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Cluster of electric thrusters for astronautic and robotic INPPS flagship space flights to Mars and Europa moon

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Abstract

This review deals with the selection of the electric propulsion system (EPS) for the internationally developed and designed, primary nuclear-electric space tug International Nuclear Power and Propulsion System (INPPS). INPPS is scheduled for interplanetary missions to Mars and Jupiter moon Europa missions by the end of decade 2020. Regarding specific technical and mission parameters preselected electric thruster (ET) types, developed by international companies and institutions, are analysed, evaluated and investigated for a possible application as propulsion system (PS), the so-called CET (Cluster of Electric Thrusters). It is analysed whether solely electric thrusters, combined in an adequate CET, enable the envisaged interplanetary missions—robotic and astronautic/crewed with the INPPS flagship.

Thruster clusters with strategic consortium considerations are analysed as a feasible PS of the INPPS. The studied CET consists of the following: (a) only European ETs, (b) combination of German and European ETs, (c) Japanese and European ETs or at least (d) Japanese, European and US thrusters. The main results are (1) Robotic and crewed INPPS mission to Mars/Europa are realizable with EPS only (no chemical propulsion is needed), (2) that every CET, except (c) of only Japanese and part of European thrusters, is capable to perform the main part of envisaged INPPS flagship mission orbit to Mars, back to Earth and to Jupiter/Europa moon.

Keywords: INPPS flagship; Electric Propulsion System; Cluster of Electric Thruster; Electric Thruster Diagnostics

1 Introduction

Since many decades in Soviet Union and in the USA several projects were carry out to establish nuclear powered space flights. The main difficulty was the successful technological development of Nuclear Power Source (NPS) as part of the energy supply subsystem on board the spacecraft. About one decade ago, the main progress came from the MW class reactor developments in Russia, as an NPS in the Russian TPM respectively in the

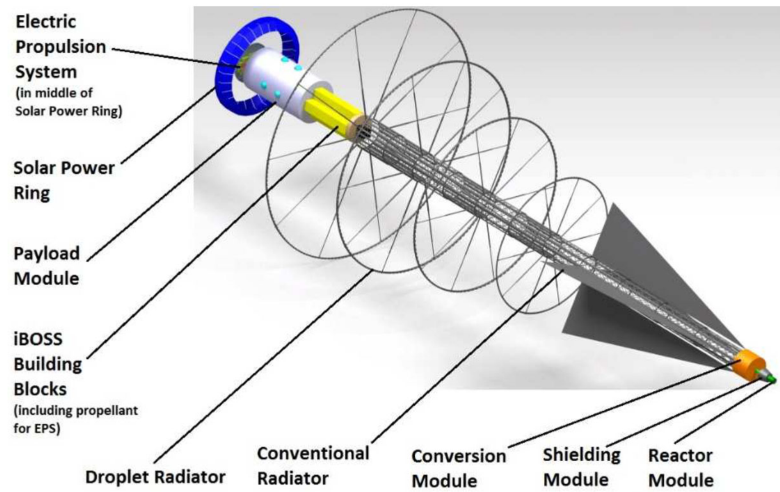

Figure 1 2021: concurrent engineering designed INPPS flagship with indications of all nuclear and non-nuclear subsystems. The focus in the paper is on the EPS, with its CET plate completely opposite to the reactor module and behind the solar power ring location

NPPS. Especially a highlight in the development was the planned and fulfilled successful MW class reactor ground based test in 2018 in Russia. In contemporary decade, the envisaged highlight is the announced and planned first space flight of the NPS space system with Nuclear Electric Propulsion (NEP) by 2030 (see in [1]). In Europe started related activities—already in 2012—by funding the DiPoP project (development of a low power NPS roadmap) via the European Commission. Hence those activities in Europe and Russia, the European Commission funded the two European-Russian projects MEGAHIT and DEMOCRITOS [2], which already included electric thruster performances. One result of these cooperation: concurrent designed space system with the Russian MW class core—the International Nuclear Power and Propulsion System INPPS flagship (in Fig. 1). NASA Glenn Research Center (GRC) Cleveland, JAXA Tokyo and Ariane Germany gave inputs to the study too. The Institute of Advanced Studies San Jose dos Campos in Brazil started to be a guest observer, for instance by means of inputs and expertise related to their core experiences. An up-to-date INPPS status related to technological, assembly/building blocks aspects, as well as scientific, commercial and communication payload proposals are published in [3–6].

In the USA—two technology developments are applicable to the flagship. On one hand, the recent successful long duration (about 88 h with 80 kW) ground based test of the high power VASIMIR electric thruster [7]. Because of the variable high power range of VASIMR, this system may potentially contribute to the flagship CET to help the reduction of electric thruster numbers—if the superconducting magnet within VASIMIR system is space qualified too (like the Antimatter Spectrometer AMS with it's superconducting magnet released in Earth orbit by the US space shuttle more than ten years ago) plus the increasing complexity of flagship electric cluster sub-system with VASIMIR is not too much complex. On the other hand due to the PROMETHEUS study with the NEP spacecraft to Jupiter—the reactor developments in the USA were successful further applied to KRUSTY. This system, with about 7 kW to 10 kW nuclear power is interesting for usage at small NPS satellites. More important—very useful is KRUSTY for nuclear power supply on Moon and Mars surfaces [8]. Insofar KRUSTY would be ideal for power supply of INPPS science payloads—like potentially foreseen— DLR leaded VaMEx on Mars and TRIPLE on Europa moon surfaces. In summary related to the cooperation with the USA: currently president Biden as well as in the former Trump administration including NASA administrators pushing and pushed NEP plus NTP for deep space exploration. Recent announcements in chronological order: (A) NASA administrator Bell Nelson underlined at GLEX 2021—the international conference of IAF for 60 years Gagarin space flight—the cooperation between USA and Russia in space. (B) In October 2021 the U.S. House of Representatives Committee on Science, Space, & Technology Subcommitee on Space and Aeronautics carried out a hearing with high level U.S. experts to accelerate deep space travel with space nuclear propulsion [9].

Complementary, in future, for flagship science payload power supply are recent micro reactor developments in Brazil [10] are usable. This heat piped cooled core, as a Stirling engine, may produce electricity in the order of several ten kW to MW in space.

During high-level space leaders plenary at 60 years Gagarin space flight celebration (GLEX conference St. Petersburg, June 2021), China National Space Administration CNSA announced (see in [11]): China prepares first step of Earth travelers by taikonauts, as a big leap of realized expertise in form of primary nuclear powered electric thrusters plus secondary chemical propulsion on board Chinese spacecraft to Mars. This important announcement is realistic, because Chinese experts published (see reference [12–15]) studies with two different NPS systems (in the order of several 100 kW_{el} power).

Documents in MEGAHIT and DEMOCRITOS already established the results of later comparisons of technologies in INPPS with UN NPS principles (see in [16–18]): a fully agreement and additional over-fulfilment (by foreseen co-flying satellites during interplanetary journey to Mars and Europa)! Due to secondary solar photovoltaic ring of INPPS (about up to 10 kW_{el} at Mars and Europa), back-up and supporting chemical (several W) as well as primary nuclear power supply the hybrid INPPS flagship is the most clean human made spacecraft in the wide, nearly empty, but with cosmic ray naturally radioactivity filled interplanetary space. For details, of UN NPS and relationship to the flagship are published in [16] to [17] and moreover, especially in the recently published book [18]. In summary: Earth originated hybrid INPPS flagship is green plus clean in natural radioactive near Earth space environment and huge interplanetary space. There is an very important link including business cases related to Earth protection: during the autonomous robotic respectively astronautic flagship assembly (around 2027) plus during new payload and subsystem reconfiguration phases in Earth orbit (between 2029 and 2031), hybrid INPPS is ideal supplement to EU & ESA and others EO protection programs—due to long usable, heavy (up to 18 t to 11 t) payload equipment for Earth ground, atmosphere and environment observation data.

In 2023, India and Pacific Nations directly recommend in [19]—the Space Conclave White Paper—key areas '… like human Mars flight, International Nuclear Power and Propulsion System flagship, deep space exploration, space-based manufacturing, mining in space, to building human habitats in space…'.

In summary: the EARTH-/MARS-/EUROPA-INPPS flagship is well prepared and can be realized in an international HST program within the next decade.

2 Sketch of INPPS flagship sub-systems characteristic

The paper focus on EP sub-system, the international CET for the INPPS flagship. The European Commission funded DEMOCITOS consortium members, including inputs from JAXA Tokyo, GRC Cleveland, RIAME/MAI Moscow scientists plus inputs from Austrian ENPULSION, German Ariane, French CNES and Italian SITAEL electric propulsion experts have been given ET inputs for the flagship CET. The main task was to specify in detail the flagship CET, for the robotic and human transport of payload with up to 18 t to Mars and up to 11 t to Jupiter moon Europa by approximately 20 ETs in the CET—a result of the EC funded MEGAHIT project.

The INPPS flagship is a high power space transportation tug with hybrid power supply. It has threefold safe power: a MW class reactor (can supply electric energy up to 1 MW_{el} for the EPS), plus secondary solar cell power (with about 10 kW_{el} at Mars and Europa locations) in case of power supply failures and third classical batteries for some non-nuclear subsystems.

To have the good sense for the necessary power supply of 750 kW_{el} to the huge CET on board of the INPPS, this practically actually only reasonable by about 1 MW (or up to about 10 MW) core with flagship droplet radiators. That also means, that 250 kW_{el} is usable on board of the INPPS flagship for all other non-nuclear sub-system by nuclear, solar and chemical produced electricity.

In the CET study [20], the focus was on an optimized CET (see Chap. 3), to perform a first autonomous mission with the INPPS to fly to Mars orbit and subsequently to the Jupiter moon Europa. During the mission, data and operational experiences will be recorded—also by artificial intelligence—to be able to build a second flagship for a crewed flight to Mars. To reach the destinations by the flagship, the usage of an EPS is—from physics point of view necessary—because electric thrusters achieve higher velocity (by two orders) compared to chemical thrusters for a given propellant mass. This also results in a higher mass transport (about one order) and decrease of flight time to Mars/Europa by the flagship.

With utilisation of nuclear electric energy, which may be provided by the most developed reactor, it is possible to operate ETs with high electric power (above about 20 kW). It is intended to combine several single thrusters to a cluster to achieve high total thrust numbers, which were calculated in the INPPS orbit calculations. By this, it is very important to diagnose in thermal vacuum test chamber laboratory experiments the selected thrusters in a cluster and to analyse the interaction of the chosen thrusters and to design a feasible arrangement depending on the participation of several international space organisations and industry. A feasible selection of suitable ETs for each orbit transfer (Earth to Mars, return to Earth and interplanetary cruising to Europa) was examined and the survey of the selected thruster parameters is yielded. Results for each strategic CET configuration are also discussed.

3 Analysis of potential electric thrusters for the INPPS

In the flagship CET study, the CET characteristics were calculated in many details and applied to the three INPPS orbits. Several electric thruster types can be a feasible part of the EPS as they achieve required values of each transfer phase with regards to determined limits of thruster quantity and reactor power of 1 MW_{el}. An electric thruster type is beneficial if eight or less thrusters are able to generate the necessary thrust to accelerate the flagship. Therefore 750 kW_{el} for the CET is considered—from 1 MW_{el} total reactor core power—to be used for operating the cluster of thrusters. Again: the residual 250 kW_{el} from the total flagship power is necessary for free disposal of the other INPPS subsystems. With reference to these limits the final selection of preselected thruster types for each consortium consideration is made and discussed. Remarkable: none of the mentioned thruster types are able to achieve required thrust levels for the end phase of trajectory Mars-Earth during the strong deceleration phase nearby Earth (the reason is the stronger gravitational force of Earth compared to the gravitational force at Mars), neither—regardless high thruster's numbers. Solutions for solving this situation are in discussion. Results of the numerical and experimental cluster validation have been made under the assumption of a single thruster type operation during the entire trajectory section with primary an unlimited thruster number. However only one specific thruster type will be used during a particular trajectory part with varying quantity depending on the mission requirements. A simultaneously operation of different thruster types is not intended here, because if a specific thruster parameter is required by a mission part, there is only one thruster type which fits best to this operation. Another thruster in combination would minimise the required parameter.

3.1 CET of German ETs in the flagship

A selection of ETs for INPPS CET, developed by German companies and institutions, is generally feasible. Here, a suitable option is shown, but this is not the only selection that is feasible with German thrusters. In general, a final selection between German thrusters, developed by IRS Stuttgart and ArianeGroup, has been leaded to use four different thruster types developed by both expert groups in Germany. The following list of thruster types were analysed: Arcjets MARC and HiPARC (IRS Stuttgart), applied-field magnetoplasmadynamic thruster (AF-MPD) SX3 (IRS Stuttgart), Hybrid-thruster TIHTUS (IRS Stuttgart), ion thrusters RIT-2X, RIT-2X-HS, RIT-2X-HS+, RIT-3X and RIT-4X (ArianeGroup).

The German arcjet HiPARC with seven thrusters, has been selected for high-thrust trajectory sections as this is the only possible German thruster that can achieve required thrust for peak acceleration during transfer to Jupiter. Eight SX3 are intended to be operated as support of HiPARC for high-thrust phases, where achieved thrust can not be modulated accurately to required thrust. These discrepancies between required and achieved thrust level are shown in Fig. 2 for the transfer from Earth to Mars with HiPARC. Maximal three ion thrusters RIT-3X will be operated during the middle-thrust phases alternating with the AF-MPDs. A detailed selection between the arcjet MARC and a further RIT named RIT-2X-HS+ has been determined to use the RIT with a thruster number of four to operate during low-thrust phases. This decision is based on a better suitability of RIT-2X-HS+ during more trajectory sections and because it features a higher Technology Readiness Level (TRL) compared to MARC. In addition, MARC consume more propellant due to the lower specific impulse.

In total, 22 thrusters are considered as German PS for the INPPS featuring an entire mass of 3901.5 kg including power processing units (PPU) and propellant feeding systems (PFS) as well. This is lower than the determined limit of PS mass, stated with 10% of the entire spacecraft at mission beginning. As the INPPS will offer an initial start mass of 100 t the PS should not be heavier than 10 t. Under these considered boundary conditions, these German thrusters are preferred for the flagship CET to Mars, back to Earth and to Jupiter

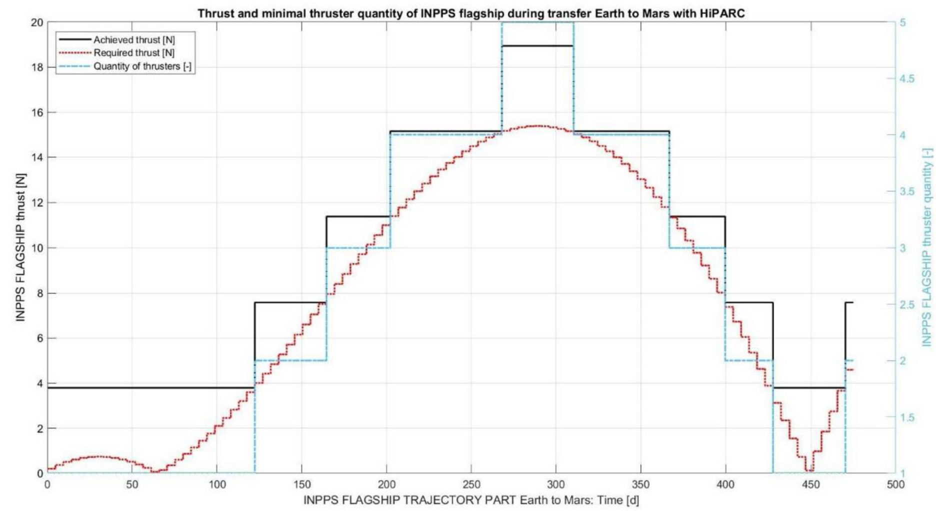

Figure 2 Plot of required and achieved thrust of HiPARC over mission time of transfer to Mars. In addition, the corresponding thruster quantity is shown in blue line

as well. The best thruster for each orbit section has been determined according to the minimal distance between required and achieved thrusts, because an accurate modulation to the thrust requirements is important to keep the trajectory as precise as possible.

The selection of only German ETs for the flagship CET is very good. On the other side, an international selection of ET's is more optimal—from industrial technology and political support points of view. To match with these arguments Austrian ETs are a very good technical answer. Because in low-thrust phases of orbit transfers, particularly for last phase of INPPS transfer to Jupiter/Europa, can be very accurately achieved with the Austrian thruster NEO^{10}, described in next paragraph. ENPULSION with NEO^{10}, have already intensive cluster experiences (up to four ETs and common PPU's) with their low power ET's. It is beneficial, that other thruster clusters for some trajectory sections are usable too, if a particular thruster type features an inadvertent failure. This is not allowed for a failure with HiPARC, because only this thruster type achieves the required thrust during transfer to Jupiter. Which trajectory sections can be operated with other selected German thruster types, can be detailed determined with the results given in reference [20]. Figure 3 shows the percentages of each enabled German thruster during the different transfers and how often they are used for the trajectory section. All thruster properties like thrust, specific impulse, considered and consumption of propellant as well as present TRL are given in reference [20] and are partially not yet published by the thruster owners. The selection of electric thrusters as options for INPPS first flight at the end of 2020th/beginning of 2030th is a sensitive issue and is strongly depending on present and nearby thruster performances. Therefore these technological relevant properties will be included in additional papers, which describes in details the INPPS flagship orbits to Mars, back to Earth and the flight to Europa for the different thruster candidates in the cluster of electric thruster on board INPPS flagship.

Detailed indications, in which particular trajectory section a thruster type is used, as well as detailed performance data of each thruster are also given in reference [20]. At the end of the transfer from Mars back to Earth no preselected electric thruster at all is able to

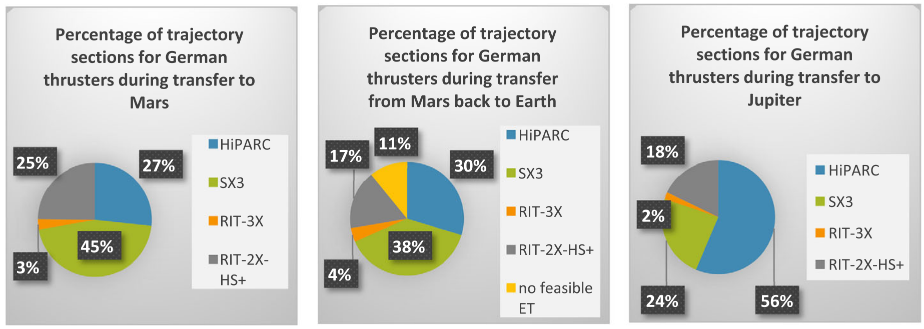

Figure 3 Percentages of trajectory sections for the cluster with German thrusters

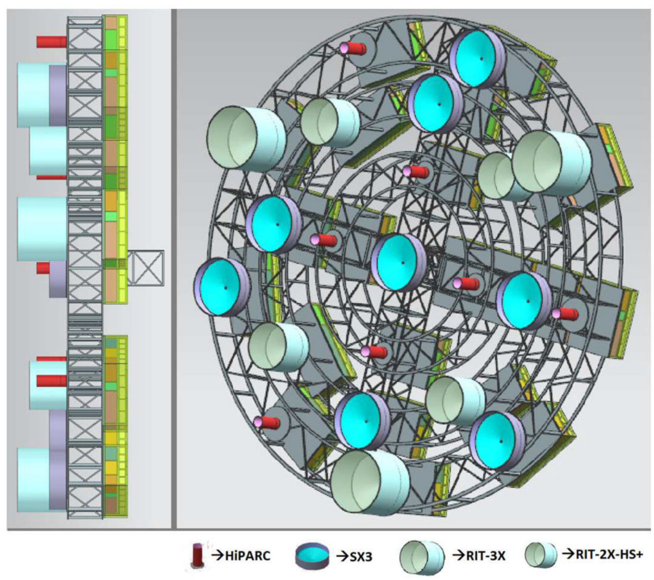

Figure 4 CAD design of gridded cluster plate including German electric thrusters with redundant PPUs for each thruster at the backside

generate the high required thrust for breaking at the Earth. By this reason it is necessary to reconsider the trajectory calculations or to use additionally chemical thrusters for breaking. In Fig. 3, 7, 9, 10, 11 this percentage of trajectory sections is shown with “no feasible thruster”.

In Fig. 4 the considered thruster arrangement of selected German thrusters is shown. According to a required symmetric thruster positioning this cluster option has been considered, trying to assemble each thruster of the same type not directly next to each other. According to the determined filling density of each thruster type, detailed explained in reference [20], area of cluster plate should be at least 8.1 m^2. This leads to a minimum diameter of a cylindrical cluster plate of approximately 3.2 m.

3.2 CET of European ETs

A possible cluster of ETs for the INPPS is shown in Fig. 5 with thruster types developed by European companies and organisations. As a suitable combination of European thrusters

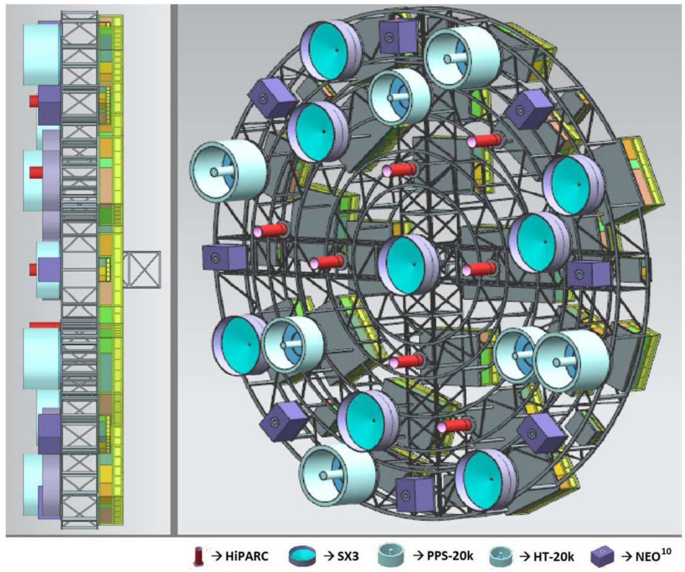

Figure 5 CAD design of gridded cluster plate including European electric thrusters with redundant PPUs for each thruster at the backside

this configuration seems to be advantageous for the INPPS with regards to determined requirements, e.g. a high TRL and a good modulation between achieved and required thrust level. Therefore, a maximum quantity of 30 thrusters on the cluster plate has been chosen for calculation purposes only. Important: this high quantity is not necessary for achieving the required thrust levels and lower number of electric thrusters very often fulfil required thrust (details are in preparation for publication). A final selection between following thruster types has been conducted: the German thrusters, revealed in previous paragraph, hall-effect thrusters HT20k (SITAEL, Italy), PPS-20k (SAFRAN Snecma, France) plus field emission electric propulsion like Nano, Nano IR^3, Nano R^3, Micro R^3 and NEO^{10} (ENPULSION, Austria).

According to the results of the achieved thrust levels, seven German HiPARC, three Italian HT20k, eight Austrian NEO^{10} and four French PPS-20k thrusters have been finally selected. As the German RIT-3X and the German AF-MPD SX3 features similar results of thrust calculations, a further selection between these both has been made. It has been decided, that SX3 features more better results, because a detailed approach to peak acceleration during the trajectory Earth-Mars is possible plus more suitable trajectory sections with an operation of the AF-MPD. By this, SX3 can relieve the German HiPARC during peak acceleration of transfer to Mars, where the arcjet is not an optimal choice. However, it is necessary to mention that this thruster selection is only one of several possible options and with further considerations other possibilities can be found regarding the results for each thruster type given in reference [20]. With this selection of ETs main European Union member states, experienced in electric thruster business like Austria, France, Germany and Italy becomes involved in the flagship CET. Additional electric thrusters can and which to be involved in the CET calculations.

The Austrian low-power thruster NEO^{10} achieves required thrusts during a few trajectory sections. Due to these reasons this thruster type is operated during the low thrust phases, e.g. when the flagship is decelerated and accelerated at Earth during trajectory

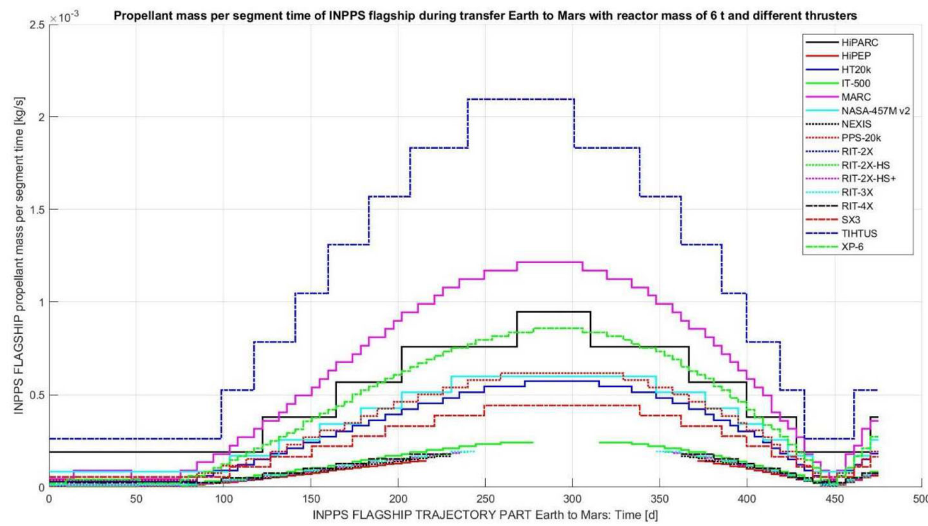

Figure 6 Plot of propellant consumption per trajectory section, which is necessary to generate the required thrust, over mission time of transfer Earth to Mars showing relevant thruster types. Breaks show that required thrust is not achieved with this thruster and therefore another thruster has to be used during this trajectory section

Earth-Mars. The German arcjet HiPARC is responsible for the high thrust phases during peak acceleration. However, SX3 achieves better performances for the absolute high-thrust section of transfer to Mars and therefore this thruster type is intended to relieve HiPARC during the absolute peak acceleration of the flagship. As shown in Fig. 6 it is important to use the high-power thrusters only during the high-thrust phases, where other thruster types can not achieve required thrust to remain at a minor propellant consumption. Due to these reasons the Italian HT20k and French PPS-20k thrusters are operated between low and high thrust sections. For the transfer from Mars back to Earth a relatively high thrust compared to other trajectory sections is necessary for deceleration nearby Earth. Therefore HiPARC is intended to be operated during this phase until required thrust is no more achieved.

In general, it is possible during each trajectory section to operate with another thruster type as indicated. Consequently, HiPARC with a quantity of one thruster can achieve required thrust levels for first flagship increasing acceleration for example during transfer to Mars as well. Here HT20k with a quantity of three thrusters is selected for this trajectory section. In this part HiPARC would be able to support the Italian HET in case of an inadvertent thruster failure. Although an operation with the high-power arcjet is not desired—due to high differences between required and achieved thrust levels -, an additional protection for an entire PS failure is ensured. This is possible for every trajectory, where other types of the selected thrusters with corresponding numbers, it is possible to achieve the required thrust. Possible arrangement on the cluster plate as well as CAD-models calculations are given in Fig. 5. These percentages of the particular thrusters are charted in Fig. 7 as well. More information about performance data of each thruster type and detailed trajectory sections are in [20].

The PS, consisting of only European thruster types, features a total mass of ETs, PPUs and PFS of approximately 4784.1 kg. This is lower than the determined limit of maximal ten percent of flagship initial mass and will not exceed this value even with an additional

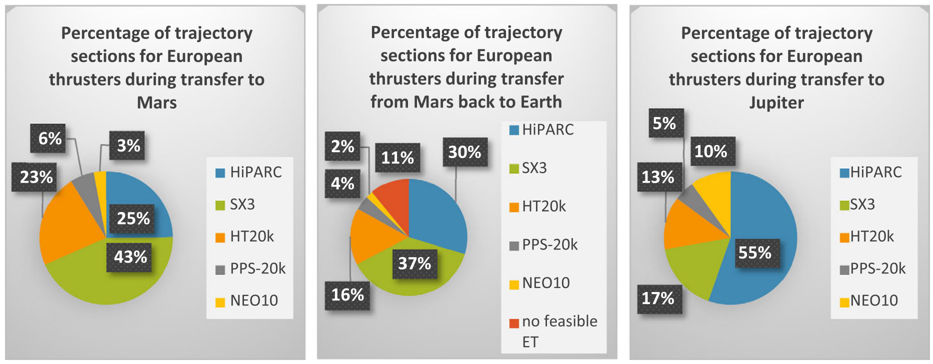

Figure 7 Percentages of trajectory sections for the cluster of European thrusters

mass of necessary electrical harness, propellant feeding components and cluster plate. Figure 5 illustrates the considered thruster arrangement of selected European thrusters. According to a required symmetric thruster positioning this cluster option has been considered, trying to assemble each thruster of the same type not directly next to each other. With regards to the filling density of arcjets and electrostatic respectively electrodynamic thrusters, area of cluster plate should be at least 9.5 m^2. This leads to a minimum diameter of a cylindrical CET plate of approximately 3.5 m.

3.3 Cluster of international ETs for the INPPS flagship

Because the configuration of European thrusters is a feasible option, a selection of European/DEMOCRITOS thrusters is possible as well. In the same way an operation with a CET plate featuring Japanese, European/DEMOCRITOS and US thrusters is feasible. For further considerations following international thrusters has been preselected to analyse its performance data as a feasible PS of the INPPS: ion thruster IT-500 (DEMOCRITOS results), HiPEP and NEXIS (NASA, USA), as well as HET XP-6 (JAXA, Japan) and NASA-457M v2 (NASA, USA). It has been analysed, whether a cluster of European and DEMOCRITOS, Japanese and DEMOCRITOS or Japanese, DEMOCRITOS and US thrusters can achieve the required thrust levels during the trajectory sections. Because only the German arcjet HiPARC and the US HET NASA-457M v2 can successfully be operated during the high acceleration transfer phase to Jupiter/Europa, the option with only Japanese and DEMOCRITOS thrusters is not feasible. In the following subchapters each considered configuration is described in detail.

Due to the ion thruster IT-500, that has been chosen instead of the Italian and French HETs compared to the European cluster of ETs, a higher specific impulse can be achieved during these trajectory sections. This leads to a minor propellant consumption, that can be achieved with this thruster combination. The other thruster types of the European selection remain to this option due to their good performance of achieved thrust levels. Therefore, the European and DEMOCRITOS PS selection is made of seven HiPARC and IT-500 thrusters as well as eight NEO^{10} and SX3 thrusters. Therefore German, DEMOCRITOS and Austrian are preferred as flagship CET. The entire quantity is up to 30 thrusters on cluster plate, but with the Austrian low-power FEEPs, lighter thrusters with smaller dimensions are chosen. The PS features a weight of 5438.9 kg and the thruster arrangement is shown in Fig. 8. The partition of trajectory sections to this cluster config-

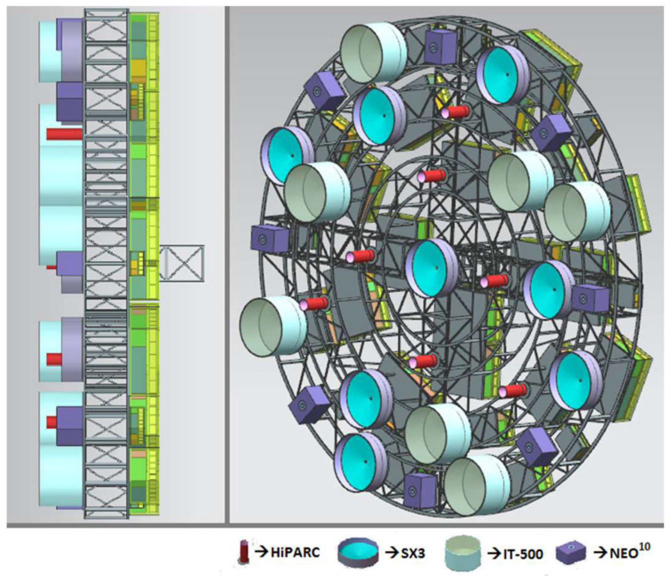

Figure 8 CAD design of gridded cluster plate including European/DEMOCRITOS electric thrusters with redundant PPUs for each thruster at the backside. Thruster colours show the colour of the plume, due to the preferred propulsion material

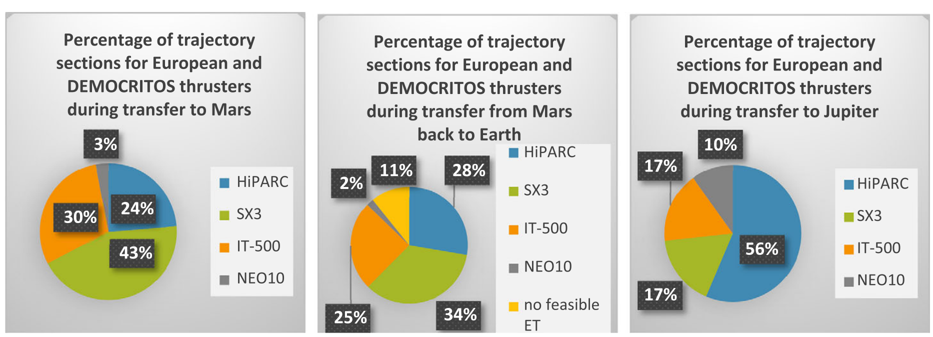

Figure 9 Percentages of trajectory sections for the cluster of European and DEMOCRITOS thruster

uration is similar to the European thruster cluster, but instead of the French and Italian HET the DEMOCRITOS ion thruster will be in operation. To ensure a most symmetric thruster positioning, this cluster option has been considered, trying to assemble each thruster of the same type not directly next to each other. With regards to the determined filling density of cluster plate, its area should be at least 9.7 m^2. This leads to a minimum diameter of a cylindrical CET plate of approximately 3.5 m.

Similar to the cluster of European thrusters, it is possible to operate with HiPARC or SX3 as substitution for IT-500 and NEO^{10}, if these thruster types have a failure. In the same way it is possible to operate with the DEMOCRITOS ET as alternative operation for the Austrian thrusters. With this thruster modification a less excellent performance of trajectories would be acceptable, but in case of a failure an alternative is possible. These percentages of the particular thrusters are charted in Fig. 9.

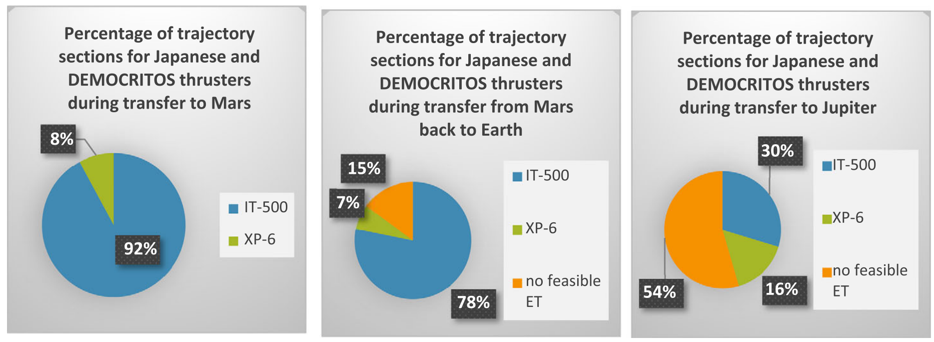

Figure 10 Percentages of trajectory sections for the cluster of Japanese and DEMOCRITOS thrusters

An operation with exclusive DEMOCRITOS and Japanese thruster types is not feasible under determined conditions as the ion thruster IT-500 is not able to achieve required thrust levels for the peak acceleration phase during trajectory Earth to Jupiter. In addition, a maximum quantity of 25 thrusters of the DEMOCRITOS ion thruster is necessary for a successfully operation during both other transfers. It became clear, to have a single additional Japanese thruster XP-6 to modulate thrust level during low-thrust phases more accurately. This quantity can be increased, if desired, to achieve better approximated thrust levels in more trajectory sections. According to the high number of IT-500, the selected PS features a total mass of 6352.3 kg. This is indeed lower than determined limit of ten percent of spacecraft initial mass, however it is the highest value of all mentioned possible thruster combinations. As the selection of only DEMOCRITOS and Japanese thrusters are not able to achieve required thrust levels for the entire transfer parts, this selection of thruster combination should be not further studied. In Fig. 10 the percentages of possible trajectory sections for both thruster types are displayed, but not explained in detail as this thruster configuration is not a feasible option for the INPPS for now.

The US thrusters are added to the DEMOCRITOS/Japanese thruster combination. This cluster of ETs is able to achieve thrust levels for every trajectory section. In addition to last mentioned thruster combination of Japanese and DEMOCRITOS thruster types, the US HET NASA-457M v2, developed by NASA, can successfully be operated during high-thrust phases too. A necessary quantity of 14 thrusters is able to achieve required thrust levels—even for peak acceleration to Jupiter. In addition to these thrusters, a further decision between eight ion thrusters HiPEP, IT-500 or NEXIS has been determined to use the IT-500 as more suitable trajectory sections are possible compared to the US thrusters. A single Japanese HET XP-6 is intended to operate during low-thrust phases as shown for the DEMOCRITOS-Japanese thruster configuration. This thruster quantity can be increased to achieve better approximated thrust levels for more trajectory sections, but that means, it has to be accepted a higher total thruster number. Every transfer is feasible with this thruster configuration except of the last deceleration at Earth for trajectory Mars-Earth. This has been mentioned before and possible solutions are given in previous section. The entire PS comprises 22 thrusters featuring a total mass of approximately 5603.8 kg.

These percentages of the particular thrusters are charted in Fig. 11 and detailed indications for particular trajectory sections of each thruster type are given in reference [20].

In Fig. 12 the considered thruster arrangement of selected Japanese, DEMOCRITOS and US thrusters is shown. According to a required symmetric thruster positioning this

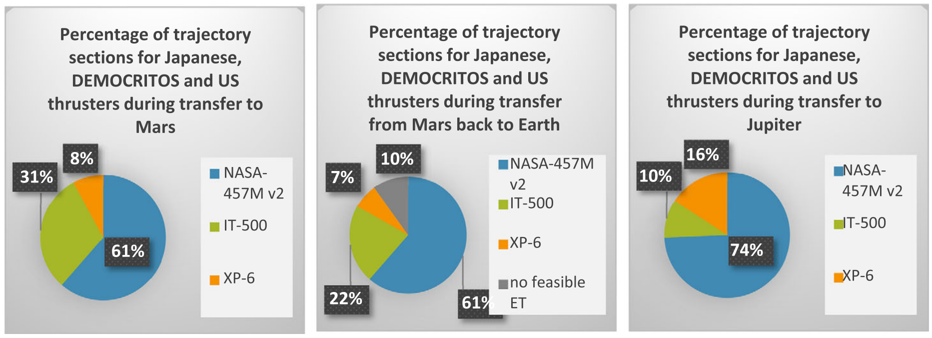

Figure 11 Percentages of trajectory sections for the cluster of Japanese, DEMOCRITOS and US thrusters

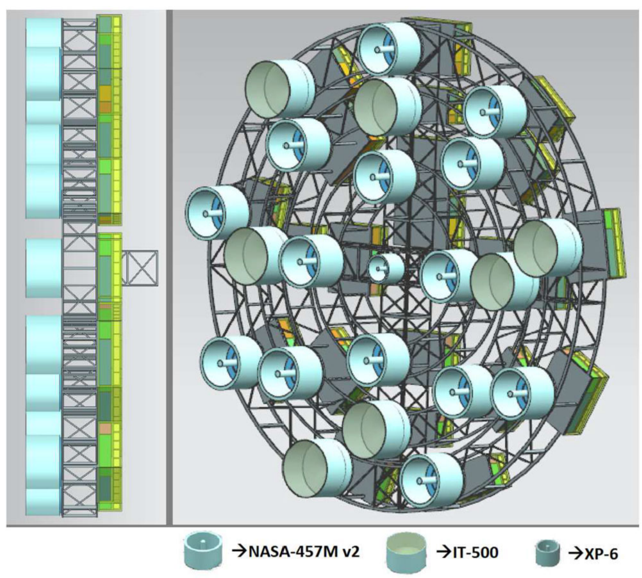

Figure 12 CAD design of gridded cluster plate including Japanese, DEMOCRITOS and US electric thrusters with redundant PPUs for each thruster at the backside

cluster option has been considered, trying to assemble each thruster of the same type not directly next to each other. As no arcjet has been considered for this thruster configuration, this cluster plate features a higher filling density according to electrostatic and electrodynamic thrusters, which must feature a higher distance to each other as the electrostatic and electromagnetic fields can interact. With regards to this, the area of cluster plate should be at least 10.7 m^2. This leads to a minimum diameter of a cylindrical cluster plate of approximately 3.7 m.

A CET of Japanese, DEMOCRITOS and US thrusters, is possible for the INPPS, but not as suitable as the European or European/DEMOCRITOS option. The Japanese thruster XP-6 can not modulate achieved to required thrust ratio, as accurately as the Austrian thruster NEO[10] is able to receive. In the same way it is necessary to operate with 14 NASA-457M v2 to achieve high-thrust levels compared to only seven thrusters of HiPARC.

In Fig. 13 is displayed the INPPS flagship propulsion system mass as versus mission time for Earth to Mars flight for all studied electric thrusters. The required thrust during this

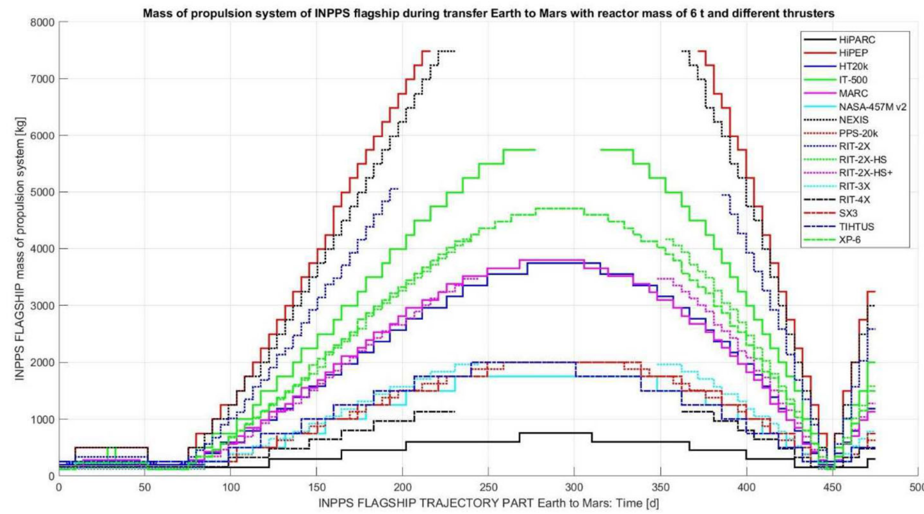

Figure 13 Plot of necessary PS mass to generate the required thrust including thruster, redundant PPU and PFS over mission time of trajectory Earth-Mars featuring relevant thruster types. Breaks show that required thrust is not achieved with this thruster and therefore another thruster in the CET has to be used during this trajectory section

mission specifies the thruster quantity and therefore the necessary entire propulsion system mass. In the middle of the mission time the propulsion system mass of some thruster is too much high. One conclusion from Fig. 13 is, that a non-European CET option is possible, even if it is not optimal. Other thruster configurations are possible as well. More calculation results about required and achieved thrust of each preselected thruster over mission time of each transfer to Mars, back to Earth and to Jupiter moon Europa is given in [20]. A publication with these details is in preparation.

4 Diagnostics of the INPPS CET

Already in the European Commission funded DEMOCRITOS project, a ground based test concepts for electric thrusters were developed. For example large thermal vacuum chambers in France, Germany and Russia were included in the concept with long duration electric thruster tests in parallel at different locations on Earth ground. However, potentially included thrusters have only partially carried out longer duration tests. The high power US VASIMIR thruster reached already about 88 hours endurance thermal vacuum chamber test (in the order of 100 hours demanded by NASA). According to the details of calculation results of the thruster time usage in the different trajectory sections, it is also necessary to carry out endurance ground based tests—not only within the CET, but with thrusters alone too. The entire operation time of the flagship (the CET operation time is much shorter) is assumed for ten years.

Ground based tests and space flights with two to four electric thrusters are already done or foreseen. For instance two examples: the flagship included Austrian electric thrusters (which are already produced up to four ones in a cluster) or a pair of electric thrusters from FAKEL company in Russia on board of an Egyptian satellite are already flying in Earth orbit. European Commission is currently funding EPIC, an electric propulsion strategic research cluster, in which French CNES, German DLR, ESA and European space companies and additional universities with electric propulsion research infrastructure are involved.

The logistic plus technical management of a high number of electric thrusters in tests of a cluster with electric thrusters with more than two to four pieces is an issue—including the question of operation ET specific high power PPUs or a common high power flagship PPU.

From the size and characteristics, as well as the internationality of the flagship, thermal vacuum chambers in Brazil, Japan, UK, USA and additional space nations must be used for the flagship CET ground based tests. In principle, the CET tests demand all standard equipment like in plasma diagnostics for single electric thrusters. This standard plasma diagnostics equipment must be adapted for multiple electric thruster test. Once more: the 100 hour test time demand to the VASIMIR high power thruster by NASA seem to be reasonable for the potential selected electric thruster endurance time tests applied in the flagship CET as well. An open question for the flagship CET is also the plumes and its interactions with the flagship itself—as well as from simulation and from thermal vacuum chamber laboratory testing points of view.

5 Summary and conclusions

The main and first precise result of the detailed CET flagship study: we can fly with humans and robotic to Mars and Europa alone with ETs. It is not necessary to add high mass chemical propulsion systems. The high power, but complex VASIMIR system would decrease the numbers of ETs in the CET. Therefore it is foreseen to study in detail the usage of VASIMIR in the flagship CET. For the internationalisation of the INPPS flagship Results of the numerical and experimental cluster validation have been made under the assumption of a single thruster type operation during the entire trajectory section with primary an unlimited thruster quantity. As it is not determined, which countries are finally involved to dispatch and fly the INPPS flagship in interplanetary space, different strategic options has been calculated for the CET—in dependence of contemporary TRL for the ET, chipped by manufacturers and organisations in Austria, France, Germany, Italy, Japan, USA and more space nations. PS versions with only European, German and a combination of European and DEMOCRITOS thrusters are highly preferred. Japanese and DEMOCRITOS thruster configuration is not optimal as PS, as it can not achieve the required high thrust levels during transfer to Mars and Jupiter. In combination with US thrusters, Japanese and DEMOCRITOS thrusters can be a feasible option for the flagship CET as well. The European or European/DEMOCRITOS based thruster cluster design is presumably an optimal selection as required thrust levels of high- and low-thrust phases. It can be modulated reasonably well with the German HiPARC and Austrian NEO[10] and moderate thruster quantities. For each strategic thruster selection possible arrangements in a dedicated cluster have been derived. ETs are symmetrical placed on the cluster plate with an adequate distance between operating thrusters to avoid additional applied moments and interactions between thrusters.

Very important: the space qualification of NPS tug is foreseen between 2028 to 2030. For the similar time period, the detailed study of usage of 22 international electric thruster in the flagship CET—allows the feasibility of crewed and non-human INPPS journeys to Mars respectively Europa moon with electric thrusters: because of the relatively nearby celestial constellation of Earth, Mars and Jupiter the INPPS flagship orbit with CET were calculated for the following orbits

1. Orbit Earth to Mars from 11 Oct 2026 to 28 Jan 2028,

2. Orbit Mars to Earth from 22 Sept 2028 to 29 Jul 2029 and
3. Orbit Earth to Jupiter from 12 Oct 2031 to 6 Dec 2035.

This first interplanetary journeys with the INPPS allows 18 t payload transport to Mars/Mars surface and stay at Mars and monitoring Mars, Phobos/Deimos for nearly eight months. After return to high Earth orbit, flagship maintenance plus mounting of up-to-date subsystems via autonomous robotic assembly of building blocks and new payload—up to 11 t—can be implemented in about 27 months period. Four years are envisaged for the most maximal space system and subsystems INPPS tests—related to space flight duration, increased space radiation in deep dark, outer space and delayed communication due to long distance. It is also important to have in mind: between 2026 and 2035 the INPPS flagship will have interplanetary flights in solar maximum as well as in cosmic ray maximum (means solar minimum) conditions for most variable and strongest non-human/robotic tests of all flagship sub-systems.

Insofar 26/35 space flight experiences with the first INPPS flagship means—mission completed-, ready to go of our ultimate aim—the fourth crewed space action (after Gagarin first space flight around Earth, Apollo astronaut missions to Moon and international crews on ISS) a giant, peaceful leap for space exploration for the good of humanity. After 26/35, the second INPPS flagship will send first time humans to Mars and safely back to Earth.

Details of the flagship CET combinations with detailed characteristics will be published soon. Electric thrusters from additional nations are foreseen to be included in the CET as well.

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Abbreviations
AF-MPD, Applied-Field Magnetoplasmadynamic Thruster; CET, Cluster of Electric Thruster; DEMOCRITOS, Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems; DiPoP, Disruptive technologies for space Power and Propulsion; EO, Earth Observation; EPS, Electric Propulsion System; ET, Electric Thruster; FEEP, Field Emission Electric Propulsion; HET, Hall-Effect Thruster; HST, High Power Space Transportation (); INPPS, International Nuclear Power and Propulsion System; IRS, Institut für Raumfahrtsysteme; JAXA, Japan Aerospace Exploration Agency; KRUSTY, Kilopower Reactor Using Stirling Technology; MEGAHIT, Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions; NEP, Nuclear Electric Propulsion; NPS, Nuclear Power Source; NPPS, Nuclear Power and Propulsion System; NTP, Nuclear Thermal Propulsion; PFS, Propellant Feeding System; PPU, Power Processing Unit; PS, Propulsion System; TRL, Technology Readiness Level; TPM, Transport and Power Module; VASIMIR, Variable Specific Impulse Magnetoplasma Rocket.

Declarations

Competing interests
The authors declare no competing interests.

Author contributions
FJ, JG, JTG, GH, LS, ME and VM were the main contributors for the CET, for orbit simulations and for flagship concurrent engineering/droplet radiator design. Electric thruster characteristics used from Austria (AR and DK), Germany (HL), Italy (AP, GC, TA and TM) and Japan (IF). In addition DiPoP, MEGAHIT & DEMOCRITOS contributors like from France (NG, FM and SO), Germany (HL) and more consortium members analyzed and designed INPPS flagship space system and sub-systems. All authors read and approved the final manuscript.

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