MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

Experiment 4: Forces and Torques on Magnetic Dipoles

OBJECTIVES

1. To observe and measure the forces and torques acting on a magnetic dipole placed in an external magnetic field.

PRE-LAB READING

INTRODUCTION

In this lab you will suspend a magnetic dipole (a small but strong bar magnet) in the field of a Helmholtz coil (the same apparatus you used in Expt. 4). You will observe the force and torque on the dipole as a function of position, and hence external field.

The Details: Magnetic Dipoles in External Fields

As we have discussed in class, magnetic dipoles are characterized by their dipole moment μ, a vector that points in the direction of the B field generated by the dipole (at the center of the dipole). When placed in an external magnetic field B, they have a potential energy

$$U_{Dipole} = -\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}$$

That is, they are at their lowest energy ("happiest") when aligned with a large external field

Torque

When in a non-zero external field the dipole will want to rotate to align with it. The magnitude of the torque which leads to this rotation is easily calculated:

$$\tau = \frac{dU}{d\theta} = -\frac{d}{d\theta}\mu B \cos(\theta) = \mu B \sin(\theta) = \left|\vec{\boldsymbol{\mu}} \times \vec{\mathbf{B}}\right|$$

Again, the direction of the torque is such that the dipole moment rotates to align with the field (perpendicular to the plane in which μ and $\boldsymbol{B}$ lie, and obeying the right hand rule that if your thumb points in the direction of the torque, your fingers rotate from μ to $\boldsymbol{B}$.

Force

In order to feel a force, the potential energy of the dipole must change with a change in its position. If the magnetic field **B** is constant, then this will not happen, and hence *the dipole feels no force in a uniform field*. However, if the field is non-uniform, such as is created by another dipole, then there can be a force. In general, the force is quite complex, but for a couple of special cases it is simple:

1) If the dipole is aligned with the external field it seeks higher field
2) If the dipole is anti-aligned it seeks lower field

These rules can be easily remembered just by remembering that the dipole always wants to reduce its potential energy. They can also be remembered by thinking about the way that the poles of bar magnets interact – opposites attract while likes repel.

In one dimension, when the dipole is aligned with the field, a rather straight forward mathematical expression may also be derived:

$$F = -\frac{dU}{dz} = \frac{d}{dz}\mu B = \mu \frac{dB}{dz}$$

Here it is important to note that the magnitude of the force depends not on the field but on the derivative of the field. Aligned dipoles climb uphill. The steeper the hill, the more force they feel.

APPARATUS

1. Teach Spin Apparatus

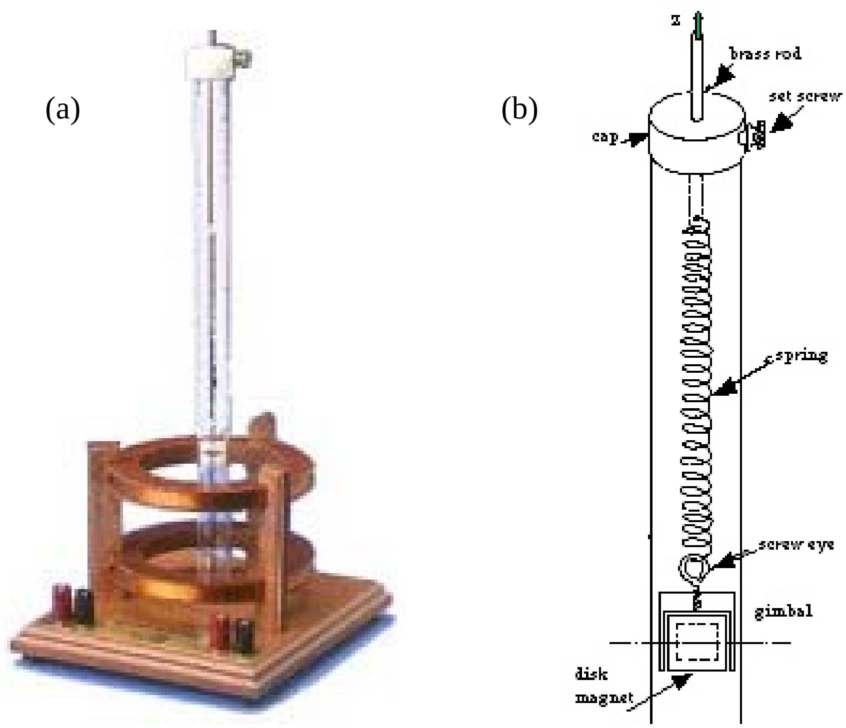


Figure 1 The Teach Spin Apparatus (a) The Helmholtz apparatus has a tower assembly (b) placed along its central axis. The tower contains a disk magnet which is free to rotate (on a gimbal) about an axis perpendicular to the tube and constrained to move vertically. The amount of motion can be converted into a force knowing the spring constant of the spring.

The central piece of equipment used in this lab is the Teach Spin apparatus (Fig. 1). It consists of the Helmholtz coil that you used in experiment 3, along with a Plexiglas tube containing a magnet on a spring. The magnet can both rotate and move vertically, allowing you to visualize both torques and the forces on dipoles.

It will be useful to recall some results from experiment 3 involving the Helmholtz coil. There are three different modes of operation – you can energize just a single coil, both coils in parallel (Helmholtz configuration) or both coils anti-parallel (anti-Helmholtz). The field profiles (as well as the derivatives of those profiles – necessary for thinking about force) look like the following:

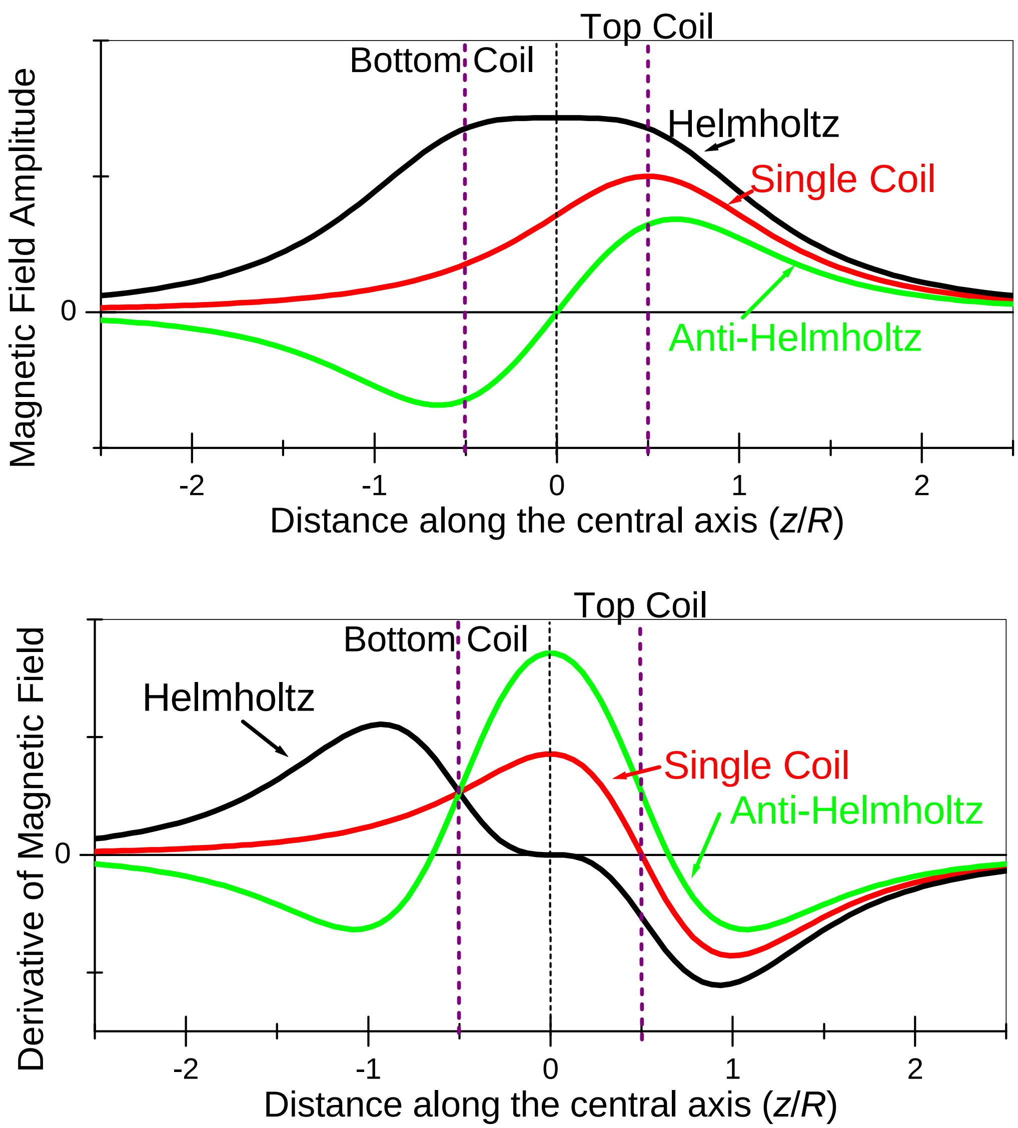


Figure 2: The *z*-component of the magnetic field and its derivative for the three modes of operation of the Helmholtz coil. See page the last page of this write-up for an "iron-filings" representation of these three field configurations.

2. Power Supply

We will also use the same power supply as in experiment 4 in order to create large enough fields in the Helmholtz apparatus to exert a measurable force on the magnet.

GENERALIZED PROCEDURE

This lab consists of five main parts. In each you will observe the effects (torque & force) of different magnetic field configurations on the disk magnet (a dipole).

Part 1: Dipole at center of Helmholtz Coil
You will move the disk magnet to the center of the Helmholtz apparatus and randomly align it and then see what happens when the coil is energized.

Part 2: Reversing the field
You will reverse the direction of the field and see what happens.

Part 3: Moving Through the Helmholtz Apparatus
Here you slowly pull the disk magnet up from the bottom of the Helmholtz apparatus (in Helmholtz mode) and out through the top, observing any torques or forces on the magnet.

Part 4: Dipole at center of Anti-Helmholtz Coil
Here you repeat part 1 in anti-Helmholtz configuration

Part 5: Moving Through the Anti-Helmholtz Apparatus
Here you slowly pull the disk magnet up from the bottom of the Helmholtz apparatus (in anti-Helmholtz mode) and out through the top, observing any torques or forces on the magnet.

END OF PRE-LAB READING

Experiment 4: Forces and Torques on Magnetic Dipoles

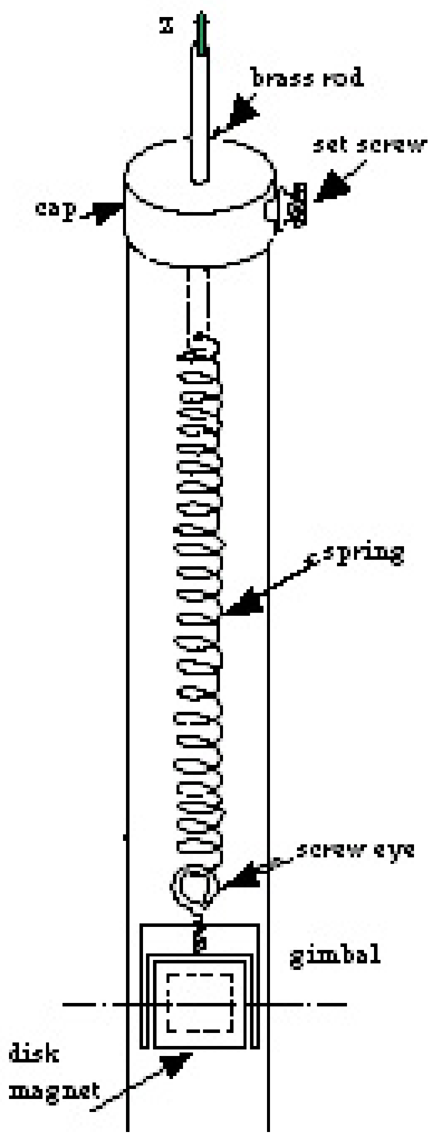
Answer these questions on a separate sheet of paper and turn them in before the lab

1. Force on a Dipole in the Helmholtz Apparatus

In class you calculated the magnetic field along the axis of a coil to be given by:

$$B_{axial} = \frac{N\,\mu_0\,I\,R^2}{2}\frac{1}{(z^2+R^2)^{3/2}}$$

where z is measured from the center of the coil.



In this lab we will have a disk magnet (a dipole) suspended on a spring, which we will use to observe forces on dipoles due to different magnetic field configurations.

(a) Assuming we energize only the top coil (current running counter-clockwise in the coil, creating the field quoted above), and assuming that the dipole is always well aligned with the field and on axis, what is the force on the dipole as a function of position? (HINT: In this situation $F = \mu\ dB/dz$)

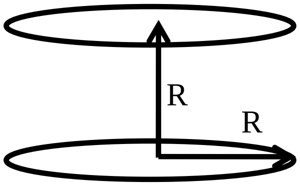
(b) The disk magnet (together with its support) has mass *m*, the spring has spring constant *k* and the magnet has magnetic moment μ. With the current on, we lift the brass rod until the disk magnet is sitting a distance z_0 above the top of the coil. Now the current is turned off. How does the magnet move once the field is off (give both direction and distance)?

(c) At what height(s) is the force on the dipole the largest?

(d) What is the force where the field is the largest?

(e) Our coils have a radius R = 7 cm and N = 168 turns, and the experiment is done with I = 1 A in the coil. The spring constant k ~ 1 N/m, and μ ~ 0.5 A m^2. The mass m ~ 5 g is in the shape of a cylinder ~ 0.5 cm in diameter and ~ 1 cm long. If we place the magnet at the location where the spring is stretched the furthest when the field is on, at about what height will the magnet sit after the field is turned off?

2. Motion of a Dipole in a Helmholtz Field



In Part I of this experiment we will place the disk magnet (a dipole with moment μ) at the center of the Helmholtz Apparatus (in Helmholtz mode). We will start with the disk magnet aligned along the x-axis (perpendicular to the central z-axis of the coils), and then energize the coils with a current of 1 A.

Recall that a Helmholtz coil consists of two coils of radius R and N turns each, separated by a distance R, as pictured above. The field from each coil is given at the beginning of the previous problem.

(a) Will the disk magnet experience a torque, a force or both?

(b) If the magnet experiences a torque:

Approximately how much time will it take for the magnet to rotate 90º, so that it is aligned with the external field? Give your answer first in terms of an approximate expression using R, N, I, and μ, and then numerically, using the values given in problem 1e above.

(c) If the magnet experiences a force:

Approximately how much time will it take for the magnet to move to its new equilibrium position? Give your answer first in terms of an approximate expression using R, N, I, k and μ, and then numerically, using the values given in problem 1e above.

<u>Record the answers to this question in your notes as you will be asked to compare them to what you observe in the lab.</u>

IN-LAB ACTIVITIES

EXPERIMENTAL SETUP

1. Download the LabView file and start up the program.
2. Without leads connected to the power supply, turn it on and set the voltage output to 12 V. Turn the current knob fully counter-clockwise (off).
3. Connect the leads to the Helmholtz apparatus, in Helmholtz mode.
4. Increase the current to approximately 1 A, then turn off the power supply (with the push button – do not change the voltage or current settings).

MEASUREMENTS

Part 1: Dipole in Helmholtz Mode

1. Slide the disk magnet to the center of the Helmholtz apparatus (0 on scale)
2. Randomly align the disk magnet using a bar magnet (try to make off axis)
3. Turn on the power supply, carefully watching the disk magnet

Question 1:

Did the disk magnet rotate? (Was there a torque on the magnet?)

Question 2:

Did the spring stretch or compress? (Was there a force on the magnet?)

Part 2: Reversing the Leads

1. Without touching the apparatus (or even bumping the table – be VERY careful) disconnect the leads from the power supply and insert them in the opposite direction (flip the current direction).
2. Carefully watch the dipole as you do this. Repeat the experiment several times.

Question 3:

What happened to the orientation of the disk magnet when you change the current direction in the coils in the Helmholtz configuration? Is this what you expect? Why?

Part 3: Moving a Dipole Along the Axis of the Helmholtz Apparatus

1. Now lower the disk magnet to bottom of the tube
2. Slowly pull the disk magnet up through the apparatus, until it is out the top. While pulling watch both the orientation of the magnet and the stretch or compression of the spring.

Question 4:

Starting from the bottom, describe the direction of the force (up or down) and the orientation of the disk magnet, paying careful attention to locations where they change.

Question 5:

Where does the force appear to be the largest? The smallest? How should you know this?

Part 4: Dipole in Anti-Helmholtz

1. Switch the apparatus to Anti-Helmholtz mode and increase the current to 2 A. Then turn off the power supply.
2. Move the disk magnet to the center (0 on scale) and randomly align it (off axis)
3. Turn on the power supply, carefully watching the disk magnet

Question 6:

Did the disk magnet rotate? (Was there a torque on the magnet?)

Question 7:

Did the spring stretch or compress? (Was there a force on the magnet?)

Part 5: Moving a Dipole Along the Axis of an Anti-Helmholtz Coil

1. Now lower the disk magnet to bottom of the tube
2. Slowly pull the disk magnet up through the apparatus, until it is out the top. While pulling watch both the orientation of the magnet and the stretch or compression of the spring.

Question 8:

Starting from the bottom, describe the direction of the force (up or down) and the orientation of the disk magnet, paying careful attention to locations where they change.

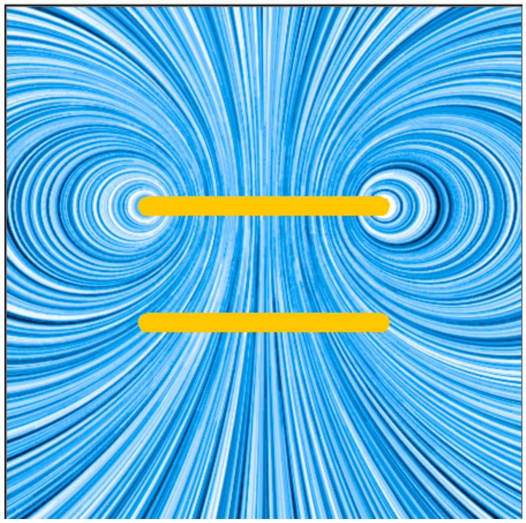
Question 9:

Where does the force appear to be the largest? The smallest? How should you know this?

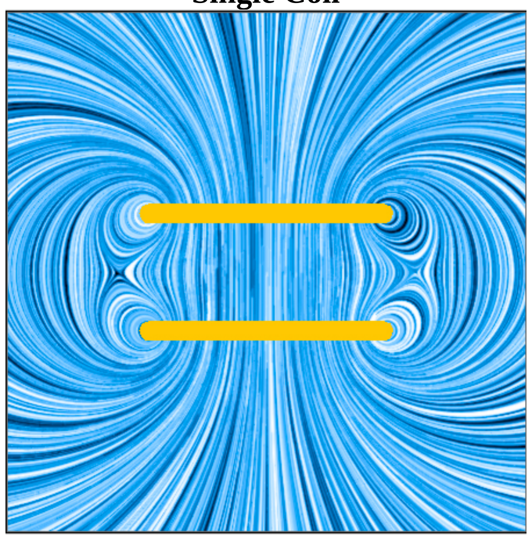
Further Questions (for experiment, thought, future exam questions…)

- What happens as we move through with just a single coil energized? Is it similar to the Helmholtz or anti-Helmholtz? How is it different?
- Are there places where we can put the disk magnet and then randomly orient it without either changing the force on it or having a torque rotate it back to alignment (in any of the 3 field configurations)?
- If you were to align the disk magnet with the x-axis (perpendicular the coil axis) and then center it in anti-Helmholtz mode, would there be a torque or force on it?

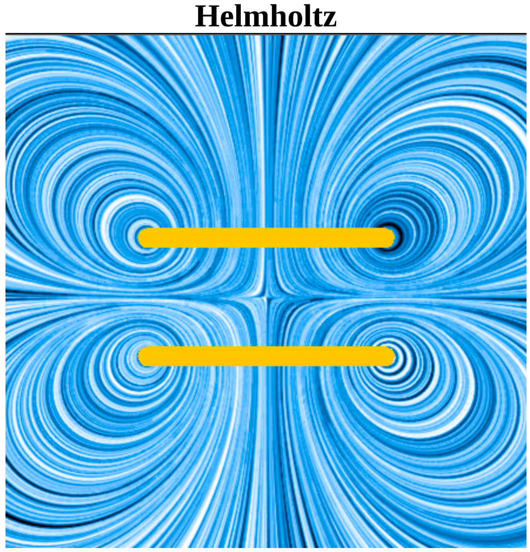
Iron Filings Patterns for Fields in the Helmholtz Apparatus



Single Coil



Helmholtz



Anti-Helmholtz