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E. A. Bering, III, M. Brukardt, Physics & ECE, UH, Houston, TX,

F.R. Chang Díaz, J.P. Squire, V. Jacobson, ASPL, JSC / NASA, Houston, TX,

Roger D. Bengtson, J. N. Gibson
UT, Austin, TX,

T. W. Glover,
Rice University, Houston, TX

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EXPERIMENTAL STUDIES OF THE EXHAUST PLASMA OF THE VASIMR ENGINE

Edgar A. Bering, III[*], Michael Brukardt[†], University of Houston, Houston, TX,
Franklin R. Chang Díaz[‡], Jared P. Squire[§], Verlin Jacobson[¶],
Advanced Space Propulsion Laboratory, JSC / NASA, Houston, TX,
Roger D. Bengtson[#], Jason N. Gibson[**], University of Texas at Austin, Austin, TX,
and Timothy W. Glover , Rice University, Houston, TX

ABSTRACT

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high power, radio frequency-driven magnetoplasma rocket, capable of Isp/thrust modulation at constant power. The physics and engineering of this device have been under study since 1980. The plasma is produced by an integrated helicon discharge. However, the bulk of the plasma energy is added in a separate downstream stage by ion cyclotron resonance heating (ICRH). Axial momentum is obtained by the adiabatic expansion of the plasma in a magnetic nozzle. Exhaust variation in the VASIMR is primarily achieved by the selective partitioning of the RF power to the helicon and ICRH systems, with the proper adjustment of the propellant flow. However, other complementary techniques are also being considered. A NASA-led research effort, involving several teams in the United States, continues to explore the scientific and technological foundations of this concept. The research is multifaceted and involves theory, experiment, engineering design, mission analysis, and technology development. Experimentally, high-density, stable plasma discharges have been generated in Helium, Hydrogen, Deuterium, Argon and Xenon. Theoretically, the dynamics of the magnetized plasma are being studied from kinetic and fluid approaches. Plasma acceleration by the magnetic nozzle and subsequent detachment has been demonstrated in numerical simulations. These results are presently undergoing experimental verification. Plasma properties of the helicon discharge and exhaust plasma have been measured under a variety of conditions. This paper will review the plasma diagnostic results obtained in 2000-2001 in a continuing series of performance optimization and design development studies and will outline plans and strategies for continued research.

INTRODUCTION

The VASIMR engine has three major subsystems, the injection stage, the heating stage and the nozzle[1,2,3,4]. The use of a separate injection system has allowed us to optimize our system for maximum power efficiency over a wide range of gas flow rates. At present, the best choice appears to be a helicon discharge[5,6]. The next

[*] Professor, Physics and Electrical and Computer Engineering, eabering@uh.edu
[†] Research Assistant, Physics Department
[‡] NASA Astronaut, ASPL Director
Senior Research Scientist, Muniz Engineering
[¶] Research Engineer, Muniz Engineering, Inc
[#] Professor, Physics, University of Texas
[**] Research Assistant, Physics, UT, Austin
[††] Research Assistant, Physics and Astronomy

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stage downstream is the heating system. Energy is fed to the system in the form of a circularly polarized RF signal tuned to the ion cyclotron frequency. ICRH heating has been chosen because it transfers energy directly and primarily to the ions, which maximizes the efficiency of the engine, as has been demonstrated in linear devices[7,8]. In large-scale flight versions, this step may take place in a mirror machine configuration, which will allow the ions multiple bounces through the ICRH RF field. In the present small-scale test version, there is no mirror chamber and the ions make one pass through the ICRH antenna. The system also features a two-stage magnetic nozzle, which accelerates the plasma particles by converting their azimuthal energy into directed momentum. The detachment of the plume from the field takes place mainly by the loss of adiabaticity and the rapid increase of the local plasma β, defined as the local ratio of the plasma pressure to the magnetic pressure. Under certain operational conditions, a hypersonic neutral gas blanket can be injected downstream of the nozzle to enhance plasma detachment while producing an afterburner effect. Moreover, the action of *ripple* coils at the exhaust may trigger plasma instabilities, which further enhance the plume detachment. A schematic representation of this system is shown in Figure 1.

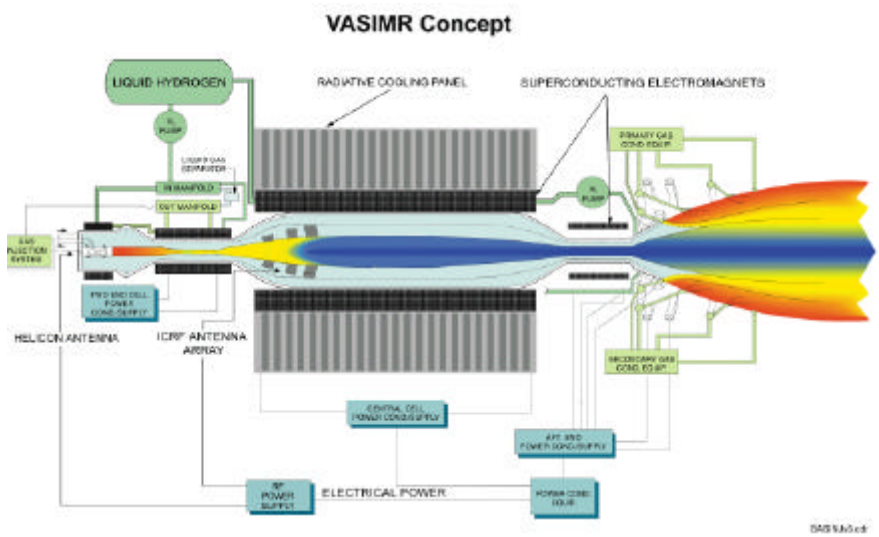


Figure 1: The VASIMR System

More recently, a NASA-led, multifaceted research effort, involving several teams in the United States, continues to explore the scientific and technological foundations of this concept, and its extrapolation as a high power, in space propulsion system[4,9]. Experimentally, two major facilities are investigating plasma performance. Both have obtained attractive results with hydrogen and helium, the two propellants of choice. In helium, densities of 10^{19} m^{-3} have been obtained at frequencies near the lower hybrid resonance[10]. Slightly lower densities, in range of 10^{18} m^{-3} have been obtained with hydrogen. Further investigations using deuterium, as well as other gas mixtures are being conducted.

A laboratory simulation of the 25 kW proof of concept VASIMIR engine has been under development and test at NASA-JSC for 30 months[4,11,12]. Available plasma diagnostics include a triple probe, a Mach probe, a bolometer, a television monitor, an H-α photometer, a spectrometer, neutral gas pressure and flow measurements, several gridded energy analyzers (retarding potential analyzer or RPA)[4], a surface recombination probe system, an emission probe, a directional, steerable RPA and other diagnostics. Reciprocating Langmuir and Mach probes are the primary plasma diagnostics. The Langmuir probe[13] measures electron density and temperature profiles while the Mach probe[14,15] measures flow profiles. Together this gives total plasma particle flux. An array of thermocouples provides a temperature map of the system. The Langmuir probe has four molybdenum tips that are biased as a triple probe, with an extra tip for measuring electrostatic fluctuations[13]. The Mach probe has two molybdenum tips biased in ion saturation, one upstream and one downstream of a stainless steel separator[14,15].

One major series of experiments has focused on power flow diagnostics[16]. We will present a power and particle balance of the VASIMR experiment, as shown in Figure 2. Power input is determined by measurements of RF voltage, currents, and their relative phase (forward and reflected power). Particle flow is set by an MKS flow controller and complemented by pressure measurements at several locations. Power losses to the walls are measured through thermocouples. Spectroscopic

measurements provide an estimate of impurity density, an estimate of radiated power, and electron temperature measurements. A bolometer gives an estimate of total radiated power and is verified with measurements of H_α at several locations. Ion flow velocities are estimated through three techniques: Mach probes, retarding potential analyzers, and spectroscopic measurements. Plasma conditions are measured using Langmuir probes designed to reduce RF interference. These measurements have been combined to present a consistent picture of power and particle flow in VASIMR experiment.

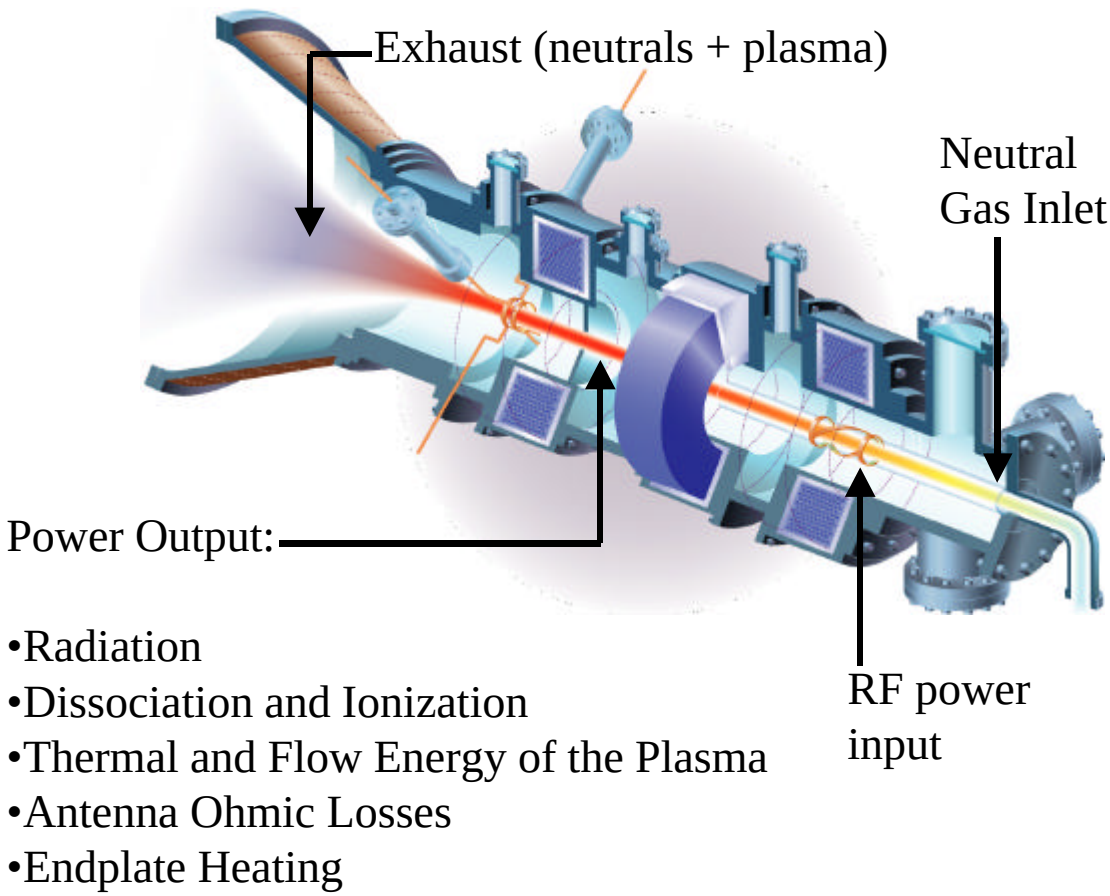


Figure 2. Schematic View of Power sources and losses in the VASIMR experiment.

MAGNETIC CONFIGURATION IN VASIMR

The VASIMR system consists of three major magnetic cells, denoted as "forward," "central," and "aft". A magnet configuration example (related to a 24 kW VASIMR thruster conceptual design) and the corresponding magnetic field profile is shown in Figure 3.

The forward end-cell provides the injection of the neutral gas to be ionized by electromagnetic waves that are produced by helicon antenna. In the central-cell, the plasma is also electromagnetically heated by waves operating near the Ion-Cyclotron Resonant Frequency (ICRF). The aft end-cell ensures that the plasma will efficiently detach from the magnetic field to provide propulsion through a highly directed exhaust stream. This magnetic configuration allows the plasma exhaust to be guided and controlled over a wide range of plasma energies and densities. In Figure 3, the forward end-cell is located at $z < 0.7$ *(m)*, the central cell at $0.7 < z < 1$ and the aft end-cell is at $1 < z$.

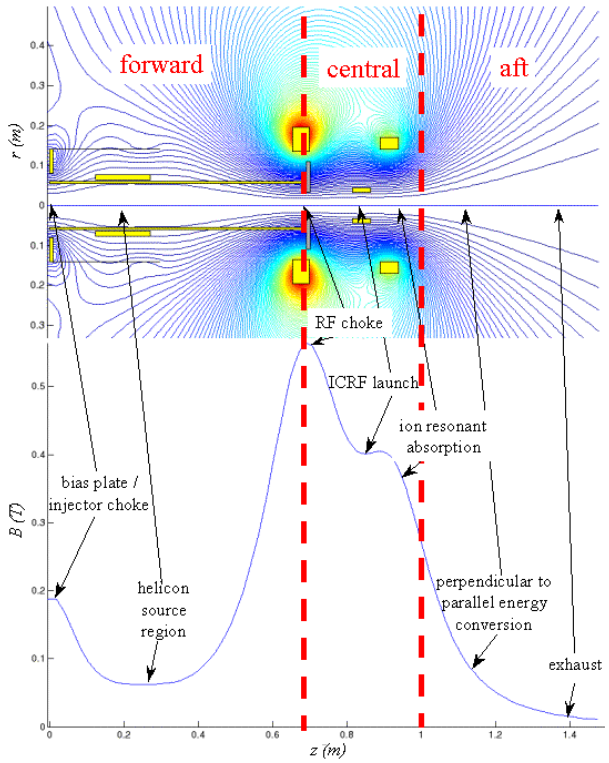


Figure 3: Geometry and magnetic field configuration for 24 kW VASIMR thruster.

RETARDING POTENTIAL ANALYZER

Retarding potential analyzer (RPA) diagnostics have been installed to measure the accelerated ions[4]. The present RPA is a planar ion trap located ~40 cm downstream from the plane of the triple and Mach probes, which corresponds to a factor of 8 reduction in the magnetic field strength. The grids are 125-wire/in nickel mesh, spaced 1 mm apart with Macor spacers. The opening aperture is 1 cm in diameter, nominally centered on the plasma beam. A four-grid configuration is used, with entrance attenuator, electron suppressor, ion analyzer and secondary suppressor grids. Preliminary RPA measurements show evidence of operationally useful exhaust velocities even in early, low power experiments (Figures 4,5).

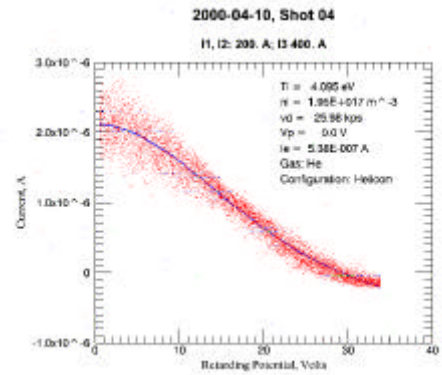


Figure 4. A sample shot of RPA data.

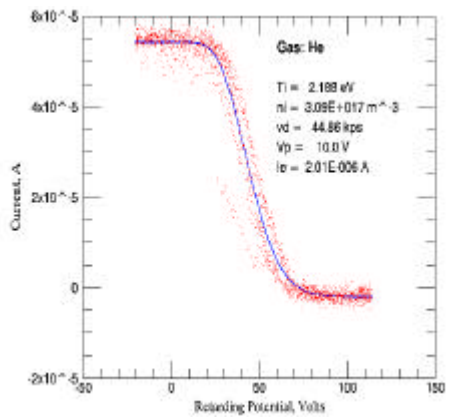


Figure 5. A sample shot of RPA data.

EXPERIMENTAL RESULTS

During 2000 and 2001, we have performed a series of experiments on the VASIMR apparatus with several objectives, to explore the parameter space that optimizes helicon operation, to learn to operate the apparatus in high power modes and to demonstrate ICRH heating of the plasma.

For example, we have studied the effect of the strength of the mirror magnet in the ICRH region on the performance of the helicon without any ICRH heating. The results of these experiments are shown in Figures 6 and 7. In looking at these figures, one point must be made regarding the comparison of the RPA and Mach probe data. When the RPA and the Mach probe are put in the same plane, which was done about 30 months ago, the inferred ion bulk flow speeds agree within 20%, as do the forward vs. backward saturation current ratios. When the RPA is placed ~40 cm downstream from the Mach probe, the inferred speeds increase by at least a factor of 2. We attribute this apparent acceleration to a

combination of adiabatic (magnetic mirror) acceleration and ambipolar electrostatic forces (see below).

The total plasma ion flux shown in figure 6 was calculated using the measured radial profile, while the total power and thrust estimates based on the RPA data were made by making the optimistic assumption that the density measured by the RPA was equal to the beam average, which means that the numbers in Figure 7 are probably 30-50% overestimates. Nonetheless, the numbers shown in these figures are very encouraging. The helicon discharge is producing 30-50% ionization efficiency and 15-30% power efficiency at what is a relatively early stage in the optimization process. We are even producing 20% of rated thrust without turning on the second stage heating. The inverse relationship between thrust and specific impulse shown in Figure 7 is an illustration of the constant power throttling concept (CPT).

We also observe an acceleration of the plasma flow past the high magnetic mirror field. The Mach probe used to measure data downstream of the magnetic mirror, for Figure 6, was moved to a location upstream of the mirror field. Figure 8 shows the magnetic field axial profile and the two locations for the Mach probe measurements. The Mach number measured upstream is half that measured downstream and is substantially subsonic, Figure 9.

The high density discharges produced by the Helicon give rise to a redistribution of the background neutrals. This neutral pumping effect has been observed in other Helicon experiments and has been attributed to the charge exchange interaction between the plasma and neutral gas[17]. The change in neutral pressure along the axis of the source when plasma is present is shown for an optimal Helium discharge in Figure 10. Pressure data were obtained using a Baratron pressure transducer attached to a pitot tube on a siding seal. A dramatic four-fold jump in upstream neutral pressure is observed in the presence of plasma.

No saturation with power has been observed to the maximum of the RF amplifier, Figure 11. The power budget includes ~700 W in Ohmic losses in the helicon antenna, and ~200-400 W of power into thermal and flow energy of plasma. For H_2 and D_2, line radiation is the largest loss mechanism. of order 1 kW. For Helium, radiation losses are less than D_2. Very little loss power is observed flowing to the end plate where gas is injected.

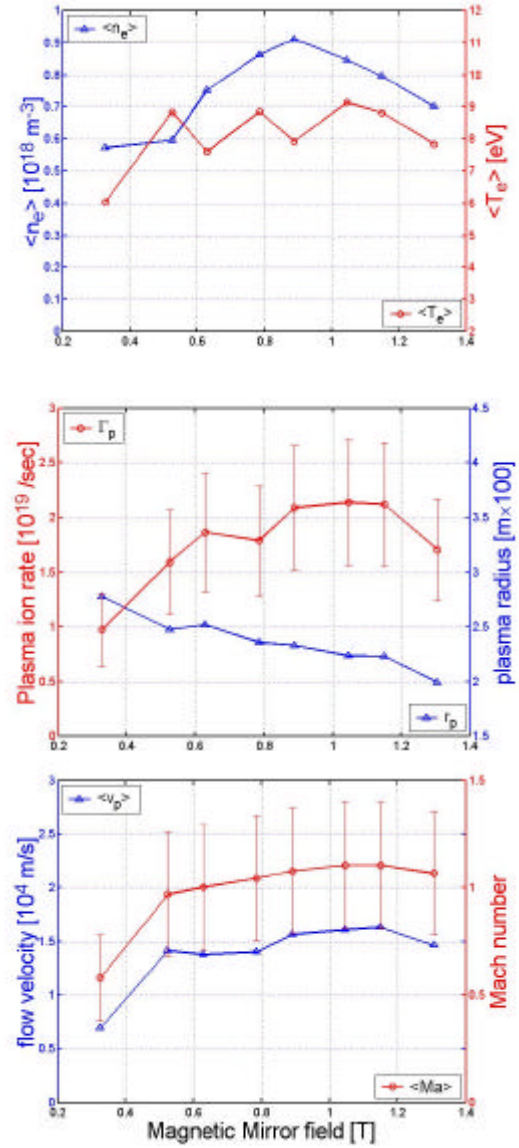


Figure 6. Triple and Mach probe data for a series of shots with the mirror field varying and all other parameters held fixed. RF at 25 MHz with 3 kW. The error bars represent the difference in Mach probe theory models.

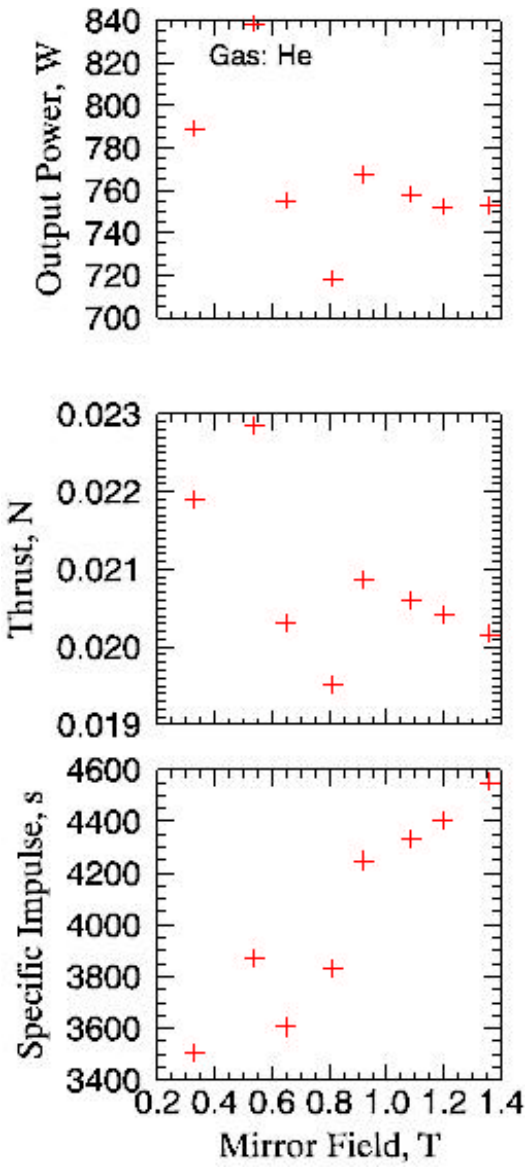


Figure 7. Power, thrust, and specific impulse inferred from the RPA data as a function of mirror magnetic field strength.

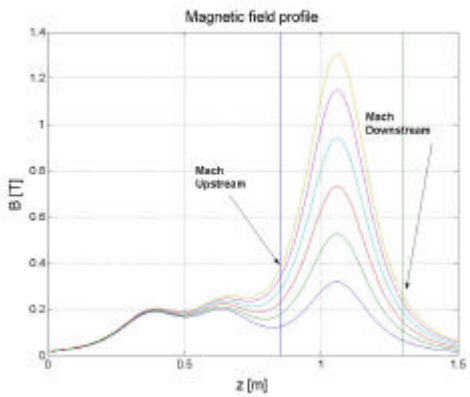


Figure 8. Magnetic field profile showing the location of the Mach probe measurements upstream and downstream of the magnetic mirror.

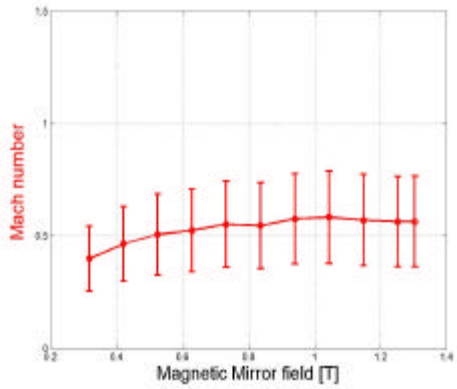


Figure 9. The Mach number measured upstream of the magnetic choke, corresponding to Figure 6.

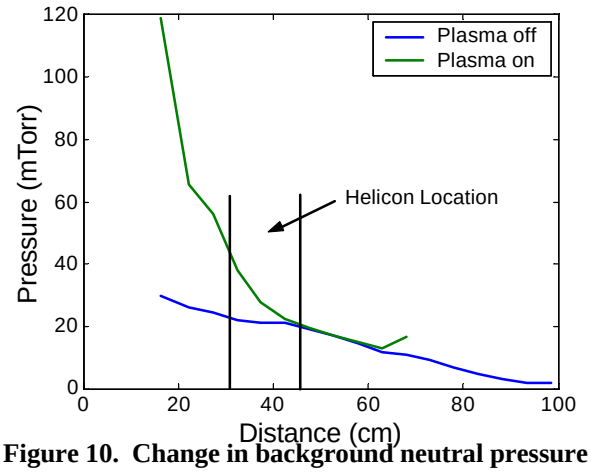


Figure 10. Change in background neutral pressure due to neutral pumping effect of the plasma.

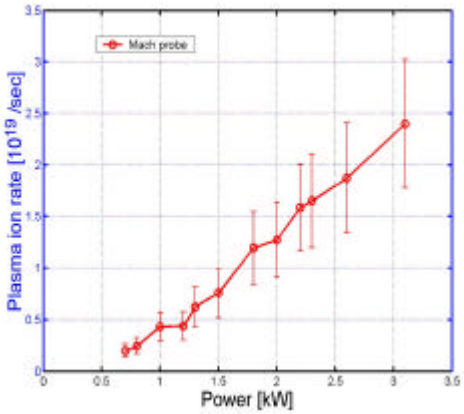


Figure 11. The plasma ion rate outputs plotted for an input helicon RF power scan. Error bars represent the difference in Mach probe theory models.

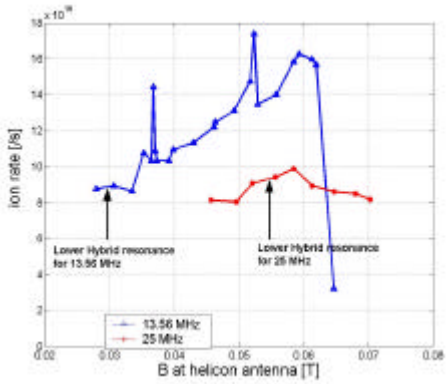
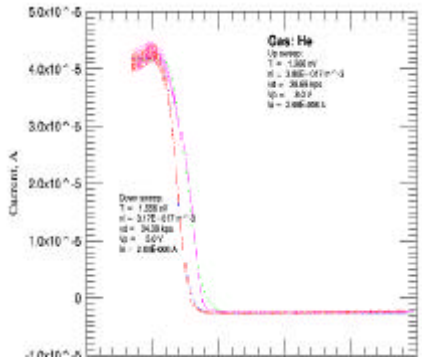


Figure 12. Scan of the magnetic field at the helicon antenna for two helicon drive frequencies, 13.56 MHz and 25 MHz at 2 kW, in deuterium. The mirror field is held constant.



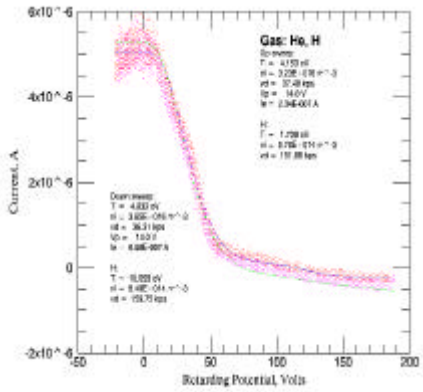


Figure 13. The two panels show RPA data taken under identical conditions, but with a 7.5% H mixture added to the inlet gas in the second panel.

We also found a surprising result while comparing the helicon performance at two frequencies, 13.56 MHz to 25 MHz. Figure 12 contains plots of the total ion output rate verses the magnetic field at the helicon antenna for deuterium discharges. The mirror magnetic field was held constant. The output rate for 13.56 MHz exceeds that for 25 MHz by almost a factor of 2. This effect was not observed for helium. For helium, if the magnetic field was scaled with the frequency, the output rate was nearly the same for both frequencies. Additionally, we notice that at 13.56 MHz the magnetic field is far above where the lower hybrid (LH) resonance is under the antenna, while for 25 MHz, the best performance was with the LH resonance under the antenna. This series of experiments were done at 2 kW because of the 13.56 MHz source limitation, so if we scale the output rates in Figure 12 by 50%, we see that the helicon performance for deuterium is nearly that for helium, as plotted in Figure 6.

In another series of experiments, we investigated the effect of introducing a minor gas constituent into the helicon discharge. The effect was startling and unexpected.

As shown in Figure 13, the introduction of hydrogen into the helium discharge reduced the ionization efficiency of the helicon by nearly an order of magnitude. At the same time, a high-energy tail appeared in the ion velocity distribution function. It appears to us most likely that this tail is comprised of protons flowing at speeds approaching 150 km/s. From the standpoint of VASIMR operation, this mode constitutes a new and unexpected tuning knob. The thrust is low in this mode, but the specific impulse is quite high. Figure 14 shows that the same effect occurs for deuterium-hydrogen mixtures. Speculation on the mechanism driving these energetic ions suggests that "cross-over" plasma wave mode

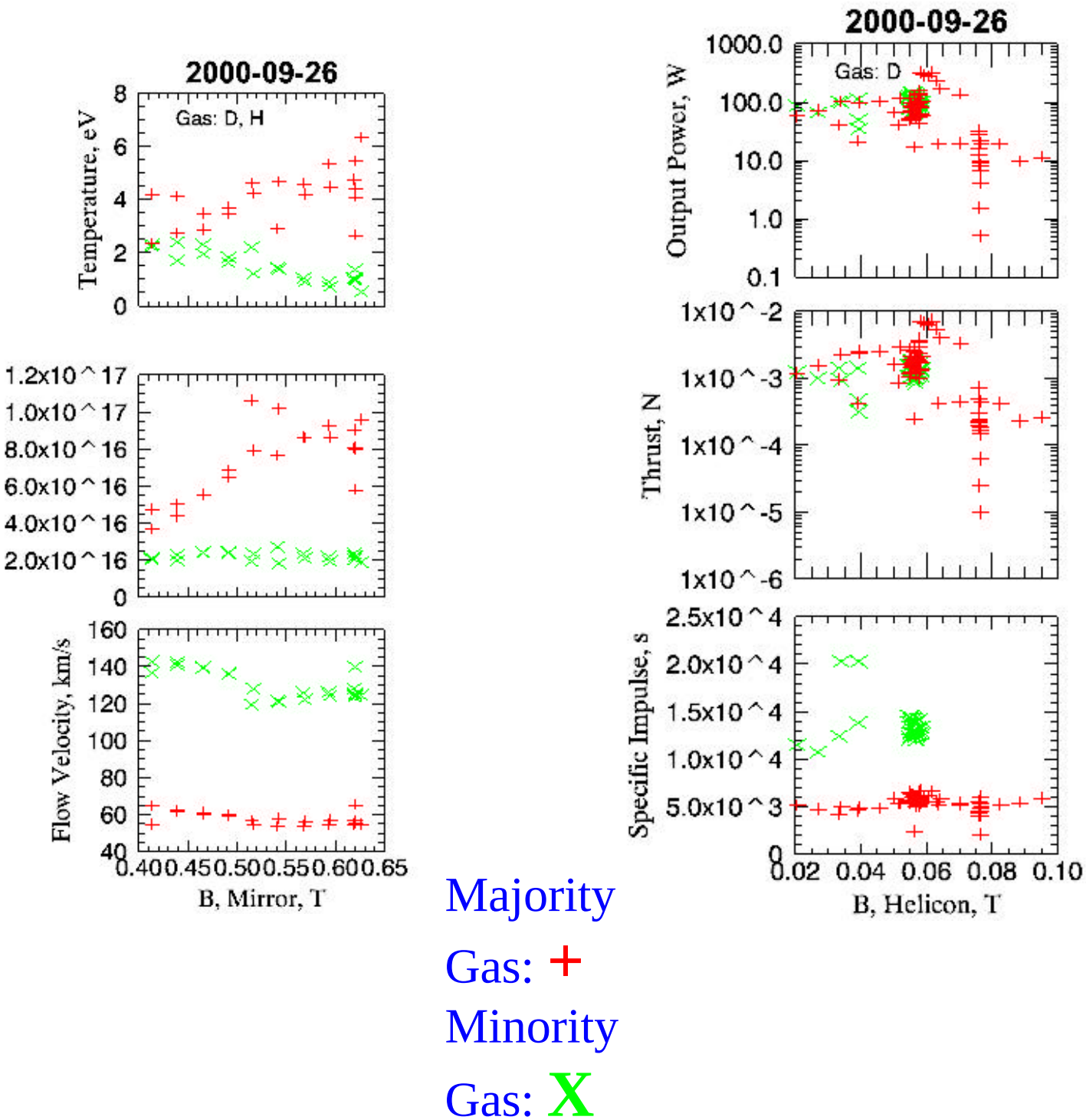


Figure 14. Plasma parameters inferred from RPA measurements during a series of mixed gas helicon experiments. The left hand column plots ion temperature, plasma density, and flow velocity as a function of mirror magnetic field. The right hand column shows inferred output power, thrust and specific impulse as a function of helicon magnetic field.

coupling may be occurring and providing a path to couple wave energy into some form of runaway acceleration. These ideas need a great deal of work.

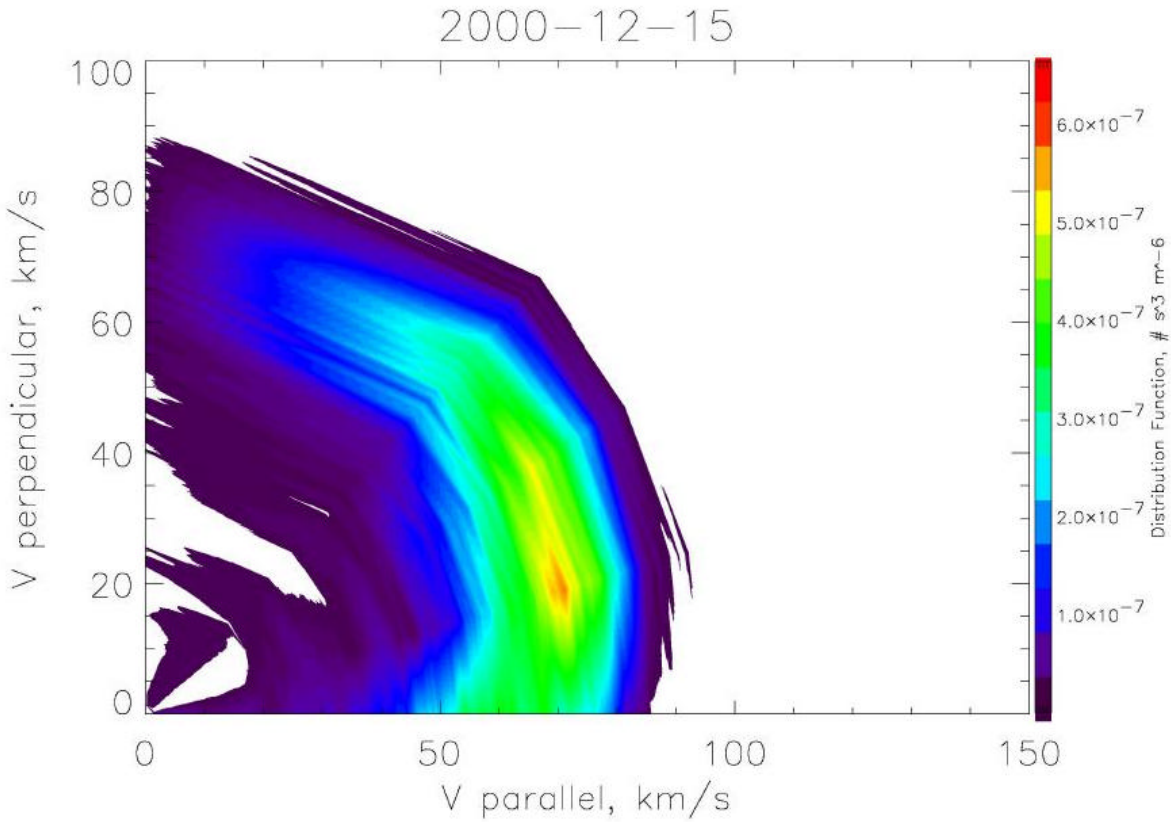


Figure 15. The velocity phase space distribution function of the VASIMR plasma.

We have also begun to investigate the details of the velocity space distribution function in the plasma. We see clear evidence for a substantial amount of elastic pitch angle scattering during the exhaust process, as shown in Figure 15. We believe that this is the result of ion-neutral collisions. However, we cannot rule out pitch angle scattering driven by the presence of ion whistlers. Figure 16 shows the results of two particle simulation studies of the ion distribution function, showing the predicted effect of the magnetic nozzle. This simulation is described in detail in the next paper in this session[18].

Ion Cyclotron Heating: Preliminary Results

Finally, we present the results of ICRF heating experiments from the summer of 2001. First attempts at ion cyclotron heating of helium produced modest results. Heating at the second harmonic produced a dramatic increase in both plasma production and ion energy (see Figures 17 and 18).

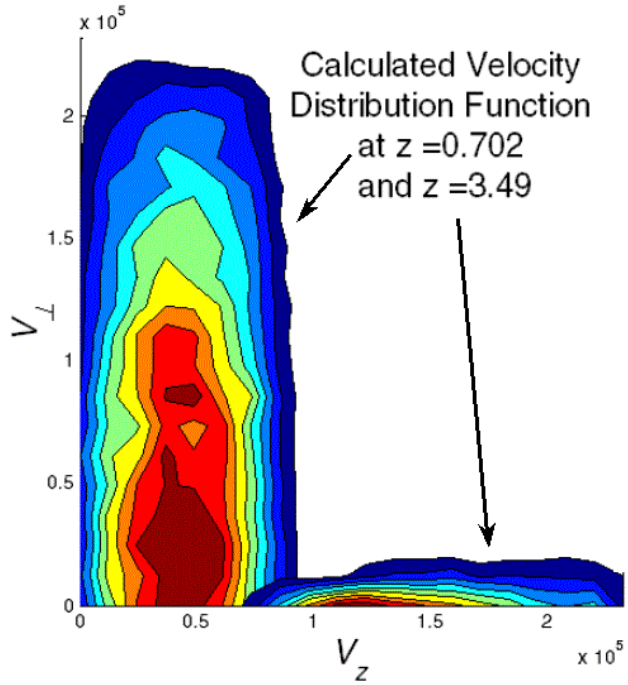


Figure 16: Calculated velocity distribution function using particle simulation. The effect of magnetic nozzle is observed.

Figure 17 displays the RPA characteristic for the helicon source alone, for the magnetic fields for helium ICRH at the fundamental (magnet currents M3 = 2400 A, M4 = 1100 A) and the second harmonic (M3 = 1200 A, M4 = 550 A). These are the two lowest curves in the figure. The magenta curve slightly displaced to the right of the lowest two is the result of heating at the fundamental, with the resonance located just downstream of the ICRH antenna. The trace above that is for heating at the second harmonic, also with the resonance just downstream of the antenna. The top trace is the result of lowering the magnetic field strength so that the resonance is on the upstream side of the ICRH antenna, near the outlet of the quartz tube.

The heating mechanism in this case does not appear to be the ion cyclotron absorption. When the polarization of the RF power was changed to right-handed, the plasma characteristics were indistinguishable from the left-hand case needed for the cyclotron mechanism. While ion-Bernstein wave excitation is a possibility, further work is needed to ascertain both the nature of the heating process and the utility of engine operation in this mode. Measurements of floating potential and electron temperature indicate substantial electron heating takes place in this operating state.

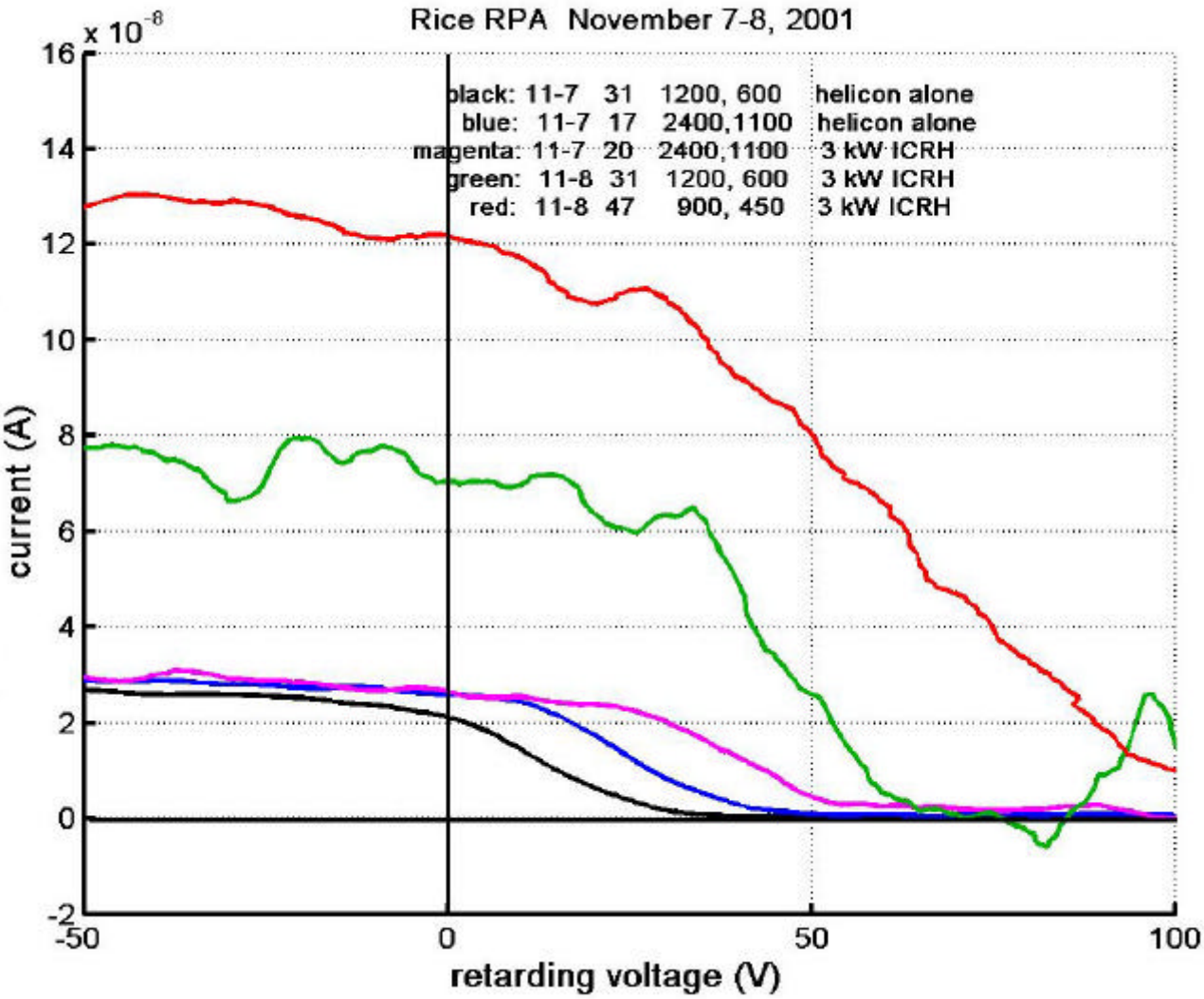


Figure 17. Current-voltage characteristics measured by one of the RPA's during 2nd harmonic He ICRH experiments.

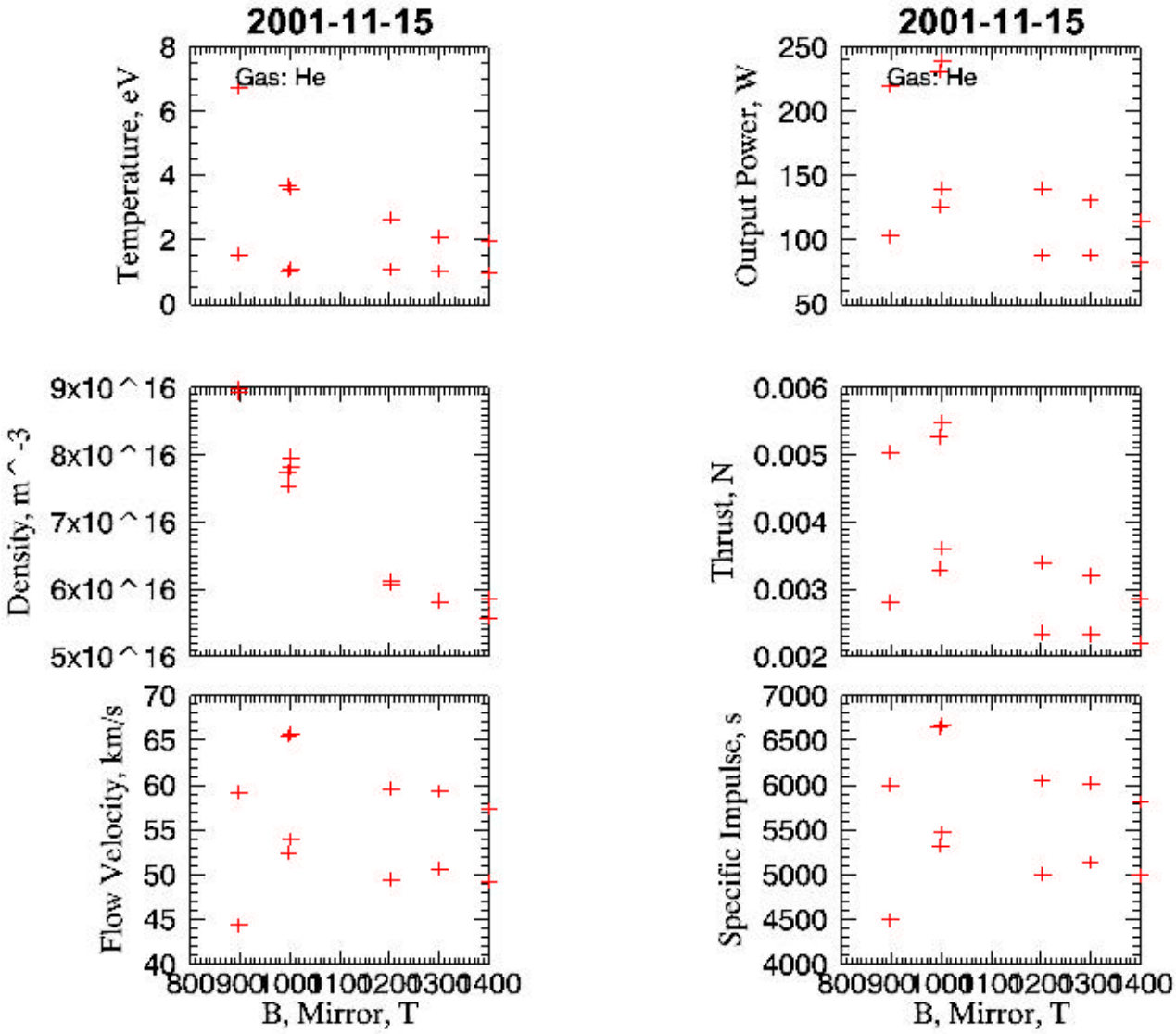


Figure 18. Plasma parameters inferred from RPA measurements during a series of 2nd harmonic He ICRH experiments. The left hand column plots ion temperature, plasma density, and flow velocity as a function of magnetic field approximately at the location of the ICRH antenna. The right hand column shows inferred output power, thrust and specific impulse. All of the panels except density show two distinct sets of points. In all of these panels, the upper row of points corresponds to 3 kW of 3 MHz ICRH input.

Figure 18 shows plasma parameters inferred from RPA measurements during another series of 2nd harmonic He ICRH experiments. The left hand column plots ion temperature, plasma density, and flow velocity as a function of magnetic field approximately at the location of the ICRH antenna. The right hand column shows output power, thrust and specific impulse. The output power and thrust were inferred from axial RPA measurements by integrating over an assumed plume profile normalized to the central measurement. All of the panels except density show two distinct sets of points. In all of these panels, the upper row of points corresponds to 3 kW of 3 MHz ICRH input. The effectiveness of the ICRH RF signal in increasing ion temperature and plasma output is clearly seen. The sharp peak in the plots as a function of B indicates that the relative location of the input antenna and resonance are crucial to successful ICRH heating.

CONCLUSIONS

The paper has presented a report on the present status of the development of the VASIMR engine. The paper has touched on a number of results, both scientific and technological.. On the scientific side, our understanding of the physics high power helicon discharges is growing steadily. We are seeing and increased level of agreement between model and experimental results. We have encountered a number of scientific puzzles that await future work, including the production of supra-thermal tails in mixed gas discharges and the mechanism of heating the 2nd harmonic ICRH discharges. On the technological side, we have seen a steady increase in the plasma output and power efficiency of our helicon discharges. The helicon by itself is proving to be a reasonably effective thruster. We have begun to solve the problems of coupling the ICRH to the narrow and fast-moving output of the helicon discharge.

ACKNOWLEDGMENTS

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