Measurement of e/m   Lab 6

Equipment CENCO E/M Apparatus (71267), CENCO Discharge Tube Power Supply (31384), leads, thin clear 30 cm plastic ruler

Reading Your textbook. Electrical Safety at the beginning of this manual.

1 Background

The orbit of a charged particle in a uniform and constant magnetic field is a circle when the initial velocity of the particle is perpendicular to the field. The radius of the orbit depends on the charge to mass ratio of the particle, q/m, the speed of the particle v, and the strength of the magnetic field B. When the strength of the magnetic field and the initial speed of the particle are known, a measurement of the radius of the orbit determines q/m. This principle was used by J.J. Thomson to measure the charge to mass ratio of the electron, e/m, in 1897. The reason for a circular orbit can be understood by the fact that a charged particle experiences a force at right angles both to the instantaneous velocity and to the direction of the magnetic field (see Fig. 1). The particle therefore moves under the influence of a force whose magnitude is constant but whose direction is always at right angles to the velocity. Like a ball whirled on a string, the orbit is a circle. The measurement of q/m in modern physics provides a way to identify atoms and molecules by a device called a mass spectrometer. Similarly the measurement of q/m by devices such as cloud chambers and bubble chambers identifies sub-atomic particles, such as the electron and the muon. In this experiment e/m of the electron is determined from the relationship between the electric potential used to accelerate the electron to a given speed, the strength of the magnetic field that influences the electron's motion, and the radius of the circular path which the electron follows.

2 Apparatus

The equipment consists of an evacuated glass tube in which the electrons will execute their orbits and a pair of coils of wire to provide a reasonably uniform magnetic field in the region of the tube. Inside the tube is an "electron gun" mounted with its symmetry line coinciding with the vertical axis of the tube. The electron gun provides a fairly mono-energetic thin beam of electrons in which the electrons move vertically upward. The gun consists of three metallic elements arranged in a vertical line. See Fig. 2. The three elements are

1. a heated cathode, which supplies the electrons by means of thermionic emission,
2. a grid, which is actually a thin circular plate with a hole, which is maintained at a positive potential with respect to the cathode, and
3. an anode or plate, which is a thin circular plate with a hole, maintained at a higher electric potential with respect to the cathode than the grid. We will call it the plate.

The designations grid and plate come from that of a triode amplifier tube, where the grid is actually a grid and the plate does not have a hole in it. The cathode is radiatively heated by a nearby filament, which is a length of resistance wire with a current through it. The electrons are focussed by the grid and accelerated by the high, positive plate potential and then pass through a small hole in the plate. With a magnetic field in the horizontal direction, the electrons passing up through the hole execute a semicircular orbit about the field, and on heading downward strike the top of the plate. To show where they strike, the glass envelope of the tube and the top of the plate are coated with a material that fluoresces when struck by the electron beam. This coating is so thin that you can easily see into the tube. Four concentric circles having radii of 0.5, 1.0, 1.5, and 2.0 cm are ruled on the disk so that the diameter of the orbit can be determined. The tube also has a small amount of the inert gas argon which emits light when excited by the electrons. This allows the position of the electron beam to be observed, both inflight and where they hit the wall of the tube. Some of the argon is ionized and helps focus the electron beam.

The reasonably uniform magnetic field that bends the beam is produced by a pair of identical circular coils whose spacing is equal to their radius. With this spacing they are called *Helmholtz coils* after the great 19th century physicist. He recognized that this arrangement produces the most uniform field near the midpoint between the coils. The number of turns of wire in each coil is marked on the base of the apparatus.

The electron tube is mounted so that the electron beam passing through the hole in the plate is perpendicular to the field and midway between the coils. The strength B of the magnetic field can be adjusted by varying the current passing through the coils. Variation of either the plate-cathode potential in the tube or the strength of the magnetic field will cause the radius of the circle described by the electron beam to change. Suppose that conditions are such that the electron beam describes a semicircle above the disk of such a size that on returning to the disk it strikes one of the four circles marked on its face. Then the diameter of the semicircular orbit is seen equal to the radius of that particular marked circle. (A common error is to forget the factor of 1/2 involved here.)

3 Theory

Let the mass, charge, radius, velocity, and accelertion of the electron be given by m, e, r, v, and v^2/r respectively. Denote the magnetic field by $\vec{B}$. Since the centripetal force $\vec{F}$ is provided by the magnetic field interacting with the electron and is given by $\vec{F} = -e\vec{v} \times \vec{B}$, we have from Newtons's second law $mv^2/r = evB$, or

$$v = \frac{erB}{m}. \tag{1}$$

To find an expression for v in terms of quantities that can be measured, we note that the energy imparted to the electrons within the tube by the potential difference through which they are accelerated is equal to their kinetic energy. The accelerating potential is the plate-cathode voltage which we denote by V. (The grid voltage does not affect the final beam energy.) We get

$$eV = \frac{1}{2}mv^2. \tag{2}$$

Substituting this into Eq. 1 gives

$$\frac{e}{m} = \frac{2V}{r^2B^2}. \tag{3}$$

In SI units the left hand side has the units of coulombs/kilogram.

The magnetic field strength near the center of a pair of Helmholtz coils is given by

$$B = 9.0 \times 10^{-7}\frac{NI}{R}, \tag{4}$$

where N is the number of turns in one coil, I is the current through each coil in amperes, and R is the average radius in meters of the turns forming a coil. For the coils, $N = 119$. Knowing the accelerating voltage, coil current, and the diameter of the semi-circle of the electron orbit, you can find the value of e/m from the last two equation as

$$\frac{e}{m} = 2.5 \times 10^{12} \left(\frac{R}{Nr}\right)^2 \left(\frac{V}{I^2}\right). \tag{5}$$

The quantities N and R are fixed. The quantities r, V, and I can be varied.

4 Discharge Tube Power Supply

This is shown in the left of Fig. 3, which also shows the base that holds the electron tube and the Helmholtz coils. The on-off switch is toward the top of the left panel. On the lower left is the AC filament supply. This is a transformer with a number of taps that give rms voltages of 1, 2, or 3 volts between adjacent wires. By choosing the appropriate two wires, you can get these voltages plus 4, 5, or 6 volts. As shown in the Fig. 3, 6 V is proper for the tube and the two outer-most connections are used.

The middle portion of the supply provides 0-500 V for the plate and 0-80 V for the grid. Each of these two voltage is controlled by a knob above the output terminals. The plate and grid voltages are zero when the knobs are fully counter-clockwise (CCW). Note how the markings above the knobs convey this information. It is a almost always a good procedure to turn all voltage and current outputs to zero when turning on a supply.

Above each knob is an LED which indicates which voltage, plate or grid, is displayed at the top of the center panel of the supply. A switch below the display selects the voltage to be measured.

The right panel of the supply delivers current to the Helmholtz coils. The current is controlled by a knob and there is also a readout at the top. This supply has a protection circuit. For currents above about 5.5 A the current shuts off and a LED above the knob lights up. When the current turns off, turn the knob for the current fully CCW and turn the supply off and then on again. This will reset the current supply. You can reverse the direction of the magnetic field and of the electron orbits by interchanging the current leads. The current should be set to zero (knob fully CCW) while doing so.

5 Procedures

- It is important that the electron tube should not be affected by stray magnetic fields. In so far as practical, set the apparatus away from sources of fields.
- Use Fig. 2 to check that the apparatus is wired correctly.
- On the inside of the coils there are notches that allow you to see the coil windings. Use the ruler to measure the mean diameter of the coils.
- The experiment needs to be done in a darkened room so that the rather faint light emitted by the argon atoms can be seen. The instructor will turn off the room lights. Use the lamp on the bench, properly turned away from the tube.

- Turn all three knobs on the supply fully CCW (voltages and currents zero) and set the voltage select switch so that the display measure the plate voltage (0-500 V). Turn on the supply. You should see light emitted by the filament from the tube. Wait one minute for the cathode to heat up and then slowly increase the plate voltage. You should see the electron beam and where the beam hits the tube when the plate voltage reaches about 200 V. When you see the beam clearly, focus it by adjusting the grid voltage. Note that changing the grid voltage slightly affects the plate voltage, and possibly vice-versa. When you measure the grid and plate voltages for data, do not change either voltage.
- The grid or focussing voltage needs to be optimized for <u>each</u> value of the accelerating voltage.
- Use the lowest plate voltage that allows you to see the beam. Apply coil current and deflect the beam so it hits the largest circle. Now switch the direction of the magnetic field by setting the current to zero and switching the current leads. Return the current to its previous value. The direction of the beam deflection should reverse, but the electrons should still be hitting the largest circle. If they are not, the earth's magnetic field is a problem. Rotate the apparatus until symmetry is achieved. (If you use too high a plate voltage in this part of the experiment, you will have to use a high coil current, and the current may switch off on you.)
- Make a series of measurements changing r, V, and I. A reminder that for each value of the plate voltage V you should focus the beam with the grid voltage. Think a bit about what data you want to take and how you will present the data.
- For each set of r, V, and I, calculate the charge to mass ratio of the electron, or e/m. Compute the average value and the standard deviation of e/m.
- Indicate the major sources of error in this experiment. Compare your value of e/m with the accepted value. What do you judge may be responsible for any significant discrepancy?

6 Questions

1. Why does the final electron energy not depend on the grid voltage?
2. Can you think of a reason as to why the cathode is not directly heated by current?
3. Do you think the electrons are emitted from the cathode with zero velocity, one velocity, or a range of velocities? Hint: The electrons inside the metal that are able to escape are a bit like a gas of molecules at finite temperature.
4. The coils are connected in series. Why would connecting them in parallel be a bad idea?
5. Why doesn't the magnetic field change the speed of the electrons? (Speed is taken to be the magnitude of the velocity. The velocity is a vector.)
6. At 5 A, what is the magnetic field produced at the center of the Helmoltz coils in gauss? About what is the magnitude of the Earth's field in gauss?

The following two questions depend on the equation for the force on a charged particle in a magnetic field, $\vec{F} = q\vec{v} \times \vec{B}$.

7. What would be the electron orbits if the initial velocity of the electrons was parallel or anti-parallel to the magnetic field?

8. What would be the electron orbits if the initial velocity of the electrons was 45 deg to the magnetic field?

7 Finishing Up

Please leave the bench as you found it. Thank you.

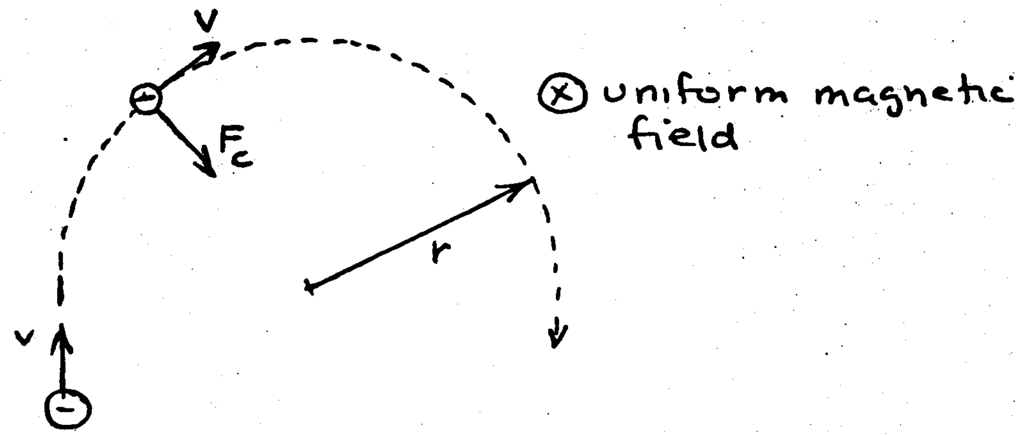

Figure 1. Velocity v and magnetic force F_c on a particle with negative charge in a magnetic field directed into the paper.

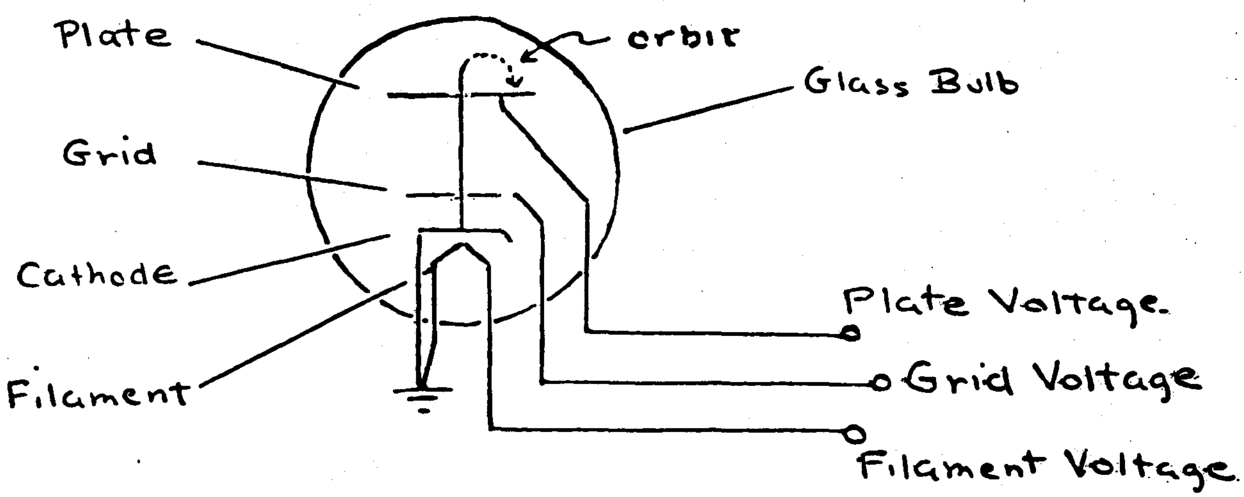

Figure 2. Electrical connections and elements within the electron tube.

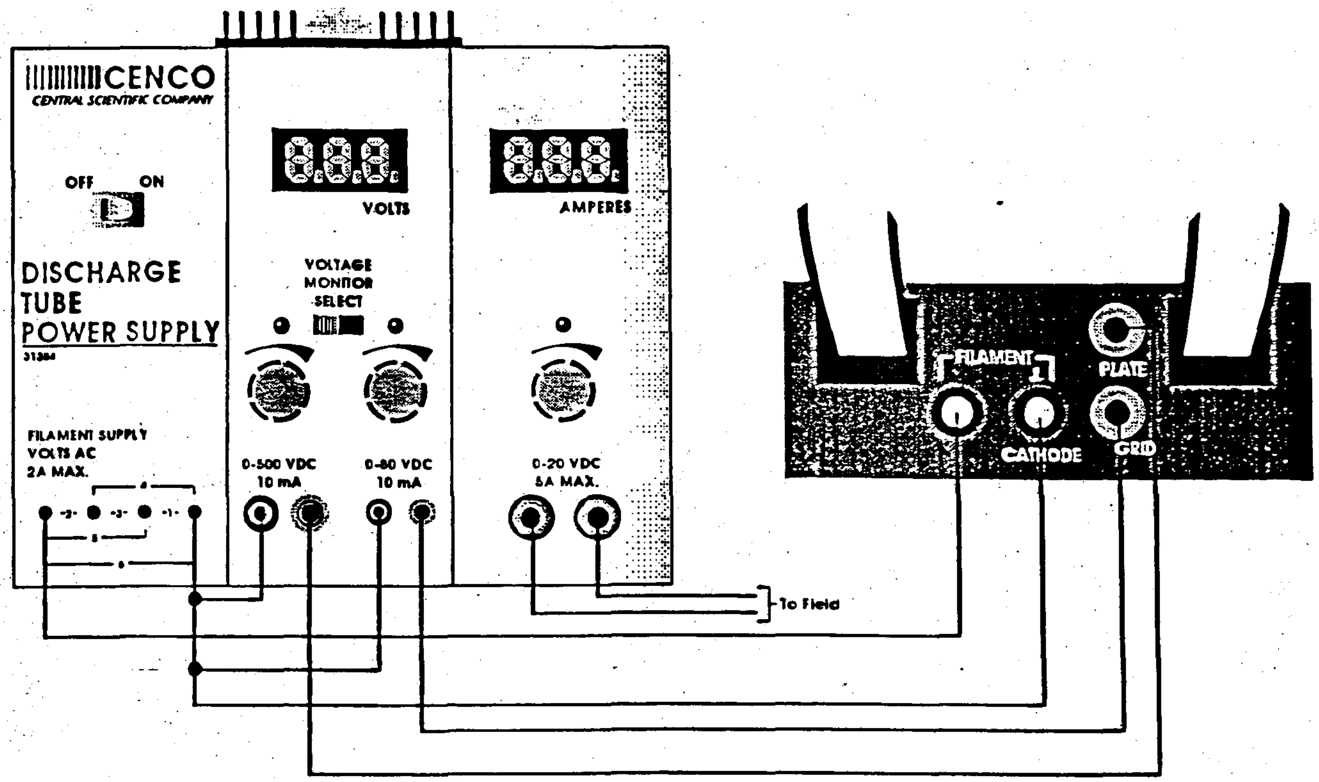

Figure 3. Wiring Connections