

SIMULATING HYPERSONIC ATMOSPHERIC CONDITIONS IN A LABORATORY SETTING USING A 15-CM-DIAMETER HELICON SOURCE

K. Lemmer^ξ, A. Gallimore, T. Smith, S. Nguyen

*University of Michigan
Ann Arbor, MI 48109*

D. Morris, C. Davis, J. Zagel

*ElectronDynamic Applications, Inc.
Ann Arbor, MI 48105*

Abstract

Hypersonic atmospheric plasmas are difficult to simulate in a laboratory setting because they are high density ($\sim 10^{15} - 10^{20} \text{ m}^{-3}$ depending on altitude) and low temperature ($\sim 2 - 5 \text{ eV}$)^{1,2}. Helicon sources are capable of creating plasma with these requirements³. A 15-cm-diameter helicon source has been designed, fabricated and tested at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL). We operate the helicon at varying input powers, axial magnetic fields, and chamber pressures in order to replicate reentry conditions. We present Langmuir probe data from helicon source operation with argon and residual gas analyzer (RGA) data from helicon source operation with argon, nitrogen and air.

I. INTRODUCTION

While a spacecraft is reentering the atmosphere or a hypersonic vehicle is in flight, low-frequency electromagnetic radiation cannot penetrate the plasma layer that forms around the high-speed vehicle. This interferes with real-time telemetry from hypersonic vehicles and interrupts spacecraft communications during atmospheric reentry. The ultimate goal of our research is to mitigate the communications blackout during hypersonic, atmospheric flight. Our first step is to simulate the atmospheric reentry/hypersonic flight conditions in a laboratory setting.

In the late 1960's a series of electrostatic probe experiments were conducted on RAM C reentry vehicles^{1,2}. The probes gathered voltage vs. current data, giving plasma density and electron temperature values for altitudes between 53 km and 85km. The results of these experiments showed that reentry plasmas have densities of $\sim 10^{15} - 10^{20} \text{ m}^{-3}$ and electron temperatures of less than 2.2 eV.

Helicon sources are capable of producing plasma with the desired parameters discussed above (densities up to 10^{20} m^{-3} and electron temperatures from 1 – 3 eV)³. Therefore, I have built a 15-cm-diameter helicon source at PEPL. We measured ion number density and electron temperature with a Langmuir probe, and species concentrations with an RGA.

II. FACILITIES AND EXPERIMENTAL SETUP

A. Facilities

All testing was performed in the PEPL Cathode Test Facility (CTF). The CTF is a 2.44-m-long, 0.61-m-diameter, aluminum-walled vacuum chamber. High vacuum is provided by a CVI M500 cryopump with a measured xenon pumping speed of 1500 l/s. The CTF base pressure is $\sim 3 \times 10^{-7}$ Torr, and the cryopump can maintain pressures up to $\sim 10^{-3}$ Torr without overheating. The helicon is attached to a 14.5-cm-diameter port located on the side of the CTF. In addition, there are two high precision linear tables with attached external motion controllers that allow for two degrees of freedom during diagnostics testing.

B. Helicon Source

The helicon source at PEPL has a double helix antenna wrapped around a 15-cm-diameter by 40-cm-long quartz tube and connected via a pi-style matching network to a 3 kW, 13.56 MHz RF power supply. The matching network allows for peak reflected power in the range of 5 – 15 watts for the majority of the operating conditions. There are also three magnets capable of creating a peak magnetic field of 415 gauss. We flow argon, nitrogen and air into the CTF at about ~ 200 sccm through an inlet nozzle at the end of the quartz tube, creating a background pressure between 1 – 5 mTorr. Fig. 1 shows the layout of

^ξ email: klemmer@umich.edu

the PEPL helicon source, and Fig. 2 shows the electrical setup of the helicon.

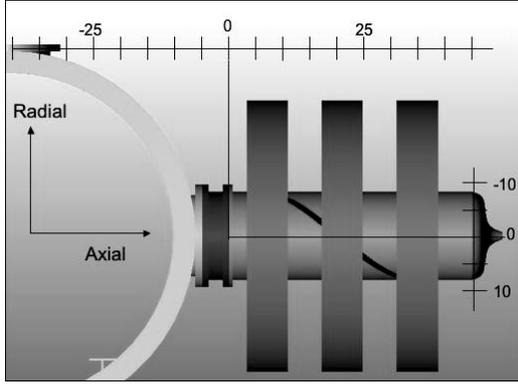


Figure 1. PEPL helicon source layout with dimensions. Units are in cm. The (0,0) location is located where the quartz tube meets with the CTF flange, in the radial center of the quartz tube. Magnets and antenna can be seen surrounding the quartz tube.

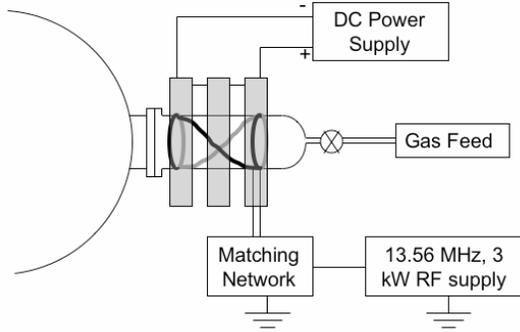


Figure 2. Electrical setup of PEPL helicon source with DC magnets and RF antenna.

C. Langmuir Probe

The Langmuir probe is mounted inside the CTF on the same horizontal plane as the helicon gas inlet. Linear tables permit axial and radial movement of the probe with respect to the helicon. Radial sweeps are taken at axial positions of +15 cm and 0 cm (at the helicon exit plane, see Fig. 1) for varying input power and magnetic field settings.

We also gathered Langmuir probe data at the (0,0) position for varying background pressures, input powers and magnetic field strengths. In addition, we took Langmuir probe sweeps along the helicon centerline at three different axial locations inside the CTF (downstream of the helicon). All Langmuir probe data were taken using only an argon gas feed.

We use Langmuir probe sweeps to verify helicon mode and to compare with the RAM C experiments. These data are interpreted using the cylindrical probe, collisionless sheath method outlined by Lieberman and Lichtenberg⁴. The probe current in the ion saturation regime (where the probe potential is much lower than the plasma potential,

$V \ll V_p$) is given by

$$I_i = 2en_i r_p l_p \frac{2e|V_p - V|^{3/2}}{M_i} \quad (1)$$

where e is the electronic charge, n_i is the ion number density, r_p is the probe radius, l_p is the probe length, and M_i is the ion mass. The electron temperature (in eV) is given by

$$T_e = \frac{\int_{V_f}^{V_p} I(V) dV}{I(V_p)} \quad \text{eV} \quad (2),$$

where $I(V)$ is the probe current, V_f is the floating potential (where $I(V) = 0$). and the plasma potential V_p is obtained at the maximum of the second derivative of the $I(V)$ curve.

C. Residual Gas Analyzer

The RGA (Kurt J. Lesker AccuQuad) is mounted on the CTF wall more than a meter downstream of the helicon source exit, on the same horizontal plane as the helicon gas feed nozzle. To maintain an RGA inlet pressure below 10^{-4} Torr, we placed an auxiliary turbopump on a tee at the RGA entrance. Keeping the conductance C_2 of the RGA-to-turbopump path well below the turbopump speed S_p or the conductance C_1 of the CTF-to-RGA path ensures that the auxiliary turbopump has a negligible effect on the gas sample pressure,

$$P_s = \frac{P_c}{1 + \frac{C_2}{C_1} \frac{S_p}{S_p + C_2}} \rightarrow \frac{P_c}{1 + \frac{C_2}{C_1}} \quad (3)$$

After the gas enters the RGA, it is ionized and the particle mass per unit charge is measured by a channel electron multiplier. We use the RGA to characterize the gas species fractions downstream of the helicon to verify that there are no “odd” species present in helicon plasmas. For this reason, the RGA was operated using air and nitrogen in addition to argon.

III. RESULTS AND DISCUSSION

A. Langmuir Probe

1) Confirming Helicon Mode

In order to confirm helicon mode, we conducted Langmuir probe tests at the (0,0) location of the helicon source. Figure 3 shows the resulting ion density as a function of RF input power for three settings of the peak magnetic field strength. The two distinct “jumps” in ion number density are characteristic of helicon plasma sources. The first jump is from capacitive to inductive mode, while the second is from inductive to helicon mode, as indicated on the plot. The lower magnetic field

settings do not contain these jumps, since they do not achieve helicon mode.

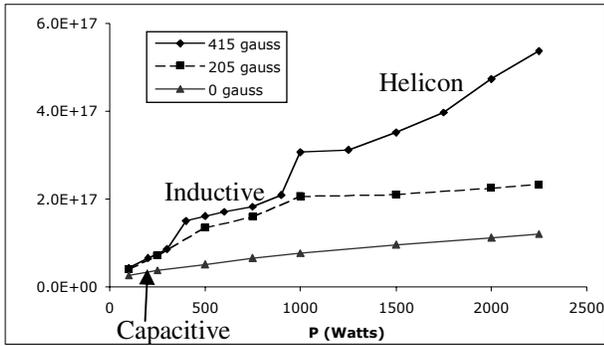


Figure 3. Ion number density as a function of input power and peak magnetic field strength, probe location: (0,0), chamber pressure: 5 mTorr

Figure 4 shows the electron temperature as a function of RF input power for the same three peak magnetic field strengths. The drop in electron temperature for the 415 gauss line at RF power levels beyond 1000 W is typical of helicon mode operation.

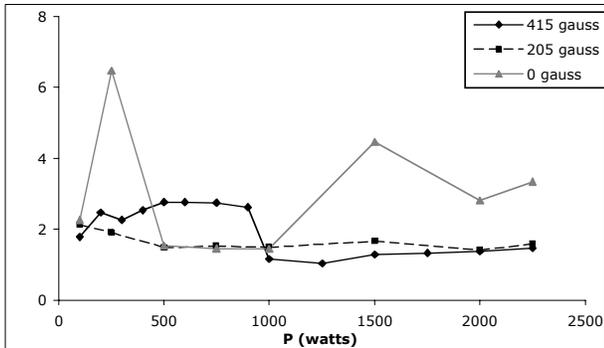


Figure 4. Electron temperature as a function of input power and peak magnetic field strength, probe location: (0,0), chamber pressure; 5 mTorr

We also carried out radial sweeps at the helicon exit plane (axial location 0 cm), looking for the high-density core normally found in helicon mode. Figure 5 shows the ion number density at an RF input power of 1750 W as a function of radial position for three peak magnetic field strengths. Though all three radial profiles show the expected high-density core, this behavior is most pronounced at the highest value of the peak magnetic field strength (415 gauss).

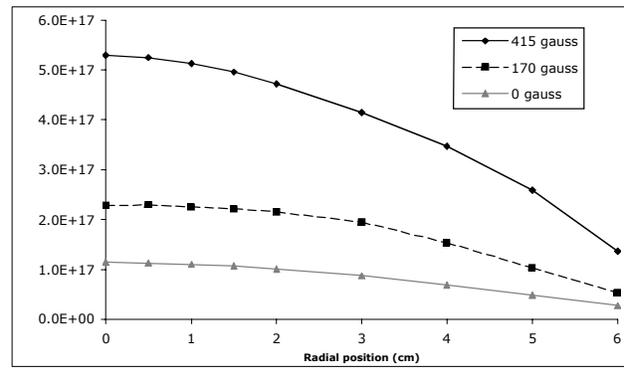


Figure 5. Ion number density as a function of radial position and magnetic field strength, axial position: 0 cm, input power: 1750 watts, chamber pressure: 1 mTorr

2) Comparison with RAM C Experiments

Future plasma mitigation experiments are planned to take place downstream of the helicon source inside the CTF. To determine how well these experiments will replicate the flight conditions recorded in the RAM C experiments, we took Langmuir probe measurements on the helicon centerline (radial position 0 cm) at three axial locations in the helicon plume. The input power during these tests was set to 1750 watts, with a peak magnetic field strength of 415 gauss and a chamber pressure of 1 mTorr. Table 1 compares the results of these measurements to RAM C flight data.

Table 1. Downstream Langmuir probe data compared with RAM C data

	Ion Number Density (m^{-3})	Electron Temperature (eV)
RAM C ^{1,2}	$10^{15} - 10^{20}$	< 2.2
13 cm downstream	$3.7 \cdot 10^{16}$	2.8
20.5 cm	$3.0 \cdot 10^{16}$	2.7
28 cm	$2.7 \cdot 10^{16}$	2.9

At the tested RF input power and magnetic field strength, ion number densities in the helicon are at the low end of those found in the RAM C experiments, while the electron temperatures that we found correspond with the flight data. Though the helicon plume at this power level compares favorably to the higher-altitude end of the RAM C operating conditions, we would like to simulate the lower altitudes as well. Achieving this goal will require further investigation of helicon performance as a function of input power and chamber pressure.

B. Retarding Potential Analyzer

We know what species to expect in reentry plasma, and we want to ensure that there are no “odd” species present in a helicon plasma. Figure 6 shows the species molar concentrations as a function of input power for air, nitrogen and argon gas feeds. Without exception, the species concentrations are independent of the input power while the plasma source operates in helicon mode.

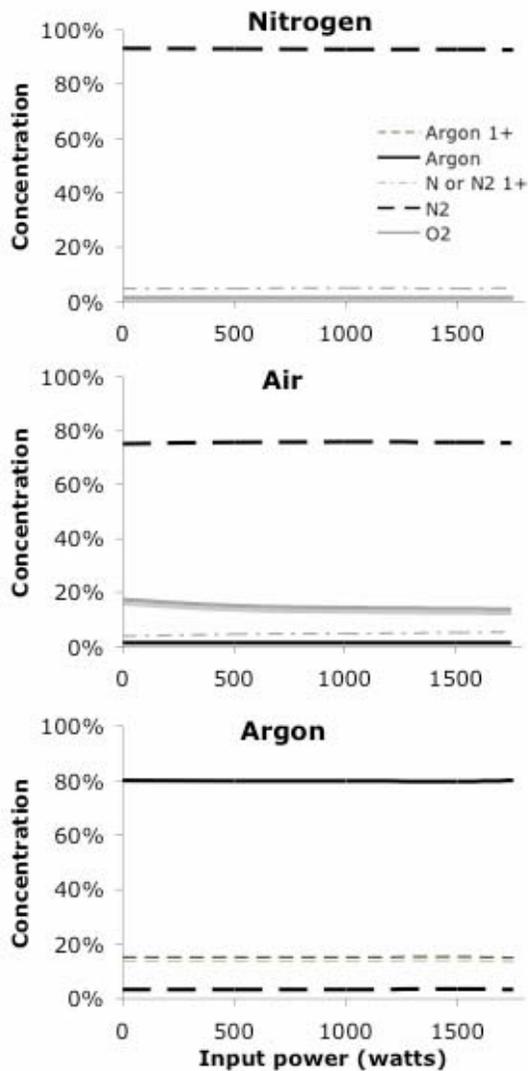


Figure 6. Molar concentration as a function of input power as measured by the RGA for various species.

IV. CONCLUSION

Langmuir probe data taken inside and downstream of the PEPL 15-cm-diameter helicon source confirmed that our plasma source was operating in helicon mode. Langmuir probe data taken downstream of the helicon source corresponded well with RAM C flight data, though ion number densities currently available in the helicon plume correspond only to flight data taken in the upper atmosphere. As a result, we plan to conduct further Langmuir probe testing downstream of the helicon source at higher RF power and chamber pressure settings.

RGA data taken over 1 meter downstream of the helicon exit confirmed that no unusual species were produced during helicon mode operation with nitrogen, air and argon gas feeds.

V. ACKNOWLEDGMENTS

We would like to thank the Michigan Space Grant Consortium and ElectroDynamic Applications, Inc.

VI. REFERENCES

- [1] W. L. Grantham, "Flight Results of a 25000-foot-per-second Reentry Experiment using Microwave Reflectometers to Measure Plasma Electron Density and Standoff Distance," Langley Research Center, Hampton, VA, NASA Technical Note D-6062, Dec. 1970.
- [2] W. L. Jones, Jr. and A. E. Cross, "Electrostatic Probe Measurements of Plasma Parameters for Two Reentry Flight Experiments in at 25000 feet-per-second," Langley Research Center, Hampton, VA, NASA Technical Note D6617, Feb. 1972.
- [3] F. F. Chen and R. W. Boswell, "Helicons – The Past Decade," IEEE Transactions on Plasma Science, vol. 25, no. 6, Dec. 1997.
- [4] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. New York, NY: John Wiley & Sons, 1994.