Name  _____  Date  _____  Time to  ____h ____m
Complete

Partner  _____  Course/  _____/_____  Grade  _____
Section

# Faraday's and Ampere's Laws

**Introduction**

In the first part of this lab you will be introduced to a magnetic field sensor whose operation is explained in terms of Faraday's Law of Induction. Then you will practice making quantitative measurements with the sensor and calibrate it. After calibrating the sensor you will use the magnetic field of a solenoid as a test system for verifying Ampere's Law.

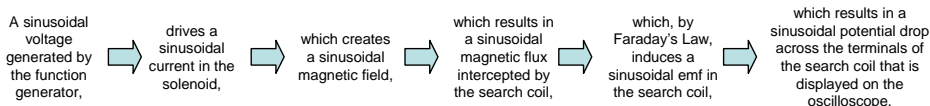# 1.    A sensor based on Faraday's Law of Induction

**Introduction**

If current in a wire, such as the large coil in this lab, is a *steady* current it produces a *static* magnetic field. You can measure the magnitude of a static magnetic field by a number of methods. The most common is to measure the *Hall effect* voltage generated across a current-carrying conductor in a magnetic field. The magnetic-field-probe used in previous magnetism labs was this type of *Hall probe*.

However, the geometry and shape and size of our Hall probes make it impossible to conduct the experiments planned for this lab. Therefore, we will use a different device to measure the magnetic field, a *search coil*. The search coil, which itself is just a small coil of wire, relies on Faraday's Law of Induction. A measurable electrical signal is generated in the search coil only if the magnetic field in which it is immersed is *changing*.

Therefore, instead of exploring the static field of a solenoid with *steady* current, a *changing* field will be produced by driving a *sinusoidal* current through the solenoid. The sinusoidal current will be driven by a device called a *function generator*.

Faraday's Law of Induction tells us that an *EMF* is induced in a loop (or coil) of wire with a magnitude proportional to the *rate of change* of *magnetic flux* intercepted by the by the loop. It follows from this that the amplitude of the search coil signal will be proportional to the amplitude of the solenoid's sinusoidal magnetic field which is produced by the sinusoidal current being driven through it by the function generator. In this way the search coil signal is a measure of the solenoid's magnetic field.

| A sinusoidal voltage generated by the function generator, | → | drives a sinusoidal current in the solenoid, | → | which creates a sinusoidal magnetic field, | → | which results in a sinusoidal magnetic flux intercepted by the search coil, | → | which, by Faraday's Law, induces a sinusoidal emf in the search coil, | → | which results in a sinusoidal potential drop across the terminals of the search coil that is displayed on the oscilloscope. |

Experimentally, the electrical signal to be measured is a potential drop across the leads of the search coil. The peak-to-peak size of this sinusoidal signal will be measured with an oscilloscope. Its size is proportional to the component of the solenoid's magnetic field parallel to the axis of the search coil.

**Procedure**

- First, acquaint yourself with two new pieces of equipment, the function generator and the oscilloscope. The function generator will be used to *generate* a sinusoidal signal of user selected frequency and amplitude. The oscilloscope can be used to *view* this signal.

  Do so by connecting the main-out of the function generator to the Channel 1 input of the oscilloscope as shown in *Figure 1*. Power on the function generator, depress the sinusoidal shape button, depress the 1 kHz coarse frequency button, dial-in 1.0 on the fine frequency knob, and turn the amplitude knob fully clockwise to maximize the amplitude. Power on the oscilloscope and adjust the settings to obtain a nice display of the sinusoidal signal.

  The instructor will provide help if you are having trouble, and you can consult the oscilloscope appendix on the last page of this handout.
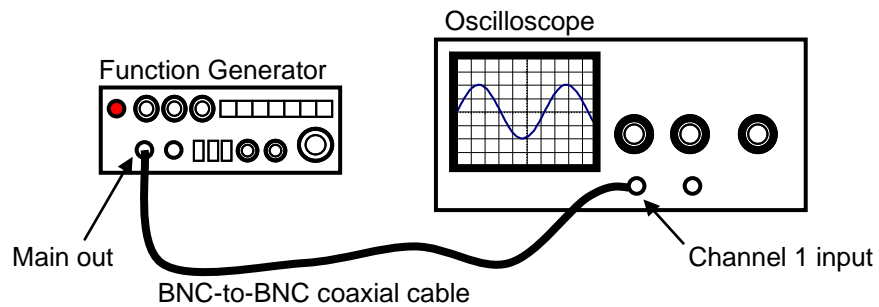


*Figure 1*: Testing the function generator and oscilloscope

- Play with the settings on the function generator to see how you can control the shape, size and frequency of the signal, but then return the settings to those described in the instructions above.

- Instead of feeding the function generator signal directly to the oscilloscope, place it across the terminals of the large coil sitting in the wood enclosure on your table as shown in *Figure 2*. You will have to exchange the BNC-to-BNC coaxial cable for a BNC-to-banana-plugs (or alligator clips) coaxial cable.
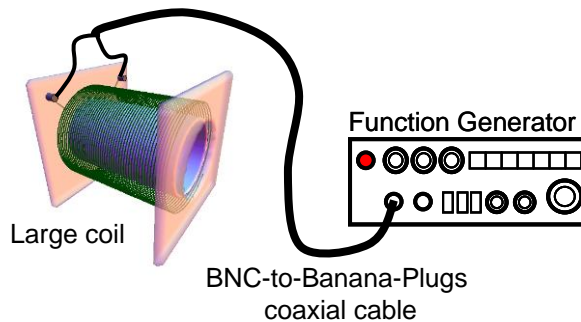


*Figure 2*: Connections to large coil

- Power on the function generator. It should still be set for a maximum amplitude 1 kHz sinusoidal signal. It will drive a 1 kHz sinusoidal current through the coil. A very dynamic system has now been established, although everything dynamic is invisible to our senses. Though it can't be seen or felt, what is being created by the sinusoidal current? Describe it in as much detail as you can.

- To probe the space around the solenoid we must augment our ineffective senses with an external sensor. Connect the search coil to Channel 1 of the oscilloscope as shown in *Figure 3*.
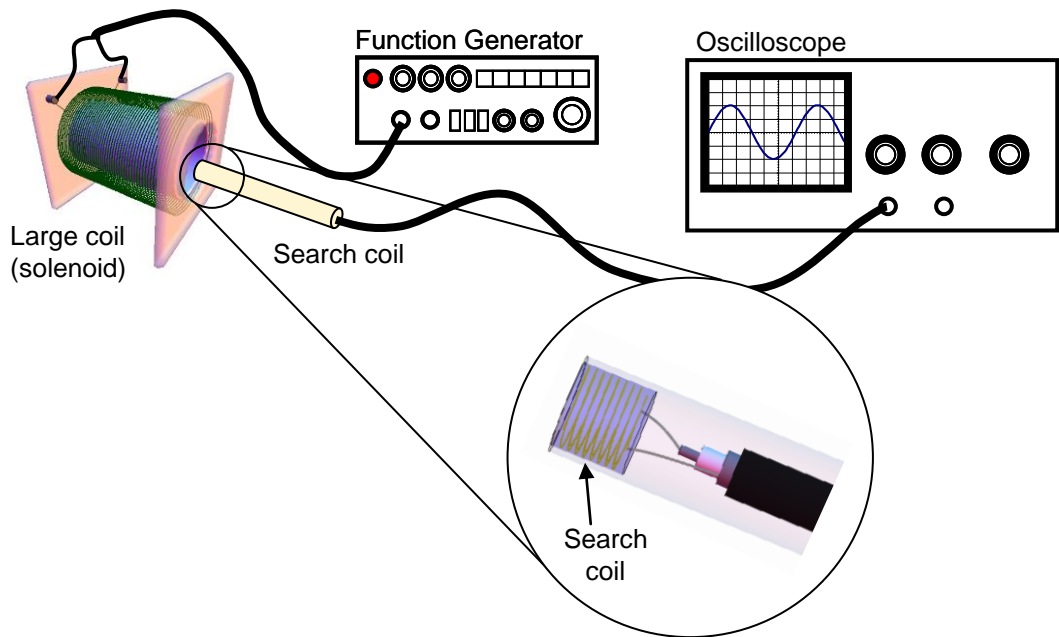
Function Generator

Oscilloscope

Large coil
(solenoid)

Search coil

Search
coil

*Figure 3*: Connections for field measurements

- Move the search coil in and around the solenoid, and while holding its tip (that's where the search coil is actually housed) fixed in one location, change the orientation of the tube that holds the coil. Observe how the signal changes as you make all these maneuvers.

3

**Check your thinking**     Does the amplitude of the signal depend on the location of the search coil? Yes or no.

For a fixed position, does the amplitude of the signal depend on the orientation of the search coil? Yes or no.

Does the frequency of the signal depend on the location of the search coil? Yes or no.

For a fixed position, does the frequency of the signal depend on the orientation of the search coil? Yes or no.

Describe the position and orientation of the search coil that results in the largest signal.

*Position*:


*Orienation*:



Finally, consider the six cases shown in *Figure 4* in which the search coil is immersed in a magnetic field.

$(a)\ B = 10\,\mathrm{T}\ \text{(static)}$         $(b)\ B = 0.1\,\mathrm{T}\ \ \text{(static)}$         $(c)\ B = 0.1\,\mathrm{T}\sin[2\pi(1000\,\mathrm{Hz})t]$

$(d)\ B = 0.1\,\mathrm{T}\sin[2\pi(1000\,\mathrm{Hz})t]$   $(e)\ B = 0.1\,\mathrm{T}\sin[2\pi(1000\,\mathrm{Hz})t]$   $(f)\ B = 0.1\,\mathrm{T}\sin[2\pi(1000\,\mathrm{Hz})t]$
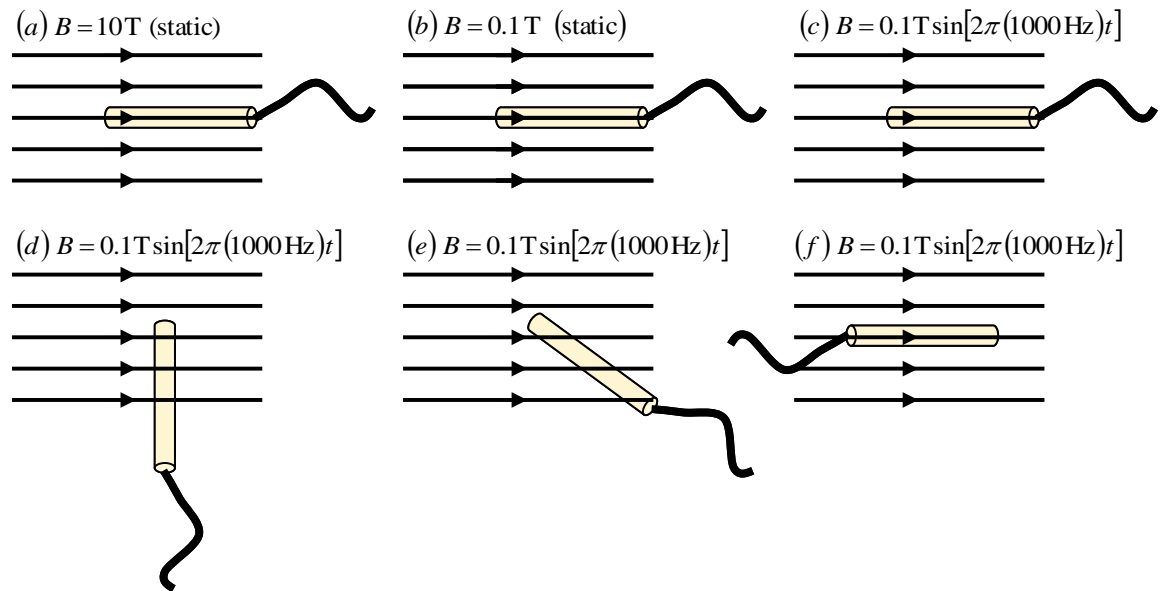
*Figure 4*: Six cases of a search coil immersed in a magnetic field

Rank the cases by the amplitude of the signal induced in the search coil. If any cases result in the same amplitude give them the same ranking. Then explain your ranking. (Note: This is a thought experiment; you should not be measuring anything.)

# 2.    Practice making quantitative measurements

**Introduction**

In this section you will practice making measurements with the oscilloscope.  The verification experiment to be conducted later in this lab requires *many* precise oscilloscope measurements.  The error in your final result is compounded by the error in each individual measurement.  To obtain a satisfying result, it is important to practice and develop good technique.

The raw data, and you should always record the raw data, of an oscilloscope measurement, consists of two things: a measured number of divisions (counted horizontally for time, vertically for voltage) and a multiplier (time-per-division for horizontal measurements, volts-per-division for vertical measurements).

In general, when making horizontal (time) measurements, precision is improved by stretching out the displayed waveform horizontally as much as possible.  When making vertical (voltage) measurements, precision is improved by stretching out the displayed waveform vertically as much as possible.  In addition, it is easier (more precise) to identify the horizontal position where a steep portion of a waveform crosses a horizontal grid line than it is to precisely mark the horizontal position of a peak.

**Procedure**

- Place the search coil somewhere near, or in, the large coil so that a strong sinusoidal signal appears on the oscilloscope.  Keep the search coil fixed in place so the signal remains steady.  You will be measuring the frequency and peak-to-peak size of this signal.

- *Measuring Frequency*:  Here you will determine the period of the signal by measuring the time between two identical points (zero-crossings) of the waveform.  Then you will calculate its frequency.  Use the technique described below.
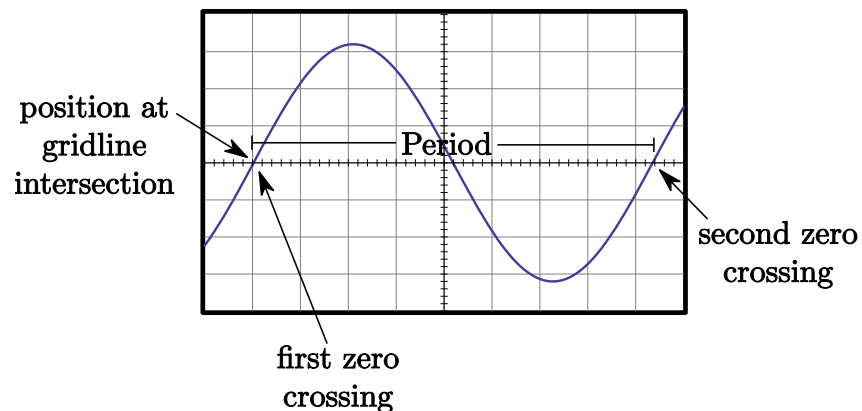


*Figure 5*:  Measuring frequency

**First**, if it isn't already, use the vertical-positioning knob to move the waveform up and down on the display so that it is centered about the central horizontal grid line. **Second**, use the volts-per-division knob so the signal fills as much of the screen vertically as possible, without extending off the screen. **Third**, use the time-per-division knob in combination with the horizontal-positioning knob to stretch-out the signal as much as possible, while keeping two consecutive (same-slope) zero-

5

crossings on the screen, and positioning the left-most zero crossing at the intersection of a horizontal and vertical gridline. Your display will look similar to *Figure* 5. **Fourth**, measure and record the number of divisions from one zero-crossing to the next (same-slope) zero crossing. Try to obtain one-tenth of a division precision. **Fifth**, record the time-per-division setting of the oscilloscope. **Sixth**, calculate the period of the signal is seconds. **Seventh**, calculate the frequency of the signal in Hertz. (Check: is the result consistent with the function generator's settings?)

- *Measuring Amplitude*: Here you will determine the peak-to-peak voltage of the signal by measuring the vertical distance (in volts) from a negative peak to a positive peak. Use the technique described below.
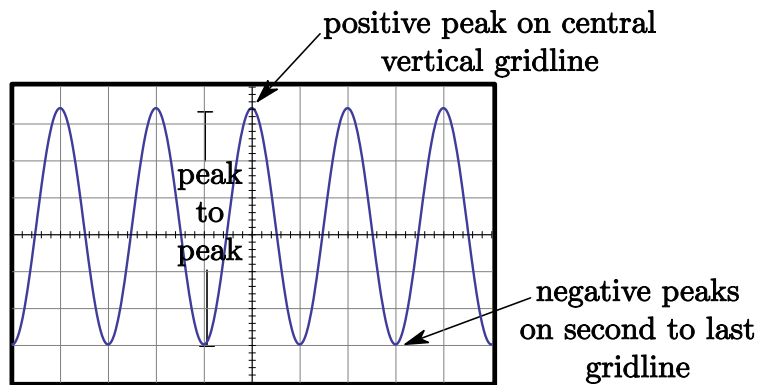


*Figure 6*: Measuring peak-to-peak voltage

**First**, use the time-per-division knob to scrunch the waveform horizontally so that four or five full cycles appear on the display. **Second**, use the volts-per-division knob in combination with the vertical-positioning knob to stretch the waveform as much as possible vertically, while keeping the entire waveform within the display area, and positioning the negative peaks so they rest on the second lowest horizontal grid line. **Third**, use the horizontal-positioning knob to position a positive peak right on the central vertical grid line. Your display will look similar to *Figure* 6. **Fourth**, measure and record the number of divisions along the central vertical axis from the next-to-lowest horizontal grid line (where the negative peaks sit) to the positive peak. Try to obtain one-tenth of a division precision. **Fifth**, record the volts-per-division setting of the oscilloscope. **Sixth**, calculate the peak-to-peak amplitude of the signal is volts.

- Consult your friendly instructor for guidance.

# 3.  Calibrating the search coil

**Introduction**

The method of measuring the field with a search coil, so long as it remains *uncalibrated*, will give only *relative* field strengths.  We must first calibrate the system to convert the *EMF* measured by the oscilloscope into magnetic field strength.  To conduct the calibration a *known* field will be measured with the search coil.  The known field will be provided by the field at the center of a current carrying wire loop.  If the loop has *N* turns of wire, radius *a,* and current *i* through it, then *B* at the exact center of the coil is given by

$$B = \frac{N\mu_0 i}{2a} \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$.

**Procedure**

- At the moment, the large coil of wire is connected to the function generator.  Now exchange the large coil with the small twenty-turn loop that is wrapped around a short section of PVC pipe.  The function generator should still be set for a maximum amplitude 1000 Hz sinusoidal signal.  Take care not to change this setting for the remainder of the lab.

- Now place the AC ammeter (just the digital multimeter set to measure AC current) in *series* with the loop to measure the current through it.  The multimeter's 300 mA range should be used.  Record this calibration current below

  Calibration current = _____

- While the ammeter is still in place measuring current, position the search coil at the center of the loop and in the orientation where the *EMF* is *largest* and record the peak-to-peak voltage from the oscilloscope screen below.  The accuracy of your final result in Part 4 relies on this measurement.  Make it with care.

  Maximum induced *EMF* = _____

- Use the Vernier calipers to measure the diameter of the loop.  To account for the thickness of the 20 turns of wire take the loop diameter to be the average of the outer diameter of the plastic support tube and the outer diameter of the coil of wires.  Record your measurements and calculations in *Table 1*.  (Learn how to read the caliper scale correctly if you don't know how.)

| | |
|---|---|
| Outer diameter of plastic support tube | |
| Outer diameter of the 20 turns of wire | |
| Loop diameter (average of the previous two measurements) | |
| Loop radius - $a$ | |

*Table 1*:  Measurements to determine loop radius

- Using *Equation 1* calculate *B* at the center of the loop.  Show your calculation here and express the magnetic field in Teslas (T).

- The ratio of the calculated *B*-field to the maximum voltage read on the oscilloscope gives a calibration constant, *c*, that can be used to convert all your *EMF* measurements into values of the field in T.  Calculate *c* in the space below.  Make sure you include the correct units with your numerical result.

- Detach and set aside the small 20 turn coil and the multimeter.  Reconnect the function generator to the large coil.

# 4.    Verifying Ampere's law

**Introduction**

Ampere found a relationship between the magnetic field around a closed path in space and the current enclosed by that path.

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i \tag{2}$$

This relationship, where $\oint \vec{B} \cdot d\vec{s}$ is the line integral of the component of the magnetic field parallel to the path around a closed path, where $i$ is the current enclosed by that path, and where $\mu_0$ is the permeability of free space, is known as Ampere's law.

But, what is the left-hand side of *Equation 2*? You can approximate $\oint \vec{B} \cdot d\vec{s}$ by measuring the magnetic field at various locations around a closed path. You will approximate $\vec{B} \cdot d\vec{s}$ as $B_{\parallel} \Delta s$ where $B_{\parallel}$ is the average component of the magnetic field parallel to the path, and $\Delta s$ is the length of the path segment over which the average is taken. You will then sum all the products. That is,

$$\oint \vec{B} \cdot d\vec{s} \approx \sum B_{\parallel} \Delta s \tag{3}$$

In the experiment you will choose your own closed path and measure the parallel components of the magnetic field around that path. You will section the path into segments of *equal* length, so *Equation 3*, since all $\Delta s$'s are the same, can be rewritten

$$\sum B_{\parallel} \Delta s = \left( \sum B_{\parallel} \right) \Delta s \tag{4}$$

The magnetic field will be determined by measuring the *EMF* induced in the search coil. The calibration constant can then be used to convert this voltage to the magnitude of the magnetic field. In this way you will experimentally determine the left hand side of *Equation 2*.

You will then use Ampere's law to *predict* the enclosed current,

$$i_{predicted} = \frac{\left( \sum B_{\parallel} \right) \Delta s}{\mu_0} \tag{5}$$

To check Ampere's law, you will then *measure* the current with an ammeter. The magnetic field is produced by a solenoid, and the measured current enclosed by the loop is equal to the current through the ammeter multiplied by the number of turns in the solenoid, $N = 3400$. That is,

$$i_{measured} = N i_{ammeter} \tag{6}$$

Your verification of Ampere's law then consists of comparing the predicted and measured currents defined in *Equations 5 & 6*.

**Check your thinking**   In the measurement to follow you will mark off a closed rectangular path that surrounds one arm of the large coil.  This path, which you will draw on a piece of graph paper resting on the surface of the wood enclosure, will look much like those in the three examples shown in *Figure 7*.
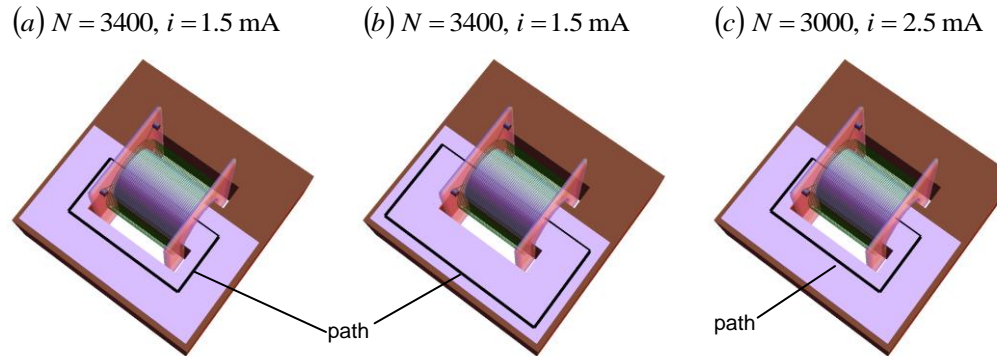
$(a)$ $N = 3400$, $i = 1.5$ mA      $(b)$ $N = 3400$, $i = 1.5$ mA      $(c)$ $N = 3000$, $i = 2.5$ mA



*Figure 7*:  Three examples of "Amperian" paths (loops).

Rank the three cases according to the magnitude of the line integral $\oint \vec{B} \cdot d\vec{s}$ .  (Note that the path is larger in case $(b)$ and the number of turns and the current are different in case $(c)$.  Justify your ranking.

**Procedure**   • You must first define a closed path around one arm of the solenoid, which you will draw on the graph paper designated for this part of the lab.  Prepare the graph paper by cutting along the lines so marked.  Place the graph paper on the wood enclosure and wrap it around one arm of the solenoid.  Secure it in place with tape.

10

- With a ruler draw a rectangle on the graph paper that encloses one arm of the solenoid. Make sure that each side of the rectangle is an integer multiple of 2 cm. (*i.e.* a side may be 14 cm or 10 cm or 18 cm, etc. but not 11 cm or 13 cm.)

- With a pen or pencil label the four sides of the rectangle with Roman numerals I, II, III and IV. Then, with a pen or pencil section the entire path into 2 cm segments.

- To take your first measurement orient the search coil so that its longitudinal axis is *parallel* to Side I of the rectangle and position the face of the search coil at the *center* of the first segment on Side I.

- Measure the peak-to-peak *EMF* and record the value in the appropriate cell of *Table* 2 below.

- Repeat this measurement for every 2 cm segment of the entire closed path. Always position the search coil in the middle of the segment with the coil's longitudinal axis parallel to the line segment in a consistent sense as you work your way around the path. (Note: Use good oscilloscope technique. If the signal becomes small, adjust the volts-per-division knob so that the signal nicely fills the screen.)

| Line Segment | Rectangular Path | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | Side I | | | Side II | | |
| | Divisions (peak-to-peak) | Volts-per-Division | *EMF* (V) (peak-to-peak) | Divisions (peak-to-peak) | Volts-per-Division | *EMF* (V) (peak-to-peak) |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 7 | | | | | | |
| 8 | | | | | | |
| 9 | | | | | | |
| 10 | | | | | | |
| 11 | | | | | | |
| 12 | | | | | | |

*Table 2*: *B*-field measurements around a closed path

| Line Segment | Rectangular Path | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | Side III | | | Side IV | | |
| | Divisions (peak-to-peak) | Volts-per-Division | *EMF* (V) (peak-to-peak) | Divisions (peak-to-peak) | Volts-per-Division | *EMF* (V) (peak-to-peak) |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 7 | | | | | | |
| 8 | | | | | | |
| 9 | | | | | | |
| 10 | | | | | | |
| 11 | | | | | | |
| 12 | | | | | | |

*Table 2(continued)*: *B*-field measurements around a closed path

**Analysis**     The theory and motivation for this measurement was described on page nine. Complete the analysis of your data by referring to that description. Your conclusion should be a comparison of $i_{predicted}$ with $i_{measured}$. Show all your work and calculations and record any further measurements that you make. Your work should be neat and organized so that it can be easily followed.

**Conclusion**   Compare $i_{predicted}$ with $i_{measured}$. At what level (you might report a percent difference) has Ampere's Law been verified.

**Appendix**          Most of you have one of the two oscilloscopes pictured below.  The boxed settings are ones you might find yourself adjusting throughout the lab.  The other settings should be as they appear (set them properly if they are not) and will not need to be altered during the lab.





14