

# Experiment 12

## Magnetic Field of a Solenoid

### 1. Introduction

A solenoid is a long, tightly wound coil carrying electric current. The magnetic field generated by the solenoid is very strong inside the coil. Outside of the solenoid the magnetic field is essentially zero, compare Fig. 1.

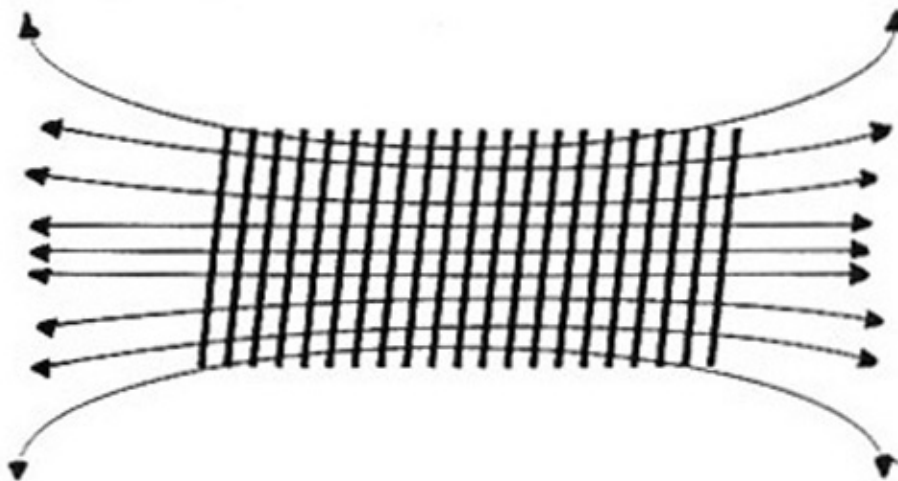


Fig. 1. Magnetic field of a solenoid.

Using Ampere's law one can derive the magnetic field inside the solenoid to be

$$B = \mu_0 n I \quad (1)$$

where  $\mu_0 = 4 \pi \cdot 10^{-7}$  Webers/A m,  $n$  is the number of turns per unit length, and  $I$  is the current. For solenoids that are not very long, we use a more accurate formulae for the magnetic field:

$$B = \mu_0 n I (L/2) / [(L/2)^2 + R^2]^{1/2} \quad (2)$$

where  $L$  is the length and  $R$  is the radius of the solenoid.

In this experiment you will measure the magnetic field using a Hall probe. Hall discovered that when a current flows through a conductor placed inside a magnetic field, a charge separation is observed on opposite sides of a conductor. The electric current  $I$  can be treated as a number of electric charges moving along the conductor. When a moving charge is placed inside a magnetic field,  $\mathbf{B}$ , the field exerts a force,  $\mathbf{F}$ , that is proportional to the velocity of the charge.

$$\mathbf{F} = q \mathbf{v} \times \mathbf{B} \quad (3)$$

The direction of the force (3) is given by the right-hand rule. For a sample where the charge carriers have positive signs, the force given by Eq. 3 results in charge separation, and the top of the conductor becomes positively charged. The electric field associated

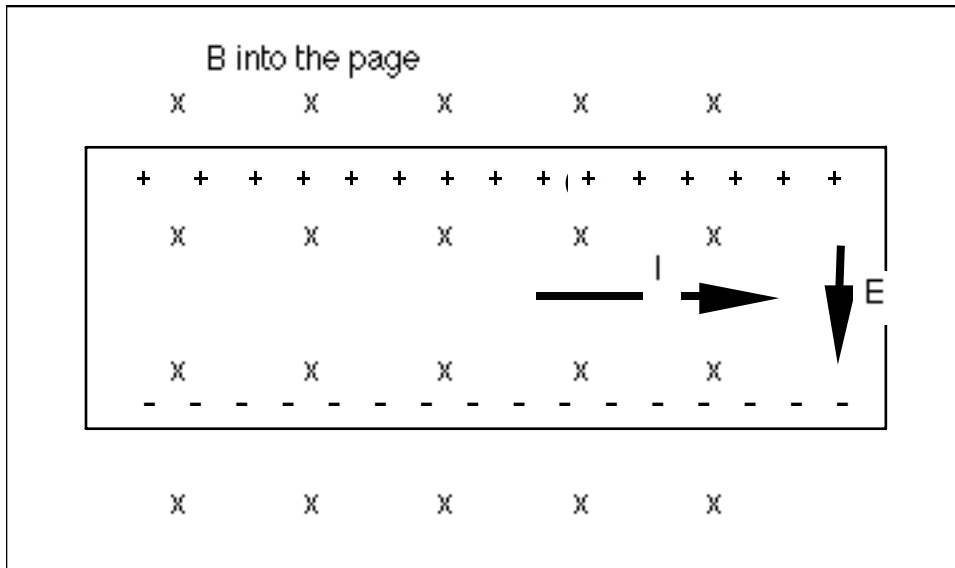


Fig. 2. The magnetic force on the conductor with positive charge carriers moving to the right, will cause a drift of the charges toward the top of the conductor resulting in a downward electric field,  $\mathbf{E}$ .

with this effect gives rise to a potential difference between the top and the bottom of the conductor. The potential difference is given by

$$V = Ed \quad (4)$$

where  $d$  is the thickness of the conductor. Measurements of the Hall effect provide information on the sign of the charge carriers. If the conductor carries a known current, the induced electric potential,  $V$ , is proportional to the magnetic field, so that the Hall potential provides a simple way to measure the magnetic field.

## 2. Procedure

The Hall potential is usually small and has to be amplified before it could be measured by a standard meter. Measurements of magnetic field are difficult by traditional methods. In the first step you will use a voltmeter to measure the Hall potential and get a general sense how difficult such measurements could be. Later you will repeat the same experiment by using a computer with LabView interface and software.

When you come to the lab you should find the equipment assembled for the measurements. It is possible that some parts had been disconnected, therefore, check the diagram in Fig. 3 and connect the wires appropriately.

The solenoid should be connected in series with a power supply and the Current Sensor. The original sensor has been modified, and it is mounted onto an aluminum block. The  $1 \Omega$  resistor can dissipate 5 W of power, which means that it can carry 5 A current. The two posts on the Current Sensor should be connected to channel 0 in the metal interface box with the National Instruments logo on it. To do this use a set of black and red posts the box. They are marked A.

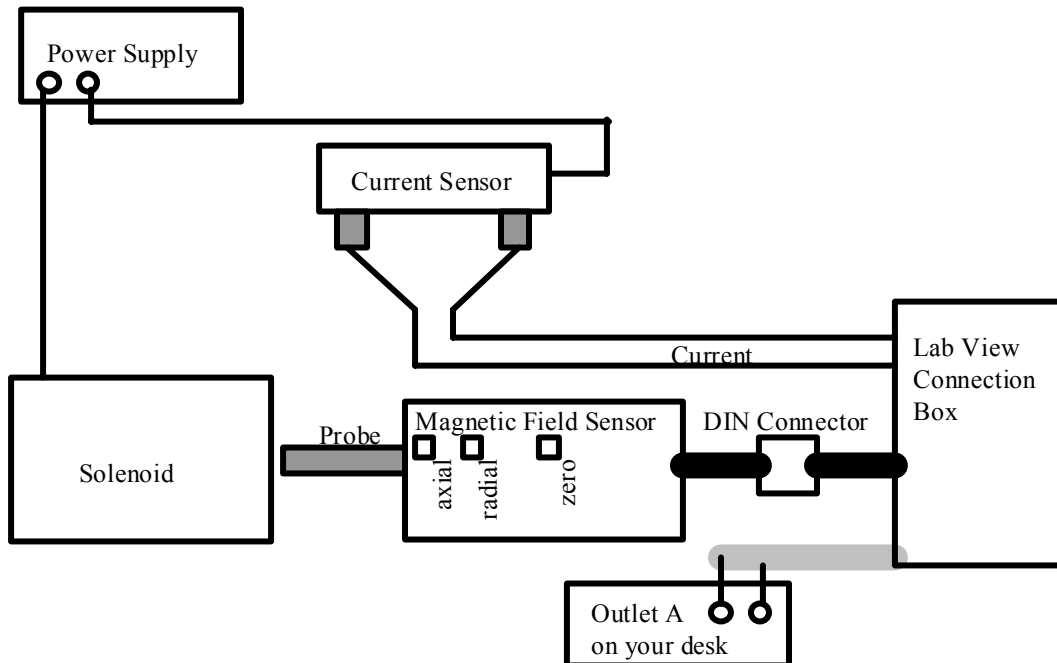


Fig. 3. Electrical connections

Do not open the box, the wires have been secured to the posts inside, but if you suspect that there is something wrong with those connections ask the instructor for help.

There is a black cable and an additional pair of leads in a gray shield coming out of the LabVIEW box. Connect the leads in the gray cable to the outlet of another power supply on your desktop. This power supply should be set to 10 V DC and there will be no need to further adjust it. The short, black cable with a 9 DIN plug on its end Move the switch to the Axial position. Now you will be able to measure axial magnetic field. Before the measurements you may have to zero the sensor. Place the tubular end of the sensor into a short metal sleeve and press Zero. Next, adjust sensitivity of the probe by moving another switch to X1 position. At this switch position 1 V in the output corresponds to 100 Gs. Place the sensor inside the solenoid and make sure that the sensor is near the center of the solenoid.

Disconnect the sensor from the LabView box and plug it into a multimeter set to measure DC volts. Increase slowly the current through the solenoid to 1.0 A, and record the value of the current and the Hall potential, which is proportional to the magnetic field inside the solenoid. Repeat for currents 2.0 A, 3.0 A, 4.0 A, and 5.0 A. Unplug the sensor from the voltmeter and plug it into the LabView Connection Box. Now, you will repeat the same measurements and the use of the computer will allow you to take hundreds of measurements in a relatively short time.

Turn the computer on and log on. On the desktop you will find icon *Shortcut to Lab12*, double click on it.

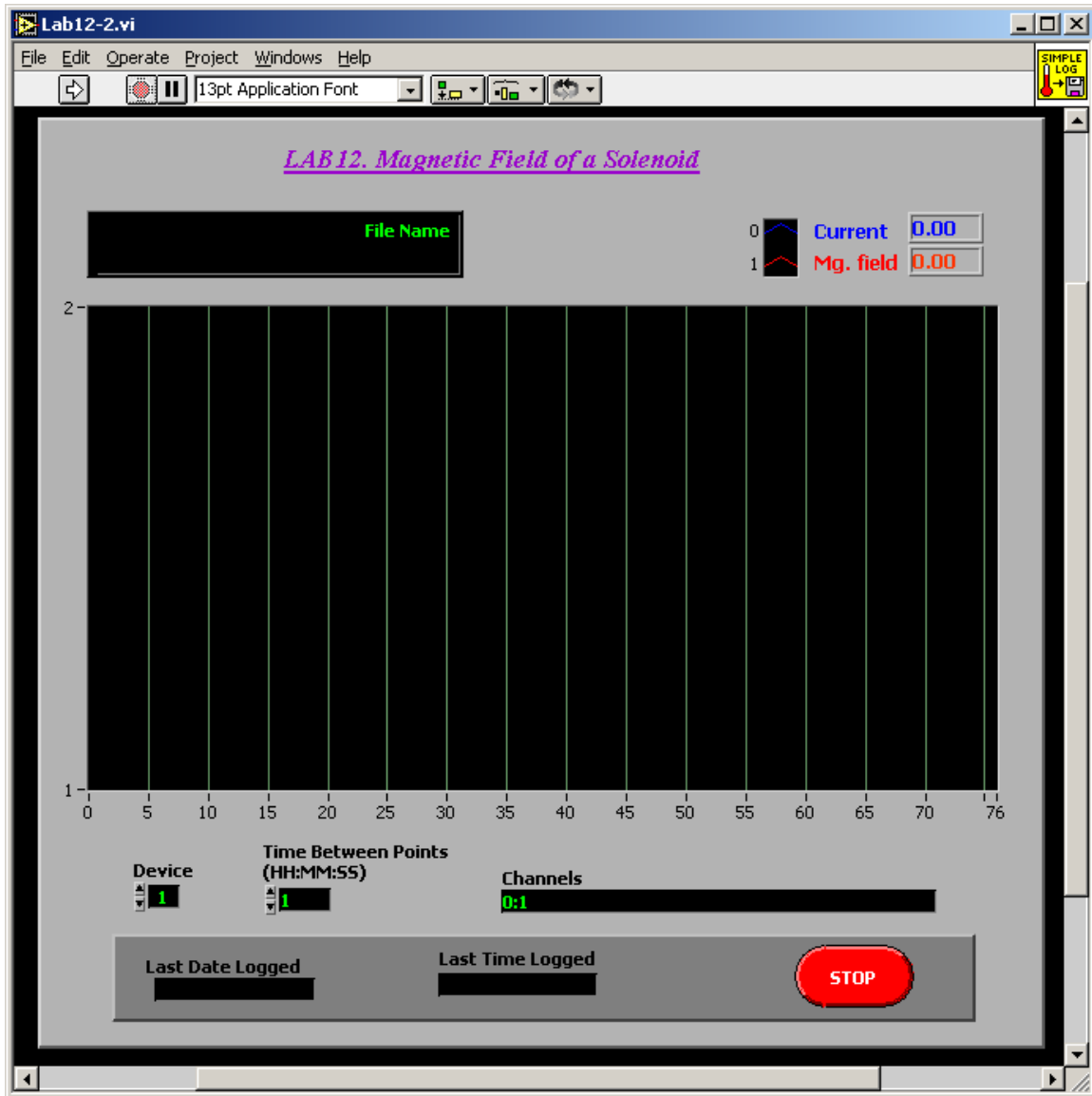


Fig. 4. Computer screen with the *Lab12* program running.

It is possible that a LabVIEW window will appear asking you to register the software – then click *Cancel* and later *OK*, ignore the warnings. A window like that shown in Fig. 4 should appear. Make sure that Device is set to **1** and Time to **1**, Channels should display **0:1**.

Write the file name in the black window near the left top corner of the screen. I suggest that you use your last name with extension *.xls*. Your data will be saved in the folder *DataLab12* on the desktop. Click on the arrow at the top of the window, or go to the pull down menu, select *Operate* and then *Run*. Alternatively you could type *CTRL R*. Increase slowly the voltage on the power supply connected to the solenoid. **DO NOT CHANGE THE VOLTAGE ON THE POWER SUPPLY CONNECTED TO THE MAGNETIC SENSOR. IT SHOULD BE SET TO 10 V DC. DO NOT CHANGE THAT SETTING – YOU MAY DAMAGE THE SENSOR!** Slowly increase the voltage

on the power supply connected to the solenoid, at a rate less than 1 Volt per second and observe the display. The line displaying channel "0" should rise slowly and finally approach level 5. When it is equal 5 reduce the voltage to zero. Again, do it slowly. The computer reads the data every second, and you enough data to get a reasonable fit. The second line in the display corresponds to the signal from the Hall probe. That signal has been amplified, but it still very small and the line depicting the magnetic field probably should vary between 0 and 0.5. Readings below zero or above 0.5 V indicate that something is wrong with the sensor. Most likely you need to zero the sensor. Remove it from the solenoid and place the end of the sensor (the black tube) inside a metal pipe and then press button zero. It is also possible that the wires are crossed and you may need to swap them to get positive values. When you recorded enough data, stop the experiment by pushing button STOP.

Go to *START*, select *Microsoft Office*, and then launch *Excel*. When the spreadsheet program appears on the screen go to *File* and *Open*. Select the file you just saved using LabVIEW. The data were saved in the folder Datalab 12 on the desktop. If you saved your data file with extension xls, Excel will recognize that format and you should see the icon depicting your document. Otherwise, you may have to go to *Type of Files* and select *All Files*. Then double click on your document and Excel will import your data. *Text Wizard* window will appear and follow the instructions. If you used the military time, all data will appear in the spreadsheet. The spreadsheet is organized as follows. The first column is the date of the experiment, the second is the time the data were recorded, the third is the current in the solenoid, and the last column in the magnetic field. In the experiment we measure the voltage across the 1  $\Omega$  resistor inside the Current Sensor. Because it is a 1  $\Omega$  resistor, the voltage across it gives directly the value of the current in the resistor. The current sensor is connected in series with the solenoid, which means that the same current flows through the solenoid. The Magnetic Field Sensor has been designed to give output voltage proportional to the magnetic field. **1.0 V corresponds to 100 Gauss or  $100 \times 10^{-4}$  T.** T is the unit of the magnetic field in the SI unit and stands for Tesla. Change the values in the third column, which are in volts, to read the magnetic field in T.

Select the third and fourth columns and click on *Chart Wizard* (the symbol with 3 color bars). Select XY graphs with the current on the x-axis. The data should lie along a straight line.

You may now go back to LabVIEW and restart the experiment. Increase the solenoid current slowly to 5 A and then decrease it slowly, repeat that cycle several times. Save the data and display them as before using Excel. If the data are not along the straight line it means that the sensor drifted and needed to be zeroed again. You do not have to repeat the experiment, if you have enough data points, you may just delete bad data. You will quickly identify the bad data points in the fourth column because they will have negative values or values exceeding 0.5.

Now you should be ready to fit the data to a straight line. Click once on the graph and go to *Chart* in the main menu. Pull *Chart* down to *Add Trendline* and select linear regression. Click on *Options* and select *Display Equation on Chart* and *Display R-Square value on Chart*. Type OK and examine the graph and the quality of the fitting. If the R-value is small, you may have to repeat the measurements. R greater than 0.95 usually indicates a very good fit. If you are satisfied with the quality of the data, label the axes and select the title for the graph. To do this go to *Chart* and *Chart Options*. Print

the graph. **Remember to log off when you finished the experiment.** Go to *START* and select *Log Off*.

Measure the length and diameter of the solenoid. The total number of turns is 570.

### **3. Report**

In the report attach the graphs depicting the magnetic field against the current. Both graphs should be prepared by Excel and both should indicate the slopes. First graph is for the data you took manually using a voltmeter to measure the Hall potential, and the second for data obtained directly from the LabView software. According to Eq.2 the graphs should show linear dependence, and the slopes divided by the number of turns per unit length and by  $\{(L/2)[(L/2)^2 + R^2]^{1/2}\}$  should give you the value of magnetic permeability,  $\mu_0$ . Compare the results obtained for the manual and the computer readings with the expected value for the empty space. You should be getting a value for magnetic permeability which is very close to the expected value.

In the introduction discuss ALL of the following topics:

1. Hall effect for a sample with negative charge carriers. Draw an illustration similar to that shown in Fig. 2, but for the negative charges.
2. What is the source of the magnetic field of Earth?
3. Why is the magnitude of the magnetic field increased when a piece of iron is placed inside the solenoid?