Experiment EB—Electrical Breakdown

Introduction

If you apply a large enough electric field to an insulating material it will break down and currents will flow through it, often as a spark, a transient flash; or as an arc, a steady glow. Gases are generally good insulators, but it's not infrequent that large fields cause breakdown. For instance:

- In dry weather if you walk on rugs or take off a jacket, you'll often get a spark when you touch a large metal object. (The electrical energy involved is not large and the sensation is really a burn—you'll feel very little if you let the spark go through a firmly held piece of metal)

- When driving along in a gasoline powered car, sparks ignite the fuel-air mixture on the order of one hundred times a second.

- Turning electric devices on and off makes sparks inside the switch.

- Electric welding uses a controlled arc to melt metal along adjoining edges of two pieces so as to join them.

- Lightning has been making really big (and sometimes damaging and deadly) sparks for eons.

All these sparks and arcs in gases and vapors have several features in common:

- Neutral molecules are torn into ions and electrons that can acquire energy from the electric field and then recombine and generate EM radiation: radio waves, heat and light.

- Ions striking the electrodes heat them, and knock out atoms.

- Breakdown fields depend on the kind of gas or vapor and its pressure. For air at 1 atmosphere (about $10^5\ N/m^2$, $15\, lb/in^2$, $760\, mm$ of mercury) the breakdown field is about $300\, V/mm$.

Theory

A *plasma* is a gas containing free charged particles. A plasma can be created by ionizing matter. Consider a volume of air containing many gases. There are also a number of free ions like electrons, or other ionized molecules present in the air. Suppose there is an external electric field that exerts a force on any ions in the air. In particular, let's consider the electric force on the free electrons. The force will cause the electrons to accelerate increasing their kinetic energy.

Consider a single hydrogen atom consisting of a proton and an electron in the air. The free electron can collide with the hydrogen atom. If the electron has enough energy, the impact will ionize the hydrogen atom creating a positively charged proton, a negatively charged electron, along with the original free electron. This process is called impact ionization (Figure 1).

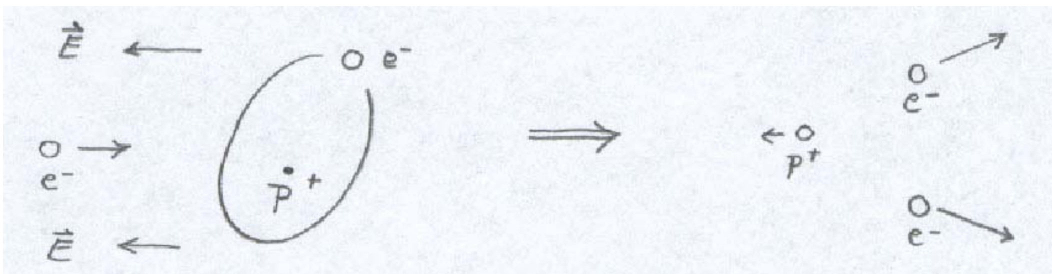


Figure 1: Impact ionization

In the atom, electrons are bound to the nucleus. A certain change in potential energy, ΔU_{ion}, is needed to extract the bound electron from the potential energy well created by the positively charged nucleus (Figure 2). This is analogous to the increase in potential energy necessary to allow a mass to escape the gravitational field of a planet.

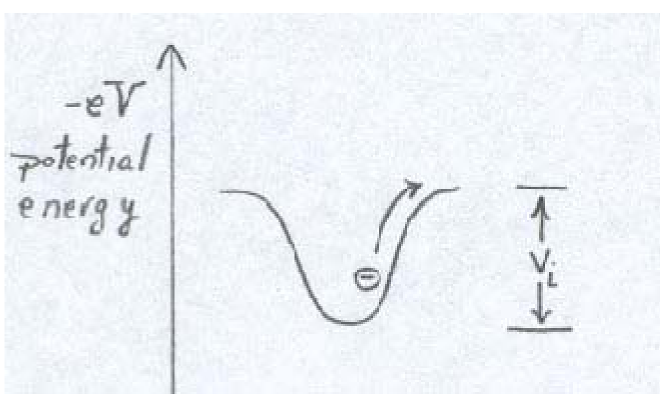


Figure 2: Potential energy well for ionization

The energy per charge necessary to ionize the electron is called the ionization potential, ΔV_{ion}, and is given by

$$\Delta V_{ion} = \frac{\Delta U_{ion}}{e}$$

where $e = 1.6 \times 10^{-19} C$ is the magnitude of the charge of the electron. For atoms, the ionization potential is on the order of $V_i \approx 10$ volts. A unit of energy for atomic processes is the electron-volt, $[ev]$, with $1ev = 1.6 \times 10^{-19} J$. So in order for a collision to ionize a hydrogen atom, an incoming free electron must have a minimum kinetic energy of about $\approx 10 ev$, equal to the change in potential energy necessary to ionize the atom,

$$K_e = \Delta U_{ion} = e\Delta V_{ion} = (1.6 \times 10^{-19} C)(10V) = 1.6 \times 10^{-18} J = 10ev$$

If the incoming electron has too much energy, it will go too fast and 'not see the atom', effectively passing right through it. A qualitative graph is shown in Figure 3 of the ionization probability plotted against incoming electron kinetic energy. There is an optimal maximum incoming kinetic energy to ionize the gas around $\approx 100 ev$ although this maximum depends on the specific gas.

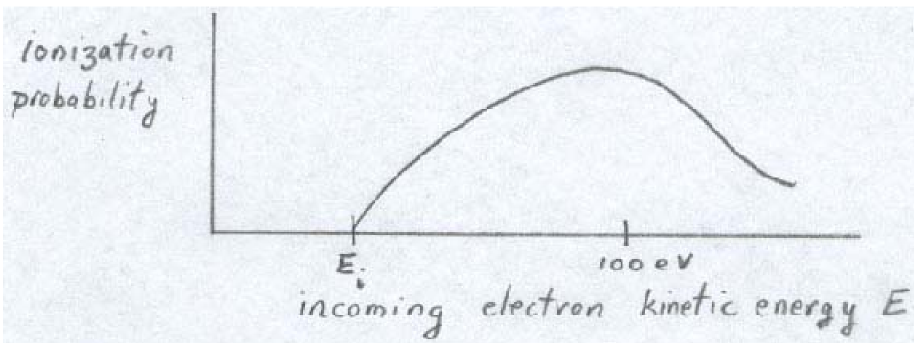


Figure 3: Ionization probability is plotted against incoming electron kinetic energy

Electrical Breakdown of Air

Suppose we establish a voltage difference, ΔV_{gap}, between two conducting plates that are separated by a distance d. The electric field in the air between the plates has magnitude,

$$E = \frac{V_{gap}}{d}.$$

This field will exert a force on any free electrons that are by chance already present between the plates according to $\vec{F} = -e\vec{E}$.

Mean Free Path

The gas between the plates is filled with molecules. What is the probability that the electron will collide with one of the gas molecules? The electron will accelerate in the gas until it collides with a gas molecule. The average distance that the electron travels between collisions, λ_{mfp}, is called the *mean free path*.

We can model each atom in the air between the plates as a sphere with a circular cross sectional area $\sigma = \pi r^2$, where r is a parameter that approximately corresponds to the radius of the atom. Consider a cylindrical volume of length λ_{mfp} and cross sectional area σ (Figure 4). If there is at least one target atom in this cylindrical volume then the incoming electron will strike the atom.

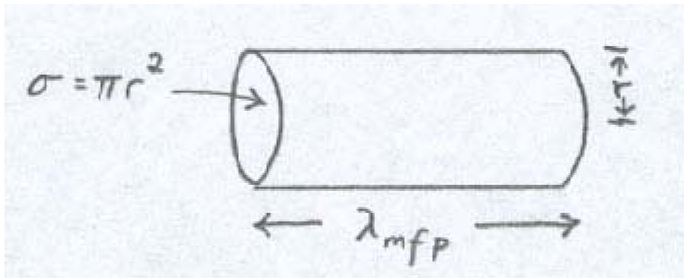


Figure 4: Mean free path

The condition for collisions is that the number of atoms per volume, n, (the number density n of atoms in the gas), is one atom per cylindrical volume of cross sectional area σ and length λ_{mfp},

$$n = \frac{1}{\lambda_{mfp}\sigma}.$$

Recall that the number density for an ideal gas at STP is given by

$$n = \frac{6.0 \times 10^{23}\ particles/mole}{22.4 \times 10^{-3} m^3/mole} = 2.7 \times 10^{25}\ particles/m^3.$$

Thus the mean free path is given by

$$\lambda_{mfp} = \frac{1}{n\sigma} = \frac{1}{n\pi r^2}.$$

Notice that the mean free path of the gas increases as the number density decreases. The approximate radius, r, of the air molecules is

$$r = \left(1/n\pi\lambda_{mfp}\right)^{1/2}.$$

Collision Energy and Ionization Condition

The kinetic energy that a free electron acquires between collisions is just the work done by the electric field on the electron between collisions. This work is the product of the force and the mean free path length that the electron travels, and is given by

$$W = eE\lambda_{mfp}.$$

When this work is greater than the ionization energy $\Delta U_{ion} = e\Delta V_{ion}$ the target atom will ionize. Thus the ionization condition is

$$eE\lambda_{mfp} \geq e\Delta V_{ion}.$$

The magnitude of the external electric field is then (using our result for the mean free path) must satisfy the following inequality,

$$E \geq \frac{\Delta V_{ion}}{\lambda_{mfp}} = n\sigma\Delta V_{ion}$$

We can estimate the approximate radius, r, of the air molecules by measuring the electric potential difference, ΔV_{gap}, between the gap, and the gap distance, d, when ionization occurs. First, our ionization condition for the magnitude of electric field is

$$E \approx \frac{\Delta V_{ion}}{\lambda_{mfp}}.$$

The magnitude of the electric field in the gap is just the electric potential difference divided by the gap distance,

$$E = \frac{\Delta V_{gap}}{d}.$$

Equating these conditions for the electric field yields

$$\frac{\Delta V_{ion}}{\lambda_{mfp}} = \frac{\Delta V_{gap}}{d}$$

Thus the mean free path can be measured according to

$$\lambda_{mfp} \approx d\frac{\Delta V_{ion}}{\Delta V_{gap}},$$

where the ionization potential is $\Delta V_{ion} \approx 10 ev$.

Since the approximate radius of the air molecule is $r = \left(1/n\pi\lambda_{mfp}\right)^{1/2}$, we can use the above condition for the means free path to give a value for the radius,

$$r = \left(1/n\pi\lambda_{mfp}\right)^{1/2} = \left(\Delta V_{gap}/n\pi d\Delta V_{ion}\right)^{1/2}.$$

Experiment

In this experiment you will study the breakdown of air using your HVPS and a simple adjustable spark gap made from a clothespin, two tungsten rods, and a screw and wingnut to adjust the gap width. Your two MMMs will serve to measure voltage and current, so that beside the breakdown field itself you could determine the voltage-current characteristic of the arc. The same apparatus with some modifications will then act as the source of microwave radiation in *Experiment MW (Microwaves).*

—BE SURE TO SAVE THE APPARATUS FOR EXPERIMENT MW—

Constructing the Spark Gap

You'll make a spark gap out of two 3/16″ long pieces of $0.040\,in$ diameter tungsten rod. Squeeze each short piece into the screw slot of a brass screw. The tungsten rod is thicker than the screw slot so you have to apply a force to squeeze the rod in. Once the rods are in place, put the two screws into the holes at the end of the clothespin. Place solder lugs on the screws that you will later use to solder on a short antenna for *Experiment MW (Microwaves)*. The spark gap for the clothspin looks like figure 5.

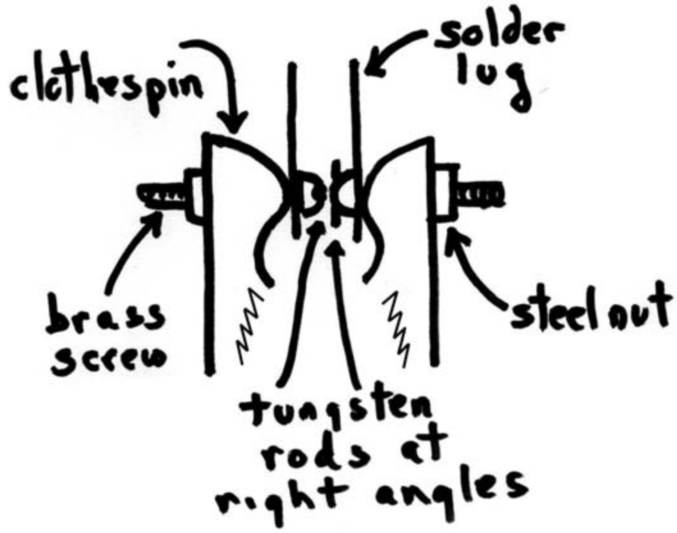


Figure 5: Tungsten rod and clothespin assembly

Procedure

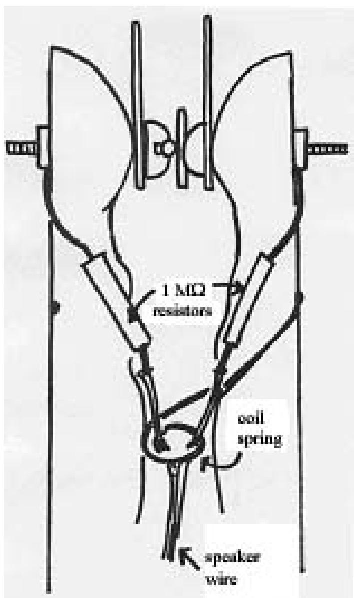
1. Use the needle nose pliers to break off two 3/16″ long pieces of tungsten rod. When you break the rod, small pieces may fly around so wrap the tungsten rod in paper before you break it to contain any flying pieces.

2. Put the solder lug onto the brass screw and place the nut on the other end with just one or two turns. The end of the nut and the screw slot will provide two surfaces for balancing the pliers while you squeeze the rod into the screw slot. If you hold the tungsten rod with your fingers you can start the squeezing process with the needle nose pliers. Once you get the rod in a bit, use your slip joint pliers to squeeze the rod into the screw slot. This may

take a little patience but it is doable. Try to keep the rods as parallel as possible to the screw slot.

3. Once you get the rod into the slot, unscrew the nut and put each screw into one of the holes at the end of the clothespin. You can push the jaws of the clothespin sideways to permit access to the drilled holes.

4. Split the ends of the two-conductor speaker wire and strip and tin all four ends. Pass the wire through the coil of the spring in the clothespin and solder one end to each of the two $1M\Omega$ resistors. Wrap the other end of the $1M\Omega$ around the brass screw between the nut and the clothespin. Tighten down the nuts using your needle nose pliers. When everything is almost tight, adjust the two tungsten rods so that they are perpendicular to each other.



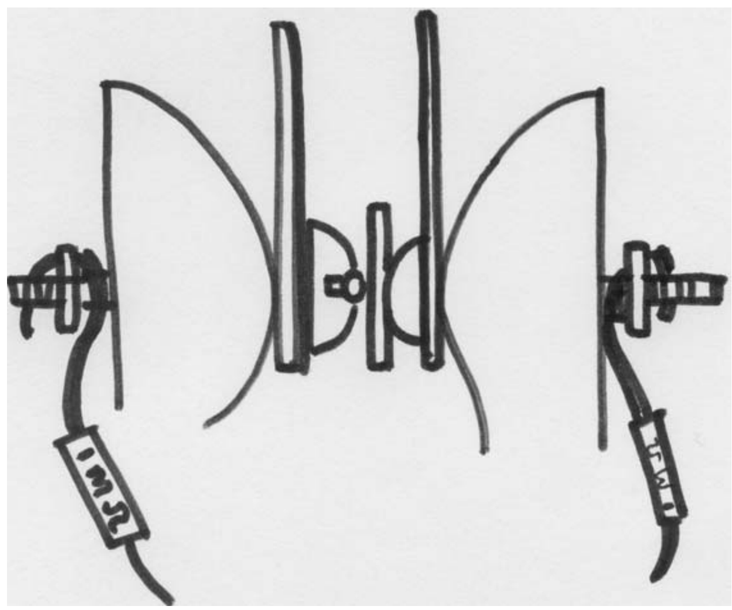


Figure 6a (left): Speaker wire attached to $1M\Omega$ resistors

Figure 6b (right): Tungsten rods perpendicularly aligned; $1M\Omega$ resistor leads clamped between nut and clothespin

5. Attach the clothespin to the corner brace with the screw, washers, and nuts in the following order:

a) The 4-40 screw with a washer on it goes through the end hole of the brace, and then through a hole in one clothespin end.

b) A nut is placed on the screw, and the screw then passes through the hole in the other clothespin end. Tighten firmly. It should be possible to open and close the clothespin without the screw rubbing on the edge of the hole. If this is not the case, try passing the 4-40 screw with a washer on it through the hole in one clothespin end and then through the end hole of the brace; then continue as before.

c) Place another washer and the adjusting wing nut on the end of the screw to complete the assembly.

d) Wedge, clamp, or tape the spark gap assembly firmly to a table or desk.

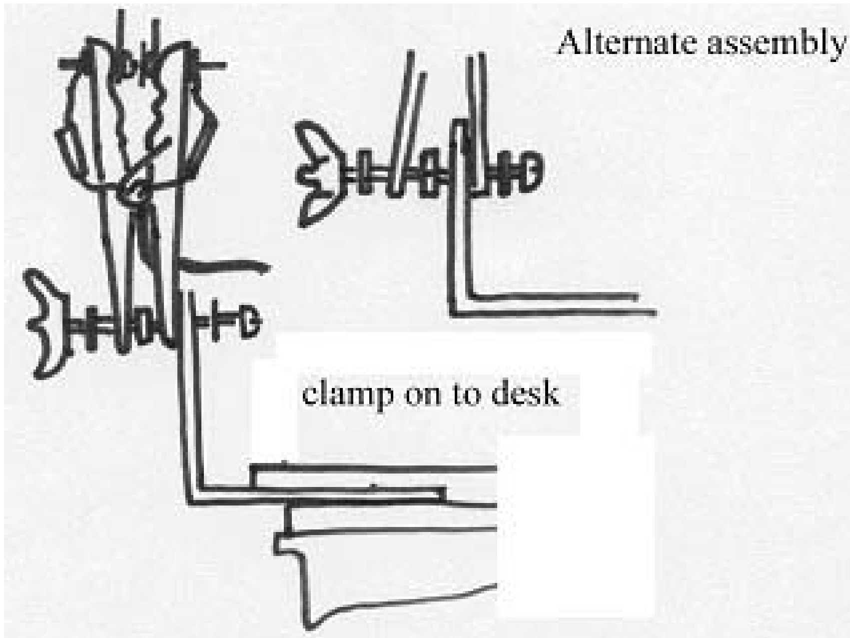


Figure 7: Spark Gap diagram

Experiment

1. Use your clip leads to connect the two ends of the speaker wire to the output of your HVPS.

2. Connect one MMM on the 1000DCV range across the HVPS output. (Use for the test lead inputs –COM and +DC1000V). We will call the voltage it reads V_0.

3. Connect a second MMM across one of the 1$M\Omega$ resistors. (Use for the test lead inputs –COM and +V-Ω-A and the same switch setting as for the on the 1000DCV range (500 & 1K DCV range). Since the input leads are input in the –COM and +V-Ω-A, the meter reads from 0 to 500 volts maximum. We will call the voltage the second MMM reads V_1 —this voltage is proportional to the current.

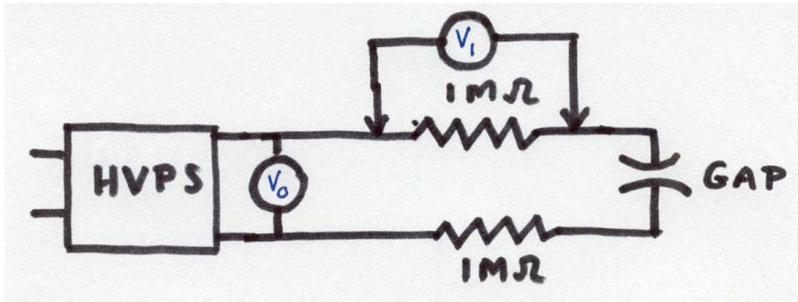


Figure 8: Multimeter connections

4. **Calibrating the Gap Setting:** Make a scale for the gap widths on the wooden clothespin using one mark for a known width ($0.1\,mm$) and a second mark for zero gap width; then you will divide the scale into four parts corresponding to $0.025\,mm$ changes in gap width. In order to set the gap to a known spacing, use a piece of photocopy paper as a feeler gauge. A package of 500 sheets is about $50\,mm$ thick, so one sheet is $0.1\,mm$ thick, close enough. Put a piece of this paper between the tungsten rods and notice that as you turn the wing nut the paper goes from being very easily moved back and forth to being quite firmly gripped.

5. Somewhere in between is when the gap separation is $0.1\,mm$ and with some judgment you can find that setting. You'll be turning the wingnut back and forth but all final adjustments to the wingnut should be made in the same clockwise direction before marking the wood. When you are satisfied that the width is right (while turning the nut clockwise) stop and make a small felt pen mark on both the nut and the wood of the clothespin as far on the right as you can.

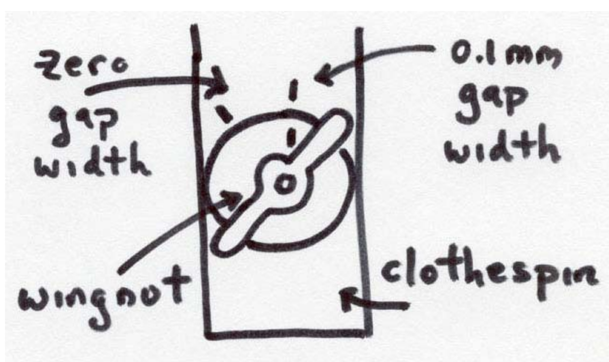


Figure 9: Calibrating the gap width

6. Now set your HVPS to $200\,V$ and proceed to reduce the gap separation by turning the wingnut counterclockwise until the tungsten rods come together and short, as indicated by a reading on the second MMM. Now turn the nut clockwise and when the gap just opens, stop. Make a small felt pen mark on the wood next to the mark on the nut. There should now be two marks on the wood about $4\,mm$ apart. You can easily estimate four $0.025\,mm$ steps starting from when the gap is shorted and going to when the gap is $0.1\,mm$ wide.

7. **Doing the Experiment:** Start with the tungsten rods touching (shorted). Turn the wingnut smoothly clockwise to the $0.025 mm$ position, 1/4 of the way to $0.1 mm$. Raise the HVPS voltage slowly until the second meter just begins to deflect, indicating breakdown. If you look you can see the arc between the tungsten rods. Record the voltage V_0 at which this happens. Repeat for the three remaining gap separations, and repeat the entire procedure three times.

8. You can enter you data in a table thus:

Data Table: Breakdown Voltages for Various Spark Gap Separations

Gap Separation d $[mm]$	Breakdown Voltage V_0 $[V]$ Run 1	Breakdown Voltage V_0 $[V]$ Run 2	Breakdown Voltage V_0 $[V]$ Run 3	Breakdown Voltage V_0 $[V]$ Average
0.025				
0.05				
0.075				
0.1				

Analysis

Plot the average breakdown voltage V_0 vs. gap separation. Since the breakdown electric field is given by

$$E = \frac{V_{gap}}{d} ,$$

use the slope of your best fit straight line to determine either a best single value of the breakdown electric field or a range of values. Express your results in kV/m.

Parts List

1	drilled wooden clothespin
1-3/4″	.040” tungsten rod
2	4-40x1/2 brass screws
3	4-40 steel nuts
2	solder lugs
1	2" corner brace
1	4-40 screw, 1 1/2″ long
3	#4 flat washers
1	4-40 nylon wing nut
2	resistors $1 M\Omega$ $1/2W$
3’	#22 speaker wire

Experiment EB (Electrical Breakdown)

Connect MMM 1 on the 1000DCV range (use -COM and +DC1000V for the test lead inputs) across the HVPS output. We will call this voltage V_0. Connect MMM 2 on the 500DCV range (use -COM and +V-Ω-A for the test lead inputs and the same switch setting as for the 1000DCV range) across one of the 1 $M\Omega$ resistors. We will call this voltage V_1.

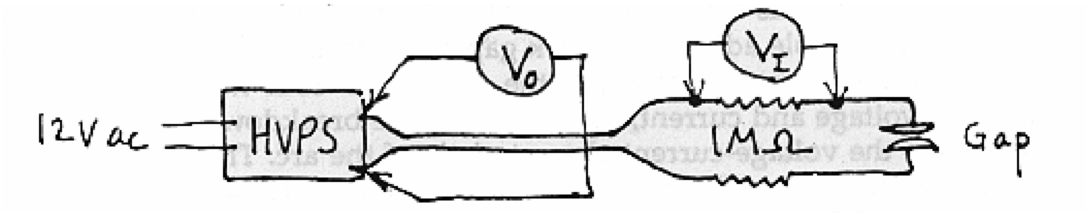


Figure 1: Multimeter connections for Experiment EB

Start with the tungsten rod touching (shorted). Turn the wingnut on the clothespin smoothly to the 0.025 position, one fourth of the way to the 0.1 mm setting. Raise the HVPS voltage slowly until the second meter just begins to deflect, indicating breakdown with the formation of an arc. Record the voltage V_0 with MMM 1 across the HVPS and the voltage V_1 with MMM 2 across the 1 $M\Omega$ resistor at which this happens. Repeat for the three remaining gap widths, and repeat the entire procedure three times. Enter your data in the tables below.

Analysis

Plot the average breakdown voltage vs. gap, and determine either a best single value of the breakdown electric field or a range of values. Express your results in V/mm.

Data Table: Breakdown Voltages for Various Spark Gap Separations

Gap Separation d $[mm]$	Breakdown Voltage V_0 $[V]$ Run 1	Breakdown Voltage V_0 $[V]$ Run 2	Breakdown Voltage V_0 $[V]$ Run 3	Breakdown Voltage V_0 $[V]$ Average
0.025				
0.05				
0.075				
0.1				

Problem 1: *Experiment EB*

a) What is the number of particles per m^3, (the number density n), for an ideal gas at standard temperature and pressure?

b) Define the mean free path for an electron in a gas to be the average distance λ an electron travels before it collides with an air molecule. If an electron travels close enough to an air molecule it will collide. The impact parameter b, is defined to be the radius of a circular cross sectional area of effective area πb^2 that the air molecule presents as a target to the electron. This means that there must be at least one air molecule in the volume $\lambda \pi b^2$ that the electron could collide with. Find an expression for the number density n of air molecules, in terms of the mean free path λ, and the impact parameter b.

c) When the electron is placed in a gap of width d and gap voltage ΔV_{gap}, how much kinetic energy per charge does the electron acquire if it travels a distance equal to the mean free path λ?

d) The energy per charge necessary to ionize air molecules, the ionization voltage, is $\Delta V_{ion} \approx 10\,V$. If the electron gains a kinetic energy per charge equal to the ionization voltage then the electron will ionize the air molecule. Using your result from part c), derive an expression for the mean free path λ in terms of the gap width d, gap voltage ΔV_{gap}, and ionization voltage ΔV_{ion}.

e) Use your experimental results where you found the breakdown electric field (average gap voltage / gap width) necessary to ionize air molecules. Use that result to calculate the mean free path λ.

Problem 2: ***I-V characteristic of the spark gap***

You can see how you could obtain the voltage-current characteristic of the discharge by setting the gap separation and varying the voltage. Suppose that when the MMM across the HVPS output reads a voltage ΔV_0, the MMM connected across the $1\,M\Omega$ resistor reads a full scale deflection, $\Delta V_1 = 500V$. Recall that the resistance of the MMM connected across the $1\,M\Omega$ resistor set on the 500DCV scale is the full scale reading in volts times 20,000 ohms/volt [Ω/V].

a) Draw a circuit diagram that shows the two MMMs, the gap, and the two $1\,M\Omega$ resistors that you used in the Experiment Electrical Breakdown. Be sure to include the internal resistance of the MMM connected across the $1\,M\Omega$ resistor in your circuit diagram.

b) What is the equivalent resistance of the MMM connected across the $1\,M\Omega$ resistor and the $1\,M\Omega$ resistor? Are these two resistors in series or parallel?

c) Show that the full scale reading of the MMM connected across the $1\,M\Omega$ resistor, $\Delta V_1 = 500V$, corresponds to $550\,\mu A$ in the circuit. Note that only a fraction of this current flows through the MMM connected across the $1\,M\Omega$ resistor.

d) Show that the voltage across the spark gap satisfies, $\Delta V_g = \Delta V_0 - 2.1\Delta V_1$.

e) Briefly describe how the above calculations can help you measure the I-V relation for the spark gap?