

# Experiment 4

## Magnetic Fields

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## 1 Introduction

In this experiment, we measure the charge to mass ratio  $e/m$  of electrons fired in a Helmholtz coil. The electrons are emitted from a hot filament, accelerated by an electric field, and then deflected by a magnetic field into a circular orbit. If the radius of this orbit is known, as well as the intensity of the magnetic field, and the accelerating potential of the electric field, we can determine  $e/m$  and the velocity  $v$  of the electrons, and an approximate value for the earth's magnetic field  $B_E$ . Using the left-hand-rule for moving charge (since we are dealing with electrons), we can also figure out the direction of the magnetic field which deflects the electrons. The charge to mass ratio is found using the following equation, of which a derivation exists in the Discussion section. The equation below is also linearized, and graphed, from which we obtain an approximate value of the earth's magnetic field using the Y-intercept, and  $e/m$  from the slope.

$$\frac{e}{m} = \frac{2V}{(B_H - B_E)^2 r^2} \quad (1)$$

In this equation,  $e$  is the charge of an electron, and  $m$  is the mass of the electron, 'V' is the DC voltage applied to the Helmholtz coil ,  $B_H$  is the magnetic field of the coil, given by

$$B_H = \frac{8\mu_0 NI}{\sqrt{125R}} \quad (2)$$

,and  $r$  is the orbit radius of the electrons. In Equation 2 above,  $\mu_0$  is the permeability of free space,  $N$  is the number of turns in the Helmholtz coil,  $R$  is the radius of the coil, and  $I$  is the measured current through the coil.

## 2 Experimental Method

### List of Equipment:

- Helmholtz coil apparatus (Figures 1 and 2)
- AC Voltage Source
- DC Voltage Source
- Voltmeter
- Ammeter
- Wires

The Helmholtz coil was set up such that its alignment is approximately opposite to the Earth's magnetic field, which in Edmonton means that the coil should be tilted upwards at an angle of about 18 degrees relative to the horizontal. The apparatus involves three separate electrical circuits. The filament,

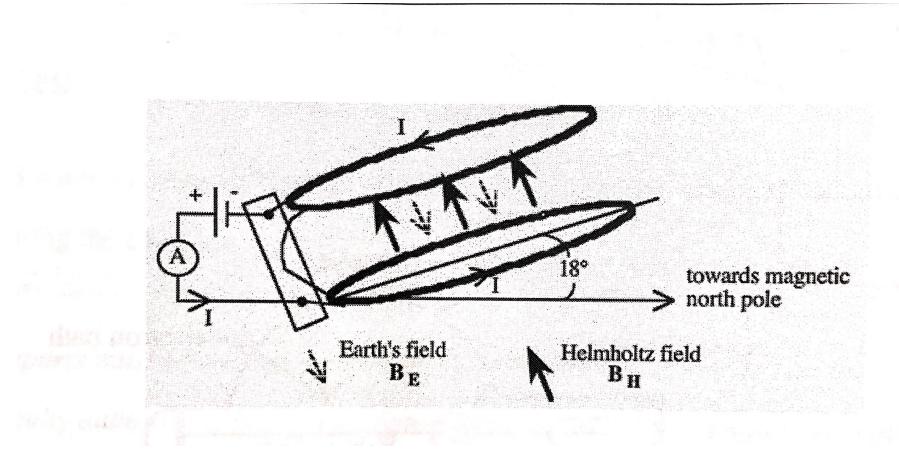


Figure 1: Helmholtz coil apparatus, and its alignment opposite to earth's magnetic field. [1]

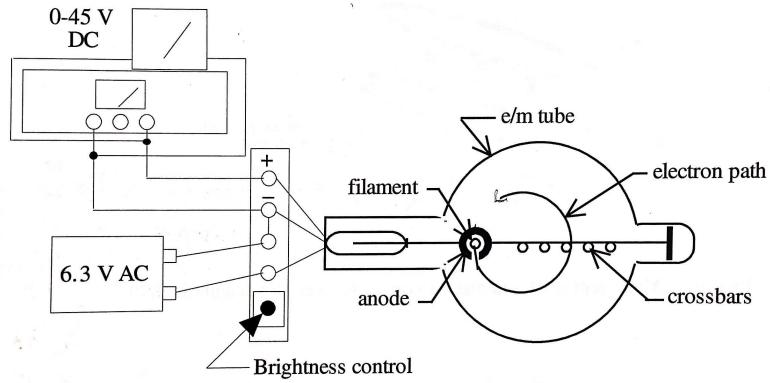


Figure 2: Circuit wiring for the apparatus [1]

anode circuit, and the Helmholtz circuit are connected as outlined below in Figure 2. We first begin by setting the DC voltage source to 20 V, then modifying the AC voltage source to change the radius of the glowing circular electron path. The current going through the Helmholtz coil is recorded in a spreadsheet at each point where the loop is on the far side of each peg, with larger currents resulting in smaller loops. Then, the DC voltage source is set to 30 V, and the Helmholtz current  $I$  is measured and recorded at the 5 points again. The same process is repeated once more when the DC voltage source is set to 40 V. It should be noted that adjusting the brightness control knob, viewing the loop

from above, and doing the experiment in a dark environment made it easier to view the electron loop. Since we have the Helmholtz currents, and the diameter of the pegs in the apparatus are known (and therefore the radius of the loops that the electrons make), a linear graph can be created by linearizing equation 1, from which we can obtain the charge to mass ratio  $e/m$  from the slope, and the earth's magnetic field  $B_E$  from the Y-intercept.

### 3 Results

Raw data recorded while measuring the Helmholtz current  $I$  required to align the beam with the far side of each peg.

Voltage (V)	Current (A)	Peg number	Radius r (cm)
20	2.68	1	0.0325
20	2.19	2	0.039
20	1.94	3	0.045
20	1.73	4	0.0515
20	1.54	5	0.0575
30	3.12	1	0.0325
30	2.66	2	0.039
30	2.29	3	0.045
30	2.1	4	0.0515
30	1.9	5	0.0575
40	3.62	1	0.0325
40	3.05	2	0.039
40	2.63	3	0.045
40	2.35	4	0.0515
40	2.12	5	0.0575

Table 1: Raw data recorded when measuring the Helmholtz current

Using the data in Table 1, a linear graph is generated with Equation 1, which is obtained through a derivation outlined in the discussion section.

The equation is linearized by the following process:

$$\begin{aligned}
 B_H &= \frac{8\mu_0 NI}{\sqrt{125}R} \\
 B_H &= \frac{8(4\pi \times 10^{-7} \text{ T m A}^{-1})}{\sqrt{125}(14.8 \text{ cm})} \\
 \Rightarrow N &= \frac{B_H \sqrt{125}R}{8\mu_0 I} \\
 \therefore N = 
 \end{aligned}$$

so we generate a graph with  $\sqrt{2V_r}$  on the X axis using our measured voltage values, and  $B_H$  on the Y axis using our measured current values.

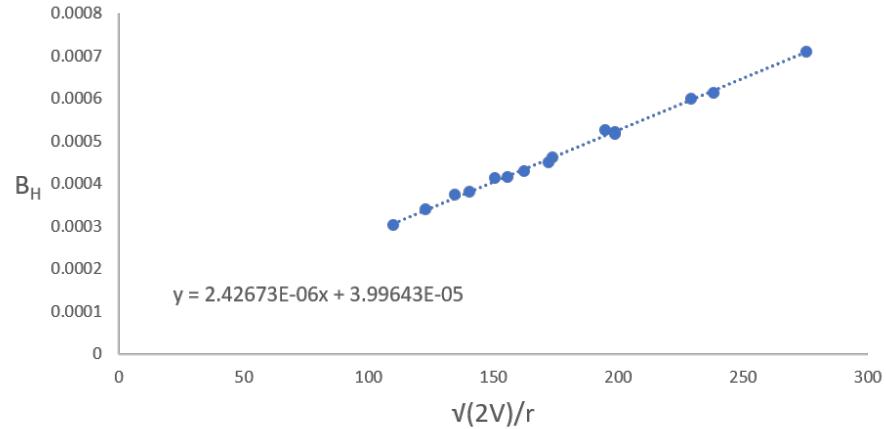


Figure 3: Measuring the voltage difference in a region between two parallel conductors.

Using Excel's LINEST function, we obtain the following data from the graph in Figure 3.

$$\begin{aligned} \text{Slope } \sqrt{m/e} : & \quad 2.426\ 725\ 593\ 841\ 1 \times 10^{-6} \pm 3.506\ 497\ 745\ 708\ 97 \times 10^{-8} \\ \text{Y-Intercept } B_E : & \quad 3.996\ 426\ 317\ 981\ 73 \times 10^{-5} \pm 6.401\ 675\ 040\ 070\ 98 \times 10^{-6} \end{aligned}$$

Table 2: LINEST data from the graph in Figure 3

To obtain the calculated value for  $e/m$ , we can see from our LINEST data (Table 2) that the slope,  $\sqrt{m/e}$  is  $2.426\ 725\ 593\ 841\ 1 \times 10^{-6}$ .

Thus, the calculated value of  $e/m$  can be found:

$$\frac{e}{m} = \left( \sqrt{\frac{m}{e}} \right)^{-2} = 1.69808200223924714236 \times 10^{11}$$

And the error  $\delta \frac{e}{m}$  can be calculated using partial derivatives:

$$\begin{aligned} \text{slope} &= \left( \frac{e}{m} \right)^{-1/2} \\ \delta \text{slope} &= \left| -\frac{1}{2} \left( \frac{e}{m} \right)^{-3/2} \delta \left( \frac{e}{m} \right) \right| \\ 2 \times \delta \text{slope} &= \left( \frac{e}{m} \right)^{-3/2} \delta \left( \frac{e}{m} \right) \\ \therefore \delta \left( \frac{e}{m} \right) &= 2 \times \delta \text{slope} \left( \frac{e}{m} \right)^{3/2} \end{aligned}$$

From our LINEST data (Table 2), we know that  $\delta \text{slope} = 3.506\ 497\ 745\ 708\ 97 \times 10^{-8}$

$$\begin{aligned} \therefore \delta \left( \frac{e}{m} \right) &= 2 \times 3.506\ 497\ 745\ 708\ 97 \times 10^{-8} \times (1.698\ 082\ 002\ 239\ 247\ 142\ 36 \times 10^{11})^{3/2} \\ &= 4.907\ 288\ 016\ 405\ 85 \times 10^9 \approx 4.91 \times 10^9 \end{aligned}$$

Thus, the calculated value for  $\frac{e}{m}$  is:<sup>1</sup>

$$\frac{e}{m} = 1.70 \times 10^{11} \pm 4.91 \times 10^9 \text{ C kg}^{-1}$$

The percent error is:

$$\frac{|1.698\ 082\ 002\ 239\ 247\ 142\ 36 \times 10^{11} - 1.76 \times 10^{11}|}{1.76 \times 10^{11}} \times 100 = 3.52\%$$

Obtaining the calculated value and error for  $B_E$  is a much simpler matter. We simply look at the data generated by LINEST, specifically, the Y-intercept (Table 2).

$$B_E = 4.00 \times 10^{-5} \pm 6.40 \times 10^{-6} \text{ T}$$

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<sup>1</sup>Value rounded to three significant digits simply for neatness. Otherwise, the full values were messy and long

The percent error is:

$$\frac{|3.996\ 426\ 317\ 981\ 73 \times 10^{-5} - 4.8 \times 10^{-5}|}{4.8 \times 10^{-5}} \times 100 = 16.74\%$$

The calculated values of  $e/m$  and  $B_E$  from the graph are summarized in Table 3.

	Expected	Calculated:	% Error
$e/m:$	$1.76 \times 10^{11} \text{ C kg}^{-1}$	$1.70 \times 10^{11} \pm 4.91 \times 10^9 \text{ C kg}^{-1}$	3.52
$B_E:$	$4.8 \pm 0.3 \times 10^{-5} \text{ T}$	$4.00 \times 10^{-5} \pm 6.40 \times 10^{-6} \text{ T}$	16.74

Table 3: Measured values of  $e/m$  and  $B_E$  compared to the calculated values obtained from the graph.

## 4 Discussion

### 4.1 Part 1

From Table 3, we can see that our calculated values for  $e/m$  ( $1.70 \times 10^{11} \pm 4.91 \times 10^9 \text{ C kg}^{-1}$ ) and  $B_E$  ( $4.00 \times 10^{-5} \pm 6.40 \times 10^{-6} \text{ T}$ ) were in the same order of magnitude as the expected values. ( $1.76 \times 10^{11} \text{ C kg}^{-1}$  for  $e/m$  and  $4.8 \pm 0.3 \times 10^{-5} \text{ T}$  for  $B_E$ .) Additionally, the percent error for the charge to mass ration seemed relatively good, being 3.52%. However, our calculated value of  $B_E$  was a fair bit off, with a 16.74% error. Unfortunately, it is clear that our calculated values do not fall within error of the expected values.

At first glance, the graph (Figure 3) produced from our raw data (Table 1) seems reasonable, especially because all the data points recorded seem to fit nicely on the trendline with no anomalous data points compared to the other values. This means that whatever error introduced in our measurement of voltages was a constant factor, since we took care to measure the currents exactly when the electron loop was on the far side of each peg, as specified in the lab manual. There are many potential sources of error, including human error, and potential miscalibration of equipment since we are dealing with electrons which are tiny in nature. We did our best to keep these factors constant.

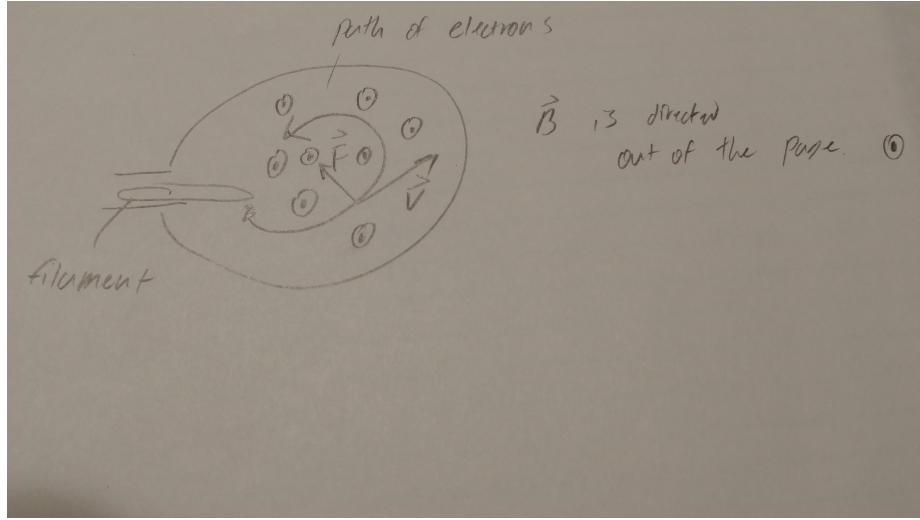


Figure 4: The direction of the  $\mathbf{B}$  field is found to be pointing out of the page when drawn this way.

Using the left-hand-rule for moving a charged particle, (since we are dealing with electrons which have a negative charge), we determine that the net magnetic field  $\mathbf{B}$  points upward, perpendicular to the radius of the coil, or upwards relative to Figure 2. Additionally, we notice that as the Helmholtz current is increased a tighter loop is formed.

Equation 1, which was manipulated to produce our graph can be derived using the following equations:

When a stream of electrons are accelerated through a potential difference  $V$ , the maximum kinetic energy is given by:

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

Next, the Lorentz force  $\mathbf{F}$  is given by:  $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$  (where  $q$  is the charge of the moving particle), and since our magnetic field is set up so that  $\mathbf{B}$  is perpendicular to the motion of the electrons (see Figure 1), the magnitude of the force  $F$  is given by

$$F = qvB$$

Next, the radius of the circle, which is the path of the electrons in this experiment is such that the centripetal acceleration is furnished by the Lorentz force. Therefore, we obtain

$$\frac{mv^2}{r} = evB$$

To obtain Equation 1, we first rearrange the first of the three equations above and substitute it into the third.

$$\frac{1}{2}mv^2 = eV \Rightarrow v = \frac{\sqrt{2eV}}{m}$$

$$\begin{aligned}\Rightarrow \frac{m(\frac{2eV}{m})}{r} &= e\sqrt{\frac{2eV}{m}}B \\ \Rightarrow \frac{4V^2}{r^2} &= \frac{2eV}{m}B^2 \\ \Rightarrow \frac{e}{m} &= \frac{2V}{r^2B^2}\end{aligned}$$

Finally, we notice that since our apparatus is aimed antiparallel to earth's magnetic field, such that the magnitude of the total magnetic field  $B = B_H - B_E$ , and substitute this result in the above equation. Finally, we obtain equation 1.

$$\frac{e}{m} = \frac{2V}{(B_H - B_E)^2 r^2}$$

### Questions:

*Why is it important to align the Helmholtz coil, so that its field is anti-parallel to the earth's magnetic field?*

**A:** Earth's magnetic field is strong enough to deflect our little electron beam, which means its effects are non-negligible. However, if we align our Helmholtz coil such that it is exactly anti-parallel to the Earth's magnetic field, we notice that in this arrangement, since  $B_E$  is pointing in the opposite direction to  $B_H$ , the magnitude of the net magnetic field can be found simply by subtracting  $B_E$  from  $B_H$  since it is anti-parallel to the earth's magnetic field. If the alignment was different, the geometry would not be so simple, and the path of the electrons would not be in the same plane as the orientation of the Helmholtz coil.

*Explain what would happen if the beam in this experiment contained several ions of different masses.*

**A:** If there were several ions of different masses, the ions with larger mass would have a larger radius of curvature, and the ions with smaller mass would have a smaller radius of curvature, by observing that the centripetal force depends on the  $F_c = \frac{mv^2}{r}$  relation. By rearranging this, we see that the mass is directly proportional to the radius of curvature, i.e.  $m \propto r$ . Experimentally, we would notice that the glowing path of the ions would be wider, and therefore it would be difficult to measure the Helmholtz currents exactly at the far side of the pegs in the apparatus, like we did for the electrons, which had unvarying masses. This ambiguity would also skew our measured charge to mass ratio, since the charged masses are varied and not constant.

## 5 Conclusions

In Experiment 2, we calculate the charge to mass ratio  $e/m$  of electrons fired in a Helmholtz coil, which are accelerated by an electric field, and deflected by a magnetic field to form a circular orbit. The apparatus was set up such that the magnetic field of the coil is aligned antiparallel to the earth's own

magnetic field to simplify the geometry. The current was varied at three different voltages to align the electron loops to known radii, so that we could use the Helmholtz currents to calculate a value for  $e/m$ , and the earth's magnetic field  $B_E$  by plotting a linear graph. We noticed that the radius of curvature of the electron loops increased as the Helmholtz current was lowered. Additionally, using the left hand rule (since electrons are negatively charged masses), we verified that the net magnetic field of the setup was directed upwards, in the same orientation of the coil (in other words, the direction of the net magnetic field was perpendicular to the radius of the coil). We calculated the charge to mass ratio of the electron to be ( $1.70 \times 10^{11} \pm 4.91 \times 10^9 \text{ C kg}^{-1}$ ) and the earth's magnetic field to be ( $4.00 \times 10^{-5} \pm 6.40 \times 10^{-6} \text{ T}$ ). While these values are in the same order of magnitude as the expected values ( $1.76 \times 10^{11} \text{ C kg}^{-1}$  for  $e/m$  and  $4.8 \pm 0.3 \times 10^{-5} \text{ T}$  for  $B_E$ ), these values do not agree within error. The graph generated from our data was linear, however, so it is likely that the source of error introduced was a constant factor, whether it's miscalibration of equipment, or human error since we took care to record our results in a consistent manner.

## References

- [1] I. Isaac, "Phys 230 lab manual," 2018.