Experiment: The Magnetic Fields due to Electric Currents

OBJECTIVES

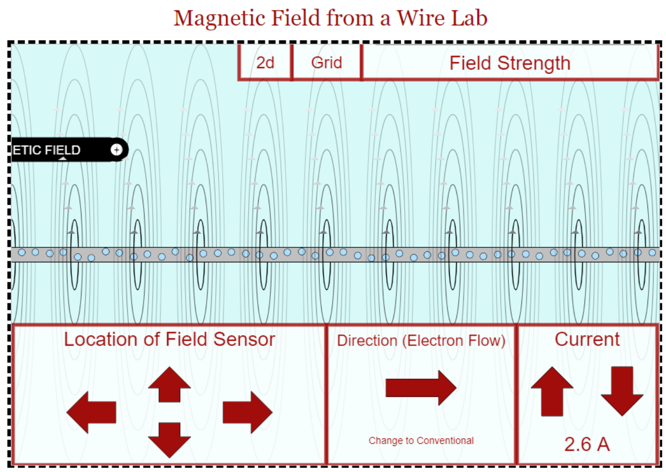
1. Determine the relationship between magnetic field and distance in a current-carrying wire
2. Determine the relationship between magnetic field and current in a current-carrying wire
3. Use graphical analysis to determine the value of μ_o

Materials

- Computer with internet access
- The Physics Aviary simulation site
- LoggerPro software

Introduction

When current flows through a long wire (i.e. length of wire >> distance from wire), a magnetic field ($\vec{B}$) is generated due to the moving charge. Clearly the magnitude of the magnetic field depends on the size of the current (i) and the distance (r) away from the wire. In this experiment, you will explore two different but related physical laws to model the relationship between $\vec{B}$, i and r: the Biot-Savart Law and Ampere's Law*.*



Screenshot from ThePhysicsAviary.com

The Biot-Savart Law for magnetism is the equivalent of Coulomb's Law for electric fields. Both physical laws describe a corresponding vector field quantity which is related to the ratio of the "source" of the field to the square of the distance from the source time a constant. One source of magnetic fields is the magnitude of current (i) that flows through a small element of wire (dl), or idl. The equation for the magnitude of a magnetic field due to this small "source" according to the Biot-Savart Law is

$$\left|d\vec{B}\right| = \frac{\mu_o idl}{4\pi r^2}\sin\theta$$

where $\mu_o = 1.256x10^{-6}\frac{T\cdot m}{A}$*,* θ *is the angle between the direction of the current element (*$id\vec{l}$*) and the distance vector is* $\vec{r}$*.*

Applying the Biot-Savart Law to calculate the magnitude of the magnetic field at a distance (r) due to a straight current-carrying wire (with current i and length L) leads to the expression:

$$\left|\vec{B}\right| = \frac{\mu_o iL}{4\pi r\sqrt{\frac{L^2}{4} + r^2}}$$

Alternatively, Ampere's Law can be used to calculate the magnitude of the magnetic field vector due to a long straight current carrying wire, applicable when L>>r:

$$\left|\vec{B}\right| = \frac{\mu_o i}{2\pi r}$$

Note: The direction of $\vec{B}$ *"curls" around the length of the wire according to the right-hand rule.*

In this experiment, you will measure the magnetic field due to a straight wire at various distances from the wire (at constant current), as well as with various electrical currents (keeping the distance constant). You will model your data using Ampere's Law. Lastly, you will use the model results to find an experimental value for the permeability constant in free space, μ_o.

Part A: *Preliminary Observations*

1. Open The Physics Aviary "Magnetic Field from a Wire" simulation: https://www.thephysicsaviary.com/Physics/Programs/Labs/FieldFromWire/
2. Get familiar with the controls*.*
   a. Click on "Field Strength" button to observe the magnitude of the magnetic field.

   Describe the shape of the field lines near the wire. Sketch some the field lines around the wire..

   b. Click on "Location of the Field Sensor". Use the arrows to move the field sensor up and down.

   How does the field strength vary with vertical position?

   How does the field strength vary with horizontal position?

   c. Click on "Current" to observe the magnitude of the electric current in the wire. Use the arrows to vary the current up and down.

   What direction are the electrons moving in the wire and what does this indicate about the direction of the current?

   How does the field strength vary with current strength?

   d. Click on "Direction" to switch the direction of the current in the wire.

   How does the field change when you switch current direction?

Part B: *Field Strength vs Distance*

3. Click on the "Grid" button. Position the field sensor to 1.0cm above the wire.
4. Set the current to 2.4A. Record the current in Table 1. Record this value in the table, as well.
5. Record the distance and magnetic field value for this distance.
6. Move the field sensor so that it is 2.0cm above the wire and record the field value at this distance.
7. Repeat step 6, increasing distance in 2.0cm increments, for a total of 5 trials.

Table 1: Field Strength vs Distance	
Current:	
Distance ( )	**Magnetic Field ( )**

8. Use LoggerPro to create a graph of field strength vs distance.
9. Fit the graph to an appropriate fit equation then record the fit equation and the calculate fit constants in Table 2 below.

Table 2: Graphical Analysis			
Fit Equation	**Fit Constants** *(including units)*	μ_o	**% Error**

10. According to Ampere's Law, the magnetic field strength near a long straight wire should be inversely proportional to the distance from the wire:

$$|\vec{B}| = \frac{\mu_o i}{2\pi r}$$

Is your graph consistent with Ampere's Law?

11. Use the calculated fit constant to estimate the permeability constant, μ_o, as well as the corresponding % Error. Record the values in Table 2.

Part C: *Field Strength vs Current*

12. Click on the "Grid" button. Position the field sensor at somewhere above the wire between 2.0cm and 4.0cm. Record the this distance in Table 3.

13. Set the current to lowest value above 0A.

14. Record the current and magnetic field value for this current in Table 3.

15. Repeat step 3, for increasing the current values, for a total of 5 trials.

16. Use LoggerPro to create a graph of field strength vs current.

Table 3: Field Strength vs Current

Distance:	
Current ( )	**Magnetic Field ( )**

17. Fit the graph to an appropriate fit equation. Record the fit equation and the calculated fit constants in Table 4 below.

Table 4: Graphical Analysis

Fit Equation	**Fit Constants** *(including units)*	μ_o	**% Error**

Under the conditions of this experiment, is your graph consistent with Ampere's Law? Why or why not?

18. For this model, what is the physical significance of the respective fit constants?

19. Use the calculated fit constant and distance to estimate the permeability constant, μ_o, and corresponding % Error. Record the values in Table 4.

Summary Questions

1. Which of experiment, Part B or Part C, yielded the most accurate estimate for μ_o? Can you explain why this might be expected OR not expected?

2. Find the overall average μ_o for your results then calculate the % Error.

3. Using Ampere's Law to model the magnetic field strength of a current carrying wire is an approximation that assumes L>>r. Based on the % Error calculated in the previous question, how might you estimate the length of the wire from the results in Part C?

   Hint: Divide the equation for the Biot-Savart Law (B_{B-S}) by the equation for Ampere's Law (B_{Amp}) and set result equal to $\left(1-\frac{\%\,Error}{100}\right)$.

   Example: *If r=0.050m and % Error=3.0% then the ratio would be:* $\frac{B_{B-S}}{B_{Amp}} = 0.97.$

   Simplifying the left side of the equality then solving for L, the length of the straight wire would need to be 0.410m.

   a. Calculate the resulting equation for the ratio of the Biot-Savart Law to Ampere's Law then solve for L in terms of r.

   b. Use the expression in (a) to estimate the minimum length of the wire in the simulation.

   c. List three things you learned from this experiment.