

## Charged Particles Moving in an Magnetic Field

### Equipment for Part 1

Qty	Item	Parts Number
1	Magnetic Field Sensor	CI-6520A
1	Zero Gauss Chamber	EM-8652
1	Dip Needle	SF-8619
1	Angle Indicator	ME-9495
1	Universal Table Clamp	ME-9376B
1	Large Rod	ME-8736
1	Adjustable Angle Clamp	ME-8744

### Equipment for Part 2

Qty	Equipment	Parts Number
1	e/m Apparatus	SE-9629
1	High Voltage Power Supply	SF-9585A
2	Low Voltage Power Supply	SF-9584B
8	Patch Cords	
1	Multimeter	
1	Compass	
1	Measuring ruler	

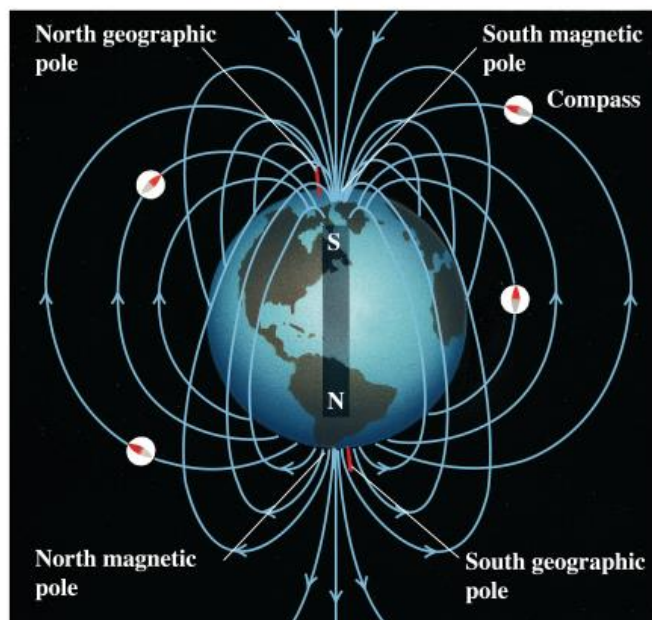
### Purpose

The purpose of Part 1 of this activity is to measure the local magnitude and direction of the Earth's Magnetic Field.

The purpose of Part 2 of this activity is to determine the charge-to-mass ratio of the electron via its movement through a locally uniform magnetic field oriented nearly perpendicular to the electron's path.

### Theory Part 1

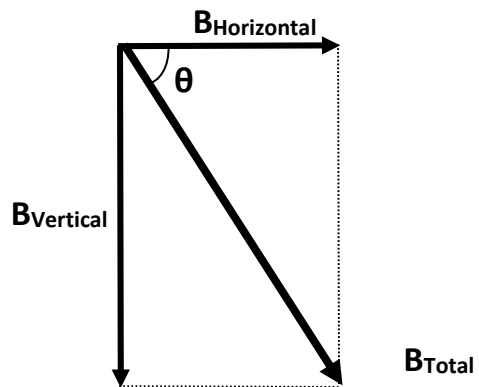
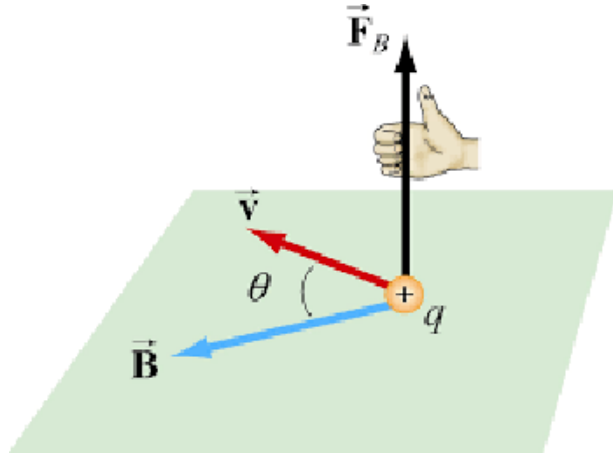
The Earth's magnetic field is rather complex and dynamic, however a decent first order approximation of it can be obtained by modeling it as a bar magnetic. The South magnetic pole of this theoretical bar magnet would be located near (but not at) the Earth's North geographical pole, and the North Pole of this theoretical bar magnet



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would be located near (but not at) the Earth's South geographical pole. Since when it comes to magnetic fields the opposite ends attract each other this is why the North Pole of a compass points North because that is the direction towards Earth's magnetic South pole!

A magnetic field is a vector field, in that it has both a local magnitude and local direction, and as you change locations the magnitude and direction of the magnetic field changes. The magnitude, and direction of the Earth's Field varies over the surface of the Earth, and like any vector it can be broken up into component form. One way to break it up is into its local horizontal and vertical components. The Horizontal component is the part of the magnetic field that points parallel with the local surface of the Earth, and the vertical component is the part of the magnetic field that points perpendicular to the local surface of the Earth. The direction of a magnetic field is defined to be pointing from the North Pole to the South Pole, and this results in the vertical component of Earth's magnetic field pointing downwards into the ground (in the Northern Hemisphere). The angle  $\theta$  that is formed between the horizontal component of the Earth's magnetic field and the direction of the Earth's total magnetic field is called the **Dip Angle**, and from the properties of the right triangle we can see that it is given by;



$$\theta = \cos^{-1} \left( \frac{B_H}{B_T} \right)$$

Where  $B_H$  is the magnetic field's horizontal component, and  $B_T$  is the total magnetic field.

## Theory/Background Part 2

According to the theory a magnetic field will exert a force on a charged particle moving through it via the equation;

$$F = qvB \sin(\theta)$$

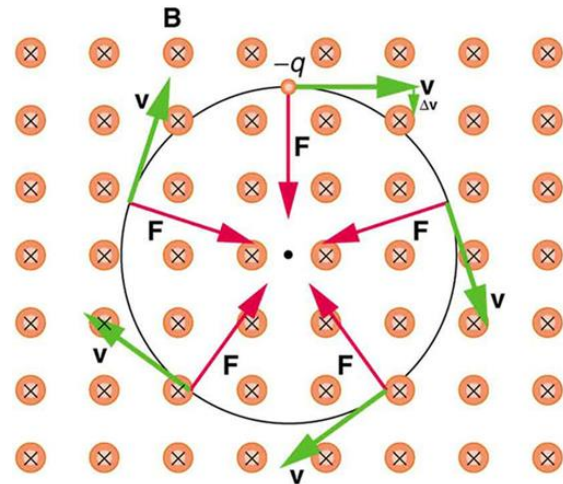
Where  $q$  is the charge of the particle,  $v$  is the velocity of the particle,  $B$  is the magnetic field, and  $\theta$  is the angle formed between the direction of the particle's velocity, and the orientation of the magnetic field. This induced force is said to point in the direction perpendicular to the plane formed by the combined directions of the velocity vector and the magnetic field vector. The direction of the induced force can be simply determined by the so called right hand rule where your fingers bend in the direction from the velocity vector to the magnetic field vector then your thumb points in the direction of the induced force

if the charge is positive, and the force points in the opposite direction of your thumb if the charge is negative.

If we let a charged particle moving with velocity  $v$  enter an uniform magnetic field  $B$  such that the two vectors are perpendicular to each other,  $\theta = 90^\circ$ , then the equation reduces too;

$$F = qvB$$

Once the charged particle enters the magnetic field the field will exert a force on the particle that is perpendicular to the directions of both the initial velocity of the particle and the direction of the field itself. This results in as the charged particle moves a little bit into the magnetic field it will begin to turn in the direction the induced force vector is pointing, but the particle's speed does not change. Since the force vector is pointing in a direction that is perpendicular to the particle's initial velocity, and the magnetic field, the particle's new velocity after having turned a little bit will still be perpendicular to the direction of the magnetic field. Which results in the process repeating, and then repeating again, and again, and again. The end result being that the particle ends up moving in a circle of radius  $r$ . The induced magnetic force acts as the centripetal force and any centripetal force has the form of



$$F_c = m \frac{v^2}{r}$$

This allows us to set the two force equations equal to each other.

$$qvB = m \frac{v^2}{r}$$

## Helmholz Coils

The apparatus that will be used today employs two Helmholtz coils to produce a magnetic field when a current passes through the wires that make up the coils. This magnetic field will be nearly uniform in the space between the two coils. This magnetic field is given by

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{\mu_0 N}{R} \cdot I$$

Where  $N = 130$  is the number of loops in each coil,  $I$  is the current in the coils,  $R = 0.140 \text{ m}$  is the average radius of the loops in the coils, and the permeability of free space is  $\mu_0 = 4 \cdot \pi \cdot 10^{-7} \frac{T \cdot m}{A}$ .

A beam of electrons will be shot into this magnetic field perpendicular to the field's orientation. The electrons are thermally emitted from the heated surface of a cathode and accelerated through a potential difference  $\Delta V$ , called the Acceleration Voltage. Assuming the electrons are accelerated from rest ( $v_i = 0$ ) then the kinetic energy of the electrons equals the energy they gain as a result of being accelerated through the potential difference;

$$\frac{1}{2}mv^2 = e \cdot \Delta V$$

$e$  in this equation is the electric charge of the electron, and  $m$  is the mass of an electron. Solving this equation for the final speed of the electron we get

$$v = \sqrt{\frac{2e \cdot \Delta V}{m}}$$

Inserting this into our previous equation of the two forces being equal to each other, where  $e = q$ , and solving for  $\frac{e}{m}$

$$evB = m \frac{v^2}{r}$$

$$eB = m \frac{v}{r}$$

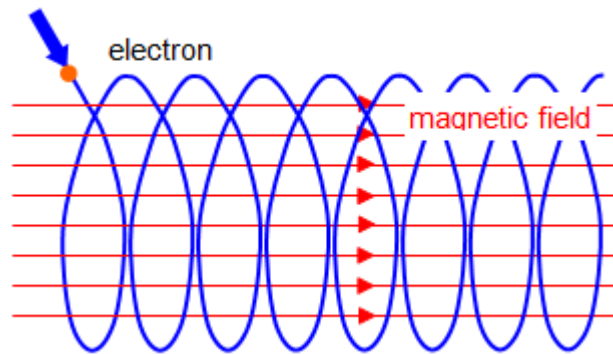
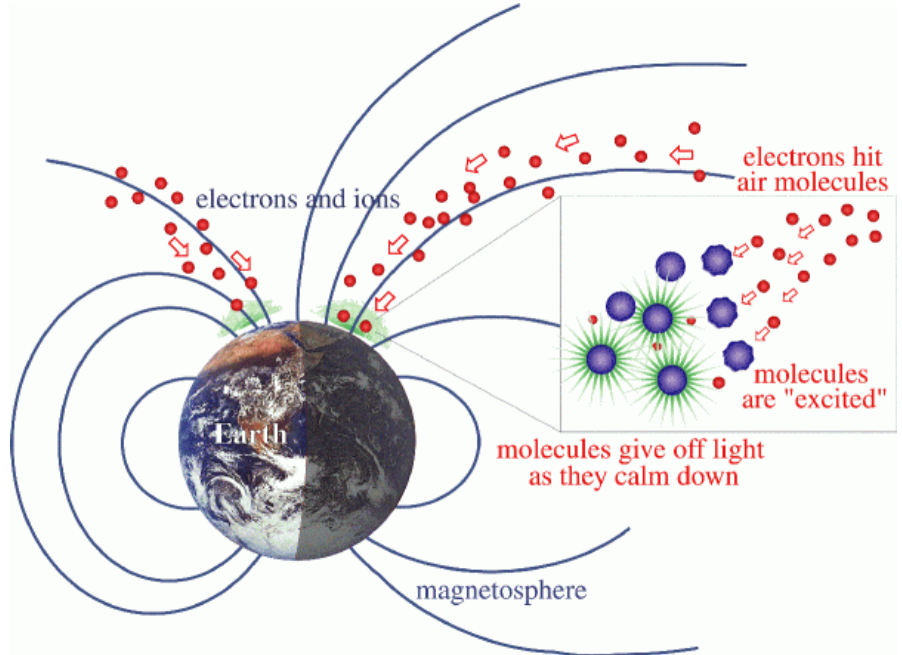
$$eB = m \frac{\sqrt{2e \cdot \Delta V / m}}{r}$$

$$e^2 B^2 = m^2 \frac{2e \cdot \Delta V}{r^2 \cdot m}$$

$$\frac{e}{m} = \frac{2 \cdot \Delta V}{(B \cdot r)^2}$$

## The Northern and Southern Lights

The Northern and Southern lights are caused by charged particles emitted from the Sun interacting with the Earth's magnetic field. The Sun emits charged particles, mostly electrons, and Hydrogen ions. All of these particles emitted from the Sun are collectively called the Solar Wind. Some of the particles eventually come into contact with the Earth's magnetic field where a similar phenomenon as discussed in the theory section of this worksheet occurs. When the charged particles enter the Earth's magnetic field they start to move in helices along the magnetic field lines, and this causes the particles to move towards the Earth's Polar Regions. Once in the Earth's upper atmosphere these particles eventually run into other particles. These collisions result in releases of energy in the form of photons, and these photons are what we call the Northern and Southern lights.



## Setup for Part 1

NOTE: During this experiment, keep the apparatus away of all sources of magnetic fields, such as electronics, computers, bar magnets, and so on. Also keep away from all ferromagnetic materials: iron, nickel, and cobalt. Best results will be obtained if preformed on a wooden, or hard plastic table.

1. Using the listed equipment construct the hardware setup as shown in the pictures.



2. Make sure the PASCO 850 Interface is turned on.
3. Double click the Capstone software icon to open the Capstone software.
4. In the Tool Bar, on the left side of the screen click on Hardware Setup to open the Hardware Setup window.
  - An image of the PASCO 850 Interface should be in the Hardware Setup window. If it is skip to step 5. If it is not then click on Choose Interface to open the Choose Interface window. In the Choose Interface window select PASPORT, then Automatically Detect, and then click OK.
5. On the image of the PASCO 850 Interface click on Digital Inputs Ch (1) to open up the digital sensors list.
  - Scroll down and select Rotary Motion Sensor.

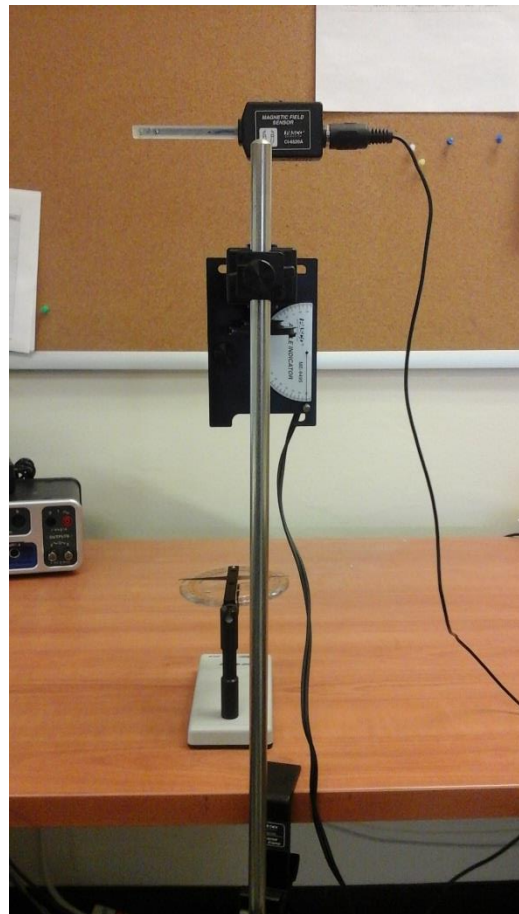
- The Rotary Motion Sensor icon should now appear in the Hardware Setup window with lines indicating that it is selected for Ch (1) and Ch (2)
  - Plug the Rotary Motion Sensor into the Digital Inputs. Yellow to Ch (1), and black to Ch(2).
6. On the image of the PASCO 850 interface click on the Analog Inputs Ch (A) to open up the analog sensors list.
    - Scroll down and select Magnetic Field Sensor.
    - The Magnetic Field Sensor icon should now appear in the Hardware Setup window with a line indicating that is selected for Ch (A).
  7. The Gain switch, which is physically on the Magnetic Field Sensor, set it to 100X
  8. Make sure orientation switch, which is also physically on the magnetic field Sensor, is set to Axial.
  9. In the Tool Bar click on the Data Summary icon to open the Data Summary window.
    - In the Data Summary window click on Magnetic Field Strength (100X) (T) to cause a properties icon to appear to its right.
    - Click on the properties icon to open the property window.
    - In the properties window click on Numerical Format.
    - Set Number of Decimal Places to 3.
    - Click ok to close the properties window.
  10. Close the Tool Bar.
  11. Near the bottom center of the screen select Common Rate for the instrument, and then set the sample rate to 20.0 Hz.
  12. In the Display Bar, on the right side of the screen, double click the graph icon to make a graph appear on Page #1.
    - Click on Select Measurement for the y-axis, and select Magnetic Field Strength (100X) (T).
    - The computer will automatically change the x-axis to time, we need to change the x-axis to Angle.
    - Along the x-axis click on Time, then select Angle (rad). Now click on the unts (rad), then change the units to (°).

## Procedure for Part 1: Horizontal Component

1. Arrange the Dip Needle into its horizontal position, and then move it to be underneath the rotary motion sensor.
  - Allow the dip needle to settle and find magnetic north.
  - Then tilt the rotary motion Sensor such that the angle indicator reads  $90^\circ$ .
  - Then rotate the magnetic field sensor till its probe is oriented in the same direction (North) as the dip needle.



2. Remove the dip needle so its magnetic field won't interfere with your measurements, but note the orientation of the magnetic field sensor.
3. Slip the zero gauss chamber over the magnetic field sensor probe, press the tare button on the top of the magnetic field sensor, and then remove the zero gauss chamber. (This isolates the sensor from the Earth's magnetic field while calibrating it.)
4. Near the bottom left of the screen click on record to start collecting data.

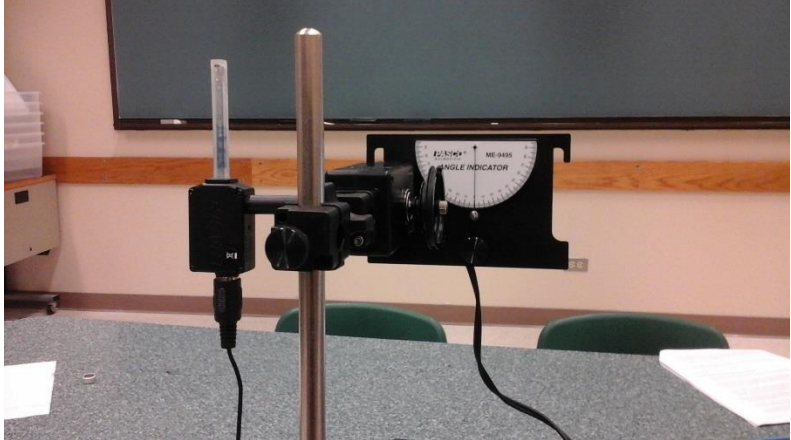


- Slowly start to rotate the magnetic field sensor through one complete  $360^\circ$  rotation. Click Stop once you have rotated through  $360^\circ$ .
  - Repeat this process to try to get a nice smooth curve. Be careful to not let the cords get tangled up.
  - Pick your smoothest graph, and then using the click on the arrow next to the Apply Smoothing to Active Data icon at the top of your graph, and then smooth out the graph as best you can.
5. Click on the Add Coordinate Tool icon at the top of the graph to add a coordinate tool to your graph.
    - Use the coordinate tool to determine the value of the measured horizontal component of the local magnetic field, when the magnetic field sensor was pointing north, and record this value in the provided Table.



## Procedure Part 1: Vertical Component

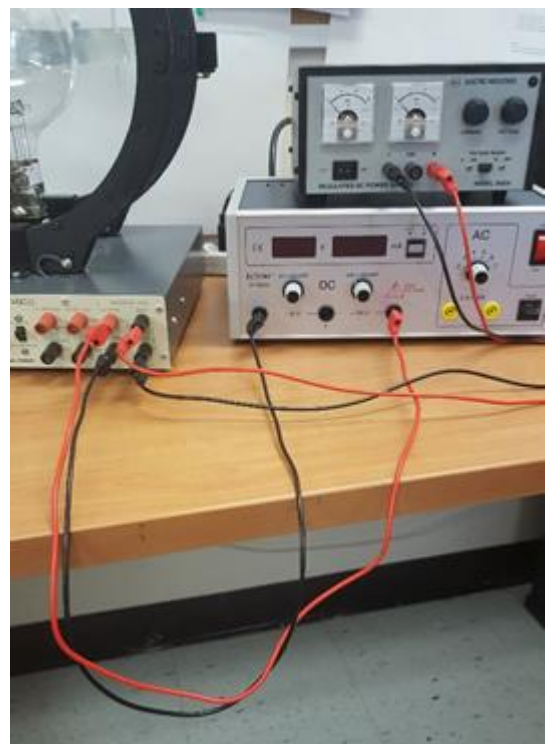
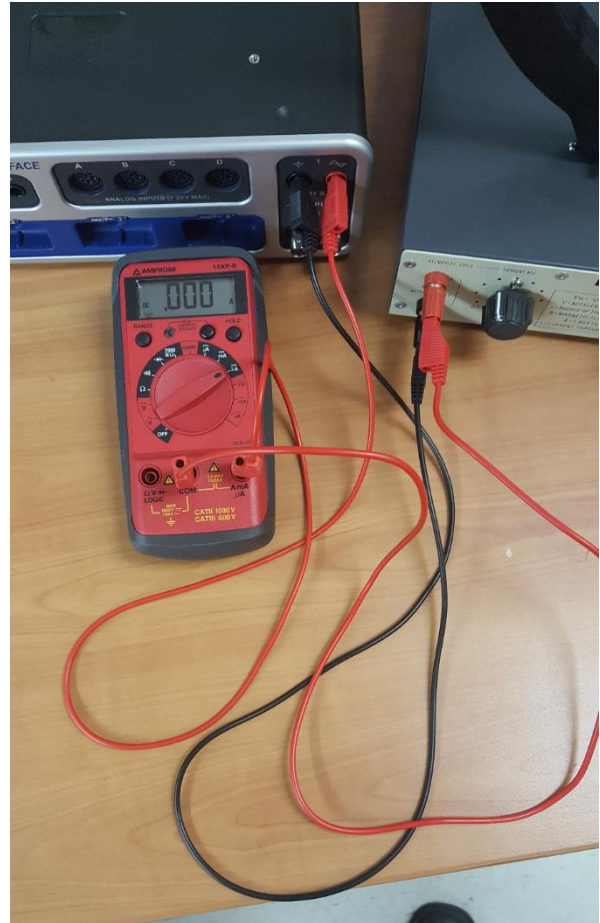
1. Rotate the setup till the angle indicator reads an angle of  $0^\circ$ .
6. Slip the zero gauss chamber over the magnetic field sensor probe, press the tare button on the top of the magnetic field sensor, and then remove the zero gauss chamber. (This isolates the sensor from the Earth's magnetic field while calibrating it.)
2. Near the bottom left of the screen click on record to start collecting data.
  - Slowly start to rotate the magnetic field sensor through one complete  $360^\circ$  rotation. Click Stop once you have rotated through  $360^\circ$ .
  - Repeat this process to try to get a nice smooth curve. Be careful to not let the cords get tangled up.
  - Pick your smoothest graph, and then using the click on the arrow next to the Apply Smoothing to Active Data icon at the top of your graph, and then smooth out the graph as best you can.
3. Click on the Add Coordinate Tool icon at the top of the graph to add a coordinate tool to your graph.
  - Use the coordinate tool to determine the value of the measured vertical component of the local magnetic field, when the magnetic field sensor was pointing downwards, and record this value in the provided Table.



## Setup for Part 2

**Note:** Part 2 will be performed at the lab instructor's desk, and under the supervision of the lab instructor.

1. In order to minimize the influence of the Earth's magnetic field using a compass align the coils of the apparatus so that they run parallel with the Earth's magnetic field.
2. Make sure the toggle switch on the e/m Apparatus is set to 'e/m Measure'.
3. Make sure the CURRENT ADJ knob on the e/m Apparatus is set to Off.
4. With the power turned off use three patch cords to connect a low voltage power supply to the low voltage (6V – 9V) sockets on the left side of the e/m Apparatus, with the multimeter connected.
  - It is with this multimeter that you will measure the current flowing through the coils.
  - Turn on the low voltage power supply, and set it to 9V. It can take up to ten minutes for the cathode tube to warm up enough to start expelling electrons.
5. With the power turned off using two patch cords connect the high voltage power supply to the electrodes sockets on the right side of the e/m Apparatus. (They are the second set of sockets on the right side of the apparatus)
  - Turn on the high voltage power supply, and set it to 200V
6. With the power turned off use two patch cords to connect a low voltage power supply to the HEATER sockets on the right side of the e/m Apparatus.
  - Turn on the low voltage power supply, and set to 5V.
  - Never allow the voltage to go higher than 5V.
7. Turn on the current in the e/m Apparatus by slowly turning the CURRENT ADJ knob, on the left side of the e/m Apparatus.
  - Soon you should be able to see the blue-green beam of electrons.



## Procedure for Part 2

1. Make sure that the high voltage power supply is at 200V. (This is the Acceleration voltage)
2. Using the CURRENT ADJ knob set the current going through the Helmholtz coils till you can see that the electrons are deflected into a circular path inside the bulb.
  - Read the current measurement from the multimeter, and record it in the provided table.
3. Using a measuring ruler measure the radius of the circular beam of electrons, and then record measurement in the table provided.
  - Repeat measurements and record in the table provided for four more current settings each at least 0.10 Amps larger than the previous measurement.

**Table for Part 1 (20 points)**

<b>Horizontal Component of Magnetic Field (T)</b>	
<b>Vertical Component of Magnetic Field (T)</b>	

1. Using your two measured components calculate the magnitude of the local Earth's magnetic field. (5 points)

2. The current accepted value of the magnitude of the Earth's magnetic field in the San Antonio area is  $4.67 \cdot 10^{-5} \text{ T}$ . Calculate the % error between this and your measured value. (5 points)

3. Calculate the Dip Angle of the local Earth's magnetic field. (5 points)

4. The current accepted value of the Dip Angle of the local Earth's magnetic field in the San Antonio area is  $58.2^\circ$  (downwards). Calculate the % error between this and your measured value. (5 points)

**Table for Part 2, Acceleration Voltage: 200V**

$I$ (A)	$B$ (T)	$r$ (m)	$B \cdot r$ (T · m)	$\frac{e}{m} \left( \frac{C}{kg} \right)$
				$\left( \frac{e}{m} \right)_{avg}$

Complete the chart, and show work in the space provided. (25 points)

5. The accepted value of the charge-to-mass ratio of an electron is  $\frac{e}{m} = 1.76 \cdot 10^{11} \frac{C}{kg}$   
Calculate the % error for your experimental value, and the accepted value. (5 points)
6. Calculate the speed of the electrons in our experiment after they have passed through the 200V acceleration voltage. Now assuming an uniform magnetic field with the magnitude of your experimental value for Earth's local magnetic field, what would be the radius of the circular path that an electron with this speed would make in it? (10 points)