LAB 9
Electron Beams in Magnetic Fields

OBJECTIVES
1. Observe magnetic forces on moving charges.
2. Predict and verify the right-hand rule (RHR) for various situations.
3. Predict and measure the velocity of a velocity selector.
4. Predict and measure the charge to mass ratio e/m.

EQUIPMENT
Electron Deflection tube set-up, Helmholtz coils, e/m apparatus, kilovolt power supply, DC power supply, Magnets, demo oscilloscope, black-and-white TV, gooseneck lamp.

THEORY
Velocity Selector (or crossed fields)
In a beam of charged particles produced by a heated cathode, not all particles move with the same speed. Many applications, however, require a beam in which all the particle speeds are the same. Particles of a specific speed can be selected from the beam using an arrangement of electric and magnetic fields called a velocity selector. If a charged particle with speed v enters a region of space where the electric and magnetic fields are perpendicular to the particle’s velocity and to each other, the electric force (qE) and magnetic force (qvB) can be made to be equal and opposite such that F_{net} = 0. Solving for the speed v for which there is no deflection, we find v = E/B. Only particles with speeds equal to E/B can pass through without being deflected by the fields.

Thomson’s e/m Experiment
In one of the landmark experiments in physics at the end of the nineteenth century, J.J. Thomson used a velocity selector to measure the ratio of charge to mass for the electron. Electrons from a hot cathode are accelerated and formed into a beam by a potential difference ∆V between the anode and cathode. The speed v of the electrons is determined by the accelerating potential ∆V. As the electrons enter a uniform magnetic field, they will travel in a circle. Applying Newton’s 2nd law to this circular motion, combined with conservation of energy, the ratio of e/m (charge to mass ratio) can be determined

\[
\frac{e}{m} = \frac{v}{rB}
\]

It is not possible to measure e or m separately by this method, only their ratio.

PROCEDURE
Part 1: The Right-Hand Rule (RHR)
Use the RHR to predict the magnetic deflection of an electron beam.

Electron beam from an Oscilloscope & TV
a. Predict the magnetic deflection of the electron beam in the old oscilloscope by a bar magnet and then observe the effect. Repeat this with a small black-and-white TV.
   Draw and explain your results using the RHR.

Electron beam from an e/m Apparatus in a Magnetic Field
b. Predict the deflection of an electron beam with its velocity only having a parallel (and antiparallel) component to the magnetic field. Now check your predictions by the appropriate rotations of the e/m globe. Draw and explain your results using the RHR.

c. Predict the deflection of an electron beam that enters the magnetic field with a velocity that has both a parallel and perpendicular components. Now check your
predictions by the appropriate rotations of the e/m globe. Draw and explain your
results using the RHR and how the helical trajectory was created.

**Force on a Conductor in a Magnetic Field**

d. Predict the magnetic deflection of a current-carrying wire in a strong magnetic field
and then observe the effect. Now reverse the direction of the current and observe the
effect? Explain your observations in terms of the RHR.

e. Bring a magnet near the filament of a gooseneck lamp and watch the filament shake
due to the alternating current. Be gentle – don't break the filament. Why does the
filament shake when the current lamp is on but not when it is off? Why does the
filament oscillate back and forth?

**Part 2: Velocity Selector**

**Part 2A: Setting up the Electric and Magnetic Fields**

**Deflection due an Electric Field**

a. Using the procedure from Lab 4 (Deflections of electrons in an electric field) to
generate a beam of electrons that travels in a straight horizontal line. Set \( \Delta V_{\text{anode}} = \Delta V_{\text{plates}} \). Starting from 0 V, increase the voltage to 2.5 kV and generate a curved
trajectory due to the electric field deflection.

b. Disconnect the parallel plates from kilovolt power supply and discharge them.

**Deflection due a Magnetic Field**

c. Center the pair of Helmholtz coils in the positions marked with "H" on the tube stand
and with the "faces of the coils" facing in the same direction. Adjust the height of the
coils so that the centers of the coils are aligned to the level of the beam axis.

d. Use the RHR to determine the current direction required to produce a magnetic field
deflection that is opposite the electric field deflection.

e. Connect the coils in series with a DC power supply and use an ammeter to measure
the current. Slowly increase the voltage/current of the DC power supply and produce
a magnetic field between the coils. The electron beam should now be deflected from
its straight line trajectory via the magnetic field.

f. Now combine the electric and magnetic deflections such that they off set each other
and that the net force on the electron beam is zero. This is accomplished by tuning
the trajectory so that it is flat at the middle of the plates.

**Question:**

- Why does the electron beam have to be flat at the middle of the plate and not
curved?

**Part 2B: Predicting and measuring the velocity for a velocity selector**

a. From Lab 4, the electric field between the two finite plates in the e/m tube is \( E_{\text{expt}} = 0.75 \Delta V_{\text{plates}} / d \). Read the plate voltage \( \Delta V_{\text{plates}} \) and calculate the electric field between
the plates.

b. Measure the current through the Helmholtz coils and calculate the magnetic field
produced by the coils using

\[
B = \frac{N \mu_0}{(5/4)^{3/2} R} \cdot i
\]

where \( N (= 320) \) is the number of turns on each Helmholtz coil, \( \mu_0 (= 4\pi \times 10^{-7} \text{ Tm/A}) \)
is the permeability constant) and \( R (10.5 \text{ cm}) \) is the radius of the Helmholtz coils.

c. Derive and predict the theoretical velocity \( v_{\text{thy}} (= E/B) \) using parts (a) and (b).

d. Read the accelerating voltage \( \Delta V_{\text{anode}} (= \Delta V_{\text{plates}}) \) and calculate the experimental
velocity \( v_{\text{exp}} \) of the electron using conservation of energy. Compare the theoretical
and experimental values using a percent difference. How do they compare?

e. Repeat the above procedure for \( \Delta V_{\text{plates}} = 5 \text{ kV} \).
• Why does the electron beam have to be flat at the middle of the plate and not curved?
• Why was the magnetic field required to deflect the electron beam or larger when \( \Delta V_{\text{anode}} \) was equal to 5kV, compared to 2.5kV?

**Part 3: e/m Measurement**

A beam of electrons is accelerated through a known potential, so the velocity of the electrons is known. A pair of Helmholtz coils produces a uniform and measurable magnetic field at right angles to the electron beam. This magnetic field deflects the electron beam in a circular path.

a. Study the e/m tube and understand which voltage accelerates the electrons and which voltage (current) generates the magnetic field of the Helmholtz coils.

b. Slowly increase the current through the Helmholtz coils, taking care not to exceed 2A. Rotate the e/m globe so that the electron beam is exactly perpendicular to the magnetic field – you should see the electron beam deflected in a circle.

c. For best results, adjust the accelerating voltage so that it is above 250 V and the radius of curvature of the electron beam is less than 5 cm. **Measure** the accelerating voltage from the voltmeter and **calculate** the velocity of the electron using conservation of energy.

d. Carefully **measure** the radius of the electron beam. Look through the tube at the electron beam. To avoid parallax errors, move your head to align the electron beam with the reflection of the beam that you can see on the mirror scale. Measure the radius of the beam as you see it on both sides of the scale, and then average the results.

e. **Measure** the current from the ammeter and **calculate** the magnetic field produced by the Helmholtz coils using part (1Bb). Use the correct values for the number of turns \( N \) and the radius \( R \) of the Helmholtz coils for the particular e/m globe you are using.

f. **Derive** and **predict** the theoretical charge to mass ratio \((e/m)_{\text{thy}}\) using parts (c), (d) and (e). Compare the theoretical value with the accepted value \((e/m)_{\text{accepted}} = 1.7588 \times 10^{11}\text{C/kg}\) using a percent difference. How do they compare?

g. Use a single bar magnet (nonuniform magnetic field) to produce a magnetic mirror effect; now use two bar magnets to trap electrons with this nonuniform field (called the magnetic bottle effect).