Unit 18 Magnetic Fields

Teaching Periods 13 **Weightage %** 09

In 2021, Pakistan has become the first country in Asia and only the third outside the USA to acquire a portable MRI (magnetic resonance imaging) system in Karachi Sindh that can be wheeled directly to a patient's bedside and make MR imaging. MRI Machines uses strong magnetic fields to create detailed images of the inside of the human body.

In this unit student should be able to:

- Magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets.
- Describe and sketch field lines pattern due to a long current carrying straight wire.
- Describe the factors affecting the force on a current carrying conductor in a magnetic field.
- Solve problems using the equation F = BILsinθ, with directions as interpreted by Fleming's left-hand rule.
- Define magnetic flux density and the Tesla.
- Understand how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance.
- Describe the concept of magnetic flux (Ø) as scalar product of magnetic field (B) and area (A) using the relation Ø = B.A.
- State and explain Ampere's law.
- Explain solenoid and toroid. Solve problems to obtain Magnetic flux density of solenoid and toroid by Ampere's law.
- Explain that a force acts on a charged particle in a uniform magnetic field.
- Solve problems using F = qvBsinθ.
- Solve problems using F = Ø = B.A.
- Describe a method to measure the e/m of an electron by applying magnetic field and electric field on a beam of electrons.
- Describe the motion of electrons in an electric field and magnetic field using a Cathode Ray tube.
- Solve problems using related equations.
- Derivation and use of τ = BANI.
- Describe the construction and working of Galvanometer and Its conversion into Voltmeter, Ammeter, and Avometer.
- Understand the turning effect on a current carrying coil in a magnetic field.
- Solve problems using: $R_x = (\frac{V}{I_g}) - R_g$ and $R_s = (\frac{I_g}{I - I_g})R_g$

Introduction:

A magnetic field is a fundamental concept in physics that describes the region around a magnet or a current-carrying conductor where magnetic forces are exerted on other magnets, conductors, or charged particles.

Permanent magnets, such as iron magnets, have their own intrinsic magnetic fields due to the alignment of their magnetic domains.

Magnetic fields have numerous practical applications, including:

- Electric motors
- Transformers
- MRI machines (Magnetic Resonance Imaging)
- Magnetic levitation trains
- Magnetic compasses
- Magnetic data storage (hard disk drives)

18.1 Magnetic Fields:

Magnetic field can be defined as ***"An area around a permanent magnet or a current carrying conductor, where they generate a magnetic force".*** Unlike in electrostatics, where electric charges create an electric field and exert electric forces on other charges, the magnetic field lacks a direct counterpart due to the absence of magnetic monopoles.

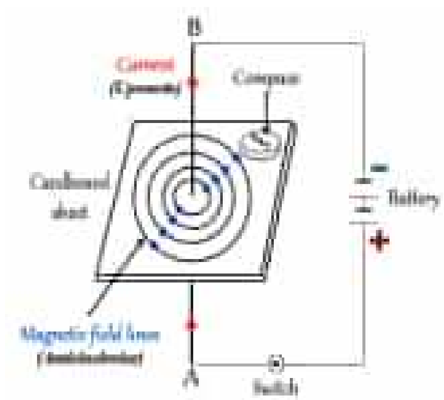


Figure 18. 1 (a) Current Carrying Wire

Magnetic fields can be generated through two primary methods:

- From permanent magnets.
- From current carrying conductors, also known as electromagnets

In 1819, Hans Christian Oersted made a significant discovery that revealed how a current Carrying conductor generates a magnetic field. The experiment depicted in Figure 18.1(a) clearly demonstrates this phenomenon. Simple setup consisting of a wire (AB) passing through a flat cardboard and connected to a battery via a switch. When the switch is closed, completing the circuit and enabling current flow through the wire, a circular magnetic field is generated around it. When iron fillings are scattered on to the cardboard, they become magnetized and arrange themselves in a circular pattern around the current-carrying wire. Additionally, a magnetic compass placed near wire AB indicates the direction of the magnetic field.

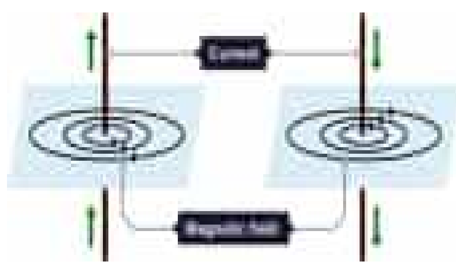


Figure 18.1 (b) Clockwise and Anticlockwise direction of magnetic fields

These observations illustrate that the magnetic field's direction produced by the current carrying wire follows the right-hand rule. According to this rule, when you grasp the wire with your right hand, your thumb points in the direction of the current, while the curl of your fingers indicates the direction of the magnetic field line. If the direction of the current is reversed, the needles also reverse their orientation. Conversely, if the current's direction is reversed, it generates a magnetic field in a clockwise direction. As shown in figure 18.1 (b).

18.2 Magnetic Force on a current carrying conductor:

Electric current is the orderly flow of charges through a conductor. As electrons move, they create a magnetic field around them, in addition to the electric field they produce. When it comes to a current-carrying conductor, the electric field generated by the moving electrons is counter balanced by the electric field produced by stationary protons within the conductor. Consequently, a magnetic field is produced around the current-carrying conductor.

When we place a current-carrying conductor with in a uniform External magnetic field, the interaction between the magnetic field produced by the conductor and the external magnetic field gives rise to external force, denoted as F, acting on the conductor, as illustrated in figure18.2.

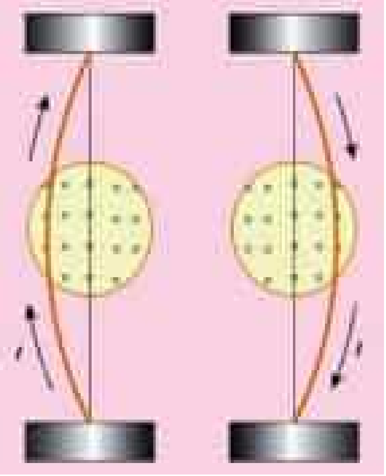


Figure 18.2 Magnetic Force on a current carrying conductor

A vertical wire is securely anchored at both ends and passes through a gap in a magnet. The external magnet generates a uniform magnetic field directed into the page. When a current flows upward through the wire, the wire deflects to the left. Conversely, reversing the current causes the wire to deflect to the right.

18.2.1 Factors on which the force acting on current carrying conductor in a magnetic field:

The force acting on a current-carrying conductor depends on several factors, such as, length, current, and the strength of the external magnetic field

The force (F) is directly proportional to the length of the conductor (L) that lies within the magnetic field

$$F \propto L$$

The force is also directly proportional to the current (I) passing through the conductor.

$$F \propto I$$

Similarly, the force is directly proportional to the strength of the external magnetic field (B).

$$F \propto B$$

Combining these factors, we will obtain the following relationship:

$$F \propto BIL$$

Here, 'k' is the proportionality constant, and in the SI unit system, its value is equal to 1. Therefore, we can express the force as: $F = BIL$…… (18.1)
If the magnetic field is not perpendicular to the wire, Equation (18.1) can be modified to:

$F = I\ (L \times B)$ where 'X' denotes the vector cross product.

The magnitude of the force **(F)** is determined by: $F = BILSin\theta$
Where, θ represents the angle between the direction of the conductor's length (***L***) and the external magnetic field (***B***).

Maximum Force:

The deflecting force reaches its maximum when the angle (θ) between the length of the conductor and the external magnetic field is θ = 90 degrees, assuming other factors remain constant.

Minimum Force:

Conversely, the deflecting force is minimized when θ=0 degrees, signifying that the magnetic field and conductor are aligned.
Since magnetic force is a vector quantity, its direction can be determined using Fleming's left-hand rule, which provides a straight forward way to establish the direction of the force in relation to the current and magnetic field.

Fleming's left-hand rule:

Fleming's left-hand rule is used to determine the direction of force acting on a current carrying wire placed in a magnetic field, also to identify the direction of the forces in an electric motor in order to apply Fleming's left-hand rule, follow these steps: Extends our fore finger, thumb, and Middle finger such that they are mutually perpendicular as shown in figure 18.3.

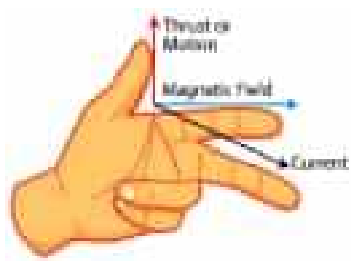


Figure 18. 3 Fleming's left-hand rule

Worked Example 18.1

A current carrying conductor of certain length placed at 90^0 to the magnetic field experiences a force F. What will be the force if the current is increased four times, length is halved and magnetic field is tripled?

Solution:

Step1: Write down the known quantities and quantities to be found.

I =*4I*, L = *L/2*, *B= 3B* $\acute{F}$ =?

Step2: Write down the formula and rearrange if necessary.

As we know that force on current carrying wire placed in magnetic field is

$$F = BIL\sin\theta$$

When current is increased four times, length is halved and magnetic field tripled then,
Force,

$$\acute{F} = (4I)\ x \left(\frac{l}{2}\right) x\ (3B)\ F = 6\,F.$$

Result: Therefore, the force increases six times.

Worked Example 18.2

A conductor of length 50cm carrying a current of 5A is placed perpendicular to a magnetic field of induction 2×10^{-3} T. Find the force on the conductor.

Solution:

Step1: Write down the known quantities and quantities to be found.

$I = 5A$, $L = 50\times10^{-2}$ m, $B = 2\times10^{-3}$ T, $F = ?$

Step2: Write down the formula and rearrange if necessary.

Force on the conductor

$$F = BIL = 5 \times 50 \times 10^{-2} \times 2 \times 10^{-3}$$

$$F = BIL = 5 \times 10^{-3}\ N$$

Result: Therefore, $F = 5\times 10^{-3}$ N

18.2.2 Magnetic Flux:

Magnetic flux is defined as **the number of magnetic lines of force passing through an area held perpendicular to it**. It is calculated by taking the dot product between the magnetic field and area vector. The dot product ensures that magnetic lines must pass perpendicular to the given area. Experimentally magnetic flux is usually measured with a Flux meter. Magnetic flux through an area A placed in uniform magnetic field (Figure18.4 is calculated by using formula as given below

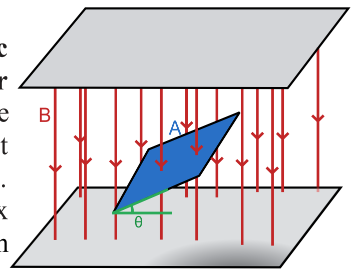


Figure 18.4 Magnetic Flux

$\phi_B = B.A$ **or** $\phi_B = BA\cos\theta$ ...(18.2)

Where B is uniform magnetic field, **A** is an area vector whose magnitude is equal to the surface element and directed perpendicular to the given surface element.

Maximum Magnetic Flux:

The magnetic flux will be maximum when the angle between magnetic field **B** and area vector **A** is zero, i.e. $=0^0$ and surface will be perpendicular to the magnetic lines. This case is shown in figure 18.5(a).

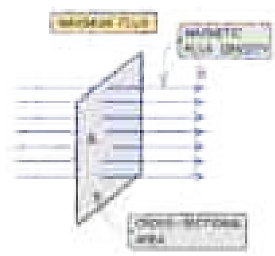


Figure 18.5 (a) Maximum Magnetic Flux

Minimum Magnetic Flux:

Similarly when the angle between area vector and magnetic field is 90^0 then lines of force donot pass through the surface and magnetic flux will be minimum as shown in figure18.5 (b).

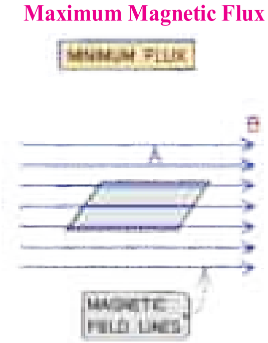


Figure 18.5 (b) Minimum Magnetic Flux

Unit of Magnetic Flux:

The SI unit of magnetic flux is Weber (Wb) =

$$1Wb = \frac{Nm}{A}$$

It is named after renowned German Physicist and co-inventor of telegraph.

$\emptyset_B = \boldsymbol{B.A}$, represents the magnetic flux $\emptyset_B$ through a surface (**A**) in a magnetic field (**B**). To solve problems using this formula, you will typically need to work with scenarios where you know the magnetic field strength(B) and the area(A) through which the magnetic field lines pass.

Worked Example 18.3

Calculate the magnetic flux through a rectangular loop with dimensions 5 cm × 10 cm placed in a magnetic field of strength 0.2 T. The loop is oriented such that the magnetic field lines are perpendicular to the plane of the loop.

Solution:

Step1: Write down the known quantities and quantities to be found.

Magnetic field strength (B)=0.2T

$$Area\ of\ the\ loop\ (A) = 0.05\ m \times 0.10m = 0.005\ m^2$$

Step2: Write down the formula and rearrange if necessary.

$$\emptyset B = BAcos\theta$$

Step 3: Put the values and calculate

$$\emptyset B = BAcos\theta$$

$$\emptyset_B = \boldsymbol{0.2T \times 0.005m^2 = 0.001\, Wb\ (Weber)}$$

Result: So, the magnetic flux through the rectangular loop is 0.001 Weber.

DO YOU KNOW?

The magnetic properties of the disk's platters and the read/write head's ability to generate and detect magnetic fields play a crucial role in storing, encoding, and accessing data in computer systems.

18.2.3 Magnetic Flux Density:

Magnetic flux density is described in relation to the magnetic force experienced by a current carrying conductor placed perpendicularly to a magnetic field. For a uniform magnetic field, the flux density B is expressed by the equation: $B = \frac{F}{IL}$

Hence magnetic flux density can be defined as:

The magnetic flux density at a specific point in space is the force experienced per unit length by along straight conductor carrying unit current, placed perpendicular to the field at that particular location.

Magnetic flux density is most pronounced near the pole of a bar magnet and gradually decreases with distance from it.

Unit of Magnetic Flux Density:

The SI unit of magnetic flux density is Tesla (T), named after the Serbian-American inventor Nikola Tesla.

One Tesla: is defined as follows, If a conductor having length 1m and carries a current of 1 A placed perpendicularly to the magnetic field experience a force of one Newton then magnetic flux density will be 1Tesla.

In essence, the Tesla provides a standardized measure of the strength of a magnetic field, with larger values indicating stronger magnetic fields and smaller values representing weaker fields.

18.3 Measurement of Magnetic Flux density by current balance:

A simple experimental setup designed for the measurement of flux density between two magnets, As shown in figure 18.6. The magnetic field within this magnet configuration is uniform. To measure the length (L) of the current-carrying wire within this uniform magnetic field, a ruler can be used. When the wire carries no current, the magnet arrangement is positioned on top of balance, and the balance is calibrated to read zero. Subsequently, when an electric current (I) flows through the wire, the ammeter displays its magnitude. The wire experience an upward force, and in accordance with Newton's third law of motion, an equal and opposite force acts upon the magnets. Consequently, the magnets are pushed down wards, causing the balance to indicate a reading. The force (F) can be calculated as F = mg, with 'm' representing the mass indicated on the balance in kilograms and 'g' representing the acceleration due to gravity ($9.81ms^{-2}$).

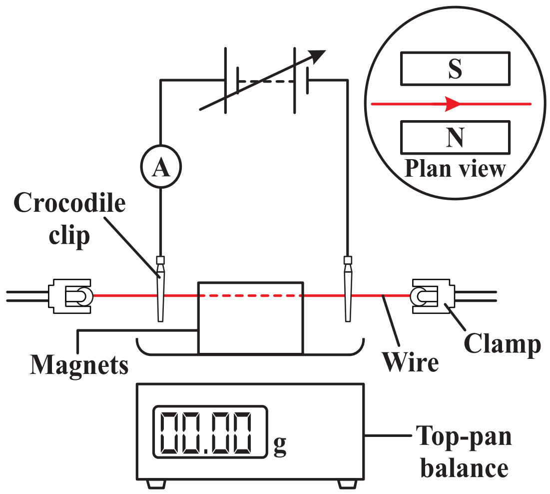


Figure 18.6
Experimental setup for the measurement of flux density

With the knowledge of F,I, and L, one can
Determine the magnetic flux density (B) between the magnets using the following equation

$$B = \frac{F}{IL} \ldots\ldots\ldots (18.3)$$

18.4 Amperes Law:

Ampere's Law is an important principle in electromagnetism. It deals with the behavior of electric currents and their associated magnetic fields. It is named after Andre-Marie Ampere, a French physicist and mathematician who made significant contributions to the study of electromagnet is mid the 19th century.

It is known that an electric current flowing through a wire creates a magnetic field in its vicinity. When we envision a closed circular path with the wire positioned at its center, the Magnetic flux density (B) within this circular region changes, depending on both the current (I) and the distance (r) from the wire as shown in figure18.7.

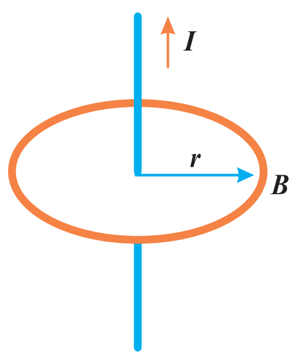


Figure 18.7
Current carrying wire

$$\boldsymbol{B \propto 2I} \text{................(i)}$$

$$\text{Or } \boldsymbol{B \propto \frac{1}{r}} \text{ ....(ii)}$$

Combing (i) and (ii), we get

$$\boldsymbol{B \propto \frac{2I}{r}}$$

$$\boldsymbol{B = \frac{\mu_0 I}{2\pi r}}$$

Where μ_0 is permeability of free space = $4\pi \times 10^{-7}$ Wb A^{-1} m^{-1}

Now consider an Amperian loop in form of a closed path around the current carrying wire as shown in figure 18.7. For any path element ΔL we can write

$$B.\Delta L = \mu_0 I$$

Since angle between B and L is zero so $B.\Delta L = B\Delta L = \mu_0 I$

Now adding up over whole closed path

$$\sum B.\Delta L = \mu_0 I \text{ ....(18.4)}$$

Equation (18.4) is the mathematical expression of Ampere law. Hence Ampere's law can be defined as the integral of the magnetic field (**B**) around a closed loop is directly proportional to the total electric current (**I**) passing through the loop.

Application of Ampere's Law:

(i) Solenoid:

A solenoid is along, tightly wound coil of wire, and often used to generate a uniform magnetic field within the coil's interior. It consists of many closely spaced turns of wire, and when an electric current flow through it, it creates a magnetic field that is similar to the field produced by a bar magnet. To determine the magnitude of B of a solenoid let us Consider an Amperian loop abcd with lengths $l_{ab}l_{bc}$, $l_{cd}$and l_{da}as shown in figure18.8.

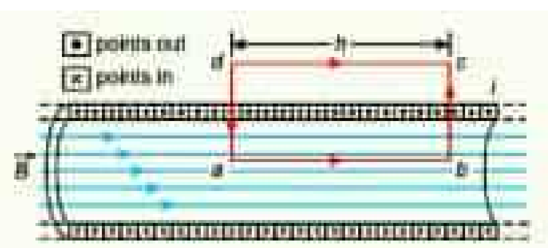


Figure 18.8 Amperian loop Solenoid

Then from Ampere's law

$$\sum B.\Delta l = \mu_o I$$

The left hand side of equation is

$$\sum B.\Delta l = B.l_{ab} + B.l_{bc} + B.l_{dc} + B.l_{da}$$

As the element al lengths along bc and da are perpendicular to the magnetic field so

$$B.l_{bc} = 0 and B.l_{da} = 0$$

Moreover, the magnetic field intensity outside of solenoid ≈ 0, so $B.l_{cd}=0$

Hence the magnetic field due to solenoid is given by

$$\sum B.\Delta l=B.l_{ab}=\mu_0 I$$

For N number of turns on the solenoid

$$\sum B.\Delta l=B.l_{ab}=\mu_0 NI$$

The number of turns per unit length is given by $\boldsymbol{n} = \dfrac{\boldsymbol{N}}{\boldsymbol{l_{ab}}}$

$$B = \mu_o nI$$

Hence it is shown that B is independent of the position within the solenoid which shows that the field is uniform with in a solenoid.

Worked Example 18.4

Suppose we have a solenoid with 500 turns per meter and a current of 2.5 amperes flowing through it. Calculate the magnetic flux density inside the solenoid.

Solution:

Step1: Write down the known quantities and quantities to be found.

The no of turns = 500I = 2.5A

$\mu_0 = 4\pi \times 10^{-7}$

Magnetic flux density inside the solenoid,

(B) = ?

Step2: Write down the formula and rearrange if necessary.

$$\boldsymbol{B = \mu_o nI}$$

Step 3: Put the values and calculate.

$\boldsymbol{B = \mu_o nI}$

$B = 4\pi \times 10^{-7} \times 500 \times 2.5$

$B = 3.14 \times 10^{-3}$ T B = 3.14 mT

Result: So, the magnetic flux density inside the solenoid is 3.14 milli-tesla.

(ii) Toroid:

A toroid can be considered as a solenoid that is bent into the shape of a circle. It also generates a magnetic field within its interior. The magnetic field lines inside a toroid are generally circular and concentrated within the coil.

Suppose a toroid consist of N closely packed turns of copper wire and carry a current I as shown in 18.9.

Imagine a hollow circular ring wound with N number of turns of current-carrying wire. In this case, within the toroid, point P is our point of interest, and we will denote the magnetic field at this location as B. Inside the toroid, we construct an Amperian loop forming a circle that passes through point P. This

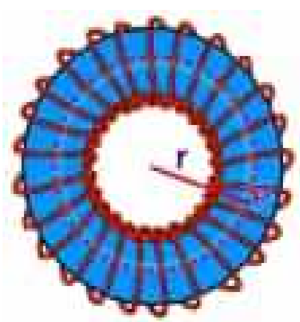


Figure 18.9 A toroid

arrangement gives rise to concentric circles within the toroid.
Because of the symmetrical nature of the magnetic field, the magnitude of the field at all points along the circle is uniform, and the field direction is tangential to the circle.
Therefore,

$$\sum B.\Delta l = \sum B\Delta l Cos(0) = B\sum \Delta l = (2\pi r)$$

Now, we can apply Ampere's law:

$$(2\pi r) = \mu_0 NI$$
$$B = \mu_0 \frac{NI}{2\pi r}$$

This is the expression for the magnetic field strength inside a toroid. It is inversely proportional to the radius r and directly proportional to the number of turns per unit length N and the current I flowing through the turns.

Worked Example 18.5

Suppose we have a toroid with 1000 turns and a current of 3 amperes flowing through it. The toroid has a circular cross-section with a radius of 0.1 meters. Calculate the magnetic flux density inside the toroid.

Solution:

Step 1: Write down the known quantities and quantities to befound.

The no of turns = 500I = 2.5A

$\mu_0 = 4\pi \times 10^{-7}$

Magnetic flux density inside the solenoid,

(B) = ?

Step 2: Write down the formula and rearrange if necessary.

$$B = \mu_0 \frac{NI}{2\pi r}$$

Step 3: Put the values and calculate

$$B = \mu_0 \frac{NI}{2\pi r}$$
$$B = (4\pi \times 10^{-7} \times 1000 \times 3)/(2\pi \times 0.1)$$
$$B = (4\pi \times 10^{-7} \times 1000 \times 3)T$$
$$B = 3.77 \times 10^{-3} T \ or\ B = 3.77 mT$$

Result: ***The magnetic flux density inside the toroid is 3.77milli-tesla.***

18.5 Force on a charged particle in a uniform magnetic field:

When a charged particle moves through a uniform magnetic field, it experiences a force known as the magnetic force. This phenomenon is described by the Lorentz force equation, which can be written as: $\vec{F} = (\vec{v} \times \vec{B})$.

In the equation, the magnitude of the charge (|q|): Determines the strength of the magnetic force. A higher charge magnitude results in a stronger force.

Velocity of the Particle (v):

The magnetic force depends on both the magnitude and direction of the velocity vector. If the particle is stationary (v = 0), it would not experience a magnetic force, as there is no velocity to interact with the magnetic field.

Magnetic Field (B):

The magnetic field vector, denoted as $\vec{B}$, represents the strength and direction of them agentic field in which the charged particle is located. A uniform magnetic field means that the strength and direction of the magnetic field are constant throughout the region. It is often represented by parallel magnetic field lines.

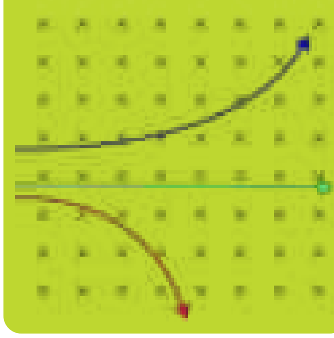
Cross Product ($\vec{v}\times\vec{B}$):

The key to understanding the magnetic force is the cross product $(\vec{v}\times\vec{B})$ in the Lorentz force equation. The cross product results in a force that acts perpendicular to both the velocity vector($\vec{v}$) and the magnetic field vector($\vec{B}$).The direction of this force is determined by the right-hand rule, which states that if you point your right thumb in the direction of the particle's velocity ($\vec{v}$) and your fingers in the direction of the magnetic field ($\vec{B}$) then the force ($\vec{F}$) will be directed perpendicular to both,either into or out of the palm of your hand, depending on the charge of the particle.

When a charged particle moves through a uniform magnetic field, a magnetic force is exerted on it. This force is always perpendicular to both the particle's velocity and the direction of the magnetic field. The charged particle will follow a curved path due to this force, known as a helical or circular trajectory, depending on the initial conditions and the specifics of the situation. The magnitude of the force depends on the charge, the velocity, and the strength of the magnetic field.

DO YOU KNOW?

When a proton, electron and neutron enters in uniform magnetic field points into the page then the neutron goes undeflected, the proton and electron moves upward and downward respectively



18.5.1 Charge to mass ratio of Electron:

Measuring the charge-to-mass ratio (e/m) of an electron is a classic experiment in the field of electromagnetism and particle physics. This experiment, known as the "e/m experiment, "involves applying both a magnetic field and an electric field to a beam of electrons. Here's a step-by-step method to measure the e/m of an electron:

Apparatus and Materials:

1. **Cathode Ray Tube (CRT)**: This is a vacuum tube that produces a beam of electrons. It consists of an electron gun, focus in, deflection plates, and a fluorescent screen as shown in figure 18.10.
2. **Magnetic Field Source**: We'll need a strong and uniform magnetic field source, such as a Helmholtz coil or a solenoid.
3. **Voltage Source**: A variable voltage source to create an electric field.
4. **Fluorescent Screen:** A screen coated with a phosphorescent material to visualize the electron beam.
5. **Rulers and Measurement Devices**: To measure the radius of the electron beam's circular path and the electric potential applied.

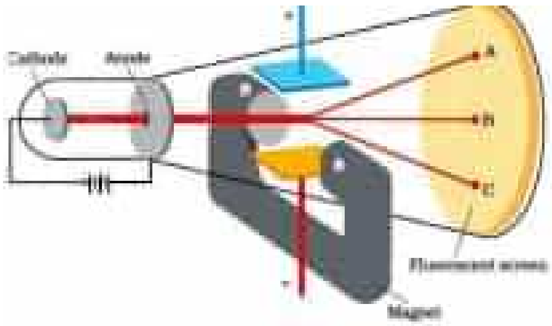


Figure 18.10 Cathode Ray Tube (CRT)

Experimental Procedure:

1. **Setup**:
   - Set up the CRT in a vacuum chamber to ensure the electron beam doesn't interact with air molecules.
   - Position the Helmholtz coil (or solenoid) around the CRT, providing a uniform magnetic field parallel to the beam path.
   - Connect the voltage source to the focusing and deflection plates to create an electric field perpendicular to the magnetic field.
2. **Calibration**:
   - Calibrate the magnetic field by measuring its strength at the location of the electron beam. We can do this using a magnetic field strength meter.
3. **Electron Beam Production**:
   - Apply a high voltage across the cathode and anode of the CRT to generate a beam of electrons from the cathode (electron gun).
   - Use the focusing and deflection plates to control and direct the electron beam.
4. **Observe the Electron Beam:**
   - Turn off the magnetic field and electric field to observe the electron beam's straight-line path on the fluorescent screen.
5. **Apply the Magnetic Field:**
   - Turn on the magnetic field, which causes the electron beam to bend in a circular path due to the Lorentz force (the interaction between the magnetic field and the moving electrons).
6. **Measure the Radius(r):**
   - Measure the radius of the circular path formed by the electron beam on the screen. Ensure the screen is marked with a scale for accurate measurement.

7. **Apply the Electric Field:**
   - Apply a known electric potential (voltage) across the focusing and deflection plates perpendicular to the magnetic field. This will introduce an electric force on the electrons.
8. **Adjust the Voltage:**
   - Adjust the voltage until the electron beam returns to its original, undeflected straight-line path.
9. **Measure the Electric Potential (V):**
   - Measure the voltage applied across the plates.

Calculations:

An electron is released from cathode and it gains speed while passing through the potential difference *V*, hence gaining kinetic energy of 1eV. This electron kinetic energy is calculated by:

$$\frac{1}{2}mv^2 = V_e$$

The magnetic field produced by Helmholtz coils is perpendicular to this velocity, and produces a magnetic force which is transverse to both v and B: this provides the centripetal force makes an electron move along the circular trajectory; the radius of this trajectory r can be found from

$$\frac{mv^2}{r} = qvB$$

From this equation, we obtain the expression for the charge-to-mass ratio of the electron,

$$\frac{e}{m} = v/rB$$

Using the measured values for the radius (r), magnetic field strength (B), and electric potential (V), we can calculate the e/m ratio of the electrons which was found to be 1.7588×10^{11} C/kg

18.6 Measuring Instruments:

Galvanometer:

A Galvano meter is an instrument used to detect and measure electric currents. It is a highly sensitive electromagnetic apparatus capable of measuring even very small currents, such as those on the order of a few micro amperes.

Figure 18.11 Galvanometer

Principle:

It works based on the principle of electromagnetic induction. When a coil carrying an electric current is positioned within an external magnetic field, it undergoes magnetic torque. The degree of deflection observed in the coil, caused by this magnetic torque, is directly proportional to the current's magnitude flowing through the coil.

Construction:

1. **Coil**: The key component of a Galvano meter is a coil of wire (usually wound around as oft iron core) suspended within a magnetic field. The coil is mounted on a spindle so that it can rotate freely.
2. **Magnet**: A permanent magnet or an electromagnet is placed around the coil. The magnetic field lines from the magnet pass through the coil.
3. **Spring**: A delicate torsion spring is attached to the coil, providing a restoring torque when the coil is deflected.
4. **Pointer**: A thin pointer or needle is attached to the coil, allowing for the measurement of the deflection.

Figure 18.12 schematic diagram of Galvanometer

Working:

- When a small electric current flow through the coil, it generates a magnetic field around the coil according to Ampere's law. This magnetic field interacts with the external magnetic field (provided by the permanent magnet or electromagnet) to exert a torque on the coil.
- The torque causes the coil to rotate, and the amount of rotation is proportional to the current passing through it. This rotation is indicated by the deflection of the pointer on a calibrated scale.
- The coil continues to rotate until the restoring torque from the spring equals the torque due to the current-induced magnetic field. At this point, the pointer comes to rest, and its position on the scale indicates the magnitude of the current.
- Consider a rectangular coil consisting of N turns, each with a current I flowing through them and across-sectional area A. When this coil is situated within a uniform radial magnetic field B, it undergoes a torque as shown in figure 18.13.

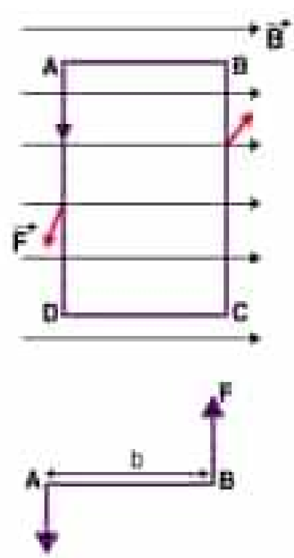


Figure 18.13 torque on rectangular coil

- Let's examine a single turn ABCD of the rectangular coil, characterized by a length L and breadth b as shown in figure 18.13. This turn is suspended within a magnetic field with strength of B, arranged so that the coil's plane is parallel to the magnetic field lines. As sides AB and DC are aligned parallel to the magnetic field, they donot experience any discernible force due to the magnetic field. However, sides AD and BC, which are perpendicular to the field's direction, encounter an effective force denoted as F, given by the equation F= BIl.
- By employing Fleming's left-hand rule, we can recognize that the forces acting on sides AD and BC are oriented in opposite directions to each other. When a pair of equal and

opposite forces, denoted as F and collectively referred to as a couple, act on the coil, they generate a torque. This torque induces a deflection in the coil.

- The torque(τ) is calculated as the product of the force(F) and the perpendicular distance (b) between these forces: $\tau = F \times b$
- Substituting the known value of F, we have:
  Torque(τ) acting on a single-loop ABCD of the $coil = BIL \times b$
  Where $L \times b$ represents the area (A) of the coil. Consequently, the torque acting on a coil with nturnsis given by: $\tau = NIAB$

This magnetic torque causes the coil to rotate, leading to the twisting of the phosphor bronze strip. Simultaneously, the spring (S) attached to the coil exerts a counter-torque, known as there storing torque (kθ), resulting in a stable angular deflection.

Under equilibrium conditions, we find: $k\theta = NIAB$

Here, k is termed the torsional constant of the spring, representing the restoring couple per unittwist. The deflection or twist (θ) is quantified as the reading displayed on a scale by a pointer connected to the suspension wire.

$$\theta = (NAB/k)I$$

Therefore $$\theta \propto I$$

The quantity (NAB / k) is a constant for a given galvanometer. Therefore, it is evident that the deflection observed in the galvanometer is directly proportional to the current flowing through it.

18.6.2 Conversion of Galvanometer to Ammeter:

To convert a galvanometer into an ammeter, a low-resistor known as a shunt is connected in parallel with the galvanometer. The selection of an appropriate shunt is based on the desired current range of the ammeter.

From the circuit as shown in figure 18.14.

- R_g represents the resistance of the galvanometer.
- G denotes the Galvanometer coil.
- I stand for the total current flowing through the circuit.
- I_g represents the total current passing through the galvanometer, which corresponds to the full-scale reading.
- R_S represent the value of the shunt resistance.

When the current Ig lows through theGalvano meter, the current passing through the shunt is determined by

$$I_s = I - I_g.$$

The voltages across both the galvanometer and shunt are equal due to their parallel connection.

Hence, we can establish the following equation:

$$R_g I_g = (I - I_g) \times R_s$$

$$R_s = \frac{R_g I_g}{I - I_g}$$

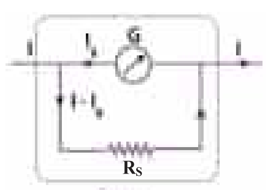


Figure 18. 14
Ammeter and its schematic diagram

Worked Example 18.6

A moving coil galvanometer of resistance 100Ω is used as an ammeter using a Shunt of 0.1Ω. The maximum deflection current in the galvanometer is 100µA. Find the current in the circuit so that the ammeter gives maximum deflection.

Solution:

Step1: Write down the known quantities and quantities to be found.

R_g=100Ω Rs= 0.1Ω, I_g=100µA

Step2: Write down the formula and rearrange if necessary.

$R_g \times I_g = (I - I_g) \times R_S$

Step 3: Put the values and calculate.

$$I = \frac{(R_g \times I_g + g \times Rs)}{Rs}$$

$$I = (1 + \frac{R_g}{Rs}) \times I_g$$

Result: We get $I = 100.1mA$

Conversion of Galvanometer to Voltmeter

A galvanometer is converted into a voltmeter by connecting it in series with high resistance as shown in figure 18.15. A suitable high resistance is chosen depending on the range of the voltmeter.

- ✓ R_g stands for the resistance of the galvanometer.
- ✓ R_X represents a high resistance component called series resistance.
- ✓ G denotes the galvanometer coil.
- ✓ I is the total current flowing through the circuit.
- ✓ I_g signifies the total current passing through the galvanometer, corresponding to a full scale deflection.
- ✓ V represents the voltage drop across the series connection of the galvanometer and the high resistance.

  When the current I_g flows through the series combination of the galvanometer and the highresistance R, the voltage drop across the branch ab can be expressed as:

$$V = V_g + V_x$$

Current in series combination remain conserved therefore;

$$I_g = I_X$$

$$V = I_g R_g + I_g R_X$$

$R_x = V - I_g R_g / I_g$

$R_x = \frac{V}{I_g} - R_g$

This equation can be used to determine the value of RX.

**Figure 18. 15
Voltmeter and its schematic diagram**

Worked Example 18.7

A galvanometer coil of 40Ω resistance shows full range deflection for a current of 4mA. How can this galvanometer be converted into a voltmeter of range 0-12V?

Solution:

Step 1: Write down the known quantities and quantities to be found.

$R_g = 40\Omega$, V = range 0-12 V $I_g = 4mA = 4\times10^{-3}A$

Step 2: Write down the formula and rearrange if necessary.

$V = I_g(R_g+R_X)$

Step 3: Put the values and calculate.

$$R_X = \frac{V}{I_g - R_g}$$

$R_X = (12/(4\times10^{-3}))-40$

$R_X = 2960\Omega$

Result: we get $\mathbf{R_X = 2960\Omega}$

SUMMARY

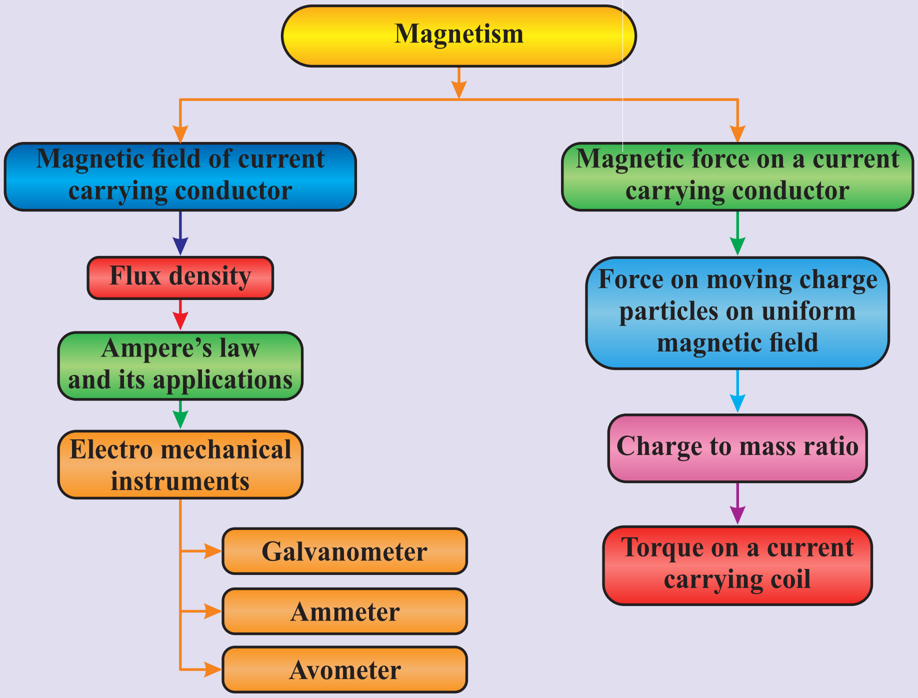
- ✓ Magnetic Field: The area around a permanent magnet or current-carrying conductor where a magnetic force is generated is called a magnetic field.
- ✓ Magnetic Force: The force exerted on a wire carrying current I in a uniform magnetic field is given by the formula: F=BILSinθ
- ✓ Measuring Magnetic Flux Density: A current balance can be used to measure magnetic flux density.
- ✓ Ampere's Law: This law quantifies how a current creates a magnetic field around it, providing a mathematical relationship between current and magnetic field strength.
- ✓ Solenoid: A long, tightly wound coil of wire used to generate a uniform magnetic field within the coil's interior. The magnetic field inside a solenoid is given by: $B=\mu_0 nI$
- ✓ Toroid: A solenoid curved to form a circular shape. The magnetic field strength inside a toroid is given by: $B = \frac{\mu o NI}{2\pi r}$ .This formula shows that the magnetic field strength is inversely related to the radius rand directly related to the number of turns per unit length N and the current I passing through the turns.
- ✓ The shunt resistance for a ammeter is given by

$$R_s = \frac{R_g I_g}{I - I_g}$$

- ✓ In case of voltmeter the high resistance is given by

$$R_X = V - \frac{I_g R_g}{I_g}$$

CONCEPT MAP



EXERCISE

Section (A): **Multiple Choice Questions (MCQs)**

Choose the correct answer:

1. If were verse the direction of electric current, then the direction of magnetic field will be:
   (a) Same (b) reversed
   (c) tangent (d) normal
2. The application of magnetic field is:
   (a) microwave oven (b) magnetic levitation trains
   (c) electrolysis (d) plant photosynthesis
3. The equation $F=BIL$ can only be used, if the magnetic field, length of conductor, and electric current are:
   (a) At right angles to each other (b) in same direction
   (c) Anti-parallel to each other (d) anti-perpendicular to each other

4. The charge on a particle is doubled, and its velocity remains the same, how then the magnetic force on the particle will be:
   (a) doubled (b) halved
   (c) Is the same. (d) quadrupled
5. Strength of magnetic field of solenoid can be increased by:
   (a) Increasing number of turns
   (b) decreasing number of turns
   (c) increasing the current through the solenoid
   (d) inserting a ferromagnetic core (e.g., iron) into the solenoid
6. The magnetic field inside along solenoid is:
   (a) equal to zero
   (b) uniform
   (c) decreases as we go away from the center to surface
   (d) increases as we go to wards the surface
7. The force between two current carrying conductor arises due to
   (a) Magnetic effect of current (b) Polarization
   (c) Electromagnetic induction (d) Electrostatic interaction
8. To measure a higher voltage, what should you do with the voltmeter's internal resistance?
   (a) Increase it (b) Decrease it
   (c) Keep it the same (d) It doesn't affect the measurement
9. A proton moves perpendicular to a uniform magnetic field. What is the direction of the force experienced by the proton?
   (a) Parallel to the magnetic field (b) In the direction of the proton's velocity
   (c) Perpendicular to the magnetic field and the proton's velocity
   (d) Opposite to the direction of the proton's velocity
10. An electron moves parallel to a uniform magnetic field. What is the magnitude of the force experienced by the electron?
   (a) Maximum, since the electron is moving in the same direction as the field
   (b) Minimum, since the electron is moving perpendicular to the field
   (c) Zero, since the electron is moving parallel to the field
   (d) Depends on the speed of the electron

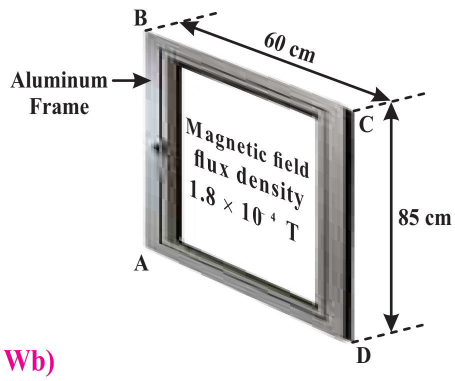
Section (B): CRQs (Short Answered Questions):

1. Charge particles are fired in vacuum tube hit a fluorescence screen. Will it be possible to know whether they positive or negative?
2. What is a solenoid, and how does it differ from a simple coil of wire?
3. Can a solenoid generate a magnetic field without any current flowing through it? Why or why not?
4. Explain why a toroid is often preferred over a straight solenoid when designing certain types of electrical components.
5. What role does the Ampere’s circuital law play in understanding them agnetic field inside a toroid?
6. What is a galvanometer, and what is its primary function in an electrical circuit?

Section (C): ERQs (Long Answered Questions):

1. Can a galvanometer measure both DC and AC currents? Explain any limitations it might have with AC measurements.
2. Why should an ammeter ideally have a very low resistance compared to the circuit it is measuring?
3. What is the potential risk of using a voltmeter with a high internal resistance in a circuit? How can this risk be mitigated?
4. Describe the basic working principle of a voltmeter. How does it measure voltage across a component in a circuit?

Section (D): Numerical:



1. An aluminum window has a width of 60 cm and length of 85 cm as shown in the figure.
   a. When the window is closed the magnetic flux density is 1.8×10^{-4} Tisnormal to window.
   b. Calculate the magnetic flux through the window. **(9.18×10^{-5} Wb)**
2. The poles of a horse shoe magnet measures 8Cm × 3.2cm.the magnetic flux density between the magnet poles is 80mT. Outside of the magnet the magnetic flux density is zero. Calculate the magnetic flux density between the poles of a magnet.**(2.048×10^{-4}Wb)**
3. A wire 1.80 m long carries a current of 13.0 A and makes an angle of 35.0° with a uniform magnetic field of magnitude B = 1.50T. Calculate the magnetic force on the wire. **(19.46 N)**
4. A solenoid has length L = 1.23 m and inner diameter d = 3.55 cm, and it carries a current I= 5.57 A. It consists of five close-packed layers, each with 850 turns along length L. What is B at its center? **(Ans:24.2mT)**
5. A moving coil galvanometer has resistance of 50 Ω and it gives full scale deflection at4mA current. A voltmeter is made using this galvanometer and a 5KΩ resistance. Calculate the maximum voltage that can be measured using this voltmeter. **(Ans:20.2V)**
6. Compute the magnitude of the magnetic field of a long, straight wire carrying a current of 1A at distance of 1m from it. Compare it with Earth's magnetic field. **(Ans:$2\times10^{-7}$and 100times than earth field)**
7. Find the current in a long straight wire that would produce a magnetic field twice the strength of the Earth's at a distance of 5.0cm from the wire. (Magnetic field of Earth $=5.0\times10^{-5}$T). **(Ans:25A).**
8. What is flux density atadistanceof0.1m in air from along straight conductor carrying a current of 6.5 A. calculate the force per on a similar parallel conductor at a distance of 0.1m from the first and carrying a current of 3A. **(Ans: 13×10^{-6}Weber/m^2$39\times10^{-6}$N).**