industry, organization and universities interests in preparation of a human Mars flight. DIPOP also contains a study for public acceptance of NPS. The European – Russian MEGAHIT was the second strategic orientated EC project - for high power NEP. The results are readable in very similar deliverables like in DiPOP project - in the high power EC MEGAHIT roadmap. This high power roadmap has already included relationships focused on MW class reactor, as well as international prospections plus usable European, Russian and US high power electric thrusters including first dependencies between specific impulses for Mars, Moon, Europa, Titan and asteroid exploration missions and transported payload mass. In the focus of the third strategic EC project for NEP – the European-Russian DEMOCRITOS project the first steps for MEGAHIT roadmap realization started – with studies for the core, ground and space concepts.

The core concept included studies towards the reactor core like nuclear physics, comparisons with US PROMETHEUS SP-100 reactor [3], operation, shielding and safety. The INPPS MW reactor will have about 3 - 4 MW_{th} and 1 MW_{el} energy available for the entire space system. In DEMOCRITOS it was studied and finally preferred a core outlet temperature of the reactor in the order of 1300K with a He-Xe gas reactor cooling.

The ground concept contain results for ground based subsystem tests like especially conversion test for example in France or long term electric thruster tests in Germany or complete subsystem test in Russia – instead with the MW reactor with a gas heater. Cost estimations for these three ground based tests are done.

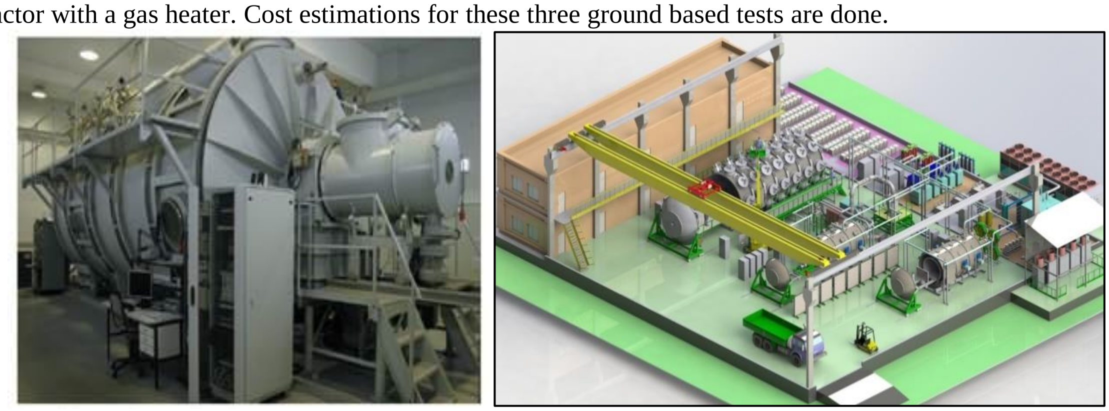

Figure 1. Example for INPPS ground demonstrator tests facility. *Left: already existing test bench facility at Keldysh Research Center Moscow foreseen to be used (see also IEPC19 [4]) and integrated into INPPS ground*

demonstrator / EP tests. Right image: the final deliverable of the DEMOCRITOS ground demonstrator was this CAD design.

In parallel with realization of the ground concept, the DEMOCRITOS space concept is intended to realize. The space concept documents contain answers to subsystem transport to high Earth orbit and the INPPS flagship first concurrent engineering study with additionally inputs from NASA Glenn Research Center, JAXA Tokyo and Airbus Germany. The study philosophy for the two futuristic like designed flagships in the Concurrent Engineering Facility at DLR Bremen: beautiful and similar layout like supersonic French-British Concorde / Soviet TU-144 aircrafts with a maximum of commonly used sub-systems (by building blocks for the non-nuclear parts). The study philosophy result – the bow with same reactor noise, same conversion plus boom plus payload plus PPU and electric thruster cluster at the rear end. Differences – due to the Mars / Europa flight destinations and radiation test aspects for the radiators are the shielding, radiator and rear secondary solar power supply sub-systems. The fulfillment of UN NPS rules for INPPS flagships were considered and are already sketched in the introduction above.

The next sub-chapters contain the description of MARS- and EUROPA-INPPS flagships.

A. Mars-INPPS Flagship

The Mars-INPPS flagship and subsystems are displayed in figure 2. It has a cone-like shielding sub-system and arrow wing like structure for the radiators. The perpendicular wings are caused by the demand to dissipate the heat directly – without interactions - into free space. The four wings and the radiation area (in the order of 1000 m^2) are necessary to radiate the heat completely into space. Notable is the comprehensive usage of building blocks, so called iBOSS [5].

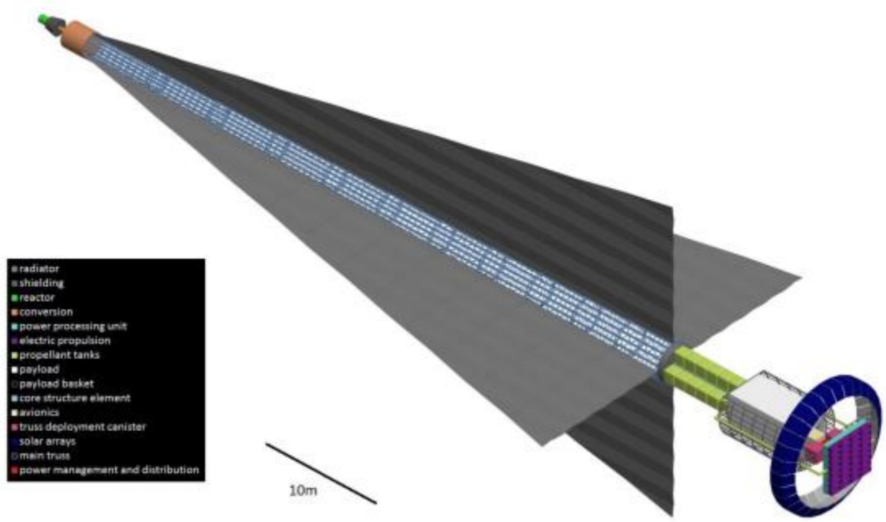

Figure 2. DEMOCRITOS MARS-INPPS flagship. *Arrow wing (radiators) designed space system – layout leaned to supersonic turbojets. From core at the bow (in front left: small green cylindrical structure) to solar light power supply ring and cluster of ion thrusters (turquoise plate with purple circles) at the rear end. The great white structure is the payload basket (for up to 18 t scientific instruments, commercial products and communication infrastructures). The colored agenda describes the other non-nuclear sub-systems. The displayed length scale is 10m.*

Mostly all non-nuclear sub-systems (but not shielding, conversion and payload parts) are mounted with / within iBOSS. The following sub-systems were studied to be hosted in about 15 – 20 iBOSS blocks: boom, tanks, partially payload, power management, PPU, core avionics and secondary solar power photovoltaic cells.

iBOSS, funded by DLR and developed in Germany offers a very important fact: box shaped units will host the sub-systems with the very important fact – it have standardized mechanical, thermal, electrical and fluid interfaces. This is an immeasurable advantage for combining both flagships designs, developments, tests, improvements (like AI systems for the sub-systems), replacements on ground, at high Earth orbit and interplanetary operations. Up-to-date usage of iBOSS: within the used iBOSS the sub-systems parameters can be directly monitored and elaborated for potential AI systems mounted within iBOSS. Thereby these AI systems are trained by empirical experiences – already during flagship's high Earth orbit flight and especially during long interplanetary flights. These trained AI systems realizes in real time potential sub-system faults and may learn to intervene. This raises considerably the (non-human / human robots) flagship safety. This tested combination of iBOSS with AI also levels up the human flagship preparation and flight safety.

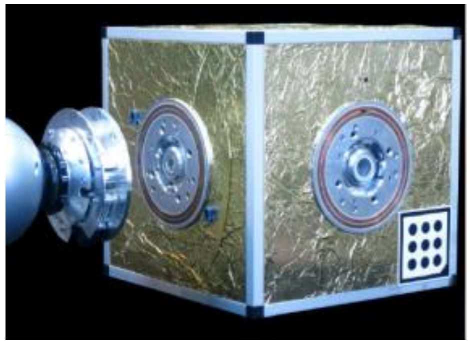

Figure 3. Building block iBOSS. *Autonomous robotic assembly will start in high Earth orbit with iBOSS sub-systems mounting of non-nuclear INPPS parts. First starts the rear end construction, continued via boom mounting – the last iBOSS equipped subsystems - and finally ends with the physical non-critical core. This to be monitored procedure displays directly the successful realization of the launch and assembly for the flagship. This order of using iBOSS – including AI – sustains the safety of the third big space project after Apollo and ISS.*

The arrow wing version of MARS-INPPS has a total mass of 45.3 t, a final mass launch (including all margins) of 95 t and a propellant mass of 31 t. These mechanical characteristics plus arrow wing INPPS width/weight/length marks it as 'quarter ISS'.

The figure 4 displays the results of calculations for the transportable payload mass via NEP by INPPS flagship to Mars. Amazing is the order of magnitude heavy payload mass transport (up to 18 t) to Mars. NEP by INPPS also offers relative short flight duration to Mars – in minimum about 10 months only. The necessary Isp of 4000 s is already available.

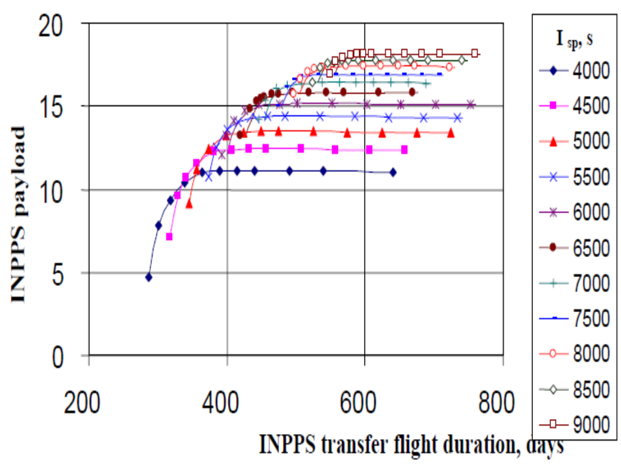

Figure 4. MARS-INPPS payload mass. *The mass is displayed as a function of Earth-Mars transfer flight duration with the specific impulse as a parameter. Isp was considered from 4000 s to 9000 s. The result: the payload mass is between 5 t to 18 t!*

B. EUROPA-INPPS Flagship

The EUROPA-INPPS flagship and subsystems are displayed in figure 5. The first visible layout difference to Mars-INPPS is the wing like shielding sub-system. Wing like shielding seemed to be necessary for an first INPPS deep space flight: the wing like shielding is crossed to shade and protect the radiators. Additionally it excludes potential radiation damage of the radiators in the intensive radiation environment of Jupiter / Europa as well as the higher energy galactic cosmic ray flux with it's higher intensity at Jupiter distance in the heliosphere. The second visible layout difference to MARS-INPPS is the wide wing like structure for the radiators. The more extended perpendicular wings are also necessary by the demand to dissipate the heat directly and completely – without any interactions - into free space. The radiator radiation area is smaller than the area in MARS-INPPS flagship.

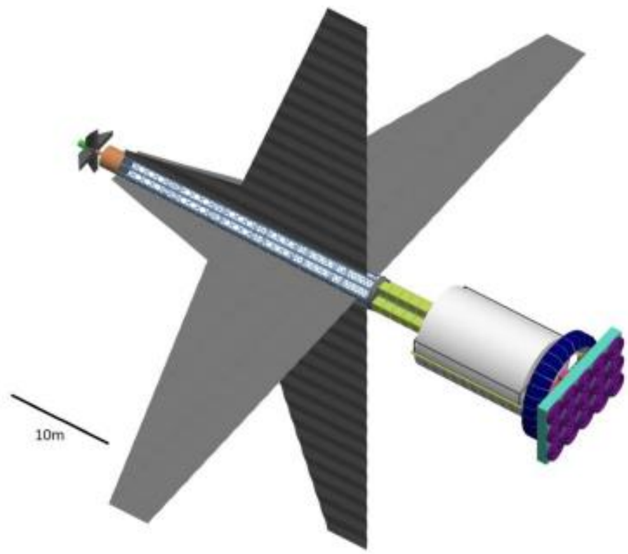

Figure 5. DEMOCRITOS EUROPA-INPPS flagship. *Wide wing (radiators) designed space system. From core at the bow (in front left: small green cylindrical structure) to solar light power supply ring and cluster of ion thrusters (turquoise plate with purple circles) at the rear end. The great white structure is the payload basket (for up to 12 t scientific instruments, commercial products and communication infrastructures). The colored agenda describes the other non-nuclear sub-systems like in figure 2 for MARS-INPPS. The displayed length scale is 10 m.*

iBOSS is applied very similar like in MARS-INPPS. AI equipped iBOSS in EUROPA-INPPS tests both systems towards deep space outer planetary exploration flight and increases strongly the reliability for MARS-INPPS human flight. The wide wing version of EUROPA-INPPS has a total mass of 56 t, a launch mass of 116 t and propellant mass of 38 t (including all margins). Insofar it is shorter and heavier than the MARS-INPPS. The weight of EUROPA-INPPS is in the order of 25% of ISS.

Figure 6 displays the calculation results of heavy payload mass via NEP by EUROPA-INPPS to Jupiter icy moons location. Amazing is the one order of magnitude heavy payload mass transport (up to 12 t) to Europa: chemical rockets with similar 100 t launch mass at Earth will transport only about less than 10% payload mass to Jupiter! EUROPA-INPPS also offers short transfer flight time to Jupiter / Europa – between 800 days and 1500 days. The minimum necessary Isp is of 5000 s. Maximum necessary Isp is 9000 s for 12 t payload mass.

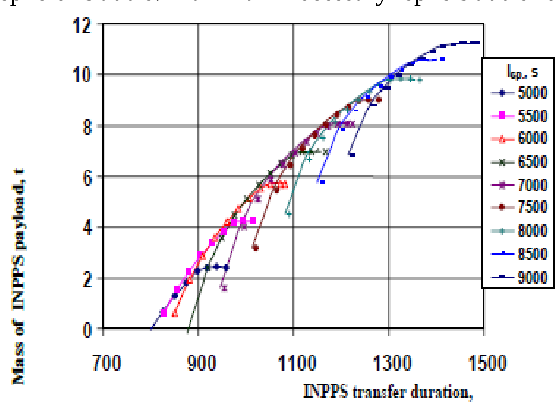

Figure 6. EUROPA-INPPS payload mass. *The mass is displayed as a function of Earth-Jupiter/Europa transfer flight duration with the specific impulse as a parameter. Isp was considered from 5000 s to 9000 s. The result: the payload mass is between 1 t to 11 t!*

First calculations done, for example – it was assumed a departure from Earth in 2029 or 2030, not earlier than 1/1/29 and not later than 12/31/30 to Europa. It includes spiral out from 800 km circular Earth orbit, spiral in to Jupiter orbit at altitude of Europa. The dry mass delivered to Jupiter orbit at Europa altitude equals 64 tons (means about 8 t payload mass, see figure 6), the specific impulse of EP thrusters is 8000 s and it was considered 65% efficient thrusters and 90% duty cycle.

C. INPPS and Real Time Radiation and Video Monitoring

It is synergy between elementary particle and space physics: originally CERN developed semiconductor chips, space qualified by ESA ProbaV and in ISS cupola are foreseen for the real time monitoring in all phases of INPPS missions. In the order of 20 – 50 MEDIPIX / TIMEPIX detectors [6] will be mounted on the INPPS surfaces. The data and processing software are available on board in real time – train also the AI learning system for INPPS safety – and arrives delayed - due to flagship locations in real space time - on Earth only seconds to hours later.

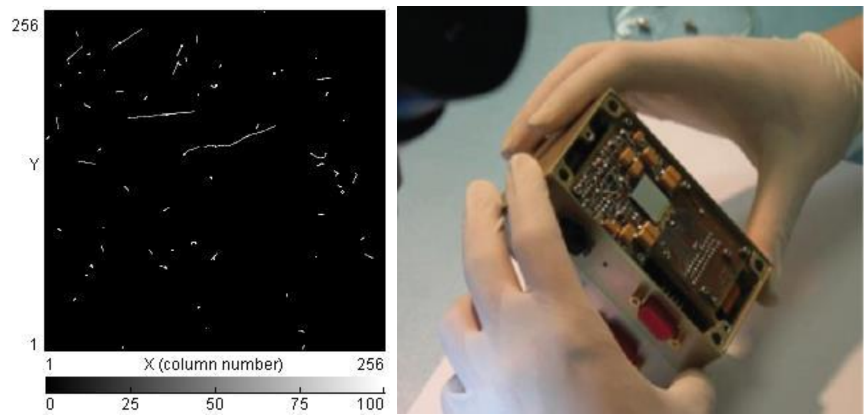

Figure 7. MEDIPIX / TIMEPIX for INPPS. *Left: the 256 x 256 detector ship for gamma-ray, x-ray, proton, electron and light nuclei / ion spur identifications. Right in the middle: advantages of the detectors for INPPS are the very high time, angle resolutions and the measurable energy ranges. Therefore MEDIPIX / TIMEPIX is also a considerable payload instrument for solar energetic particles and high energy galactic cosmic ray measurements. In addition, these data alerts in real time humans on board for space weather forecast purposes.*

In figure 8 are shown two years data measured successfully in high Earth orbit by MEDIPIX / TIMEPIX.

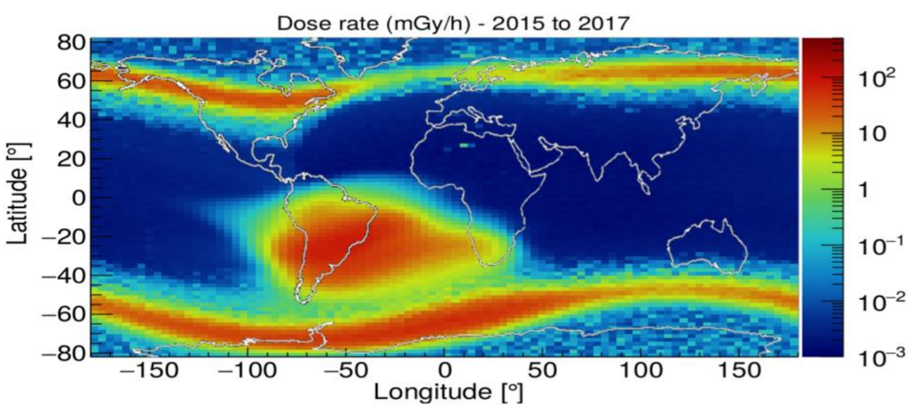

Figure 8. Radiation dose rate observed in a three years period in low Earth orbit by MEDIPIX / TIMEPIX. *The dose rates are increasing orders of magnitude in SAA and Earth high altitude regions. Drawn conclusions - from very high flux elementary particle beam exposures and the displayed data - for acceptance during INPPS flights: the periods from Earth orbits periods are longer than the INPPS flight to Mars including return to Earth and is in the order of Europa flight timeline.*

Data plus simulations based on GEANT4 software - for the flagship resulted into an about 10^{-4} lower neutron flux after reactor core shielding. After the additional INPPS spacecraft shielding and behind the deployed boom distance (20 m), the payload basket and the other non-nuclear subsystems of INPPS exposed by an extra 10^{-6} lower neutron flux. As it was also simulated for the US SP-100 space reactor, the result here is very similar: in summary, a

10^{-10} lower flux ratio – means practically a near zero neutron flux at the flagship. The natural radioactive radiation in space – from Sun and Galaxy – remains an issue. However not anymore like during Apollo astronaut flights to Earth moon in the 1960th / 1970th. Because the relative short INPPS flight duration to Mars with human plus the world-wide space weather services with their alerts – also applied to interplanetary space weather prediction in near real time – empower flagship Mars flights to do under relative radiation save conditions. Especially when the MARS-INPPS with humans will fly during solar activity maximum period. Because the more dangerous galactic cosmic ray flux is lower (for instance at nearby Earth space environment by about 20%) due to adiabatic interaction of outward moving solar wind and inward moving galactic cosmic ray particles. The rotation of INPPS against a predictable arriving solar storm is feasible too. INPPS sub-systems and humans on board itself are protectable technically - by increased grammage wall parts, for example within the payload basket (like ISS astronauts are more protected in the Russían ISS module).

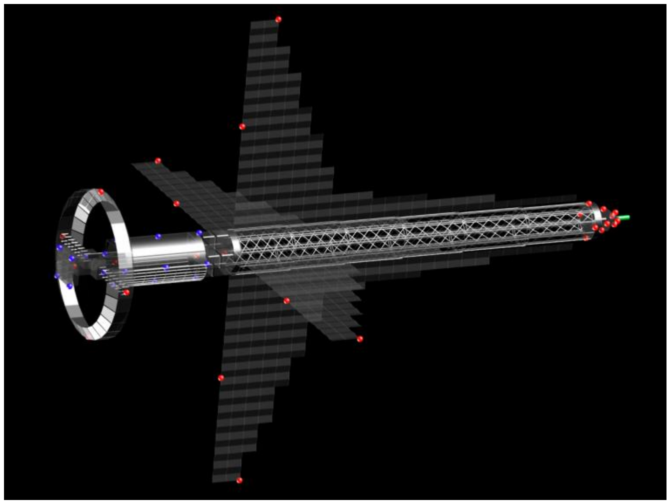

Figure 9. Illustration of EUROPA-INPPS with MEDIPIX / TIMEPIX detectors and video cameras. *Red and blue spheres are the widely distributed radiation detectors respectively video cameras. The detectors completely monitor the flagship. The cameras offer brilliant real time view on operating, entire flagship and celestial sky including disappearing Earth and approaching Earth moon, Mars, asteroids as well as Jupiter / Europa.*

III. Conclusions and INPPS Realization

The main points of the paper are:

- the progress for NEP is evident from nuclear power source and electric propulsion points of view,
- on high level the ground, core and space demonstrator concepts are prepared,
- Mars and Europa NEP space systems are studied in detail,
- UN NPS were studied, applied to INPPS flagship and fulfilled

Because of the four main points of the paper, the importance is the high level of INPPS flagship preparations. The main, nearby extension of the work is the focus on complete space flight qualification in 2025 time frame. The necessary extensions are directed towards – again focused on 2025 flight qualification – on low level, very detailed studies with subsequent laboratory plus flight preparations. Additional extensions are the envisaged re-design by a concurrent design study of the INPPS flagship due to the confirmed successful ground based 1MW reactor test with droplet radiators. It must follow the robotic assembly concurrent engineering study of the re-designed INPPS flagship. Extensions are started for an INPPS flagship co-flying small satellite. This would be a remarkable add-on to UN NPS regulations. However and moreover, this strengthening the world-wide public and politic support. Suggested application is the first international payload study for the 2025 INPPS flagship qualification. In this context the kW KRUSTY success and the thermal nuclear propulsion progress in the USA is in a high ranking breakthrough for international prospection of cooperation.

Acknowledgments

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In memory for Hartwig Bischoff (†), who was a colleague and friend. He was in charge for NEP at EC and initiated and strongly supported the three projects.

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