An Investigation of Striations Occurring in Glow Discharge Plasma

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Abstract

In this experiment, glow discharge plasma was created between two pin-to-pin electrodes in order to observe the spacing between striations formed at a low pressure. Plasma striations, alternating light and dark bands in the positive column, are the result of electrons colliding with gas particles and releasing energy in the form of light. The relationship between pressure and striation distance as a function of the gas-specific constant is described by the Goldstein-Wehner law. It was determined that air has a gas-specific constant of 0.66 ± 0.6. This result is only valid for plasma created in a cylindrical tube with pin-to-pin electrodes. The distance between striations was measured by capturing an image of the striations and measuring the spacing between them on ImageJ, an image processing software. Striations were observed between pressures of 5 Pa and 300 Pa. A model was also created to determine the voltage between the electrodes at various pressures for which striations can be observed.

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1. Introduction

The goal of the experiment is to model and describe the relationships between plasma striations in a vacuum tube and the pressure and voltage. It is intriguing to see how glow discharge plasma forms and how it is affected by various parameters. This type of plasma is created by high energy electrons colliding with gas particles to emit light [1]. It requires a large potential between two electrodes in a low-pressure environment. Striations are created because it reduces the amount of energy dissipated between the anode and cathode. The distance between striations changes because the mean free path of electrons decreases at higher pressures [2]. They were first recorded in the journals of Michael Faraday in the 1830s, with Abria publishing the first description of standing striations in 1843 [1]. A primary application of plasma is in plasma screen televisions. Televisions have thousands of cells filled with xenon and neon, and when a current is directed through it, the plasma emits UV light which interacts with a phosphor screen to create the image on the television screen [3]. Striations are interesting as they are a widespread phenomenon in gas discharge, and their presence can affect the performance of laser cutting and lamp emissions [4]. To quantitatively analyze plasma, the applied voltage and striation distance was measured at various low pressures.

2. Model and Predictions

An electric glow discharge is a specific kind of plasma formed when a high voltage and low current are passed through a low-pressure gas. Glow discharge plasma gets its name because of the light emission. This luminosity is produced because electrons emitted from the anode are accelerated by the electric field and gain enough energy such that photons are generated when they collide with other particles [5]. The basic structure of a glow discharge plasma is shown in Figure 1Error! Reference source not found.. The coloured areas in the picture emit significant amounts of light, while the grey regions do not.

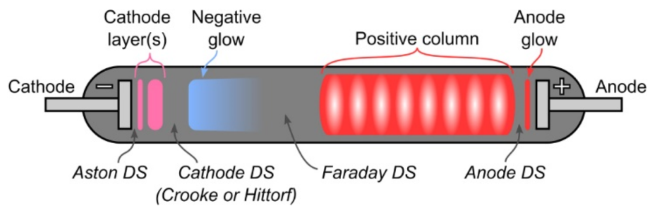

Figure 1 - An electric glow discharge tube outlining its most important characteristics [5]

When there is a significant amount of space between the anode and cathode, the positive column will develop alternating regions of dark and bright regions, called striations [1]. Striations will either be standing still or moving along the discharge axis [1]. The standing waves occur in molecular gases (such as air), while the moving waves typically occur in noble gases (argon, neon etc.). The travelling waves move at such a high velocity that the positive column appears continuous, and the striations are only visible with specialized equipment. At low pressures, the stratified state is energetically advantageous since the power dissipated in the positive column is lower when striations are present as opposed to when they are absent. Electrons acquire the necessary energy for ionization more easily if a voltage is concentrated across a short section, resulting in the bright regions (regions with high ionization activity) having a large electric field and the dark regions (regions with low ionization energy) having a very low or negative electric field [4].

Striations can be described by the Goldstein-Wehner law, which relates the distance between the striations, *d*, to the radius of the discharge tube, *R*, and two gas-specific constants, *m* and *C*. The coefficient *m* is always between 0 and 1, and *C* is typically between 1 and 10. The equation takes the following form [4]:

$$\frac{d}{R} = \frac{C}{P^m R^m} \tag{1}$$

It should be noted that the distance between the striations only depends on the radius of the tube, the gas pressure, and the type of gas, with the spacing between the anode and the cathode having no effect. In this experiment the only parameter that will be changed is the pressure inside the tube, with only air being used and the tube radius staying constant. The equation can be rearranged into a more useful form, with the constants moved to one side:

$$dP^m = \frac{RC}{R^m} \tag{2}$$

A reference pressure, P_0, can be taken along with its corresponding striation distance, d_0, and set equal to the right-hand side of the equation, as follows:

$$dP^m = d_0 {P_0}^m \tag{3}$$

This allows the equation to be rearranged again, moving the striation distance terms to the right side of the equation and the pressure terms to the left side.

$$\left(\frac{P}{P_0}\right)^m = \frac{d_0}{d} \tag{4}$$

Now, it can clearly be seen that there is an inverse relationship between the pressure of the gas in the tube and the distance between striations, scaled by the exponent *m*. By taking the natural logarithm of both sides of the equation, it can be converted to a linear form:

$$\ln\left(\frac{d_0}{d}\right) = m \ln\left(\frac{P}{P_0}\right) \tag{5}$$

This equation is now in the form $y = mx$, with $\ln\left(\frac{d_0}{d}\right)$ as the dependent variable, $\ln\left(\frac{P}{P_0}\right)$ as the independent variable, and *m* is the slope of the line.

It is expected that a stratified positive column (2-10 cm) will be produced at pressures between 33 Pa and 20 kPa, based on previous experiments with low-pressure plasmas [2] [6]. Also, striations should form when the electrodes are spaced between 2 cm and 10 cm, based on the same experiments. The positive column should be entirely contained between the two electrodes, with the positive column near the anode and a negative glow near the cathode. As the pressure in the tube increases, the spacing between the striations should decrease until a continuous plasma is formed [4]. Additionally, in air the colour of the plasma at the cathode should be pink, then change to blue at the negative glow, and become red/yellow in the positive column [7].

3. Apparatus

Various components were assembled to create the required conditions for low-pressure plasma striations. A summary of each component and its purpose is shown in Table 1.

Table 1: List of apparatus used in the experimental design. The labels correspond to Figures 14,15, 16 in Appendix A.

Apparatus	Use	Label
Ace Glass: Chromatography Column. (600mm long, 50mm diameter)	Vacuum sealed tube to create a low-pressure environment	A
Wooden Vacuum Tube mount	Support the vacuum tube on the wall	B
¼" Brass Rod tapered to a point	Cathode connected to ground	C
¼" Copper Rod tapered to a point	Anode connected to the power source	D
3-D Printed Electrode Stands	Support the electrodes inside the tube	E

Voltage Divider Circuit	Connect to multimeter to measure voltage between electrodes	F
Multimeter	Measure the voltage across the voltage divider circuit	G
Regulated HVDC Power Supply (Glassman High Voltage, Inc.)	Apply high voltage across the electrodes in the vacuum tube	H
Barometer (Inficon Pilot Pulse)	Measure the pressure in the tube	I
Air Compressor (Solid State Switch)	Remove air from tube to create the vacuum	J
Black Felt	Placed behind the vacuum tube to make striations easier to observe	K
O-rings	Secure vacuum seal between connections	L

The first design aspect of the experiment was ensuring the vacuum tube was capable of maintaining a low enough pressure to create striations (~100 Pa). This was accomplished with 1/4" copper and brass rods and rubber O-rings which sealed the ends of the glass vacuum tube. The glass nipple on one end of the tube was attached to a mesh hose and valve. The other end was connected to the Inficon Vacuum Gauge and Solid State Air Compressor. Each connection used an O-ring, vacuum grease, and a clamp to create a reliable seal. This successfully held a low pressure at approximately 100 Pa. The second design aspect was to tapper the brass rod (Anode) and copper rod (Cathode) to create a pin-to-pin relationship. Electrode stands were modeled on AutoCAD, 3D printed and placed inside the tube to support the electrodes. At this point in the experiment the following goal was to pump argon into the vacuum tube and maintain a low pressure. The valve was removed and the hose was connected to an argon gas tank through a regulator. When attached to the regulator, the tube was unable to hold a low enough pressure. Due to the time constraint, it was decided that the experiment would only be conducted with air.

The final aspect of the design was connecting the high voltage source across the vacuum tube. The regulated HVDC power supply was connected to a voltage divider circuit so that a multimeter could measure the voltage across the vacuum tube. Using copper clamps, the power supply was connected at one end, covered by a plastic box, and grounded at the other end. For safety purposes the voltage divider circuit and part of the anode protruding from the vacuum tube was enclosed in a removable plastic box. This was done to cover any potential arcing outside of the vacuum, and prevent individuals from coming in contact with the anode. Overall, the experimental design was able to hold a minimum constant pressure at 3 Pa. The power supply was capable of producing a maximum current of 6.2. Each component of the design is labelled in the block diagram in Figure 2.

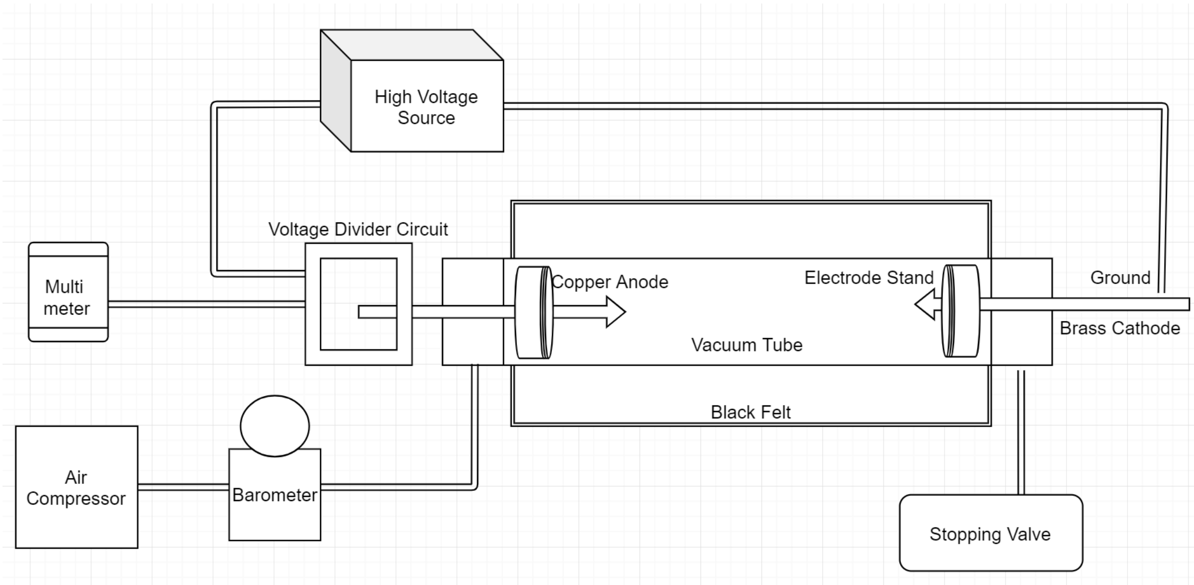

Figure 2: Block diagram of apparatus used to create plasma striations at a low-pressure

4. Procedure

The goal of this experiment was to create plasma striations in a low-pressure environment. To do so, multiple components had to be properly connected to prevent air from leaking in. The main set-up, as described in Section 3, has a vacuum pump connected to a glass vacuum chamber with a pressure gauge in between. Two electrodes extended into the vacuum tube and the voltage between them was controlled by a DC power source. Originally, tests were going to be conducted with low-pressure air and argon, but due to the time constraint, argon was not used.

The electrodes were positioned such that they were in contact inside the tube, and a mark was made where the cathode exited the tube. This was used as the reference point to measure the spacing between the electrodes. The cathode was then separated from the anode to create a gap between the two electrodes. By measuring the distance from where the cathode exited the tube to the mark previously made on it, the distance between the pins could be found. This was measured to be 25.3 ± 0.1 cm using a meter stick. The valve on the opposite end was then closed, and the vacuum pump was turned on. The pressure was monitored through the Inficon Vacuum Gauge, connected between the pump and the tube. Once the tube was at the desired pressure, the valve controlling the vacuum pump was adjusted until the pressure remained constant. While collecting data, the plasma was ignited at pressures between 3 Pa and 7 Pa. The power source was plugged in to the outlet and the dial on the power source was slowly rotated to raise the voltage between the electrodes. After roughly 2 rotations of the dial, the plasma ignited in the vacuum chamber. The vacuum pump was turned off, and the pressure was left to rise to the desired value, as monitored from the vacuum gauge. Once the desired pressure was reached, the pump was turned back on to keep the tube at the desired pressure.

Voltage measurements were made by measuring the voltage through a multimeter connected to a voltage divider circuit in parallel with the electrodes. The current was measured and shown on a gauge on the power source. Photos of the striations were taken using a DSLR camera from approximately 10 cm away. The photos were taken with shutter speeds ranging from $1/60^{th}$ to $1/80^{th}$ of a second. The distance between striations could then be measured on ImageJ using a known distance of 25.3 ± 0.1 cm between the pins.

The length of the positive column was measured, and then divided by the total number of striations to get the average distance between striations. While initially testing the apparatus, arcing was heard inside of the plastic box covering the anode. This was because the resistor in the circuit was damaged due to the high voltage. It was replaced with a resistor that was rated for higher power dissipation. One issue that was encountered was dust inside the air hose entering the vacuum tube upon opening the valve. This was fixed by swapping it for a newer and cleaner hose.

Another issue that was encountered was the power source would occasionally shut off unexpectedly. After approximately 10 minutes of applying a voltage across the electrodes at max current, the power source would turn off. This was likely due to the power source overheating. It had to be unplugged and left to sit for approximately 5 minutes before it could be used again. This made it difficult to continuously make measurements at different pressures.

5. Data

Initially, the pressure in the vacuum tube was brought down to approximately 3 Pa using the vacuum pump. The power supply was turned on and plasma was generated between the electrodes. The voltage across the electrodes was measured as the pressure in the tube increased to approximately 250 Pa, and was recorded in Figure 3. The error in the voltage measurements was estimated to be ± 10 V, based on the accuracy of the multimeter used. The uncertainty in pressure was approximately ± 3 Pa, since the pressure was fluctuating slightly inside the chamber.

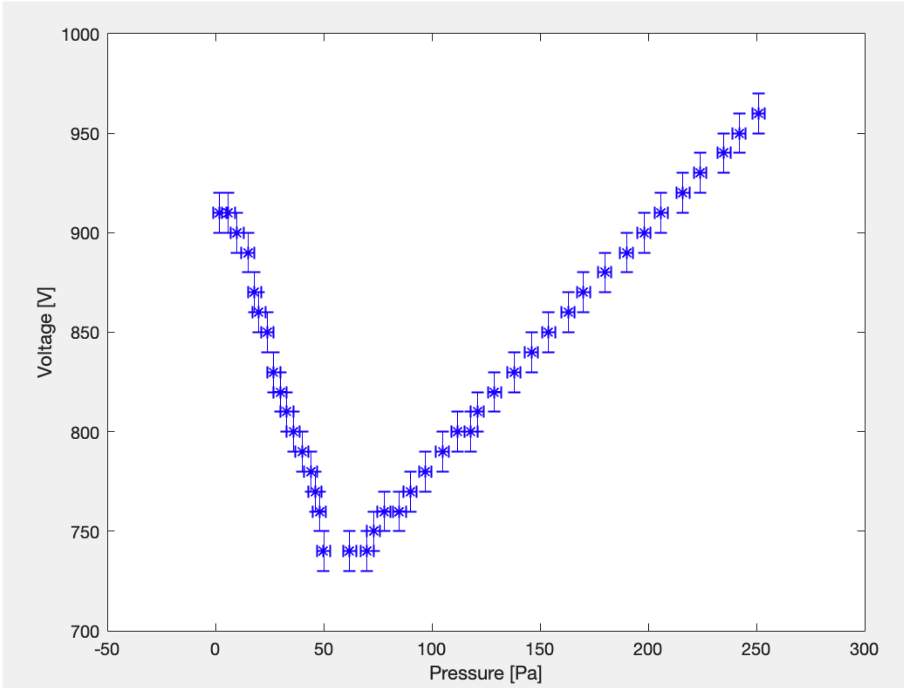

Figure 3 - Pressure inside the vacuum tube plotted against the dc voltage supplied to the anode of the vacuum tube.

The resistance between the electrodes was calculated using Ohm's Law. The current was constant at 6.2 ± 0.1 mA, the maximum allowed by the power supply, so the plot of the resistance follows the same shape as the voltage plot. This can be seen in Figure 4.

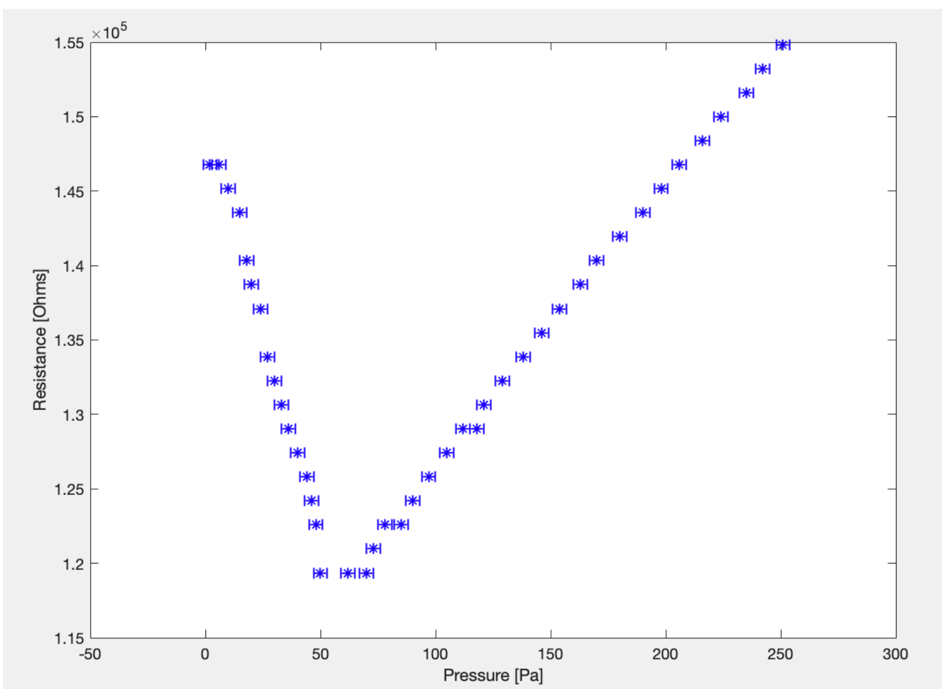

Figure 4 - Pressure inside the vacuum tube plotted against the resistance of the air inside the tube.

Once the plasma ignited, pictures were taken of the striations using a Sony a57 DSLR camera. These images were uploaded to an imaging software called ImageJ, which was used to measure the average distance between the striations. The data is shown in Figure 5 below.

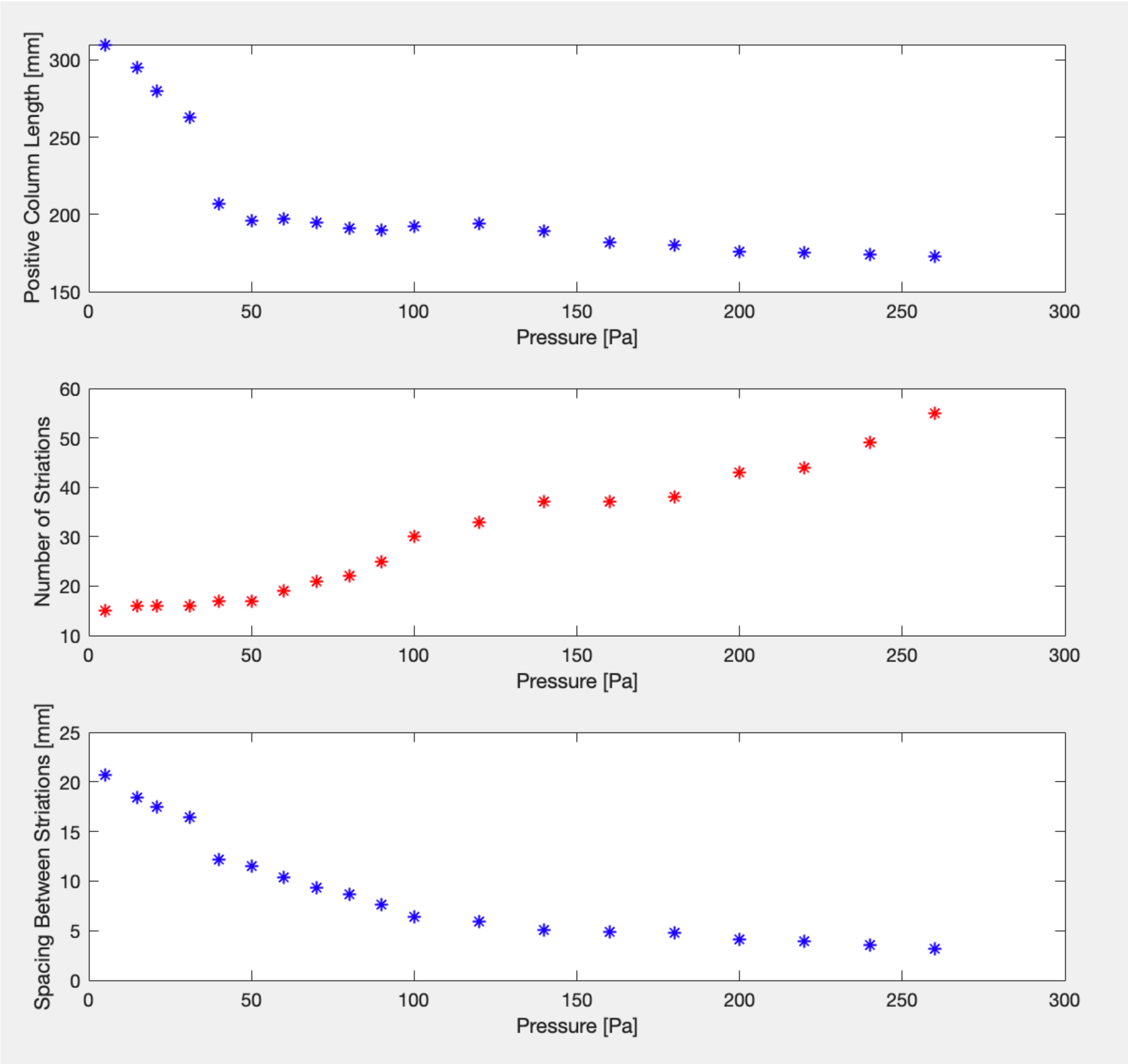

Figure 5 - Positive column length of the plasma, number of striations produced, and the spacing between the striations are plotted against the corresponding pressure measurement.

6. Analysis

Using a curve fitting package on MATLAB, an exponential function of the following form was fit to the voltage and pressure values:

$$V = a_1 e^{\left(\frac{P-b_1}{c_1}\right)^2} + a_2 e^{\left(\frac{P-b_2}{c_2}\right)^2} \tag{6}$$

Where V is the operating voltage in volts, P is the pressure in pascals, and a_1, b_1, c_1, a_2, b_2, and c_2 are coefficients determined by MATLAB to best fit the data. This form was chosen because it gave the best fit to the data and passed through the majority of the data points within error. The values of the coefficients and error are included in Appendix II.

The line of best fit was plotted along with the data points and is shown in Figure 6.

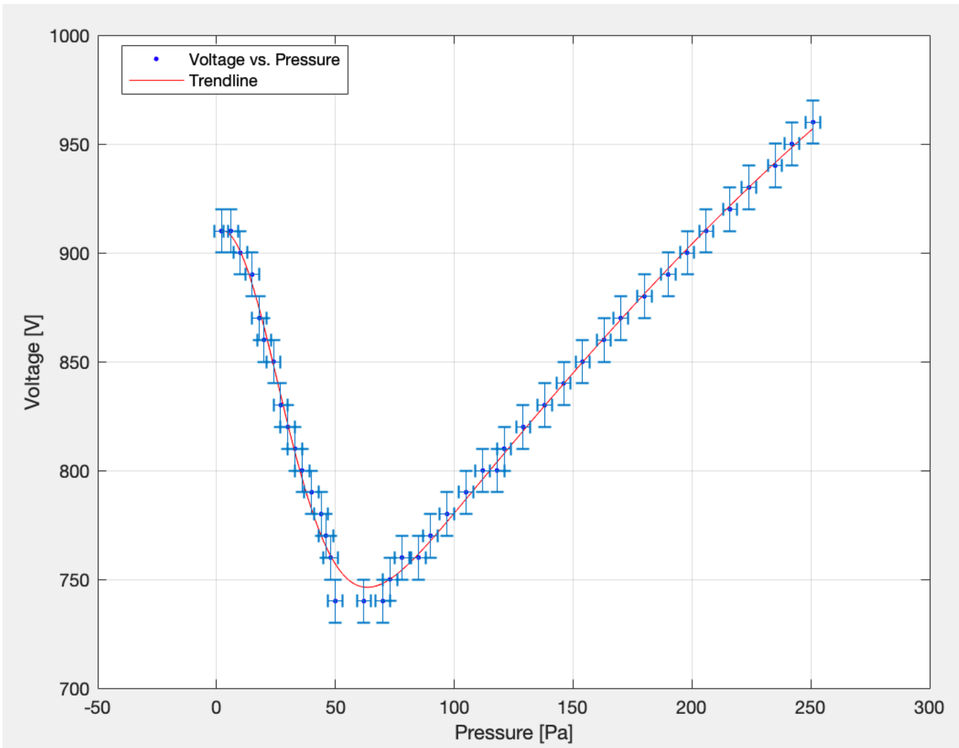

Figure 6 – Operating voltage plotted against the pressure inside the vacuum tube. Error in voltage and pressure is ± 10 V and ± 3 Pa respectively.

The equation above shows the relationship between the voltage applied across the electrodes and gas pressure related by a series of constant values. The uncertainty in the constants was determined based on the program's confidence ($R^2 = 0.9951$) in fitting the data.

The voltage and pressure data were plotted according to the linearized Goldstein-Wehner equation (Equation (5)). A reference pressure (P_0) of 50 ± 3 Pa was chosen, and the corresponding striation spacing (d_0) was 11.5 ± 0.1 mm. A line was fit to the data, and the gas-specific constant, *m*, was determined from the slope of the line.

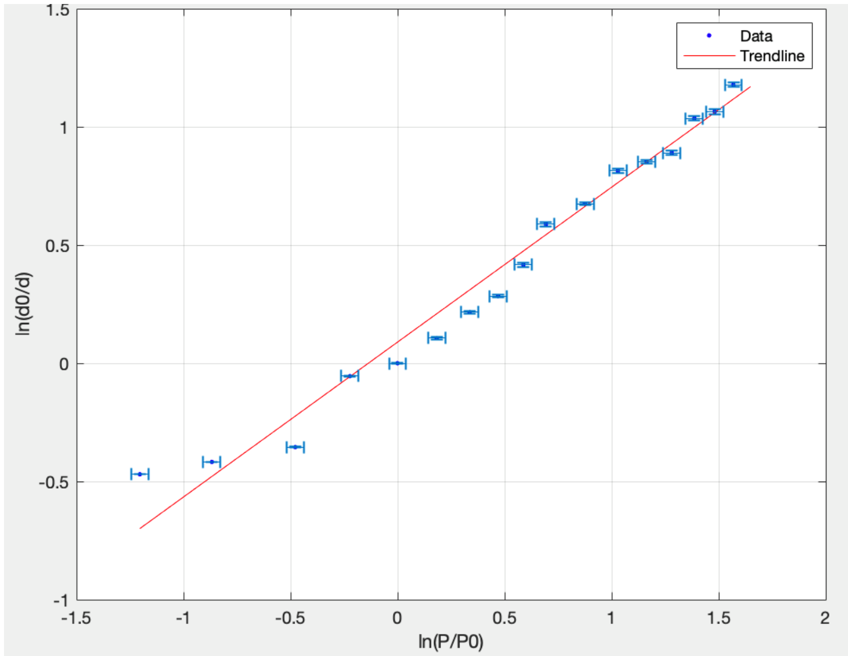

Figure 7 – The linearized distance between striations is plotted against the linearized pressure (ln(d_0/d) vs. ln(P/P_0)). The majority of the points fall within error of the trendline. The error on linearized distance is determined independently at each point based on the errors in striation distance measurement. The R^2 value for the fit is 0.9732.

For higher pressures, the data appears to follow a linear trend, where the trendline is within error of each point. At pressure values below approximately 31 Pa, the data begins to deviate from the trendline. In Figure 5, it can be seen that the length of the positive column at these low pressures are also outliers from the general trend. Note that the lowest pressure value was omitted in order to prevent further skewing of the trendline. The gas constant, determined by the MATLAB curve fitting package, was found to be 0.66 ± 0.06.

The voltage and pressure values were also plotted in Figure 8 with different reference pressures (60 ± 3 Pa and 70 ± 3 Pa) to see how the relationship would change using different reference values.

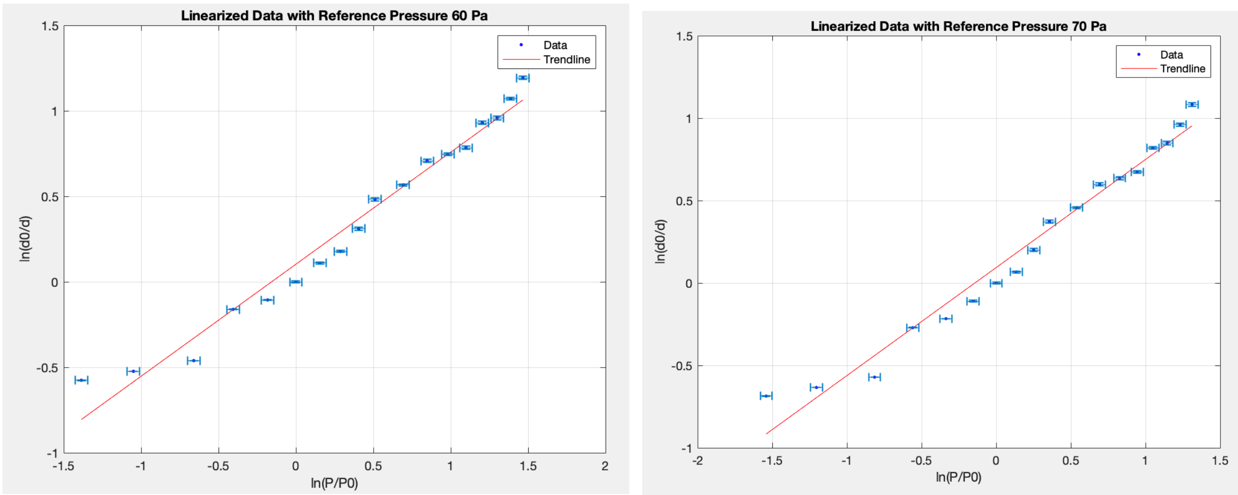

Figure 8 – The linearized distance between striations is plotted against the linearized pressure ($ln(d_0/d)$ vs. $ln(P/P_0)$). The majority of the points fall within error of the trendlines. Reference pressure, P0 and distance are 60 ± 3 Pa and 10.4 ± 0.1 mm respectively for the right graph, and 70 ± 3 Pa, 9.3 ± 0.1 mm respectively for the left graph.

While the y-intercept of the trendline varies by approximately 0.1, the slopes for line (gas constant value) stays exactly the same at 0.66 ± 0.06.

In order to obtain a more accurate measurement of the gas constant, the first 3 values which appear to be outliers were removed. These points are deemed outliers because they appear to have a lower slope than the remainder of the data. This change is shown in Figure 9.

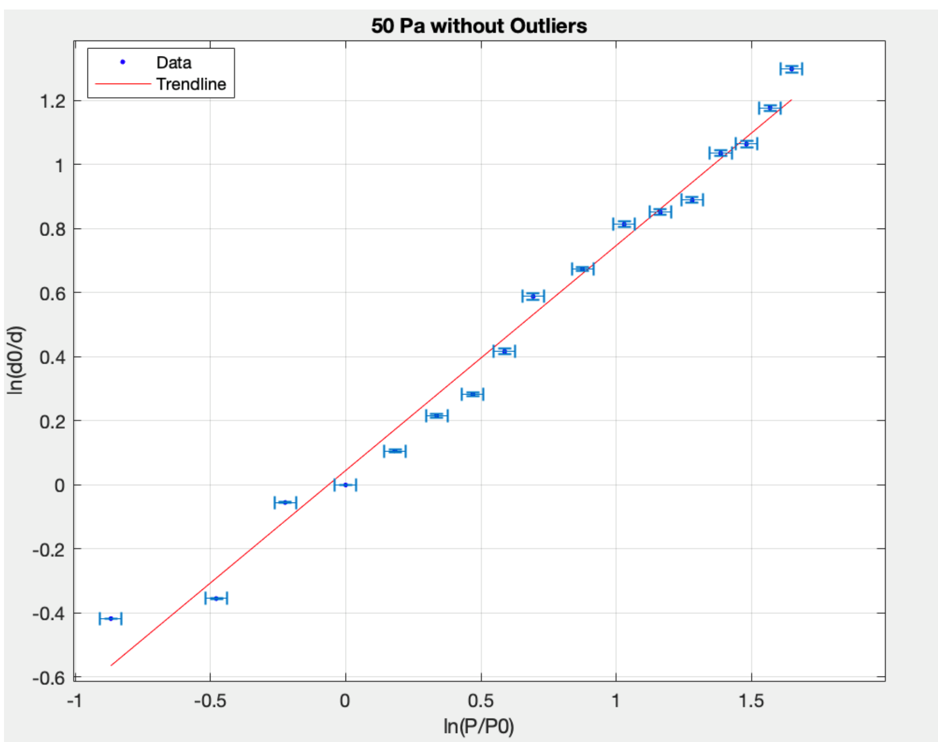

Figure 9 – The linearized distance between striations is plotted against the linearized pressure ($ln(d_0/d)$ vs. $ln(P/P_0)$ with outliers removed. The trendline passes through most of the points, within uncertainty. Reference pressure, P_0 and distance d_0 are 50 ± 3 Pa and 11.5 ± 0.1 mm respectively. The R^2 value for the plot is 0.9847.

The gas constant determined from the refined set of data is 0.70 ± 0.05. This fit is deemed more accurate than the plot in Figure 7 since the R^2 value is higher by 0.0115 in Figure 9 than in Figure 7.

The pictures taken of the striations were analyzed in MATLAB to determine how the light intensity of the striations relative to its surroundings changed based on the pressure inside the tube. Figure 10, below, shows the striations and brightness analysis at approximately 20 Pa.

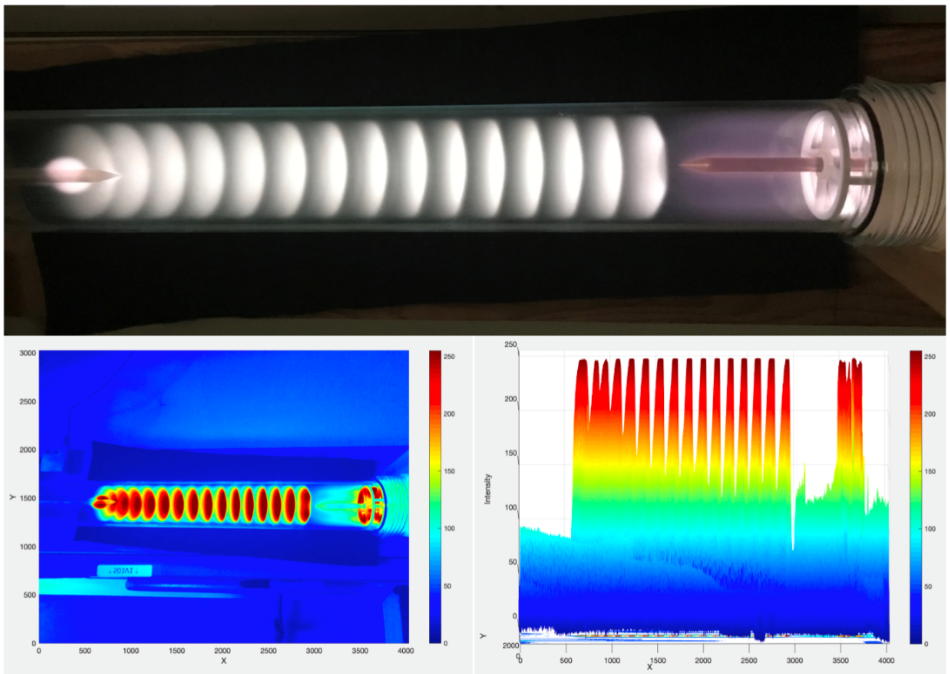

Figure 10 – Plasma striations at 20 Pa. Images of the striations, as well as their light intensities are graphed.

In Figure 10, there are 15 striations with little to no Faraday dark space seen near the cathode. The light intensity reaches approximately 256 Candela (relative to the darkest spot in the image). Note that 256 Candela is the maximum intensity value for this kind of image, leading to clipping at higher intensities. The negative glow around the anode is a darker shade of violet compared to the positive column.

Figure 11, below, shows the plasma striations produced in the vacuum tube at approximately 35 Pa.

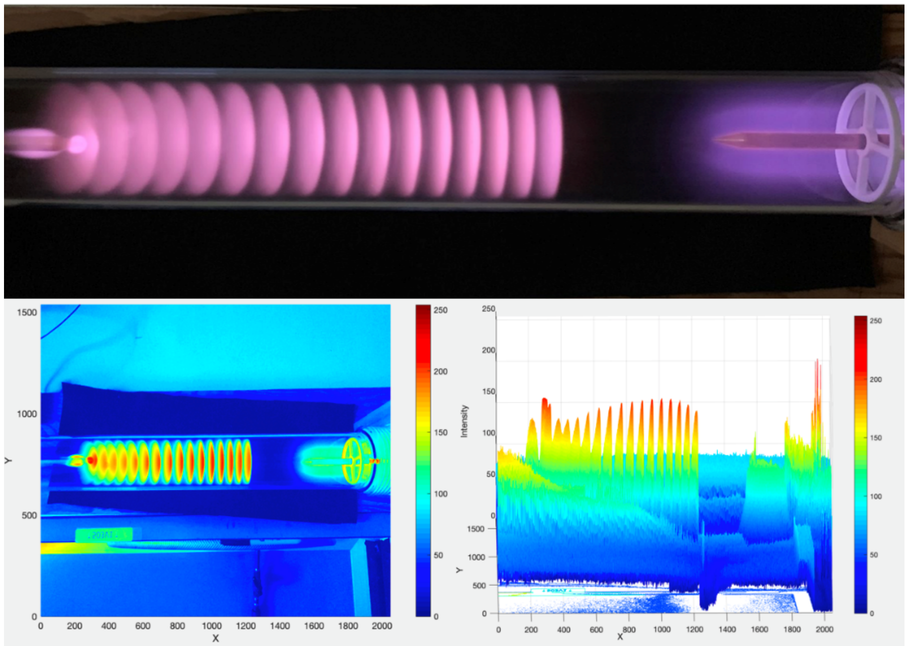

Figure 11 – Plasma striations at 50 Pa. Images of the striations, as well as their light intensities are graphed.

In Figure 11 there are 16 striations with light intensities reaching approximately 230 Candela (relative to the darkest spot in the image). The dark space has increased significantly compared to Figure 10. The positive column and negative glow appear to have more pronounced pink and violet hues, respectively. While the light intensities of the striations appear to decrease towards to the anode, this is due to the angle the image was taken at. The striations appear as semi-transparent discs in the tube. When looking at the striations from an angle, they appear to overlap thus giving the impression of less defined striations. Figure 12, below, shows an image of the striations at 200 Pa.

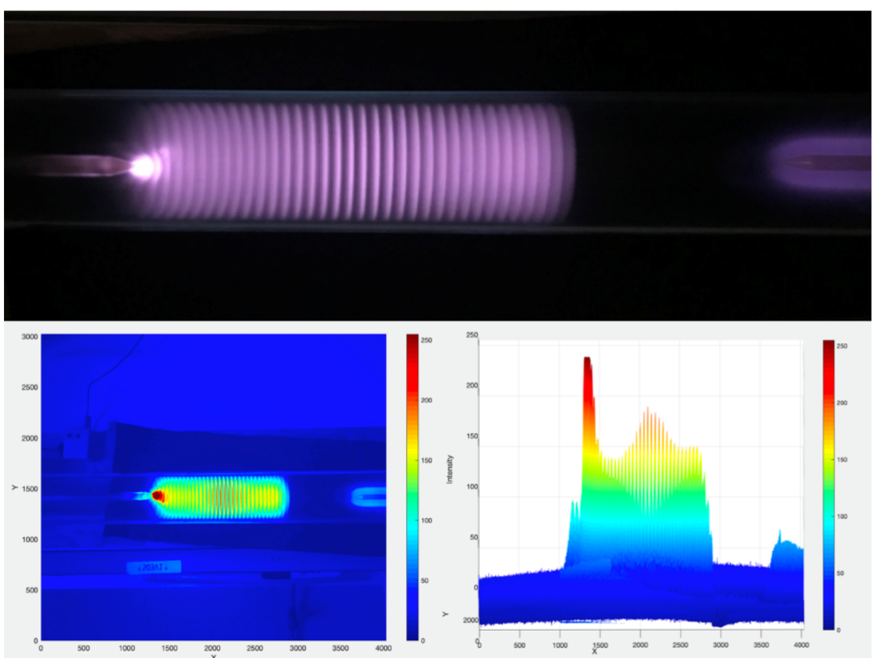

Figure 12 – Plasma striations at 200 Pa. Images of the striations, as well as their light intensities are graphed.

In Figure 12, there are 40 striations with light intensities reaching approximately 180 Candela (relative to the darkest spot in the image). The peak seen in the figure is the anode glow, and is significantly brighter than the rest of the striations. Compared to Figure 9 and Figure 10, the Faraday dark space increased and the striations moved closer together. The colour continues to turn more violet compared to the plasma at 20 Pa.

A photo of the striations at each pressure is available in Table 2, Appendix I.

7. Discussion

7.1 Initial Results

Initially, the electrodes were spaced approximately 2 cm apart, and it was expected that a striated plasma would form between them. When voltage was applied across the electrodes, plasma was formed but took an unexpected structure, as shown in Figure 13, Appendix I. The power was turned off and the electrodes were spaced as far apart as the tube would allow, 25.3 ± 0.1 cm, and striated plasma formed between the electrodes. This is likely because in the experiment referenced, the electrodes were placed in a stainless-steel chamber that was 450 x 205 x 195 mm in size, which is smaller than the glass tube that was used in this experiment [6]. It is known that the structure of the plasma depends on the geometry of the container, however it was unexpected that it would vary by such a large amount.

The colour of the plasma was expected to be pink at the cathode, blue in the negative glow, with a red and yellow positive column. This was not observed when the plasma was formed at a pressure of 5 Pa, nor as it increased. The plasma was a uniform pale blue colour that slowly changed to a darker shade of violet as the pressure increased seen in Table 2, Appendix I. Once the pressure was increased to about 800 Pa, the positive column was pink while the cathode end was violet.

The data collected from measuring the distance between striations and pressure followed the expected trend. When linearizing the data, the trendline had an R^2 value of 0.9732. This implies that the line is an appropriate fit for the data. This may also be an indication that the uncertainty on the values is overestimated. The value for the gas specific constant was determined to be 0.66 ± 0.6, which is less than 1 as expected [2]. The distance between striations decreased as the pressure in the tube increased. This is expected because the mean free path of the electrons decreases.

7.2 Discussion of Results Between 5 Pa and 17 KPa

Photos and observations were taken at increasing pressures from 5 Pa to 17 KPa seen in Table 2, Appendix I. At each observed pressure, the behaviour of the plasma striations was compared to the known relationships from past studies done at Bard College [2].

Between 5 Pa and 15 Pa the striations vibrated without clear dark bands between each node. An unexpected warping of the plasma striations occurs around the brass cathode with no faraday dark space. Negative glow, intense non-striating plasma, is observed to surround the cathode and extend all the way to the end of the tube [5]. The negative glow phenomena can be seen in Figure 16, Appendix I. At pressures between 15 Pa and 80 Pa, the striations are uniform and clearly visible at each node with distinct dark and light bands. The striations around the cathode are also more uniform without warping and eventually vanish at 40 Pa. At pressures from 40 Pa to 80 Pa, the Faraday dark space is visible between the striations and the cathode. The negative glow at this pressure range remained constant around the cathode. From 90 Pa to 375 Pa, the number of striations increased and the distance between striations decreased as the pressure increased. This was expected based on the known relationships established in model section of this report. The luminosity of the negative glow appeared to increase as pressure increased within this pressure range. At 300 Pa, the colour changed partially due to the use of an iPhone XR camera instead of the DSLR. However, around half of the striations began to vibrate preventing clear dark and light bands from forming. At a pressure of 375 Pa, most of the striations are blurred together with about one quarter remaining visible.

The striations became indistinguishable from one another at pressures ranging from 600 Pa to 1000 Pa. The diameter of the plasma also decreases at this pressure range and assumed an "arrowhead" shape with the section with the larger diameter occurring furthest from the anode. At 800 Pa, the negative glow only occurred at the very end of the cathode. At pressures between 1000 Pa and 17 kPa, the plasma began to dissipate with the cathode plasma glowing dark violet and the anode plasma glowing a lighter pink-violet. At pressures above 17 kPa, arcing between the electrodes was observed indicating that the max current of 6.2 mA was insufficient to maintain a glow discharge plasma.

A second test starting at a pressure of 330 Pa and decreasing to 15 Pa was conducted and recorded in Table 3, Appendix I. Comparing the observations to Table 2, Appendix I, at 215 Pa the decreasing pressure trial had a significantly larger Faraday dark space with a larger portion of blurry striations. The increasing pressure test had a smaller Faraday dark space with clear striations and a constant plasma colour at pressures around 200 Pa. Between 115 Pa and 32 Pa, the striations for both tables followed the same striation structure. However, the colours of the anode and cathode were different from each other for the decreasing pressure tests. At a pressure of 15 Pa, the observations for both tests were the same.

The final design produced distinguishable plasma striations at pressures between 5 Pa and 300 Pa with a current of 6.2 mA from the power supply. At pressures between 300 Pa and 17 KPa plasma formed between both anode and cathode. Pressures above 17 KPa produced arcing between the electrodes due an inability to create a stable glow discharge plasma.

7.3 Sources of Uncertainty and Limitations

A major source of uncertainty in this experiment is the pressure gauge. There were many instances where the gauge gave inconsistent readings with observations. For example, while raising the pressure in the tube back to atmospheric pressure, the gauge would read 101 kPa but air could be heard flowing into the tube through the valve, indicating that the tube was not at atmosphere. One possible explanation for this was the placement of the gauge. The gauge was placed in between the vacuum tube and the pump. Due to the large hose length between the gauge and the vacuum tube, it is possible that the pressure measured from the gauge is not an accurate representation of the pressure in the tube. As a result, it is expected that the reading from the gauge is lower than the pressure in the vacuum tube. This was accounted for by including an uncertainty of ± 3 Pa on each measurement of pressure. This value was used because that was the magnitude of pressure fluctuations while trying to form a stable vacuum. If this experiment were to be redone, the gauge should be attached closer to the tube, and ideally connected directly to one of the glass nipples on the vacuum chamber. This would give a more accurate measurement of the pressure inside the tube.

Additionally, a different pressure gauge would be used instead of the Inficon Barometer. There were some instances where the reading on the gauge would begin to decrease, despite the tube being at atmospheric pressure. The gauge would not read atmospheric pressure until the pressure in the tube was lowered, and then raised back to atmosphere. It was unclear what caused this effect, but it raised concerns regarding the reliability of the gauge. Therefore, it would be beneficial to switch gauges if re-doing this experiment. The striations created for this lab followed the theory as expected because the distance between striations decreased as pressure increased. However, the data collected is only valid for creating striations in a cylindrical vacuum tube. It is known that the shape of the tube can alter the shape and spacing of striations [2]. Additionally, the shape of the electrodes has a significant effect on the shape and spacing of the striations. Pin-to-pin electrodes result in sharper transitions between dark and light striations, making it easier to measure the distance between striations (as opposed to plate-to-plate). Therefore, the data collected is only valid for plasma created in a cylindrical tube with pin-to-pin electrodes. It would be beneficial to use plate to plate or pin to plate if re-doing this experiment to determine the optimal connection.

8. Conclusions

In this experiment, the spacing of striations and applied voltage of glow discharge plasma at low pressures was analyzed. Using a vacuum pump, a low pressure was produced and sustained inside a glass vacuum tube. Electrodes were placed inside the tube and connected to a high DC voltage power supply. Using pin-to-pin electrodes, plasma was generated between the cathode and anode.

Corresponding voltage and pressure values, as well as images of striations at specific pressures were collected and compared to see how the pressure of the system related to the striations. It was found, as expected, that as the pressure inside the vacuum tube increased, the size of the striations decreased.

In this experiment, the spacing of striations and applied voltage of glow discharge plasma at low-pressures was analyzed. A glass vacuum tube with pin-to-pin electrodes was brought down to a pressure below 300 Pa using a vacuum pump. A DC voltage was passed through the electrodes causing plasma to form between them.

In addition to voltage measurements, images of the striations were taken at various pressures. As the pressure of the system increased, the number of striations increased and the distance between the striations decreased. It was expected that the distance between striations would decrease. However, the increase in the number of striations was unexpected. It was also observed that at higher pressures, the light intensity of each striation decreased.

Corresponding striation spacing and pressure values were recorded in order to determine a gas constant for the system. Using the Goldstein-Wehner equation, a constant of 0.66 ± 0.06 was obtained for the air inside the tube. At pressures below 31 Pa, the data appeared to diverge from the linear relationship as shown in Figure 6. This is the same pressure where striations began to form around the cathode, eliminating the Faraday dark space. The measured gas constant agreed within uncertainties with the values obtained when using a different initial pressure and striation distance. Additionally, the gas constant was between 0 and 1, as expected.

The Faraday dark space was first seen at approximately 31 Pa and continued to grow as the pressure increased. Once a pressure of 300 Pa was obtained inside the vacuum tube, striations did not form. The system began to arc at a pressure above 17 kPa. It was also observed that the colour of striations became more violet as the pressure of the system increased.

9. Contributions

Matt Ahrens contributed to the Model and Theory and a portion of the Analysis and Data sections. Ryan Chu contributed to the Apparatus and a portion of the Procedure. Lorne Cohen contributed to the Introduction and Procedure and contributed to the Abstract and Conclusion. Kyle Singer contributed to the Data and Analysis sections and a portion of the Abstract and Conclusion. The Discussion was completed as a group along with the Appendices and References.

10. References

[1] V. Kolobov, "Striations in Rare Gas Plasmas," *Journal of Physics D: Applied Physics,* vol. 39, no. 24, 2006.

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[4] V. A. Lisovskiy, "Validating the Goldstein-Wehner law for the stratified positive column of dc discharge in an undergraduate laboratory," *European Journal of Physics,* vol. 33, pp. 1537-1545, 2012.

[5] Plasma-Universe, "Electric Glow Discharge," [Online]. Available: https://www.plasma-universe.com/electric-glow-discharge/.

[6] H. Zhu, Z. Su and Y. Dong, "Experimental studies on striations in helium glow discharge," *Applied Physics Letters,* vol. 111, 2017.

[7] J. T. Gudmundsson and A. Hecimovic, "Foundations of DC plasma sources," *Plasma Sources Science and Technology,* vol. 26, no. 12, 2017.

11. Appendix I – Apparatus and Striation Photos

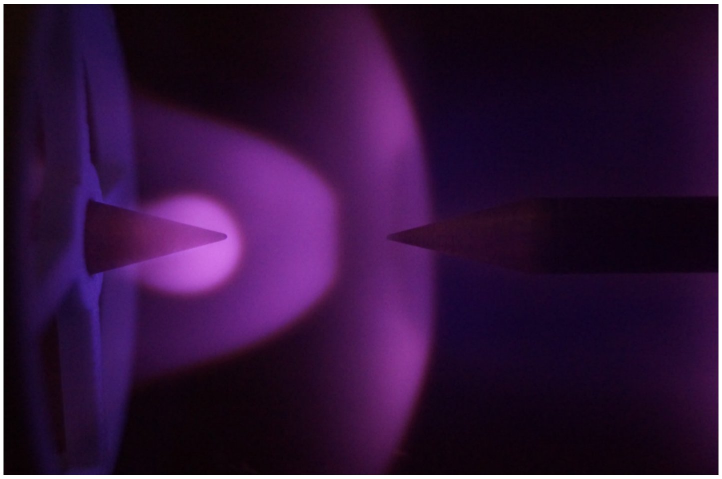


Figure 13 – Initial plasma striation test at electrodes 2cm apart.

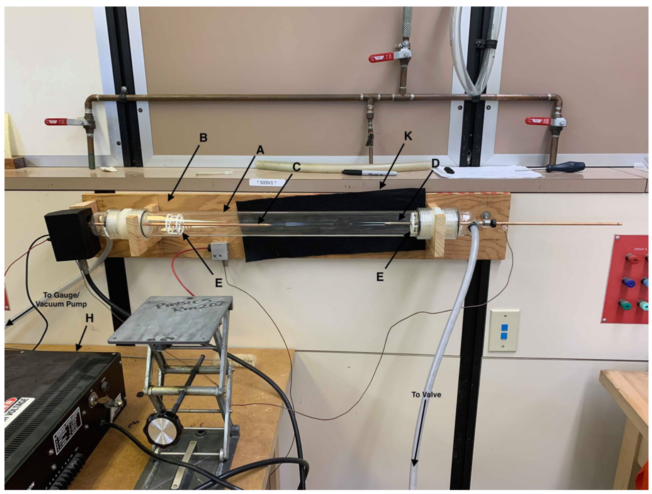


Figure 14 - Labelled vacuum chamber from Table 1.

Figure 15 - Labelled air compressor from Table 1.

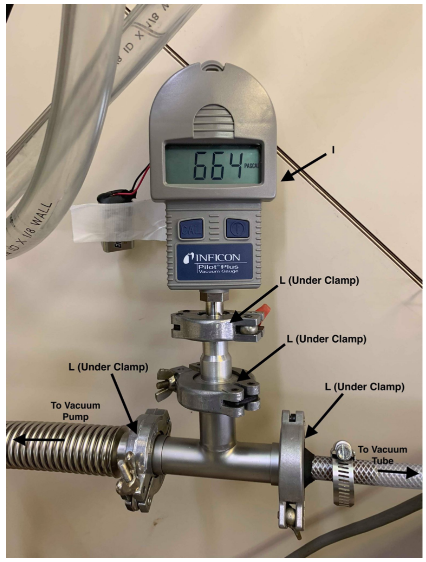


Figure 16 - Labelle Barometer from Table 1.

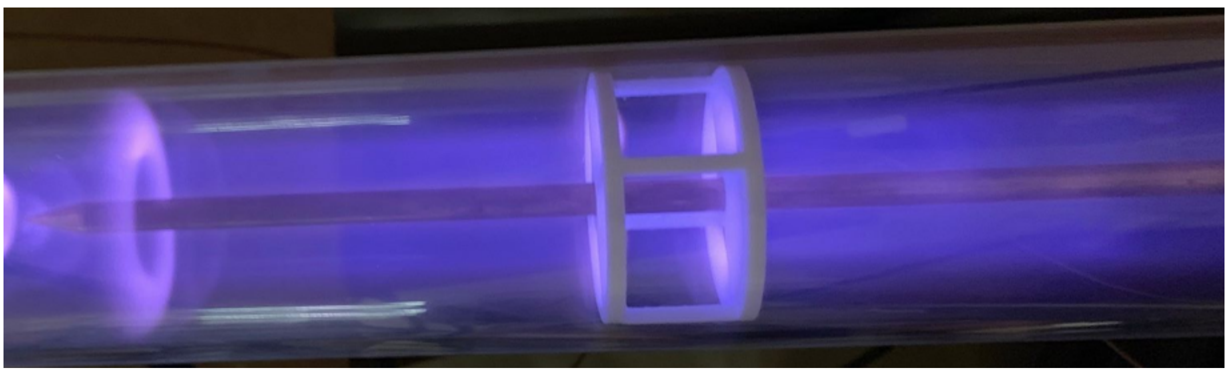
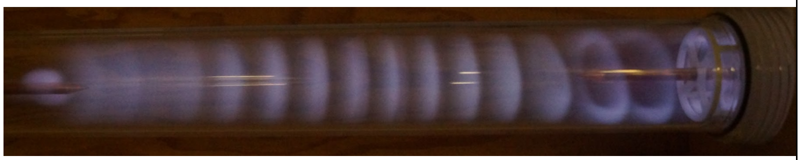
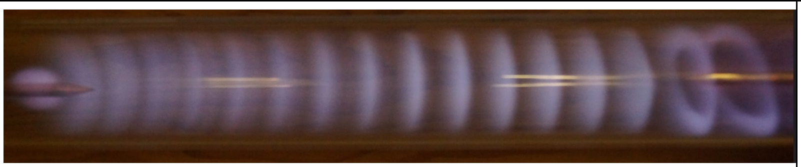
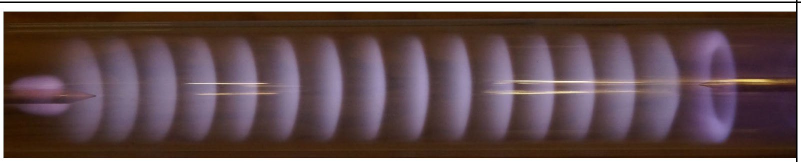
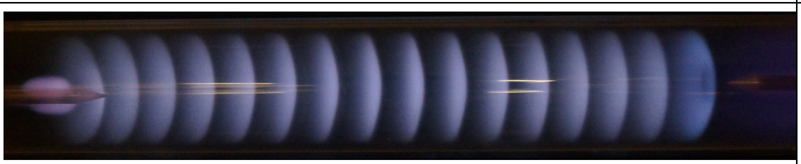
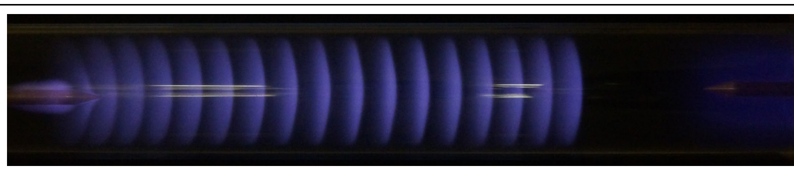
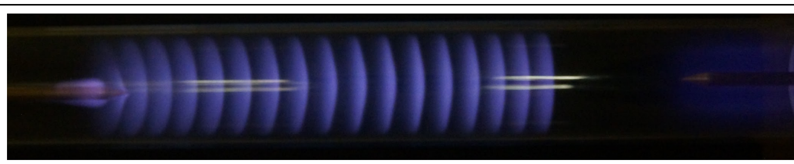
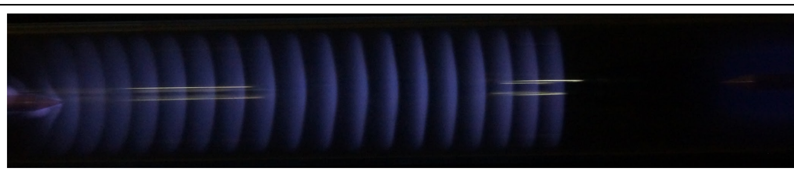
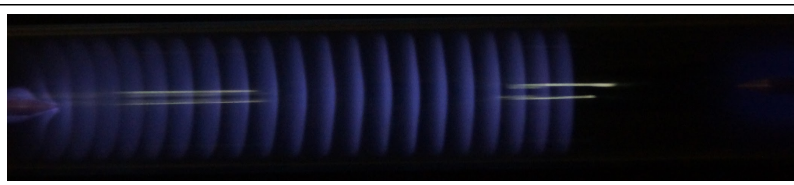
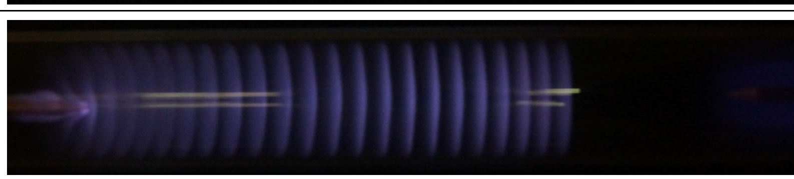
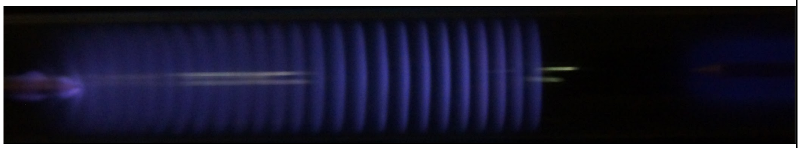
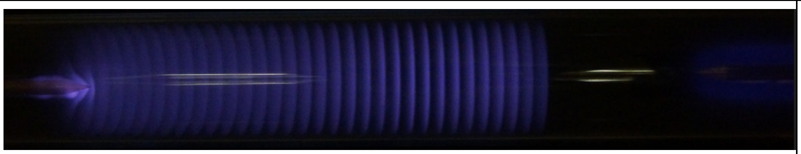
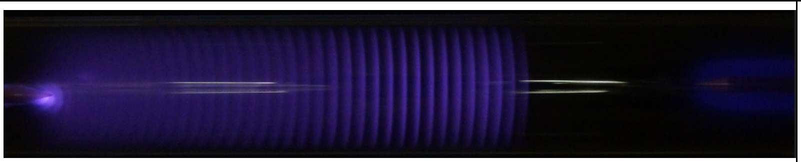
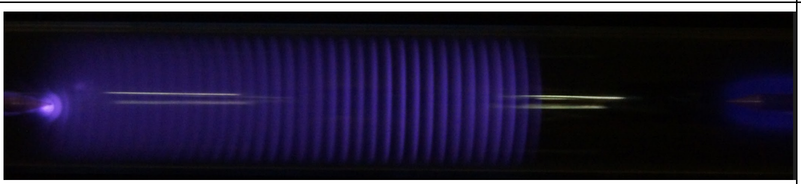
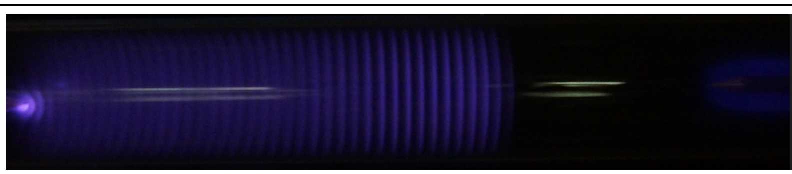
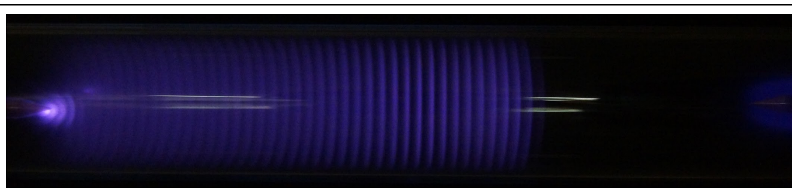
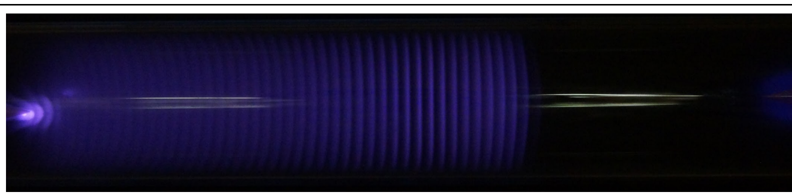
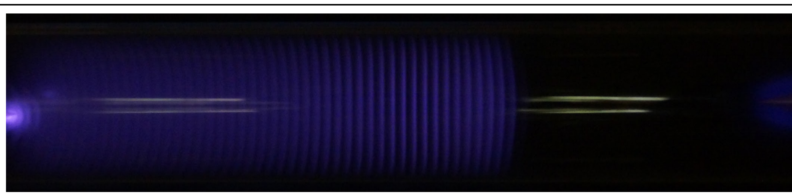
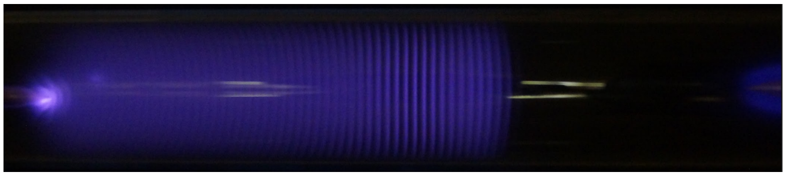
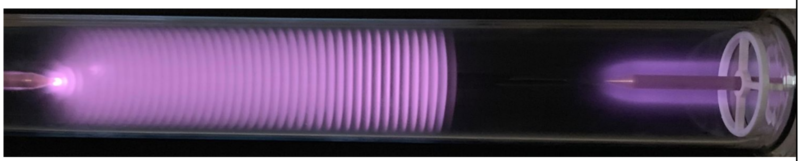
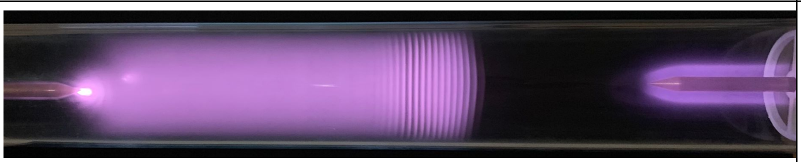
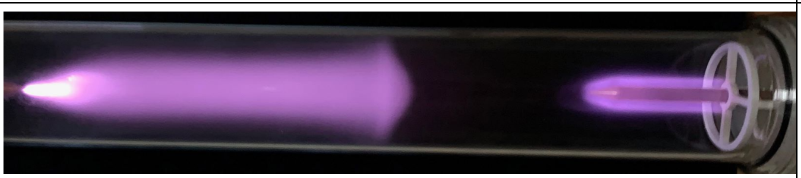
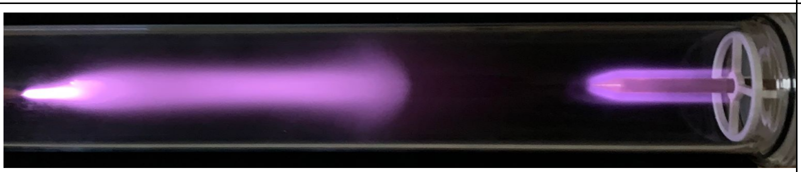
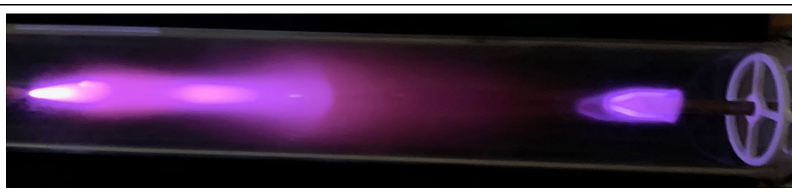
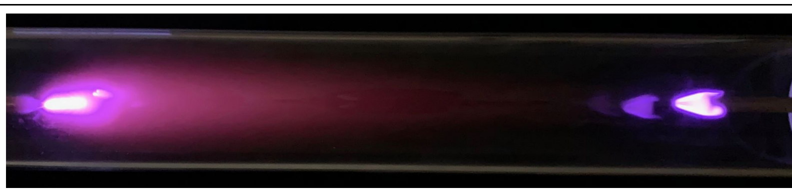
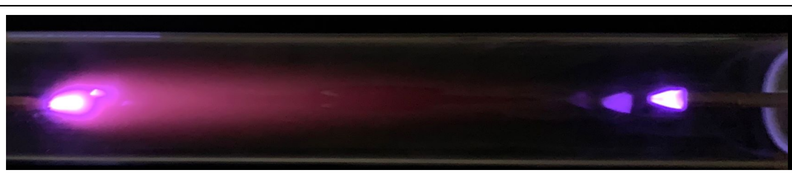


Figure 17 – Negative glow around the cathode end of the vacuum tube.

Table 2 - Qualitative results of plasma striations of increasing pressure from 5Pa to 17 KPa

Pressure (Pa)	Figure at Pressure	Qualitative Observations
5 ±3		Unclear striations with warping around the cathode. Plasma extends to past electrode stand.
15 ±3		Uniform striations with warping around cathode. Plasma extends past electrode stand.
21 ±3		Clear striations with no warping on the cathode.
31 ±3		No more striations past the cathode end.
40 ±3		Decrease in striations size and start of faraday dark space.
50 ±3		Larger faraday dark space than at 40pa with thinner striations.
60 ±3		Same faraday dark space, little change in striations.
70 ±3		Same faraday dark space, little change in striations.
80 ±3		Same faraday dark space, little change in striations.

90 ±3		Same faraday dark space, little change in striations.
100 ±3		Same faraday dark space, Increase in number of striations.
120 ±3		Dark space increasing, increasing in number of striations, decrease in striation size.
140 ±3		Similar observations as 120 Pa
160 ±3		Similar observations as 140 Pa
180 ±3		Similar observations as 160 Pa
200 ±3		Similar observations as 200 Pa
220 ±3		Similar observations as 200 Pa
240 ±3		Similar observations as 220 Pa

260 ±3		Similar observations as 240 Pa
300 ±5		Note: Colour change do to use of IPhone camera rather that DSLR. Similar observations as 260 Pa, vibrations in 50% of striations near anode.
375 ±5		Vibrations in 75% of striations new anode. Negative glow only surrounding cathode.
600 ±5		No visible striations with thinning diameter
670 ±5		No visible striations with thinning diameter
800 ±5		Negative glow only on end of cathode, thinning plasma diameter.
1000 ±20		Similar observations at 800 Pa
1450 ±20		Only small intensity plasma with different colour plasma at cathode.
2440 ±20		Similar observations to 1450 Pa

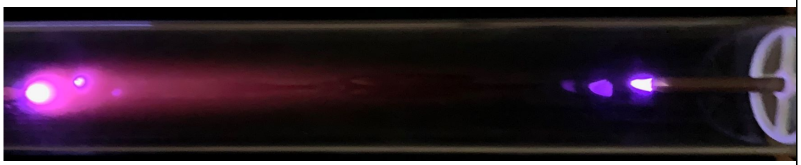
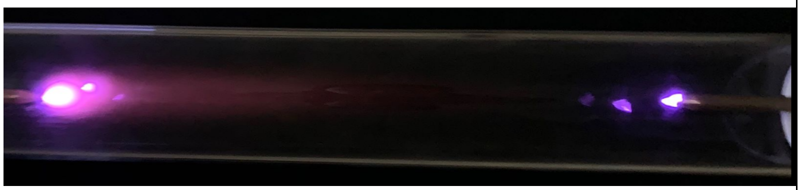
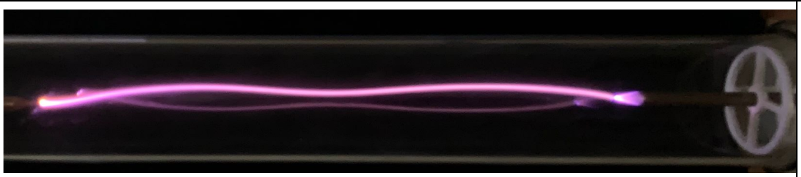
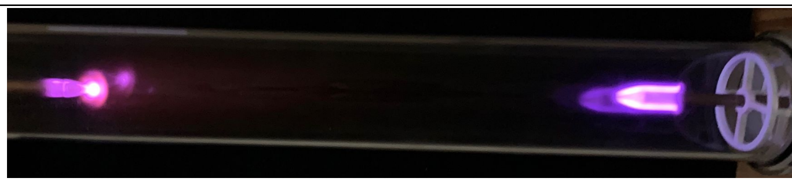
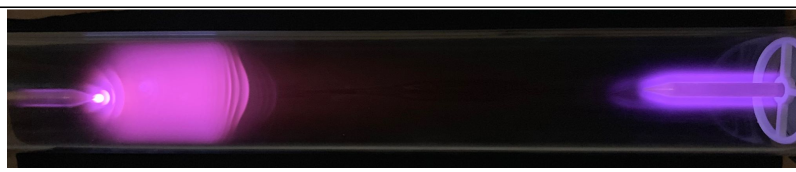
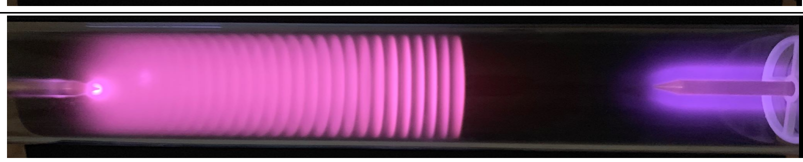
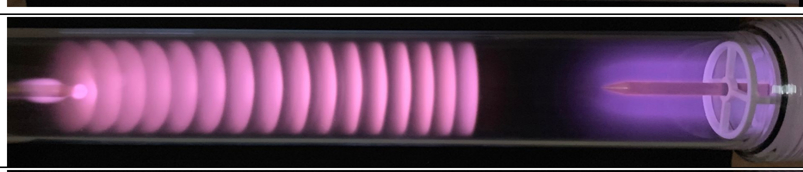
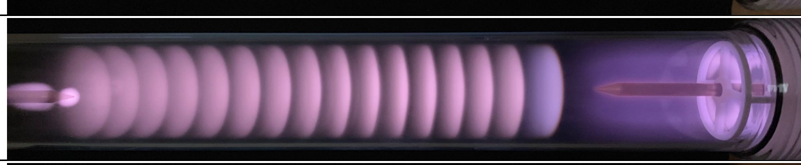
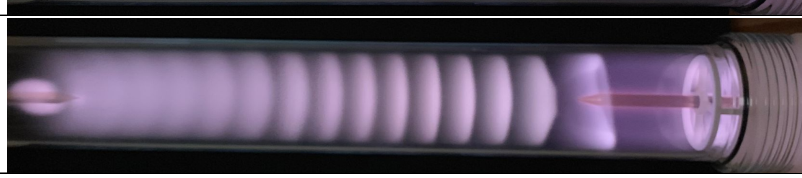
10000 ±100		Similar observations to 2440 Pa
17000 ±100		Similar observations to 10 KPa
Greater than 17 KPa		Arching occurs between electrodes.

Table 3 - Qualitative results for decreasing pressure from 330 Pa to 15 Pa.

Pressure	**Picture**	**Observations**
330 ± 5		Different coloured plasma at cathode end (Violet) and anode end (Pink)
215 ± 2		90% of the striations are vibrating and unclear with differing colours.
115 ± 2		Visible striations with 50% vibrating.
50 ± 2		Clear striations with large negative glow.
32 ± 2		Clear striations with large negative glow
15 ± 2		Slightly unclear striations with warping around cathode end.

Appendix II – Coefficients and Raw Data

Coefficients of Voltage-Pressure relationship:

a_1 = 1060 ± 90

b_1 = 500 ± 100

c_1 = 700 ± 100

a_2 = 270 ± 20

b_2 = -2 ± 4

c_2 = 39 ± 4

Raw Data:

Operating Voltage (kV) ± 0.01	Pressure (Pa) ± 2
0.91	2
0.91	6
0.90	10
0.89	15
0.87	18
0.86	20
0.85	24
0.83	27
0.82	30
0.81	33
0.80	36

0.79	40
0.78	44
0.77	46
0.76	48
0.74	50
0.74	62
0.74	70
0.75	73
0.76	78
0.76	85
0.77	90
0.78	97
0.79	105
0.80	112
0.80	118
0.81	121
0.82	129
0.83	138
0.84	146
0.85	154
0,.86	163

0.87	170
0.88	180
0.89	190
0.90	198
0.91	206
0.92	216
0.93	224
0.94	235
0.95	242
0.96	251