Coulomb Balance Lab 4

Equipment Coulomb balance, 5x5 inch plastic plate, Vernier calipers, power supply, set of small weights (less than 500 mg) with tweezers, Resistance box set at 1 MΩ, 5 leads

Reading Coulomb's Law in your text book

Important Information

1. HIGH VOLTAGE FROM A POWER SUPPLY IS APPLIED TO TWO CAPACITOR PLATES. DO NOT TOUCH THE WIRES PROVIDING THIS VOLTAGE. BE SURE THAT A 1 MΩ RESISTOR IS IN SERIES WITH THE CAPACITOR.
2. This experiment uses a laser beam as an optical lever arm. DO NOT LET THE LASER BEAM OR ITS REFLECTION ENTER YOUR EYE. SERIOUS DAMAGE TO YOUR EYE MAY RESULT.
3. A capacitor plate pivots on two knife edges. The knife edges rest on flat surfaces. Both the knife edges and flat surfaces are easily damaged. Please handle them with care, using the centering rod, described below, to center the knife edges and to gently lower the knife edges onto the flat surfaces.

1 Introduction

In SI units the magnitude of the force F between two charges q_1 and q_2 in vacuum is given by

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 R^2}, \tag{1}$$

where R is the distance between the two charges and ϵ_0 is a constant called the vacuum permittivity. The unit of charge in SI units is the coulomb. This equation shows that $1/\epsilon_0$ plays the role of a proportionality constant, which for any values of the charges gives the correct magnitude and dimensions for the expression so that the quantity on the left properly represents a force. The inverse of permittivity therefore expresses the scale for the strength of the electrostatic interaction between charges. In this sense the permittivity plays a role for electrical forces which is analogous to that played by the gravitational constant in Newton's expression for the gravitational force between two masses. The experiment to be performed with a Coulomb Balance is to measure the force between two separated charged objects having a known voltage between them and having a known configuration. From these data the value of ϵ_0 can be deduced. The experiment is the electrical analog of the Cavendish experiment for gravitational forces, which measures the gravitational force between two known masses.

Maxwell showed in the mid-19th century that by combining his equations containing the electric and magnetic fields he could predict the existence of a propagating wave containing both types of fields. He predicted that the speed c of the wave in vacuum is given by

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}. \tag{2}$$

The new constant μ_0 is called the "vacuum permeability." It appears in the expression for the force between two electrical currents separated by vacuum and is a magnetic effect. The predicted value for c, approximately 3×10^8 meters per second, has proved to be identical to the value obtained by Michelson for the speed of light, thereby supporting the theory that light is an example of electromagnetic radiation. Consequently, by measuring ϵ_0 and μ_0 we have an indirect way of determining c, the speed of light. This experiment is concerned with measuring the permittivity ϵ_0. In a later experiment the permeability μ_0 will be examined.

2 Description of the Experiment

See Fig. 1 and Fig. 2. A parallel plate capacitor has one fixed horizontal plate. The other plate pivots above the fixed horizontal plate so that the separation d between the plates is variable. The position of the movable plate can be accurately monitored by a laser beam reflected off a mirror attached to the movable plate assembly. A small weight is placed in the center of the movable plate and the position of the plate determined. The weight is removed which causes the plates to separate a bit. A voltage is applied between the plates so that the plate separation is the same as when the weight was in place. The applied voltage is now producing a force of attraction between the plates that is equal to the weight. A simple equation relates the force, voltage, plate area, and plate separation to the permittivity.

3 Theory

Consider a parallel plate capacitor whose dielectric is vacuum or air, which we consider to be equivalent for the purposes of this experiment. If a voltage V is maintained between the plates by a power supply the plates will have charges that are equal in magnitude and opposite in sign. The charges of opposite polarities on the plates causes an attractive force between the plates. This force, for plates of equal area, is given by

$$F = \frac{\epsilon_0 A V^2}{2d^2}, \tag{3}$$

where

- F is the force of attraction in newtons,
- A is the area of each plate in square meters,
- V is the potential difference between the plates in volts, and
- d is the distance separating the plates in meters.

In this experiment everything in Eq. 3 is measured or determined except ϵ_0. The analysis of the results will be based on Eq. 3 written in the form

$$\epsilon_0 = \frac{2Fd^2}{AV^2}. \tag{4}$$

4 The Apparatus

Fig. 1 is a photograph of the Coulomb Balance and Fig. 2 is a sketch of the entire set-up in cross-section. During the experiment, the bottom capacitor plate is normally fixed in position. This plate is held by two rods that are secured by four thumbscrews. This allows the bottom plate to be rotated and tilted if necessary. The top capacitor plate is held by two rods that are attached to a "pivot arm" that pivots on two knife edges. This allows the top plate to freely rotate toward and away from the bottom plate. This top plate assembly has a counter weight or "position adjustment" weight that allows the equilibrium vertical position of the top capacitor plate to be adjusted. There is a mirror attached to the pivot arm. A laser beam is directed onto the mirror and then reflected back to a piece of paper taped to the front of the laser. This allows you to return the top plate to a given position with great accuracy.

The "period adjustment" weight changes the oscillation period of the top plate. Moving this weight down makes the period of oscillation longer, and lengthens the times necessary for the top plate to stop oscillating. This weight, being below the pivot points, also serves to make the equilibrium position of the top plate stable. The lower this weight is, the more stable the mechanical equilibrium of the top plate.

There is a "centering rod" (not shown) that is a rod with two knobs at the ends and two off-set points. When the centering rod is rotated, the two points fit into two tapered holes in the bottom of the pivot arm, and one can lift the pivot arm a bit. When the pivot arm is lowered back down, the knife edges should be centered on their supports. This should be done gently so as not to damage the knife edges.

There is a plane plastic plate the size of the capacitor plates. This is temporarily inserted between the capacitor plates so that the two plates can be set parallel to one another at a fixed separation d, where d is the thickness of the plastic plate. With the plastic plate inserted and the plates pressed together, the laser beam is used "mark" the position of the upper plate so that this position can be recovered after the plastic plate has been removed.

A metal plate attached to the pivot arm is positioned in the gap of a small permanent magnet. As the pivot arm swings back and forth, this arrangement provides eddy current damping.

5 Apparatus Set-Up

This apparatus is sensitive. Once you start adjusting it and taking data, do not lean on the bench or breath in the direction of the plates. It is all too easy to start the top plate oscillating. As you will find out, setting the top plate into oscillation is a bad idea.

1. Check that the board on which the apparatus is mounted does not wobble. If it does, adjust one of the two thumbscrews on the front of the board.

2. Measure and record the length and width of the two capacitor plates. It is not necessary to measure the thickness of the capacitor plates.

3. Connect the apparatus, power supply, and voltmeter as shown in Fig. 2. Leave the power supply off and the voltage control knob fully CCW.

4. Try setting the period adjustment weight toward the lower end of its range. If you decide to move it, you will have to realign the apparatus as described below.

5. Center the pivot arm by gently raising it and lowering it with the centering rod.

6. Check that the top capacitor plate oscillates freely. The damping plate should not touch the magnet, and the points on the centering rod should not touch the pivot arm.

7. Measure and record the thickness of the plastic plate.

8. Put the plastic plate between the capacitor plates, put a penny in the center of the top plate to force it down onto the plastic plate, and check that the top plate lies flat on the plastic. If it does not, loosen the four screws holding the bottom plate and make the two plates as parallel as possible. At this point you will probably observe that the capacitor plates are not perfectly flat. Make an estimate as to how much you think the deviations from flatness are. The thickness of the plastic will be the minimum distance between the plates. The average distance between the plates will be more than this. Leave the plastic plate in place and the penny on the top plate.

9. WITH THE LASER OFF, familiarize yourself with the knobs on the tripod mount so that you can raise, lower, and rotate the laser with ease. In adjusting the laser beam, you may also have to move the tripod sideways.

10. Tape a piece of paper to the front of the laser and to one side of the laser beam opening. REMINDER: DO NOT LET THE LASER BEAM OR ITS REFLECTION ENTER YOUR EYE. Turn on the laser, open the shutter, and adjust the position and orientation of the laser beam so that it reflects off the mirror and back onto the paper taped to the laser. Make a horizontal mark where the laser beam strikes the paper. You might consider making the mark not at the center of the laser beam, but at the top or bottom of the laser beam.

11. Remove the penny and the plastic plate, taking care not to disturb the position of the top plate. Place a 50 mg mass in the center of the top plate. Rotate the position adjustment weight until the laser beam hits the mark you have already drawn on the paper attached to the laser. The top plate should now be in the same position it was in with the plastic between the plates.

12. Remove the 50 mg mass, taking care not to disturb the apparatus. The capacitor plates will swing apart to a new equilibrium position.

13. Check your wiring and that the resistance box is set for 1 MΩ. Leave it at that value throughout the experiment. It is more than likely that the capacitor plates will short (touch) several times during the experiment. The 1 $M\Omega$ resistor will limit the current to a safe value.

6 Procedures

Set your voltmeter on the least sensitive scale. Turn on the power supply. Starting from zero, increase the voltage between the capacitor plates. This will bring the plates toward one another. Your goal is to swing the top plate so that the reflected laser beam hits the mark on the paper attached to the laser, and record the voltage V necessary to do this. The task is very difficult because as the plates get closer together, the situation gets unstable. This is due to the fact that even if the voltage is held constant, the force varies as $1/d^2$. If the top plate, due to some perturbation, moves toward the lower plate, the Coulomb attractive force between the plate increases, and may be larger than the restoring force supplied by the period adjustment weight. The top plate will accelerate into the bottom plate. Hence the need for the 1 meg resistor. As the plates approach the desired separation, increase the voltage very slowly so as not to give the top plate too much momentum toward the lower plate. If you have trouble, try moving the period adjustment weight to a new position. If you do this, you will have to realign the apparatus. Make a number of runs, obtaining multiple values of the necessary voltage V that will result in the plates being at the same position as with the 50 mg on the top plate. At that voltage, the Coulomb force between the plates will be the weight of the 50 mg mass. Use Eq. 4 to obtain multiple values of ϵ_0. Compare your values to the accepted value.

Note. If you are using an external voltmeter that has a sensitivity switch, you should start with the switch in the least sensitive position so as to protect the meter. Then choose the most sensitive scale that keeps the needle of the meter on scale. If your voltmeter has more than one set of numbers on its scale, choose the numbers that correspond to the full scale value as given by the sensitivity switch, adjusting the decimal point as necessary.

7 Comment I

This is a difficult experiment, and you should not be unduly up-set if your results differ substantially from the accepted value. Identify and discuss what you consider to be the main sources of error. Could you suggest how some of these errors might be reduced?

8 Comment II

The Coulomb and Gravitational forces are similar in that their strength varies inversely with the square of the distance. They differ in that the Coulomb force can be repulsive as well as attractive, and in that the Coulomb force between elementary particles is orders of magnitude stronger than the gravitational force. In analyzing the hydrogen atom and other atoms, the gravitational force is totally ignored.

9 Question

In placing the 50 mg mass on the top plate, you are advised to place this mass in the center of the top plate. Would you get the same result if the mass were not placed in the center, but perhaps closer or further away from the balance beam? Discuss.

10 Finishing Up

Please leave the bench as you found it. Thank you.

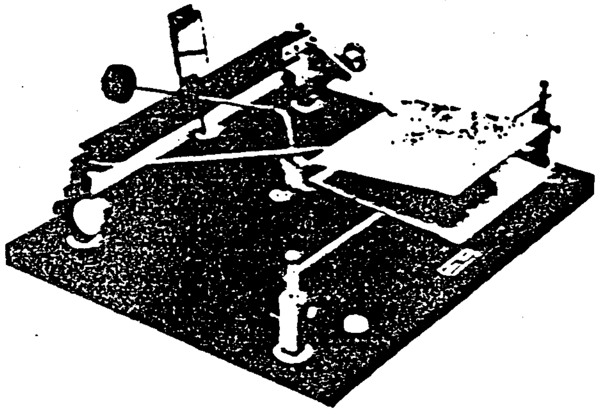

Figure 1

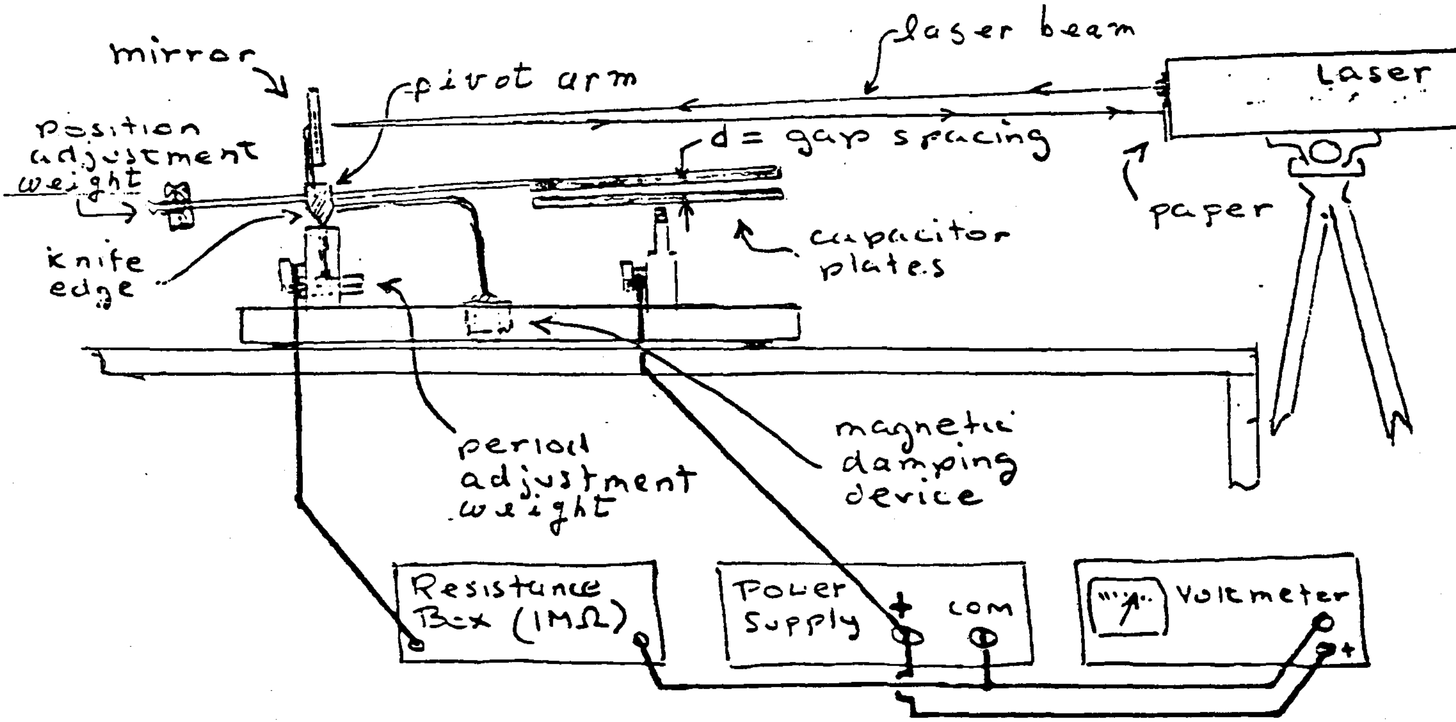

Figure 2