Space Technology and Applications International Forum
February 13-17, 2005, Albuquerque, NM

Principal VASIMR Results and Present Objectives

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Abstract. Principal achievements of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project at the NASA Johnson Space Center's Advanced Space Propulsion Laboratory (ASPL) are reviewed and objectives for continuing development are described. The evolution of the VASIMR design from the 1994 concept to the present device is summarized. In its present configuration (VX-10), the VASIMR device consists of a 10 kW helicon plasma source and a 1.5 kW radio-frequency booster stage. At modest power levels, the measured plasma exhaust velocity implies a specific impulse spanning the range of 5,000 – 12,000 seconds using deuterium propellant. Experimental results indicate very high efficiency for the RF booster stage. Given sufficient power, the helicon source approaches 100 % mass utilization (ionization); however, the ionization cost of the present source must be reduced for satisfactory overall system efficiency. Immediate goals are measurement of thrust in the exhaust plume, reduction of ionization cost, and observation of detachment of the plasma from the magnetic field of the thruster.

INTRODUCTION AND BACKGROUND

Since 1994, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) has been under development at the Johnson Space Center's Advanced Space Propulsion Laboratory (Chang Diaz, 2004). The essential feature of the VASIMR concept is specific impulse that can be easily varied over a wide range at constant power. Trajectory studies have shown that such a propulsion system offers substantial savings in system mass and/or flight time relative to fixed Isp thrusters (Chang Diaz, 1995; Rauwolf, 2001) for interplanetary flights. In VASIMR, the available power is divided between the plasma source and the ion cyclotron resonant absorption (ICRA) system, which delivers additional energy to the ion component of the plasma. For low specific impulse operation, a large fraction of the power goes to the source, and the propellant rate is relatively high. To raise the specific impulse, the propellant flow rate is reduced and power is shifted from the plasma source to the ICRA system.

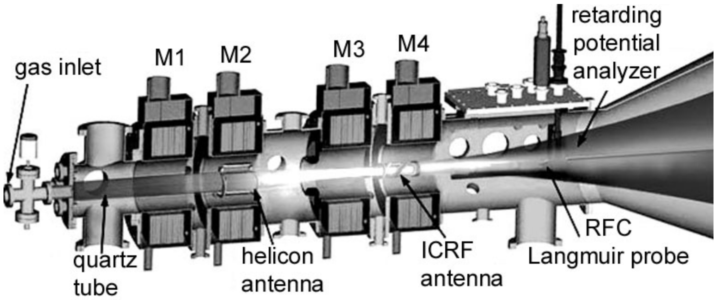

FIGURE 1. Three-Dimensional Cross-Section of the VX-10 Experiment at ASPL.

VX-10, the 10 kW VASIMR experiment at ASPL, is shown in Figure 1. Operation of the device is as follows: neutral gas metered by a commercial flow controller enters the quartz tube. Power applied to the helicon antenna drives a helicon discharge, ionizing the propellant. The resulting plasma flows downstream (to the right in Figure 1), passing through the ICRF (ion cyclotron range of frequencies) antenna, also known as the ICRF booster. Current in the ICRF antenna, driven at a frequency slightly lower than the local ion cyclotron frequency, launches an ion cyclotron wave (ICW) in the plasma. Though the wave propagates both upstream and downstream away from the antenna, the antenna's asymmetric design delivers the majority of the power to the downstream wave. As the plasma proceeds downstream, the ion gyrofrequency drops with the declining magnetic field strength. Near the downstream side of the ICRF antenna, the ion gyrofrequency matches the ion cyclotron wave's frequency. At this resonance, the rotating electric field of the ICW accelerates the ions, and the wave is damped. As the magnetic field lines flare out, the high gyrovelocity of the ions emerging from the resonant region is converted to axial velocity by the magnetic nozzle effect. With growing distance from the magnets, a number of phenomena (diamagnetic current, turbulent reconnection, super-Alfvénic flow) contribute to detachment of the plasma from the rocket, resulting in thrust on the vehicle. ASPL's goal is to develop this experimental device into a useful space propulsion system.

Evolution from Concept to VX-10

At ASPL, the VASIMR experiment acquired features somewhat different from the original concept described in the early 1980's (see Figure 2). The original magnetoplasmadynamic (MPD) plasma source was replaced by a helicon source by the mid-1990's. Later, the "magnetic bottle" (formed by the central cell coils and the mirror magnets in Figure 2) in which trapped ions underwent ion cyclotron resonant heating (ICRH) in the same manner as in a magnetic mirror machine or a tokamak, was eliminated. These changes were made to simplify the system and to improve its anticipated lifetime.

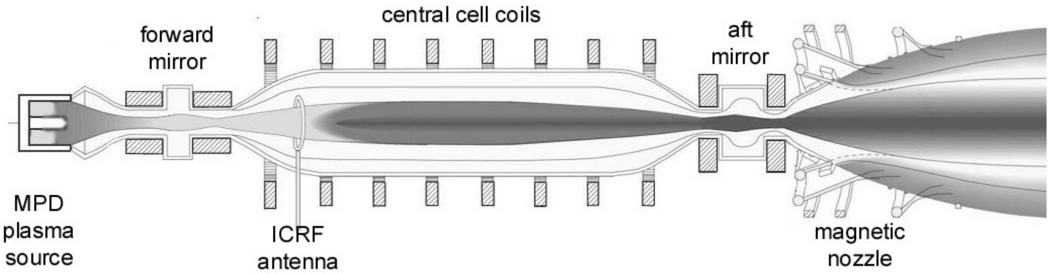

FIGURE 2. Early 1980's VASIMR Concept.

The MPD source was replaced by the helicon for several reasons. First, it is an electrodeless device, so that the only solid surface with which the plasma makes contact is a rugged dielectric material shielding the helicon antenna. Here the ion energy is quite low, so erosion of nearby surfaces should be minimal. Second, the helicon produces plasma of sufficient density for the ion cyclotron absorption process (typically 10^{19} m^{-3} entering the ICRF antenna). Third, the helicon is a rugged source, capable of processing large amounts of power (approximately half a megawatt in the Archimedes nuclear waste processing project). Finally, while most research has focused on Argon, the helicon can ionize virtually any gas. Nonetheless, when ASPL began using the helicon source, the research literature describing light-gas helicon discharges was scant. Furthermore, little was known about the helicon as a source of plasma *flux* rather than as a source of dense, stationary plasma. Consequently, a great deal of ASPL's effort has focused on developing the helicon as an effective source of high-density *flowing* plasma using light gases.

Elimination of the magnetic bottle was motivated by theoretical modeling of single-pass absorption of the ion cyclotron wave on a magnetic field gradient by ASPL collaborators at the University of Texas at Austin (Breizman and Arefiev, 2001). While the cyclotron heating process in the confined plasmas of fusion experiments results in approximately thermalized ion energy distributions, the non-linear absorption of energy in the single-pass process results in a boost, or displacement of the ion kinetic energy distribution. The ions are immediately ejected through the magnetic nozzle before the ion distribution has had time to thermalize. Hence, VASIMR is not an electrothermal rocket, and the fusion term "ICRH" for ion cyclotron resonant heating may be misleading in describing the process now used in VASIMR, if the term “heating” implies a thermalized distribution. “ICRA”, with the “A” standing for absorption or perhaps acceleration, is more accurate if we are referring to the non-linear, non-thermal absorption process first modeled by our UT-Austin collaborators.

EXPERIMENTAL RESULTS

For the data presented here, helicon power was limited to 3.5 kW and power to the ICRF antenna was limited to 1.5 kW. Two results from this experimentation stand out as significant steps toward a practical thruster: the capability of the modified helicon to ionize virtually all of the propellant gas, and the high efficiency of the ion cyclotron absorption mechanism in accelerating the plasma flow.

Helicon Full Mass Utilization

Helicon discharges have been run in the VX-10 using hydrogen, deuterium, helium, nitrogen, argon and xenon, with most work done using deuterium and helium. For both of these gases, a baffle inserted into the quartz tube exit to reduce neutral gas conductance (without affecting plasma conductance) results in a fully ionized plasma emerging from the source, given enough power to the antenna. This conclusion is based on the output flux as measured by a radially scanning langmuir probe, calibrated for density by comparison with microwave interferometer measurements. Results for helium are shown in Figure 3. For a fixed gas flow rate, the output plasma flux is roughly proportional to the power input to the helicon antenna until the output flux reaches the input neutral gas rate. As antenna power is increased beyond this point, the output flux remains constant while downstream probes indicate rising electron temperature and higher ion flow energy. These observations suggest that once all of the gas downstream of the antenna is ionized, the additional antenna power goes into heating electrons.

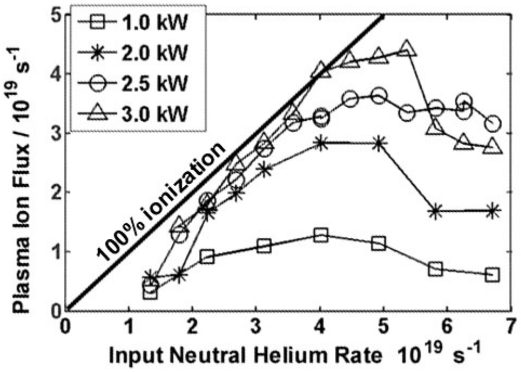

FIGURE 3. Experimental Demonstration of 100% Propellant Utilization.

Dividing the input power by the input neutral rate yields the ionization cost. The data in Figure 3 indicate a cost of approximately 500 eV per ion, too high for a practical thruster using Helium propellant. This is because exhaust ion kinetic energies are less than this ionization cost, for specific impulses of interest, making the overall efficiency of the present experiment low. No substantial effort has been made yet to minimize the ionization cost; rather, the primary goal of the helicon effort to date has been to achieve sufficiently dense plasma for the RF booster experiments. However, empirical helicon data (Yoshitaka, 2004) and helicon physics models indicate that dramatic reduction of the cost is possible. Plans are in progress to test more efficient helicon configurations at ASPL.

ICRF Booster

While the helicon portion of the thruster requires improved efficiency, the second stage process has been a striking success. The novel theoretical work performed by the UT-Austin contributors was awarded the American Physical Society’s Division of Plasma Physics’ Rosenbluth Award for best theoretical plasma physics dissertation in 2002. A summary paper of the ASPL team’s experimental studies of the single-pass absorption process (Bering, 2004) was cited for excellence at the 2004 AIAA Aerospace Sciences Meeting.

Single-Pass Ion Cyclotron Absorption

In earlier conceptions of VASIMR, plasma with a high ion temperature was produced in a magnetic bottle, as indicated in Figure 2. This magnet arrangement was based on experience with ion cyclotron resonant heating in two types of fusion experiments: tokamaks and mirror machines. In both of these devices there is a large volume in which the magnetic field strength causes the local ion cyclotron frequency to match the frequency of the input power, i.e. there is a large resonance volume in which ions are continuously accelerated to high energies. In contrast to this conventional scheme, the theoretical analysis performed by Breizman and Arefiev indicated that virtually all of the energy in an ion cyclotron wave (ICW) would be transferred to ion perpendicular energy in a very small volume at a point on the gradient of a magnetic nozzle. This non-linear model predicted highly efficient absorption and that all ions would receive nearly the same energy boost. Ions would therefore leave the magnetic nozzle with a narrower energy distribution than that of a thermalized plasma escaping from a magnetic bottle. The VASIMR experiment at ASPL was reconfigured to test this prediction. The resulting magnetic field geometry and the location of two diagnostics used to detect the predicted acceleration are shown in Figure 4.

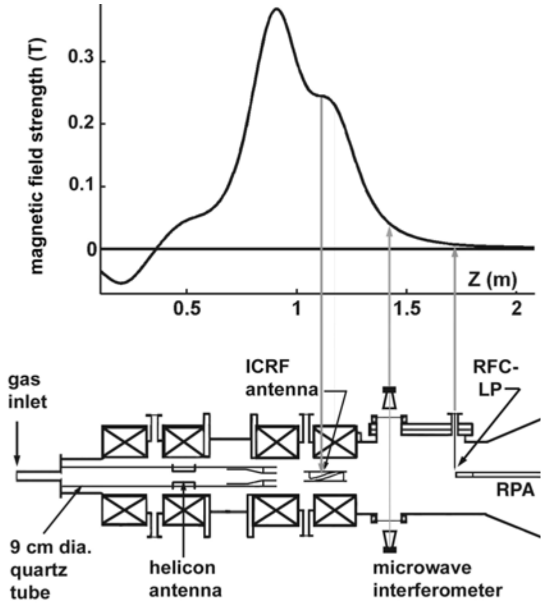

FIGURE 4. Top: On-Axis Magnetic Field Profile. Bottom: Cross-Section of VX-10, Showing Location of ICRF Antenna and Acceleration Diagnostics.

Upon acceleration of the plasma flow by the ICRF power, the microwave interferometer should see a sudden drop in density, assuming that the plasma flux is unchanged by the ICRF power. Simultaneously, the flow velocity measured by the retarding potential analyzer (RPA) and radio-frequency compensated Langmuir probe (RFC-LP) should increase. The ratio of density with ICRF power to density without should be equal to the reciprocal of the flow velocity with ICRF power to flow velocity without, by continuity. These two ratios are plotted in Figure 5 as a function of power applied to the ICRF antenna. Error bars for the RPA data are based on the standard deviation of six successive measurements of the ion energy made over 160 ms. Further details of these measurements and their interpretation are discussed in a prior paper (Glover, 2004). The main point to be taken from Figure 5 is that multiple measurements of the acceleration over a wide range of power made by two independent methods are in close agreement.

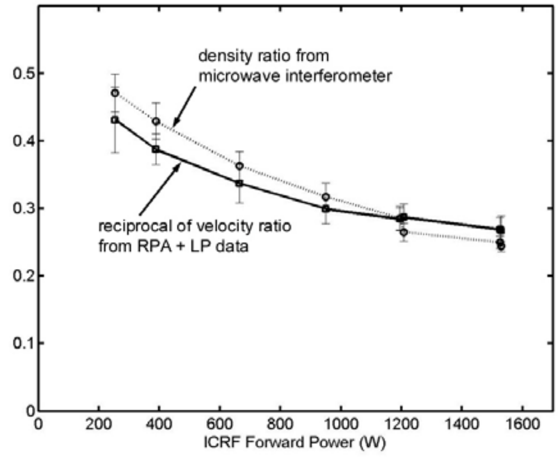

FIGURE 5. Agreement Between Independent Diagnostics Sensitive to the Ion Cyclotron Resonant Acceleration (Deuterium Propellant).

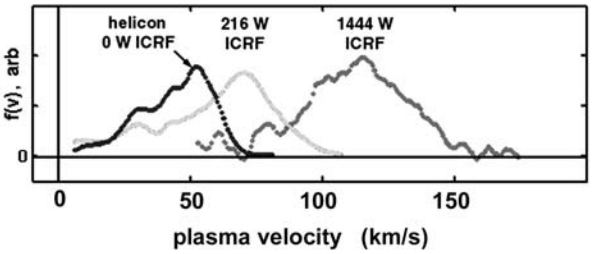

FIGURE 6. Exhaust Plume Ion Distributions are Shifted to Higher Velocity by Application of ICRF Power.

The RPA and Langmuir probe data can be combined to yield the distribution of ion velocities in the exhaust. This quantity is plotted in Figure 6 for three cases. From left to right, the three peaked distributions were obtained for: no applied ICRF power (plasma flow from the helicon source), 216 W of ICRF power (middle peak), and 1444 W of ICRF power (right-hand peak). The ion velocity distribution moves to higher velocities as more power is applied to the ICRF antenna. To put the results in some perspective, the electrodeless ICRA process can accelerate plasma that is two to three orders of magnitude denser than that of an ion engine source to velocities as high as 120 km/s. With the planned upgrade in ICRF power, we expect to demonstrate even higher velocities in future.

Scaling to Higher Power

To more clearly indicate the behavior to be expected at higher power levels, Figure 7 shows the average ion energy as a function of ICRF power. The Langmuir probe data shows that this gain is almost entirely in the form of kinetic energy, because the plasma potential at the location of these measurements (1 m downstream from the ICRF antenna) typically increases by less than 3 V with the application of 1.5 kW of ICRF power, and by lesser amounts at lower ICRF power levels. The linearity of the plot indicates that the increase in the ion parallel kinetic energy is directly proportional to the applied ICRF power, an encouraging trend for extension to higher-power operations.

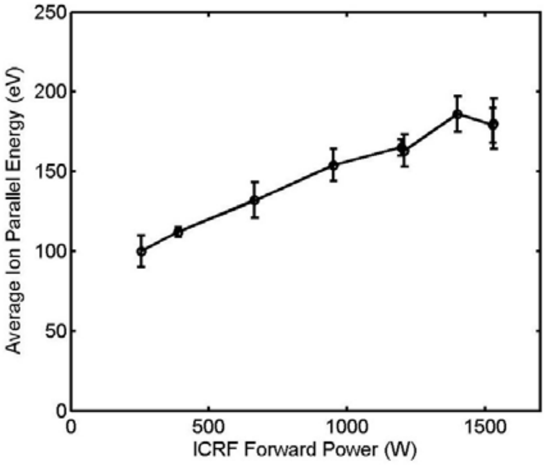

FIGURE 7. Linear Dependence of Ion Parallel Energy on Power Applied to the ICRF Antenna.

Power is transferred from the ICRF antenna to the ions via the electric field associated with the ion cyclotron wave. The fraction of the power input to the antenna that is transferred to the ion cyclotron wave is indicated by the plasma loading. The loading increases with the density and diameter of the plasma passing through the ICRF antenna, and is also affected by the antenna design. Based on loading calculations made by our collaborators in the fusion group at the Oak Ridge National Laboratory for the plasma density and diameter achievable with the 3.5 kW helicon, the estimated power in the exhaust jet appears to account for *all* of the input power launched into the plasma from the antenna; that is, the data does not preclude the theoretical prediction of near-100 % efficiency for the cyclotron absorption process. Precise measurement of efficiencies of individual processes in the RF booster stage requires improved diagnostics, whose construction is presently underway.

Next Technical Objectives

Having demonstrated the physics of the ICRF booster stage, ASPL’s efforts will turn towards questions of overall system efficiency and thrust. The immediate objectives of the project are to reduce the ionization energy cost of the helicon source, to make reliable thrust measurements using a thrust target, to operate with heavier species (N_2, NH_3, possibly H_2O), and to observe plasma detachment phenomena in the downstream exhaust plume. The apparatus needed to achieve these goals is now being designed and built.

Improved Diagnostics

Two new diagnostics will be brought to bear on measurements of thrust and efficiency. More precise determination of the jet power in the exhaust requires improved precision in the estimate of the total ion flux in the exhaust plume. Therefore, a radially moveable Faraday cup has been designed for the plasma conditions in the downstream exhaust plume. To obtain the radial density distribution in a single shot, we plan to deploy a linear array of planar Langmuir probes in the plume at the same axial location as the Faraday cup. With the flow velocity measured by the RPA and RF-compensated Langmuir probe combination, it would be possible to infer the thrust from the plume characteristics. However, a more direct measurement is the subject of an ongoing study using a circular thrust target inserted into the plume (Chavers, 2002). A new version of this device, with a lightweight ceramic plate, has been installed on an axial translation stage in the ASPL vacuum chamber. This line of research is conducted by our collaborators at the Marshall Space Flight Center's Propulsion Research Laboratory, who plan to study the response of the thrust target in the plumes of other thrusters for comparison with the VASIMR results. Through the comparison studies, we hope to demonstrate that the thrust target technique can yield an accurate measurement of thrust, with enough precision to make useful estimates of VASIMR efficiency.

Higher Power

Since the coupling of ICRF antenna power to the ICW increases with plasma density, and since higher plasma density is possible only with additional gas input and higher power to the helicon, raising the helicon power raises the efficiency of the ICRF booster stage. In late April, 2004, the helicon power was upgraded for operation at 10 kW from 3.5 kW. The accompanying measured increase in ICW plasma loading agreed well with the increase predicted by our ORNL collaborators' model. A second upgrade to 20 kW of helicon power is in progress. With the encouraging results of the 1.5 kW ion cyclotron absorption experiments, the ICRF power is also being upgraded for operation at 10 kW, for a system total of 30 kW.

Detachment

With the additional power, analytical and numerical computer models suggest that detachment phenomena may be detectable in the exhaust plume, at an estimated distance of 2 m from the ICRF antenna. The two detachment effects we will search for are steady-state field line dragging, and reconnection phenomena. The principal reconnection effect that appears in MHD computer models of the exhaust plume is the formation of closed field-line "islands". Given the ~100 km/s plasma flow velocities in VASIMR and the ~0.1 m island scale length indicated by the MHD computer models, field reversals and correlated density fluctuations should be observed in the plume at frequencies on the order of 1 MHz. Prototype B-dot probes to search for these signatures have been constructed and will be deployed with associated Langmuir probes after the helicon and ICRF power upgrades are complete.

Efficiency

Satisfactory overall efficiency of the VASIMR thruster now appears to depend on reducing the ionization cost of the plasma source. Higher electron energies are generally associated with more efficient ionization of molecular gases (Miles, 2001) because the cross-section for vibrational excitation drops with increasing incident electron energy, so most strategies for improving helicon efficiency are focused on altering the electron energy distribution. The simplest strategy is to raise the ratio of input power to gas flow rate, since this will raise the electron temperature, as has been demonstrated in VASIMR (Batischev, 2003a, 2003b). In addition, other magnetic field profiles and gas baffle geometries may reduce recycling of ions to neutrals in the helicon. If these approaches alone do not yield a satisfactory source, applying additional power to the electron population by electron cyclotron resonant heating or via an auxiliary high-energy electron beam are other modifications that may be explored to reduce ionization cost.

Heavier Propellants

Another field of inquiry planned for 2005 is operation with heavier propellant gases to achieve lower specific impulse. This effort will begin by first developing a sufficiently dense nitrogen discharge with the helicon for reasonable ICW coupling to the plasma, and applying ICRF power at approximately 700 kHz. Operation with ammonia is also being studied.

CONCLUSIONS

The VASIMR project at Johnson Space Center has successfully demonstrated the effectiveness of the radiofrequency ion cyclotron absorption process as a method to accelerate dense (10^{19} m^{-3}) plasma. Plasma exhaust velocities spanning the range of 50 to 120 km/s have been achieved with a total power level of 5 kW. The helicon plasma source has been modified to achieve what appears to be 100% propellant utilization for helium and deuterium, given sufficient power. Over the next year, operation at a higher total power level of 30 kW is expected to demonstrate that VASIMR system efficiency improves with higher power operation. At these power levels, detachment phenomena may become observable in the far exhaust plume. Existing plasma diagnostics are being improved to reduce the uncertainties in quantities needed for useful estimates of thruster efficiency, such as ion flux in the plume. New diagnostics are being deployed to search for signatures of detachment of the plasma from the thruster.

NOMENCLATURE OF DEFINITIONS

ASPL = Advanced Space Propulsion Laboratory at NASA JSC
eV = electron-volt
ICRA = ion cyclotron resonant absorption
ICRF = ion cyclotron range of frequencies
ICRH = ion cyclotron resonant heating
ICW = ion cyclotron wave
I_{SP} = specific impulse
JSC = Johnson Space Center
LP = Langmuir probe
MPD = magnetoplasmadynamic
MSFC = Marshall Space Flight Center
ORNL = Oak Ridge National Laboratory
PRL = Propulsion Research Laboratory at NASA MSFC
RF = radio-frequency
RFC-LP = radio-frequency compensated Langmuir probe
RPA = retarding potential analyzer
VASIMR = Variable Specific Impulse Magnetoplasma Rocket
VX = VASIMR experiment

ACKNOWLEDGMENTS

Much of this work was performed under a NASA contract to Muniz Engineering, with essential support from staff and technicians of the fusion group at Oak Ridge National Laboratory.

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