

Chapter = 14

Electromagnetism

Electric current produces magnetic field.

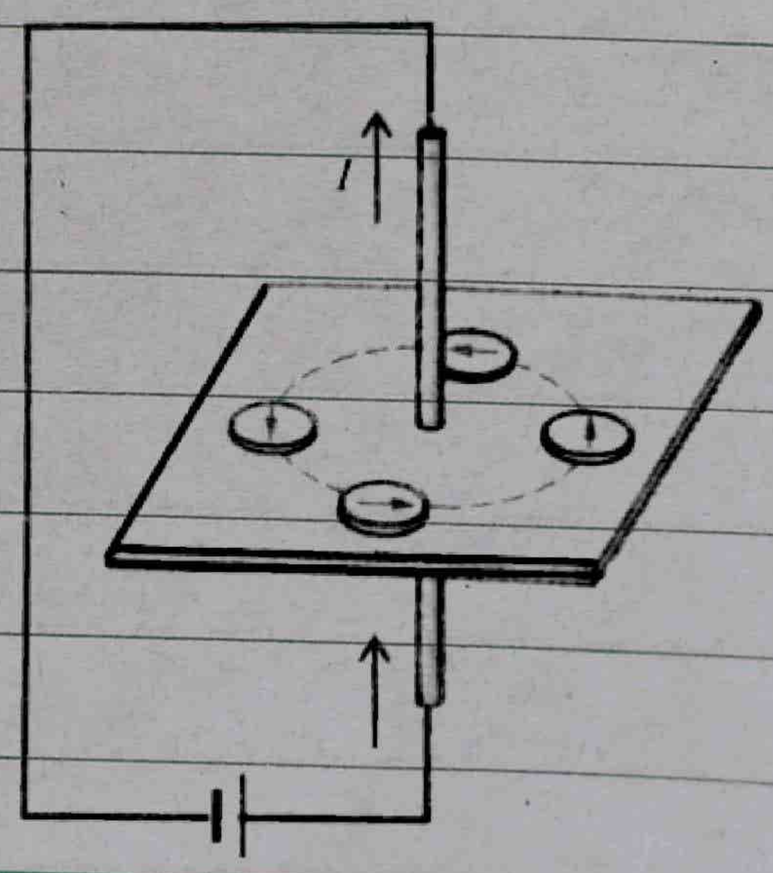
At the same time, a changing magnetic field produces electric current.

This interplay of electricity and magnetism is widely used in electrical devices.

14.1 Magnetic field due to current in a long straight wire

Experiment:

Take a straight thic cooper wire. Pass it vertically through a hole in horizontal card board. Place small compas needles along a circle with the centre at the wire. All the compas needles will



point in the North - South (N-S) direction.

Now pass a point in the wire. It is seen that the needles will rotate and will set themselves tangential to the circle in fig.

On reversing the direction of the current, the direction of the needels is also reversed.

When the current through the wire is stopped, all the needles again point in N-S direction.

Conclusions:

i) A magnetic field is set up in the region sorrounding a current carrying wire. Magnetic field strength B is directly proportional to the current and inversely proportional to the distance from the wire.

$$B \propto I \quad ; \quad B \propto \frac{1}{r}$$

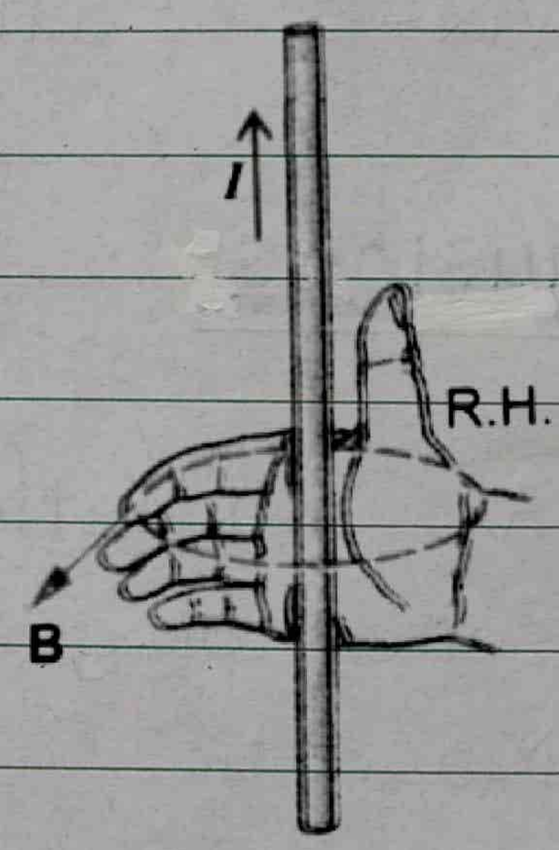
ii) The magnetic lines of force are circular and their direction depends upon the direction of current.

iii) The magnetic field lasts only as long as the current is flowing through wire.

Right hand rule:

The direction of lines of force is found by the right hand rule.

"If the wire is grasped in the fist right hand with the thumb pointing in the direction off the current, the fingers of the right hand will circle the wire in the direction of the magnetic field."

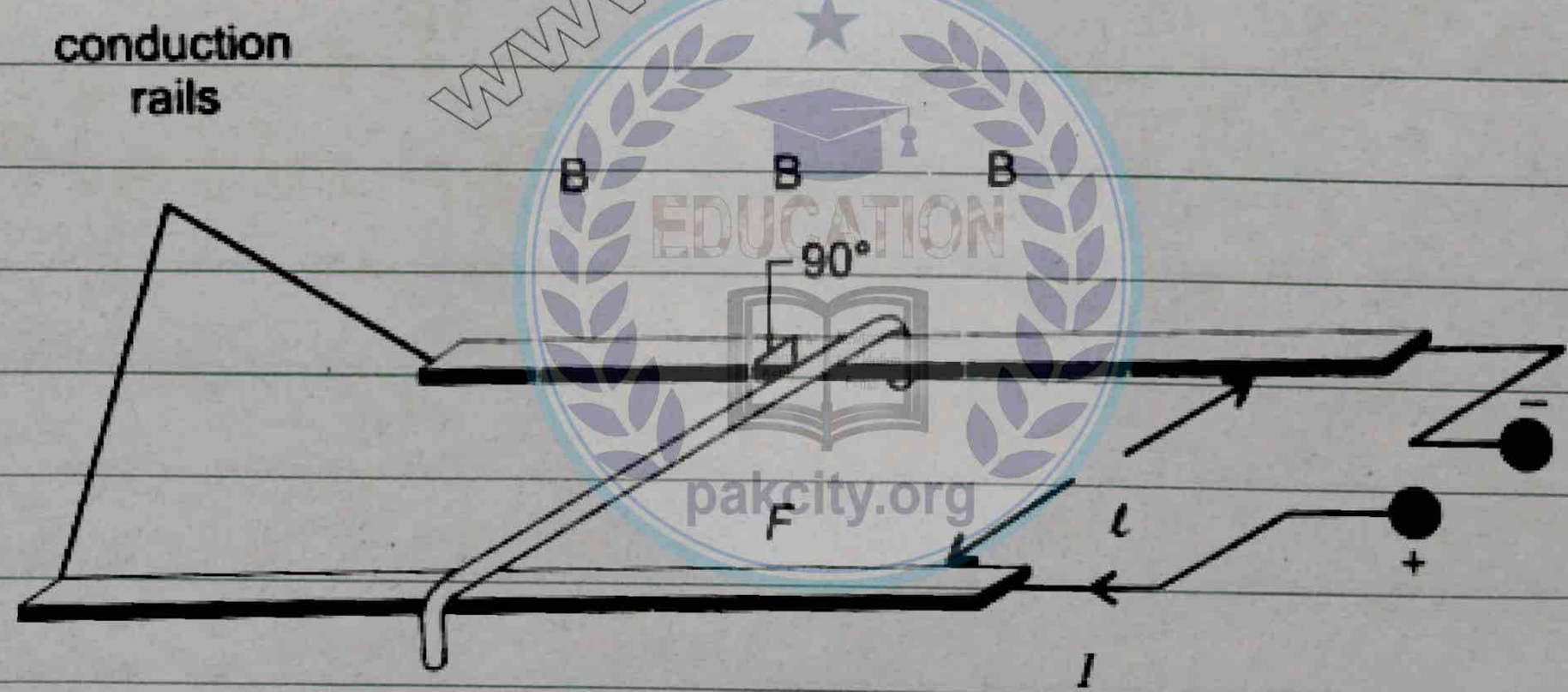


14.2 Force on a current carrying conductor placed in a uniform magnetic field.

We know that a current carrying conductor produces its own magnetic field.

If such a conductor is placed in an external magnetic field, the magnetic field of conductor interacts with the external magnetic field.

As a result, the conductor may experince a force.



Consider a rod of copper, which can move on a pair of copper rails. The whole arrangement is placed between the pole of pieces of a horseshoe

magnet.

The magnetic field of the horse-shoe magnet is directed vertically up wards.

When a current is passed through the copper rod from a battery, the rod moves on the rails.

The direction of the current magnetic field and force (motion of the conductor) is shown in fig 1.

It can be seen that the force on a conductor is always perpendicular to the plane containing the rod and the direction of the magnetic field.

The magnitude of the force depends upon the following factors.

1- $F \propto \sin \alpha$

Force is proportional to $\sin \alpha$. α is the angle between the direction of flow of current rod and magnetic field.

i) If the rod is parallel to the magnetic field force is zero

$F \propto \sin \alpha$; $\alpha = 0^\circ$

$\sin 0^\circ = 0$

$F = 0$

ii) If the rod is perpendicular to the magnetic field force is maximum.

$F \propto \sin\alpha$

$\sin 90^\circ = 1$

$\alpha = 90^\circ$ (max. value)

2- $F \propto I$

The force is directly proportional to the current flowing through the conductor.

3- $F \propto L$

The force F is directly proportional to the length L the conductor inside the magnetic field.

4- $F \propto B$

The force F is directly proportional to the applied magnetic field.

Combining all these factors.

$F \propto ILB \sin\alpha$

$F = ILB \sin\alpha$

In SI-unit, the constant of proportionality $k = 1$.
So, in SI units.

$$F = ILB \sin\alpha \longrightarrow (1)$$

$$B = \frac{F}{IL \sin\alpha}$$

$$B = \frac{F}{1A \cdot 1m \cdot \sin 90^\circ}$$

$$B = \frac{F}{1 \cdot 1 \cdot 1}$$

$$B = F.$$

$$B = \text{Force}$$

The strength of the magnetic field B is also know as Magnetic Induction B.

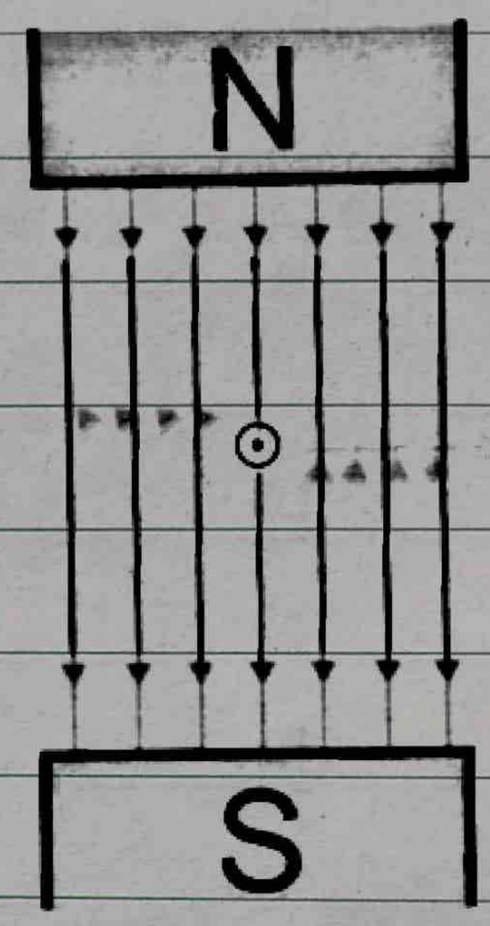
Defination:

The magnetic inductin B is defined as the force acting on one meter length of the conductor placed at right angle to the magnetic field, when 1A current is passing through it.

The SI-unit of B is Tesla.

Tesla:

"The magnetic field strength or magnetic induction B is one tesla, if it exerts a force of one Newton on one meter length of the conductor placed at right angle to the field. when a current of one ampere is passing through the conductor."



$$B = \frac{F}{ILSin\ \alpha}$$

$$B = \frac{1N}{1A \cdot 1M\ Sin 90^\circ}$$

$$B = \frac{N}{A \cdot M}$$

$$Tesla = \frac{N}{A \cdot M}$$

$$\boxed{T = NA^{-1}m^{-1}}$$

Eq. (1) can be written in vector form.

$$\boxed{\vec{F} = I(\vec{L} \times \vec{B})}$$

The direction of $\vec{L}$ is in the direction of flow of current.

$$\vec{F} = I(\vec{L} \times \vec{B}) \sin\alpha\, n$$

Its magnitude $F = ILB \sin\alpha$

α = Angle between $\vec{L}$ and $\vec{B}$

The direction of force $\vec{F}$ is given by the right hand rule of the cross product.

An other rule of to find the direction of force $\vec{F}$.

Consider a straight current carring conductor held at right angle to magnetic field.

Current through the conductor is out of the plane of the paper i.e towards the reader as shown in fig (1).

It is a convention to represent a current flowing towards a reader by a dot (•) and current flowing away from the reader by a cross (x).

This direction of force is same as given as by the direction of the vector $\vec{F} = I(\vec{L} \times \vec{B})$ given by the right hand rule of cross product.

14.3 Magnetic flux and density.

Magnetic flux:

"The dot product of magnetic field $\vec{B}$ and vector area $\vec{A}$ is called magnetic flux."

$$\boxed{\phi = \vec{B} \cdot \vec{A}}$$

or

$$\phi_B = BA\cos\theta$$

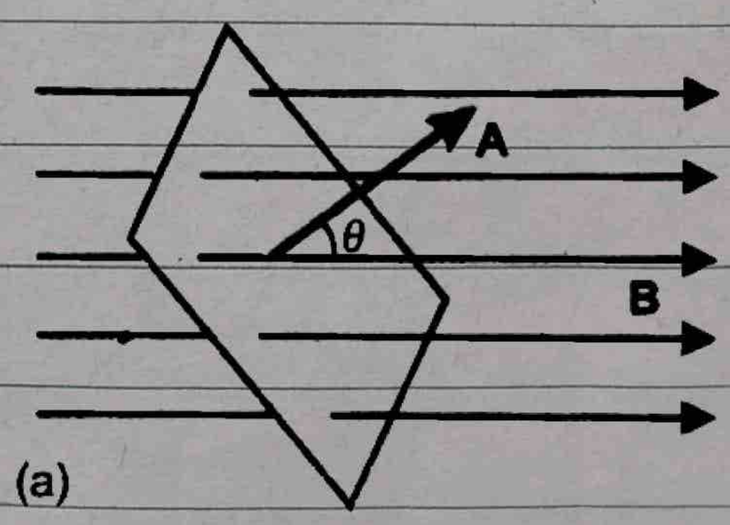
The direction of $\vec{A}$ is along the normal to the plane surface element. θ is the angle between vectors $\vec{B}$ and $\vec{A}$ fig - a.

Maximum flux:

When $\vec{B}$ is directed perpendicular to the area.

then $\theta = 0^\circ$ and Flux is maximum.

$$\phi_B = \vec{B} \cdot \vec{A}$$



(a)

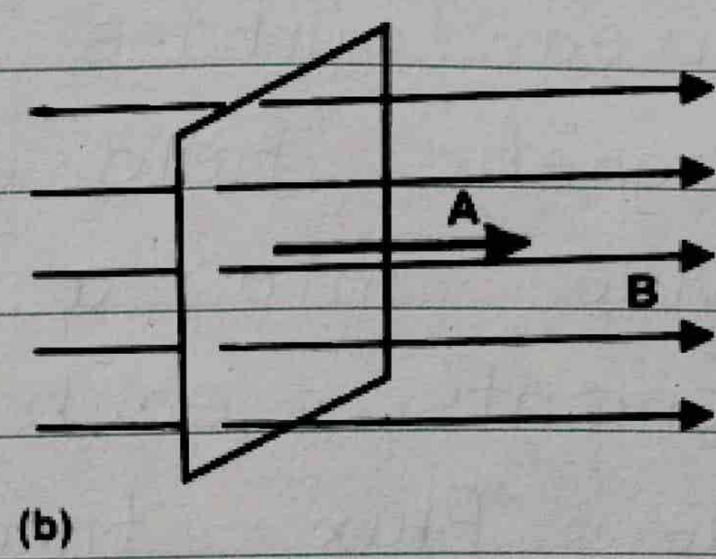
$\phi_B = BA\cos\theta$

$\phi_B = BA\cos 0^\circ$

$\phi_B = BA\,(1)$

$\phi_B = BA$ (max)

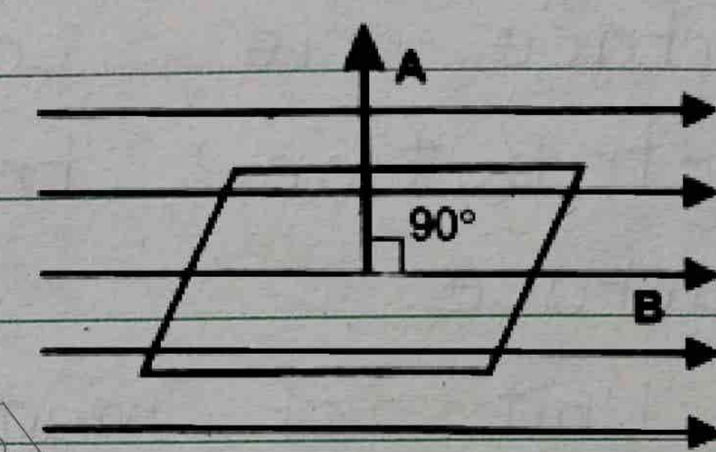
Fig - b.



(b)

Minimum flux:

When $\vec{B}$ directed parallel to the area, then $\theta = 90^\circ$, and flux is minimum (zero)



(c) Fig.

$\phi_B = \vec{B}.\vec{A}$

$\phi_B = BA\cos\theta$

$\phi_B = BA\cos 90^\circ$

$\phi_B = BA\,(0)$

$\phi_B = 0$ (Minimum).

Flux through a curved surface:

When a curved surface is placed in a non-uniform magnetic field, the curved surface is divide into a number of small surface elements, each element act as a plane and the flux through the whole curved surface is calculated by sum of the contribution from all the elements of the surface.

Unit of magnetic flux ϕ_B is $\frac{Nm}{A}$ which is called Weber (Wb).

$$\phi_B = \vec{B} \cdot \vec{A}$$

$$\text{Weber} = \frac{N}{A\cancel{m}} \times \cancel{m^2}$$

$$\text{Weber} = \frac{Nm}{A}$$

$$\boxed{\text{Weber} = NA^{-1}m}$$

Magnetic flux density B

$$\phi = BA$$

or

$$\boxed{B = \frac{\phi}{A}}$$

or

Flux density $B = \frac{\text{Flux}}{\text{Area}}$

Definition:

Magnetic field strength (Magnetic induction) B is also called magnetic flux density.

It is defined as magnetic flux per unit area placed perpenicular to the magnetic field.

$$\phi = BA$$

$$B = \frac{\phi}{A}$$

$$1\,\text{Tesla} = \frac{1\ \text{Weber}}{1\ m^2}$$

$$T = Wb\ m^{-2}$$

$$\text{Tesla} = \frac{\text{Weber}}{m^2}$$

Tesla = Weber per meter squre

14.4 Ampere's Law and determination of flux density, B

" Ampere's circuital law states that the sum of the quantities $(\vec{B} \cdot \Delta\vec{L})$ for all path elements into which the complete loop has been divided is equal to μ_0 times the total current enclosed by the loop."

$$\sum_{r=1}^{N} (\vec{B} \cdot \Delta\vec{L})_r = \mu_0 I$$

So,

$\vec{B}\cdot\vec{\Delta L}$ = $\Delta L\,(B\cos\theta)$ product of length of element ΔL and the component of $\vec{B}$ parallel to $\vec{\Delta L}$.

Ampere stated that " the sum of the quantites $(\vec{B}\cdot\vec{\Delta L})$ for all path elements into which the complete loop has been divided is equal to μ_o times the total current enclosed by the cloop.

$$(\vec{B}\cdot\vec{\Delta L})_1 + (\vec{B}\cdot\vec{\Delta L})_2 + (\vec{B}\cdot\vec{\Delta L})_3 + \cdots\cdots + (\vec{B}\cdot\vec{\Delta L})_N$$

$$= \mu_o \text{ times } \times I$$

$$\sum_{r=1}^{N} (\vec{B}\cdot\vec{\Delta L})_r = \mu_o I$$

μ_o = A constant called permability of free space.

$$\mu_o = 4\pi \times 10^{-7}\ Wb\,A^{-1}\,m^{-1}$$

$$\boxed{\sum_{r=1}^{N} (\vec{B}\cdot\vec{\Delta L})_r = \mu_o \times \text{current enclosed}.}$$

Uses:

Using Ampere's circuital Law the magnetic flux density B at any point due to a current carring conductor can be calculated.

Explanation:

Consider a closed path in the form of a circle enclosing the current carring wire.

Fig 1.

This closed path is called Amperian path. Divide this path into small elements of length like $\vec{\Delta L}$.

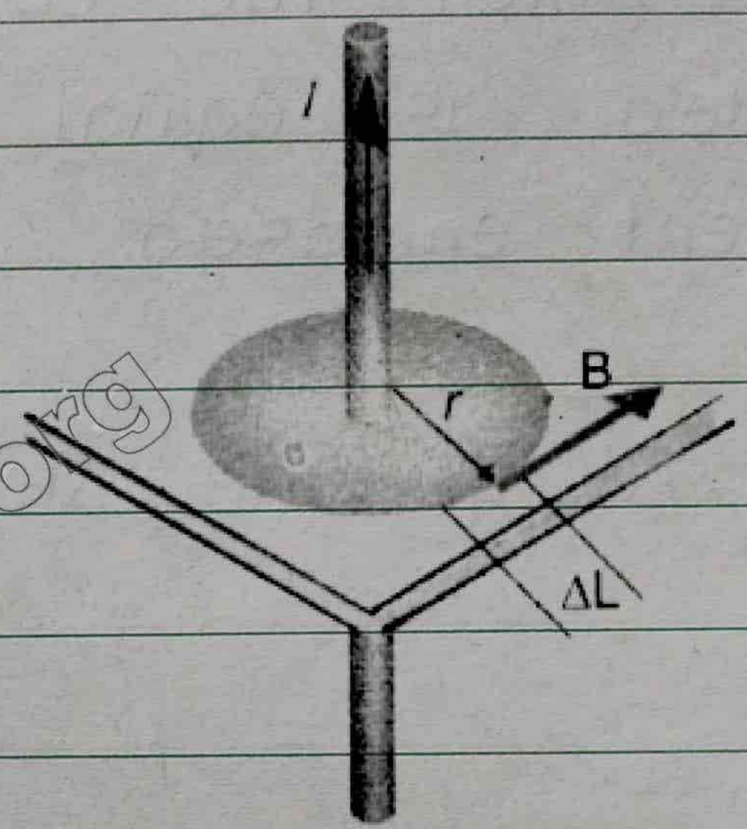


Fig. Ampere's law to find the magnetic field in the vicinity of this long, straight, current-carrying wire.

$\vec{B}$ is the magnetic flux density at $\vec{\Delta L}$.

If θ is the angle between $\vec{B}$ and $\vec{\Delta L}$ then

$$\vec{B}.\vec{\Delta L} = B\Delta L \cos\theta$$

$$B.\Delta L = (B\cos\theta)\Delta L$$

Here

$B\cos\theta$ = Component of $\vec{B}$ parallel to $\vec{\Delta L}$.

Field due to a current carrying solenoid

Application of Ampere's law

Solenoid:

A solenoid is a long, tightly wound, cylinderical coil of wire.

When current passes through such a coil, it behaves like a bar magnet.

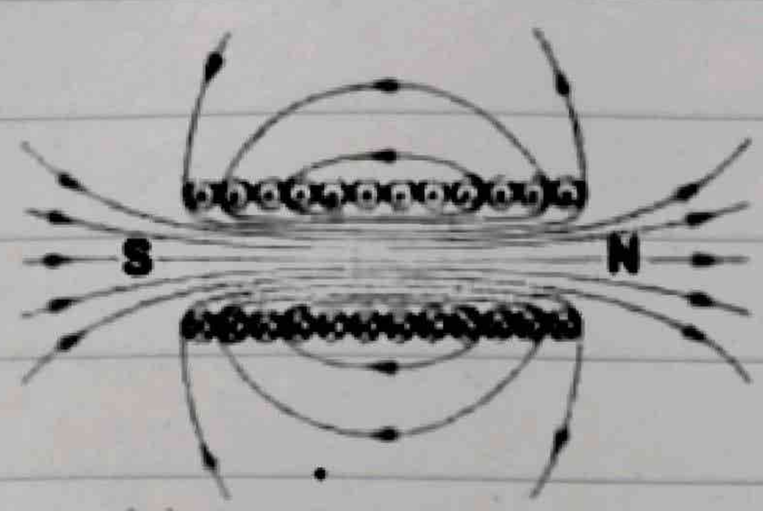
The magnetic field inside a long solenoid is uniform and much strong, while out side the solenoid is very weak, negligible.

$$B_3 \cong 0$$

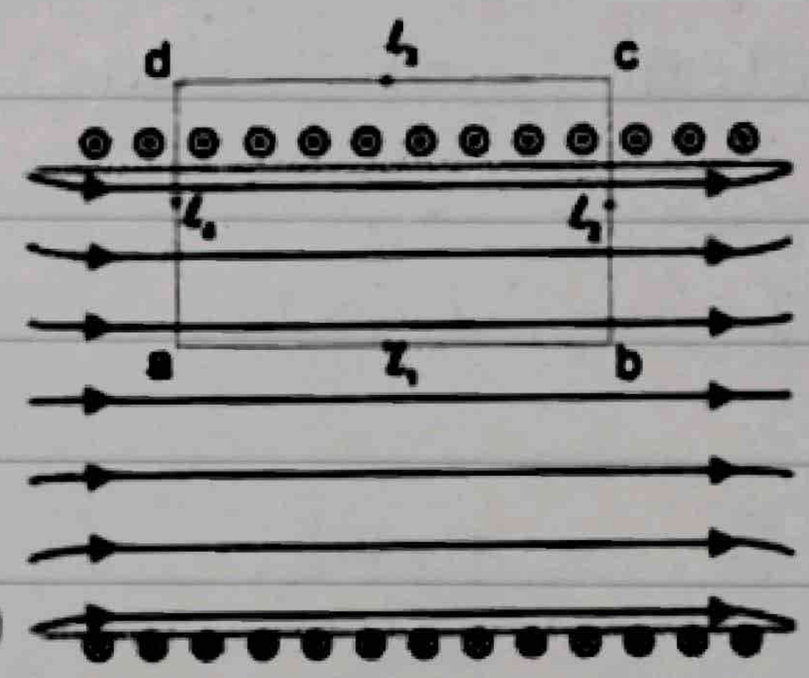
Consider a rectangular loop abcda as shown in fig.
Its has four elements.

$ab = l_1$, $cd = l_3$

$bc = l_2$, $da = l_4$



(a)



(b)

Apply Ampere's Law.

$$\sum_{r=1}^{4} (\vec{B}.\Delta\vec{L}) = \mu_o \times \text{current enclosed}$$

$$(\vec{B}.\Delta\vec{L})_1 + (\vec{B}.\Delta\vec{L})_2 + (\vec{B}.\Delta\vec{L})_3 + (\vec{B}.\Delta\vec{L})_4 = \mu_o \times \text{current}$$

$$\vec{B}.\vec{l}_1 + \vec{B}.\vec{l}_2 + \vec{B}.\vec{l}_3 + \vec{B}.\vec{l}_4 = \mu_o \times \text{current}$$

$$B.l\cos 0^\circ + B.l_2\cos 90^\circ + 0.l_3 + B.l_4\cos 90^\circ = \mu_o \times \text{current}$$

$$B.l_1 + B.l_2(0) + 0 + B.l_4(0) = \mu_o \times \text{current}$$

$$B.l_1 + 0 + 0 + 0 = \mu_o \times \text{current}$$

$$B.l_1 = \mu_o \times \text{current enclosed}$$

Let,

I = current in one turn.

n = Number of turns per unit length of the solenoid.

nl_1 = Total number of turns in the length l_1
$nl_1 i$ = current enclosed.

$$B l_1 = \mu_0 \times n l_1 I$$

$$B = \mu_0 n I$$

Or,

$$n = \frac{N}{L} = \frac{\text{NO. of turns of the coil}}{\text{Length}}$$

$$B = \frac{\mu_0 N I}{L}$$

The magnetic field "B" is along the axis of the solenoid and its direction is given by the right hand rule, which states that

"Hold the solenoid in the right hand with fingers curling in the direction of the current, the thumb will point in the direction of the field."

Magnetic field at a distance "r" from a straight wire is

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

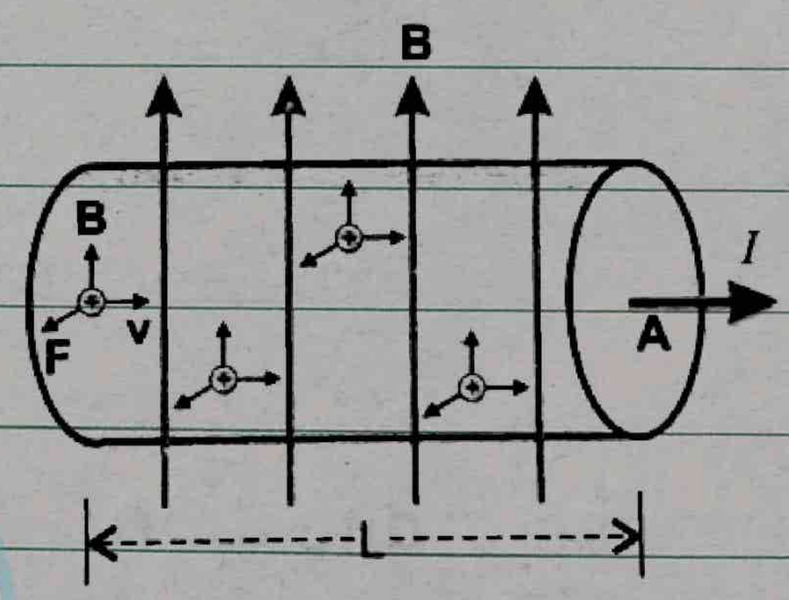
14.5 Force on a moving charge in a magnetic field

When a charge "q" moves in a magnetic field $\vec{B}$ with velocity $\vec{v}$, it experiences a force which is perpendicular to both $\vec{v}$ and $\vec{B}$.

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Proof:

Consider a segment of wire of length L area of crossection A and current I is flowing through it. The wire segment is placed in a magnetic field B.



n = Number of charge carriers per unit volume of wire.

AL = Volume of the wire segment.

nAL = Total number of charge carriers in the wire segment.

ΔQ = nALq = Total charge on all the charge carriers that exit through the end area in a time Δt.

The current "I" throgh the conductor is

$$\because S = vt$$

$$t = \frac{S}{L} = \frac{L}{v}$$

$$\because \Delta t = \frac{L}{v}$$

$$I = \frac{\Delta Q}{\Delta t}$$

$$I = \frac{nA\cancel{L}q}{\frac{\cancel{L}}{v}} = nAqv$$

$$\boxed{I = nAqv} \longrightarrow (1)$$

Force on the segment L of the current carrying conductor is

$$\vec{F_L} = I(\vec{L} \times \vec{B})$$

$$\vec{F_L} = nAqv(\vec{L} \times \vec{B})$$

The direction of the segment L is the same as the direction of the velocity of charge carriers.

$$\vec{F_L} = nAq(\vec{vL}) \times \vec{B} \qquad \because \vec{vL} = \vec{v}L$$

$$\vec{F_L} = nAq(\vec{v}L) \times \vec{B}$$

$$\vec{F_L} = nALq(\vec{v} \times \vec{B})$$

So, force on all (nAL) charge carriers in conductor is

$$\vec{F_L} = nALq(\vec{v} \times \vec{B})$$

Force on one charge carrier is

$$\vec{F} = \frac{\vec{F_L}}{nAL} = \frac{nALq(\vec{v} \times \vec{B})}{nAL}$$

$$\boxed{\vec{F} = q(\vec{v} \times \vec{B})} \longrightarrow (2)$$

This is a general equation and it holds for any charge carrierers moving in a magnetic field.

Force on a Proton:

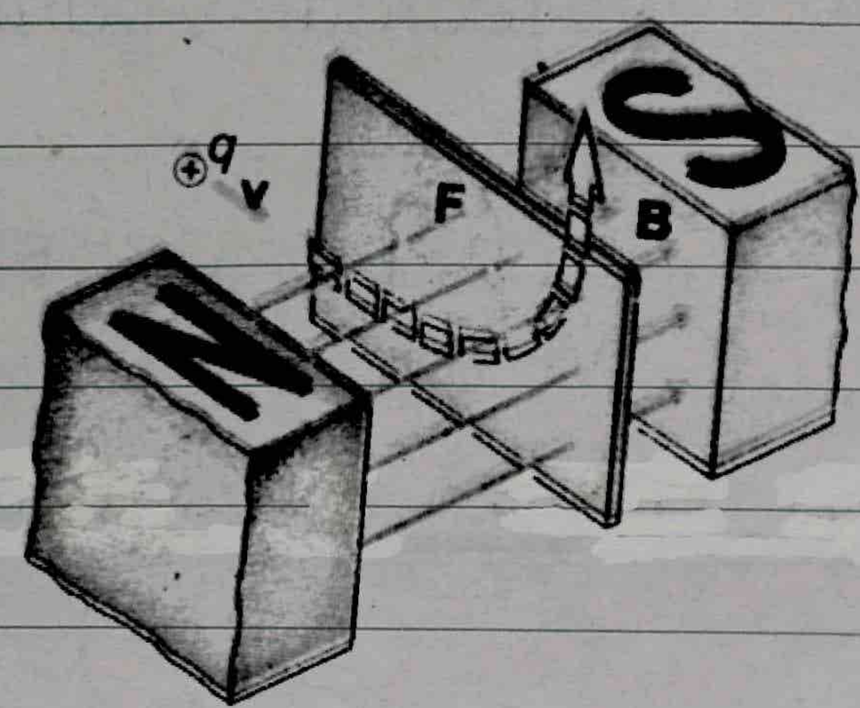
$\because q = +e$

$$\vec{F} = +e(\vec{v} \times \vec{B})$$

It experiencies a force in the upward direction as given by the vector $\vec{v} \times \vec{B}$. As a result of this force, the proton is deflected upward as shown in fig.

Magnitude of the Force:

The magnitude of the force on a moving charge carrier is



$$\boxed{F = qvB\sin\theta}$$

Force on an Electron:

$$\vec{F} = -e(\vec{v} \times \vec{B}) \qquad \because q = -e$$

The direction of force will be opposite to that of +ve chage. In fig, the electrons would be deflected downwards as they enter in the magnetic field.

Special cases:

1) Force is maximum:

When a charged particle is projected perpendicular to the magnetic field ($\theta = 90°$)

$$F = qvB\sin 90° = qvB(1)$$

$$\boxed{F = qvB}$$

2) Force is zero:

When a charge particle is projected parallel to the magnetic field.

$$\boxed{F = qvB\sin(0) = qvB(0) = 0}$$

3) Force is zero:

When charge is at rest.

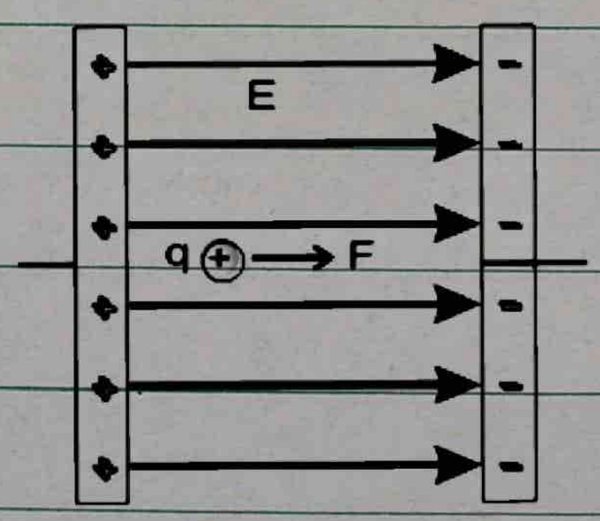
$V = 0$ then $F = 0$

14.6 Motion of charged particles in an electric and magnetic field

Force due to electric field E :

When a charge "q" is placed in an electric field "E", it experiences a force $\vec{F}$ parallel to electric field

$$\vec{F_e} = q\vec{E} \longrightarrow (1)$$



If the charge is free to move, then it will accelerate according to Newton's 2nd Law as

$$a = \frac{F_e}{m} = \frac{qE}{m}$$

If the electric field is uniform, then the acceleration is also uniform and hence, the position of the particle at instant of time can be found by using equations of uniformly accelerated motion.

Force due to a Magnetic field :

Force on a moving charge due to a magnetic field is

$$\vec{F_b} = q(\vec{v} \times \vec{B})$$

Force due to $\vec{E}$ and $\vec{B}$:

When a charged paticle "q" is moving with velocity "v" in a region where there is an electric field $\vec{E}$ and magnetic field $\vec{B}$, the total force $\vec{F}$ is the vector sum of $\vec{F_e}$ and $\vec{F_b}$.

$$\vec{F} = \vec{F_e} + \vec{F_b}$$

$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})$$

This force is called Lorentz's force.

The electric force F_e does work. The magnetic force F_b does no work. It is simply a deflecting force.

The electric force $\vec{F_e}$ that acts on a +ve charge is parallel to the electric field $\vec{E}$ and causes the particles trajectory to bend in a horizontal plane.

14.7 Determination of e/m of an Electron

Consider a narrow beam of electrons moving with constant speed v is projected at right angle $\theta = 90^\circ$ through a uniform magnetic field $\vec{B}$ directed into the page. Value of $\vec{B}$ is know.

$$\boxed{\vec{F} = q(\vec{v} \times \vec{B})}$$

The electrons will experience a force

$\because q = -e$

$$\vec{F_b} = -e(\vec{v} \times \vec{B})$$

The direction of this force will be perpendicular to both $\vec{v}$ and $\vec{B}$. This deflecting force will change the direction of velocity. The magnitude of the v locity remains unchanged.

The magnitude of the force is

$$F_b = evB\sin 90^\circ = evB\,(1)$$

$$\boxed{F_b = evB}$$

This magnetic force F_b provides

necessary centripetal force "F_c" to the electrons, each having a mass "m". So, the electrons move in circular path of radius "r".

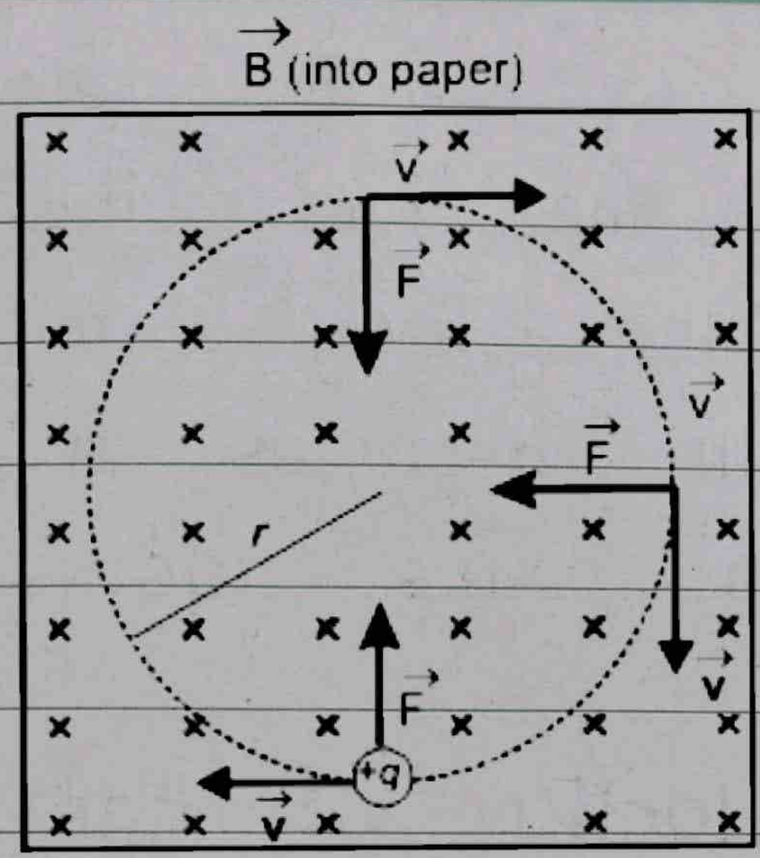


Fig. An electron is moving perpendicular to a constant magnetic field. The magnetic force F causes the particle to move on a circular path.

$$F_b = F_c$$

$$e\cancel{v}B = \frac{mv^{\cancel{2}}}{r}$$

$$eB = \frac{mv}{r}$$

$$\boxed{\frac{e}{m} = \frac{v}{Br}} \longrightarrow (1)$$

If radius "r" and velocity "v" are known $\frac{e}{m}$ can be found.

Radius r :

The radius "r" is measured by making the electronic trajectory visible. This is done by filling a gass tube with a gas such as a Hydrogen at low pressure.

This tube is placed in a region occupied by a uniform magnetic field of known value. As electrons are shot into this tube, They begin to move in a circle under the action of magnetic force.

The electrons collide with the atoms of the gas. This excites the atoms due to which they emit light. In this way their path becomes visible as a circular ring of light. The radius of the ring is measured.

Velocity of the electrons :

When an electron of charge "e" falls throgh a potential difference "V", it gains kinetic energy equal to Ve.

$$KE = Ve$$

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

$$v^2 = \frac{2Ve}{m}$$

$$\boxed{V = \sqrt{\frac{2Ve}{m}}} \longrightarrow (2)$$

put in equation (1), then we get.

$$\frac{e}{m} = \frac{1}{Br} \times \sqrt{\frac{2Ve}{m}}$$

taking squaring both sides.

$$\left(\frac{e}{m}\right)^2 = \left(\frac{1}{Br} \times \sqrt{\frac{2Ve}{m}}\right)^2$$

$$\frac{e^{\cancel{2}}}{m^{\cancel{2}}} = \frac{1}{B^2r^2} \times \frac{2V\cancel{e}}{\cancel{m}}$$

$$\frac{e}{m} = \frac{2V}{B^2r^2}$$

$\because \frac{e}{m} = 1.7588 \times 10^{+11}$

$\frac{e}{m} = \frac{\text{coulomb}}{\text{kilogram}}$

$\frac{e}{m}$ ratio is called charge to mass ratio.

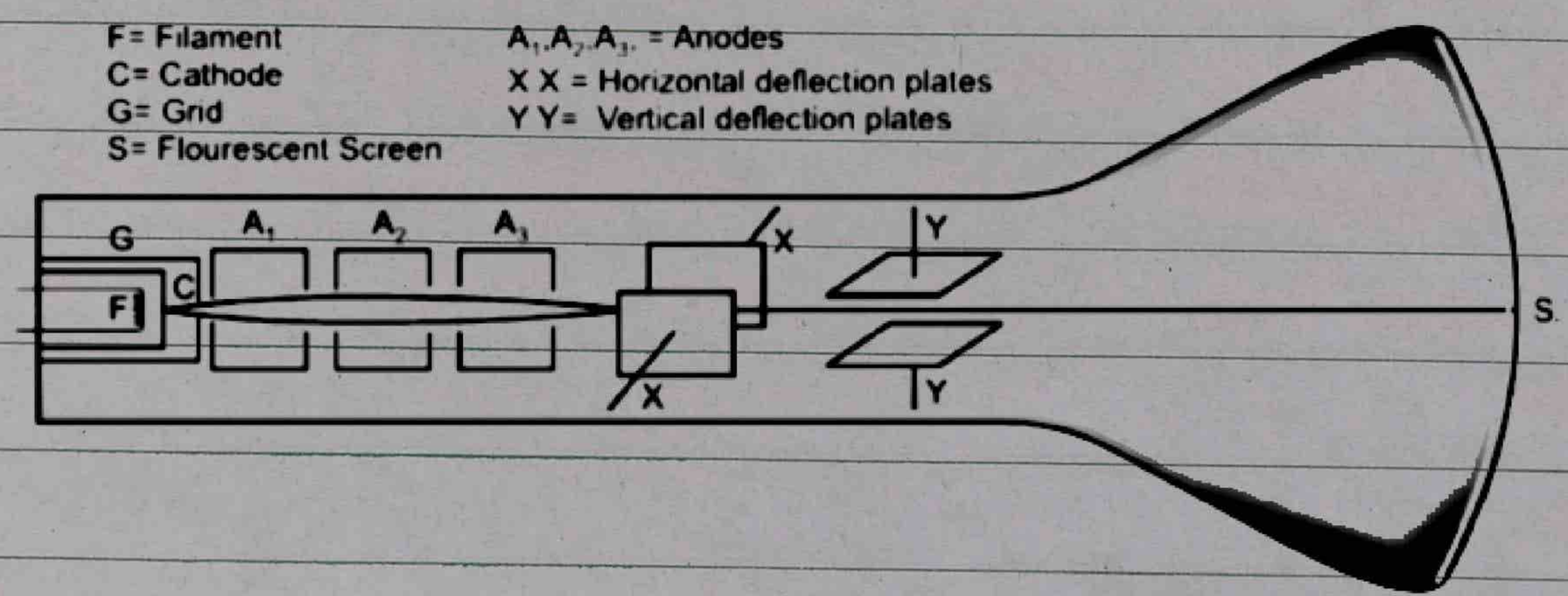
Robert. A Millikan found the charge "e" of the electron, then mass "m" of an electron can be calculated.

14·8 Cathode Ray Oscilloscope

Cathode ray oscilloscope (CRO) is an electronic instrument which is a high speed graph plotting device.

Principle :

It works by a deflecting beam of electrons as they pass throug uniform electic



field between the two sets of parallel plates as shown in fig. The deflected beam then falls on flourescent screen which it makes a visible spot.

Construction and Working:

CRO consists of the following components.

Electoron Gun:

The beam of the electrons is provided by an electron gun which consists of an indirectly heated cathode, a grid and three anodes. The filament "F" heats the cathode "C" which emits electrons.

The anodes A_1, A_2, A_3 which are at high positive potential with respect to cathode accelerate and focus the electronic beam to fixed spot on the screen "S".

Grid:

The grid "G" is at negative potential with respect to cathode. It controls the number of electrons which are accelerated by anodes. In this way it controls the brightness of the spot formed on the screen.

Deflecting Plates:

These plates help to from wave shape of various voltage on CRO.

The two sets of deflecting plates are known as "X" and "Y" deflection plates. When a voltage is applied between the X-plates, it deflects the beam horizontally on the screen i.e. parallel to X-axis. When a voltage is applied across the Y-plates, it deflects the beam vertically on the screen i.e. along the y-axis.

Sweep or Time Base Generator:

The voltage that is applied across X-plates is usually provided by a circuit that is built in the CRO. It is known as sweep or time base generator. Its output waveform is a saw tooth voltage of period "T".

The voltage increases linearly with time for a period "T" and then drop to zero. As this voltage is applied across the X-plates, the spot is deflected linearly with time along the X-axis for a time "T". Then the spot returns to its starting point on

the screen very quickly because a saw tooth voltage rapidly falls to its initial value at the end of each period. We can actually see the spot moving on x-axis.

If the time period "T" is very short, we see just a bright line on the screen.

Synchronization Controls:

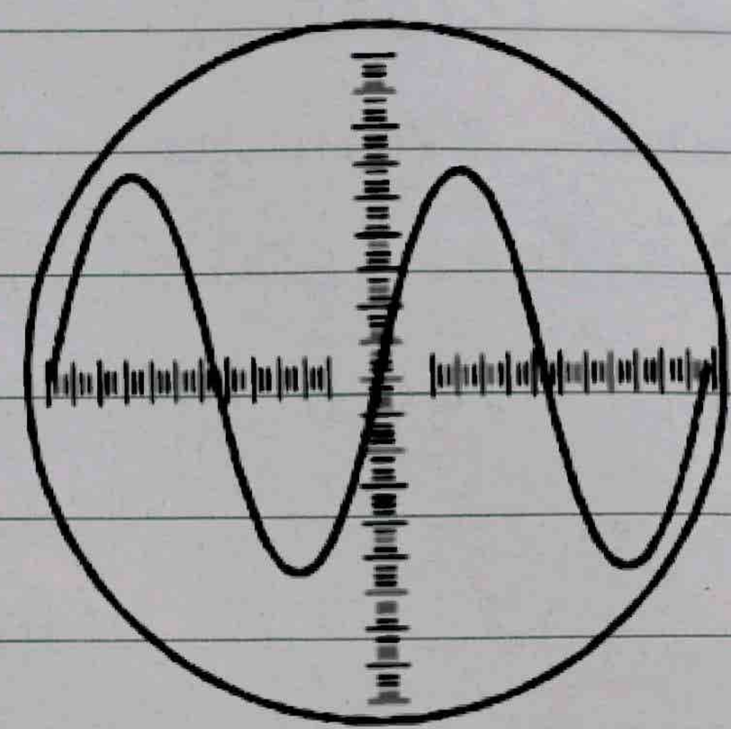
The pattern will appear stationary only if the time period T is equal to the time of one cycle of voltage on y-plates. It is necessary to synchronize the frequency of time base generator with the frequency of the voltage at the y-plates. This is possible by adjusting the synchronization controls that is provided on the front panel of the CRO.

Uses of CRO:

CRO is used to display the waveform of a given voltage. Once the waveform is displayed, we can measure the voltage, its frequency and phase.

Waveform:

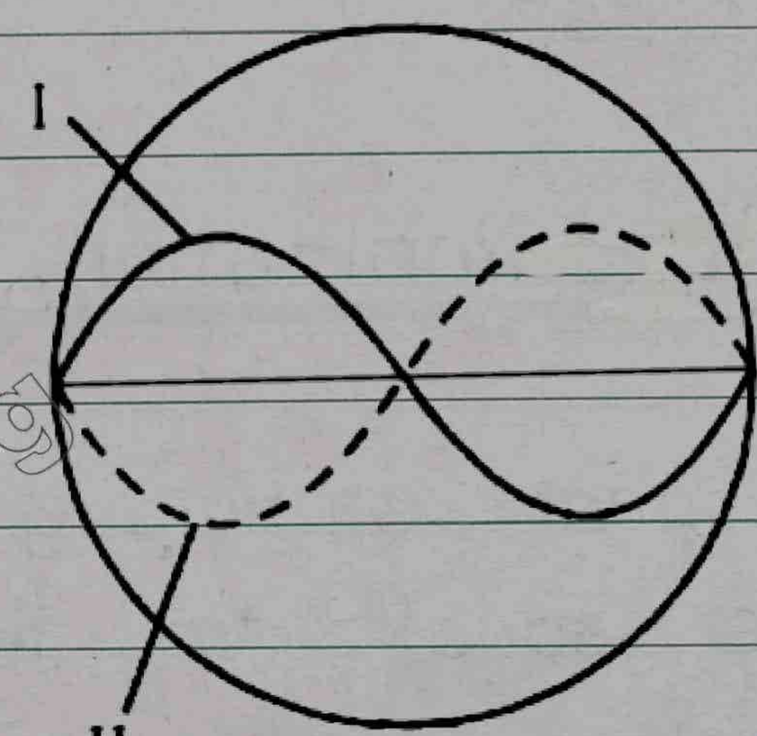
Fig (a) shows the waveform of an alternating voltage.



(a)

Voltage:

As the y-axis is calibrated in volts and x-axis in time, we can easily find the instantaneous value and peak value of the voltage.



(b)

Time Period:

The time period can also be determined by using the time calibration of x-axis.

Phase Difference:

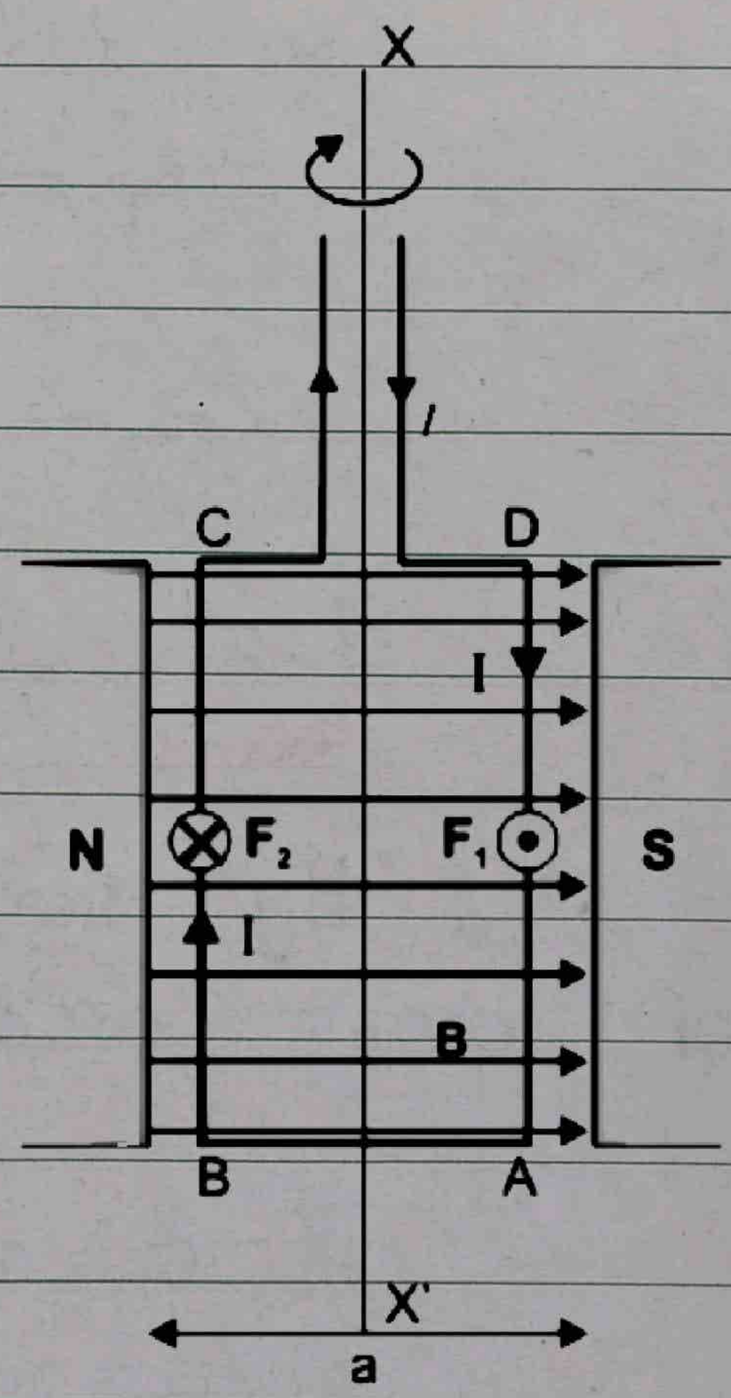
Information about the phase difference between two voltages can be obtained by simultaneously displaying their waveforms.

For example, the waveforms of two voltages are shown in fig (b). These waveforms shown that when the voltage of "I" is increasing, that of "II" is decreasing

and vice versa. Thus the phase difference between these voltages is 180°.

14.9 Torque on a Current carring Coil

Consider a rectangular coil carrying a curren "I". When it is placed in uniform magntic field "B", it will experience a toque due to two forces F_1 and F_2, (couple).



We know that force on a current carrying con. ductor (wire) of length "L" placed in a magnetic field is

$$\vec{F} = I(\vec{L} \times \vec{B})$$

Magnitude,

$$F = ILB \sin\theta$$

θ is the angle between the conductor and magnetic field $\vec{B}$.

Sides AB and CD of the coil are

parallel to $\vec{B}$. So force on them is zero.

$$F_{AB} = ILB \sin 180^\circ = ILB(0)$$

$$F_{AB} = 0$$

$$F_{CD} = ILB \sin 0^\circ = ILB(0)$$

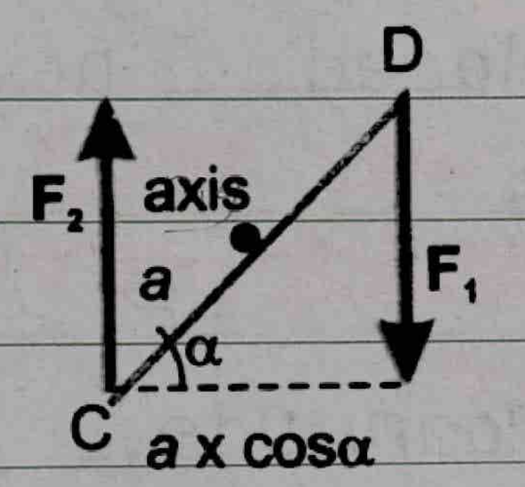
$$F_{CD} = 0$$

Sides DA and BC are perpendicular to $\vec{B}$, so $\theta = 90^\circ$

$$F_{AB} = ILB \sin 90^\circ = ILB$$

$$F_{CD} = ILB \sin 90^\circ = ILB$$

$$\boxed{F_1 = F_2 = ILB}$$



(Top view of coil)

By the right hand rule of cross product $\vec{F} = I(\vec{L} \times \vec{B})$

$\vec{F_1}$ is out of the page. ⊙
$\vec{F_2}$ is into the page. ⊕

$\vec{F_1}$ and $\vec{F_2}$ are equal in magnitude but opposite in direction. They form a couple

which tends to rotate it about the axis. Torque of this couple is given by.

$$\tau = \tau_1 + \tau_2$$

$$\tau = F_1 \times \frac{a}{2} + F_2 \times \frac{a}{2}$$

$$\tau = ILB \times \frac{a}{2} + ILB \times \frac{a}{2}$$

$$\tau = 2\left(ILB \times \frac{a}{2}\right)$$

$$\tau = ILB \times a$$

$$\tau = IB(La)$$

$\because La = A$ = Area of the coil.

$$\boxed{\tau = IBA}$$

This is the torque when the plane of the coil is parallel to $\vec{B}$.

But, when the plane of the coil makes an angle α with B then moment arm $= a\cos\alpha$ from fig. Then torque is

$$\tau = ILB \times a\cos\alpha$$

$$\tau = I(La)B\cos\alpha$$

$\because \alpha$ = Angle between the plane of the coil and $\vec{B}$.

$$\boxed{\tau = IAB\cos\alpha}$$

14.10 Galvanometer

A galvanometer is an electrical instrument used to detect the passage of current.

Principle:

When a conductor is placed in a magnetic field, it experiences a force when a current passes through it. Due to this force a torque "τ" acts upon the conductor if it is in the form of a coil or loop.

$$\tau = NIAB\cos\alpha$$

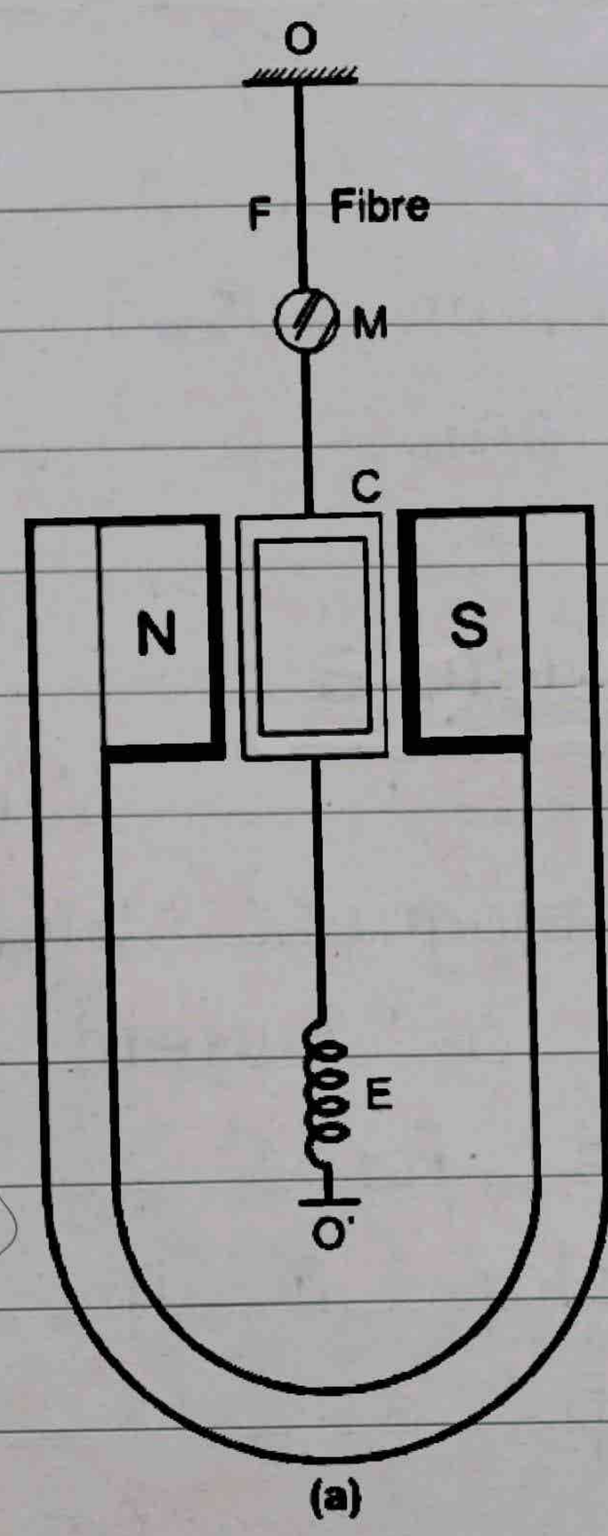
Where "N" is the number of turns in the coil, "A" is the area, "I" is the current passing through it, "B" is the magnetic field in which the coil is placed. α is the angle between the plane of the coil and the direction of magnetic field B.

Due to the action of the torque, the coil rotates. It detects the current.

Construction:

The construction of a moving

coil galvanometer is shown in fig.



(a)

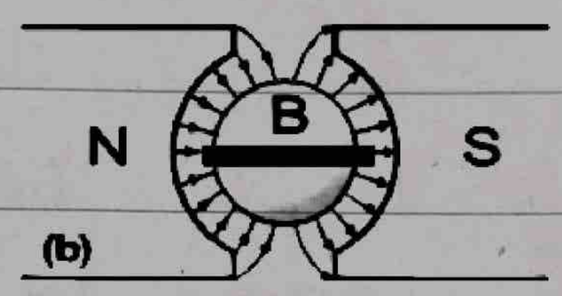
A rectangular coil "C" is suspended between the concave shape pole pieces N and S of a U-shaped magnet with the help of a fine metallic suspension wire "F". A mirror M is also attached to this wire "F".

The rectangular coil is made of enameled copper wire. It is wound on a frame of non-magnetic material.

The suspension wire "F" is also used as one current lead to the coil. The other terminal of the coil is connected to a loosely wound spiral "E" which serves as the second current lead.

The pole pieces of the magnet are made concave to make the field radial and stronger near the coil as shown in

fig (b).



Working:

When a current is passed through the coil, it is acted upon by a couple which tends to rotate the coil. This is called deflecting couple.

$$\text{Deflecting couple} = NIAB\cos\alpha$$

As the coil is placed in a radial magnetic field, then $\alpha = 0$, plane of the coil is always parallel to the magnetic field.

$\because \cos\alpha = \cos 0^\circ = 1$

$$\text{Deflecting torque} = NIAB$$

As the coil turns under the action of the deflecting torque, the suspension wire "F" tries to bring the coil back to its orignal position, i.e., it tries to restore the orignal position. This couple is called restoring couple.

$$\text{Restoring torque} = C\theta$$

"C" is a constant of the suspension wire "F" and is called torsional couple.

$$\frac{\text{Restoring couple}}{\theta} = C$$

"C" is defined as couple per unit twist (θ). Under the action of these two couples coils come to rest

Deflecting torque = Restoring torque

$$NIAB = C\theta$$

$$I = \frac{C\theta}{BAN}$$

$$I = \left(\frac{C}{BAN}\right)\theta$$

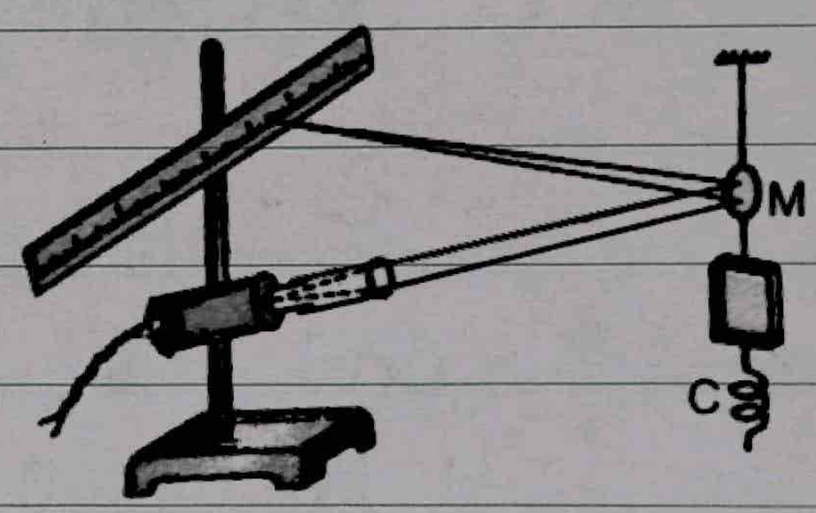
$I \propto \theta$ as $\frac{C}{BAN}$ = constant

Hence, the current "I" passing through the coil is directly proportional to the angle of deflection "θ".

Two Methods to find the angle of Deflection θ:

1) Lamp and scale Arrangement:

In sensitive galvanometers the angle of deflection "θ" is observed by means of small mirror attached to the coil along with a



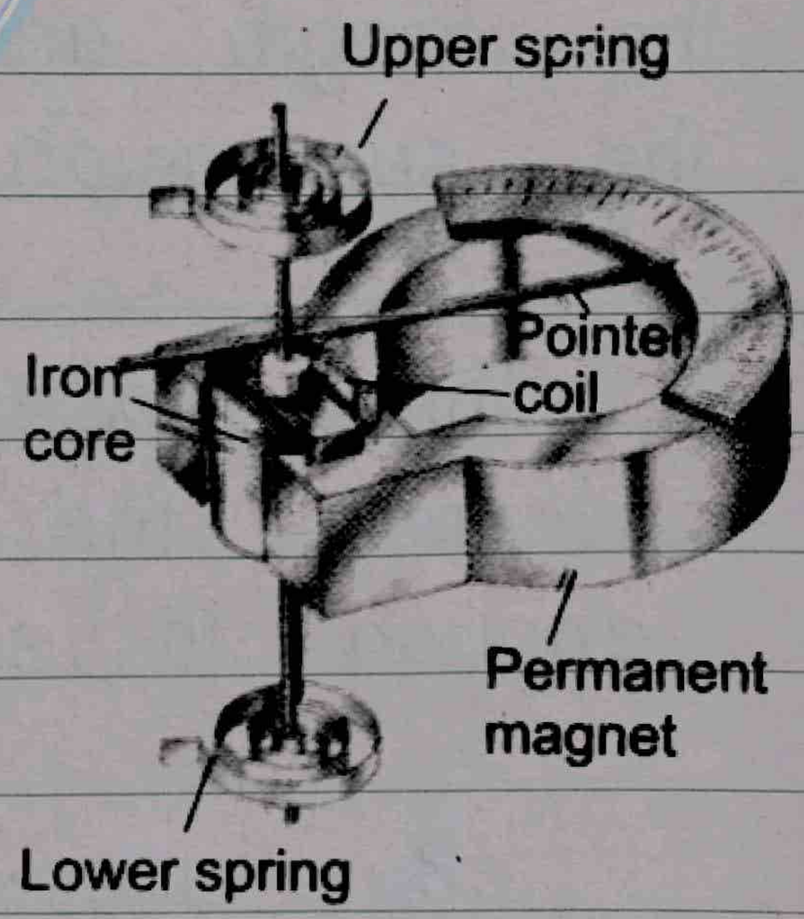
Lamp and scale arrangement. In fig.

A beam of light from the lamp is directed towards the mirror of the galvanometer. After reflection from the mirror it produces a spot on a scale placed at a distance of 1m from the galvanometer.

When the coil rotates, the mirror attached to the coil also rotates and spot of light moves along the scale. The displacement of the spot of light on the scale is proportional to the angle of deflection.

2) The coil is Pivoted between the Jewelled Bearings:

The galvanometer used in laboratories is a pivoted type galvanometer. The coil is pivoted between two jewelled bearings. The restoring torque is provided by two hair springs which also serve as current leads.



A light alluminium pointer is attached to the coil which moves over a scale. In fig. It gives the angle of deflection of the coil.

3) Sensitivity of Galvanometer:

A galvanometer which gives large deflection for a given small current is known as a sensitive galvanometer.

$$I = \left(\frac{C}{BAN}\right)\theta$$

Galvanometer is made more sensitive if $\frac{C}{BAN}$ is made small and consequently "θ" becomes large for a given current "I". Thus to increase the sensitivity of the galvanometer, "C" may be decreased, or B, A, N may be increased.

i); "C" can be decreased by increasing the length and decreasing the diameter of the suspension wire.

This process cannot be taken too far because the suspension must be strong enough to support the coil.

ii); By increasing the number of coil

N, the coil becomes heavy. So there is a certain limit.

iii); To compenstat for the loss of sensitivity, in case of fewer turns are used in the coil, we increase the value of the magnetic field B used.

4) Stable or Dead Beat Galvanometer:

A galvanometer in which the coil comes to rest quickly after the current passed through it or the current is stopped from flowing through it, is called a stable or a dead beat galvanometer.

Unstable Galvanometer:

When the current passing through the galvanometer is discontinued, the coil will not come to rest as soon as the current flowing through the coil is stopped.

It keeps on oscillating about its mean position before coming to rest. In the same wave if the current is established suddonly in a galvanometer, the coil will shoot

beyond its final equilibrium position and will oscillate several times before coming to restat its equilibrium. Artificial ways are used to make the coil come to rest quickly.

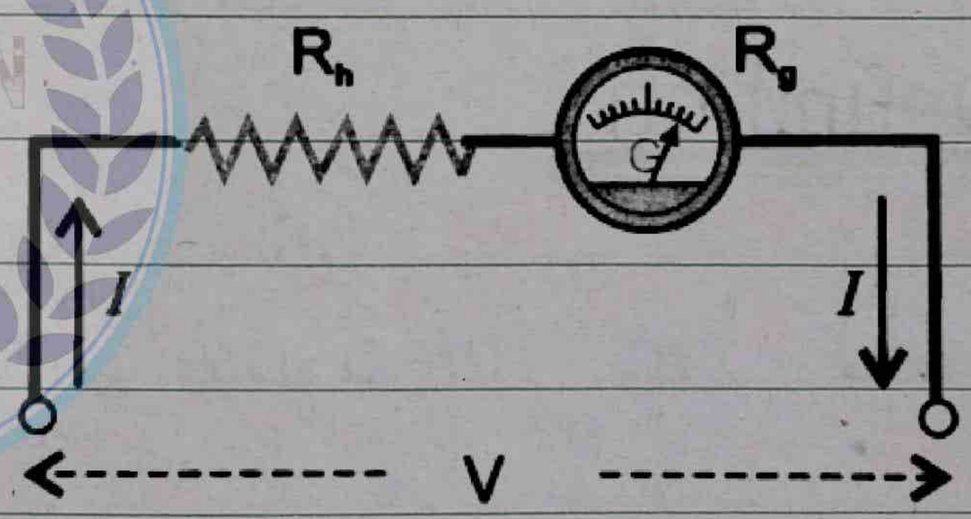
b) Voltmeter:

Definition:

"A voltmeter is a device which is used to measue the potential difference in volts between two points."

Construction and Working:

Voltmeter is the modified form of a galvanometer in which a very high resistance R_h is connected in series with the galvanometer



Let,

R_g = Resistance of meter_movement coil of galvanometer.

I_g = Current for full scale deflection through galvanometer.

V = Range of voltmeter (Potential difference to be measured).

R_h = High Resistance.

$$V = I_g (R_g + R_h)$$

$$R_g + R_h = \frac{V}{I_g}$$

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

High resistance "R_h" is directly proportional to the range of voltmeter "V".

∵ 1. voltmeter possesses a high resistance.

C) Ammeter:

Definition:

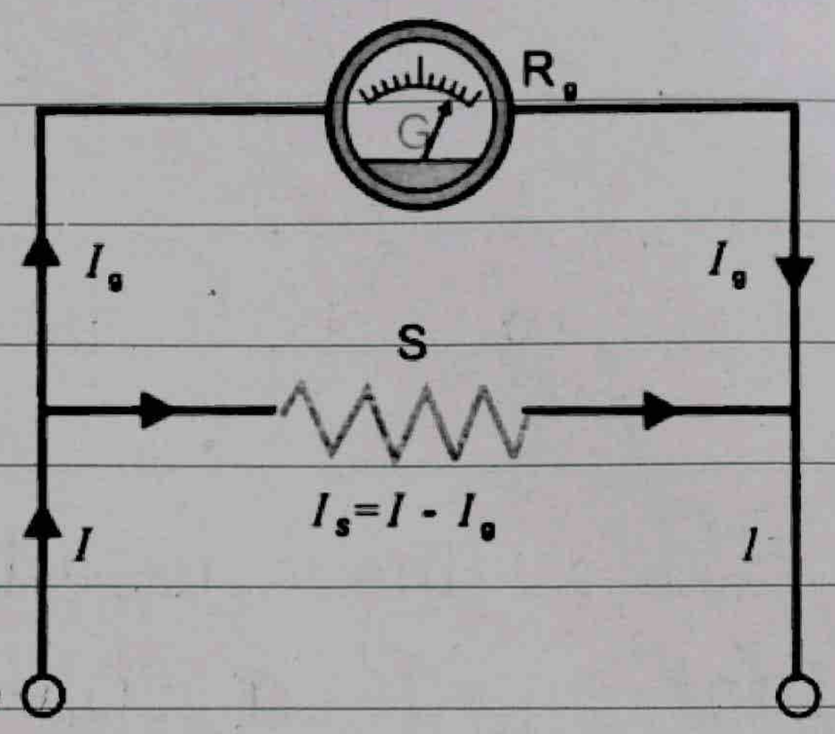
"An ammeter is a device which is used to measure current in amperes."

An ordinary galvanometer cannot be used to measure large current with out proper modification.

Construction and Working:

Ammeter is

basically a galvanometer in which a resistance of very low value is connected in parallel with the galvanometer. This is called shunt Resistance "R_s".



The shunt resistance is of such a value so that current I_g for full scale deflection passes through the galvanometer and the remaining current $(I - I_g)$ passes through the shunt "R_s".

R_g = Resistance of meter movement (coil) of galvanometer.

I_g = Current for full scale deflection through the galvanometer.

I_s = Current through the shunt resistance

I = Range of Ammeter (Maximum current to be measured).

$$I = I_s + I_g$$

$$I_s = I - I_g$$

$$V_s = V_g$$

$$I_s R_s = I_g R_g$$

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

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

The resistance of the shunt is small that just a piece of copper serves the purpose.

∵ An ammeter is a low resistance galvanometer and is always put in series with the circuit.

Ohmmeter:

"It is a device used for the rapid measurement of resistance."

Construction:

It consists of a galvanometer, adjustable resistance "R" of known value and a cell connected in series.

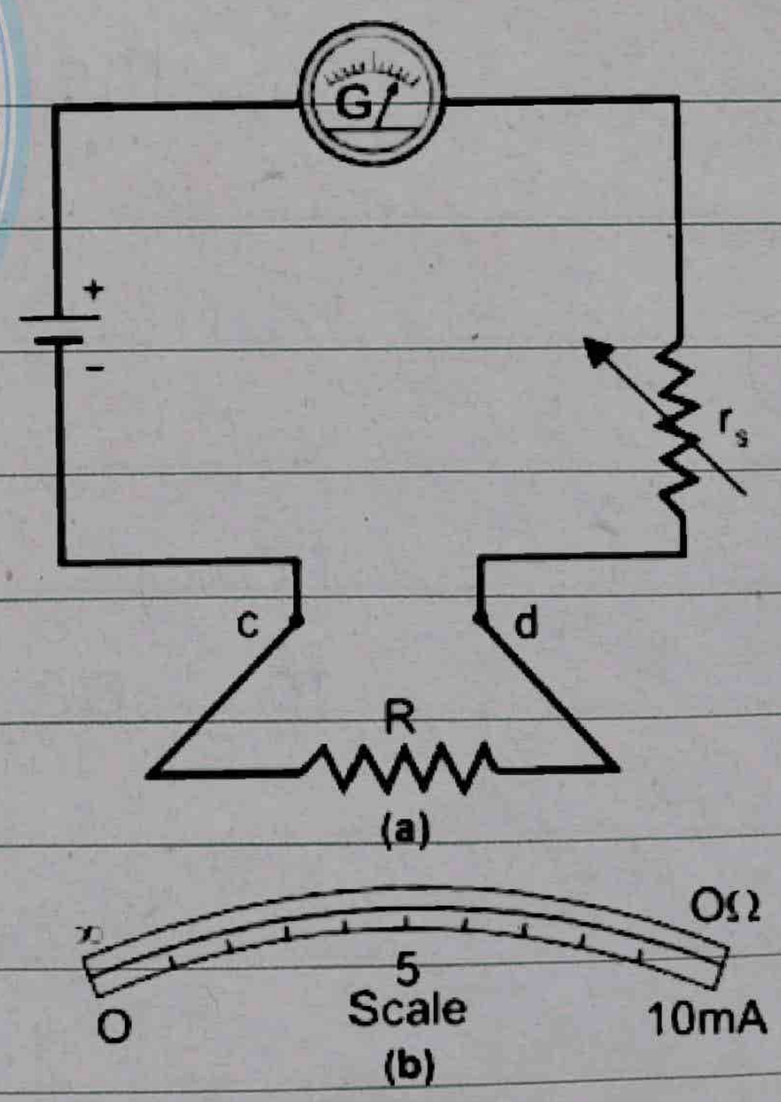


Fig. A moving coil galvanometer is converted into an ohmmeter.

The resistance "R" to be measured is connected between the terminals

"c" and "d". The series resistance "R" is so adjusted that when terminals "c" and "d" are short circuited i.e., when R = 0, the galvanometer gives full scale deflection.

So, the extreme graduation of the usual scale of the galvanometer is marked "0" for resistance measurements.

When terminals "c" and "d" are not joined no current passes through the galvanometer and its deflection is zero. Thus zero of the scale is marked as infinity (∞). in fig (b).

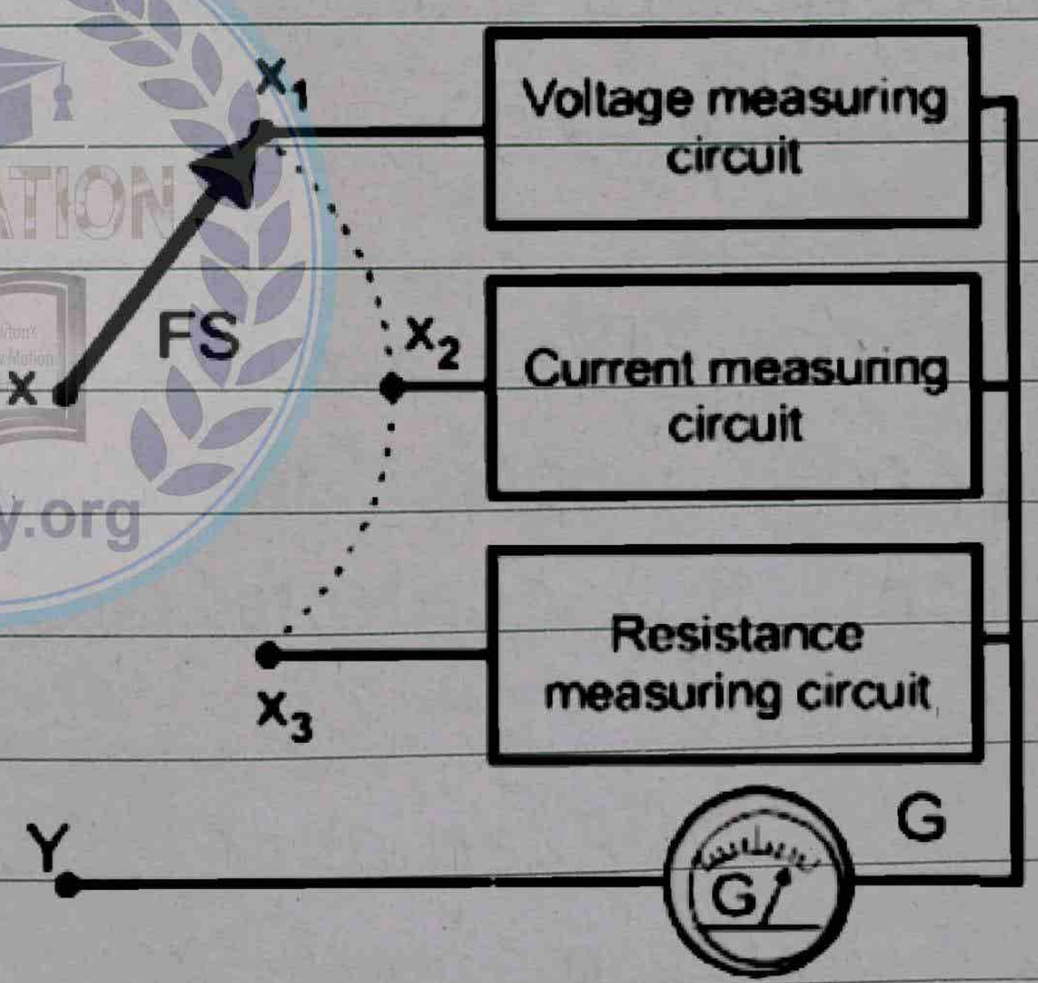
When "R" is not infinite, the galvanometer deflects to some intermediate point depending on the value of "R" and hence the galvanometer scale can be calibrated to read the resistance directly.

14.11 Avometer _ Multimeter

Avometer is an instrument which can measure current in amperes, potential difference in volts and resistance in ohms. It actually consists of a single galvanometer which by the help of a switch is converted into an ammeter, a voltmeter or into an ohmmeter.

Construction:

Avometer basically consists of a sensitive moving coil galvanometer which is converted into a multi_range ammeter (current measuring circuit), a volt meter (voltage measuring circuit) or an ohmmeter (resistance measuring circuit).

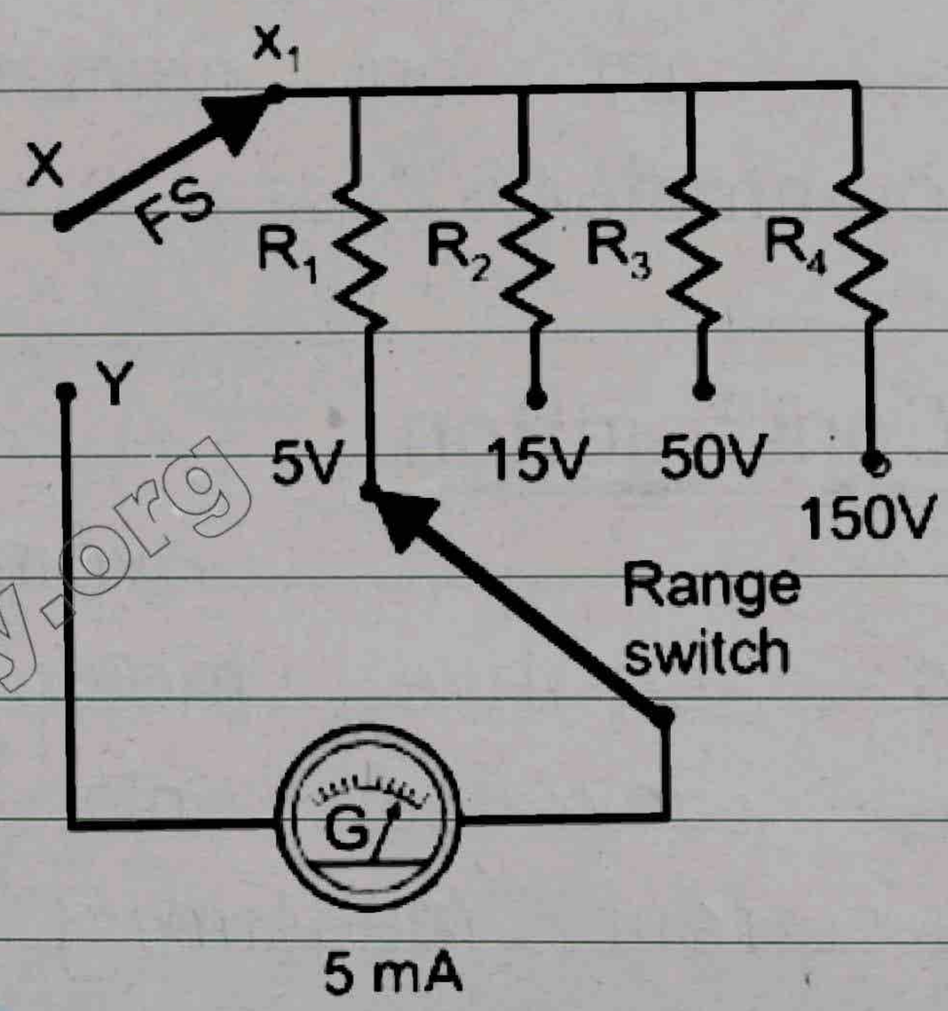


This is done with the help of a function switch FS in fig. X, Y are the main terminals of the AVO meter which are connected with the circuit in which measurement is required.

FS is the function selector switch, which connects the galvanometer with relevant measuring circuit.

Voltage measuring Part of AVO meter:

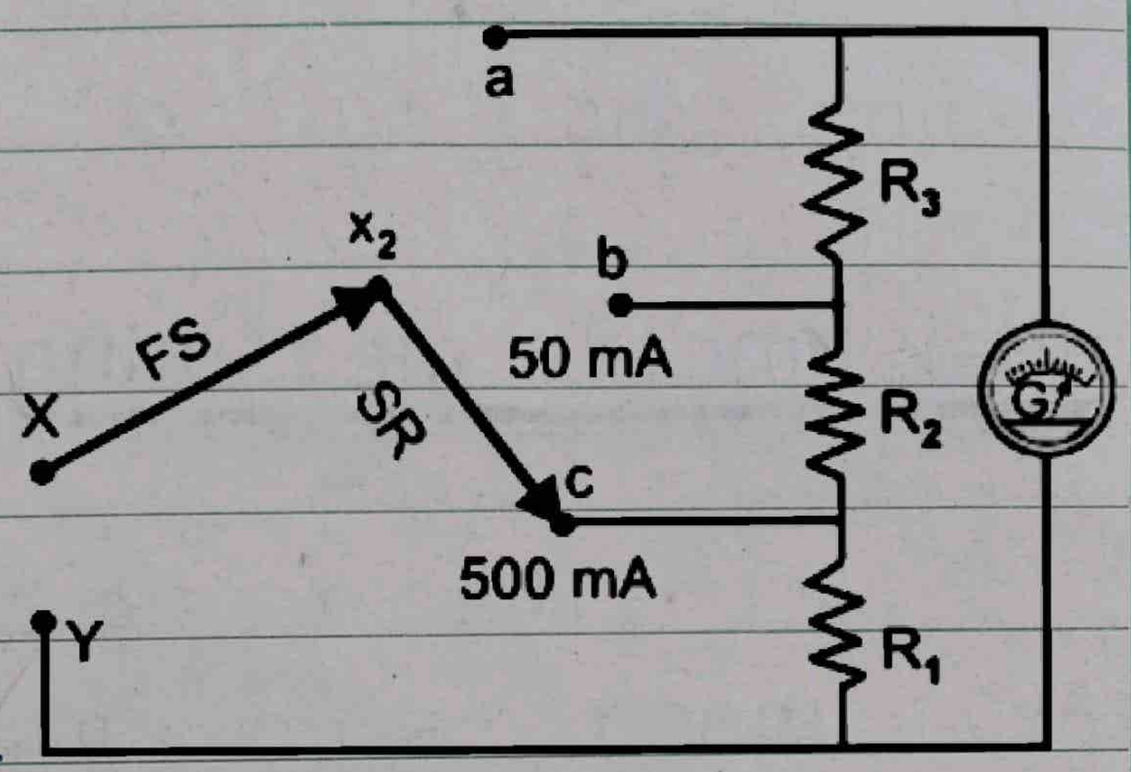
The voltage measuring part of the AVO meter is actually a multirange voltmeter. It consists of a number of resistances each of which can be connected in series with the moving coil galvanometer with the help of a switch called the range switch (in fig).



The value of each resistance depends upon the range of the voltmeter which it controls.

Alternating voltages are also measured by AVO meter. AC voltage is first converted into DC voltage by using diode as rectifier and then measured as usual.

Current measuring Part of AVO meter:



The current measuring part of the AVO meter is actually a multirange ammeter. It consists of a number of low resistances connected in parallel with the galvanometer. The valves of these resistances depend upon the range of the ammeter. in fig.

The circuit also has a range selection switch "SR" which is used to select a particular range of the current.

Digital Multimeter:

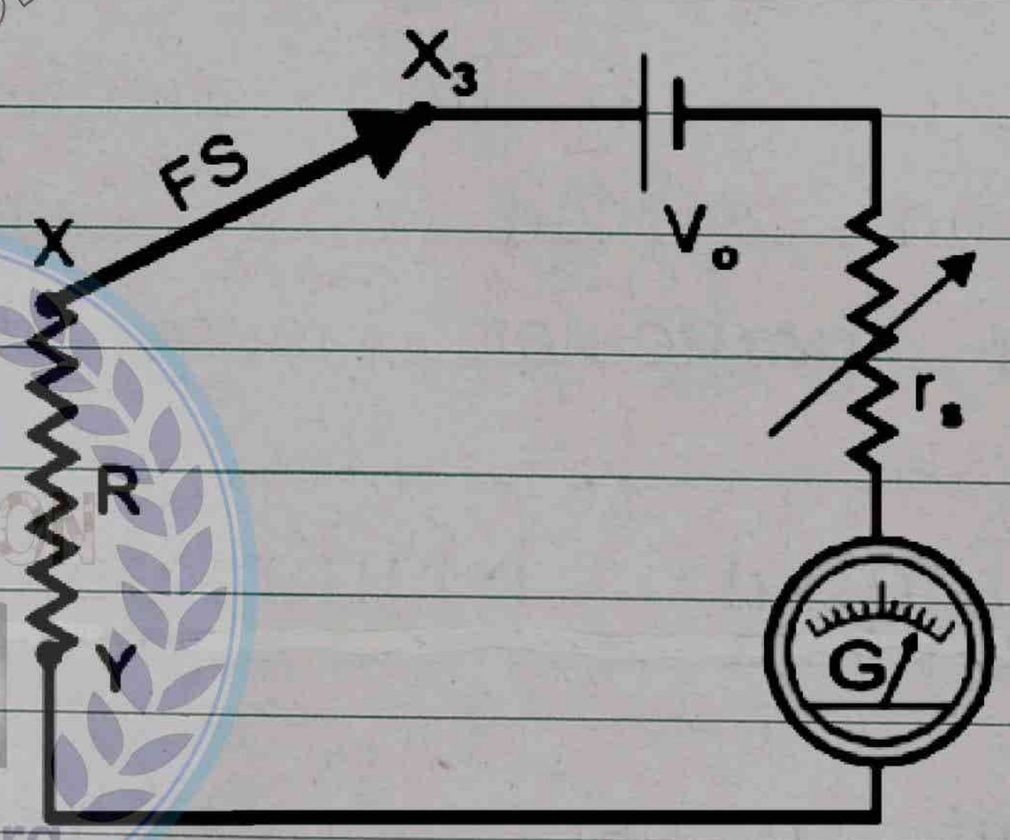
Another useful device to measure resistance, current and voltage is an electronic instruments called digital multimeter. It is a digital version of an AVO meter.

It is a very popular testing device becaue the digital values are displayed automatically with decimal point, polarity

and the unit for V, A or Ω. These meters are generally easier to use becaue they eliminate the human error that often occurs in reading the dial of an ordinary AVO meter.

Resistance measuring Part of AVO meter:

The resistance measuring part of AVO meter is a multirange ohm-meter. Circuit for each range of this meter consists of a battery of emf "V_o" and a variable resistance "r_s" connected in series with galvanometer of resistance "R_g".



When the function switch is switched to position "X" this circuit is connected with the terminals X, Y of the AVO meter.

Before measuring an unknown resistance by an ohm-meter it is first zerod which means that we short circuit the terminals X, Y and adjust r_s to produce full scale deflection.

Chapter = 14

Questions

Question 14.1

Answer:

Maximum Flux:

When $\vec{B}$ is directed perpendicular to the area.
Then $\theta = 0^\circ$ and flux is maximum.

$$\phi_B = \vec{B}.\vec{A} = BA\cos\theta$$

$$= BA\cos 0^\circ = BA(1)$$

$$\phi_B = BA\ (Max)$$

Minimum Flux:

When $\vec{B}$ is directed parallel to the area, then
$\theta = 90^\circ$, and flux is minimum (zero)

$$\phi = \vec{B}.\vec{A} = BA\cos\theta$$

$\phi_B = BA \cos 90^\circ = BA(0)$

$\phi_3 = 0$ (Minimum).

Question 14.2

Answer:

Stationary charge produces only electric field.

It does not produce magnetic field. A charge moving produces magnetic field.

Question 14.3

Answer:

Magnetic lines of force always from a closed path.

As the solenoid behaves like a bar magnetic.

So, the lines of magnetic field goes from one end of a solenoid to the other end, thus forming of a closed path.

Question 14.4

Answer :

The magnetic field of a solenoid is

$$B = \mu_0 n I$$

As

$$n = \frac{N}{L} = \text{Number of turns per unit Length}$$

(a) if $N =$ constant and L is doubled

$$\left(B \propto \frac{1}{L}\right)$$

So,

B is halved.

(b) if $L =$ constant and N is doubled

$$(B \propto N)$$

so,

B is also doubled.

Question 14.5

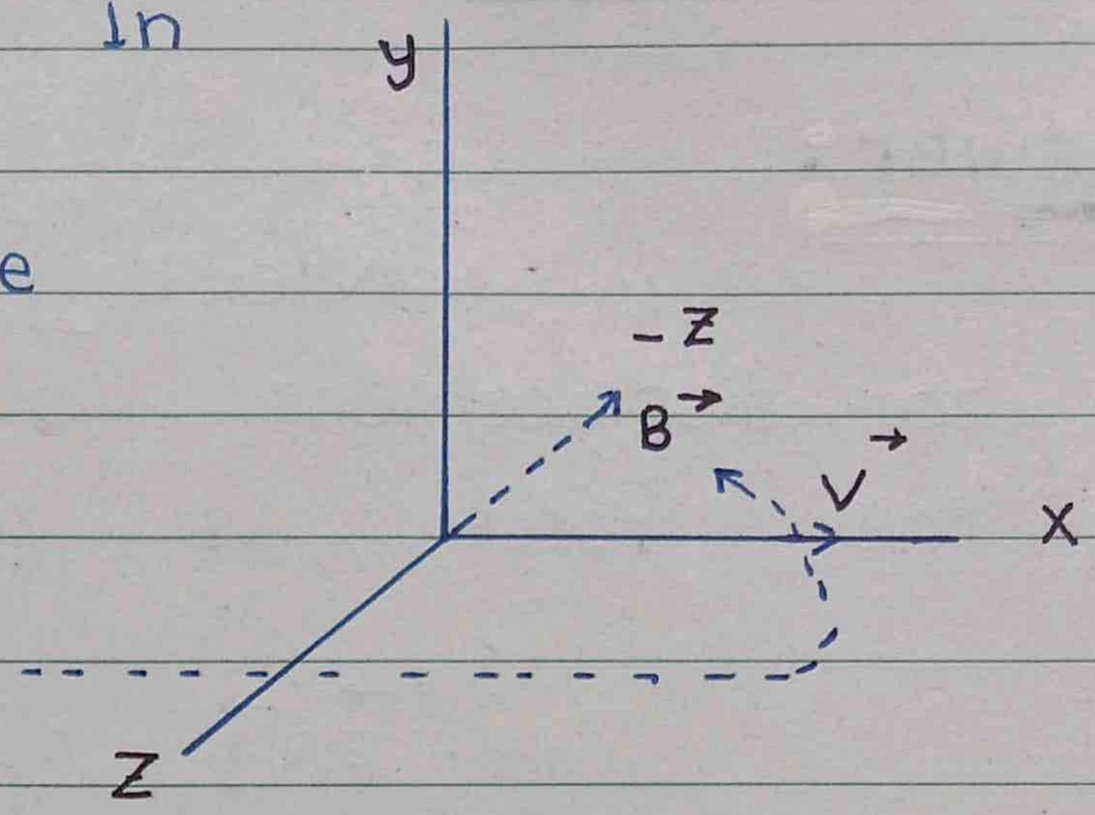
Answer :

$\vec{V}$ is in X- direction

$\vec{B}$ is in -ve Z direction.

By using the right hand rule of cross product in formula

$\vec{F} = q(\vec{V} \times \vec{B})$, the direction of $\vec{F}$ is along y-axis. It will be deflected along y-axis and will trace a curved path in x-y-plane.



Question 14.6

Answer:

When two charged particles are projected in a uniform magnetic field perpendicularly, then their path becomes circular due to the magnetic force.

The direction of the magnetic force on the two charged particles will be opposite when the two point charges have oposite sign.

So,

they are deflected in opposite direction.

$$\vec{F} = +q(\vec{V} \times \vec{B})$$
$$\vec{F} = -q(\vec{V} \times \vec{B})$$

Question 14.7

Answer:

When force $\vec{F}$ is perpendicular to displacement $\vec{d}$ then work done by the force is zero.

$$W = \vec{F} \cdot \vec{d}$$

$$W = F \cdot d \cos 90^\circ$$

$$W = F \cdot d\,(0)$$

$$W = 0$$

The magnetic force $\vec{F} = q(\vec{v} \times \vec{B})$ always acts at right angle to velocity $\vec{v}$ or direction of motion.

So,

the work done by the magnetic force is zero.

Question 14.8

Answer:

As,

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Force is zero

$F = 0$ (i) If either $\vec{B} = 0$

OR

(ii) $\vec{v}$ and $\vec{B}$ are parallel or antiparallel to each other.

$$F = qvB\sin 0^\circ$$

$$F = qvB(0)$$

$$F = 0$$

Hence

there is posibility that magnetic field is present in that region and the direction of motion of the charged particle is either along or opposite to the direction of magnetic field.

Question 14.9

Answer:

As, we know that

$$\vec{F} = q\ (\vec{v} \times \vec{B})$$

For electron $\vec{F} = -e\ (\vec{v} \times \vec{B})$

When a is brought near a TV screen, force acts on the electrons moving towards the TV-screen. The magnet charges the path of electrons and the picture is distorted.

Question 14.10

Answer:

As

$$\tau = NIAB \cos\alpha$$

Here

α = Angle b/w the plane of the coil and the magnetic field $\vec{B}$.

if $\alpha = 90^\circ$

$\cos\alpha = \cos 90^\circ$

$\cos\alpha = 0$

And

so, $\tau = 0$

Thus,

when the plane of the coil is perpendicular to $\vec{B}$

$\tau = 0$

and the coil will not tend to rotate.

Question 14.11

Answer:

If a freely suspended current loop experiences a torque in a given region of space, then a magnetic field is present in region.

$$\tau = NIAB\cos\alpha$$

Question 14.12

Answer:

The radius of the circular path of a charged particle in a magnetic field depends on its mass

$$r = \frac{mV}{qB}$$

So

$$r \propto m$$

Isotopes of a chemical element has same charge q but different mass m.
So, when the element (in ionic form) is projected from the same spot in a perpendicular magnetic field, they will move in orbits of different radit according to their mass.
So, they can be seperated from each other.

$$F_c = F_b$$
$$\frac{mv^{\cancel{2}}}{r} = q\cancel{v}B$$
$$\frac{mv}{r} = qB$$
$$r = \frac{mv}{qB}$$

Question 14.13

Answer:

Torque is $\tau = NIAB \cos\alpha$

α = Angle between the plane of coil and $\vec{B}$

(a) If $\alpha = 0^\circ$ i.e, plane of coil is parallel to $\vec{B}$ Torque will be maximum.

$$\tau_{(max)} = NIAB \cos 0^\circ$$

$$\tau = NIAB\ (1)$$

$$\boxed{\tau = NIAB}$$

(b) If $\alpha = 90^\circ$, i,e, plane of coil is perpendicular to a Torque will be zero (Minimum).

$$\tau_{(Min)} = NIAB \cos 90^\circ$$

$$\tau = NIAB\,(0)$$

$$\boxed{\tau = 0}$$

Question 14.14

Answer:

When the plane of the loop is parallel to pole faces $\alpha = 90^\circ$.
So, no Torque is produced in the loop whetherwe pass a direct curve or alternating current through the loop.

$$\tau = NIAB \cos \alpha$$

$$\tau = NIAB \cos 90^\circ$$

$$\tau = NIAB\,(0)$$

$$\boxed{\tau = 0}$$

Question 14.15

Answer:

A sensitive galvanometer is one which produces large deflection even for very small current.

But galvanometer is stable if its pointer quickly comes torest.

When the current is passed through it or current is stopped through it.

Usually, the pointer of a sensitives g vano-meter does not come to rest quickly but vibrates about its equilbrium position for some time before coming to rest.

Thus a sensitive galvanometer cannot be stable.

If a galvanometer is not sensi-tive, then small torque does not effect its position and it remains stable.

Question 14.16

Answer:

An ammeter is always placed in series in a circuit.

Whose current is to be measured. If the resistance of ammeter used is large.

it will increase the resistance of the circuit.
Hence, current is decreased.
A good Ammeter should not charge the circuit current.
So, it must have very small resistance as compared to the resistance of the circuit itself.

Question 14.17

Answer:

A voltmeter is connected in parallel with the circuit across which the potential difference is to be measured.
If the voltmeter has a small resistance, it will draw some current from the circuit and will alter decrease the circuit.
If should draw either no current or very small current from the circuit.
This is only possible when the resistance of the voltmeter is very high as compared to the circuit resistance.

Chapter = 14

Examples

Example 14.1

Solution:

$$L = 20\,cm$$

$$L = \frac{20}{100}\,m$$

$$L = 0.20\,m$$

$$I = 10\,A$$

$$B = 0.30\,T$$

$$\alpha = 40^\circ$$

$$\boxed{F = ILB\sin\alpha}$$

$$F = 10 \times 0.20 \times 0.30 \times \sin 40^\circ$$

$$F = 0.39\,N.$$

Example 14.2

Solution :

$$\vec{B} = 40\hat{i} - 18\hat{k}$$

$$A = 5\,cm^2$$

$1\,cm = 10^{-2}\,m$

$1\,cm = 10^{-4}\,m^2$

$$A = 5 \times 10^{-4}\,m^2$$

$$\vec{A} = 5 \times 10^{-4}\,m^2\,\hat{k}$$

$$\phi_B = ?$$

$$\phi_B = \vec{B} \cdot \vec{A}$$

$$\phi_B = (40\hat{i} - 18\hat{k}) \cdot (5 \times 10^{-4}\,\hat{k})$$

$$\phi_B = 40 \times 5 \times 10^{-4}\,\hat{i} - 18 \times 5 \times 10^{-4}\,\hat{k} \cdot k$$

$$\phi_B = 40 \times 5 \times 10^{-4}(0) - 18 \times 5 \times 10^{-4}\,(1)$$

$$\boxed{\phi_B = -90 \times 10^{-4}\,Wb}$$

Example 14.3

Solution:

$L = 15\ cm$

$L = 0.15\ m$

$N = 300$

$I = 5A$

$\mu_o = 4\pi \times 10^{-7}\ Wb\ A^{-1}\ m^{-1}$

$n = \frac{N}{L}$

$n = \frac{300}{0.15}$

$n = 2000\ turns/m$

n = No. of turns per unit length.

$$B = \mu_o\ n\ I$$

$B = 4\pi \times 10^{-7} \times 2000 \times 5$

OR

$B = 1.3 \times 10^{-2}$ Tesla

$$B = 1.3 \times 10^{-2}\ Wb\ m^{-2}$$

Example 14.4

Solution:

$r = ?$

$V = 2 \times 10^{7}\ ms^{-1}$

$B = 1.20 \times 10^{-3}\ T$

$m = 9.11 \times 10^{-31}\ kg$

$e = 1.6 \times 10^{-19}\ C$

$$\frac{e}{m} = \frac{v}{Br}$$

$$r = \frac{mv}{eB}$$

$$r = \frac{9.11 \times 10^{-31} \times 2 \times 10^{7}}{1.6 \times 10^{-19} \times 1.20 \times 10^{-3}}$$

$$\boxed{r = 9.43 \times 10^{-2}\ m}$$

$r = 9.43\ mm$

Example 14.5

Solution:

$$E = 300\ Vm^{-1}$$

$$B = 0.20\ T$$

$$V = ?$$

$$F_b = F_e$$

$$qVB = qE$$

$$VB = E$$

$$V = \frac{E}{B}$$

$$V = \frac{300}{0.20}$$

$$\boxed{V = 1500}$$

Example 14.6

Solution:

$R_g = 50.0\ \Omega$

$I_g = 20\ mA$

$I_g = 2 \times 10^{-3}\ A$

$I = 10\ A$

$R_s = ?$

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

$$R_s = \frac{2 \times 10^{-3}}{10 - 2 \times 10^{-3}} \times 50$$

$$\boxed{R_s = 0.01\ \Omega}$$

Chapter = 14.

Problems

Problem 14.1

Solution:

$B = ?$

$F = 7.0 \times 10^{-3}\ N$

$L = 20.0\ cm$

$L = \frac{20}{100}\ m$

$L = 20m$

$I = 10 \cdot A$

$$\boxed{F = BIL}$$

$B = \frac{F}{IL}$

$$B = \frac{7.0 \times 10^{-3}}{10 \times 0.20}$$

$$B = 3.5 \times 10^{-3} T$$

$$\boxed{B = 3.5 \times 10^{-3} \text{ Tesla}}$$

Problem 14.2

Solution:

$$V = ?$$

$$m = 1.67 \times 10^{-27} \text{ kg}$$

$$q = 1.6 \times 10^{-19} \text{ C}$$

$$B = 2.50 \times 10^{-3} \text{ T}$$

$$F_b = F_g$$

Magnetic Force = Gravitational Force

$$qVB = mg$$

$$V = \frac{mg}{qB}$$

$$V = \frac{1.67 \times 10^{-27} \times 9.8}{1.6 \times 10^{-19} \times 2.5}$$

$$\boxed{V = 4.09 \times 10^{-5} \text{ m/s}}$$

Problem 14.3

Solution:

$B = 0.30\,T$

$E = 10{,}000\ Vm^{-1}$

$V = ?$

Magnetic force = Electric force

$F_b = F_e$

$\cancel{q}VB = \cancel{q}E$

$VB = E$

$$V = \frac{E}{B}$$

$$V = \frac{10.000}{0.30}$$

$$\boxed{V = 3.33 \times 10^{4}\ m/s}$$

Problem 14.4

Solution:

$A = 0.1\,m \times 0.1\,m$

$A = 0.01\,m^2$

$N = 200$

$I = 1.0\,mA$

$I = 1 \times 10^{-3}\,A$

$B = 0.1\,T$

$\tau = ?$

$$\tau = NIAB\cos\alpha$$

For maximum

Torque $\alpha = 0^\circ$

$$\cos\alpha = \cos 0^\circ = 1$$

$$\tau_{max} = NIBA\,(1)$$

$$\tau_{max} = NIBA$$

$$= 200 \times 1 \times 10^{-3} \times 0.01 \times 0.1$$

$$\boxed{\tau_{max} = 2.0 \times 10^{-4}\ Nm}$$

Problem 14.5

Solution:

$r = 10\,m$

$I = 200\,A$

$B = ?$

$\mu_o = 4\pi \times 10^{-7}\ Wb\ m^{-1} A^{-1}$

$$B = \frac{\mu_o I}{2\pi r}$$

$$B = \frac{4\pi \times 10^{-7} \times 200}{2\pi \times 10}$$

$$B = 4 \times 10^{-6}\ T$$

$$B = 4\mu T$$

Problem 14.6

Solution:

$B = 0.10\ T$

$I = 10.0\ A$

$n = ?$

$\mu_o = 4\pi \times 10^{-7}\ Wb\ m^{-1} A^{-1}$

$$B = \mu_o n I$$

$$n = \frac{B}{\mu_0 I}$$

$$n = \frac{0.10}{4\pi \times 10^{-7} \times 10}$$

$$n = \frac{0.10}{4 \times 3.14 \times 10^{-7} \times 10}$$

$$\boxed{n = 7.96 \times 10^{3}}$$

Problem 14.7

Solution:

$I = ?$

$L = 0.5\ m$

$N = 10,000$

$B = 0.4\ T$

$\mu_0 = 4\pi \times 10^{-7}\ WbA^{-1}m^{-1}$

$$B = \mu_0 n I$$

But $n = \frac{N}{L}$

$$B = \frac{\mu_0 N I}{L}$$

$$I = \frac{BL}{\mu_0 N}$$

$$I = \frac{0.4 \times 0.5}{4\pi \times 10^{-7} \times 10,000}$$

$$I = 15.91 \text{ A}$$

Problem 14.6

Solution:

$R_g = 15.0\ \Omega$

$I_g = 20.0 \text{ mA}$

$I_g = 20 \times 10^{-3} \text{ A}$

$I = 10 \cdot A$

$R_s = ?$

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

$$R_s = \frac{20 \times 10^{-3}}{10 - 20 \times 10^{-3}} \times 15.0$$

$$R_s = 0.03 \ \Omega$$

Problem 14.9

Solution:

$R_g = 50.0 \ \Omega$

$I_g = 2.0 \ mA$

$I_g = 2 \times 10^{-3} \ A$

$V = 200 \ V$

$R_h = ?$

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

$$R_h = \frac{200}{2} - 50$$

$$R_h = 99,950\ \Omega$$

Problem 14.10

Solution:

$R_g = 10.0\ \Omega$

$I_g = 1.0\ mA$

$I_g = 1 \times 10^{-3}\ A$

Current ranges

$I_1 = 100\ A$

$I_2 = 10\ A$

$I_3 = 1.0\ A$

$R_1 = ?$

$R_2 = ?$

$R_3 = ?$

As

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

$$R_1 = \frac{1.0 \times 10^{-3}}{100 - 1 \times 10^{-3}} \times 10$$

$$R_1 = 0.0001\ \Omega$$

$$R_2 = \frac{I}{I_2 - I_g} \times R_g$$

$$R_2 = \frac{1.0 \times 10^{-3}}{10 - 1 \times 10^{-3}} \times 10$$

$$R_2 = 0.001\ \Omega$$

$$R_3 = \frac{I_g}{I_3 - I_g} \times R_g$$

$$R_3 = \frac{1.0 \times 10^{-3}}{1 - 1 \times 10^{-3}} \times 10$$

$$R_3 = 0.01\ \Omega$$