ELECTRIC AND MAGNETIC FORCES

PURPOSE: To study the deflection of a beam of electrons by electric and magnetic fields.

APPARATUS: Electron beam tube, stand with coils, power supply, multimeters

CAUTION!!! THIS EXPERIMENT USES A VERY HIGH VOLTAGE POWER SUPPLY! BE EXTREMELY CAREFUL! DO NOT MAKE CONNECTIONS WITH THE POWER SUPPLY ON. DO NOT TOUCH THE HV WIRE OR ITS CONNECTORS WHEN THE SUPPLY IS ON.

WHEN IN DOUBT - ASK YOUR INSTRUCTOR

INTRODUCTION: This experiment uses a large vacuum tube which contains an "electron gun". The gun is a metal filament that is heated so hot that some of the electrons of the metal have enough kinetic energy to leave the filament. They are then accelerated by a potential difference $V_a$ which gives them a kinetic energy $m \frac{v^2}{2}$, equal to $e V_a$. ($e$ is charge of an electron, -1.6x10^{-19} coulombs, and $m$ is its mass, 9.1 x 10^{-31} kgm.) The electron beam becomes visible when the electrons strike a fluorescent screen.

As the electrons move in the horizontal ($x$) direction, an electric force may be applied in the vertical ($y$) direction by applying a potential difference $V_y$ between two deflecting plates. The apparatus also permits vertical deflection by a magnetic force produced by a "Helmholtz coil". In the first part of the experiment we will study just the magnetic deflection; in the second part only the electric deflection; and, in the third part a combination of both forces applied in opposite directions so as to cancel each other's effect.

A. MAGNETIC FIELD DEFLECTION: In this part of the experiment, the speed of the electron, $v_x$, will be determined by measuring the effect of a magnetic field on the path of the electrons. The magnetic field ($B$) of the coils is horizontal, and at right angles to the direction of the electron beam. It produces a force on the electrons whose magnitude is

$$F_m = e v_x B$$

The magnetic force is at right angles to the electron velocity; thus, the direction of motion of the electrons will be changed but their speed will remain constant. The electrons will move in a circular path of radius $R$ with the force toward the center of motion being the magnetic force. The relation between the radial force and the magnetic force is

$$e v_x B = \frac{m v_x^2}{R}$$
or

\[ v_x = \frac{e}{m} BR \]

(1)

The magnetic field is produced by a pair of current-carrying coils. The field \( B \) produced by the coils is proportional to the current \( I \) flowing in the coils. For the coils used for this experiment use the relationship:

\[ B = 4.23 \times 10^{-3} \times I. \]

where \( B \) is in Tesla and \( I \) is in amps. \( R \) is measured on the screen. The diagram on the next page shows that, for the deflected beam, \( x, y, \) and \( R \) are related by

\[ R^2 = (R - y)^2 + x^2 \]

or

\[ R^2 = R^2 - 2Ry + y^2 + x^2 \]

so that

\[ R = \frac{x^2 + y^2}{2y} \]

(2)

**Figure 1:** The electron beam travels to the left and becomes visible on the fluorescent screen. The circular motion is caused by the magnetic field directed into the page.

**PROCEDURE:** Study the vacuum tube, its contents and their connections to outside voltage supplies. In the neck are a wire filament which will emit electrons when heated red hot and an accelerating electrode in a sidewise cylinder. At the center of the glass chamber, you will see a screen grid coated with a material which fluoresces under electron impact and top and bottom horizontal metal plates for vertical electrostatic deflection of the electron beam. On either side, in front and behind the glass chamber are two coils of wire which produce a somewhat uniform magnetic field at the chamber's center for magnetic deflection of the electron beam.
FIGURE 2: The electron beam tube.

In this apparatus has the same essential features as the display tubes in such devices as oscilloscopes, computer monitors, and televisions.

For the electric deflection (Part B) and electric with magnetic deflection (Part C) experiments high voltage applied to the accelerating electrode is the same voltage applied to the electrostatic deflection plates.

**Never alter the connections to the tube's filament.**

Disconnect the high voltage cable from the top electrostatic deflection plate connector. Let it lie on the table, but do not touch it when the supply is turned on. Disconnect the ground cable from the bottom electrostatic deflection plate to the power supply. Next, connect the alligator clip lead (jumper cable) to both the bottom and top plates to ensure that charging of the plates by the beam does not occur which would produce an unwanted electric field. Ask your instructor to check the connections before turning the supply on. Once your set-up has been checked, recheck that the high voltage and coil current supply control knobs are fully off (counter-clockwise). Only then turn the supply on.

The small multimeter should be set to a scale of 200 mv and its reading should be multiplied by 100 to get the high voltage output. (A reading of 32.3 means 3,230 volts.) Increase the high voltage to 3000 volts. You should see a blue beam trace on the screen. Observe the deflection caused by the magnetic field. Change the magnetic field by varying the coil current. Observe the change in deflection.

Set the coil current to 0.30 amperes. For say $x \approx 5$ cm or so, measure and record the $y$ deflection. Next, **turn the voltage controls down**, then **turn off** the power supply. Reverse the direction of current through the coils, using the reversing switch. Repeat the experiment with the same accelerating voltage, 3000 volts. The beam will be deflected in the opposite direction because the magnetic field is now in the opposite direction.
Measure the y deflection and calculate \( v_x \). Take an average of the two values of \( v_x \) to cancel the effects of the earth's magnetic field and any misalignment of the screen.

Repeat for an accelerating voltage of 4000 volts, to obtain a new \( v_x \). How does \( v_x \) depend on the accelerating voltage? Explain your observation.

For future reference, remember the sense of deflection.

**B. ELECTRIC DEFLECTION:** In this part of the experiment, a y deflection is produced by an electric field \( E_y \). The vertical electric force is \( eE_y \) and the vertical acceleration is \( eE_y/m \). The force acts for a time \( t \) so that (with \( v_{y\rightarrow 0} = 0 \))

\[
y = \frac{1}{2} a_y t^2 = \frac{1}{2} \frac{e E_y}{m} t^2
\]

The \( x \)-component of the velocity of the electrons is constant at a value \( v_x \), with \( x = v_x t \), so that we can write

\[
y = \frac{1}{2} \frac{e E_y x^2}{m v_x^2}
\]

In this relation, all quantities except \( x \) and \( y \) are constant, so that the relation has the form \( y = nx^2 \), where \( n \) is a constant. This is the equation of a parabola.

The value of \( v_x \) is given by conservation of energy (electric potential energy = kinetic energy)

\[
e V_a = \frac{1}{2} m v_x^2
\]

so we can substitute \( 2eV_a \) for \( mv_x^2 \),

\[
y = \frac{E_y}{4 V_a} x^2
\]

If the deflection plates were very large compared to their separation \( d \), then \( E_y \) would be given by \( V_y/d \). Since this is not the case, \( E_y \) will be different by a correction factor \( k \), so that

\[
E_y = k \frac{V_y}{d} \tag{3}
\]

Because we use the same voltage for the acceleration \((V_a)\) as for the deflection \((V_y)\) \((V_a = V_y)\) we can therefore write

\[
y = k \frac{V_y}{4d V_a} x^2
\]

and, finally,

\[
y = k \frac{1}{4d} x^2 \tag{4}
\]
PROCEDURE: **Turn all voltages to zero and turn off the power supply.** Disconnect the jumper cable between the top and bottom plates and set it aside. Connect the high voltage cable you previously set aside to the top plate and to the power supply. Connect the ground cable that you previously set aside to the bottom plate and to the power supply. Note that the same high voltage is applied both to the electron gun and to the deflection plates. **Do not turn the power supply on until the instructor has checked your connections.** Check that both the high voltage and the coil current control knobs are turned fully counterclockwise. Turn on the power supply and vary the high voltage.

Observe the deflected beam and record the values of $y$ for $x = 2, 3, \ldots$ cm. Remember to convert everything to SI units (specifically meters); mixing units will give you an erroneous result. Plot $y$ against $x^2$ and determine the slope $k/4d$ and then $k/d$ from the graph. From this value, calculate $k$.

Why is the beam path independent of high voltage setting? Why does the trace intensity increase with increasing high voltage? What are your units for $k/d$? Are these SI (m, kg, s) units?

Show your values of $k$ (and of $v_x$ from Part A) to your instructor.

C. MAGNETIC AND ELECTRIC DEFLECTION: In this part you will determine what magnetic field applied perpendicularly to the electron velocity will offset the electric field force to result in a straight path. That is for a certain $E$ and $B$, there is only one velocity $v$ that results in a straight line, hence this is called a velocity filter (it is also called a Wien filter, after Wilhelm Wien, 1864-1928). The equation giving this velocity is

$$v(x, E \otimes B) = \frac{E}{B}$$

This means the velocity in the x direction through a perpendicular $E$ and $B$ is the magnitude, $E$, divided by the magnitude, $B$. [The meaning of $\otimes$ is called a "cross product which is somewhat like the multiplication of perpendicular components." You will have to figure out the direction of $E$ and $B$ to get this velocity filter to work.]

PROCEDURE: **Turn all voltages to zero and turn off the power supply.** Connect the coil supply wires so the deflection produced by the magnetic field will oppose that caused by the electric field in the previous part. Turn on the power supply.

Starting with high voltage of 3,000 volts, increase the magnet coil current until the beam is horizontal in the central portion of the coil. You may have to change the direction of the magnetic field to accomplish this. If you do, please don't forget to turn the power supply off before switching the current direction switch.

Repeat for other accelerating voltages up to the maximum output of your power supply.

Think about what you are doing in this part of the experiment - you are balancing the electric and magnetic forces on the electron beam. For given values of $E$ and $B$, should this velocity depend on the charge of the electron?
Calculate $E$ from Eq. 3 using your experimental value of $k/d$ (watch units) from above, $B$ from coil current $I$, and then, the expected velocities. How do the velocities compare with those obtained in part A, for the same accelerating voltages?

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Names: ___________________________________________________

Section: ________ Date: _____________

A. Magnetic deflection. Velocity determination from \( v_B = \frac{e}{m} BR \).

Do experiment for the maximum voltage your apparatus can supply, the minimum voltage that still shows a trace, and two other voltages between the highest and lowest.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>( I_{magnet} )</th>
<th>( B )</th>
<th>( y (x=0.05m) )</th>
<th>( R )</th>
<th>( vB )</th>
</tr>
</thead>
<tbody>
<tr>
<td>volt</td>
<td>amp</td>
<td>tesla</td>
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<td>( m )</td>
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You will use the same voltages in Part C.

B. Electric deflection. \( B = 0 \); Voltage: \( V = \)_______

Remember that the horizontal accelerating voltage is the same as the vertical deflecting voltage. Make sure the magnetic coils are off. Turn the voltage to the maximum. The circular path is defined by Eq. 4: \( y = \frac{k}{4d} x^2 \) where \( d \) is the plate separation. Convert measurements to MKS units (namely, meters).

<table>
<thead>
<tr>
<th>( y )</th>
<th>( x )</th>
<th>( x^2 )</th>
</tr>
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</table>

From a linear graph of Eq. 4 plot \( y \) vs. \( x^2 \) and determine the following with their units:
slope \( \{k/(4d)\} = \ \ (k/d) = \ \ k = \ \ \) 

**C. Wien \((E \otimes B)\) velocity filter** Magnetic and Electric forces are equal and opposite.

Use the same voltages as Part A. Calculate the horizontal velocity from your data. Recall that the velocity is given by \(v_{E \otimes B} = E/B\).

\[
\begin{array}{|c|c|c|c|c|}
\hline
V \ \text{volt} & E = (k/d)V \ \text{volt/m} & I_B \ \text{amp} & B \ \text{tesla} & v_{E \otimes B} \ \text{m/s} \\
\hline
\hline
\hline
\hline
\end{array}
\]

On a linear graph plot \(v_{E \otimes B}\) vs. \(v_B\). Determine the slope = \[\text{__________} \]

What does this graph mean?

What is the direction of the electric field, \(E\) ?

What is the direction of the magnetic field, \(B\) ?

What is the direction of the electrons, relative to \(E\) and \(B\) ?