MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02 **Spring 2005**

Experiment 8: Magnetic Forces

OBJECTIVES

1. To investigate the magnetic force between two current carrying wires.
2. To measure the permeability constant μ_0.

INTRODUCTION

The magnetic force on a current-carrying conductor underpins every electric motor - turning the hands of electric watches and clocks, transporting tape in Walkmans, starting cars, operating refrigerator compressors, etc. In this experiment, you will investigate the magnetic force between two current carrying wires. One wire will be a coil of 10 turns and the other will be a coil of 38 turns. The 10-turn coil will be taped to one end of a pivoted balance beam. The beam pivots on two pins. It also makes electrical contact through the two pins, allowing current to flow onto the beam and through the 10-turn coil. The 38-turn coil will be positioned on the table directly below the 10-turn coil. A current traveling through both coils will produce a magnetic force between the coils, either attraction or repulsion, depending on the relative direction of the currents. You will measure the magnitude of this force by noting when the magnetic torque produced by this force between the coils is balanced by the torque due to the force of gravity on known weights.

In this experiment we will determine a value for the constant μ_0. To do this we will depend on the multimeter calibration of the amount of current flowing through the coils in amperes. Usually we *define* the ampere so that the constant $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T \cdot m/A}$, using measured forces between current-carrying wires. Here we will do the inverse—we assume our multimeter gives an accurate value for the current, and we measure forces to determine the constant μ_0. This requires a calculation of the force expected between two current-carrying coils.

THEORY

Consider a system of two coils having currents flowing in opposite directions, as shown in Figure 1. What is the force between the coils? Is it attractive or repulsive? In the figure, $\vec{\mathbf{B}}_2$ is the magnetic field *at* coil #2 produced *by* the current in coil #1.

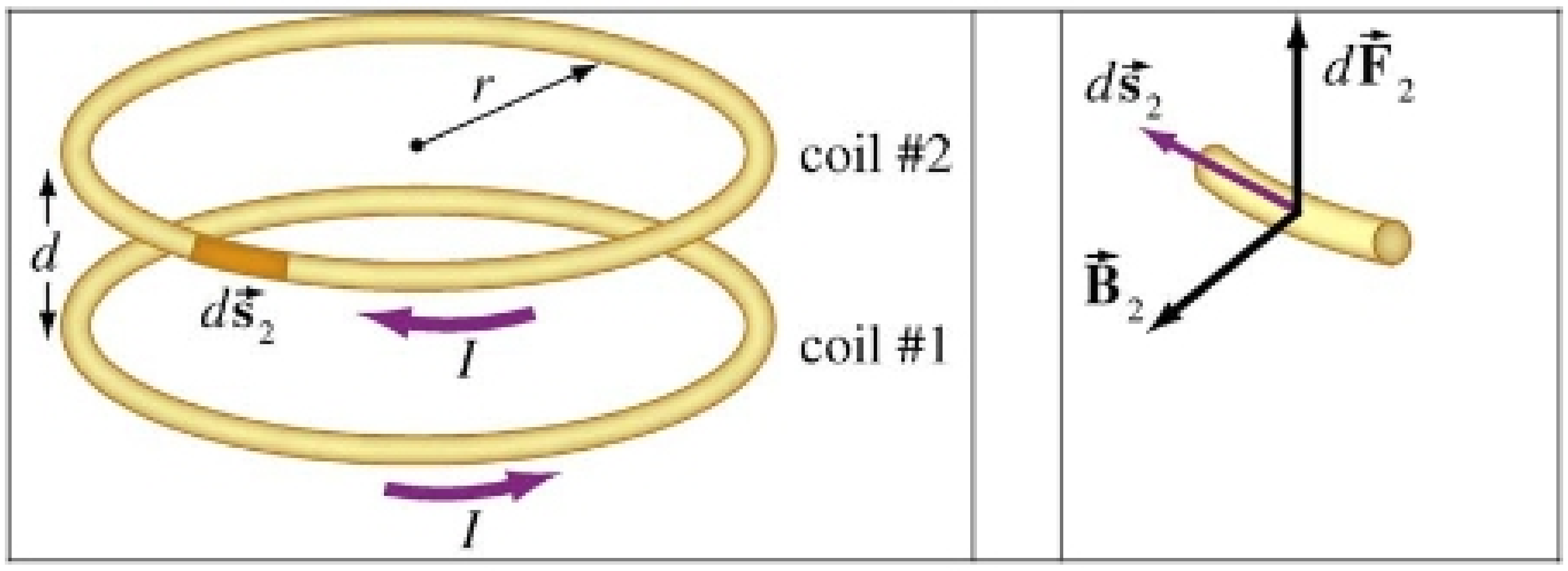

Figure 1 Force diagram on coil # 2 for repulsive force

In our experimental setup, the two coils are separated by a distance d which is much smaller than r, the radius of either coil (for purposes of clarity, the figure is not to scale). As a first approximation, we can treat the two coils as if they were parallel wires separated by a distance d. In this limit we neglect the contribution to the magnetic field, $\vec{\mathbf{B}}_1$, from parts of the lower coil that are not directly below the small current element in the upper coil. This will over-estimate the force somewhat (can you see qualitatively why?) but the error is not more than about 10% with your arrangement.

The expression for the magnitude of the force per unit length between two infinite wires (an approximation to very long wires or, in our case, the coils separated by a distance small compared to the common coil radius) is derived in the 8.02 *Course Notes*, **Section 9.2**;

$$\frac{force}{length} = \mu_0 \frac{I_1 I_2}{2\pi d} \tag{8.1}$$

where I_1 and I_2 are the currents and the separation is d. The force will be attractive if the currents in the coils are in the same direction, repulsive if in opposite directions.

For this experiment the currents will be $I_1 = n_1 I$ and $I_2 = n_2 I$, where n_1 and n_2 are the numbers of turns in the coils and I is the common current. The length to be used is the circumference of the coils, $2\pi r$, where r is the common radius. The result is that the magnitude of the force is

$$F_{mag} = (2\pi r)\frac{force}{length} = \mu_0 \frac{n_1 n_2 I^2 r}{d} \tag{8.2}$$

By Newton's third law, the total force on coil #1 is equal in direction and opposite in magnitude of the force on coil #2.

The magnetic force is balanced by aluminum foil weights that are placed at an equal distance from the pivot as the center of the upper coil. If the weights are all the same – $2\text{ cm} \times 1\text{ cm}$ rectangles of aluminum foil – their weight will be

$$F_g = n\,mg = n\,\rho A t\,g \tag{8.3}$$

where $g = 9.8\ \text{m/s}^2$, $A = 2\times10^{-4}\ \text{m}^2$ is the area of each piece of foil, $t = 1.8\times10^{-5}\,\text{m}$ is the thickness of the foil, $\rho = 2.7\times10^3\,\text{kg/m}^3$ is the density of the foil and n is the number of pieces of foil. The balance reaches equilibrium when the magnitude of the torque from the magnetic force equals the magnitude of the torque from the aluminum weight. Since the moment arms are equal, the forces must also be equal;

$$F_g = F_{\text{mag}}, \tag{8.4}$$

or

$$n\,\rho A t\,g = \frac{\mu_0\, n_1 n_2\, I^2 r}{d}. \tag{8.5}$$

This equation shows us that the current squared depends linearly on the number of foil pieces present, specifically

$$I^2 = \left(\frac{\rho A t\, g\, d}{\mu_0\, n_1 n_2\, r}\right) n. \tag{8.6}$$

The slope of the I^2 vs. n plot is given by

$$\text{slope} = \frac{\rho A t\, g\, d}{\mu_0\, n_1 n_2\, r}. \tag{8.7}$$

From this slope, determined from your data, you can in principle calculate the magnetic permeability of space using

$$\mu_0 = \frac{1}{\text{slope}}\left(\frac{\rho A t\, g\, d}{n_1 n_2\, r}\right). \tag{8.8}$$

EXPERIMENTAL SETUP

The setup of the experiment is depicted in Figures 2 –7 below: