Physics 1402

TA Manual

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Preface

As always, rule #1 in Honors Physics labs is to do all of the labs before your students have to do them. There are some subtle points in these labs, particularly some of the later ones. If you can't get the experiment to work, or do not know what the experiment should produce, it is better to know this before you are confronted with helping students do it. It is the goal of this guide to help with this process, but you really won't know the lab until you do it yourself.

While 1100, 1200, and 1300 are designed to lead students through the steps of a well-defined experiment, the 1402/1502 labs are designed to be a little more open ended/self-motivated. Each lab is different in how it incorporates this idea: some ask students to decide which variable they will test, some are very open ended on procedure, and others are pretty straight-forward, step-by-step labs. Honors students can figure out a lot on their own, so give them a chance to work out some of the lab themselves, but it's good for you to have a default plan for students should they lose their way (this guide attempts to provide such a plan, but do not see it as the only possibility). As the TA you have the ability to provide as much additional direction as you see fit.

Also, there are no "Warm-up" questions or other pre-lab activity. If you do not encourage/demand that students look at the labs ahead of time, they will come to class unprepared. There are certain labs that will suffer if students come unprepared. It is up to you to encourage preparation before lab.

Laboratory 1

Your instructor will probably choose Problem 1.2 (first week) and Problem 1.3 (second week). Make sure you are prepared.

The tubes for the standing wave lab (1.2) need to be filled each year. Fill the nitrogen and argon at the beginning of the week. **Helium tubes need to be filled every day** Make sure that the tubes are purged and filled properly. Make sure the students analyze the data while in lab.

Problem 1.1 is often skipped, but is a good lab if you choose to do it. It is used as a demonstration for the student's lab notebook, and thus is included.

Laboratory 1: Waves

This lab will serve as an introduction to the topic of waves, a concept that is very important in virtually all fields of science and engineering.

Problem 1.1 : Standing Waves on a String

Summary: Students will make standing waves on wires using a function generator. The students can predict the resonance frequencies and compare to found frequencies OR use the found resonance frequencies to measure the T/μ of the wire and compare to the directly measured values (using a scale).

Topics: Standing waves, wave speed, properties of the medium (string, which is actually a wire)

Equations used

You will use two equations for sound

$$v = \lambda \cdot f \,, \qquad (1.1)$$

$$v = \sqrt{T/\mu} \,. \qquad (1.2)$$

Note that: $\lambda = \frac{2*L}{N}$ in the case of a standing wave

Where v=velocity, f=frequency, T= tension (m*g of hanging weights), L is the length of the wire, N is the mode, λ is the wavelength, and μ is the linear density of the wire.

Depending on how you want to direct them students may test:

$$f = \frac{N}{2L}\sqrt{\frac{T}{\mu}}$$

or

$$\frac{T}{\mu} = (\frac{2Lf}{N})^2$$

Predicting f and comparing it to the 'measured' f tends to have less error as the square root effectively halves the uncertainty on the T/μ term, which is one of the main sources.

Equipement

Needed equipment:

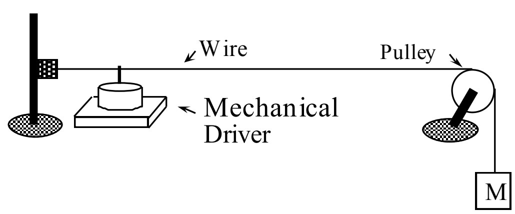
- a mechanical driver,
- wires of various sizes,
- a collection of masses,
- a pulley,
- a Pasco function generator (PI-95873),
- a meter stick
- a mass balance.
- metal post with wire clamp

Make sure you use the pasco function generator. The BK precision is tricky to use at the low frequencies this lab requires (its response time is slow for updating what frequency it generates, precision is almost impossible), so don't use it unless you absolutely must. The "Adjust" knob on the Pasco used to change frequency can be very sensitive. If you turn it slowly a set distance, it changes a small amount; if you move it quickly the same distance it may change a much greater amount. This can frustrate students.

Make sure the wire is relatively loose and flexible. If it holds its shape it will not be very good.

Procedure

Using the materials listed above, set up an experiment to observe standing waves on a wire. A diagram is shown on the next page that will help guide your setup.



The placement of the mechanical driver is important, and you should try to let the students figure this out at the beginning of the lab. The best place is at just to the left or right of a natural node in the resonance. I would suggest getting it as close to the attachment point as possible, so that you do not need to keep moving it. You may need to adjust the placement of the driver as you change the frequency. You may also need to adjust the amplitude at times if the amplitude the string wants to vibrate at is too big.

There should be a 'wire clamp' which has an 's' shape the wire can be fed into and then clamped tight. Simply tying the wire to the post introduces literal wiggle room.

Finding the resonance can be tricky since there will appear to be several different frequencies that make standing waves of a certain N-value. The main trick is to start low, find the first frequency that looks like a resonance, note it, but keep going. You will likely find a higher, better looking resonance, keep going until the resonance fails, and then decide which resonance was the best. In my experience the highest frequency that gave an N-resonance tended to look the best, have the highest amplitude, etc. A couple of other tricks are:

1. If the weight or pulley is bouncing, you are too low. At resonance the weight and pulley will be perfectly still.
2. If wire is bouncing like a jump rope (for N >1) you are too low. The wire/wave will look like it is perfectly straight at a resonance.
3. If there is a pulsing sound, or the amplitude of the waves seems to pulse, you are too high. Usually the resonance is just before this point.
4. Listen for the sound, when the best resonance is hit, it will sound like a balanced fan or airplane engine taking off. Rattling or unpleasant noises imply you are not quite there.
5. At best you will be within 0.2 Hz, the equipment and the human brain can't handle more than that.

Students should try to get up to the N=6 resonance. You can get 11^{th} or more from some, but it's a waste of time. Students can probably do 8 total wire/tension combinations, so let them know if you want them to do 1 wire with 8 tensions or combination of 3 wires and 3 tensions, etc.

Table of wires		
red wire		
length	mass	density
m	kg	kg/m
2.03	0.008	0.003941
white wire		
length	mass	density
m	kg	kg/m
2.016	0.0226	0.011210
green wire		
length	mass	density
m	kg	kg/m
2.017	0.0115	0.005702
black wire		
length	mass	density
m	kg	kg/m
2.026	0.0158	0.007799

Analysis

The most useful plot is f vs N. From this one can compare to the predicted f or use the slope of the line to compute T/µ.

Make sure you include the weight of the wire that is hanging as part of the weight creating tension (T). If anything I think Tension is where most error comes from, as it is hard to be sure that the hanging weight is the only cause of tension.

The densities of wires you are likely to use are provided in the table to the left. Uncertainty of the density is a dominating uncertainty; 6%-2% for if you are .5g uncertain on the mass, ~1% for .1g uncertainty.

Comparing predicted frequency to predicted frequency will have less error than calculating T/µ using the slope of the f vs N plot and comparing that to scale and ruler values. However, making T/µ is probably a better focus because it's a deeper concept, more befitting an honors course.

Sample data

Additional data in 1402.xlsx, sheet 'lab 1.1'

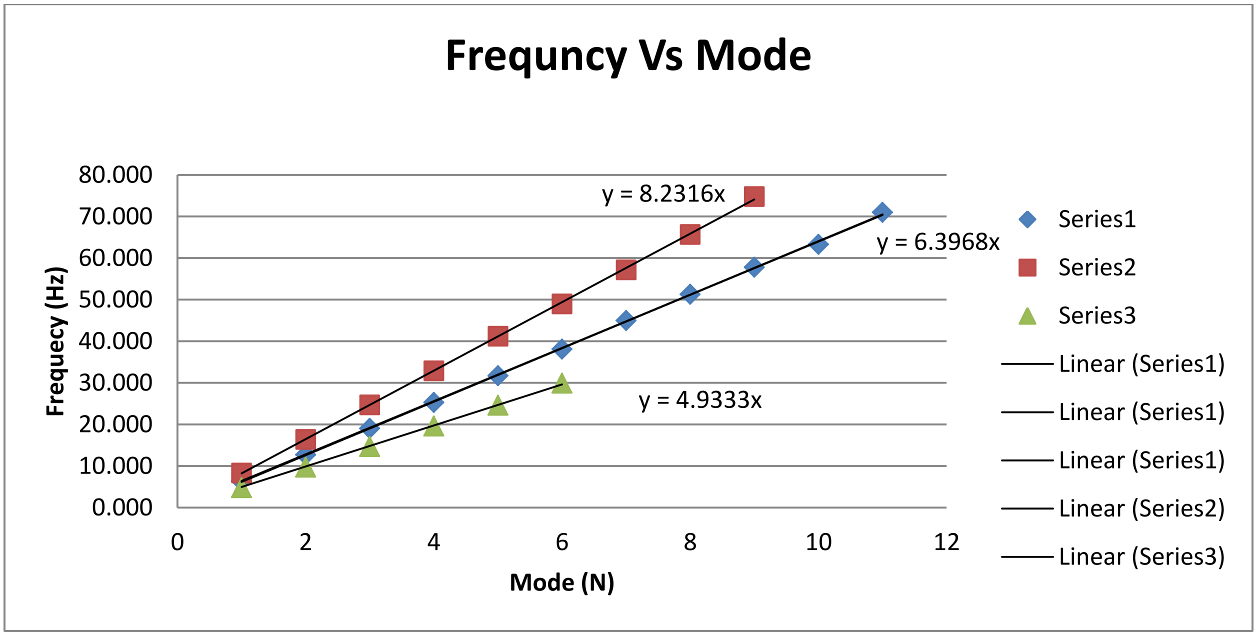


Figure 1.1a: A sampling of f vs N for a number of wires and tensions. Series 1: Red wire with 150g, Series 2: Red wire with 250g, Series 3 with 250g

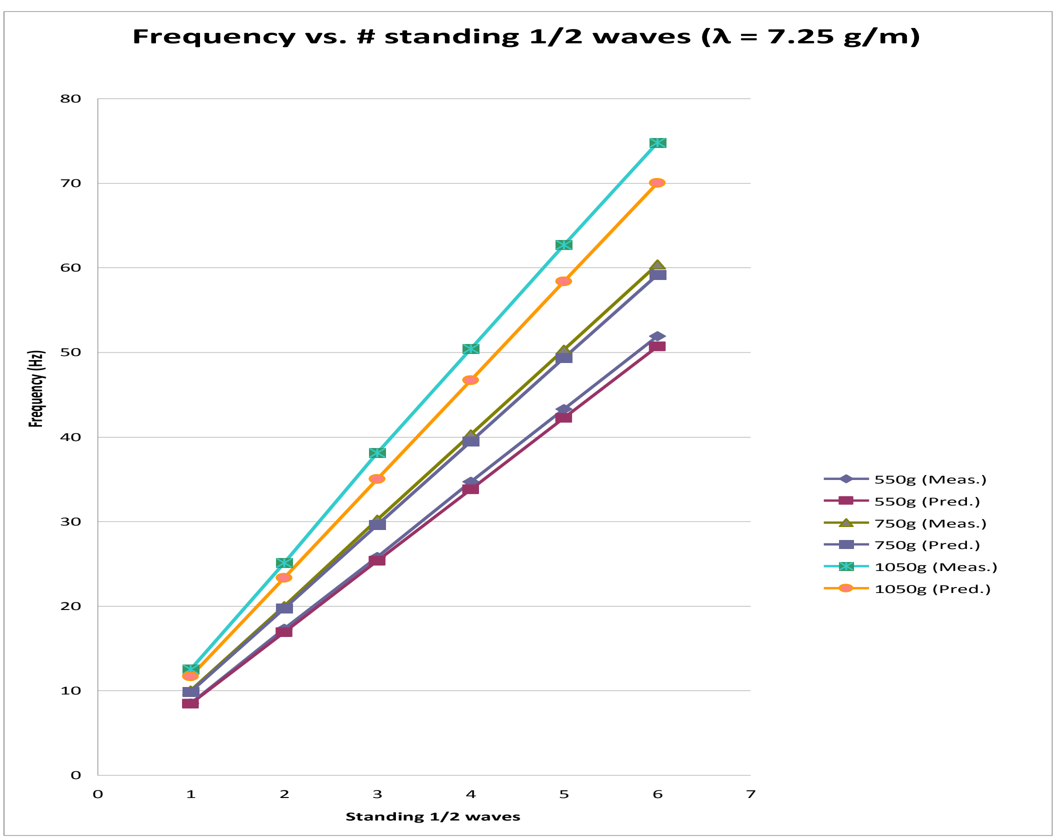


Figure 1.1b: Predicted vs measured f Vs N

Problem 1.2 : Standing Waves of Sound

Summary: Students will input sound into tubes of unknown gas and read out the waves generated in an oscilloscope. By finding the resonance frequencies the students can calculate the speed of sound in the gas and find the identity of each gas.

Concepts: Speed of sound, ideal gases, and resonances.

Equations used

In this lab we ask the students to identify the medium through which the waves propagate. The velocity, *v*, of the waves through a gas can still be calculated by the usual v= λ·*f*, but we can also use the equation

$$v = \sqrt{\gamma \cdot P/\rho},$$

where *γ* is a constant (5/3 for a monatomic gas, and 7/5 for a diatomic gas), *P* is the pressure of the gas, and *ρ* is the density of the gas. We can refer to the ideal gas law,

$$PV = NRT,$$

where *V* is the volume, *T* is the temperature, *N* is the number of moles of the gas, and *R* is the universal gas constant. Using this to eliminate *P* and *ρ* from the above equation, we find that the velocity of the gas can be written in terms of *γ*, *T*, and the molar mass, *M*:

$$v = \sqrt{\gamma RT/M}\ .$$

Students can play around with this equation a number of ways, they may find the speed of sound in the tube using v=2Lf/N and compare that to the determined velocities of a number of potential gasses. Or they could solve for the M of the gasses in the tubes (make sure they find one for monoatomic, one for diatomic since they will not know for sure what the tube has) and compare that to the candidates, etc.

Equipment

- 3 gas tubes with piezoelectric transducers on both ends,
- Helium, Nitrogen, and Argon gases (to fill the tubes the week of lab),
- a BK prescision function generator,
- an oscilloscope, and
- BNC cables.

Don't use the Pasco function generator, it will not go high enough, the BK function generators are perfect for this lab.

Procedure

Each tube needs to be filled with one of the three gases the first day of lab: Helium, Nitrogen, or Argon. You should be able to find some supply of these in the physics building. The Machine Shop should have a supply of Argon that you can use to fill one of the tubes. Professor Crowell, or other professors, should have some tanks of Helium and Nitrogen in their labs. To fill the tubes, connect one of the valves to the gas supply while holding the valve on the other end open. We want the gas pressure to be close to 1 atm, though it is not entirely important. Most importantly, you need to have the tube filled with only one gas, so all of the air already inside the tube needs to be expelled.

Problem: The Helium gas will escape daily. After a few days it will lose enough to introduce significant error (the true v for He is around 1000 m/s, which testing on Monday agreed with, by Wed it was measured at around 900 m/s and Fri it was ~800 m/s). Make sure the He tubes are refilled at least every two days for best results!

Pick one of the tubes. Connect one of the piezoelectric transducers to a function generator with the BNC cable. This will drive the waves in the tube. Also connect the output of the function generator to a channel of the oscilloscope. The other channel on the scope should be connected to the other end of the tube – the receiver transducer.

Sweep through the frequencies on the function generator and look for resonant frequencies for the gas in the tube. The fundamental frequency is generally not as precisely measured as the 2nd through the 10th standing wave modes. Sometimes you will find waves that are not very 'sine'-like; **these are not resonances!** The 1st resonance you find should be in the low 100s Hz. The progression is linear, so if you find the 1st resonance, you can guess the approximate location of the others. Likewise if you don't find the first, you can go back and search for it based on 2nd and 3rd resonances.

Channel one will be a square signal (you can't change this) coming from the TLL/CDMOS port. This should be the frequency you record.

Oscilloscopes can measure amplitude, frequency, etc. of the inputs. By hitting the "measure" button (top row, third from the left) you can select a channel and a variable to measure. I suggest measuring the peak-peak amplitude (Pk-Pk) of channel 2, and the frequency of channel 1. The resonance will be found at the maximum "pk-pk' value in channel 2, and the frequency should be taken from channel 1. If the frequency is bouncing around too much, decrease the horizontal scale so it is as short of time as possible (if you hit '??' you've gone too far).

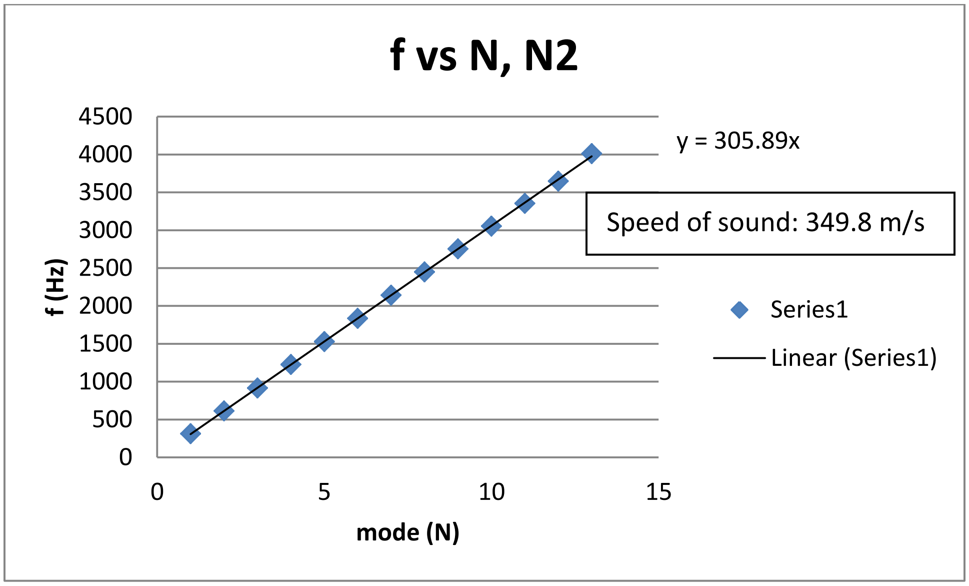
Problem: Once again helium has a little quirk. Around the 5th or 6th resonance the amplitude drops greatly. They may not be visible at all. This is likely a resonance with the tube itself. Keep going to the frequencies of the 7th and 8th and you should start getting good signal again. Students will sometimes hit the missing 6th and stop, **don't let them!** Even after 5 days of He leaking out I was still able to get the 13th resonance! (but not the 6th). Also of note, the slopes before and after the gap may be different, with the higher nodes' slope seeming to give better results.

In the end, the students should get ~13 frequencies for each gas. Make sure they also measure the length of the tube (start from the end of the speaker inside the tube, not just the length of the plastic) and the temperature of the room.

Analysis

The analysis of the data is pretty straight forward, and you should be able get N2 and Ar to within about 0.5% error of their speed of sound. He will be between 5-20% depending on how long it's been in the tube (20% is after 5 days). Even so, nothing else will be very close, so He is still the most likely candidate.

Problem: Ar may confuse some students because it has a very similar speed of sound to O2, but they should be closer to Ar (their 'error' to the speed of O2 will be around 2-8%)



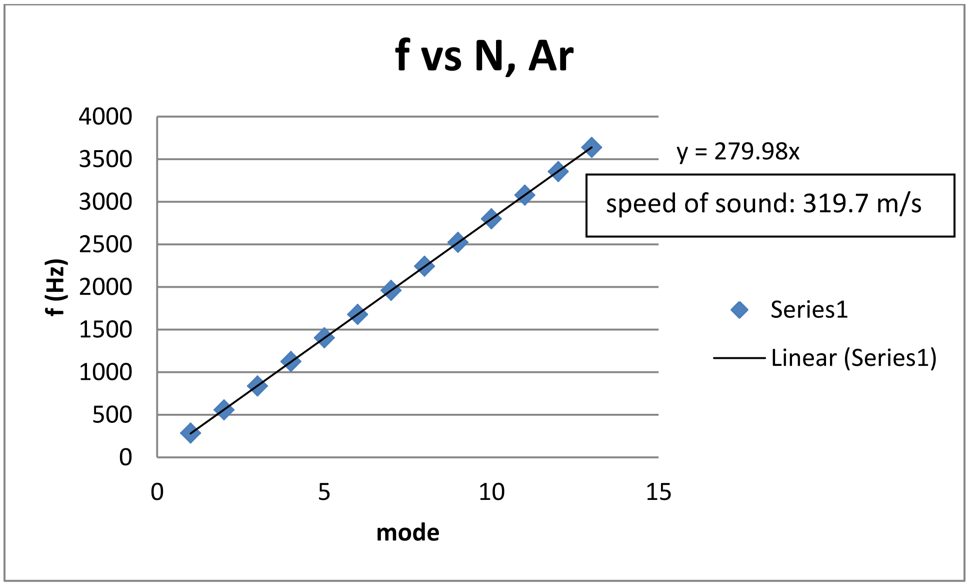


Figure 1: Plots of f vs N for Nitrogen and Argon. Note: The slopes are deceptively similar to the speed of sound, but NOT exactly.

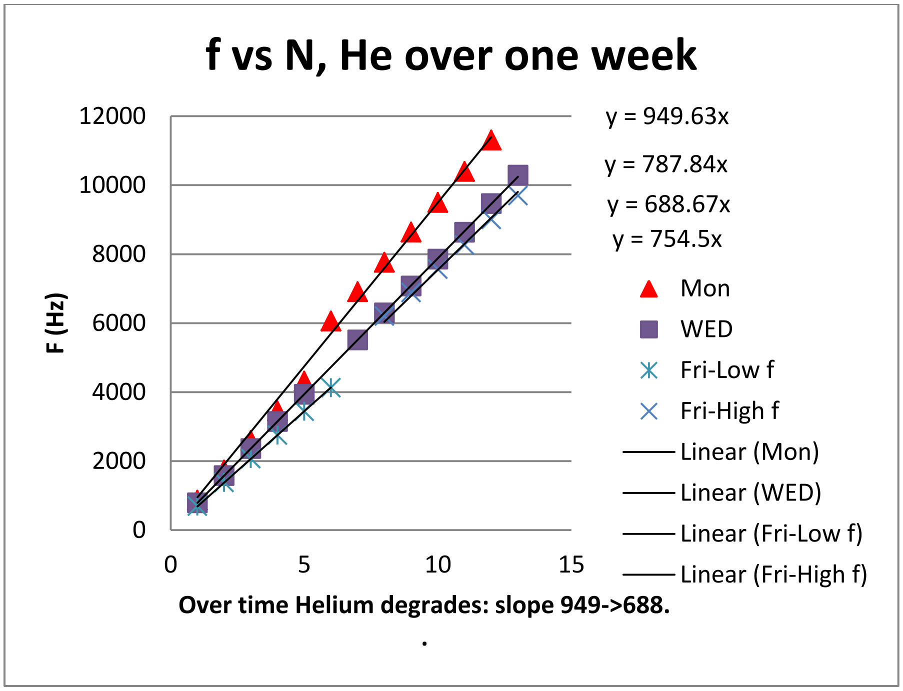


Figure 2: F vs N for Helium over a week of testing. As time goes on, the slope decreases. Also note the 'gap' around node 6. The friday data was split up to investigate this and show that the higher node data was more accurate. Equations on plot are in same order as data series.

Also see 14002Labs.xlsx sheets 'lab 1.2' and 'graphs lab 1.2' if available.

Table 1: The values for possible gasses, including the expected speed of sound at 295K

Theoretical velocities for various elements and temperatures											
element	H2	O2	N2	Cl2	He	Ne	Ar	Kr	Xe	Rn	Uuo
M (kg/mol)	1.0079	15.999	14.007	35.453	4.0026	20.18	39.948	83.8	131.29	222	294
gamma	1.4	1.4	1.4	1.4	1.67	1.67	1.67	1.67	1.67	1.67	1.67
R (J/K*mol)	8.314462	8.3145	8.3145	8.31446	8.31446	8.3145	8.3145	8.3145	8.3145	8.3145	8.314
T=295 K, v (m/s)	1305.17	327.59	350.11	220.06	1010.6	450.1	319.89	220.9	176.46	135.70	117.92

Problem 1.3: Interference of Visible Light

Summary: Students will look at patterns of light to explore the concepts of interference and diffraction

Concepts: Single slit diffraction, double slit interference, proper times to use human hair in an experiment

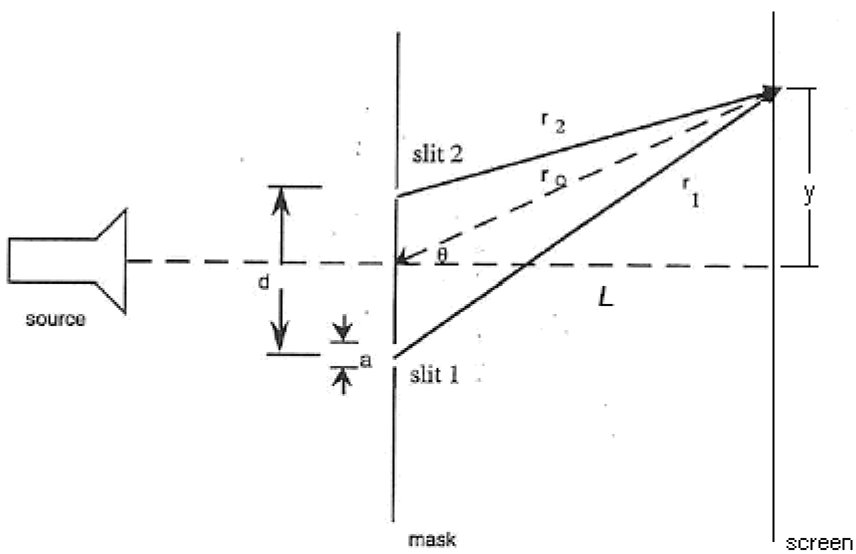
Equipment and Equations

Equipment:

- a red Laser, (wave length 650 nm, or 6.50e-7 m)
- slides with single, double and multiple slits,
- an optical track , and
- a white screen
- human hair

SAFETY: Lasers are not safe if pointed into eyes. This lab will often have students get 'eye-level' with the experiment, so make sure they are careful and never looking in the direction of the laser when they do so. **Do not allow any misuse of lasers by students!**

Double Slit: For the double slit experiment (we'll look at its derivation first as it is really the 'star' of this lab) the objective is for the students to determine the wavelength of the light emitted by the laser beam. They will do this by measuring the positions of the maximums and minimums on their interference patterns for a couple of different double slits.



Because of the dimensions of the apparatus and the wavelength of light, we can make some very simple approximations. Refer to the diagram above. Very close the slits, the two emerging beams are almost parallel. For some position, *y*, along the screen, the path difference, *δ*, between the two beams is

$$\delta = d \cdot Sin(\theta),$$

where *d* is the slit separation, and *θ* is the angle from the center of the slits to the point on the screen.

The condition for ***constructive interference*** is

$$\delta = n\lambda,$$

where *n* is an integer, and λ is the wavelength of the light. Likewise, the condition for ***destructive interference*** is

$$\delta = \left(n + \frac{1}{2}\right)\lambda$$

Using a little trigonometry, we can approximate the sine of the angle, *θ*:

$$\sin(\theta) = {y}/{\sqrt{y^2 + L^2}}\,.$$

The approximation that y<<L is accurate enough for the set-up used. I found <1% variation between the final results when using this approximation and keeping it ‘precise. Thus:

$$\sin\theta = \frac{y}{L}$$

Substituting this into *δ* and then rearranging the equation for ***constructive interference*** we find that:

$$\frac{L}{y} = \frac{d}{n\,\lambda}$$

$$y = \frac{nL\lambda}{d}$$

For ***destructive interference:***

$$y = \frac{\left(n + \frac{1}{2}\right)L\lambda}{d}$$

Wavelength can then be found by plotting *y* vs n (or n+1/2) for constructive (destructive) and using the slope *C*:

$$\lambda = \frac{Cd}{L}$$

Alternatively, students may simply calculate the average difference between nodes (since it should be constant. This leads to:

$$\lambda = \frac{\Delta y_{ave} d}{L}$$

Single slit: Single slit diffraction has all the same physics, but a factor of ½ sneaks in when you convert form using distance between the slits, *d,* to the width of the slit, *a*. This ‘switches’ the appearance of the constructive and destructive forms of the final equations to:

$$y_{constructive} = \frac{\left(n + \frac{1}{2}\right) L\lambda}{a}$$

$$y_{destructive} = \frac{nL\lambda}{a}$$

However the final calculation of wave length is the same.

Human Hair: Width of a human hair can be found by plotting y (destructive or constructive, preferable students will perform both) vs n for the pattern formed:

$$a_{hair} = nL\lambda/y$$

Procedure

The Basics: Students will make 3 types of patterns: single slit, human hair, double slit. They will then be asked to make a (simulated) plot of Intensity Vs distance that should be comparable with results with the double slit pattern . Lastly they can look at multiple slits (3+) and see what that looks like.

Get the room as dark as possible. If you can arrange for the weather to be cloudy, do so, otherwise make sure you can cover the windows, turn off lights, and block as much light (other than the laser) from the screen. Make sure that students can still get close enough to the screen to make their measurements, so don’t get too carried away with tents and such. If the patterns are too dim, students ability to take data will be seriously compromised.

Common Problem: The lasers are tricky to set up and aim, and VERY easy to bump off the track. They have screws on the back that allow limited horizontal and vertical controlled movement, but often not enough to travel the entire screen. Sometimes only one of the two slits gets hit, or the angle of the laser to the slit puts the pattern off of the screen. **Often if the image is too faint it is also due to the laser being off centered to the slits.**

Students should set up the laser a long way from the white screen. If too close the light will be much more visible, but the distances in the pattern will be much smaller and thus have higher percent uncertainty and in the case of double slits, the patterns will actually blur into invisibility. Technically, the *single slit* and *hair* section can be done fairly well at near distances BUT when you switch to double slit it needs to be as far as possible. Since the double slit pattern has a single slit diffraction pattern super imposed on it, its better to keep the distances the same so that the single slit pattern is recognizable (it will be the same size etc.)

Have the students get as much data as possible, using both destructive and constructive points. Make sure they mark points on both sides of “0”. For hair I was able to go out to the 9^{th} node.

Common Problem: Students will sometimes not know which pattern is from the diffraction and which is from the double slit interference. The answer is that the long patterns will be from the slit width diffraction while the **much** shorter patterns will be from the double slit. This is seen in the equations where the diffraction equations have a smaller number in the numerator (the width), and thus the distance will be larger. Try to get them to reach this conclusion with coaching rather than just handing them the answer.

Analysis

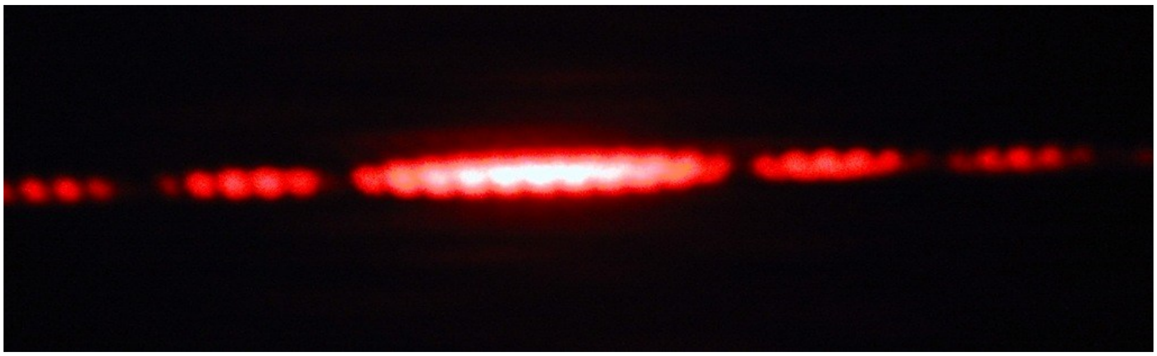
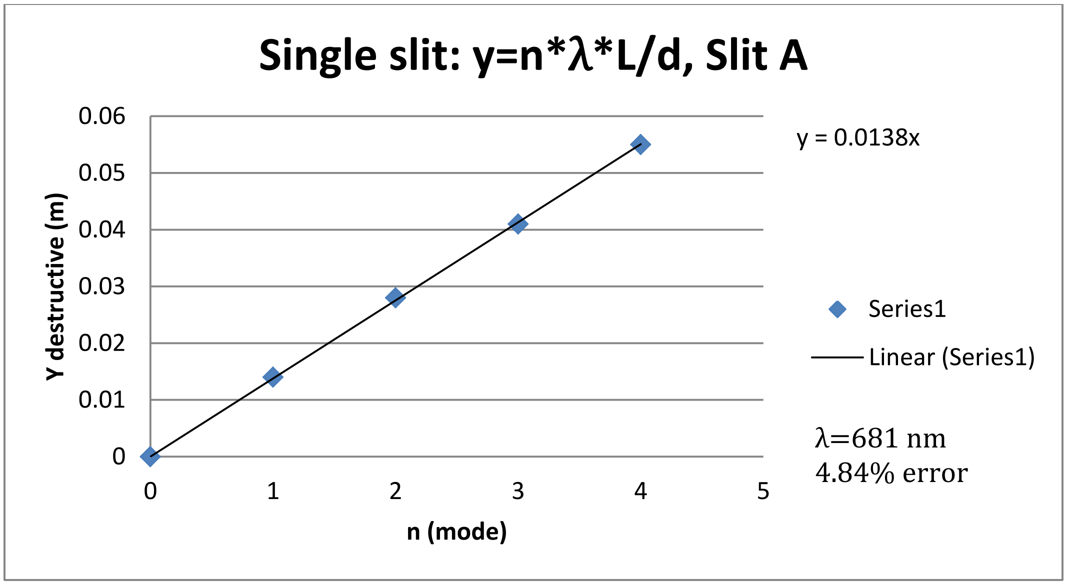


Figure 1.3.1: A double slit diffraction pattern. The large scale pattern (causing 5 distinct bright patches) is from the single slit diffraction, while the much smaller pattern (making it look like a string of 'bubbles) is from the double slit interference. Students will be able to get a MUCH sharper image than this.

In general: I found that taking the slope of y vs n plots gave more accurate results, as did slits with higher values of w and d, and double slit in general.

Step 1, Single Slit: It is difficult to accurately make the center of the patterns, so there is high uncertainty in y measurements in this step. Also, since the pattern length is long, you will get less data points automatically (especially at low slit widths). All this leads to the data from this having higher uncertainty and error (especially at low slit widths).



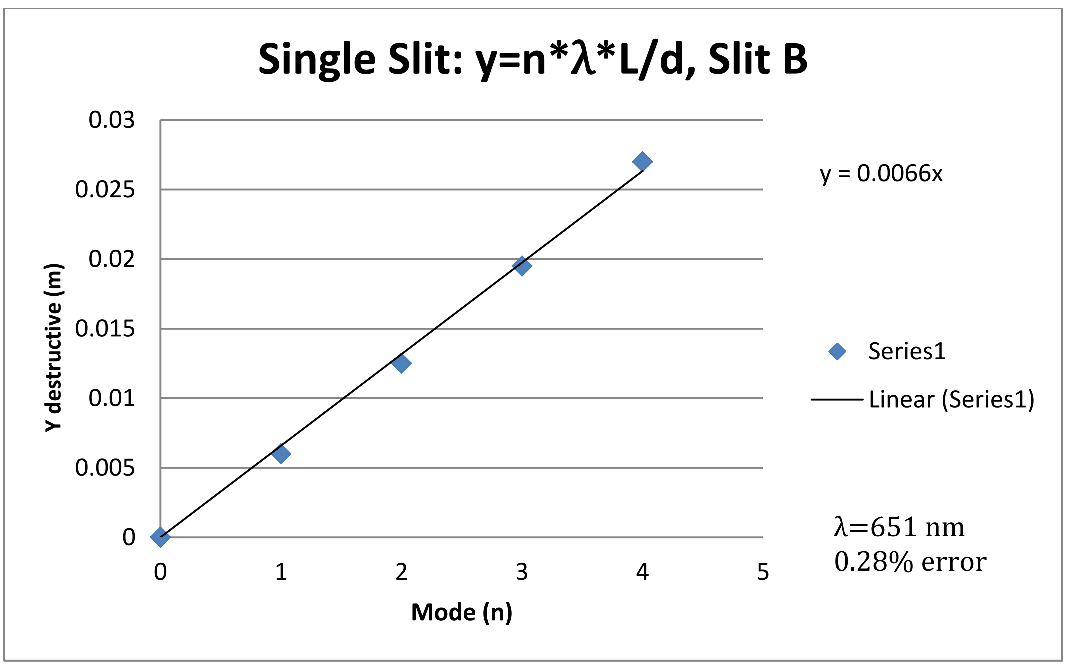
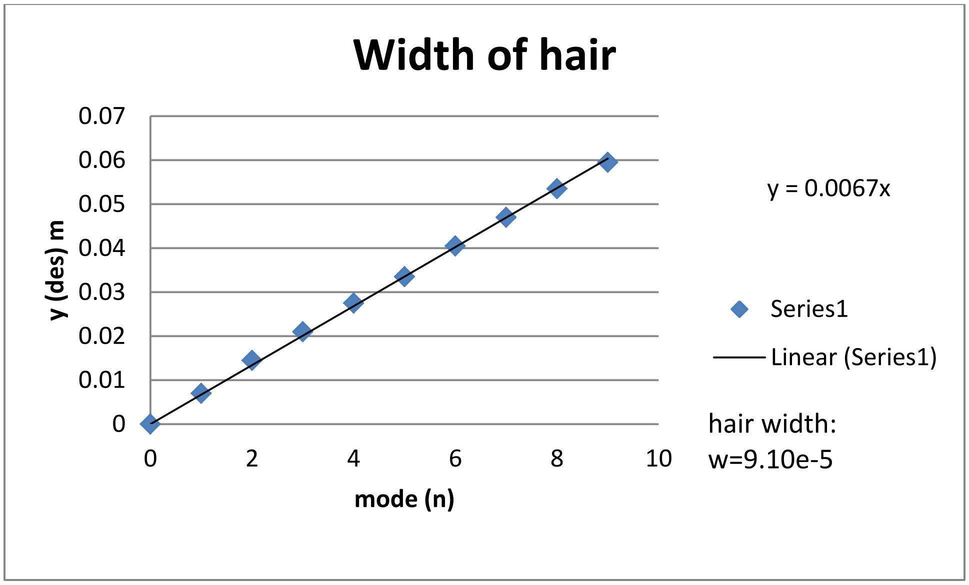


Figure 3: Two plots of distance between points of destructive interference for single slit diffraction.

Step 2, Hair: The Hair section is simple enough; its plots are similar to Step 1. There is no direct way to measure a hair. The Internet gives 181-24 micormeters (1.81E-4 to 2.4E-5 m) as the basic range of human hair thickness. Mine was measured to be about 90 micrometers.



Step 3, Double slit: It is difficult to mark and measure the individual distances for each node, but it is fairly easy to count how many nodes are in a given distance. If they can measure the total length of 20-40 nodes, they should get pretty good results using the Δy_{ave} calculation. Single slit diffraction can cause dark points where seeing dots is difficult. If they can still make them out, encourage students not to stop at these points. More data is more important.

Table 2: Data taken from the Double slit experiment.

Slit name	L	d	w	length dots	number of dots	delta y ave	Wave Length	% error
	m	m	mm	m		m	m	(650 nm)
A	1.04	0.00025	0.04	0.039	14	0.00279	6.69643E-07	3.02%
B	1.04	0.0005	0.04	0.027	20	0.00135	6.49038E-07	-0.15%
C	1.048	0.00025	0.08	0.117	43	0.00272	6.49077E-07	-0.14%

the main culprit for A's error is probably the small number of dots, despite being over a longer distance than B. Encourage students to take as many data points as they can.

Step 4, Intensity plot: students should use values from one of the double slits

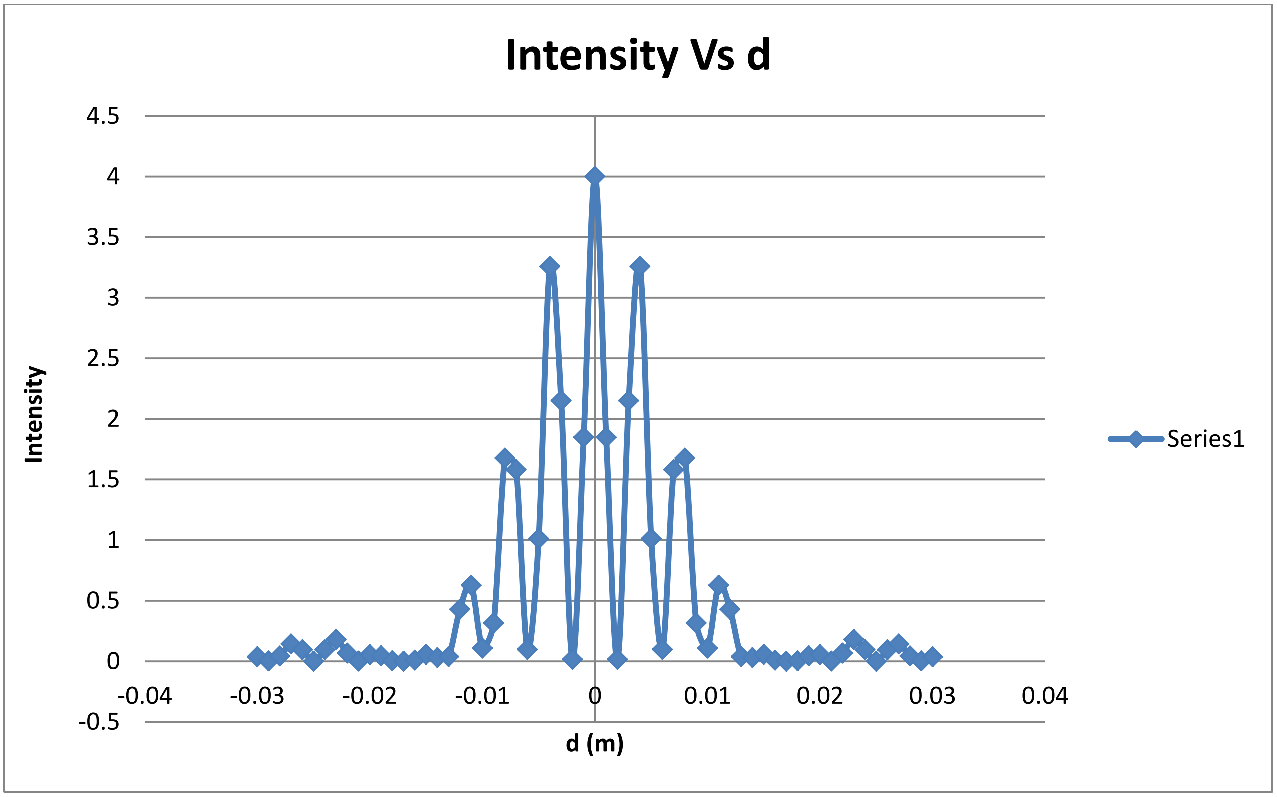


Figure 4: A plot of intensity simulated using the provided equation (step size 0.001 m). It's important to make sure the steps in the points are fine enough that it shows all the detail. Connecting the dots with lines is also important for seeing the desired shapes.

Step 5, Multi-slits: Conceptually these will look like super-positions of all the possible combinations of two slits patterns. This is easiest to see if you put the patterns of the double slit A and B next to each other and imagine adding them together and then compare that to what you see with the 3-slit pattern. There need not be any quantitativeness in this step, and it can be seen as optional and/or just for fun.

However, if you have time or an ambitious group, coach them towards discovering an approximation for the intensity of this set up such as:

$$I = 4I_0\left(\frac{\sin\beta}{\beta}\right)^2 cos^4\alpha\cos^2\gamma$$

Where $\gamma = 2\alpha$, representing the slit 1-slit 3 contribution, and the slit 2-slit 3 contribution ups the power on the alpha term to 4. This give a good 1st order approximation of the pattern students will see.

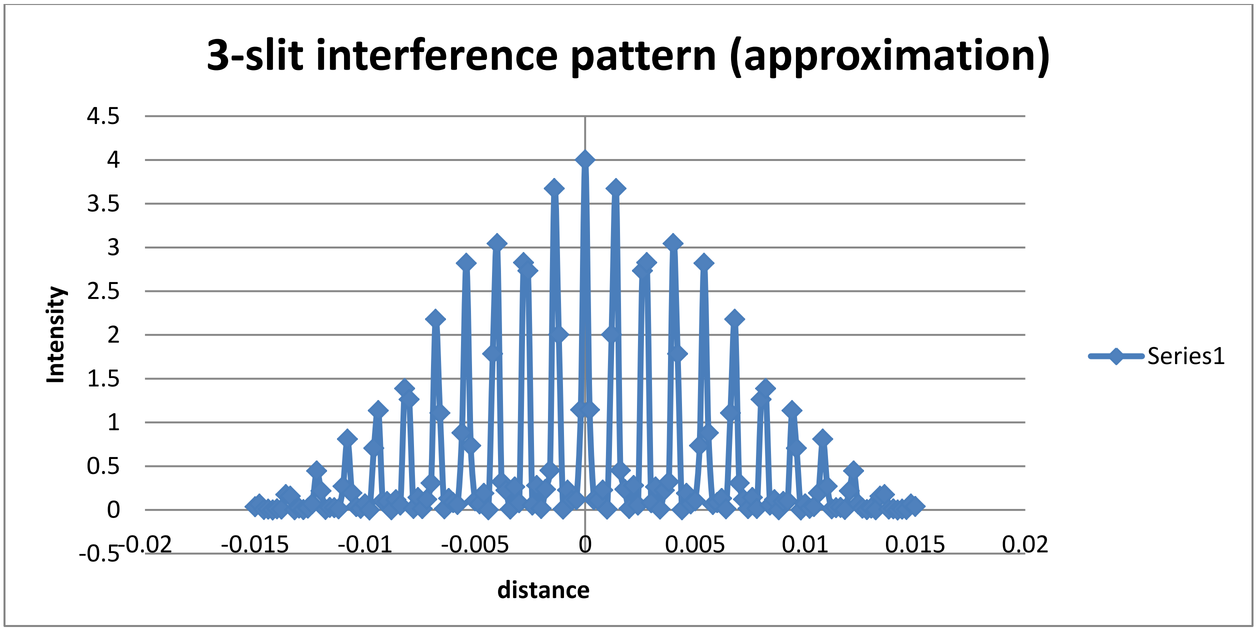


Figure 5: Simulated intensity for 3 slits (only the first diffraction 'envelope').

This can be extended to 4- and 5- slits:

$$I_{4slit} = 4I_0 \left(\frac{\sin\beta}{\beta}\right)^2 cos^6\alpha \cos^4\gamma \cos^2\delta$$

$$I_{5slit} = 4I_0 \left(\frac{\sin\beta}{\beta}\right)^2 cos^8\alpha \cos^6\gamma \cos^4\delta \cos^2\epsilon$$

Where $\gamma = 2\alpha, \delta = 3\alpha, \epsilon = 4\alpha$.

Again, step 5 is the least important part, so only go into this depth if you have time and opportunity.

Problem 2.1 : Electric Field Vectors

Summary: Using simulation software, students explore comparing their predictions to simulation.

Equipment

Students need the computers and a protractor or ruler.

Procedure

The procedure is fairly straight forward. The program makes it simple to make the charge set-up and provides the values directly on the screen. The only active measurement is direction.

Students should compare the simulated values to what they calculate for a point at the same distance *r* from the same charge *q*.

$$\vec{E}_{point} = \frac{q}{4\pi\epsilon_0 r^2}\hat{r}$$

$$E_{dipole} = \frac{qd}{4\pi\epsilon_0 r^3}(3\cos\theta\,\hat{r} - 1\hat{x})$$

Where *d* is the distance between the charges and points in the *x* direction, *r* is measured from the mid-point between the charges, and θ is the angle between *r* and the *x* axis. This is true when r>>d, otherwise just use the super position principal.

For 2D: $\vec{E}_{point} = \frac{q}{2\pi\epsilon_0 r}\hat{r}$

Analysis

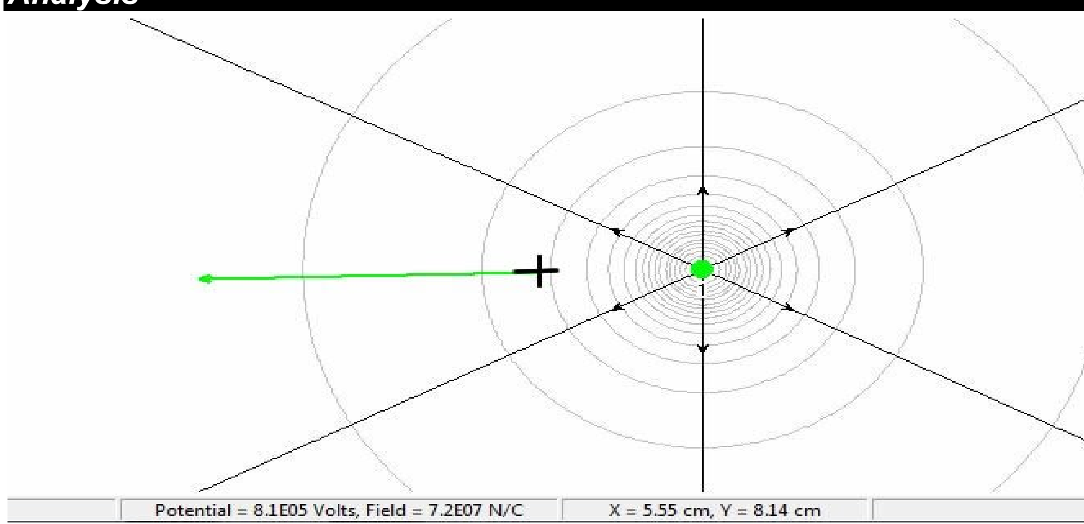


Figure 6: students can get the position, field strength and direction. Note, (x,y)=(0,0) is in the upper left hand corner, NOT the center of the charge.

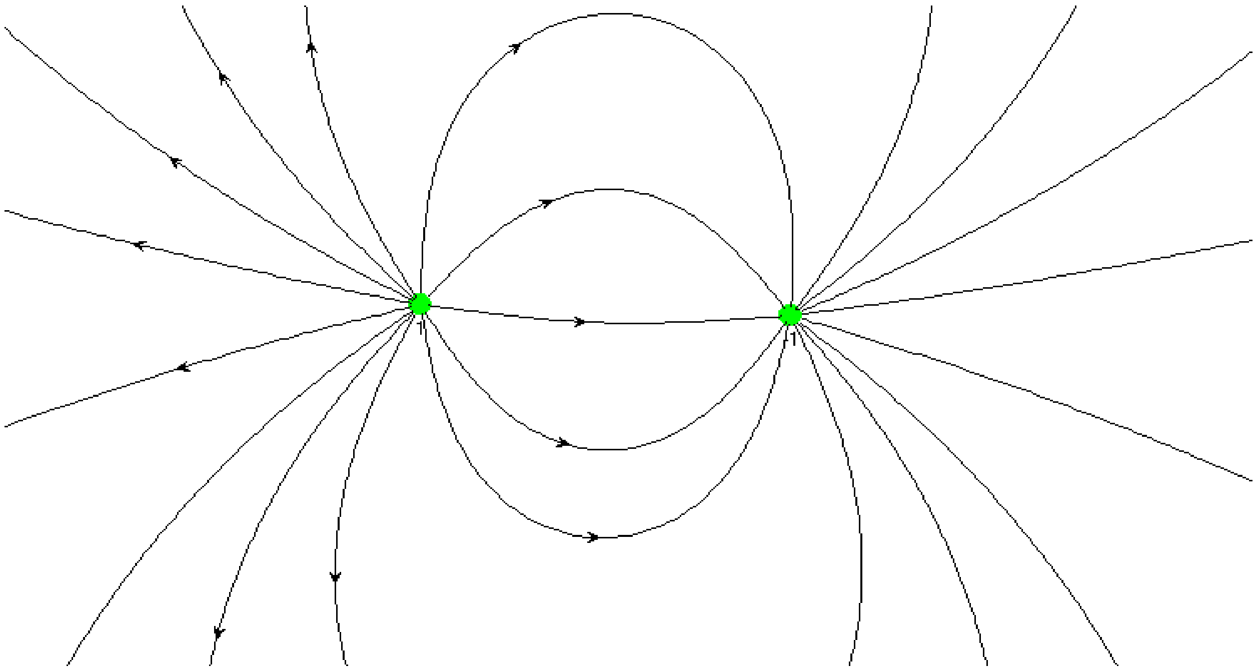


Figure 7: 3-dimensional dipole

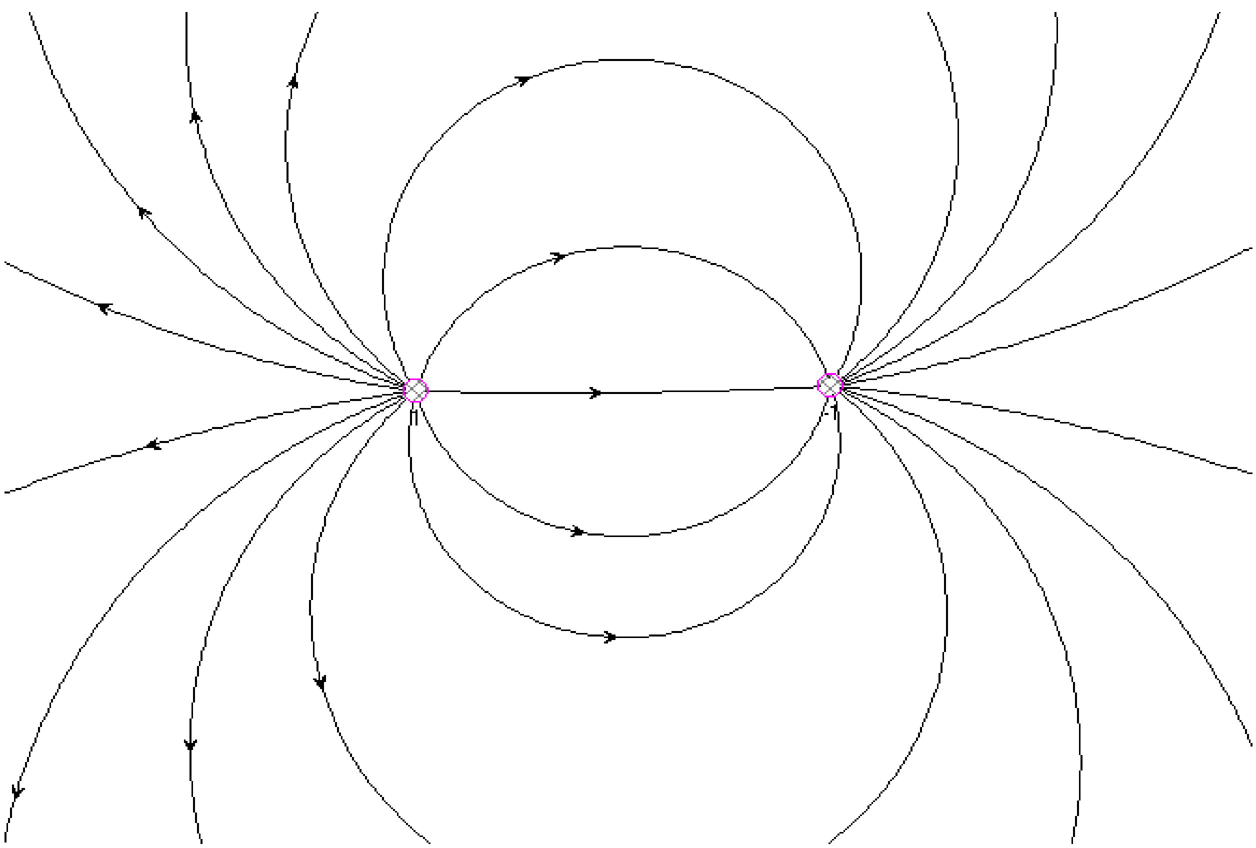


Figure 8: 2-dimmesional di-pole (using vertical line charges). Should be more similar to Lab 2.2 results

Problem 2.2: Electric Field from a Dipole

Summary: students will make a physical dipole and “measure” the electric field it creates.

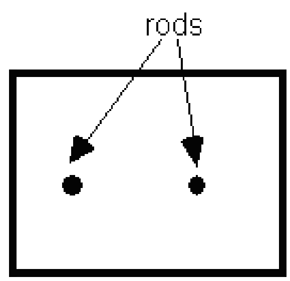
Concepts: Electric fields, Electric potential

Equipment and Equations

Equipment:

- conductive paper
- 2 brass rods
- Plastic rod stands
- Digital Multi-Meter
- Electric field probe
- 6-volt battery
- Various wires and connectors
- Wood blocks

You will be using the conductive paper setup described in the student’s Appendix D. There is a coordinate grid drawn on the conductive paper. Two brass rods (electrodes) stand upright with their tips in contact with the conductive paper and connected to opposite terminals of a battery (for safety reasons, a power supply simply isn’t a great idea, but if kept below 6 volts it works in a pinch). The electric field probe is connected to a digital multimeter (DMM) set to read volts. You will also have the EM Field program. A white sheet of paper with a grid similar to the grid on the conducting paper is useful for recording the field (do not write on the conductive paper).



Overhead view of conductive paper for this problem.

An easy point to miss but a mathematically important point in the lab is that it is a **two-dimensional problem**. The field is constrained to stay on the contact paper, and thus its laws are slightly different. Students have mostly only dealt with 3D electric stuff. In 2D, gauss’s law shows that, for a point charge:

$$E(r) = \frac{q}{2\pi\epsilon_0 r}\hat{r}$$

And thus:

$$V = -\int E dr = \frac{q}{2\pi\epsilon_0}\ln r$$

(This should look familiar if you’ve worked with ‘infinite’ line charges at all.)

The total 2d dipole electric field and voltage is a ‘simple’ super-position of the two rods, you’ll never get far enough away to do a reasonable dipole approximation unless the rods are almost touching, and that defeats the purpose of making the map.

For the purpose of calculating the E-field, use the simple approximation

$$|E|=V/s$$

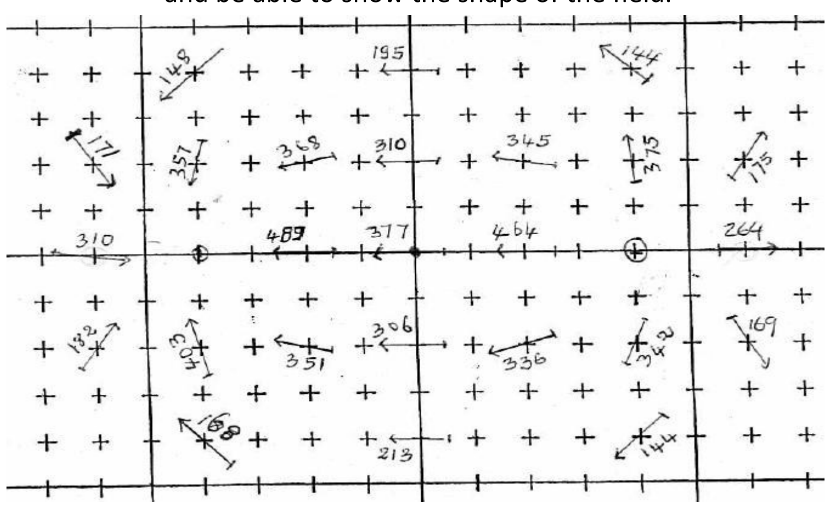
It works best when $s<<L$, but is never great on the scale achievable on the paper.

Procedure

The best set-up is for the rods to be parallel to each other and wooden blocks places across them to press them into contact paper. Students should space the rods far enough apart that they can take a few measurements in between them. Good contact is very important so make sure students use wood blocks to weigh down the rods. Students should place the probe so it straddles the point they want to measure and rotate the probe around that midpoint, not with one end fixed. Taping down the paper to avoid movement is a good idea or it may slide while students take measurements.

Common Problem: sometime the voltage reading jumps around a lot. Possible solutions are: more weight on the rods), pressing harder on the, check the connections on the probe, switch probes or DMM, and make sure nothing is touching the paper other than the rods and the probes (I didn’t find having my hand on the paper change it much, but better safe than sorry) .

Students should take a bunch of points so that they can see the shape well. Have them take several points that are reflected in symmetry and compare what they see. They should take around 20 points and be able to show the shape of the field.



The data display the appropriate symmetries to within roughly 10%.

Analysis

Since the simulation in lab 2.1 is in 3D space, its magnitude and directions will not line up (the curves on the conductive paper will be slightly different because it’s a super-position of 1/r’s, not of inverse squares). Thus an overly quantitative comparison will not work. If you simulated infinite wires in 2.1 that will in fact be much more accurate for comparison. Treatment of this lab breaks down to two styles at this point:

A. Ignore the differences between 2D and 3D and just let students qualitatively demonstrate that the 3D pattern looks a lot like the 2D pattern
B. Have the students do the infinite wires in lab 2.1 and compare measured fields from the paper to the sim, perhaps looking for proportionality.

Problem 2.3: Deflection of an Electron Beam by an Electric Field

And Problem 2.4: Deflection of an Electron Beam and Velocity

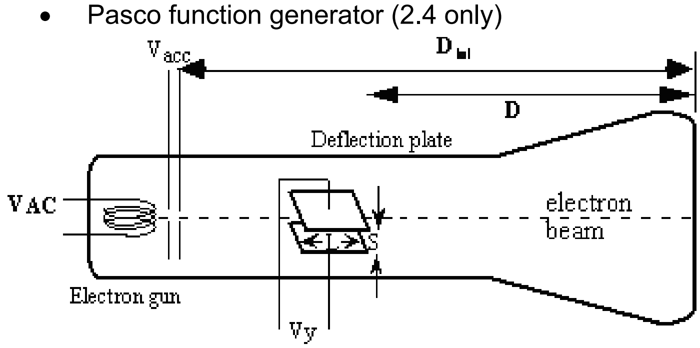
Summary: Use CRT tubes to examine how electic fields effect charged particles

Concepts: Electric force, Conservation of energy, kinematics

Equipment

Equipment:

- a CRT tube
- a CRT power supply box
- a standard DC power supply
- a Digital Multi-Meter (DMM)
- various wires
- Pasco function generator (2.4 only)



This is a simplified version of the interior of the CRT. It does not show the x-deflection plates, which are infact in front of the Y-deflection plate.

WARNING
Your students will be working with electrical equipment that generates **large voltages**. Improper use can cause **painful burns**. To avoid danger, make sure that they know the safe way to operate the equipment: the **power** must be turned **OFF** and they must **wait** at least **one minute** before any wires are disconnected from or connected to a power supply; they must **never touch** the conducting **metal** of any **wire.**

The CRT's connect to the CRT power supplies with four wires. Students often have a hard time following instructions at this point (most likely because the instructions are hard to follow). I use the phrase “*Green to Green, Red to Red, not-Red to not-Red*” to simplify remembering how to connect the heater (green ports on both the CRT and power supply) and the anode-cathode (red- blue ports on the CRT, and a corresponding red +250 V and several lesser voltages with non-red ports). It has yet to catch on with any of my students, so your mileage may vary.

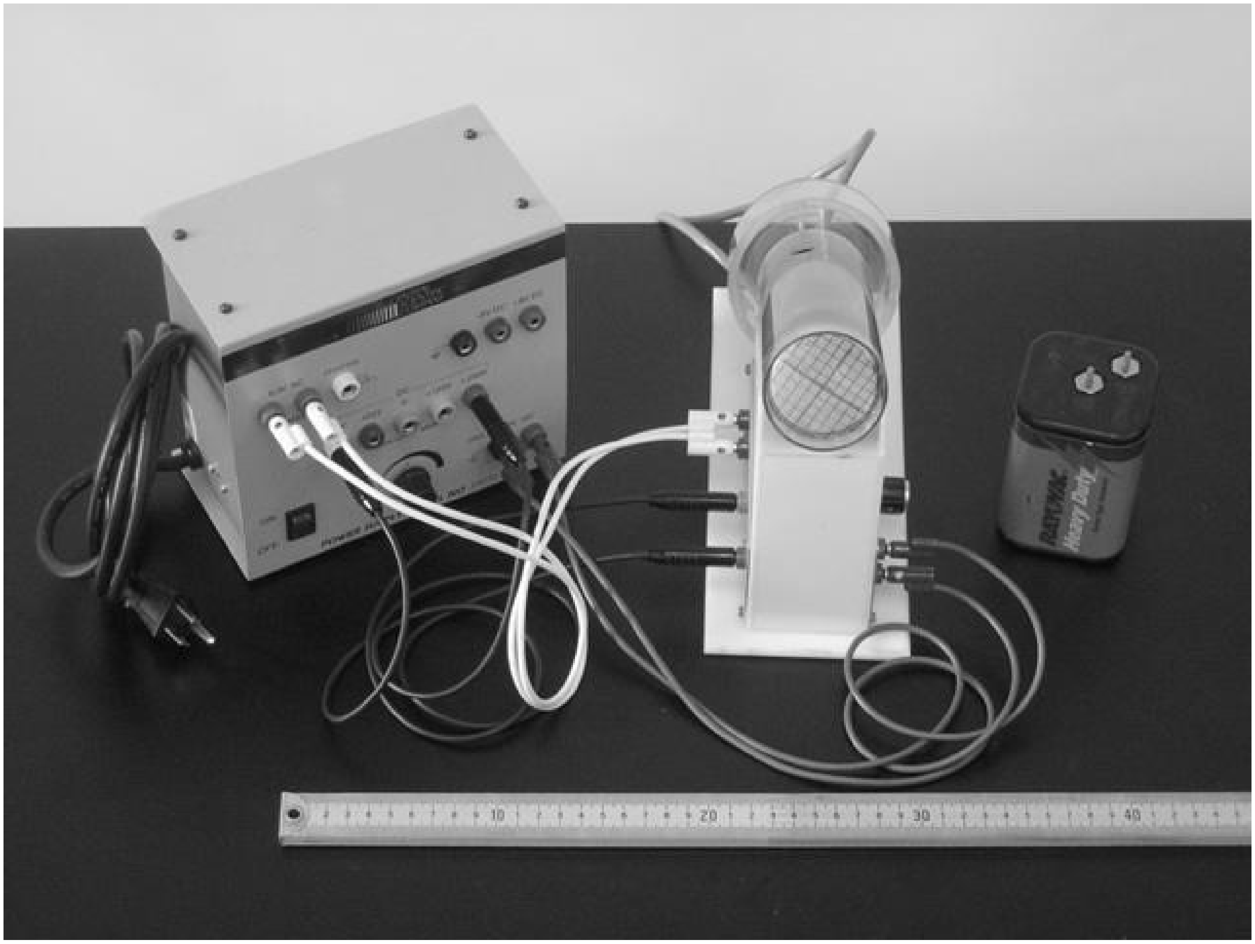


Figure 9: the set-up of the CRT. Note that this diagram uses the variable plugs in the lower right of the power supply for the deflection plates. Do not do this as the standard power supplies are much better for the deflection plates.

Note: the calculated acceleration voltages (500, 375, 250 volts) are not exact! Make the students measure them with a DMM!

The velocity of the electron is found using energy conservation:

$$Vq = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2Vq}{m}}$$

A 500eV electron has a speed of 1.32 x 10^7 m/s (about 4.4% the speed of light). At this speed, the electron moves ~10^{-16}m, which is not measurable.

The total deflection is gained in two regions of the CRT. First, the deflection is caused by the electric field between the plates; the rest of the deflection occurs after the electrons leave the plates and continue along a straight line path until they hit the screen.

The final result for the deflection is:

$$y = \frac{V_y L}{2SV_{acc}}(D + \frac{L}{2})$$

where V_y is the voltage applied to the deflection plates, *Vacc* is the accelerating potential, *L* is the length of each plate, S is the distance between the deflection plates, and *D* is the distance from the plates to the screen. It's interesting to note that the result is independent of the mass and charge of the electron. In the lab summary you might conduct a discussion on why that might be reasonable.

For lab 2.3 students will vary Vy (and then Vx). The x-deflection plates have a different set-up, with the x plates set in front of the Y plates (closer to the screen) If students use the values same values for L, S, and D, they will not get agreement with predictions.

From appendix D: For the Y deflection plates,

- L = 2.5 cm
- S = 0.35 cm
- D= 7.25 cm
- D_{tot} = 12.5 cm

$$y \cong 0.30\left(\frac{V_y}{V_{acc}}\right)[\,meters]$$

For X

- L = 2cm (NOT given to students)
- S = 0.35 cm
- D= 4.75cm (Not given to students)
- D_{tot} = 12.5 cm

$$x \cong 0.16\left(\frac{V_y}{V_{acc}}\right)[\,meters]$$

The lab has them calculate the X values for L and D, given information on where the plate starts which should lead them to the constraint Dx=Dy-Lx-0.5cm, so simply by varying Lx they can match data, hopefully getting the result of 2 cm or so.

For lab 2.4: you can only get 3 different V_{acc} to work, 500, 375, and 250. 125 V simply won't work. As such you can really only get three data points. You should have them take a few different trial at various Vy and Vx.

Other tubes: There are other brands of tubes with slightly different internal structures. The numbers above are for national electronics. Magnavox brand has measurements of:

For the Y deflection plates,

- L = 1.75 cm
- S = 0.35 cm
- D= 8.0 cm
- D_{tot} = 12.5 cm

For X

- L = 1.75 cm (NOT given to students)
- S = 0.35 cm
- D= 5 cm (Not given to students)
- D_{tot} = 12.5 cm

Procedure

If the students can set up the CRT, the data taking is fairly straight forward. There are a few places students get stuck:

1. They forget to take the initial point with no deflection as point (0,0) and plot their deflection distances with regards to the origin of the grid on the screen.
2. They only count movement in the y direction. They assume that the CRT 'knows' which direction is up, even though they've turned it all over the place. They need to count total displacement because the x-y grid on the screen has NOTHING to do with the orientation within the CRT
3. They don't take enough data. You can get 20 points. If the dot moves off the screen, simply reverse polarity on the voltage and take some "negative" deflections

Analysis

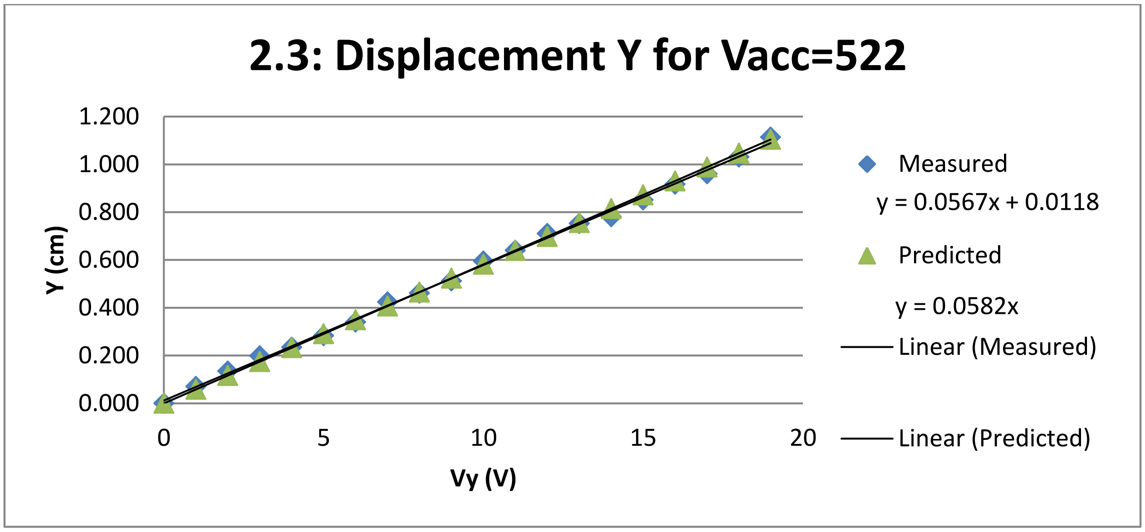


Figure 10: Displacement due to Y-deflection plates.

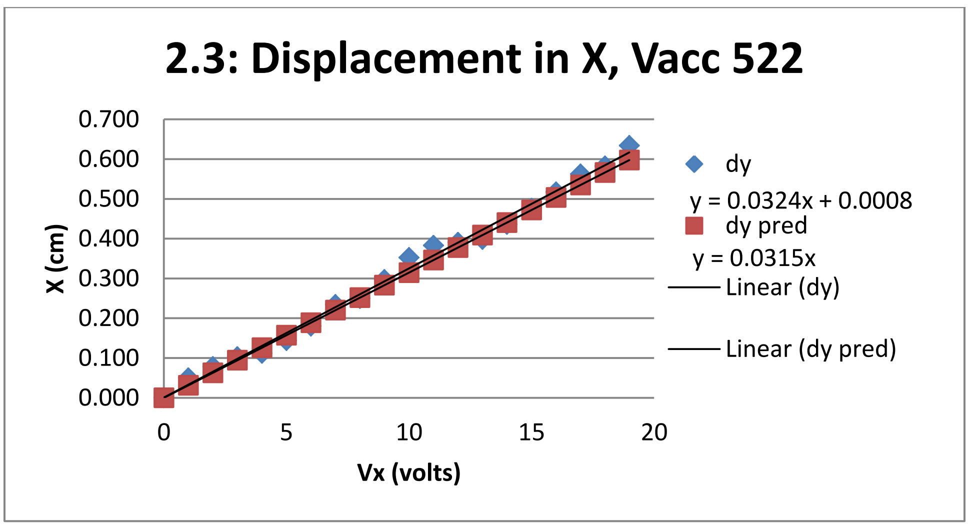
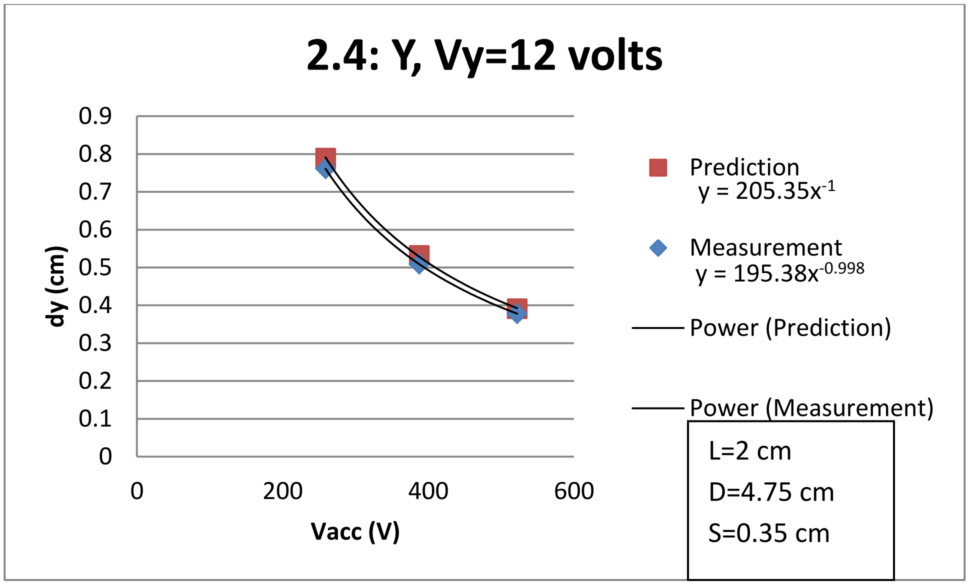


Figure 11: Displacement vs voltage over x-defelction plate for measured (dy) and predicted (dy pred) values. Made with L=2.0 cm and D=4.75.



You can also plot vs V^-1, espeacially if they are having troubles fitting a power equation to it. Students will try and fit a linear line to the 1/V line, and try to pass the bad fit off as bad data. Do not accept this.

Lissajuous Figures

Start with frequencies low. Increase frequency one at a time until so the path becomes a solid line. You should be able to get it to make an oval. By increasing just one, you should get more loops to appear (for my set-up a new loop appeared every 60 hz)

Problem 2.5 : The Electric Field from a Line of Charge

Equipment

Same as problem 2.1

Procedure

For an infinite line:

$$\vec{E}_{line} = \frac{\lambda}{2\pi\epsilon_0 r}\hat{r}$$

For a finite line (with total charge q):

$$E_x = \frac{kq}{x(x+L)}, \quad E_y = \frac{kq}{y\sqrt{y^2 + \frac{1}{4}L^2}}$$

Students can make the wire short (allowing them to measure the E on the x-axis), and make it long (only measure y-axis, but should approximate an infinite wire.

Students need to measure the length (using on screen values) to get the total charge, students set the charge density when placing the line.

Analysis

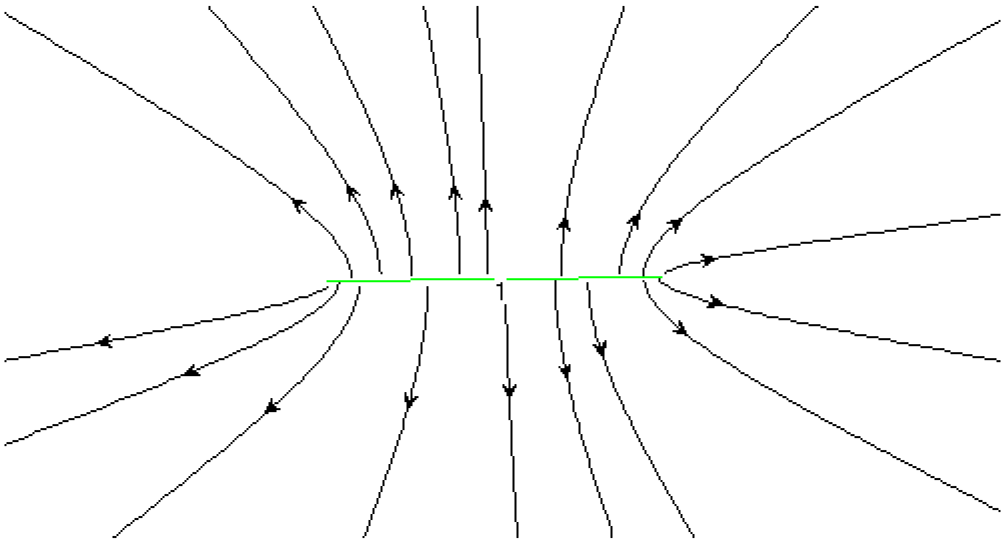


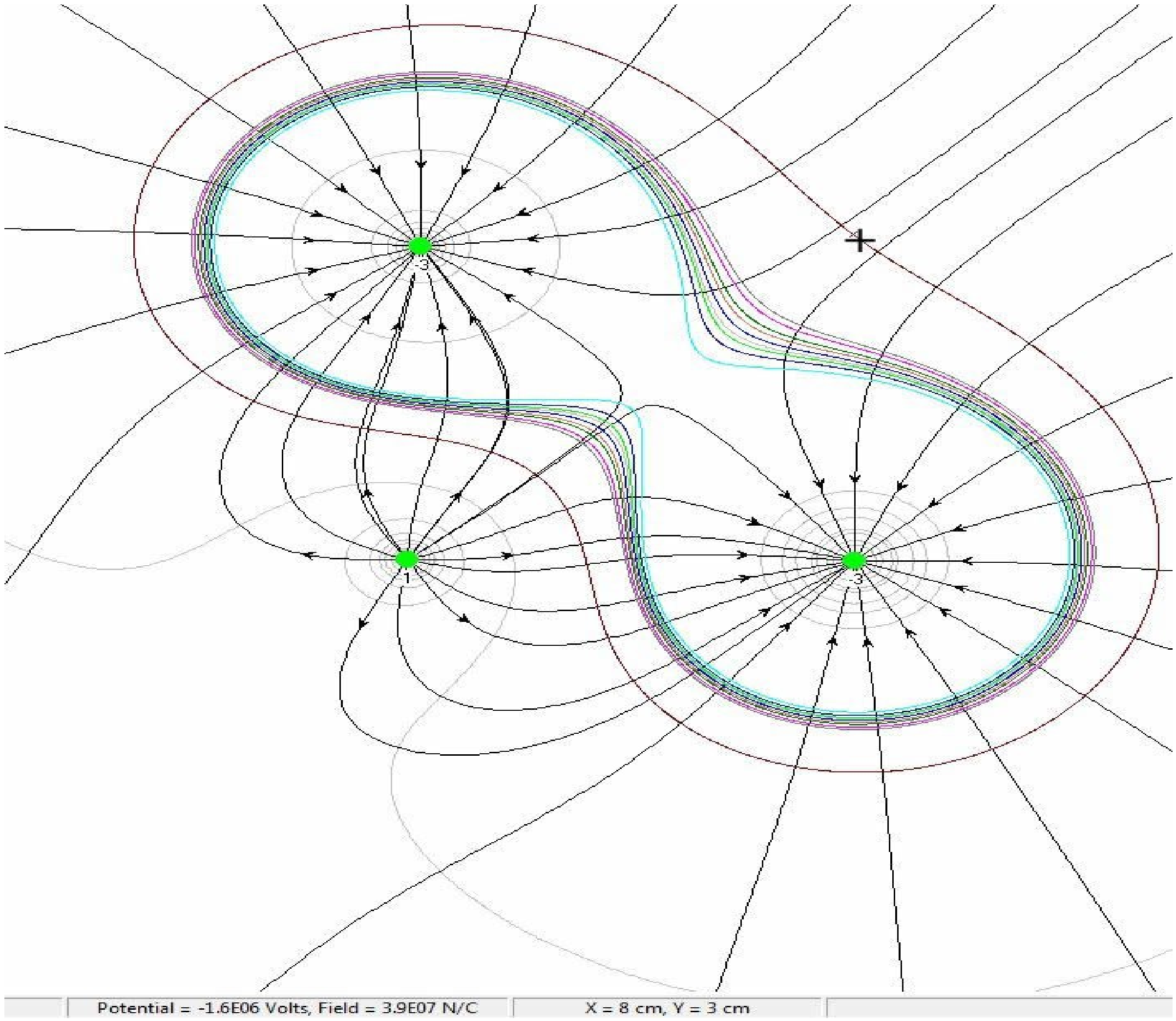
Figure 12: as L>>y, it approximates an infinite line. Students should only worry about measuring points along the x and y axis.

Problem 2.6: Electric Potential

Students simply make a box of charges and measure the electric potential at various points. This lab is fairly simple to calculate, set-up, and do. Since voltage isn't a vector, you simply sum up the voltage from each position:

$$V_{tot} = \Sigma_i \frac{kq_i}{r_i}$$

Students can do several set-ups following the basic three corners of a square model



Problem 3.1: Simple RC Circuits

Summary: Students make simple DC RC circuits and measure the time constant for them.

Concepts: RC circuits, time constants

Equipment and Equations

Equipment:

- Vernier differential probe
- labPro input box
- A computer with LoggerPro
- 6-volt battery
- Various resistor in the kΩ to MΩ range
- Various capacitors in the μF to nF range

- Various wires

The lab function on the equation: $V(t) = V_0 e^{\left(-\frac{t}{RC}\right)}$, where then RC is the time constant.

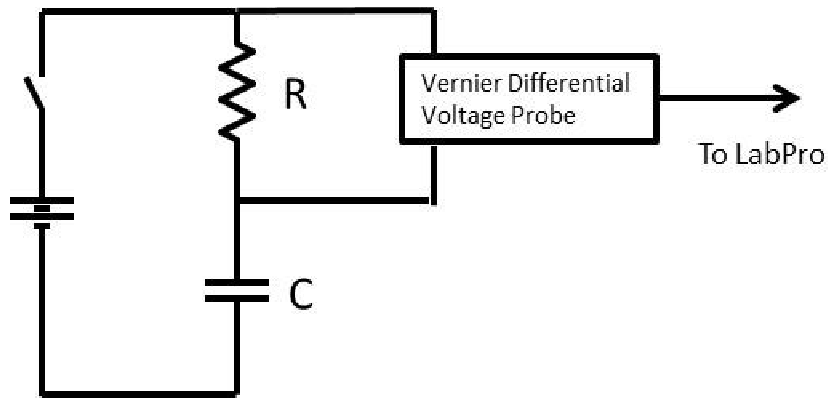


Figure: 3.1.1 Basic set-up for Problem 1. You will be changing the values of R and C as well as the location of the voltage probes.

For part 2: the end result should be that for the longest time constant they should connect the resistors in series and the capacitors in parallel, as these are the configurations in which the values add together.

Procedure

The vernier voltage probe plugs into the LabPro interface box and is used just like a DMM to measure voltage. It will take Voltage reading as a function of time. Students should make sure they take a large number of readings every second, at least 250, but 2000 can be taken. The icon that looks like a stopwatch will let them change this value, and also change how long the data taking is, which shouldn't be much more than 5 sec (to give them time to make the connection after starting).

Keep in mind, if you value for 1/RC is greater than the number of reading per second, you will not get many data points. If students go below 1 kOhm and 1 microfarad, they will likely run into this problem.

A difficulty often arises in that the student takes too long in closing the circuit, or don't make the connection well. This results in the first part of the plot looking jumpy and some of the important data not getting recorded. If students are having a hard time connecting the circuit, **have them make the connection at a different, easier, point.** Find a point where the student can make a simple fast connection. Usually this is quickly shoving a prong into a port. Alligator clips almost never work well for a fast, clean connection.

Make sure students discharge capacitors between measurements, a fully charged capacitor will not do anything.

For Part 1: Students can simply take a variety of different combinations of R and C. As long as the RC value isn't too small (less than 0.01), it seems to work well.

For Part 2: The only mistakes that happen here are students not correctly connecting in series or parallel. If students have odd results, the first thing to check is their wiring.

Analysis

There are two ways to plot the data, *V vs t* and *LN V vs t. LN V vs. t* is the better choice in general as it is a linear fit and can be done by hand if needed. When using either method, be warned that:

1. For V vs t, it is vital they address the off-set of time. The time at which voltage first rises should be set to 0. If they do not do this, they will have bad luck fitting an e^-ct line to fit their data.
2. For LN V vs t, it is important that you start the plot when the connection is made and cut off the plot when the voltage is done dropping These eventss will not be as obvious on the LN V plot, they may simply look like a fanning out of the data points. Including these regions of data will greatly decrease their accuracy. They must only plot as the Voltage is actually changing, which is best seen on the V vs t plot (or just look at the data: at less than ~0.05 volts, it's not doing anything you should be measuring).

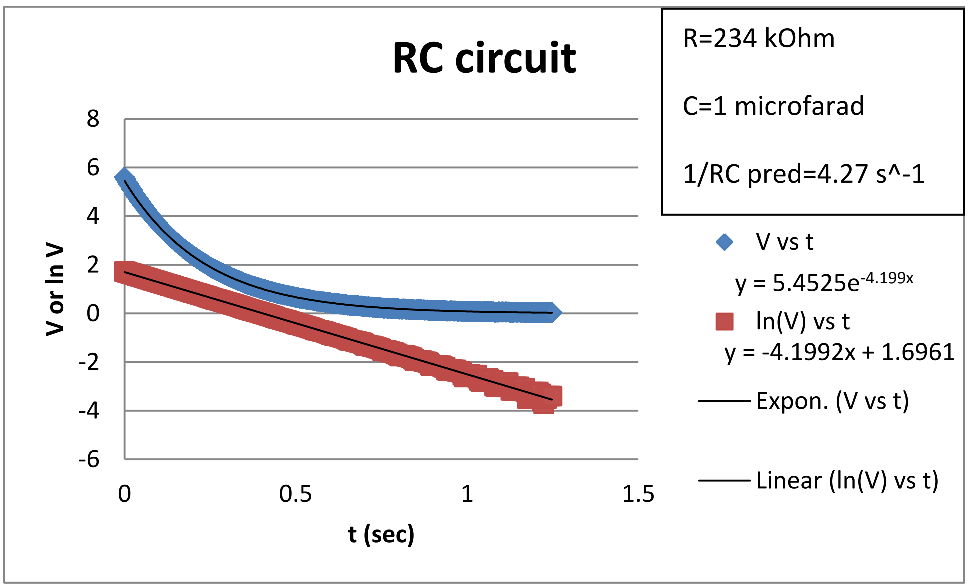


Figure 13: examples of both types on one graph. The measured value of 1/RC is taken from the exponent for the V vs t plot, and the slope for the lnV vs t plot.

Problem 3.2: Measurements of Capacitance and Dielectric Constants

Summary: Students will make a "home-made" capacitor and test its properties using a scale.

Equipment

Equipment:

- Electric scale
- Bottom plate
- Top plate with ring stand attachment and translation stage

- DC to DC converter
- Power supply
- Super thin wire
- Conductive tape
- Various wires
- Plexiglas dielectric plate (round)

The top plate has a translation stage, a dial you can turn to move the plate small amounts. On the outside of the dial are numbers that go from 0-50, this translates to 0-0.5 mm. as the stage moves up a second set of number appears vertically. These are in millimeters. Thus two full turns of the dial moves the stage up 1 mm or 0.001 m. The area of the plates should be ~0.0184 m^2.

The equation for the force on the bottom plate has a factor of ½ that many don't think to include. Normally F=Eq for a particle between two charged plates, but when the 'q' is actually the bottom plate, it only feels half that much, because while the top plate is pulling on it, the bottom plate doesn't exert a force on itself. Thus, assuming infinite plates:

$$F = \frac{Eq}{2}, \qquad E = \frac{V}{d}, \qquad q = CV, \qquad C = \frac{\kappa\epsilon_0 A}{d}$$

$$F = \frac{\kappa\epsilon_0 A V^2}{2d^2}$$

As these plates have finite size there will be edge effects which change this equation, thus, the exponents on *V* and *d* can vary a little. It is likely that set-up (how parallel they manage to get, etc.) also effects this. Leading to:

$$F = \frac{\kappa\epsilon_0 A V^n}{2d^m}$$

Where 'n' and 'm' are close to 2. Students should use Ln F vs ln x plots to find the correct exponent on each variable. 'n' should be 2 (it isn't part of the capacitor equation), but 'm' won't be.

Procedure

This can be a very fussy lab. It is a very good lab, when done right, but will fall apart if care is not taken in the set-up.

1. The plates must be as parallel as possible, the distance must be determined as accurately as possible (finding 'zero' distance is the tough part here, and where the need for parallel is most obvious). Any time they bump or move of change anything the need to make sure they are back to parallel and 'zero' before moving on, or the data will show it.
2. Furthermore: The scale can be very sensitive to wind, people leaning on the table, the tension of the thin wire connecting them to the power-supply, etc. Moving the wires will change the tare point of the scale. **Leaning on the table while taking data can change the apparent weight by up to a gram!** Make sure no-one moves anything near the capacitors while taking take or the scale reading will be off.
3. Lastly: it takes time for the capacitor to 'settle in'. I noticed this especially with the dielectrics. The mass reading of the scale will change a fair amount, usually increasing for a while, then decreasing. It can a **minute or more** for it to come to rest on a repeatable value. Likewise, when voltage is turned off it can take a while for the scale to return to zero EVEN AFTER

DISCHARGING THE CAPACITOR AND THE VOLTAGE READS ZERO. Make sure students give it time, or they will get useless results (especially in the dielectrics!) The best fix for this is to reduce the resistance in the connection between the plates and the thin wires as much as possible, and then to have patience.

Measuring the voltage over the plates should be done at where the plates connect to the high voltage output box, NOT at the co-axial 'monitor' on the DC-DC box. The values differ and the true value is the one taken from the plates.

The thin wires have an insulating coating that is removed at the points it connects to the plates and voltage supplies. If this isn't removed properly, or the connections are simply bad, the resistance can be in the hundreds of MEGA-ohms. Test the resistance of each wire to each plate. A good connection can have just a few ohms resistance, and this helps the lab immensely.

Part 2:

For dielectrics, the *d* is easy to measure (use calipers) since it is the same as the width of the dielectric. Getting the top plate parallel and 'zero' distance from to the dielectric is pretty tough. The plate needs to be so close that any closer changes the mass shown on the scale permanently (sometimes if you wait it will return to zero). For this reason varying Voltage is perhaps the easiest choice, and it allows you to take far more readings. The possible dielectrics for this lab are limited. The glass is too thick and too heavy, the thin films are too thin (any air gap becomes very relevant), and so you need something light and around 2-3 mm in thickness. This pretty much limits you to the thin plexiglass disc (not the octagonal one). **<u>Don't use anything else</u>**. In lab 6.1 there is a much better method for measuring the dielectrics, the other dielectric are for then.

Analysis

In general measuring capacitance (part 1) works pretty well. The Ln F vs ln x plots does a good job of showing how the capacitor the students set up is behaving. If done correctly, F should vary as V^2 (within 5%) but *d* seems to be off from squared by as much as 20% (d^-1.6 in my trials). Either way, Log-log plots are actually quite nice for a couple of reasons:

1. They are always "linear" in a nice y=mx+b form that students can fit by hand.
2. The slope (m) gives the power to which the variable is taken, and is easier to fit than a power function (you can fit an X^-2/3 plot by hand hand!).
3. The y-intercept (b) is the natural log of the coefficient, so e^b gives you the coefficient back . In this problem it should be $\frac{\kappa\epsilon_0 A}{2} * (V^n or \left(\frac{1}{d^m}\right))$ so you check that part of the equation as well.
4. It's better than plotting vs V^2 or d^-2 because you needn't "guess" the power the variable should be at beforehand.
5. Note: it's not good with polynomials (really muddles it up, lny=5 lnx could be y = x^5, x^4+x, x^3+x^2, etc).

Essentially, it's a great data analysis trick to teach the students, and can be used in future labs. Consider spending some time going over it and its advantages, as part of the goal of the labs is to teach students how to do good analytical lab.

F vs d: Data at small distances often isn't very stable; the values change a lot over time. I think it may just need time to settle down. Once you get out a few mm it is very stable. If students have trouble at low distances, let them move on since you can take a lot of data even further out. Students should pick a fairly large constant voltage, and there is no reason not to use the maximum the power supply gives.

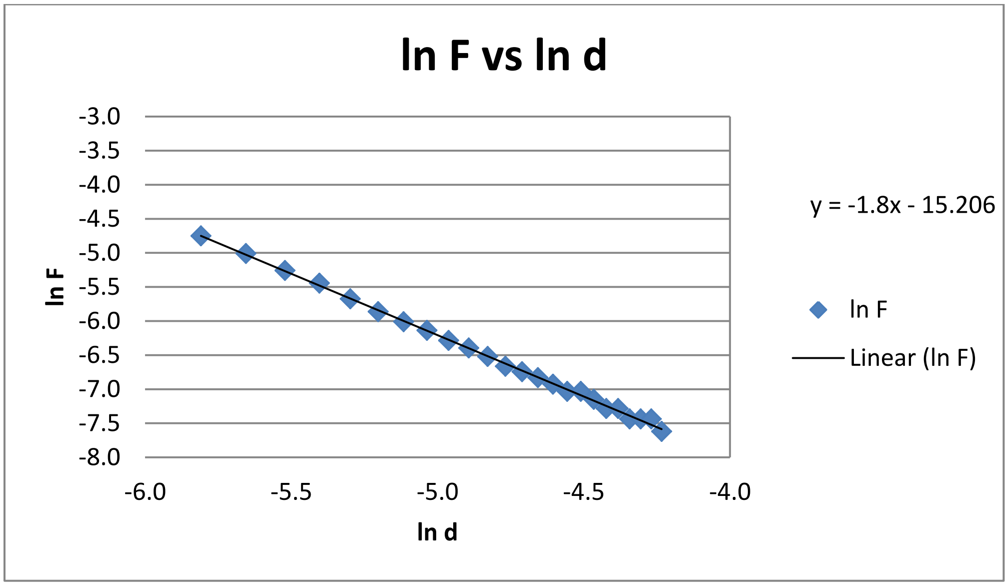


Figure 14: log-log plot of Force vs distance. Implies that distance is raise to the -1.8 power and that $\epsilon_0 A \frac{V^n}{2} = e^{-15.21} = 2.490 \times 10^{\wedge} - 7$ [N*m^2] . Data was plotted only after d=3 mm, as the data before this was unstable. Voltage was kept at 1040 volts.

F vs V: set distance to be the minimum stable position, this allows the greatest range to measure over. Too close and you will spend time waiting for unstable readings to calm down, too far and you will not have a good range on the scale.

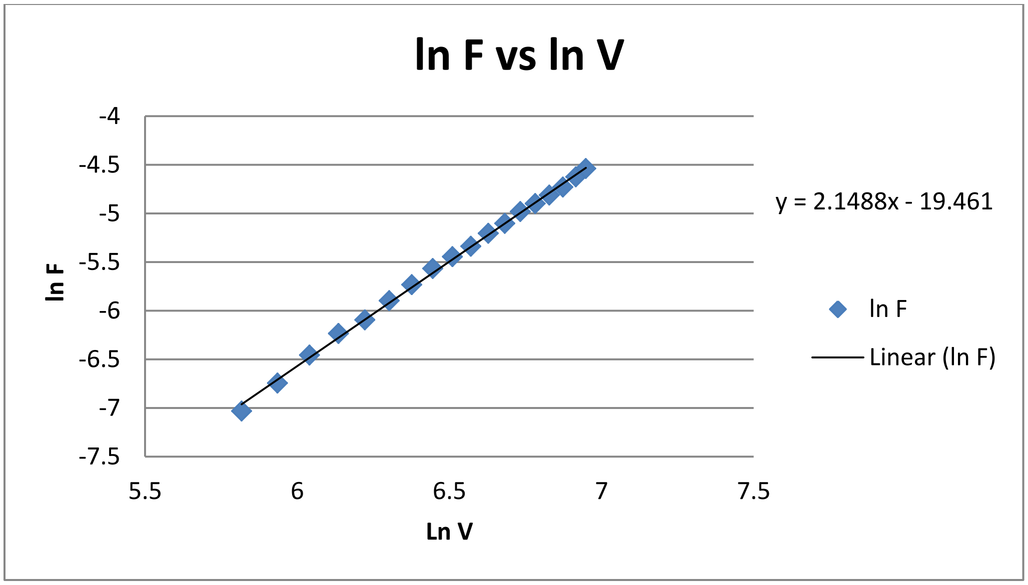


Figure 15: Log-Log plot of force vs distance. This implies that Voltage is raised to the power 2.15, which is within uncertainties of 2. Intercept implies that $\epsilon_0 A \frac{1}{2d^m} = e^{-19.461} = 3.533 \times 10\^{} - 9$ [N/V^2]

The best analysis of the data seems to be when you apply both exponents to the data.

Table 3: Comparison of measured 'coefficients' ($\epsilon_0 A \frac{V^n}{2}$ for F vs d and $\epsilon_0 A \frac{1}{2d^m}$ for F vs V)

Coefficients		F vs d		F vs V
measured	n=2.15	2.489E-07	m=1.8	3.533E-09
Predicted	n=2	8.816E-08	m=2	1.302E-08
Predicted	n=2.15	2.500E-07	m=1.8	3.929E-09

PART 2: Dielectrics

This part is tough to do. For some reason the dielectrics are not very stable, so their values on the scale will vary with time.

Through much experimentation I've come to this method to get reasonable values.

1. Set the voltage to the desired value
2. Turn off the power and let the scale return to 0.0 g
3. Turn on the power and watch for the maximum value, record that value (your accuracy here is only to the .1 g). It changes very quickly (the whole thing is over in a second), so you have to be ready for it.
4. Repeat and make sure you get the same result.

All other methods resulted in data that change every time I did them, this was the only one that was consistent AND followed the predicted shape of the equation. Students find the dielectric constant by dividing the data by the predicted values with k=1.

The given values for plexiglass vary from source to (between 2 and 4, 2.8 and 3.4 come up a lot) and we are not sure precisely which type of plexiglass-like material the disk is. For this reason precision is less important than qualitatively seeing that the data still follows the same equation as part one, and that the dielectric constant is in the correct ball park.

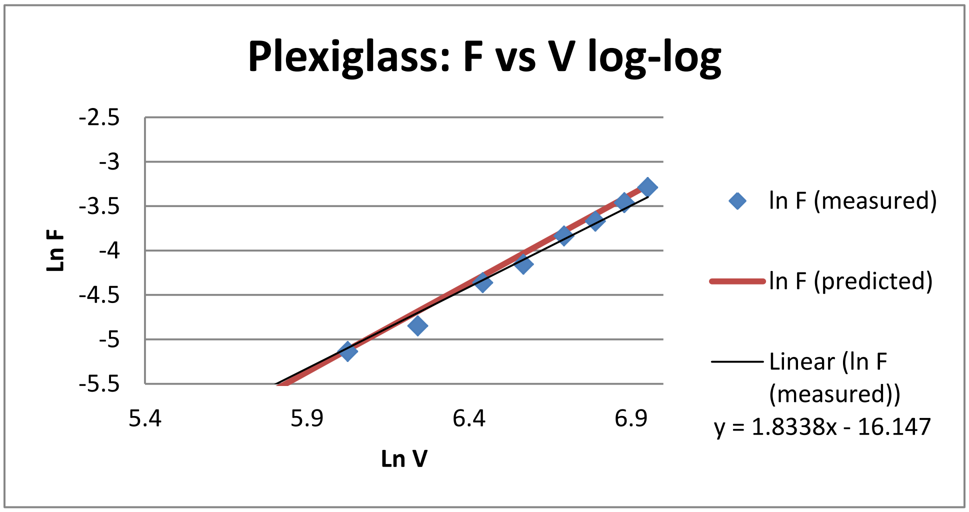


Figure 16: Comparison of data and fitted prediction (using k=4.4, V^2, 1/d^2).

Problem 3.3: RC Circuits with AC

Summary: Students look at two interesting types of AC circuits

Equipment

Equipment:

- BK precision function generator
- oscilloscope
- various wires and connectors
- Collection of resistors and capacitors

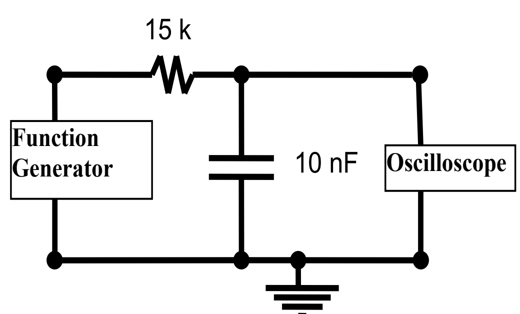


Figure 3.3.1: Integrator circuit

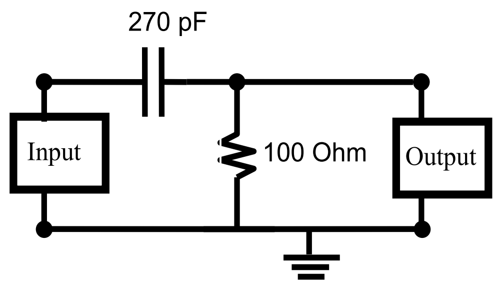


Figure 3.3.2: The differentiator. Note positions of the capacitor and resistor. This is important when using the scope, for which the negative terminal is always ground!

Procedure

This is a very qualitative lab. Students need to look at the waves and see the shapes and explain why things look the way they do rather than make a lot of measurements.

Analysis

The natural frequencies for the circuits presented are 6667 Hz (6.67 kHz) and 37037037 Hz (37.0 MHz).

Using sin waves are not very useful since the integration/differentiation of a sin wave still looks like a sin wave.

Answers:

1. At lower frequencies (500Hz) The signal is similar to a square wave except the “verticle” parts of the square wave are replace with exponential decay/growth that then merge into the horizontal section. The time constant should correspond to the 1/RC of the circuit
2. As frequency increases, the horizontal section becomes shorter, until it will be an series of exponential decay.
3. The plot of amplitude of V vs f (or better yet lnV vs f) will look like an exponential decay with a time constant of RC.

$$V(f) = Ae^{-RCf}$$

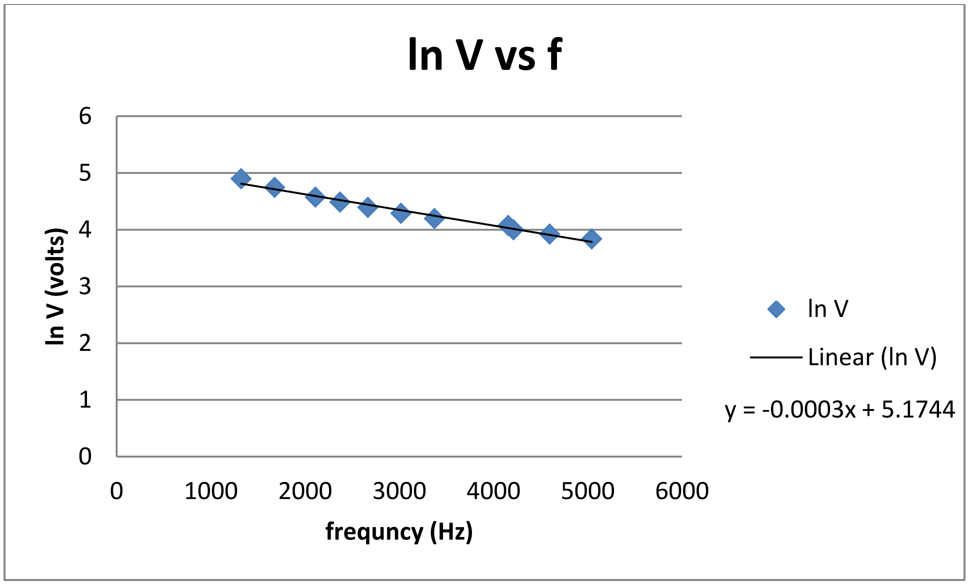


Figure 17: measured RC=0.0003 sec, predicted RC=0.0002 sec.

4. At the limit it begins to look like a series of triangles, essentially the integral of the square wave. If you change to a triangle wave you get a series of parabolic curves that can easily be mistaken for a sin wave.
5. You should find that it looks like a normal wave.
6. For square waves, this voltage looks like an exponential that decays to zero, but with such a small RC (and thus a high f0) it will look like a series of spikes, the differentiation of a square wave. If you use a triangular wave you get what looks like a square wave.

Problem 4.1: the Magnetic Field of One Coil

And Problem 4.2: Measuring the Magnetic Field of Two Parallel Coils

Equipment

Equipment:

- Power Supply
- Helmholtz 200 turn coils
- Hall probe
- labPro input box
- Digital Multi-Meter
- Compass
- Various wires and connectors

For 4.1:

On the "x-axis" (what the lab calls it, cylindrical co-ordinates would call it 'z')

$$B(x) = \frac{\mu_o I N R^2}{2(x^2 + R^2)^{\frac{3}{2}}}$$

In the "y-axis", the qualitative prediction should be that near the center of the loop the value should be close to the B(x) equation, but near the actual wires it will increase, and then decrease (perhaps more quickly) as you go outside the coils.

For 4.2, you simply add the B(x) from each loop and get:

$$B(x) = \frac{\mu_0 I N R^2}{2}\left(\frac{1}{\left(x^2 - xR + \frac{5}{4}R^2\right)^{\frac{3}{2}}} + \frac{1}{\left(x^2 + xR + \frac{5}{4}R^2\right)^{\frac{3}{2}}}\right)$$

where x is the midpoint between the two loops.

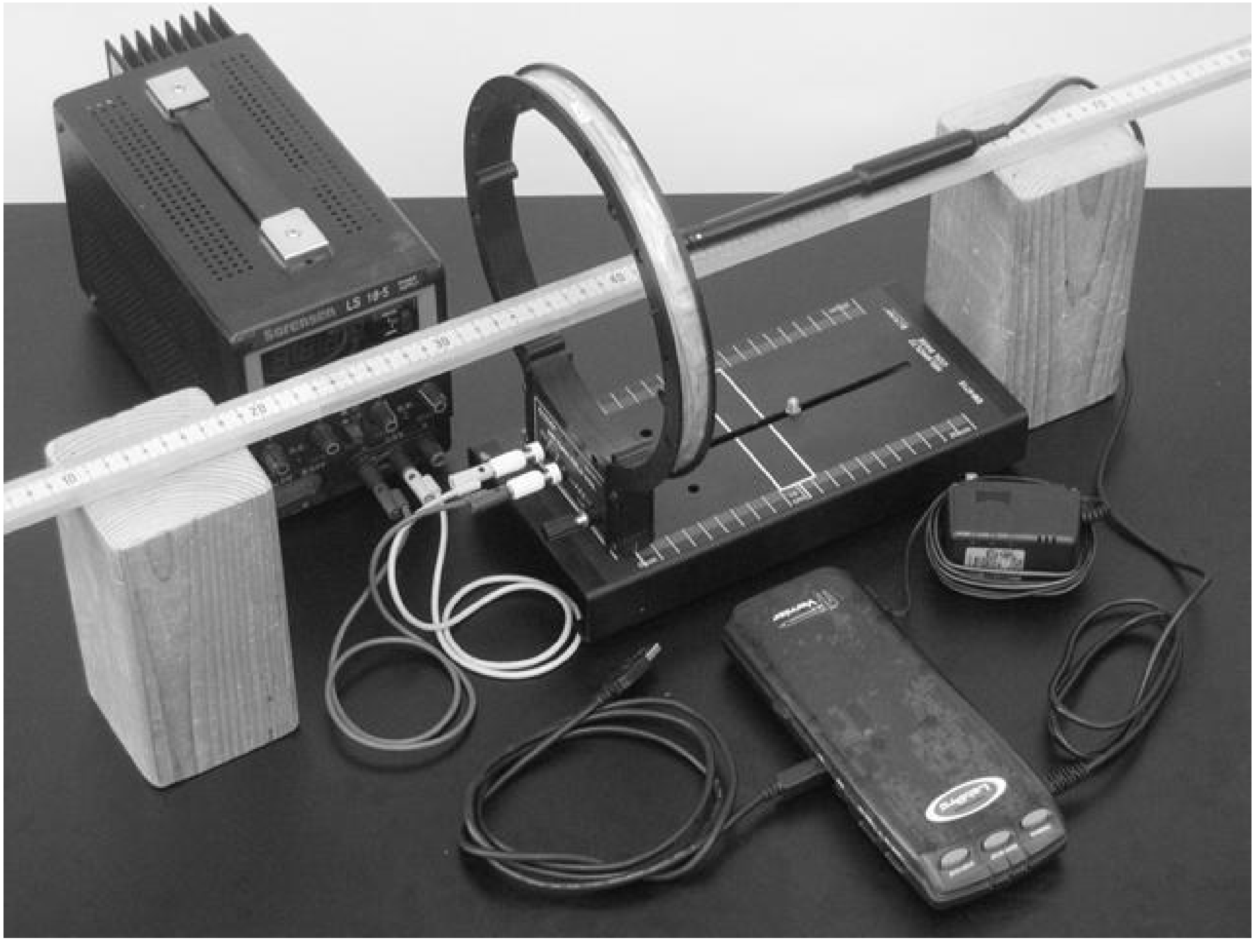


Figure 18: single loop set-up

The field in between the coils should be approximately:

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{R}$$

Which using N=200 turns, R=0.105 m, comes out at around 0.00171 Tesla per Amp (which scaled to the return of the hall probe is 1.17 mT/A).

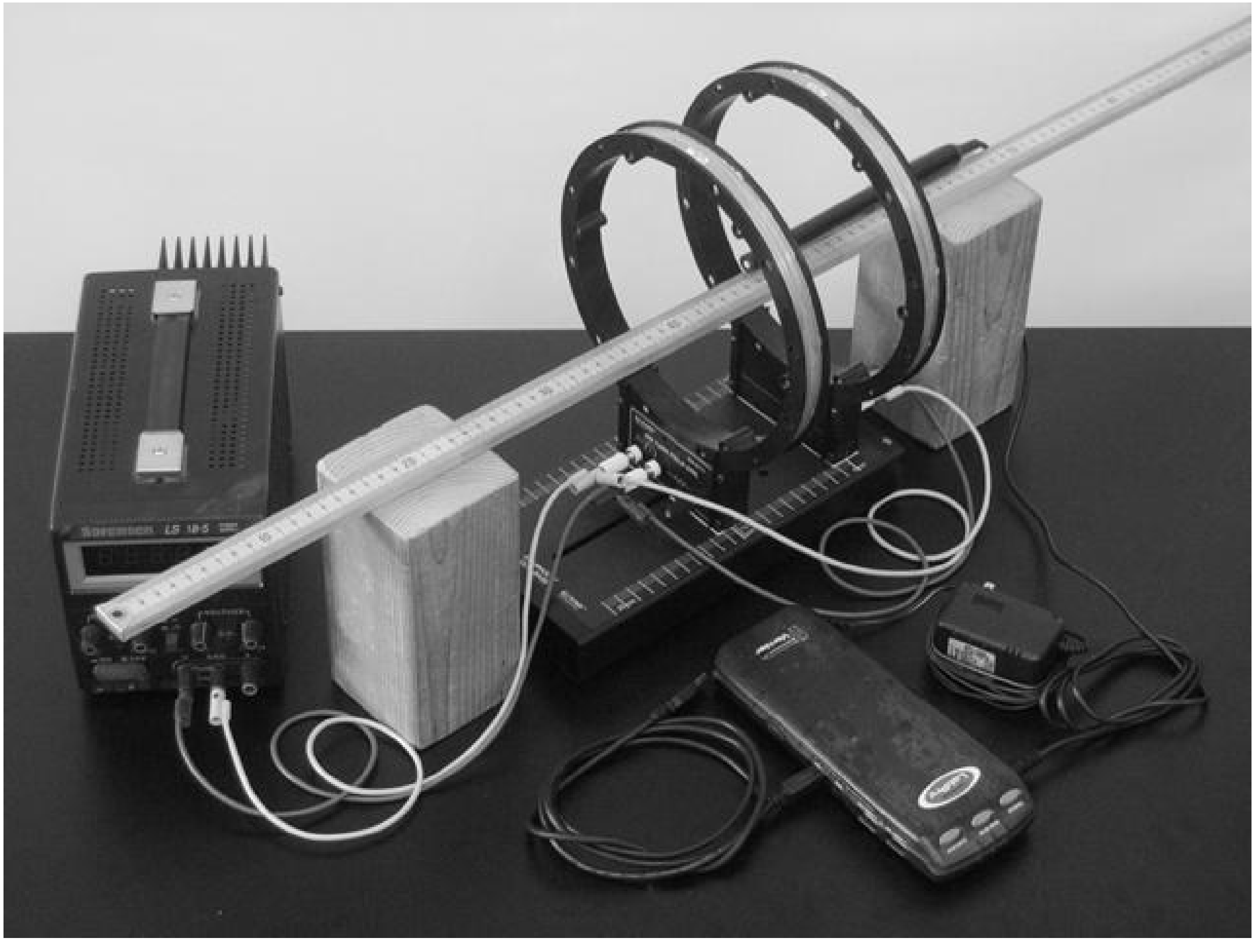


Figure 19: set-up for the Helmholtz coils.

Procedure

Make sure that the students are measuring as close to the axis as possible. With wood blocks and rulers they should be able to make a nice track they can move the probe down and take measurements easily with.

The hall probes have a yellow sleeve around them to prevent the end from bending. Bending the end will REALLY mess up the readings. This can often happen as they hold it firmly to the ruler. It will cause the data taken to be nonsense.

Make sure they Zero the probe when using the LoggerPro to take measurements or they will have significant background. Zeroing the probe will only give good readings at that one point. Some deviation from prediction will be from background fields.

The measured values also fluctuate a bit. Having students take 0.5 seconds of B-field data and finding the mean is a good way to consistently take the points.

When hooking up the two coil system, if they are in series, you will can measure the current through each from the power supply. If they are in parallel, each loop will receive current based on its own resistance, which can varying enough to have noticeable effects, so the approximation that each loop gets half the measured current is not advised.

Analysis

For 4.1:

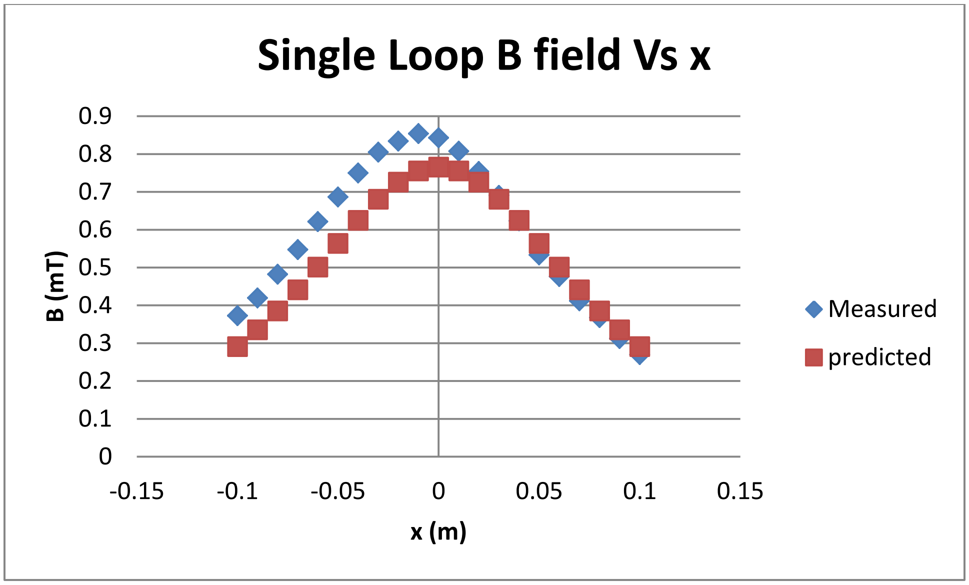


Figure 20: Data and prediction for the single loop. The deviation from predicted is likely due to background field changing along x.

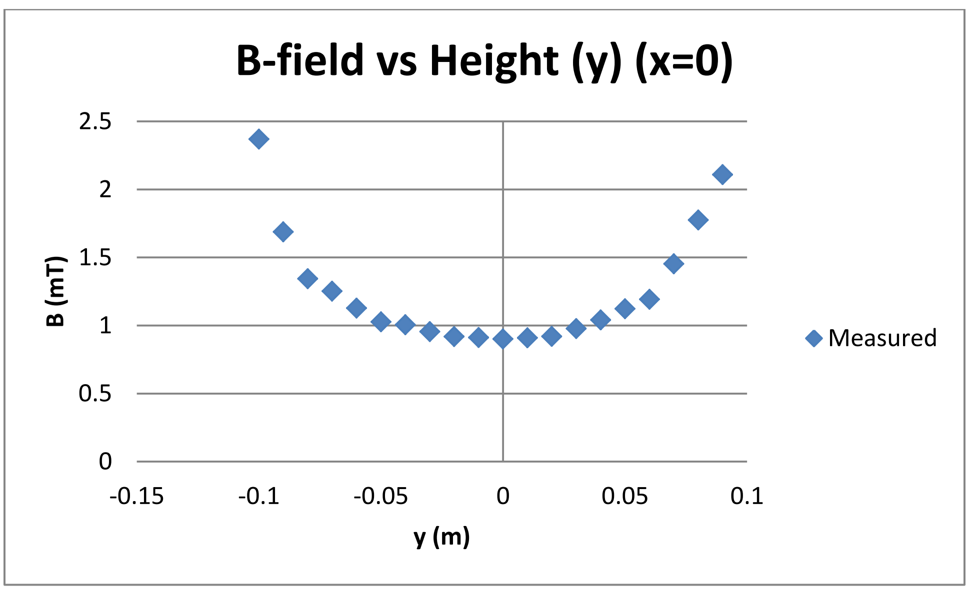


Figure 21: Vertical data for the single loop. This is what students should qualitatively predict. The data here ends at the loop itself.

For 4.2:

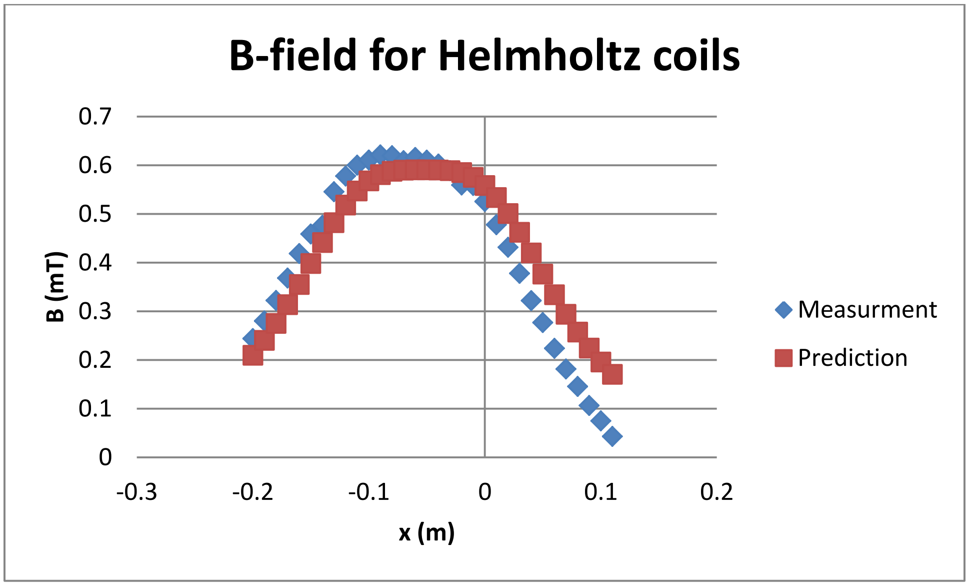


Figure 22: Helmholtz data for measurement and prediction. Here x=0 is for the center of one of the coils. Its possible that background magnetic fields are still responsible for the disagreement.

If students are off by more than a little shape distortion, look for: Factor of 2 differences (usually means they hooked it up in parallel and didn't split the current in their calculations) factor of 1000 (didn't convert from T to mT. Other factors could be a dropped term of I or N or R, etc. If the shapes REALLY don't agree, it may mean the hall probe has been compromised.

Problem 4.3: Magnetic Force on a Moving Charge

Equipment

Equipment:

- a CRT tube
- a CRT power supply box
- a standard DC power supply
- a Digital Multi-Meter (DMM)
- Helmholtz 200 turn coils
- Hall probe
- labPro input box
- Digital Multi-Meter
- Compass
- Various wires and connectors

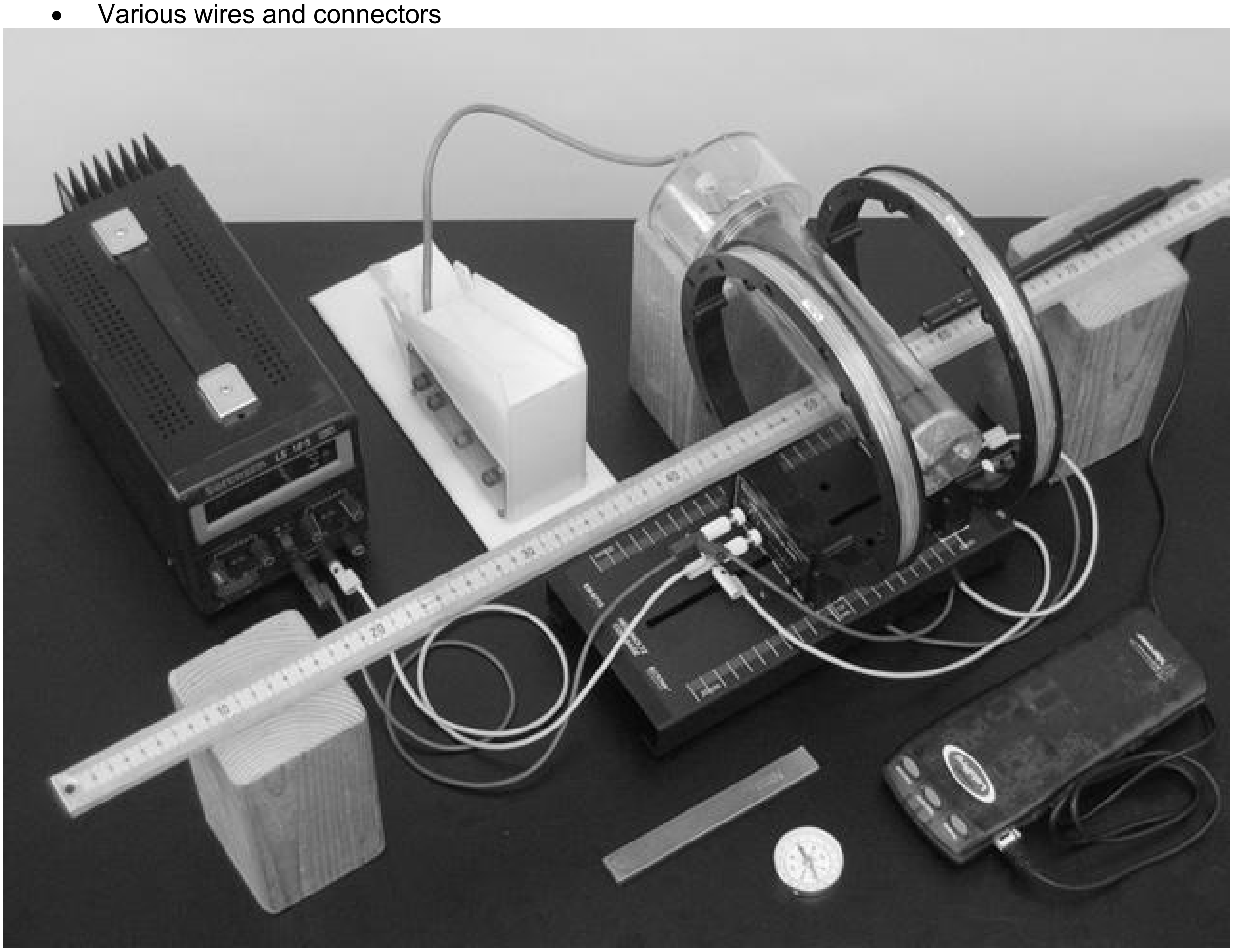
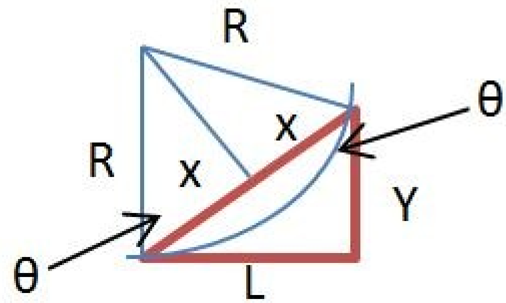


Figure 23: Set-up for lab 4.2

In this lab, the correct solution requires geometry to correctly solve it. The main idea is that the electron curves at radius R=mv/qB over a horizontal distance of Dtot=12.5cm. Using geometry you will find that:



$$R = \frac{mv}{qb}, \qquad v = \sqrt{\frac{2qV_{acc}}{m}}$$

$$y = R - \sqrt{R^2 - L^2}$$

If students try to use kinematics (ie treating the force from the magnetic field as always pointing down) they will instead get:

$$y = \frac{L^2}{2R}$$

which is a first order approximation of the above, and yields 'decent' results. However, it is a flawed assumption and students should be forced to think about the problem correctly.

The lab goes on to ask students to calculate the ratio e/m:

$$\frac{e}{m} = \frac{8\,V_{acc}y^2}{B^2(y^2 + L^2)^2}$$

Procedure

You can use a hall probe and a Vernier voltage probe to quickly find the proportionality constant between Current and B-Field. Simply connect the hall probe in CH 1, the volt probe in CH 2, and then take a measurement in which you hold the hall probe in the center, connect the voltage probe over a resistor in series with both loops, and then take data while changing the power supply (you could use the voltage over the loops, but their resistance will change with temperature, albeit slowly). Then simply plot B vs I (using V=IR). This is a time saver since they've already done a lot of slow magnetic measurements. This method can be used in many labs that want the students to make B vs I plots.

The biggest problems are: 1) CRT isn't entirely in field and 2) CRT is in non-constant parts of the field. There is a 'zone' of effectively constant field that the entire CRT can fit in. If it's in this zone only, data should fit match predictions, if they are not, anything can happen. Students should have mapped the zone a little bit in the previous Lab.

Analysis

Lower V_acc gives you less range of data, the electrons will curve off the screen at lower field strength. However, for the e/m measurement it seems that low Vacc gives better results.

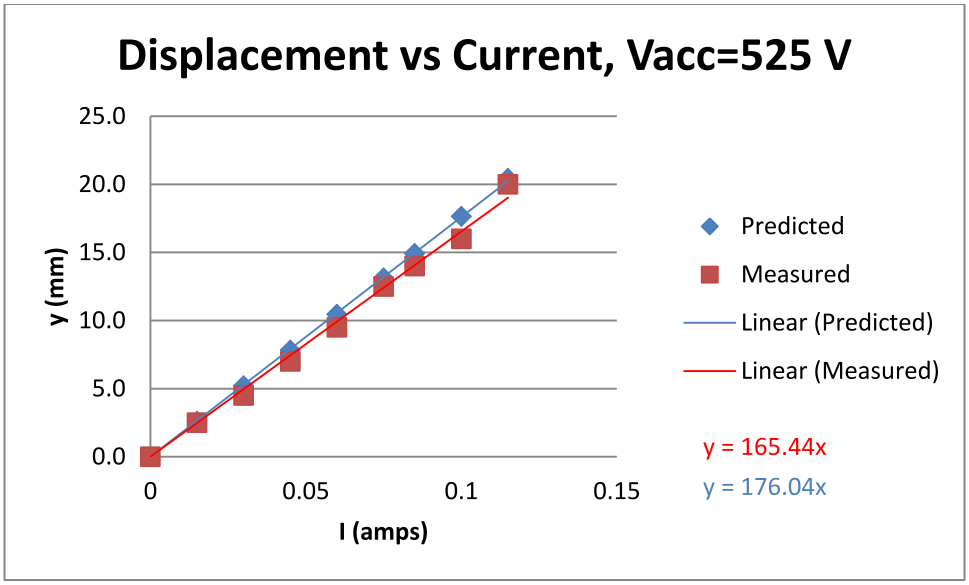


Figure 24: Data from measurements and prediction.

Table 4: Measuements of e/m. The accepted value is 1.76x10^11 C/kg. The average from the table is 1.73x10^11, an error of 2%. This data was taken with a Vacc of 394 V (525 volts gave less accurate results, around 13% error).

I (amps)	y (mm)	e/m (C/kg)
0.015	3	1.79E+11
0.03	6	1.78E+11
0.045	9	1.76E+11
0.06	12	1.74E+11
0.075	14.5	1.6E+11
0.085	17	1.69E+11

Problem 4.4: Hysteresis Curve

Equipment and Equations

Equipment:

- Power supply
- Nickel and soft iron rod
- Solenoid
- Hall probe
- Vernier voltage probe
- labPro interface
- compass
- Digital MultiMeter
- Wires and connectors

There are several types of solenoid. Some have a large radius, some a smaller one, some have dark red wire, some bright red. They all seem to be slightly different. The large radius solenoid has around 600 turns, the skinnier ones have 660-680.

For the interior of the solenoid:

$$B_{interrior} = \frac{\mu_0 I N}{L}$$

The precise B(x) equation is very complex. Don't fret over calculating it.

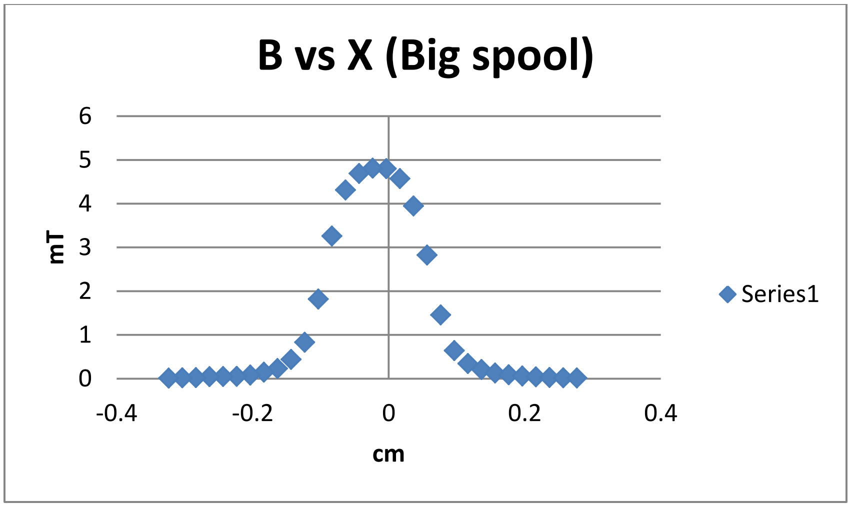


Figure 25: B(x), 0 is the one edge of the solenoid.

Procedure

You can use a hall probe and a vernier voltage probe to measure B-field and current through the solenoid at the same time. Simply connect the hall probe in CH 1, the volt probe in CH 2, and then take a measurement in which you hold the hall probe in the solenoid, connect the voltage probe over a resistor in series with the solenoid (the solenoid's resistance will change with time and temperature, albeit slowly), and then take data while changing the power supply. Then simply plot B vs I (using V=IR). This is a huge time saver for the hysteresis!

Demagnetizing the nickel is a little tricky. Use a probe to measure its magnetization and set up the solenoid to give a field in the opposite direction. Turn the power on low, then off and check to see that the magnetization has decreased. Then keep slowly increasing the solenoid power (turning off in between to check progress) until you get it to zero.

Analysis

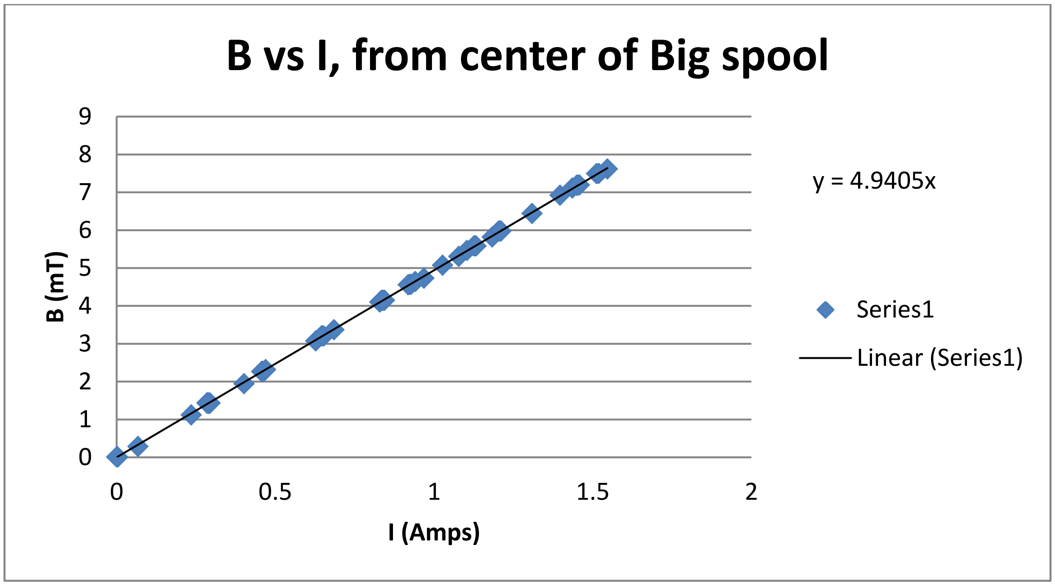


Figure 26: B vs I, can be used to calculated the number of loops (N=~600)

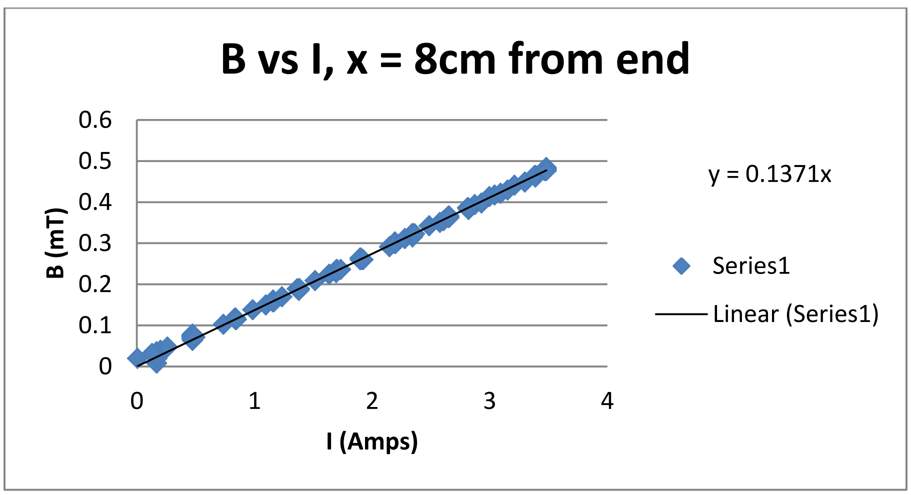


Figure 27: B vs I at a distance of 8 cm from the end.

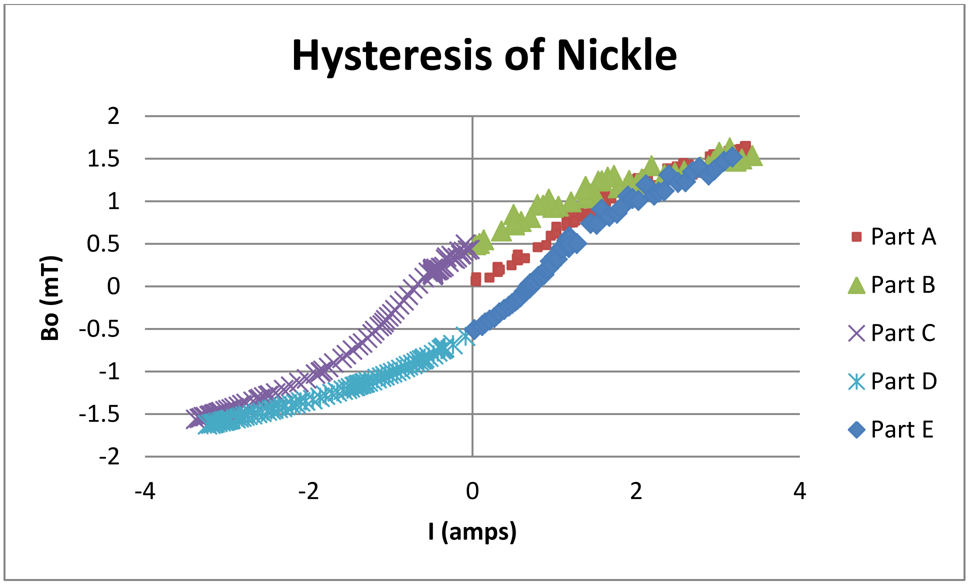


Figure 28: Hysteresis curve for Nickle. Note the wide thickness of the curve implying its high coercetivity.

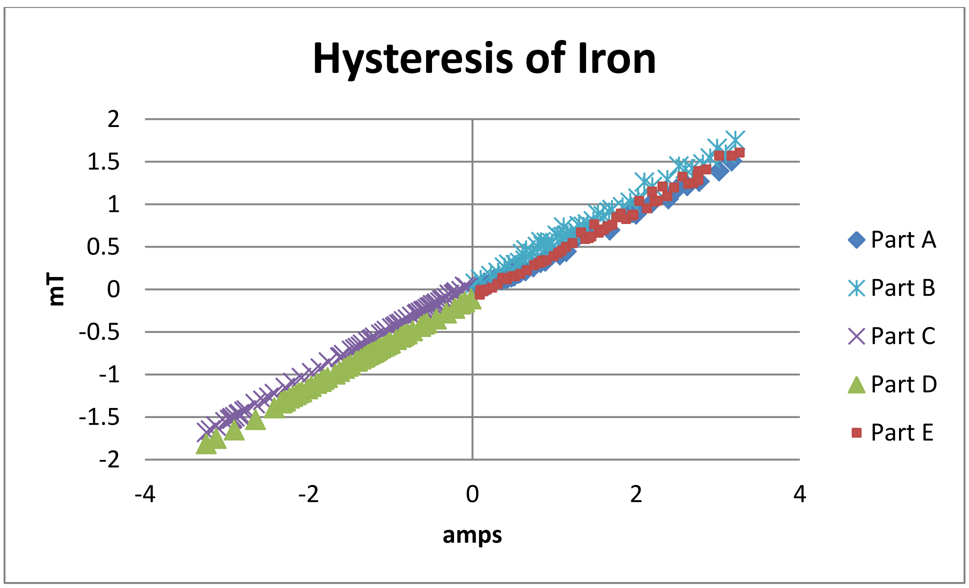


Figure 29: Hysteresis curve for soft Iron. Soft iron has almost no hysteresis, it will immediately align with the field.

Problem 4.5 : Torque on a magnetic moment; precession in a field

Summary: Perform experiments on the behavior of rotations and oscillations in the magnetic field .

Concepts: Precession, simple harmonic motion.

Equipment

Equipment:

- Cue ball with embedded magnet
- Air bearing and pump
- A set of Helmholtz coils (diameter = 22 cm, 150 turns)
- Sorenson DC power supply and cables
- Video camera
- Stopwatch
- Hall magnetic field probe
- labPro input box
- Voltage probe (optional: for measuring B vs I)

Part 1: The basic equation is:

$$\Omega = \frac{\tau}{L sin\phi}$$

where

$$\tau = \mu B sin\phi$$

which leads to

$$\Omega = \frac{\mu B}{I\omega}$$

Since the students can't really control ω it is best to plot:

$$\Omega\omega = \frac{\mu B}{I}$$

This equation is true when ω >> Ω, and thus the experiment works best when the ball is spun faster.

Part 2:

$$T = 2\pi\sqrt{\frac{I}{\mu B}}.$$

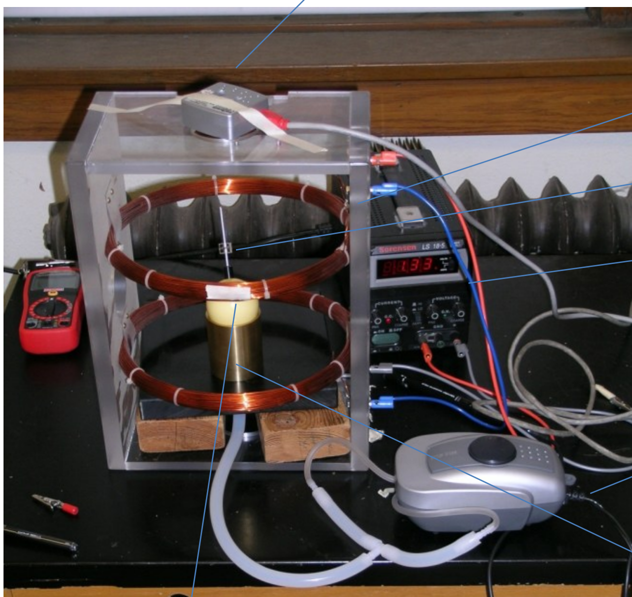
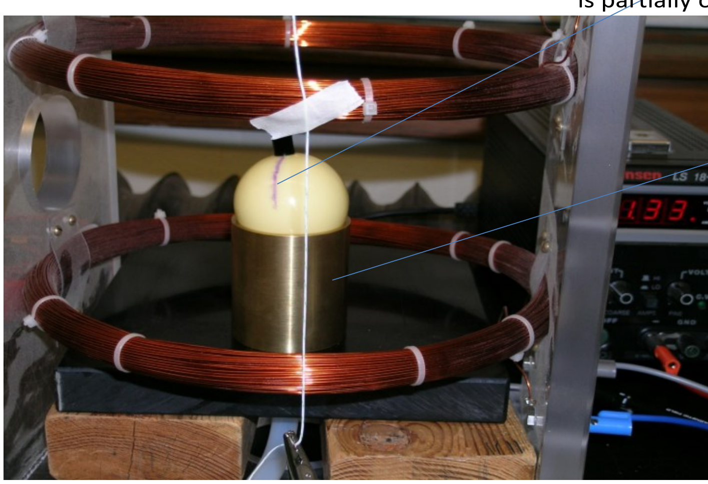


Figure 30: Set up for 4.5



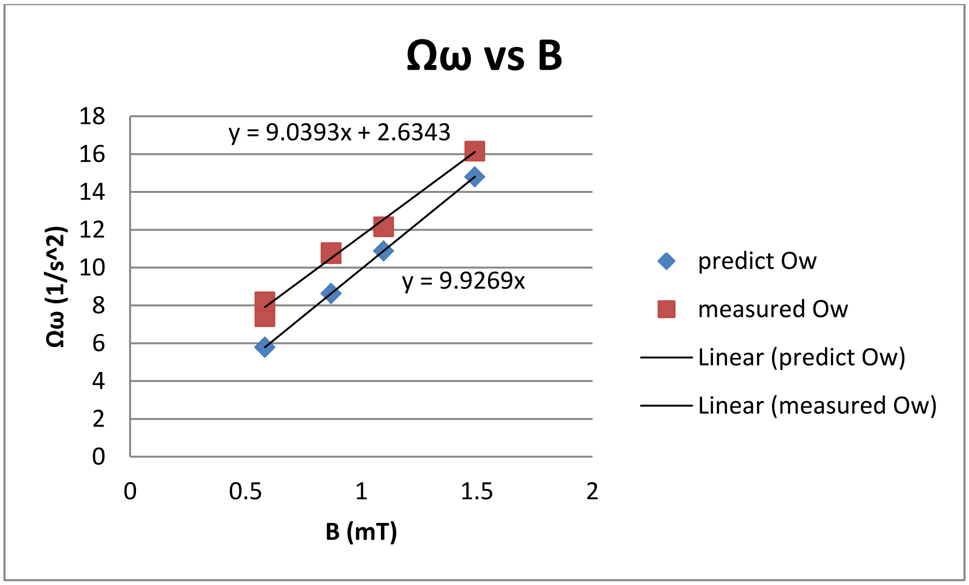
The equations for part 2 are given in the manuel.

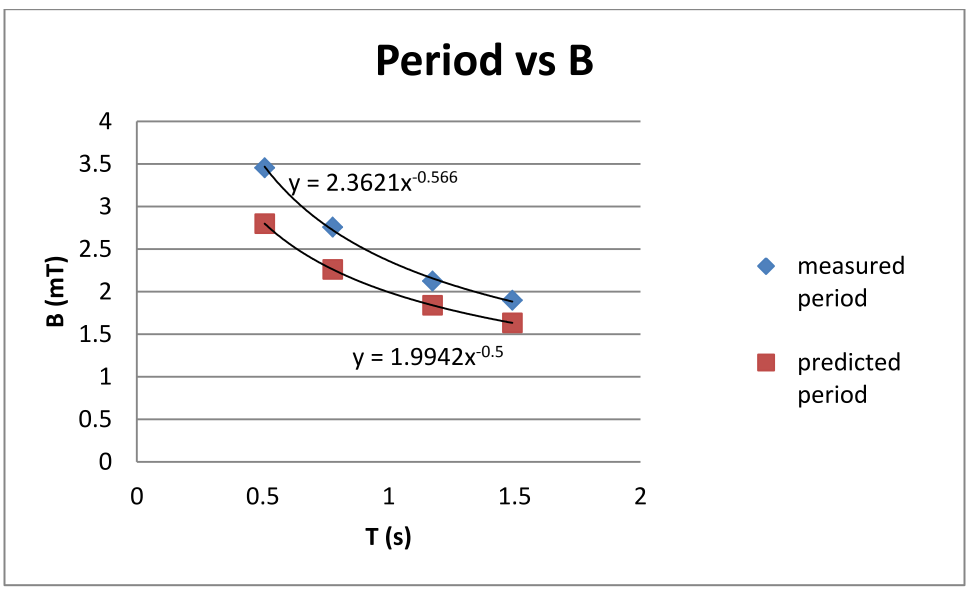
Procedure

This lab works really well, as long as the camera is working. As you haven't used the cameras yet this semester, it's possible they won't be set-up well, so make sure that they are set to have very short exposure and very high gain.

The data taking is pretty straight forward and works really well. The biggest difficulty is getting the ball to spin fast enough and removing the wobble.

Analysis





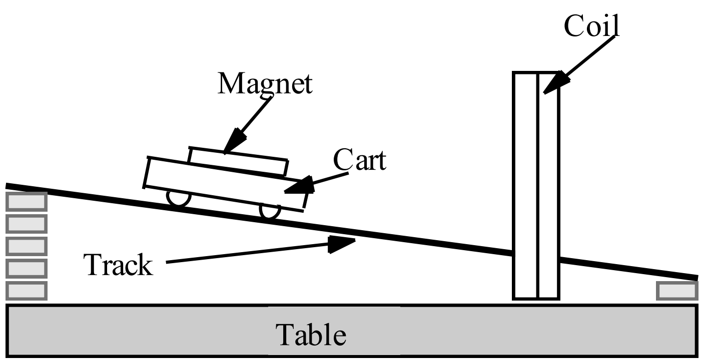
Uncertainties are high enough that a fair amount of error will sneak in. You won't see perfect agreement, but if you do error analysis, you should be able to see you are within expected parameters.

Problem 5.1 : Magnetic Induction

Equipment

Equipment:

- Coil of wire encased in plastic, 200 turns,
- Aluminum Track,
- Bar Magnet, and bar magnet remagnetizer
- Cart,
- LabPro Interface,
- Vernier Voltage Probe.



The prediction for this is very math intensive, and requires that they do some non-trivial integrals. In the following equations z is the distance along the axis through the loop (and the direction the magnetic moment is pointing), *m* is the magnetic moment of the magnets (many source use μ, but that is confusing with μ0), R is the radius of the loop, r is the distance of the magnet to the loop, y is the distance along the radius of the loop (from 0 to R), Θ is the angle between *r* and *z,* and *v* is the dz/dt.

$$Emf = N\frac{d\Phi}{dt} = N\frac{d}{dt}\int \vec{B} \cdot d\vec{A}$$

$$\vec{B}_{dipole} = \frac{3\mu_0 m}{4\pi r^3}\cos\theta\,\hat{\boldsymbol{r}} - \frac{\mu_0 m}{4\pi r^3}\hat{\boldsymbol{z}},\ d\vec{A} = \vec{y}dyd\phi,\quad r = \sqrt{(z^2+R^2)}$$

$$v = at,\quad z = \frac{at^2}{2},\qquad a = g\ sin\ \theta_{ramp}$$

$$Emf = \frac{3\mu_0 N R^2 m(vz)}{2(z^2+R^2)^{\frac{5}{2}}}$$

Students can test what *m* should be by testing the magnetic field along the axis of the di-pole as a function of distance from the center of the bar (x).

$$B(x)_{dipole} = \frac{\mu_0 m}{2\pi r^3}$$

The further from the dipole the better the diploe approximation is, so try to be at least 20 cm away. This is a case where a log-log plot works well with B vs x because the linear fit will be:

$$\ln B = 3 \ln x + \ln \frac{\mu_0 m}{2\pi}$$

Making *m* fairly extractable.

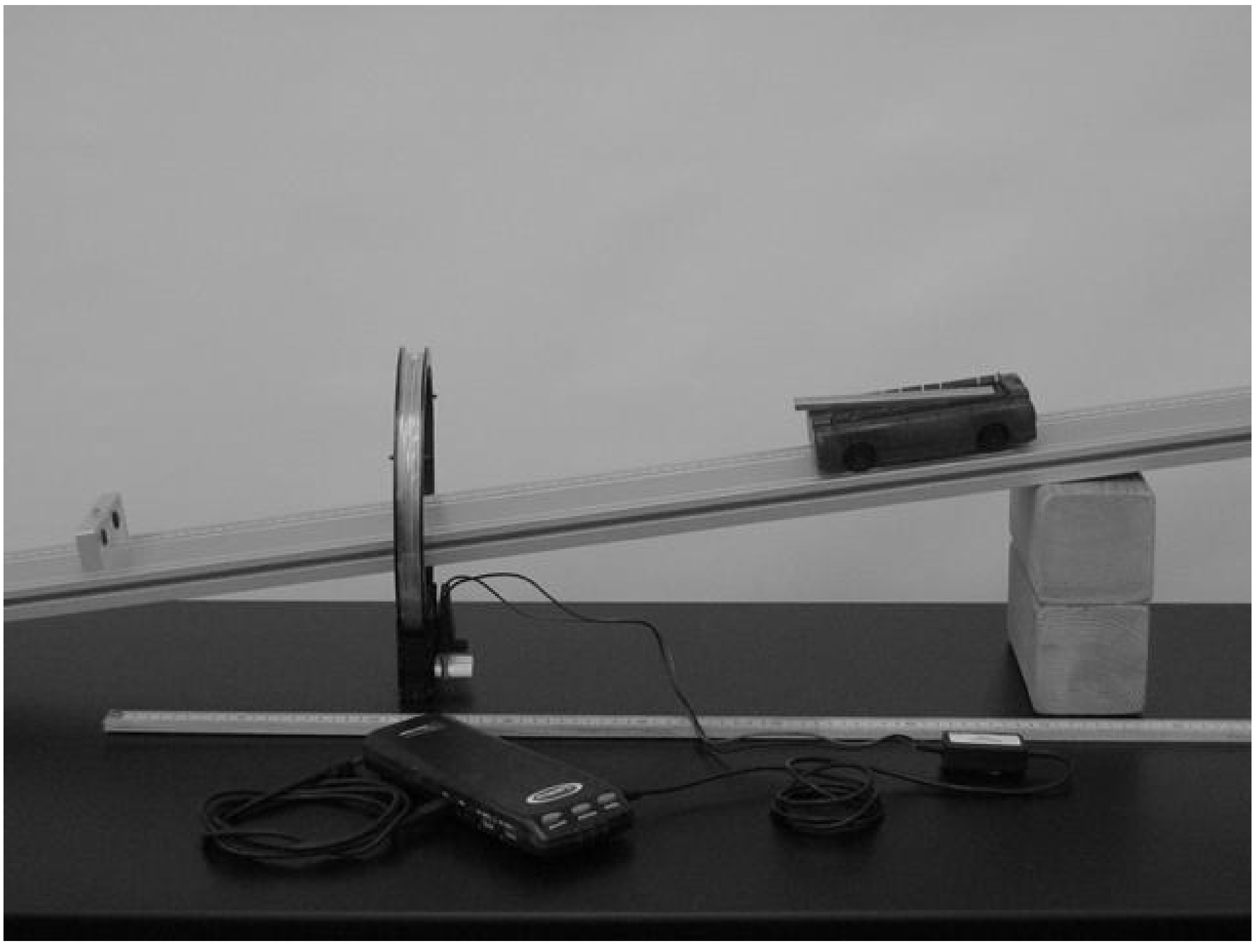


Figure 31: set up for problem 5.1.

Procedure

Students should set up the tack at a low angle and then release the cart at several different points along the track. They may want to take a few trials with no magnets just to see what the cart does (it has small magnets on it) and to figure out the best configuration.

> **NOTE:** the bar magnets do not keep magnetism well. Always re-magnetize the bar magnets before class and encourage students to do it again before they take data (but not in-between data because the magnetization process is not consistent. Make sure you know how to use the magnetizer and instruct students how to

Analysis

Students can predict everything except the magnetic moment, which they can find by taking the ratio of measured to predicted.

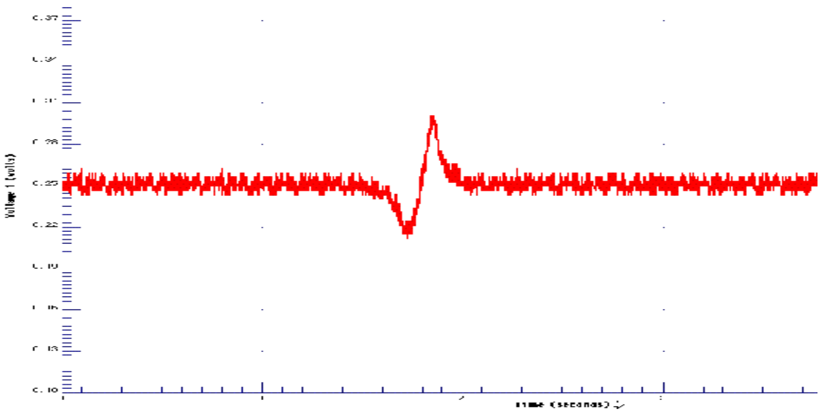


Figure 32: What the Volt probe reading will look like.

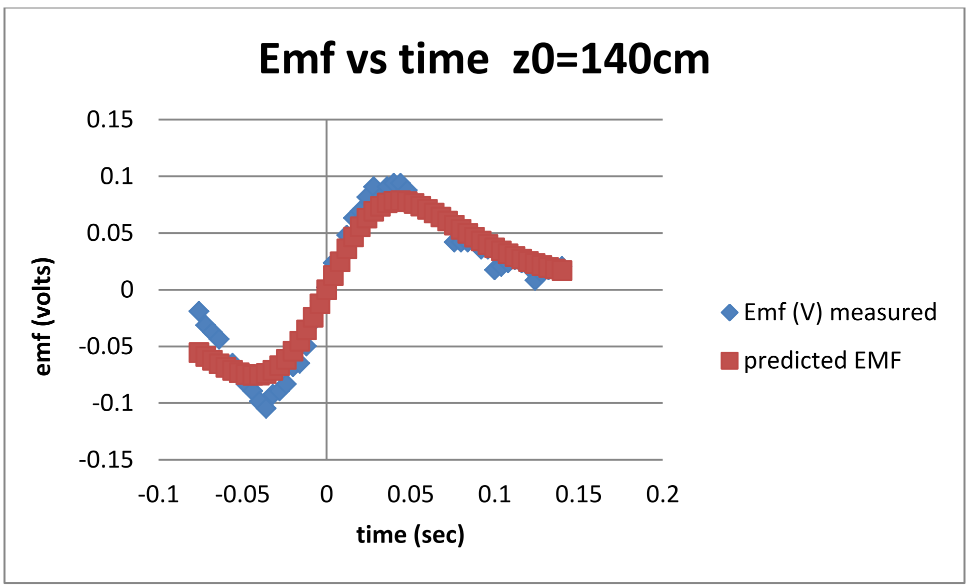


Figure 33: fit with magnetic moment = 0.135. Don't expect to ever get perfect agreement, but with multiple trials one can certainly get a reasonable estimate for the magnetic moment.

Problem 5.2: the Generator

Equipment

Equipment:

- Helmholtz 150 turn with motor and 4000 turn loop
- Two power supplies
- Hall probe field sensor
- Voltage probe
- labPro input box

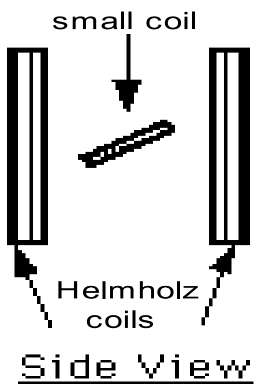
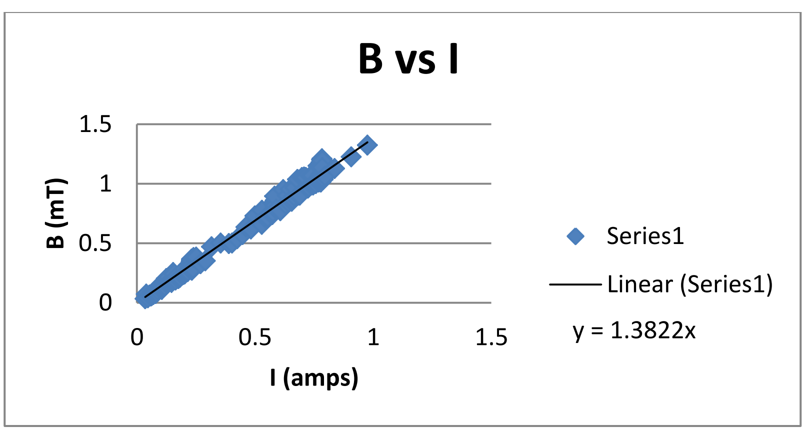


Figure 34: set-up for 5.2

$$Emf = \frac{d\Phi}{dt} = \omega NBAcos\,(\omega t)$$

Students should find that the amplitude goes as ωNBA. Students can find amplitude and ω by fitting the voltage vs time.

Students should calibrate B vs I so they can convert the current from the power supply to the coils for this and the next lab quickly. They can measure B and current (voltage over a series resistor) simultaneously to save time.



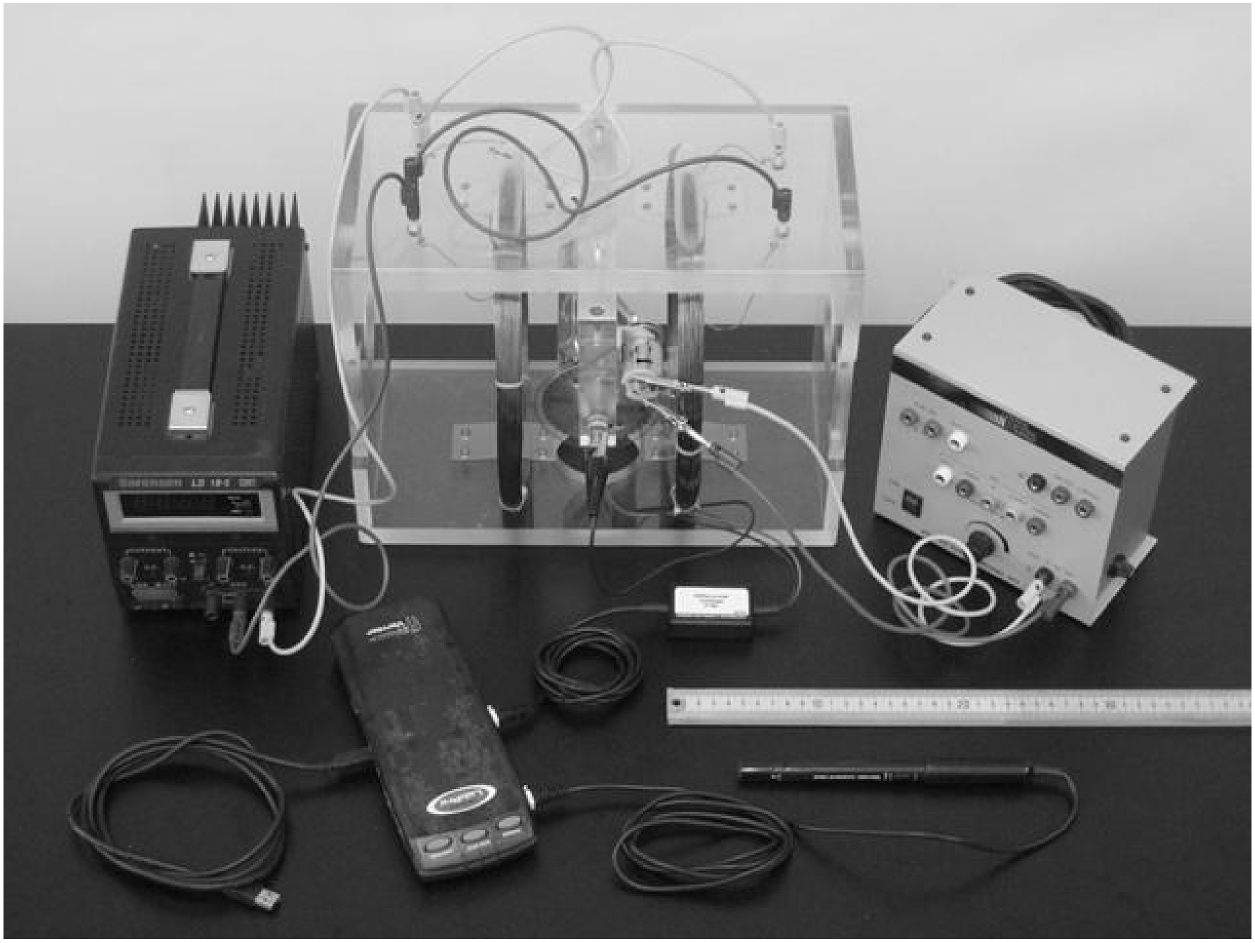


Figure 35: set-up for lab 5.2. Note the CRT power supply is replaced by a normal power supply in current labs.

Procedure

1. The motor should limited to under 9V (around 1 amp) when using the power supply. Increasing the voltage increases the motor speed, but too high a voltage will burn out the motor. A rubber belt connects the motor to the spinning coil.

2. The Helmholtz coils should be connected to a separate power supply. Make sure your students make the connections so that the same amount of current goes through both coils in the same direction. Ask them to check by qualitatively predicting the direction of the field from each coil at the midpoint between the two coils.

3. You can use this problem to drive home the idea that even if the **field** is constant, the flux through the loop may be changing.

4. There are two vertical pins at the edges of the spinning coil. Attach the alligator clips to these in order to measure potential difference across the coil. Your students can check that these pins are connected together through a conductor by using their ohmmeter.

5. Your students must decide on the area of the pick-up coil. This is not obvious since the wire has a non-negligible width. The flux through the inner coils of wire is significantly different from the flux through the outer coils. Just using the inner lengths of the coils or the outer lengths gives a significantly incorrect result. The average between inner and outer lengths works well enough.

6. With the LabVIEW program one can directly read the frequency of the coil from the graph of the magnetic field as a function of time.

Analysis

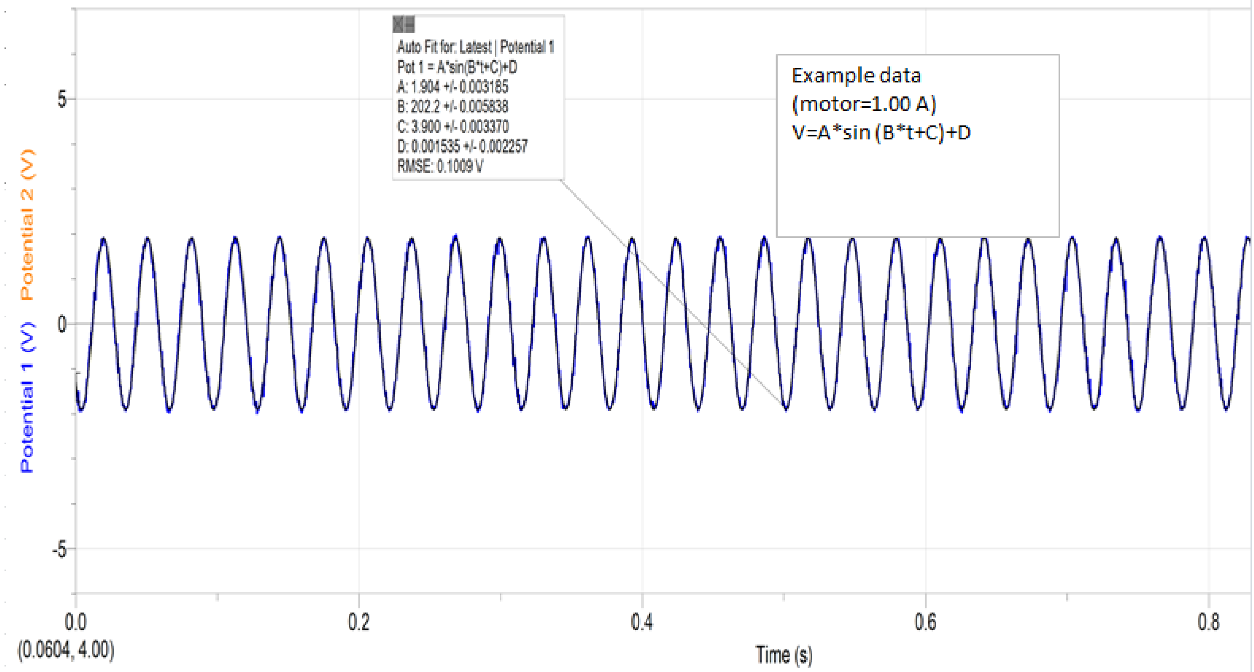


Figure 36: voltage vs time, fit to find amplitude and omega

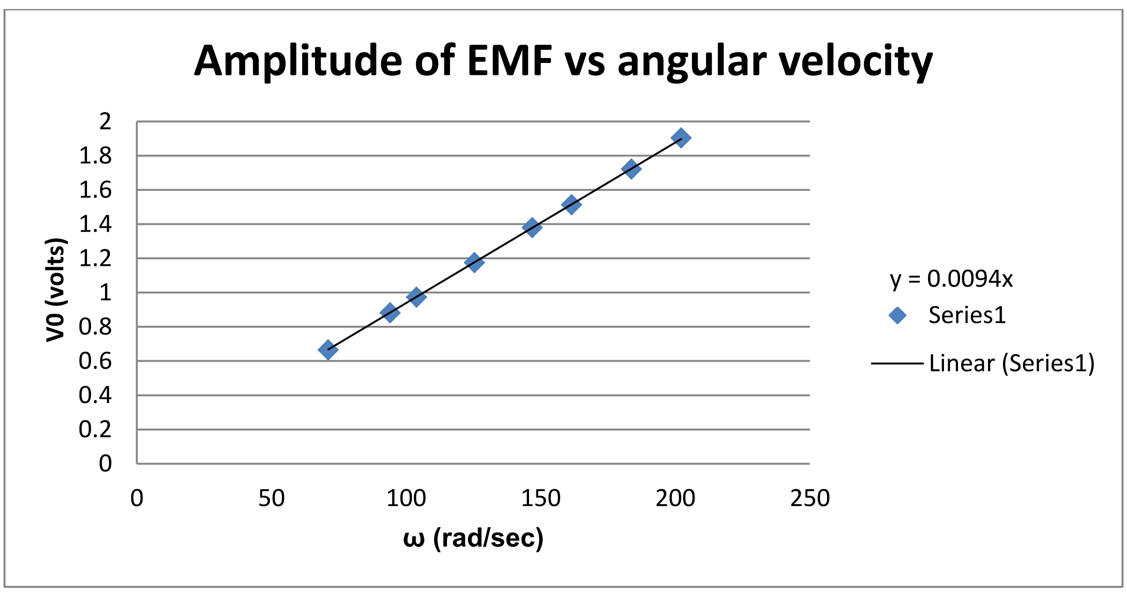


Figure 37: Data from lab 5.2. The slope (0.0094) should be equal to NBA. N is given (4000 turns), B can be measured (0.5992 mT), but measurement of A is not obvious. This slope implies an area of 0.00392 m^2, which falls within the range of the interior area (0.0032 m^2) and exterior area (0.0059 m^2) of the loop.

Problem 5.3: Time-Varying Magnetic Fields

Equipment

Equipment:

- Helmholtz 150 turn with motor and 4000 turn loop
- Pasco function generator
- Hall probe field sensor
- Voltage probe
- labPro input box
- a DMM

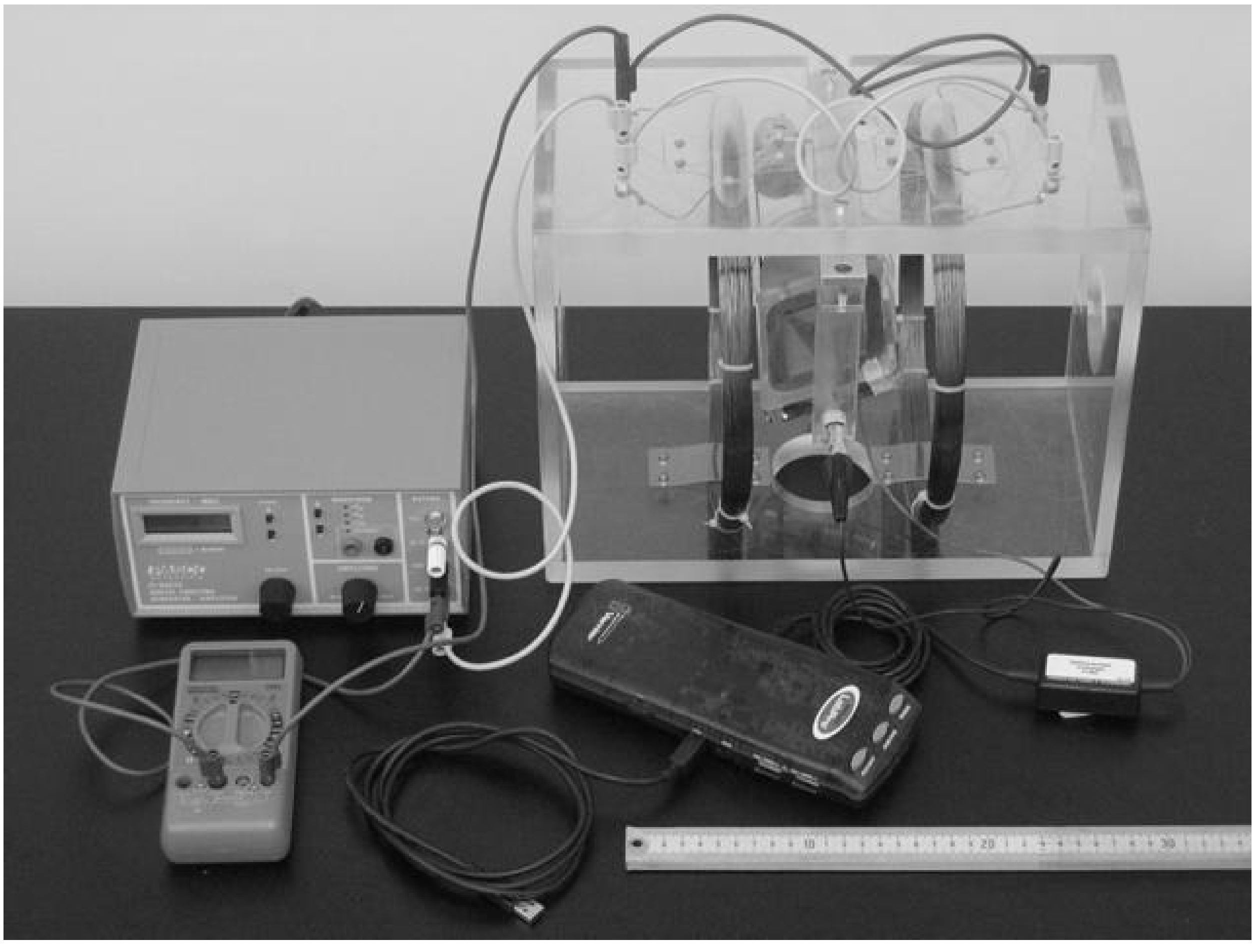


Figure 38: Set-up for lab 5.3.

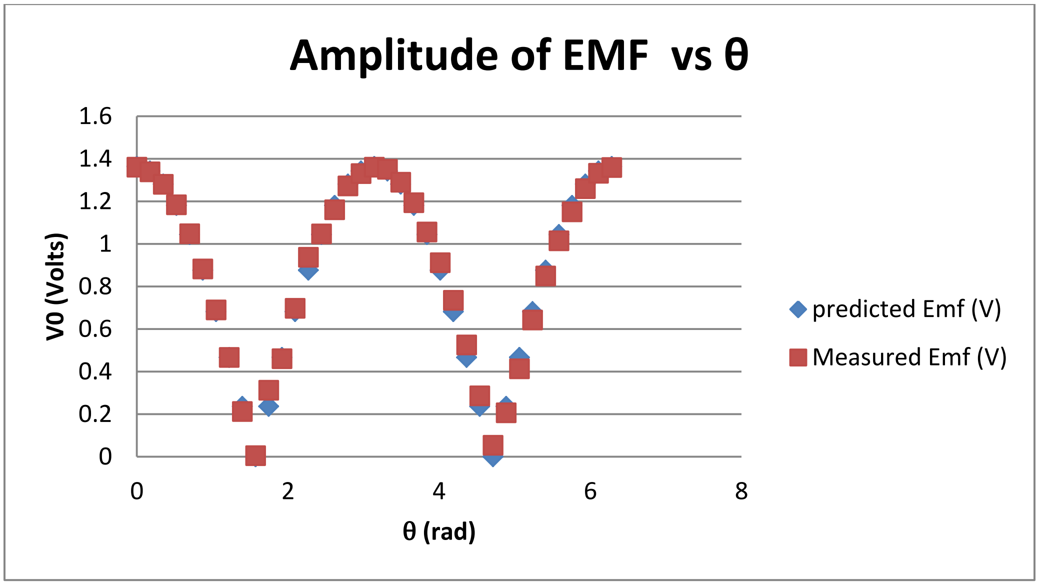
$$B = B_0 \sin(\omega t + \phi)$$

$$Emf = \omega N B_0 A cos\theta \cos(\omega t + \phi)$$

Procedure and Analysis

Step 1: The Emf vs ω (omega) will not 'work' past 20 Hz. There is a π/2 phase shift between the Emf created and the B field generating it. This is because of the $\frac{d\sin(\omega t)}{dt} = \cos(\omega t)$ (which is a π/2 phase shift see data at L66). This causes the Emf to have a max value at around 20 Hz)

Step 2: measure Emf vs θ works pretty well. Make sure you either look at the absolute value of the predicted values OR make sure you correctly enter the measured value with negative values at the right time.



Problem 6.1: RLC Circuits and Resonance

Equipment

Equipement:

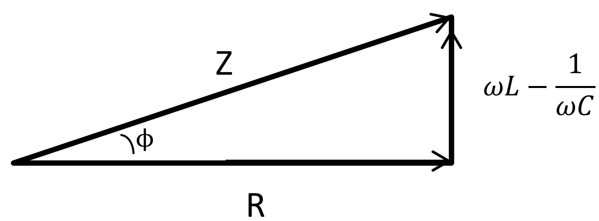
- BK precision function generator
- Oscilloscope
- Parallel plate capacitor set-up
- Various capacitors and resistors
- Coaxial adaptors
- Various wires and connectors
- Plexiglass, pyrex, and mylar dielectrics

Equations:
Part 1:

$$I(t) = \frac{V}{Z}\sin(\omega t - \phi)$$

Where

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$



Where Z is the impedence. At the natural frequency, Z=R and the resonance occurs.

$$\omega_0 = \frac{f_0}{2\pi} = \frac{1}{\sqrt{LC}}$$
$$Q = \frac{f_0}{\Delta f} = \frac{\omega_0 L}{R}$$
$$\tan(\phi) = \frac{1}{R}\left(\omega L - \frac{1}{\omega C}\right)$$

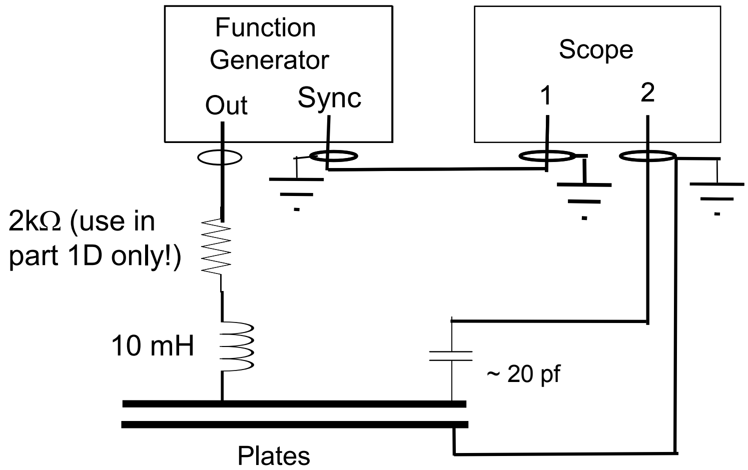
Δf is the width of the frequency peak at the value of V_{rms}. Φ is the phase. Q is the quality of the peak.

Part 2: measuring the dielectric constant:
Students should end up plotting $\frac{1}{\omega_0^2}\ vs \frac{1}{d}$

$$\frac{1}{\omega_0^2} = \frac{LA\epsilon_0\kappa}{d} + LC_s$$

Where A is the area of the top plate of the capacitor, κ is the dielectric constant, C_s is the stray capacitance (which is why this method is good as it removes this unpredictable value from the measurement.

Procedure



Step 1: Resonance: Students should be able to set-up this circuit with minimal difficulty. It is important to make sure that all the grounds are the same. You can set the oscilloscope to measure Pk-Pk voltage and phase of channel 2 to get these measurements easily. Find the resonance is as simple as finding the maximum Pk-Pk value.

Stray capacitance can sneak into the set-up, you can often see the effects of this by moving your hand near the capacitor or shifting wires around and watching the output. Once you have things set-up, don't change the placement of wires and keep students as far away from the set up as the table allows (they will need to keep the generator and scope near them for tuning and reading obviously but the capacitor should be isolated). The addition of the 2 KΩ resistor helps mute the effects of stray capacitance, but it will affect other parts noticeably.

Step 2: Dielectric

Students can use this to measure the dielectric constant of air, but it is more interesting to use the various dielectric materials. They can vary 'd' by stacking them on top of each other. The goal is to find the 'f0' of the circuit at various 'd's. By plotting $\frac{1}{\omega_0^2}\ vs\frac{1}{d}$ they can get the dielectric constant quite simply.

Analysis

Step 1: Resonance:

They should have a capacitance of around 6.2e-11 Farads.

Measurements of Q show that there is

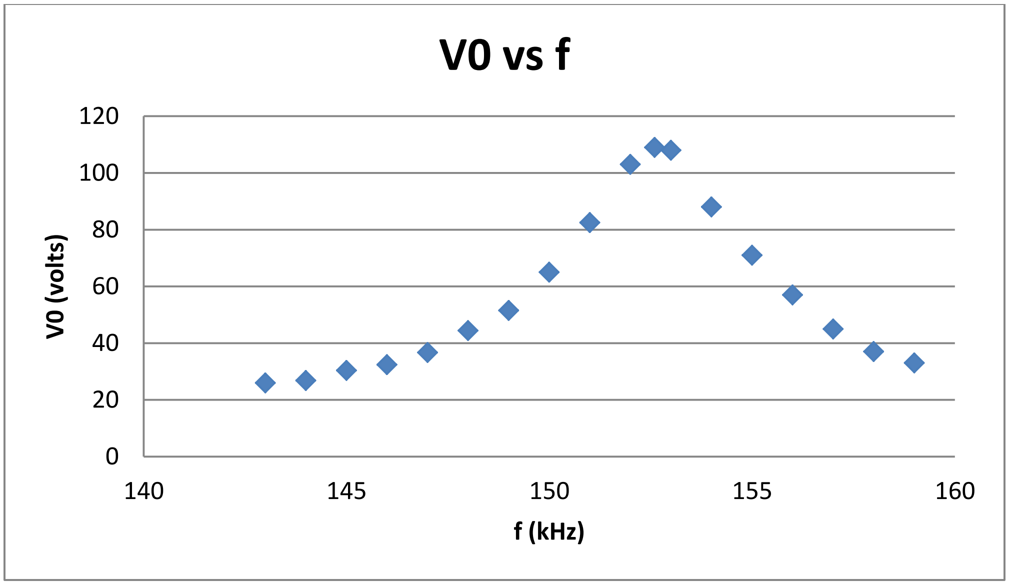


Figure 39: Part 1, step C, resonance plot. Measured f0= 152 kHz, predicted was 199 kHz. Measured Q (30.52) implies a series resistance of 320 ohms, only 66.4 ohms are measure over the inductor. The extra resistance is inherent to the function generator.

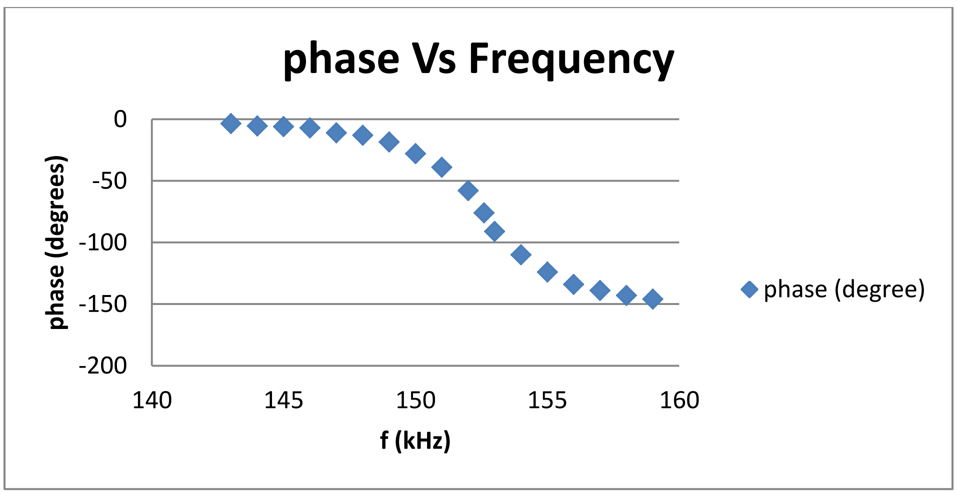


Figure 40: Part 1 step C phase vs f.

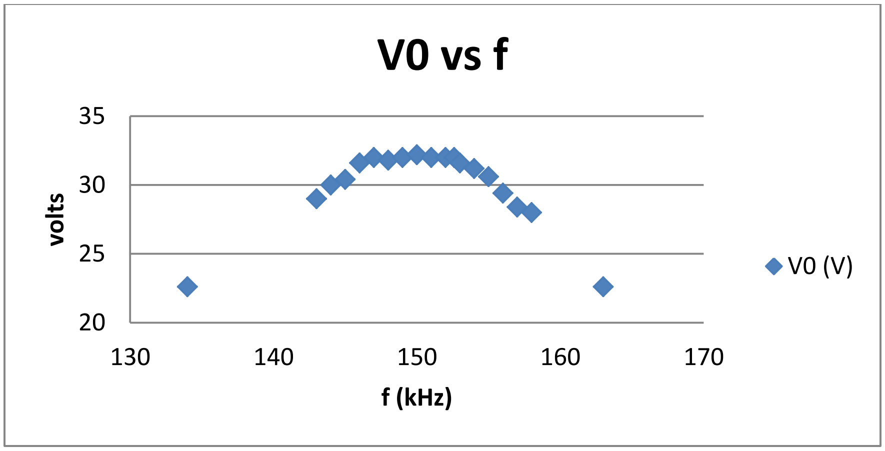


Figure 41: Step 1, part D a much broader resonance peak due to the large resistor added. Measured Q (5.26) implies a series resistance of 1850 ohms, compared to the measured 2050 ohms over the resistor and inductor.

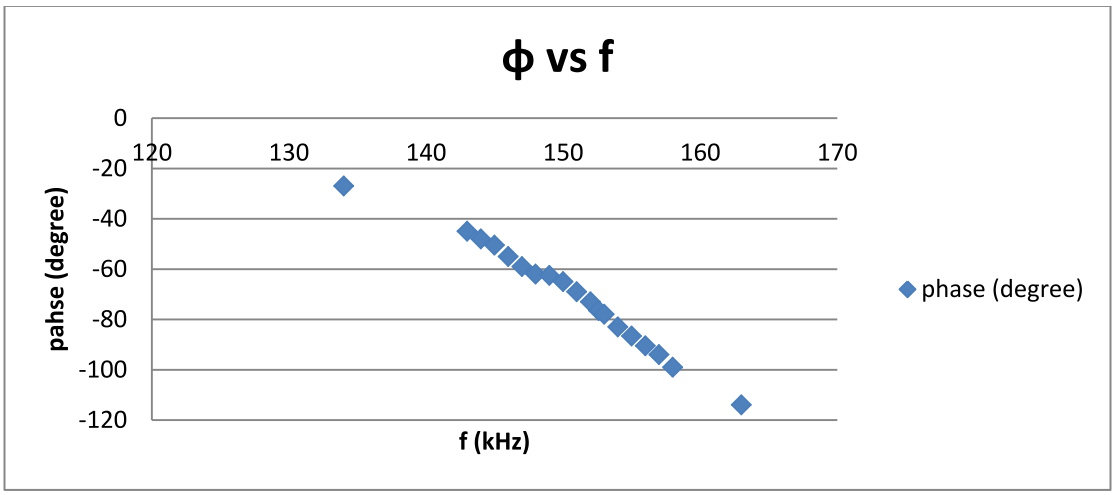


Figure 42:Part D: with the increased resistance, the phase vs f plot is much closer to a straight line.

Step 2: Dielectric:

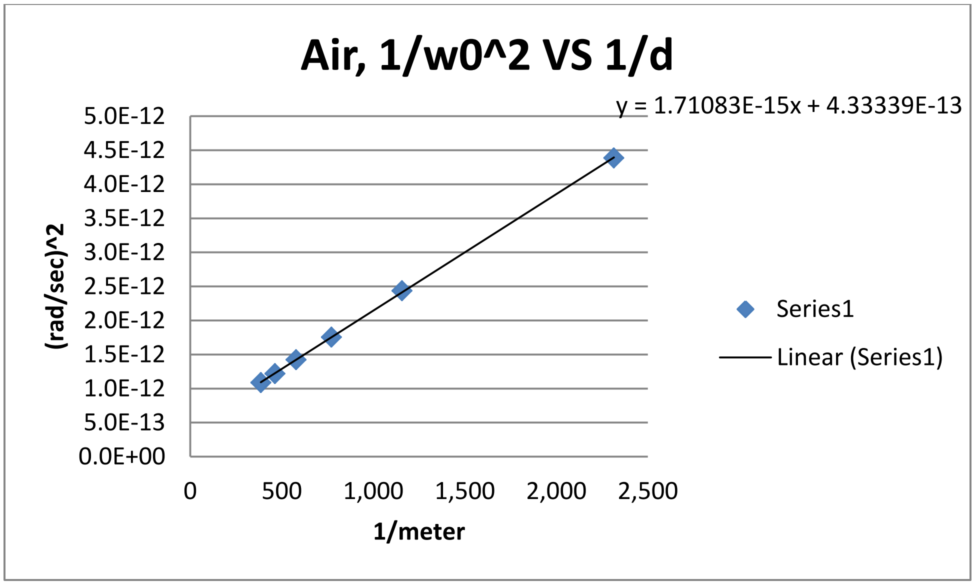


Figure 43: Measured k=1.038 for air.

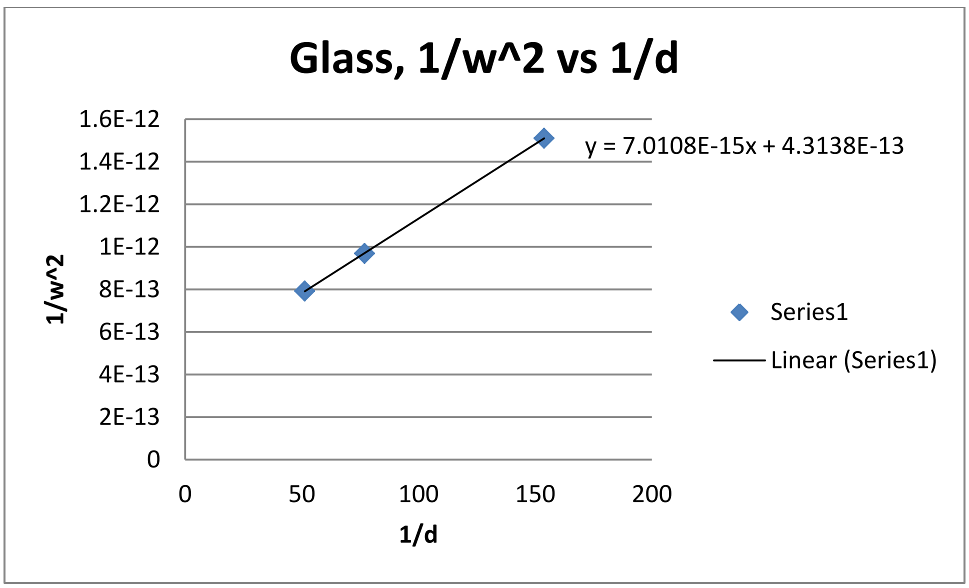


Figure 44:Pyrex k=4.26, see more results in table below.

	Air	Pyrex	Plexiglass	PVC
Measured k	1.038	4.26	2.63	2.17
“official” k	1.00054	5.1	2.2-3.4	3

Problem 6.2: Construction of an AM Radio

Equipment

Equipement:

- Oscilloscope

- BK function generator
- Diodes, resistor, and capacitors
- a tunable capacitor (range is from about 10 - 350 pF)
- "tank circuit" inductor
- BNC cables and adaptors
- Various wires and clips
- Battery powered speakers
- Antenna
- Braided grounding wire

Procedure

Perhaps more than any other lab, it is essential for the TA's to do this first and make sure they can get it to work well. Since each set-up is different (because of antenna placement, tank circuit construction, etc) you will need to confirm that each lab station's set-up works. This means making the radio four or five times. This is by far the best preparation you can have for teaching this lab.

1. We have found that the antennae must be strung out the window. The further form walls and windows the better.

2. The ground connection must be very good. Double check it. Triple check it…..the ground braid for each table must be hard-wired to the building ground with a screw. Do not daisy chain the grounds by clipping one ground braid to the one used by the next table.

3. You must choose the appropriate taps on the coil. The goal is for the students to understand that they are using the tuned circuit to measure a very weak signal. They will find that everything matters: exactly how the antenna is hooked up, the quality of the ground, loading by the diode, etc. Reality is complicated by stray capacitance, series inductance, etc.

4. Do not plug the speakers into the wall, only use battery power. Plugging speakers into the walls can cause a constant buzz that is loud enough to drown out any desired radio stations

5. A couple pointers:
    a. The lowest tap on the inductor is ground.
    b. Where you hook up the capacitor determines the total inductance in the tank circuit and hence the tuning range.
    c. Keep in mind that the minimum capacitance you will be able to achieve is a few picoF and careless layout can increase this substantially.
    d. Both the antenna and the detection diode circuit have inductance and capacitance to ground and hooking them up will change the tuning range. If you connect them to higher taps, then you will have stronger coupling (more signal) but lower Q (worse frequency resolution).

6. Common mistakes:

A. Bad ground connections and poor antenna placement.
B. Incorrect choice of taps on the inductor. Clipping the alligator lead to a tap that does not have the insulation removed!
C. Leaving the antenna coiled up so that it has a huge inductance and no reception.
D. A short in the capacitor due to the plates touching. This can happen if someone drops the capacitor. It is not easily fixed. Get a new one and tell Sean.
E. Bad connection to speakers (hopefully addressed this year by the speaker jacks on the Lucite boards).

7. Some set-ups simply will not work. Some locations in the room simply will not work (likely antenna problems). You may need to completely swap out equipment or drastically move a table to get better antenna placement.

The fastest way to test the lab is to set up figure 6.5, set the function generator for the expected radio stations frequency, and vary tap connections until you can find the resonance just by varying the capacitor. Then switch to the set-up in figure 6.6 and vary the capacitance until you hear the radio station.

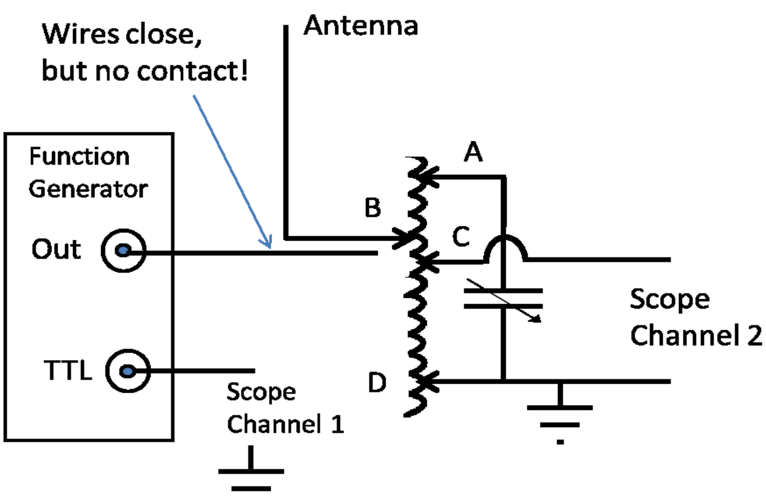


Figure 45: figure 6.5 in the manual

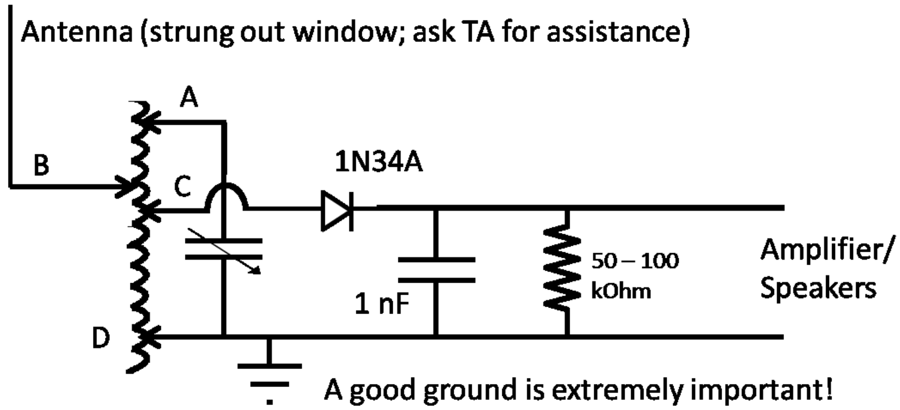


Figure 46: figure 6.6 from manual, the final radio.

Analysis

The only result that really matters is whether or not students can get a radio station to play on their speakers.