Hall Effect in a Plasma

Physics 111B: Advanced Experimentation Laboratory

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Abstract

We investigated the Hall effect in a plasma using a glow discharge tube. By measuring the Hall voltage under varying currents, magnetic fields, and gas pressures, we calculated the electron density and drift velocity within the plasma. Our results showed a linear relationship between the Hall voltage and magnetic field strength across different pressures. The calculated electron drift velocities and densities matched typical values found in low-pressure plasmas. However, we noted that the electron mobility and collision cross-section were higher than expected, indicating possible measurement errors or simplifications in our calculations. This experiment provided practical insights into plasma behavior and reinforced key concepts in physics.

Introduction

The purpose of this lab is to investigate the Hall effect in a plasma, specifically within a glow discharge tube, and to measure the Hall voltage as it varies with current, magnetic field strength, and gas pressure. The data collected will be used to determine key parameters such as electron density and drift velocity. This experiment provides an introduction to plasma physics and reinforces important concepts from electricity and magnetism, atomic physics, and thermal physics.

In this lab, we will use a combination of electrical and magnetic fields to observe the Hall effect, which occurs when a voltage develops across a conductor due to charged particles moving in a magnetic field. We will also apply plasma discharge techniques, such as controlling gas flow and pressure, and measuring discharge current and voltage. Tools like an oscilloscope and a gaussmeter will help monitor plasma stability and measure the magnetic field strength.

Historically, Edwin Hall first discovered the Hall effect in 1879. The effect is now widely studied in both solid conductors and plasmas to gain insights into electron behavior. In a plasma, where electrons and ions move freely, the Hall effect provides valuable information about electron mobility and interactions with magnetic fields. This experiment will emphasize the measurement of the Hall voltage, the effects of magnetic fields on charged particles, and how changes in parameters like pressure influence plasma behavior.

The techniques that we used are:
- Measurement of Hall voltage across a plasma discharge tube.
- Control of gas flow and pressure in the plasma system.
- Use of a gaussmeter to measure magnetic field strength.
- Observation of glow discharge structure and stability through oscilloscope monitoring.

The key concepts which we explore are:

- Hall effect: where a voltage develops transverse to the current in a plasma within a magnetic field.
- Lorentz force: which causes charged particles to move perpendicular to both their velocity and an applied magnetic field.
- Drift velocity: representing the average velocity of electrons under an applied electric field.
- Electron collision frequency: which describes how often electrons collide with atoms in the plasma.
- Plasma discharge: where ionization of gas occurs, creating a conductive path for current.

Theory & Background

Introduction

This experiment explores how the Hall effect manifests in a plasma, providing valuable insights into electron dynamics in ionized gasses. The measurements of Hall voltage and current help us understand electron mobility, drift velocity, and plasma resistance under varying conditions of electric and magnetic fields.

Hall Effect in Plasma

The Hall effect occurs when a current-carrying conductor is placed in a magnetic field, leading to the development of a transverse voltage, we call this the Hall voltage. This voltage is caused by the Lorentz force, which deflects moving charges, such as electrons, perpendicular to both the current and the magnetic field. In this experiment, the Hall effect is studied in a plasma rather than a solid conductor, allowing us to observe how free electrons in a low-pressure gas behave under the influence of electric and magnetic fields.

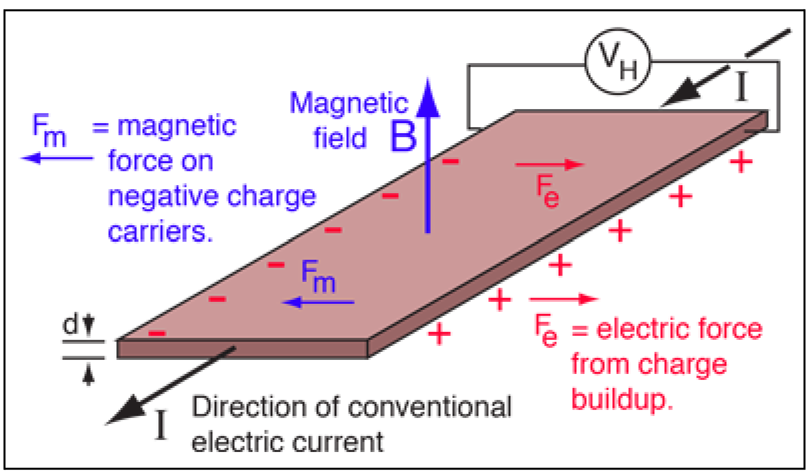


Figure 1: The Hall effect in an Plate
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html

Electron Drift and Forces

In the case of plasma, the electrons are in constant random motion due to their thermal energy. However, when an electric field is applied, the average velocity of the electrons (drift velocity) increases in the direction of the field. The relationship between the drift velocity (v_d) and the electric field (E) is given by:

$$v_d = (q \tau / m) E$$

where q is the charge of the electron, τ is the mean free time between collisions, and m is the mass of the electron.

When a magnetic field is applied perpendicular to the electric field, the electrons experience a force that deflects them sideways. This deflection sets up an electric field in the transverse direction, which counters the magnetic force and prevents further deflection. The transverse voltage generated is the Hall voltage. The magnitude of the Hall voltage (V_H) is proportional to the applied magnetic field (B) and the drift velocity of the electrons.

Force Balance and Hall Angle

To fully understand the Hall effect, it is essential to balance the forces acting on the electrons. The electric force is given by:

$$F_E = qE$$

and the magnetic force by:

$$F_M = q v_d \times B$$

In equilibrium, the transverse electric field generated by the Hall voltage balances the magnetic force, leading to the Hall angle (Θ_H), which is the ratio of the transverse electric field to the longitudinal field:

$$\Theta_H = (q B \tau / m)$$

This ratio depends on the cyclotron frequency (ω_c), which describes the frequency at which electrons rotate in a magnetic field, and the collision rate of the electrons.

Plasma Behavior and Measurements

In this experiment, we measure both the Hall voltage and the longitudinal current to deduce key plasma properties, such as electron density and collision frequency. The plasma used here is created in a glow discharge tube, where gas atoms are ionized, producing free electrons. These electrons interact with both the electric and magnetic fields, allowing us to study their behavior.

Electron Distribution and Striations

The Hall effect in plasma differs from solid conductors due to the non-uniform distribution of electrons. In a plasma, the electron density is highest at the center of the tube and decreases toward the walls. As a result, the Hall voltage is not uniform across the plasma, and the measured Hall voltage is typically about half of what would be expected in a solid conductor. This non-uniformity is crucial when analyzing data from this experiment.

Additionally, the plasma discharge is influenced by instabilities, oscillations, and striations. Striations are alternating bright and dim regions in the glow discharge caused by ionization waves. These can interfere with the measurements of the Hall voltage and must be accounted for. The gas mixture in the tube, composed of helium with traces of argon and nitrogen, ensures that free electrons are consistently available for measurement.

Instabilities, Oscillations, and Striations

Plasmas are naturally unstable, influenced by various factors such as current, voltage, pressure, magnetic field, and even less obvious elements like contaminant gasses and ambient conditions. These instabilities arise when waves within the plasma grow from small thermal fluctuations to larger amplitudes. In our discharge setup, most of these instabilities are driven by the electric current. Small changes in current or gas density can significantly alter the plasma's behavior, so it’s important to keep the gas pressure and flow rate constant during measurements. Oscillations in the discharge can reach multi-kilohertz frequencies, with amplitudes sometimes exceeding a few volts. To ensure stable operation, low-pass filters with RC time constants of about 0.2 seconds are used to protect measuring instruments, allowing for oscillation-free conditions.

In this experiment, we use a helium-argon-nitrogen gas mixture. Argon is easily ionized, providing free electrons, while nitrogen helps stabilize the gas against contamination. A slow gas flow rate is necessary to avoid turbulence. At lower pressures, alternating bright and dim regions called striations may appear in the plasma. These striations are large-amplitude ionization waves but do not significantly affect the Hall voltage measurements. Their impact on the electric field is minor and can be averaged out if the distance between probes is large enough.

Experimental Setup

Apparatus and Equipment

The equipment used for this Hall effect experiment is primarily contained within the Plasma Hall Effect rack. This rack contains the controls necessary for managing the gas flow and electrical setup. Key external components include:

- Gaussmeter: For measuring magnetic field strength.
- Oscilloscope: Used to monitor discharge stability.
- Gas Supply Cylinder: Supplies helium/argon/nitrogen gas mixture.
- Vacuum Pump: Located under the bench, used for establishing a vacuum in the system.

Each component has been labeled in a way that reflects its function, but remember that schematic labels might not always match the physical valve handles. Care should be taken to familiarize yourself with the functional descriptions like “Gas Input Adjust” for proper operation.

Using the Equipment

1. <u>General Info about Gas and Plasma</u>

    The vacuum and gas system is designed to be leak-free and capable of maintaining a low-pressure environment (below 2 Torr). However, note that pressure will slowly rise due to back-pressure after shutting off the pump and closing the valves. This pressure build-up should not affect your experiment significantly.

    Glow discharges, which are sensitive to contamination, will stabilize after a period of plasma flushing (flowing gas through the discharge tube). After running the discharge for some time, the system becomes more stable, allowing for better reproducibility of results. For best results, keep changes to control parameters (pressure, flow rate, and discharge voltage) gradual. Rapid changes can extinguish the discharge or make it difficult to achieve the desired stable state.

    Changes to pressure should not exceed 1 Torr every 10 seconds, and voltage adjustments should be made slowly—100V in 5 seconds. If the glow turns pink, this indicates the gas composition is as expected for the helium/argon/nitrogen mixture. Adjustments to the 'Gas Input Adjust' valve may be required to keep the gas flow slightly above atmospheric pressure.

2. <u>Gas Pressure and Flow Rate</u>

    Setting the gas pressure and flow rate correctly is essential for maintaining a stable discharge. The system consists of a gas source connected to the discharge tube, with a needle valve controlling the gas flow and a throttling valve regulating the vacuum pump's capacity.

    Here's how to set it:

    1. Technique 1 (Traditional): Open the outflow valve (v4) by 1/2 turn, then adjust the gas input valve (v2) until the discharge pressure reads about 10 Torr. Once flow is set, control further pressure changes with v4.

    2. Technique 2 (Fixed Conductance): Open v4 fully and adjust v2 until the pressure reaches 15 Torr. To increase pressure, open v2 further. This technique allows more control over flow and pressure, especially at higher ranges (10-30 Torr).

    Establishing stable flow requires small and careful adjustments to the valves. Ensure no air enters the system and monitor the pressure closely. Keeping the gas mixture constant is crucial for obtaining reliable results.

3. <u>How to Set Gas Pressure</u>

    To get the desired pressure in the discharge tube:

    1. Pump Out the System: Open the coarse pump-out valve (Throttle Coarse) to pump out the system, then close it once the vacuum meter reads near zero.

2. Open the Gas Input Valve: Turn the gas input valve (Gas Input Adjust) one turn and open the main valve on the gas cylinder. Adjust the pump-out needle valve to fine-tune the gas pressure for the first set point.

For acceptable discharge conditions, maintain a pressure between 3 and 35 Torr and a current of 0.5 to 2 mA. At the lower pressure ranges, stationary striations may appear and interfere with measurements, so keep the current low if possible.

Plasma Discharge and Electrical Instruments

The plasma discharge tube is powered by a high-voltage (0-3 kV) supply, which is connected to earth ground through a resistor divider. The potential difference between electrodes is measured using a high-impedance voltmeter with a full scale of 2500 V to 250 mV.

To ensure proper measurements:

1. Zero the Voltmeter: Select the “zero” range and use the “meter zero” knob to set the voltmeter to zero with no discharge current.
2. Monitor Discharge Stability: Connect the oscilloscope to the “discharge monitor” port to observe the discharge. Voltage fluctuations larger than 0.1 V indicate instability, requiring adjustment of gas flow, pressure, or voltage settings.

Monitoring Noise in the Discharge

To minimize noise in the plasma discharge:

- Ensure the voltage across the discharge tube does not exceed 3 mA, as the plasma requires at least 1.5 kV to sustain.
- Small probe currents should be minimized by grounding the probes properly.
- Adjust the biasing potentiometer as needed to keep the Hall probes and measurement circuits near ground potential, preventing large unwanted currents that could affect the measurements.

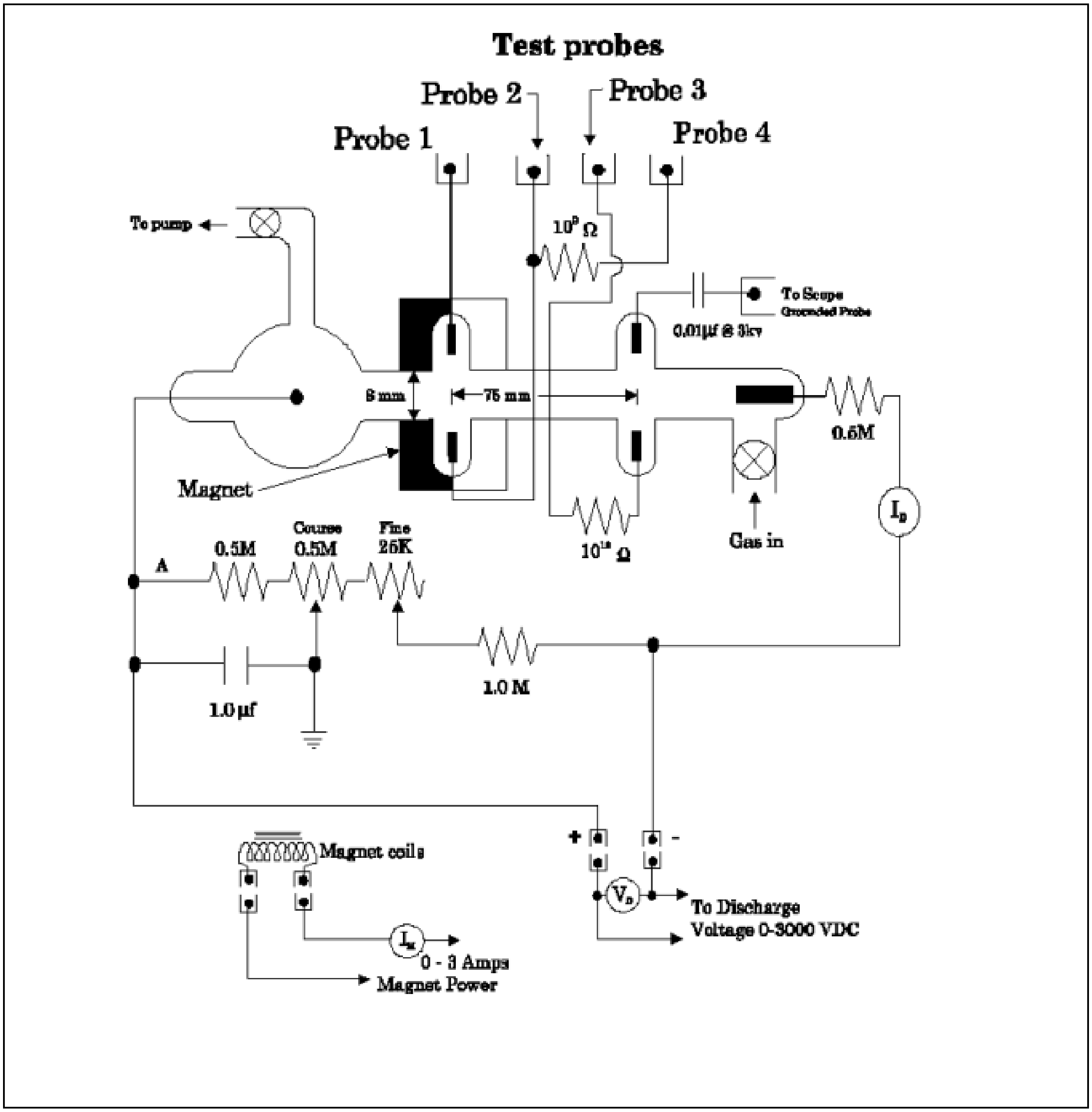


Figure 2: Electrical diagram with probes
https://experimentationlab.berkeley.edu/sites/default/files/writeups/HAL_Manual_2024-05-03.pdf

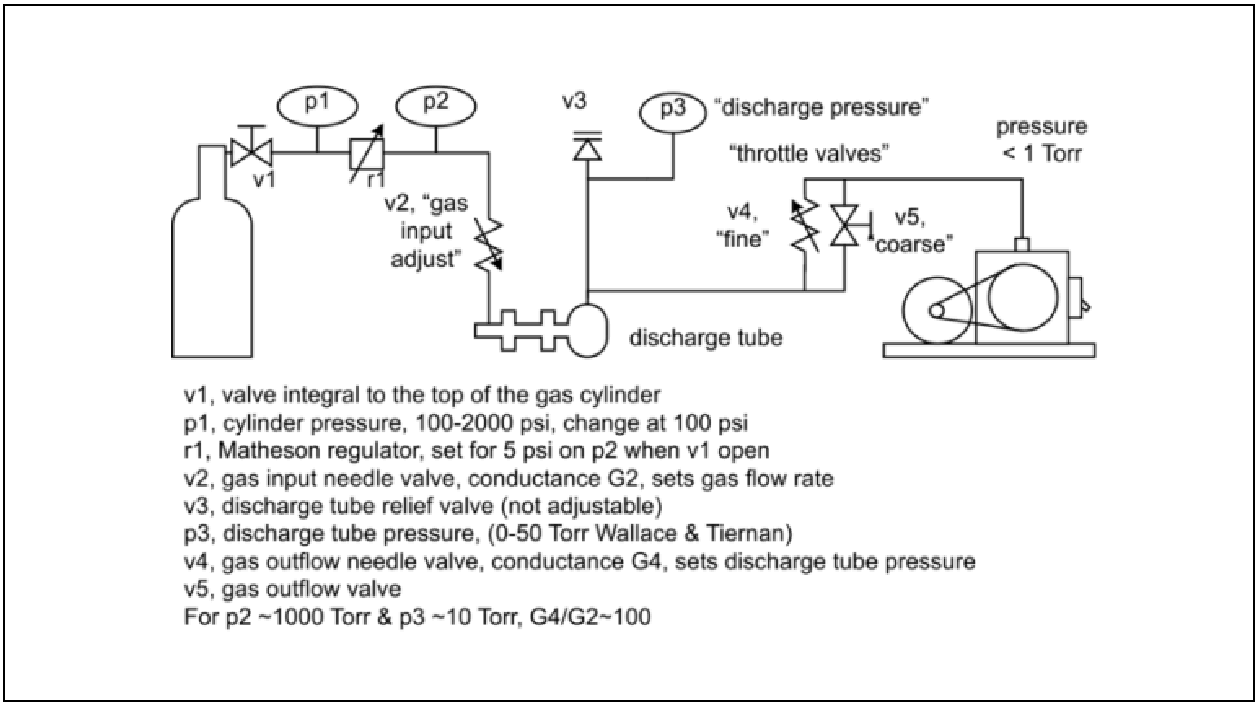


Figure 3: Diagram of gas system

https://experimentationlab.berkeley.edu/sites/default/files/writeups/HAL_Manual_2024-05-03.pdf

Shutting Down the System Safely-

<u>Turn off the electrical equipment (magnet and oscilloscope)</u>:Begin by switching off the probe circuits and the oscilloscope. Ensure the magnet power and the high-voltage power supply are also turned off.

<u>Open the pump-out valve</u>: Gradually open the pump-out valve to relieve pressure in the system.

<u>Close the gas cylinder valve</u>: Fully close the main valve on the helium gas cylinder to prevent any further gas from entering the system.

<u>Release internal pressure</u>: Open the inflow valve fully until the high-pressure regulator gauge shows approximately 0.5 Torr. You may not be able to pump it down to zero, but this is normal. After reaching this value, close the inflow valve.

<u>Close the outflow valve</u>: Shut the outflow valve to ensure no more gas flows out. Then, turn off the vacuum pump.

<u>Shut remaining valves</u>: Ensure all valves that haven't been closed yet are shut.

<u>Monitor back pressure</u>: After the system has been shut down, a slow back-pressure buildup is normal inside the tube. Don't worry if the pressure increases slightly over time.

Experimental Procedure

1. Check that all electrical and gas flow connections are secure. Ensure all gas valves are closed, and the electrical power is off.

2. Turn on the vacuum pump and open the pump-out valve (Throttle Valve Coarse). The vacuum gauge should read about 2 Torr.
3. Open the main valve on the helium supply tank (v1). The high-pressure gauge (p1) should read between 100 and 2,000 psi. If it reads below 50 psi, you'll need a new tank.
4. Close the pump-out valve once the desired vacuum is achieved. If the pressure in the discharge tube rises quickly, there may be a leak.
5. Open the outflow valve (Throttle Valve Fine) one full turn.
6. Open the 'Gas Input Adjust' needle valve slowly, about a quarter turn, until the pressure rises. Adjust the gas cylinder regulator (r1) to match the blue mark on the p2 gauge.
7. Adjust the pump-out needle valve (Throttle Valve Fine) to maintain a pressure between 10 and 20 Torr. Avoid adjusting the gas input valve once a small flow rate is established, and instead use the outflow valve for finer control.
8. After allowing the flow to stabilize, turn on the high voltage to about 2,500V. There may be a slight discrepancy between the reading on the kilovolt meter and the value set by the knob. The glow in the discharge tube should be purple-pink, and the ammeter should read about 1 mA. Consider how tube pressure affects discharge current.
9. Turn on the oscilloscope to monitor fluctuations in plasma potential using the grounded probe. Oscillations should be below 0.1V, ideally around 50mV. If oscillations are too high, adjust gas pressure, flow rate, and voltage until steady. What helped for us is that if stability isn't possible just restart the system.
10. Once stable, turn on the Hall probe circuits. Set the voltmeter range to 250V or 2500V. Keep the magnet power off.
11. Adjust the discharge ground using the potentiometer so probe #2 floats near ground potential. Set the 'Scale' to zero and adjust 'Meter Zero' until the voltmeter reads zero. Select 'Ground-to-2' on the dial, and fine-tune the potentiometer to ground probe #2. If conditions are stable, the probe potential should not drift more than a few volts.

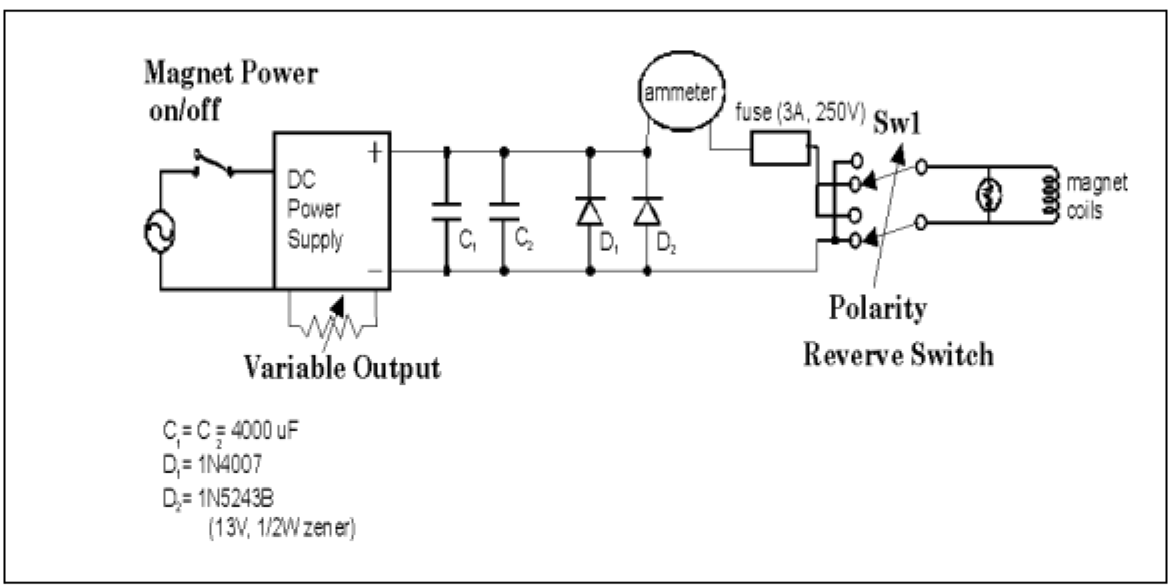


Figure 4: Electrical diagram of Magnet
https://experimentationlab.berkeley.edu/sites/default/files/writeups/HAL_Manual_2024-05-03.pdf

Measurements & Raw Data

1. Measuring Discharge Current and Voltage (Id and Vd)

The goal of these first measurements is to explore some interesting properties of plasma discharge. For discharge tube pressures between 15 and 30 torr, measure the discharge current (Id) and discharge voltage (Vd) as a function of high voltage. The discharge voltage is measured between probes 2 and 3. Note that there is a 10^{10} ohm resistor in series with probe 3 to keep the current flow around 10^{-8} A.

Before taking measurements, experiment with high voltage, discharge current, gas pressure, and gas flow to understand the limits of these parameters. When collecting data, start by setting the pressure to 15 torr and adjusting the high voltage until the discharge is stable. Record the current and voltage. Gradually increase the high voltage, measure the current, and record both values until you have enough data points to plot a curve.

Repeat this process for pressures of 20, 25, and 30 torr, or until you have six pressure plots. Think about what additional information might be needed, such as converting current to current density or determining the relationship between the power supply voltage and discharge tube voltage.

Pressure (torr)	High voltage (V)	HIgh Voltage error (V)	Id (mA)	Id error (mA)	Vd (V)	Scale (V)	Vd error (V)
15	2000	50	0.8	0.05	125	250	12.5
15	1800	50	0.3	0.05	125	250	12.5
15	1900	50	0.5	0.05	125	250	12.5
15	2100	50	1	0.05	120	250	12.5
15	2200	50	1.1	0.05	117.5	250	12.5
15	2300	50	1.3	0.05	117.5	250	12.5
15	2400	50	1.5	0.05	115	250	12.5
15	2500	50	1.7	0.05	115	250	12.5
17	2400	50	1.4	0.05	125	250	12.5
17	2300	50	1.2	0.05	125	250	12.5
17	2200	50	1	0.05	125	250	12.5
17	2100	50	0.8	0.05	125	250	12.5
17	2000	50	0.6	0.05	125	250	12.5
17	1900	50	0.4	0.05	125	250	12.5

20	2500	50	1.1	0.05	142.5	250	12.5
20	2400	50	0.95	0.05	145	250	12.5
20	2300	50	0.75	0.05	147.5	250	12.5
20	2200	50	0.5	0.05	147.5	250	12.5
20	2100	50	0.3	0.05	150	250	12.5
22	2500	50	1	0.05	150	250	12.5
22	2400	50	0.8	0.05	150	250	12.5
22	2300	50	0.6	0.05	150	250	12.5
22	2200	50	0.4	0.05	150	250	12.5
25	2500	50	0.5	0.05	167.5	250	12.5
25	2400	50	0.3	0.05	175	250	12.5
25	2600	50	0.8	0.05	155	250	12.5
25	2700	50	1	0.05	155	250	12.5
27	2700	50	0.9	0.05	157.5	250	12.5
27	2600	50	0.7	0.05	162.5	250	12.5
27	2500	50	0.5	0.05	167.5	250	12.5

High voltage error (V)	50
Pressure error (torr)	0.25
Id error (mA):	0.05

2. Measuring Magnetic Field vs. Magnet Current (B vs. Im)

Using a Gauss meter (model 5180) and with the high voltage supply off, measure the magnetic field (B) as a function of magnet current (Im) in both directions. You can do this by flipping the COIL POLARITY switch to measure both forward and reverse directions of magnet current. Select Auto Zero: Press the ZERO button. The unit will automatically return to normal operation.

Select Auto Range: Press the SHIFT button followed by the RANGE button. To exit Auto Range, repeat the process. To manually adjust the range, press RANGE and use the UP and DOWN arrows.

Record the magnetic field for different values of magnet current and plot B against Im. Check if the magnet shows significant hysteresis by observing the plot. In this experiment, errors due to hysteresis are usually small, so avoid spending too much time calculating these errors.

FORWARD	
I (A)	B (kG)

0.2	0.08
0.4	0.13
0.6	0.18
0.8	0.24
1	0.3
1.2	0.34
1.4	0.4
1.6	0.46
1.8	0.51
2	0.57
2.2	0.62
2.4	0.69
2.5	0.72

BACKWARD	
I (A)	B (kG)
0.2	-0.06
0.4	-0.11
0.6	-0.16
0.8	-0.21
1	-0.27
1.2	-0.33
1.4	-0.38
1.6	-0.44
1.8	-0.49
2	-0.55
2.2	-0.61
2.4	-0.67
2.5	-0.7

For both:

B error (kG)	uncertainty I (A)
0.005	0.025

3. Measuring Hall Field vs. Magnetic Field (EH vs. B)

For pressures between 15 and 30 torr, measure the Hall field (EH) between probes 1 and 2 as a function of magnetic field. Note that probes 1 and 2 are roughly 8 mm apart. Measure data for the entire range of magnet current, making sure to adjust the potentiometer to keep the probes near ground potential.

Plot EH for each pressure as a function of the magnetic field. Check if EH is linearly dependent on B, particularly for magnetic fields below 300 gauss. For the linear parts of the data, calculate values for the electron gas properties (e.g., drift velocity, number density, collision frequency, etc.). Consider whether your results are reasonable and how these quantities change with pressure.

Pressure (torr)	**high voltage (V)**	**Magnet Current (Im) [A]**	**Magnetic Field (B) [kG]**	**Eh scale**	**Hall Field percent**	**Eh (V)**
15	N/A	0.2	0.07	25	0.3	7.5
15		0.4	0.13	25	0.4	10
15		0.6	0.18	25	0.5	12.5
15		0.8	0.23	25	0.55	13.75
15		1	0.29	25	0.65	16.25
15		1.2	0.35	25	0.75	18.75
15		1.4	0.4	25	0.85	21.25
15		1.6	0.46	25	0.95	23.75
15		1.8	0.52	25	1.08	27
15		2	0.57	25	1.2	30
15		2.2	0.63	25	1.27	31.75
15		2.4	0.69	25	1.4	35
17	2300	0.2	0.07	25	0.32	8
17		0.4	0.12	25	0.42	10.5
17		0.6	0.18	25	0.52	13
17		0.8	0.24	25	0.62	15.5
17		1	0.29	25	0.7	17.5
17		1.2	0.35	25	0.8	20
17		1.4	0.4	25	0.89	22.25
17		1.6	0.46	25	0.97	24.25
17		1.8	0.52	25	1.02	25.5
17		2	0.57	25	1.15	28.75

17		2.2	0.63	25	1.3	32.5
17		2.4	0.69	25	1.49	37.25
20	2700	0.2	0.07	25	0.2	5
20		0.4	0.12	25	0.3	7.5
20		0.6	0.18	25	0.47	11.75
20		0.8	0.24	25	0.57	14.25
20		1	0.29	25	0.7	17.5
20		1.2	0.34	25	0.8	20
20		1.4	0.4	25	0.9	22.5
20		1.6	0.46	25	1	25
20		1.8	0.52	25	1.12	28
20		2	0.57	25	1.22	30.5
20		2.2	0.63	25	1.32	33
20		2.4	0.69	25	1.4	35
22	2700	0.2	0.08	25	0.38	9.5
22		0.4	0.13	25	0.45	11.25
22		0.6	0.18	25	0.52	13
22		0.8	0.24	25	0.6	15
22		1	0.29	25	0.69	17.25
22		1.2	0.35	25	0.75	18.75
22		1.4	0.4	25	0.8	20
22		1.6	0.46	25	0.9	22.5
22		1.8	0.52	25	0.99	24.75
22		2	0.57	25	1.03	25.75
22		2.2	0.63	25	1.1	27.5
22		2.4	0.69	25	1.2	30
25	2700	0.2	0.07	25	0.3	7.5
25		0.4	0.13	25	0.4	10
25		0.6	0.18	25	0.5	12.5
25		0.8	0.24	25	0.55	13.75
25		1	0.29	25	0.62	15.5
25		1.2	0.35	25	0.7	17.5
25		1.4	0.4	25	0.79	19.75
25		1.6	0.46	25	0.82	20.5
25		1.8	0.51	25	0.9	22.5

25		2	0.57	25	0.98	24.5
25		2.2	0.63	25	1.02	25.5
25		2.4	0.69	25	1.1	27.5
27	2700	0.2	0.07	25	0.3	7.5
27		0.4	0.13	25	0.39	9.75
27		0.6	0.18	25	0.45	11.25
27		0.8	0.24	25	0.51	12.75
27		1	0.29	25	0.6	15
27		1.2	0.35	25	0.65	16.25
27		1.4	0.4	25	0.71	17.75
27		1.6	0.46	25	0.8	20
27		1.8	0.52	25	0.86	21.5
27		2	0.57	25	0.92	23
27		2.2	0.63	25	1	25
27		2.4	0.69	25	1.07	26.75

Eh uncertainty (V)
1.25

Analysis

1. Measuring Discharge Current and Voltage (Id and Vd)

The main focus of this part is to explore the relationship between Id and Vd at different gas pressures in a plasma discharge tube. By adjusting the high voltage and measuring the resulting current and voltage across the plasma, we aimed to understand the behavior of the plasma under different conditions.

Relationship Between Discharge Current and Voltage
At each pressure setting—15, 17, 20, 22, 25, and 27 torr—we recorded how *Id* changes as we varied the high voltage. Our data showed that at a constant pressure, increasing the high voltage generally led to an increase in the discharge current. This indicates that higher electric potentials facilitate greater current flow through the plasma.

For instance, at 15 torr, as we increased the high voltage from 1,800 V to 2,500 V, the discharge current rose from 0.3 mA to 1.7 mA. This trend was consistent across other pressure settings, suggesting a direct relationship between high voltage and discharge current within the plasma.

Effect of Pressure on Discharge Current

Pressure played a significant role in the behavior of the plasma. At higher pressures, the discharge current at a given high voltage was generally lower compared to lower pressures. For example, at 15 torr and a high voltage of 2,300 V, the discharge current was 1.3 mA. However, at 25 torr and the same high voltage, the discharge current was only 0.5 mA.

This inverse relationship between pressure and discharge current can be attributed to the increased number of gas molecules at higher pressures. More gas molecules mean more collisions between electrons and atoms, which can impede the flow of current. The higher collision frequency at increased pressures reduces the mean free path of electrons, making it harder for them to contribute to the current.

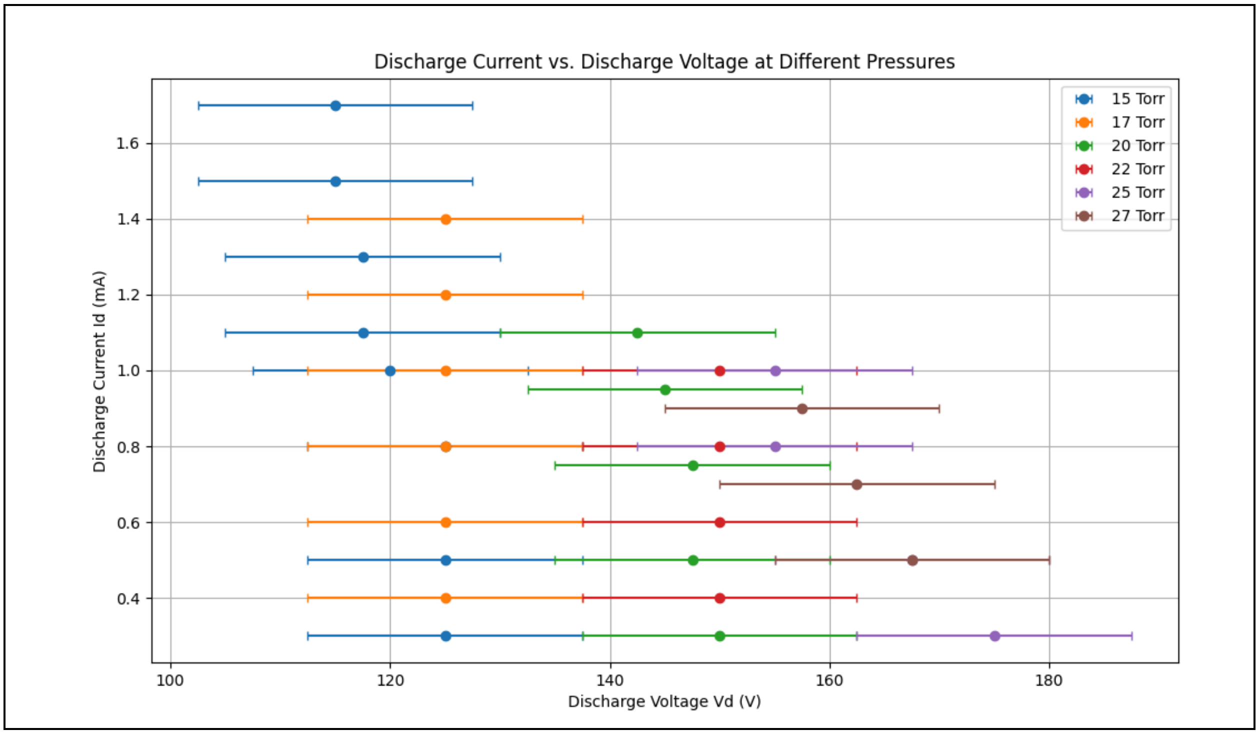
Consistency of Discharge Voltage

An interesting observation was that the discharge voltage (*Vd*) remained relatively constant at each pressure, even as we varied the high voltage and discharge current. For example, at 17 torr, *Vd* stayed at 125 V across different high voltages and currents. This suggests that the voltage drop across the plasma is mainly determined by the gas pressure and is less sensitive to changes in the high voltage once the discharge is established.

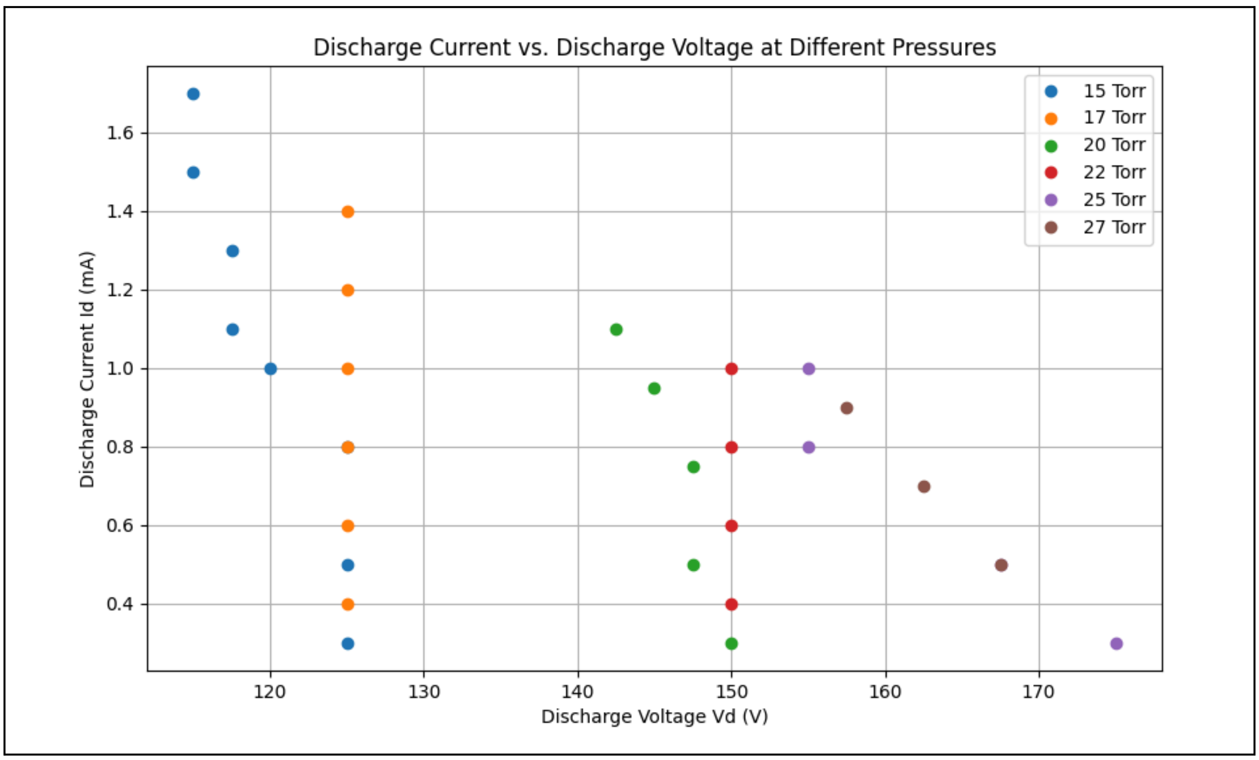
The consistent discharge voltage at a given pressure indicates that the plasma reaches a stable state where the electric field within the discharge tube balances the processes of ionization and recombination. The electric field must be sufficient to maintain the plasma by providing enough energy to free electrons from gas atoms, sustaining the ionization process.

The decrease in discharge current with increasing pressure implies that higher pressures require higher voltages to maintain the same current flow. This is due to the increased likelihood of collisions at higher pressures, which makes it more difficult for electrons to accelerate and contribute to the current.

Here is a graph which summarizes what I found above and has the measurements we took:



It does look a bit cluttered with the error bars so I also graphed it without the bars:



To deepen our understanding, we calculated the current density (J) and the electric field (E) within the plasma. Using the actual tube radius of 4 mm (since the tube diameter is 8 mm) and a probe distance of 0.075 m, we found the following:

1. **Current Density**: The current density ranged from approximately **5.97 ± 0.99 A/m²** to **33.82 ± 0.99 A/m²**. Higher current densities were observed at higher discharge currents, which is consistent with the direct relationship between current and current density given a constant cross-sectional area.
2. **Electric Field**: The electric field within the plasma varied from about **1,533 ± 166.67 V/m** to **2,333 ± 166.67 V/m**, corresponding to the measured discharge voltages and the fixed distance between the probes.

These calculations shed light on the energy conditions within the plasma. A higher current density indicates that more charge carriers are moving through a given area, which can influence the plasma's temperature and conductivity. Similarly, variations in the electric field affect the acceleration of electrons, impacting ionization rates and overall plasma behavior.

Here is a table showing all the values from the calculations next to the value:

Pressure (torr)	Vd (V)	Id (mA)	Current_density A/m²	Electric_field V/m
15	125	0.8	15.915494	1666.666667
15	125	0.3	5.96831	1666.666667
15	125	0.5	9.947184	1666.666667
15	120	1	19.894368	1600
15	117.5	1.1	21.883805	1566.666667
15	117.5	1.3	25.862678	1566.666667
15	115	1.5	29.841552	1533.333333
15	115	1.7	33.820425	1533.333333
17	125	1.4	27.852115	1666.666667
17	125	1.2	23.873241	1666.666667
17	125	1	19.894368	1666.666667
17	125	0.8	15.915494	1666.666667
17	125	0.6	11.936621	1666.666667
17	125	0.4	7.957747	1666.666667
20	142.5	1.1	21.883805	1900
20	145	0.95	18.899649	1933.333333
20	147.5	0.75	14.920776	1966.666667

20	147.5	0.5	9.947184	1966.666667
20	150	0.3	5.96831	2000
22	150	1	19.894368	2000
22	150	0.8	15.915494	2000
22	150	0.6	11.936621	2000
22	150	0.4	7.957747	2000
25	167.5	0.5	9.947184	2233.333333
25	175	0.3	5.96831	2333.333333
25	155	0.8	15.915494	2066.666667
25	155	1	19.894368	2066.666667
27	157.5	0.9	17.904931	2100
27	162.5	0.7	13.926058	2166.666667
27	167.5	0.5	9.947184	2233.333333

Uncertainty errors were propagated to get:

E_field Error V/m	0.99
Current Density Error A/m²	166.67

In case you're wondering here is an example calculation by hand:

Tube radius: $r = 0.008/2 = 0.004$ meters

Cross-sectional area: $A = \pi r^2 = \pi(0.004)^2 = \pi \times 1.6\times10^{-5} = 5.0265\times10^{-5}$ m²

Discharge current: for $I_d = 0.8\times10^{-3}$ A (First data point in table above)

Then we have to just divide for current density-

Current density: $J = I_d/A = 0.8\times10^{-3}/5.0265\times10^{-5} = 15.915$ A/m²

(This matches the value in the output on the first line above)

Now onto the Electric Field:

$E = V_d/d = 125/0.075 = 1666.6667$ V/m

(Again, this matches the value in the output on the first line above)

The python code for the graphs / calculations can be found here:
https://docs.google.com/document/d/1X8qgvojzq5QVjyJlYh954-sULS9y2qHAouesTDTMFiU/edit?usp=sharing

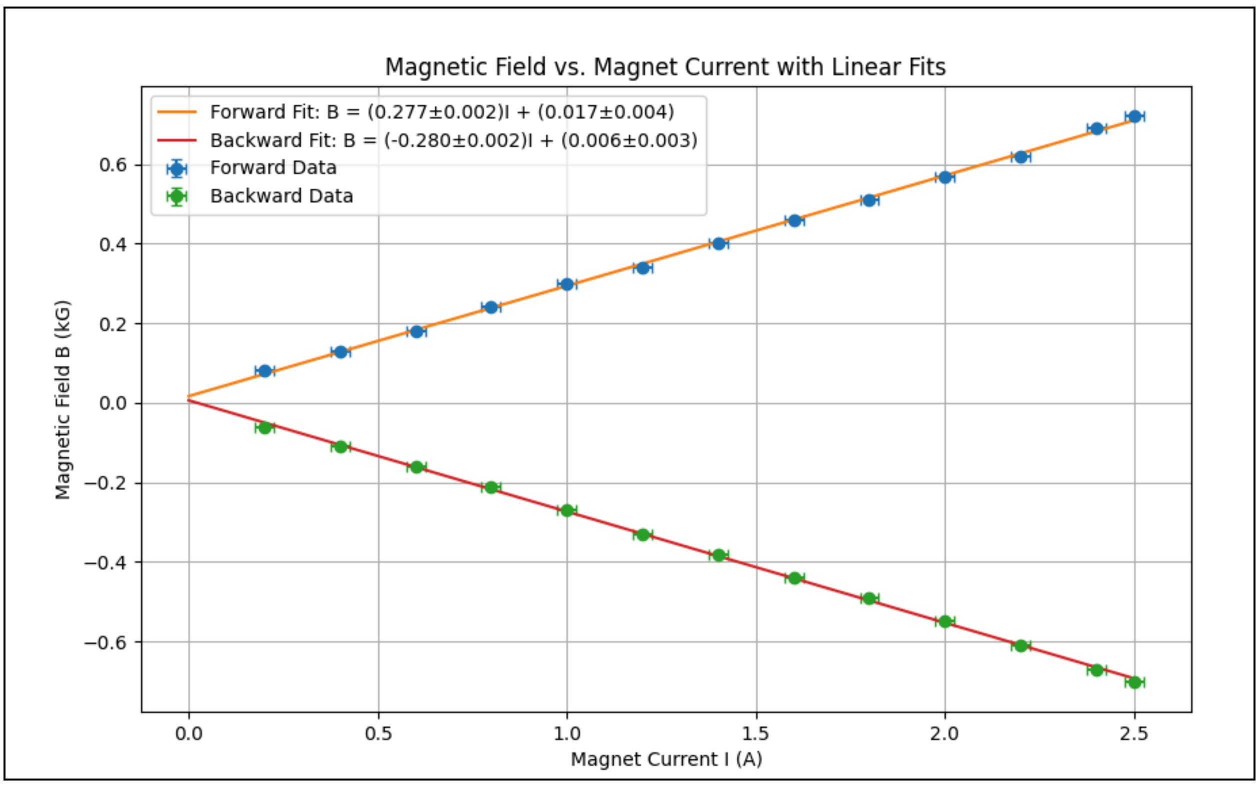
2. Measuring Magnetic Field vs. Magnet Current (B vs. Im)

In this part of the experiment, we measured how the magnetic field strength (B) changes with the magnet current (I) for both forward and reverse current directions. Our aim was to determine if the B-I relationship is linear and to assess any hysteresis effects in the magnet.

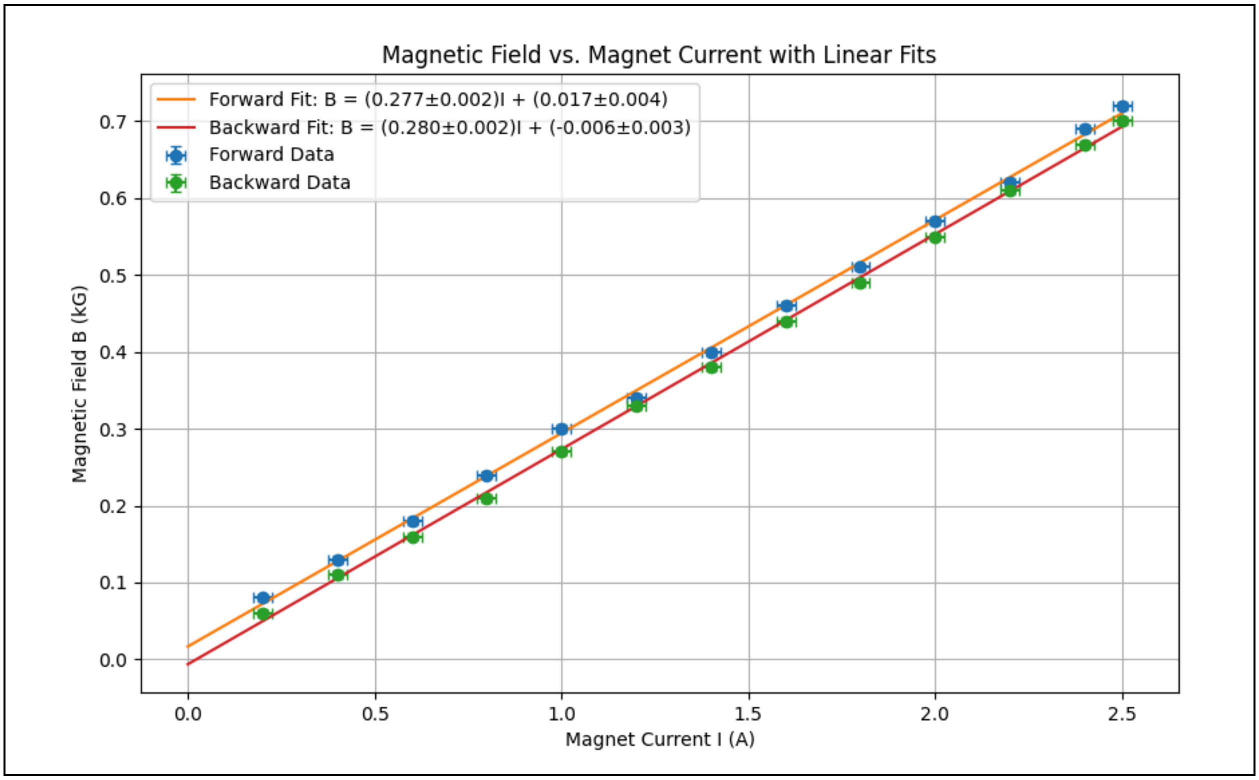
Linearity of the *B*-*I* Relationship

Our data showed a strong linear relationship between the magnetic field and the magnet current. For the forward current direction, the linear fit yielded a slope of 0.2880±0.0035 kG/A and an intercept of 0.0207±0.0060 kG. For the reverse direction, the slope was −0.2765±0.0037 kG/A with an intercept of −0.0078±0.0063 kG.

These results indicate that the magnetic field increases proportionally with the magnet current. The near-zero intercepts suggest that there is minimal residual magnetic field when the current is zero, confirming the linearity of the relationship.



I inverted the axis for a better visualization of how both line up:



Hysteresis Effects

Hysteresis refers to the phenomenon where the magnetic properties of a material depend on its previous history of magnetization. To assess hysteresis, we compared the forward and reverse measurements. The slopes for both directions are similar in magnitude but opposite in sign, and the intercepts are close to zero within the experimental uncertainties.

The small differences between the forward and reverse measurements suggest that hysteresis effects are minimal in our magnet. These discrepancies are within the range of measurement errors, indicating that the magnet's prior magnetic state does not significantly influence its current behavior.

Significance

The linear B-I relationship confirms that the magnet produces a predictable magnetic field when the current is varied. This predictability is crucial for experiments that require precise control of the magnetic environment. The minimal hysteresis implies that the magnet can reliably reproduce the same magnetic field for a given current, enhancing the accuracy of experimental results.

Goodness of fits

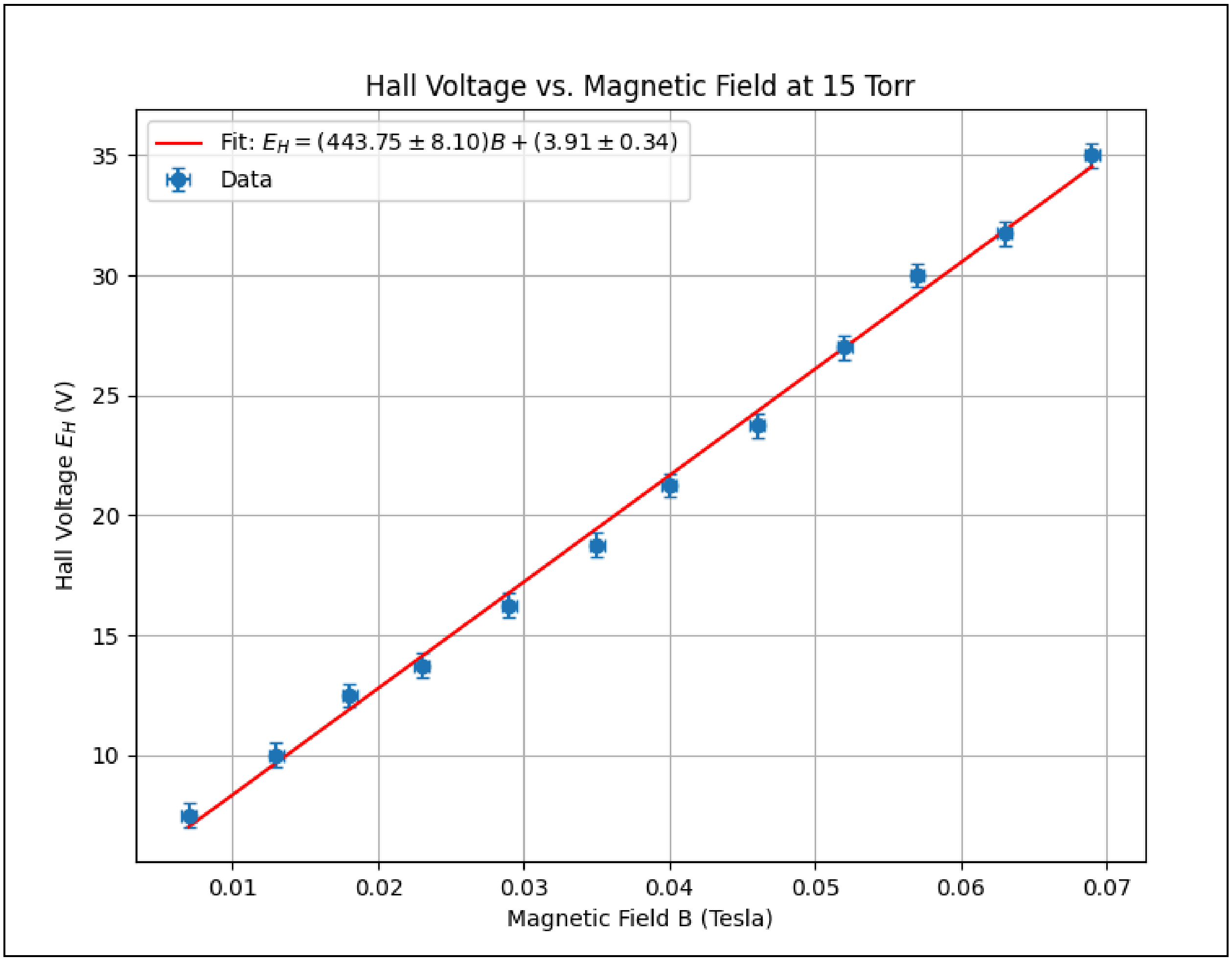
How good is the linear fit we have? I can calculate the R^2 Values and if you do you get-

Forward Direction:
$R^2 = 0.999132$
Backward Direction:
$R^2 = 0.999342$

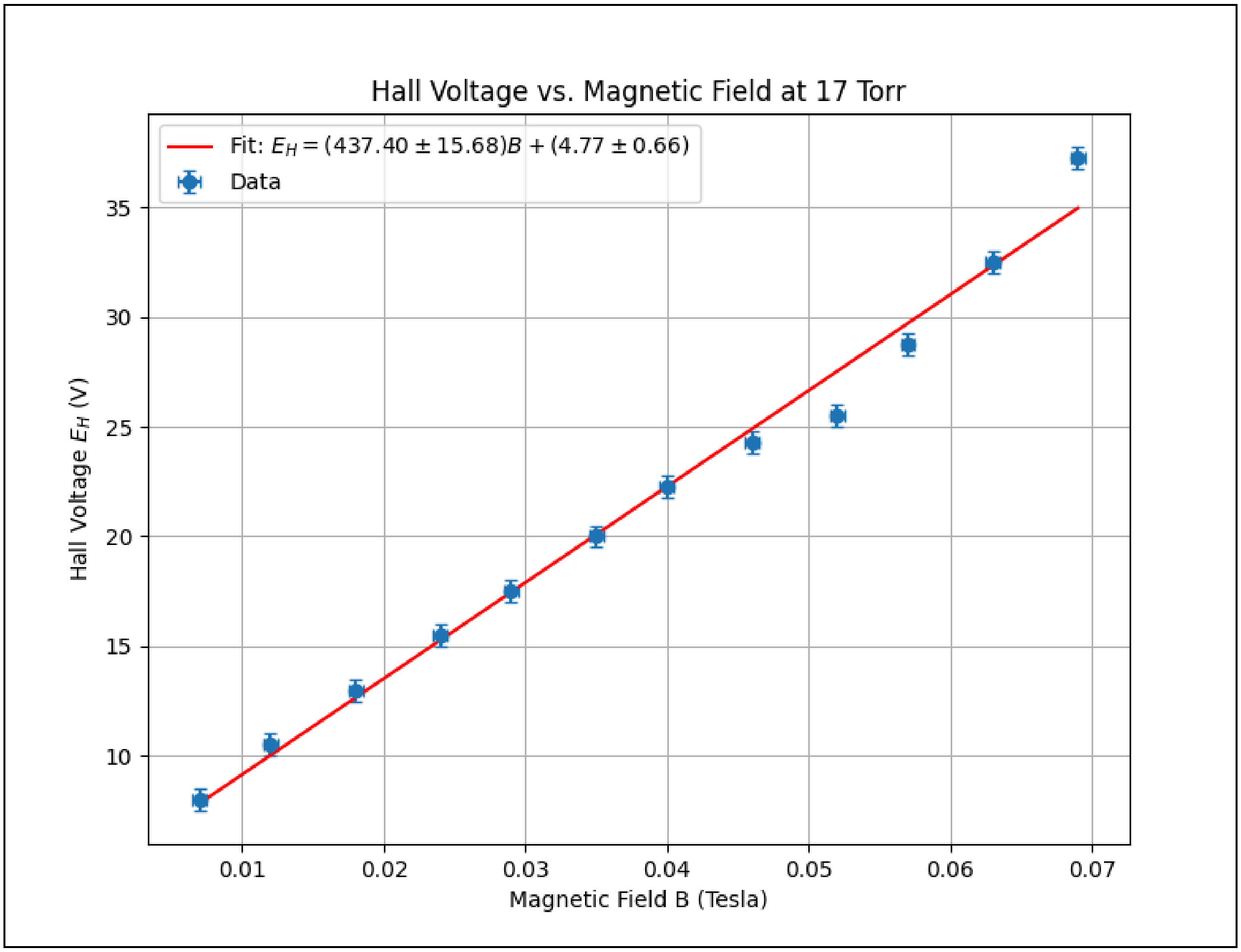
I also calculated the reduced chi-squared (χ^2) values in python code (found at the link above in part 1), for both forward and backward current directions, χ^2 was approximately 0.21, indicating an excellent fit given the measurement uncertainties. This confirms that our linear model accurately describes the relationship between B and I in our experiment.

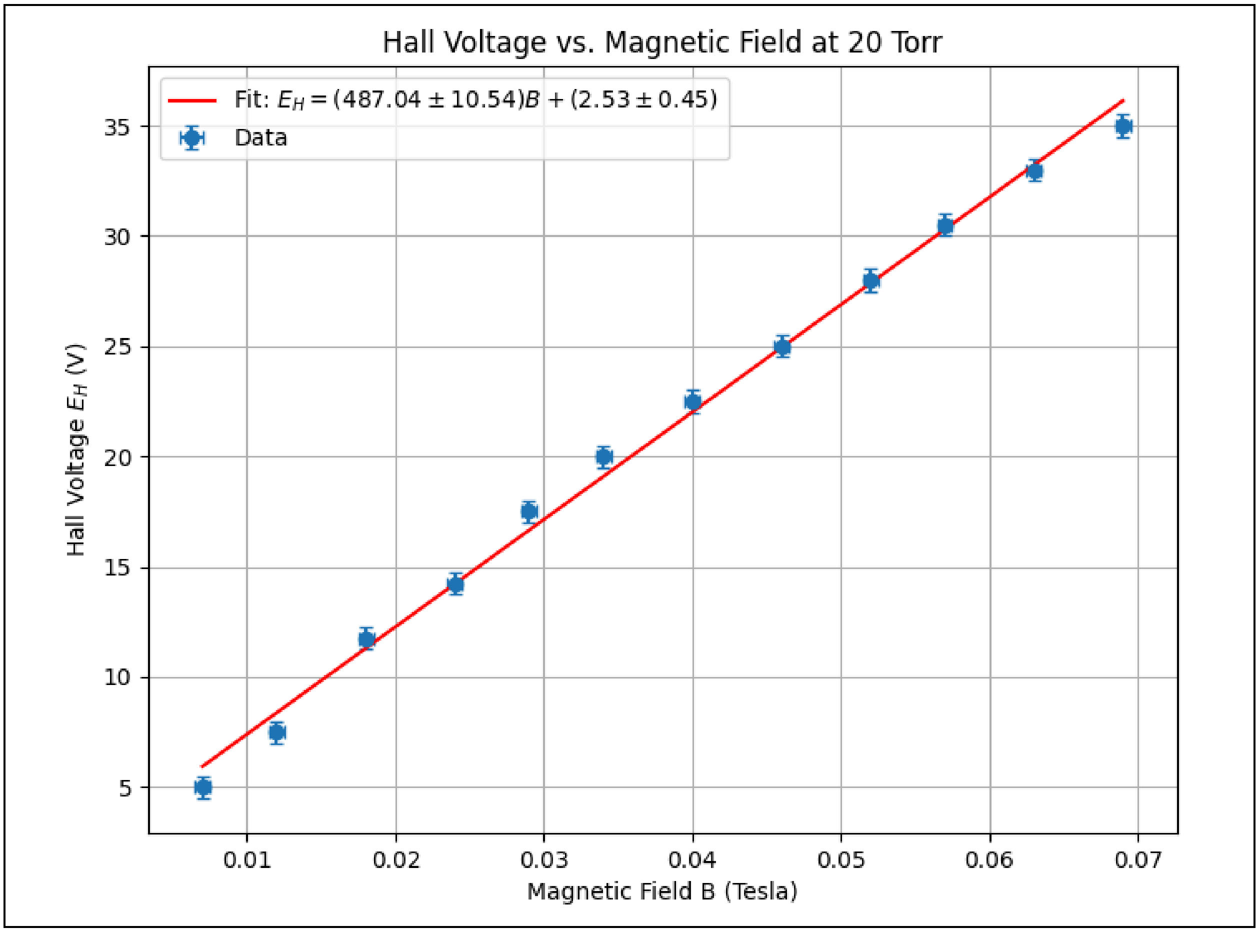
3. Measuring Hall Field vs. Magnetic Field (E_H vs. B)

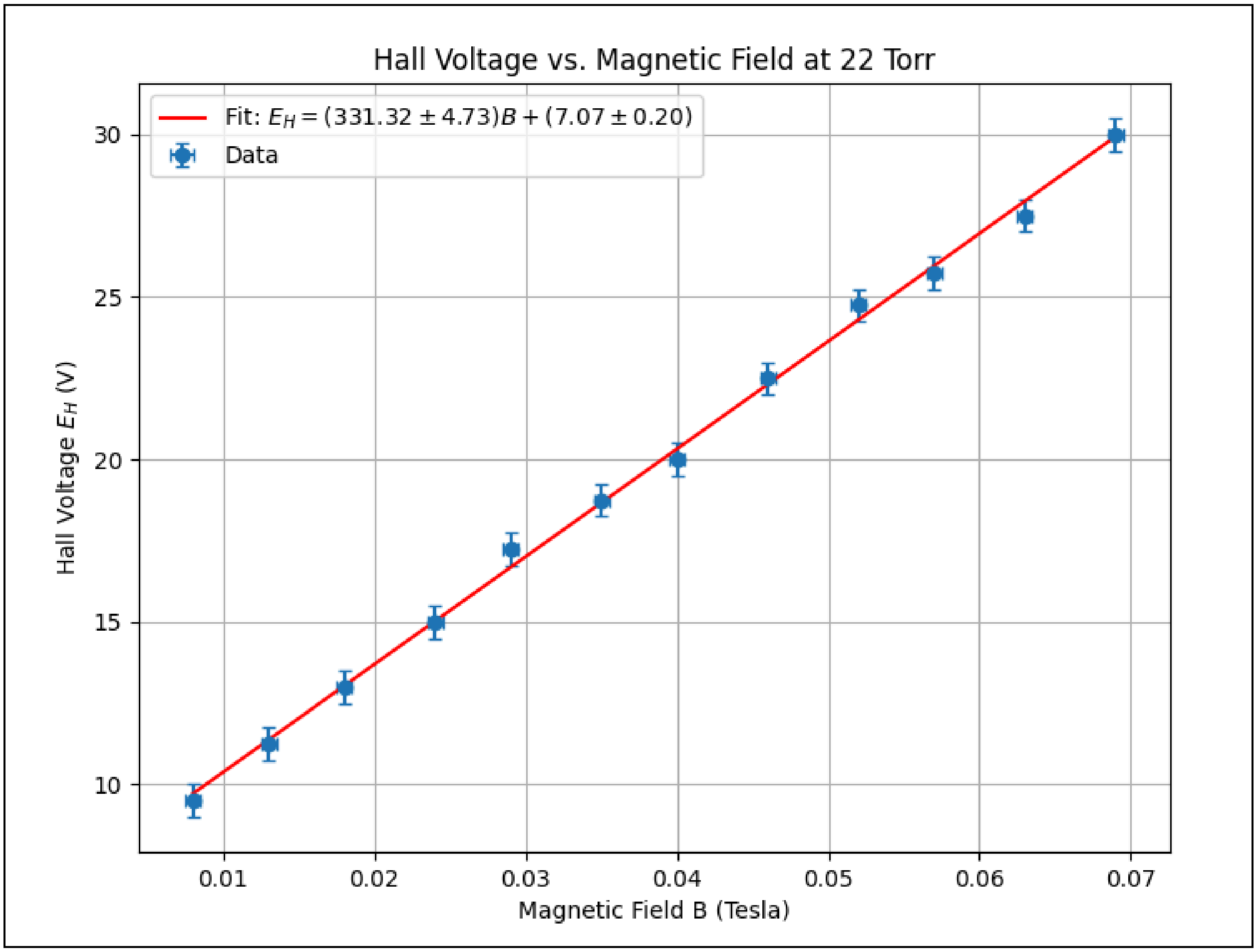
Here are the graphs of my data

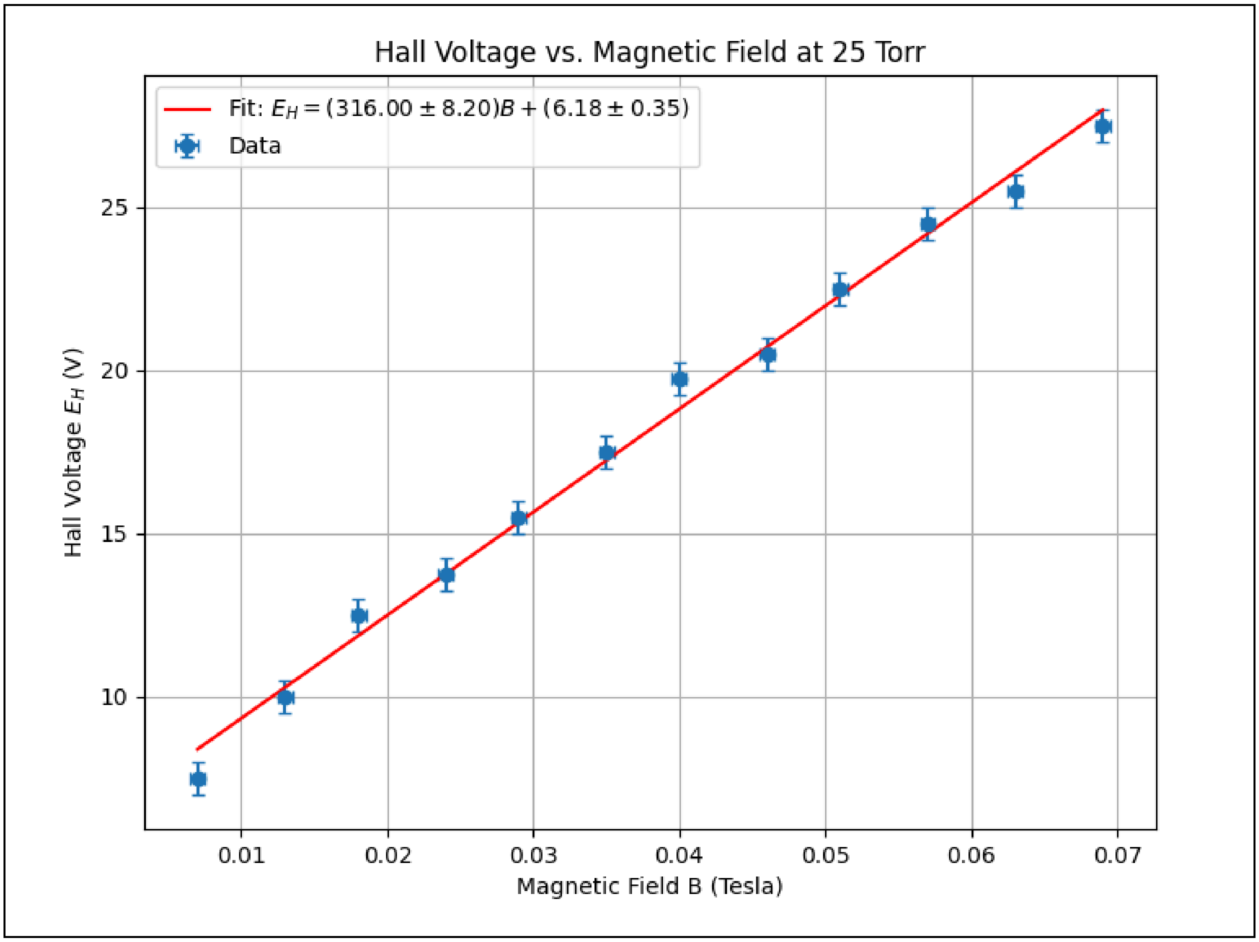

Hall Voltage vs. Magnetic Field at 15 Torr
Fit: $E_H = (443.75 \pm 8.10)B + (3.91 \pm 0.34)$
Data
Hall Voltage E_H (V)
Magnetic Field B (Tesla)
35
30
25
20
15
10
0.01
0.02
0.03
0.04
0.05
0.06
0.07

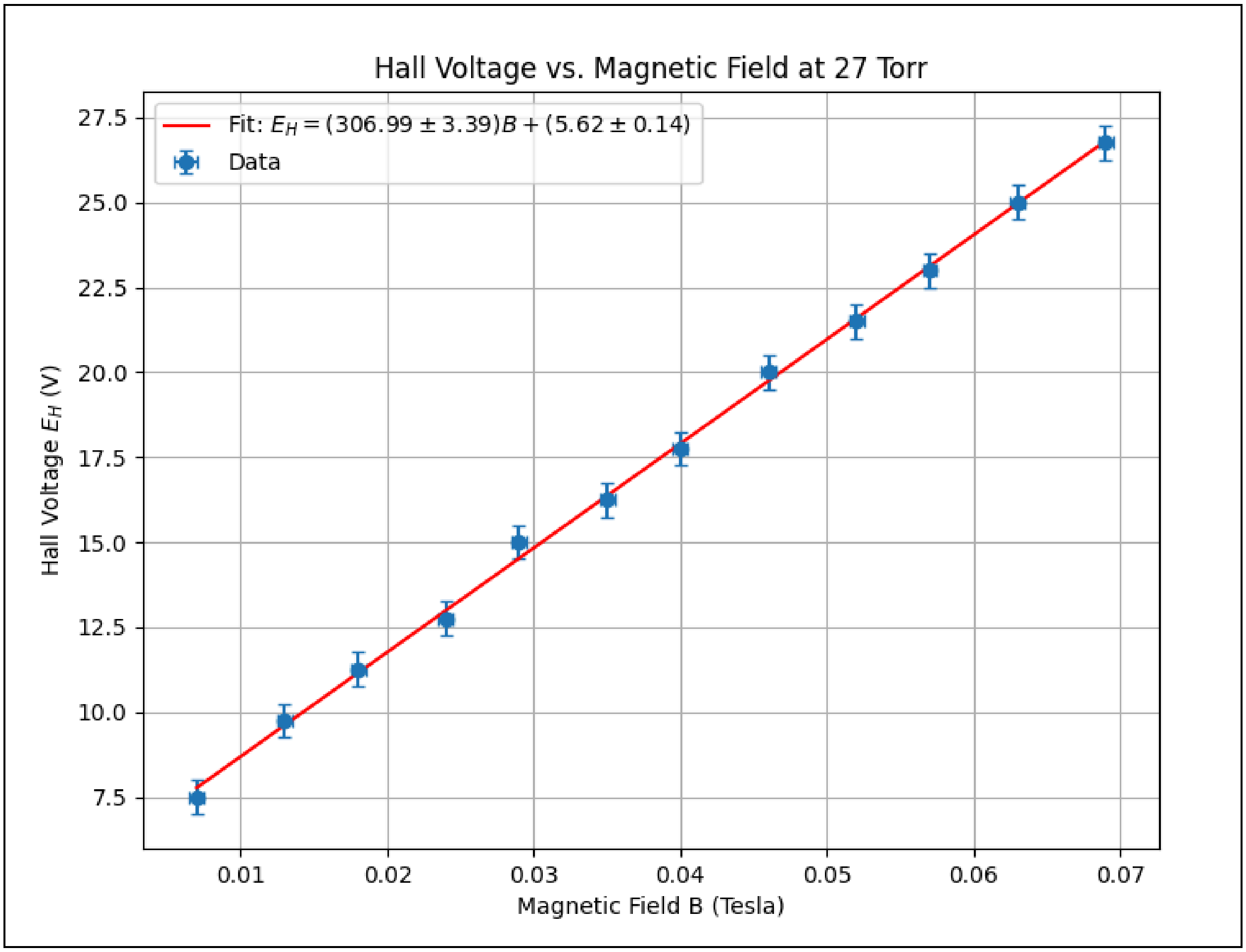
\


Hall Voltage vs. Magnetic Field at 17 Torr
Fit: $E_H = (437.40 \pm 15.68)B + (4.77 \pm 0.66)$
Data
Hall Voltage E_H (V)
Magnetic Field B (Tesla)
35
30
25
20
15
10
0.01
0.02
0.03
0.04
0.05
0.06
0.07


Hall Voltage vs. Magnetic Field at 20 Torr
Fit: $E_H = (487.04 \pm 10.54)B + (2.53 \pm 0.45)$
Data
Hall Voltage E_H (V)
Magnetic Field B (Tesla)
5
10
15
20
25
30
35
0.01
0.02
0.03
0.04
0.05
0.06
0.07


Hall Voltage vs. Magnetic Field at 22 Torr
Fit: $E_H = (331.32 \pm 4.73)B + (7.07 \pm 0.20)$
Data
Hall Voltage E_H (V)
Magnetic Field B (Tesla)
30
25
20
15
10
0.01
0.02
0.03
0.04
0.05
0.06
0.07


Hall Voltage vs. Magnetic Field at 25 Torr
Fit: $E_H = (316.00 \pm 8.20)B + (6.18 \pm 0.35)$
Data
Hall Voltage E_H (V)
25
20
15
10
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Magnetic Field B (Tesla)



Values:

Pressure: 15 Torr
Slope: 443.7474 ± 8.0976 V/T
Intercept: 3.9105 ± 0.3430 V
Reduced Chi-Squared: 1.18

Pressure: 17 Torr
Slope: 437.4006 ± 15.6814 V/T
Intercept: 4.7746 ± 0.6646 V
Reduced Chi-Squared: 4.46

Pressure: 20 Torr
Slope: 487.0438 ± 10.5393 V/T
Intercept: 2.5286 ± 0.4460 V
Reduced Chi-Squared: 2.02

Pressure: 22 Torr
Slope: 331.3237 ± 4.7254 V/T
Intercept: 7.0691 ± 0.2005 V
Reduced Chi-Squared: 0.39

Pressure: 25 Torr
Slope: 316.0045 ± 8.2042 V/T
Intercept: 6.1805 ± 0.3471 V
Reduced Chi-Squared: 1.20

Pressure: 27 Torr
Slope: 306.9930 ± 3.3880 V/T
Intercept: 5.6193 ± 0.1437 V
Reduced Chi-Squared: 0.21

For all pressures we can confirm a linear relationship with a pretty reasonable and low chi-squared value for each.

Now we will try to calculate quantities describing the electron gas and check if these values are reasonable:

Electron Drift Velocity (v_e)
v_e = E_H / B
Electron Density (n_e)
n_e = J / e*v_e *(We found J values in part 1)*
Electron Mobility (μ)
μ = v_e / E *(We found E field values in part 1)*
Collision Frequency (ν_e)
ν_e = e/ m_e*μ
Mean Free Path (λ)
λ = v_th / ν_e
where v_th = sqrt(8*k_B*T/π*m_e) (Thermal velocity)
Average Collision Cross-Section (⟨σ⟩)
⟨σ⟩=1/ngλ

With those calculations in mind I wrote python code (again, found in part 1 or the references) and I saved the data sheet in a csv so I uploaded it to google sheets for better viewing:
https://docs.google.com/spreadsheets/d/1tU_vFHIkrfrdH-BnDE8E5y2gszwdxI0sfPutYO_Px2E/edit?usp=sharing

Are the resulting values reasonable?
From what I looked online the Electron Drift Velocity, Electron Density, Mean Free Path, Thermal Velocity, Collision Frequency are all consistent.
But the Collision Cross-Section and electron Mobility are both just a little bit high

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Notable Errors
The most likely potential error could come from inaccurate readings of the discharge voltage and current. Changes in gas pressure, flow rate, or high-voltage settings may impact plasma stability, causing variations in measurements. Calibration issues with the oscilloscope or misalignment of probes could also lead to errors. In the lab it was difficult to maintain stable conditions sometimes but adjusting control settings helped reduce these issues along with just restarting the system.

Conclusion

This experiment allowed us to explore the Hall effect in a plasma and measure important electron properties in a glow discharge tube. We confirmed that the Hall voltage increases linearly with magnetic field strength, aligning with theoretical predictions. The electron drift velocities and densities we calculated fell within expected ranges for low-pressure plasmas, supporting the validity of our measurements. The higher values for electron mobility and collision cross-section suggest that further refinement in measurement techniques is needed. Overall, the study enhanced our understanding of plasma physics and demonstrated how electric and magnetic fields interact within a plasma.

References

1. https://experimentationlab.berkeley.edu/sites/default/files/writeups/HAL_Manual_2024-05-03.pdf
2. *http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html*
3. https://docs.google.com/document/d/1X8qgvojzq5QVjyJlYh954-sULS9y2qHAouesTDTMFiU/edit?usp=sharing