High Power VASIMR Experiments using Deuterium, Neon and Argon

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Abstract: We have significantly upgraded the capability of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) experiment (VX-50) to process over 50 kW of total Radio Frequency (RF) power. The VASIMR system is comprised of three main stages, plasma production using a helicon, ion cyclotron resonant frequency (ICRF) acceleration, and exhaust into a magnetic nozzle. Power capability of up to 30 kW is demonstrated in the plasma source and over 30 kW is coupled into the ICRF stage. Efficient plasma production is achieved with ion-electron pair investment costs of 100 eV. We measure plasma flux exceeding 10^{21} ion/s. Significant ion acceleration is observed using deuterium, neon and argon. Ion energies in excess of 300 eV are measured, with calculated ion velocities from 30 to 150 km/s. Efficient coupling of the RF power to the plasma (90 %) is also demonstrated. Calculated momentum flux is as high as 0.5 N. We introduce a new more powerful and optimized device, VX-100. This device is designed to rapidly develop spaceflight-like components and test system operation in excess of 100 kW.

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Nomenclature

η_A = antenna plasma coupling efficiency. Plasma load resistance divided by the total of the circuit plus plasma load resistances.

η_B = ion energy boost efficiency. Ion exhaust power divided by the coupled ICRF power.

f_{ci} = ion cyclotron frequency.

$ICRF$ = ion cyclotron resonant frequency.

I. Introduction

The VASIMR propulsion concept has been described in many publications and the advantages discussed.[1,2,3] VASIMR fundamentally is attractive at high power, >100 kW, due to its high power density RF coupling to a magnetized plasma stream, without DC electrodes. The efficiency of the RF coupling to the plasma, the plasma production by RF wave absorption, and ion acceleration by ion cyclotron resonance are critical functions of this rocket system. The first stage of VASIMR consists of a helicon[4,5] plasma source. Utilizing this type of source at substantial power, > 10 kW, to directionally produce a plasma flow into a high magnetic field, ~ 1 T, with no wasted propellant, is a key challenge of our development. Scaling to high magnetic field and power has proven to enhance the plasma production efficiency.[6] Producing the plasma with an ion-electron investment cost of 100 eV or less is important for achieving a good total rocket efficiency. Demonstrating these features has been one of our main experimental goals and we present data that indicate our achievement of these goals.

In the second stage, we have the challenge of efficiently coupling high RF power to the ion cyclotron wave[7] to ion cyclotron resonant frequency (ICRF) accelerate the ions[3] and efficiently transition the ions axial motion in the subsequent expansion in a magnetic nozzle. This process has been shown to be effective for light gasses at modest power.[6,8] Other experimenters have also demonstrated this process.[9] We present here the demonstration of this process at over 20 kW with deuterium, without evidence of nonlinear saturation. Another important capability to

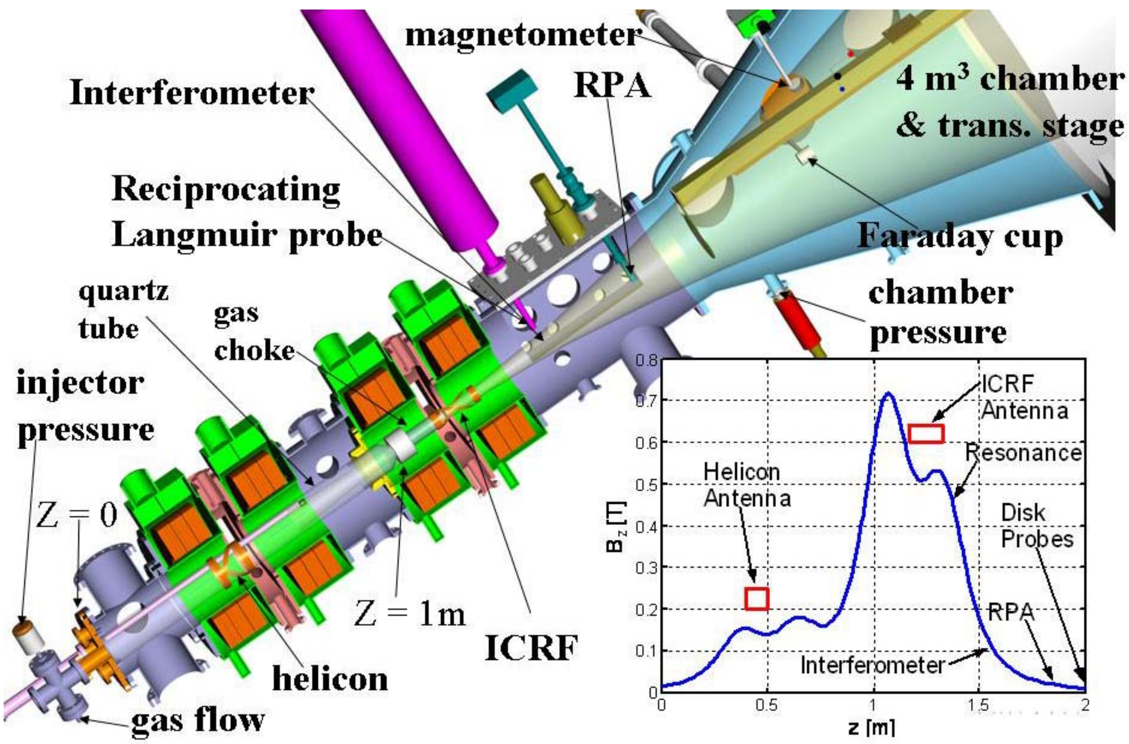

Figure 1. VX-50 configuration.

explore is the application of these techniques to much heavier atomic species, such as argon. This enables the efficient operation of the rocket at lower specific impulses, ~ 4000 seconds. We present data to support the conclusion that VASIMR can efficiently operate at high power with argon as a propellant. Efficient operation with neon is also demonstrated.

Most recently, we have a rapid engineering development effort to bring these exciting results to practical application. A major step in this direction is the replacement of the NASA-developed physics demonstrator, VX-50, with a new higher power and optimized experimental device, VX-100, designed and built solely by the Ad Astra Rocket Company. We also present recent performance results from this new device.

II. Experiment Configuration

The majority of the data were taken in the VASIMR experiment (VX-50) that is shown in Fig. 1. Figure 1 also shows a typical axial magnetic field profile for deuterium operation. The magnetic field is generated by four cryogenic electromagnets that are integrated into the vacuum chamber and are driven independently. The peak magnetic field capability is 1.4 T. The helicon plasma source section has a magnetic field of up to 0.4 T. The magnetic field peaks downstream and then plateaus at up to 1 T, where the ICRF antenna is located. The magnetic field then expands into a large vacuum chamber. A quartz tube with an inner diameter of 9 cm is sealed against the upstream end plate and passes through the helicon antenna. It stops just upstream of the ICRF antenna. A quartz gas baffle is located at the peak of the magnetic field to help prevent neutral gas from escaping the plasma source and to act as a plasma limiter for the ICRF antenna. Deuterium, neon and argon gasses are regulated through the end plate into the quartz tube.

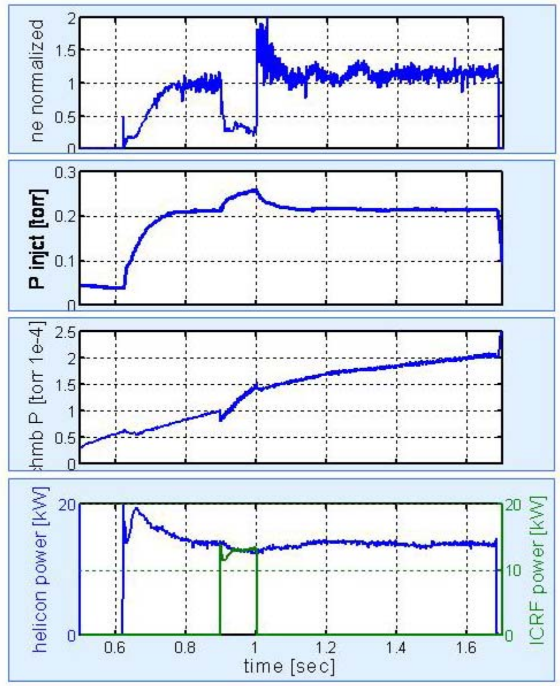

Figure 2. Temporal plots of electron density, pressure of the neutrals injected into the helicon, pressure in the main chamber and RF power.

The total RF power capability of the system is over 50 kW. The helicon plasma source is driven by a 25 kW RF transmitter at 13.56 MHz. For deuterium experiments, the ICRF system is driven by a 25 kW transmitter operating from 2 to 4 MHz; the drive frequency for ICRF powered experiments is 3.6 MHz. For neon and argon experiments, the ICRF system is driven by a 50 kW highly efficient solid-state transmitter (Nautel Limited) operating at 300 and 550 kHz. Plasma loading measurements were performed using a network analyzer and the high Q resonant impedance matching circuit.

The primary plasma diagnostics include a 70 GHz density interferometer located approximately 0.2 m downstream of the ICRF antenna, a reciprocating Langmuir probe with a molybdenum tip biased into ion saturation, two independently designed retarding potential analyzers (RPA) for ion energy measurements, a swept RF compensated Langmuir probe to measure local plasma potential, and an array of 10 planar flux probes made of 25 mm diameter tungsten disks facing into the plasma flow and biased into ion saturation. Neutral pressure is monitored at the gas injection and in the expansion chamber. Light emission spectra are monitored to assure that impurities in the plasma are not a large effect.

Plasma flux measurements are performed using two separate instruments for cross verification. The first is the reciprocating Langmuir probe; with the second the planar tungsten flux probe array. The interferometer in the same axial region is also used to verify consistency of the data.

Figure 2 shows the temporal behavior of a typical discharge. The pulse length is limited to about one second, mostly because of the neutral pressure buildup in the expansion chamber. Once the input gas flow reaches the set point, the helicon RF power is applied. When the discharge is established, the pressure at the injection point increases by almost a factor of 10 to over 0.3 torr. We apply the ICRF power once the discharge appears to reach a steady state. The ICRF pulse typically lasts for 300 ms.

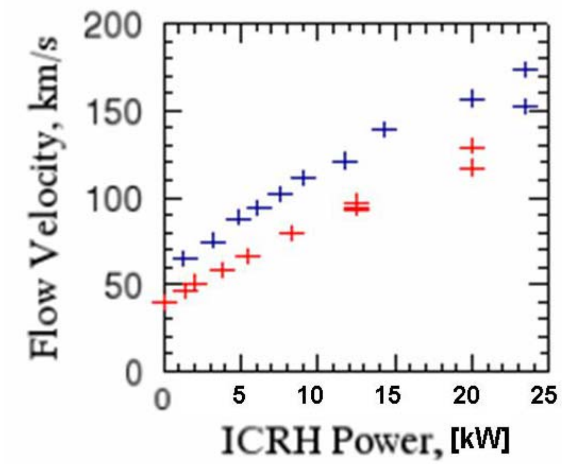

Figure 3. Ion flow velocity versus ICRF power as measured by the RPA, two component fit.

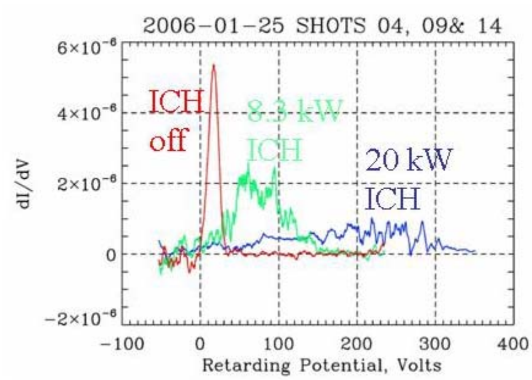

Figure 4. The derivative of the RPA characteristic for three different ICRF power levels. This indicates the ion energy distribution acceleration..

III. VX-50 Experimental Data

A. Acceleration of Deuterium

ICRF acceleration experiments are carried out using deuterium with powers exceeding 20 kW. We measure significant ion flow energies exceeding 200 eV. Two different designs of gridded RPAs are used to measure the ion energies for cross verification. Figures 3 and 4 show representative data from ICRF power scans. We observe ion energies up to 300 eV and calculate bulk exhaust flow velocity well over 100 km/s, which corresponds to a potential specific impulse in excess of 10,000 seconds. The calculated momentum flux is 0.15 to 0.2 Newtons. Preliminary impact target experiments confirm a significant momentum flux in the flow due to ICRF action.

We have confirmed and optimized the plasma coupling performance by examining the plasma loading behavior as a function of frequency near the resonant frequency. We performed a shot-to-shot frequency sweep of the plasma loading, with highly repeatable plasma conditions. We find a clear peak of almost 2 ohms when the resonance is located at the downstream end of the ICRF antenna. This is consistent with computational modeling using the EMIR code.[10,11] Figure 5a shows the plasma loading plotted as a function of the drive frequency normalized to the ion cyclotron frequency, f_{ci}, at the center of the antenna. Quantities of $f/f_{ci} < 1$ place the resonance downstream of the antenna center. The peak in the loading at $f/f_{ci} = 0.95$ indicates that the RF power is propagating downstream and taking axial distance to penetrate into the plasma. With a circuit resistance of 0.24 ohms, a plasma coupling efficiency (η_A) of over 90% is achieved (Fig. 5b). This is critical for an efficient rocket. We chose to run ICRF power experiments with the resonance about one antenna diameter downstream, putting the normalized frequency at $f/f_{ci} = 0.9$ and f = 3.6 MHz.

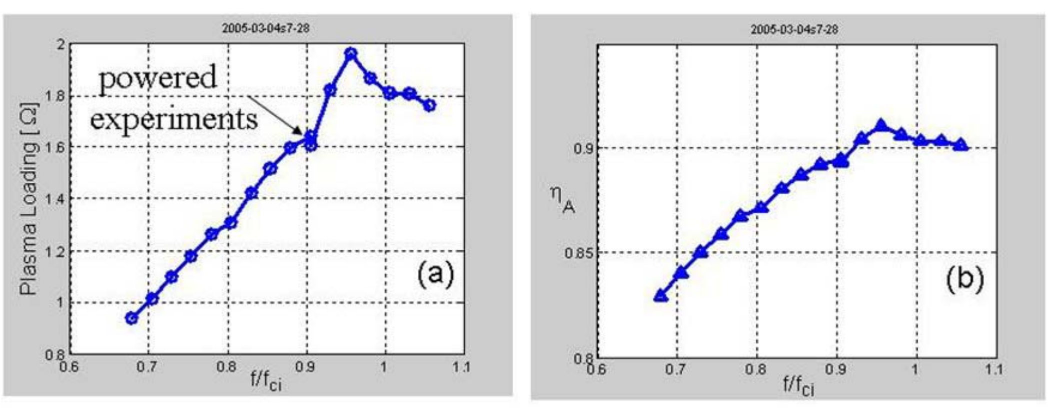

Figure 5. a) ICRF antenna plasma loading measurements for a range of frequencies, f_{ci} = 4 MHz at the center of the antenna. Indicates the loading point where high power was applied. b) Antenna circuit efficiency for coupling power to the plasma, exceeding 90 %.

B. Plasma Production with Argon

With argon gas, a plasma source energy investment cost of approximately 100 eV per ion-electron pair is measured, as Figure 6 shows. A 100 % propellant utilization was also maintained with an ion flux exceeding 4×10^{20}/sec, where the ion flux, measured by two separate diagnostics, equals the input neutral flux. The source performance was found to improve with higher applied magnetic fields at the helicon antenna, up to 0.38 T for the data shown here. Higher plasma fluxes were limited by the mass flow controller in this experiment and vacuum pumping. The other propellants perform well, with ionization costs closer to 150 eV.

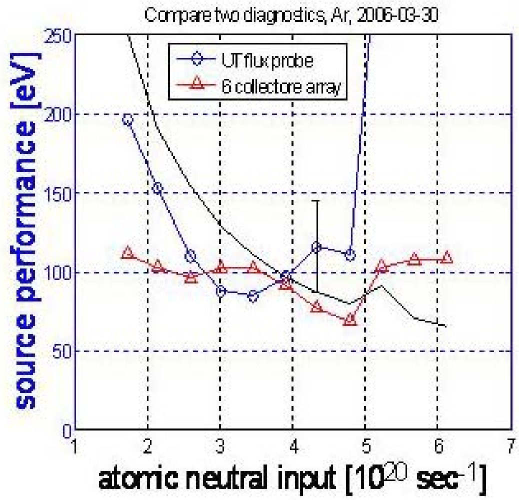

Figure 6. Ion-electron energy cost measured verses a neutral gas input scan.

C. Acceleration of Argon

With an efficient argon plasma source, we proceeded to demonstrate efficient ion acceleration, as we observed with deuterium. Given the limited magnetic field capability of VX-50, we set the ICRF transmitter frequency to 300 kHz. The ICRF antenna location and design was similar to the deuterium configuration. However, it was modified to adjust for the lower frequency. The acceleration results are similar to the deuterium case reported above. The charge exchange reaction, however, is more evident in the data because of the large atomic background pressure due to the large mass flow of argon. Figure 7 shows the signature density drop due to acceleration, although now observed in two locations because of the addition of a second density interferometer further downstream. The chamber pressure effect is evident in the downstream location by noting the steady density rise through the shot as the plasma slows down by charge exchange.

Power of over 30 kW was applied and ion energies of over 200 eV were observed. Figure 8 contains the derivative of the RPA characteristic that indicates the ion energy distribution. We have identified an upper limit of the ion energy in this case and surmise that this is due to finite Larmor radius (FLR) effects because at these energies the ion orbit size is comparable to the plasma size. We fit the RPA data with a two component distribution model and conclude that the slower component is a result of charge exchange. The slower component flows at the same speed as without ICRF applied and the relatively slow population is smaller early in the shot when the chamber pressure is lower. Therefore, the fast component is indicative of the plasma stream velocity without the background neutrals. A fast component flow velocity of nearly 30 km/s is achieved, as Figure 9 presents.

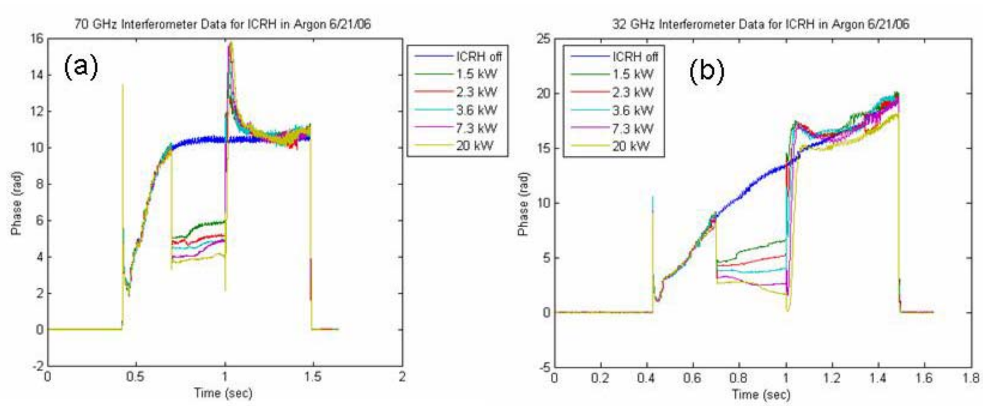

Figure 7. a) 70 GHz interferometer data located near the plasma exit. b) 32 GHz interferometer data located about 0.5 m downstream. Both show the signature density drop due to plasma acceleration.

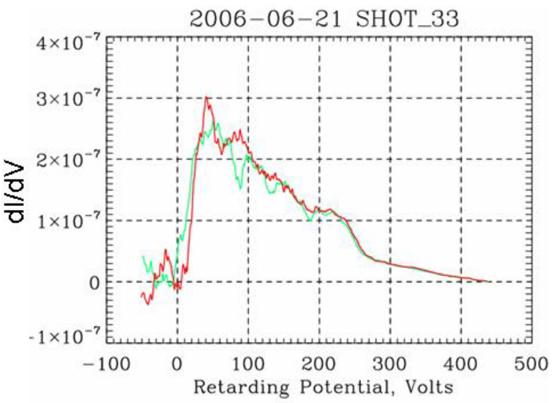

Figure 8. Ion energy distribution.

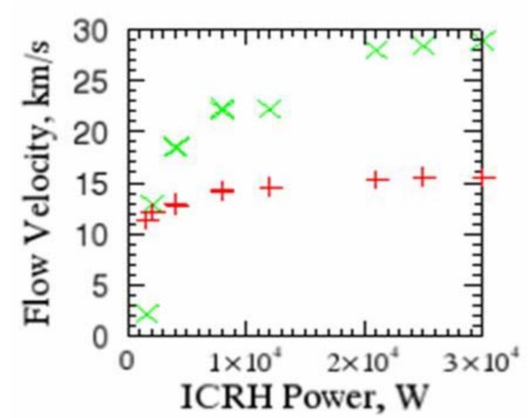

Figure 9. Flow velocity for a two component fit..

D. Acceleration of Neon

Due to the limited magnetic field capability of VX50, we used neon to represent the achievable results for argon at double the magnetic field strength. By using neon, we were able to nearly double the applied ICRF frequency to 550 kHz. This reduces the Larmor radius by a factor of nearly four for the same ion energy. We applied ICRF power again up to 30 kW, limited only by an RF arc due to the difficult vacuum conditions. The ion energy measurements do not indicate a limit to the ion energy. Bulk plasma flow velocities were measured at about 40 km/s, Figure 10a. This time, we also made a flow velocity measurement by combining the plasma flux density profile measured by the probe array together with a microwave interferometer measurement of density along the same chord, Figure 10b. We also had a second RPA of a different design operating. There is good agreement from the multiple diagnostics and analysis methods. The calculated momentum flux is $0.5 \pm 0.1N$ and the ion energy boost efficiency is $\eta_B = 65 \pm 15\%$, in good agreement with predictions. The charge exchange component in the plasma flow appeared to have less impact in these experiments. We believe that the intense plasma flow has pushed the neutral atoms from the core of the stream in the exhaust where these measurements were made.

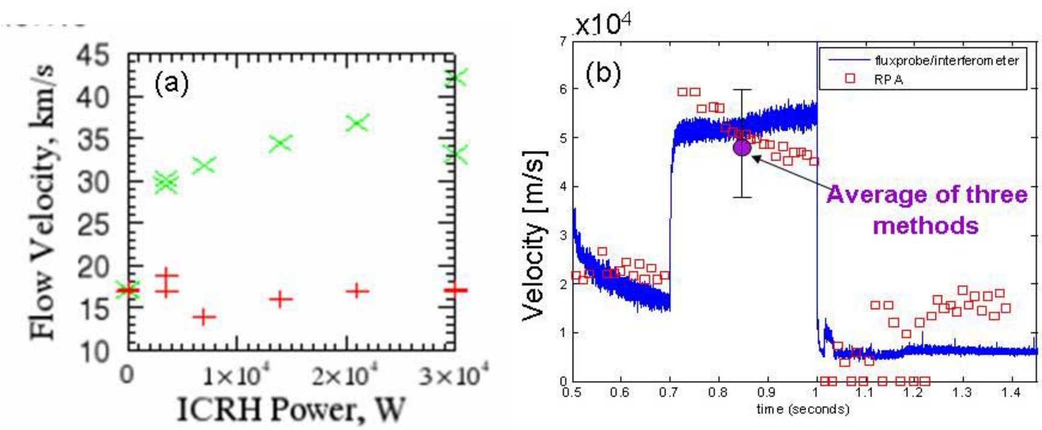

Figure 10. a) Two component ion velocity measured by an RPA show the fast component at 40 km/s with 30 kW. b) Data from another RPA and the velocity calculated from the flux and density measurements.

IV. A New Experimental Device and the Future

With the demonstration of the neon plasma acceleration, VX-50 had reached its limit of usefulness for demonstrating the effectiveness of the VASIMR plasma physics processes. We have produced a much more optimized and capable device for continuing experiments at power levels in excess of 100 kW, which we refer to as VX-100. Figure 11b contains a photograph of this device running an argon discharge. Figure 11a shows the

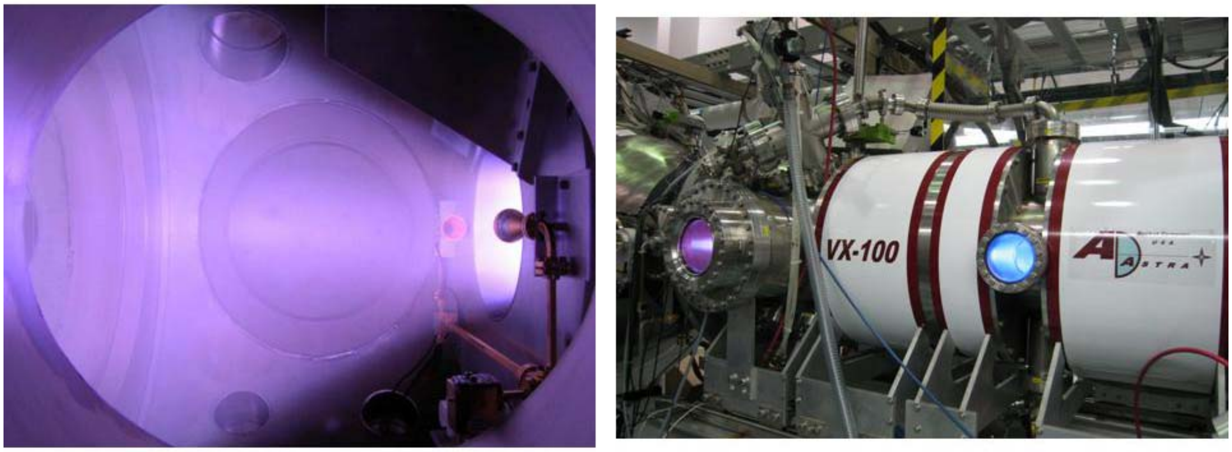

Figure 11. a) Photo of the exhaust of VX-100 with argon. b) Photo of VX-100 operating.

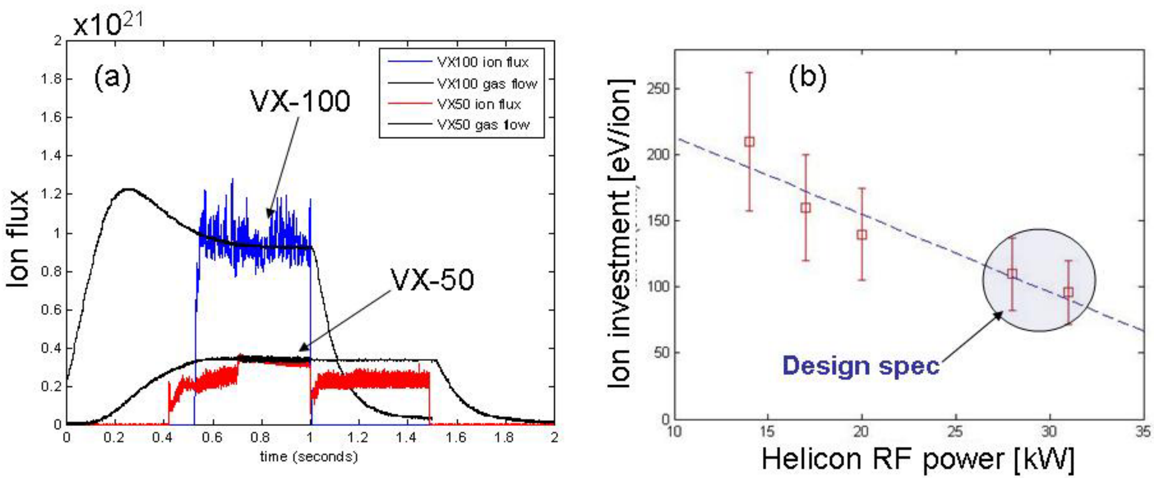

Figure 12. a) Plasma flux versus time for typical VX-100 and VX-50 discharges. b) Ion-electron pair investment cost for a power scan.

exhaust with the helicon running at high power. A 70 GHz density interferometer right at the plasma exit can be seen in the photo. The purpose of the VX-100 device is to demonstrate full power components that are relevant to a spaceflight-capable rocket and to measure end-to-end plasma performance in the laboratory. The magnet system is water cooled and capable of a steady-state peak magnetic field of 2 T.

A. VX-100 Performance Results

We have operated the VX-100 helicon at up to 30 kW with argon. The plasma source operates with the desired performance. The plasma flux of VX-100 is triple the capability of VX-50, over 10^{21} ions/second, and 100% propellant utilization is maintained (see Fig. 12a.) Figure 12b presents the ion-electron pair energy investment cost measured with an RF power scan. The performance improves with higher power, with the power only limited by our RF source. At full power, the density

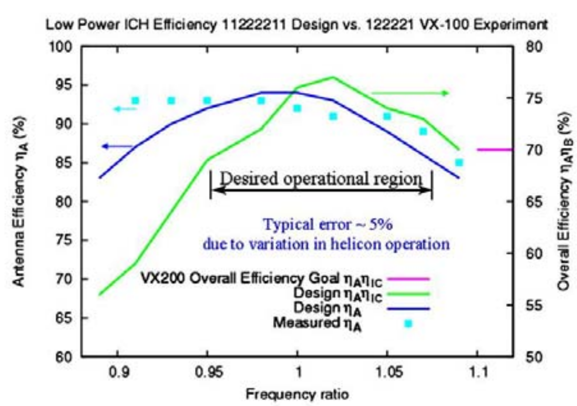

Figure 13. Antenna efficiency for a range of frequencies.

interferometer was having difficulty measuring a reliable density, over 10^{19} m^{-3} at the exit.

Efficient ICRF coupling to the plasma stream has also been demonstrated for argon, > 90 %, as was done with deuterium. We measured the plasma antenna loading and circuit efficiencies. The results are contained in Figure 13, where we plot the antenna coupling efficiency for a frequency scan. We also present the predicted ion energy boost efficiency, η_B, which should exceed 80%, based on the same modeling predictions that were in good agreement with VX-50 results. High power experiments to measure this have begun.

B. Significant Vacuum System Upgrade

To support the testing of the VX-100 device and future spaceflight relevant devices, we have invested in the installation, late this year, of a 120 m^3 vacuum chamber with a significant cryopumping capability, initially 200,000 liters/s. A rendering of the vacuum chamber upgrade is contained in Figure 14. We are increasing the chamber size and pumping by more than an order of magnitude from the system used in the experiments described above. Even so, the VX-100 output will seriously task the new capacity.

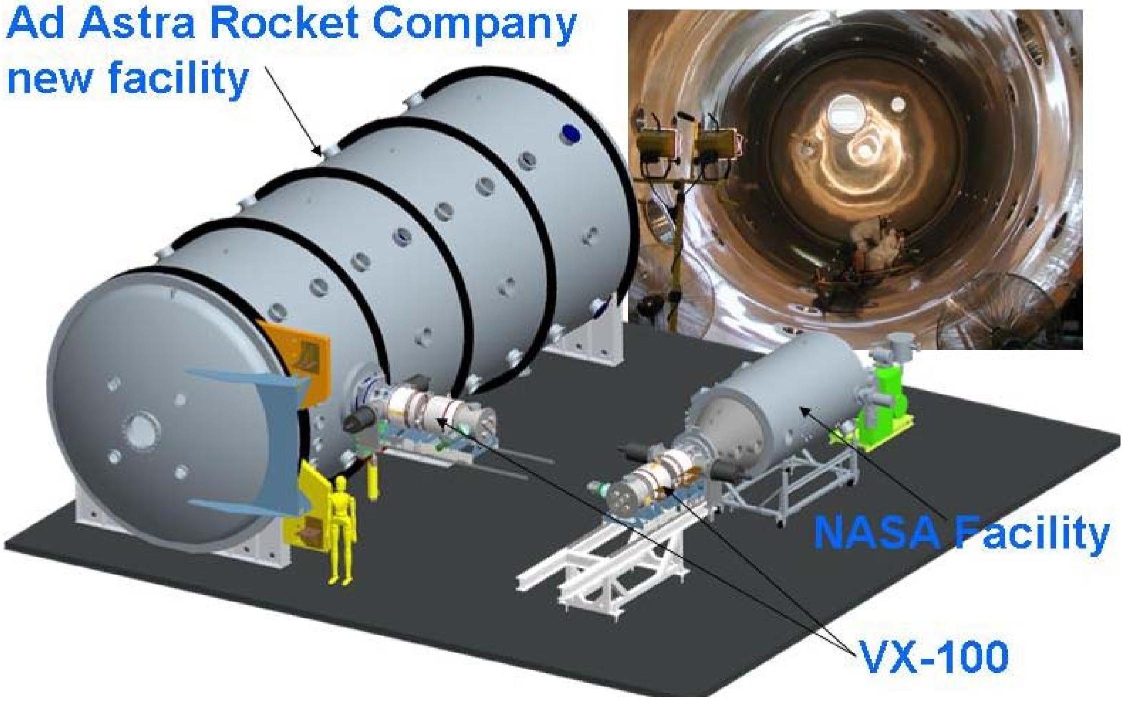

Figure 14. Ad Astra Rocket Company's new vacuum facility for testing VASIMR engines.

C. An Integrated Superconducting Device, VX-200.

We are presently developing a 200 kW device, VX-200, with superconducting magnets and highly efficient solid state RF transmitters. The integrated experimental system is intended for full vacuum operation and end-to-end system performance measurements. The transmitters are being developed by Nautel Limited, leaders in high power solid state RF systems, and conversion (DC to RF) efficiencies are expected to exceed 90%. The system performance models based on experimental results are very promising. Tests will begin by 2008.

V. Conclusion

We have tested the VASIMR plasma system at total power levels exceeding 50 kW and high magnetic fields. No fundamental power limits have been identified and in fact, performance improves at the higher power levels. The plasma production efficiency and Ion Cyclotron Resonant Frequency (ICRF) acceleration experiments have produced promising results. Furthermore, these processes have been tested with heavier atomic species, neon and argon. These results show that the VASIMR system is capable of utilizing a broad range of propellants and has the ability to efficiently operate at lower specific impulses, ~ 4000 seconds, and well above 10,000 seconds. Development of a practical spaceflight device is proceeding.

Acknowledgments

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