Measuring Breakdown Voltage, Electron Temperature, and Spectral Emission Lines of Argon and Helium Plasma

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We measured the properties of argon and helium plasma at various pressures and voltages, in order to confirm the Paschen curves, electron temperatures according to the Maxwell Distribution, and emission lines of each gas. We first measured the breakdown voltage of each gas at different pressures. Then we inserted a biased Langmuir probe into the plasma and measured the current in the probe as a function of bias voltage, which we used to calculate the temperature of each plasma. Finally, we used a spectrometer to find the emission wavelengths of each plasma, compared them with known emission spectra of helium and argon, and calculated electron temperature from the spectra.

I. INTRODUCTION

Plasma is the fourth fundamental state of matter, after solids, liquids and gases. It consists of a gas with a high ratio of ionized particles to neutral atoms, and it can be created by strong electric fields or intensely high temperatures. Plasma appears naturally in lightning or in stars like our Sun, and can be generated artificially by subjecting a neutral gas to a strong electromagnetic field. Initial studies of plasma began in the 1920s, with Irving Langmuir and his colleagues [1], and it remains a far-reaching and signifiant discipline of study to this day, with applications in fields such as astrophysics and fusion energy research.

Over the course of this experiment, we vary the gas species, the voltage, and the pressure of plasma inside a vacuum in order to probe various physical properties of plasma, and confirm existing laws that describe plasma's behavior. In this particular experiment, we worked with two different gases, argon and helium, to study the behaviors of each gas and see the similarities and differences between their properties.

We conducted three separate experiments to confirm preexisting knowledge of plasma's properties, which will be discussed in further detail in their respective sections. The first experiment is relating to the breakdown voltage of plasma: at various pressures for each gas, we measure the voltage at which the gas is able to sustain an ionization cascade and thus form a plasma. The relationship between breakdown voltage and pressure draws the Paschen curve of that gas. The second experiment involves inducing a voltage on a Langmuir probe inserted in the plasma, and using the resulting IV characteristics on the probe to determine the electron temperature. In the final experiment, we measured spectral lines from argon and helium and used these to determine the electron temperature near the cathode and the anode.

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II. SETUP/APPARATUS

1 **[Vacuum System]** The setup consists of a glass commercial chromatography tube, approximately 120cm in length and 6cm in diameter. The glass tube is encased in a transparent plastic tube for safety, since the glass can be dangerous if broken under vacuum. There are connections at each end for the stainless steel electrodes (approximately 5cm diameter), and the anode is movable along the axis of the chromatography tube. The distance between the diodes for this experiment is 12.5 cm. There are also connections in the tube for the vacuum pump and gas input. Five ports along the top of the glass tube provide potential locations for the Langmuir probe.

The gas is generally contained at pressures ranging from a few mTorr to about 2 Torr. A gas tank is used to leak in a flow of gas in conjunction with the pump to remove gas, together used to maintain the tube at a constant pressure. We use two pressure gauges: the Pirani thermal conductivity gauge, called "Convectron," which measures accurately the pressure range from 2 Torr to atmosphere, and the "Baratron," which measures accurately from 0 to 2 Torr.

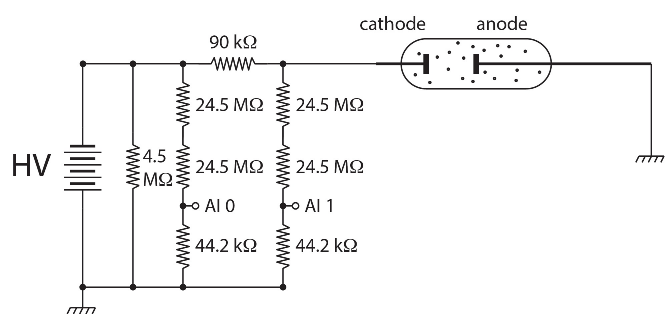


FIG. 1a: The circuit diagram for the plasma tube and voltage measurement, including the High Voltage supply (HV), the Voltmeters (AI0 and AI1), and several resistors in both series and parallel.

2 **[High Voltage Supply]** An Ortec 456 high voltage supply provides an energy to ionize the plasma. A 90

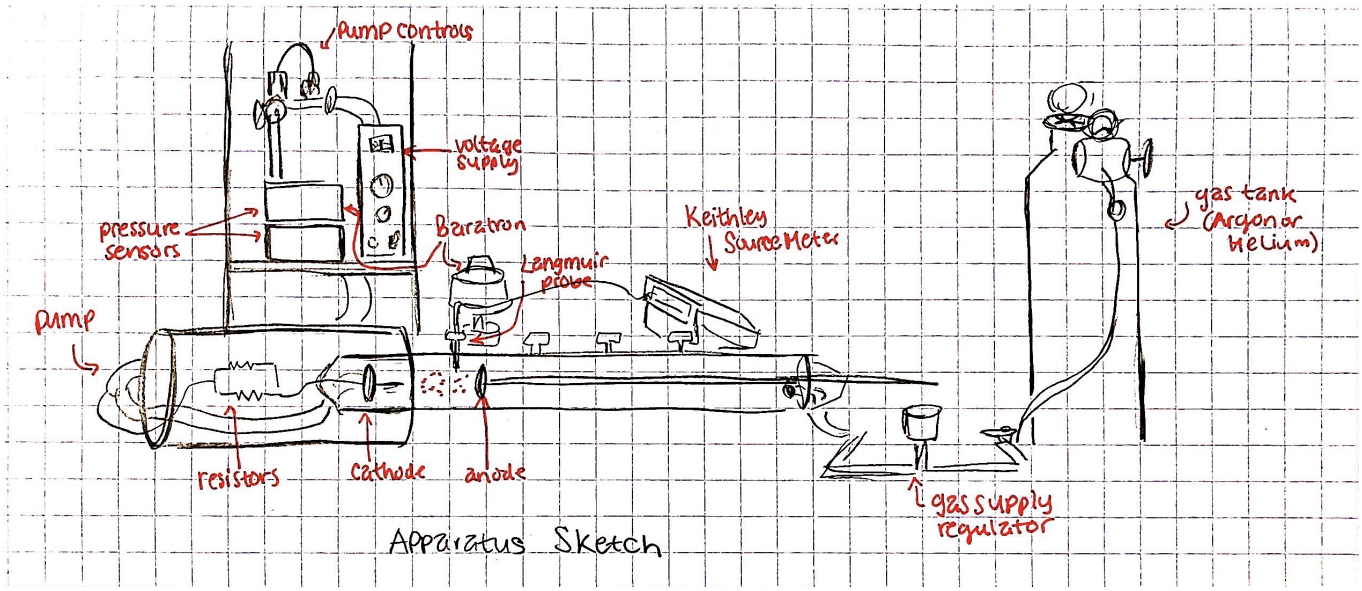


FIG. 1b: A drawn schematic of the full setup, including glass vacuum chamber, pump, pressure gauges and high voltage power supply, and gas supply.

kΩ series resistor limits current to the plasma. Voltage dividers in parallel measure voltage on both sides of the series resistor.

A circuit schematic of the system is included, as well as a drawing of the full setup (see Figure 1).

3 **[LabVIEW programs for Paschen and Langmuir]** Using combinations of AI0 and AI1 from Figure 1a, a LabVIEW program computes the voltage across and the current through the plasma tube. One of the analog outputs from a National Instruments PCIe-6361 X series data acquisition board programs the Ortec 456 output, so the IV curve for the plasma can be recorded automatically in LabVIEW on a computer.

A similar LabVIEW program measures IV curves for a biased probe. The program communicates with a Keithley 2400 SourceMeter, which both provides bias voltage into the Langmuir probe, and measures current flowing to or from the probe.

4 **[Spectrometer]** We used a Silicon Photomultiplier (SiPM) to collect the emission lines from the plasma, which sent this data to an OceanView program which visualized and collected the data. We then compared these lines to known emission lines using the NIST Atomic Spectra Database[2].

III. BREAKDOWN VOLTAGE & PASCHEN CURVES

The breakdown voltage of a gas is the voltage threshold at which a gas can sustain a plasma, and is related to the gas species and pressure. Plasma is generated by applying a current to a dielectric gas. As we increase the voltage, the electric field increases in intensity, accelerating free electrons enough to cause collisions with neutral atoms; these collisions form ions and free up more electrons. At the breakdown voltage, collisions between ions and the cathode free secondary electrons, causing a cascade of ionization which forms and sustains the plasma. For the plasma to be sustained, the mean free path of these liberated electrons (or the distance over which a flux of electrons is reduced via collisions to $1/e$ of its initial value) must be long enough for them to gain the energy needed to ionize more atoms and continue the cascade [3]. The mean free path must also be much smaller than the plasma's container.

These bounds on the mean free path of the electron give us an equation for the breakdown voltage of the gas as a function of its pressure, known as Paschen's law:

$$V_{\text{breakdown}} = \frac{Bpd}{\ln(Apd)\ln(\ln(1+\frac{1}{\gamma})} \tag{1}$$

where A and B are constants depending on the gas species, γ is a property of the electrode material, p is the pressure, and d is the distance between the diodes.

In our experiment, d is 12.5 cm, and γ is 0.02 for our stainless steel cathodes. The table from Fridman and Kennedy [4] gives the A and B values for several gases, including helium and argon (Figure 2).

In order to confirm Paschen's law, we balanced the pressure in the plasma tube at 15, 25, 50, 100, 200, 400, 800, 1200, 1600, and 1800 mTorr. We then slowly increased the voltage across the chamber at each pressure using the LabVIEW software until the breakdown voltage was reached and the ionization cascade formed the plasma. The breakdown voltage was marked by the visual appearance of glowing plasma (as opposed to trans-

Numerical Parameters A and B for Calculation of the Townsend Coefficient α

Gas	A (cm^{-1} $Torr^{-1}$)	B (V cm^{-1} $Torr^{-1}$)
Air	15	365
Ar	12	180
CO_2	20	466
H_2	5	130
H_2O	13	290
He	3	34
Kr	17	240
N_2	10	310
Ne	4	100
Xe	26	350

FIG. 2: Numerical parameters for A and B values of different gases.

parent Ar or He) in the tube, an instantaneous decrease in voltage applied across the chamber by the Ortec 456 High Voltage Supply, and in increase in current across the tube by about two orders of magnitude. After collecting the IV characteristics across the plasma tube using the LabVIEW software, we picked out the breakdown voltages at each pressure manually at the last voltage before the decrease in voltage at which the current increased drastically. The Paschen curves for each gas can be found in Figure 3.

For both helium and argon, we noticed a significant hysteresis in the breakdown voltage at each of the pressures. The breakdown voltage on the way "down" (i.e. switching from plasma to unionized gas) was always considerably higher than the breakdown voltage when turning the plasma on. A figure graphing the hysteresis for argon can be found in Figure 4.

IV. LANGMUIR PROBE & IV CURVE

In order to determine the electron temperature inside a plasma, we can use its current and voltage, measured with a biased probe inserted into it. A Langmuir probe is a bare wire or metal disk inserted into the plasma and biased with a particular voltage to measure the electron current.

Early uses of the probes mistook the potential of the plasma at the location of the probe relative to the anode as the plasma potential. This is not the case, however; an unbiased probe in the plasma will accrue an additional negative charge due to the faster thermal velocity of electrons relative to the ions. The actual potential measured in the probe here is the floating potential V_f, and is smaller than the plasma potential V_p.

When the probe is negatively biased, it collects ions, and when it is positively biased, it collects electrons. As the probe transitions between negative and positive bias, the current and voltage in the probe can be used to give information about the electron density and temperature. If the electron velocities are distributed according to the Maxwell distribution, the temperature can be determined with the following equation:

$$I(V) = I_{\mathrm{es}} e^{-e(V_{\mathrm{plasma}} - \frac{V}{k_B T})} \tag{2}$$

where I_{es} is the electron saturation current, k_B is the Boltzmann constant, and e is the electron charge.

The probe we used is a tungsten wire, 0.032 inch diameter and 0.165 inch length. For each gas, we took a large sweep of voltage across the probe, from -200V to 10 V, to find where the current through the probe flipped from negative to positive. We then narrowed our sweep to the voltage range around the sign flip. Example wide voltage sweeps at 800 mTorr are shown for argon and helium respectively in figures 5a and 6a. Example narrow voltage sweeps at 800 mTorr are shown for argon and helium respectively in figures 5b and 6b.

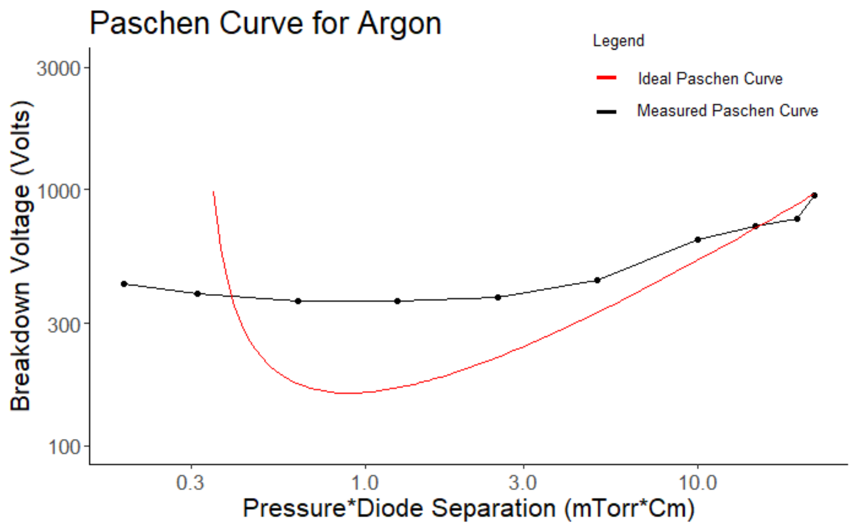
We can use the IV curves taken in the narrow voltage range to calculate the electron temperature of the plasma. By taking the ln of both sides of equation 2, we obtain the following equation:

$$\ln(I(V)) = \ln(I_{\mathrm{es}}) - e(V_{\mathrm{plasma}} - \frac{V}{k_B T}) \tag{3}$$

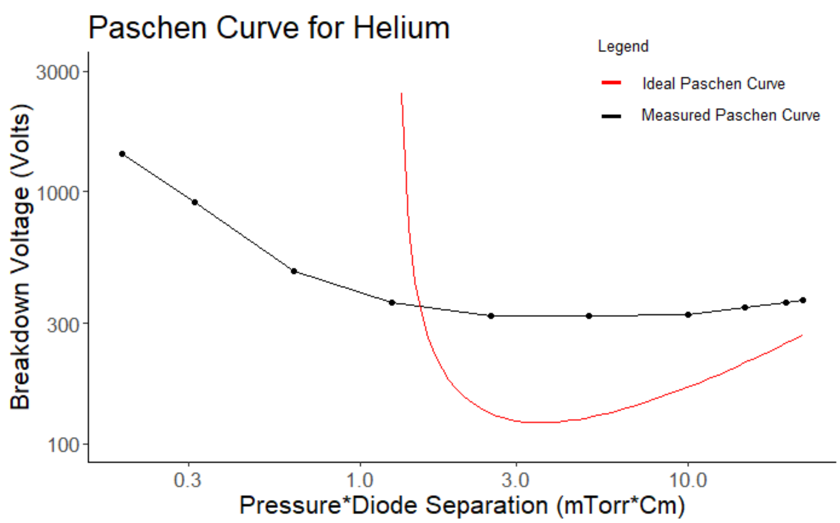
with slope

$$m = \frac{1}{k_B T} \tag{4}$$

The above process was repeated at several pressures for both helium and argon: 25, 50, 100, 200, 400, 800, 1200, 1600, and 1800 mTorr. Ideally, at each of these pressures, the input voltage of the plasma should be kept constant, so that the temperature is only varying as a function of pressure and not voltage. However, we were not aware of this when taking the IV curves for argon, and for the various pressures measured, the plasma was kept at different voltages for each of the pressures (anywhere between -500 V and -1000V). For helium, though, we were able to keep all of the pressures at the same voltage (-600V) save for two: The plasma at 25 mTorr, which had a much higher breakdown voltage, was kept at -1500V, and the plasma at 1800 mTorr was kept at -400V, since at higher voltages, it would cause the circuit to short out during our voltage sweep. Example linear fits of the Langmuir probe IV curve based on equation 3 are shown for argon and helium respectively in figures 5c and 6c, both at 800 mTorr. The temperatures found from those linear fits for all pressures are shown in figure 7.



(a)



(b)

FIG. 3: The Paschen curves for argon (3a) and helium (3b), graphed on logarithmic axes, comparing the breakdown voltage of each gas at various pressures with a constant diode separation of 12.5 cm. The data is compared with idealized Paschen curves for each gas as derived from Paschen's law (Equation 1).

V. SPECTROSCOPY

We analyzed the emission spectrum of the plasma in the range 350 nm to 1000 nm. The emission spectrum represents the most common energies at which the atoms of the gases release photons due to electrons moving from a higher energy orbital to a lower energy orbital. Since there are limited possible orbital transitions for electrons of a given element, each element has a characteristic set of possible emission lines at specific wavelengths in its spectrum.

In order to collect this data, we clamped the SiPM against the plastic tube that surrounds the glass plasma chamber in a darkened room. To maximize the accuracy of the data, we chose a pressure and voltage for each gas which caused the brightest possible plasma to form; that way, the light from the plasma would be at the greatest possible intensity relative to the ambient light in the room. We measured spectra at 200 mTorr and 500 volts for argon, and 200 mTorr and 700 volts for helium. We took two spectra for each gas in those conditions; one above the cathode, and one above the anode. The SiPM recorded the intensity in counts at each whole number wavelength between 350 and 1000 nm and sent that data to the OceanView software on a computer. Those four spectra are pictured in figures 8. Emission lines appeared as the peaks of the graph; the wavelengths at which intensity was the highest.

We then compared these results with the known spectral emission lines of helium and argon as given on the NIST Atomic Spectra Database. Not all emission lines matched; the cathodes tended to have higher intensity and more corresponding lines in the lower wavelength domain and therefore were hotter and bluer. The anodes tended to have higher intensity and more corresponding lines in the higher wavelength domain and therefore were cooler and redder.

The paper by Wissel and Zwicker et al[5] provides a method for finding the electron temperature using the emission spectrum of a plasma:

$$\ln(\frac{\lambda_{ik} I_{ik}}{g_k A_{ik}}) = -\frac{E_k}{k_B T_e} \tag{5}$$

Where $\mathrm{I_{ik}}$ is the observed intensity of a spectral line, λ_{ki} is the observed wavelength, $\mathrm{A_{ki}}$ is the transition probability for spontaneous emission a wavelength, $\mathrm{g_k}$ is the quantum degeneracy factor for a wavelength, $\mathrm{E_k}$ is the upper energy limit for wavelength, $\mathrm{T_e}$ is the electron temperature, and k is the Boltzmann constant. The NIST Atomic Spectra Database provides values for $\mathrm{A_{ki}}$, $\mathrm{g_k}$, and $\mathrm{E_k}$ at each of the emission wavelengths for argon and helium. So, we plugged those in at wavelengths corresponding with our experimental emission wavelengths and intensities yields a function which is linear in $\mathrm{E_k}$ with a slope of $\mathrm{-1/k_BT_e}$. Taking the slope from a linear fit of the points found from equation 5, multiplying out the Boltzmann constant, and taking the inverse thus yields the electron temperature. This process is pictured in figures 9. We found an electron temperature of 5358 K for the argon anode, 7704 K for the argon cathode, 1908 K for the helium anode, and 6223 K for the helium cathode.

VI. CONCLUSIONS

A. Paschen Curves

For both helium and argon, we found a relationship between the pressure and breakdown voltage of a gas consistent with Paschen's law. Both of our Paschen curves matched the idealized Paschen's law more closely at the higher pressures (above 200 mTorr), but each still took on the general trend of breakdown voltage first decreasing to a minimum with pressure, and then increasing again with higher pressure.

As mentioned before, there was significant hysteresis in the breakdown voltage. Specifically, we noticed that the breakdown voltage wherein the voltage was rising and plasma formed for the first time was always higher than the breakdown voltage wherein the voltage was falling and plasma disappeared. In addition, this difference became more pronounced at higher pressures. Figure 4 below shows this hysteresis.

We speculated that the cause of this hysteresis is due to inertia. For the ionization cascade to begin and form the plasma as the voltage rises, it requires a certain voltage to accelerate the particles enough to begin the cascade. As the voltage falls, the ionization cascade needs less energy and therefore lower voltage to sustain itself than to start because the particles are already in motion. The collective inertial energy of the particles in motion maintains the cascade, lowering the requirement for external acceleration. As an analogy, consider accelerating a block on a frictional surface. The block needs a certain amount of force to begin its motion, due to the need to overcome its inertia. However, it needs a smaller amount of force to continue its motion, due to the inertia it has gained.

B. IV Curves/Temperature

After converting the IV curve around the current sign flip to a graph on logarithmic axes, we were able to take the slope of these graphs and use them to find the electron temperature of the plasma as a function of pressure. The temperatures we found were generally on the order of 10^4K, or a few eV. Instead of the ion current saturating and plateauing like the idealized graphs in [1], however, we saw that the electron current continued to increase. This is likely due to the effective surface area of the Langmuir probe increasing from accumulating ions: the higher the voltage applied to the Langmuir probe, the more passing charges are attracted by the probe, and the further the "saturation" current increases.

Due to our systematic error when collecting argon's data, varying the voltage too drastically as well as the temperature, we are unable to draw any substantial conclusions from the relationship between temperature and pressure from the argon data. However, the behavior of the helium curve is a little more illuminating: it seems to roughly obey a similar shape to the Paschen (or pressure vs voltage) curve, the temperature of the helium increasing at both the higher and the lower extremes of pressure. This behavior is particularly exemplified at pressures around and lower than 500mTorr. This is, however, only speculation.

C. Spectroscopy

We found spectra with emission lines that matched the known lines of helium and argon. Due to the different intensities in the cooler and hotter wavelengths at the cathode and anode, we can hypothesize the different temperatures at those locations – for both gases, the bluer end of the spectrum was more intense at the cathode, thus implying a higher temperature, and the reverse was true for the anodes. This implication was confirmed in our calculations of the temperature at the cathode and anode.

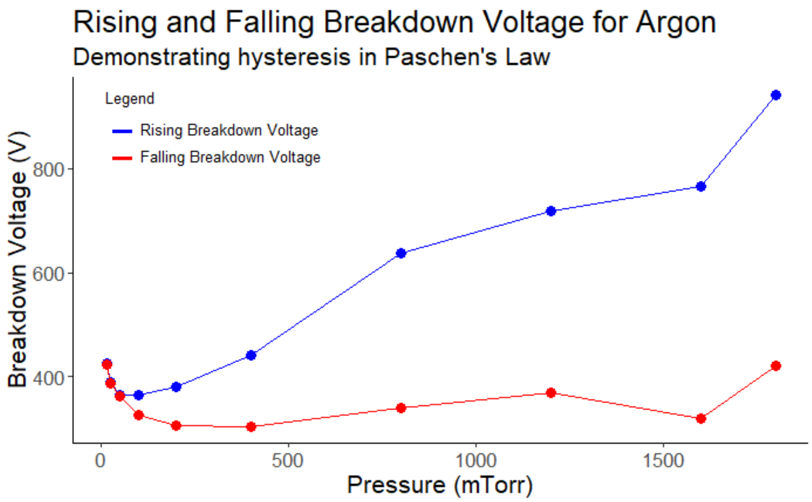


FIG. 4: The upwards breakdown voltage of argon compared with the downwards breakdown voltage, or the hysteresis of the breakdown voltage.

VII. PHOTOS

Just for fun! See Figure 10.

VIII. ACKNOWLEDGMENTS

Abstract: Sahar
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Breakdown Voltage/Paschen Curve: Sahar
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Spectroscopy: Em
Discussion and Conclusions: Sahar
Coding Graphs and Linear Fits: Em
Photos: Sahar
Accidentally making baby lightning: Em and Sahar
Confusing 4 PhD.'s at once: Sahar and Em
The 4 PhD.'s in question: Joe Peidle, Matteo Mitrano, Jenny Hoffman, Jieping Fang

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[5] S. A. Wissel, A. Zwicker, J. Ross, and S. Gershman, The use of dc glow discharges as undergraduate educational tools, American Journal of Physics **81**, 10.1119/1.4811435 (2013).

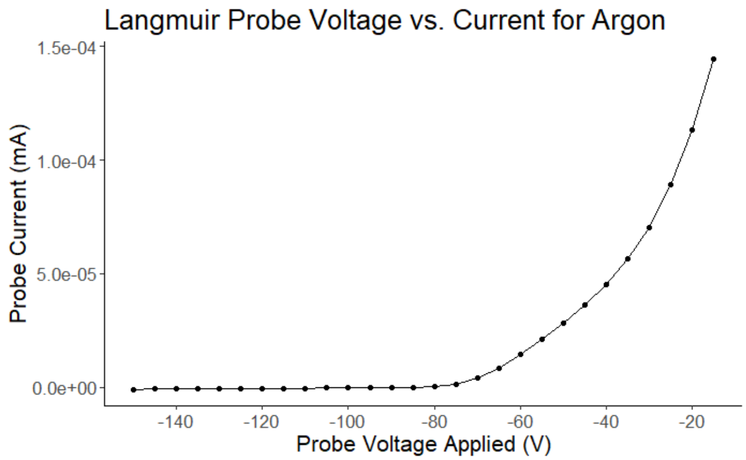

FIG. 5a: IV curve of Langmuir probe inserted into argon plasma at 800 mTorr and 900 volts. Shows a large range of voltages from -150 volts to -20 volts.

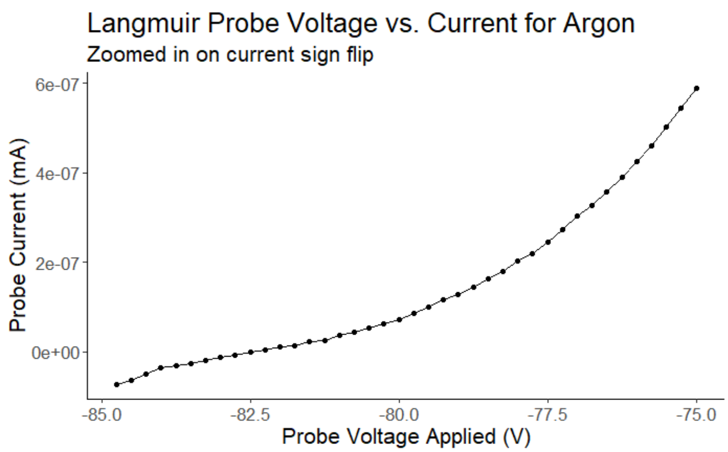

FIG. 5b: IV curve of Langmuir probe inserted into argon plasma at 800 mTorr and 900 volts. Shows the voltage range from -85 to -75 in which the current switches from a negative sign to a positive sign.

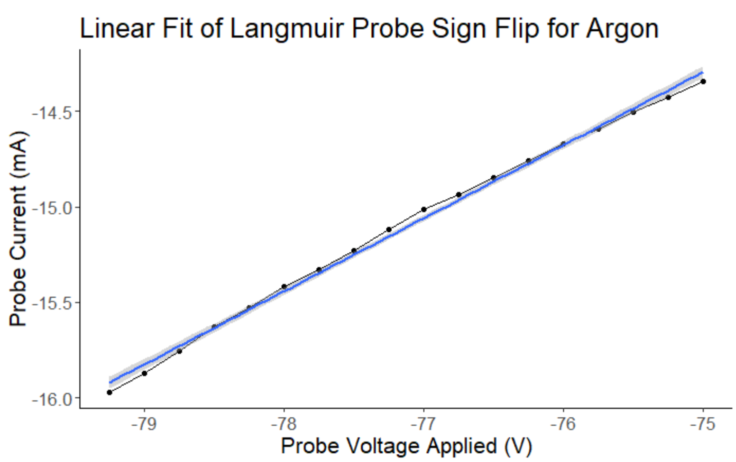

FIG. 5c: IV curve of Langmuir probe inserted into argon plasma at 800 mTorr and 900 volts. The probe current (vertical) axis is scaled logarithmically so that the slope of the linear fit in blue approximates $1/k_BT$ according to equations 3 and 4. Multiplying by the Boltzmann constant and taking the inverse yields a temperature of 26,583 K. Voltages with negative current are excluded since the logarithm of a negative number does not exist.

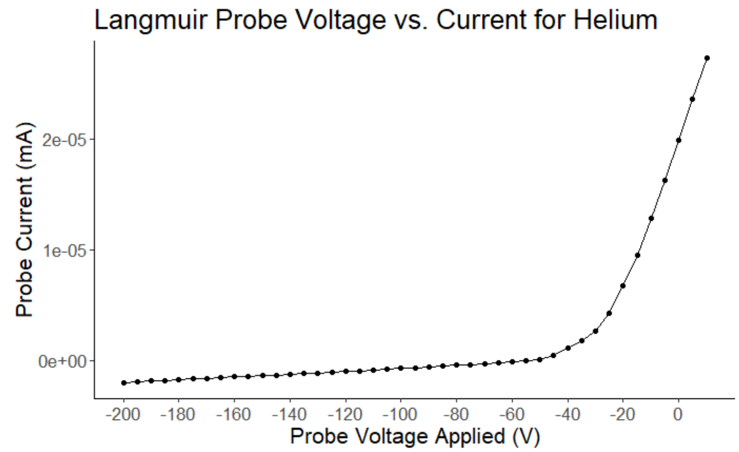

FIG. 6a: IV curve of Langmuir probe inserted into helium plasma at 800 mTorr and 600 volts. Shows a large range of voltages from -200 volts to 20 volts.

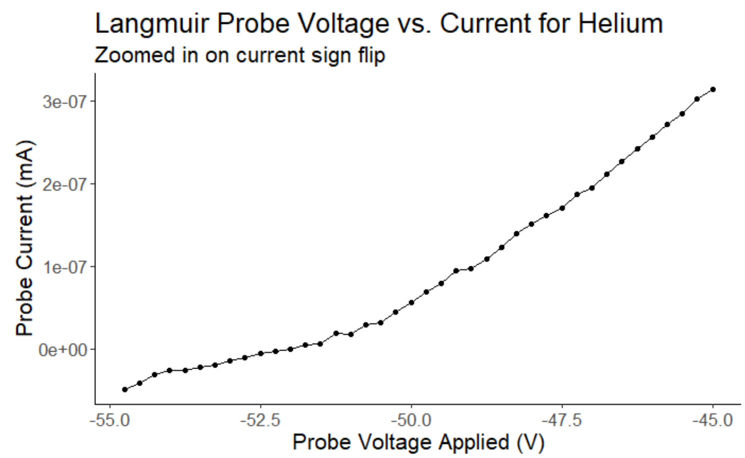

FIG. 6b: IV curve of Langmuir probe inserted into helium plasma at 800 mTorr and 960 volts. Shows the voltage range from -55 to -45 in which the current switches from a negative sign to a positive sign.

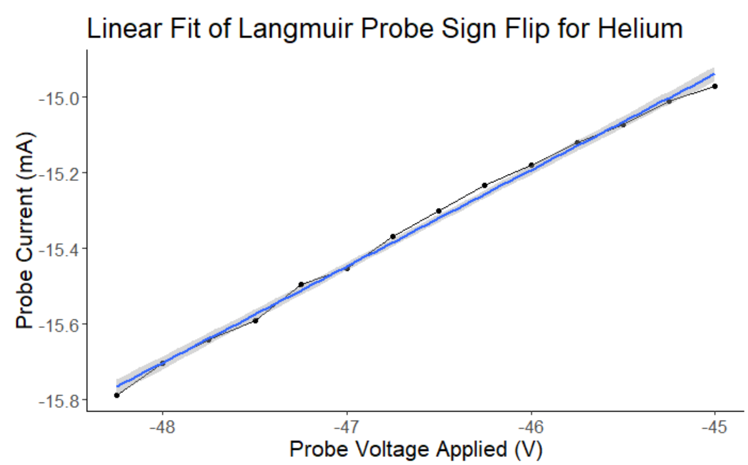

FIG. 6c: IV curve of Langmuir probe inserted into argon plasma at 800 mTorr and 600 volts. The probe current (vertical) axis is scaled logarithmically so that the slope of the linear fit in blue approximates $1/k_B T$ according to equations 3 and 4. Multiplying by the Boltzmann constant and taking the inverse yields a temperature of 35,727 K. Voltages with negative current are excluded since the logarithm of a negative number does not exist.

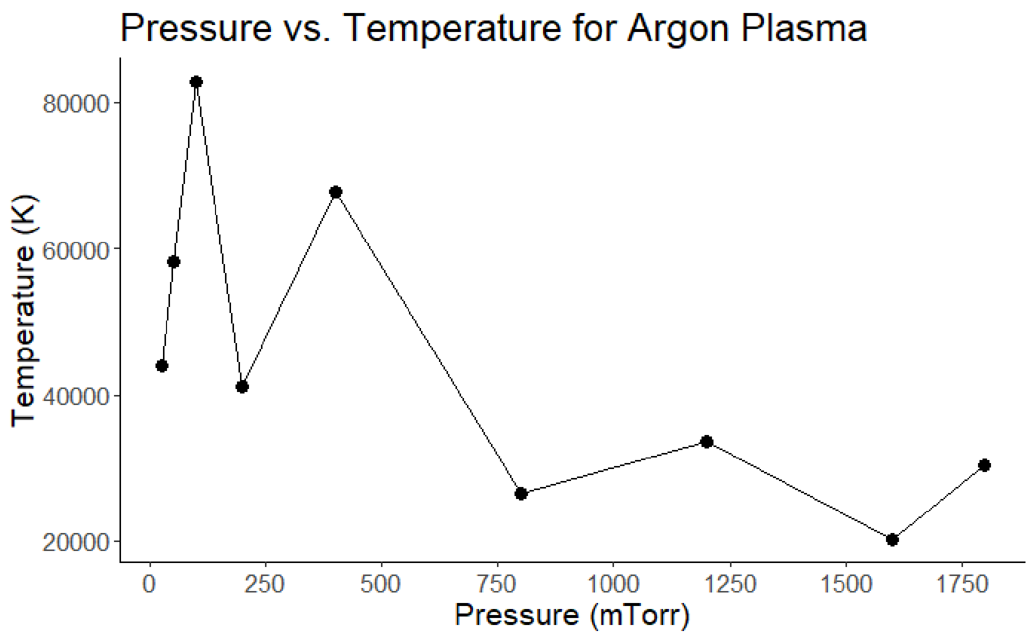

FIG. 7a: Each point represents the temperature of argon plasma calculated at each pressure using equations 3 and 4. As in figure 5c, the slope of the linear fit of the IV curve of the Langmuir probe with a logarithmic probe current axis yields the temperature of the plasma. Temperatures were found to be in the order of 10^4 Kelvin, which is one order of magnitude higher than expected.

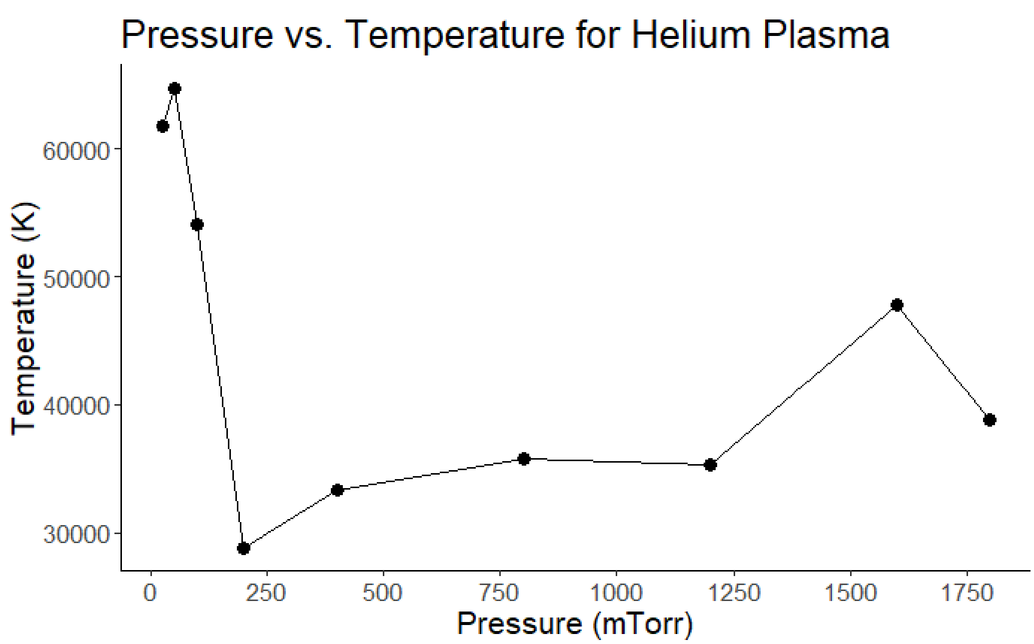

FIG. 7b: Each point represents the temperature of helium plasma calculated at each pressure using equations 3 and 4. As in figure 6c, the slope of the linear fit of the IV curve of the Langmuir probe with a logarithmic probe current axis yields the temperature of the plasma. Temperatures were found to be in the order of 10^4 Kelvin, which is one order of magnitude higher than expected.

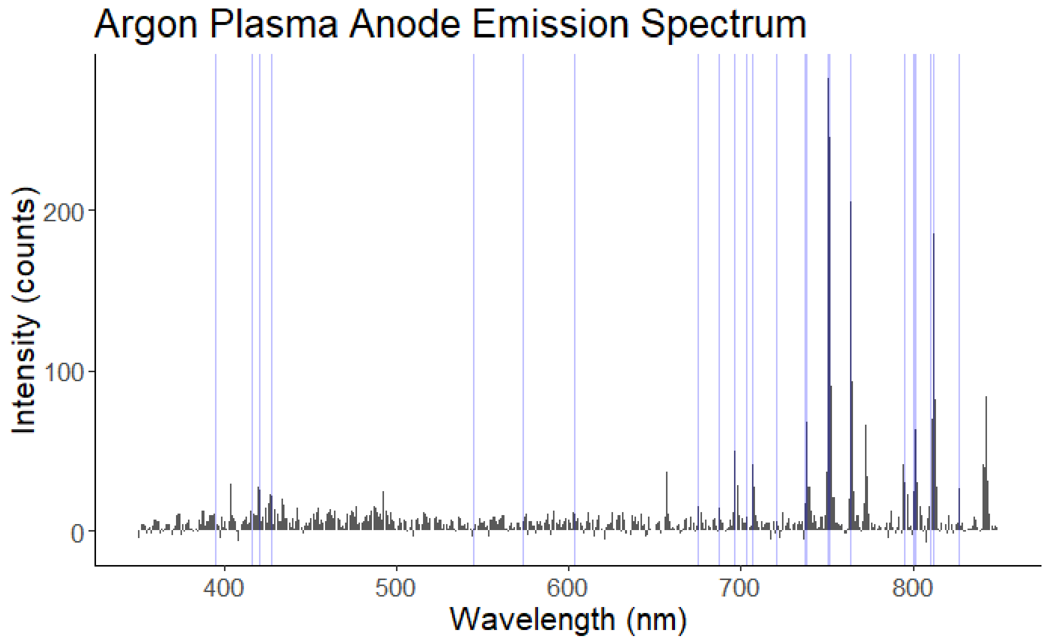

FIG. 8a: Emission spectrum from anode of argon plasma at 200 mTorr and 500 volts. Blue lines represent the known spectral emission lines for argon. The anode shows higher intensities in the higher wavelength domain, meaning it is cooler and redder than the cathode.

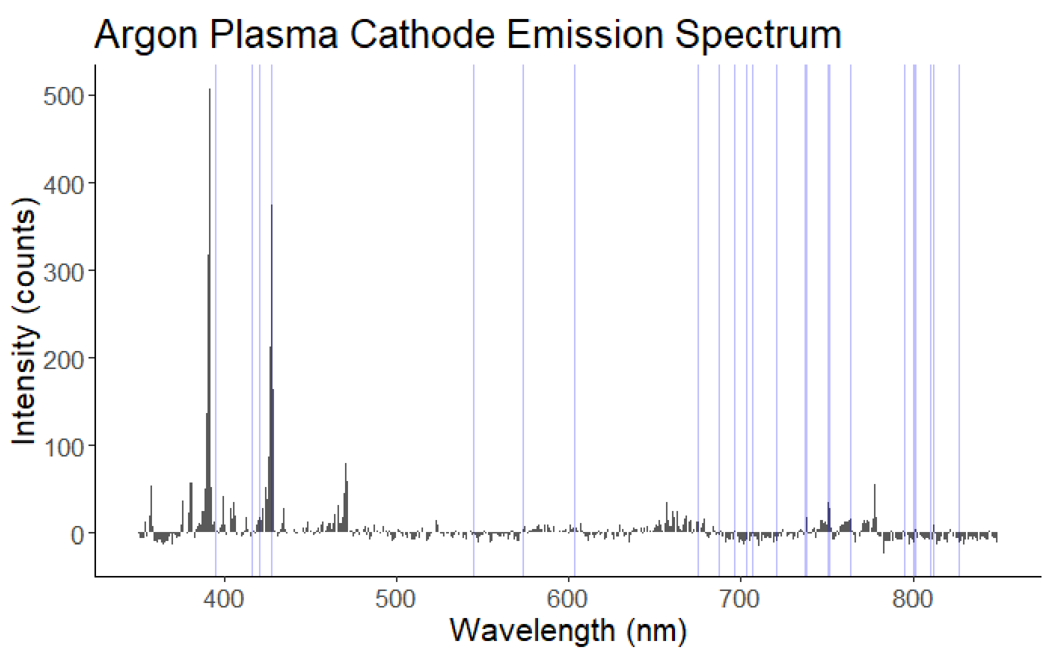

FIG. 8b: Emission spectrum from cathode of argon plasma at 200 mTorr and 500 volts. Blue lines represent the known spectral emission lines for argon. The cathode shows higher intensities in the lower wavelength domain, meaning it is hotter and bluer than the anode.

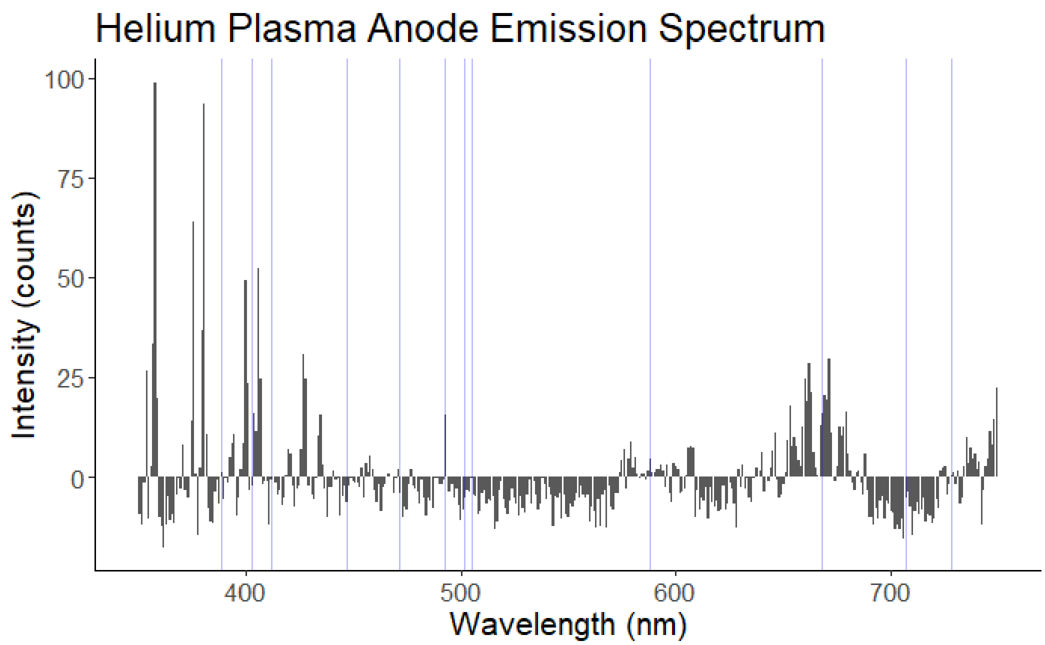

FIG. 8c: Emission spectrum from anode of helium plasma at 200 mTorr and 700 volts. Blue lines represent the known spectral emission lines for helium. The anode shows higher intensities in the higher wavelength domain, meaning it is cooler and redder than the cathode.

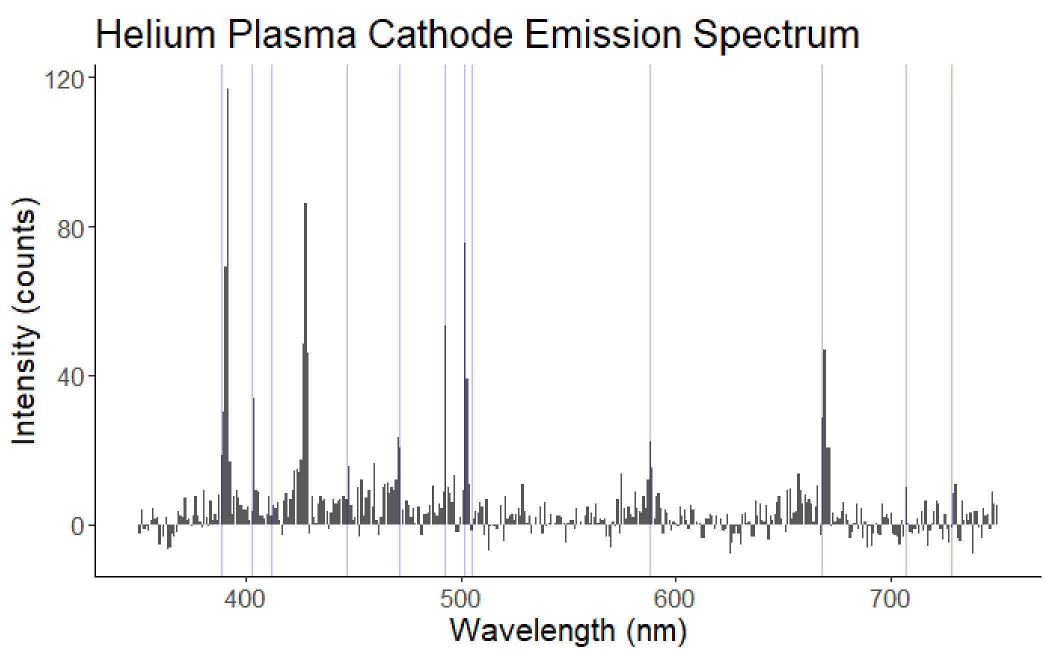

FIG. 8d: Emission spectrum from cathode of helium plasma at 200 mTorr and 700 volts. Blue lines represent the known spectral emission lines for helium. The cathode shows higher intensities in the lower wavelength domain, meaning it is hotter and bluer than the anode.

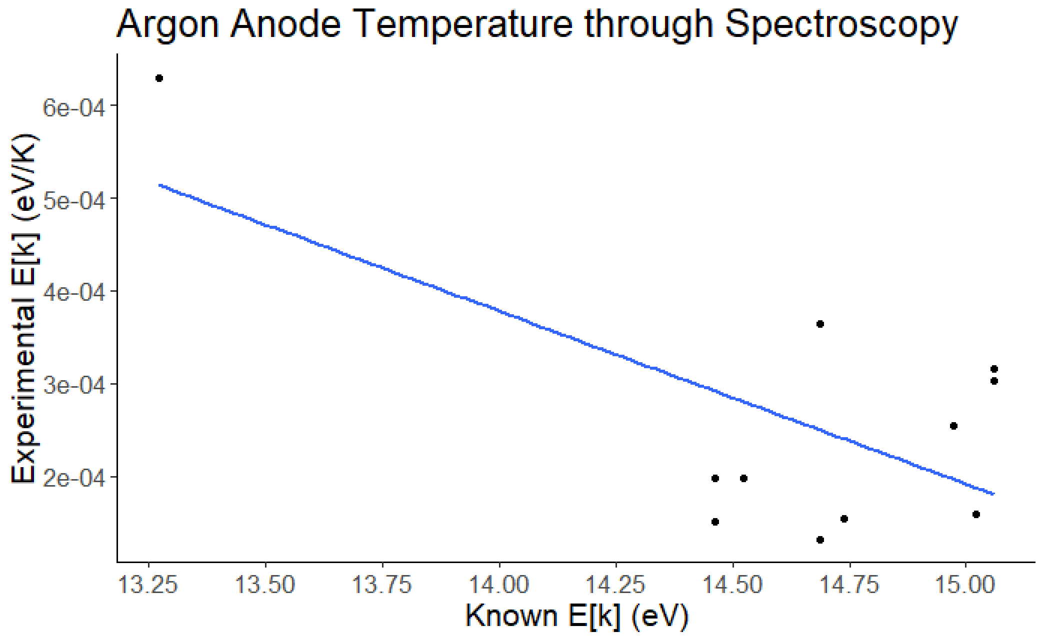

FIG. 9a: Points on the graph are found from the argon anode spectrum in figure 8a using equation 5 to compare the experimentally found energy to the known energy of argon at emission wavelengths. The blue line is a linear fit of those points, and its slope is equal to $-1/kT_e$, which yields an electron temperature of 5358 K or 0.461 eV.

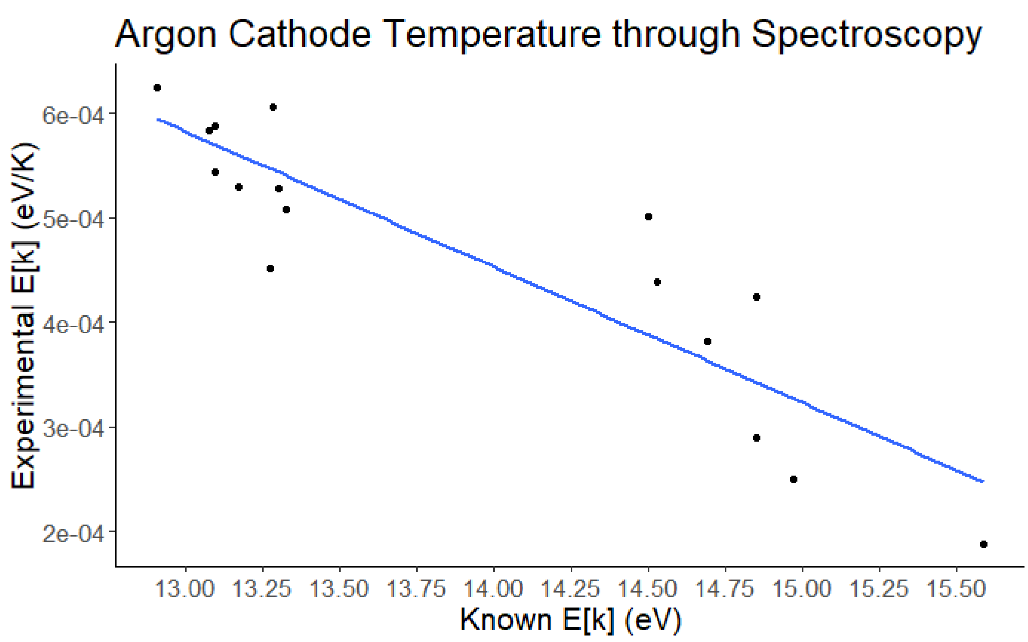

FIG. 9b: Points on the graph are found from the argon cathode spectrum in figure 8b using equation 5 to compare the experimentally found energy to the known energy of argon at emission wavelengths. The blue line is a linear fit of those points, and its slope is equal to $-1/kT_e$, which yields an electron temperature of 7704 K or 0.664 eV.

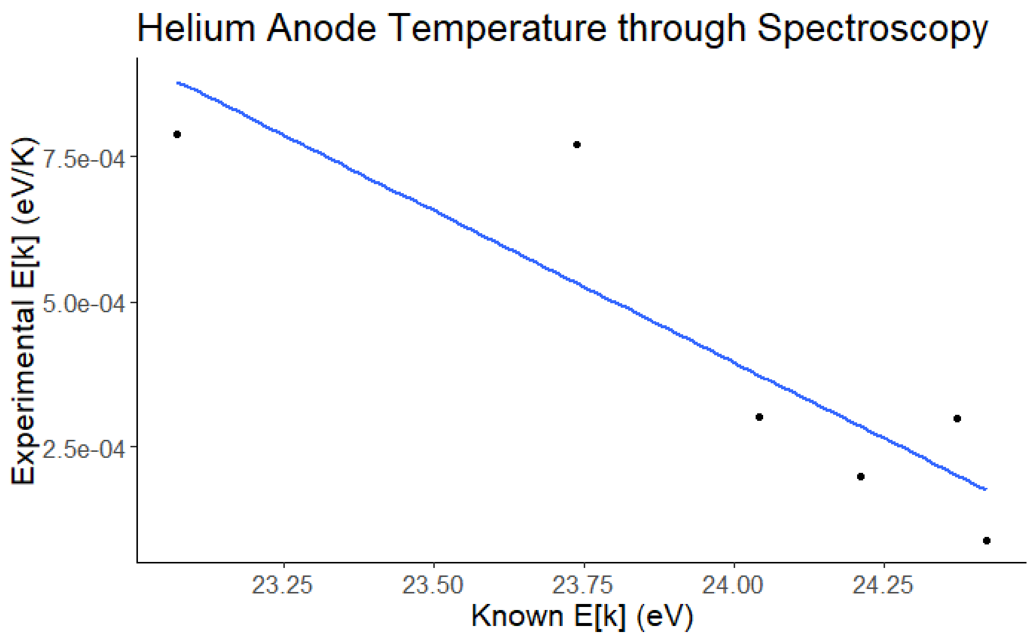

FIG. 9c: Points on the graph are found from the helium anode spectrum in figure 8c using equation 5 to compare the experimentally found energy to the known energy of helium at emission wavelengths. The blue line is a linear fit of those points, and its slope is equal to -1/kT_e, which yields an electron temperature of 1908 K or 0.164 eV. Due to a lack of experimental intensity peaks which matched known emission lines on the NIST Atomic Spectra Database, only 6 points are shown. The linear fit here is therefore unreliable.

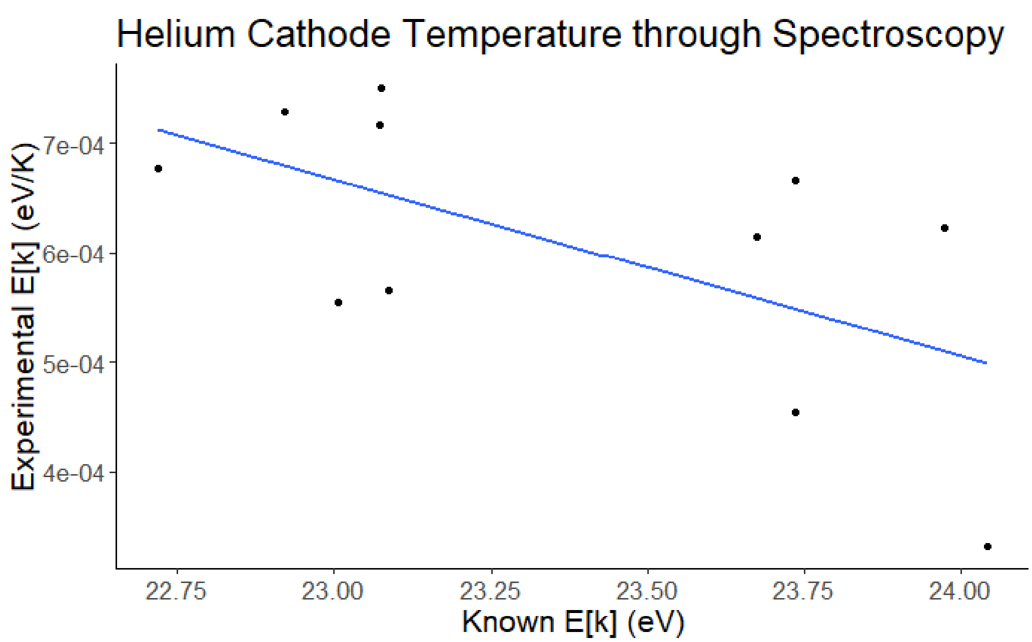

FIG. 9d: Points on the graph are found from the helium cathode spectrum in figure 8d using equation 5 to compare the experimentally found energy to the known energy of helium at emission wavelengths. The blue line is a linear fit of those points, and its slope is equal to -1/kT_e, which yields an electron temperature of 6223 K or 0.536 eV.

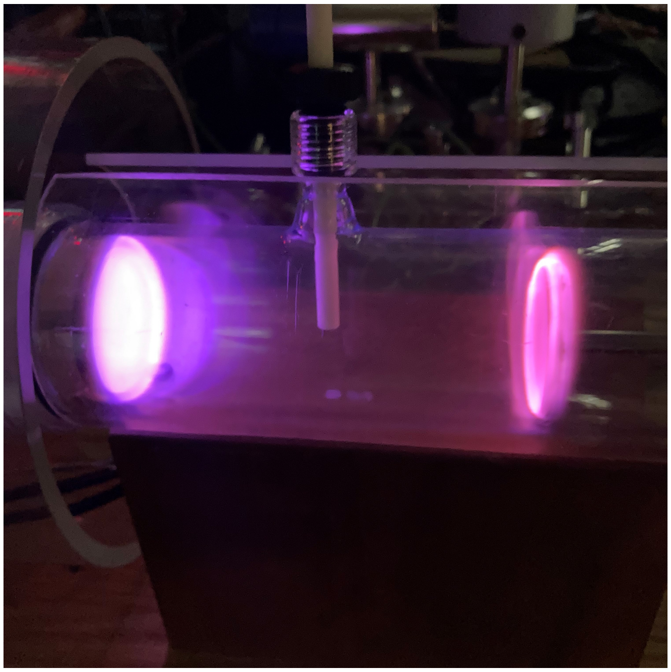

FIG. 10a: A photo of the argon plasma.

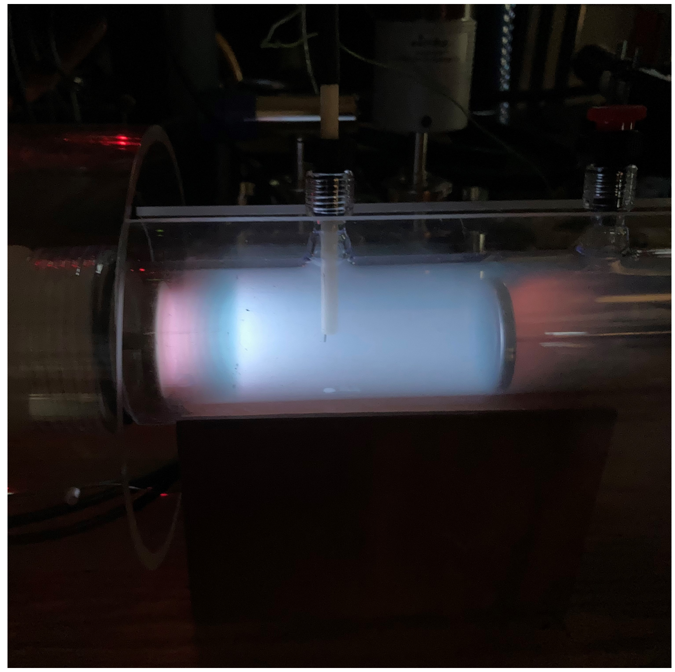

FIG. 10b: A photo of the helium plasma.

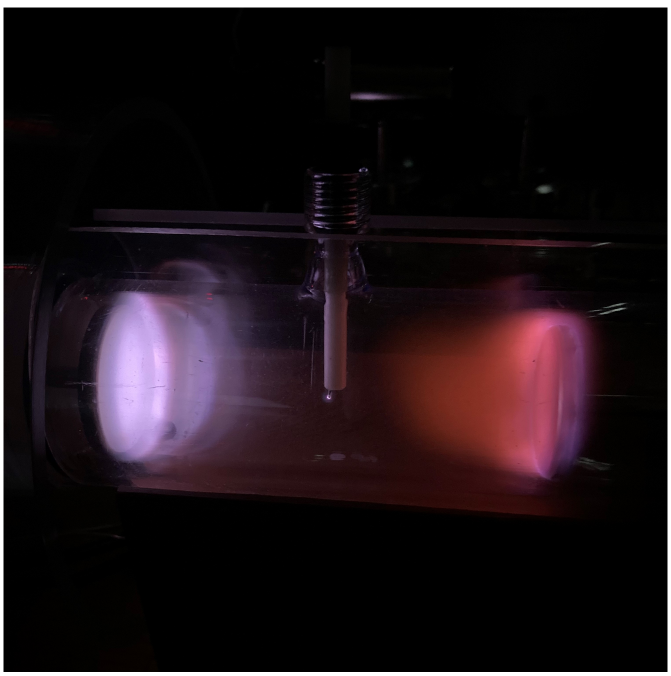

FIG. 10c: A photo of the helium plasma at a low voltage and pressure.

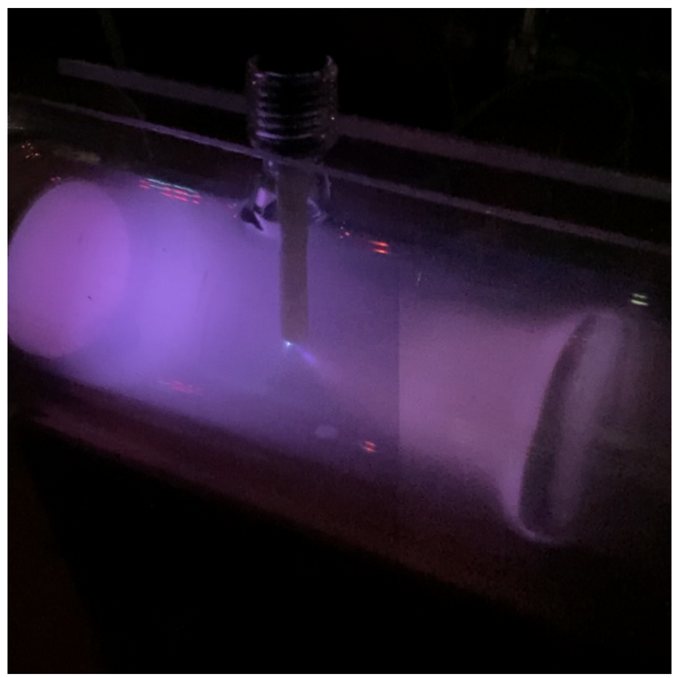

FIG. 10d: A photo of the accidentally-created "baby lightning" in argon plasma, at low pressure/high voltage. Likely happening because the probe was biased with a very negative voltage in an area of the plasma that was close to ground, and so is creating its own cathode and therefore its own plasma (baby lightning).