

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 magnetic forces on an electron beam. First we will use a magnet to set up a magnetic field that will exert a force on one electric current, the electron beam. Then we will use a second current in a solenoid to set up a magnetic field to exert a force on the electron beam. We think of the magnet or the second current in the solenoid as establishing a magnetic field in space. The electron beam (or first current) then moves through this field and experiences a magnetic force.

Consider first the solenoid current. The solenoid current will set up a magnetic field inside the coil such that the magnitude is directly proportional to the current in the solenoid: $B_{sol} \propto I_{sol}$. (This relationship is derived in your text.) The direction of the solenoid field can be determined by the right hand rule: curl your fingers in the direction of the current, and your thumb points in the direction of the magnetic field. Recall that the magnetic field goes out of a North pole and into a South pole, so that the solenoid acts like a magnet with one end being the North pole and the other end the South pole. 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. 1.

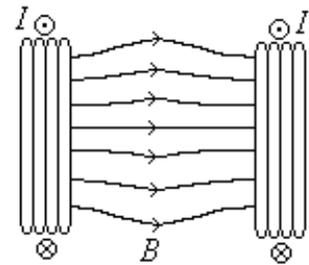


FIGURE 1

Since the solenoidal current, I_{sol} , is directly proportional to the voltage difference, V_{sol} , driving the current ($V_{sol} = I_{sol}R_{sol}$), and since the magnetic field B_{sol} set up by the solenoid is also directly proportional to the current ($B_{sol} \propto I_{sol}$), then B_{sol} is directly proportional to V_{sol} ,

$$B_{sol} = k V_{sol} \quad (1)$$

where k is the constant of proportionality. We can thus control B_{sol} by controlling V_{sol} .

Now consider the electron beam in 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 $(\frac{1}{2})m_e v^2 = e V_a$. Thus, the electrons have a speed of

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

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.

In the first CRT experiment, the beam passed through an electric field set up between two parallel plates. This electric field was set up by establishing a potential difference between the plates. As the electrons passed through the electric field they experienced an electrical force of $\vec{F} = -e\vec{E}$ and were thus deflected opposite to the field direction (opposite since the electron has a negative charge).

In this experiment the beam will pass through a magnetic field \vec{B} oriented such that, like the electric field in the first CRT experiment, the initial electron velocity will be perpendicular to the field. The beam will then experience a magnetic force given by

$$\vec{F} = -e\vec{v} \times \vec{B} \quad (3)$$

and the dot on the screen will be deflected. Eq. (3) 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:

$$evB = m_e v^2 / R \quad (4)$$

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. 2.

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:

$$D = L^2 / 2R \quad (5)$$

This expression is only an approximation, but it is a very good one as long as the angle θ in Fig. 2 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 :

$$R = m_e v / eB \quad (6)$$

This can then be used in Eq. (5) to express D in terms of B and v . Thus, to a good approximation for small θ ,

$$D = (eL^2 B) / (2m_e v) \quad (7)$$

Thus D should increase in approximately a linear way with B , and in an approximately inverse relation with v . If the magnetic field is provided by the solenoid, then Eq. (1) states that B_{sol} is proportional to V_{sol} , and so D should be approximately proportional to V_{sol} . From Eq. (2), v is proportional to $V_a^{1/2}$, and so D should also be approximately proportional to $1/V_a^{1/2}$. Putting all this together gives us

$$D = KV_{sol} / \sqrt{V_a} \quad (8)$$

where K is a constant that incorporates all the other constants in Eq. (7). We will test Eq. (8) in Part 1 of this experiment. We will use Eq. (7) in Part 2 to find Earth's magnetic field in the room.

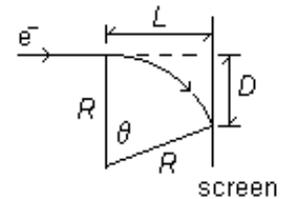


FIGURE 2

WIRING: DO NOT CONNECT ANY POWER CORDS YET!

Connect the high voltage power supply (HV) to the CRT as you did in the CRT experiment with one exception. In this lab, we do not want to use an electric field between the deflection plates to deflect the beam. To make sure there is no electric field between the deflection plates, connect both the horizontal and vertical terminals of the connection box to the green ground terminals on the box using four banana plug wires. Now connect another wire from one of these green terminals to the ground terminal (middle terminal) on the variable DC power supply. This supply will be used to send the current to the solenoids. To achieve a common ground, connect the negative side of this supply to its middle ground terminal. Finally, be sure that the 500 V output of the tube high voltage power supply is also connected to a green ground terminal.

Part 1: Magnetic Deflection Due to Magnets and Electromagnets

PROCEDURE:

1. 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 and turn on the tube HV supply. Allow the heater coil in the CRT to warm up. Set the accelerating voltage to 500 V on the tube HV supply and adjust the potentiometer knob to focus the dot. Rotate the CRT about an axis perpendicular to the table top until the dot is centered on the central horizontal axis of the tube. Record its position. When reading the CRT, put your eye so that the dot, your eye, and your eye's reflection are in the same line. Record V_a from the meter on the HV supply.

3. Place one solenoid near the CRT on one of the sides with the hole facing the CRT, and connect the solenoid to the variable DC power supply. Make sure the current limit knob is turned all the way up.
 - a) Determine which way the current will flow through the solenoid, and using the right hand rule determine which side of the solenoid is the North pole and which is the South pole.
 - b) Now turn up V_{sol} and watch which way the dot moves as you increase V_{sol} . Using the basic magnetic force law ($\vec{F} = -e\vec{v} \times \vec{B}$) determine the direction that \vec{B} must be to give the proper deflection direction for the dot. Compare this direction with the direction \vec{B} of you determined from the current direction. Do they agree?
 - c) Now turn down V_{sol} to zero, and place one end of a bar magnet through the hole of the solenoid and watch the deflection of the dot. Recall that the direction of the field due to a magnet is out of the North pole and into the South pole of a magnet. Does the direction of the dot deflection due to the bar magnet's magnetic field agree with your previous analysis of the dot's deflection due to the magnetic field of the solenoid?

4. Next place the other solenoid coil next to the CRT on the other side with the hole also pointing at the CRT. Connect the two solenoids in series to the PS.
 - a) Check to see which way the current will flow through each of the solenoids (clockwise or counterclockwise as viewed from the left [or right] side) and make sure the current direction is the same. Determine the direction of the resultant \vec{B} using the right hand rule.
 - b) Now turn V_{sol} up and analyze the direction of the two fields based on the movement of the dot. Do the two magnetic fields add or subtract?
 - c) Now turn V_{sol} down to zero and place one bar magnet inside each coil to verify your analysis of the two field's directions. Record the results of the dot's deflection due to both the solenoids' and the bar magnets' fields.

5. Now reverse the field in one of the solenoids by reversing the current in one of the solenoids (but not both). Turn V_{sol} up and see how the dot reacts. Are the two fields adding or subtracting? Explain what is going on. (Seek help from your instructor if necessary.)

6. Reconnect the solenoids so that the two fields will add rather than subtract. Connect the DMM so that you can measure V_{sol} with the DMM (in parallel with the two solenoids). Now vary V_{sol} and record both V_{sol} and the displacement, D , that it causes. Is the deflection of the dot proportional to V_{sol} ? Should it be? (See Eq. (8).)

7. Now decrease V_a by about 100 volts, refocus the dot, and repeat Step 6. Is the deflection of the dot still proportional to V_{sol} ? If it is, is the slope the same, greater or smaller? What should it be according to Eq. (8)? Do your experimental results agree with the prediction of Eq. (8)? According to theory, a moving charged particle should go in a circle in the presence of a magnetic field with radius $R = mv/qB$. As V_a decreases, v should decrease (why?); as v decreases, R should decrease. Will a smaller R give rise to a smaller or bigger deflection, D ? Are your experimental results consistent with this analysis?

REPORT:

1. Answer the questions about directions and about qualitative behavior posed in the procedure.
2. If this is a written report, graph D vs V_{sol} 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.
3. If this is a written report, graph D vs $V_{sol}/\sqrt{V_a}$. Your graph will thus contain both sets of data but they should fall on one line. Why? Again comment on what your graph says and how well this corresponds to the theory.

Part 2: The Earth's Magnetic Field

PROCEDURE:

1. Remove the solenoids from near the CRT and turn off the variable DC supply ($V_{sol} = 0$). 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 furthest 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 furthest 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. (7) where $L = 4$ inches.

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?

NOTE: The metal frame supporting the grid and face of the CRT is made of steel and is usually magnetized. You can confirm this with a compass held near the screen. This seems to sometimes affect the measured Earth's field direction more than it does the size.