2EM7

Magnetic fields of Helmholtz coils (HC)

THEORY

Single coil

For a coil of wire having radius R and N turns of wire, the magnetic field along the perpendicular axis through the center of the coil (x is the distance from the center of the coil) is given by

$$B = \frac{\mu_o NIR^2}{2\left(x^2 + R^2\right)^{\frac{3}{2}}} \qquad (1)$$

The magnetic field at the center of the coil is obtained by setting x=0, to give

$$B_0 = \frac{\mu_0 NI}{2R}$$

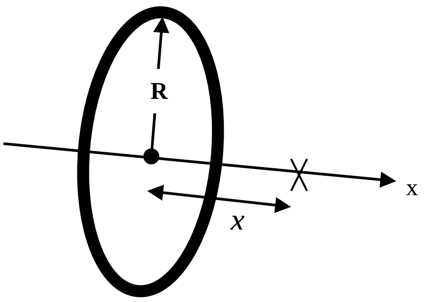

Figure 1: Single coil

Two coils

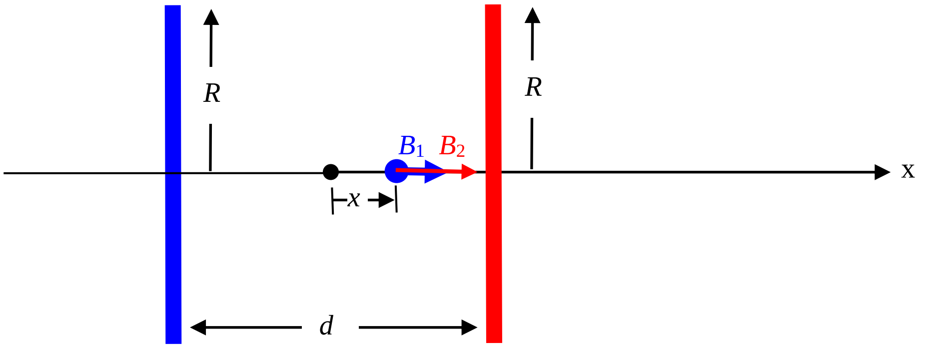

Figure 2: Two coils with arbitrary separation

For two coils, the total magnetic field is the sum of the magnetic fields from each of the coils.

$$\vec{B} = \vec{B}_1 + \vec{B}_2 = \frac{\mu_o NIR^2}{\left(\left[\frac{d}{2} - x\right]^2 + R^2\right)^{\frac{3}{2}}}\hat{x} + \frac{\mu_o NIR^2}{\left(\left[\frac{d}{2} + x\right]^2 + R^2\right)^{\frac{3}{2}}}\hat{x} \qquad (2)$$

For Helmholtz coils, the coil separation (d) equals the radius (R) of the coils. This coil separation gives a uniform magnetic field between the coils. Plugging in $x = 0$ gives the magnetic field at a point on the x-axis centered between the two coils:

$$\vec{B} = \frac{8\mu_o NI}{\sqrt{125}R}\hat{x} \qquad (3)$$

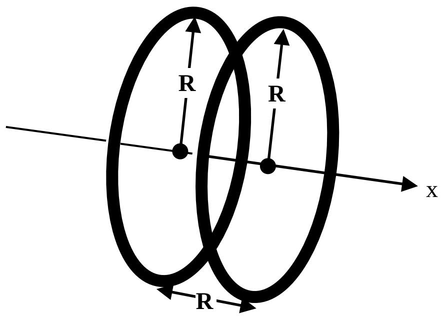

Figure 3: Helmholtz coils

INTRODUCTION

The magnetic fields of various coils are plotted versus position as the Magnetic Field Sensor is passed through the coils, guided by a track. The position is recorded by a string attached to the Magnetic Field Sensor that passes over the Rotary Motion Sensor pulley to a hanging mass.

It is particularly interesting to compare the field from Helmholtz coils at the proper separation of the coil radius to the field from coils separated at less than or more than the coil radius.

Preparatory Procedure for the Magnetic field sensor and Rotary motion sensor

1. Switch on the computer, without the PASCO ScienceWorkshop 750 USB connected to it. After Windows has been up, switch on and connect the ScienceWorkshop 750 interface to the PC's USB interface.

2. Launch Data studio, either by clicking the icon in the desktop or Start → All Programs → Data Studio → Data Studio.

3. When the Data studio is launched you will be prompted a 'Welcome to DataStudio' message. You should click 'Create Experiment'. A screen with the title `Experimental Setup` will be launched. If everything goes accordingly, you should also see at the bottom of the screen the statement ‘The interface is ready for use.’

4. Plug in both the yellow and black jacks of the rotary motion sensors into the holes labeled '1' and '2' of the 750 interface. Point the mouse to the hole '1' on the picture of the Scientific Interface 750 on the screen. You will be prompted a drop-down windows 'choose sensors or instrument'. Choose 'rotary motion sensor`.

5. In the `visibility, name` (under the `measurement` tab), check `position, Ch 1 & 2`. Leave the sample rate at the default value of 10 Hz. If the instrument is successfully added, you shall see the icon of labeled `position, Ch 1 & 2 (m)` appears on the upper left-hand panel ('data').

6. On the lower left panel, under the 'Displays' tab, double click on 'graph' to display the graph of position (m) vs. time. Click on 'start' to see if the rotary motion is responding correctly by manually rotate the rotational sensor. Note that the Rotary Motion Sensor can be reversed in Channels 1 and 2 to change which direction of rotation is positive. You may also have to adjust the scale of the *y*-axis so that the change in the reading of position of the rotary motion is visually more apparent. The rotary motion sensor has to be also properly calibrated. There are three pulleys of different sizes on the rotary motion sensor. Choose the pulley of a right size. Calibrate the rotary motion sensor such that when the string is displaced for a distance of 60 cm along the tract over the pulley, the reading on the screen also shows a corresponding reading of 60 cm.

7. For current connection to the Helmholtz coil (HC): connect the terminals in series to the output of the power supply. You should use d.c. source. This can be done by setting the frequency of the power supply to 0. Connect the ammeter in series to measure the current through the HC. The current has to measure at the order of ~1A (but less than 2A) to deliver a detectable magnetic field to the HC.

8. Plug in pin of the magnetic sensor into the holes labeled 'A' of the 750 interface. Point the mouse to the hole 'A' on the picture of the Scientific Interface 750 on the screen. You will be prompted a drop-down windows 'choose sensors or instrument'. Choose 'magnetic field sensor`.

9. In the `visibility, name` (under the `measurement` tab), check only `Magnetic field strength (10x), Ch A (gauss)`. Leave the sample rate at the default value of 10 Hz. If the instrument is successfully added, you shall see the icon of labeled ` Magnetic field strength (10x), Ch A (gauss)` appears on the upper left-hand panel ('data').

Now, calibrate the magnetic field sensor as follows:

1. Set the ‘Range Select’ switch on the magnetic sensor to ‘10X’.

2. Click 'Calibrate Sensors' tab. Choose 'Magnetic Field Strength (10X), Ch A (gauss). Click on the drop-down window, choose ' Magnetic field strength (10x), Ch A (gauss)`.

3. Leave the 'Calibrate all similar measurements simultaneously' unchecked.

4. Check '2 point (Adjust Slope and Offset)' in the calibration Type.

5. Set standard value to '0 gauss' for Calibration Point 1.

6. Put the magnetic sensor aside where it is far from any strong magnetic source. In the `Calibration Point 1’ panel, click 'Read from Sensor' while pressing 'TARE' button on the magnetic sensor.

7. Leave the Calibration Point 2 at Standard Value 100 gauss, Sensor Value at 10 V.

8. In the 'Display' panel on the lower left of the DataStudio screen, double click 'graph' to show the graph of Magnetic field strength (10x)(gauss) vs. Time (2). Click 'start'.

9. Check that the magnetic sensor is responding properly by drawing it close to and from a magnetic source, such as a Helmholtz coil with d.c. current running. You may also have to adjust the scale of the *y*-axis so that the change in the reading of the magnetic sensor is visually more apparent.

Once the above preparation actions have been carried out, try to familiarise yourself with the functionality of the DataStudio. Then, begin the experiments proper as instructed in the next session.

Experiment 1: Single coil

SET UP

1. Attach a single coil to the Helmholtz Base. Connect the DC power supply across the coil, i.e., between the two while jacks (NOT across the coil's internal resistor of 1.2 kΩ). To measure the current through the coil, connect the ammeter in series with the power supply and the coil. See Figure 5. The current should not exceed 2A.

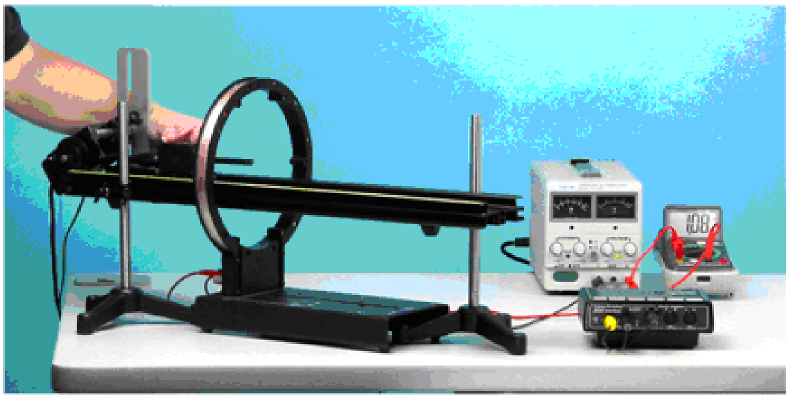

Figure 5: Single Coil Setup

2. Make sure that the magnetic field sensor and the rotary motion sensor are working properly according to the section *Preparatory Procedure for magnetic field sensor and Rotary motion sensor* earlier.

3. Pass the optics track through the coil and support the two ends of the track with the support rods or aluminium table (with adjustable height). Level the track and adjust the height so the Magnetic Field Sensor probe will pass through the center of the coil when it is pushed along the surface of the track.

4. Attach the Rotary Motion Sensor to the track using the bracket. Cut a piece of thread long enough to reach from the floor to the track. Tape one end of the thread to the side of the Magnetic Field Sensor and pass the other end of the thread over the middle step of the Rotary Motion Sensor pulley and attach the 20-g mass. Place the Magnetic Field Sensor in the center of the track and adjust the position of the Rotary Motion Sensor so the thread is aligned with the middle step pulley.

5. Turn on the DC power supply and adjust the voltage so about 1 Amp - 2 Amp flows through the coil. Turn the DC power supply off at the switch.

PROCEDURE

1. Find the radius of the coil *R* by measuring the diameter from the center of the windings on one side across to the center of the windings on the other side.

2. Turn on the DC power supply. Measure the value of current with the ammeter. Fix (using the 'amplitude' knob of the current generator) and measure the current *I* using the ammeter.

3. Measure *B* by varying the position in one direction. Do this by Clicking on START in DataStudio and slowly move the Magnetic Field Sensor along the center of the track, keeping the probe parallel to the track. On your DataStudio screen, you now have two graphs displayed: displacement traversed by the Magnetic Field Sensor measured from the point where you start to push the sensor (ℓ) vs. *t* graph, and a *B* vs. *t* graph.

4. Combining the graphs of magnetic field vs. time (from magnetic field sensor) and ℓ vs. time from rotary motion sensor will allow you to obtain the information of magnetic field strength as a function of position along the optics track. The *B* vs. ℓ graph can be obtained as follow: Create a blank graph by right clicking on the `graph` icon in the 'Display' panel on the lower left of the DataStudio screen. Drag the *B* vs. *t* graph and drop it to the blank graph. Then drag the ℓ vs. *t* graph and drop it on the ℓ-axis of the *B* vs. *t* graph. Combination of both graphs can alternatively be done using Excel sheet if you prefer not to do it in the DataStudio.

5. Repeat steps 3, 4 in the opposite direction.

6. Obtain the corresponding value of *x* for each ℓ measured using Excel sheet. Note that the value of ℓ measured is not the quantity *x* appearing in Eqs. (1), (2) and Figures 1, 2. Here, you have to figure out a proper way to relate ℓ and *x*.

   Before performing the procedure above, please read the following:

   By symmetric argument, if the detector is moving along the symmetric axis of the HC, the form of *B* as a function of ℓ should also be symmetric about the center of the HC; it is otherwise if the detector is not moving along the symmetric axis. Optimise your measurement using this argument as a guidance to produce a measurement of *B* that is as closed as possible stick on the axis of symmetry.

Data manipulation and interpretation

1. By using Excel sheet, plot a graph of *B* vs. *x* based on the theoretical function Eq. (1). Overlap the data points of *x* and *B* measured from the experiment on the same plot. Compare and comment on the agreement of both plots.

2. Plot the theoretical (based on Eq. (1)) and experimental (based on experimental data) curves of $\ln B$ vs. $\ln\left[1+\left(\frac{x}{R}\right)^2\right]$ on the same graph. Deduce the theoretical and experimental gradient of both log-log graphs. Also deduce the standard error of the gradient of the experimental curve. To this end,

you have to use the least-square method to calculate the gradient and its standard error.

3. Compare the measured value of the gradient with the theoretical one. Your comparison should take into account of the standard error of the gradient as deduced from step (2) above.

Note that if your measurement is done properly (with *B* field symmetric about the center of HC along the symmetric axis), with the magnetic field sensor being moved on a perfect straight line in parallel to the axis and going through the center of and the HC, you would have a perfect fit between the experimental and theoretical curves of the log-log graph. Any deviation from the ideal axis will show up in the mismatch of your experimental data when fitted against the theoretical curve.

4. From the experimental graph obtained, deduce the experimental value of B_0, the magnitude of **B** when $x = 0$.

5. Using the values of *I*, *N*, *R* as measured, deduce the value of μ_0. Compare this value with the theoretical one, which is $\mu_0 = 4\pi \times 10^{-7}$ (tesla·meters)/amps.
   Hint: to do so, you have to deduce the value of the intersect of the experimental log-log curve at the vertical axis. You also need to deduce the standard error of the intersect

6. Comment on your results in step 5.

Experiment 2: Helmholtz coils

For this experiment, you have to refer to Eq. (2).

PROCEDURE

1. Attach a second coil to the Helmholtz Base at a distance from the other coil equal to the radius of the coil (this makes $d = R$) in Eq. (2). Make sure the coils are parallel to each other. See Figure 6.

2. Connect the second coils in series with the first coil, as shown in Figure 7. Make sure that the direction of the current in the wiring is taken care of correctly. This ensures that the magnetic field produced in both coils is in the same direction.

3. Fix the current *I*. Measure the magnetic field *B* at various position as in experiment 1 with the help of rotary motion sensor.

4. Now change the separation between the coils to 1.5 times the radius of the coils. Repeat step 3.

5. Now change the separation between the coils to half the radius of the coils. Repeat step 3.

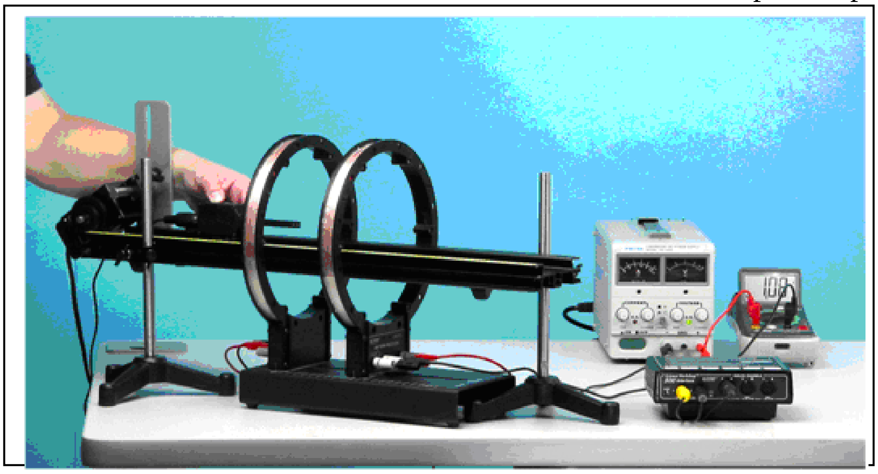

Figure 6: Helmholtz Coil

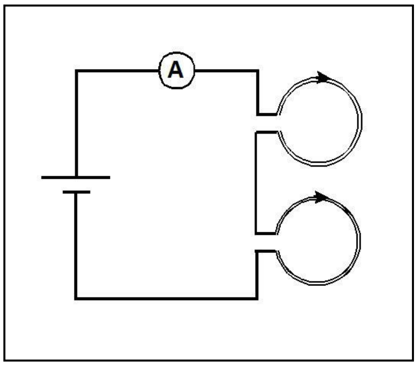

Figure 7: Helmholtz Wiring

Data manipulation and interpretation

1. For each coil-coil separation distance, *d:*

   a. Plot a graph of B vs. x. Comment on the graph obtained. In particular, comment on the quality of the region where the magnetic field remains constant.

   b. Plot also the theoretical curve of Eq. (2) on the same graph.

   From the graphs plotted, Plot B_0 (experiment) vs. d, B_0 (theory) vs. d on a same graph. B_0 is the value of the magnetic field at the midpoint between the Helmholtz coils.

2. Comment on your results of your measurements. In particular, discuss the factors that may have caused the difference between these.

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