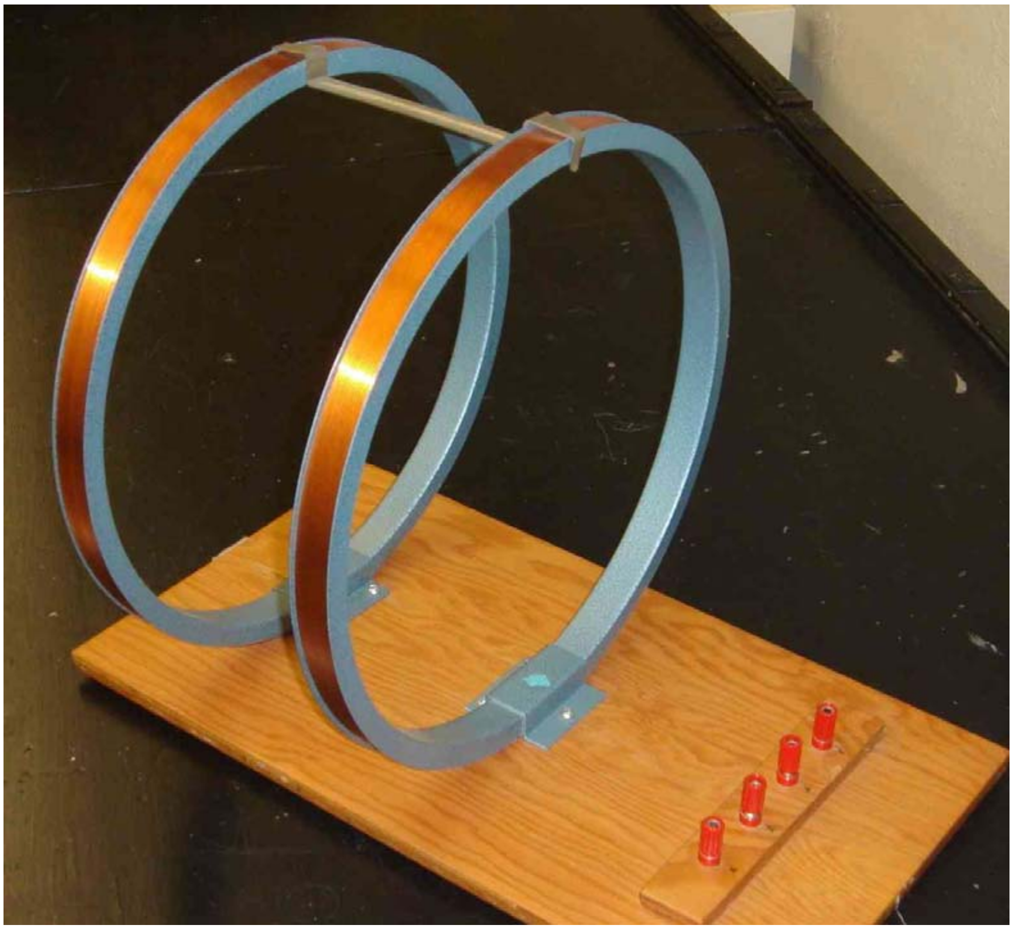
Magnetic field measurements, Helmholtz pairs, and magnetic induction.



Part 1: Measurement of constant magnetic field:

1. Connections and measurement of resistance:

    a. Pick up the entire magnet assembly (shown above), flip it over, and look underneath. Observe how it is wired up.

    b. Use the digital multimeter (DMM) to measure the resistance of each loop of the Helmholtz pair, individually.

    c. Use a cable to connect the two loops in series, thereby forming the actual “pair”. Measure the resistance of the complete coil.

d. Connect the Helmholtz pair to the DC power supply. Connect the DMM across the input leads to the magnet to allow you to monitor the voltage across the coil during the experiment.

2. Initial power-up, and dissipated power:

   a. Adjust the voltage on the power supply until the current is 3 A. Note the voltage reading on the DMM and check that this is consistent with the coil resistance you measured earlier.

   b. Calculate the power deposited within the coil structure. *Compare this to the power produced by common household appliances (such as a toaster or hair-dryer). Or even better, think about the power dissipated by a 100 W light bulb, and how hot they get. Would you expect the coils to get hot? This heating effect is a common feature of "resistive electromagnets" and limits their application in many circumstances.*

   NOTE: during this experiment, it is possible that the coils of the magnet will become very hot to the touch. Be aware of the temperature of the coils and if they become very hot, shut down the current and inform the instructor.

3. The Gaussmeter (or "tesla-meter"):

   a. There is a Gaussmeter and associated equipment provided.

   b. Note that there are actually 2 different probes in the kit: one measures magnetic field components that are "along the probe", and the other measures magnetic field components that are "across the probe". To begin with, you need the one that measures along the probe (the z-component). It is the probe with the "002" on the model number (the right-hand probe in the figure below).

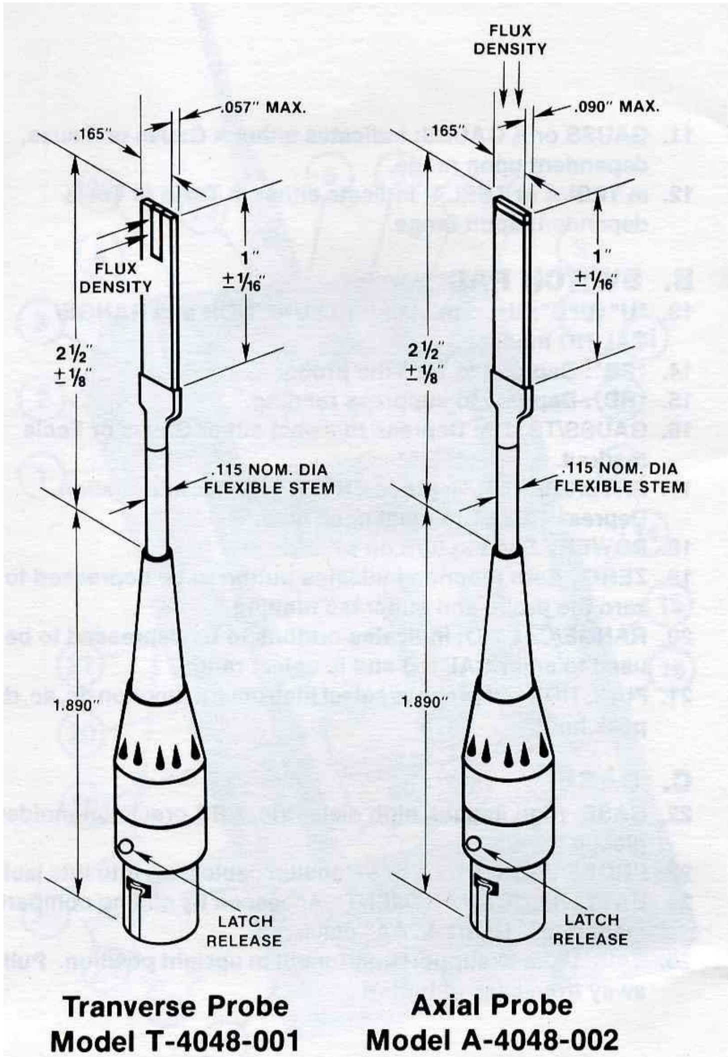


Figure 2

c. Configure the Gaussmeter and probe as described in the document: "Information for Bell Gaussmeter (Hall Probe)".

d. Check that the meter is reading the ambient magnetic field in the room correctly. It should read between 0.2 and 1.0 G (0.02 and 0.1 mT). Also note that the probe reading has a "sign", meaning that it is sensitive to north versus south poles.

   Set the meter in mT mode for the remainder of the experiment. "T" is the SI unit for magnetic field (Gauss is an older unit), and mT is an appropriate scale for many measurements:

   $$1 \text{ T} = 10{,}000 \text{ G}$$
   $$1 \text{ mT} = 10 \text{ G}$$

   Turn the probe around and try to figure out in what direction Earth's magnetic field is in the lab. It will be at an angle with respect to the ground. It also varies with position on the Earth.

4. <u>Rough check on the Helmholtz pair:</u>

   a. Turn the magnet back on, 3 A.

   b. Place (just by hand) the probe within the approximate centre of the Helmholtz pair. The probe needs to be aligned along the axis of the coils. Turn the probe around in the field. You should be able to see that the magnetic field produced by the Helmholtz pair is entirely along the axis of the coils (which we call the z-direction). If you flip the probe 180 degrees, the sign of the measured field should reverse.

   c. The magnetic field at the centre of the Helmholtz pair is given by the following equation:

$$B_z(z) = \frac{\mu_o N I a^2}{2} \cdot \left(\frac{1}{((z + a/2)^2 + a^2)^{3/2}} + \frac{1}{((z - a/2)^2 + a^2)^{3/2}} \right)$$

   where ‘a’ is the radius of the coils, and it is assumed that the coils are separated by a distance ‘a’ (this is the definition of the Helmholtz pair configuration - that is, two round coils separated by their radius, carrying current in the same direction).

   d. Calculate the approximate field efficiency (mT/A) of the coil. This is simply the amount of magnetic field produced at the centre, divided by the current.

   e. Estimate (roughly) the number of turns on the magnet windings, based on your efficiency estimate and the equation for magnetic field strength (above). Use the above equation, with z = 0 (the coil centre).

      NOTE: don’t spend more than 5 minutes doing this. If you are having trouble working with the above equation, save this for after the lab session and work on it then.

      Just make a visual estimate of the dimensions of the coils (no rulers necessary). Then make a quick calculation in your lab book. This sort of thing is important to be able to do, to make rapid “reality checks”. Does the number of windings you estimate seem to make sense, based on looking at the coils?

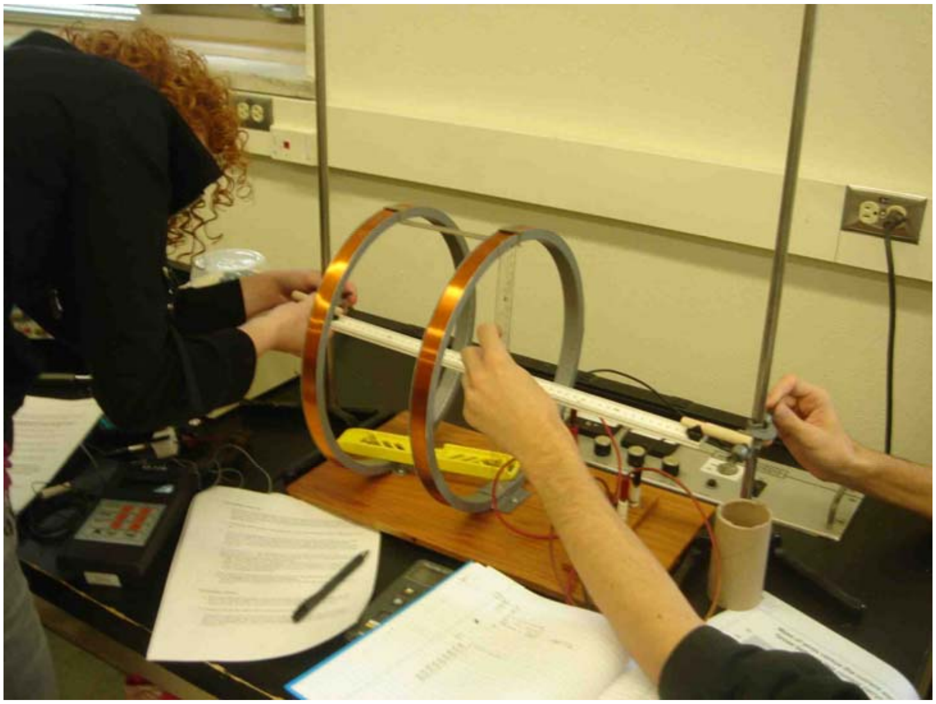
5. <u>Dimensions of the Helmholtz pairs:</u>

   a. Measure, as carefully as you think necessary, the dimensions of the coils. You will need these values in the work later on. It’s easiest to do this now, before the rest of the apparatus is set up. This should only take a few minutes.

6. <u>Field mapping, centre line:</u>

   a. Set-up the structural apparatus to position the guide ruler such that it is along the coil axis, and as close to the centre of the magnet as possible. Use the levels and rulers as necessary to position these. Set-up the probe attachments and fix the z-direction (axial) probe within the mount.

This should only take minutes. No need to rush, but don't get too carried away trying to position the guide ruler to sub-mm accuracy. Keep in mind that there are other significant sources of uncertainty that are already present in your measurement.



b. Position the active portion of the probe as close to the geometric centre of the coils as you can.

Note: the probes detect magnetic field only at the very tip (recall the previous figure showing the probes in schematic).

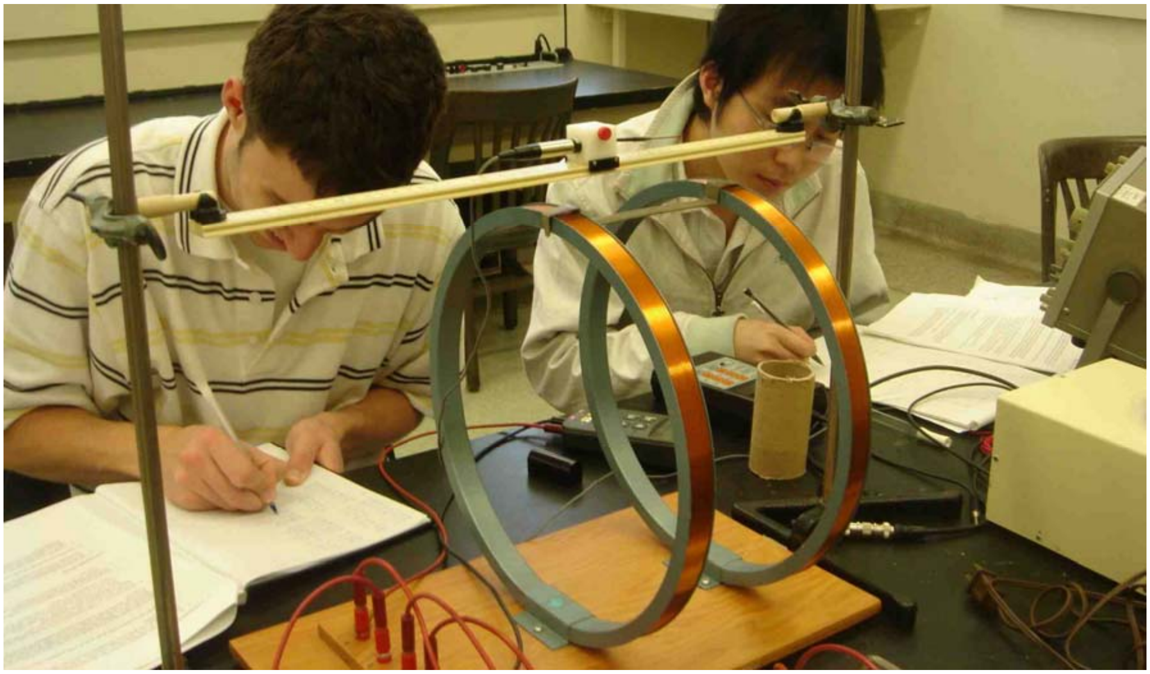
c. Set the current accurately to a value between 0.5 and 3 A. Measure the magnetic field strength and recalculate the field efficiency (mT/A) at the centre of the coil. Use this value, along with your more accurate dimensional measurements, to produce your best calculation of the number of windings on the coil.

d. Set the current to 3A. Take measurements of the Bz field component as a function of z down the centre axis of the coil. Take measurements every 2 cm. Extend as far as possible with the ruler provided.

Note: the helmholtz pair is "designed" to be quite uniform over a region in the centre of the coils. Check your measurements as you are taking them to see if this is the case. If you are seeing large changes in the magnetic field in the vicinity of the coil centre, something may be wrong.

7. Field mapping, off-axis:

   a. Set-up the structural apparatus to position the guide ruler such that you can measure the field down a line (along z) that is at a radius of 20 cm above the centre line. This is actually just above the tops of the coils.



   b. Measure the Bz field as a function of z, just as before. Note that the field will change quite rapidly in the vicinity of the windings. Also note that the field is of the opposite sign as compared to the previous measurement. Does that make sense? Use the right-hand-rule to get a sense for the magnetic field directions inside and outside the coils.

   c. Change the field measurement probe to the other "transverse probe" (model "T-4048-001). Position the probe such that it can measure the vertical (y) component of magnetic field (refer to the above diagram to see how to do this). The probe must be recalibrated using the same procedure as for the other probe.

   d. Measure the By field component as a function of z along this same line (20 cm above the centre line, just above the tops of the coils). Measurements every 2 cm.

8. Disassembly:

   a. Remove all the structural apparatus and shut off the power supply.

   b. Check the resistance of the coil. Has it changed? If so, why?
      If the resistance has changed, what is the effect on your measurements?

9. Analysis:

   a. Produce plots of the following. I suggest at this point that you use Matlab or Excel for this, although you may use whatever package you have access to. All plots are to be handed in for marking. All fields should be in mT/A, and all spatial dimensions should be in cm.
      i. Bz versus z for the centre-line measurement.

      ii. Bz versus z, centre-line measurement, with the theoretical field profile overlayed (use the field equation given above).

      iii. Bz versus z, both measurement lines together on the same plot.

      iv. Bx and Bz versus z (for the last line measurement), both on the same plot.

Part 2: Measurement of alternating magnetic fields:

10. Connections:

    a. Make sure the dial on the top of the AC power supply (the "Variac") is set to zero, and the switch on the front is off. The Variac should not be plugged into the wall outlet at this stage.

       Connect the Helmholtz pair to the AC power supply provided. Connect the DMM across the input leads to the magnet to allow you to monitor the voltage across the coil during the experiment.

11. Power-up:

    a. Make sure the dial on the Variac is set to zero. Plug the Variac into the outlet and turn the front switch "on". Change the setting of the DMM to AC voltage mode. Check the voltage reading on the DMM and verify that it is reading zero. If it is not, turn the Variac off and recheck the connections and settings.

Note: when making power connections, use the following principle: make connections starting at the "load", and work backwards towards the supply. The very last thing you should do is to plug the supply into the outlet.

NOTE: Under NO circumstances during this experiment are you to turn the variac to more than 20 (corresponding to 20V output). High AC voltages represent a serious shock hazard and should not be used unless further precautions are taken.

b. Turn the dial to 1 or 2. Check that the DMM is reading the same values. The dial on the top of the Variac roughly corresponds to the output voltage, peak-to-peak.

c. Turn the dial up, until the DMM reads 10 V. Touch the coils of the magnet - they should not be warm yet. They will warm up slowly during the course of the experiment.

d. Set the dial such that you will get close to 3 A through the circuit (recall the measured value of resistance, and use this to determine the required voltage setting).

e. Leave the Variac at this level and replace the shield on the top of the dial. Do not remove the shield unless adjustments are being made. The shields should remain in place for the majority of the experiment.

f. Monitor the temperature of the coils throughout the experiment. They should become noticeably warmer, just as they did during the DC measurements. If they become hot, shut down power and inform an instructor.

NOTE: Shutting off power to an inductor. You should avoid turning off the current through an inductor simply by flipping the Variac switch to off. As we will talk about in coming lectures, inductors store energy within the magnetic field, and rapidly switching them off results in a phenomenon often called "flyback". You should always try to turn the current to zero with the Variac dial first, then move the switch to the off position.

12. Creating, testing the magnetic field probe:

a. Using the length of wire provided and the cardboard tube as a former, wind as many turns onto the tube as you can, while leaving about 50cm of wire at the start and finish ("leads"). You should be able to get between 10 and 20 windings around the tube.
What is the effect of changing the number of windings?

b. Twist the leads together down the length of the lead wires. This is called a "twisted pair". Why do you think twisting the leads together is important for this experiment?

c. Connect the ends of the wire to the oscilloscope input, using the connectors provided.

Note: you expect to see a 60 Hz signal on the scope, so what time scale should you have the scope set to? Think about how long the period of a 60 Hz sinusoidal waveform is.

d. Just by hand, hold the probe within the magnet (the AC current should still be flowing - check the DMM). You should be able to detect a 60 Hz signal on the scope. Adjust the trigger level if necessary. Adjust the amplitude as necessary to visualize the signal.

13. <u>Calibrating the probe:</u>

Now you have to determine how to relate the induced voltage in the probe to the size of the average magnetic field experienced by the probe.

a. Estimate as best you can the area enclosed by the wire loops. Also remember that you have more than one winding.

b. Calculate the relationship between the magnetic field experienced by the loops, and the corresponding induced voltage. See example 29-1 on page 997 in Young & Freedman ed. 12.

c. You now have an equation that can be used to convert the voltage amplitudes you are measuring on the scope, to the magnetic field through the loop.

14. <u>Positional apparatus and the field measurements:</u>

a. Repeat the set-up of the positioning apparatus as described in Part 1. Note that the loop probe you've built here is also directional. However, in these measurements, you only need to measure the Bz component of the magnetic field. Set-up your positional apparatus accordingly.

b. Record the magnetic field efficiency as a function of z down the line through the centre of the magnets. Every 2 cm, as far out either end as the apparatus will allow.

c. Reconfigure the positional apparatus, and make a measurement for a line that is above the coils, 20cm radially from the centre line (just like for the DC measurements previously).

15. <u>Disassembly:</u>

a. Dial down the voltage to the inductor using the dial on the top of the Variac. Once to zero, flip the power switch to off. Then unplug the Variac from the outlet. Then disconnect the Variac from the magnets.

b. Check the resistance of the coil. Has it changed? If so, why?
If the resistance has changed, what is the effect on your measurements?

c. Remove all the structural apparatus, break down the experiment.

16. Analysis:

a. Produce plots of the following. All plots are to be handed in for marking. All fields should be in mT/A, and all spatial dimensions should be in cm.
   i. Bz versus z for the centre-line measurement.

   ii. Bz versus z, centre-line measurement, with the theoretical field profile overlayed.

   iii. Bz versus z, both measurement lines together on the same plot.

Part 3: Computer simulation and final analysis:

17. Construct a computer simulation that can calculate the magnetic field at any location, produced by a Helmholtz pair:

a. The input parameters to your simulation should be: the radius of the loops, the separation of the loops, the number of windings on the loops, and the location(s) at which the magnetic field is to be calculated.

b. You may write this simulation program in either matlab (my suggestion) or excel (which can work just fine for this purpose, and is similar to what you have been asked to do in Physics 2101a).

18. Check your simulation.

a. Make a plot that shows both your simulation and the known analytic solution for the magnetic field down the centre line of a Helmholtz pair. If your simulation does not closely reproduce the analytic solution, something is wrong with the simulation.

19. <u>Apply your simulation to this experiment:</u>

   a. Compute the Bz component of magnetic field down the lines that correspond to the data collected in this experiment. Two lines, one at radius 0 and one at radius 20cm.

   b. Produce a plot with the following 4 data sets all together: (1) the analytic solution for magnetic field down the axis of the coils, (2) the computer simulation (same line), (3) the static magnetic field measurements (Bz only, same line), and (4) the AC magnetic field measurements (Bz only, same line).

   c. Produce a plot of the following, all together in a single plot, all for the case of a line at radius 20cm: (1) computer simulation results, (2) DC measurements, (3) dynamic field measurements.