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Single Electrode A.C. Plasma Anemometer in High Speed H2 Jet With Background RF Plasma

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Measurements in a high-speed, low pressure hydrogen jet using a cylindrical single-electrode AC-driven glow discharge flow sensor are presented. These results examine the sensitivity and voltage-current characteristics of the plasma sensor with and without the presence of a background RF plasma. These results extend the utility of the plasma sensor to a regime of rarefied, high speed gases. This sensor is being developed to fill a gap in diagnostic capabilities for use in Extreme Ultra-Violet (EUV) lithography systems that use hydrogen as a purge gas within the main vacuum chamber. The plasma sensor utilizes a high frequency (0.05-2 MHz+) AC discharge between two electrodes as the main sensing element. The voltage drop across the discharge correlates to changes in the external flow which can be calibrated for mass-flux (ρU) or velocity. Recent experiments examine the effects of electrode geometry, AC frequency, and background ionization on the plasma sensor response. The velocity sensitivity was improved by the new electrode geometry with good response even while operating in a background plasma.

I. Introduction

Laser produced plasma (LPP) light sources have been developed in recent years as the primary approach for Extreme Ultra-Violet (EUV) scanner imaging of circuit features for high volume manufacturing in the semiconductor industry.

LPP EUV lithography light sources generate short wavelength radiation at 13.5 nm by focusing a 10.6 μm CO2 laser beam onto tin (Sn) droplet targets creating highly ionized plasmas with electron temperatures of several 10's of eV. EUV photons are radiated isotropically by these ions. Photons are collected with a temperature-controlled, graded multilayer coated, normal-incidence mirror (collector), and focused to an intermediate point from where they are relayed to the scanner optics and ultimately to the wafer.[1]

Collector lifetime is a critical source characteristic for the economic viability of an EUV source to be used in mass production of cost sensitive semiconductor devices. The 650mm diameter ellipsoidal collector must survive in the vacuum environment in close proximity to a Sn plasma. Surface coating by tin is an undesirable by-product of the plasma which severely impacts collector lifetime. Debris mitigation and contaminate purging is provided by a high speed, high-temperature hydrogen gas jet at a pressure and flow rate required for protection needed to keep the optic clean and damage free, thus increasing its lifetime. Hydrogen gas is used because it is relatively transparent to the CO2 laser used to vaporize the tin droplets.

The hydrogen jet becomes turbulent as it propagates into the collection space where the Sn droplets are introduced. The unsteadiness associated with this turbulence can interfere with the uniformity and

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reproducability of the Sn droplet, impacting performance and reliability of the EUV source. Factors such as jet spreading rate and turbulence intensity are important flow features that if known would help to maintain desired conditions within the collector. However the high temperatures, speeds, low pressures, poor visible access, and ionization of the gas in the chamber complicate a full characterization of the hydrogen jet with conventional diagnostic approaches. Survivability of point-wise in-situ diagnostics are limited by these conditions, leaving designers with an incomplete knowledge of the hydrogen-Sn droplet interaction and thus limiting the means to control the system or provide improvements to next generation technologies.

A new diagnostic approach has been developed at the University of Notre Dame for robust velocity measurements in high-enthalpy and ionized flows. This sensor does not use a conventional transducer but relies instead on a local ionization between miniature electrodes as the main sensing element. The operating principle of this device, summarized by Marshall et al.,[2] involves an interaction between an AC-driven discharge and the external flow field through an ion convective loss mechanism that provides a voltage drop which correlates uniquely to the external velocity. The advantages of this approach include a native high-bandwidth, cost-effective robust design which is able to operate in conditions of local ionization at high-temperatures.

II. Experimental Configuration

The current work describes recent results obtained in a high-speed, 1.5 Torr static pressure hydrogen jet. The experiments were performed in the Radiation Laboratory at the University of Illinois in a vacuum chamber facility designed for rarefied gas measurements. These results, described below, provide comparisons between operation in neutral versus ionized Hydrogen flow. The sensor system consists of an AC voltage source and a novel single electrode design. The electrode was made from a cylindrical aluminum tube 0.75 inches in length with an OD of 0.5 inches and a wall thickness of 0.05 inches. A photograph of the electrode is shown in Figure 1.

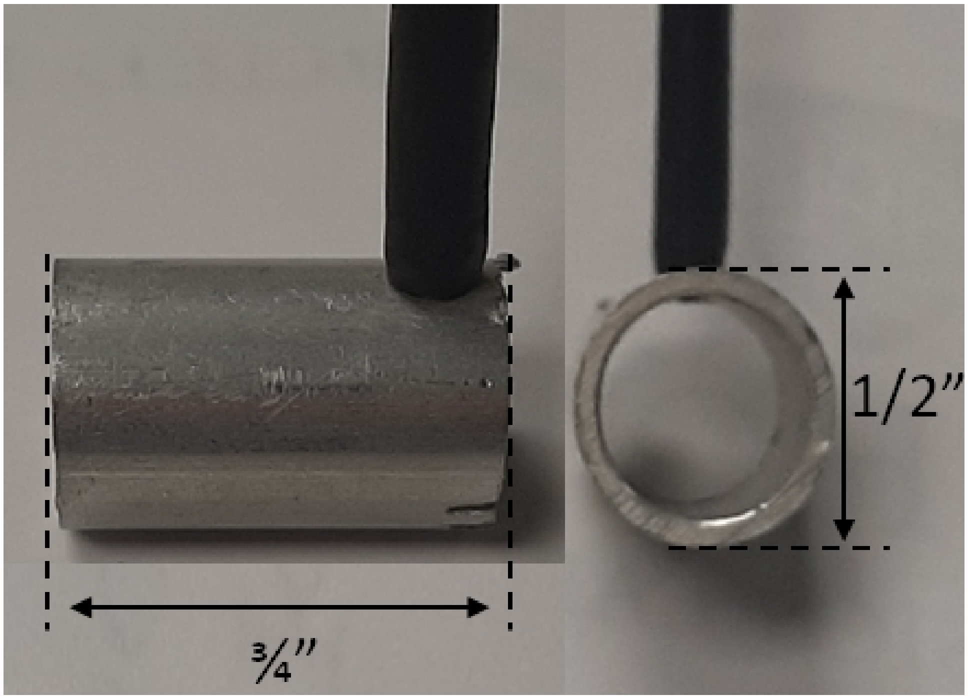

Figure 1. Single-electrode plasma sensor.

Two different H2 nozzles were used, a 1 inch and a 2 inch, in order to provide a full range of velocities within the limitations of the mass flow controller. The 2 inch nozzle was used to reduce the achievable velocity. The nozzles were made from PVC piping with adapters to mate with the 1/4 inch H2 gas line.

The circuit developed to implement a constant-current approach is shown in Figure 2. The main elements

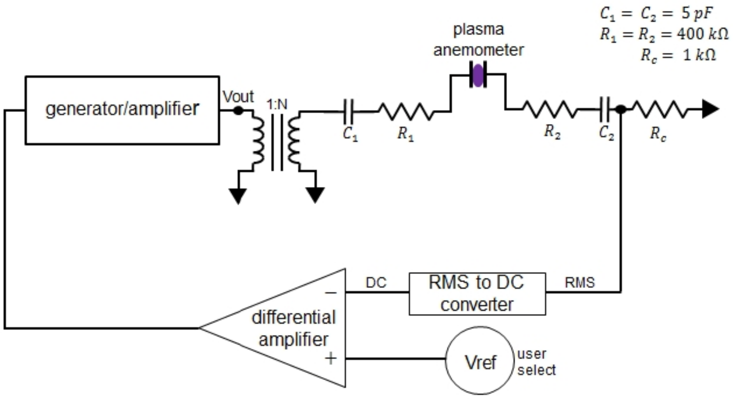

Figure 2. Plasma anemometer circuit designed for constant current control.

of the circuit include a power amplifier/generator unit capable of several 10's of watts at up to several MHz, a step-up transformer to generate the required 1-2 kV p-p voltage, a current-limiting resistor-capacitor network, the plasma sensor, a voltage sense resistor, and an optional feedback current monitor with user control. This analog approach can reliably maintain a constant current over a range of flow velocities from 0-140 m/s. However for simplicity, in this test the plasma sensor was powered using an open-loop circuit that eliminated the feedback component.

The AC frequency of the power system is determined by the inductance and capacitance of the transformer, high voltage leads, and the sensor itself, which forms a reactive load on the power amplifier. These loads include leakage inductance and parasitic capacitance from the transformer, lead capacitances and inductances from the high voltage (H.V.) cables, and the capacitance between the electrodes in the sensor. Together these determine the overall system resonant frequency. The amplifier/generator is then tuned to that resonant frequency for operation. Adjustment of the core-gap in the transformer can provide a measure of frequency adjustment if needed by changing the transformer leakage inductance. Generally, the velocity sensitivity of the sensor improves with frequency, which motivates high frequency operation. However, as frequency of the system increases, capacitive losses through the leads also increase, which increases the overall power required to maintain the plasma. For this reason, it is desirable to reduce lead length. Where long lengths are anticipated, it may be necessary to use a lower frequency transformer to prevent excessive losses through the leads which could prevent reliable starting of the plasma sensor. Once tuned, the output voltage across the electrodes is measured to provide the velocity information. A key question examined in this study is the effect that gas density and composition has on the plasma voltage response. This paper will document the plasma sensor voltage as a function of gas velocity in hydrogen at low density and examine differences in that response compared to prior measurements in air.

A photograph of the device in the vacuum facility is shown in Figure 3. The system consists of a custom AC transformer followed by a current limiting 2-ohm resistor, a Pearson inductive current monitor, a 100:1 voltage oscilloscope voltage probe, and finally the circular electrode. Two transformers were used, one to resonate at 1.7 MHz, the other designed for 57 kHz.

III. Results

A. Measurements in Neutral Gas

Measurement in neutral gas were conducted using the nozzles to direct gas flow onto the cylindrical electrode, which was placed at the exit plane of the nozzle. A photograph of the device placed downstream of the 1 inch nozzle is shown in Figure 4. At the conditions of the experiment at 1.5 Torr of gas pressure the plasma formed internally in the cylindrical electrode. The current path from the powered electrode was completed by grounding via capacitive coupling to the vacuum chamber walls.

Gas flow rates were varied from 3-4 slm to about 100 slm. A photographic survey of the sensor response to the variation in H2 flow rate is shown in Figure 5. The red jet emanating from the plasma sensor electrode

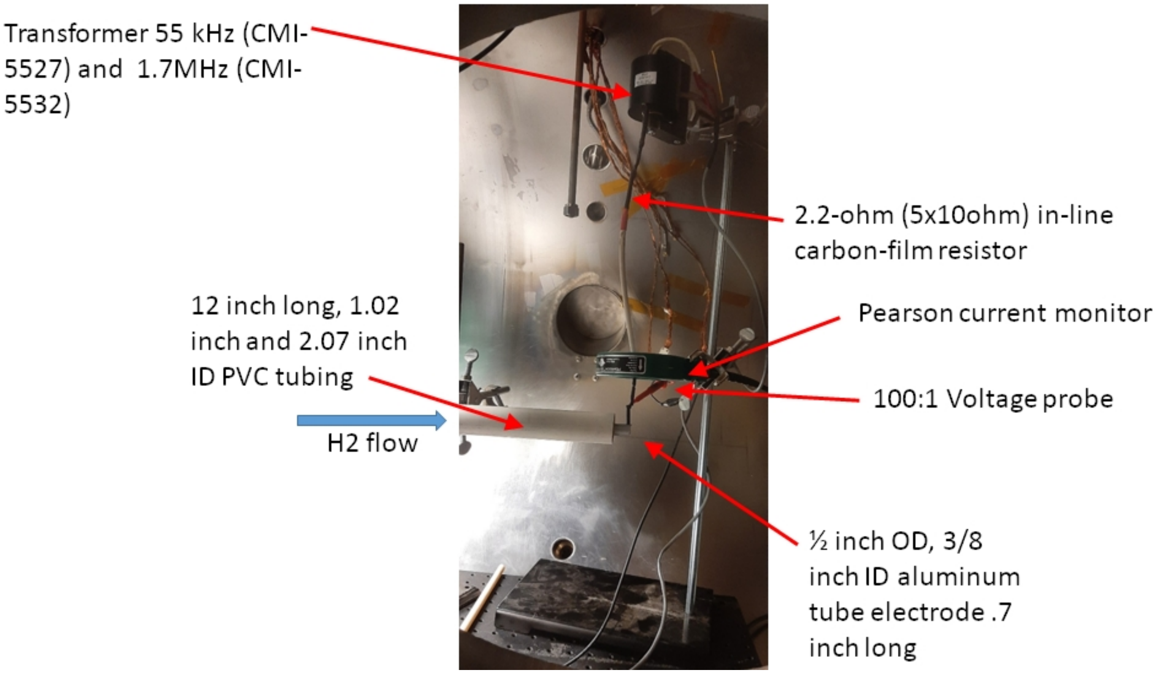

Figure 3. Experimental layout for H2 experiment.

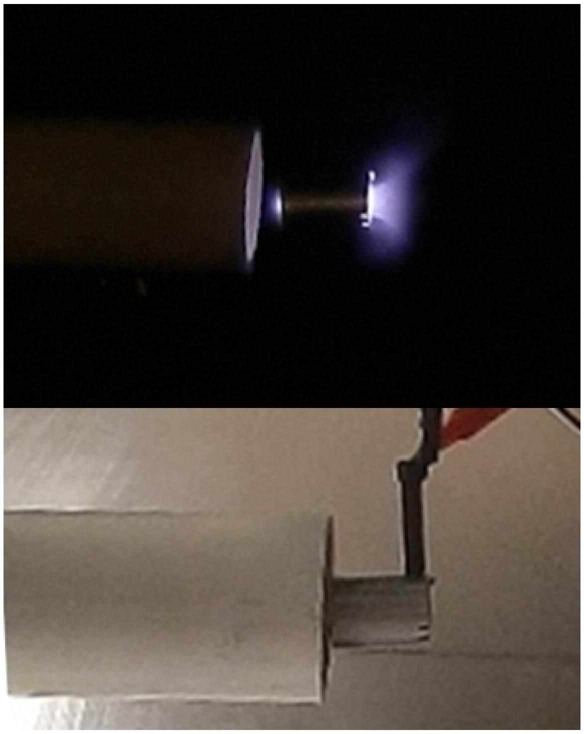

Figure 4. Plasma sensor placed downstream of H2 nozzle (bottom) and operating in darkened lab (top).

is surmised to be due to alpha-emission, verifying that a convective interaction occurs between the AC ionization and the H2 flow.

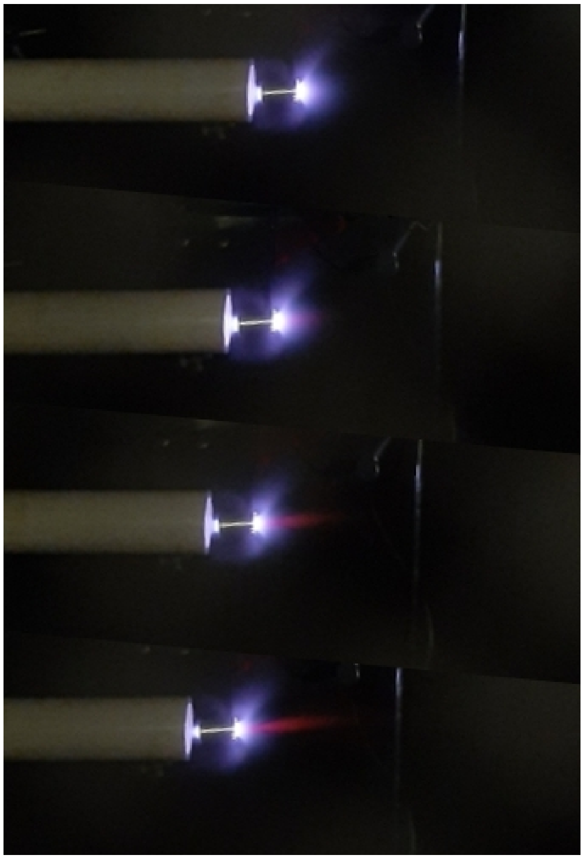

Figure 5. Plasma response to flowrate.

A velocity calibration was obtained by varying the mass flow rate while recording both voltage and current in a time resolved manner. A 12-bit Lecroy oscilloscope was used as the data acquisition system. Gas flow was regulated with an H2 mass-flow controller, balanced by a vacuum pump system to maintain a continuous static pressure independently of gas flow rate. Velocities are extrapolated from volumetric flow rates in the range of 27 m/s - 1770 m/s based on continuity arguments. Sample velocity calibrations are shown in Figure 6. Plots are shown for the two different H2 nozzles at the two resonant frequencies. Generally, the trends show two distinct regions; a linear region at lower velocity, and a non-linear region at higher velocity. The trend is generally a decrease in voltage with increase in flow velocity in the linear region. The cause of this behavior is not fully understood but may be related to dynamics of the sheath formation. Within the linear region, the sensitivity, taken as the local slope, appears favored by the lower frequency AC system at about 0.07 V/m/s compare to 0.11 V/m/s for the higher frequency.

A plot of the voltage and current waveforms at 1.7 MHz is shown in Figure 7. The current appears somewhat discontinuous, with sharp short-duration spikes.

In contrast, at the lower frequency the current waveform is more sinusoidal, as shown in Figure 8.

Phase shift of the voltage-relationship is related to impedance of the plasma sheath, which is in turn related to the ionization characteristics of the plasma. Phase was found to vary significantly as a function of gas velocity, on the order of 20 degrees. This is shown in Figure 9.

Power absorbed by the plasma can be determined by this phase angle. Generally, the reactive power goes as the sin of the phase angle. This is shown in Figure 10. The amount of total power in the plasma is quite low at less than 1 Watt. This was calculated power is confirmed by the reflectometer on the generator unit.

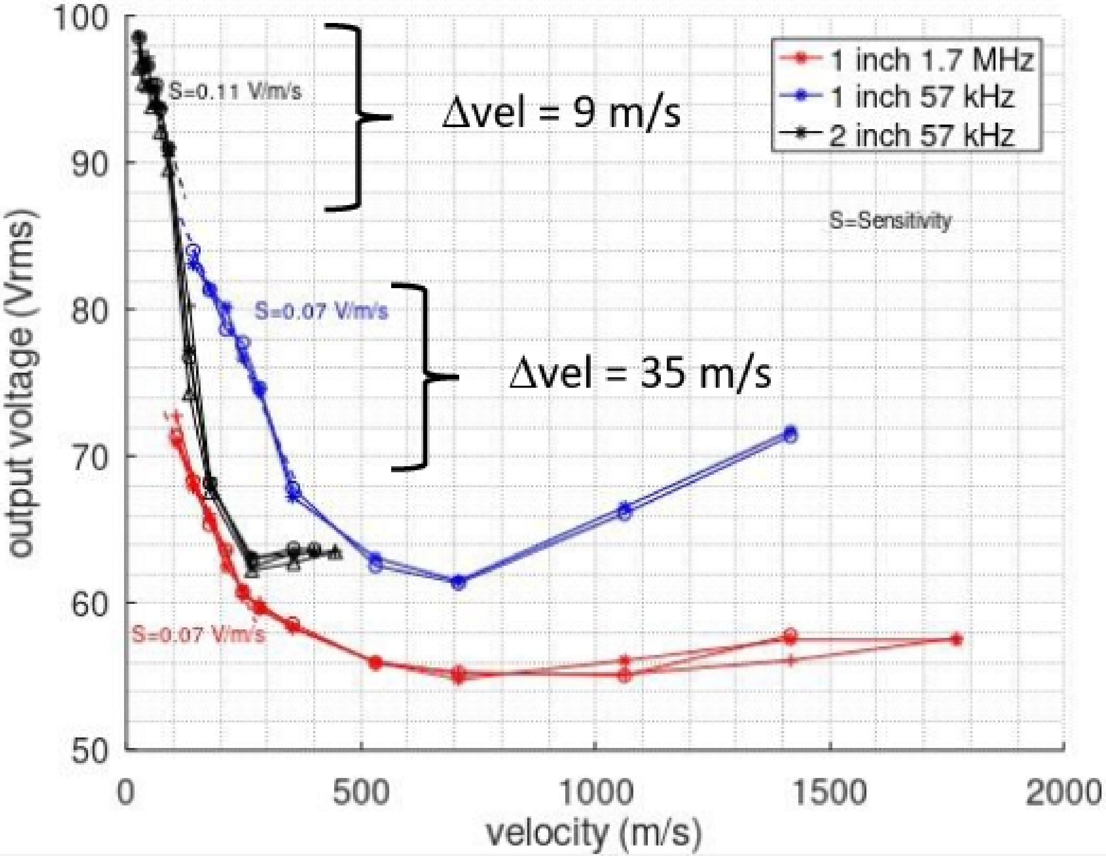

Figure 6. Plasma voltage response to flowrate.

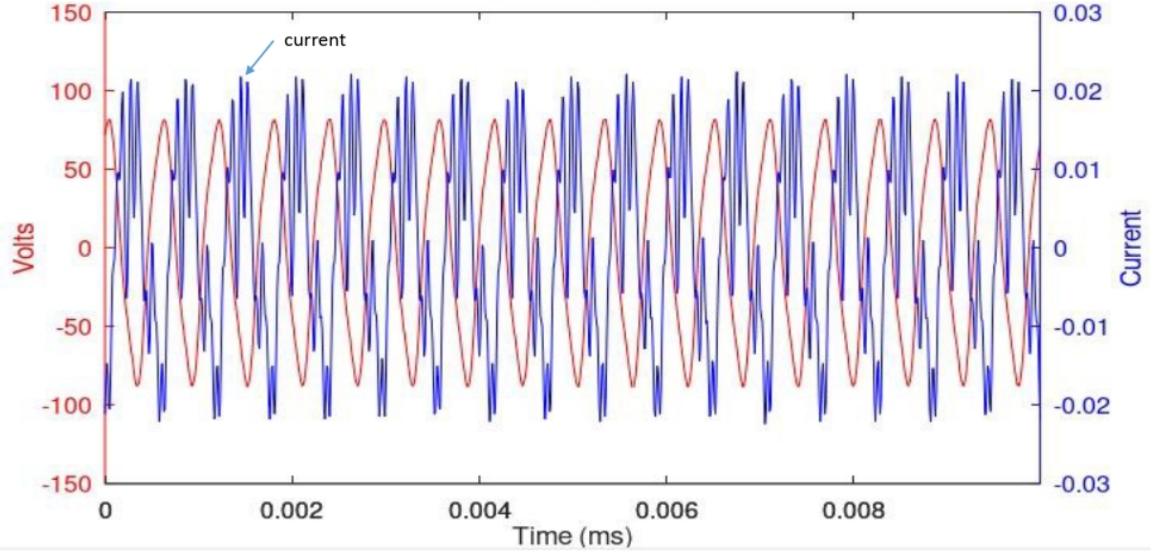

Figure 7. Voltage and current waveforms for 1.7 MHz operation.

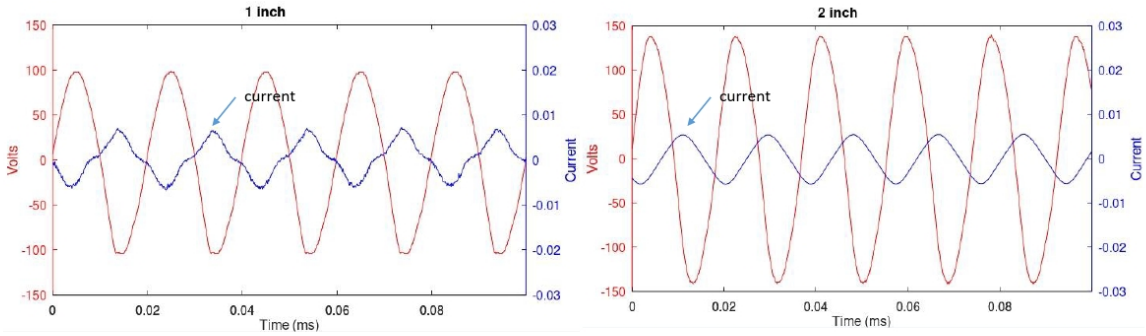

Figure 8. Voltage and current waveforms for 57 kHz operation. 1 inch nozzle (left), 2 inch nozzle (right).

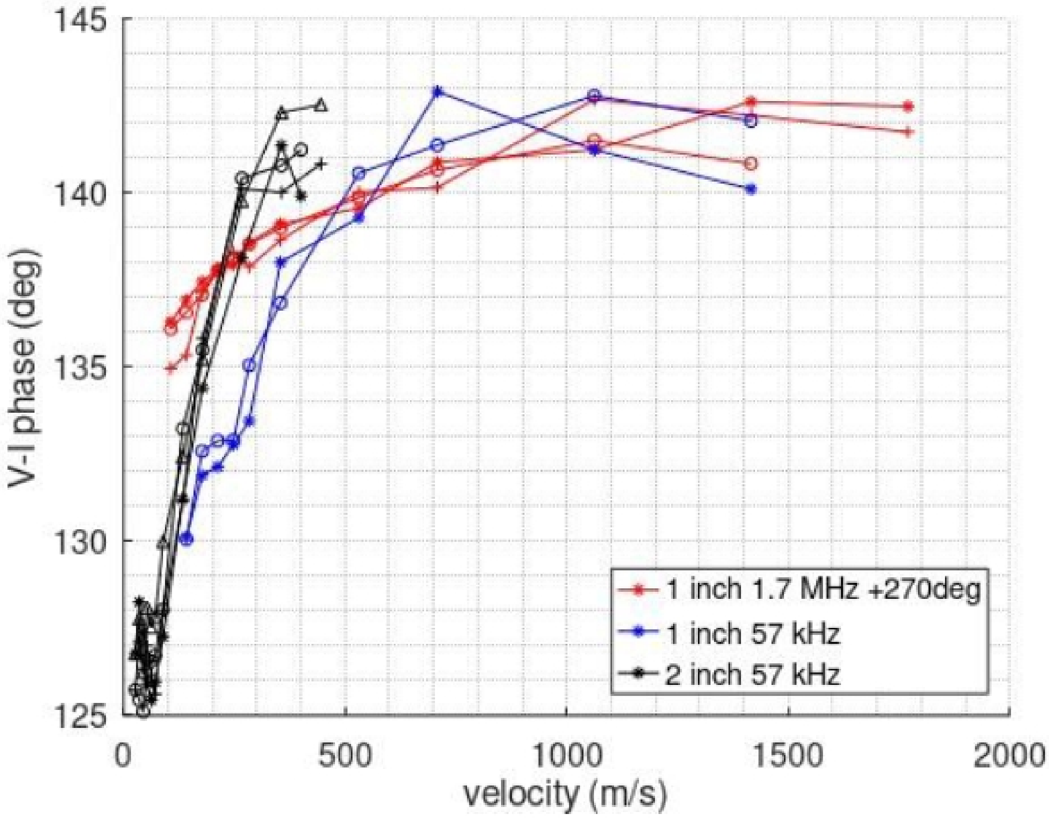

Figure 9. Phase angle between current and voltage for both 1.7 MHz and 57 kHz operation.

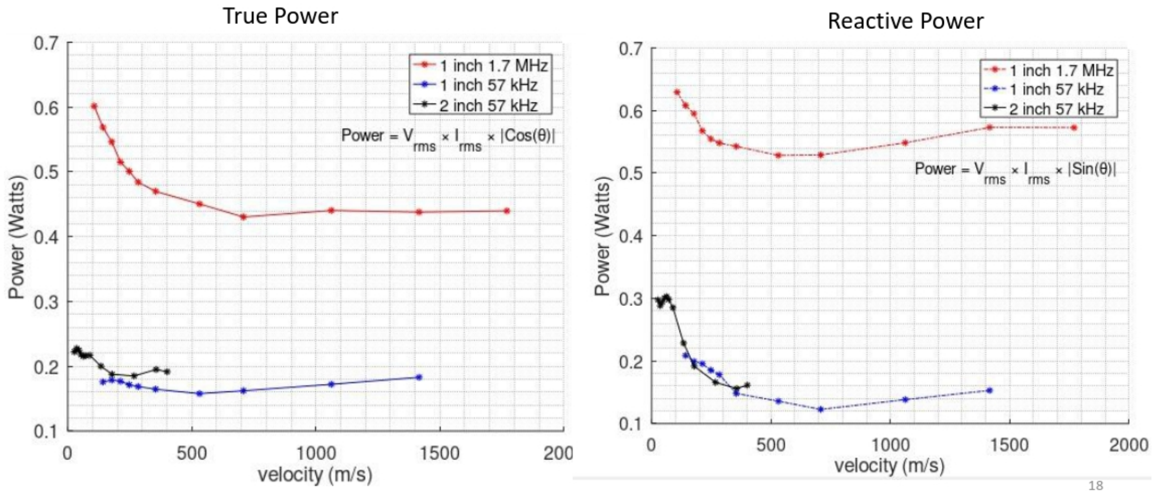

Figure 10. Plasma power measurements.

B. Estimations of Plasma Electron Density

Measurements of the plasma phase angle, voltage and current, along with knowledge of the electrode geometry and some basic assumptions of the collision dynamics makes it possible to calculate estimates of the plasma electron density. The forumulation of this is derived from an electric circuit model of the plasma discharge as a simple resistor, with sheath capacitance defined as discrete capacitors in series to the plasma resistance. A simple analysis of this model reduces to a an equation that states that:

$$R = V/I * cos(\phi) = \frac{l * m_e * \nu_e}{A * n_e * e^2} \tag{1}$$

where: ϕ is the phase angle, l is the electrode gap (radius), m_e is the mass of an electron, ν_e is the electron-neutral collision frequency, A is the electrode area $(pi * D * length)$, n_e is the electron density, and e^2 is the electron charge. The collision frequency was derived using data from Lieberman et al.,[3] with the formulation that

$$\nu_e = n_g * \kappa \tag{2}$$

where n_g is the neutral number density, and κ is the collision rate constant.

Using the measured data, estimates of electron density on the order of $1e-9/cm^3$ were calculated, which is in line with expectations for a weakly ionized plasma. This data is shown in Figure 11.

C. Measurements in Ionized Gas

One potential use of the plasma sensor is to provide diagnostic capabilities in a background ionization. To test this, a 433 MHz source was used to introduce background RF plasma near the gas flow. The RF source was controllable from just over 10 Watts to about 100 Watts. This provided a test of the response of the sensor in varying conditions of background ionization density. A photograph of the RF source is shown in Figure 12. The RF source is visible at the bottom of the image and consists of an insulated shaft about 12 inches in length. The plasma sensor electrode and nozzle are also visible in the image.

Measurements of velocity were repeated for this configuration. This is shown in Figure 13. Two power conditions are presented. The higher power resulted in a reduction of voltage compared to the lower power. Compared to the neutral case, the voltages were significantly reduced.

IV. Analysis and Discussion

This experimental campaign provided the first insights into operation in a conductive medium such as an ionized gas. The results indicate that the presence of background ionization does not inhibit the capability

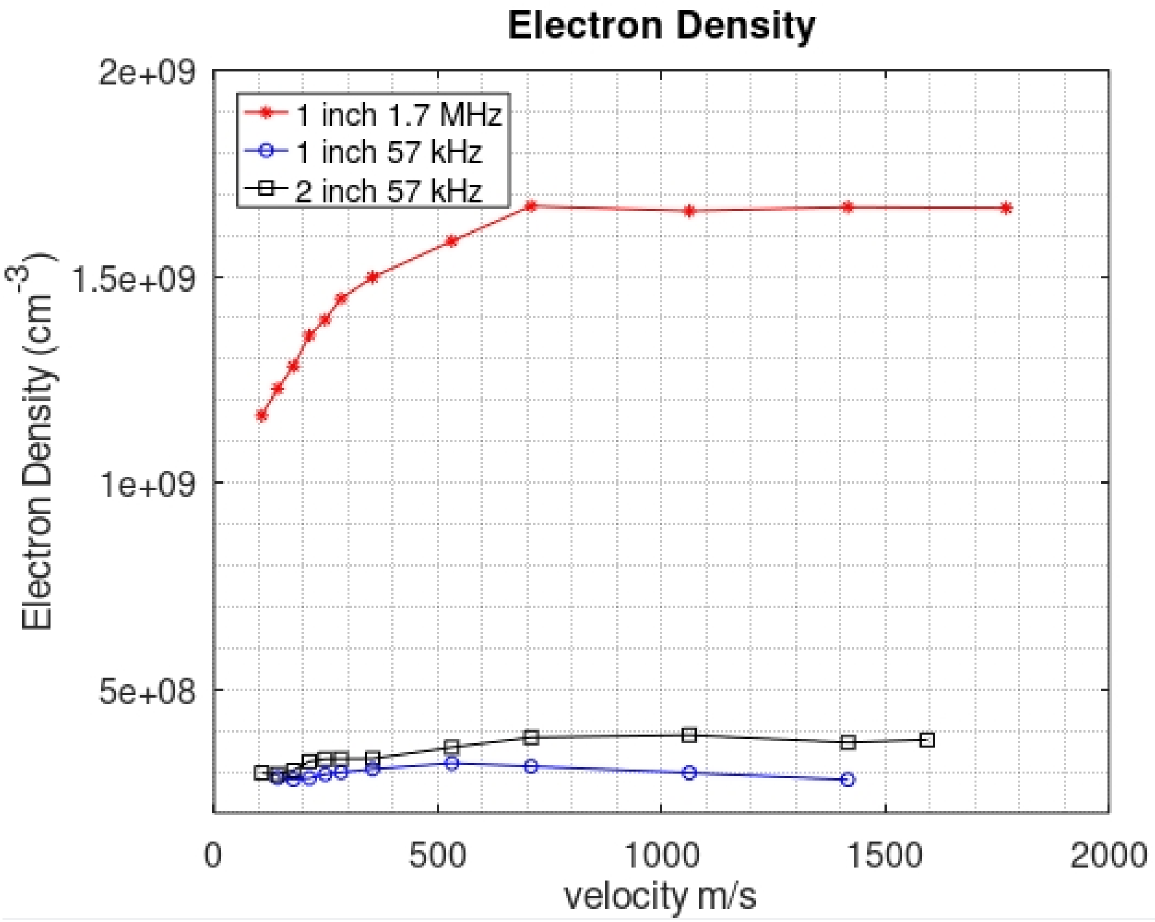

Figure 11. Plasma electron density measurements.

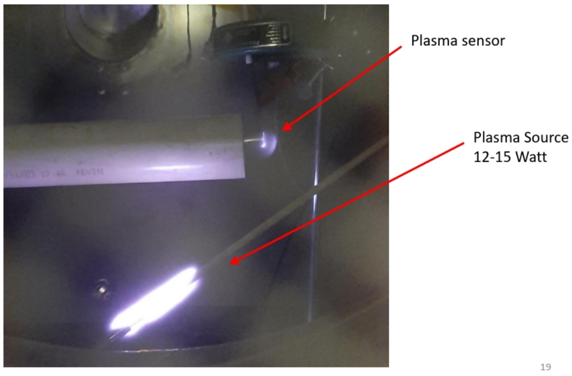

Figure 12. Photograph of background plasma source used to test operation in an ionized gas.

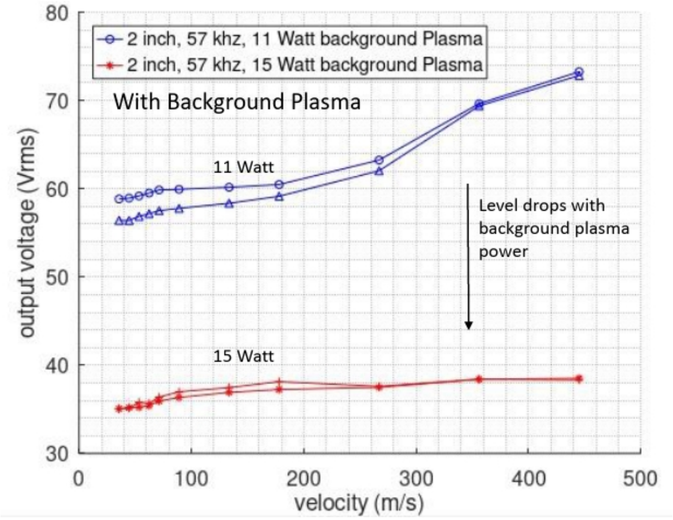

Figure 13. Velocity measurements in ionized gas.

of the sensor to respond to external fluid flow. In addition, the overall sensitivity of the sensor, taken as the local voltage vs velocity derivative, was improved with the new single-element cylindrical design of the electrode over prior measurements that utilized more conventional flat-blade pairs of electrodes.[4] This is thought to be due to an increase in the effective surface area generating plasma, with the additinal benefit of improved concentration of the plasma in the region of flow.

Results also showed that the slope switched when going from the neutral to conducting background gas. In the neutral gas case, at 1.5 Torr in Hydrogen, the voltage ***decreases*** with velocity. However in the conducting background gas produced by the external RF source, the voltage ***increases*** with velocity. This is consistent with a shorting mechanism in which the ionization effectively shorts out the electrode resulting in reduced output voltages. Greater H2 flows are more effective at removing the local ionization from the electrode, thus reducing the shorting condition.

It should be noted that in a neutral atmospheric pressure air, the voltage also increases with velocity, a result which is consistent with a space-charge convective loss mechanism. It is unknown if the opossite behavior while in neutral conditions is related to the reduced densities or the difference in gas composition between Hydrogen and air.

Testing at two radically different AC frequencies indicate that the carrier frequency used to generate the plasma discharge has only a relatively small effect over a broad range of frequency. Generally speaking, lower frequencies are favored which also simplifies the AC electronic circuit.

V. Summary and Future Work

A new, single-electrode geometry plasma sensor was tested in a low density supersonic hydrogen jet. The response of the sensor in neutral gas was found to be opposite to that observed in atmospheric air. A change in the sign of sensitivity was observed when operating in the presence of an externally excited ionization which produced a conductive medium. Where as the voltage normally rises with velocity, in this campaign in low pressure hydrogen, the opposite was true. A wake interaction with the H2 flow was observed through the production of visible H-alpha emission downstream of the electrode. This confirmed the convective mechanism at that explains the basic sensitivity of the plasma sensor ionization to the H2 flow. Lastly, two very different AC frequencies were used, with a slight advantage shown for the lower frequency. Electron density calculations are consistent with weakly ionized plasmas and may provide additional diagnostic methods to provide simultaneous velocity and plasma density characteristics.

References

[1] Brandt, D., Fomenkov, I., and Rafac, R. e. a., "LPP EUV source readiness for NXE 3300B," *Proceedings of SPIE*, 2014, SPIE Advanced Lithography, San Jose, CA.

[2] Marshall, C., Matlis, E., and Corke, T., "A.C. plasma anemometer-characteristics and design," *Measurement and Science Technology*, Vol. 26, 2015, pp. 1–16.

[3] Lieberman, M. A. and Lichtenber, A. J., *Principles of Plasma Discharges and Materials Processing*, Wiley, New Jersey, 2005.

[4] Matlis, E. and Corke, T., "A.C. Plasma Anemometer Measurements in a Supersonic Hydrogen Jet," AIAA 2021-1378, 2021, Scitech 2021 Forum.