

ELECTRON DYNAMICS

I. Equipment

electron gun vacuum tube
Hemholtz coils
Kilovolt power supply
High voltage power supply
Low voltage current supply
2 multimeters
banana leads for connections

II. Introduction

By the later part of the nineteenth century, physicists had discovered that if you put a thin wire in a vacuum, heated it red-hot, and applied a voltage to it, some kind of mysterious something would come off it. Since the hot wire was known as a cathode, the mysterious somethings were called “cathode rays”. These mysterious rays had mysterious properties: if they struck a phosphor screen, they would cause the phosphor to glow brightly. But they were otherwise so weak that they could not penetrate the glass walls of the vacuum container in which they were created. But in 1896, Roentgen discovered that if the cathode rays were made to strike e.g., a piece of copper, then the copper would emit some new kind of ray that would penetrate lots of things, including flesh and (not quite as well) bone—he named these x-rays. In 1897, the British physicist J. J. Thomson figured out that cathode rays were actually electrons, and measured their charge-to-mass ratio, q/m .

In this lab, you will use an apparatus similar to Thomson’s—known as an electron gun—to explore the dynamics of electrons in response to electric fields (which we have discussed quite a bit in class) and to magnetic fields (which we haven’t discussed yet).

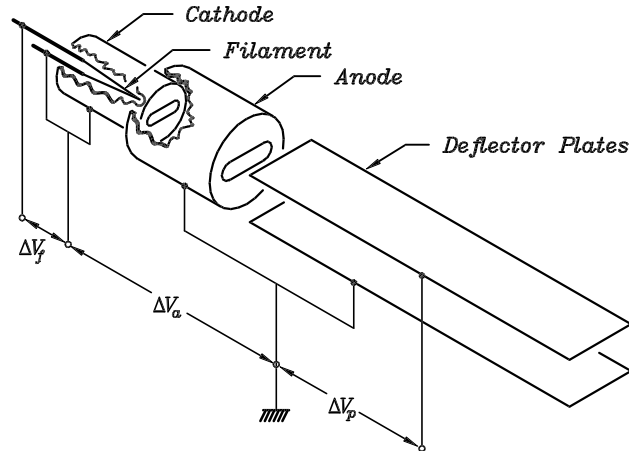
Electron guns are common devices. There is one in every TV and computer screen.† The oscilloscopes we use in lab have them as well. In fact, it used to be quite common to refer to a computer monitor or similar screen as a “CRT,” short for “cathode ray tube.”

A. Description of the gun

The figure at the top of the next page shows a simplified sketch of the gun. There are two essential elements: a tungsten filament housed inside a cylindrical metal shield called the “cathode,” and a second cylindrical metal cap with a hole in it called the “anode.” The figure also shows a pair of deflector plates, which are not strictly part of the gun. You will use them to apply an electric field

† OK, not *every* TV and computer screen. If you have a laptop, the screen does not use an electron gun. Nor do some of the new flat TVs. But there are a large number of physicists and engineers feverishly working to develop what are known as “field emitter” displays. When they finally succeed, your laptop or flat screen TV will have three micro-scale electron guns for *each* pixel on the screen—literally millions of them altogether. These screens will be much brighter and faster than current flat screens. The eventual winner of this race will make a lot of money. There is quite a way to go yet, so it could be you.

to the beam, which emerges from the hole in the anode.



The electron beam is produced in the following simple fashion: The filament is made very hot by passing a current through it. This is exactly the same principle as a light bulb, and although you cannot look directly at the filament in the gun, you will be able to see that there is a bright light source in there somewhere. Electrons are literally “boiled” off the surface of the hot filament, just like heating a kettle of water causes H_2O molecules to evaporate from the water surface. (Often the tungsten filament is coated with thorium, which makes it easier for the electrons to get out of the metal. Thorium is a nasty heavy metal poison. Try not to accidentally eat the gun.) The evaporated electrons form a little cloud around the hot filament. In general, the electrons are not moving very fast, and they are in a region with no electric field to speak of, so they just move around like the molecules in a gas. Some of them make it over to the hole in the cathode and drift out. *Now* they are in a region of high electric field—the anode is at earth ground potential, but the cathode is held at minus a few thousand volts. So these electrons feel a big force and accelerate rather smartly, right smack into the anode. Except some miss, and fly out the hole instead. Those guys are your electron beam.

The glass tube that houses the whole affair is evacuated. Otherwise, the electrons could not travel more than about 10^{-4} cm before colliding with a molecule. To make the beam observable, there is a phosphor coated screen placed almost edge-on to the beam. The phosphor glows wherever the beam hits it (same as your TV screen). (The mechanism here is essentially the same one that produces visible light in a spark—the incoming electron knocks an electron of a phosphorous atom. The atom captures another electron, and emits light as the electron settles into its final energy state. Want to know more? Take a course on atomic physics and quantum mechanics.) The angle of the card, and the fact that the beam is purposely made wide and flat, makes the beam visible along its whole length of travel. Be sure to check this out when you meet the actual device.

A final word on the two applied voltages—oops, potential differences—in the gun. The big one, ΔV_a , is constant in time. You get to vary it, but when your hand is off the knob, it is steady—a dc voltage, in electronics-speak. The small one, ΔV_f , which is used to heat the filament, is a time varying or “ac” voltage. This is purely a practical matter. If you need to stack a small, separately controlled voltage on top of a very large one, it is technically easier to do with an ac voltage. The filament doesn’t care. It will get hot either way.

III. Pre-Lab Questions

It may help to re-read the discussion of electric potential and voltage in the introduction to the circuits lab.

1. The potential difference applied between the cathode and the anode is ΔV_a . A particle of charge q starts out at the cathode with zero velocity, but it is accelerated by the large electric field between the anode and cathode. What is its kinetic energy when it reaches the anode? What is its velocity? (Note how you don't need to know the distance between the cathode and anode to answer this one. Pretty neat, huh?)
2. A particle of charge q emerges with velocity v from the hole in the anode into the region between the deflector plates. The plates are spaced by $L = 8.00$ mm, so the electric field between them is $E_p = -\Delta V_p/L$. The minus sign is important. This field is, of course, not perfectly uniform, because if you think of the plates as a capacitor, the spacing is pretty large. Ignore that.

Find the force on the particle. What is the geometric shape of the path the particle will follow?

3. Consider a particle with charge q travelling with constant speed v . We have not covered this in class yet, but if this charge is in a region filled with a uniform magnetic field \vec{B} , then the charge feels a force (in Newtons) given by

$$\vec{F} = q\vec{v} \times \vec{B} \quad (1)$$

in MKS units. The MKS unit for \vec{B} is the Tesla. This force is commonly known as the Lorentz force.

Suppose \vec{v} is in the \hat{x} direction and \vec{B} is in the \hat{z} direction. What is the magnitude of the force on the charge? And what is the geometric shape of the path the charge follows?

In the lab you will apply the magnetic field with some coils known as a Hemholtz pair. We will eventually learn how to calculate the field of such an arrangement, but for now, it will suffice for you to know that, in terms of the conventional current I_{coil} flowing in the wire, the magnetic field produced by these coils is

$$B = I_{\text{coil}} \times 4.17 \times 10^{-3} \text{ Tesla/Ampere.} \quad (2)$$

There is a fourth (!) power supply in this experiment used to supply I_{coil} .

4. If there are no applied fields, the electrons from the gun will obey Newton's first law and travel in a straight line. Suppose there is an electric field along x from the deflector plates *and* a magnetic field along z from the Hemholtz pair. Then the total force on the charge is just the sum of the force due to \vec{E} and the force due to \vec{B} (superposition strikes again). Is a straight trajectory possible? What condition must be true?
5. In lab, you will be able to measure ΔV_a , ΔV_p , and I_{coil} . Devise a procedure to measure q/m . You could take just one reading at a particular set of values. This amounts to fitting a straight line through two points. Does this sound like a good idea? Maybe figure out some parameter to vary instead? And a way to plot the data as a straight line?

IV. Procedure

You will have worked out how you will measure q/m already. The steps below will take you through the start-up of the apparatus and provide a few hints.

1. There are a lot of connections. Don't start pulling stuff apart just yet.
2. **Supplies** Identify three power supply boxes: the "Kilovolt Digiramp" contains two supplies: a low voltage, high current supply for heating the filament, and a high voltage (up to 5,000 V), low current supply for applying ΔV_a . We will call these the filament supply and the HV supply, respectively. There is a rather ancient looking Heathkit supply capable of a few hundred volts, for applying ΔV_p . We'll just call this the Heathkit. And finally, there is a 15 volt supply for driving current through the coils.
3. **Connections** The + terminal of the HV supply and the + terminal of the Heathkit should be connected together and to pin A₁ on the stand for the electron gun. This pin connects to both the anode and one of the deflector plates inside the tube. The + terminal on the HV supply should also be connected to the ground terminal on the HV supply.

The left hand terminal on the filament supply should be connected to both pin C₅ (the cathode) and the - terminal on the HV supply. The right hand terminal just connects to pin F₃.

The - terminal of the Heathkit should be connected to pin G₇. There should also be a voltmeter hooked up across the output of the Heathkit. The analog meter on the front of Heathkit is a general indicator, but not very accurate.

Look at the magnet power supply and the coils. You should be able to trace the following long path for the electrons: out of the - terminal on the magnet supply → into the A terminal on one of the coils → out of the Z terminal on that same coil → into the Z terminal on the second coil → out of the A terminal on the second coil → into the - terminal on the multimeter (used as an ammeter) → out of the + terminal of the meter → back into the + terminal of the supply.

4. **Warm-up** Make sure the knob on the Heathkit is all the way counter clockwise and that the output switch is in the "standby" position. Then turn the supply on. Make sure the output knobs on the HV supply and the magnet supply are all fully counter clockwise, and switch these two on. The switch for the HV/filament box is on the back. The front panel of this box is obscure. To get the meter to read the value of ΔV_a , you need to press the second button from the right in the bottom row. The red "kV" indicator above the button should come on. In a minute or so, you will be able to see a glow from the back of the electron gun. Switch the Heathkit out of standby mode. Slowly turn up the knob on the HV supply. You should start to see a beam emerge from the anode. The bright blue you see is not the beam itself, but fluorescence from the phosphor where the beam is hitting it.
5. **Check it out** Examine (and report on) the behavior of the beam as a function of ΔV_a . Is the beam straight? Is it parallel to the deflector plates? If not, start thinking about how this will affect things.

With ΔV_a set to some value, apply a ΔV_p with the Heathkit. Is the trajectory as you expected?

Turn off ΔV_p and apply a magnetic field. The supply has two knobs to separately limit the current and voltage. Pick one, turn it all the way up, and then use the other to control the field.

In principle, you should use the current knob for control, but it probably doesn't matter much. Using the voltage knob may offer you finer control. Observe the deflection of the beam by the field. Is the shape as you expected? Is the deflection opposite to the deflection produced with ΔV_p ? If not, figure out how to reverse the direction of the applied magnetic field.

If you don't think seeing how a moving electron responds to these fields is way cool, there is no hope for you.

6. Use your procedure to determine a value for q/m . Plot your data as you go along in a way that will give you a straight line if everything is going as you expect. Judgements will be required about just when the beam is straight, etc. Be sure to take turns making readings to reduce systematic errors that might come from individual "styles" for making these judgements.

If you can't decide how to cope with the fact that you can't make the beam straight over its whole length, remember that the relationship between your external controls and the two applied fields is most accurate in the very center of the tube.

V. Analysis

1. Report your value for q/m with uncertainty estimates.

The equipment you are using is actually very similar to that originally used by Thomson, so you can judge the accuracy of your result against his. He found $e/m \approx 1 \times 10^{11}$ C/kg, which is about half the accepted value.