VIII. MAGNETIC FIELD

INTRODUCTION

Use of compass dates back to at least thirteen century B.C. Compass is a small permanent magnet which can rotate freely. It orients itself along direction from the South to North pole of the Earth. In fact, the Earth is a big magnet by itself. The compass has its own "North" and "South" poles at the opposite ends. North (South) pole of the compass is attracted to the South (North) pole of the Earth. We can say that the Earth creates magnetic field in the surrounding space and the compass orients itself in the direction of this field. In nineteen century A.D. Danish physicist Oerst discovered that electric current flowing in a wire deflects nearby compass, therefore it must create magnetic field. It was soon understood that motion of electric charge, for example of electrons in electric current flow, is the only source of magnetic field. Magnetic field of permanent magnets is due to the motion of electrons in molecular current loops.

Electric charge at rest with respect to magnetic field does not experience any magnetic force. If it moves, magnetic force on the charge will be perpendicular to its velocity and to the direction of the magnetic field. Forces between permanent magnets are due to magnetic force on electrons moving inside the magnets.

PURPOSE

In this experiment you will study magnetic fields created by current loops and permanent magnets and interactions among them.

PRE-LAB ASSIGNMENTS

A. Readings:

A compass shows us direction of magnetic field lines and can be used to map out magnetic field in space around a conductive wire flowing electric current or around a permanent magnet. Magnetic field lines created by a current loop are illustrated in Figure 1a. Unlike electric field lines which originate from positive electric charges and terminate at negative charges, magnetic field lines always create closed loops (this can be translated into the statement that there are no "magnetic charges"). You can imagine that the field lines in Fig. 1a which leave the area of the drawing, eventually bend back to connect to their other end. Value of magnetic field in the middle of the loop is given by:

$$B = \mu_0 \frac{I}{2R} \tag{1}$$

where μ_0 is a constant equal to $4\pi \cdot 10^{-7}$ $[N/A^2]$, I is the electric current flowing through the wire, and R is the radius of the loop. SI unit of magnetic field (B) is Tesla $[T]$. People often use a different unit called Gauss $[G]$. One Tesla is equal to 10,000 Gauss.

Although magnetic field lines of a permanent magnet (Fig. 1b) may seem to originate from its North pole and terminate at the South pole, they also create closed loops penetrating material of the magnet. There is no explicit North and South pole in the conductive loop. However, the direction of the magnetic field created by the loop depends on the direction of the current flow in the loop. If you direct fingers of your right hand to point in the direction of the current flow, your right thumb will point in the direction of the magnetic field. We can call this side of the loop its North pole. The other side of the loop will be then South pole of the created magnetic field.

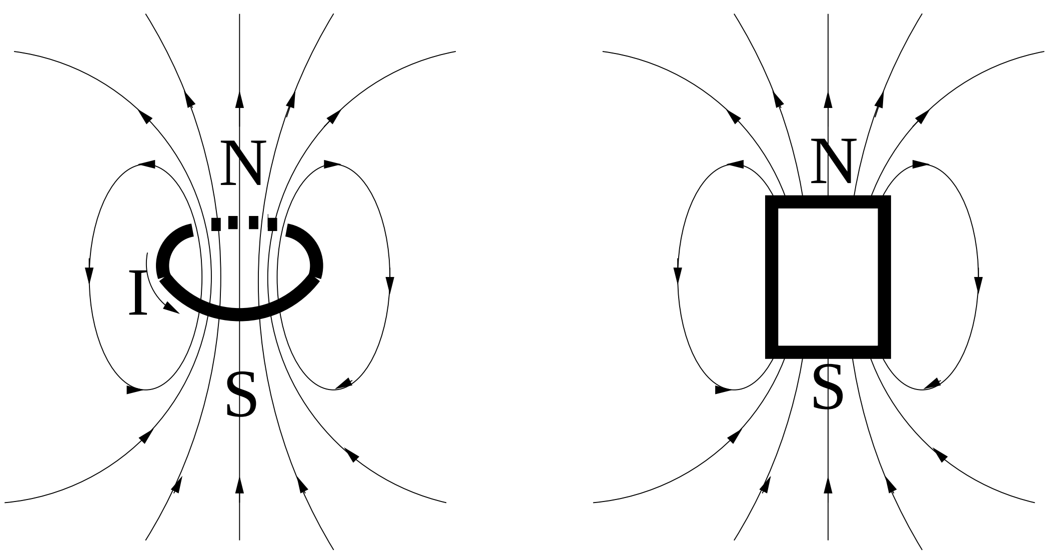


Figure 1. Magnetic field lines created by (a) current loop (b) permanent magnet

Instead of single loop, a wire can be wound many times to create the so called solenoid, as illustrated in Figure 2. For long solenoids the magnetic field inside becomes uniform (i.e. the same at any point). For infinitely long solenoid strength of magnetic field inside can be obtained from the following formula:

$$B = \mu_0 \, n \, I \tag{2}$$

where n is the number of turns of the wire per unit length. Notice that B does not depend on radius of the solenoid in this approximation.

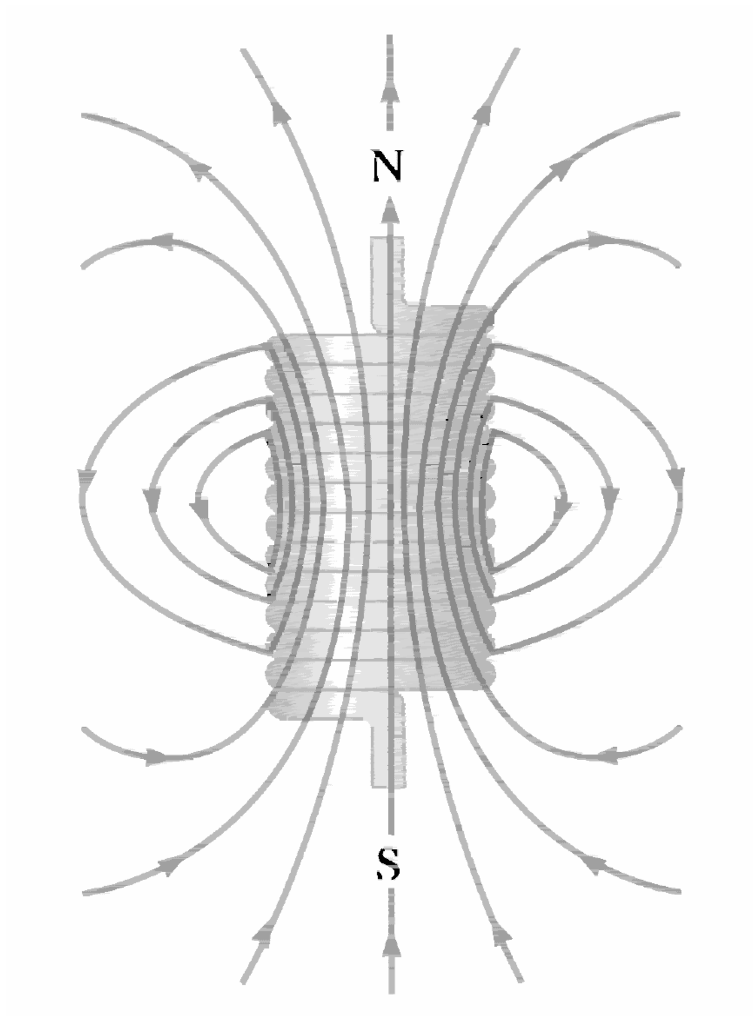


Figure 2. Magnetic field lines of a solenoid created by a wire tightly wound and carrying a steady current. Density of lines is proportional to magnetic field strength. The field in the space enclosed by the solenoid is nearly uniform and much stronger than on the outside. Note also how the magnetic field changes direction on the outside to create closed loops of the field lines.

Magnetic field can be measured quantitatively with help of a Hall probe. The Hall probe is a piece of conductor with current flowing through it (see Fig. 3) . Electrons moving in the conductor will experience magnetic force (F) proportional to the magnetic field (B). The force will be directed perpendicularly to the current flow (I) (i.e. electrons are moving in the opposite direction to the current flow). Under influence of this force electrons will go to one side of the conductor leaving excess of positive charge on the other side, thus generating potential difference between the two sides of the conductor in the direction perpendicular to the current flow. This potential difference is proportional to the component of magnetic field which is perpendicular to both: the current flow in the Hall probe and the direction across which the potential difference is measured.

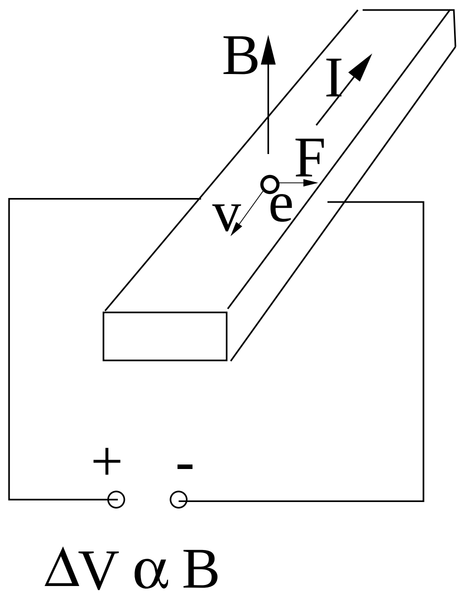


Figure 3. Principle of operation of a Hall probe

When two magnets (permanents or created by wire loops) are placed next to each other they will either attract or repel each other depending on the orientation of their magnetic fields. Like-type poles repel each other, whereas unlike-type poles attract each other. Magnetic force between the magnets will depend on the strength of magnetic fields created by each magnet. Since the magnetic field strength drops with increasing distance from the magnet (this can be seen in Fig. 1 since the density of the field lines decreases with the distance from the center), the force between magnets will also decrease when magnets are moved away from each other.

B. Exercises:

Please answer the questions on Report Sheet VIII–1, which will be collected at the *beginning* of the laboratory session and graded by your instructor.

LABORATORY ASSIGNMENTS

Experiment A: *Magnetic field dependence on electric current*

The Task:

To verify that magnetic field strength is proportional to the electric current which creates it.

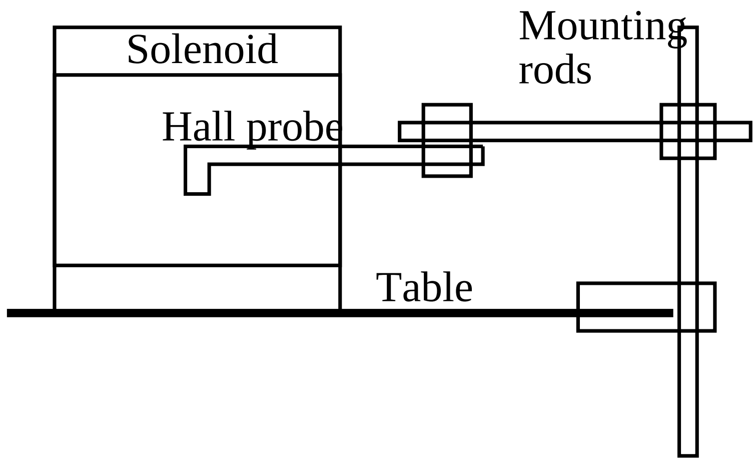
Materials Needed:

- Solenoid
- Resistors: 2Ω, 220Ω
- Power Supply
- Dual Channel Amplifier with one voltage probe
- Hall probe
- Mounting rods and brackets
- Permanent magnet suspended on a string
- ULI computer interface box
- 4.5V Battery (for calibration only)
- Voltmeter (for calibration only)
- Cables
- Metric ruler

Procedures

A-1. Before we do any measurement observe interactions of a solenoid with a permanent magnet. Orient the tube of the solenoid vertically. Hook up the solenoid directly to the power supply. Switch the supply on and set it to maximal voltage. Holding the magnet by the string, lower it to the solenoid. Try to approach the solenoid from a different distance from its axis. Switch the polarity of the power supply connection (whenever changing the connections, switch the power supply off!). Experiment with permanent magnet again.

A-2. Switch the power supply off. Move the permanent magnet far away from the solenoid. Connect 220Ω and 2Ω resistors in series with the solenoid. Orient the solenoid axis horizontally. Mount the Hall probe in the middle of the solenoid as shown below. Connect the voltage probe across the 2Ω resistor. It will serve as current meter. Its output should be connected to DIN1 port of the ULI interface box. Connect the Hall probe to DIN2. Set the Hall probe switch to "Low" sensitivity.



Side view of the solenoid with its axis in horizontal direction. The Hall probe is positioned inside the solenoid in its center. In this orientation the probe will measure horizontal component of the magnetic field.

A-3. Start the computer, and click on the PHY222 icon to start the program. To load the proper initialization file, choose “Open…” from the “File” menu. Open the file “magnets-probe” in PHY222 subdirectory.

Check calibration of the voltage probe using a test battery and hand-held voltmeter. Re-calibrate if necessary.

With the power supply off go to “Experiment” menu and select “Zero”, then “Zero magnetic field” from the pop-out window.

Switch the power supply on and set it to some non-zero value. If the current reading on the computer screen is negative switch the polarity of the connection of the voltage probe to the 2Ω resistor.

A-4. Start collecting data. Turn the knob of the power supply in a full range from zero to the maximum within the data collection time.

Copy Magnetic field vs. Current graph onto Report Sheet VIII–2. Is the dependence linear as expected?

A-5. Fit the straight line to B vs. I graph (select it be clicking on it, go to “Analyze” menu and click on “Linear Fit”). Copy the fitted slope to Report Sheet VIII–2.

Let us compare your result to the expectations. If the solenoid had been infinitely long, the slope would have been given by $m = \mu_0 \, n$ from Eq. (2). Read number of turns of the solenoid (N) given on its label. Measure the length of the wire solenoid (l) with a ruler (only the part covered with the wire matters). Report your measurements and calculations in Report Sheet VIII–2.

A-6. Since our solenoid is not infintely long Eq. (2) should have given you an overestimate of the slope.

Let us now use the opposite extreme and pretend that our solenoid is infinitely short. In this limit we can think of it as single current loop. The current in this "loop" is $I_{tot} = N\,I$. Then from Eq. (1) the slope should be $m = \mu_0 \frac{N}{2R}$.

Measure inner and outer diameter of wire windings. Average them and use for $2R$ in this formula. Report your measurements and calculations in Report Sheet VIII–2.

Experiment B: *Map of solenoidal magnetic field*

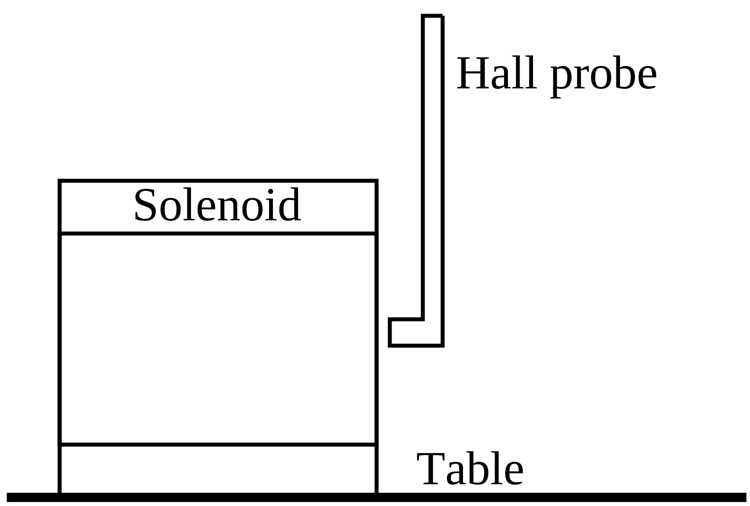
The Task:

To verify that magnetic field does not change much inside the solenoid and to observe its variation on the outside of the solenoid coil.

Materials Needed:
See the previous experiment.
Procedures

B-1. Hold your probe in your hand instead of having it mounted in a fixed position. Set the power supply to the maximum. Read magnetic field value at various points in the middle plane of the solenoid: in its center and closer to the coil. Keep the handle of the Hall probe parallel to the axis of the solenoid. (You don't need to collect data; just read the magnetic field off the box near bottom of the computer screen). Report you measurements in Report Sheet VIII–3.

B-2. Now measure magnetic field at the spots indicated in the second plot in Report Sheet VIII–3. Keep the handle of the probe oriented the same was as in the previous step. Report you measurements in Report Sheet VIII–3.



Side view of the solenoid with its axis in horizontal direction. In this orientation the probe will measure vertical component of the magnetic field.

B-3. Now orient the handle of the probe vertically as shown above. This will measure the vertical component of magnetic field. Measure this component at the spots indicated in the third plot in Report Sheet VIII–3. Report you measurements in Report Sheet VIII–3.

B-4. Switch the power supply off. Bring the permanent magnet close to the probe. Report the maximal value of magnetic field you can measure for this magnet in Report Sheet VIII–3.

Experiment C: *Magnetic force between two magnets*

The Task:

To verify that magnetic force is proportional to the magnetic field strength.

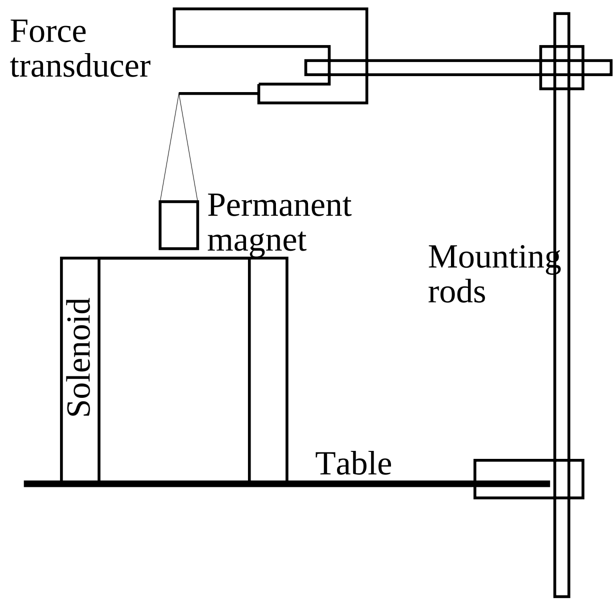
Materials Needed:

- Solenoid
- Resistors: 2Ω, 220Ω
- Power Supply
- Dual Channel Amplifier with one voltage probe
- Force transducer
- Mouting rods and brackets
- Permanent magnet suspended on a string
- ULI computer interface box
- 4.5V Battery (for calibration only)
- Voltmeter (for calibration only)
- Ruler
- Cables

Procedures

Since we have already verified that magnetic field is proportional to the current in the solenoid we will study dependence of magnetic force on I rather than B.

C-1. Orient the solenoid axis vertically. Disconnect the Hall probe. Connect the Force Transducer into DIN2. Mounted it as shown below. Remove the 220Ω resistor from the circuit. Leave the 2Ω resistor with the probe connected in series with the solenoid. The permanent magnet should be suspended from the Force Transducer just above the solenoid in its center.



Side view of the solenoid with its axis in vertical direction. The permanent magnet is suspended above the solenoid from the Force Transducer

C-2. Load "magnets-force" set-up file ("File" → "Open…").

Check calibration of the voltage probe using a test battery and hand-held voltmeter. Re-calibrate if necessary.

To calibrate the force transducer select DIN2 and then "Perform Now" in the calibration pop-out window. With the permanent magnet suspended as shown in the picture and power supply off, enter zero into Value 1 box and click on "Keep". Add known weight to the permanent magnet and enter into Value 2 box the corresponding gravitational force value (e.g. force on 500g weight is $F = m\,g = 0.5[kg] \cdot 9.81[m/s^2] = 4.905[N]$). Click on "Keep" and then "OK". Take the weight off after the calibration. The transducer is now ready to measure magnetic force.

C-3. Switch the power supply on. See if the solenoid attracts the magnet. Switch the polarity of the power supply connection if necessary. Start collecting data. Turn the knob of the power supply in a full range from zero to the maximum within the data collection time.

Copy Force vs. Current graph onto Report Sheet VIII–4. Is the dependence linear as expected?

C-4. With the power supply set to the maximum, measure force on the permanent magnet at different heights above the solenoid. You don't need to collect data, just read the force value of the computer screen. For each position of the magnet measure distance between the center of the solenoid and the center of the permanent magnet. Graph your measurements in Report Sheet VIII–4. Draw a smooth line going through your measurement points.

REPORT SHEET VIII–1

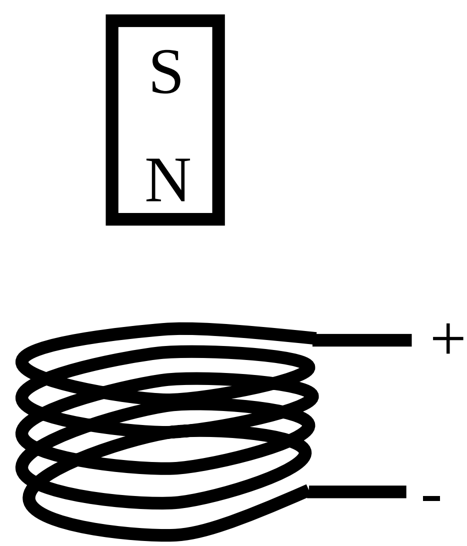
Date____________________ Name____________________

Instructor____________________

PRE-LAB EXERCISES

Exercise 1.
Electric current of 2A is flowing through the solenoid with 20000 turns. Solenoid is 0.5m long. Assuming that the formula for infinitely long solenoid is a good approximation what is the magnetic field strength B inside the solenoid?

Exercise 2.
A permanent magnet is placed in front of a solenoid and potential difference is applied to the two ends of the solenoid wire as shown. Will solenoid attract or repel the permanent magnet?

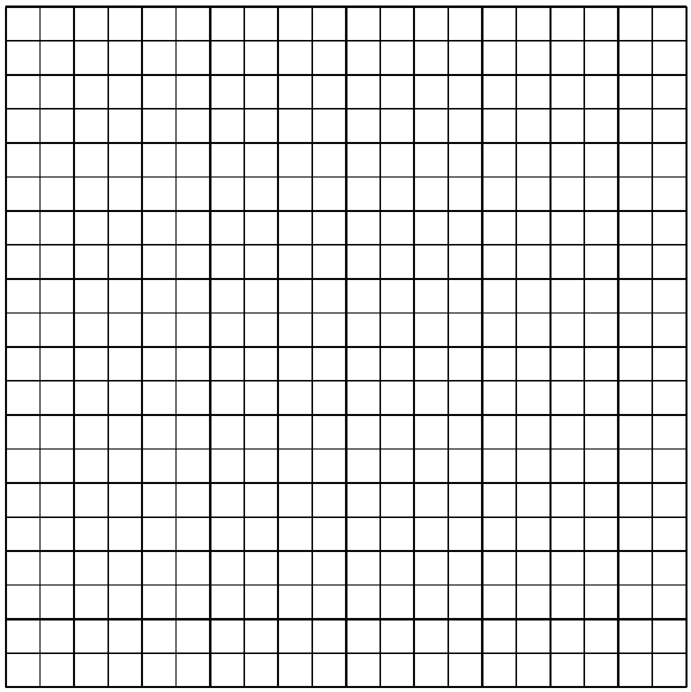


REPORT SHEET VIII–2

Date ____________________ Name ____________________

Instructor ____________________ Partner(s) ____________________

A-4. Magnetic Field vs. Current



Is the dependence linear?

☐ yes ☐ no

A-5

Measured slope of the B vs. I dependence:	$m =$	$[Gauss/A]$
Number of turns of the wire in the solenoid:	$N =$	
Length of the solenoid:	$l =$	$[m]$
Linear density of wire windings:	$n = N/l =$	$[1/m]$
Expected slope from formula (2):	$m = \mu_0\, n\, 10000 =$	$[Gauss/A]$

A-6

Average diameter of the solenoid coil:	$2R =$	$[m]$
Expected slope from formula (1):	$m = \mu_0 \frac{N}{2R}\, 10000 =$	$[Gauss/A]$

Is your measured slope of the same order of magnitude as predicted for infinitely long solenoid or a wire loop?

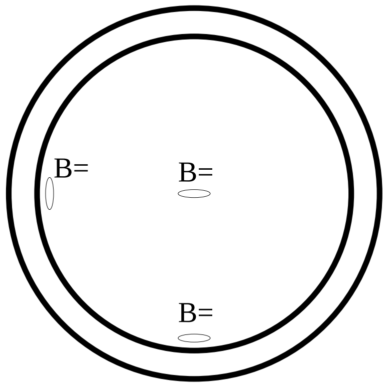
☐ yes ☐ no

REPORT SHEET VIII–3

Date________________ Name________________

Instructor________________ Partner(s)________________

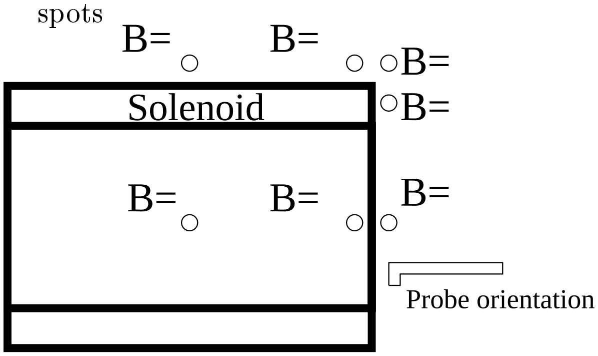
B-1



Front view of the solenoid. Measure horizontal component of magnetic field in the middle plane of the solenoid at three spots indicated in the drawing.

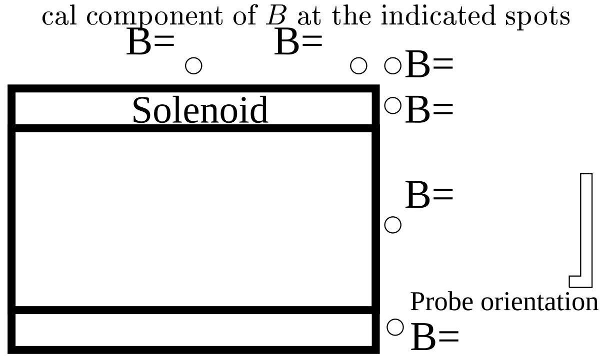
B-2

Side view of the solenoid. Measure horizontal component of B at the indicated spots



B-3

Side view of the solenoid. Measure vertical component of B at the indicated spots



Do measurements in B-1 compared to measurements in B-2 and B-3 show that magnetic field inside the solenoid vary slowly compared to the magnetic field outside?

☐ yes ☐ no

Do measurements in B-2 and B-3 qualitatively agree with magnetic field expected for solenoid (see Fig. 2)? Explain your answer (use the other side of this page if needed).

B-4

Maximal value of magnetic field measured for permanent magnet: $B =$ [Gauss]

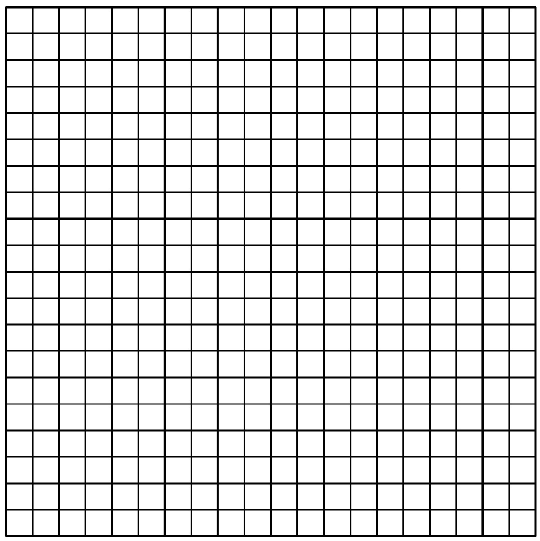
REPORT SHEET VIII–4

Date________________________ Name________________________

Instructor______________________ Partner(s)______________________

C-3. Force vs. Current

F (N)



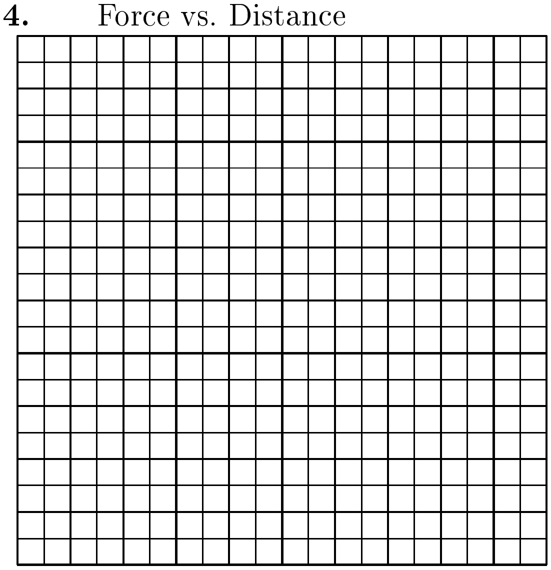
I (A)

Is the force linearly dependent on current, therefore also on magnetic field?

☐ yes ☐ no

C-4. Force vs. Distance

F (N)



Distance (cm)

Does the force between magnets decrease with their separation?

☐ yes ☐ no

Is the dependence linear?

☐ yes ☐ no