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Probe Development for Electrical Conductivity Analysis in an Electron Gun Produced Helium Plasma

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The use of magnetohydrodynamic (MHD) power conversion systems, potentially coupled with a fission power source, is currently being investigated as a driver for an advanced propulsion system, such as a plasma thruster. The efficiency of a MHD generator is strongly dependent on the electrical conductivity of the fluid that passes through the generator; power density increases as fluid conductivity increases. Although traditional MHD flows depend on thermal ionization to enhance the electrical conductivity, ionization due to nuclear interactions may achieve a comparable or improved conductivity enhancement while avoiding many of the limitations inherent to thermal ionization. Calculations suggest that nuclear-enhanced electrical conductivity increases as the neutron flux increases; conductivity of pure ^{3}He greater than 10 mho/m may be achievable if exposed to a flux greater than 10^{12} neutrons/cm^2/s.[1] However, this remains to be demonstrated experimentally.

An experimental facility has been constructed at the Propulsion Research Center at the NASA Marshall Space Flight Center, using helium as the test fluid. High energy electrons will be used to simulate the effects of neutron-induced ionization of helium gas to produce a plasma. These experiments will be focused on diagnosis of the plasma in a virtually static system; results will be applied to future tests with a MHD system. Initial experiments will utilize a 50 keV electron gun that can operate at up to a current of 200 μA. Spreading the electron beam over a four inch diameter window results in an electron flux of 1.5×10^{13} e/cm^2/s. The equivalent neutron flux that would produce the same ionization fraction in helium is 1×10^{12} n/cm^2/s. Experiments will simulate the neutron generated plasma modeled by Bitteker, which takes into account the products of thermal neutron absorption in ^{3}He, and includes various ion species in estimating the conductivity of the resulting plasma.[1] Several different probes will be designed and implemented to verify the plasma kinetics model. System parameters and estimated operating ranges are summarized in Table 1. The predicted ionization fraction, electron density, and conductivity levels are provided in Figure 1 for an equivalent neutron flux of 1×10^{12} n/cm^2/s.

Understanding the complex plasma kinetics throughout a MHD channel is necessary to design an optimal power conversion system for space propulsion applications. The proposed experiments seek to fully characterize the helium plasma and to determine the reliability of each measurement technique, such that they may be applied to more advanced MHD studies. The expected value of each plasma parameter determined from theoretical models will be verified experimentally by several independent techniques to determine the most reliable method of obtaining each parameter. The results of these experiments will be presented in the final paper.

Bulk gas temperature	300 K
Gas pressure	10^{-4} – 1.0 atm
Electron gun parameters Current Energy Beam area	 ≤ 200 μA 50 keV 81.1 cm^2
Maximum electron flux	1.5 x 10^{13} e/cm^2/s
Equivalent neutron flux	1.0 x 10^{12} n/cm^2/s

Table 1: Experimental operating conditions.

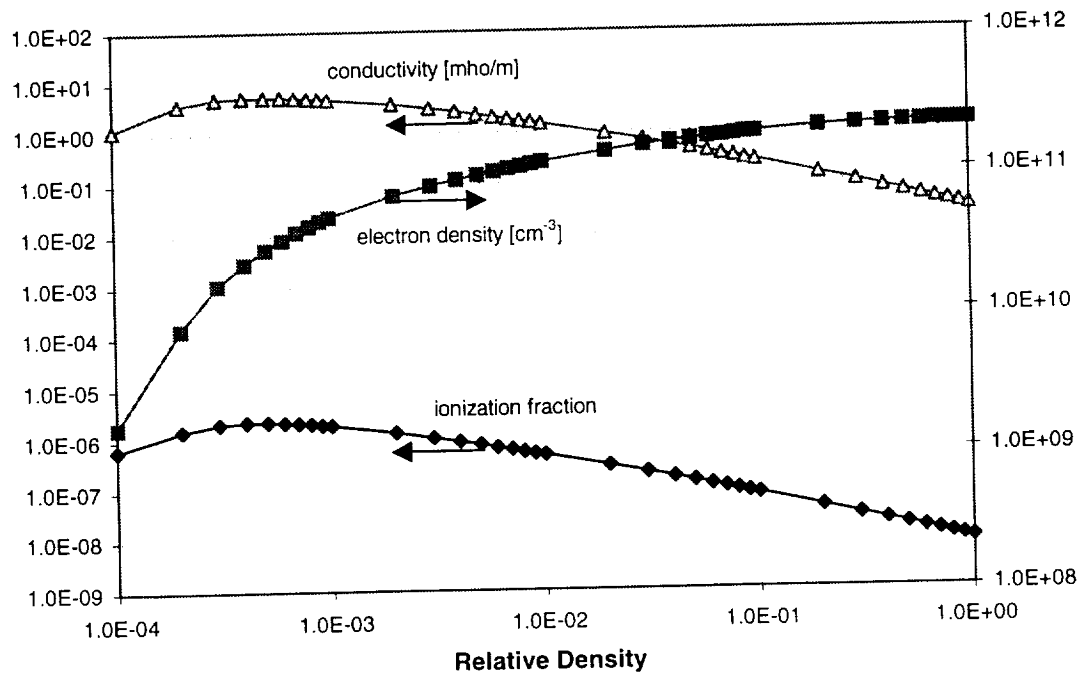

Figure 1: Calculated plasma parameters as a function of relative helium density, given as a fraction of helium density at standard temperature and pressure (2.45×10^{19} cm^{-3}), for an equivalent neutron flux of 1.0 x 10^{12} n/cm^2/s.

Experimental Configuration

The experimental setup, shown in Figure 2, consists of a double vacuum chamber that includes an electron gun chamber and a plasma chamber. The electron gun is held at vacuum and is separated from the main plasma chamber by a thin polyimide window, such that the electrons may traverse the window without losing significant energy.

Because experimental parameters allow the plasma chamber to be held at up to 1 atm of pressure, a wire support grid is required to prevent failure of the thin window. Multiple ports are included along the plasma chamber for probe insertion to measure plasma pressure, plasma conductivity, electron temperature, and electron and ion densities.

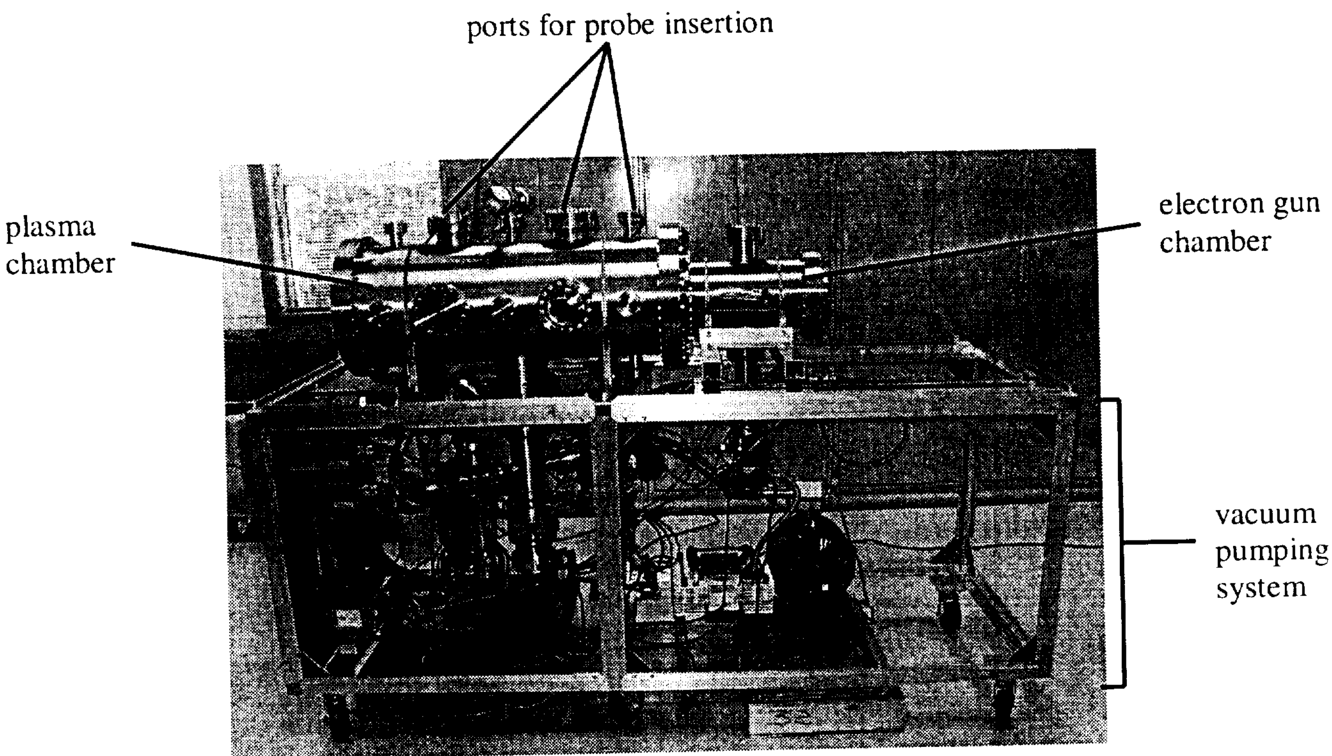

Figure 2: Electron gun and vacuum chamber arrangement.

Development of appropriate system diagnostics is of primary interest to accurately measure properties of the weakly ionized plasma. One property of interest is the electrical conductivity and the persistence of elevated conductivity levels under varying conditions. This measurement will be accomplished by redundant means to verify theoretical results.

Conductivity Probe Design

A radio frequency (rf) probe will be constructed to infer plasma conductivity by measurement of the rf power dissipated in a small volume of plasma that surrounds the probe, providing a local conductivity measurement.[2] The probe includes a rf antenna constructed using a thin copper wire to form a cylindrical, single-layer solenoid that will be enclosed in a glass insulating tube, as shown in Figure 3. Only a small amount of rf power will be transmitted to the probe to prevent any additional ionization of the helium by the diagnostic. Resistive heating in the conducting plasma results in a time-averaged power input per unit volume

$$P = \langle \vec{J} \cdot \vec{E} \rangle \,, \qquad [1]$$

where P corresponds to power density, $\vec{J}$ to current density, and $\vec{E}$ to the electric field. The plasma current density is related to the plasma conductivity by

$$\vec{J} = \sigma\vec{E} \ , \qquad [2]$$

where σ is the electrical conductivity of the plasma. Substitution of the electric field for a dipole reveals the proportionality between the dissipated power density and conductivity: [3]

$$P \ \alpha \ \sigma\omega^2 B^2 r^2, \qquad [3]$$

where ω is the transmitting frequency of the probe, B is the magnetic field of the solenoid, and r is the penetration distance into the plasma. The probe may be calibrated using conductivity measurements of known electrolytic solutions. The rf field penetrates the plasma to a certain skin depth dependent on the rf transmission frequency and the plasma conductivity, yielding the plasma volume for dissipation of the rf power from the solenoid. For a good conductor, the skin depth, δ, is approximately given by

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \ , \qquad [4]$$

where μ is the permeability of the plasma.[3] In this application, we may assume $\mu \approx \mu_o$, the permeability of free space.

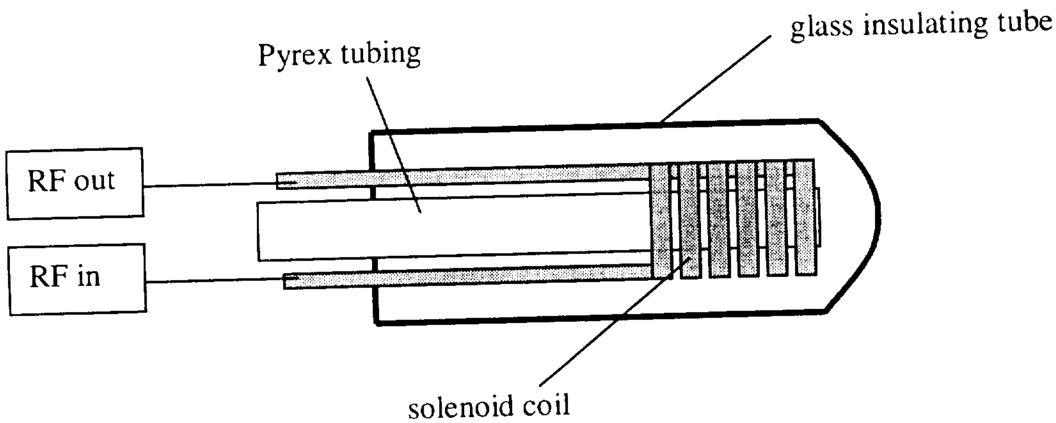

Figure 3: Simplified schematic of the rf conductivity probe. *Note: Figure not to scale.*

For a second, independent conductivity measurement, a cylindrical set of electrodes will be constructed. A rough schematic is provided in Figure 4. This configuration will allow us to deduce the plasma conductivity by measuring the plasma resistance, assuming that the plasma acts as an ohmic resistor.[4] In this design, the cylindrical probe will be inserted into the plasma, with rf voltage applied to the outer electrode at a frequency ω, yielding $V(t) = V_o e^{-i\omega t}$. The inner electrode will be segmented such that the outer pieces act as guard electrodes to maintain parallel electric field lines in the center electrode. A measuring resistor, R_M, connected to the center electrode allows us to calculate the plasma resistance by measuring the voltage drop across the resistor. Assuming that the electric field between the inner and outer electrodes is not affected much by the plasma, an expression for the measured voltage, V_M, across R_M may be derived. A further assumption of constant electron density, n_e, in the region between the electrodes, yields a simplified expression for the measured voltage

$$V_M = \frac{V_o R_M 2\pi l \mu_e e n_e}{\ln(r_1/r_2)} , \qquad [5]$$

where e is the elementary charge, μ_e is the electron mobility, l is the height of the central inner electrode, and r_1 and r_2 correspond to the radii of the inner and outer electrodes, respectively.

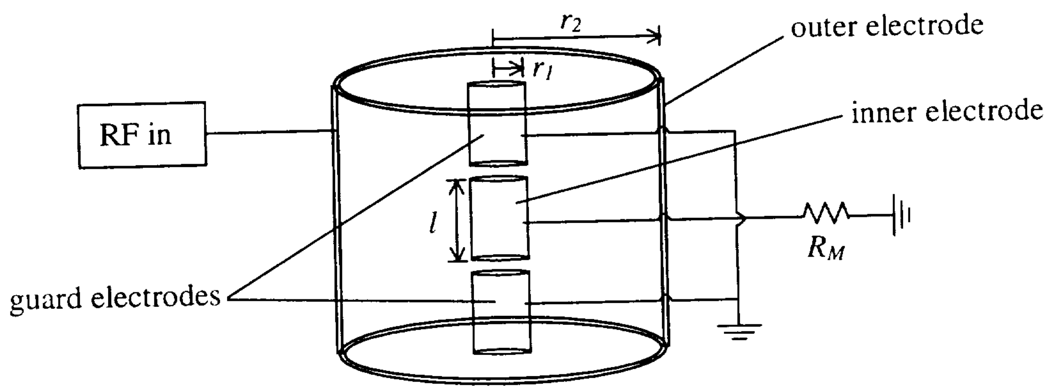

Figure 4: Schematic of the cylindrical electrode probe that will be used to determine plasma conductivity. *Note: Figure not to scale.*

Assuming that electron mobility is considerably greater than the ion mobility, the ion contribution to the electrical conductivity of the weakly ionized gas may be neglected, yielding

$$\sigma = e n_e \mu_e . \qquad [6]$$

Substituting this expression into equation [5], we see that the conductivity can be determined directly from the voltage measured across R_M. One should note that the above analysis assumes the imaginary component of the plasma impedance is small, and the effect of adding an expression for plasma inductance is negligible. Johnsen indicates that the phase shift due to the complex impedance for electrons in helium plasma at standard temperature and pressure is on the order of 10^{-4} radians and, hence, may be neglected.[4]

The conductivity measurements may be used to determine the local electron density in the region of each probe. Using equation [7], the electron density can be computed from the measured conductivity if μ_e is accurately known. For helium at 300 K, μ_e is 9×10^3 $cm^2/V/s$.[5] One may also use the alternate expression for conductivity

$$\sigma = \frac{n_e e^2}{m\nu} \qquad [7]$$

to determine an experimental value of n_e, where m is the electron mass, and ν is the electron collision frequency. A measurement of the gas pressure and the electric field in the plasma column may be used to determine ν from the literature.[6]

Measurements will be taken with each probe at several locations along the chamber to evaluate conductivity at increasing distances from the ionization source and to evaluate n_e on a larger, volumetric scale. Wall effects will also be characterized by varying the probe depth in the plasma.

Verification of Results

In addition to comparing measured conductivity levels and the corresponding electron densities to predicted values provided in Figure 1, the calculated electron density from each conductivity measurement will be compared to that determined from more standard plasma diagnostics. Instruments such as Langmuir probes, microwave interferometry, and laser interferometry may be employed. Much like the conductivity probes described above, Langmuir probes are useful for making local measurements, but they are also invasive and may present a significant perturbation to the plasma. In addition to verifying electron density results, Langmuir probe measurements will be used to estimate the ion density and the electron temperature. Interferometry, on the other hand, is a non-invasive diagnostic technique that provides a measurement of a line-averaged electron density along the transmission path of the laser or microwave signal. With some correction for local versus average electron densities, interferometry measurements may be compared to results from the conductivity probes. Finally, it may be useful to study the composition of the plasma with regard to the expected ionization states of helium using atomic line spectrometry to more accurately assess the ionization fraction of the plasma. The final paper will discuss the results of the research introduced here, with an initial comparison to theoretical models and standard plasma diagnostic techniques.

References

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