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VASIMR® Technological Advances and First Stage Performance Results

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A 200 kW VASIMR® engine designed specifically to demonstrate the end-to-end DC electrical power conversion to thrust power has undergone initial testing in a new vacuum facility and successfully operated with a low temperature superconducting magnet, two solid-state RF generators, and improved RF coupler designs. This engine is given the name VX-200 for a VASIMR® experimental device that operates at 200 kW input electrical power. The VX-200 has shown through its successful operation that the primary technologies required for a spaceflight version of the VASIMR® are compatible with each other and can operate at practical efficiencies. The first stage, or helicon section, of the engine has operated at full power with maximum magnetic field. The second stage, or booster, has operated at nearly full power with a lower magnetic field. Ion flux measurements were taken in a new 150 m^3 vacuum chamber with 100,000 liters/second of pumping that contained the VX-200. The first stage generated an argon plasma jet with a cost to extract an electron-ion pair of 78 $\pm$ 11 eV/ion at 32 kW and a flow rate of 135 mg/s. A record power of 149.2 kW was coupled to the plasma with the booster RF coupler.

I. Introduction

High-power electric propulsion systems have the capability of reducing the propellant mass for heavy-payload orbit raising missions and cargo missions to the moon and can even reduce the trip time of piloted planetary missions.[1–5] The Variable Specific Impulse Magnetoplasma Rocket (VASIMR®), is one of the few electric propulsion devices capable of processing a great amount of power (>100 kW) with a long lifetime. A simplified concept is shown in figure 1. The advantages of the VASIMR® are high power, high specific impulse, and potentially long lifetime due to the magnetic control of the plasma stream. The rocket relies on efficient plasma production in the first stage using a helicon plasma source.[6,7] 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. End-to-end testing of the VASIMR® with spaceflight relevant components, the optimum magnetic field configuration, and a vacuum facility large enough and with enough pumping to allow for plume measurements with low background pressure had not been achieved until recently. The VX-200 operating in a new, large vacuum facility have demonstrated that the VASIMR® does operate as a system and efficiently produces plasma.

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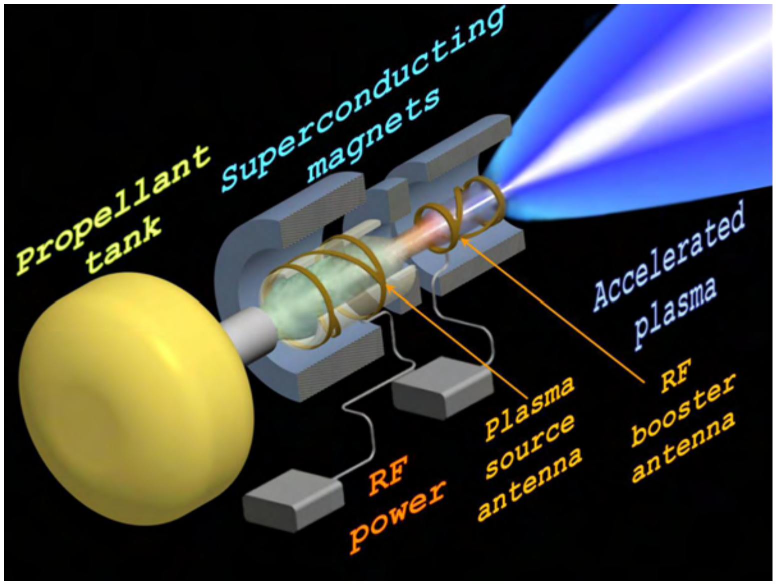


Figure 1. Image of the VASIMR concept.

Previous VASIMR® experiments were accomplished with magnetic field strengths that did not allow for efficient ion cyclotron heating of argon, background pressures that could have affected plume measurements, and components that were not spaceflight relevant. The previous version of the VASIMR®, the VX-100, utilized a vacuum tube RF amplifier for the first stage and water-cooled copper magnets.[8,9] A vacuum tube amplifier and copper magnets are too massive for use in a spaceflight device. Also, the vacuum facility at the Advanced Space Propulsion Laboratory reached pressures of greater than 10 millitorr during rocket operation, which could have affected performance measurements. The results were very promising, with argon ion production costs of 80 eV/ion and significant acceleration of neon and deuterium via ion cyclotron heating, but improvements in the rocket components and testing facilities were required.

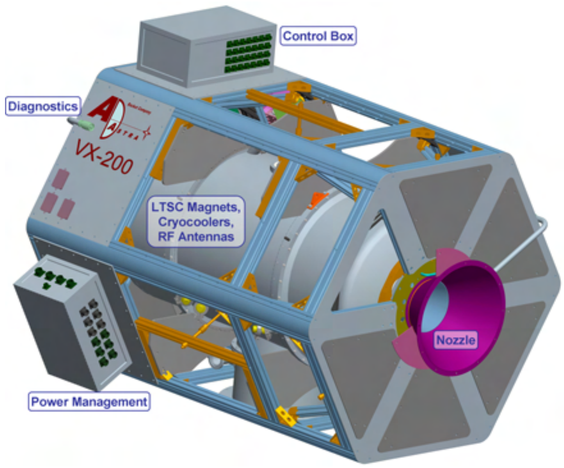
In this paper we demonstrate that a VASIMR® comprised of mostly spaceflight relevant components can operate together as a system and produce an argon plasma efficiently. We present results of a new VASIMR® engine, the VX-200, that uses spaceflight relevant components and was tested within a new vacuum chamber capable of providing pressures below 4×10^{-4} torr during plasma operations. Plasma flux, RF power measurements, and neutral argon gas flow rate measurements, combined with knowledge of the kinetic energy of the ions leaving the rocket are used to show ionization cost of the argon and propellant utilization fraction.

We first present a description of the VX-200, and the vacuum facility that it operates in. Next, we present the experimental results.

II. The VX-200

The VX-200 is an experimental version of the VASIMR® engine that utilizes 200 kW of input DC electrical power. The rocket was 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 and the picture of the rocket installed inside the vacuum chamber. A key component of the VX-200 is the superconducting magnet with a maximum field of approximately 2 Tesla that allows for efficient 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 superconducting magnet. The VX-200i configuration was used to test the non-magnet systems while



(a) Image of simplified 3-D model of the VX-200 with a point of view from the aft end.

(b) Picture of VX-200 installed in the large chamber at Ad Astra Rocket Company.

Figure 2. The VX-200.

waiting for delivery of the superconducting magnet, including the solid-state RF generators, control system, propellant feed system, and sensors with the water-cooled magnet.

The VX-200 can operate in a long-pulse (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 containment wall that follows the plasma flux tube. Up to 40 kW of RF power (RF generator limited) can be deposited into up to 150 mg/s of flowing argon plasma. The second stage, or Ion Cyclotron Heating (ICH) stage, deposits energy directly into the ions via ion cyclotron resonance interaction of an ion cyclotron wave that is launched into the plasma via a specially designed, proprietary coupler. The exhaust velocity of the ions increases as the RF power is coupled into the ICH section increases.

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. 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 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 ~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 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.

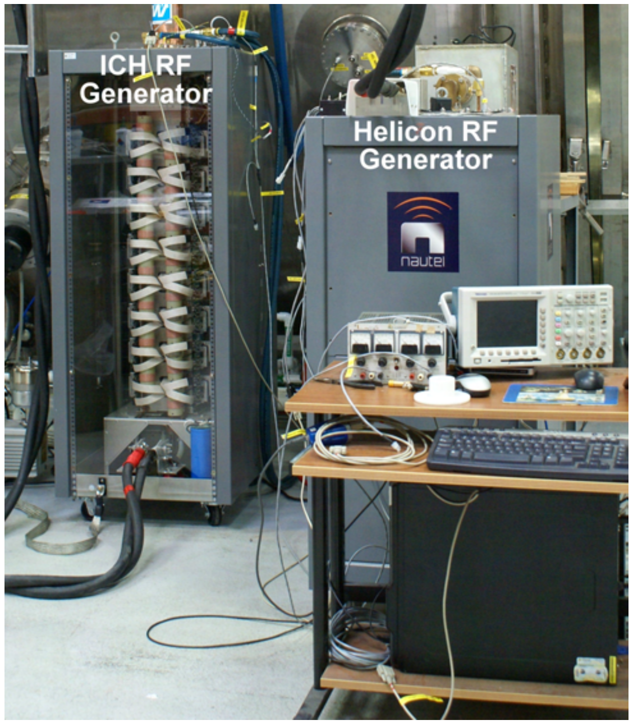


Figure 3. Picture of ICH RF generator and the helicon RF generator.

B. Low Temperature Superconducting Magnet

The VASIMR® relies on magnetic fields to limit plasma contact with 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 cyclotron radius. The gyro radius should be much less than the plasma radius, which corresponds to a field strength of greater than 1 T. 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. The magnet is shown in figure 4. 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

Ad Astra Rocket Company has a new stainless steel vacuum chamber (see figure 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-200i is firing. This is done to prevent arcing and glow discharges near the high voltage transmission lines and matching circuit components. 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. The facility has the capability of pumping 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 4. Picture of low temperature superconducting magnet with alignment fixtures mounted to the ends.

Figure 5. Picture of the "El Monstro" large vacuum chamber at Ad Astra Rocket Company.

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 6 shows a picture of the VX-200 plume.

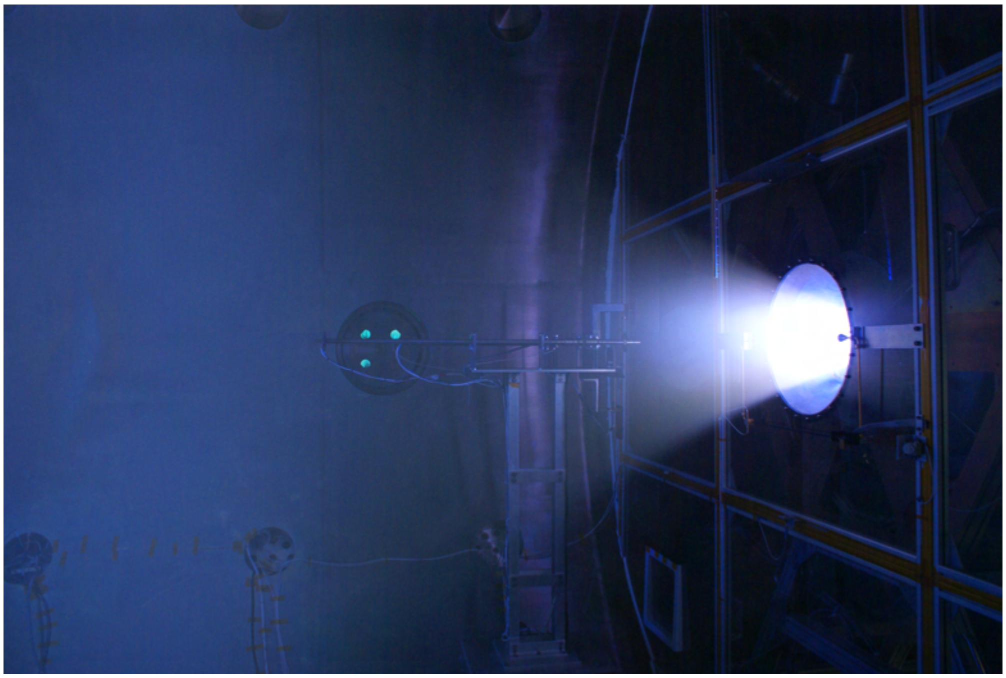


Figure 6. Picture of VX-200 plasma plume.

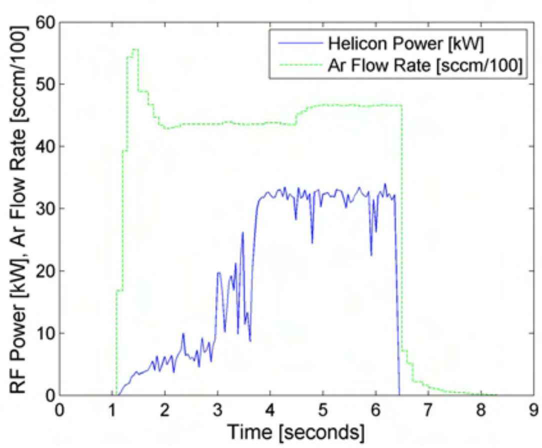
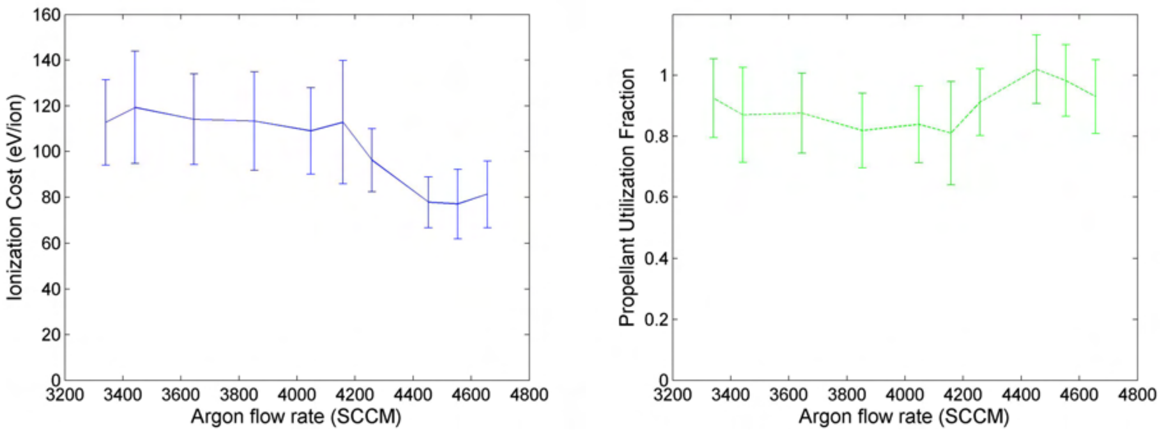


Figure 7. Helicon RF power and argon flow rate as a function of time throughout a shot.

A. Gas Flow Rate Scan

To determine the minimum ionization cost, a set of experiments were conducted where 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 an 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 being off 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 7 for a 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.



(a) Ionization cost as a function of argon flow rate.

(b) Propellant utilization fraction.

Figure 8. VX-200 experimental results. The input RF power is 31.5 ± 1.5 kW.

In order to calculate the ionization cost, the power lost in the RF transmission line and carried out of the helicon section as kinetic energy by the ions must be estimated. 30.4 kW of the 32 kW that the RF generator produces is coupled to the plasma because the RF transmission system is 95% efficient. The circuit resistance is 100 $m\Omega$ and the plasma loading is about 2 Ω, giving the above efficiency. We assume 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,[9] the present experiment, and other helicon thruster results[10–12] 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 deadline for this paper.

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 8. 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. Booster power

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. Figure 9 shows the time history of the RF power and argon gas flow rate. The helicon RF generator turned off for an unknown reason as booster RF generator was commanded on in the the VX-200, 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. As of this writing, work continues to push the booster RF generator to full power at full magnetic field.

V. Conclusions

The VX-200 experiments have demonstrated that the solid-state RF generators successfully operate with a superconducting magnet at maximum magnetic field strength. The first stage has been shown to produce an argon plasma jet with a low ionization cost of 78 ± 11 eV/ion. The second stage has been shown to operate at moderate powers, and work continues to operate at full power. The large vacuum chamber with its high

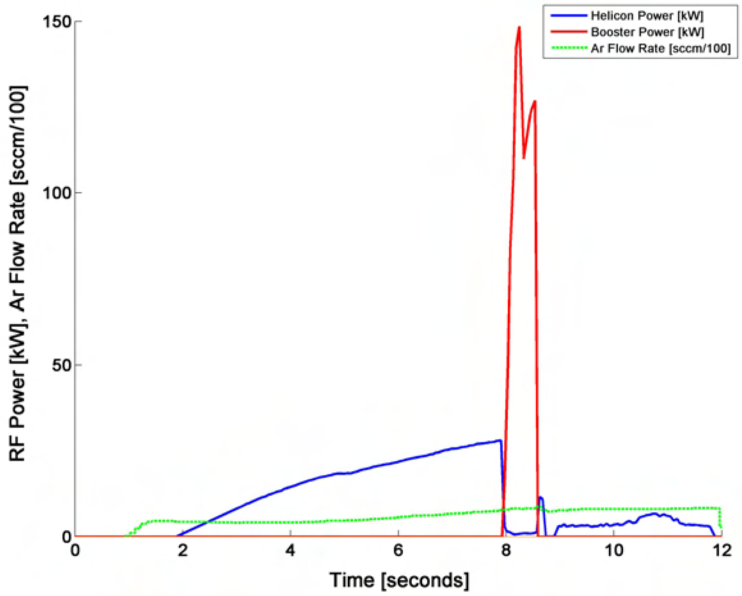


Figure 9. RF power input to VX-200i.

pumping has reduced the effects of background gas and wall interaction on the performance measurements.

Ad Astra Rocket Company will continue to test the VX-200 until a total of 200 kW is input to the rocket and a high overall efficiency is achieved. A wide range of plume diagnostics will be utilized to characterize the plasma, including RPAs, multiple flux probes, force targets, and magnetic field probes.

Acknowledgments

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