Lab Report

A Low Pressure DC Plasma

Report by: **Jamie Somers**

Lab Partner: Daniel Khaletsky

Grader: Bert Ellingboe

October 15, 2021

Abstract

The purpose of this experiment was to calculate the pumping speed of a vacuum pump used to vacuum to generate a low pressure DC plasma, find unknown variables A and B of an equation which describes breakdown potential and find the value of n using the slope of VI curves. We do this by measuring the pressure over time, a voltage change and the current at different pressures. We found the pumping speed to be -67.8 ± 0.6 Torr / s, the values of A and B to be 234 ± 34 V $\cdot$ cm$^{-1}\cdot$ Torr^{-1} and 7.3 ± 0.2 cm$^{-1}\cdot$ Torr^{-1} respectively. We also found the value of n (the slope of our VI curves) to be decreasing along with the pressure, this is consistent with what we had expected to observe. Using these conclusions we can state that from the preliminary data it appears as though the equation accurately describes breakdown potential and the number of electrons in a gas to decrease with pressure however more data should be obtained to get a more definitive conclusion.

1 Introduction

Plasma's are an extremely important part of the observable universe. Since plasmas are one of the four fundamental states of matter and also the most common form of ordinary matter in the universe it follows that physicists would attempt to study this matter and expand our knowledge about the universe just as we have done with solids, liquids and gases. The one thing that sets plasma apart is its infrequent occurrence in everyday life, typically plasmas are only observed during lightning strikes or when neutral gases are heated or subjected to strong electrical fields. To this end, when trying to produce plasma in the laboratory there are a certain number of conditions that must be met. One such condition is that most systems that produce a plasma require a vacuum to begin the process, we need to create a "void" where the pressure inside a particular chamber is so low that any particles that remain will not interfere with the generation of a plasma.

The first goal of our experiment is to investigate the effectiveness of our vacuum pump which we will use to reduce the pressure inside the chamber we hope to observe a low pressure DC Plasma. We will take a number of measurements using an automatic logging system which will record the pressure inside the chamber in 1 second intervals, we will then plot the pressure values versus time and obtain the effective pumping speed and its uncertainty.

Once we have achieved a vacuum inside the chamber, we can produce a potential difference across the two conducting plates placed inside. We will increase the voltage across these two conducting plates until we observe an ionisation of the background gas and an increase in the current, this will be known as the Townsend region. Once we reach this position we will continue to increase the voltage until the current becomes self sustaining without the need of the background radiation. At this potential difference we have arrived at the stage when the gas begins to glow and we can begin measuring the *breakdown potential / breakdown voltage*. We will also be observing the relationship between voltage and current and how they vary within a plasma, this will allows us to observe the VI characteristics of the discharge.

2 Background and Theory

When attempting to produce a vacuum within a chamber, the most important factor for a vacuum pump is the rate at which a certain volume of gas is being removed from the chamber. This is more formally known as the pumping speed of the vacuum pump. We can define the pumping speed mathematically as follows:

$$S = \frac{dV}{dt} \tag{1}$$

where dV is the volume of gas removed, dt is the time taken and S is the pumping speed.

We can treat the volume inside the chamber as constant and calculate the rate of change of the pressure inside the chamber against the pressure of the pump and pumping speed, as follows:

$$-V_c \frac{dP_c}{dt} = P_p S \tag{2}$$

Where V_c is the volume of the chamber, dP_c is the change in the pressure inside the chamber, dt is the time taken and P_p is the pressure of the pump. The change in the pressure inside the chamber is negative as the pressure is being reduced as the pump

In the above equation, the dP_c is negative as the pressure inside the chamber is decreasing over time.

If we consider our chamber and pump to be one closed system connected by a pipe then they will have the same pressure $P_p = P_c$. If we consider the speed to be constant we can integrate Eq.3 to get:

$$P_c(t) = P_{c0} \exp \left\{ \frac{-S}{V_c}(t - t_0) \right\} \tag{3}$$

Where P_{c0} is the initial pressure inside the chamber.

We can get rid of the exponential part of the function by using logarithms

$$\ln \left\{ \frac{P(t)}{P_{c0}(t)} \right\} = -\frac{S}{V_c}(t - t_0) \tag{4}$$

If we don't consider the speed to be constant we can use:

$$S = -\frac{V_c}{P_c}\frac{dP_c}{dt} \tag{5}$$

Once the glow discharge section of the experiment is reached, the breakdown potential can be found by measuring variables such as the pressure, the separation distance of the electrodes as well as characteristics about the background gas in the discharge. The equation for breakdown potential / breakdown voltage is as follows:

$$.V_b = \frac{Bpd}{ln(Apd/ln(1 + 1/\gamma))} \tag{6}$$

where p is the pressure, d is the electrode separation, γ is the secondary electron emission coefficient and A and B are constants.

We can linearise our equation as follows:

$$\ln(pd) = B\frac{pd}{V_b} - \ln \left(\frac{A}{\ln(1 + 1/\gamma)} \right) \tag{7}$$

Using Eq.7 we can plot $\ln(pd)$ vs $\frac{pd}{V_b}$ and determine B from our slope and A from solving for it using our y-intercept and the value of γ.

In order to calibrate the pirani vacuum gage for argon to obtain the rue pressure we will use:

$$p_T = 0.16e^{11p_P} \tag{8}$$

where p_T is the true pressure in Torr and p_P the pressure that the Pirani gauge reads in Torr.

3 Experimental Design and Procedure

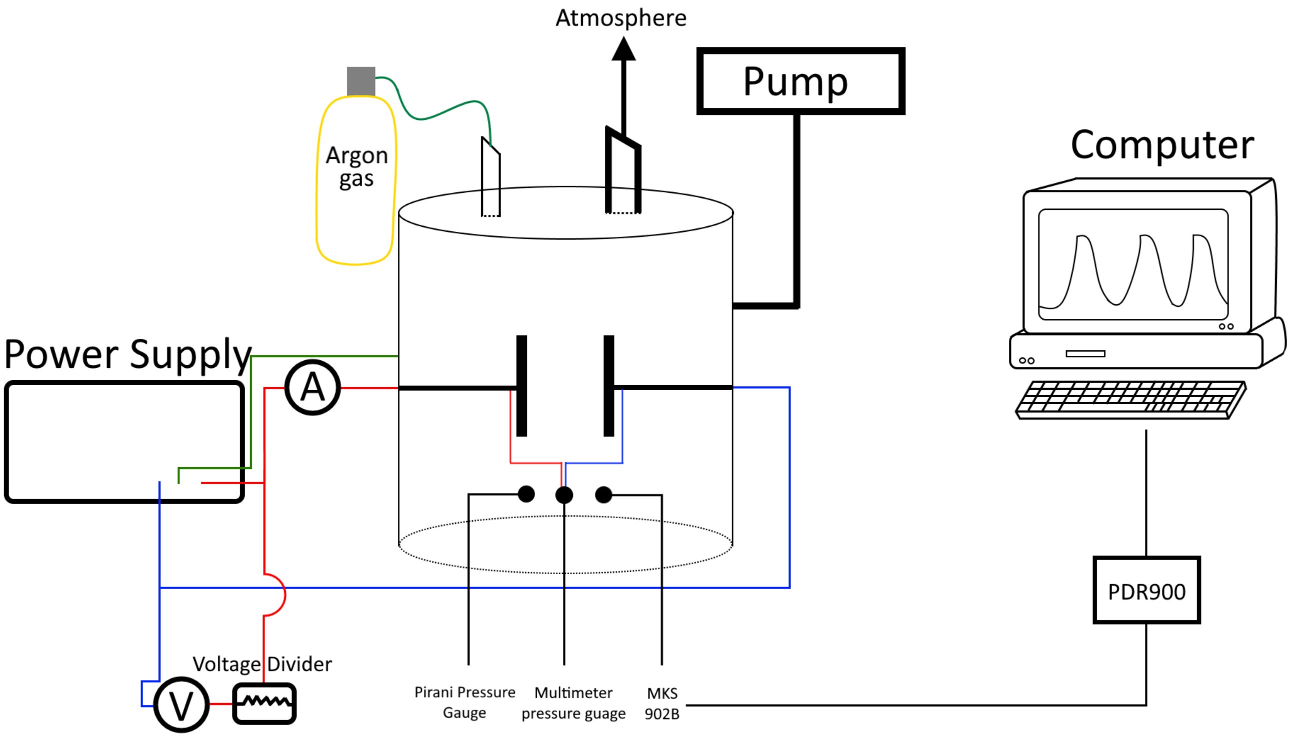

Figure 1: Schematic drawing of the experimental set-up

This experimental set-up included a vacuum chamber containing two electrodes and a valve to allow a gas (argon) to enter the chamber and a valve to allow air from the room back into the chamber. An Ammeter is connected to the electrodes in series with a power supply (which has a green cable attached to the vacuum chamber for grounding) meanwhile the voltmeter is connected to the electrodes in parallel using a voltage divider to reduce the voltage being supplied. A vacuum pump is connected to the chamber which allows us to generate a vacuum by removing effectively all of the air molecules within the chamber. Three pressure sensors are used to measure the pressure inside the chamber, this includes an MKS Instruments 902B Absolute Piezo Vacuum Transducer which is connected to an MKS Instruments PDR900 Vacuum Gauge Controller which connects to a computer used to log the effective pumping speed of our vacuum pump. The other two pressure guage's are a Pirani gauge and a multimeter which measures a voltage we can divide by 10 to calculate the pressure inside the chamber in torr.

The first step of experiment is to set up the apparatus so that the vacuum valves are tightly sealed, the pump is connected and the computer has been turned on. Once that has been done successfully the vacuum data logger software can be launched on the computer and a new file can be created, after this the program will run and the chamber can be cycled turning on the pump to reduce the pressure and create a vacuum and turning off the pump and allowing the chamber to reach air pressure. The vacuum data logger will graph the pressure change in real time and once enough cycles have been completed the readings can be stopped and the data can be saved.

Next we need to be able to produce a plasma within the vacuum chamber so the circuit needs to be set up exactly as shown in the schematic drawing in Fig. 1. The pressure inside the chamber was initially set to 1.9 torr, then to 1 torr and decreased in intervals of 0.2 torr. The voltage was varied until a glowing plasma discharge appears within the vacuum and a voltage drop is detected on the voltmeter, when these two conditions were met the voltage before this was recorded as the breakdown voltage / breakdown potential, this was repeated 10 times for each pressure and an average breakdown voltage / breakdown potential was taken.

Finally, the pressure was set to 0.1 torr inside the chamber and the voltage was set to 224 V, the voltage and current was recorded as the voltage is increased in 10 V increments until the current reaches roughly 1.5 mA. This process was repeated for 0.08, 0.06 and 0.04.

4 Results

4.1 Data

Table 1: List of data collected from the Vacuum Logger program

t (s) ±0.1	P_c (torr)	t (s) ±0.1	P_c (torr)	t (s) ±0.1	P_c (torr)	t (s) ±0.1	P_c (torr)	t (s) ±0.1	P_c (torr)
1	748.7 ±1%	47	0.1 ±0.05	84	300.2 ±1%	131	73.9 ±5%	187	181.9 ±1%
2	748	48	316.8 ±1%	85	735.1	132	488.9 ±1%	188	446.2
3	747.5	49	708.9	86	749.6	133	742	189	694.7
4	657.7	50	747.8	87	750.1	134	749.3	190	747.6
5	341.3	51	745.1	88	750	135	749.8	191	749.4
6	184.4	52	735.6	89	749.8	136	749.1	192	749.7
7	113.7	53	731.9	90	746.7	137	742.5	193	749.7
8	67.6 ±5%	54	358.1	91	743.5	138	739.6	194	746
9	41.7	55	204.5	92	740.9	139	736.9	195	742.5
10	23.7	56	117.6	93	600.6	140	734.6	196	739.8
11	14.7	57	73.7 ±5%	94	296.9	141	433.9	197	738
12	8.3 ±0.05	58	44.5	95	166.5	142	227.1	198	736.7
13	5.7	59	25.7	96	103	143	138.1	199	735.6
14	3.5	60	16.8	97	60.6 ±5%	144	80.7 ±5%	200	735
15	2	61	10.7	98	37.7	145	51.2	201	748.3
16	1.2	62	6.4 ±0.05	99	23	146	30.3	202	749.2
17	0.6	63	3.8	100	14.2	147	18.7	203	748.6
18	0.3	64	2.1	101	7.5 ±0.05	148	11.8	204	748
19	0.1	65	1.3	102	5.3	149	7.6 ±0.05	205	747.5
20	0.1	66	0.7	103	3.1	150	4.3	206	595.7
21	0.1	67	0.3	104	1.9	151	2.5	207	315.9
22	0.1	68	0.1	105	1	152	1.4	208	176.4
23	0.1	69	0.1	106	0.5	153	0.8	209	109.1
24	0.1	70	0.1	107	0.2	154	0.4	210	64.9 ±5%
25	0.1	71	0.1	108	0.1	155	0.2	211	38.3
26	0.1	72	0.1	109	0.1	156	0.1	212	23.8

The mks instruments website states that the accuracy of the Absolute Piezo Vacuum Pressure Transducers is 1% in the range of 100 to 1,000 Torr and 5% in the range of 10 to 100 Torr[1]. The website doesn't state the accuracy for readings below 10 so we used half the smallest measurable value.

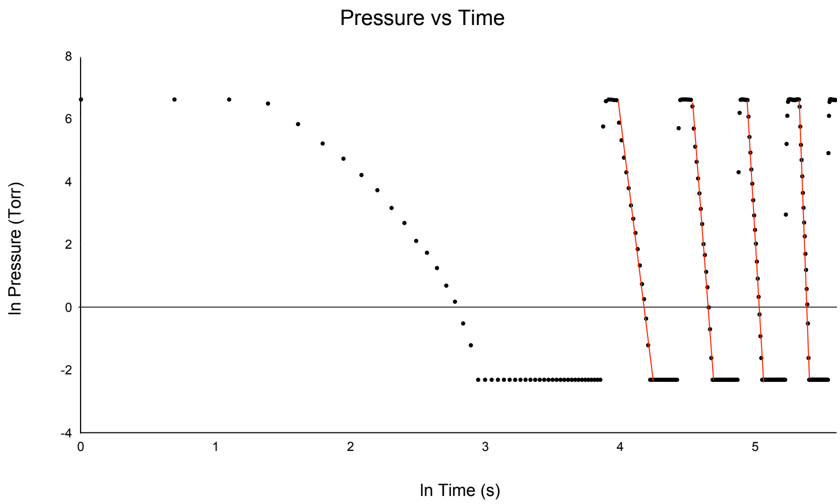

Figure 2: Pump down curve on ln-linear scales. The red lines represent the slope of the linear part of the curves which represents the effective pumping speed.

The slopes and uncertainties of the linear parts of the curves were as follows:

Effective pumping speed 1: -30.5 ± 0.9 Torr / s
Effective pumping speed 2: -51.8 ± 1.4 Torr / s
Effective pumping speed 3: -79.2 ± 1.4 Torr / s
Effective pumping speed 4: -109.6 ± 1.0 Torr / s

We can get an average value for the effective pump speed of

$$\frac{-30.5 - 51.8 - 79.2 - 109.6}{4} = -67.8 \pm 0.6 \text{ Torr / s}$$

Error analysis:

$$\Delta Z = \sqrt{(0.9)^2 + (1.4)^2 + (1.4)^2 + (1)^2} = 2.4$$

$$\Delta Z = \left|\frac{-67.8}{4}\right| \sqrt{\left(\frac{2.4}{-67.8}\right)^2 + \left(\frac{0}{4}\right)^2} = 0.6$$

Since the distance between the two electrodes inside the vacuum d is constant, the minimum value of pd. Is the smallest value of pressure we were able to measure a breakdown potential at. In our experiment we achieved a breakdown voltage of 233V at 0.4 torr, with a measured electrode separation of 1.3cm this gave us a pd_{min} of 0.52 ± 0.07 cm Torr.

Error Analysis:

$$\Delta z = |0.4 \times 1.3| \sqrt{\left(\frac{0.05}{0.4}\right)^2 + \left(\frac{0.05}{1.3}\right)^2} = 0.07$$

Table 2: List of data collected from the Breakdown Potential measurements

V (V) ± 0.1	P_c (torr)
253.2	0.2 $\pm$1%
233	0.4 $\pm$1%
235.4	0.6 $\pm$1%
237.4	0.8 $\pm$1%
246.2	0.85 $\pm$1%
276	1 $\pm$1%
319.5	1.9 $\pm$1%

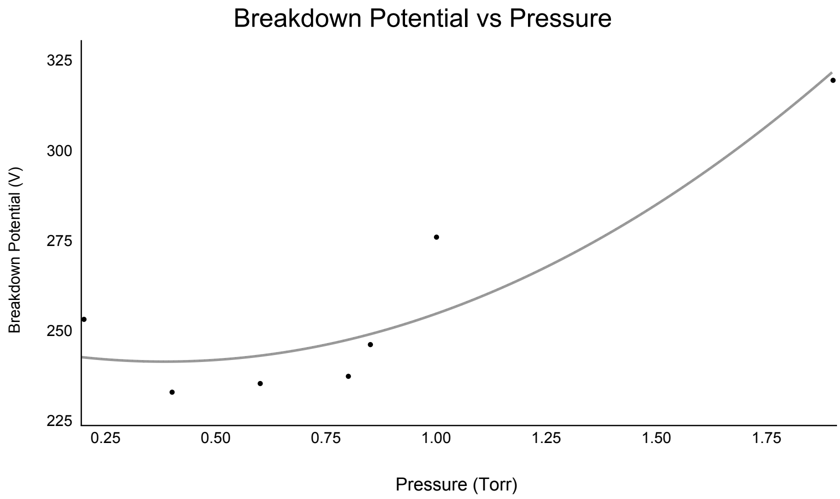

Figure 3: Graph of breakdown potential as a function of pressure.

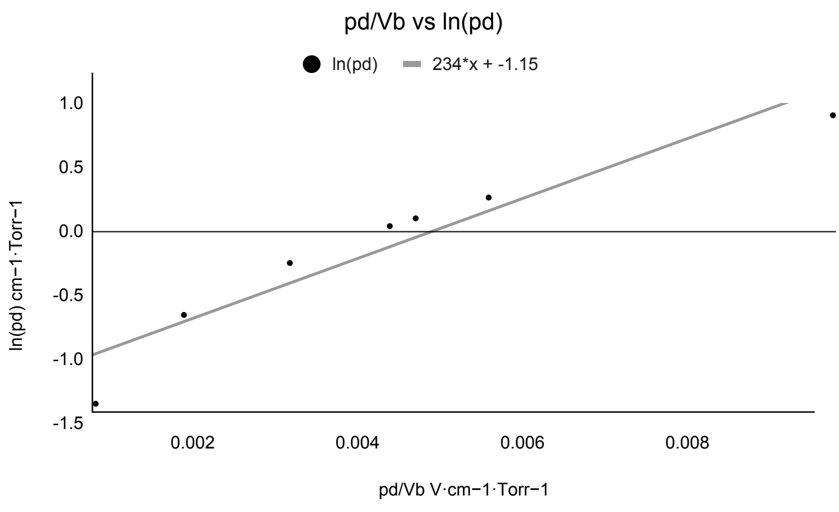

Figure 4: Plot of the natural log of pd vs $\frac{pd}{V_b}$. We will use the equation of the line of best fit to extract B from the slope and A from Eq. 7

From the slope of our graph we can conclude that the value of B is 234 $\pm$ 34 and we can calculate the value of A as follows:

$$\ln(\frac{A}{\ln(1+1/\gamma)}) = 1.15$$

$$\ln(\frac{A}{\ln(1+1/0.11)}) = 1.15$$

$$\ln(\frac{A}{2.311634929}) = 1.15$$
$$\frac{A}{2.311634929} = e^{1.15}$$
$$A = (2.311634929)e^{1.15}$$
$$A = 7.300589043$$

Therefore our two values we have determined are B = 234 ± 34 V $\cdot$ cm$^{-1}\cdot$ Torr^{-1} and A = 7.3 ± 0.2 cm$^{-1}\cdot$ Torr^{-1}.

We can compare these values to the book values of B = 176 V $\cdot$ cm$^{-1}\cdot$ Torr^{-1} and A = 11.5 cm$^{-1}\cdot$ Torr^{-1}. We can observe that the value of our slope (B) is within the correct magnitude of the book value, the same is true for our A value. We can more accurately measure the difference between the two values as follows:

$$\frac{(234 - 176)}{176} \times 100 = 33\%$$
$$\frac{|7.3 - 11.5|}{11.5} \times 100 = 37\%$$

Our value for B differed from the book value by 33% meanwhile our value for A differed from the book value by 37%.

4.2 Paschen's law

At low pressures, as the pressure in the chamber decreases it was noticed that a higher breakdown potential was obtained in order to form a plasma. This is most likely due to the mean free path of the electron becoming longer, relative to the gap between the two electrodes. This means the electrons have enough energy to ionise the gas however there is fewer ionising collisions occurring, for this reason the breakdown potential increases to ionise enough of the gas molecules to form a plasma.

At high pressures, as the pressure increased it was noticed that a higher breakdown potential was obtained. This is most likely due to a greater number of collisions occurring in the gas and thus a greater amount of energy loss. The breakdown potential increases to provide the electrons with enough energy to ionise the gas despite the higher number of collisions.

These two physical mechanisms make up the equation given by Paschen's law.

4.3 VI Curves

Table 3: List of VI-data at 0.1 torr

V (V) ±1	I (mA)
224	0.031 $\pm1\%$
234	0.414 $\pm1\%$
244	0.767 $\pm1\%$
254	1.082 $\pm1\%$
264	1.463 $\pm1\%$

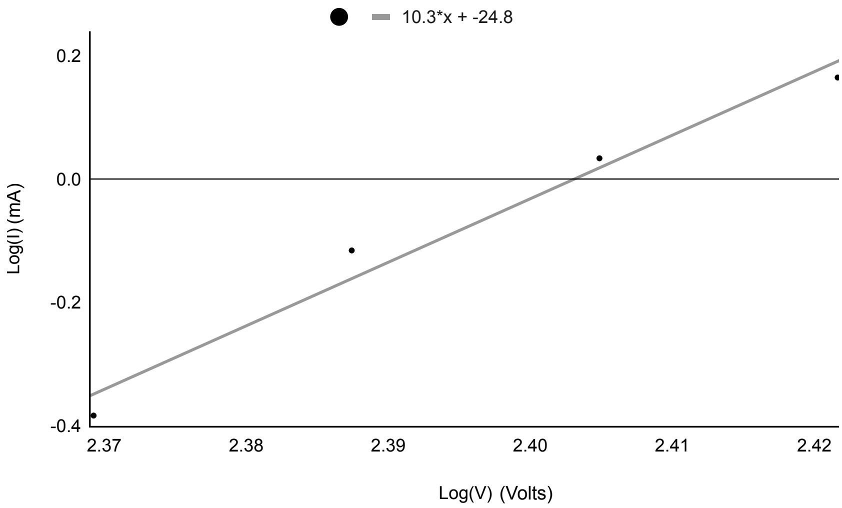

Figure 5: Log Log Plot of Voltage vs Current at 0.1 torr, the slope of the graph is n and the intercept is equal to $\ln A$

$$n = 10.3 \pm 1.2 \text{ and } A = e^{-24.8} = 1.7 \times 10^{-11} \pm 1.9 \times 10^{-12}$$

Table 4: List of VI-data at 0.08 torr

V (V) ±1	I (mA) ±0.0005
228	0.046
238	0.394
248	0.596
258	0.827
268	1.126
278	1.480

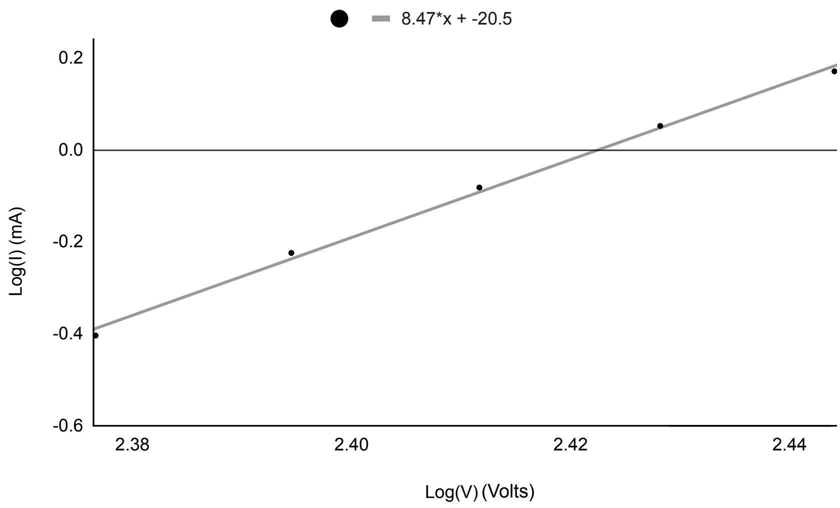

Figure 6: Log Log Plot of Voltage vs Current at 0.08 torr, the slope of the graph is n and the intercept is equal to ln A

$$n = 8.47 \pm 0.3 \text{ and } A = e^{-20.5} = 1.25 \times 10^{-9} \pm 4.09 \times 10^{-11}$$

Table 5: List of VI-data at 0.06 torr

V (V) ± 1	I (mA) ± 0.0005
233	0.05
243	0.283
253	0.476
263	0.653
273	0.925
283	1.161
293	1.447
203	1.770

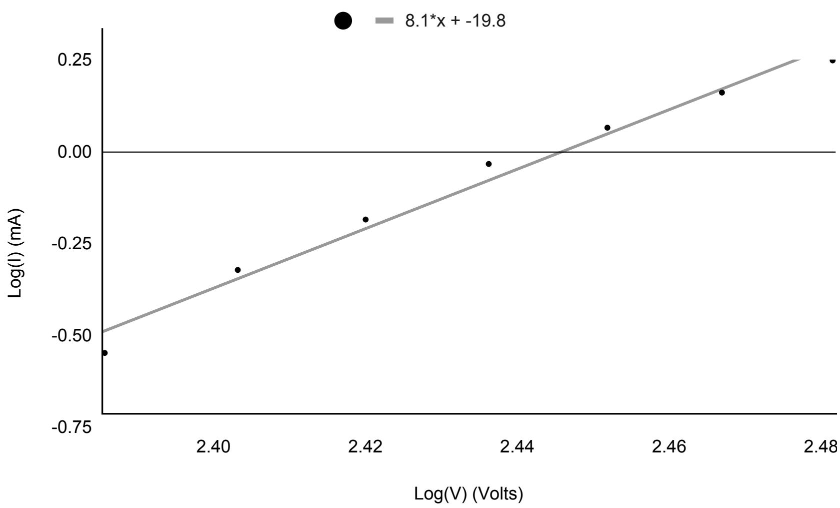

Figure 7: Log Log Plot of Voltage vs Current at 0.06 torr, the slope of the graph is n and the intercept is equal to $\ln A$

$$n = 8.1 \pm 0.5 \text{ and } A = e^{-19.8} = 2.52 \times 10^{-9} \pm 1.54 \times 10^{-10}$$

Table 6: List of VI-data at 0.04 torr

V (V) ± 1	I (mA) ± 0.0005
250	0.076
260	0.216
270	0.390
280	0.576
290	0.836
300	1.059
310	1.314
320	1.624

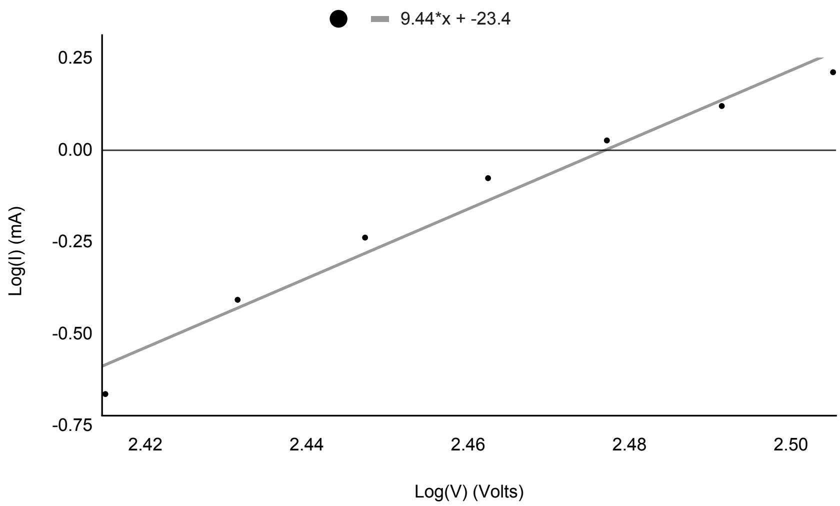

Figure 8: Log Log Plot of Voltage vs Current at 0.04 torr, the slope of the graph is n and the intercept is equal to ln A

$$n = 9.44 \pm 0.71 \text{ and } A = e^{-23.4} = 6.88 \times 10^{-11} \pm 5.18 \times 10^{-12}$$

5 Discussion and Conclusion

During the course of the experiment we were able to verify many of the hypotheses set out prior to the experiment. We have been able to determine an effective pumping speed by obtaining the slopes from the linear sections of the ln pressure vs ln time graph. This effective pumping speed was determined to be -67.8 ± 0.6 Torr / s. We also found the minimum value of pd to be 0.52 ± 0.07 cm Torr. We had expected to obtain a negative slope for our pumping speed as this represents the speed at which pressure is removed from the vacuum.

From our $\ln(pd)$ vs $\frac{pd}{V_b}$ graph we obtained a linear graph which is what we expected to see from the relationship and also determined a value from the slope of $B = 234 \pm 34 \cdot \text{cm}^{-1} \cdot$ Torr^{-1} and $A = 7.3 \pm 0.2$ $\text{cm}^{-1} \cdot$ Torr^{-1}. These values have a 33% and 37% difference of the expected book values. Although these values are not orders of magnitude bigger there is still some extremely large room for improvement.

We were able to determine values for n and A for our VI curves using the slope and the exponential of our y-intercept. We obtained values of n = 10.3 ± 1.2, 8.47 ± 0.3, 8.1 ± 0.5 and 9.44 ± 0.71. We obtained values of A = $1.7 \times 10^{-11} \pm 1.9 \times 10^{-12}$, $1.25 \times 10^{-9} \pm 4.09 \times 10^{-11}$, $2.52 \times 10^{-9} \pm 1.54 \times 10^{-10}$ and $6.88 \times 10^{-11} \pm 5.18 \times 10^{-12}$ for 0.1, 0.08, 0.06 and 0.04 torr respectively. We observed that the value of n is decreasing as the pressure decreases, this implies that there are fewer number of electrons in the plasma at low pressure. This is consistent with what we know about low pressure plasmas. It should be noted that the value of n increased at the last pressure 0.04 torr.

In the future it would be better to take more values for the $\ln(pd)$ vs $\frac{pd}{V_b}$ graph so that we have a wider range we can isolate in order to get a better linear fit, during the process of data analysis it was found that excluding any of the data points drastically shifted the slope or y-intercept and resulted in far less accurate values. If more values were available to choose from a linear fit would become much more apparent and wouldn't affect the accuracy as much. This would most likely lead to a reduction in the 33% and 37% difference between experimental value and book value.

The increasing n value at 0.04 torr on the VI curves is an outlier in the typical trend we would expect to observe from this type of graph. It would be a good idea to carry out follow up experiments on this specific pressure to find out if the n value continued to be higher than the two previous pressures, If so some alternative explanation would be needed to explain why more electrons were found at the lowest pressure than at 0.06 and 0.08 torr.