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The VASIMR Engine: Project Status and Recent Accomplishments

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ABSTRACT

The development of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) was initiated in the late 1970s to address a critical requirement for fast, high-power interplanetary space transportation. Its high-power and electrodeless design arises from the use of radio frequency (RF) waves to create and accelerate plasma in a magnetic nozzle. While not being a fusion rocket, it nevertheless borrows heavily from that technology and takes advantage of the natural topology of open-ended magnetic systems. In addition the system lends itself well for Constant Power Throttling (CPT,) an important ability to vary thrust and specific impulse over a wide operational range, while maintaining maximum power. This allows in-flight mission-optimization of thrust and specific impulse to enhance performance and reduce trip time. A NASA-led, research team, involving industry, academia and government facilities is pursuing the development of this concept in the United States. The technology can be validated, in the near term, in venues such as the International Space Station, where it can also serve as both a drag compensation device and a plasma contactor for the orbital facility. This paper outlines the most recent advances in VASIMR research and presents the near-term experiments being pursued in the development of the technology.

INTRODUCTION

Research on the VASIMR engine began in the late 1970's, as a spin-off from investigations on magnetic divertors[1] for fusion technology. A simplified schematic of the engine is shown in Figure 1. Three linked magnetic stages perform specific interrelated functions. The first stage handles the main injection of propellant gas and its ionization; the second, also called the "RF booster" acts as an amplifier to further energize the plasma; the third stage is a magnetic nozzle, which converts the energy of the fluid into directed flow.

VASIMR is a radio frequency (RF,) driven device where the ionization of the propellant is done by a helicon type discharge[2]. The plasma ions are further accelerated in the second stage by ion cyclotron resonance heating (ICRH), a well-known technique, used extensively in magnetic confinement fusion research.

Due to magnetic field limitations on existing superconducting technology, the system presently favors the light propellants; however, the helicon, as a stand-alone plasma generator can efficiently ionize heavier propellants such as Argon and Xenon.

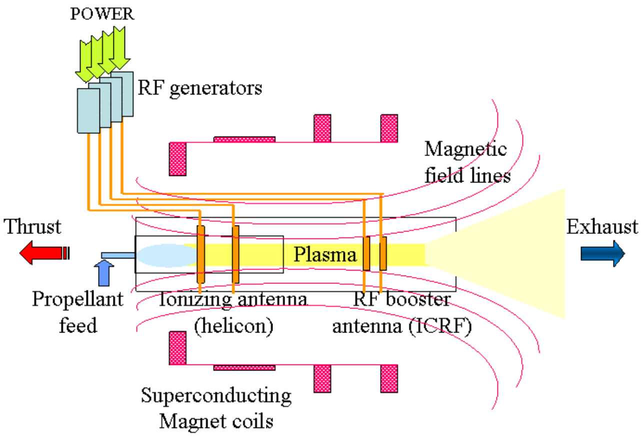

Figure 1: Simplified system schematic of the VASIMR engine.

SYSTEM PERFORMANCE

The performance of this concept can be examined by considering that of the various subsystems and their interrelationships. The block diagram in Figure 2 illustrates this process.

In Figure 2, electric power P is partitioned into two legs by the power partition fraction *f*. The RF generators convert this electrical power into RF at efficiency h_{RF}. The transmission lines and antennas also have associated efficiencies h_A, which for the sake of simplicity we can assume are equal. The power transfer efficiencies of the ionization and booster stages, h_i and h_b respectively, are not equal however, and much of the physics investigations of the current experiments are focused on understanding these quantities. Finally, the plasma output at the RF booster is further scaled by the magnetic nozzle efficiency h_N.

A representative set of expected component efficiency values for various propellants has been used to develop a realistic performance chart for a hypothetical 1MW engine[3]. These come from a review of recent experiments in similar geometries, reasonable extrapolations of system performance and theoretical estimates[4, 5].

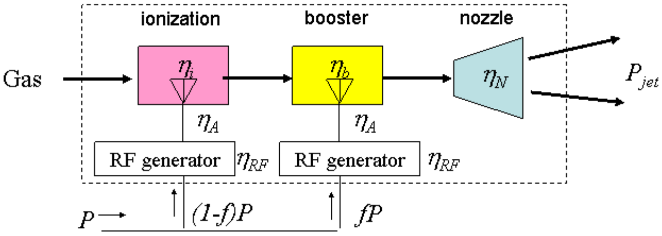

Figure 2: VASIMR power flow diagram

The curves in Figure 3 show the expected performance values of the booster power fraction *f*, the system efficiency *h*, and the thrust *F* for a 1 MW engine as functions of the specific impulse. The efficiency curves are relatively flat for the high I_{sp} values of the different propellants. We have used Lithium as the heaviest propellant in which ICRH can be attempted with current magnet technology; however, the difficulties associated with Lithium handling may render this propellant unattractive.

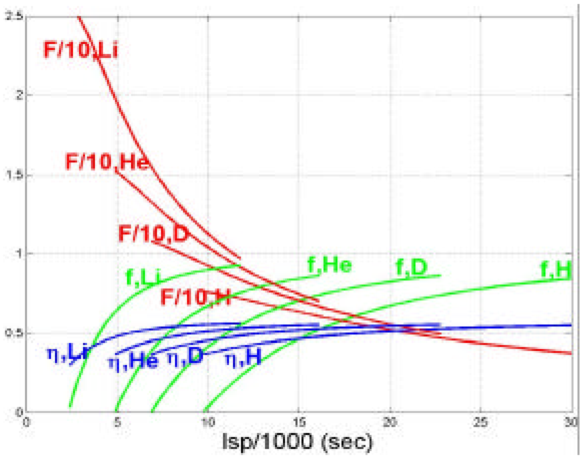

Figure 3: Performance parameters as functions of I_{sp} for various propellants. The system efficiency *h*, the RF booster power partition *f* are dimensionless, the thrust *F* has units of Newtons.

ENGINE SIZE AND WEIGHT

Preliminary estimates of engine size and weight for a 1MW VASIMR have been conducted. These assume present state-of-the-art technology for high power RF equipment, high-temperature superconducting magnets and cryocooler technology. A simplified schematic of a 1MW engine, including its power processing equipment and magnet power supplies is shown in Figure4. Estimates of total mass yield about 1.2 MT, which translates into an engine *alpha* value of just over 1Kg/KW.

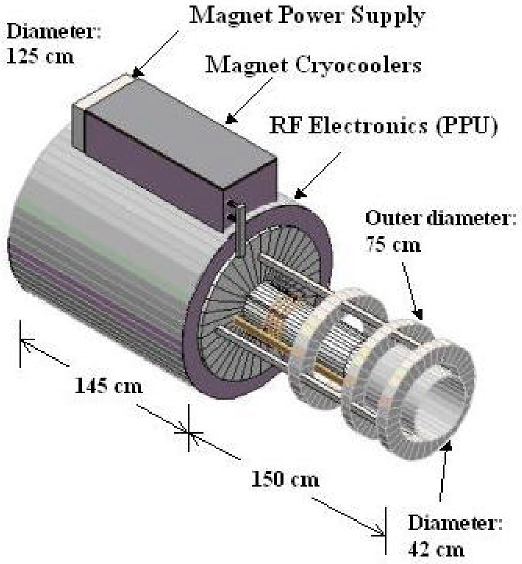

Figure 4. Simplified schematic of 1MW VASIMR engine package, including RF power processing equipment, magnet power supply and cryocoolers.

EXPERIMENT STATUS

The physics of the VASIMR engine are being investigated primarily in the VX-10 device at the NASA Johnson Space Center (JSC.) However, supporting investigations are also being carried out at the Oak Ridge and Los Alamos National Laboratories, The University of Texas at Austin and the NASA Marshall Space Center in Huntsville Alabama. A trimetric view of the JSC device and associated diagnostics is shown in Figure 5. The axial magnetic field profile is also shown on the lower-right corner of the graph. Present operations use a cusp field at the upstream end of the helicon antenna, but future configurations will move away from this feature.

The helicon first stage is critically important inasmuch as its performance sets the tone for that of the second stage or RF booster. The present helicon source has now been well characterized theoretically and experimentally, with hydrogen, helium, deuterium and other propellants[6, 7, 8]. Stable plasma discharges are now routinely produced with densities in the 10^{18} to 10^{19} m^{-3} range. The present configuration features a 9 cm. inner diameter helicon tube threaded through a water-cooled, double saddle “Boswell” type antenna.

Unlike more conventional helicon discharges used in plasma processing and other applications, the VASIMR source operates in a flowing mode, which requires careful control of the pressure field within the discharge tube. Discharges with nitrogen, argon and xenon have also been studied but data with these propellants is still rather sparse.

While the helicon is mainly a plasma production stage, its operation produces non-negligible trust. Direct measurements of the flow momentum have been carried out[9]. The standard 3kW helicon discharge produces about 6-7 mN of force on a target placed a few centimeters away from the magnetic throat. The neutral propellant input rate (about 3×10^{-7} Kg/sec) leads to an I_{sp} estimate of about 2000 sec. However, present pumping limitations increase the neutral background pressure downstream of the helicon throat, leading to collisions, which tend to reduce the flow momentum measured at the sensor; therefore, this measurement is presently only qualitative in nature.

The helicon I_{sp} estimates are considered reasonable, as nearly complete gas burn-up in the helicon tube has now been measured. This important result relating to the ultimate propellant utilization efficiency of the device is shown in Figure 6. In that figure, measured ion output and neutral particle input fluxes are compared and show a one to one correspondence in the range between 2×10^{19} and 4×10^{19} particles per second.

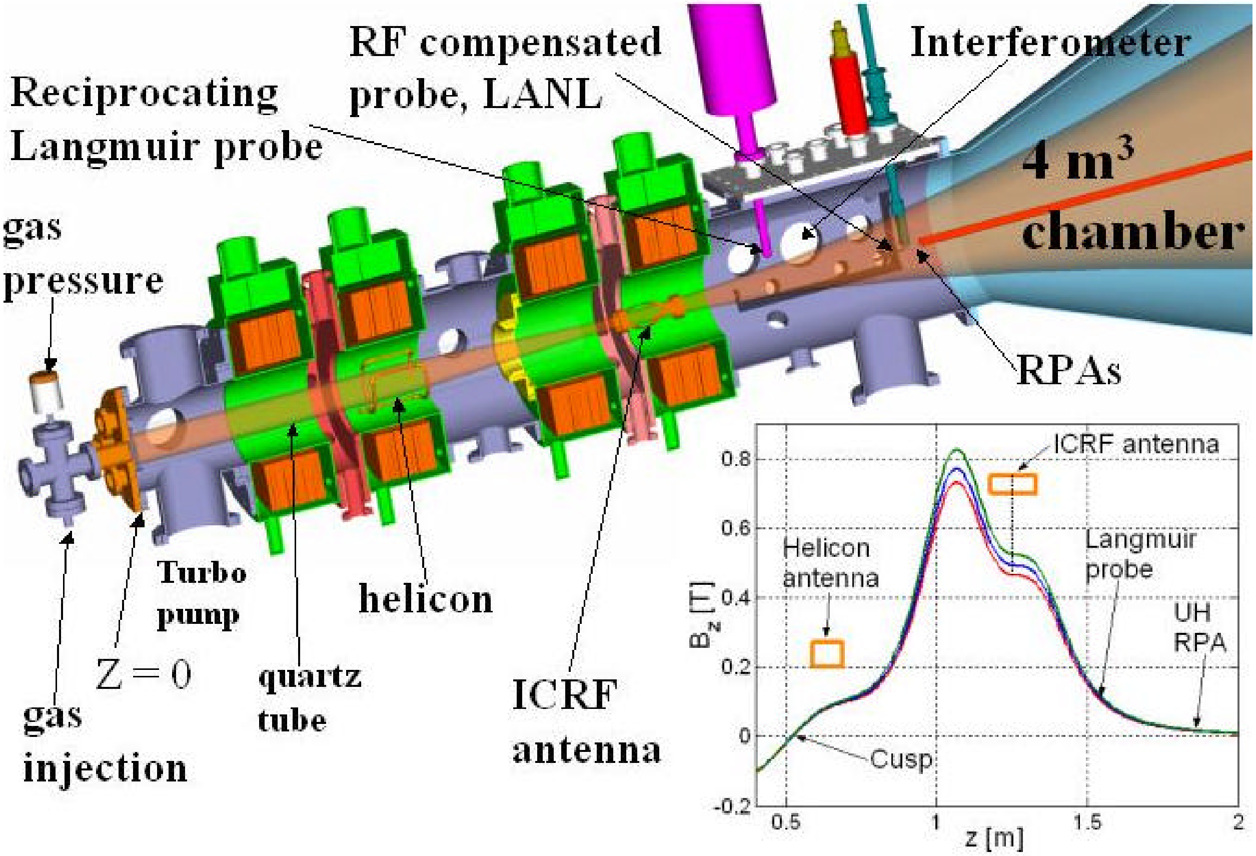

Figure 5: Trimetric view and axial field profile of the VX-10 device at JSC and associated diagnostics.

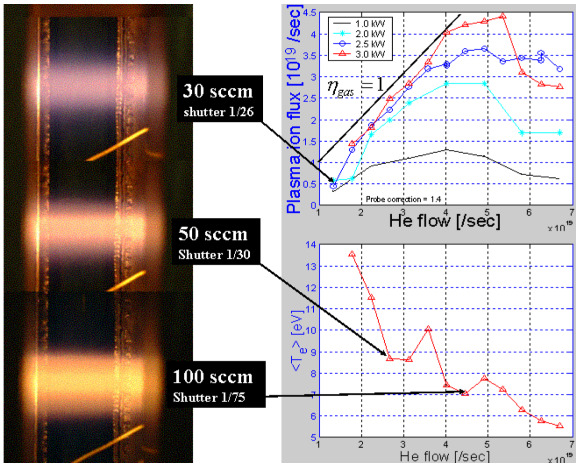

Figure 6: Plasma production and electron temperature as functions of the neutral gas injection rate for helium. Discharge brightness at various flow rates is shown at left. Visible color change, and elevated electron temperature confirm neutral gas depletion.

RF BOOSTER EXPERIMENTS

With a well-characterized helicon stage, present activities now focus on the physics of the RF booster, or ion cyclotron stage. An important consideration involves the rapid absorption of ion cyclotron waves by the high-speed plasma flow. This process differs from the familiar ion cyclotron resonance utilized in tokamak fusion plasmas as the particles in VASIMR pass under the antenna only once. Sufficient ion cyclotron wave (ICW) absorption has nevertheless been predicted by recent theoretical studies[10, 11, 12].

Recent experiments have confirmed these theoretical predictions with a number of independent measurements. What follows are brief highlights of some of these results.

The plasma acts as a resistive load on the RF circuit. Measurement of the plasma loading on the ICRF antenna is therefore a good measure of power absorption. This quantity has been measured and compared with theoretical predictions. Figure 7 shows these results plotted as functions of the RF frequency normalized to the ion cyclotron resonance frequency at the axial mid point of the antenna.

Several conclusions can be drawn from Figure 7. First, loading values of the order of 200 mOhms are considered acceptable for achieving a preliminary demonstration of the ICRH process (our goal in 2003.) These values are mainly a result of the high plasma density produced by the helicon source and the ICRH antenna design. Second, as a significant check, it was verified that loading with Argon is virtually zero as expected, as cyclotron resonance does not exist for heavy gases in our configuration. Third, in comparing theory and experiments, two models are considered: a reduced order one, which neglects electron collisions and a collisional one, which does otherwise. It is seen that the collisional model fits experimental data best. Fourth, a 5% shift in the measured vis-à-vis predicted resonance, may be due to a number of things, including a possible Doppler effect caused by the plasma flow, which was not accounted for in the theoretical simulation. All of these features of the data are undergoing further evaluation and verification.

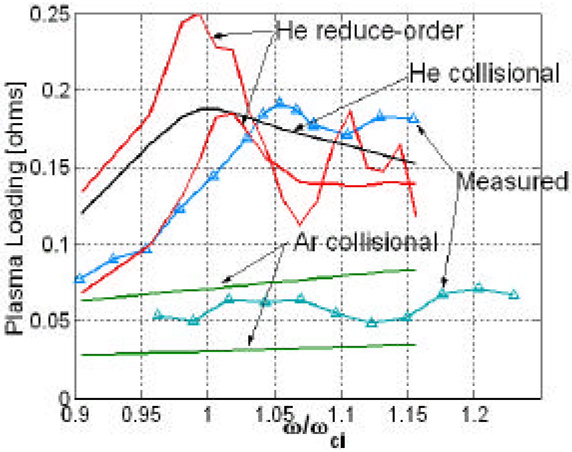

Figure 7. Measured (blue and green traces) and predicted (red, black and olive traces) plasma loading as functions of applied RF frequency, near the ion cyclotron resonance.

Two other measurements provide further evidence of significant RF absorption in the booster stage. First, the data from two distinct retarding potential energy analyzers (RPAs) show a shift in the energy distribution of the collected ions when 1.5KW of ICRH is applied. These results are shown in Figure 8a and 8b.

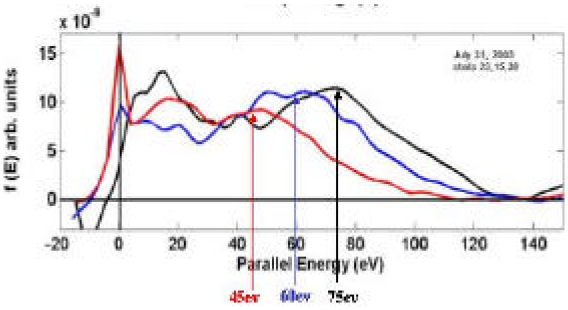

Figure 8a. The collimated RPA measures axially moving ions at three different axial locations (35, 55 and 90 cm) downstream from the booster antenna. Ion kinetic energy increases downstream.

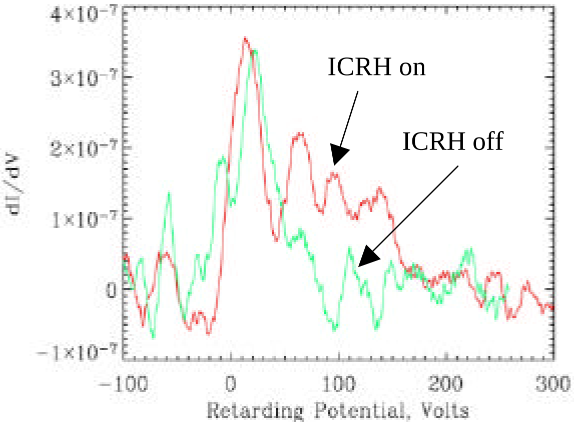

Figure 8b. The un-collimated RPA measures the kinetic energy distribution of downstream moving ions with pitch angles within a 10° cone about the beam axis. A high-energy population appears when ICRH power is applied.

The second evidence for ion acceleration by the booster stage comes from a 70GHz microwave interferometer placed several centimeters downstream of the antenna. Integrated line density measurements are done with the ICRH on and off. The resulting data, shown in Figure 9, indicates a sudden decrease in the line density upon application of ICRH power. The density trace recovers as the RF is turned off. Total flux measurements carried out during these experiments confirm that the ion flux does not decrease with the application of ICRH (some measurements have actually shown an increase, but these are under investigation.) We conclude that the local density decrease is mainly due to plasma acceleration.

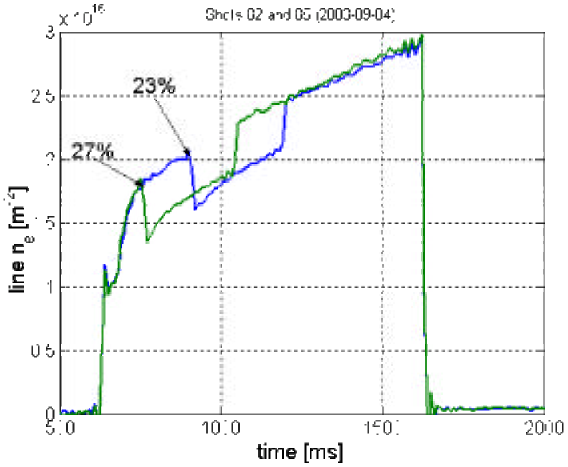

Figure 9. The 70GHz microwave interferometer measures the local line-integrated density downstream from the antenna. Two separate (but under the same conditions) plasma shots are shown. A sudden drop in the line-integrated density is observed during ICRH application, indicating plasma acceleration. Applying ICRH power earlier in the shot produces a slightly larger effect probably due to better vacuum conditions.

OTHER ONGOING ACTIVITIES

Present efforts continue to expand the experimental database on the RF booster, in particular, the demonstration of similar wave absorption behavior with deuterium. In addition, improvements in the diagnostics suite are being studied; specifically the gradual integration of non-invasive and spectroscopic measurements to validate the probe data.

Another important focus area continues to be the validation of the thrust measurements with the use of the MSFC developed force sensor[9]. This activity is being coordinated with sensor measurements on known thrusters, mounted on calibrated thrust stands at MSFC, the University of Michigan and others. These measurements aim to produce a versatile and transportable thrust sensor, which can be used on a number of thrusters and locations.

The physics experiments accomplished thus far point to an improving of the rocket performance at higher power levels. For example recent helicon experiments by our collaborators at the Oak Ridge National Laboratory have uncovered a high-density mode of helicon operation at higher power and magnetic fields than those used thus far[13]. A higher helicon density will, in turn, translate in higher loading at the booster stage and hence increased coupling of the ion cyclotron waves. Accordingly, our experiments in 2004 are strongly geared to high power operation.

However, while experiments proceed, a major physics objective continues to be the demonstration of plasma/field detachment after expansion in the magnetic nozzle. To this end, resources are also being allocated to numerically model the expansion physics and describe the mechanisms at play in the detachment process. A leading theory proposes detachment at the so-called super alfvenic transition, when the flow velocity surpasses the Alfven speed. As the plasma flows past the nozzle throat, its b increases rapidly, as the magnetic pressure drops faster with B than does the plasma density. Results for a 50kW VASIMR simulation show transition to $b > 1$ taking place a couple of meters downstream of the nozzle throat. Our collaborators at Los Alamos National Laboratory and the Hannes Alfven Laboratory in Sweden are pursuing important experimental initiatives along these lines.

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