Name: Section: 202L- Date:

Experiment 2: Electric Force

Objectives

- To learn the basics of good lab practice
- To learn how to estimate uncertainties
- To learn how to propagate uncertainties
- To study the velocity of an electron produced by an accelerating voltage.
- To study the electric force on a beam of moving electrons.

Equipment

- One (1) Cathode Ray Tube (CRT) fixture.
- One (1) Cathode Ray Tube (CRT) containing an electron gun, fluorescent grid, and deflection plates.
- One (1) Package of Cables containing:
  - Two (2) long (86 cm) black cables
  - One (1) long red cable
  - Two (2) medium (61 cm) blue cables
  - Four (4) short (36 cm) black cables
  - Two (2) short (36 cm) red cables
  - Three (3) red male-to-female cables
  - One barrel connector
- Two (2) Frederiksen 3670 6 kV Power Supplies

Safety---Electrical Shock Hazards

You will be working with voltages significantly above 50 V. You must be ***extra cautious*** when working with the energized equipment in this experiment. Following these instructions will help keep you and the equipment safe:

- ***No food or drink is allowed.*** Water and electrical equipment do not play well together.
- ***Never "get between" a voltage source and ground.*** Do not touch metal parts unless you are **certain** that they do not have voltage on them. Currents as low as 10 mA are painful and currents of 20 mA and higher can do harm if they are allowed to travel through your body---especially across your chest.
- ***Never touch the positive and negative leads together to form a "short" circuit.*** Doing so may cause a spark which can destroy sensitive equipment or cause an electrical fire.
- ***Always turn off the power supply before connecting or disconnecting new circuit elements.*** Doing so will minimize the chance of causing sparks.

Introduction

The interaction of electric *currents* with electric and magnetic fields was first proposed by James Clerk Maxwell when he published his famous equations in *A Dynamical Theory of the Electromagnetic Field* in 1864.

In 1897, J.J. Thompson discovered the electron by studying the "cathode rays" that appeared in a Crooke's tube (also known as a "Cathode Ray Tube"). One of the experiments that he performed to show that these "cathode rays" were actually a beam of charged particles was to push them around using both electric and magnetic fields. He was able to easily move them around using magnetic fields, but had a hard time affecting the electrons using electric fields until he was able to produce a much better vacuum within the tube.

Using somewhat more modern equipment, you will be able to reproduce J.J. Thompson's experiment and verify that the electric force on an electron obeys the law

$$F = qE \tag{1}$$

where q is the charge on an electron and E is the applied electric field.

Below is a schematic of the Teltron tube that you will be using. The electrons are "boiled" off of a filament in the electron gun (4). They are accelerated towards the fluorescent screen (1) by the application of an accelerating voltage to pin (6).

The fluorescent screen is bordered by two capacitor plates (2 and 7). By placing a voltage across these plates, we develop an electric field in the region. This electric field will deflect the electrons. The physical distance between these plates is about 54 mm.

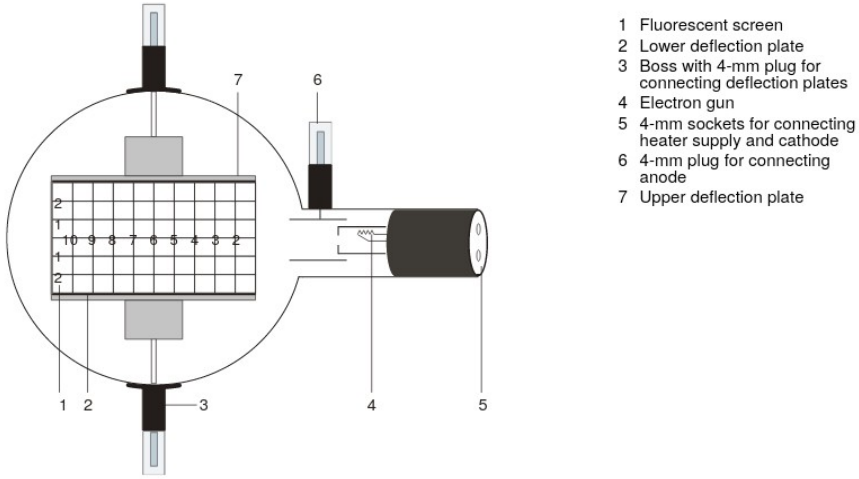

Figure 1: Schematic of the Teltron Tube

Theory

In order to determine the force on the electrons using equation (1), we will need to determine the electric field between the plates.

Computing the Electric Fields

We could compute the electric field from the plate voltage, V_p, from

$$E=\frac{V_p}{d_{eff}} \tag{2}$$

where d_{eff} is the *effective* distance between the plates. It is not the *actual* distance because the parallel-plate capacitor approximation isn't quite good enough for these long, thin plates. By measuring the deflection of the electron beam after it travels the 10 cm across the measurement grid, we can deduce this electric field and, therefore, the effective distance between the plates.

If equation (1) is correct, the vertical acceleration of the electrons is given by

$$a=\frac{F}{m}=\frac{qE}{m} \tag{3}$$

The vertical distance that the electron then travels is given by kinematics:

$$\Delta y=\frac{1}{2}a(\Delta t)^2=\frac{1}{2}\left(\frac{qE}{m}\right)(\Delta t)^2 \tag{4}$$

We need to know the time taken for the electrons to traverse the screen. Kinematics tells us that the time taken for a particle moving at constant velocity to traverse some distance, Δx, is

$$\Delta t=\frac{\Delta x}{v} \tag{5}$$

But how fast are the electrons traveling?

Determining the Speed of the Electrons

From conservation of energy, we know that the electron will be ejected from an "electron gun" with a kinetic energy that is related to the accelerating voltage, V_a:

$$\frac{1}{2}mv^2 = qV_a \tag{6}$$

We can re-arrange this equation for the speed of the electron:

$$v = \sqrt{\frac{2qV_a}{m}} \tag{7}$$

where *m* is the electron's mass.

Determining the Path of the Electrons

We now put together equations (4), (2), (5), and (7) to find that

$$\Delta y = \frac{1}{2}\left(\frac{qE}{m}\right)\left(\frac{\Delta x}{v}\right)^2 = \frac{1}{2}\left(\frac{q(V_p/d_{eff})}{m}\right)\frac{(\Delta x)^2}{2qV_a/m} = \frac{1}{4d_{eff}}\frac{V_p}{V_a}(\Delta x)^2 \tag{8}$$

Therefore, if equation (1) is correct, the path of the electrons should be a parabola. You will be checking this.

Determining the Effective Plate Separation

Notice that, in equation (8), if we keep the beam set so that it always passes through the point $(\Delta x, \Delta y)$, then the ratio of voltages, V_p/V_a, should remain the same. Rearranging equation (8) we find that ratio to be:

$$\frac{V_p}{V_a} = \frac{4\Delta y}{(\Delta x)^2} d_{eff} \tag{9}$$

The second part of the lab will have you set the beam so that it goes through the point (10 cm, 2 cm). You will plot the values for the plate voltage vs. the accelerating voltage. The slope of this line is the ratio V_p/V_a. By rearranging equation (9) we find

$$d_{eff} = \frac{V_p}{V_a}\frac{(\Delta x)^2}{4\Delta y} \tag{10}$$

Uncertainty Analysis

The easiest way to get the uncertainty will be to allow the Capstone fitting algorithm to do it for us. By using the quadratic fit to equation (8) and a linear fit to equation (9), we can get the uncertainties for the quadratic fit and the ratio V_p/V_a. Given the uncertainties in determining the locations Δx and Δy, we can use the power and product/quotient rules to determine the uncertainty in the effective plate separation.

Experimental Procedure

Measuring the Electric Field Produced by the Deflection Plates

I. Electron Gun Connections:

   A. Pick one of the two HV power supplies to run the electron gun. **Ensure that it is switched OFF and the voltage knob is rotated fully CCW**. It will have two high-voltage terminals, a ground terminal, and two AC voltage terminals. You will need:

      1. Two (2) **blue** banana plug cables
      2. One (1) short **red** banana plug cable

3. One (1) short **black** banana plug cable
4. One (1) long **red** female-to-female banana cable.

B. **Power the heater:** Connect the AC voltage sockets (yellow) to the heater inputs on the back of the black cap of the Cathode Ray Tube (CRT) with the two **blue** banana plug cables.

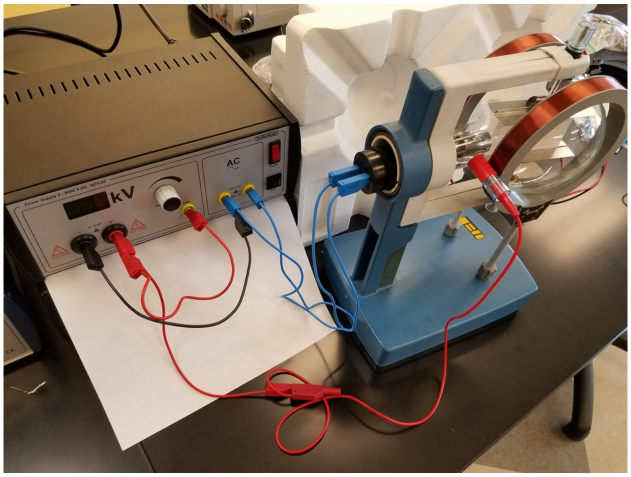

Figure 2: Electron Gun Configuration

C. **Power the accelerating grid:**

1. Connect the **negative (black)** high-voltage terminal to one of the blue heater cables (it doesn't matter which one) with a short **black** cable.
2. Plug the short **red** cable into the **positive (red)** high-voltage terminal.
3. Plug the other end of the **red** cable into the "plastic brick" end of the long **red** female-to-female cable.
4. Connect the other end of the long **red** female-to-female cable to the anode pin on the neck of the CRT. <u>*Be gentle:*</u> you're working with a thin glass tube!
5. Connect the **positive (red)** high-voltage terminal to the ground (GND) terminal with a short **black** cable.

   At this point, the connections should look like those in Figure 2.

II. Electric Field Plate Connections:

A. Your other HV power supply will power the electric field plates. You will only need to use the black and red HV connections and the ground terminal. You will not need the AC connections. **Again, make sure the power supply is switched off and the voltage control knob is fully CCW.** You will need:

1. One (1) barrel connector
2. One (1) long **black** cable
3. One (1) short **red** cable
4. One (1) **red** female-to-female cable
5. One (1) short **black** cable

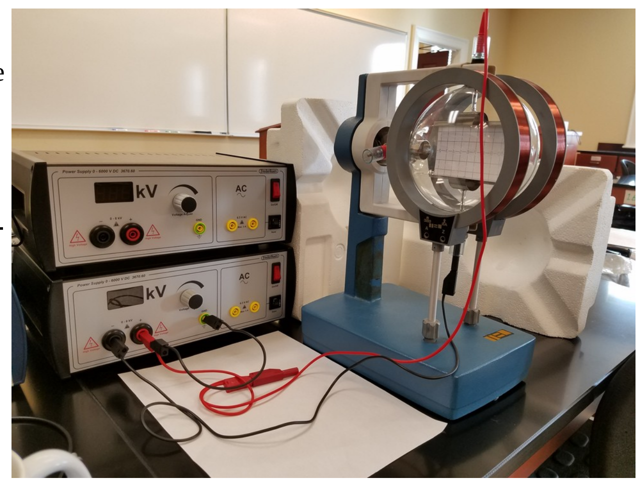

Figure 3: Electric Field Plate Configuration

B. Attach a barrel connector to the lower pin on the CRT. <u>Be Gentle.</u> It should not need too much force.

C. Connect the **negative (black)** terminal of the HV power supply to the barrel connector with a long **black** cable.

D. Plug the short **red** cable into the **positive (red)** terminal of the HV power supply.

E. Plug the other end of the **red** cable into the "plastic brick" end of the long **red** female-to-female cable.

F. Connect the other end of the long **red** female-to-female cable to the upper pin on the CRT. <u>Be gentle</u>. It should not need much force.

G. Connect the **positive (red)** high-voltage terminal to the ground (GND) terminal with a short **black** cable.

These connections should look like those in Figure 3.

<u>Have your instructor check all of these connections before continuing!</u> (Instructor Initials:)

III. Data Acquisition

You are now ready to verify that the path of the electrons follows a quadratic (equation (8)).

A. Verifying the quadratic path for the electrons (equation (8)):

1. Turn on the HV power supply connected to the electron gun and set the accelerating voltage to 4.5 kV.
2. Wait until you see the glowing blue trail of electrons on the mica screen.
3. Turn on the HV power supply connected to the electrode plates and slowly increase the plate voltage until the beam is 2 cm above its original height at x=10 cm.
4. Record the position of the beam at many locations so that you can plot it and fit it to a quadratic.
5. Repeat steps 1--4 for accelerating voltages of 3.5 kV and 2.5 kV

B. Plotting the slope of V_p/V_a and determining the effective plate spacing.

1. With the accelerating voltage set to 2.6 kV, set the plate voltage so that the beam passes through the point (10 cm, 2 cm).
2. Record the values of the accelerating voltage and plate voltage.
3. Increase the accelerating voltage by 0.2 kV and set the plate voltage so that the beam passes through (10 cm, 2 cm). Record the values of the accelerating voltage and plate voltage.
4. Repeat step 3 until you reach an accelerating voltage of 5 kV.
5. Plot the data of plate voltage vs accelerating voltage and perform a linear fit to get the slope.
6. Use equation (10) to determine the effective plate separation.

Clean Up

Once you've completed the experiment, return your apparatus to a safe state by following these steps *in this order*:

1. Ensure you have all the data you need to write your report (see the next page). You might consider uploading your data to your Google Drive.
2. Rotate all knobs on all Power Supplies fully CCW and turn them off.
3. *Gently* unplug all cables from your assembly and return them to the bag.
4. Shut down the Capstone program and reboot the computer.

Troubleshooting Capstone’s Curve Fitting Algorithm

To determine the slopes of your plotted data, you will use Capstone’s curve fitting algorithm (most notably, the quadratic and linear fit). Sometimes this algorithm needs help in finding the correct fit. You can tell that this is true when the drawn curve poorly matches the data points. The slope might be exactly zero or one and the Mean Squared Error (MSE) will also be over 0.1.

To help Capstone attempt a better fit, first, click on the box where the incorrect values are reported. On the left pane will be a “Curve Fit Editor” tab that you should click. Within that tab are the starting values Capstone is assuming. Some of these values will be “locked” (not be allowed to vary) when they should be and vice versa. You will need to make some educated guesses as to the correct fit parameters, enter them into the boxes, and click “Update Fit.” You will know if the fit has updated properly, but if you’re not sure, ask your instructor because incorrect data will lead to incorrect results!

Raw Data

Accelerating Voltage:		**Accelerating Voltage:**		**Accelerating Voltage:**	
X Beam Pos. (cm)	**Y Beam Pos. (cm)**	**X Beam Pos. (cm)**	**Y Beam Pos. (cm)**	**X Beam Pos. (cm)**	**Y Beam Pos. (cm)**

Uncertainty in these positions:

Plate Voltage (V)	Accelerating Voltage (V)

Your Lab Report

Introduction

Write a few sentences about what you set out to measure and how you will compare the measured values with theory. Do *not* include details here. That is the job for the rest of your report. (Hint: write this section *last*. This way you'll have the whole experiment in your head when you write it and can properly foreshadow the results.)

Theory

Your theory section should describe the mathematical model that you expect the experiment to match. It should also detail the mathematical method by which you will compute your uncertainties. Make a prediction of your results in this section. Read your Lab Manual for instructions on how to format equations for this section.

Procedure

In one or two paragraphs, describe the methods you used to take your data, any problems you encountered and how you solved them. **You will be graded on your ability to clearly describe what <u>you</u> did.** The description should be clear enough that someone else could reproduce your results by reading this section. **Never use the second person "you" in your lab report.** ***Be Careful:*** There is a fine line between giving enough information so that a competent student could reproduce your results and writing *way too much detail*. The idea is to be <u>concise.</u> If this section is longer than two pages, it is too long.

Data

You must provide the following plots and report their fit values:
(1--3) The three electron path plots.
(4) Your Plate Voltage vs. Accelerating Voltage plot.

These plots must appear as separate figures in your report. If you need help, ask your instructor how to create a new graph of each from your data using Mathematica, Matlab, Python/MatPlotLib, Excel, or Capstone to create an image you can import into your report.

Consult your Lab Manual for instructions on proper formatting of graphs.

<u>Also</u> report the slope of the fourth plot and the effective plate spacing (with uncertainties!)

Results and Conclusion

This is the most important section of your report as this section must compare your results with your theoretical predictions. It must be in paragraph form. Make sure you address the following points:

- How does the path of the electron beam compare to the theoretical path (equation (8))?
- Is the force law $F=qE$ appropriate?
- Is your Plate Votage vs. Accelerating Voltage plot well-modeled as a linear relationship? How can you tell?
- How does the effective plate separation compare to the physical distance between the plates? You can use the grid on the fluorescent screen to estimate the physical distance.
- What sources of uncertainty did you have? How could you have removed or reduced them?

Every comparison you make must be numerical!! Use percent errors. You will lose points if you use subjective comparisons such as (but not limited to): "about," "almost," "close to," "kind of," "roughly," or "sort of." You must quote uncertainties for every value you present!

Appendix

Include your signed and completed raw data sheet(s) and Capstone graphs.
Include a sample calculation for every computation you made.