

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02

Spring 2005

Experiment 2: Electrostatic Force – Measuring ϵ_0

OBJECTIVES

1. To measure ϵ_0 , the permittivity of free space. Later on we will combine this measurement of ϵ_0 with a measurement of μ_0 in Experiment 8 and from these we will calculate an “8.02 Spring 2004” measurement of the speed of light, $c = 1/\sqrt{\mu_0\epsilon_0}$.
2. To become familiar with the data analysis features of Excel.

INTRODUCTION

In this experiment, you'll set up a horizontal parallel plate capacitor and find the voltage at which one side of a square piece of aluminum foil of known weight is lifted off the bottom plate, creating a conducting path between the plates. The electric force then just balances the force of gravity:

$$\vec{\mathbf{F}}_e = -\vec{\mathbf{F}}_g \quad (2.1)$$

The electric field between the plates is proportional to the voltage difference between the plates, and also to the surface charge density on the plates. When the electric field is measured in SI units, the constant of proportionality between the field and the surface charge density is determined by ϵ_0 , the *permittivity of free space*. From the relations between measured or known electrical quantities, material properties and apparatus dimensions you can determine the constant ϵ_0 .

APPARATUS

To carry out the experiment, you will need the parallel plates that are made from two large washers (2.5-inch diameter). The washers are separated by 3 pieces of insulating perf-board having a thickness of approximately 1.5 mm, at about 120° separations, as illustrated in Figure 1:

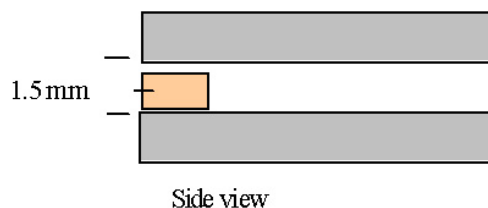


Figure 1 Perf-board used as spacers on washer

1. You will place a small piece of aluminum foil on the lower washer, and apply a voltage generated by HVPS (high voltage power supply) across the washers. You will use three foils of different thicknesses: 0.0003 in , 0.0005 in and 0.0007 in . ***Make sure the foils are flat.***



Figure 2 Charge flows to edge of foil

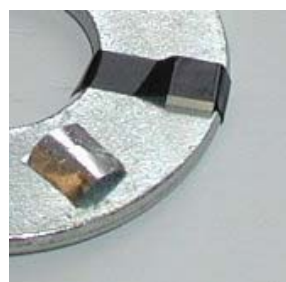


Figure 3 Charge flows to center of foil

2. The circuit should be set up as shown schematically in Figure 4 and in the photograph shown in Figure 5. The lower washer is connected to the negative side of the HVPS, and the upper washer to the positive side, connected through one multimeter set on the +DC 1000 V scale. This meter is on the left in both Figures 4 and 5, and is labeled as meter “B” in Figure 5. A second meter, on the right in both Figures 4 and 5 and labeled as meter “A” in Figure 5, is used to read the HVPS output by connecting the meter leads across the output of the HVPS. (Meter A is in “parallel” with the gap and meter B is in “series.”)

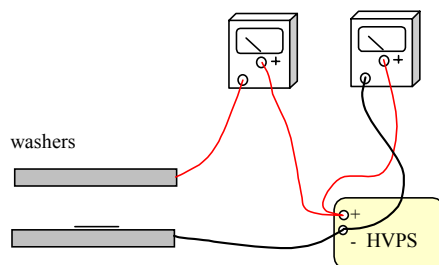


Figure 4 Experimental setup: Meter B is on the left, meter A is on the right.

3. When the foil lifts and shorts the gap, meter B will register a voltage and meter A will register a drop in the voltage. You want to determine the voltage across the gap just before the foil moves.
- Watch the multimeter readings as you slowly increase the voltage. When the foil lifts and shorts the gap, meter A's reading will drop. You will want to record the voltage on meter A just before the drop.

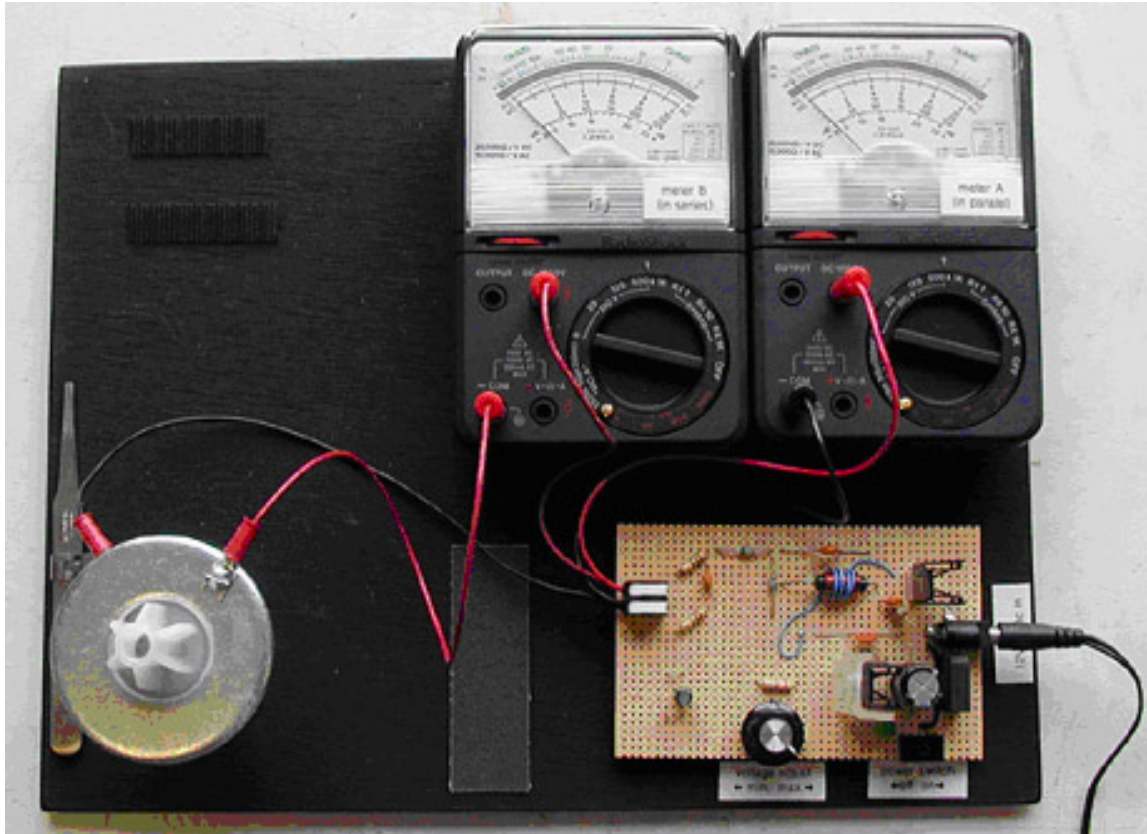


Figure 5 Experimental setup

PROCEDURE

Note: The HVPS has a very high internal resistance so you *cannot* get a serious shock from it. The experiment depends on the smoothness and cleanliness of the washers and the cleanliness of the foil. This is because charge from the bottom washer must be distributed to the foil.

During the experimental runs, *avoid touching the aluminum foil with your fingers so as to avoid getting any oil on the foil.* Tweezers (provided) work well.

Using the grid on the paper accompanying the foil to obtain a square of uniform size (for all three thicknesses), cut a piece of the 0.0003-in aluminum foil with scissors. Take care not to crumple the edges of the foil.

The foil should be clean and flat (see Figures 2 and 3 above), but it also needs to be given a rough texture to allow air to pass under the foil when it lifts off. Take the square piece of aluminum foil, and press it firmly on the abrasive cloth (located on the experiment board) with a piece of tissue (*e.g.*, Kleenex,) between the foil and your finger.

Use the tweezers to transfer the foil to the bottom washer, and making sure that the piece of foil remains flat.

First put the top washer in place and just turn up the HVPS all the way. Watch what happens to the foil; you should see the foil move in such a way as to “short” the gap (that is, provide a path for conduction of charges between the lower and upper plates). Turn down the voltage and repeat. You may have to tap or even remove the upper disk in order to have the piece of foil return to its flat position on the lower disk.

Now, once the apparatus is working well, carefully and slowly raise the voltage and read the voltmeter when the foil lifts off. A suggestion is for one member of each group to adjust the HVPS voltage while reading meter A while another member watches meter B and the third member watches the piece of foil when it rises to short the gap. You will likely want to develop your own set of signals to let the other members of your group know what you observe.

Since the reading of meter A will drop when the foil shorts the gap, you want to make sure that you read meter A just *before* the gap is shorted. This is tricky!

Record your result in the data table (see the tear-off sheets at the end of this write-up). Repeat for a total of three measurements. Then cut and use the 0.0005-in and 0.0007-in foils and repeat the above procedure for each case.

ANALYSIS

You want to equate the magnitudes of the gravitational and electric forces on the foil. The magnitude of the gravitational force is just the weight of the foil. The density of the aluminum foil material is $\rho = 2.7 \text{ gm/cc}$ ($2.7 \times 10^3 \text{ kg/m}^3$). The volume of the foil is then its area (A) times its thickness (t). Therefore the magnitude of the gravitational force is

$$F_g = |\vec{F}_g| = m g = \rho t A g . \quad (2.2)$$

To find the electric field, treat the closely spaced, metal portions of the washers as two equal-sized but oppositely-charged parallel disks. The electric force on the foil will be the product of its charge and the electric field experienced by the charge. The field in the capacitor is just $E = \Delta V/d$ where ΔV is the applied voltage and d is the spacing between the plates.

From Equation 5.2.1, Page 5-5 of the 8.02 *Course Notes*, we see that the electric field between two infinite oppositely-charged parallel plates is uniform and given by

$$E = \frac{\sigma}{\epsilon_0}, \quad (2.3)$$

where σ is the charge density (charge/area) on the upper plate. Since the field between the plates is approximated as uniform, the electric potential difference between the plates (the voltage difference) is

$$\Delta V = E d. \quad (2.4)$$

The charge density σ is therefore

$$\sigma = \epsilon_0 \frac{\Delta V}{d}. \quad (2.5)$$

To find the electric force on the foil, assume that σ , the charge density on the foil, is the same as that of the lower washer. Now we need to bring up a subtle point, one explained in Section 4.4, “Force on a Conductor,” Page 4-22 in the 8.02 *Course Notes*. By thinking about the electric field from the charged sheets on the inner surfaces of the plates (positive on top and negative on the bottom) we come to the conclusion that half the total field comes from the upper plate and half from the lower plate. Charges on the foil feel only horizontal forces from other charges on the bottom plate, so the vertical force on the foil is due to the electric field of just the top charge sheet:

$$F_e = |\vec{F}_e| = |Q_{\text{foil}} \vec{E}_{\text{top}}| = \sigma A \frac{\Delta V}{2d} = \frac{\epsilon_0 (\Delta V)^2 A}{2d^2}. \quad (2.6)$$

Equating the magnitudes of the electrical and gravitational forces,

$$\frac{\epsilon_0 (\Delta V)^2 A}{2d^2} = \rho t A g. \quad (2.7)$$

The area A cancels and we obtain

$$(\Delta V)^2 = \left(\frac{2d^2 \rho g}{\epsilon_0} \right) t. \quad (2.8)$$

If you plot $(\Delta V)^2$ vs. t , you should get a straight line whose slope is the coefficient of t . You can calculate the permittivity of free space ϵ_0 from your experimental value for the slope:

$$\epsilon_0 = \frac{2d^2 \rho g}{\text{slope}}. \quad (2.9)$$

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Tear off this page and turn it in at the end of class.

Note:

Writing in the name of a student who is not present is a Committee on Discipline offense.

Experiment Summary 2: Electrostatic Force

Group and Section _____ (e.g. 10A, L02: Please Fill Out)

Names _____

DATA COLLECTION

We have set up an Excel spreadsheet to help you enter and analyze data from this experiment. Go to the 8.02 Web Page, "Current Assignment", and download the Excel spreadsheet file there, saving it on to desktop. If you are in the afternoon session, save over the spreadsheet from the morning session. Open the spreadsheet and record your data in the tables provided.

DATA ANALYSIS

1. Record your three values for the 0.0003 inch foil in the table below. Average the three voltages for a given foil thickness. The spreadsheet will automatically average the three voltages for a given foil thickness.

Thickness (inches)			
		Voltage	
0.0003	Trial 1		
	Trial 2		your measured values go here
	Trial 3		
	Average Voltage This Thickness		

2. Now repeat this for the other two foil thicknesses. You do not need to enter the data for those runs into this tear-sheet, just into your Excel spreadsheet.

3. You now have three numbers: the voltages required to lift 0.0003-in , 0.0005-in and 0.0007-in thickness foil. The conversion from inches to meters is done on the spreadsheet. (Recall that 1 in = 2.54 cm = 25400 μm). From the previous question and the theory section, the voltage squared is proportional to the thickness of the foil;

$$(\Delta V)^2 = \left(\frac{2d^2 \rho g}{\epsilon_0} \right) t$$

where:

- Thickness of perf-board, $d \approx 1.5 \times 10^{-3} \text{ m}$ (d is given on the upper disk, or you can measure d with the plastic rule provided).
 - Density of Aluminum foil, $\rho = 2.7 \times 10^3 \text{ kg/m}^3$;
 - Acceleration due to gravity, $g = 9.8 \text{ m/s}^2$.
4. Plot the voltage squared $(\Delta V)^2$, the square of the average value of the measured voltage difference, as a function of the thickness of foil, t . Do this using Excel, following the instructions for plotting data given to you.
5. Your graph of the experimental values of $(\Delta V)^2$ vs. t should be a straight line with the slope being the factor $\left(\frac{2d^2 \rho g}{\epsilon_0} \right)$. Use Excel to find the slope of the best-fit line.
6. Calculate the free permittivity of space ϵ_0 , from your experimental value for the slope, using the formula $\epsilon_0 = \frac{2d^2 \rho g}{\text{slope}}$. Most of this is done for you by the Excel Spreadsheet—you need only need enter your slope from the best fit and the value for the separation of your washers.
- Answer:** (the accepted value is $8.85 \times 10^{-12} \text{ C}^2 / \text{N} \cdot \text{m}^2$).

Congratulations, you have just measured one of the fundamental constants of nature!

7. Enter your answer above into the on-line record for all the class results following the directions in your Spreadsheet. At the end of the class we will display the spread of our results for this measurement of ϵ_0 .