3.1.1. INVESTIGATION OF THE MAGNETIC FIELD OF A SOLENOID

3.1.1.1. PART I: MAGNETIC FIELD OUTSIDE THE SOLENOID

MAIN PRINCIPLE

Calculation of the magnetic field generated by a solenoid at a point on its axis using direct current.

EQUIPMENT

Multi-turn Coil, Power Supply, Connection Cable, Compass

Figure 3.11: Experimental setup

THEORY

An electric charge in motion generates a magnetic field in the surrounding space. Within the magnetic field, a second charge in motion is influenced by a force. The unit of magnetic field is Tesla in the SI unit system. It is defined as,

$$1\,Tesla = 1\ {}^{Newton}/_{Ampere.Meter}$$

A device through which current i flows and which is tightly wound along a helix is called a solenoid. The length of the helix is taken to be quite large compared to its radius. A winding close to a turn in the solenoid

The observer at the point does not realize that the single turn is along a curve. To this observer, the wire looks like a long wire in terms of its magnetic properties. Therefore, the magnetic field lines generated by a single turn are approximately like circles with the same center. The total magnetic field generated in the solenoid is equal to the sum of the magnetic fields generated by the individual turns.

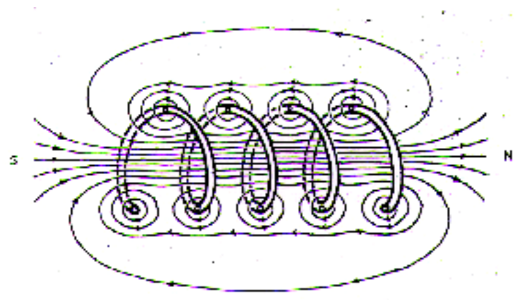

Figure 3.12: Turns and magnetic field lines of a solenoid

A detailed look at Figure 3.12 shows that the magnetic field between the windings is mutually destructive. At points far enough away from the windings, the magnetic field $\vec{B}$ is parallel to the axis of the solenoid.

A very densely wound solenoid looks like a cylindrical sheet through which current flows. The field at point P in Figure 3.12 is generated by the upper windings of the solenoid. In this region, the field is directed to the left. The field created by the lower windings of the solenoid is directed to the right and is such that they destroy each other. If the number of windings increases and the windings become denser, it approaches the ideal solenoid, which is characterized by a cylindrical layer through which current flows. The magnetic field $\vec{B}$ at the outer points of such a long cylindrical current system is approximately zero. By taking the length of the solenoid longer than its diameter, it is correct to assume that the magnetic field at the outer points is zero. The places where the field is zero are outside the solenoid, away from the ends, and close to the midpoint. If the length of the solenoid is not greater than its radius, the magnetic field lines are as shown in Figure 3.13. The frequency of magnetic lines in the center of the solenoid indicates that the magnetic field in the center is more intense than the magnetic field at the outer points. The direction of the magnetic field generated by a solenoid in the direction of its axis is also in the direction of the axis of the solenoid. Its direction is determined by the right-hand rule depending on the direction of the current flowing through the solenoid.

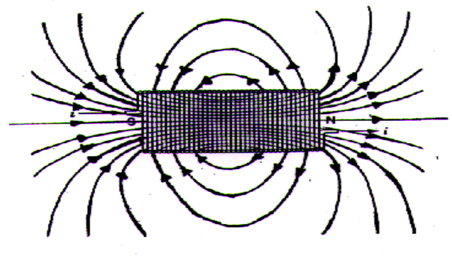

Figure 3.13

Figure 3.13 shows the magnetic field $\vec{B}$ generated by the solenoid at point O in the direction of its axis. However, if the B_y the horizontal component of the earth's magnetic field is also considered as in Figure 3.14, the magnetic field at point O will be B_r. At point O, when there is no magnetic field generated by the solenoid, a compass needle at this point will point in the north-south direction. If current is passed through the solenoid and a magnetic field $\vec{B}$ is generated at this point, the compass needle will deviate from its initial position by angle α and the total magnetic field will take the direction B_r.

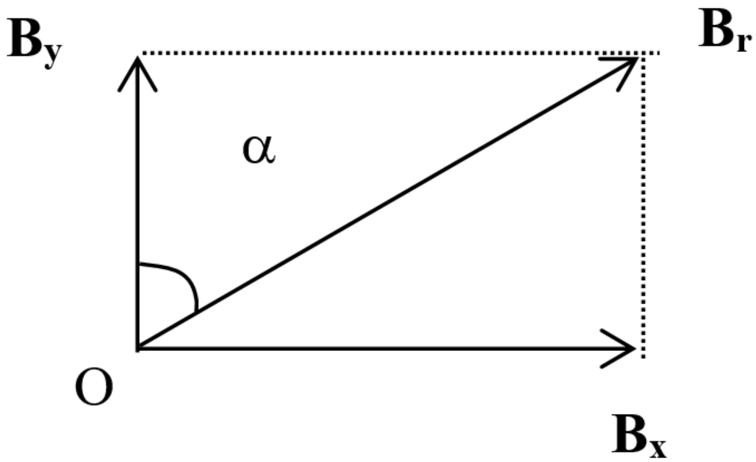

Figure 3.14

From Figure 3.14; $\tan\alpha = B/B_y$ and $B = B_y \tan\alpha$ can be written. Since it is known that the horizontal component of the Earth's magnetic field is $B_y = 26\ \mu T$, the intensity of the magnetic field B to be generated by the coil at the point in question at the angle of deviation α of the compass can be calculated.

SETUP AND PROCEDURE

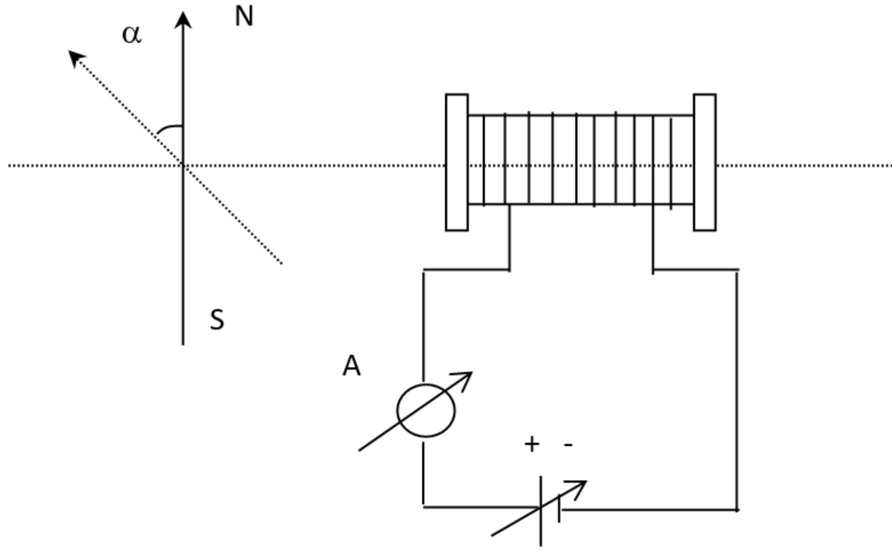

Figure 3.15

The experimental setup consists of a solenoid, an ammeter, a variable direct current source, and a compass needle as shown in Figure 3.15.

1- The compass needle is placed in the north-south direction pointing to zero degrees and the coil is placed in the west-east direction with its axis pointing in the compass direction.

2- Maximum current i ($i \cong 1.5\ A$) is passed through the circuit and the compass-coil distance is adjusted so that the needle of the compass needle deviates about 70° and the current is reset.

3- The current values shown in the table are passed through the current source and solenoid and the deviation angles α on the compass needle are measured and recorded in the Table 3.1. From here $I = f(\alpha)$ graph is drawn as shown in Figure 3.16.

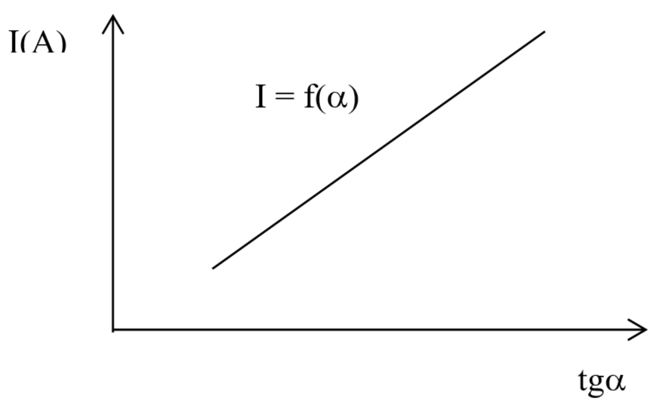

Figure 3.16

4- Taking $B_y = 26\ \mu T$ from the expression $B = B_y \tan\alpha$, the intensity of the magnetic field B created by the solenoid at the point in question corresponding to each current value is determined and recorded in the Table 3.1.

Table 3.1

I (A)	α	$\tan\alpha$	B (μT)
0			
0.2			
0.4			
0.6			
0.8			
1			
1.2			
1.4			
1.6			
1.8			
2.0			

3.1.1.2. PART II: MAGNETIC FIELD INSIDE THE SOLENOID

MAIN PRINCIPLE

1. Measurement of the magnetic flux density in the center of different rings with a Hall bar and determination of its dependence on radius and number of turns.

2. Finding the magnetic field constant.

3. Measurement of magnetic field intensities along the axis of long coils and comparison with theoretical values.

EQUIPMENT

Coils of various sizes and turns, Power Supply, Ruler, Tesla meter, Connection Cable, Ammeter, Voltmeter

Figure 3.17: Biot-Savart experiment setup

THEORY

Magnetic flux in a vacuum according to Maxwell's equations:

$$\oint \vec{B}.d\vec{l} = \mu_0 I \tag{3.39}$$

where l is the length of the closed ring, B and μ_0 are the magnetic flux density and the permittivity of the vacuum respectively. Theoretically, the permittivity of the cavity is $\mu_0 = 1.2566x10^{-6}\ {}^{H}/_{m}$. According to the notation in Figure 3.18 using the Biot-Savart law,

$$d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{d\vec{l}x\vec{r}}{r^3} \tag{3.40}$$

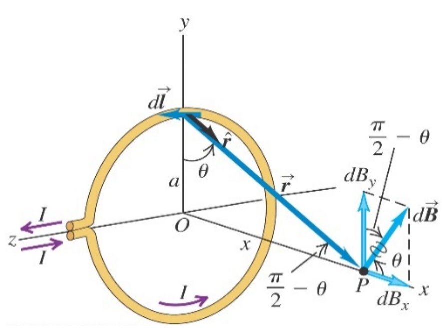

Figure 3.18: Magnetic field vectors at a point on the wire ring axis

The result of the calculation is dB as follows.

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{dl}{a^2 + x^2} \tag{3.41}$$

dB can be solved for the angular dB_y and vertical axis dB_x components.

The dB_x components of each turn are in the same direction as the length unit element dl and can therefore be summed, but the angular components dB_y cancel each other out.

Hence,

$$B_y(x) = 0 \tag{3.42}$$

$$B(x) = B_x(x) = \frac{\mu_0 I}{2} \frac{a^2}{(a^2 + x^2)^{3/2}} \tag{3.43}$$

If a small number of closely similar-sized rings are used, the magnetic flux density can be found by multiplying n by the number of turns.

1- At the center of the rings ($x = 0$)

$$B(0) = \frac{\mu_0 n I}{2a} \tag{3.44}$$

2- Ampere's law is applied to calculate the magnetic flux density of coils of length l and the number of turns n consisting of homogeneously wound windings.

$$B(x = 0) = \mu_0 n I, \qquad (at\ the\ center) \tag{3.45}$$

and

$$B = \frac{\mu_0 n I}{2}, \qquad (at\ the\ ends\ of\ the\ solenoid\ ) \tag{3.46}$$

SETUP AND PROCEDURE

1- The experimental setup is prepared as shown in Figure 3.17. With the help of the power supply, the desired constant current of 0.5 $Amperes$ is applied to the circuit.

2- For multi-wound coils, the magnetic flux densities are measured at various distances by moving the axis bar along the x-axis. ($at\ I = 1\ ampere$)

3- Draw the $B(x)$ curves between the magnetic flux densities B and x for coils with different turns for fixed diameter $2a$ and length l ($l = 160\ mm, 2a = 26\ mm, n = 75{,}150{,}300$)

4- Draw the $B(x)$ graphs of the coils with a fixed number of turns n and the same length and different radius a. ($l = 160\ mm, n = 300, 2a = 26, 33, 41\ mm$)

5- Using the table, you created in item 3, determine the constant μ_0 by plotting $B(n)$ for different turns for a fixed distance x and using the slope of the line you found.

Table 3.2

	n: 75 turns 2a: 26 mm	**n: 150 turns 2a: 26 mm**	**n: 300 turns 2a: 26 mm**	**n: 300 turns 2a: 33 mm**	**n: 300 turns 2a: 41 mm**
$\boldsymbol{x\ (mm)}$	$\boldsymbol{B_x\ (mT)}$	$\boldsymbol{B_x\ (mT)}$	$\boldsymbol{B_x\ (mT)}$	$\boldsymbol{B_x\ (mT)}$	$\boldsymbol{B_x\ (mT)}$
0					
10					
20					
30					
40					
50					
60					
70					
80					
90					
100					
110					
120					
130					

140					
150					
160					
170					
180					
190					
200					
210					
220					

Questions

1) Why do we use the Biot-Savart law?

2) Does electric current create a magnetic field?

3) Does a magnetic field create an electric field?

4) Write three units of the magnetic field.

5) Explain the constant μ_0.