VASIMR Performance Measurements at Powers Exceeding 50 kW and Lunar Robotic Mission Applications

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Efficient plasma production and acceleration is observed in a new high power Variable Specific Impulse Magnetoplasma Rocket (VASIMR^{TM}) experiment, the VX-100, using argon propellant. The Radio Frequency (RF) power exceeds 50 kW. A 100 % propellant utilization is achieved with ion fluxes up to 1.7×10^{21}/sec. We measure an ionization cost of 80±10 eV per ion-electron pair. Bulk argon ion flow velocities are measured up to 20 km/s. Thrust values based on plasma exhaust measurements exceed 1 N. A 200 kW superconducting device, the VX-200, and 150 m^3 vacuum facility are described.
We outline the operations concept for a solar-electric lunar cargo tug whose performance is extrapolated from the VX-100 experiment results. Due to the 5,000 second specific impulse of the VASIMR engine, the fraction of the initial mass in low Earth orbit (IMLEO) that arrives in low lunar orbit (LLO) is approximately double that of a chemical propulsion system that performs at a specific impulse of only 450 seconds. The effect of space photovoltaic power cost on the economic advantage of the solar-electric system is examined.

1. Introduction

Over the past two years, the Ad Astra Rocket Company has upgraded the capability of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR^{TM}) experiment [1] to process up to 100 kW of total Radio Frequency (RF) power. This new device is called the VX-100 and is a precursor to a 200 kW superconducting prototype, the VX-200. The VASIMR space propulsion concept has been described in several previous papers. [2, 3] A simplified drawing of the concept is shown in Fig. 1. The advantages of the VASIMR system are high power, high specific impulse and long lifetime potential, due to the magnetic control of the plasma stream. The concept relies on efficient plasma production in the first stage using a helicon plasma source [4, 5]. 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. The single pass RF booster acceleration mechanism has been observed for light gasses [6, 7, 8]. The plasma flow in the magnetic nozzle and efficient detachment from the rocket has been theoretically predicted [9].

Modern superconducting technology enables practical operation with high magnetic field strengths that provide efficient VASIMR operation with heavy propellants, such at argon. Thrust levels of 5 N and specific impulses of 4000 to 5000 seconds can be achieved using argon propellant in a 200 kW VASIMR system. The VX-200 is designed to demonstrate this performance level. Experimentally verified parameters show that an attractive system efficiency of 60 % is possible [1].

Given the physics of this system, higher specific impulses (2×10^4 seconds with hydrogen) and power levels (MW) are achievable for deep space applications. In the near term, robotic applications in the earth-lunar system can take advantage of VASIMR technology using argon propellant. Large cargo delivery to the moon is a growing interest, particularly for human exploration of the lunar surface. Such a high power VASIMR propulsion system combined with modern solar power technology can greatly enhance the payload delivery mass to the moon and other locations near the Earth.

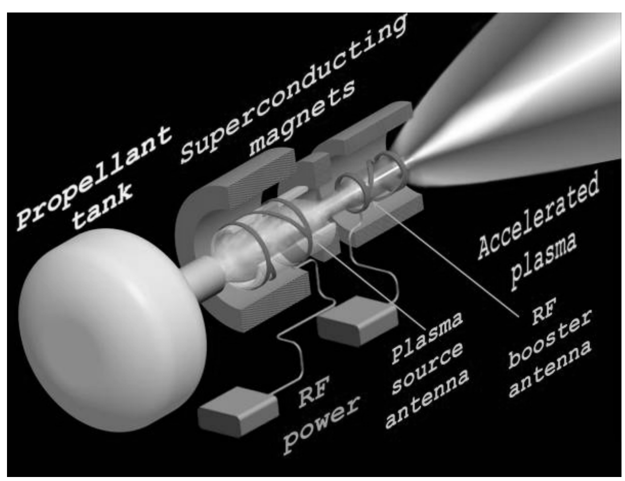


Fig. 1: The VASIMR concept.

2. VX-100 Experiment

The VX-100 is composed of three primary customized water cooled electromagnets that are integrated into a stainless steel vacuum chamber. Figure 2 shows the VX-100 in operation. The first section provides a region for a helicon plasma source in a magnetic field strength up to 0.4 T. This connects to a high field constrictor

Fig. 2: VX-100 in operation.

downstream with a peak steady-state magnetic field strength of 1.6 T. The final magnetic section provides for ion cyclotron resonance at over 1 T, so that high energy (500 eV) heavy ions are magnetized. The axial magnetic field profile is based on that of the VX-50 device that was previously reported [1]. The magnetic nozzle is formed by the natural expansion of the magnetic field of the device without further tailoring.

Argon gas is regulated at up to 5000 sccm into a ceramic containment tube in the helicon section that is surrounded by a specially designed antenna. The antenna is driven at 6.78 MHz at up to 30 kW. A gas baffle at the peak of the magnetic field is employed as was in VX-50 [1]. The plasma facing components in the helicon section are electrically floating. A ceramic tube is also located in the ion cyclotron resonance section and an antenna specially designed to launch the ion cyclotron slow wave [10] is place around the outer surface of this tube. This antenna is driven at approximately 0.5 MHz at power levels up to 75 kW by a high efficiency solid-state transmitter [Nautel Limited]. The plasma then freely expands into a vacuum chamber section containing plasma diagnostics and a 5000 liter/s cryopump to reduce the background neutral pressure in this region. This section connects to a 5 m^3 vacuum chamber with a turbo pump. The high mass throughput causes the chamber pressure to rise rapidly to greater than 10^{-4} torr.

Plasma diagnostics include a 70 GHz density interferometer, a 10-collector planar probe array, a retarding potential analyzer (RPA) and an impact target for measuring potential thrust. We call this *potential* thrust since the plasma has not yet detached from the rocket. Figure 3 shows the chamber section with the probe array and interferometer. The interferometer is located approximately 0.3 m downstream of the ion resonance location. The probe array consists of 10 tungsten disk collectors, biased into ion saturation, facing into the plasma flow and located just downstream of the interferometer. The array is mechanically swept across the plasma exhaust profile from a pivot point below the plasma edge, much like that of a windshield wiper on a car. The sweep takes approximately 1.5 s. The RPA contains four grids biased and swept in voltage to measure ion energy distributions and can scan radially from shot-to-shot.

The impact target is based on a previously developed design [11] using a sensitive strain gauge that holds a ceramic rod that extends down to a flat target in the plasma stream. Figure 4 contains a photograph of such a target in the plasma stream. The target in this experiment is made of graphite to reduce sputtering effects. The total potential thrust of the plasma stream is determined by integrating the radial ion saturation current profile shape scaled by the measured force on the target. RPA radial profile measurements in the VX-100 show a nearly constant velocity profile across the plasma exhaust and the profiles are used to further refine the impact target measurement technique. Measuring thrust using this target method has since been validated against a Hall thruster mounted on a traditional thrust stand [12]. The agreement to the thrust stand measurement is excellent and within 6 % accuracy. This gives us high confidence that these measurements are strong indicators of the thrust produced by the VX-100 device.

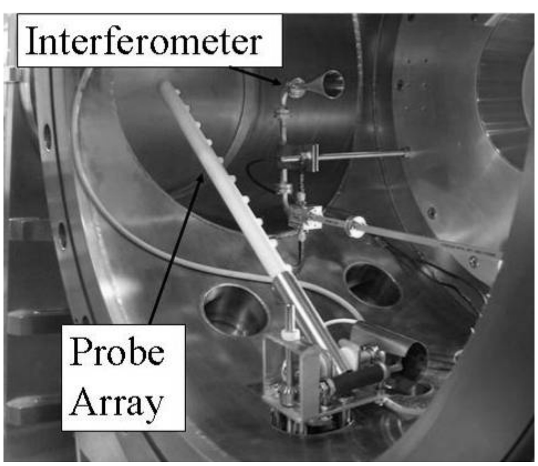


Fig. 3: 10-collector probe array and density interferometer.

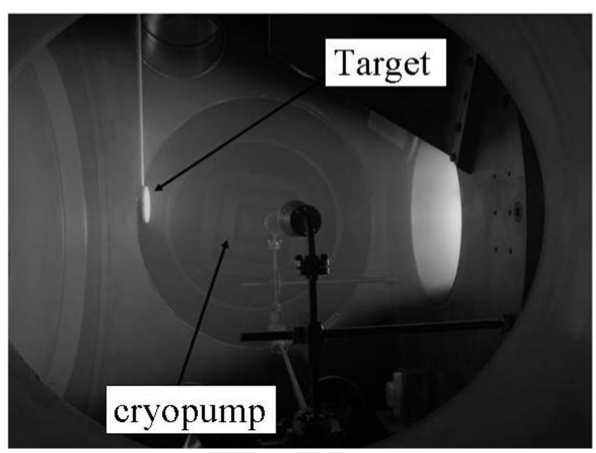


Fig. 4: Impact target in the VX-100 exhaust.

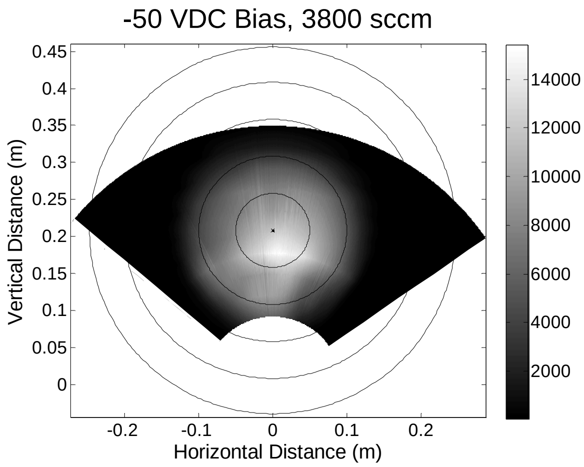
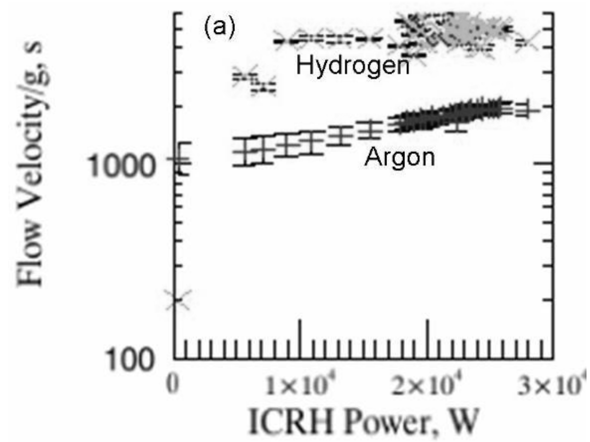


Fig. 5: Plasma ion current density contour plot, [A/m^2].



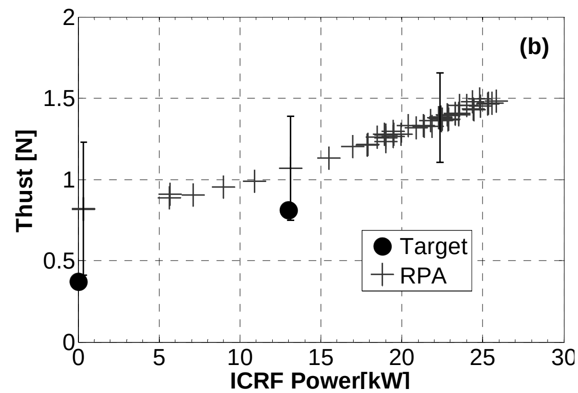


Fig 6.: a) Plasma flow velocity measured by the RPA. A two component energy distribution is observed with the higher velocity component assumed to be a hydrogen impurity. b) Calculated thrust based on the RPA velocity data and assuming a constant argon ion flux. The impact target measurement is also shown.

3. Results

High plasma production efficiency, the total ion current per input RF power (A/W), is critical for an electric rocket. The inverse of this quantity (W/A), minus the ion kinetic energy, is the cost (eV) to produce an ion-electron pair in the plasma stream. We measure the total ion current from the helicon alone by integrating the 2d profiles from the probe array, Fig. 5. The plasma is not centered and the peak is about 2 cm below the axis. This does not affect the total measured ion current. The net RF power coupled to the plasma source is measured by a directional coupler. The measured losses in the RF antenna circuit are approximately 10 % in this experiment. The ion kinetic energies for such a plasma source typically exceed 10 eV, so we use this value as a conservative quantity, which is difficult to accurately measure without precise plasma potential measurements. Ion current measurements were taken at a power level of 25 kW in the helicon plasma source. Total ion current is measured as 280±50 A, or a flux of $1.7\pm0.3\times10^{21}$ ions/s. The density interferometer nears cutoff and has difficulty tracking the phase. The input gas flow is scanned until the plasma flux equals the neutral atom input rate. In this experiment, spectral data show that the plasma exhaust is primarily argon, with a small amount of impurities. This demonstrates 100 % propellant utilization and a plasma source ion cost of 80±10 eV, which is better than our design goal.

RF booster power is applied to this plasma source and significant acceleration is observed. The power is only limited by the voltage stand off of the circuit and no plasma instability or saturation effects are observed. RPA measurements are made in a power scan up to 26 kW, Fig. 6. There is a large component of hydrogen in this discharge due to contamination and the argon ion flux is lower, 1.1×10^{21}/s, than in the data described above. Nevertheless, the argon ion acceleration works well, showing the robustness of the process. Argon ion velocities are measured up to 2×10^4 m/s and a thrust quantity is calculated approaching 1.5 N, Fig. 6b. At about half the maximum RF booster power, 13 kW, a careful impact

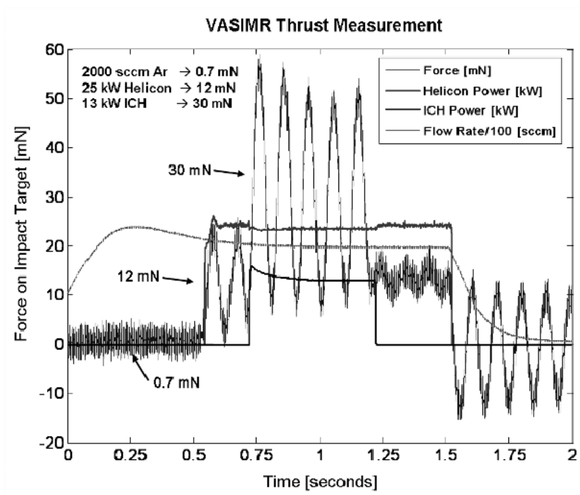


Fig. 7: Temporal plot of the force on the target.

target measurement is performed. When this power is applied, the force on the target more than doubles, Fig. 7. A potential thrust of 0.81 N is determined and in agreement with that calculated using the RPA flow velocity and constant argon ion flux, within the error, Fig 6b.

The high background neutral pressure, > 10^{-4} torr, and significant impurities from a material surface in this experiment, give rise to uncertainty in the maximum potential thrust at these high mass flow rates. In addition, the plasma is still magnetized at the location of these measurements; therefore, the divergence of the plume is not accounted for fully. To accurately measure a thrust value, these measurement need to be repeated in a much larger vacuum facility, and at a distance where the plasma beta is high, $\beta > 1$, and the plasma plume has detached from the rocket. Nevertheless, there is high confidence based on theory [9] that the measured quantities in this experiment would manifest in significant thrust, about 90 % of the potential value.

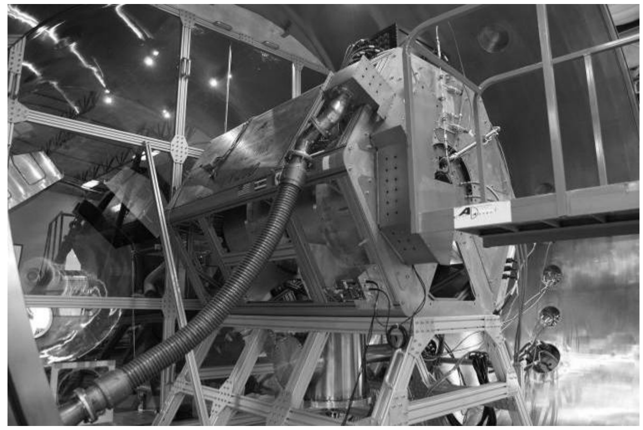


Fig. 8: VX-200 installed in the large vacuum chamber.

Fig. 9: The new 120 m^3 vacuum chamber.

4. VX-200 experiment and a new large vacuum facility

A new superconducting device (VX-200) is coming into operation with a total power capability of 200 kW driven by high-efficiency, as high as 98 %, solid-state DC-RF power-processing units [manufactured by Nautel Limited]. The device demonstrates an end-to-end, DC power to thrust, test of relevant technology to enable spaceflight. A photograph of the VX-200 installed in our new vacuum chamber is in Fig. 8. The magnetic field capability exceeds that of the VX-100 by 50%, so more efficient operation with argon is expected. Based on experimental data from the VX-100 and theoretical predictions of the plasma flow in the magnetic nozzle, we expect a thruster efficiency at about 60 %.

A large vacuum chamber, 4.2 m diameter by 10.2 m long, plus end caps for at total volume of 150 m^3 (see Fig. 9) with a 200,000 liter/s pumping rate capability is coming on-line for testing the VX-200 system and performing detailed measurements in the plasma plume. With the large internal volume and high pumping rate, the mean free path for neutral background interaction exceeds several meters for a long enough time to accurately characterize the plume and measure force on the impact target. A translation stage with a range of 2.5 m by 5 m is being installed to measure the plasma flow profiles to a distance well beyond the point of $\beta = 1$. At this distance the impact target and other measurements are a more accurate measure of thrust performance than previously with the VX-100. Plasma detachment from the rocket will also be clearly observed.

5. Lunar cargo application

As far back as the early years of the Apollo program, it was appreciated that electric propulsion could transfer payloads from low Earth orbit to low lunar orbit more economically than chemical propulsion [13]. We illustrate this here by comparing the performance of a hypothetical LOX-hydrogen chemical propulsion system operating at a specific impulse of 450 seconds with a solar-powered VASIMR™ propulsion system capable of operating over a wide range of specific impulse. At present, the optimal specific impulse for a VASIMR™-based system appears to be approximately 5,000 seconds.

For the chemical system, we assume that a heavy-lift launcher places 100 metric tons into low Earth orbit. We assume that the same engines that provide the 3,000 m/s translunar injection burn that puts the vehicle onto a lunar trajectory are also used for the 1,000 m/s burn that brakes the vehicle into a 100 km altitude lunar orbit. Using these delta-v's, each of which lies in the range of actual delta-v's effected in the Apollo flights, we find that the fraction of the 100 metric ton vehicle in low

Earth orbit that is needed for LOX-hydrogen propellant to achieve the needed delta-v's is as follows: $\frac{m_{LEO}-m_{LLO}}{m_{LEO}} = 1-\frac{m_{LLO}}{m_{LEO}} = 1-e^{-\Delta v/gIsp} = 1-e^{-4,000/4410} = 0.60$. Assuming that the mass of tanks, engines and associated hardware that doesn't contribute to payload is 10% of the propellant mass, or 6 metric tons, we find the useful mass delivered to low lunar orbit (LLO) to be 34 metric tons.

In the VASIMR™ system contemplated, a reuseable solar-powered Orbital Transfer Vehicle (OTV), or lunar tug, is launched into low Earth orbit without payload or propellant. This is followed by the launch of a 100 metric ton Cargo Delivery Vehicle (CDV) that contains the cargo to be transferred to low lunar orbit (LLO), nominally a 100 km altitude circular polar orbit. The CDV includes a propellant tank carrying enough propellant for a round trip, so that the OTV, after depositing its cargo into LLO, is able to return to LEO to pick up another shipment. For an outbound transit time of six months, the effective delta-v needed is 9,000 m/s, higher than the impulsive burn chemical case because of the gravity losses associated with conveying a larger fraction of the propellant to high altitudes along the spiral lunar trajectory.

A lightweight power system is essential to the effectiveness of this lunar transport concept. In our model, we assume that the OTV is powered by a large-scale version of the Stretched Lens Array – Square Rigger (SLASR) technology [14] developed by Entech, Inc. and Alliant Tech Systems (ATK). This concentrator array, deployed by ATK's Square Rigger support structure, features a specific mass of 3 kg/kW, with the potential for lower specific mass as multijunction photovoltaic performance improves. If the cost of the array is on the order of hundreds of dollars per watt, the system affords cost savings only if the OTV can make several roundtrips between the Earth and Moon. In estimating the amortized cost per kilogram of cargo delivered to LLO, we assume that a sufficiently thick layer of cover glass is applied to the solar cells to permit seven six-month round trips. Based on Entech's published characterization of the array technology [14], this radiation-hardening would raise the array specific mass to approximately 5 kg/kW.

The OTV capabilities include rendezvous and docking with the CDV in low Earth orbit, and guidance, navigation, and control functions. A mass model for the OTV's VASIMR™ thrusters - based on laboratory prototypes of RF amplifiers, superconducting magnets, radiators and other subsystems - leads to a thruster specific power of 1.5 kg/kW, for power levels above 100 kW. Thruster efficiency in the lunar cargo model is assumed constant at 65% for all values of specific impulse.

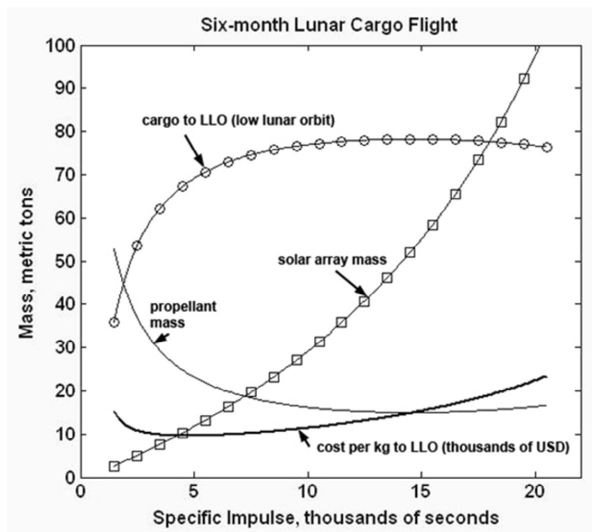


Fig. 10: Performance of a solar-electric lunar cargo system with varying specific impulse. v for the trajectory, including 5% margin, is 9,000 m/s.

Figure 10 indicates the performance of this lunar cargo architecture in terms of cargo delivered to low lunar orbit, as a function of specific impulse, for a six-month outbound transit. Recall that the cargo delivered to low lunar orbit by the high-performance LOX-hydrogen chemical system described above is 34 metric tons.

As specific impulse increases, propellant usage decreases, with a minimum near 15,000 seconds. Accordingly, this results in increased cargo, with a maximum of approximately 75 metric tons, more than twice the mass delivered by the LOX-hydrogen chemical system. As specific impulse is raised beyond 15,000 seconds however, the power requirement grows so rapidly that the increasing mass of the array requires more propellant mass to be carried in the CDV, thus reducing the cargo delivered. With regard to cargo mass only, the optimum specific impulse is therefore 15,000 seconds.

With regard to economics, the optimum specific impulse is much lower. This is due to the high cost of space photovoltaic power. Included in Figure 10 is a plot of the cost per kilogram of cargo delivered to low lunar orbit, calculated according to the following assumptions. Each launch of the 100 mT CDV is set at $500 million, similar to the launch cost of the US Space Shuttle, for a cost per kilogram to low Earth orbit of $5,000. At $40 per kg, the cost of the Argon propellant used by VASIMR™ is negligible (this is not the case for electric propulsion technologies that use thruster-grade Xenon, which costs $5,000 per kilogram). Space photovoltaic power cost has to date typically been in the range of $300 - $400 per watt. Assuming $300 per watt and combining this with the specific power of 5 kg/kW of the radiation-shielded SLASR array, the cost to build the array is $60,000/kg, significantly exceeding its launch costs. In the model used to generate Fig 10, the cost of building and launching the OTV, including the array, is amortized over seven round trips. This is combined with the CDV launch cost to generate the cost per kilogram to deliver cargo to low lunar orbit as a function of specific impulse, shown by the heavy black line. By this metric, optimum performance is in the range of 5,000 to 7,000 seconds, and is approximately

$10,000/kg. The array mass in this range is approximately 10 metric tons, with an output power of 2 megawatts. In short, propellant reduction favors higher specific impulse, while the cost of space photovoltaic power favors low specific impulse. If space photovoltaic power costs can be lowered, minimum cost will be achieved at higher specific impulse.

Transit times longer than six months do not significantly improve the cargo mass delivered, but do reduce the power requirement, and hence the cost [15]. For payloads that can tolerate transit times on the order of a year, the cost per kilogram to low lunar orbit enabled by the VASIMR™ system offers substantial savings to lunar exploration programs.
It should be noted that the power levels and launch masses of the system could be reduced to as little as 10% of the values presented here without reducing the VASIMR™ propulsion efficiency, based on Ad Astra experimentation with the VX-100 prototype. A scaled-down system could deliver payloads of several tons to lunar orbit, approximately doubling the payload deliverable by chemical only propulsion.

6. Summary

Performance data from a 100 kW VASIMR™ experiment (VX-100) using argon propellant is measured. Plasma source performance is determined from a measured 2d map of the ion flux. The data determines an ionization cost of 80±10 eV at 25 kW of coupled power in the helicon plasma source. Significant acceleration of the plasma using ion cyclotron resonance on argon is demonstrated. The flow velocity approximately doubles to as high as 20 km/s with the application of 26 kW in the RF booster.

RPA and impact target measurements from VX-100 indicate thrust as high as 1.5 N; there is good agreement between these two methods. Furthermore, the impact target method has been demonstrated as a reliable measure of thrust in a direct comparison with a traditional thrust stand [12]. Magnetic nozzle theory predicts that about 90 % of this momentum flux, measured upstream of the detachment region in VX-100, would manifest farther downstream as full thrust of the rocket.

A new 200 kW superconducting device (VX-200) is coming into operation. At a location 4 m downstream from this thruster in Ad Astra's new 150 m^3 vacuum facility, measurements will accurately determine the end-to-end performance of the VASIMR™ system. At this location, where the plasma is fully detached from the rocket, detachment phenomena and a thrust quantity based on an impact target and other data will be characterized. Components that are being incorporated into VX-200, including the RF amplifiers, propellant flow controller, and control computer, are either flight-capable or approaching that level of readiness. Design of the VF-200, a flight-ready engine to follow VX-200, has already begun. An OTV using this engine, combined with a ground launch capability of 10 metric tons to LEO, could transfer a 7 metric ton payload from LEO to LLO in a six-month transit. This payload is approximately twice that which can be transferred from LEO to LLO with chemical propulsion.

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