

Use of a Helicon Source to Simulate Atmospheric Re-entry Plasma Densities

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Abstract: A 15-cm-diameter helicon source was used at the Plasmadynamics and Electric Propulsion Laboratory at the University of Michigan to simulate the density present in the plasma layer surrounding an atmospheric re-entry vehicle. In order to most closely simulate a re-entering vehicle, a “spacecraft surface” was created with a sheet of mica placed so that the bulk of the plasma would be above it. A 13.56 MHz RF-compensated single Langmuir probe was used to determine the plasma properties directly above the mica surface, and those results were compared with measured density data from re-entry vehicles on a ballistic trajectory. We found that near the mica surface (at 0.5 cm and 1.0 cm above the mica surface), the plasma densities were representative of those found at altitudes between 80 km and 85 km during atmospheric re-entry.

Nomenclature

A_p	=	Surface area of Langmuir probe tip
f_p	=	plasma frequency, cutoff frequency
e	=	elementary charge
I	=	probe current
m_e	=	mass of an electron
M_i	=	mass of an ion
n_e	=	electron number density
n_i	=	ion number density
T_e	=	electron temperature
V	=	probe bias voltage

I. Introduction

During atmospheric re-entry and hypersonic flight a bow shock forms around the leading edge of the vehicle. As air passes through the shock wave, it becomes superheated and ionizes. The ionized gas forms what is known as the re-entry plasma layer surrounding the vehicle, and such a layer prevents the transmission of electromagnetic waves with frequencies similar to those used for radio and telemetry communications. This phenomenon is commonly referred to as the “communications blackout” period. In order to overcome this communications blackout, it is important to be able to simulate the blackout conditions in a laboratory setting. Previous work has shown that the Plasmadynamics and Electric Propulsion Laboratory (PEPL) 15-cm-diameter helicon source produces plasma densities similar to those found at altitudes ranging between 70 km and 80 km during the re-entry

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process between 2.5 cm and 8.5 cm above a mica sheet present to simulate a spacecraft surface [1]. In this paper, we determine whether the same helicon source can be used to simulate the plasma density and electron temperature present very near the mica sheet, in an area where a system for ameliorating the communications blackout would be used.

The number density in the re-entry plasma layer ranges from 10^{14} m^{-3} to 10^{18} m^{-3} [2, 3]. These values were measured in the 1960's when NASA performed a series of flight experiments called the Radio Attenuation Measurements (RAM). Project RAM employed electrostatic probes and microwave interferometers to find the number density as a function of altitude. The results are shown in Figure 1. The plot also shows the electron number densities, and therefore the altitude during re-entry, at which the communications frequencies commonly used by NASA and the global positioning system (GPS) equal the plasma frequency. This is referred to as the cutoff frequency and is calculated from (1) below where f_p is the plasma, or cutoff frequency, n_e is the electron number density, e is the elementary charge and m_e is the mass of an electron [4].

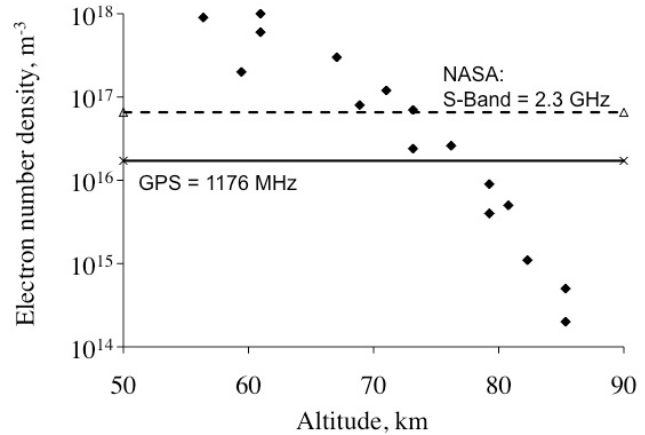


Figure 1. Measured electron number density from the Project RAM re-entry experiments. Also shown are the plasma number densities at which commonly used communications frequencies are cutoff.

$$f_p = \sqrt{\frac{n_e e^2}{m_e \pi}} \quad (1)$$

In addition, the electron temperature of the helicon source plasma should be of a similar value to that measured during re-entry in order to ensure that the plasma is not too energetic compared with an actual re-entry plasma layer. The electron temperatures measured during Project RAM varied between 0.5 eV and 1.0 eV [2, 3].

II. Experimental Setup

All experiments for this research were performed at PEPL at the University of Michigan. The experimental apparatus contained a 2.44-m-long by 0.6-m-diameter aluminum-walled vacuum chamber referred to as the

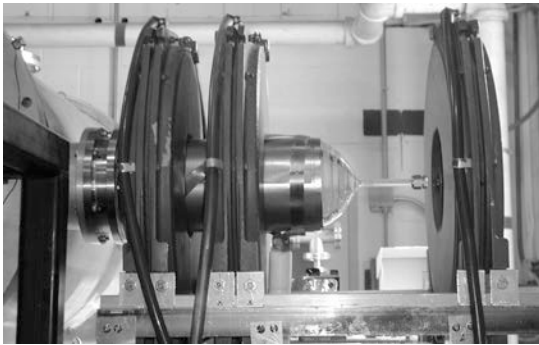


Figure 2. 15-cm-diameter helicon source attached to the Cathode Test Facility.

Cathode Test Facility (CTF). An attached cryopump is able to pump the system to a base pressure of 3×10^{-7} Torr with no gas flow and maintain pressures up to 1×10^{-3} Torr while argon gas is fed into the chamber. A 15-cm-diameter helicon source that has been extensively described previously [1, 5] is shown in

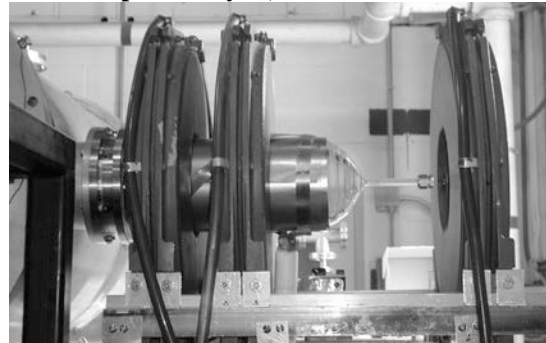


Figure 2 attached to the CTF. Inside to the vacuum chamber, there was a sheet of mica present to represent the dielectric surface surrounding an antenna of a re-entry vehicle. Mica was chosen to simulate the

spacecraft because it is a non-conducting material with good thermal insulation. While the surface of a spacecraft is usually made of a conducting material, the communications antenna is surrounded by non-conducting material. The mica sheet was located immediately downstream of the helicon source exit plane, at a vertical position along the bottom of the 15-cm-diameter quartz cylinder. Testing was performed in a region between 35 cm and 39 cm downstream of the helicon source exit plane, between 0 cm and 4 cm from the radial centerline of the helicon source and at 0.5 cm and 1.0 cm above the mica sheet, as shown in

Figure 3, indicated by the white regions.

A. Langmuir Probe

A 13.56-MHz RF-compensated commercial Langmuir probe was used to measure the plasma density and electron temperature of the plasma layer in the areas of interest indicated by the white areas on Figure 3. The Langmuir probe (LP) system from the Hiden Corporation consists of a data acquisition software package, a tungsten LP collector, RF-compensation circuitry, a power supply and an ammeter. The software communicates with the power supply to provide a varying voltage to the LP tip and then measures the collected current with the ammeter. This data is recorded and exported for analysis.

Raw LP data are stored as current versus voltage sweeps (I-V curves) and are smoothed using a 7-point-box smoothing spline built into the Hiden software package in order to remove any RF noise the system may pickup. This step facilitates the calculation of the plasma density and the electron temperature. Then, the data are exported to Matlab for analysis. A detailed explanation of the analysis process is given by Lemmer, et al. in reference [6]. Briefly, the plasma density was calculated from the Orbital Motion Limited (OML) assumption, using techniques developed by Laframboise that assume a cylindrical probe is immersed in a cold, collisionless plasma [7, 8]. With these assumptions, the ion number density, n_i , was calculated using (2).

$$n_i = \frac{1}{A_p} \sqrt{\frac{2\pi M_i}{1.27e^3} \left(\frac{dI_i^2}{dV} \right)} \quad (2)$$

where A_p is the collector surface area, M_i is the mass of an ion, I_i is the ion probe current and V is the probe bias voltage. Electron temperature, T_e , was calculated assuming that the electron energy distribution function is Maxwellian [9]. The electron temperature is a measure of the inverse-slope of the natural log of the electron current versus the probe bias voltage in the region where the LP was collecting the electron current [10].

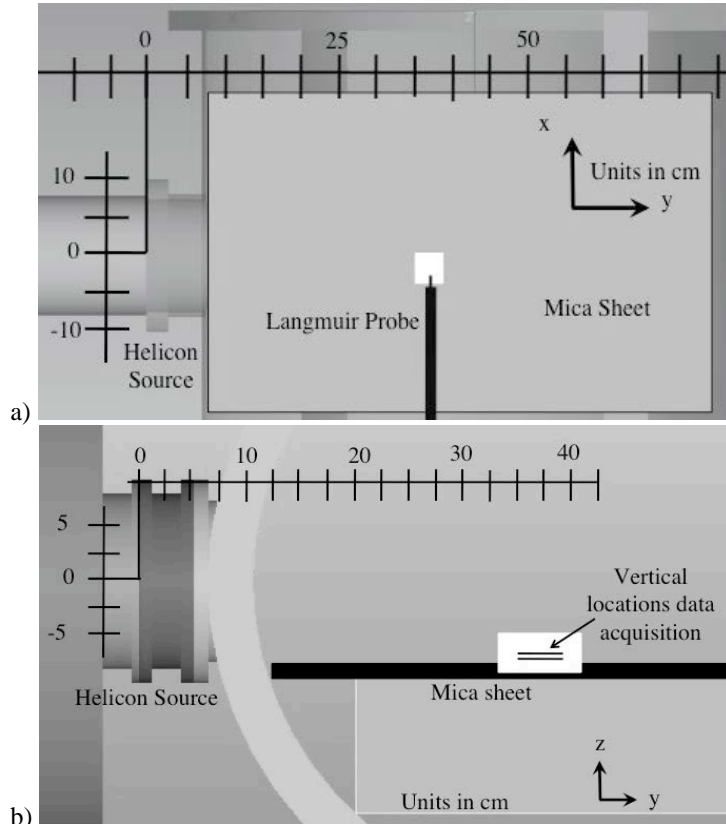


Figure 3. Data acquisition locations downstream of the helicon source are indicated by the white areas. a) is a view looking down on the mica sheet and b) is a side view showing the two vertical planes where data were acquired.

$$T_e(eV) = \frac{V_2 - V_1}{\ln\left(\frac{I_2}{I_1}\right)} \quad (3)$$

Traditional LP error estimates are 20% for electron temperature and 50% for ion number density. Although these errors are high with respect to absolute values, this value decreases considerably when looking at trends in the measurements between points measured using the same apparatus and methods [11]. In addition, common sources of error are avoided by ensuring that the plasma is not flowing and that there are no magnetic field effects in the region of LP operation [1].

III. Results and Discussion

We found results for the ion number density and electron temperature as a function of LP position in the region downstream of the helicon source near to the mica surface.

A. Ion Number Density

The ion number density ranged from $1.5 \times 10^{16} \text{ m}^{-3}$ to $3.1 \times 10^{16} \text{ m}^{-3}$, as shown in Figure 4. The figure shows the ion number density as a function of axial and radial probe position for two vertical planes: a) 1.0 cm above the mica sheet and b) 0.5 cm above the mica sheet. The density is lower nearer to the mica sheet. This trend is the same as that found from previous experiments where the plasma density becomes lower close to the “spacecraft surface” [1]. This is also similar to data found during Project RAM where the number density increased by about $1 \times 10^{16} \text{ m}^{-3}$ over a distance from 1 cm to 7 cm from the vehicle surface [3]. For both vertical planes, the highest densities were measured closer to the helicon source exit, as would be expected since plasma is produced inside the helicon source. The higher densities in the negative radial region are unexpected since helicon sources are most dense along their centerline [12]. This may be an artifact of the proximity of the mica sheet to the measurement area. Comparing Figure 4 with Figure 1, we can see that the helicon source is able to produce plasma very near a surface that is similar in density to plasma produced during atmospheric re-entry altitudes ranging from 80 km to 85 km. In addition, the minimum communications frequency that can pass at those altitudes ranges from 1.1 to 1.6 GHz. The GPS frequency lies within this range, so the helicon source is able to produce densities that can effectively block GPS frequencies.

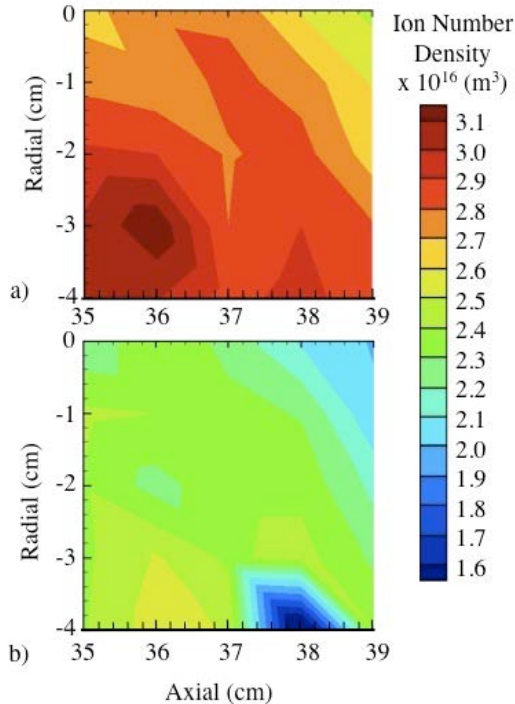


Figure 4. Ion number density. a) Ion number density measured along a plane 1.0 cm above the mica sheet. b) Ion number density measured along a plane 0.5 cm above the mica sheet.

B. Electron Temperature

The electron temperature ranged from 2.5 eV to 5 eV for the region of interest in these experiments. Figure 5 shows the electron temperature as a function of the axial and radial LP position for two vertical planes: a) 1.0 cm above the mica surface and b) 0.5 cm above the mica surface. These values are similar to what was expected based on previous experiments done inside and downstream of similar helicon sources [1, 13]. Although these temperatures are greater than those measured during the Project RAM experiments, the difference is acceptable since matching the number density is the primary concern of this research. Electron temperature was measured to verify that the downstream helicon source plasma was of a similar order of magnitude to that found during re-entry. The electron temperature is, in general, slightly lower closer to the mica sheet. This is expected since the higher temperature electrons will lose energy as they collide with the stationary mica sheet.

IV. Conclusion

We found that the ion number densities near a mica surface in the downstream region of a 15-cm-diameter helicon source range from $1.5 \times 10^{16} \text{ m}^{-3}$ to $3.1 \times 10^{16} \text{ m}^{-3}$. These densities are similar to those found during atmospheric re-entry altitudes between 80 km and 85 km. Therefore, in the simulated re-entry plasma produced by the PEPL helicon source, communications with frequencies less than 1.1 GHz will be attenuated. Electron temperature was found to range from 2.5 eV to 5.0 eV. Although this is higher than the 0.5 eV to 1.0 eV measured during the Project RAM experiments, the values are of the same order of magnitude. This is important to ensure that the PEPL helicon source does not create plasma that is too energetic compared with what actually exists during atmospheric re-entry. In conclusion, the PEPL helicon source can effectively create plasma with temperatures and plasma number densities similar to those found during the re-entry of a vehicle on a ballistic trajectory.

Acknowledgments

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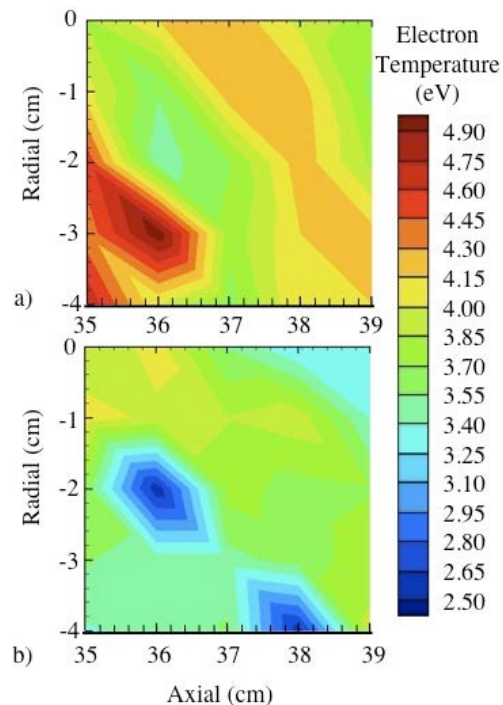


Figure 5. Electron Temperature. a) Electron Temperature measured along a plane 1.0 cm above the mica sheet. b) Electron Temperature measured along a plane 0.5 cm above the mica sheet.

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