Superconducting 200 kW VASIMR® Experiment and Integrated Testing

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Jared P. Squire[1], Leonard D. Cassady[2], Franklin R. Chang Díaz[3], Mark D. Carter[4], Tim G. Glover[5], Andrew V. Ilin[6], Benjamin W. Longmier[7], Greg E. McCaskill[8], Chris S. Olsen[9]
Ad Astra Rocket Company, Webster, Texas, 77598, USA

and

Edgar A. Bering, III[10]
University of Houston, Houston, Texas, 77004, USA

A superconducting Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) experiment (VX-200) is in operation. This device demonstrates the spaceflight relevant VASIMR® technology at the 200 kW electrical power level, from DC to plasma jet. The VX-200 is a two stage system using a helicon for plasma production and ion cyclotron heating for the primary plasma acceleration (RF booster). Five key technology elements are combined in this integrated test. The first is the efficient and light weight conversion of DC electrical power (~ 400 VDC) to RF power. The helicon RF generator operates at power levels up to 40 kW with an efficiency of about 92% and the ICH RF generator operates at power levels up to 170 kW with an efficiency of 98%. The RF generator alpha is less than 1 kg/kW. The second element is a superconducting high field (2 T) magnet that is a cryogen-free low temperature (5 K) superconductor. Though not intended to be flight-like, it is a significant step toward realizing a flight version. The third element is the high field helicon plasma source operating in a superconducting system. We have measured an argon plasma jet with an energy cost to extract an electron-ion pair of 78 ± 11 eV/ion at 32 kW and flow rate of 135 mg/s. The fourth element is the RF booster acceleration stage. A record power of 149.2 kW was coupled to an interim reduced magnetic field configuration for a test of the RF booster power train. Finally, the VX-200 operates in a large 150 m^3 vacuum chamber with over 100,000 l/s of cryo-pumping to accurately measure the plasma flow properties in the plume.

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[1] Director of Research, jared.squire@adastrarocket.com
[2] Lead Project Engineer, lcassady@adastrarocket.com
[3] President and CEO, aarcinfo@adastrarocket.com
[4] Director of Technology, mark.carter@adastrarocket.com
[5] Director of Development, tim.glover@adastrarocket.com
[6] Computational Research Lead, andrew.ilin@adastrarocket.com
[7] Research Scientist, ben.longmier@adastrarocket.com
[8] Senior RF Engineer, greg.mac@adastrarocket.com
[9] Research Scientist, chris.olsen@adastrarocket.com
[10] Professor, Physics, eabering@uh.edu

I. Introduction

Propulsion technology must advance to enable the expansion of human exploration of space. As a significant step, this can be achieved while creating the ability to move large cargo masses (tons) beyond low earth orbit more economically, e.g. the moon or on to Mars. High power (>100 kW) solar electric propulsion systems could deliver twice the mass to the moon as compared to an all chemical propulsion solution.[1, 2] Advances in solar photovoltaic technology performance for space application[3] enables lower system alphas that favor a high specific impulse (> 4000 s) thruster technology.[1, 4] The transit times are on the order of 6 months and the economics require that the solar arrays are utilized for multiple trips. Therefore, the electric propulsion technology must have lifetimes of several years. The Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) experimental goals are to demonstrate these features in a practical system.

The VASIMR® concept (Fig. 1) relies on efficient plasma production in the first stage using a helicon plasma source.[5, 6] Ion cyclotron resonance enables efficient ion energy boost in the second stage (RF booster). Thrust is realized in the final stage as the plasma accelerates in a magnetic nozzle. Efficient plasma production has previously been demonstrated in a high background pressure environment.[4, 7] The efficient single pass RF booster acceleration mechanism has been observed for neon and argon propellants.[4, 7] The plasma flow in the magnetic nozzle and efficient detachment from the rocket have been theoretically predicted.[8]

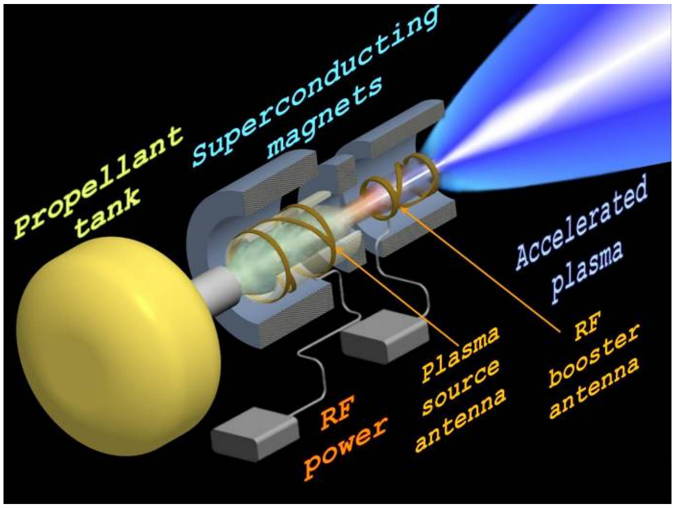

Figure 1. The VASIMR concept.

We are now demonstrating five key technology elements in an integrated 200 kW system test in a device called VX-200. The first element is the efficient and light weight conversion of DC electrical power (~ 400 VDC) to RF power. The second is the superconducting generation of the high magnetic field profile required for the VX-200. The present magnet is not intended to be flight-like, though it is a significant step toward realizing a spaceflight version. The third element is the helicon plasma source, which has already been demonstrated at full performance in our earlier VX-100 device.[4, 7] This is the first time that the helicon plasma source has been operated in a superconducting system at a magnetic field strength 30 % higher than previous VASIMR® devices using copper electromagnets. The fourth element is the RF booster acceleration stage, which has also been fundamentally demonstrated in VX-100.[4, 7] The superconductor magnet's large bore and higher magnetic field strength, greater than 1 T, enables higher efficiency demonstration of the ICH acceleration process on argon propellant. Finally, the VX-200 operates in a large 150 m^3 vacuum chamber with over 100,000 l/s of pumping to demonstrate the plasma flow in the plume going from magnetized to unmagnetized ions with the plasma beta exceeding unity.

At the time of this writing we are able to report results up to a high power functional test of the RF booster stage power train. We describe the RF generators, superconducting magnet, and a fully operational helicon with the plasma flux measured in the large vacuum chamber. High field RF booster work and plasma plume studies are in progress.

II. The VX-200 Experiment

The VX-200 is an experimental version of the VASIMR® engine that utilizes 200 kW of input DC electrical power. The rocket is designed to be an end-to-end test of spaceflight relevant components in a vacuum environment. Most components of the rocket are located within the vacuum chamber, with only the RF generators, magnet power supplies, and magnet cryocoolers at atmospheric pressure outside of the vacuum chamber. The superconducting magnets, structural components, rocket core, and most electronic components are operated within the chamber. Figure 2 shows an image of the VF-200 3-D model and a photograph of the rocket installed inside the vacuum chamber. A key component of the VX-200 is the superconducting magnet with a maximum field strength of approximately 2 tesla that allows for efficient radial containment and acceleration of the plasma.

The VX-200 has been tested in two different configurations: one with water-cooled copper coils to generate a magnetic field at 10% of the desired field called the VX-200i and the nominal configuration with the

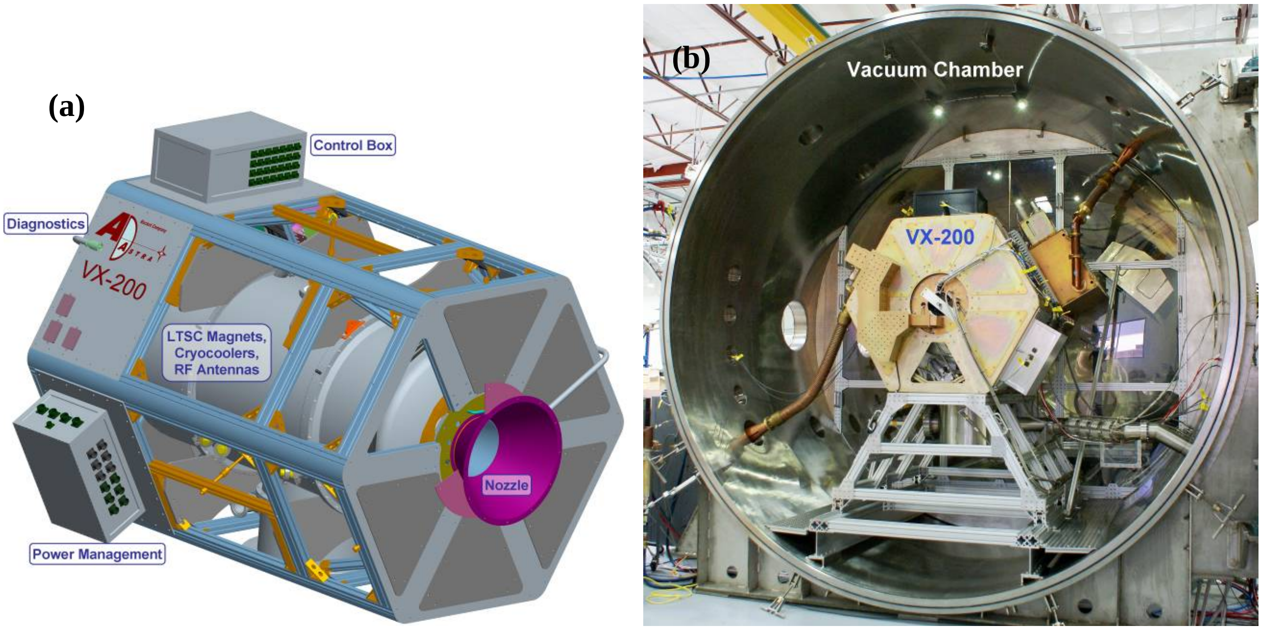

Figure 2. a) Image of a simplified 3-d model of the VX-200 with a point of view from the aft end. b) Photograph of the VX-200 installed in the large chamber at Ad Astra Rocket Company.

superconducting magnet. The VX-200i configuration was used as an interim test (while waiting for delivery of the superconducting magnet) of the non-magnet systems including the solid-state RF generators, control system, propellant feed system, and sensors.

The VX-200 can operate in a long-pulse (only up to 1 minute) mode in the current configuration due to temperature limitations of certain seals and joints. We will use the thermal data gathered from the pulsed operation to design the optimal thermal solution for the actual heat flux. Most VX-200 pulses are between 8 and 15 seconds in length.

The first stage, or helicon stage, launches a right-hand circularly polarized wave into the plasma. The plasma diameter is reduced by more than a factor of 2 as it flows downstream through a ”magnetic choke” and gas containment wall that follows the plasma flux tube. Up to 40 kW of RF power (RF generator limited) can be deposited in up to 150 mg/s of flowing argon plasma. The second stage of the rocket, the RF booster, or Ion Cyclotron Heating (ICH) stage, deposits energy directly into the ions via an ion cyclotron resonance interaction of an ion cyclotron wave that is launched into the plasma by a specially designed proprietary coupler. The exhaust velocity of the ions increases as more RF power couples into the ICH section.

The primary components are the control computer, propellant flow controller, RF generators, and magnet. The rocket is controlled by an Aitech Inc. E900 chassis mounted on the VX-200 inside the chamber. Argon gas flow control is provided by a Moog flow controller that can supply up to 150 mg/s. The other two components are described in the following subsections.

A. High Efficiency Solid-State RF Generators

The VX-200 utilizes two solid-state RF generators developed by Nautel Limited of Canada specifically for this application. The helicon section RF generator converts power supplied at 375 VDC into approximately the industrial standard of 6.78 MHz RF with an efficiency of greater than 92 % at

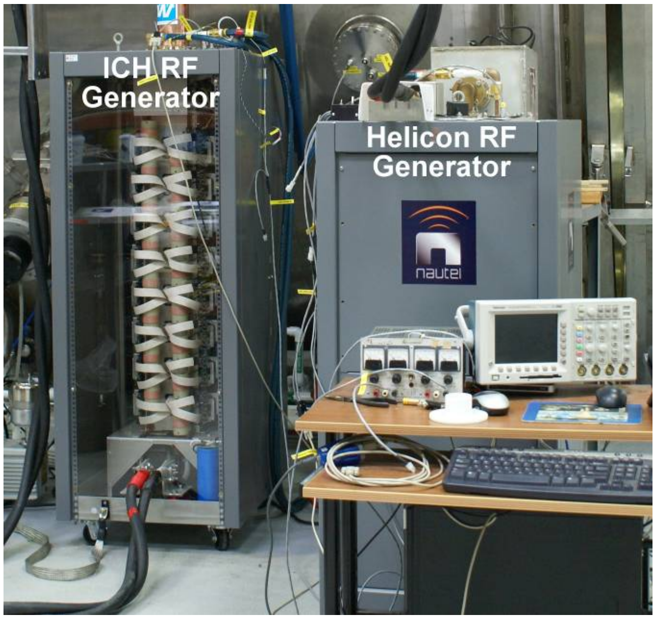

Figure 3. Picture of the ICH and helicon RF generators.

up to 40 kW. The specific mass of the helicon section RF generator is less than 1 kg/kW. The ICH section RF generator converts power supplied at 375 VDC into approximately 500 kHz RF with an efficiency of greater than 98 % at up to 170 kW. The specific mass of the ICH section RF generator is less than 0.5 kg/kW. These RF generators are not located within the vacuum chamber, but transmit the RF into the vacuum chamber and to the VX-200 through high-voltage, high-power RF feedthroughs. The components of the generators were not designed to operate in vacuum to ensure their availability for testing with the VX-200, although they are designed to easily be fitted into a pressurized container that then could be placed within the vacuum chamber.

Figure 4. Photograph of the low temperature superconducting magnet with alignment fixtures mounted to the ends.

B. Low Temperature Superconducting Magnet

The VASIMR® relies on magnetic fields to limit plasma bombardment of the surrounding materials as well as to provide the field strength necessary for ion cyclotron resonance at a frequency that does not excessively excite electrons and limits the ion gyro-radius. The gyro-radius should be much less than the plasma radius, which corresponds to a magnetic field strength of greater than 1T. In order to have an efficient electric propulsion device, the magnet must consume a small amount of power compared to thrust power. The only feasible method to generate such a strong magnetic field in space is with a superconducting magnet. The VX-200 is utilizing a state-of-the-art low temperature superconducting magnet designed and developed by Scientific Magnetics, LLC of the United Kingdom specifically for the VX-200. Figure 4 shows the magnet. The spaceflight VASIMR® will utilize a high temperature superconducting magnet so that the heat-rejection systems that chill the magnet can operate with a high efficiency.

III. Vacuum Facility and Plume Measurements

Ad Astra Rocket Company has a new stainless steel vacuum chamber (see Fig. 5) that was designed for testing the VASIMR® engine. The vacuum chamber is 4.2 m in diameter and 10 m long with a volume of 150 m^3 (including the end caps). One end opens fully for access to the entire inner diameter. The vacuum chamber is partitioned into two sections, a rocket section and an exhaust section. The rocket section stays at a lower pressure than the exhaust section while the VX-200 is firing, to better simulate the environment of space. This is done to prevent arcing and glow discharges near the high voltage transmission lines and matching circuit components. The facility has the capability of pumping more than 200,000 liters/s Argon and 300,000 liters/s Nitrogen with four PHPK Technologies CVI Torr Master® internal cryopumps. Presently, only two pumps are being operated, which reduces the pumping speeds by a factor of two, but allows for adequate pressures to take experimental measurements of first stage performance. The pressure is less than 1×10^{-7} torr before each shot. The pressure rises to a maximum of 4×10^{-4} torr during a shot.

Figure 5. Photograph of the "El Monstruo" large vacuum chamber at Ad Astra Rocket Company.

There is a 2.5 m by 5 m translation stage that carries a suite of plasma diagnostics for plume characterization. The translation stage uses 2 independent ball screws and is driven by vacuum compatible stepper motors which yield a positional resolution of 0.5 mm. A fixed 70 GHz microwave interferometer measures the electron density at the VX-200 exit. Plasma flux measurements are performed using a planar molybdenum 10-collector Langmuir probe array biased into ion saturation and mounted on the translation stage. Retarding potential analyzers (RPA) are also installed on the translation stage to measure ion energy. To determine a quantity for thrust, in addition to the calculated quantity from the other instruments, we rely on a force target technique that has been validated against a Hall thruster on a thrust stand. [9] The force target is a graphite disk mounted to a sensitive strain gauge and scanned across the plasma profile to integrate a total force. The data in this paper results primarily from the Langmuir probe array, since there was an electrical connection problem with the force target.

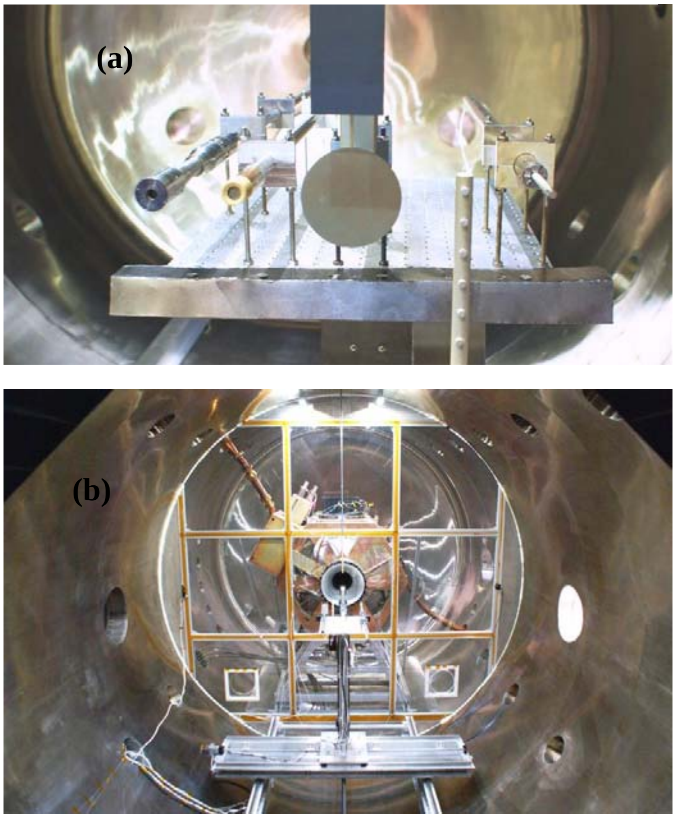

Figure 6. a) Diagnostic package close up picture b) Translation stage from the end of the chamber.

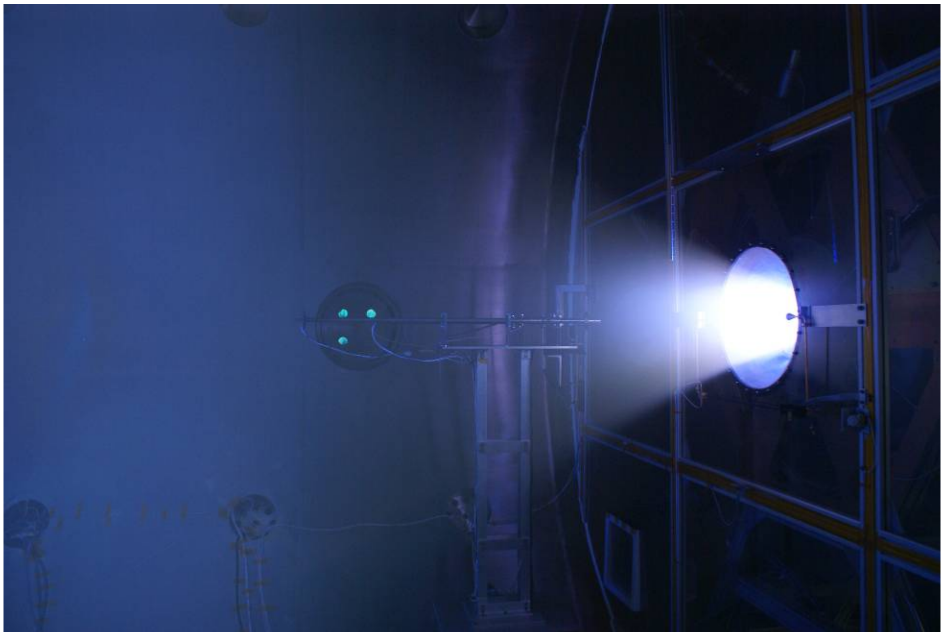

Figure 7. Photograph of the VX-200 plasma plume at full helicon power.

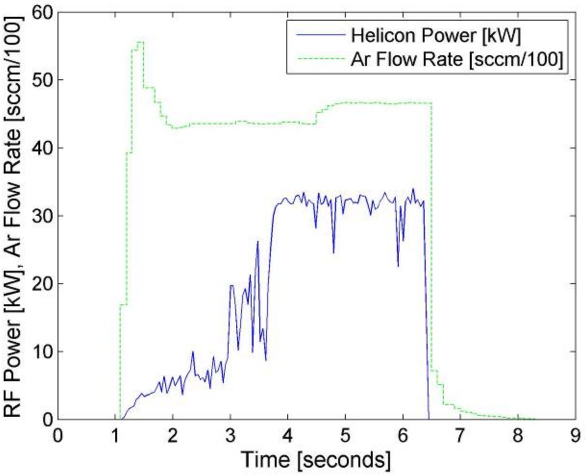

Figure 8. Helicon RF power and argon flow rate as a function of time during a representative shot.

IV. Results

The results from the first experimental campaign of the VX-200 operating at maximum magnetic fields will be presented in this section. The performance of the system is expected to improve as experience is gained with the solid-state RF generators at high powers coupling to plasmas with high magnetic fields. Figure 7 shows a picture of the VX-200 plume with the helicon running at full power.

A. Propellant Input Scan and plasma source performance

To determine the minimum ionization cost, a set of experiments was conducted in which the helicon RF power was set to 32 kW and the propellant flow rate was varied. The plasma flux was measured just downstream of the rocket using the array of planar Langmuir probes. The helicon RF generator was commanded to deliver 32 kW of power for the final seconds (4 to 8 s depending on the conditions) of every shot. It took up to 4 seconds for the RF power to reach the full power state as the plasma transitioned from startup into the helicon mode. In all cases, there was more than one second at the end of each shot with a stable gas flow rate and RF power. See figure 8 for a

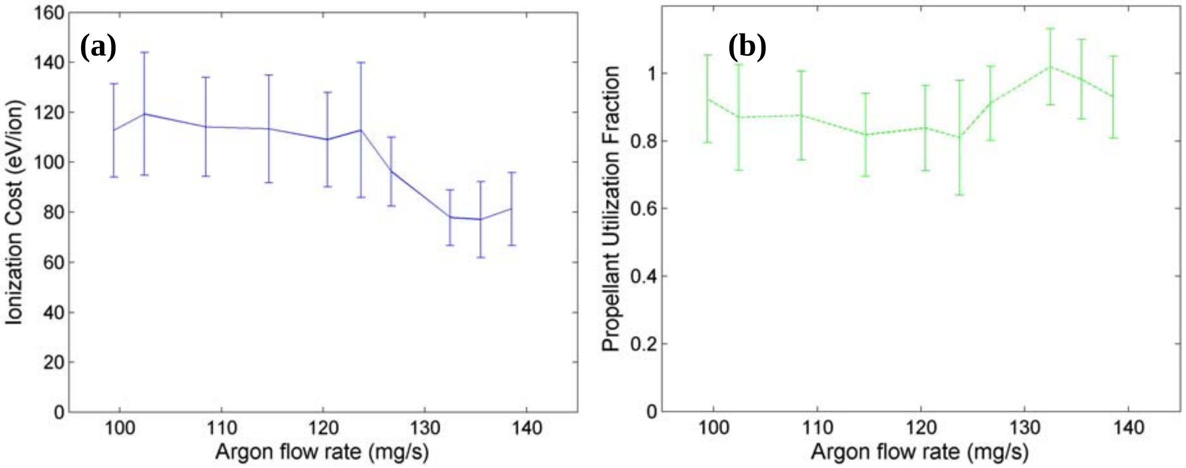

Figure 9. VX-200 results with input helicon RF power of 31.5 ± 1.5 kW. a) Ionization cost as a function of argon flow rate. b) Propellant utilization fraction.

representative shot sequence. The RF power had a standard deviation of 1.5 kW, and the flow rate was varied from 95 to 144 mg/s (3200 to 4850 SCCM) to within 0.3 mg/s (10 SCCM) for those shots.

In order to calculate the ionization cost, the power lost in the RF circuit and carried out of the helicon section as kinetic energy by the ions must be estimated. A network analyzer characterization and circuit current measurement under load determine that the RF transmission system is 95 % efficient; therefore, 30.4 kW of the 32 kW that the RF generator produces is coupled to the plasma. We take that the kinetic energy of the ions leaving the helicon section is 15 eV for all shots. We consider this a conservative value because RPA data obtained from similar discharges in previous VASIMR® experiments,[4] the present experiment,[10] and other helicon thruster results[11] suggest ion energies of 20 eV or greater. The data from the VX-200 experiments are limited because only two weeks of successful shots were possible prior to the beginning of major upgrade work to the experiment.

The ionization cost was at the minimum and propellant utilization fraction the highest with an argon flow rate in the range of 4450 to 4550 SCCM (132 to 135 mg/s), as shown in figure 9. Four more shots were accomplished at a flow rate of 132 mg/s to determine the repeatability of the performance. It was found that the minimum ionization cost was 78 ± 11 eV/ion.

B. RF Booster Power System Test

Although time has not yet permitted both full power helicon and booster operation simultaneously with the VX-200, the second stage RF generator delivered 149.2 kW while operating with the VX-200i plasma load, as a circuit functionality test. Figure 10 shows the time history of the RF power and argon gas flow rate. The helicon RF generator turned off for an unknown reason as the booster RF generator was commanded on in the VX-200i, and operation with the superconducting magnet in the VX-200 proceeded before determining the cause of this problem. Recent experiments at maximum magnetic field in the VX-200 have had the helicon operating at 32 kW with the booster operating at up to 25 kW without a reduction in helicon power. The RF booster plasma load was measured at full magnetic field and the value matched predictions, which means the RF booster circuit couples power to the plasma with better than 95 % efficiency. As of this writing, work continues to push the booster RF generator to full power at full magnetic field.

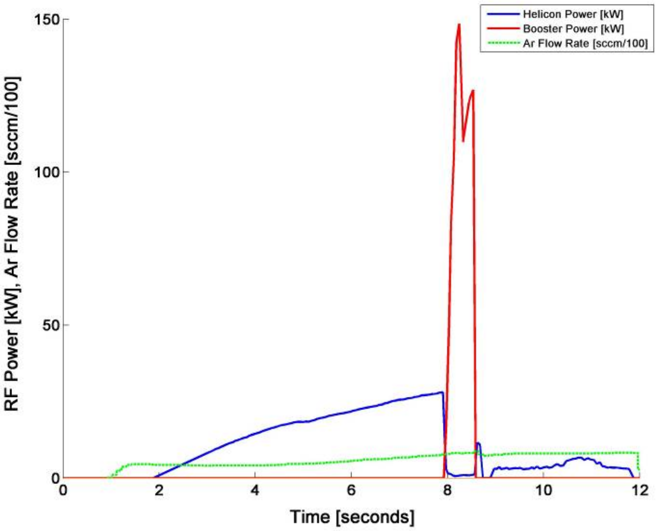

Figure 10. RF power input into VX-200i.

V. Conclusion

A superconducting VASIMR® experiment called VX-200 with a peak magnetic field strength of 2 T is now in operation. The magnet is a state-of-the-art conduction cooled low temperature (5 K) superconductor that is a major step toward spaceflight. High power RF generators with a combined alpha less than 1 kg/kW for both stages have been demonstrated with plasma loads. A high power (32 kW) and high performance helicon plasma source has been operated in the high-strength superconductor-generated magnetic field. The plasma flux is as high as 135 mg/s with a 100 % propellant utilization. Plasma flux measurements show the energy cost for production of a flowing ion-electron pair as 78 ± 11 eV/ion, better than the design specification for the system. The power train of the second stage of VX-200, the RF booster, has been tested with a low field plasma load to a record power of 149.2 kW. RF circuit measurements at high magnetic field show a power coupling efficiency to plasma greater than 95 %. The VX-200 is operating and plume measurements are being performed in a new 150 m^3 vacuum chamber with over 100,000 l/s of pumping.

Work is in progress to operate the VX-200 at full magnetic field strength together with both stages at full power, totaling 200 kW. Detailed plume measurements will be carried out to determine a total input DC to output jet power efficiency and a value for thrust. Plume expansion characterization over a scale length greater than 2 m is also an experimental goal.

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