MAGNETIC DEFLECTION

OBJECTIVE: To observe the effect of a magnetic field on an electron beam. To measure the Earth's magnetic field.

THEORY: Moving charges exert forces on one another that are not observed when the charges are stationary. These forces can be described in terms of a magnetic field just as the electric forces between charges can be described in terms of an electric field. In this experiment we will observe a force on one electric current (beam) due to (1) a magnet, (2) an electromagnet, and (3) the earth's magnetic field.

In the first case, we will see the direct effect of a magnet on an electron beam provided by a CRT (Cathode Ray Tube). In the second case, we actually have the force of one electric current (the electromagnet) on another electric current (the beam). In this second case we think of one current as establishing a magnetic field in space. The second current (the beam) then moves through this field and experiences a magnetic force. In particular we will drive a current through a pair of solenoids to establish a magnetic field in a region of space. Then we will fire the electron beam in a CRT into this region and observe the deflection of the beam. In the third part we will fire the electron beam in the earth's magnetic field, but since we cannot control the earth's field, we will control the orientation of the CRT's beam to try to determine the strength of the earth's magnetic field.

We first consider the electron beam in the CRT. (See the last page for a diagram of the CRT.) In the CRT a filament heated by an AC power supply provides the electrons for the beam. These electrons are accelerated through a potential difference V_a so that they have a kinetic energy $(½)m_e v^2 = e V_a$. Thus, the electrons have a speed of

$$v = (2 e V_a / m_e)^{1/2} \quad . \qquad (1)$$

The velocity of the electrons is thus controlled by V_a .

If there are no forces on the moving electrons, they move in a straight line until they hit the center of the screen and cause a dot of light to appear. If the moving electrons are subjected to a force, then the beam will be deflected in the direction of the force and the dot of light will be deflected from the center of the screen.

One way to bend the beam (to make it go to where we want it to) is to pass it through an electric field set up between two parallel plates. This electric field can be set up by establishing a potential difference, V_d, between the plates. As the electrons pass through the electric field $\vec{E}$ they experience an electrical force of $\vec{F} = -e\vec{E}$ and are deflected opposite to the field direction (opposite since the electron has a negative charge).

In this experiment we will employ a **second way** of bending the electron beam. We will have the beam pass through a magnetic field, $\vec{B}$, oriented such that the electron velocity will be perpendicular to the field. The beam will then experience a magnetic force given by

$$\vec{F} = -e\vec{v} \times \vec{B} \qquad (2)$$

(here the charge $q = -e$) and the dot on the screen will be deflected. Since $\vec{v}$ will be perpendicular to $\vec{B}$, the size of the magnetic force will be $F = evB$.

In Part 1, we look at the direction of the magnetic force (and hence of the deflection). By knowing the direction of the force and velocity, we should be able to determine the direction of the magnetic field provided by both the North pole and South pole of a bar magnet. (Be careful to remember that the electron has a NEGATIVE charge!)

In Parts 2 and 3 we will get more quantitative. Eq. (2) involves the vector cross product which states that the component of $\vec{B}$ perpendicular to $\vec{v}$ will give a force perpendicular to both $\vec{v}$ and $\vec{B}$. Thus $\vec{F}$ will be perpendicular to $\vec{v}$. This is recognized as the condition that gives circular motion ($a_c = v^2 / R$). Hence, Newton's Second Law ($\sum \vec{F} = m\vec{a}$) leads to the equation (with the magnetic force being the centripetal force):

$$evB = m_e v^2/R \qquad (3)$$

where m_e is the mass of the electron, e is the size of the charge of the electron, and R is the radius of the circle in which the electron moves while in the magnetic field, B. See Fig. 1. In this figure, L is the effective diameter of the solenoid and D is the amount of deflection of the dot on the CRT screen. From geometric considerations, an expression for D in terms of R is found to be:

$$D = L^2 / 2R \qquad (4)$$

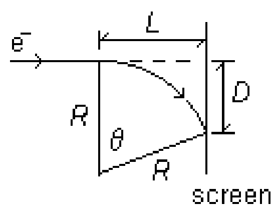

FIGURE 1

This expression is only an approximation, but it is a very good one as long as the angle θ in Fig. 1 is not too large. (If you are curious about the derivation and the approximation, ask your instructor.)

By rewriting Eq. (4) above, an expression for R can be obtained in terms of v and B:

$$R = m_e v / eB \qquad (5)$$

This can then be used in Eq. (4) to express D in terms of B and v. Thus, to a good approximation for small θ,

$$\mathbf{D = L^2 eB / 2m_e v} \qquad (6)$$

Thus D should increase in approximately a linear way with B_1 and in an approximately inverse relation with v.

In Part 2, the solenoid current will set up a magnetic field inside the coil that is directly proportional to the current in the solenoid. In this experiment we will use two solenoids connected in series, one placed on either side of the CRT. The field due to these two solenoids will still be directly proportional to the current in the solenoids, and a picture of the field lines is drawn in Fig. 2.

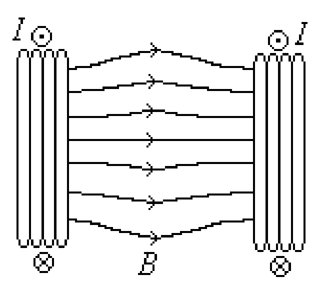

FIGURE 2

Since the magnitude of the magnetic field B_s set up by the solenoid is directly proportional to the current in the solenoid, I_s ,

$$B_s = k\, I_s \qquad (7)$$

where k is the constant of proportionality. We can thus control B_s by controlling I_s .

From Eq. (7), B_s is proportional to I_s ; and from Eqs. (6) & (7), D should be approximately proportional to I_s. From Eq. (1), v is proportional to $V_a^{1/2}$; and so from Eq. (6), D should also be approximately proportional to $1/V_a^{1/2}$. Putting all this together gives us:

$$\mathbf{D = K\, I_s / \sqrt{V_a}}, \qquad (8)$$

where K is a constant that incorporates all the other constants in Eqs. (1), (6) & (7). **We will test Eq. (8) in Part 2 of this experiment.**

In Part 3, we will look to determine the magnetic field of the earth. We will use Eq. (6) since we can use Eq. (1) to find v and we can directly measure D.

CRT POWER SUPPLY WIRE CONNECTIONS

DO NOT CONNECT ANY POWER CORDS YET. Coming out of the back of the CRT are three sets of wires. One set contains six color coded wires that produce the electron beam. The other two sets each contain two wires that control the vertical and horizontal deflection plates of the beam. All of the wires terminate inside the connection box. A wiring diagram appears on the last page. You may wish to refer to it as you make the connections with the banana plug wires.

Connections for the heater coil: With the tube high voltage supply turned off and unplugged, connect two wires from the yellow ac voltage outputs on the tube supply to the yellow terminals marked “Filament” on the connection box. Set the ac voltage knob on the supply to 6 V.

Connections for the accelerating plates:
1. With the tube high voltage supply turned off and unplugged, connect the 500 V output on the tube supply to the red A terminal of the V_a inputs on the connection box.
2. Connect the 0 V output on the tube supply to the black B terminal of the V_a inputs on the connection box.
3. With another wire, connect the red A terminal of the V_a inputs to one of the green ground inputs on the connection box.

Connections for proper grounding: We need to ensure that all of the voltages we measure are with respect to the same reference voltage, which we call the ‘ground’. We will use the ground on the variable DC power supply (PS) which is the middle terminal on its front. The PS will be used in Part 2 to send the current through the solenoids.
1. First, connect the negative terminal of the PS to its middle ground terminal.
2. Now connect this ground terminal to one of the green ground terminals on the connection box.
3. Then, use another wire to connect the red A terminal of the V_a inputs on the connection box to one of the green ground terminals on the connection box.
4. Finally, to insure that there are no electric fields between the deflection plates in the CRT, connect the horizontal and vertical deflection terminals on the connection box to the green ground terminals. (Referring to the wiring diagram, we are making V_d = 0 so that there is no electric field between the deflection plates.)

Part 0: Poles of a Magnet

It was noted that a sliver of special rock when floated on a leaf or balanced on a pin would orient itself to point North and South. The end, or pole, that pointed North was then called the North Pointing Pole and the end that pointed South was called the South Pointing Pole. We often do not use the middle name of "Pointing" and simply call the two poles the North Pole and the South Pole of the special rock. We call those special rocks "magnets". Later we found that iron, nickel, and cobalt metals could be made into magnets, but other materials like copper or aluminum could not.

We find by experiment – you can test this yourself with two magnets – that like poles repel and unlike poles attract. This is similar to electricity where like charges repel and unlike charges attract.

1. To verify which pole is which on the magnets, take a compass and remove the magnets from the area of the compass and place the N pole of one magnet on the S pole of the other magnet (these two poles should attract). This will tend to cancel the magnetic effects of the two magnets.

2. You need to determine which end of the room is the North wall. Confirm your directions with your instructor. Now note which end of the compass points North. This North pointing end will be the North pole of the magnet in the compass.

3. Take one of the magnets, and bring the pole labelled S on the magnet near the compass. If the magnet is properly labelled, the S pole of the magnet will attract the North Pointing Pole of the compass. If the South Pointing Pole of the compass is attracted to the S pole of the magnet, then the magnet is mis-labelled. This is possible as we'll talk about in class. Tell your instructor if the magnet is mis-labelled.

4. Take the magnet and now bring the pole labelled N and bring it near the compass. The South Pointing Pole of the compass should be attracted to it. Confirm this yourself.

We are now ready to proceed with the rest of the experiment.

Part 1: Magnetic Deflection by a Magnet

PROCEDURE:

1. Make the connections as prescribed on the previous page, and then call your instructor over to check your wiring.

2. Make sure both power supplies are turned off and the voltage controls turned all the way down. Plug in both supplies. Turn on the HV supply and allow the heater coils in the CRT to warm up. Turn up the voltage on the HV to 500 V and adjust the potentiometer knob (on the connection box) to focus the dot.

3. Bring the North pole of the bar magnet in toward the CRT from above. Note the direction of the deflection of the dot. From this, determine the direction of the magnetic field coming from the North pole of the magnet using the right hand rule. [*Recall that the right hand rule gives directions according to the following: Let your hand point in the direction of the first vector (here* $\vec{v}$*), then bend your fingers in the direction of the second vector (here* $\vec{B}$*- unknown), and then*

your thumb should point in the direction of the resultant vector (here $\vec{F}$, same direction as D).] Remember that the electron has a negative charge!

4. Bring the South pole of the bar magnet in toward the CRT from above. Note the direction of the deflection of the dot. Determine the direction of the magnetic field coming from the South pole of the magnet.

5. Bring the North and then the South pole of the bar magnet in **from the side** and confirm your results of parts 4 and 5 above.

REPORT:

1. Record and report all the data from the previous steps.

2. State the general conclusion about how magnetic fields are related to North and South magnetic poles, and support your conclusion by referring to your results from parts 4 through 6.

Part 2: Magnetic Deflection and Currents

PROCEDURE:

1. ADDITIONAL WIRING FOR PART 2:

Next place the two solenoid coils next to the CRT, one on each side, with the hole in each solenoid pointing at the CRT. Run a wire from the PS positive terminal to one terminal of one of the solenoids (it doesn't matter which) - we'll call this solenoid #1. Check to see which way the current will flow through the solenoid (clockwise or counterclockwise as viewed from the left [or right] side). Now run a wire from the other terminal of solenoid #1 to the other solenoid (#2) and hook it up to the terminal so that the current will flow in the same way as in solenoid #1 (clockwise or counterclockwise as viewed from the left [or right] side). Finally, complete the circuit by connecting a wire from the other terminal of Solenoid #2 to the negative terminal of the PS.

To measure the current I_s through the solenoids, we will use a DMM. Set the DMM to measure a DC current (up to 10 A). Connect the DMM in series with the two solenoids. Call your instructor over to check your wiring.

2. Remeasure and record the value of V_a.

3. Now turn on the PS. Vary I_s and record both I_s and the displacement, *D*, that it causes for at least three different values of I_s. Record also the direction of the deflection of the dot caused by the current in the solenoids. Use the right hand rule to determine the direction of the magnetic field from the solenoids. [Remember that the charge of an electron is negative!] Also record the direction of the currents in the solenoids (e.g., clockwise or counterclockwise as viewed from the North - the front of AH 001 is toward the East). [You should see that if you curl your right hand fingers in the direction of the current, your thumb should point in the direction of the field due to the circular current.]

4. Now decrease V_a by ~100 volts and refocus with the potentiometer knob. Repeat Step 3.

5. Reverse the current direction in both solenoids and qualitatively describe what happens.

6. Reverse the current direction in only one of the solenoids and qualitatively describe what happens.

REPORT:

1. Graph D vs I_s for each of the two values of V_a . Your graph will thus contain two lines. Comment on what your graph says and how well this corresponds to the theory developed in this hand-out. In particular, comment on the relative slope values of your two lines. Refer to Eq. (8).

2. Determine the direction of B_s in Step 3, and relate this to the direction of I_s .

3. Describe the "what" and "why" of Steps 5 & 6.

Part 3: The Earth's Magnetic Field

PROCEDURE:

1. Remove the solenoids from near the CRT and turn off the variable DC PS ($V_s = 0$). Note that the beam is still slightly displaced from the center. By rotating the CRT around in a horizontal circle find the orientation of the CRT for which the dot is half way in between its furthermost deflections. This is the horizontal "undeflected" orientation.

2. Now with the CRT oriented horizontally in its "undeflected" position, rotate the CRT in a vertical circle and again find the orientation of the CRT in which the dot is half way in between its furthermost deflections. This is the complete "undeflected" orientation. Record the position of the dot on the screen in this "undeflected" orientation. What does this orientation of the CRT say about the direction of the magnetic field in the room?

3. Now find the orientation in which the deflection is a maximum (it should be 90° from the "undeflected" orientation). Record the position of the dot and the orientation of the CRT.

4. Determine the amount of deflection of the dot from its "undeflected" position to its most deflected position. From this deflection, determine the strength of the magnetic field in the room using Eq. (6) where $L = 4$ inches. The speed v can be determined from Eq. (1).

REPORT:

1. What is the direction of the earth's magnetic field in the room? Be sure to explain how you came to your conclusion.

2. What is the magnitude of the earth's magnetic field in the room? Express your answer in Teslas and in Gauss. Typically quoted values for the Earth's magnetic field on its surface range from 0.5 to 1 Gauss. Is your value consistent with these values?

CRT Wiring Diagram
(Magnetic Deflection)