Investigation of a Light Gas Helicon Plasma Source for the VASIMR Space Propulsion System

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Abstract. An efficient plasma source producing a high-density (~10^{19} m^{-3}) light gas (e.g. H, D, or He) flowing plasma with a high degree of ionization is a critical component of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) concept. The high degree of ionization and a low neutral background pressure are important to eliminate the problem of radial loss and axial drag due to charge exchange. We have performed parametric (e.g. gas flow, power (0.5 – 3 kW), and magnetic field studies of a helicon operating with gas (D_2 or He) injected at one end, with a high magnetic mirror downstream of the antenna. The downstream mirror field has little effect on the exhaust flux up to a mirror ratio of 10. We have explored operation with a cusp and a mirror field upstream. The application of a cusp increases the plasma flux in the exhaust by a factor of two. Plasma flows into a large (5 m^3) vacuum (< 10^{-4} torr) chamber at velocities higher than the ion sound speed. High densities (~ 10^{19} m^{-3}) have been achieved at the location where ICRF will be applied, just downstream of the magnetic mirror.

INTRODUCTION

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high power rf driven magnetized plasma rocket, capable of high exhaust velocities, > 100 km/s.[1] Research focuses on three major areas: helicon[2,3] plasma production, ion cyclotron resonant frequency (ICRF) acceleration[4] and plasma expansion in a magnetic nozzle. The present VASIMR experiment (VX-10) performs research to demonstrate the thruster concept at a total rf power on the order of 10 kW. The helicon must produce a plasma stream from light gases (H_2, D_2, and He) with a high degree of ionization that flows into a high magnetic field, ~ 0.5 T, where rf power at about 2 MHz can be converted to particle energy at the ICRF fundamental resonance. The high degree of ionization is critical to reduce charge exchange losses. This paper focuses on recent experimental results in developing such a light gas helicon plasma source.

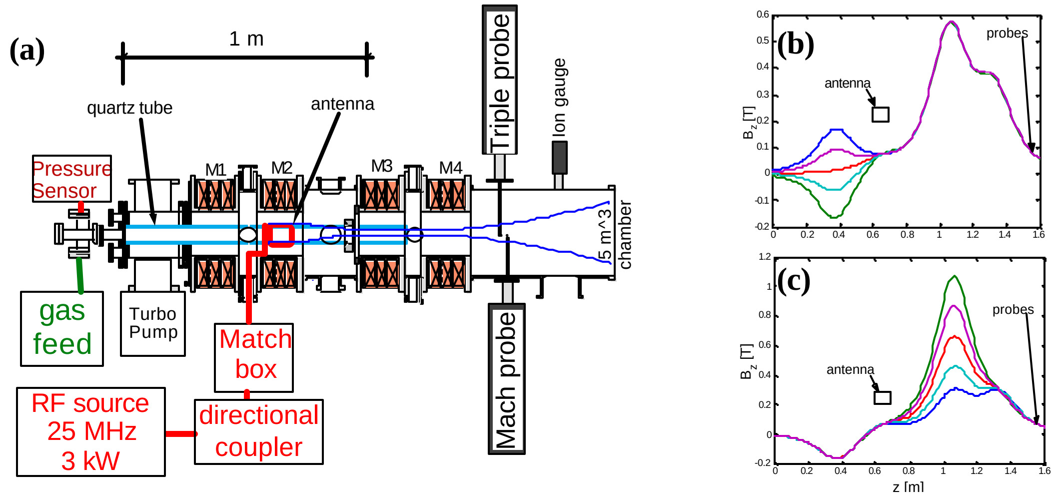

FIGURE 1. a) Schematic of the VX-10. b) Axial magnetic profile with an upstream field scan; c) magnetic profile with peak field scan.

EXPERIMENT

Figure 1(a) shows a schematic of the VX-10 experimental system. The system consists of four cryogenic electromagnet coils integrated into the vacuum chamber. Figure 1(b) shows typical magnetic field profiles for helium discharges. A quartz tube passes down the axis inside the vacuum and is sealed against the port cover on the upstream end. A gas choke located near the magnetic field maximum greatly reduces the neutral gas flow from the helicon to the main chamber. A 25 MHz, 3.3 kW source drives a water-cooled Boswell type double-saddle antenna (10 cm long) located inside the vacuum around the quartz tube and roughly centered under the M2 coil.

Gas (He or D_2) flows into the upstream end of the quartz tube. The discharges are pulsed for approximately 3 seconds to keep the pressure in the exhaust region below 10^{-4} torr. Data presented here are measured downstream of the peak magnetic field in the exhaust. We use two reciprocating probes, Langmuir triple probe and Mach probe.[5] The Langmuir probe density profiles, with helium, were normalized (factor 1.4) with the line averaged density measurement using an interferometer. The Mach number is calculated as the average of two models[5,6] with the error bars representing the difference between models. We calculate the total plasma flux from the probe radial profiles. Uncertainties in Mach probe models dominate errors, with shot-to-shot variations of less than 5%.

RESULTS

Others[7,8,9] have reported that helicons operate most efficiently near the lower hybrid frequency, $w_{rf} \approx w_{LH} \approx (w_{ce} w_{ci})^{1/2}$. We also find this for VX-10. Densities measured at the probes are approximately 10^{18} m^{-3} and are flowing at or greater than the ion sound speed. Field line mapping indicates densities near 10^{19} m^{-3} at the location of the ICRF antenna. Measurements nearer to the helicon antenna[10] indicate slower flow velocities and higher densities.

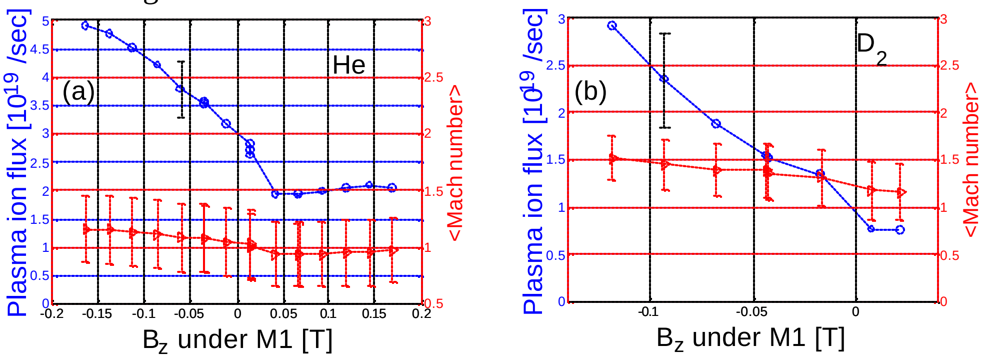

FIGURE 2. Plasma flux (○) and Mach number (▷) with a B_z scan at M1, z = 0.38 m. a) He and b) D_2.

Other experiments have reported increased plasma density when a cusp is placed in the vicinity of the helicon antenna.[11] We have observed a similar increase in the plasma flux with application of a cusp upstream of the antenna. As Fig. 1(b) shows, we have performed a scan of the field upstream of the antenna while keeping the field strength at the antenna location approximately constant. The measured plasma flux with a strong reversed field is more than double the case without the cusp, for both He and D_2, as shown in Fig. 2. For deuterium, positive upstream field gave rise to difficulty with plasma startup.

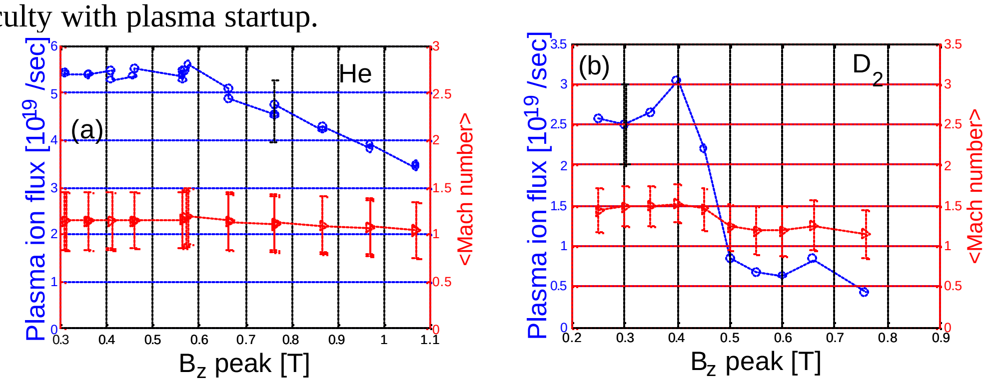

FIGURE 3. Plasma flux (○) and Mach number (▷) for a scan of the peak B_z. a) He and b) D_2.

We scanned the peak field downstream of the antenna while keeping the field strengths at the antenna and probes constant, as shown in Fig. 1(c). We do not find a strong effect on the plasma flux due to the mirror field, up to a mirror ratio of about 10, as shown in Fig. 3. For deuterium, we see a mode change at about a mirror ratio of 10, indicated by the flux reduction. We note, however, that the stray field from M3 changes the gradient at the antenna for the high mirror ratios.

Finally, we find that with the installation of a gas choke that there is evidence that we achieve a plasma stream with a high degree of ionization (~100%) as desired for ICRF experiments. We previously have reported these results with helium[12] and show the similar results for deuterium here. When we decrease the injected gas rate below a critical value, the plasma flux decreases proportionally and the electron temperature (T_e) begins to rise up to nearly double, shown in Fig. 4(a). The rise in T_e is corroborated by a gridded energy analyze, but the indicated value is likely higher than the actual value. Much above the critical input gas rate, the output flux degrades substantially. Also, a helicon power scan, with the gas flow near the critical value, shows plasma flux proportional to power up to a value that starts to saturate, as shown in Fig 4(b).

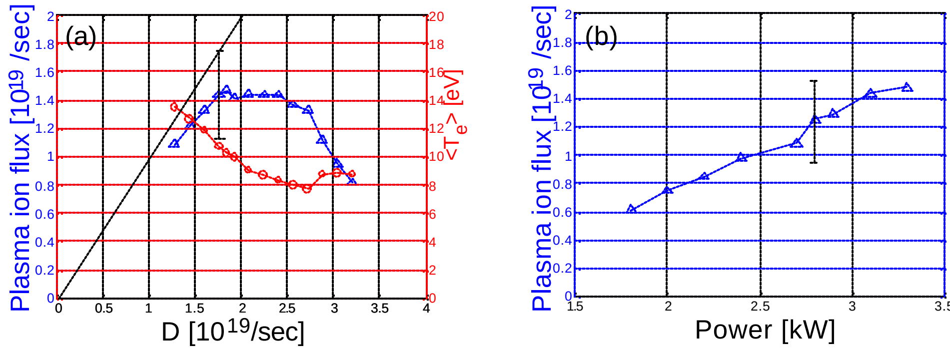

FIGURE 4. a) Plasma flux (△) and T_e (○) with a scan of the input neutral flux. b) Plasma flux with a power scan.

SUMMARY

We have explored the plasma flux from a flowing helicon discharge with helium and deuterium when a magnetic cusp is applied upstream of the antenna and a magnetic mirror downstream. We find that the cusp increases the plasma flux measured in the exhaust by more than a factor of two. The mirror field has little effect on the flux below mirror ratios of 10. Lastly, we achieve a plasma stream with a high degree of ionization that will make a good target for future ICRF experiments.

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