# Experimental Analysis of a Low-Power Helicon Thruster

Douglas Palmer[†], Mitchell L. R. Walker[‡]
*High-Power Electric Propulsion Laboratory*
*Georgia Institute of Technology, Atlanta, GA, USA*

M. Manente, D. Pavarin
*CISAS University of Padua Via Venezia 15 35131 Padova Italy*

J. Carlsson
*Txcorp Boulder Colorado USA*

C. Bramanti
*Advanced Concept Team ESA ESTEC*

## ABSTRACT

**A low-power helicon thruster (LPHT) is an electric propulsion system that utilizes a helicon plasma source with high magnetic field strength to achieve specific impulses of up to 1500 s using argon propellant. The Center of Studies and Activities for Space (CISAS) has created a prototype design, and the Georgia Institute of Technology (GA Tech) has designed and built a nominally 1.5 kW LPHT device that sustains high density, steady state plasma over a range of operating conditions. GA Tech is conducting an experimental characterization of this device to validate the 1-D and 2-D code developed at CISAS, which simulates plasma acceleration during vacuum expansion. The LPHT has been tested at an RF frequency of 13.56 MHz, RF power levels from 100 - 1700 W, magnetic field strengths of 0 – 1100 G, and argon mass flow rates of 0 – 4.45 mg/s. All tests are performed in the GA Tech vacuum test facility at an operating pressure less than 3.1 x $10^{-5}$ Torr. Ion saturation current measurements are taken with an RF-compensated Langmuir probe as a function of both RF forward power (0 – 1.5 kW), magnetic field (0 – 1100 Gauss), and mass flow rate (0.74 to 4.45 mg/s Ar). Ion saturation current measurements are used to determine ion number density. The maximum ion number density is 5.47 x $10^{12}$ cm$^{-3}$. The measurements are compared with several known helicon plasma sources.**

### *Introduction*

Helicon plasma sources sustain steady-state plasma production through absorption and propagation of helicon waves[1]. Helicon waves are launched by applying an axial magnetic field and coupling an RF antenna to the plasma column[2]. Ionization in a helicon wave mode is much more efficient and can provide plasma densities an order of magnitude greater than previous inductive methods for the same input power[3]. Currently, there is a lack of simulation capability for helicon plasma sources, and the Georgia Institute of Technology (GA Tech) seeks to gather experimental data for use in validating 1-D and 2-D simulation codes developed by the Center of Studies and Activities in Space

---

[†] Graduate Student Researcher, Aerospace Engineering, dougpalmer@gatech.edu
[‡] Assistant Professor, Aerospace Engineering, mitchell.walker@ae.gatech.edu

(CISAS). This work seeks to characterize the mode of plasma generation within the thruster by using the ion saturation current versus RF power profile. This profile has been shown to indicate the mode of coupling within the plasma by observing jumps in ion saturation current as RF power increases[1].

### *Facility*

All experiments are performed in the Vacuum Test Facility (VTF), shown in Figure 1. The VTF is a stainless steel vacuum chamber that has a diameter of 4 m and a length of 7 m. Two 3800 CFM blowers and two 495 CFM rotary-vane pumps evacuate the facility to moderate vacuum (30 mTorr). To reach high-vacuum ($10^{-7}$ Torr), the VTF employs six 48" diffusion pumps, with a combined nominal pumping speed of 600,000 l/s on air, 840,000 l/s on hydrogen, and 155,000 l/s on xenon. The VTF pumping speed is varied by changing the number of diffusion pumps in operation. The VTF is able to reach a base pressure of $4.1 \times 10^{-4}$ Pa ($1.6 \times 10^{-6}$ Torr).

Table 1 shows the VTF operating pressure for each flow rate. Previous investigations show these pressures are adequate for plume and interior device measurements[1]. The chamber pressures listed in Table 1 are the indicated pressures from the ionization gauge, corrected for argon using the known base pressure on air and a gas correction factor (GCF) of 1.20. Equation 1 shows the method that the observed pressure ($P_{ob}$) can be corrected to the operating pressure (P) by use of the GCF and base pressure ($P_b$).

$$P = \frac{P_{ob} - P_b}{GCF} + P_b \qquad (1)$$

A Varian model UHV-24 ionization gauge with a Varian senTorr vacuum gauge controller monitors the chamber pressure. The UHV-24 ionization gauge is calibrated for air by the manufacturer. The ionization gauge measures pressure over the range of $10^{-2}$ Pa ($10^{-4}$ Torr) to $10^{-10}$ Pa ($10^{-12}$ Torr) with an accuracy of ±20% as reported by Varian.[4] The VTF also utilizes a KJLC Accu-Quad residual gas analyzer as an alternate source of pressure measurement, all located on the top of the chamber.

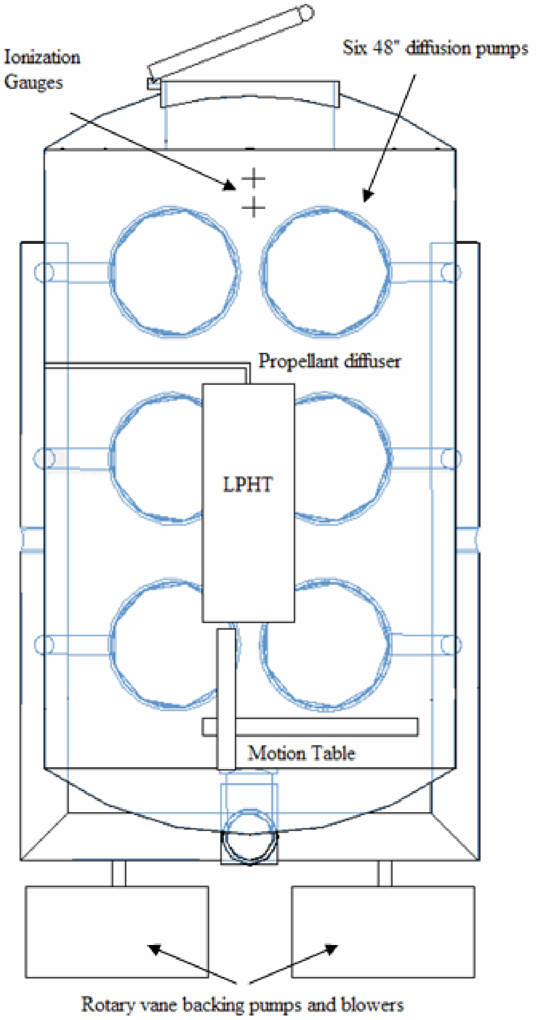

**Figure 1. Schematic of the VTF.** *The LPHT is mounted on an inverted pendulum thrust stand on the chamber centerline. Note: drawing is not to scale.*

**Table 1 – Facility operating pressures as a function of argon mass flow rate.** *These pressures are with only three of the six diffusion pumps in operation.*

| Mass flow rate (mg/s) | Operating Pressure (Torr-Ar corrected) |
|---|---|
| 0.74 | 2.2E-05 |
| 1.49 | 2.5E-05 |
| 2.23 | 2.8E-05 |
| 2.97 | 3.0E-05 |
| 3.71 | 3.1E-05 |
| 4.45 | 3.3E-05 |

### *Low-Power Helicon Thruster*

All experiments are performed on the low-power helicon thruster source shown in Figure 2. A schematic of the low-power helicon thruster RF power, solenoid, and mass flow system is shown in Figure 3. The plasma is insulated by a 45 mm diameter Pyrex glass tube. A 132.8 mm long, 49 mm diameter copper right-helical pitch antenna is wrapped around the tube. The power leads to the antenna as well as the solenoids are EMF shielded with tinned copper mesh to minimize RF radiation. All wiring to the vacuum chamber is shielded with ferrite cores and tinned copper mesh to minimize RF radiation. The solenoid generates steady-state axial magnetic fields of up to 1100 Gauss, and is powered by a 60-kW EMHP DC power supply. High purity (99.9995% pure) argon gas is fed through an MKS 1179JA mass flow controller through stainless steel feed lines to the propellant diffuser. A custom calibration system is employed to calibrate the mass flow controller. The mass flow controller has an accuracy of ±1%.

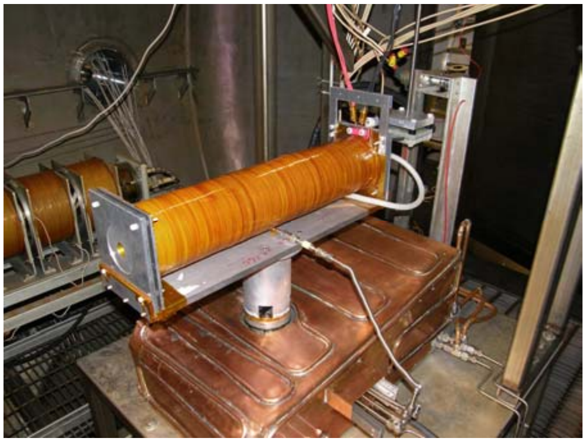

**Figure 2. Low-power helicon thruster mounted on thrust stand.**

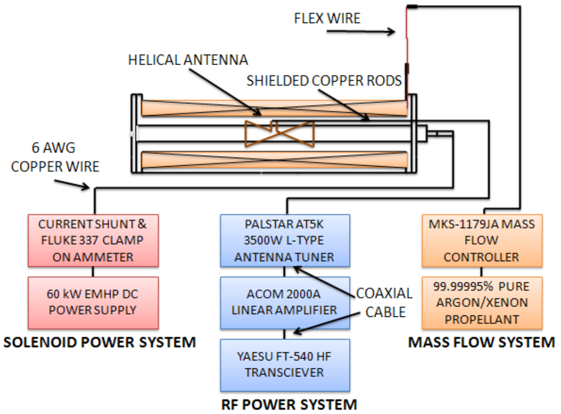

**Figure 3. Schematic of low-power helicon thruster subsystems.**

### *RF-compensated Langmuir Probe*

Two RF-compensated Langmuir probes are constructed for this experiment based upon the Chen type-B probe design. Figure 4 shows the probes[2]. The probes are identical, except the collection tip is parallel to the probe body axis in one case and perpendicular in the other. This allows for higher resolution in both radial and axial

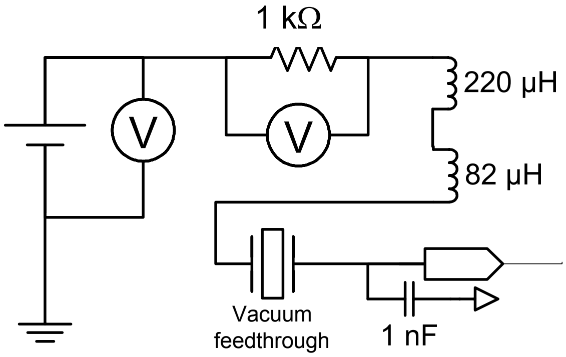

**Figure 4. Wiring Schematic for RF-compensated Langmuir probes.**

measurements, respectively, as the probe may be oriented entirely along the axis where the measurement is desired. This is necessary for radial profiles, where the LPHT exhaust width is only 21 mm. The RF compensation electrode is large compared to the probe radius, improving probe accuracy[2]. Self-resonating RF-chokes and a 1000 pF capacitor are required to achieve the necessary impedances at the operating frequencies, and were selected based on the requirements set forth by Sudit and Chen[3].

The probe consists of a 0.005” diameter tungsten electrode, 0.005” thickness nickel foil compensation electrode, and 1000 pF capacitor. The probe lead attaches to a 1-kΩ resistor and terminates at the chamber ground. A LabView VI reads the probe voltage and calculates the probe current from the voltage drop across the resistor. A Keithley 2410 Sourcemeter supplies the probe bias, with the voltage across the resistor measured by a Fluke multimeter. The probe is mounted to a 1.5-m by 1.5-m Parker Daedel automated motion control system. The motion tables provide linear axial and radial motion with an accuracy of ±1 μm. The probe has been validated for use on both DC hollow cathode plasmas and RF helicon plasmas previously.

### *Experimental Results*

The solenoid is modeled and designed with the MagNet magnetic field simulation pack. The magnetic field of this device is measured with a model HHG-22 Gauss meter, which has an accuracy of +/-1% of the magnetic field strength.

The solenoid is first probed with a model HHG-22 high performance Gauss meter, accurate to +/- 1% of magnetic field. This Gauss meter has two probes, one which measures the magnitude of the total magnetic field at that point, and another that only measures the magnetic field in one direction. The omni-directional probe measures the magnitude of the magnetic field, while the single-component probe is used to measure Bx, By, and $B_z$ profiles produced by the solenoid. The positive x-axis points in the downstream axial direction of the LPHT, while the y and z axes are in the radial directions for a right-hand coordinate system. The Gauss probe is attached to the Parker-Deadal motion table and translated in both an axial and radial profile to ensure accurate spatial resolution. Figure 5 shows the magnetic field magnitude versus the simulated value. The solenoid magnetic field strength follows the simulated value reasonably well, with a maximum overshoot of +4.8%. Figure 6 shows the x-direction magnetic field strength versus the simulation. The results show that nearly all of the magnetic field strength is in the x-direction (along the solenoid centerline in the “exhaust” direction), with a maximum deviation from the simulated value of 3.1%. The $B_y$ and $B_z$ components are taken to verify there is no magnetic field components in these directions. The difference between the simulated and measured magnetic field

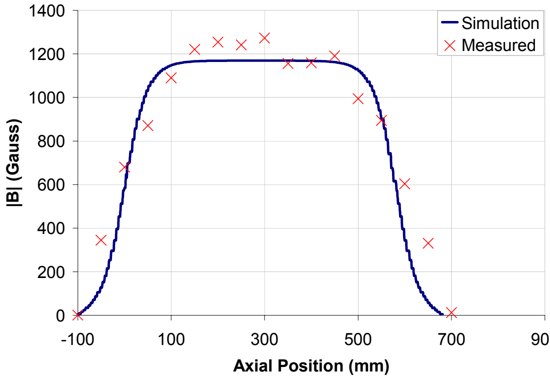

**Figure 5. Measured magnetic field strength on solenoid center line versus simulation.**

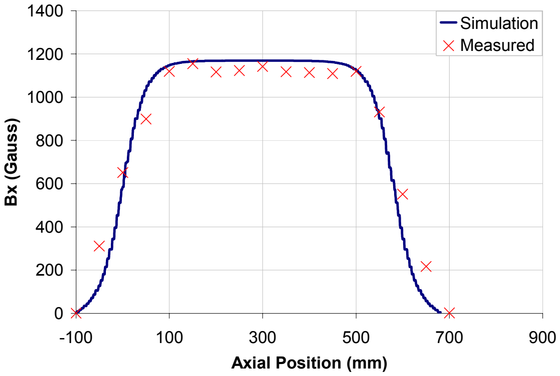

**Figure 6 - Axial magnetic field strength (Bx) measure on device centerline at the solenoid exit plane versus the simulation.**

strengths in these directions is less than 9 Gauss, which is within the error limit of the Gaussmeter.

The radial magnetic field profile is now considered at the exit plane of the device. Figure 7 shows the radial magnetic field strength on soleniod centerline at the exit plane of the device. The measured magnetic field and the simulation are within +/-4.2% of the simulation. Figure 7 also shows that the radial magnetic field profile is constant throughout the ionization chamber region.

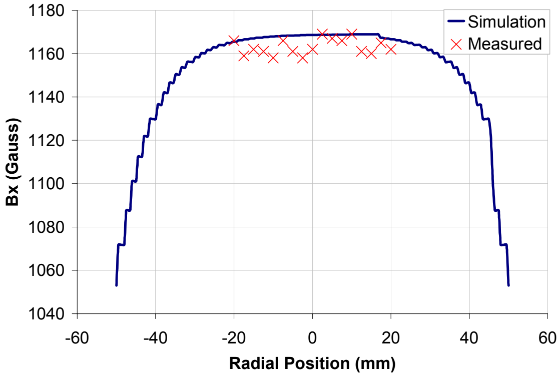

**Figure 7. Radial $B_x$ versus simulation.**

### *Ion Saturation Current versus RF Forward Power*

The body parallel RF-compensated Langmuir probe is positioned on the centerline of the exit plane of the LPHT. The RF forward power is varied from 100 W to 1.2 kW in 100 W intervals, and the ion saturation current is recorded at each power level. This is done by biasing the RF-compensated Langmuir probe to -100V, which is well below the ion saturation bias required to saturate the probe[1]. The ion saturion current profile within the device is measured at two operating coditions. Condition one has a mass flow rate is 2.23 mg/s, the magnetic field strength is 1100 Gauss. Condition two has a mass flow rate of 2.23 mg/s, and magnetic field strength of 500 Gauss. The operating pressure is 2.4 x $10^{-5}$ Torr (3.1 x $10^{-3}$ Pa). Figure 8 shows the results of these measurements. The thruster is operated for two hours steady-state at 1200 W RF forward power.

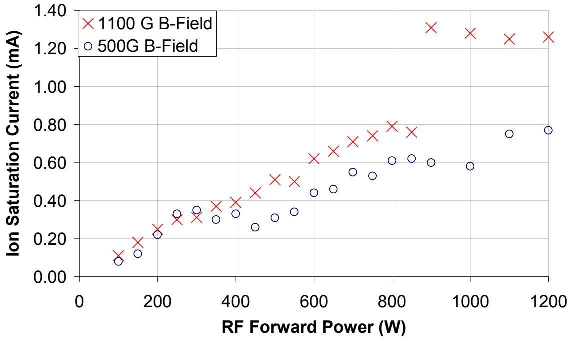

**Figure 8. Ion saturation current versus RF forward power.** *13.56 MHz RF frequency, 2.23 mg/s, 3.1 x $10^{-4}$ Pa operating pressure.*

Figure 9 shows the variation of ion saturation current as a function of magnetic field strength. The operating condition for this measurement is 2.23 mg/s, at 500 W and

1000 W RF forward power, the magnetic field is varied at intervals between 0 and 1100 Gauss. The operating pressure for this set is 2.4 x $10^{-5}$ Torr (3.1 x $10^{-3}$ Pa).

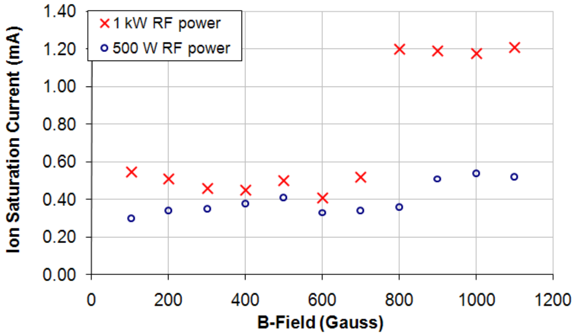

**Figure 9. Ion Saturation current versus Magnetic field strength.** *13.56 MHz RF frequency, 2.23 mg/s, operating pressure 3.1 x $10^{-4}$ Pa.*

Figure 10 shows the ion saturation current is measured as a function of argon mass flow rate. The thruster is operated at 1100 Gauss magnetic field, 500 W and 1000 W RF forward power, with an operating pressure varying from 2.9 x $10^{-4}$ Pa at 0.74 mg/s to 3.3 x $10^{-5}$ Pa at 4.45 mg/s.

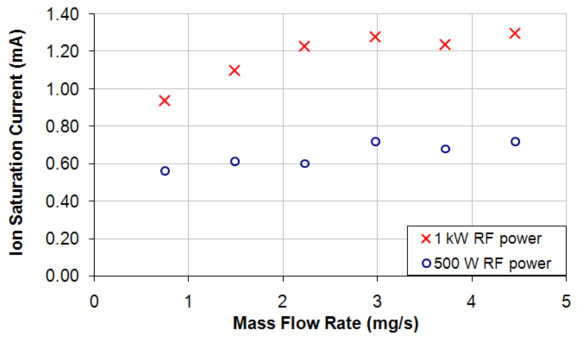

**Figure 10. Ion saturation current versus mass flow rate.** *13.56 MHz RF frequency, 1100 Gauss magnetic field.*

### *Discussion*

The ion saturation current can be used to calculate the ion number density by the expression shown in Equation 2.

$$n = \frac{I_{sat}}{0.6eA_p\sqrt{\frac{kT_e}{M}}} \qquad (2)$$

Where $I_{sat}$ is the measured ion saturation current, e is electron charge, $A_p$ is the probe collection area, $T_e$ is the electron temperature, and k is Boltzmann's constant.

In this analysis, $T_e$ is assumed to be 5 eV, which is comparable to many helicons of this type, and results in the most conservative estimate of the electron number density.

Based on this assumption, the ion number density is calculated across all cases. The maximum ion number density is 5.47 x $10^{12}$ $cm^{-3}$, the minimum ion number density is 4.59 x $10^{11}$ $cm^{-3}$, with an error of +/- 14% based on probe collection surface area and electron temperature assumption. Maximum ion number density occurs at 1200 W RF forward power, 1100 Gauss magnetic field strength, and 2.97 $mgs^{-1}$ mass flow rate.

The magnetic field profiles indicate a purely axial component providing the magnetic field strength, which is a requirement for m = 1 mode wave propagation; as well as maintains a uniform magnetic field strength throughout the device. This prevents localized non-uniformities within the plasma.

Ion saturation current measurements along the centerline of the device at the exit plane provide the ideal location for initial characterization of the LPHT. This location will have the peak electron number density and electron temperature, since in the presence of a large magnetic fields, the plasma will be largely confined to this region.

The ion saturation current trends are consistent with observations of other similar platforms[1, 4, 5]. The slow increase in ion saturation current as RF power increases is highly indicative of the low operating pressure in which these measurements take place. The gradual increase in $I_{sat}$ at low RF power levels followed by a large jump in $I_{sat}$ at approximately 825 W can be interpreted as capacitive coupling followed by a jump to inductive coupling, particularly at such low operating pressures[1]. The 500 Gauss magnetic field curve does not indicate as large of a jump in $I_{sat}$, showing that a 500 Gauss magnetic field is insufficient to support strong mode coupling[5].

The magnetic field profile indicates a lower (capacitive or inductive) coupling mode at low magnetic field strengths, followed by a large discontinuity in $I_{sat}$ at approximately 800 Gauss. The $I_{sat}$ values reached after the jump coincide with the highest values in the RF profile, as well as occurring near the same RF forward power and magnetic field strength levels as in the other profiles, indicating that the same coupling mode within the plasma has likely been reached in both cases[1]. If the jump observed in the RF power profile does indicate passing to the inductive mode, then the 800 Gauss point can be seen as the minimum required magnetic field to sustain helicon inductive mode coupling at this operating condition[5]. Lower ion saturation currents are measured at 500 W, even at high magnetic field strengths. This suggests the plasma is not able to achieve the same coupling mode as with 1 kW of RF power.

The mass flow rate profile indicates a shallow trend as compared to the other cases. It appears that 0.74 mg/s through 4.45 mg/s all can sustain the $I_{sat}$ levels coincident with the third coupling mode viewed in the RF profile, provided the RF power and magnetic field strengths are large enough to sustain wave mode coupling[6].

## *Conclusion*

GA Tech has designed and built a LPHT device based on a CISAS prototype. The helicon plasma source measurements are characteristic of those of past helicon plasma sources, proving the LPHT suitable for use as an experimental platform for the validation of 1-D and 2-D simulation codes under development at CISAS. The device has been operated through the 100 W to 1.7 kW RF power range, at an RF frequency of 13.56 MHz, magnetic field of 0 – 1100 Gauss, and mass flow rates of 0.74 – 4.45 mg/s Ar, for periods of up to two hours steady-state. Initial measurements of the ion number density have been taken at the exit plane of the device, which show discontinuities in ion saturation current that are consistent with past observations for helicons of this type. The maximum ion number density recorded is $5.47 \times 10^{12}$ $cm^{-3}$, while the minimum ion number density is $4.59 \times 10^{11}$ $cm^{-3}$. These values are comparable to those of similar devices[1, 4, 5].

## *Acknowledgments*

The authors wish to thank the Marshall Space Flight Center for supplying the RF power system, and Scott Elliott and Scott Moseley the Georgia Tech Aerospace Engineering Machine Shop for fabrication of hardware.

## *References*

[1] Chi, K.-K., Sheridan, T E, Boswell, R W, Resonant cavity modes of a bounded helicon discharge. *Plasma sources Sci. Technol.* 1999**,** 8, 421-431.

[2] Chen, F. F., RF Langmuir Probes,

revisited. In *58$^{th}$ Gaseous Electronics Conference*, San Jose, CA, 2005.

[3] Sudit, I. D., Chen, F. F., RF compensated probes for high-density discharges. *Plasma Sources Sci. Technology* 1994**,** 3, (162).

[4] Palmer, D., Akinli, C., Walker, M. L. R., Characterization of an Annular Helicon Plasma Source. In *International Electric Propulsion Conference*, Florence, Italy, 2007.

[5] Chen, F. F., Helicon Wave Plasma Sources. In *Proceedings of the International Conference on Plasma Physics*, Kiev, USSR, 1987; Vol. 2, p 1378.

[6] Yano, M., Palmer, D, Williams, L, Walker, M. L. R., Design and Operation of an Annular Helicon Plasma Source. In *43rd Joint Propulsion Conference*, Cincinatti, OH, 2007; Vol. AIAA-2007-5309.