ELECTRIC PROPULSION RESEARCH AND DEVELOPMENT AT NASA

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Electric propulsion (EP) is an important technology for NASA. It has already played a major role on three missions, namely Deep Space 1, Dawn and Space Technology 7, and it is planned for use on many more. The ion propulsion system for the ongoing Dawn mission has achieved several notable accomplishments, including providing a total velocity change (ΔV) of over 11 km/s to the spacecraft. As a result of these successes, solar electric propulsion (SEP) is now broadly recognized as an essential technology for both robotic and human exploration. NASA is currently conducting many projects focused on research and development of EP for a variety of applications. All three of NASA's mission directorates that deal directly with space exploration are actively engaged in supporting work in this area. This paper describes these projects in more detail, including the specific engineering activities being conducted at NASA's main centers for EP technology development, namely Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL).

I. INTRODUCTION

The fact that three of NASA's four mission directorates are supporting EP research and development testifies to the agency's strong interest in this technology. These include the Science Mission Directorate (SMD), the Human Exploration and Operations Mission Directorate (HEOMD). and the Space Technology Mission Directorate (STMD). A summary of NASA's EP technology development activities in 2018, broken down by Mission Directorate, is shown in Table 1.

SMD conducts a wide range of robotic planetary science missions and supports EP technology development because of its potential to provide significant benefits for future deep-space and astrophysics applications. SMD's current focus is on flight development of NASA's Evolutionary Xenon Thruster - Commercial (NEXT-C) [1]. This project's goal is to develop and flight qualify two ion thruster/power processing unit (PPU) strings, based on the NEXT technology development work completed in 2012. NEXT-C hardware is being considered for multiple science missions including the Double Asteroid and Redirection Test (DART) mission led by the Applied Physics Laboratory (APL) [2]. SMD is also continuing to support the HiVHAc Hall thruster system project that was started in 2002 [3]. The focus now is on development of a flexible 4.5 kW prototype PPU capable of operating with several different NASA and commercially available Hall thrusters.

HEOMD has several EP technology development projects underway as part of the Advanced Exploration Systems (AES) program. The NextSTEP project is supporting work on three high power EP technologies, which could ultimately evolve for use on crewed transportation systems to Mars and other destinations. These include: Aerojet Rocketdyne's XR-100 Nested Hall Thruster [4]; Ad Astra's VAriable Specific Impulse Magnetoplasma Rocket (VASIMR) [5]; and MSNW's Electrodeless Lorentz Force (ELF) Thruster [6]. The AES program is also supporting development of the Morehead State University (MSU) Lunar IceCube mission [7], which will utilize Busek Co. Inc.'s BIT-3 Radiofrequency (RF) Ion thruster [8].

A significant number of NASA's EP projects are conducted by programs within NASA's Space Technology Mission Directorate (STMD). Most prominent of these is the Advanced Electric Propulsion System (AEPS), which is developing and flight qualifying a 13.3-kW string consisting of the thruster, PPU, and Xenon Flow Controller (XFC) [9].

The AEPS system is intended for use as the main propulsion system for the Power and Propulsion Element (PPE) of the Gateway crew-tended cislunar orbital station [10].

Table. 1 NASA's Electric Propulsion Development Activities

Mission Directorate	Activity	Mission Application
Science Mission Directorate (SMD)	NEXT-C (7-kW gridded ion thruster/PPU)	Deep-space robotic science
	HiVHAc (4.5-kW Hall thruster/PPU)	Deep-space robotic science
	Colloid Thruster/PPU	Laser Interferometer Space Antenna (LISA)
Human Exploration and Operations Mission Directorate (HEOMD)	NextSTEP (thruster/PPU) • XR-100 Nested Hall Thruster • VASIMR • Electrodeless Lorentz Force (ELF)	Human exploration missions beyond low-Earth orbit
	BIT-3 Radiofrequency ion thruster/PPU	Lunar IceCube Mission
Space Technology Mission Directorate (STMD)	Advanced Electric Propulsion System (AEPS): 13.3-kW Hall thruster/PPU string	Power and Propulsion Element (PPE) of the Lunar Orbital Platform—Gateway (LOP-G)
	Advanced In-Space Propulsion (AISP)—Iodine-fueled EP thrusters	Deep-space robotic science using small spacecraft
	Small spacecraft technologies • Electrospray thrusters/PPU • Small iodine Hall thrusters/PPU • Sub-Kilowatt Electric Propulsion (SKEP): 500-W Hall thruster/PPU •	Deep-space robotic science using small spacecraft
	SBIR/STTR Multiple EP Technologies	Multiple mission applications

Under STMD's Game Changing Program, the Advanced In-space Propulsion (AISP) Iodine project [11] is systematically advancing iodine EP technology across a wide range of components and subsystems. This activity is focused on risk reduction for future missions that may potentially benefit from the use of iodine-propelled EP systems. STMD's Small Spacecraft Technology Program is also funding work on several EP technologies including electrospray propulsion and small Iodine Hall EP systems.

II. CURRENT AND FUTURE MISSIONS

NASA's most visible current application of EP is the Dawn mission [12]. The Dawn spacecraft (shown in Fig. 1) was launched in September 2007 with the objective of exploring Vesta and Ceres, the two most massive bodies in the main asteroid belt.

Figure 1: Dawn spacecraft pre-integration

Dawn is the first attempt at orbiting a main-belt asteroid and the first mission to orbit two planetary bodies with a single spacecraft. The capability to perform this mission was enabled by its gridded ion propulsion system (IPS). Dawn entered Vesta's orbit in July 2011, and completed a 14-month survey before leaving for Ceres in late 2012. It entered Ceres' orbit in March 2015, where it remains to this day. Dawn has completed one operational extension to its baseline mission, and is currently executing its second extension, which involves approximately three months of operations in a low resonant orbit.

The Dawn IPS utilizes the NASA-developed NSTAR thruster technology, which first flew on the Deep Space 1 mission from 1998 to 2001 [13]. The Dawn IPS consists of three thrusters operating one at a time. The system has accumulated record-breaking statistics for an onboard propulsion system. The spacecraft has amassed over 50,000 hours of ion engine thrusting and delivered over 11 km/s of ΔV to the spacecraft, which is greater than the ΔV provided by the launch vehicle used to deploy the probe into space.

NASA participated in the LISA Pathfinder mission, which was led by the European Space Agency (ESA) [14]. Launched in December 2015, the mission tested technologies needed for the Laser Interferometer Space Antenna (LISA), an ESA-led gravitational wave observatory planned for launch in 2034 [15]. LISA Pathfinder's scientific phase started in March 2016 and lasted almost sixteen months. In April 2016, ESA announced that LISA Pathfinder successfully demonstrated that the LISA mission was feasible. LISA Pathfinder carried a European Technology Package comprising inertial sensors, interferometer and associated instrumentation, as well as two drag-free control systems: a European unit using cold gas micro-thrusters, and a U.S.-built Space Technology 7 (ST-7) Disturbance Reduction System (DRS) using European sensors and a cluster of micronewton colloid thrusters (shown in Fig. 2) [14].

Figure 2: LISA Pathfinder ST-7 DRS

The ST-7 system was the culmination of work that originally started in 1998 through a NASA Phase I SBIR involving Busek and JPL. Following successful demonstration of colloid thruster performance in flight on ST-7, the challenge now is to demonstrate that the thrusters have sufficient lifetime to meet LISA requirements. JPL, Busek and UCLA are supported to perform this work from July 2017 to the end of September 2022.

In addition to operational missions, NASA is in the formulation phase of several missions which would utilize EP. The competitively-selected Psyche mission, currently in Phase B, is one of two mission concepts selected by SMD's Discovery program. It is a JPL-managed orbiter mission that seeks to explore the metallic asteroid Psyche [16]. It originally had a planned launch in 2023 as the 14th Discovery mission. But in May 2017, the scheduled launch date was moved up to target a more efficient trajectory, launching in 2022 and arriving in 2026 with a Mars gravity assist in 2023. The baseline Psyche spacecraft uses the SPT-140 Hall thruster system integrated into a commercially-available Space Systems Loral (SSL) bus.

Another future mission concept is the Double Asteroid Redirection Test (DART) [17], which would demonstrate the kinetic effects of crashing an impactor spacecraft into an asteroid moon, and thus test whether a spacecraft impact could successfully deflect an asteroid on a collision course with Earth. DART is directly funded by the Planetary Defense Coordination Office of SMD . John Hopkins Applied Physics Laboratory (APL) manages the mission, which would demonstrate a kinetic impact on the binary asteroid Didymos. The baseline spacecraft concept utilizes a single NEXT-C thruster/PPU string. The Preliminary Design Review (PDR) for the mission was held on 10-12 April 2018, with a planned launch readiness date in 2022.

Another mission which is still in the early concept definition phase (Phase A) is the Comet Astrobiology Exploration Sample Return (CAESAR) mission [18]. This proposed sample-return mission to comet 67P/Churyumov-Gerasimenko was one of two finalists selected by the New Frontiers program in SMD for further concept development. If selected after July 2019, it would launch between 2024 and 2025, with a capsule delivering a sample to Earth in 2038. The mission is managed by Goddard Space Flight Center (GSFC). The spacecraft would employ three NEXT-C/PPU strings in a 2 + 1 operational configuration (two thrusters operating with one employed as a spare).

The highest power mission application of EP currently planned by NASA would be for the Gateway crew-tended cislunar orbital station (shown in Fig. 3). This a concept for an international crew-tended cislunar space station involving NASA, ESA, Roscosmos, JAXA and CSA. The Gateway would serve as a staging point for missions to the surface of the Moon and future crewed missions to Mars. It would consist of several elements, all incrementally deployed and assembled in cislunar space. These include the Power and Propulsion Element (PPE), a small habitat for crew, a docking module, an airlock and logistics module.

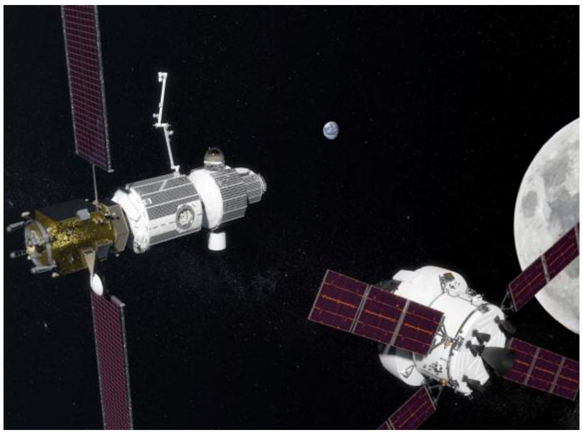

Figure 3: Gateway with the Orion spacecraft

The first element to be deployed is the PPE, which would provide primary propulsion for the entire Gateway station. It is baselined to employ the 13.3-kW Hall thruster strings being developed under the AEPS project. Current plans call for launch of the PPE in 2020 on a commercial launch vehicle. It is envisioned that future Space Launch System (SLS) and Orion flights would carry up the remaining elements for integration in cislunar space.

III. FLIGHT SYSTEM DEVELOPMENT

III.I NEXT-C

NASA's Evolutionary Xenon Thruster (NEXT) is a 7-kW class gridded ion thruster (shown in Fig. 4) that was initially developed from 2002 to 2012 under NASA's In-Space Propulsion Technology Program to meet future science mission requirements. In 2014, GRC released a solicitation for the design, fabrication and test of two flight NEXT thrusters and PPUs, with the expectation that these units would then be made available as Government Furnished Equipment (GFE) for a future NASA mission. In April 2015, Aerojet Rocketdyne (AR) and subcontractor ZIN Technologies were competitively selected for the contract, called the NEXT-Commercial (NEXT-C) project. Aerojet Rocketdyne is responsible for the overall project management, systems engineering, development test and fabrication/assembly of the thrusters, along with overall integrated system testing. ZIN Technologies is responsible for the development, fabrication, assembly, and test of the PPUs.

The NEXT-C propulsion system is designed for SEP applications that must accommodate variable input power resulting from changes in solar range over the mission. The NEXT-C thruster (shown in Fig. 4) has a nominal input power range of 0.5 to 6.9 kW, and utilizes 2-grid dished-out ion optics, capable of producing thrust levels of 25 to 235 mN and specific impulses (Isp) of 1,400 to 4,220 seconds (s).

Figure 4: NEXT-C thruster

Following completion of the Preliminary Design Review (PDR) in February 2016, NEXT-C transitioned into its hardware development phase. AR and ZIN Technologies used the designs from the previous NEXT technology development phase as a baseline and made modifications to improve manufacturability and resolve residual issues with the original design. The Critical Design Review (CDR) was successfully held in March 2018. The delivery date for flight hardware to NASA is May 2019, to enable support of the DART mission.

III.II AEPS

Since 2012, NASA has been developing a 13.3-kW Hall thruster EP string to serve as the building block for a 40 kW-class SEP vehicle. In March 2017, NASA presented a new reference exploration architecture at the HEOMD Committee of the NASA Advisory Council meeting. The new architecture was based on an evolutionary human exploration strategy that focuses on flight testing and validation of exploration capabilities in cislunar space prior to conducting missions to Mars. An important aspect in achieving this goal was prioritizing the technologies best suited for such missions based on this stepping stone approach to exploration. High-power solar electric propulsion was one of those key technologies. A high-power, 40 kW-class Hall thruster propulsion system, along with flexible blanket solar array technology, represented a readily scalable technology with a clear path to much higher power systems.

The 13.3-kW Hall thruster string development, led by GRC and JPL, began with maturation of the high-power Hall thruster (shown in Fig. 5) and PPU. The technology development work transitioned to Aerojet Rocketdyne via a competitive procurement selection for the AEPS contract, which included the development, qualification and delivery of multiple flight-qualified electric propulsion strings. Each string consists of a 12.5-kW Hall thruster, 13.3-kW PPU, Xenon Flow Controller (XFC), and associated intra-string harnesses. NASA supports the AEPS development through in-house EP expertise, plasma modeling capabilities, and unique world-class test facilities. NASA also conducts risk reduction activities in support of AEPS development and mission applications.

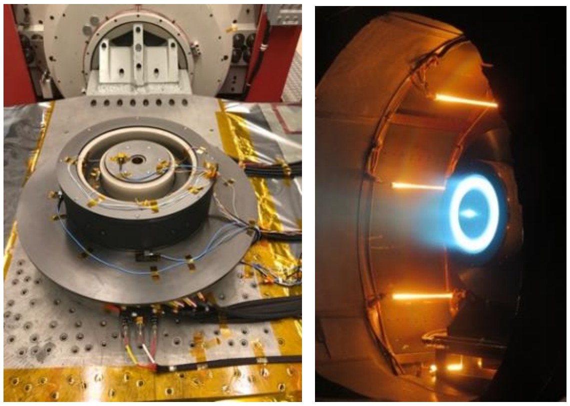

Figure 5: Random vibration testing (left) and performance testing (right) of Technology Demonstration Unit (TDU) thruster at JPL

Each AEPS thruster is designed to deliver a maximum Isp of 2,600 s with a propellant throughput capability of 1,700 kg. Each PPU is designed to operate over input voltages ranging from 95 to 140 V.

The PDR for AEPS was held in August 2017, followed by a PDR Closure Review for the PPU in March 2018. The Engineering Development Units (EDU) are currently being fabricated for a test campaign that is planned to begin in late 2018.

III.III OTHER FLIGHT DEVELOPMENTS

GRC, in partnership with JPL, is managing a Phase III SBIR contract with Colorado Power Engineering (CPE) to develop, fabricate and test a TRL 6 Prototype Development Unit (PDU) PPU. This PPU would be capable of operating at 4.5 kW and be compatible with the NASA-developed HiVHAc+ Hall thruster, SSL's SPT-140 thruster and Aerojet's XR-5 Hall thruster. GRC will conduct integrated system testing with the HiVHAc+ thruster after PDU PPU delivery. The CDR for the PPU was completed in September 2017. The authority to proceed with fabrication was given in January 2018. PDU PPU testing will take place in late-2018, with the plan to enable development of flight hardware in a follow-on or separately funded contract.

NASA is working with Busek under a Space Technology Announcement of Collaborative Opportunity (ACO) to perform life testing of the company's BHT-600 Hall thruster (shown in Fig. 6), including the BHC-2500 cathode. GRC is providing test facilities and support for a 5,000-hour qualification life test that would take place between June 2018 and July 2019. It is envisioned that performing this testing now will reduce the cost for future customers interested in flying this thruster system.

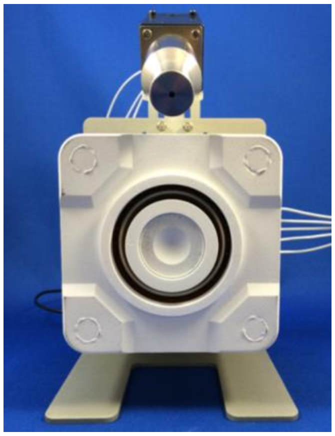

Figure 6: BHT-600 Hall thruster

For the AES-funded Lunar IceCube mission, NASA is supporting Busek to qualify its BIT-3 thruster for use with iodine propellant. Busek's BIT-3 RF ion thruster is currently designed to operate at 60 W to produce a thrust of 1.4 mN at an Isp of 3,500 s using xenon propellant. An iodine-compatible version of the BIT-3 thruster may offer several potential advantages for small spacecraft and cubesats, including Lunar IceCube. Under a Phase II SBIR extension, Busek will conduct up to 4,000 hours of wear and integration testing starting in April

2018. The iodine-compatible BIT-3 hardware is scheduled for delivery in the summer of 2018.

IV. Research and Technology

IV.I 500-W Hall Thruster Technology

NASA has significant interest in the development of sub-kilowatt electric propulsion technologies for potential application to small spacecraft, i.e., spacecraft with wet masses in the range 100-500 kg. As a result, NASA has two parallel technology development activities: the STMD-funded Sub-Kilowatt Electric Propulsion (SKEP) project; and the JPL-funded Magnetically Shielded Miniature (MaSMI) Hall thruster technology (shown in Fig. 7) [19]. Both of these activities seek to develop long-life, high-performance Hall thruster/PPU strings with input powers in the range of 200 to 800 W.

Figure 7: MaSMI Hall thruster

IV.II Electrospray Thruster Technology

NASA has conducted several activities over the last few years focused on Microfluidic Electrospray Propulsion (MEP). JPL has developed an MEP thruster based on microfabrication techniques [20]. The resulting emitter array chip has demonstrated electrospray operation with excellent stability and controllability. The thruster has demonstrated a thrust of 100 μN and an Isp greater than 3,200 s in a very compact size. Larger arrays of microfabricated emitters have the potential to enable scaling up to thrust levels of 1 mN.

IV.III Iodine Thruster Technology

NASA is investigating the implications of iodine-based EP technology for smaller spacecraft. Through STMD's Advanced In-Space Propulsion (AISP) project, NASA is focusing on developing and demonstrating a 600-W iodine Hall thruster-based propulsion system, which includes thruster, cathode, PPU, propellant storage and feed system [21]. The focus is to mature critical propulsion components and perform integrated system testing. The tasks in this effort are aimed at addressing critical technology gaps and risks, namely scaling up to higher power and increased propellant throughput, evaluation of engineering/material changes between xenon and iodine, durability testing for more than 1,000 hours for both thruster and cathode, iodine flow control and metering, and material chemical interactions testing. This effort has resulted in a successful 1,174 hour durability test, which concluded after a second load of iodine was exhausted.

Tests performed with the Busek BHT-600-I thruster performed very similarly with iodine and xenon. Although there were minor material compatibility issues, these were viewed as being readily resolvable. A GRC designed and manufactured hollow cathode operating on xenon was used for the test as a result of prior work that revealed compatibility issues between Barium Oxide (BaO) emitters and iodine propellant. It was also shown that the GRC-developed iodine storage and feed systems were very stable and reliably delivered gaseous iodine throughout the test, with no clogging of feed system component degradation. Several technical challenges still need to be addressed before iodine-based EP could be fully implemented for flight. The AISP project also supported work on a wide range of topics associated with development of iodine-based EP systems, including thrusters, PPUs, materials and coatings, cathodes, storage and feed systems, test facilities, along with test procedures and concept of operations (CONOPs).

IV.IV 100-kW Thruster Technology

For the deep-space transportation of very large payloads and potentially even human crews to Mars, NASA is developing high power EP technologies (>100 kW). The AES program established the Next Space Technologies for Exploration Partnership (NextSTEP) Broad Area Announcement (BAA) to solicit proposals for high-power propulsion. The primary goal of this activity was to demonstrate 100 hours of continuous, steady-state operation of an advanced plasma-based propulsion system operating at 100 kW. Three contracts were selected: the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) led by Ad Astra; the Electrode-less Lorentz Force (ELF-250) thruster led by MSNW; and the Nested Hall Thruster led by Aerojet-Rocketdyne (shown in Fig. 8).

The demonstrations also required development and successful operation of a PPU, feed system and other key components. Key performance goals included specific impulses ranging from 2,000 to 5,000 s, total system efficiency greater than 60%, projected operational life of over 10,000 hours, and a total subsystem specific mass less than 5 kg/kW. In addition, the technologies had to be scalable to megawatt power levels.

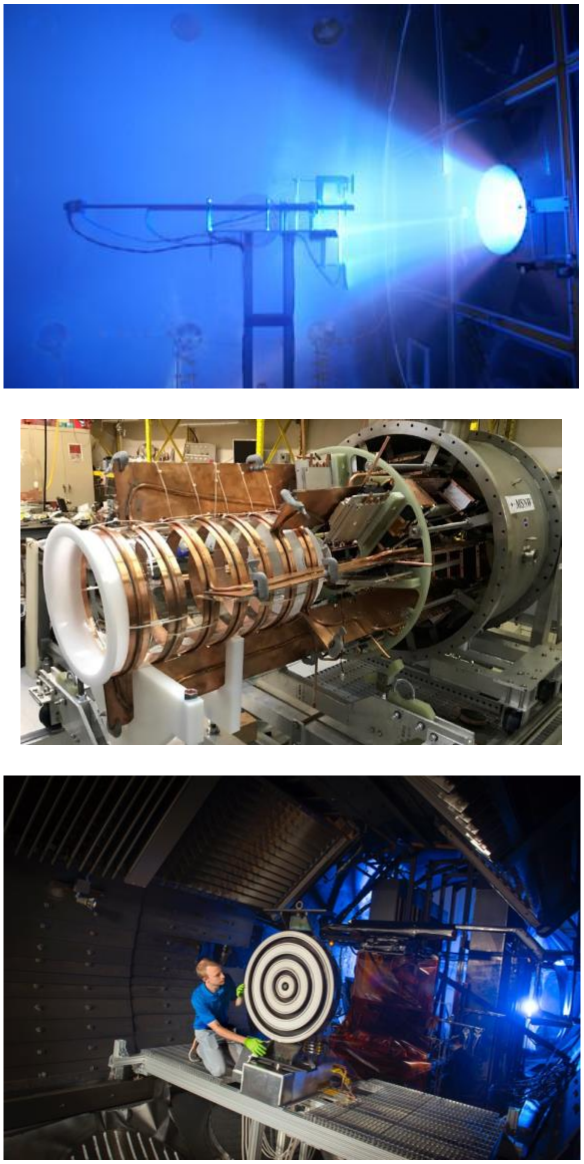

Figure 8: VASIMR Tests (top), ELF-250 thruster (middle), and Nested Hall thruster tests (bottom)

The three projects have made significant progress since they started. After exercising its 3-year contract option in August 2017, Ad Astra's VASIMR demonstrated 100 hours of cumulative operation in 6.5-minute intervals at power levels of 100 kW. The 3-year option for MSNW's ELF-250 was exercised in November 2017, and preparations are underway for the demonstration tests at MSNW in Redmond, WA. For Aerojet-Rocketdyne, the 3-year option was exercised in February 2018. In addition, thruster/facility risk reduction tests were completed over last year at GRC, where the thruster operated at 100 kW for 10 minutes and 80 kW for 3 hours. In addition, a 10 kW test of the thruster, PPU and feed system was completed at the University of Michigan in February 2018.

The 100-hour, 100-kW steady-state tests for VASIMR and ELF-250 concepts are expected to be completed by at their respective company facilities by November 2018. Demonstration of the Nested Hall configuration is expected to be completed at GRC in November 2018.

IV.V EP TECHNOLOGY FOR PLANETARY DEFENSE

JPL is also evaluating the use of ion beam deflection for planetary defense. This approach transfers momentum to a potentially hazardous object by directing a high-energy ion beam to impact the object. This approach has several potential advantages relative to other proposed planetary defense techniques for asteroids in the size range of 50-150 km diameter [22]. The key technology challenge with this approach is the development of ion optics that produce an ion beam with a divergence angle of less than four degrees.

IV.VI ULTRA-HIGH SPECIFIC IMPULSE TECHNOLOGY

JPL is developing lithium-fueled, gridded ion thruster technology with the goal of demonstrating operation at a specific impulse an order of magnitude greater than the current state-of-the-art for gridded ion thrusters. With a specific impulse of approximately 50,000 s, this technology would be applicable to missions that require ΔV's in the range 100-200 km/s [23]. One such mission is an interstellar precursor mission to deliver a spacecraft to a distance of approximately 550 Astronomical Units (AU) from the Sun in a flight time of less than 15 years (shown in Fig. 9).

A solar range of 550 AU is the location of the solar gravity lens focus, where theoretically high-resolution images of exoplanets could be obtained [24]. The propulsion architecture is a type of directed energy propulsion and is the subject of a Phase II NASA Innovative Advanced Concept (NIAC) study led by JPL. The use of lithium propellant has several benefits including the ability to obtain specific impulses on the order of 50,000 s with net accelerating voltages on the order of 6 kV.

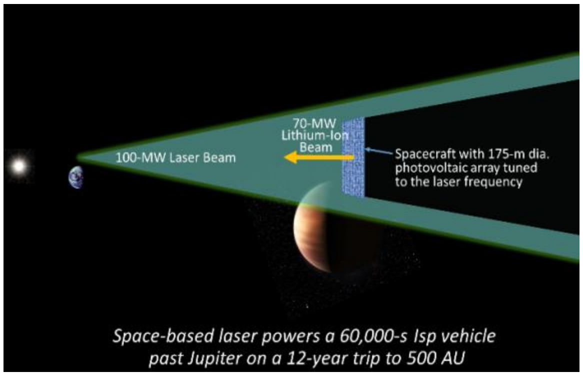

Figure 9: Interstellar precursor mission enabled by very high Isp EP with beamed energy source

V. Summary

Electric propulsion (EP) is an important propulsion technology for NASA. It has played a major role on several missions and has the potential to impact a wide range of NASAs interests including advanced deep-space science missions; human exploration missions; astrophysics missions (e.g., LISA); and planetary defense. Ultimately, advanced power and electric propulsion technologies could enable rapid transportation throughout the solar system. NASA currently has many projects focused on research and development of EP for a variety of applications. All three of NASA's mission directorates that deal directly with space exploration are actively engaged in supporting work in this area. Almost all of the EP research and development work within NASA is being performed by Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL).

VI. Acknowledgements

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