Breakdown of Gases and Paschen's Law

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We attempt to verify Paschen's law and for dielectric breakdown of argon, helium, and air by increasing the voltage across a capacitor inside a low-pressure gas chamber until we observe a current moving through that capacitor. We then fitted the theoretical equation for breakdown voltage as a function of pressure and distance to our data in order to extract the first and second Townsend coefficients for each gas.

I. SUMMARY

II. INTRODUCTION

In any gas, there is always a very small proportion of atoms which are ionized. When an electric field is applied to the gas, the electrons will accelerate, and when they collide with neutral gas particles with sufficient energy, they can ionize the neutral atom. In the right conditions, this causes a chain reaction called plasma breakdown. Paschen's law predicts the minimum voltage V_b that needs to be applied over a gas in order to achieve plasma breakdown. According to Paschen's law, V_b can be expressed by the following equation, where p is the pressure of the gas, d is the distance over which a voltage is being applied, and A, B, γ are constants which depend on the type of gas used.

$$V_b = \frac{Bpd}{\ln(Apd) - \ln(\ln(1 + 1/\gamma))} \tag{1}$$

In the case where $\ln(Apd) \leq \ln(\ln(1 + 1/\gamma))$, the breakdown voltage is infinite, meaning no matter how strong the electric field is, it cannot cause plasma breakdown. In the other case, where $V_b < \infty$, we see that the second derivative of V_b with respect to pd is always positive, meaning there is a unique pd such that V_b is minimized.

III. EXPERIMENTAL SETUP

To collect data on V_b as a function of pd, we applied a voltage across a parallel-plate capacitor inside a low-pressure gas chamber.

The dashed box in the circuit diagram represents the vacuum chamber. The pressure in the chamber was controlled by a vacuum pump, and measured by a digital barometer which we forgot to calibrate. The distance between the capacitor plates was controlled by a linear actuator, and we manually measured that distance using a measuring tape which was accurate to roughly the nearest millimeter.

To measure the breakdown voltage for a given configuration, we slowly increased the voltage from the voltage source by hand until the voltage measured by the multimeter suddenly increased from less than a millivolt to multiple Volts, and remained there for at least a second. We then recorded the voltage measured by the voltage source as the breakdown voltage. The resistance of the resistor remained at 53.4 Ohms for the duration of the experiment, so using Ohm's law, we divided the voltage recorded on the multimeter by 53.4Ω to obtain the current across the resistor at the breakdown voltage.

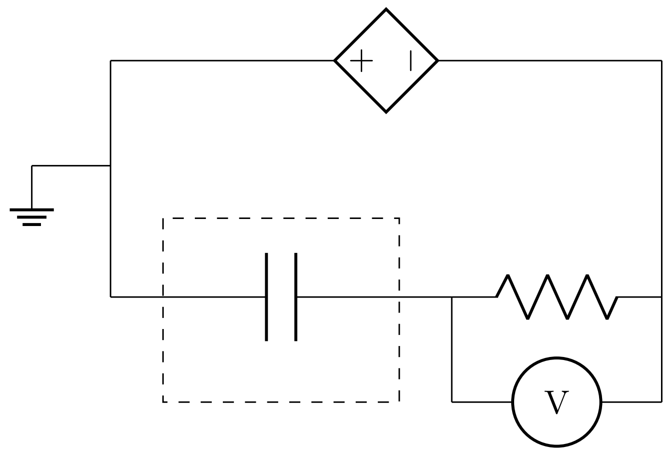

FIG. 1. Circuit diagram of experimental setup

In FIG 2, the plates are touching on the left side, but an "eyeball measurement" says that on the rightmost side, the plates are roughly 1 millimeter away from touching. Therefore, even after calibrating the distance measurement, we cannot be confident the distance measurement is precise.

IV. RESULTS

Since the voltage measurement from the voltage source was accurate to the nearest Volt, I considered the confidence interval in breakdown voltage to be $\pm 2V$. Similarly, since distance measurements used a measuring tape that was accurate to the millimeter, and the barometer appeared to not fluctuate more than 1 milliTorr, I considered the confidence interval in pd to be $\pm((2mTorr)d + (2mm)p)$.

The plot of V_b as a function of pd is shown below for each gas. I attempted to use the SciPy function

FIG. 2. The voltage source measures our applied voltage, and the voltmeter measures the voltage drop across the resistor

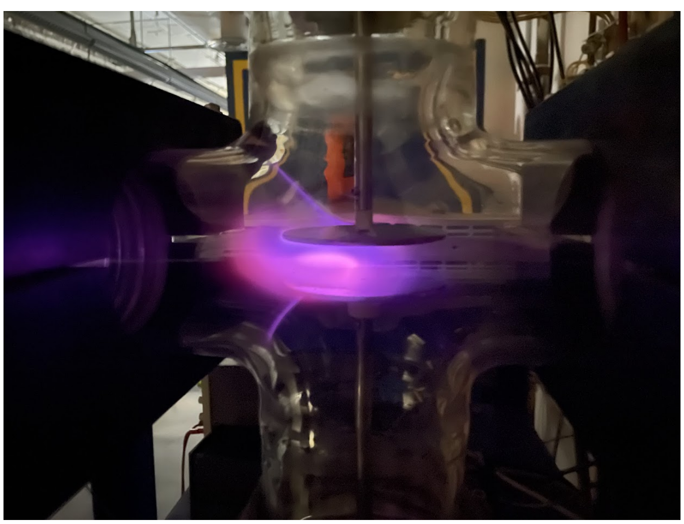

FIG. 3. A "dirty nitrogen" plasma which is not evenly distributed between capacitor plates

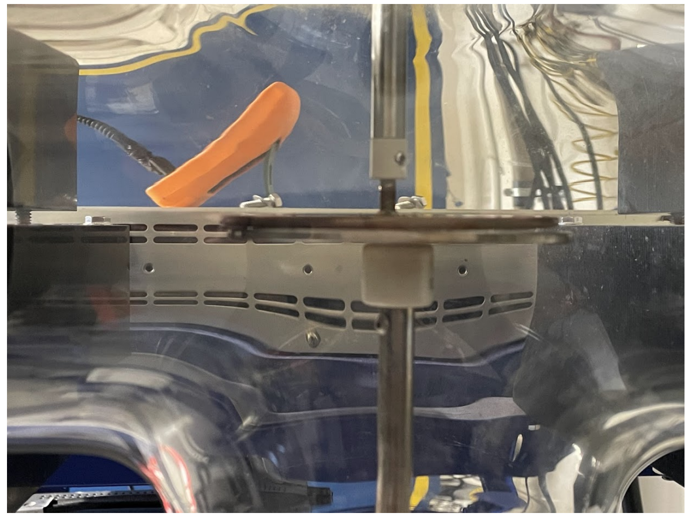

FIG. 4. Moving the anode and capacitor plates together until they touch reveals they are neither concentric nor parallel

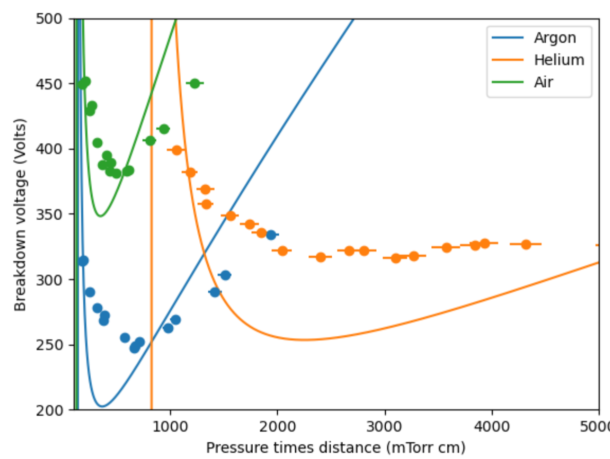

FIG. 5. Large gaps between our data and the optimal curve fits suggest there may be systematic error in our experiment

"scipy.optimize.curve_fit" with initial parameter guesses $p0 = [1, 1, 1]$ and default settings to find the constants A, B, γ which minimize the total square error. The optimal curve fits are also shown in FIG 5.

The vertical error bars in that figure are so small that they don't show up, and the fact that the optimal curve fit does not go through most of the confidence intervals indicates that our data does not match theoretical predictions. The optimal parameters we found and the uncertainties in each are given in the following table. Note that A and B are both given in $(mTorr \cdot cm)^{-1}$.

Gas	A	B	γ
Argon	0.00156 ± 10.7	0.553 ± 0.0779	4.28 ± 32500
Helium	0.000862 ± 2.01	0.112 ± 0.0136	0.958 ± 3120
Argon	0.00594 ± 160	0.996 ± 0.134	0.872 ± 33500

Since the uncertainties are so large compared to the actual parameters, we can conclude that the data does not fit the theoretical prediction. Notably, the minimum breakdown voltage in our data is $247V$ for argon, $316V$ for helium, and $381V$ for air. All of those values are much large than their theoretically expected values[1]. Systematic and random error in pd could not have caused our measured minimum breakdown voltages to be so far from the theoretical value.

The linear trend in the current at breakdown voltage is clearest for argon. This may be because our measurements for air and for helium weren't as consistent – even after the voltage was high enough to create an avalanche breakdown and a visible plasma, the voltage measured by our multimeter continued to fluctuate, and especially with the helium plasma, it would occasionally disappear a few seconds after forming.

V. ANALYSIS

- plasma is less bright when pressure times distance is low
- helium plasma was fairly unstable. nitrogen plasma occasionally had arcing above top plate of capacitor which increased in frequency as we cranked up voltage. nitrogen plasma occasionally appeared to not be distributed evenly between capacitor plates
- talk about "diatomic nature of nitrogen", and how that affects ionization energy
- plasma fringes appeared beyond sides of capacitor plates, indicating the electric field is not perfectly vertical, but bulges out a bit
- expected values of parameters, and expected value of minimum breakdown voltage

VI. CONCLUSION

We were unable to fit our data to the theoretical prediction given by Paschen's law. An interesting future experiment would be to vary the size of the capacitor plates, to see if the fringing electric fields were responsible for any systematic error in measurements of the breakdown voltage.

[1] K. Burm, Calculation of the townsend discharge coefficients and the paschen curve coefficients, Contributions to Plasma Physics **47**, 177 (2007).

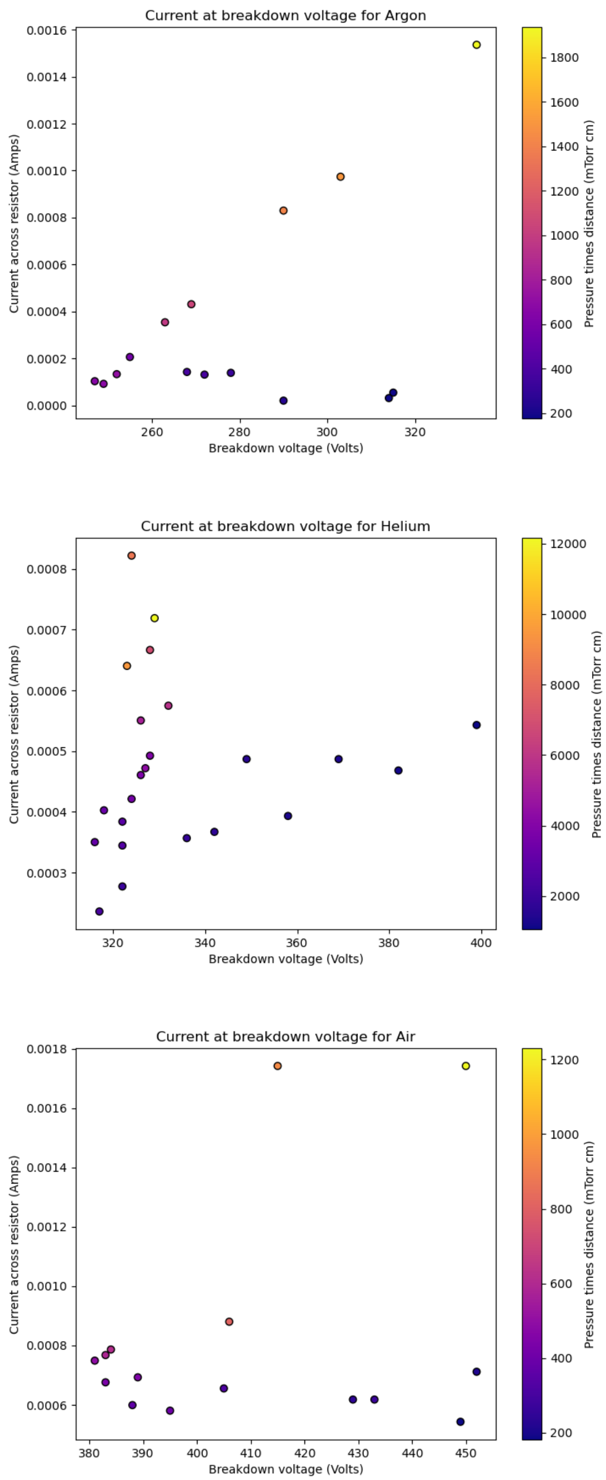

FIG. 6. Plots for each gas of the amount of current flowing through circuit when the applied voltage is equal to the breakdown voltage

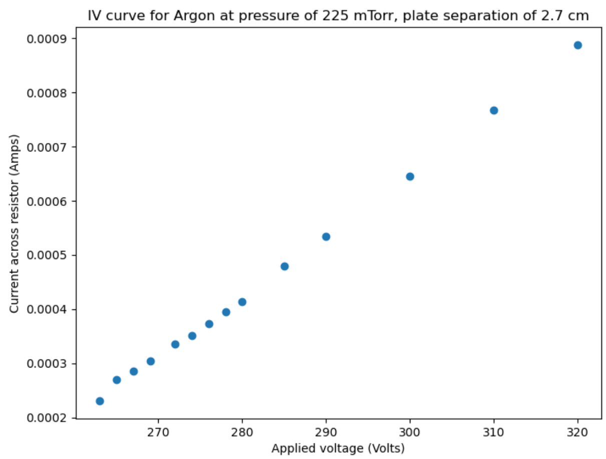

FIG. 7. Plots of current flowing through circuit as a function of applied voltage, for an argon gas with $V_b = 263V$