Study of mechanics of plasma detachment in a magnetic nozzle

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Abstract—The researchers are studying the mechanics of plasma detachment in a magnetic nozzle. To this end, a robust and low-cost plasma momentum flux sensor (PMFS) was designed, fabricated, and tested in the plasma plume of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR™), formerly located at NASA's Advanced Space Propulsion Laboratory (ASPL) in Houston, Texas. A separate experimental campaign conducted by University of Houston researchers at the University of Michigan revealed the PMFS to be an accurate plasma-force diagnostic, commensurate with state-of-the-art inverted pendulum ion thruster force stands.

INTRODUCTION

A fundamental problem in human and robotic planetary exploration is the intrinsic limitation of today's chemical rocket. After remarkable advances in the last 50 years, the engineering of these devices has matured to the point where further refinement brings only limited performance gains. While the chemical rocket will continue to provide excellent surface-to-orbit transportation, new technologies must be called upon to transport humans and cargo on long journeys to the planets and ultimately the stars. Developing a high-power electric propulsion system suitable for use as sustainer engines for manned missions beyond Earth orbit is directly relevant to NASA's mission of enabling human space flight.

One candidate system, the plasma rocket, opens up new and exciting possibilities for fast space transportation. Figure 1 shows a concept human Mars mission utilizing three high-power VASIMR engines.[1]

Utilizing ionized gases accelerated by electric and magnetic fields, these devices expand the performance envelope of rocket propulsion far beyond the limits of the chemical rocket. With a properly shaped magnetic duct, the internal energy of plasma could be extracted in the form of rocket thrust. The duct becomes a magnetic nozzle, the magnetic equivalent of a conventional nozzle. Moreover, the non-physical nature of such a nozzle also suggests an inherent adaptability, which (in analogy to the transmission in an automobile) could continuously tailor the exhaust plume to respond to the conditions of flight. An adaptable nozzle better utilizes the available rocket power, leading to better performance. Although much earlier work identified this benefit, its implementation in chemical rockets with fixed material nozzles is impractical.

Magnetic mirrors enable the heating of plasmas to tens of millions of degrees by providing an insulating magnetic field between the plasma and its nearest material surface. Because of their open topology, however, these devices are inherently leaky, a feature that, while a detriment to controlled fusion, is actually useful in propulsion applications.

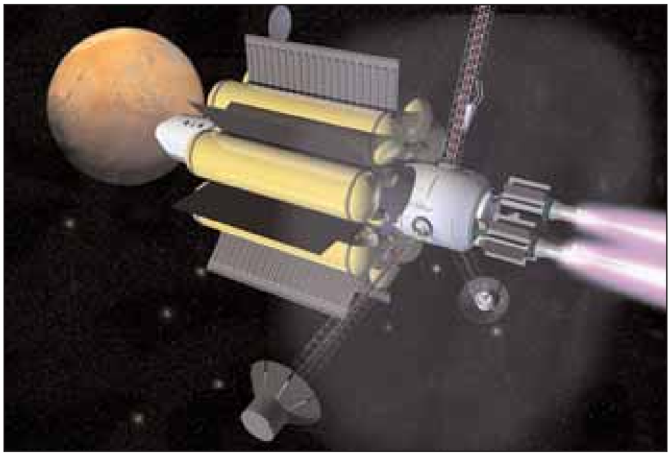

Figure 1. A concept human Mars spacecraft utilizing three high-power VASIMR engines

The genesis of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) dates back to the late 1970s. The concept is a natural derivative of mirror machines and their applications to fusion.[1] A proposed use of VASIMR as primary propulsion for robotic spacecraft is shown in Figure 2.

At present, we are using the VX-100 experimental device, shown in Figure 3, in the Ad Astra Rocket Company laboratory at the NASA Johnson Space Center to explore the physics and engineering of the VASIMR. Similar experiments at the University of Texas at Austin and the Oak Ridge National Laboratory support this research in a collaborative effort involving seven universities, private industry, and two national laboratories.

The VASIMR consists of three main sections: a helicon plasma source, a radio frequency (RF) power booster, and a magnetic nozzle.[2,3] Figure 4 shows these three components integrated with the necessary supporting systems. One key aspect of this concept is its electrode-less design, which makes it suitable for high-power density and long component life by reducing plasma erosion and other materials complications.

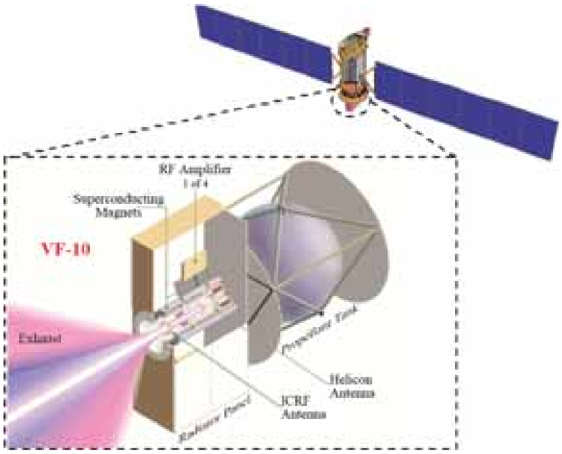

Figure 2. A 10kW VASIMR thruster provides main propulsion capability to the proposed Radiation and Technology Demonstrator (RTD) satellite.

Figure 3. The VX-100 VASIMR experiment in the Ad Astra Rocket Co. facility at Johnson Space Center

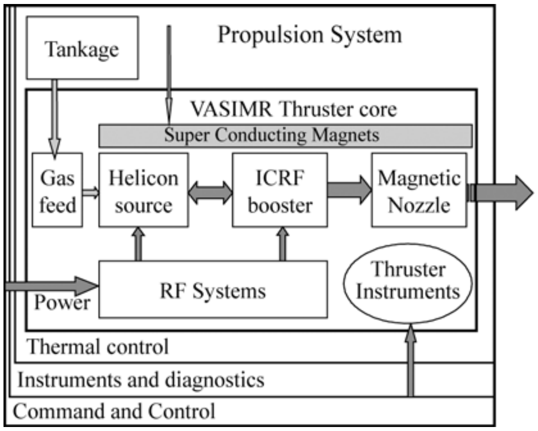

Figure 4. System schematic of the VASIMR

The magnetic field ties the three components together and, through the magnet assemblies, transmits the exhaust reaction forces that ultimately propel the ship.

While the three components must work together, they have distinct functions. The helicon plasma source handles the main injection of propellant gas and its ionization, the RF booster acts as a power amplifier to further heat the plasma, and the magnetic nozzle converts the energy of the fluid into directed flow. VASIMR operates typically with light gases, as the RF booster generally operates near the ion cyclotron resonance frequency. However, the helicon source works effectively with a wide range of gases and gas mixtures, suggesting additional operational modes yet to be explored.

METHODOLOGY

In many respects, the magnetic nozzle is the most controversial and speculative aspect of the VASIMR concept. If one considers only first order plasma physics, one naively expects the plasma produced in a magnetic bottle configuration to remain in a magnetic flux tube attached to the rocket, thus producing no thrust. In fact, detailed consideration of the expected plasma dynamics indicates that one should expect the exhaust plasma to detach from the engine magnetic field and become a true exhaust plume when axial distance is such that the plasma pressure exceeds the effective pressure of the magnetic field (in other words, when high pressure makes the plasma parameter $\beta > 1$). Since this model is both controversial and somewhat contrary to expectation based on zeroth order naïve models, the occurrence of detachment must be tested experimentally. Since the VASIMR engine won't function as a thruster if detachment does not occur, demonstrating that it does is a critical step in the development of this concept. In addition to its important practical applications in electric propulsion, the problems of understanding plasma detachment and the expansion of a magnetized plasma into a vacuum are long-standing problems of fundamental importance to disciplines such as aerospace engineering, space plasma physics, and astrophysics. The principal goal of this project is to demonstrate that plasma detachment is occurring in the VASIMR engine. This result will show that real thrust generation can be efficiently produced in the VASIMR engine and related magnetized plasma devices. Recent improvements to the laboratory version of the VASIMR engine and associated vacuum hardware will facilitate this research goal.

EQUIPMENT AND SPECIAL TECHNOLOGY

The experimental plasma diagnostic campaign entails three complementary sets of activities. First, the existing set of diagnostics that are installed on the translation stage in the exhaust bell are operated during all appropriate VASIMR runs to investigate the plasma dynamics of the extended exhaust plume. These diagnostics include a momentum flux probe, plasma probes, and gridded energy analyzers, also known as retarding potential analyzers (RPAs).[2,3] There is considerable controversy regarding the validity of momentum flux probe data in electric propulsion applications. Much attention has been paid to identifying and characterizing plasma and facility effects on the momentum flux probe. These instruments will allow us to determine if the exhaust plume is expanding entire-

Figure 5. Ad Astra Rocket Co.'s new 35-foot-long, 15-foot-diameter vacuum chamber

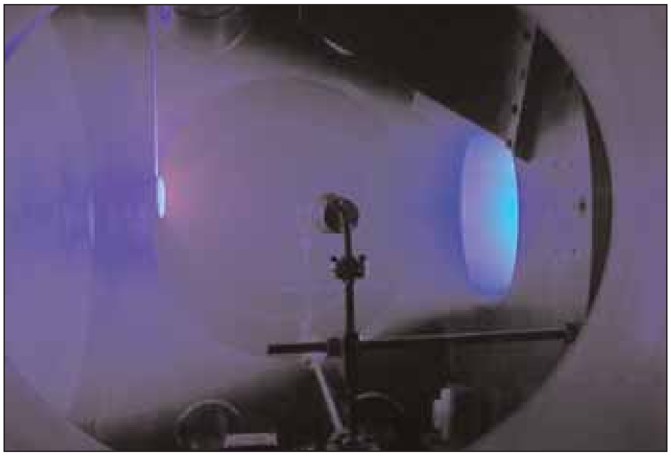

Figure 6. Plasma momentum flux sensor (PMFS) operating in the argon plasma exhaust from the VX-100

ly along the lines of the vacuum field or if, as expected, it is pulling the field out into an extended configuration. The most critical data will be the radial profiles of plasma density and directed ion energy as a function of axial distance.

Second, additional instruments have been procured or developed for use on the translation stage. These additional instruments include DC magnetometers, for mapping the magnetic field configuration to look for evidence of stretching, and induction magnetometers (B-dot) probes to look for evidence of reconnection. Further, an additional transverse degree of freedom has been added to the translation stage to facilitate taking radial profiles. This transverse translation stage mounts multiple probes, including Langmuir probes to determine electron temperature and assess energy balance, a steerable collimated RPA, a three-axis Hall magnetometer, and induction magnetometers (B-dot) probes to look for impulsive, time-varying reconnection. All the magnetic probes are meant for dynamic measurements of reconnecting structures. At this point we cannot say whether the detachment will occur as a single coherent "blob" or rather as a collection of scattered, smaller "islands."

Third, Ad Astra Rocket Co. plans to purchase an LIF instrument from Earl Scime, Ph.D., of the University of West Virginia in the near future. The UH team met with Scime in January 2008 to discuss this plan. By measuring the line profile, intensity, and Doppler shift of optical line emissions from the ions in the exhaust plume plasma, the LIF system measures the details of the ion velocity phase space distribution function. Because the ion must have reasonably strong emission lines in the visible range to use this technique, it is only practical with heavier ions such as neon or argon. The technique provides a non-intrusive, very accurate alternative to the RPA as a method of measuring ion energy and flow velocity.

The Ad Astra Rocket Co. has recently taken up residence in a new private laboratory. The most prominent feature of the state-of-the-art lab is a new 150 m^3 vacuum chamber (Figure 5). The chamber will be used to simulate the vacuum of space and will provide a large testing ground for the new VASIMR prototype, the VX-200.

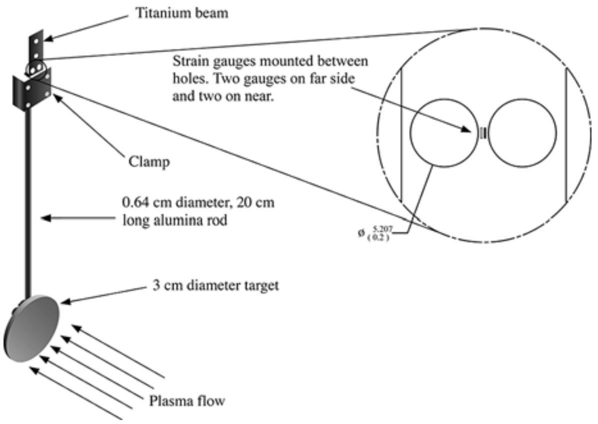

Figure 7. Schematic of PMFS assembly, zoom-in of strain gauge arrangement on the titanium isthmus

RESULTS AND DISCUSSION

A plasma momentum flux sensor (PMFS) was developed and constructed based on a previous NASA-Marshall Space Flight Center design.[4] The PMFS, shown in Figure 6, consists of a 3 cm diameter alumina target disc attached to a 20 cm long insulating alumina rod. The stiff alumina rod then connects to a small titanium bar (5.72 cm x 1.30 cm) where a series of four high-output semiconductor strain gauges are mounted on an 'isthmus' between two holes in the titanium bar. The isthmus acts as a stress concentrator and increases the sensitivity of the device. The strain gauges are connected electrically in a Wheatstone bridge configuration so that changes in temperature of the titanium bar do not affect the linearity of the strain gauge output, Figure 7.

When the alumina disc is immersed into flowing plasma, e.g., the plume of a VASIMR™, the force from the plasma impacting the alumina target is translated into a strain in the titanium beam through a moment arm equal to the length of the alumina rod. A small graphite shield was also used to keep the entire titanium bar and strain gauges out of the flowing plasma, for thermal and electrical noise-related reasons.

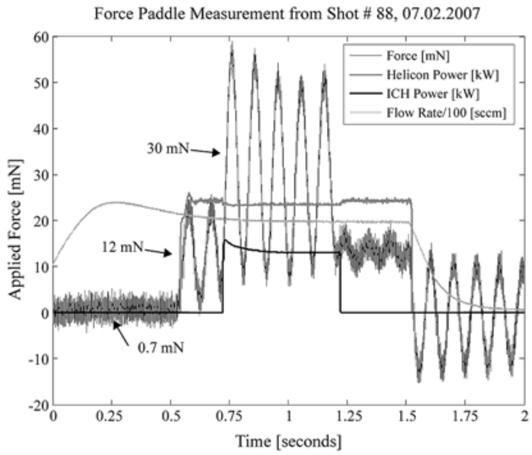

Figure 8. A graph of the time response of the PMFS, the neutral gas flow rate, the helicon power, and the ICH power within VASIMR. The shot parameters were 25 kW absorbed helicon power, 13 kW ICRH power, 2800 sccm Ar.

The design of the PMFS used for VASIMR in 2007 experiments allowed for a resolution of the measured force equal to 0.1 mN. The natural oscillating period of the device was tuned so that it was much shorter than the pulse duration of each VASIMR shot. That is, the alumina target would oscillate back and forth 5-10 times during each plasma shot, as seen in Figure 8.

The forces from the neutral gas puff, the helicon discharge, and the ions accelerated by the ICRH boost on the 3 cm diameter alumina target were 0.7 mN, 12 mN, and 30 mN, respectively. Figure 8 shows that a significant amount of force was imparted to the alumina target when only 13 kW of ICRH power was added to the existing 25 kW of helicon power.

Because the size of the alumina target used in this experiment campaign was smaller than the diameter of the plasma exhaust plume, the target only measured a portion of the total force generated by VASIMR. A radial profile of the ion flux was used to account for the portion of the plasma plume that was not intercepted by the alumina target, as seen in Figure 9. The ion flux was measured at a different upstream location from the PMFS, therefore the alumina target diameter was scaled down based on the magnetic field profile, a reasonable assumption because the ion gyroradius is much smaller than the force target.

The integrated ion flux from $r = 0$ to $r = 15$ cm assuming azimuthal symmetry is given by

$$\Phi_{Total} = \sum_{x=0}^{x=10000} \pi\left[r_{x+1}^2 - r_x^2\right] I(r_x), \tag{1}$$

where I is the ion flux as measured by a Langmuir probe biased into ion saturation, and r_x is the plasma exhaust radius at point x, where x ranges from 0 to 10,000.

The integrated ion flux from $r = 0$ to $r = 3$ cm (the alumina target radius) assuming azimuthal symmetry is given by

$$\Phi_{Total} = \sum_{x=0}^{x=2000} \pi\left[r_{x+1}^2 - r_x^2\right] I(r_x). \tag{2}$$

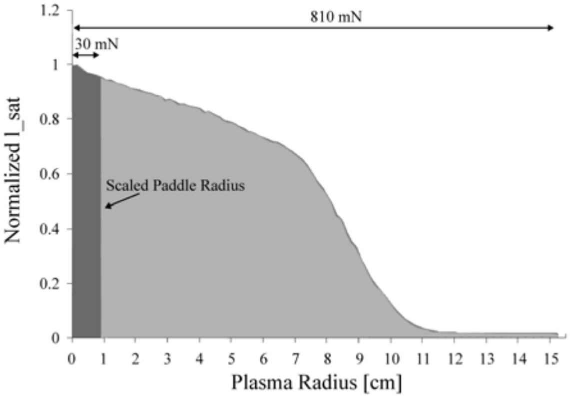

Figure 9. A representative radial ion flux profile of the VASIMR exhaust plume, in this case 20 cm from the exit plane of the thruster

The total force produced from the thruster is found by multiplying the force measured by the alumina target by the ratio of Equations (1)/(2). Charge exchange and doubly ionized ions do not affect the accuracy of the PMFS as long as the fraction of such afflicted ions is small compared to singly ionized ions that have not gone through a charge exchange event and/or the distribution of charge exchange and doubly ionized species is uniform over the majority of the plume angle.

An entire experiment campaign, conducted at the University of Michigan's electric propulsion lab, conclusively showed that the PMFS agreed with the more commonly used force measuring technique, an inverted pendulum thrust stand, to within 3 percent throughout a large range of thrust values from 10 mN to 500 mN. The University of Michigan's vacuum chamber, shown in Figure 10, is roughly the same internal volume as the new Ad Astra Rocket Co.'s new chamber, ~150 m^3.

CONCLUSION

The researchers hope to solve the plasma detachment issues and questions related to VASIMR through the use of conventional and novel experimental plasma diagnostics. Though plasma detachment from magnetic fields is not a controversial topic within the space physics community, it remains largely unproved in laboratory plasma physics communities. The researchers have made significant steps toward the goal of proving VASIMR plasma detachment and have laid the groundwork for future experiments. If demonstrated, laboratory plasma detachment will have significant implications for solar and magnetospheric plasma physics and will open new doors to the space plasma physics community to test detachment theories on a new and entirely different scale.

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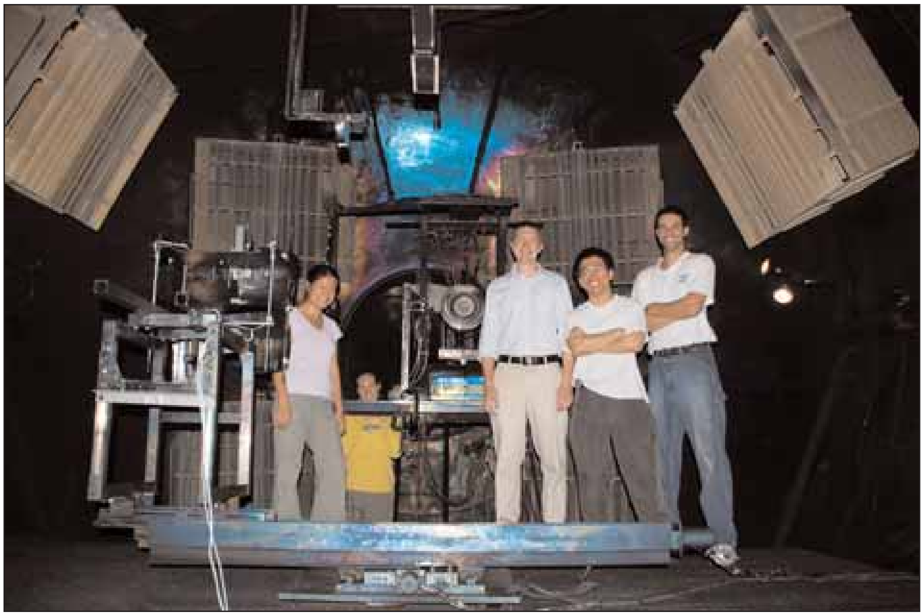

Figure 10. University of Michigan's large vacuum chamber used for testing ion thrusters. ISSO post-doctoral fellow Benjamin Longmier (middle) poses with UM graduate students in front of a 5 kW Hall thruster.

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