Lab # 8 – On axis Magnetic Fields of Various Coils

Objectives

In this lab you will:

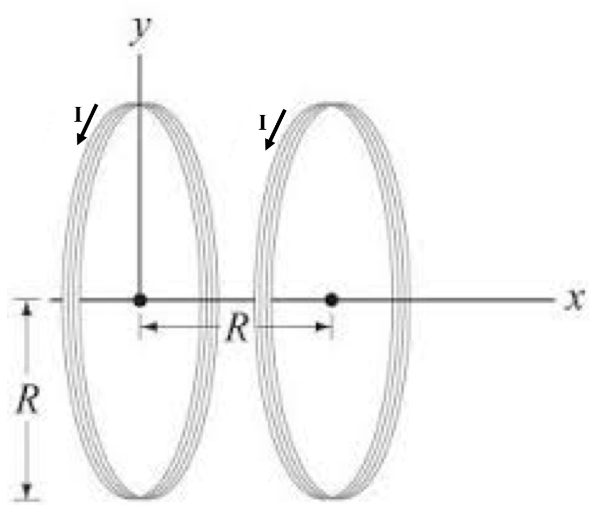
- Measure the magnetic field of various coils along their central axes and compare your measurements to the theoretical predictions coming from the Biot-Savart law. We will do this for four types of coils: single coils, Helmholtz coils, Anti-Helmholtz coils, and solenoids. Make extra effort to treat this equipment carefully.

For this lab, you will need:

- Two red banana cables
- Two black banana cables
- One PASCO track with magnetic field sensor, a rotary motion sensor, two 500–turn coils, and a PASCO red solenoid

1: Warm-Up Problem

Consider two coils that share a common central axis, which we call the x-axis. The coils are at positions $x = 0$ and $x = +R$, each carry a current I, and have N turns of wire. This coil configuration is called a "Helmholtz coil." (Although not drawn, if one of the coils would have had current in the oppoiste direction, the coil configfuration is called an "anti-Helmholtz coil.")

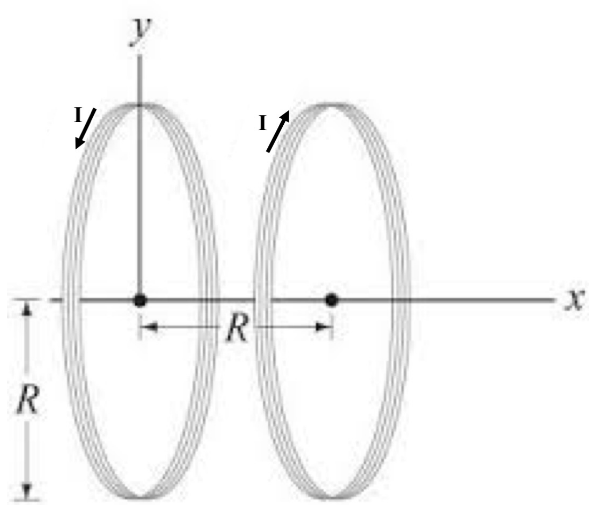


1. Write down a symbolic expression for the magnetic field along the x-axis. Do not erase any of your work until you are done with the whole warm up problem.

2. What is the magnetic field along the central axis at position $x = +\frac{R}{2}$? Save your reselt for later in the lab.

3. What is the derivative of the magnetic field along the x-axis with respect to x? Evaluate it at $x = +\frac{R}{2}$. (It might be more time-efficient to make sure you are on the right path with a TA now.)

4. If the direction of the current in the second coil is the opposite direction (new figure below), what is the expression for the the magnetic field along the x-axis? This coil configuration is called an "anti-Helmholtz coil."



5. Now what is the magnetic field along the central axis at position $x = +\frac{R}{2}$?

6. Now calculate the derivative for the magnetic field along the x-axis as a function of x. Evaluate it at $x = +\frac{R}{2}$ and save the result for later in the lab.

Checkpoint 1: Ask an instructor to check your work for credit.
You may proceed while you wait to be checked off.

2: $|\vec{\mathbf{B}}_{\mathbf{Axis}}|$ of a Single Coil

We will investigate how the magnetic field produced by a coil changes along its central axis. You will be using the first tab in the PASCO Capstone workbook to record your data in this section. For this lab, assume that magnetic fields are measured in Tesla, current in amps, and distances in meters unless otherwise stated.

1. Connect the coil furthest from the rotary motion sensor to the PASCO universal power supply so that current flows in the same direction as the figure in the warm up problem. Consider the manner in

which you have connected the banana plugs to the coil. Which way will the current flow through the coil? What will the direction of the resultant magnetic field at the center of the coil be? You need to make sure that the magnetic field that the probe measures is positive (which is for fields pointing into the tip toward the base of the sensor), or the fit may not work. This is also true for the Helmholtz Coil and the solenoid.

2. Check that the coils are near the 25/35 cm mark on the track.
3. Align the magnetic probe with the axis of the coil such that its tip is at the 0 cm mark on the track and that the tip points away from the rotary motion sensor.
4. Use banana cables to electically connect output 1 of the power supply to the coil furtherest from the rotary motion sensor. Hook the positive end up to the off white connection at the base of the coil, and the ground terminal to the black connection.
5. Throughout the lab, inspect to make sure that the central axis of the coils lines up with the path that the magnetic probe will take as it slides down the track. You may adjust the height of the track only if it needs adjustment.
6. "Tare," i.e. zero the magnetic field sensor.
7. Click on the *Signal Generator* menu option on the left hand side of your Capstone workbook.
8. Under *850 Output 1* click *On* to apply 15 V to the output of the power supply (the resistance of the each coil is $\approx 18 \pm 1\,\Omega$).
9. Click the *Signal Generator* button again to close the Signal Generation menu.
10. Hit the *Record* button on the bottom of the workbook.
11. Slowly pull the sensor along the central axis of the coils. Make sure that the distance sensor pulley has the string over the largest diameter circle. The rotary motion sensor needs to rotate freely or the position of the probe will not be recorded correctly. When you are ready to take data, gently lower the weight until it is hanging off of the table so it puts some tension on the string. Data taking needs to have the magnetic field sensor go slowly towards the rotary motion sensor.
12. Hit the *Stop* button on the bottom of the workbook once you have covered as much distance as is possible.
13. Click the *Signal Generator* button again.
14. Under *850 Output 1* click *Off*.
15. Does the direction of the magnetic field you observed correspond to what you expected?
16. Click on *Curve Fit Editor* and enter the equation for the magnetic field of a single coil:

    ```
    y=2*3.1415*10^(-7)*500*I*R^2/(R^2+(x-x0)^2)^(3/2)
    ```

17. You may copy the formula, but you must understand what all of the symbols physically refer to. What does 500 correspond to? What is x0? What is x? What is I? What is R?
18. Make sure that the correct data run is selected
19. Click *Apply* in the *Curve Fit Editor* window.
20. Click on the *Curve Fit Editor* button again to close the Curve Fit Editor menu.

21. Adjust the data points using the highlight tool until the experimental data is well fit by the continuous (theoretical) curve. You may have to remove the last data point by right clicking on it in the table, or retake your data.

22. Based on the fit, you will see two different parameters displayed below the graph, namely the current I and the radius of the coil R. How do these values compare to the actual value of the current and the radius of the coil?

23. The magnetic field at the center of the coil is theoretically $\frac{\mu_0 NI}{2R}$, how does your experimental value compare to this?

24. Suppose that you had 3.14m of coil available, and wanted to use it to create a magnetic filed with the greatest strength possible, which arrangement would achieve that: a coil of 10cm in diameter and 100 turns, or a coil of 20cm in diameter and 50 turns?

Checkpoint 2: Ask an instructor to check your work for credit.
You may proceed while you wait to be checked off.

3: $|\vec{\mathbf{B}}_{\mathbf{Axis}}|$ of a Helmholtz Coil

A Helmholtz coil consists of two identical coils, placed symmetrically along a common central axis. The defining characteristic of a Helmholtz coil is that the two coils are separated by a distance equal to the radius of each coil and that current is driven in the same direction through both. This creates a nearly uniform magnetic field at the center of the coils. Connect the second coil into your circuit from section 1, in parallel with the first coil. Make sure to connect the coils such that the current flows through each coil in the same direction. You will be using the second tab in the PASCO Capstone workbook, labelled *Helmholtz*, to record your data in this section. The steps for measuring the magnetic field along the axis are basically the same as before, and are repeated below.

1. Taking into consideration the expression for the magnetic field you derived in the warm-up problem, sketch the expected magnetic field strength along the central axis of the Helmholtz coil pair.

2. Align the magnetic probe with the axis of the coils such that its tip is at the 0 cm mark on the track and that the tip points away from the rotary motion sensor.

3. "Tare," i.e. zero the magnetic field sensor

4. Assuming that you left the first coil connected to the power supply, connect the second coil as follows: use a bannana cable to connect the off white connector of the coil furthest from the rotary motion sensor to the black connector of the coil closer to the rotary motion sensor and use a second cable to connect the black connector of the furthest coil to the white connector of the coil closer to the rotary motion sensor. Make sure that your coils are connected in parallel and not in series.

5. Click on the *Signal Generator* menu option on the left hand side of your Capstone workbook.

6. Under *850 Output 1* click *On* to apply 15 V to each coil.

7. Click the *Signal Generator* button again to close the Signal Generation menu.

8. Hit the *Record* button on the bottom of the workbook.

9. Slowly pull the sensor along the central axis of the coils. Make sure that the distance sensor pulley has the string over the largest diameter circle.

10. Hit the *Stop* button on the bottom of the workbook once you have covered as much distance as possible.

11. Click the *Signal Generator* button again.
12. Under *850 Output 1* click *Off*.
13. How does the observed variation of the magnetic field strength correspond to the your expected behavior? Think back to your answers to the warm up problem.
14. Click on *Curve Fit Editor* and enter the equation for the magnetic field of a Helmholtz coil.

```
y=(2*3.1415*10^(-7)*500)*I*R^2*(1/(R^2+(x-x0+0.05)^2)^(3/2)+1/(R^2+(x-0.05-x0)^2)^(3/2))
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15. You may copy the formula, but you must understand what all of the symbols physically refer to. What does 500 correspond to? Why do +.05 and -.05 appear in the denominators? What is x0? What is x? What is I? What is R?
16. Make sure that the correct data run is selected.
17. Click *Apply* in the *Curve Fit Editor* window.
18. Click on the *Curve Fit Editor* button again to close the Curve Fit Editor menu.
19. Adjust the data points using the highlight tool until you see that the experimental data is well fit by the continuous (theoretical) curve.
20. What is the behavior of the magnetic field between the two coils? Try to estimate the rate of change along the central axis of the Helmholtz coil, in the region between the two coils. Does the behavior match the theoretical prediction?
21. Considering the observed behavior of the magnetic field between the two coils, suggest possible applications of Helmholtz-coils.
22. Suggest how you would try to alter the experimental setup to reduce any observed variations in the magnetic field strength between the the coils.
23. Based on the fit, you will see four different parameters displayed below the graph, namely the current I, radius of each of the coils R, x_0, and the root-mean square error $RMSE$. Compare the values of I, R and x_0 from the fit with the actual values. If any of them are inconsistent, explain the cause of that inconsistency.
24. The theoretical value of the magnetic field of a Helmholtz coil is $\frac{8}{5\sqrt{5}}\frac{\mu_0 NI}{R}$ at its center, how does your experimental value compare to this?

Checkpoint 3: Ask an instructor to check your work for credit.
You may proceed while you wait to be checked off.

4: $|\vec{\mathbf{B}}_{\mathbf{Axis}}|$ of an Anti-Helmholtz Coil

Anti - Helmholtz coils, like Helmholtz coils, are also widely used in physics experiments. They differ from the Helmholtz coils in that, instead of producing a constant magnetic field near their center, they produce a magnetic field that varies linearly along the central axis, that is, the magnetic field has a constant spatial gradient. (In fact, Anti-Helmholtz coils produce a magnetic field with zero magnitude at their center). The coils of an Anti-Helmholtz coil are aligned to produce opposing magnetic fields along their shared central axis. (The coils of a Helmholtz coil produced magnetic fields in the same direction along the central axis.) The steps for measuring the magnetic field along the axis are basically the same as before, and are repeated below.

Experimental steps:

1. In the PASCO Capstone workbook, click the third tab which says Anti-Helmholtz. This will open a blank workbook which will record data from the magnetic field probe.
2. Align the magnetic probe with the axis of the coil with its tip at the 0 cm mark on the track and such that the tip points away from the rotary motion sensor.
3. "Tare," i.e. zero the magnetic field sensor
4. Swap the bannana cables on the coil between furthest coil and the rotary motion sensor. You now have an anti-helmholtz coil.
5. Click on the Signal Generator menu option on the left hand side of your Capstone workbook.
6. Under 850 Output 1 click on. Current is now running through your circuit.
7. Click the Signal Generator button again to close the Signal Generation menu.
8. Hit the Record button on the bottom of the workbook. It will turn into the Stop button.
9. Slowly pull the sensor along the central axis of the coils. Make sure that the distance sensor pulley has the string over the largest diameter circle.
10. Hit the Stop button on the bottom of the workbook once you have covered as much distance as is possible.
11. Click the Signal Generator button again.
12. Under 850 Output 1 click off.
13. Click on Curve Fit Editor and make sure the equation is correct for an Anti-Helmholtz coil configuration:

    ```
    y=(2*3.1415*10^(-7)*500)*I*R^2*(1/(R^2+(x-x0+0.05)^2)^(3/2)-1/(R^2+(x-0.05-x0)^2)^(3/2))
    ```

14. You may copy the formula, but you must understand what all of the symbols physically refer to. What does 500 correspond to? Why do +.05 and -.05 appear in the denominators? What is x0? What is x? What is I? What is R? Why is there a - in this equation but in the formula for the Helm-Holtz coils, there was a +?

15. Make sure that the correct data run is selected
16. Click Apply in the Curve Fit Editor window.
17. Click on Curve Fit Editor button again to close Curve Fit Editor menu.
18. Adjust the data points using the highlight tool until you see that the experimental data is well fit by the continuous (theoretical) curve. You may have to remove the last data point by right clicking on it in the table.

Observe the plots. See how the magnetic field varies nearly uniformly near the center of the anti-Helmholtz coils. From your graph, estimate the rate (in T/m), near the center, at which the magnetic field varies with respect to the distance along the central axis. This is the most important property for an Anti-Helmholtz coil. Compare your experimental value to the theoretical value for the magnitude of that rate of change:

$$\frac{48}{5^{2.5}}\frac{\mu_0 NI}{R^2} \tag{11.1}$$

Based on the fit, you will see 4 different parameters displayed below the graph: the current I, the radius of each coil R, the initial position of the magnetic probe sensor x0, and root-mean square error RMSE. How do I, R and x0 compare with their actual values? If any of them are inconsistent, explain the cause of that inconsistency or try retaking the data.

Checkpoint 4: Ask an instructor to check your work for credit.
You may proceed while you wait to be checked off.

5: $|\vec{\mathbf{B}}_{\mathbf{Axis}}|$ of a Solenoid

Like a Helmholtz coil, a solenoid is another device that creates a reasonably uniform magnetic field on its inside. A solenoid is a coil whose length is greater than its diameter, with many turns of coil. You will measure this constant magnetic field along the central axis of the solenoid and compare it to the theoretical value, you will also see when the magnetic field begins to deviate from this constant value.

Place the provided red solenoid such that its square edge is aligned with the 0 cm mark of the track. Connect the power supply just to the solenoid using two of the banana cables. In the PASCO Capstone workbook, click the fourth tab labelled Solenoid. This will open a blank workbook which will record data from the magnetic field probe. The steps for measuring the magnetic field along the axis are basically the same as before, and are repeated below.

Experimental steps:

1. Place the probe of the magnetic field sensor inside the solenoid, with the probe aligned with the solenoid axis and such that the tip points away from the rotary motion sensor.
2. "Tare," i.e. zero the magnetic field sensor
3. Disconnect all the bananan cables from the coils, from other bannana cables. Then hook up the positve terminal of output one to the connection of the solenoid furthest from the rotary motion sensor, and the ground terminal to the end closer to the rotary motion sensor.
4. Click on the Signal Generator menu option on the left hand side of your Capstone workbook.
5. Under 850 Output 1 click on to apply $15V$ to output 1 (the resistance of the solenoid is $\approx 76 \pm 3\,\Omega$). Current is now running through your circuit. The solenoid should be receiving 0.2 A of current.
6. Click the Signal Generator button again to close the Signal Generation menu.
7. Hit the Record button on the bottom of the workbook. It will turn into the Stop button.
8. Slowly pull the sensor along the central axis of the solenoid. Make sure that the distance sensor pulley has the string over the largest diameter circle.
9. Hit the Stop button on the bottom of the workbook once the probe is 5-10 cm away from the solenoid.
10. Click the Signal Generator button again.
11. Under 850 Output 1 click off.

12. Click on Curve Fit Editor and make sure the equation is correct for the Solenoid configuration, that is, y =

```
10^(-7)*2*3.14*2920*I/0.12*((x-x0+0.06)/((x-x0+0.06)^2+R^2)^(1/2)-(x-x0-0.06)/((x-x0-0.06)^2+R^2)^(1/2)
```

11. You may copy the formula, but you must understand what all of the symbols physically refer to. What does 2920 correspond to? Why does +.06 appear in the denominators? What does .12 correspond to? What is x0? What is x? What is I? What is R?

12. Make sure that the correct data run is selected.

13. Click Apply on the Curve Fit Editor.

14. Click on Curve Fit Editor button again to close Curve Fit Editor menu.

15. Adjust the data points using the highlight tool until you see that the curve fits well with the continuous (theoretical) curve. You may have to remove the last data point by right clicking on it in the table.

Observe the plots. How uniform is the magnetic field within a distance of 1cm from the center of the solenoid? By what percentage does it vary? What could be possible reasons for any discrepancies? Also examine the region where the magnetic field begins to deviate from the constant value. Does the position that it begins to deviate make sense?

Based on the fit, you will see 4 different parameters displayed below the graph: current I, radius of solenoid R, initial displacement between the probe tip and the center of the solenoid x0, and the root-mean square error RMSE. Compare I, R and x0 with their actual values. Are they reasonable? What could be possible reasons for the differing values?

Inside a solenoid, the constant magnetic field should be $\frac{\mu_0 N I}{L}$, how does your experimental value compare to the predicted value? If it disagrees significantly, explain the disagreement or try redoing the experiment.

Make sure that the you turn your power supply off and clean up your lab station.

Checkpoint 5: Ask an instructor to check your work for credit.
You may proceed while you wait to be checked off.