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High Power (200kW) Solar Electric Propulsion Upper Stage for In-space Transport

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Abstract

As the U.S. and other nations embark on extensive cis-lunar and deep space exploration, the need for a system to provide large mass space transportation becomes critical to provide cost effective transportation. There are currently several government and commercial programs seeking lunar and Mars exploration by the 2020s. Highly efficient in-space propulsion systems will be required to power the spacecraft that will build the space infrastructure and transport large masses to deep space and lunar destinations. Solar electric propulsion (SEP) is emerging as a key propulsion system for space propulsion. Currently, several SEP platforms are using the Hall-Effect thruster at 13.5 kW. The system has proven to be an excellent propulsion module for satellites in various orbits. However, the Hall system has limited ability to move large masses in space. This paper approaches the problem from a different direction. A new space transport system is being explored to meet the needs of large space mass transport for cis-lunar and deep space. The Zonal Electro-Plasma Upper Stage (ZEUS) is a high power (HP) SEP upper stage under development and test to support these bold programs.

I. Nomenclature

ACS	=	attitude control system
AM	=	Avionics Module
C&DH	=	command and data handling
CIU	=	controls interface unit
CNT	=	carbon nano-tube
GEO	=	geosynchronous earth orbit
HP	=	high power
IDSS	=	international docking system
Isp	=	specific impulse
kg	=	kilogram
km	=	kilometer
kW	=	kilowatt
LEO	=	low earth orbit
Li	=	lithium
MEO	=	medium earth orbit
NASA	=	National Aeronautics and Space Administration
P	=	power
PLA	=	payload adapter
PLF	=	payload fairing
PM	=	Propulsion Module
RF	=	radio frequency
s	=	second
SEP	=	solar electric propulsion
SIP	=	standard interface plane
TCM	=	thermal control management
TDM	=	Test Demonstration Mission
UHF	=	ultrahigh frequency
V	=	volt
VASIMR	=	Variable Specific Impulse Magnetoplasma Rocket
ZEUS	=	Zonal Electro-Plasma Upper Stage

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II. Introduction

In recent years, there has been an increasing commercial and governmental interest in developing high-power electric propulsion for long-range, fast and efficient cargo missions. This includes lunar, Mars and return, along with other taxing maneuvers such as Keplerian and non-Keplerian orbits. To make this a reality, the fundamental need for a high-energy, efficient and economical solar electric propulsion (SEP) upper stage is paramount. This type of stage is designed to transport large in-space cargo long distances in a timely manner to enable exploration, security and commerce. The challenge to this technology is the availability of a stable and economical in-space high power (HP) source (>100kW) for any electric propulsion system. Current thruster technology uses flight-proven elements (P<13.5kW, Isp 1000 to 3000s, xenon) and is a viable solution for applications such as station keeping or orbit raising. However, to advance a high-energy SEP upper stage (P>100kW, Isp 3000 to 5000s) for long-range missions, an innovative approach to system power, thrust, propellant usage, and Isp needs to be optimized. This paper discusses the technical approach, benefits, challenges, and a practical phased approach to advance HP SEP upper stage technology through Test Demonstration Missions (TDM).

III. Technical Approach

All HP SEP systems face the same challenges. This includes the optimal propellant, thermal management, and solar array power capability. The Zonal Electro-Plasma Upper Stage **(**ZEUS) seeks to solve the problem from a different direction looking at total life-cycle cost and availability of technology. This approach consists of incremental steps proving existing capabilities and advancing technology.

A. Technical Challenges

Propellant Optimization: Electric propulsion thruster technology has focused on using some form of noble gas (krypton, xenon, and argon) to provide the needed propellant. There are significant tradeoffs in the propellant selection for optimization that include: ionization, high Isp, thrust, propellant mass, availability, and cost.

Solar Power Capability: A common challenge for all HP SEP systems is the capability and cost of solar arrays to generate the required power needed for the mission duration. This includes generation of adequate power in the form of kW across the mission trajectory and lifetime. Currently, SEP is typically less than 13.5 kW. The HP SEP will require >100 kW and ideally hundreds of kW continually to support large mass or fast transport missions. The current cost estimate for solar power is ~$1M/kW.

The driving constraints for solar power in the hundreds of kW are the massive array size required and cost of the array. The ability to fold and stow panels for launch is a constraining factor for the massive size required. Continued development of solar arrays and energy storage devices will advance the HP SEP opportunity for long-range large-cargo mass and fast transit missions.

High power solar array technology is advancing. A 32-foot diameter high-fidelity development system demonstrating the potential of [1]MegaFlex® solar array has been built and tested for NASA. ZEUS is configured to use two 20 kW arrays to provide 40kW of sustained power to the upper stage

The primary objective for ZEUS is to develop and demonstrate a >150kW propulsion and power element as part of an integrated system, extensible to HP in-space transportation systems. This objective supports in-space testing and lab validation of a HP SEP system in the demanding environments of space. This is an essential step forward to advancing this technology. An artist's rendition of the ZEUS TDM configuration is shown in Figure 1.

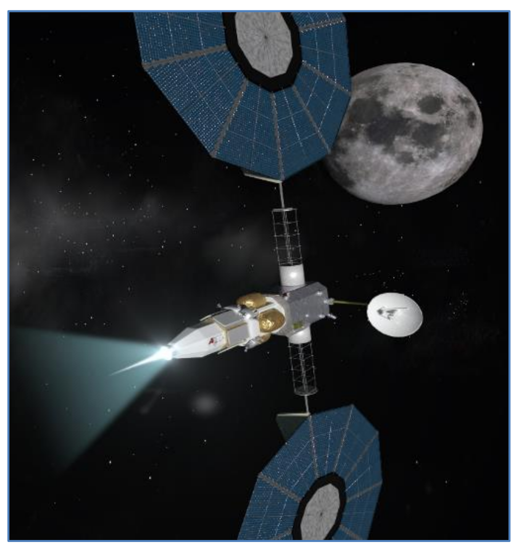

Fig. 1 ZEUS Test Demonstration Mission configuration.

ZEUS is a reusable 150kW to 200kW HP SEP upper stage with a high-efficiency plasma thruster that provides new capabilities. ZEUS is scalable to enable additional propulsion modules for greater performance and redundancy.

ZEUS consists of two distinct modules; the Propulsion Module (PM) and the Avionics Module (AM). The PM consists of the following subsystems; electric propulsion thruster, thermal radiators, HP solar arrays, battery energy store, cryogenic argon supply system and controls interface unit (CIU). The AM consists of integrated avionics, instrumentation, and payload interface. The

ZEUS functional architecture is shown in Figure 2. These integrated modules create a high power/mass ratio, highly efficient, and affordable in-space HP SEP upper stage.

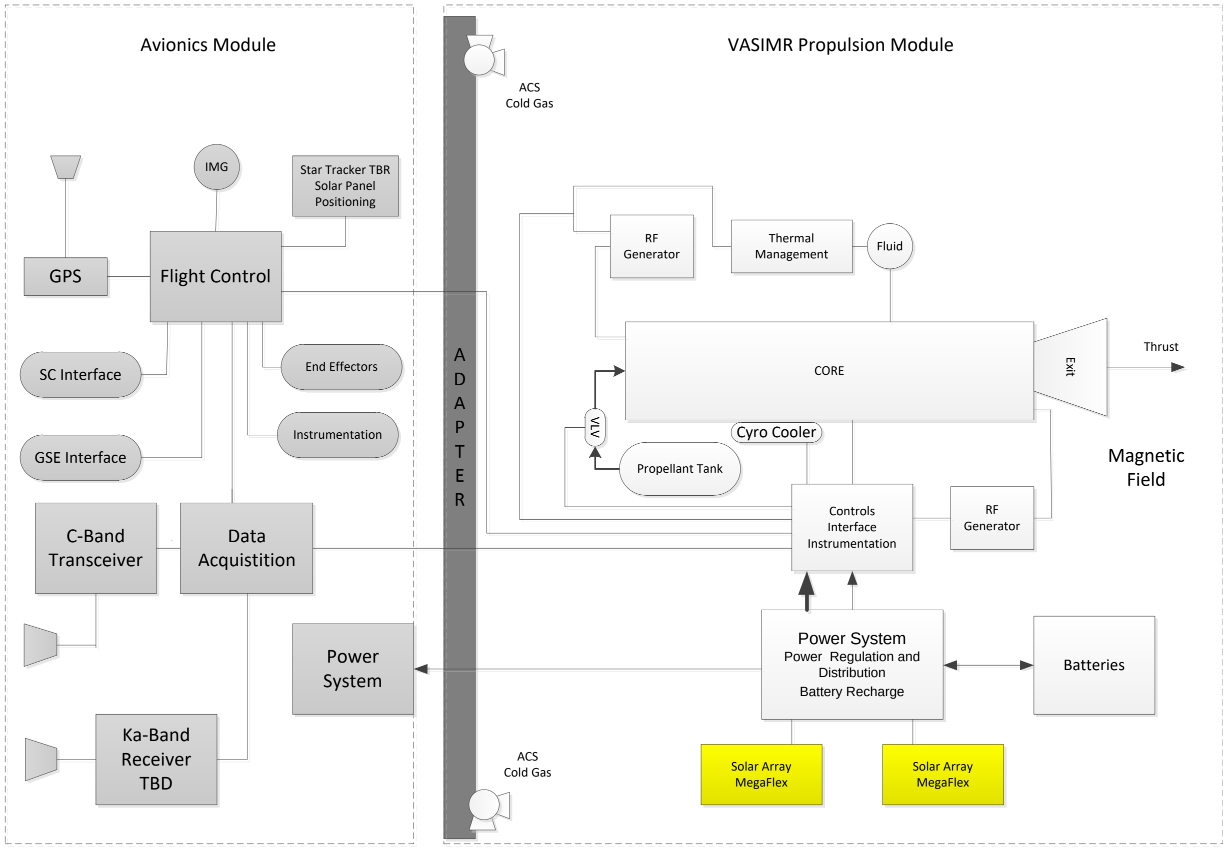

Fig. 2 ZEUS functional architecture.

B. Propulsion Module (PM)

High Power Solar Electric Propulsion (VASIMR®). ZEUS incorporates a robust high power magnetoplasma thruster to achieve high power electric propulsion. The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is currently in long duration testing[2]. The system is available for next-generation HP SEP spacecraft. The VASIMR® thruster, developed by Ad Astra Rocket Company, is the most advanced HP electric thruster in development and test today. The VASIMR thruster is shown in Figure 3. It is a HP density electric rocket engine, scalable (50 kW to multi-MW). It is a paradigm shift in space transportation that covers the full spectrum of applications from robotic to human, from commercial to exploration. VASIMR is a HP, highly efficient engine with an operating range of Isp from 3000 to 5000s at >100kW with argon. Extended Isp ranges have been achieved using propellants containing hydrogen, nitrogen, and ammonia. Currently, in-space power >100kW is prohibitively expensive and technically challenging. However, the

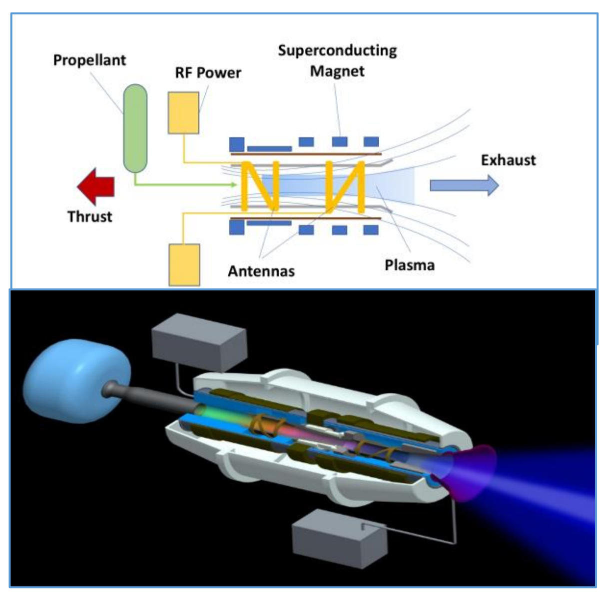

Fig. 3 VASIMR simplified diagram and cutaway.

ZEUS product development roadmap leverages current advanced technologies to accomplish next-generation missions and incorporates high power of >150kW. ZEUS is leveraging the plasma thruster technology to enable it to deliver a larger mass in less time at lower cost to deep space destinations. This requires a HP SEP currently beyond the Hall-Effect or ion thruster capability.

Propellant Supply System. The propellant supply system provides the storage and flow control into the electric propulsion core. The system is sized based on the propellant selected for the SEP mission. Xenon has been the electric propulsion gas selection for the low-power Hall-Effect thruster. Argon has been selected for ZEUS as the propellant for the VASIMR® thruster.

Argon was selected due to its terrestrial and extraterrestrial availability, low cost, lower storage mass, ease of handling and higher Isp. Kilogram-for-kilogram, argon (39.95g/mol) puts twice the total mission impulse in the storage tank compared to xenon (131.29g/mol). Argon can achieve twice the Isp of xenon.

Argon is an industrial gas and readily available. The cost is a fraction of xenon where argon costs $0.50/100g compared to xenon at $120/100g. For large-cargo transport, the cost of xenon becomes a significant cost driver of the mission. The cost of xenon for a long duration SEP mission rivals the current estimated cost of a large solar array at ~$1M/kW.

A ZEUS refueling concept of transporting cargo from Earth to Mars, refueling at Mars, and returning to Earth on a small amount of fuel is feasible. Scientific probes have shown argon is present in space and specifically in the atmosphere of Mars. The layer of gases surrounding Mars contains an argon composition of 1.93%, which is greater than twice that of Earth's argon atmosphere at 0.9%. An in-situ resource utilization plant could be designed to convert Mars atmosphere into argon for use as propellant for ZEUS.

Advanced Solar Array System - 40kW MegaFlex, (2 at 20kW per unit). For ZEUS to operate in space efficiently, VASIMR must operate at power levels greater than 50kW. Therefore, the ZEUS PM incorporates a HP energy store rated at 150kW for engine burn and two 20kW advanced solar arrays (40kW), known as MegaFlex®, for a sustained power supply. Since a sustained in-space power supply of 150kW is not viable today, VASIMR® will employ a series of engine burns followed by a recharge period and subsequent engine burn.

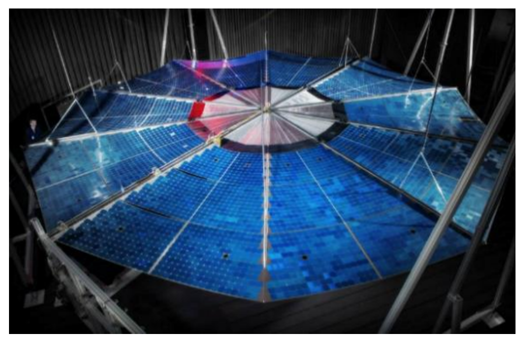

Fig. 4 20 kW MegaFlex testing at NASA GRC Plumbrook facility.

A nominal mission for a 100kW TDM was designed. The design analysis looked at specific variables for propellant, transient time, and power to determine a propulsion duty cycle. The duty cycle consists of a specific engine on time and engine off time. The engine off time is used to charge the energy store to an appropriate charge level to support the engine on time power required. The energy store supplements the solar arrays to provide the 100kW power during engine on time. The analysis provided a baseline mission design that had a duty cycle of 682 seconds for 100kW power. This consists of a nominal 261-second burn and 421-second recharge period. The duty cycle is unique to a specific configuration based on mission-unique requirements and parameters. The avionics system is capable of in-flight re-targeting and recalculation of duty cycle to optimize the mission trajectory based on any changes to the system. For example the time to recharge the energy store will increase as the distance from the sun increases and the expected degrading of the solar array at ~1.5%/year. That will cause a change in duty cycle.

ZEUS will demonstrate an advanced integrated SEP system capability that is extensible to future human Mars class missions. The MegaFlex® array, shown in Figure 4, is a larger version of Northrup Grumman's spaceflight-proven advanced solar array technology Ultra Flex®. This technology proposes to achieve power levels of 250kW or higher and greatly improve mass and packaging efficiency of current solar arrays.

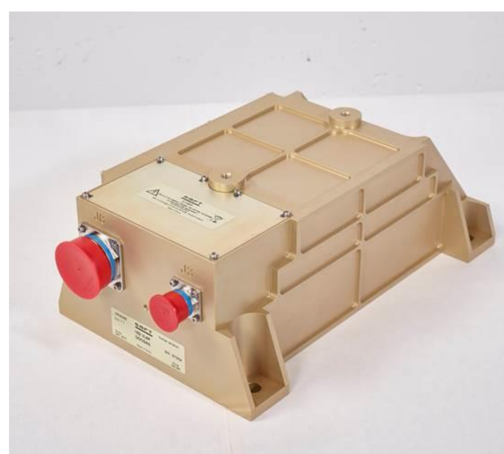

Fig. 5 270v Li-ion battery energy store.

150kW High Density Battery Energy Store. ZEUS incorporates a 150kW HP batteries energy storage produced by SAFT for engine burn. This unit, shown in Figure 5, is continuously recharged by the 40kW MegaFlex® array while providing 150kW to VASIMR®. The energy store consists of 270v lithium ion (Li-ion) high-power cells based on military (joint strike fighters) and space applications. These cells have been proven for high voltage and high power with a capability of a 15-year life/30,000 cycles. The cells have various features for safety related to Li batteries. This includes over charge, over discharge, crush, overheating and short circuit. Two energy store packs are planned for use to limit the deep cycling on a single pack and enabling redundancy if a single energy store fails. These energy store packs are needed for the TDM(s).

The SAFT concept for ZEUS is a modular scalable battery energy store system. These HP energy store systems, ranging from 150kW to 200kW energy levels, can be directly inserted into HP SEP systems enabling highly efficient in-space propulsion systems and associated subsystems.

A thruster power supply of 150kW was selected to optimize performance, provide for HP operations and to follow our methodology of "Test as You Fly". Ad Astra is currently testing a single VASIMR® unit, in a 100kW long duration ground test, per the NASA Next Space Technology Exploration Partnerships (NextSTEP[3]) contract. The system has been tested at 200kW.

For the TDM, the solar panels will provide continuous 40kW power for recharging. The energy store supplies the 150kW for the engine on time while the solar arrays provide 40kW power for recharging. The duty cycle for the 150kW configuration will be calculated when the TDM mission is planned. As ZEUS evolves the solar panels will provide the primary power to the SEP propulsion system without need for a large energy store.

SEP Controls Interface Unit. The CIU is designed to enable the PM of transferring up to 24kW of electrical power to the payload without power decrease during SEP thrusting.

C. Avionics Module

The AM is located forward of the PM. The two modules combined form the complete ZEUS upper stage element. The AM houses the mission control avionics. The subsystems within the AM are the command and data handling (C&DH), communications, attitude control system (ACS), thermal control management (TCM), and other stage control activities.

Avionics Controls Unit. The highly integrated avionics control unit (ACU) concept is based on the high-performance processing and small form factor electronics demonstrated on subsystems in launch vehicles, satellites, and crew capsules. The ACU is a highly integrated, reconfigurable, and fault tolerant system platform that incorporates data processing, controls, encryption, decryption, mass storage, and multi-band radio frequency (RF) communications into a single line replaceable unit. The ACU module(s) support a variety of sensor interfaces and are reconfigurable on orbit in order to support mission enhancements and re-tasking after deployment. The integrated multi-band RF communications modules provide inter-satellite communications links for satellite constellations, mission data downlinks, and ground telemetry, tracking, and control links for on orbit reconfiguration, commanding and telemetry.

High levels of integration of the avionics control functions are possible because the ACU platform leverages the Vita78 Next Generation Space Interconnect Standard; as well as system-on-a-chip field programmable gate array / application-specific integrated circuit technologies. The standard defines a modular, 3U VPX form factor and fault-tolerant open system architecture that supports high performance, high throughput interconnects fabrics. The standard accommodates various configurations of payload modules and redundancy, which allows integrators to scale the number of plug-in cards to their needs

The ACU system platform can be employed as a sensor payload processor for meeting customer mission requirements due to an open standard architecture that is configurable for the mission and sensor agnostic. The architecture supports high-speed interface modules that can accommodate various types of sensor data interfaces. Standardized interfaces that use RIO, PCIe, Camera Link, or XAUI are preferred; however, the interface can also be customized to accommodate various sensor types with unique interface

Attitude Control System. An attitude control system (ACS) is needed to provide for trajectory corrections as well as correcting the rotational or attitude position for the ZEUS upper stage. A nontoxic argon cold gas system is used for the ACS to increase efficiency, resiliency, and safety. The ZEUS design is simple, low cost, and integrated into the PM's argon supply system, eliminating storage tanks on the AM. This enables ZEUS to use a common propellant system for the SEP and ACS. This design allows for ease of refueling of only one propellant and provides ZEUS with a larger propellant supply for attitude adjustments and maneuverability to complete more missions, e.g. transports, space base interceptor/sensor platform, etc.

The ACS is incorporated in the AM and operates throughout the flight providing control torques and forces for the stage. The system consists of a supply line to the PM argon storage system, two axial 4.4-N gas thrusters, two 4.4-N tangential thrusters, valves, pyro valves and miscellaneous hardware. This system is designed for the optimizing control of the ZEUS stage by the magnitude of the total impulse, the number, thrust level, and direction of the thrusters, and by their duty cycles. The entire system weighs 12 kg without fuel and is approximately 15% of the AM's dry mass.

Communication Subsystem. The communication subsystem provides communication between ZEUS, orbiting vehicles, satellites and ground stations. The communication subsystem baseline consists of S-band, X-band, Ka-band, and ultrahigh frequency (UHF) communication systems. ZEUS will provide a Ka-band downlink with the ground for high bandwidth data transfer and S-band for nominal telemetry up and down link for the payload. ZEUS will provide an interface for accommodating an optical communication demonstration, if required by the mission.

Standard Interface Plane. ZEUS's payload interface is designed to accommodate additional capabilities that directly support the need of the customer. The ZEUS standard interface plan (SIP) provides a standardized bolted interface for ZEUS and customer-provided payload adapters. The ZEUS payload interface design meets the requirements of currently defined spacecraft and offers the flexibility to adapt to mission-unique needs. These components are designed to provide mechanical and electrical interfaces required by the spacecraft and to provide a suitable environment during integration and launch activities. The standard interface is designed for integrating two compliant international docking system (IDSS), one forward and one aft. These berthing locations will support unpressurized logistics, robotic arm logistics, robotic arm interfaces and grapple fixtures. The IDSS specification will include interfaces for power, command, and data handling and fluids as standard interfaces.

D. PM/AM Ultra-Lightweight Structural Bus.

The ZEUS bus consisting of the PM and AM modules leverages advanced material ultra-lightweight structures that reduce mass by 25% and size and provide other unique properties that increase the durability of the bus. These advanced structures have been developed through independent research and development and flight tested in conjunction with NASA. The ZEUS structure is designed to house the propulsion system, solar arrays, AM and forward adapter.

IV. Benefits of HP SEP Space Transport

ZEUS seeks to provide a highly efficient system for the niche need of large-cargo transport or fast human transport to deep space. It provides an excellent solution for HP SEP. ZEUS achieves the unprecedented capability to:

1. Cargo back and forth between lunar space faster, using 40% less propellant than any other state-of-the-art SEP system
2. Enables placing and maintaining spacecraft in non-Kelperian orbits
3. Enables cost effective missions within cis-lunar and deep space robotic science missions
4. Enables missions to be launched on smaller, lower cost launch vehicles with larger payloads at reduced launch costs
5. Provides a new national capability that dramatically enhances competitiveness of the U.S. in space transport minimizing the requirement of on-orbit propellant

ZEUS supports U.S. National Space needs by providing spacecraft and payload mobility as a service in geosynchronous and cis-lunar space. Both the Department of Defense Space Science and Technology Strategy and NASA's Human Exploration and Operations objectives point to the need for this capability within 10 years. In-space HP SEP and power systems enable resilient national security, civil, and commercial space visions and needs for high impulse, high delta-V maneuvering.

The rationale for a ZEUS TDM is a practical approach to advance HP SEP to form the technological basis for a lightweight, high power, high density, and highly mobile and affordable in-space upper stage platform. ZEUS's performance characteristics can be summarized by using the Tsiolkovsky rocket equation resulting in: high Isp, less propellant, high power, and faster transits. By using the VASIMR thruster and associated ZEUS subsystem, technologies benefits are as follows:

- Provides high power (150kW) and high Isp (5000sec) to move large payloads faster
- Uses 40% less propellant than state-of-the-art electric propulsion systems (i.e., Hall) for an equivalent payload
- Provides comparable thrust and enables faster transit times than state-of-the-art electric propulsion systems at high power
- Delivers three times the payload mass of conventional chemical stages
- Provides higher plasma power density and low mass footprint as shown in Figure 6[4]
- Uses an abundant and affordable argon propellant
- Provides mission flexibility through variable throttling

These benefits are only obtained if the HP SEP system is optimized for the customer's specific mission design. ZEUS enables the ability to adjust thrust level, Isp, propellant type and stacking of engines to meet unique mission needs such as payload mass, mission duration and cost requirements.

V. Challenges of HP SEP Space Transport

The need for efficient and economical energy for an in-space upper stage to transport large cargo, long distances in a timely manner to enable exploration, security, and commerce is paramount. The challenges associated with producing this type of energy and a HP SEP stage is complex. Specific challenges to ZEUS are as follows:

- High power source – need for high input power >100kW
- Management of power systems
- Thermal management
- Optimizing power, propellant usage, Isp, and thrust for a mission
- Demonstrate management of high power in orbit
- Adequate ground test facilities

ZEUS seeks to solve these challenges from a different direction looking at total life-cycle cost and availability of technology. Key technologies are currently emerging for the implementation of ZEUS. ZEUS leverages advanced technology in ultra-lightweight (carbon nano-tube [CNT]-based) structures, plasma propulsion, Li-ion energy store and high-power 40kW solar arrays. As the development and advancements in solar array power continue, the opportunity to increase the SEP power is available. The TDM mission will enable significant advancement in the technology.

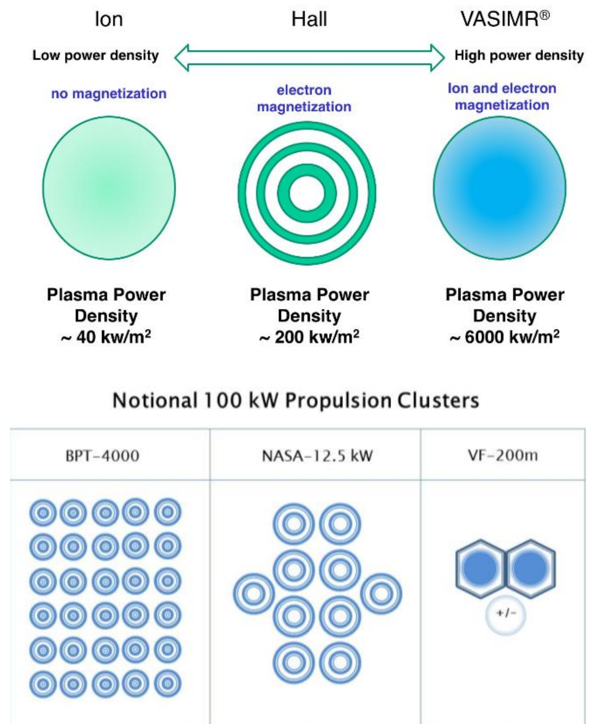

Fig. 6 SEP power density and mass footprint comparison.

VI. ZEUS's Practical Approach - Roadmap

ZEUS's evolutionary development roadmap, as shown in Figure 7, is a practical low-risk, high-gain approach that provides early risk reduction for deep space power and propulsion elements and cargo and habitat transport. It provides an "in-space" technology demonstration of a HP SEP upper stage that advances new capabilities in SEP technology.

Block I and II configurations are planned starting with the initial flight capability in 2021 as shown in Figure 8. The Block I configuration will demonstrate the basic elements of HP SEP in a low cost approach. The system is less than 3,300kg mass and capable of being launched on a small to medium launch vehicle. The Block I configuration will be a 150kW single thruster with 40kW MegaFlex® solar arrays and batteries to provide the required engine on power. Block I is capable of achieving three different DRM's with a small payload. The Block II configuration will incorporate lessons learned and advancement in technologies from Block I. It will have a docking ring installed on the forward end for cargo docking maneuver demonstrations. Block II will be capable of launching on larger launch vehicles such as Atlas V and Falcon 9. ZEUS is capable of various configurations to support user mission-unique program requirements. This includes single or multiple plasma propulsion modules, various power levels, and different propellant storage capability. ZEUS may also be configured to fly in an Evolved Expendable Launch Vehicle secondary payload adapter configuration to provide a multi-manifested spacecraft transportation system to various orbits by a single launch. Specific mission requirements would be used to optimize the ZEUS configuration.

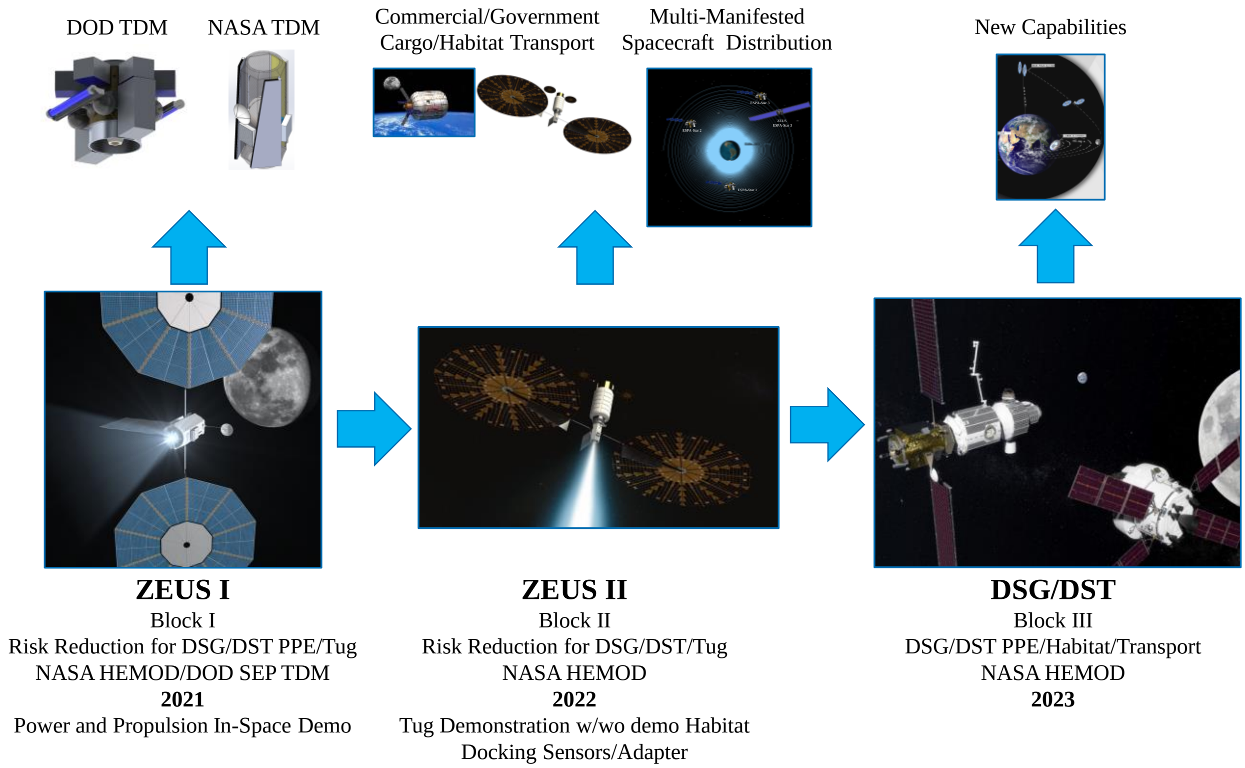

Fig. 7 ZEUS phased approach roadmap.

Key technologies are currently emerging for the implementation of ZEUS. ZEUS leverages advanced technology in ultra-light-weight (CNT-based) structures, plasma propulsion and high-power 40kW solar arrays. ZEUS will use a building block approach to test and evolve this space transportation system.

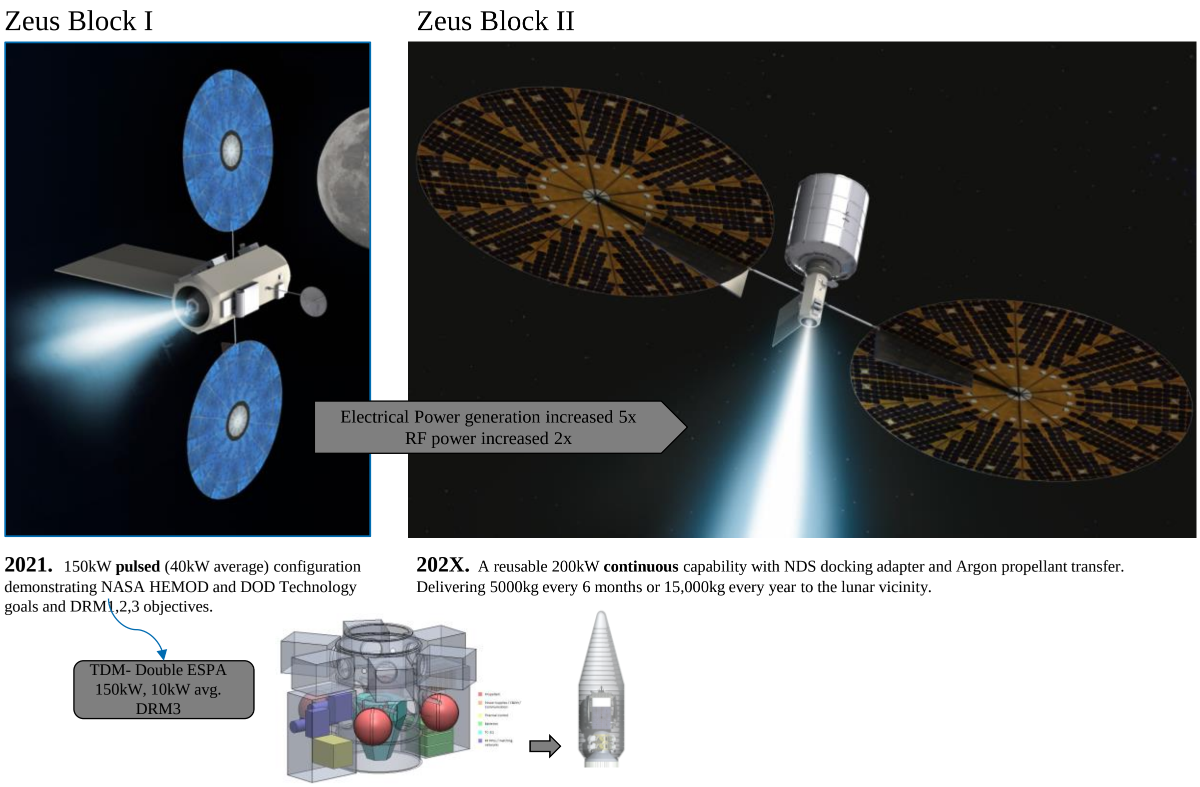

Fig. 8 Block I ESPA and Block II configuration.

DRM1 – [5]Pole Sitter (7.6 km/s transit, 0.46 km/s per month station keeping)
This DRM uses the ZEUS SEP stage to transfer a payload from low earth orbit (LEO) into a high orbit 1 to 2 million miles above the Earth's pole and maintain a non-Keplerian orbit over a long operational life. The DRM1 Pole Sitter mission is shown in Figure 9. To maintain this orbit, near continuous thrusting is required. From this vantage point, nearly all cis-lunar space and half of the Earth's hemisphere are constantly in view.

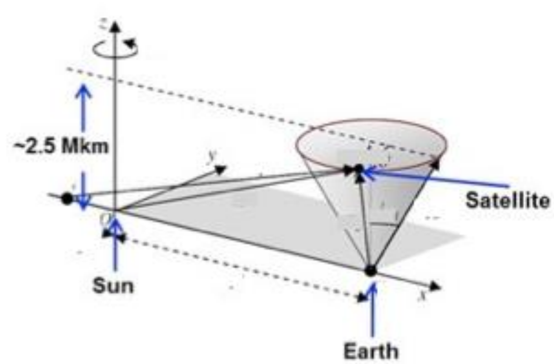

Fig. 9 DRM1 Pole Sitter.

DRM2 – Earth-Moon L-1, 2, Near Rectilinear Halo Orbit Transport (7 km/s class transit each way)
This DRM uses the ZEUS SEP stage to transfer a payload from LEO to variety of Earth-Moon halo orbits and return to LEO. This delivers three times the payload mass of conventional chemical stages and uses 40% less propellant than a state-of-the-art Hall thruster for an equivalent payload.

DRM3 – Super Synchronous Geosynchronous Earth Orbit (GEO) -Transfer (4.6 km/s transit each way)
DRM3 is focused on the ZEUS SEP stage capable of transferring a spacecraft from LEO to GEO and back. This DRM has a unique opportunity to monitor the environment in-situ for better understanding of LEO, medium earth orbit (MEO) and GEO space weather risks.

ZEUS Block II will provide a capability for a reusable 150kW continuous capability with a NASA docking system docking and propellant transfer, delivering 5000kg every 6 months or 15,000kg every-year to the lunar vicinity.

VII. Conclusion

The need for a HP SEP to meet the requirements of large payloads and fast human transport is achievable. This paper addressed a practical path to develop and fly a low risk, low cost, HP SEP and system enabling future in-space transportation systems. This supports national security, civil, and commercial space users in defense, commerce, and exploration opportunities.

ZEUS's product evolution roadmap is practical and scalable. It develops a HP SEP system and associated space vehicle technologies in a cost effective and rapid time to market by an incremental approach. TDMs will advance this system and associated game changing technologies via an in-space demonstration of a high-power SEP upper-stage at various orbits. This approach matures technology readiness levels of various systems through incremental development and produces products that enable mass reductions, ultra-lightweight structures, HP energy storage and new manufacturing techniques for launch vehicles and spacecraft.

The ZEUS system using TDMs to advance the HP SEP technology will greatly enhance our capability to achieve HP SEP when needed.

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