ELECTROMAGNETISM

ELECTROMAGNETISM

That branch of physics which deals with the magnetic effect of moving charges is called electromagnetism.

MAGNETISM

That branch of physics which deals with the behaviour and properties of magnetic materials is called magnetism.

NOTE

Electric current or moving charges produces magnetic field and at the same time, a changing magnetic field produces electric current.

This process is widely used in many electrical devices and appliances in modern technology.

MAGNETIC FIELD DUE TO CURRENT IN A LONG STRAIGHT WIRE

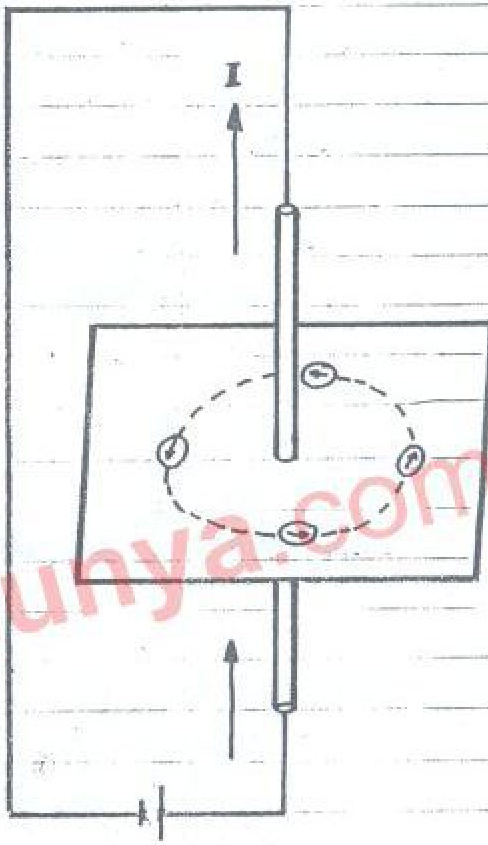
It is experimentally observed by Hans Oersted in 1820 that when a current flows through a wire then a magnetic field is produced around it. The magnitude of magnetic field is directly proportional to the current flowing through the wire and inversely proportional to the distance from the wire.

EXPLANATION

Consider a straight, thick copper wire which passes vertically through a hole in a piece of horizontal cardboard. Now place small compass needles on the cardboard along a circle with the centre at the wire. All the compass needles pointed in the direction of N-S. Now pass a heavy current the wire. It will be seen that the compass needles will rotate and set themselves in the direction tangent to the circle, as shown in figure. If the direction of current is reversed, then the direction of compass needles is also reversed. When current through the wire is stopped, then all the needles again set themselves along the N-S direction.

Results

The following results are obtained from the above experiment.



(i) A magnetic field is set up in the region surrounding a current carrying wire.

(ii) The 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 flowing through the wire.

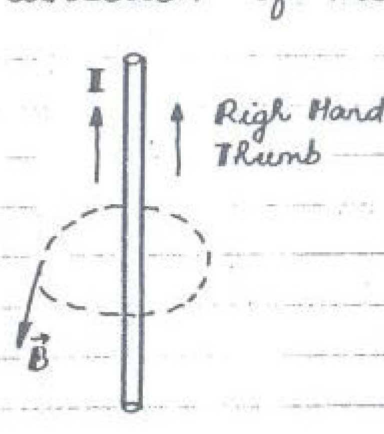
Direction Of Field

The direction of magnetic lines of force can be determined by right hand rule.

Right Hand Rule stated as:

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

The right hand rule is illustrated as shown in figure.



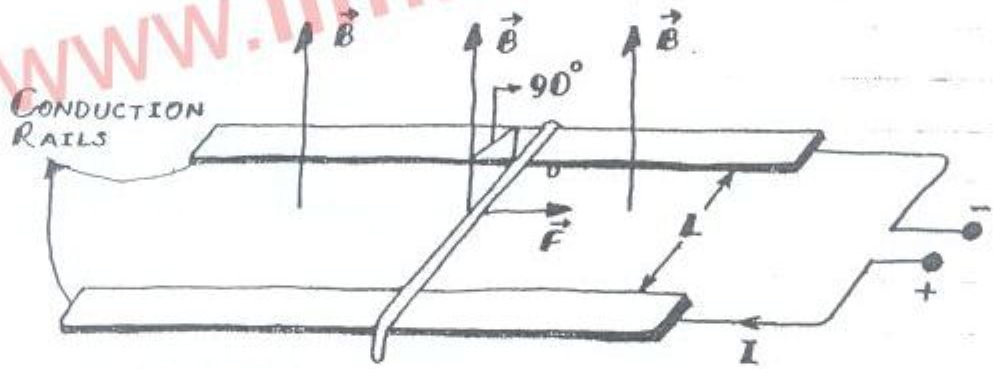
FORCE ON A CURRENT CARRYING CONDUCTOR IN A UNIFORM MAGNETIC FIELD

As we know that magnetic field is produced around a current carrying wire in its surrounding space. If such a wire or conductor is placed in an external field, then the magnetic field of the conductor will interact with the external magnetic field. As a result of which the conductor may experience a force.

This effect can be demonstrated as:

DEMONSTRATION

Consider a copper rod which can move on a pair of copper rails. The whole arrangement is placed in between the pole pieces of a horseshoe magnet so that the copper rod is subjected to a magnetic field directed vertically upward as shown in figure.



When a current is passed through the copper rods from a battery, then due to interaction between magnetic field due to current carrying conductor and the external magnetic field, rod moves on the rails in a particular direction as shown in figure. It can be seen that the force on a conductor is always right angle to the plane containing the rod and the direction of the

magnetic field.

The magnitude of the force depends upon the following factors

(i) The magnetic force F is directly proportional to $\sin\alpha$ i-e;

$$F \propto \sin\alpha$$

Where α is the angle between the conductor and the magnetic field. If rod is parallel to the field, then the magnetic force is zero i-e; minimum and force is maximum if conductor is at right angles to the field.

(ii) The magnetic force F is directly proportional to the current flowing through the conductor. i-e;

$$F \propto I$$

It means that more the current, greater is the force.

(iii) The magnetic force F is directly proportional to the length L of the conductor inside the magnetic field. i-e;

$$F \propto L$$

(iv) The magnetic force F is directly proportional to the strength of the applied magnetic field B. The greater the field, the greater is the force. i-e;

$$F \propto B$$

Combining all the above factors, we get

$$F \propto ILB\sin\alpha$$

or $\quad F = (\text{Constant})\, ILB\sin\alpha$

or $\quad F = KILB\sin\alpha \longrightarrow (1)$

Where K is constant of proportionality. In SI-units, the value of K is one ($K = 1$).

So, in SI-units, equation (1) becomes as

$$\boxed{F = ILB\sin\alpha} \longrightarrow (2)$$

Which is the magnetic force act on a current carrying conductor placed in an external magnetic field.

Equation ② can be written in vector form as

$$\vec{F} = ILB\sin\alpha \cdot \hat{n}$$

or

$$\vec{F} = I(\vec{L} \times \vec{B}) \longrightarrow ③$$

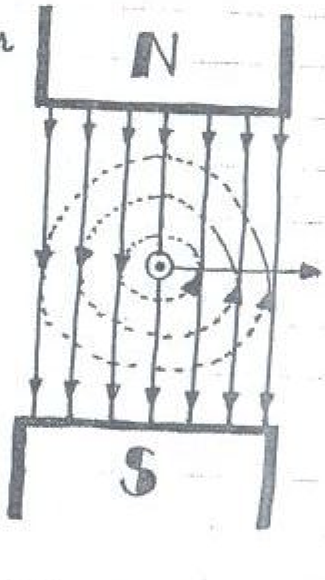
Where the vector $\vec{L}$ is in the direction of flow of current. The magnitude of magnetic force $\vec{F}$ is $ILB\sin\alpha$ and α is the angle between vectors $\vec{L}$ and $\vec{B}$. The direction of force $\vec{F}$ is perpendicular to the plane containing vectors $\vec{L}$ and $\vec{B}$. Its direction can also be determined by right hand rule.

RIGHT HAND RULE

Curl the fingers of right hand in the direction of rotation i-e; rotate $\vec{L}$ towards $\vec{B}$ through the smaller angle. Then the thumb points in the direction of force.

DIRECTION OF MAGNETIC FORCE ACT ON A CURRENT CARRYING CONDUCTOR

Consider a straight current carrying conductor placed perpendicular to a magnetic field. The current flows through the conductor out of the plane of the paper i-e; towards the reader as shown in figure. The current flowing towards the reader represented by a symbol dot (•) and a current flowing away from him represented by a cross (X).



In order to find the direction of force, consider the interaction of field lines as shown. The two fields tend to reinforce each other on right hand side of the conductor and cancel each other on the left side of the conductor. The conductor moves from stronger to the weaker part of the magnetic field. So, the force on the conductor will be directed towards right in a direction at right angle to both the conductor and the magnetic field.

It can be seen that this direction is the same as given by right hand rule. So, this rule is referred as the extension of right hand rule.

MAGNETIC FIELD STRENGTH OR MAGNETIC INDUCTION ($\vec{B}$)

As magnitude of magnetic force act on a current carrying conductor is

$$F = ILB \sin\alpha$$

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

If $I = 1A$, $L = 1m$ and $\alpha = 90°$, then

$$B = \frac{F}{1A \times 1m}$$

or $$\boxed{B = F}$$

So, magnetic field strength or magnetic induction is defined as

"The magnetic force acting on one metre length of the conductor placed at right angle to the magnetic field when a current of one ampere is passing through it, is called magnetic induction $\vec{B}$."

UNITS OF MAGNETIC INDUCTION

The SI-units of magnetic induction is tesla (T).

As

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

If $F = 1N$, $I = 1A$, $L = 1m$ and $\alpha = 90°$, then

$$\boxed{1T = \frac{1N}{1A \times 1m} = 1N \cdot A^{-1} \cdot m^{-1}}$$

TESLA

The magnetic field strength is said to be one tesla if a force of one newton act on a conductor of length one metre placed at right angle to the field when a current of one ampere passes through conductor.

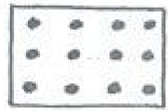
The smaller unit of $\vec{B}$ is gauss (G).

$$\boxed{1T = 10^{-4} G}$$

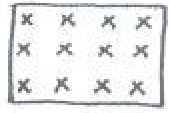
Conventions Of Magnetic Field

There are two conventions to represent the magnetic field given as

(i) The magnetic field directed out of the plane of the paper is denoted by dots (•) as shown.



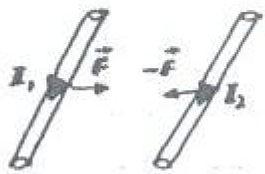
(ii) The magnetic field directed into the plane of the paper is denoted by cross (x) as shown.



For Your Information

(i) Two straight parallel wires carrying currents I_1 and I_2 in opposite direction repel each other

(ii) Two straight parallel wires carrying currents I_1 and I_2 in same direction attract each other.



Magnetic Flux

The number of magnetic field lines passing through a certain surface placed at any angle in the field, called magnetic flux.

OR

The scalar or dot product of magnetic field strength ($\vec{B}$) and vector area ($\vec{A}$) is called magnetic flux. It is denoted by ϕ_B and given as

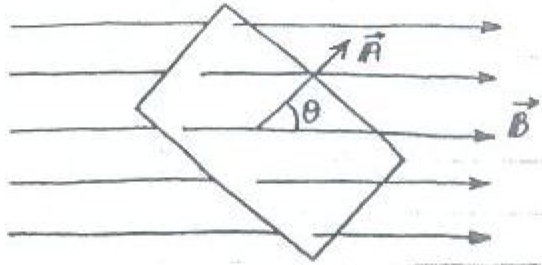
$$\phi_B = \vec{B} \cdot \vec{A}$$

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

Where $\vec{A}$ is vector area whose magnitude is equal to the area of given surface element and its direction is along the outward normal drawn to the surface element, while θ is the angle between the directions of the vectors $\vec{B}$ and $\vec{A}$.

EXPLANATION

Consider a magnetic field of strength $\vec{B}$. A surface of vector area $\vec{A}$ is placed at certain angle θ with the direction of the field as shown. Then the magnetic flux through the surface is

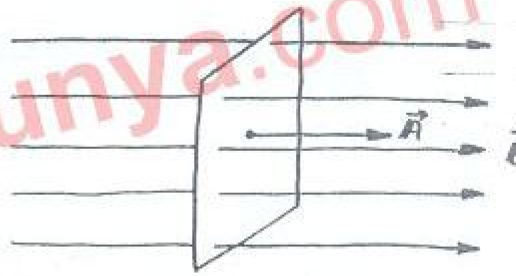


$$\phi_B = \vec{B} \cdot \vec{A}$$

or $$\phi_B = BA\cos\theta \longrightarrow (1)$$

MAXIMUM FLUX

If surface element is placed perpendicular to the magnetic field i-e; magnetic field is parallel to the direction of vector area, then angle between them is $0°$ i-e; $\theta = 0°$.



So, equation (1) becomes as

$$\phi_B = BA\cos 0°$$

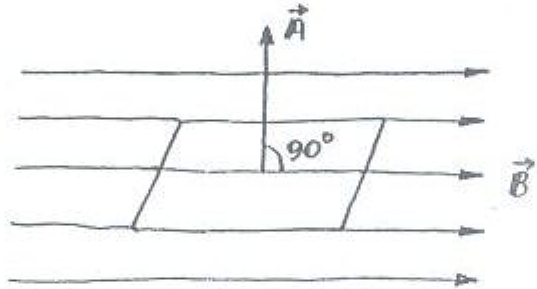
or $$\phi_B = BA(1)$$

or $$\phi_B = BA$$

Hence maximum flux through the surface is equal to BA.

MINIMUM FLUX

If surface element is placed parallel to the direction of magnetic field then magnetic field is at right angle to the direction of vector area, so angle between them is $90°$ i-e; $\theta = 90°$.



So, equation (1) becomes as

$$\phi_B = BA\cos 90°$$

or $$\phi_B = BA(0)$$

or $$\phi_B = 0$$

Hence at $\theta = 90°$, flux will be minimum.

Flux For Curved Surface

If a curved surface is placed in a non-uniform magnetic field. To find magnetic flux for curved surface, divide the curved surface into a large number of small surface elements such that each surface element assumed to be plane. Now the flux through the curved surface is calculated by taking sum of all the fluxes through each surface element.

Units Of Magnetic Flux

The SI-units of magnetic flux is $N \cdot m \cdot A^{-1}$ or $T \cdot m^2$ which is called weber (Wb).

Weber

The magnetic flux is said to be one weber if a surface of area one square metre placed perpendicular to the magnetic field of strength one tesla.

Flux Density ($\vec{B}$)

As magnetic flux is given as

$$\phi_0 = BA$$

or

$$\boxed{B = \frac{\phi_0}{A}}$$

"The flux density or magnetic induction is defined as the magnetic flux per unit area of a surface perpendicular to magnetic field."

Units Of Flux Density

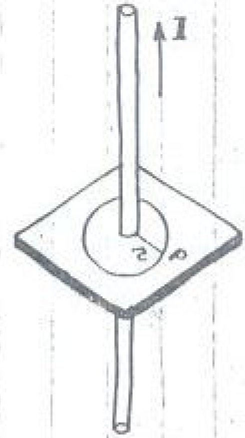
The SI-units of flux density or magnetic induction $\vec{B}$ is tesla (T) or $Wb \cdot m^{-2}$ or $N \cdot A^{-1} \cdot m^{-1}$.

Ampere's Law

Statement: The magnetic field strength at a point around a current carrying conductor is directly proportional to the current flowing through the conductor and inversely proportional to the distance from the conductor.

Explanation

Consider a conductor in which current I is flowing as shown. Let we want to find the magnetic field at point P having distance r from the conductor, then according to Ampere's law, we have



$$B \propto I \longrightarrow (1)$$

and $$B \propto 1/r \longrightarrow (2)$$

Combining equation (1) and (2)

$$B \propto I/r$$

or $$B = (\text{Constant})\, I/r$$

or $$\boxed{B = \frac{\mu_o}{2\pi} \cdot \frac{I}{r}} \longrightarrow (3)$$

Where μ_o is called permeability of free space. Its numerical value is $4\pi \times 10^{-7}\, Wb.A^{-1}.m^{-1}$.

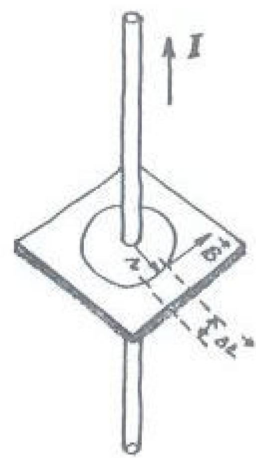
Ampere performing a number of experiment and generalized his results into a law known as Ampere's Circuital Law.

Ampere's Circuital Law

Statement: Ampere stated that the sum of the quantities $\vec{B} \cdot \Delta\vec{L}$ for all path elements into which the complete loop has been divided equals μ_o times the total current enclosed by the loop.

Explanation

Consider a closed path in the form of a circle of radius r around a current carrying wire in which current I is flowing as shown in figure. The closed path around a current carrying wire is known as Amperean path. Divide this path into a small patches each of



Now, for side $cd = l_3$, we have

$$(\vec{B}\cdot\Delta\vec{L})_3 = \vec{B}\cdot\vec{l_3} = Bl_3\cos\theta$$

As side $cd = l_3$ lies outside the solenoid, so

$$B = 0$$

$$\therefore (\vec{B}\cdot\Delta\vec{L})_3 = (0)\,l_3\cos\theta$$

$$\Rightarrow (\vec{B}\cdot\Delta\vec{L})_3 = 0$$

Put these values in equation ①

$$\therefore \quad Bl_1 + 0 + 0 + 0 = \mu_o \times \text{Current enclosed}$$

$$\text{or} \quad Bl_1 = \mu_o \times \text{Current enclosed} \longrightarrow ②$$

Now, we have to calculate the current enclosed by the rectangular loop abcda as

No. of turns per unit length of solenoid $= n = N/l_1$

$\Rightarrow$ No. of turns of solenoid $= N = nl_1$

Current through each turn of solenoid $= I$

So,

Current enclosed by the loop $= NI$

$$= nl_1 I$$

Put this value in equation ②

$$\therefore \quad Bl_1 = \mu_o \times nl_1 I$$

$$\text{or} \quad \boxed{B = \mu_o n I}$$

Which is the value of magnetic field B due to a current carrying solenoid and it is directed along the axis of the solenoid. Its direction is given by the right hand rule.

RIGHT HAND RULE

It states that "hold the solenoid in right hand with fingers curling in the direction of the current, the thumb will be point in the direction of the field"

Force On A Moving Charge In A Magnetic Field

As we know that when a current carrying conductor is placed in a magnetic field, then it experiences a force. The current is due to the flow of charges through the conductor. Actually, the magnetic field exerts force on the moving charges due to which the conductor experiences a force.

Now we calculating the force exert on the moving charges as:

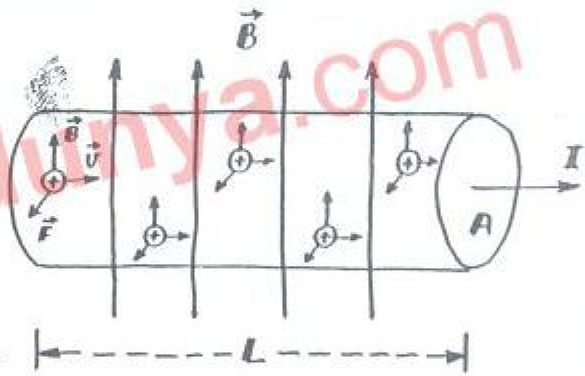
Consider the portion of a wire of length L and area of cross-section A carrying current I and placed in a uniform magnetic field of strength B as shown in figure.

As

Length of wire $= L$

Area of wire $= A$

$\therefore$ Volume of wire $= V = AL$



Let

$$\left.\begin{array}{l}\text{Number of charge} \\ \text{carriers per unit} \\ \text{volume of conductor}\end{array}\right) = n = \frac{N}{V}$$

So,

Total no. of charge carriers $= N = nV = nAL$

If q is the charge on each charge carrier moving with velocity v through the conductor, then the time taken by the charge carrier from left to right face of the wire segment is given as

$$\Delta t = \frac{L}{v} \longrightarrow (1)$$

During this time Δt, the total charge carriers nAL will exit through the right face of the wire segment, so total charge ΔQ passes through the right face in time Δt is

Now, for side $cd = l_3$, we have

$(\vec{B}\cdot\Delta\vec{L})_3 = \vec{B}\cdot\vec{l}_3 = Bl_3 \cos\theta$

As side $cd = l_3$ lies outside the solenoid, so

$$B = 0$$

$\therefore (\vec{B}\cdot\Delta\vec{L})_3 = (0)\, l_3 \cos\theta$

$\Rightarrow (\vec{B}\cdot\Delta\vec{L})_3 = 0$

Put these values in equation ①

$\therefore \quad Bl_1 + 0 + 0 + 0 = \mu_0 \times$ Current enclosed

or $\quad Bl_1 = \mu_0 \times$ Current enclosed $\longrightarrow$ ②

Now, we have to calculate the current enclosed by the rectangular loop abcda as

No. of turns per unit length of solenoid $= n = N/l_1$

$\Rightarrow$ No. of turns of solenoid $= N = nl_1$

Current through each turn of solenoid $= I$

So,

Current enclosed by the loop $= NI$

$= nl_1 I$

Put this value in equation ②

$\therefore \quad Bl_1 = \mu_0 \times nl_1 I$

or $\quad \boxed{B = \mu_0 n I}$

Which is the value of magnetic field B due to a current carrying solenoid and it is directed along the axis of the solenoid. Its direction is given by the right hand rule.

RIGHT HAND RULE

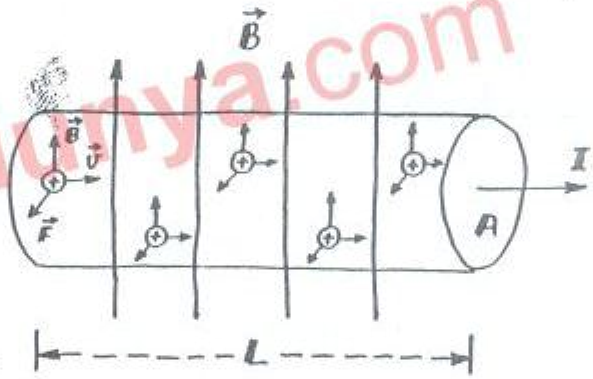
It states that "hold the solenoid in right hand with fingers curling in the direction of the current, the thumb will be point in the direction of the field"

FORCE ON A MOVING CHARGE IN A MAGNETIC FIELD

As we know that when a current carrying conductor is placed in a magnetic field, then it experiences a force. The current is due to the flow of charges through the conductor. Actually, the magnetic field exerts force on the moving charges due to which the conductor experiences a force.

Now we calculating the force exert on the moving charges as:

Consider the portion of a wire of length L and area of cross-section A carrying current I and placed in a uniform magnetic field of strength B as shown in figure.



As

Length of wire $= L$

Area of wire $= A$

$\therefore$ Volume of wire $= V = AL$

Let

Number of charge carriers per unit volume of conductor $= n = \frac{N}{V}$

So,

Total no. of charge carriers $= N = nV = nAL$

If q is the charge on each charge carrier moving with velocity v through the conductor, then the time taken by the charge carrier from left to right face of the wire segment is given as

$$\Delta t = \frac{L}{v} \longrightarrow (1)$$

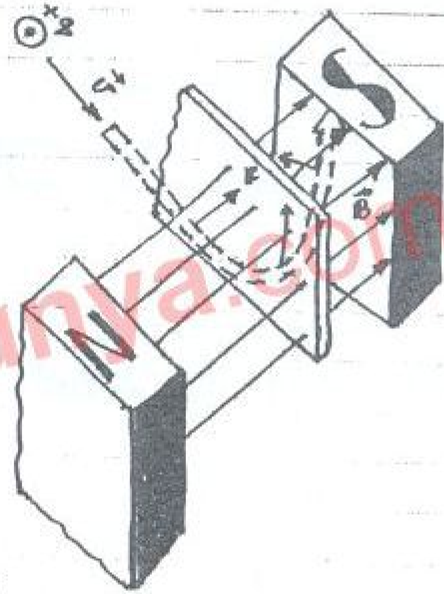
During this time Δt, the total charge carriers nAL will exit through the right face of the wire segment, so total charge ΔQ passes through the right face in time Δt is

Direction Of Force Act On A Charge Carrier In A Magnetic Field

As magnetic force act on a charge carrier in a magnetic field is

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

So, the direction of magnetic force $\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. In order to explain it, consider a positive charge enters a magnetic field along the direction of the dotted line as shown.

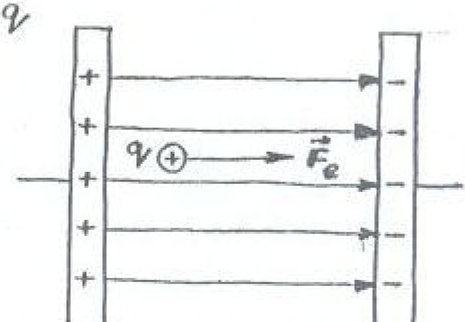


The positive charge experiences a force in the upward direction i-e; perpendicular to both $\vec{v}$ and $\vec{B}$. In case of a negative charge, the direction of force will be opposite to that of a positive charge.

So, a proton will be deflected upward and an electron will be deflected in the downward direction as it enters into a magnetic field as shown.

Motion Of Charged Particle In An Electric And Magnetic Field

When an electric charge q is placed in an electric field $\vec{E}$, then an electric force $\vec{F}_e$ act on q parallel to the electric field given as



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

If charge q is free to move, then it will accelerate in the electric field. The acceleration produced in the charge q according to Newton's second law is given as

$$\vec{F} = m\vec{a}$$

$$\text{or} \qquad \vec{a} = \frac{\vec{F}}{m} = \frac{q\vec{E}}{m} \longrightarrow (2)$$

If electric field is uniform, then acceleration produced in the charge is also uniform and the position of the particle at any instant can be calculated by using above equation.

Now if electric charge q is moving with velocity $\vec{v}$ in a magnetic field of strength $\vec{B}$, then magnetic force $\vec{F}_b$ act on q is

$$\vec{F}_b = q(\vec{v} \times \vec{B}) \longrightarrow (3)$$

If electric charge q is moving in a region where both electric field $\vec{E}$ and magnetic field $\vec{B}$ exist, then the total force $\vec{F}$ act on q is the vector sum of the electric and magnetic forces act on the charge is

$$\vec{F} = \vec{F}_e + \vec{F}_b$$

Put values from equation (1) and (3)

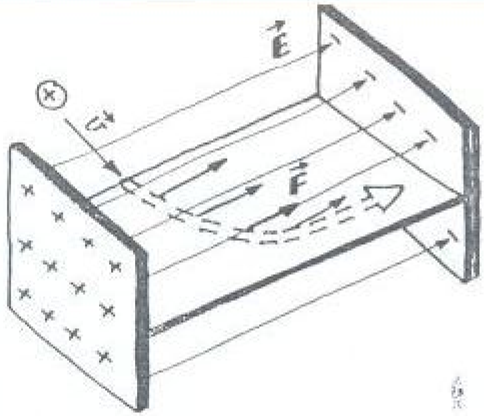
$$\boxed{\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})}$$

This force is known as 'LORENTZ FORCE'.

It should be noted that only the electric force does work while magnetic force does no work. Magnetic force simply deflect the electric charge, so it is only a deflecting force.

DIRECTION OF FORCE ACT ON A CHARGE CARRIER IN AN ELECTRIC FIELD

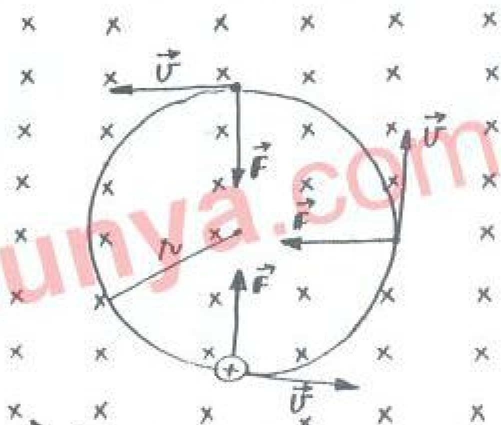
The electric force $\vec{F}$ act on a positive charge is parallel to the electric field $\vec{E}$ and causes the charge to bend in a horizontal plane as shown



In case of negative charge, the electric force act on it opposite to the electric field.

DETERMINATION OF e/m OF AN ELECTRON

Consider a narrow beam of electrons moving with a constant speed v. This narrow beam of electrons enter at right angles to a known uniform magnetic field of strength $\vec{B}$ directed into the plane of paper as shown in figure.



($\vec{B}$ into the paper)

As, the magnetic force act on the electrons is given by

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

$$\text{or} \quad \vec{F} = -e\,v\,B\,\sin\theta \cdot \hat{n}$$

The direction of this force is always perpendicular to both $\vec{v}$ and $\vec{B}$. As the electron experienced a force at right angle to its velocity, so this force changes the direction of the velocity.

Now, the magnitude of magnetic force is

$$F = e\,v\,B\,\sin\theta$$

Here $\quad \theta = 90^\circ$

$$\therefore \quad F = evB \sin 90^\circ = evB(1)$$

or $$F = evB \longrightarrow (1)$$

As v and B do not change, so the magnitude of force F is constant. Hence, the electrons experienced a constant force $F = evB$ at right angle to their direction of motion. Under the action of this force, the electrons will move along a circular path of radius 'r' as shown in figure.

So, the centripetal force required by the electrons to move along a circular path of radius 'r' is

$$F = \frac{mv^2}{r} \longrightarrow (2)$$

This centripetal force is provided by the magnetic force act on the electrons.

Hence, comparing equation (1) and (2)

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

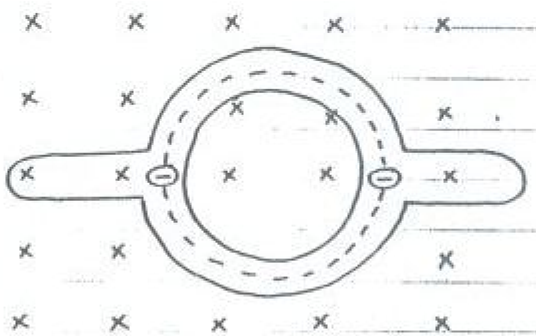
or $$eB = \frac{mv}{r}$$

or $$\boxed{\frac{e}{m} = \frac{v}{Br}} \longrightarrow (3)$$

As B is known while r and v are unknown. So e/m of electron can be determined if r and v are known.

Determination Of Radius

The radius r of the circular path is measured by making the path of electron visible. This is done by filling the glass tube with a gas like hydrogen at low pressure. A uniform magnetic field B of known value is also applied to the glass tube. As the electrons are shot into this tube, they begin to move along a circular path under the action of magnetic force. As electrons move in the glass tube, they collide with the atoms of the gas and gas atoms are excited. On de-excitation, the atoms of the gas emit light and their path becomes visible as a circular ring of light. The diameter and the radius r of circular ring can be easily measured.



DETERMINATION OF VELOCITY

In order to find the velocity v of electrons, the electrons are accelerated by applying potential difference V before entering into the magnetic field. So, the energy gained by the electrons during their acceleration by applying P.D. V is

$$\text{Energy Gained} = Ve \qquad \left(\because V = W/e \Rightarrow W = Ve \right)$$

This energy appear as the K.E. of electrons given as

$$K.E. = \frac{1}{2} m v^2$$

So

$$K.E. = \text{Energy Gained}$$

$$\Rightarrow \frac{1}{2} m v^2 = Ve$$

$$\Rightarrow v^2 = \frac{2Ve}{m} \quad \text{(Taking square root)}$$

$$\Rightarrow \boxed{v = \sqrt{\frac{2Ve}{m}}} \longrightarrow (4)$$

Put this value in equation (3)

$$\therefore \frac{e}{m} = \frac{v}{Br} = \sqrt{\frac{2Ve}{m}} \cdot \frac{1}{Br}$$

Taking square on both sides

$$\therefore \frac{e^2}{m^2} = \frac{2Ve}{m} \cdot \frac{1}{B^2 r^2}$$

$$\Rightarrow \boxed{\frac{e}{m} = \frac{2V}{B^2 r^2}} \longrightarrow (5)$$

Hence, charge-to-mass ratio i-e; e/m of electron can be calculated. The value of e/m of electron is given as

$$\boxed{e/m = 1.7592 \times 10^{11} \ C/Kg}$$

Cathode Ray Oscilloscope (CRO)

CRO is an electronic instrument which plot graphs with very high speed.

Principle

The working principle of CRO is that "the beam of electrons is deflected as they pass through the uniform electric field between the two sets of parallel plates. The deflected beam then falls on a flourescent screen where it makes a visible spot."

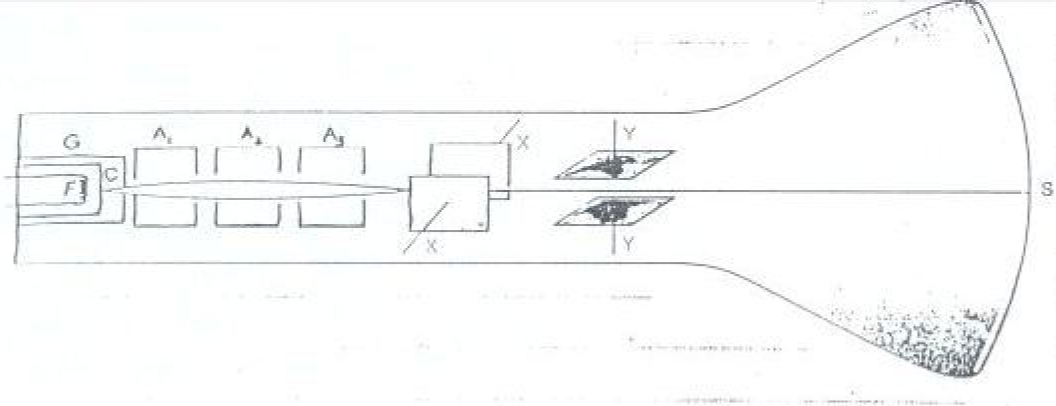
CRO is called cathode ray oscilloscope because it traces the desired waveform with a beam of electrons which are also called cathode rays. It can display graphs of functions which rapidly vary with time.

Construction And Working

The various parts of CRO and their functions are given as

1. Electron Gun

It produces a beam of electrons. It consists of an indirectly heated cathode, a grid and three anodes. The filament F heated the cathode C which emit electrons. The anodes A_1, A_2, A_3 are at high positive potential with respect to cathode C. These anodes accelerate and focus the electronic beam to create spot on the screen S as shown in figure.



2. Grid

Grid G is at a negative potential with respect to cathode C. It controls the number of electrons which are accelerated by anodes. Hence, the brightness of the spot formed on the screen can be controlled.

3. Deflecting Plates

There are two sets of deflecting plates in CRO, known as X and Y deflecting plates. These plates help to form wave shapes of various voltages in CRO. If a voltage is applied between the X-plates, it deflects the beam horizontally on the screen S i-e; parallel to X-axis and when a voltage is applied across the Y-plates, it deflects the beam vertically on the screen S i-e along Y-axis.

4. Sweep or Time Base Generator

The voltage applied across the X-plates is usually provided by a circuit that is built in the CRO, known as sweep or time base generator. The output waveform of time base generator is a saw tooth voltage of period T. The voltage increases linearly with time for a period T and then drops to zero. As this voltage is applied across the X-plates, the spot is directed linearly with time along the x-axis for a period T. Then the spot returns to its starting point on the screen very quickly because a saw tooth wave falls to its initial value at the end of each period. If the time period T is very small, then we just see a bright line on the screen.

If a sinusoidal voltage is applied across the Y-plates and the time base voltage across the x-plates, then the sinusoidal voltage will appear as a sinusoidal wave on the screen S.

5. Synchronization Controls

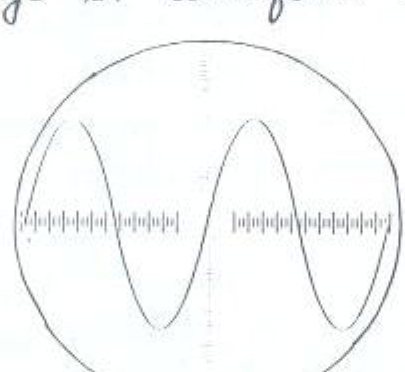
The waveform produced on the screen will appear stationary only if the period T is equal to the time of one cycle of the voltage on Y-plates. For this, it is necessary to synchronize the frequency of the time base generator with the frequency of the voltage on Y-plates. This can be done by adjusting the synchronization controls that is provided on the front panel of the CRO.

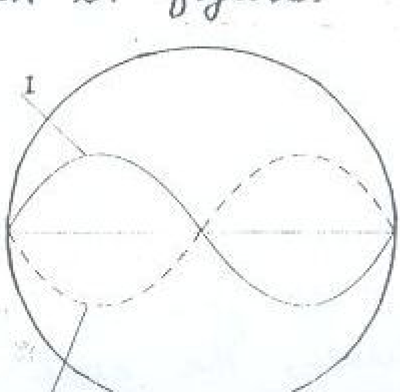
Uses Of CRO

It is used for displaying the waveform of a given voltage. Once the waveform is displayed, we can measure the voltage, its frequency and phase.

1. Waveform

CRO is used to display the signal voltage in waveform as shown in figure.





2. Voltage Measurement

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

3. Time Period Measurement

Time period can also be measured by using the time calibration of X-axis.

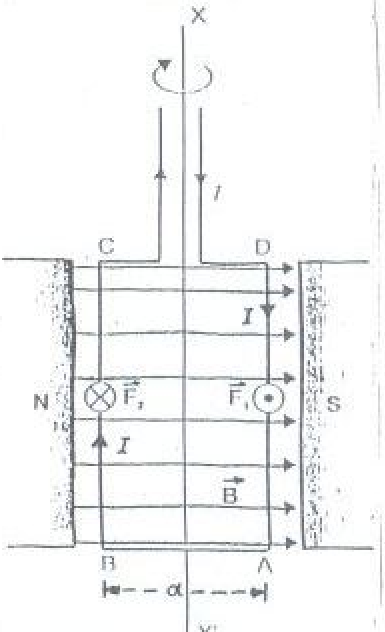
4. Phase Difference

CRO also give information about the phase difference between two voltages can be obtained by simultaneously displaying their waveforms.

For example, the waveforms of the two voltages are shown in figure above. These waveforms show that when the voltage of wave I is increasing, then voltage of wave II is decreasing and vice-versa. Hence, the phase difference between these two voltages is 180°.

Torque On A Current Carrying Coil

Consider a rectangular coil ABCDA which can rotate about an axis XX′ placed in a uniform magnetic field of strength $\vec{B}$ such that the plane of the coil is parallel to the magnetic field as shown in figure. Let 'L' be the length of sides BC and DA while 'a' be the width of sides AB and CD as shown.



Let 'I' be the current flowing through the rectangular coil. We know that when current is flowing through a conductor of length L placed in a magnetic field, then it experiences a force given as

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

or $\quad F = ILB \sin\theta$

Where θ is the angle between the conductor and the magnetic field.

From figure, it is clear that the angle θ for sides CD and AB is $0°$ and $180°$ resp.

For $\theta = 0°$, $F = ILB \sin 0° = ILB(0) = 0$

For $\theta = 180°$, $F = ILB \sin 180° = ILB(0) = 0$

So, the magnetic force act on sides CD and AB is zero.

Now in case of sides DA and BC, the angle θ is $90°$, so force act on these sides is

For side DA, $F_1 = ILB \sin 90° = ILB(1)$

$$F_1 = ILB$$

For side BC, $F_2 = ILB \sin 90° = ILB(1)$

$$F_2 = ILB$$

Hence, force due to sides DA and BC is

$$F_1 = F_2 = ILB$$

Let

$$F = F_1 = F_2 = ILB$$

It can be seen that the direction of force $\vec{F_1}$ is out of the plane of the paper and the direction of force $\vec{F_2}$ is into the plane of the paper as shown in figure. As, the forces $\vec{F_1}$ and $\vec{F_2}$ are equal in magnitudes but opposite in direction. Such forces act on a body form a couple which tends to rotate it about the axis. So the couple rotates the coil ABCDA and torque is produced in it given as

$$\tau = \text{Force} \times \text{Moment arm}$$

or $\quad \tau = F \times AB$

or $\quad \tau = ILB \times a \qquad (\because AB = a)$

or $\quad \tau = IB(L \times a)$

Where

$$L \times a = A = \text{Area of coil}$$

$$\therefore \quad \boxed{\tau = IBA} \longrightarrow (1)$$

This equation gives the value of torque when the plane of the coil is parallel to the magnetic field $\vec{B}$. If the field $\vec{B}$ makes an angle α with the plane of the coil, then the moment arm of couple as shown in figure is given as

$$\text{Moment arm} = a \cos\alpha$$

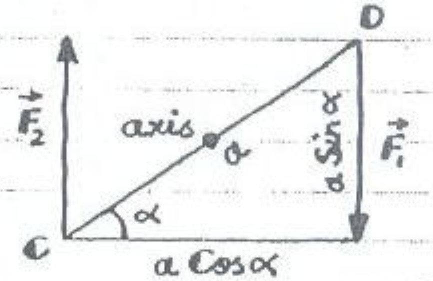
Now torque acting on the coil is

$$\tau = \text{Force} \times \text{Moment arm}$$

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

or $\tau = IB(L \times a)\cos\alpha$

or $\boxed{\tau = IBA\cos\alpha} \longrightarrow (2)$



(Top View Of Coil)

For N no. of turns of the coil, we have

$$\tau = NIBA\cos\alpha$$

or $\boxed{\tau = BINA\cos\alpha} \longrightarrow (3)$

Galvanometer

An electrical instrument used to detect the passage of electric current is called a galvanometer.

Types Of Galvanometer

There are two types of galvanometer.

Moving Magnet Galvanometer

That galvanometer in which magnet is moving and coil is stationary.

Moving Coil Galvanometer

That galvanometer in which coil is moving and magnet is stationary.

Principle

The working principle of moving coil galvanometer depends upon the fact that when a conductor is placed in a magnetic field, it experience a magnetic force as soon as 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. The torque act on the coil is

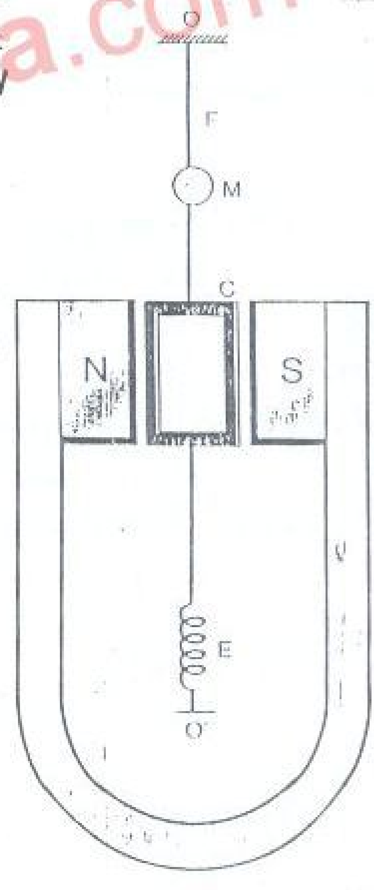
$$\tau = BINA \cos\alpha$$

Where

B = Magnetic field in which coil is placed.
I = Current passing through the coil.
N = Number of turns in the coil.
A = Area of the coil.
α = Angle between magnetic field and plane of the coil.

CONSTRUCTION OF MOVING COIL GALVANOMETER

It consists on a rectangular coil C suspended between the concave shaped poles N and S of a U-shaped magnet with the help of a fine metallic suspension wire. The coil C is made of enameled copper wire wound on a frame of non-magnetic material. The suspension wire F act as one current lead and also provides restoring torque to the coil. A plane mirror M is also attached with the wire F in order to find the angle of deflection θ. The other end of the coil is connected to a loosely wound spiral E which serves as second current lead.



WORKING

When a current I is passed through the coil, then magnetic field is produced around it which interact with the field of the magnet and hence a couple is acted upon the coil which tends to rotate the coil. This couple is known as deflecting couple or deflecting torque given as

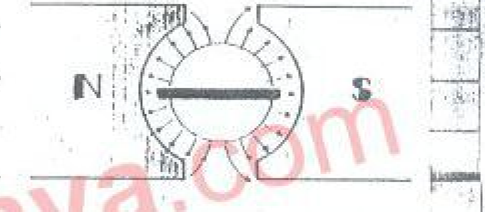
$$\text{Deflecting Couple} = \tau_{def} = BINA\cos\alpha \longrightarrow (1)$$

The magnetic field near the coil will be stronger if the field becomes radial and it can be done by making the pole pieces of the magnet concave. So in this case, the plane of the coil becomes parallel to the magnetic field as shown.

$$\therefore \alpha = 0^\circ$$

Put in equation (1)

$$\therefore \tau_{def} = BINA\cos 0^\circ$$



$$\text{or} \quad \tau_{def} = BINA(1)$$

$$\text{or} \quad \tau_{def} = BINA \longrightarrow (2)$$

When coil rotates, then twist is produced in the suspension wire which gives rise to a torsional couple. It tends to untwist the suspension wire and restore the coil to its original position. This torsional couple is known as restoring couple or restoring torque. The restoring torque of the suspension wire is directly proportional to the angle of deflection 'θ' as long as the suspension wire obeys Hooke's law. Thus

$$\text{Restoring Torque} = \tau_{res} \propto \theta$$

$$\text{or} \quad \tau_{res} = (\text{Constant})\,\theta$$

$$\text{or} \quad \tau_{res} = C\theta \longrightarrow (3)$$

Where C is constant of proportionality and known as torsional couple. It is defined as "Couple for unit twist".

Under the effect of deflecting and restoring torques, the coil comes to rest and it is only possible when both torques becomes equal, so

Deflecting Torque = Restoring Torque

or $\tau_{def} = \tau_{res}$

or $BINA = C\theta$

or $$\boxed{I = \frac{C\theta}{BNA}} \longrightarrow (4)$$

Here

$$\frac{C}{BNA} = \text{Constant}$$

$$\therefore \quad I = (\text{Constant})\,\theta$$

$$\Rightarrow \quad \boxed{I \propto \theta}$$

Thus the current passing through the coil is directly proportional to the angle of deflection.

SENSITIVITY OF GALVANOMETER

The galvanometer is said to be sensitive if it give large angle of deflection for a small current passing through the coil.

As for a galvanometer, the relation for current passing through the galvanometer coil is

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

Thus a galvanometer can be made sensitive if the factor C/BNA is made small. This can be done if

(i) C is decreasing.
(ii) B is increasing.
(iii) N is increasing.
(iv) A is increasing.

The torsional couple C of the suspension wire can be decreased by increasing its length and by decreasing its diameter. However, it cannot be taken too far, as the suspension wire must be strong enough to support the coil.

The sensitivity of galvanometer can be increased by increasing the number of turns N and area A of the coil. But N and A can not be increased beyond a limit because it will make the coil heavy and the resistance of coil also increased.

In order to compensate for the loss of sensitivity due to less number of turns used in the coil, we increase the magnetic field B used.

CURRENT SENSITIVITY OF GALVANOMETER

It is defined as "the detection of current in micro-amperes from a galvanometer, required to produce one millimetre deflection on a scale placed one metre away from the mirror of the galvanometer".

UNSTABLE AND STABLE GALVANOMETER

UNSTABLE GALVANOMETER

When 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. The coil keeps on oscillating about its mean position before coming to rest. In the same way, if the current is passing suddenly in a galvanometer, the coil will shoot beyond its final equilibrium position and keeps on oscillating several times before coming to rest at its final equilibrium position. As it is boring and time consuming to wait for the coil to come to rest.

For this, artificial methods are used to make the coil come to rest quickly. Such type of galvanometers in which the coil will not come to rest quickly are called unstable galvanometers.

DEAD BEAT OR STABLE 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 stable or a dead beat galvanometer.

It should be noted that unstable galvanometer is more sensitive than the stable or dead beat galvanometer.

METHODS FOR MEASURING ANGLE OF DEFLECTION

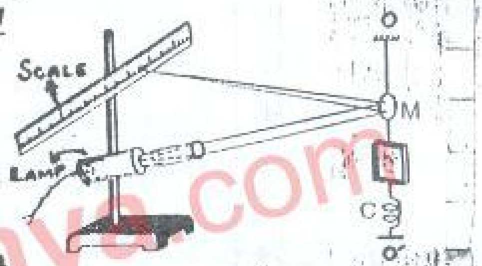
There are two methods for measuring the angle of deflection of galvanometer given as

(i) Lamp and scale arrangement.

(ii) Pivoted or Weston type galvanometer.

LAMP AND SCALE ARRANGEMENT

In sensitive galvanometers, the angle of deflection is observed by means of a small mirror M attached to the coil along with lamp and scale arrangement as shown in figure. A beam of light from the lamp is directed towards

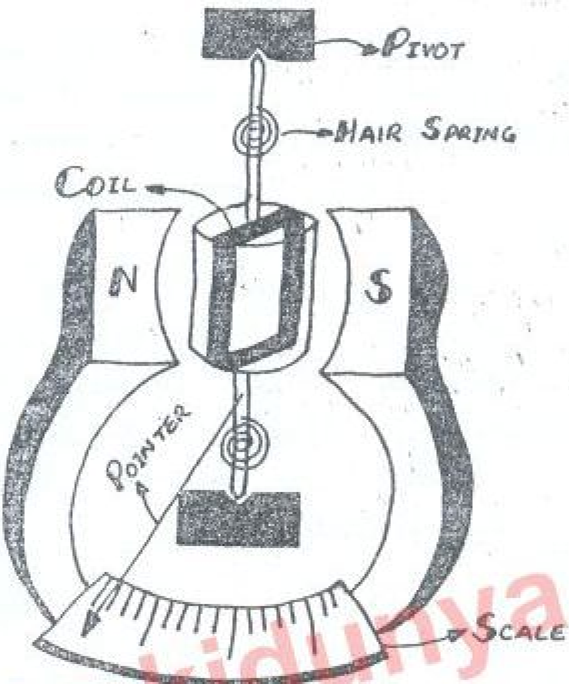


the mirror M of galvanometer. After reflection from the mirror, it produces a spot on a scale placed at a distance of one metre from the galvanometer. When the current is passing through the coil, it rotates and the mirror attached to the coil also rotates and spot of light moves along the scale. The displacement of the spot of light on the scale is directly proportional to the angle of deflection. It should be noted that here angle of deflection is small.

PIVOTED OR WESTON TYPE GALVANOMETER

The galvanometers used in college and school laboratories are pivoted type galvanometers.

In this type of galvanometer, the coil is pivoted between two jewelled bearings. The two hair springs act as two current leads and provided the restoring torque to the coil. A light aluminium pointer is attached to the coil which moves over a scale which gives the angle of deflection of the coil as shown in diagram.



AMMETER

An electrical instrument used to measure current is called ammeter. It is also known as low resistance galvanometer.

CONVERSION OF GALVANOMETER INTO AMMETER

In order to convert a galvanometer into ammeter, we connect a low resistance or bypass, called shunt resistance R_S in parallel with the galvanometer. Now, to find R_S, we proceed as

Consider

R_g = Resistance of galvanometer coil.

I_g = Current passed through the galvanometer for full scale deflection.

According to Ohm's law, the potential difference drop across the galvanometer is

$$V_g = I_g R_g \longrightarrow (1)$$

Now let

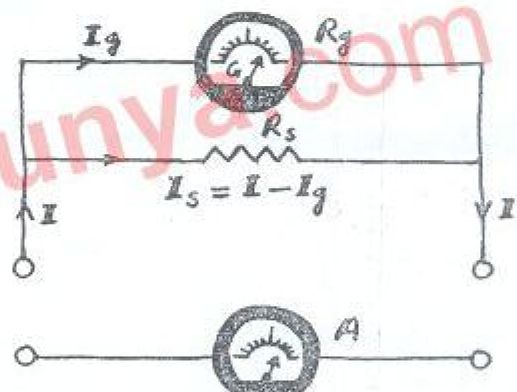
I = Maximum current to be measured or ammeter range

R_s = Shunt resistance. It has such value so that current I_g passes through the galvanometer for its full scale deflection.

I_s = Current passes through shunt resistance.
$= I - I_g$

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

Now the potential difference drop across the shunt resistance is



$$V_s = I_s R_s$$

or $$V_s = (I - I_g) R_s \longrightarrow (2)$$

As, R_s and R_g are connected in parallel, so the potential difference across them will be same.

$$\therefore \quad V_s = V_g$$

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

or $$\boxed{R_s = \frac{I_g R_g}{I - I_g}} \longrightarrow (3)$$

Actually, the shunt resistance R_s is so small that a piece of copper wire uses for the purpose of ammeter. <u>Ammeter always connected in series in order to measure the current of the circuit</u>. An ammeter must have very low resistance so that it does not disturb the circuit in which it is connected.

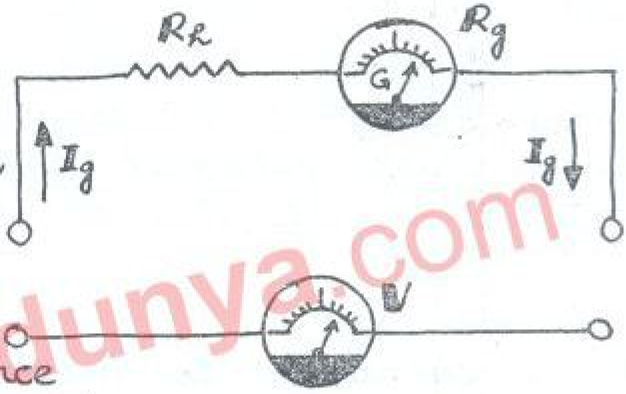
VOLTMETER

An electrical instrument used to measure the potential difference between two points, is called voltmeter. It is also known as high resistance galvanometer.

CONVERSION OF GALVANOMETER INTO VOLTMETER

In order to convert a galvanometer into voltmeter, we connect a high resistance R_R in series with the galvanometer. Now, to find R_R, we proceed as

Consider



R_g = Resistance of the galvanometer coil.

I_g = Current passed through the galvanometer for full scale deflection.

According to Ohm's law, the potential difference drop across galvanometer is

$$V_g = I_g R_g \longrightarrow (1)$$

Now let

V = Maximum voltage to be measured or voltmeter range.

R_R = High resistance connected in series with the galvanometer should be such that full scale deflection will be obtained when it is connected across a P.D. of V volts and current I_g passed through it.

So, the potential difference drop across the high resistance R_R is

$$V_R = I_g R_R \longrightarrow (2)$$

Now, the maximum voltage V is given as

$$V = V_g + V_R$$

or $$V = I_g R_g + I_g R_R$$

or $\quad V = I_g(R_g + R_h)$

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

or $$\boxed{R_h = \frac{V}{I_g} - R_g} \longrightarrow (3)$$

If we calibrate the galvanometer scale from 0 – V volts, the combination of galvanometer and the high resistance R_h in series act as a voltmeter with range 0 – V volts. So, by adjusting high resistance R_h, any voltage can be measured.

It should be noted that a voltmeter is always connected in parallel betwee two points across which potential difference is to be measured. It should also be noted that the resistance of the voltmeter is very high in comparision with the resistance of the circuit across which it is connected to measure the potential difference. Otherwise, voltmeter loaded the circuit and the exact potential difference of the circuit will not be measured.

OHMMETER

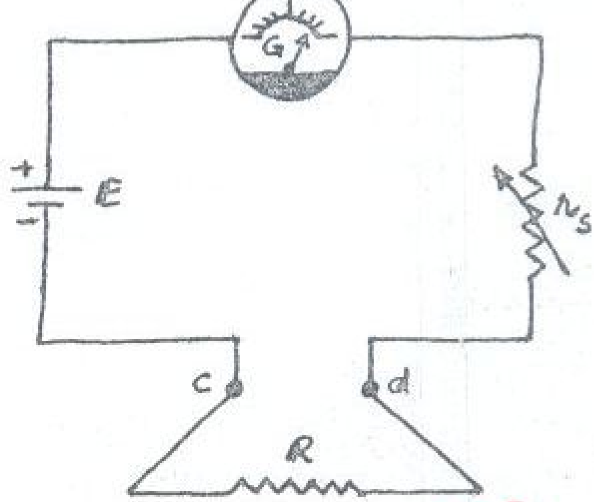
An electrical instrument used for rapid measurement of the resistance of a conductor, is called ohmmeter.

CONSTRUCTION OF OHMMETER

It consists of a galvanometer and an adjustable resistance 'r_s' of known value and a cell of emf 'E' connected in series between points c and d as shown in circuit diagram. The resistance R to be measured is connected between points c and d as shown.

CALIBRATION OF OHMMETER SCALE

In order to calibrate the ohmmeter scale, first we short circuited the points c and d by adjusting the series resistance r_s i-e; when $R=0$, the galvanometer gives full scale deflection. So, the extreme reading of the usual scale of galvanometer is marked $0\,\Omega$ for ohmmeter. When the points c and d are not connected, then no current passes through the galvanometer and its deflection is zero. The zero of the scale is marked as infinity (∞) for ohmmeter scale. When R is not infinity, the galvanometer deflects to some intermediate position depending on the value of R and hence the galvanometer scale can be calibrated to read the resistance directly.



AVO METER OR MULTIMETER

An instrument which can measure current in amperes, potential difference in volts and resistance in ohms, called AVO meter or multimeter. In AVO meter

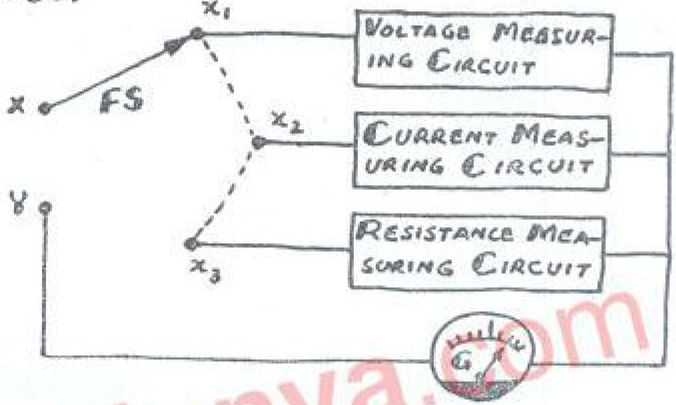
A stands for ampere or ammeter.
V stands for volt or voltmeter.
O stands for ohm or ohmmeter.

PRINCIPLE

The working principle of AVO meter is same as that of a galvanometer.

Construction

It consists of a sensitive galvanometer having number of low resistance for multi-range ammeter and a number of high resistances for multi-range voltmeter. An internal battery and an adjustable resistance is also connected in series with the galvanometer to convert it into multi-range ohmmeter.

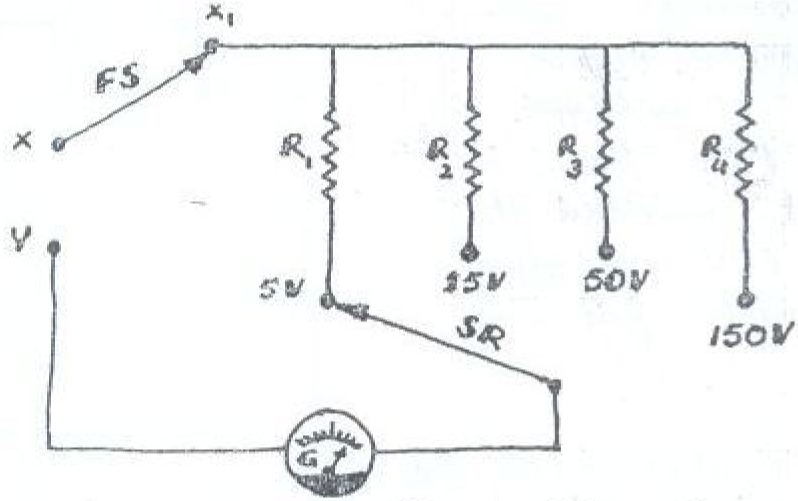


The galvanometer is connected with a voltage measuring circuit, or a current measuring circuit or a resistance measuring circuit with the help of a switch known as function switch or function selector denoted by FS as shown in diagram. In diagram X and Y are the main terminals of the AVO meter which are connected with the circuit in which the measurement is required. FS is the function selector switch which connects the galvanometer with relevant measuring circuit.

AVO meter can measure both direct and alternating voltages. A rectifier circuit is also connected with the galvanometer to convert AC voltage into DC voltage.

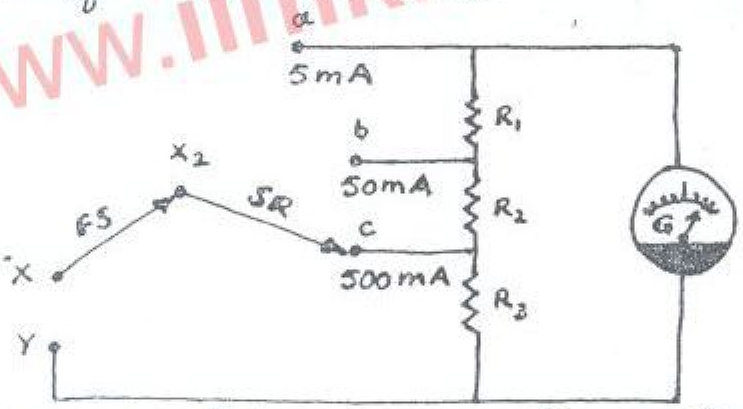
Voltage Measuring Part Of AVO Meter

AVO meter can be used as a multi-range voltmeter. For this, moving coil galvanometer is connected with a number of high resistances in series with the help of a switch, called the range switch SR as shown in circuit diagram. The value of each resistance depends upon the range of the voltmeter.



CURRENT MEASURING PART OF AVO METER

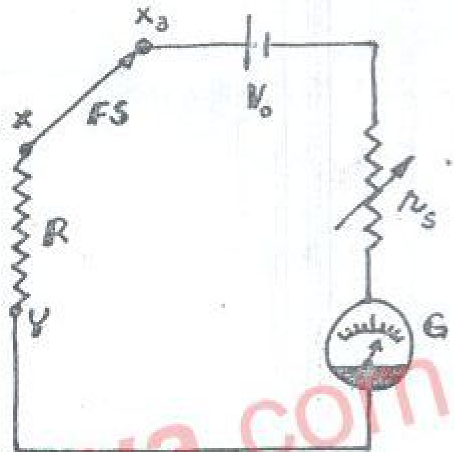
AVO meter can be used as a multi-range ammeter. For this, moving coil galvanometer is connected with a number of low resistances or shunt resistances in parallel with the help of a switch, called range switch SR as shown. The value of these resistances depend upon the range of the ammeter.



RESISTANCE MEASURING PART OF AVO METER.

AVO meter can be used as a multirange ohmmeter. Circuit for each range of ohmmeter consists of a battery of emf V_0 and a variable resistance r_s connected in series with moving coil galvanometer. When the function selector switch FS is attached with position X_3, this circuit is connected with the terminals X, Y of the AVO meter as shown.

The ohmmeter scale must be zeroed before measuring an unknown resistance. For this, we first short circuited the terminals X, Y and adjust r_s to produce full scale deflection.



DIGITAL MULTIMETER (DMM)

An electronic instrument used to measure the voltage, current and resistance is called digital multimeter (DMM).

DMM is a digital version of an AVO meter. It has become a very popular testing device because the digital values are displayed automatically with decimal point, polarity and unit as V, A and Ω. These meters are generally easier to use because they eliminate the human error that often occurs in reading the dial of an ordinary AVO meter.

QUESTIONS

14.1. *A plane conducting loop is located in a uniform magnetic filed that is directed along the x-axis. For what orientation of the loop is the flux a maximum? For what orientation is the flux a minimum?*

Ans. As magnetic field is directed along x-axis so plane of loop must lie in y z-plane to become perpendicular to direction of magnetic field to get maximum flux.

14.2. *A current in a conductor produces a magnetic field, which can be calculated using Ampere's law. Since current is defined as the rate of flow of charge, what can you conclude about the magnetic field due to stationary charges? What about moving charges?*

Ans. The moving electric charge makes electric current which produces magnetic field in a region around it. If electric charge moves in straight line, then it produces magnetic field whose line are in the form of concentric circles but the stationary electric chares do not produce magnetic field.

14.3. *Why is B non-zero outside a solenoid?*

Ans. The current carrying solenoid produces magnetic field whose value is considerably large inside the solenoid. The lines of this magnetic field pass through the solenoid from one end to the other. These lines of magnetic field complete their closed path and pass through the region outside the solenoid also. This is the reason why value of $\vec{B}$ is not zero outside the solenoid.

14.4. *Describe the change in the magnetic field inside a solenoid carrying a steady current I, if (a) The length of the solenoid is doubled, but the length remains the same.*

Ans. (a) Keeping number of turns same and changing the length of solenoid, the value of magnetic field inside a current carrying solenoid decreases. This is due to the reason that value of '$\vec{B}$' inside the solenoide depends upon the number of turns per unit length, which decreases due to increase of length of the solenoid. By doubling length, the magnetic field is halved.

(b) When number of turns on the same length of solenoid are doubled, then number of turns per unit length is doubled. Due to which value of '$\vec{B}$' is also doubled according to following formula

$$B = \propto n I$$

Here n = number of turns per unit length

14.5. *At a given instant, a proton moves in the positive x direction in region where there is magnetic field in the negative z direction. What is the direction of the magnetic force? Will the proton continue to move in the positive X direction? Explain.*

Ans. The proton carries positive charge when it moves along positive x – direction and magnetic field is along negative z-direction. Then using right-hand – rule, the direction of magnetic force is along positive Y-axis. Due to magnetic force the moving proton traces a curved path is x – y plane.

14.6. *Two charged particles are projected into a region where there is a magnetic field perpendicular to their velocities. If the charges are deflected in opposite directions, what can you say about them?*

Ans. When two charged particles are projected in uniform magnetic field, at right angle to the direction of their velocity then their path becomes circular, due to magnetic force acting on then. The direction of the magnetic force on the two particles will be opposite when the two point charges have opposite signs. So that these are deflected in opposite direction.

14.7 *Suppose that a charge q is moving in a uniform magnetic field with a velocity v. Why is their no work done by the magnetic force that acts on the charge?*

Ans. When a force acts at right angle to the direction of displacement of a moving body then work done by that force is always equal to zero.

The magnetic force always acts at right angle to the velocity (or small displacement). Therefore, the value of work done by the magnetic force is also zero.

14.8 *If a charge particle moves in a straight line through some region of space, can you say that the magnetic field in the region is zero.*

Ans. A charge particle crosses a region and its direction of motion is unchanged. Then there is possibility that magnetic field is present in that region, but direction of motion of charge is either along or is opposite to the direction of magnetic field.

14.9 *Why does the picture on a TV screen become distorted when a magnet is brought near the screen?*

Ans. The T.V. picture is formed by the help of beam of electrons fall on screen. If magnetic is brought near the picture tube, the picture is deformed. It is due to the reason that motion of charged particle (electrons) is effected by the presence of magnetic field and their target on the screen of T.V. is disturbed by the magnetic field of the magnet.

14.10. *Is it possible to orient a current loop in a uniform magnetic field such that the loop will not tend to rotate? Explain?*

Ans. A current carrying loop placed inside magnetic field experiences torque which is give by

$$\vec{T} = N I A B \cos \propto$$

When $\propto$ 90° then $\vec{T}$ = o and the loop will not tend to rotate. And $\propto = 90°$ only when plane of loop is at right angle to the direction of magnetic field.

14.11. *How can a current loop be used to determine the presence of a magnetic field in a given region of space?*

Ans. A freely suspended current loop can be used to detect magnetic field in a region. If it experiences rotational effect, then it confirms the presence of magnetic field otherwise not.

14.12. *How can you use a magnetic field to separate isotopes of chemical element?*

Ans. In a chemical reaction isotopes of an element are in ionic form. These have electric charge of equal amount on them, but these have different masses. Magnetic field applied on the moving isotope, exert equal force on them and their path becomes circular. The isotopes of small mass make circular path of large radius as compared with heavy isotope. If their circular path is interrupted then it becomes possible to separate these isotopes.

14.13. *What should be orientation of a current carrying coil in a magnetic field so that torque acting upon the coil is (a) maximum (b) minimum?*

Ans. The mathematical formula for the torque experienced by a current loop inside a magnetic field is.

$$\vec{T} = N I A B \cos \propto$$

(1) This torque is maximum when the plane of coil is parallel to the direction of magnetic field ($\propto$ = o)

(2) This torque is minimum when $\propto = 90°$ or the plane of coil is at 90° to the direction of magnetic field.

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