Lab 8: Solenoids

Overview
In this laboratory exercise, you will explore the magnetic field produced by a solenoid. In the process, you will use some basic physics from last semester to determine the magnitude of that magnetic field near the center of the solenoid. In the process, you will encounter the presence of the Earth’s magnetic field and its impact on your measurements as well.

Learning Objectives
- Analyze the magnetic field produced inside a solenoid
- Apply Newton’s Laws to a magnetic force problem
- Understand the impact of the Earth’s magnetic field on your results

Introduction
One hypothesis to be tested during the course of this laboratory exercise is that the magnetic field at the center inside a solenoid is directly proportional to the electric current flowing in the windings of the solenoid:

\[ B = \mu_0 n I_s \]  \hspace{1cm} (1)

where \( \mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m/A} \), \( n \) is the number of turns (“windings”) per unit length of the wire that forms the solenoid, and \( I_s \) is the current in the solenoid windings. This equation assumes that the solenoid is infinitely long, so is clearly an approximation.

In this lab, we’ll measure the magnetic field in the solenoid by measuring the force exerted on a wire (designated as the “balance wire”) carrying current inside the solenoid. If the current is set to flow perpendicularly to the magnetic field, the balance wire will feel force of

\[ F_B = ILB \]  \hspace{1cm} (2)

where \( I \) is the current flowing in the wire, \( L \) is the length of the balance wire feeling the force, and \( B \) is the magnitude of the magnetic field. Therefore, if we put a known amount of current through the balance wire and measure the force acting on it, we can find the magnetic field magnitude. Experimentally, even though this may seem backwards, the most straightforward and rigorous way to do this is to combine equations (1) and (2) to eliminate the magnetic field, giving

\[ F_B = IL(\mu_0 n I_s) \]  \hspace{1cm} (3)

Furthermore, it will be convenient to have the same current flowing in the solenoid as in the balance wire, so that we get
which shows that we should get a force that is proportional to the square of the current. Plotting the measured force versus the measured current squared, we should get a straight line. If we do, we have proven that the magnetic field inside a solenoid is linearly proportional to the current flowing in its windings. The slope of the line will also give us $\mu_0 n L$, which we can measure directly to compare against the fit.

**Procedure**

**Set up the balance**

The balance wire is printed onto a piece of plastic that can balance on pegs attached to the solenoid. Stick the part with the wire into the solenoid and adjust the position such that the piece is balanced. You may need to use small bits of masking tape to achieve balance. You will use this makeshift balance to determine the magnetic force on the wire by placing weights at the end to counteract the magnetic force. When balanced, the magnetic force will be equal to the counterweight. Use the supplied block of wood to mark the equilibrium position of the balance (you may place a mark on the wood).

![Balance wire diagram](image)

Figure 1. The balance wire is printed on a piece of plastic that will balance on pegs attached to the solenoid. Current flows through the pins to the wire. Insert the end of the balance with the connected wire into the solenoid.

**Set up the circuit**

Set up the circuit shown above. You want the current to come from the power supply, go through the ammeter, go through the balance wire, go through the solenoid, and then return to the power supply. **Do not turn on the power supply until I have checked your circuit. You must keep the current below 5 A otherwise you can melt the printed wire and its connectors.** Make sure that the voltage knob is turned all the way down before turning on the power supply. Turn
the power supply on, and then increase the voltage slowly while watching the balance. If the outside end of the balance moves **down**, reduce the voltage, turn off the power supply, and reconnect the circuit so that the outside end of the balance moves **up** when a current flows.

You may want to consider the physical orientation of your apparatus. Try to set it up so that the Earth’s magnetic field will have a minimal impact on your results.

**Prepare the counterweights**

Because the magnetic force will be quite small, you will need to use lightweight counterweights. You will use pieces of string or ribbon.

Carefully measure out about 1.0 m of the ribbon or string and weigh it. Figure out how much mass per unit length the ribbon has. Then cut off a length of the ribbon such that you have a piece that has a mass of about 20 mg. Make another piece with roughly twice this mass, and another with about 4 times the mass. Make sure to write down the mass of each piece in your notebook, along with the estimated uncertainty in each mass value.

**Take data**

Place the shortest piece of ribbon or string on the outer end of the balance. Try to place it as close to the edge as possible (why is this important?).

Slowly increase the current flowing in the current element and solenoid by slowly increasing the voltage from the power supply until the balance reaches the same equilibrium position as when no current was flowing and no string weights were present. In Excel, record the length of the string and the current needed to achieve balance.

Repeat these measurements using a different piece of string, so that you have at least 5 data points. The upper limit on the force is determined by the current at which the balance wire connections start to melt. This is approximately 5 Amperes. **Keep the current below 5 A.**

**Analyze the data**

Use Excel to make a plot of the magnetic force (which is equal to the counterweight) versus the square of the current. As discussed in the introduction, this should be a straight line. In your figure caption and your analysis section, discuss the shape of the curve and its implications. Add a trendline to determine the slope. Also perform a regression analysis for more complete information.

One of the simpler items to check is the intercept value. What should the intercept be? Does your value agree with the theory? If not, try to explain the discrepancy.

You can calculate the expected value for the slope by making measurements of the solenoid. Measure the length of the solenoid, then count the number of turns on the solenoid (OUCH! There are a lot of them!)
How does your calculated value of the slope compare to the value given by the regression? Likely, it will be a bit different.

**Turn it in!**

- Completed worksheet.
- A plot (correctly labeled) made using Excel of the $F_b$ vs $I^2$. Add the regression line (line-of-best-fit) to the plot.
Worksheet for Lab 8: Solenoids

Measurements:

Length of balance wire: ____________
Length of solenoid: ____________ Number of turns on the solenoid: ____________
Number of turns per unit length: ____________
Show calculation here:

Mass of string: ____________ Length of string: ____________
Mass per unit length of string: ____________
Show calculation here:

Apparatus Orientation:

Sketch here the orientation of your solenoid and the balance wire with respect to the Earth’s field. Justify your orientation.
Data:

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<thead>
<tr>
<th>Mass (kg)</th>
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Regression Fit:

Slope (with units & uncertainty): __________________________ +/- __________________________

Intercept (with units & uncertainty): __________________________ +/- __________________________

Calculated number of turns per unit length based on data above: _________________

Percent difference from actual value (see last page): _________________ %

Show calculation for percent difference:

Comments:

Discuss the quality of your results. From where do the errors come? How could you improve this experiment if you did it again from scratch?