

Steady-state Testing at 100 kW in the VASIMR® VX-200SS™ Project

*Presented at the American Institute of Aeronautics and Astronautics (AIAA) Propulsion and Energy Forum
JW Marriott, Indianapolis, Indiana
19–22 August 2019*

Jared P. Squire¹, Mark D. Carter², Franklin R. Chang Díaz³, Aidan M. H. Corrigan⁴, Lawrence Dean⁵, Joseph Farrias⁶, Matthew Giambusso⁷, Greg McCaskill⁸, and Tiffany Yao⁹
Ad Astra Rocket Company, Webster, Texas, 77598, USA

High-power Solar Electric Propulsion (SEP) cargo delivery systems with more than 50 kW of power in each engine are valuable for a sustainable lunar presence, Mars exploration and human sustained expansion into space. A single VASIMR® engine easily meets this requirement and readily scales to the higher power levels that space-faring humans will eventually require. VASIMR® technology also has more immediate utility for satellite raising and servicing between low- and high-Earth orbits. The VX-200SS™ program aims to demonstrate a thermally steady-state 100 kW VASIMR® prototype at a Technology Readiness Level of 5. The program is nearing completion of the ongoing NASA NextSTEP BAA contract. Testing has included radio frequency power processing units, a superconducting magnet, propellant management system, control system, internal thermal management subsystems and the rocket core. Cooling solutions for the rocket core have been iteratively developed and tested, and the most recent version of which intends to enable 100 kW operations at thermal steady-state. Forty-five high power (> 50 kW) long duration (~hour or longer) firings have been completed. A series of back-to-back, nearly one hour, 62 kW input DC power firings were accomplished during a 15-hour test, automated and partially unattended. A continuous firing at 72 kW was demonstrated for two hours and temperature measurements were approaching thermal steady-state. A power level of 87 kW ran for nearly an hour and 106 kW ran for 6.9 min. Vacuum pressure rise due to outgassing generally has been the primary duration limit. Modifications that will extend long duration testing at 100 kW of the VX-200SS™ are nearly complete. In parallel, a 120 kW, light weight (52.9 kg), highly efficient (~98%), TRL-5 Radio Frequency (RF) Power Processing Unit (PPU) has been built by Aethera Technologies Ltd with partial support from the Canadian Space Agency. Testing of the PPU in vacuum at full power is expected to be completed in the next few months.

I. Nomenclature

HEL	=	helicon stage
ICH	=	Ion Cyclotron Heating stage
I_{sp}	=	specific impulse [s]

¹ Senior Vice President Research, AIAA Associate Fellow.

² Senior Vice President Technology Development, AIAA Member.

³ Chief Executive Officer, AIAA Senior Member.

⁴ Research Engineer, AIAA Member.

⁵ Manufacturing Director.

⁶ Designer.

⁷ Research Scientist, AIAA Member

⁸ Senior Electrical Engineer.

⁹ Electrical Engineer.

J_{ion}	=	ion current density [A/m ²]
\dot{m}	=	propellant flow rate [kg/s]
P_{DC}	=	total input DC power [kW]
P_{RF}	=	total input RF power [kW]
P_{jet}	=	propulsive jet power [kW]
T	=	thrust [N]
η_T	=	thruster efficiency, jet power / RF power

II. Introduction

High-power electric propulsion is a vital capability for supporting long term space exploration to the moon and beyond [1 – 7]. Solar Electric Propulsion (SEP) on the order of hundreds of kilowatts matches the capability of medium to heavy lift launchers that provide payload masses of 15 tons or greater to Low Earth Orbit (LEO). Technology to produce these levels of solar electric power are on the horizon [8, 9]. High-power SEP cargo tugs could significantly reduce the cost of sustaining a permanent presence on the moon and then Mars [4,6,10]. Providing single engine power levels in the class of 100 kW reduces clustering complexity for the higher power level (~ 600 kW) systems. Additionally, fundamental high thruster power capability enables growth as power levels further increase with continued innovation. The VASIMR® technology [11,12] at 50 kW power levels and higher becomes more advantageous in mass and propulsive efficiency as compared to other high-power technologies [13, 14]. Using radio frequency (RF) driven magnetized plasma enables very high output power-density (10 MW/m²), with which the benefit grows as the engine power rating increases. In turn, the thermal management in a compact system becomes the primary challenge. The VX-200SS™ program is designed to demonstrate thermal management techniques implemented in an efficient system while operating in thermal steady-state.

The VX-200SS™ program was authorized to proceed in August 2015 under contract with NASA to develop a VASIMR® prototype engine at technology readiness level 5 (TRL-5), along with radio frequency (RF) Power Processing Units (RF-PPUs), and to test the device at 100 kW for 100 hours continuously. The first year of the contract focused on manufacturing the engine's rocket core and upgrading the vacuum chamber and facility to handle these power levels in thermal steady-state. The second year of the contract began pulsed high power plasma testing with limited active cooling so that the rocket core materials reached full planned temperature. At the beginning of the third year of the contract, Phase-b of the program was completed with the accumulation of approximately 100 hours at power levels equal to or greater than 100 kW with water cooling. [15]

The program is based on an iterative development and testing process. It advances through three operational phases of various durations, each precluded by a preparatory step building on lessons-learned from the previous phases. The three operational phases are:

Phase-a: Shake out basic systems, optimize operational parameters, and accumulate approximately 1 hour of experience with plasma and facility operations. Completed in February 2017.

Phase-b: Implement lessons learned from Phase-a, cool all rocket core components, and establish procedures for testing for extended periods of time. Accumulate approximately 100 hours of run-time at a 100 kW power level. Completed in December 2017. [15]

Phase-c: Further implement lessons-learned, upgrade the cooling infrastructure to manage 100 kW continuous heat rejection from the device waste and plume heat, and then execute a test at 100 kW for 100 continuous hours. Separately test a 100 kW RF-PPU inside the vacuum chamber in preparation of integrating with the plasma device. Phase-c is near completion.

This paper describes the latest testing results that are leading up to the full power long duration test, and development of a TRL-5 RF-PPU. A more detailed VX-200SS™ program description can be found in Ref. [16].

III. VASIMR® Engine System

A VASIMR® engine is a two-stage RF-driven magnetized-ion plasma rocket. The first stage is a helicon-type plasma source and is referred to as HEL in this paper. The second stage uses ion cyclotron resonance heating to efficiently couple RF power into ion kinetic energy and is referred to as ICH in this paper.

Basic descriptions of a VASIMR® engine's function have been included in several previous papers [11, 12]. Four unique elements of a VASIMR® engine are: the RF-PPUs, the superconducting magnet, the thermal management system, and the rocket core. The RF-PPUs are based on a robust and highly efficient single-stage solid-state power amplifier and combining design. These amplifiers have heritage from the radio broadcast industry and have been

proven to operate at full power in steady-state operation in the VX-200SS™ system. Magnet technology based on high-temperature superconductors is progressing rapidly for a wide range of terrestrial applications and is readily adapted to this application. The VX-200SS™ is presently using an existing low temperature superconducting magnet for functional testing that has known magnetic field shaping limitations. The thermal management system is based on robust fluid-loop technology integrated into the rocket core. The rocket core element resides within the bore of the magnet and is designed to utilize the RF power in conjunction with the high strength magnetic field (2 T) to create and accelerate a high power-density plasma stream at about 10 MW/m² at the exit. The rocket core also manages any waste heat from the plasma.

The planned VX-200SS™ system comprises six basic subsystems: 1. Rocket Core (RC); 2. RF Power Processing Units (RF-PPU), including both helicon (HEL) and ICH RF-PPUs with impedance matching; 3. Superconducting (SC) Magnet; 4. Thermal Management, including process fluid heat rejection (at ~ 25 °C) and separate heat rejection fluid (water for present testing and later upgradable to high temperature, ~ 200 °C); 5. Propellant Management (PM); and 6. Command & Data Handling (C&DH). Figure 1 contains a simplified block diagram of the VASIMR® VX-200SS™ system. For comparison to traditional EP systems: the magnet, rocket core, and high-temperature thermal management subsystems together are analogous to a thruster unit — while the RF-PPUs are simpler variations of a DC Power Processing Unit.

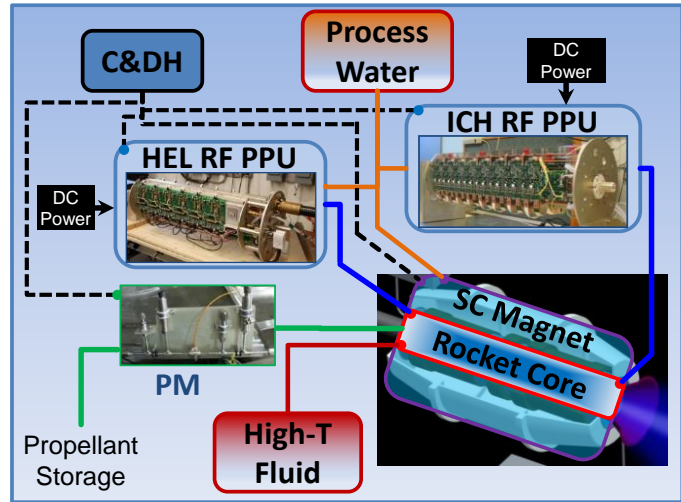


Figure 1 Block diagram of the VASIMR® VX-200SS™ system.

IV. Testing Configuration

The VX-200SS™ test device, shown in Fig. 2, consists of a rocket core with most of its plasma-facing components manufactured from ceramic. Steady-state thermal designs are tested with the rocket core operating inside the bore of a low temperature superconducting magnet (operating below 6 K). The magnet is the same cryogen-free unit used from 2010 through 2012 in the VX-200™ experiments [17] with recent cryostat modifications and maintenance to support full-field steady-state operation of the engine. The TRL-4 RF-PPUs for plasma testing to date are refurbished steady-state capable Nautel Ltd units from the VX-200™ experiments and operate outside the vacuum chamber. The RF-PPUs are planned to be replaced with new TRL-5 vacuum-compatible units. A new TRL-5 ICH RF-PPU is

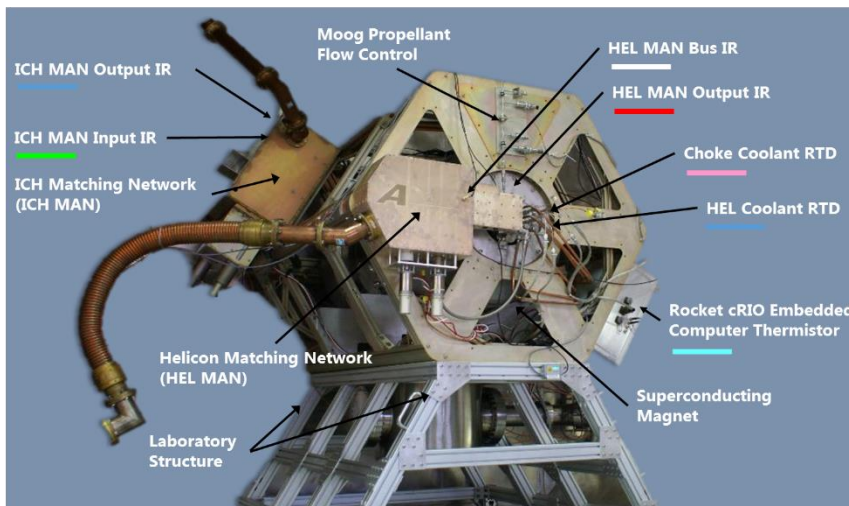


Figure 2 VX-200SS™ as installed in the vacuum chamber for laboratory testing

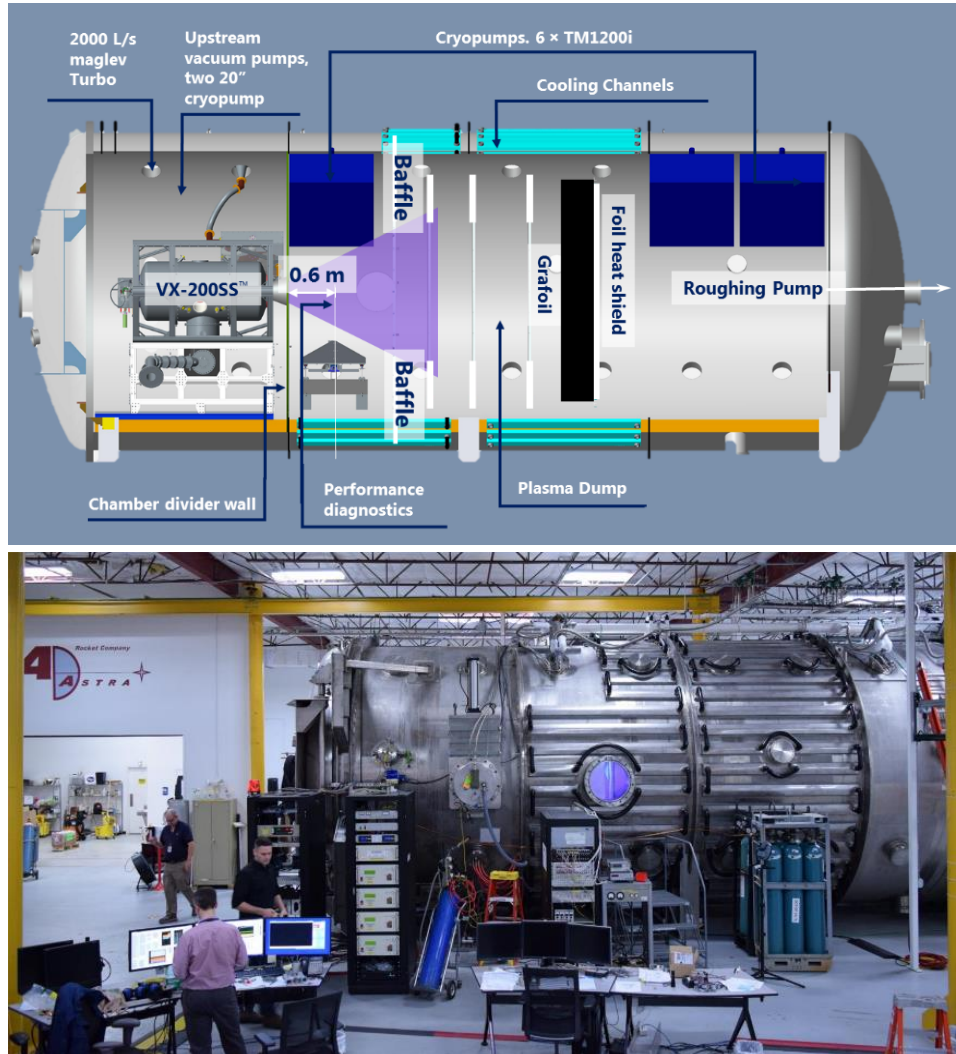


Figure 3 VX-200SS™ test setup and photograph of the system in operation.

complete and in the process of testing and integration into the vacuum chamber. The control system for the engine uses a ruggedized National Instruments cRIO system operating inside the vacuum chamber with Ethernet communications. Gas flow and other systems are described in more detail by Ref. [13]. Performance is determined by measuring the input power, gas flow rate and thrust as described by Ref. [18].

The vacuum chamber has two sections separated by a divider wall to allow the plasma exhaust (downstream) to be collected separately from the electrically energized rocket components (upstream). Figure 3 shows the test configuration. The sections are divided by a stainless-steel wall with passive protection to prevent differential over-pressure. The rocket core exit is sealed to the divider wall by a facility interface. The chamber uses six PHPK Technologies TM1200i cryopanel with a pumping rate of 348,000 l/s to remove the argon plasma exhaust downstream (expansion is possible to ten cryopanel). A 2000 L/s turbopump and two CTI-500 20" cryopumps maintain pressures in the 10^{-6} Torr range on the upstream-side of the divider wall during firing. The vacuum chamber and facility infrastructure are controlled using a dedicated National Instruments cRIO system. Plasma power is intercepted by grafoil panels that radiate the power to the water-cooled chamber walls.

Measurement of the temperatures of critical components and fluids is important for high power operations in steady state. The rocket core is primarily fluid cooled. RTDs (Resistance Temperature Sensor) are used to measure input and output fluid temperatures and are reliable in the high-power RF environment. The conductively cooled high voltage RF connections are other critical locations. Infrared (IR) temperature sensors looking at blackened spots on

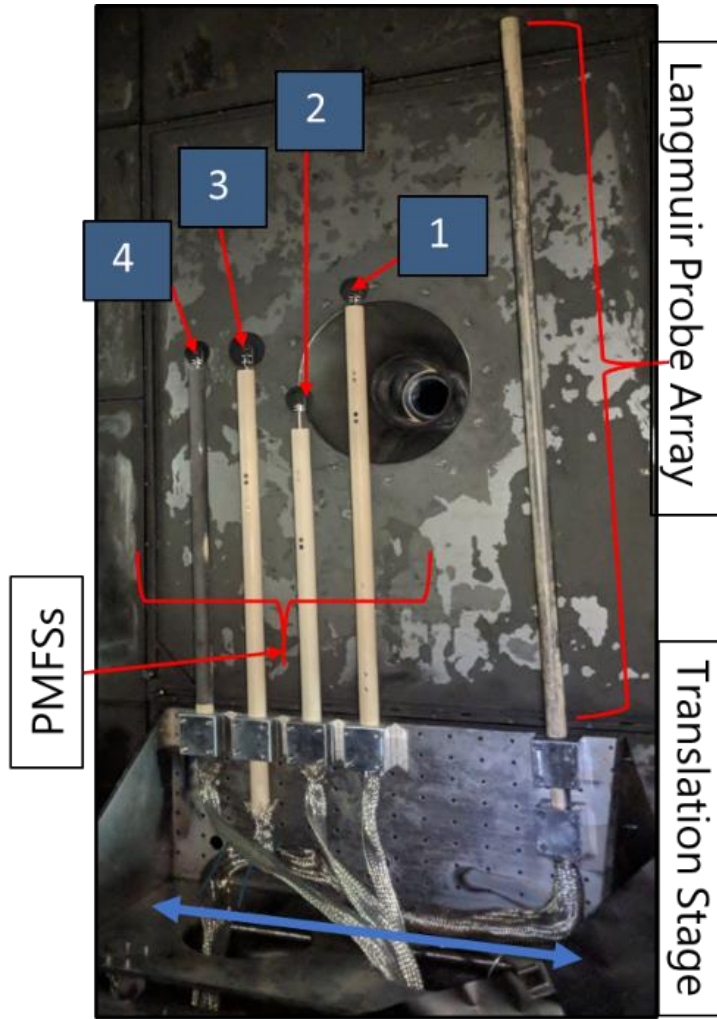


Figure 4 Four PMFSs and Langmuir probe array installed.

the high voltage components have proven reliable. Some of the locations and sensors are identified in Fig. 2 with color coding to help identify data in the results section.

For performance diagnostics, calibrated plasma momentum flux sensors (PMFS) scan through the diameter of the plume to accurately and economically measure the value of thrust and appends data with information about the momentum flux density profile [19]. Ad Astra has proven that this technique accurately infers thrust with background neutral pressures in excess of 10^{-4} Torr. The pressure in this configuration maintains pressure below 10^{-4} Torr in steady state during testing. Four PMFSs are installed with two varied sizes on the central translation chord to test target size effects and one each above and below the center to improve accounting for potential up-down asymmetry in the plasma momentum flux profile. A Langmuir probe array also spans the full plasma diameter to measure a 2D map of plasma flux. Figure 4 contains a photograph of the plasma diagnostics installation

Table 1 Summary of parameter measurements and techniques

Parameters	Diagnostics
Propellant Flow (\dot{m})	<ul style="list-style-type: none"> Precision MKS mass flow meter VX-200™ Moog TRL-7 gas flow controller
Input Power (P_{DC}, P_{RF})	Helicon and ICH RF PPU systems <ul style="list-style-type: none"> DC voltage and current Integrated and vendor calibrated RF power and impedance sensors. (P_{RF})

	<ul style="list-style-type: none"> • RF power and impedance sensors at the Rocket Core interface.
Thrust (T)	Plasma momentum flux sensors (PMFS). <ul style="list-style-type: none"> • Four PMFSs scanned across the diameter per the published method.
Thermal Fluid Input/Output ΔT and flow rate.	Rocket core <ul style="list-style-type: none"> • Sensor wells with temperature sensors, e.g. RTD. • Flow rate meters
Thermal Structure	<ul style="list-style-type: none"> • Shielded temperature sensors, e.g. RTD. • IR temperature sensors for high RF field regions.
Plasma properties Flux, T_e , etc.	Langmuir probes scanned across the plasma diameter <ul style="list-style-type: none"> • Array of 24 planar Langmuir probes biased in ion saturation in pairs as double-probes. Reversing the polarity refines spatial detail.
Magnetic Field	<ul style="list-style-type: none"> • Superconducting coil currents • Magnetometer verification
Neutral Gas Pressure	<ul style="list-style-type: none"> • Commercial gas pressure sensors (convector and ion gauges) on the chamber, in the rocket region and three in the plume and plasma dump regions. • Residual Gas Analyzer (RGA) to check for purity

The data from the PMFS, Langmuir probes, and other existing sensors confirm predicted power performance of the VX-200SS™ system. The VX-200SS™ thermal control advancement also enables long and/or rapid pulsing capability for thrust measurement at low background pressure. PMFS diameter scans can be completed in less than 30 seconds with stable rocket core temperatures to enable extensive exploration of varying input parameter values, when not interfering with emphasis on increasing the power level and extending duration. The parameters that are measured and methods for measurement are listed in Table 1.

V. Results

High power (> 50 kW) long duration (~hour or longer) plasma operations were accomplished in a series of operational campaigns from mid-2018 to early 2019. These campaigns focused on iteratively identifying and finding solutions to any issues that inhibited high power for long duration testing and demonstrating thermal steady-state. In the power range of 50 to 75 kW, forty-five long duration plasma firings have been carried out. Duration lengths at higher power levels were limited by pressure rise that led to plasma breakdown at high voltage RF components. Nearly an hour run was achieved at 87 kW DC input power and 6.9 minutes at over 100 kW. Figure 5 shows plasma operation at over a 100 kW power level. Limited effort was spent optimizing the system parameters for thruster efficiency. Performance consistency was periodically checked to verify that the thruster system was running similar to a more optimized condition as reported earlier. [15, 20] In this way, the thermal systems were tested at a somewhat more challenging condition.



Figure 5 Photographs of typical 100 kW pulse

While operating for long durations at 50 kW and higher, the chamber walls felt significantly warm to the touch, even with water flowing through the cooling channels. A rental auxiliary water chiller successfully managed the steady-state heat load and has the rating to handle 100 kW operations in steady state. A shutter was used to prevent carbon buildup on the main viewing window through which the photograph in Fig. 5 was taken. Without the shutter, the window becomes obscured after about 10 hours of operation. The plasma probes functioned reliably throughout testing. The TRL-4 RF-PPU power systems functioned

exceptionally throughout testing and measurements indicated 95% total power conversion efficiency, DC input to reported RF power.

A. Plasma measurements

Plasma probes scanned across the plume diameter are used to measure plasma ion and momentum fluxes and are located approximately 1 m from the thruster exit. The probes move on a motorized translation stage that can rapidly

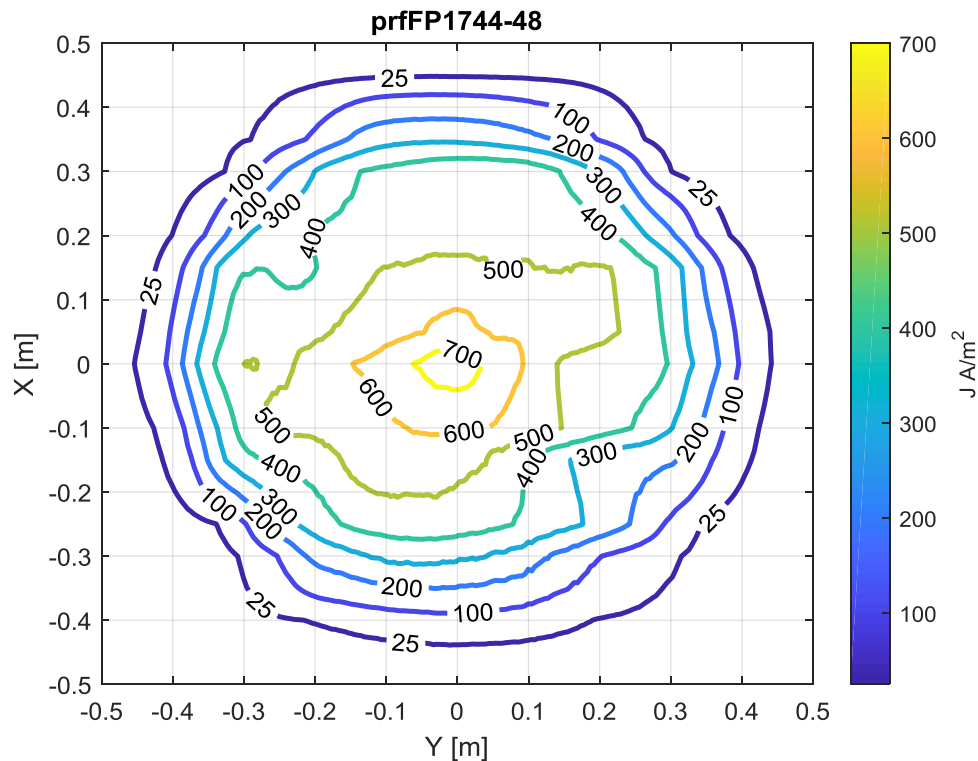


Figure 7 Contour plot of the ion current density at 100 kW.

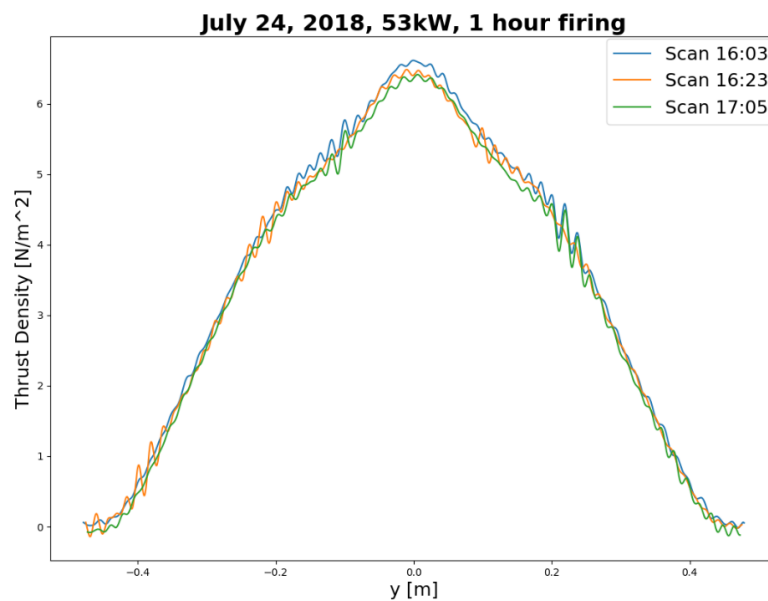


Figure 6 Force density profiles at 3 times over an hour at 53 kW.

scan the plasma plume diameter. Up to 24 chords of plasma ion flux are measured to produce a 2D map of the plasma flux profile. Peak ion current density (J_{ion}) were measured at over 700 A/m² at this location. Figure 6 contains a typical contour plot of J_{ion} for a 100 kW firing. The integrated plasma data together with input RF power (P_{RF}) and propellant flow (\dot{m}) determine system performance, such as: thrust (T), thruster efficiency (η_T), and specific impulse (I_{sp}). Near 100% propellant utilization is verified and modest (~ 10%) plume neutral ingestion is indicated. The 2D current density profile allowed ion flux integration without assuming profile symmetries and gave 203 ± 30 A total ion current. The input neutral flow rate corresponded to 188 A of ion current assuming 100% singly ionized argon. The 8% additional measured ion current is consistent with the plume ingestion of background neutrals flowing into the region upstream of the probe measurements. PMFS measurements are not impacted by this plume ingestion because the additional ions do not add to or remove from the total momentum. Additionally, thrust performance values are not impacted by thruster neutral ingestion, since the flux of neutrals into the narrow region upstream of the acceleration zone is negligible. The flux profiles show mostly azimuthally symmetric profiles so that PMFS integration across the plasma profile diameter, as done for previously reported data [15, 20], produces accurate measurement of total thrust, with only a small under integration of the total inferred thrust by less than 5%. The PMFS data from above and below the center confirm good up-down symmetry.

The PMFS measurements showed consistency over a one-hour duration. During a 53 kW RF power test firing, the diagnostics probe stage scanned the plume across the diameter three times: once near the beginning, another at 20 minutes in, and the last over one hour after the initiation. Figure 7 shows the measured profiles in comparison to each other. The small oscillations in the data are remnants of filtering the data to smooth out higher frequency oscillations excited by translation stage movement. These oscillations do not affect the integrated value. The integrated inferred thrust was 1.53 ± 0.08 N.

B. Long Duration Testing

In the process of conditioning the system for higher power levels, a series of 62 kW DC input power firings were performed back-to-back for 15 hours using an automated system. As a simple protection for unattended operations, a 30 second pause was preprogrammed to prevent prolonged off-nominal operations. Critical safety inhibits were continuously monitored and the system would shut off to protect against any equipment damage. The firings were 59.5 minutes on and 0.5 minutes off, repeatedly. During this phase, a module in the cRIO in-vacuum control system monitoring the RTD fluid temperature measurements failed. Subsequent higher power long duration firings were carried out using external thermocouple monitors for safe testing, and the RTD data does not show in the later plots. Figure 8 contains a 4 hour segment of thermal data from the 15 hour run, enlarged to show details. A slower temperature variation on the order of an hour can be seen in the data due to the water chiller cycling. The 30 second pauses can be seen as momentary drops in temperature that quickly return to a near steady-state value.

Shortly after the 15 hours of conditioning, a 106 kW input DC power level firing was accomplished for 6.9 minutes. A rapid pressure rise limited the pulse length, so a lower power level conditioning effort was continued. The system readily performed a 72 kW DC input power firing for nearly two continuous hours. The long-term chamber pressure

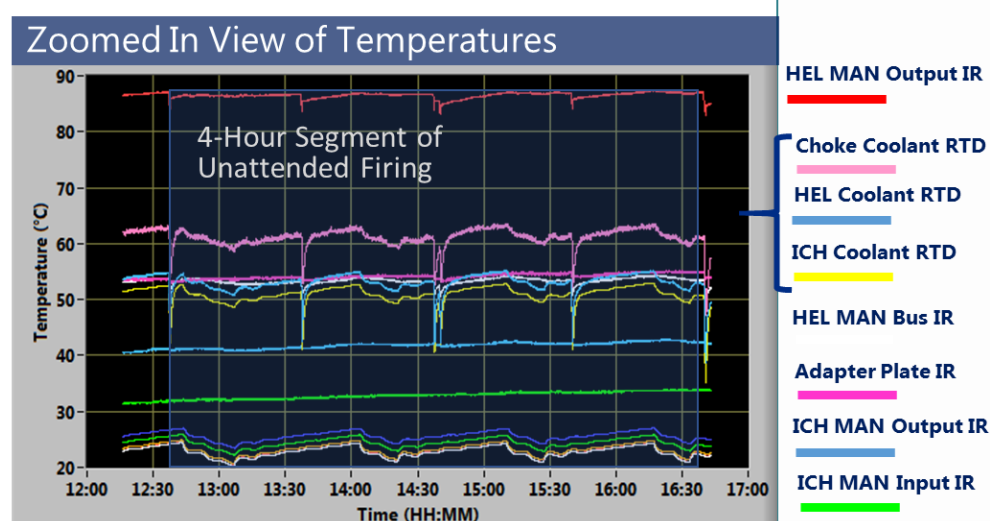


Figure 8 Four-hour segment of the temperature data in a 15-hour test 62 kW run

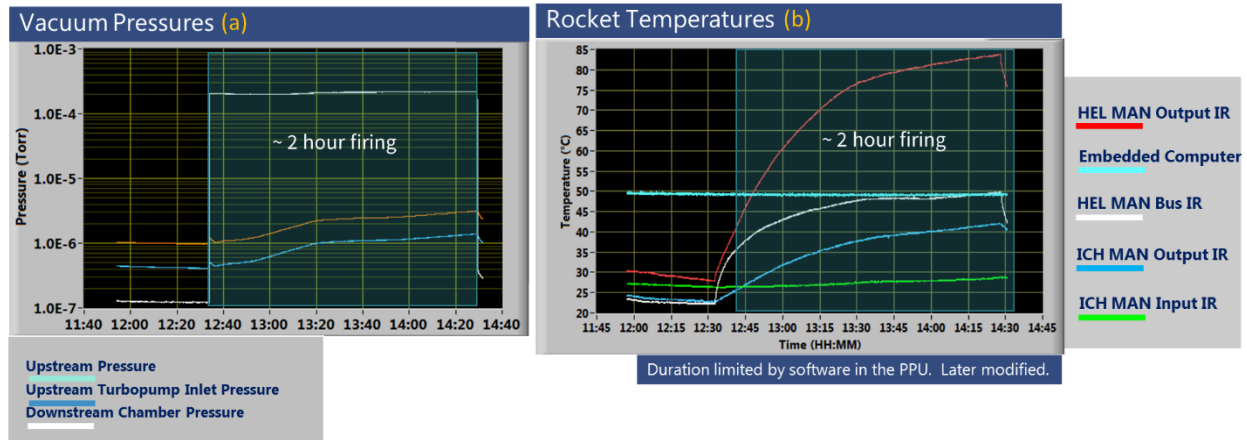


Figure 9 Nearly 2-hour firing at 72 kW DC input power (a) Chamber vacuum pressure at several locations (b) IR sensor data; RTD data had failed.

rise is apparent in Fig. 9a and approaching a stable condition. The temperature data from the still active IR type measurements on conductively cooled high voltage components are shown in Fig. 9b. This behavior is consistent with remote components heating up on a very slow time scale and outgassing. This firing was terminated due to a previously unidentified software programming detail. The software has since been modified to eliminate that limit to the firing length. After this successful test, the power level focus was increased to the order of 80 kW.

A test firing at 87 kW input DC power was accomplished for 50 minutes. Figure 10 shows a series of 8 firings that led up to the 87 kW case. The orange and blue lines in Fig. 10a shows the significant rocket section chamber pressure rise that occurred at the higher power levels. This is consistent with the higher power levels causing heat to reach remote areas that rapidly start outgassing. There is no evidence that the pressure rise was due to leaks. As can be seen in this sequence, the pressure rise started rolling over and conditioning may work past this pressure limitation. This productive campaign stopped due to a leak that opened and prevented further testing. Lessons learned from this campaign have led to several needed system modifications before resuming 100 kW long duration testing

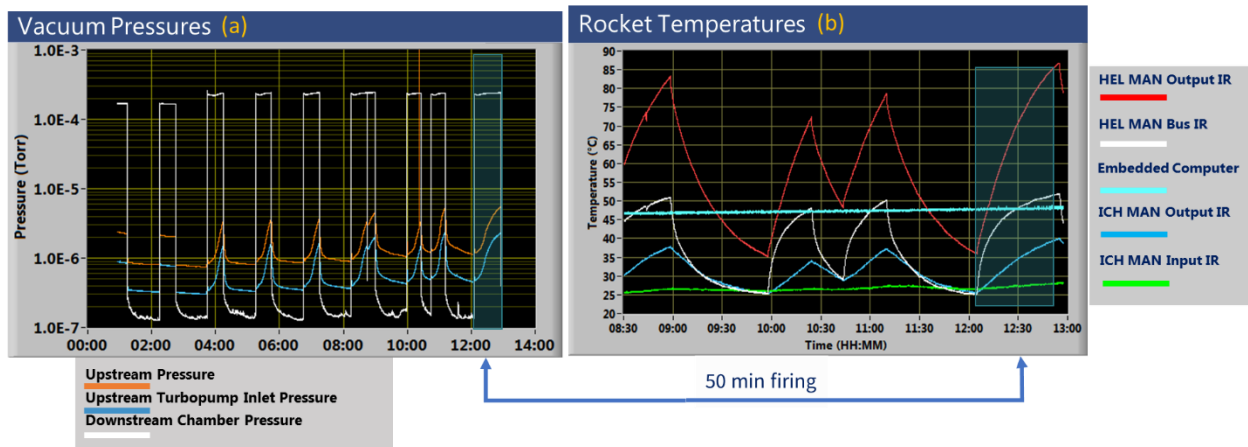


Figure 10 Series of firings that led up to 87 kW for nearly an hour. (a) Chamber vacuum pressure at several locations. (b) IR sensor data; RTD data had failed.

VI. New TRL-5 RF-PPU

A new TRL-5 RF-PPU was developed and built by Aethera Technologies Limited with support from the Canadian Space Agency. This new unit will replace the second stage TRL-4 RF-PPU and will operate within the vacuum chamber. It weighs 52.9 kg complete with magnetic shielding and has a 120 kW output power rating with a DC to

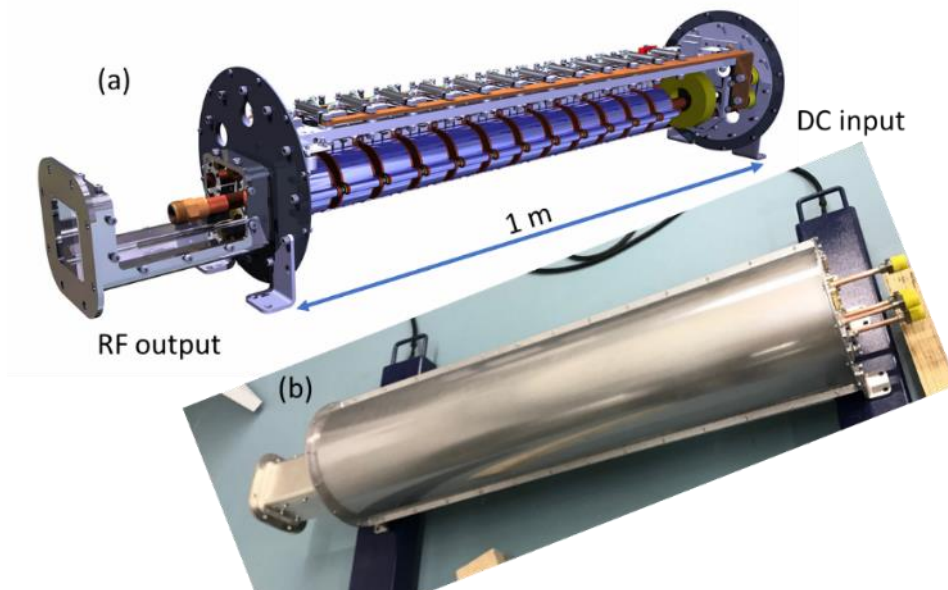


Figure 11 (a) RF-PPU rendering. (b) Photograph of the complete unit being weighed.

RF processing efficiency of approximately 98%. Figure 11 shows a rendering of the RF-PPU without the shield and a photograph of the complete unit with shield being weighed. Magnetic shielding weighing 15 kg is only needed to mitigate potential loss in the RF power combiner transformers while near the VX-200SS™ dipole magnet. If located in a low magnetic field region, the RF-PPU would weigh less than 50 kg with a typical enclosure. One complete 10 kW power element (12 in this PPU) has been tested in vacuum at 12 kW in thermal steady-state. The DC to RF power efficiency at full power in this element was measured as 98.6% and verified by measuring the loss of the elements in vacuum by water calorimetry. The complete RF-PPU was tested at Aethera to 20 kW and in off-nominal impedance

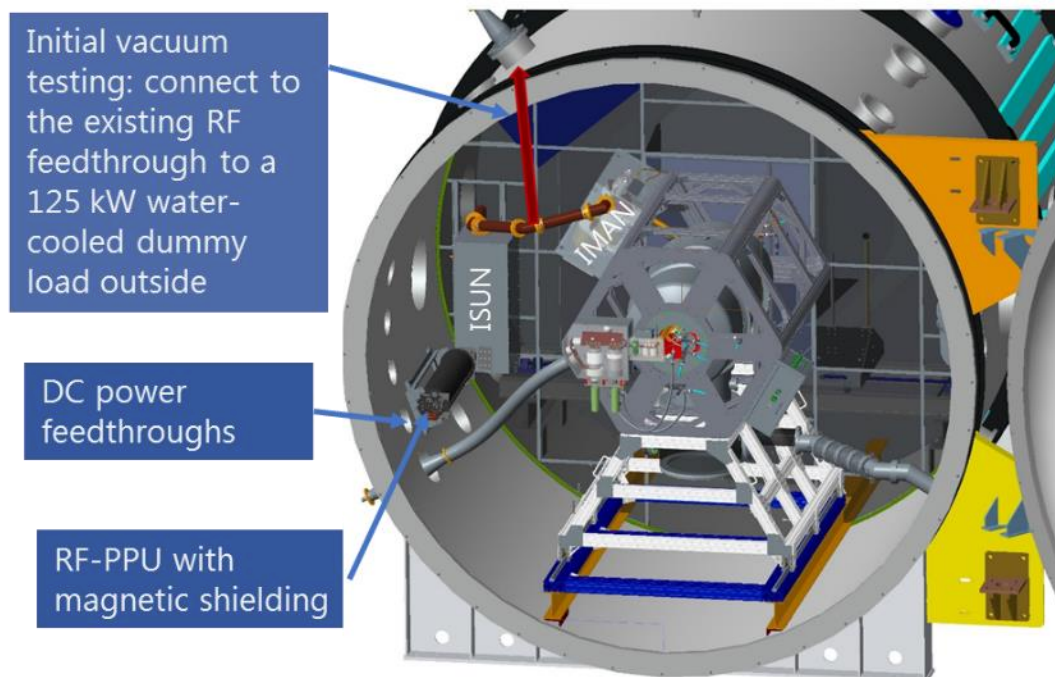


Figure 12 ICH RF-PPU planned installation

loads that simulated full power loss in the critical components. It demonstrated full function in the desired frequency range of 0.4 to 1 MHz. This frequency band will accommodate both a magnet upgrade and potential testing with krypton propellant. The RF-PPU is commanded and controlled via an ethernet interface.

The ICH RF-PPU is in the process of testing to full power in the Ad Astra facility and then integration into the vacuum chamber with VX-200SS™. We will then perform in-vacuum full power testing and feeding the power out via a vacuum feedthrough to a water-cooled dummy load located outside of the chamber. A standard 50 Ω impedance and oversized flexible laboratory impedance matching networks were chosen to ease high power testing and then rapid connection of the system for plasma testing. Figure 12 contains a rendering of the planned in-vacuum configuration.

A design study was completed to assess the application of the ICH RF-PPU design to the higher frequency (~ 7 MHz) desired for the HEL stage. Modern power conversion components now enable the identical system topology to successfully apply to both HEL and ICH RF-PPUs. Design and prototype development are ongoing to demonstrate hardware functionality that will enable the production of a TRL-5 HEL RF-PPU within the next year.

VII. Activities and Plans

Several key modifications have been identified and are being implemented now to enable operation at over 100 kW in thermal steady-state. Some of these modifications involve long lead-time ceramics that have affected the schedule. The system has already demonstrated long duration operation approaching the 100 kW goal, so we are confident that these few remaining modifications will accomplish the goal.

Beyond the near term 100 kW goal, there has been a large body of lessons-learned collected from our series of campaigns. Details of rocket core fabrication and ceramics can now be significantly improved. Since the beginning of the project, capabilities in ceramics fabrication have advanced and we can take advantage of that to eliminate design risk factors. Additive manufacturing is being explored to produce the specially shaped RF components. The new RF-PPU brings control capability enhancements and the possibility of much more simplified and robust RF impedance matching networks. The ICH RF-PPU design will have direct application for a new HEL RF-PPU.

Most importantly, a new high temperature superconducting magnet has been proposed that would have a more spaceflight-relevant design. The magnet also addresses known limitations of the existing magnet in magnetic field shaping and strength. A magnetic field shape that is better aligned with the wave field patterns and ceramic walls will directly improve performance and shrink the size. Higher magnetic field strength has also shown a direct improvement in performance. The ICH stage will run at a higher frequency which enhances plasma coupling, reduces the size of impedance matching components, and decrease ion Larmor radii sizes that enhances the acceleration mechanism.

VIII. Summary

The VX-200SS™ program has made great strides in the lead-up to demonstrating 100 kW plasma operation in thermal steady-state for long durations. The vacuum chamber is operating well with significant gas and heat loads. The RF power systems have operated efficiently (95% DC to RF power conversion) and reliably throughout the program. Plasma diagnostics have been successfully upgraded to rapidly measure plasma momentum flux profiles on multiple chords and 2D mapping of the ion flux profile. Near 100 % propellant utilization was measured. Inferred thrust measurements have shown consistency, though with duration as the primary emphasis, short repeated firings for parameter optimization were not completed. Profiles are now acquired in less than 30 seconds.

Long duration (~hour or longer) testing has been performed at significant power levels (greater than 50 kW) for as many as 45 test firings. A series of 15 firings for 59.5 minutes at 62 kW DC input power were repeated back-to-back with only 30 second pauses between firings for cautious 15-hour operation, partially unattended. All the temperatures were in near steady-state and varied primarily with the water chiller cycling. At 72 kW input DC power, a firing was maintained for nearly two hours. A power level of 87 kW produced a firing for nearly an hour and was limited by a vacuum pressure rise. Repeated firings at 100 kW were also limited by vacuum pressure rise. The longest firing at 106 kW input DC power was 6.9 minutes. Additional modifications are near completion and long duration testing at 100 kW will resume soon after this writing.

A new 120 kW TRL-5 ICH RF-PPU is complete. It weighs 52.9 kg and demonstrates 98% DC to RF power conversion efficiency. One complete power section, of 12 total identical sections, has been tested in vacuum to 12 kW. Testing of the complete RF-PPU to full power in vacuum is in process over the next few months.

Acknowledgments

This work is supported under the NASA Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) NNH15ZCQ001K.

References

- [1] NASA, “Pioneering Space: NASA’s Next Steps On the Path To Mars”, May 2014.
- [2] NASA Technology Roadmaps, “TA 2: In-Space Propulsion Technologies”, May 2015 Draft, <http://www.nasa.gov/offices/oct/home/roadmaps/index.html>
- [3] National Research Council, “NASA Space Technology Roadmaps and Priorities: Restoring NASA’s Technological Edge and Paving the Way for a New Era in Space”, 2012, ISBN 978-0-309-25362-8.
- [4] Carpenter, C.B., Myers, R., and Kimbrel, S., “A Space Logistics System Based on Efficient In-space Transportation”, *AIAA SPACE 2012 Conference & Exposition*, 11 - 13 September 2012, Pasadena, California.
- [5] Prasad, N., Moss, R., Collett, K., Nelessen, Adam, Edwards, S., Mavris, D.N., “A Systematic Method for SME-Driven Space System Architecture Down-Selection”, *AIAA SPACE 2014 Conference and Exposition*, 4-7 August 2014, San Diego, CA.
- [6] Naderi, F., “Affordable Human Missions to Mars”, The Humans to Mars Summit 2015, May 5-7, 2015, The George Washington University, Washington D.C.
- [7] Mercer, C.R., McGuire, M.L., Oleson, and S.R., Barrett, M.J., “Solar Electric Propulsion Concepts for Human Space Exploration,” *AIAA SPACE 2015 Conference and Exposition*, Pasadena, CA, 31 Aug – 2 Sep, 2015
- [8] Orbital-ATK, “MegaFlex”, <https://www.orbitalatk.com/space-systems/space-components/solar-arrays/>
- [9] Deployable Space Structures, “Mega-ROSA”, http://www.dss-space.com/products_solar_array.html
- [10] Spores, R., et al. “A Solar Electric Propulsion Cargo Vehicle to Support NASA Lunar Exploration Program,” *29th International Electric Propulsion Conference*, IEPC-2005-320, Nov., 2005.
- [11] Chang Díaz, F. R., Scientific American 283 (2000) 72.
- [12] Glover, T. W., Chang-Díaz, F. R., et al.: “Principal VASIMR Results and Present Objectives,” *Space Technology and Applications International Forum*, Albuquerque, NM, 2005.
- [13] Squire, J.P., et.al., IEPC-2013-149, *Proceedings of the 33rd International Electric Propulsion Conference, The George Washington University, USA*, October 6 – 10, 2013
- [14] Squire, J.P., Carter, M.D., Chang Díaz, F.R., Giambusso, M., Ilin, A.V., Olsen, C.S., and G.E., Bering, E.A., III, “Development Toward a Spaceflight Capable VASIMR® Engine and SEP Applications”, *AIAA SPACE 2014 Conference and Exposition*, 4-7 August 2014, San Diego, CA.
- [15] Squire, J.P., Carter, M.D., Chang Díaz, F.R., Corrigan, A.M.H., Dean, L., Farrias, J., Giambusso, M., McCaskill, G., Yao, T., Glover, T.G., “Run-time Accumulation Testing of the 100 kW VASIMR® VX-200SS™ Device” *AIAA Propulsion and Energy 2018 Forum and Exposition*, Cincinnati, Ohio, 9 – 11 July, 2018
- [16] Squire, J.P., Carter, M.D., Chang Díaz, F.R., Dean, L., Giambusso, M., Glover, T.G., Jose Castro, J., and Del Valle, J., “Advances in Duration Testing of the VASIMR® VX-200SS System” *AIAA Propulsion and Energy 2016 Forum and Exposition*, Salt Lake City, Utah, July 25 – 27, 2016
- [17] Cassady, L. D., et.al., “VASIMR® Performance Results” *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 25 - 28 July 2010, Nashville, TN
- [18] Longmier, B.W., Squire, J.P., Olsen, C.S., Cassady, L.D., Ballenger, M.G., Carter, M.D., Ilin, A.V., Glover, T.W., McCaskill, G.E., Chang Díaz, F.R., and Bering, E.A. III, “Improved Efficiency and Throttling Range of the VX-200 Magnetoplasma Thruster”, *Journal of Propulsion and Power*, Vol. 30, No. 1, Jan.-Feb 2014, pp. 123-132.
- [19] Longmier, B.W., Reid, B.M., Gallimore, A.D., Chang-Díaz, F.R., Squire, J.P., Glover, T.W., Chavers, D.G., Bering, E.A., “Validating a Plasma Momentum Flux Sensor to an Inverted Pendulum Thrust Stand”, *Journal of Propulsion and Power*, Vol. 25, No. 3, 2009, pp. 746-752.
- [20] Giambusso, M., Carter, M.D., Squire, J.P., Chang Díaz, F.R., Dean, L., Corrigan, A.M.H., McCaskill, G., and Tim G. Glover, T.G., “Progress in the VASIMR® VX-200SS Plasma Testing Program” *AIAA Propulsion and Energy 2017 Forum and Exposition*, Atlanta, Georgia, July 10 – 12, 2017