Plasma Physics

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Plasma physics is cool!

I. INTRODUCTION

Plasma–or ionized gas–is a simultaneously unusual and quite useful state of matter. Typically formed by initiating breakdown in a gas, plasmas are characterized by a significant proportion of charged particles, with ions, electrons, and neutral gas particles all occurring within the plasma. Crucially, plasmas display a number of unique properties, with charge separation between ions and electrons giving rise to electric fields within the material, and charged particle flow giving rise to currents and magnetic fields.

These characteristic behaviors give rise to complex phenomena of great beauty, and, occasionally, great utility. For example, some gas lasers depend on excitation of energetic states in partially ionized atoms of a plasma. Additionally, some plasmas are particularly useful for etching and deposition processes in semiconductor fabrication, or even in the production of energy from thermonuclear fusion. [1]

Specifically, argon plasmas serve as an ideal vehicle for the study of these phenomena because of argon's availability and ease of ionization. [2] These species can be studied using a number of techniques from electrical probes to optical spectroscopy to understand their characteristics. Such understanding is necessary in utilizing and exploring the possible applications of plasmas. Of particular interest are characteristics such as the plasma's breakdown voltage, plasma density, electron temperature, and plasma potential.

To that end, we prepare an argon plasma in two different setups and characterize its electron temperature, electron density, and construct its Paschen curve.

Specifically, in one setup, we generate a plasma in a vacuum chamber equipped with high-voltage electrodes, and subsequently map the voltage needed to generate a plasma across a wide range of argon gas pressures. Additionally, in the same chamber, we set up a Langmuir probe to map the I-V characteristics of the plasma under various bias voltages and measure characteristics such as plasma density, electron temperature, and plasma potential.

Finally, in another setup, we generate a plasma in a spectral discharge tube, using optical spectroscopy techniques to measure gas spectra, which we then integrated to find the electron temperature.

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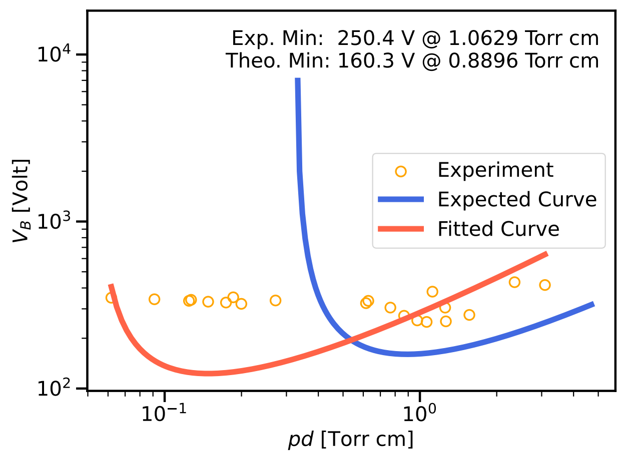

FIG. 1. Paschen Curve. We compare the experimental breakdown voltage values to the theoretical curve for an Ar plasma. We fit the experimental data to the functional form of Paschen's law and report the fitted constants A, B and γ

II. RESULTS AND DISCUSSION

A. Paschen Curve

1 [**Introduce Paschen's law**] Introduce's Paschen's law and explain its origin from statistical mechanics arguments

2 [**Experimental results**] Show and discuss figure

B. Langmuir Probe

3 [**Explain setup**] Explain setup. Introduce Langmuir probe and measure the current at different points in the plasma.

4 [**Introduce theory behind experiment**] Explain main equations relating measured current and electron temperature and density

5 [**Experimental results**] Show and discuss figure. Mention experimental shortcomings as well as shortcomings of the method. Explain in what regimes these measurements are not a reliable estimate of the desired quantities. Motivate the necessity of spectroscopy to compare and validate temperature measurements.

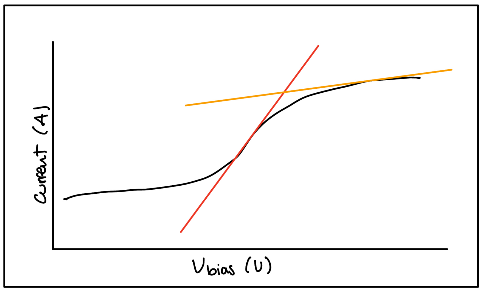

FIG. 2. The temperature and density of the plasma electron is obtained with a Langmuir probe

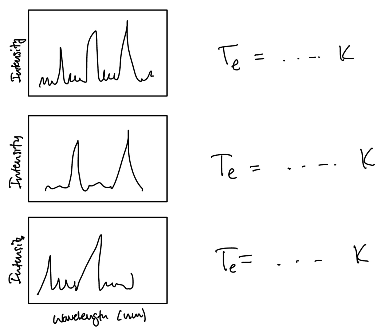

FIG. 3. Temperature of plasma at different regions determined by integrating its spectrum

C. Spectroscopy

6 [**Explain setup**] Explain alternative setup with chromatography chamber.
7 [**Explain method to obtain electron temperature from emission spectroscopy**] Explain the theory that allows to estimate electron temperature from the emission spectra of plasma.
8 [**Experimental results**] Again, show the experimental data and discuss it. Discuss the shortcomings of this technique (collection time/signal to noise ratio/sensitivity) and how it compares to the Langmuir probe experiment. Explain in which regimes this can be trusted and how they can both be used together.

III. METHODS

A. Gas Flow System

WILL INSERT PHOTO/LABELLED DIAGRAM OF GAS FLOW SETUP HERE!

To control the pressure of the Ar plasma, we work with a gas flow system that allows us to continuously and simultaneously pump out and leak Ar into the chamber until a steady-state pressure is achieved. This is necessary because air continuously leaks into our setup.

Concretely, for the data acquisition we pumped down the gas flow system to a base pressure of around 2×10^{-2} torr, subsequently leaking argon gas in to the desired pressure for measurements taken. Depending on the relative rates at which gas was being leaked in and pumped out, the steady state pressure for the system could be altered at will. Thus, we controlled the pressure inside our measurement chamber via this mechanism.

B. Paschen Curve Measurement

We measured the breakdown voltage of the Ar plasma at different pressure inside the stainless steal tee vacuum chamber. To generate the plasma, a disk-shaped stainless steel electrode is connected to controllable high-voltage source. The rest of the stainless steal chamber is grounded, and at the bottom of the chamber we placed a cylindrical aluminum electrode to shorten the distance between the high voltage electrode and the grounded bottom electrode (see Fig (INSERT FIGURE) for full experimental setup diagram). Importantly, the environment in which the ar plasma is formed must closely resemble an infinite parallel plate electrode setup to adequately match the theoretical predictions of Paschen's law.

The "T" shaped chamber allows for a small window to look into the chamber and observe the plasma formation. However, to reliable measure the breakdown voltage (particularly at low pressures when the plasma emission becomes too faint to the eye) we used the circuit in Fig 4. If the Ar is not ionized and no plasma is present, current is not flowing throw the plasma chamber and thus there is no voltage drop between the two terminals $A0$ and $A1$. However, if the plasma is present, there is a current flowing from the cathode to the anode and thus we observe a voltage drop between the terminals. This circuit thus allows us to continuously monitor the voltage difference across terminals as we sweep the voltage and allows ut to detect the formation of a plasma by recording the first voltage value at which we observe a difference in voltages at the two terminals.

The experimental setup thus consists of achieving a stable pressure inside the chamber and conducting voltage sweeps. Our experimental software will then linearly vary the high-voltage applied at the top electrode of the chamber and periodically record the voltage drop at the two terminals. Once the plasma is formed, we see a stark difference in measured voltages at both terminals, from which we are able to calculate the total current flow through the plasma and plot an $I-V$ curve for the sweep. At voltages below the breakdown voltage V_B, there is no current flowing through the plasma electrodes and this the $I-V$ curve remains flat at zero. However, right at V_B the plasma is formed and observe a sudden jump in the $I-V$ curve. This sudden change translates in a discontinuity of the curve $\frac{dI}{dV}$ which we are able t o numerically estimate. We thus estimate the breakdown voltage by recording the first voltage at which this discontinuity

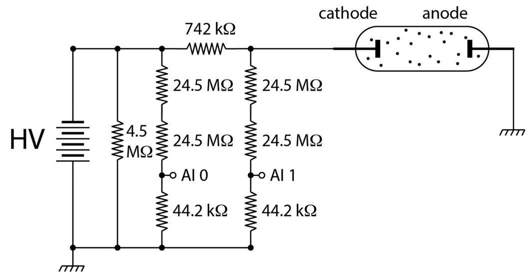

FIG. 4. Temperature of plasma at different regions determined by integrating its spectrum

occurs.

C. Spectroscopy

To gather our spectra, we first generated a plasma in the glow discharge tube. The discharge tube is configured with a cathode and an anode in a glass vessel. The cathode is connected to a high voltage supply, allowing us to generate a voltage high enough such that the argon gas inside the tube breaks down. We leaked argon into the tube system via the method described in section A above, then slowly turned up the voltage on the power supply until a plasma was generated. We generated a plasma initially at 1500 V, but then turned down the voltage to 900 V so that the different regions could be seen more clearly.

After generating our plasma, we used a lens to focus light from the plasma onto the slit of an optical spectrometer. We first used a lower-resolution spectrometer to test our setup before using a higher-resolution spectrometer (model?). At this point, we collected data for runs of 500ms, ensuring that the signal observed was not on the order of noise.

To reduce contamination of the signal by ambient lights, we turned off all other lights in the room to prevent the measurement of signal from other light sources. We measured in two different regions–the pink region that occupied most of the tube, and the purple region which was near the cathode.

[1] R. J. Goldston and P. H. Rutherford. *Introduction to plasma physics*. Institute of Physics Pub, Bristol, UK ; Philadelphia, 1995.

[2] Ersyzario Edo Yunata and Muhammad Ghufron. The study of argon plasma based on experimental and modeling diagnosis. *AIP Conference Proceedings*, 2314(1):030005, December 2020.

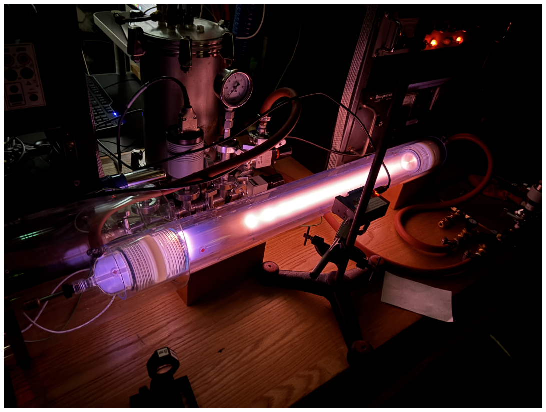

FIG. 5. Generated plasma in glow discharge tube.