MAGNETIC EFFECT OF CURRENT AND MAGNETISM

(i) A static charge produces only electric field and only electric field can exert a force on it.
(ii) A moving charge produces both electric field and magnetic field and both electric field and magnetic field can exert force on it.
(iii) A current carrying conductor produces only magnetic field and only magnetic field can exert a force on it.
(iv) Magnetic charge (i.e.current), produces a magnetic field. It can not produce electric field as net charge on a current carrying conductor is zero.
(v) A magnetic field is detected by its action on current carrying conductors (or moving charges) and magnetic needles (compass).
(vi) The vector quantity $\vec{B}$ known as **MAGNETIC INDUCTION** is introduced to characterise a magnetic field, It is a vector quantity which may be defined in terms of the force it produces on electric currents. Lines of magnetic induction may be drawn in the same way as lines of electric field.
(vii) The number of lines per unit area crossing a small area perpendicular to the direction of the induction bring numerically equal to $\vec{B}$.
(viii) The number of lines of $\vec{B}$ crossing a given area is referred to as the magnetic flux linked with that area. For this reason B is also called magnetic flux density .

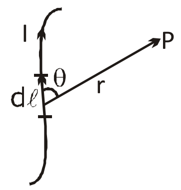
MAGNETIC INDUCTION PRODUCED BY A CURRENT

(BIOT-SAVART Law):

The magnetic induction dB produced by an element dl carrying a current I at a distance r is given by:

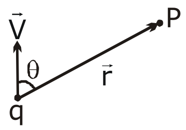
$$dB = \frac{\mu_0\mu_r}{4\pi}\frac{Id\ell\sin\theta}{r^2} \Rightarrow \overrightarrow{dB} = \frac{\mu_0\mu_r}{4\pi}\frac{I(d\vec{\ell}\times\vec{r})}{r^3}$$

here, the quantity $Id\ell$ is called as current element strength.
μ = permeability of the medium = $\mu_0\mu_r$
μ_0 = permeability of free space
μ_r= relative permeability of the medium
(Dimensionless quantity).
Unit of μ_0 & μ is NA^{-2} or Hm^{-1} ;
$\mu_0 = 4\pi \times 10^{-7}\ Hm^{-1}$.



Magnetic induction due to a moving charge

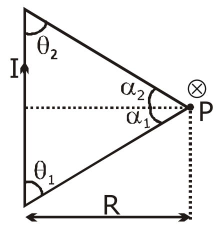
$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}$$



In vector form it can be written as $d\vec{B} = \frac{\mu_0}{4\pi}\frac{q(\vec{v}\times\vec{r})}{r^3}$

Magnetic Induction due to a current Carrying Straight Conductor

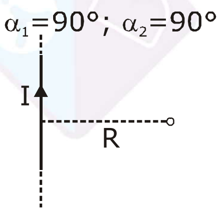
(i) Magnetic induction due to a current carrying straight wire



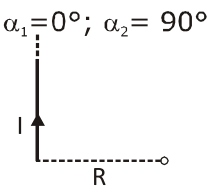
$$B = \frac{\mu_0 I_r}{4\pi R}(\cos\theta_1 + \cos\theta_2) = \frac{\mu_0 I}{4\pi R}(\sin\alpha_1 + \sin\alpha_2)$$

$\rightarrow$ If the wire is very long $\theta_1 \cong \theta_2 \cong 0^\circ$ then, B = $\frac{\mu_0 I}{2\pi R}$

- Magnetic indicution due to a infinitely long wire B = $\frac{\mu_0 I}{2\pi R}\otimes$

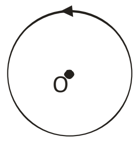


- Magnetic induction due to semi infinite straight conductor B = $\frac{\mu_0 I}{4\pi R}\otimes$



Magnetic field due to a flat circular coil carrying a current

(i) At its centre $B = \frac{\mu_0 NI}{2R} \odot$



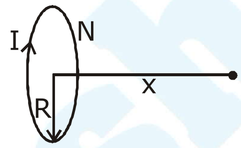
where

N = total number of turns in the coil

I = current in the coil

R = Radius of the coil

(ii) On the axis $B = \frac{\mu_0 NIR^2}{2(x^2 + R^2)^{3/2}}$



where x = distance of the point from the centre:

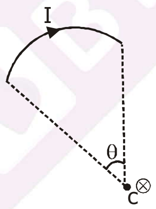
- It is maximum at the centre $B_c = \frac{\mu_0 NI}{2R}$

(iii) Magnetic induction due to falt circular ARC : $B = \frac{\mu_0 I\theta}{4\pi R}$

Magnetic field due to infinite long solid cylindrical conductor of radius R

- For $r \geq R : B = \frac{\mu_0 I}{2\pi R}$

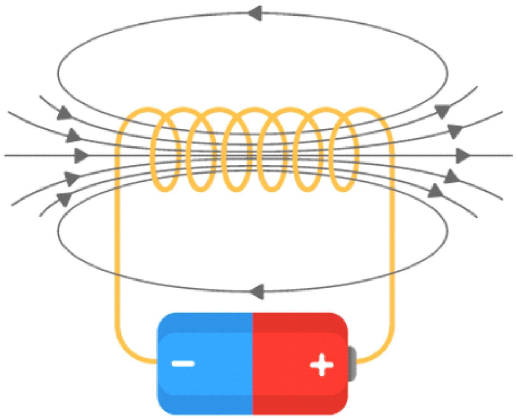
- For $r < R : B = \frac{\mu_0 Ir}{2\pi R^2}$



SOLENOIDS

What is Solenoid?

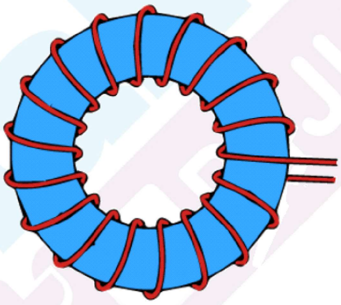
Let us consider a solenoid, such that its length is large as compared to radius. Here, the wire is wound in the form of the helix with a very little gap between any two turns. Also, the wires are enameled, thus rendering them insulated from each other. As a result, each turn can be taken as a closed circular loop. The magnetic field thus generated is equivalent to that generated by a circular loop and the total magnetic field generated by the solenoid can be given as the vector sum of force generated by each such turn. The magnetic field lines generated inside a finite solenoid has been shown in the figure below.



Solenoid

We can see from the figure that the magnetic field inside the solenoid is uniform in nature and is along the axis of the solenoid. The field at the exterior at any point immediately to the solenoid is very weak and the field lines cannot be seen near the close vicinity. It is important to note that the field inside it is parallel to its axis at every position.

From the Ampere's Law, the magnetic force produced by a solenoid can be given as,
$F=\mu_0 nI$
where n is the number of turns of the wire per unit length, I is the current flowing through the wire and the direction is given using the right-hand thumb rule.



Toroid

Toroid

What is Toroid?

A toroid is shaped like a solenoid bent into a circular shape such as to close itself into a loop-like structure. The toroid is a hollow circular ring, as can be seen in the image shown below, with many tums of enameled wire, closely wound with negligible spacing between any two turns.

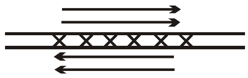
The magnetic field inside and outside the toroid is zero. The magnetic field inside the toroid, along with the circular turn, is constant in magnitude and its direction inside the toroid is clockwise as per the right-hand thumb rule for circular loops.
The magnetic field due to a toroid can be given as,

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

Where N is the number of turns of the toroid coil, I is the amount of current flowing and r is the radius of the toroid.

MAGNETIC INDUCTION DUE TO CURRENT CARRYING SHEET

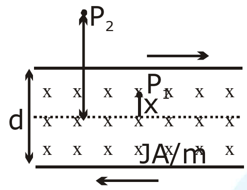
$B = \frac{1}{2}\mu_0 I$, where I = Linear current density (A/m)



MAGNETIC INDUCTION DUE TO THICK SHEET

At Point P_2, $B_{out} = \frac{1}{2}\mu_0 Jd$

At Point P_1, $B_{in} = \mu_0 Jx$



GILBERT'S MAGNETISM (EARTH'S MAGNETIC FIELD)

(a) The line of earth's magnetic induction lies in a vertical plane coinciding with the magnetic North - South direction at that place. This plane is called the **magnetic meridian**. Earth's magnetic axis is slightly inclined to the geometric axis of earth and this angle varies from 10.5° to 20°. The Earth's Magnetic poles are opposite to the geometric p-oles i.e at earth 's north pole, its magnetic south pole is situated and vice versa.

(b) On the magnetic meridian plane, the magnetic induction vector of the earth at any point, generally inclined to the horizontal at an angle called the **MAGNETIC DIP** at that place, such that $\vec{B}$ = total magnetic induction of the earth at that point.

$\vec{B}_V$ = the vertical component of $\vec{B}$ in the magnetic meridian plane = B sin θ

$\vec{B}_H$ = the horizontal component of $\vec{B}$ in the magnetic meridian plane = B cos θ.

$$\frac{B_V}{B_H} = \tan\theta$$

(c) At a given place on the surface of the earth ,the magnetic meridian and the geographic meridian may not coincide, The angle between them is called **declination at that place.**

Amperes law

$\oint \vec{B}.d\vec{\ell} = \mu \sum I$, where $\sum I =$ algebraic sum of all the currents.

MOTION OF A CHARGE IN UNIFORM MAGNETIC FIELD

(a) **When $\vec{v}$ is || to $\vec{B}$:** Motion will be in a straight line and $\vec{F}$ = 0.

(b) **When $\vec{v}$ is $\perp$ to $\vec{B}$:** Motion will be in circular path with radius

$R = \frac{mv}{qB}$ and angular velocity $\omega = \frac{qB}{m}$ and F = qvB.

(c) **When $\vec{v}$ is at $\angle\theta$ to $\vec{B}$:** Motion will be helical with radius

$R_k = \frac{mv\sin\theta}{qB}$ and pitch $P_H = \frac{2\pi mv\cos\theta}{qB}$ and F = qv B sinθ.

LORENTZ FORCE

An electric charge 'q' moving with a velocity $\vec{v}$ through a magnetic field of magnetic induction $\vec{B}$ experiences a force $\vec{F}$, given by $\vec{F} = q\vec{v} \times \vec{B}$. Therefore, if the charge moves in a space where both electric and magnetic fields are superposed.

$\vec{F}$ = net electromagnetic force on the charge $= q\vec{E} + q(\vec{v} \times \vec{B})$

This force is called the **Lorentz Force**.

MOTION OF CHARGE IN COMBINED ELECTRIC FIELD & MAGNETIC FIELD

• When $\vec{v} \parallel \vec{B}$ & $\vec{v} \parallel \vec{E}$, motion will be uniformly accelerated in straight line as $F_{magnetic} = 0$ and $F_{electrostatic} = qE$

So the particle will be either speeding up or speeding down

• When $\vec{v} \parallel \vec{B}$ & $\vec{v} \perp \vec{E}$, motion will be uniformly accelerated in a parabolic path

• When $\vec{V} \perp \vec{B}$ & $\vec{V} \perp \vec{E}$ the particle may more undeflected & undeivated with same uniform speed if $v = \frac{E}{B}$ (This is called as velocity selector condition)

MAGNETIC FORCE ON A STRAIGHT CURRENT CARRYING WIRE

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

I = current in the straight conductor

$\vec{L}$ = length of the conductor in the direction of the current in it

$\vec{B}$ = magnetic induction (Uniform throughout the length of conductor)

Note: In general force is $\vec{F} = \int I(d\vec{\ell} \times \vec{B})$

MAGNETIC INTERACTION FORCE BETWEEN TWO PARALLEL LONG STRAIGHT CURRENTS

When two long straight linear conductors are parallel and carry a current in each , they magnetically interact with each other, one experiences a force. This force is of:

(i) Repulsion if the currents are anti-parallel (i.e. in opposite direction) or

(ii) Attraction if the currents are parallel (i.e, in the same direction)

This force per unit length on either conductor is given by F = $\frac{\mu_0 I_1 I_2}{2\pi r}$

Where r = perpendicular distance between the parallel conductors

MAGNETIC TORQUE ON A CLOSED CURRENT CIRCUIT

When a plane closed current circuit of 'N' turns and of area 'A' per turn carrying a current I is placed in uniform magnetic field , it experience a zero net force, but experience a torque given by $\vec{\tau} = NI\left(\vec{A} \times \vec{B}\right) = \vec{M} \times \vec{B} = BINA \sin\theta$ where $\vec{A}$ = area vector outward from the face of the circuit where the current is anticlockwise, $\vec{B}$ = magnetic induction of the uniform magnetic field. $\vec{M}$ = magnetic moment of the current circuit = IN $\vec{A}$

Note :- This expression can be used only if $\vec{B}$ is uniform otherwise calculus will be used.

GALVANOMETER

What is a Moving Coil Galvanometer?

A moving coil galvanometer is an instrument which is used to measure electric currents. It is a sensitive electromagnetic device which can measure low currents even of the order of a few microamperes.

Moving-coil galvanometers are mainly divided into two types:

- Suspended coil galvanometer
- Pivoted-coil or Weston galvanometer

Moving Coil Galvanometer Principle

A current-carrying coil when placed in an external magnetic field experiences magnetic torque. The angle through which the coil is deflected due to the effect of the magnetic torque is proportional to the magnitude of current in the coil.

Moving Coil Galvanometer Construction And Diagram

The moving coil galvanometer is made up of a rectangular coil that has many turns and it is usually made of thinly insulated or fine copper wire that is wounded on a metallic frame. The coil is free to rotate about a fixed axis. A phosphor-bronze strip that is connected to a movable torsion head is used to suspend the coil in a uniform radial magnetic field.

Essential properties of the material used for suspension of the coil are conductivity and a low value of the torsional constant A cylindrical soft iron core is symmetrically positioned inside the coil to improve the strength of the magnetic field and to make the field radial. The lower part of the coil is attached to a phosphor-bronze spring having a small number of turns. The other end of the spring is connected to binding screws.

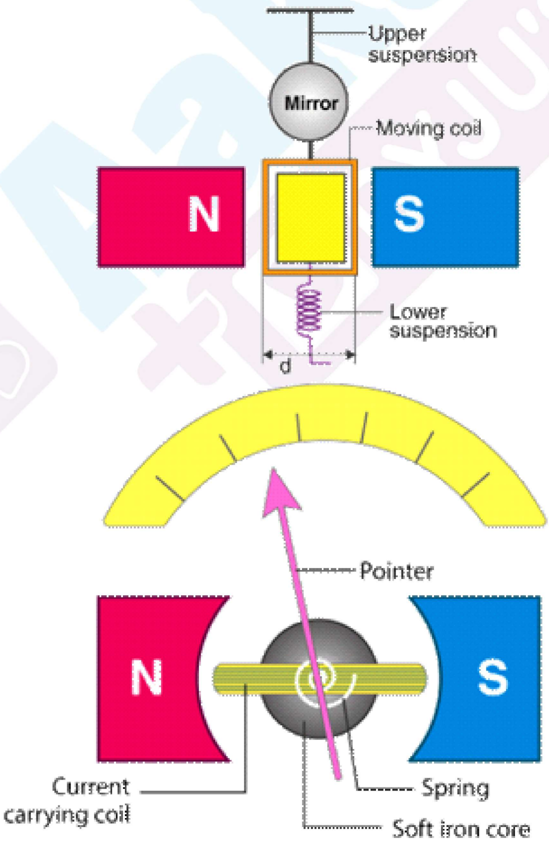
The spring is used to produce a counter torque which balances the magnetic torque and hence helps in producing a steady angular deflection. A plane mirror which is attached to the suspension wire, along with a lamp and scale arrangement, is used to measure the deflection of the coil. Zero-point of the scale is at the center.

The deflection is directly proportional to the torque.

$NIAB = K\theta$

$I = \left(\frac{K}{NAB}\right)\theta;$ K elastic torsional constant of the suspension

$I = C\theta;\ C = \frac{K}{NAB}$ Galvanometer Constant



Moving coil galvanometer

Sensitivity of Moving Coil Galvanometer

The general definition of the sensitivity experienced by a moving coil galvanometer is given as the ratio of change in deflection of the galvanometer to the change in current in the coil.

$$S = \frac{d\theta}{dI}$$

The sensitivity of a galvanometer is higher if the instrument shows larger deflection for a small value of current.
Sensitivity is of two types, namely current sensitivity and voltage sensitivity.

- **Current Sensitivity**

The deflection θ per unit current I is known as current sensitivity $\frac{\theta}{I}$.

$$\frac{\theta}{I} = \frac{nAB}{K}$$

- **Voltage Sensitivity**

The deflection θ per unit voltage is known as Voltage sensitivity $\frac{\theta}{V}$, Dividing both sides by V in the equation $\frac{\theta}{I} = \frac{nAB}{K}$

$$\frac{\theta}{V} = \left(\frac{nAB}{Vk}\right) I = \left(\frac{nAB}{k}\right)\left(\frac{I}{V}\right) = \left(\frac{nAB}{k}\right)\left(\frac{1}{R}\right)$$

R stands for the effective resistance in the circuit.
It is worth noting that voltage sensitivity = Current sensitivity/Resistance of the coil. Therefore, under the condition that R remains constant: voltage sensitivity? Current sensitivity.

Factors Affecting Sensitivity of A Galvanometer

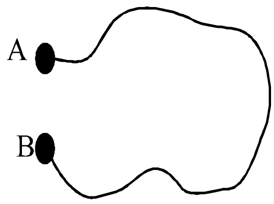
a) Number of turns in the coil
b) Area of the coil
c) Magnetic field strength B
d) The magnitude of couple per unit twist $\frac{k}{nAB}$

FORCE EXPERIENCED BY A MAGNETIC DIPOLE IN A NON-UNIFORM MAGNETIC FIELD

$$|\vec{F}| = \left| M \frac{\partial B}{\partial r} \right|$$

where M = Magnetic dipole moment.

FORCE ON A RANDOM SHAPED CONDUCTOR IN A UNIFORM MAGNETIC FIELD

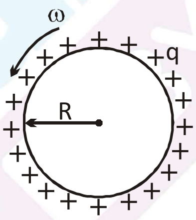


- Magnetic force on a closed loop in a uniform $\vec{B}$ is zero
- Force experienced by a wire of any shape is equivalent to force on a wire joining points A & B in a uniform magnetic field.

MAGNETIC MOMENT OF A ROTATING CHARGE

If a charge q is rotating at an angular velocity ω, its equivalent current is given as $I = \frac{q\omega}{2\pi}$ &

its magnetic moment is $M = I\pi R^2 = \frac{1}{2} q\omega R^2$.



NOTE: The ratio of magnetic moment to angular momentum of a uniform rotating object which is charged uniformly is always a constant. Irrespective of the shape of conductor $\frac{M}{L} = \frac{q}{2m}$.

Magnetic dipole

- **Magnetic moment** $M = m \times 2l$ where m = pole strength of the magnet
- **Magnetic field at axial point (or End-on) of dipole** $\vec{B} = \frac{\mu_0 2\vec{M}}{4\pi r^3}$

• **Magnetic field at equatorial position (Broad-on) of dipole** $\vec{B} = \frac{\mu_0}{4\pi}\frac{(-\vec{M})}{r^3}$

• **At a point which is at a distance r from dipole midpoint and making angle θ with dipole axis.**

→ **Magnetic Potential** $V = \frac{\mu_0}{4\pi}\frac{M\cos\theta}{r^2}$

→ **Magnetic field** $B = \frac{\mu_0}{4\pi}\frac{M\sqrt{1+3\cos^2\theta}}{r^3}$

• **Torque on dipole placed in uniform magnetic field** $\vec{\tau} = \vec{M} \times \vec{B}$

• **Potential energy of dipole placed in an uniform field** $U = -\vec{M}.\vec{B}$

→ **Intensity of magnetisation I = M/V**

→ **Magnetic induction B = μH = μ_0 (H + I)**

→ **Magnetic permeability** $\mu = \frac{B}{H}$

→ **Magnetic susceptibility $\chi_m = \frac{I}{H} = \mu - 1$**

Curie law

• For paramagnetic materials, $\chi_m \propto \frac{1}{T}$

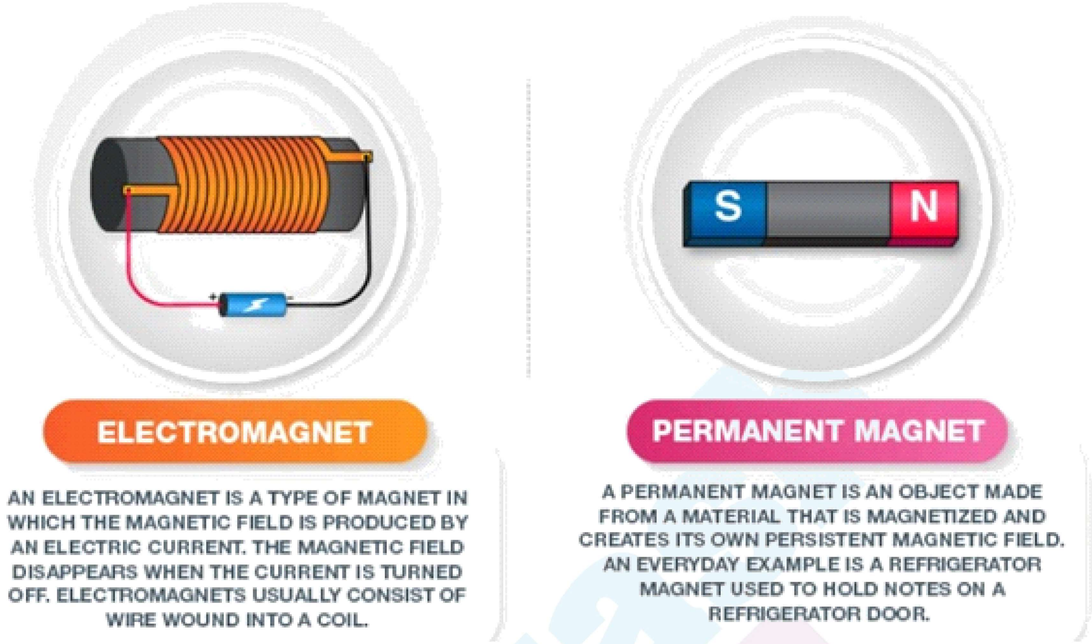
Curie Wiess law

• For Ferromagnetic materials, $\chi_m \propto \frac{1}{T - T_c}$

Where T_c = curie temperature

A MAGNETIC MATERIAL AND PERMANENT MAGNET

Difference Between Electromagnet and Permanent Magnet



As the name suggests permanent magnet magnetic field is permanent and electromagnets magnetic field depends upon the flow of the electrical current. The electromagnet constitutes a coil made of wire which acts as a magnet when current is passed through it. Usually, a ferromagnetic material like steel is wrapped by an electromagnet to enhance its magnetic field.

Difference Between Electromagnet and Permanent Magnet	
Electromagnet	**Permanent Magnet**
The magnetic properties are displayed when current is passed through it.	Magnetic properties exist when the material is magnetized.
The strength is adjusted depending upon the amount of flow of current.	The strength depends upon the nature of the material used in its creation.
Removal of magnetic properties is temporary.	Once magnetic properties is lost, it becomes useless.
It requires a continuous supply of electricity to maintain its magnetic field.	It doesn't require a continuous supply of electricity to maintain its magnetic field.
It is usually made of soft materials.	It is usually made of hard materials.
The poles of this kind of magnet can be altered with the flow of current.	The poles of this kind of magnet cannot be changed.

KEY POINTS

• A charged particle moves perpendicular to magnetic field. Its kinetic energy will remain constant but momentum changes because magnetic force acts perpendicular to velocity of particle.

• If a unit north pole rotates around a current carrying wire then work has to be done because magnetic field produced by current is always non-conservative in nature.

• In a conductor, free electrons keep on moving but no magnetic force acts on a conductor in a magnetic field because in a conductor, the average thermal velocity of electrons is zero.

• Magnetic force between two charges is generally much smaller than the electric force between them because speeds of charges are much smaller than the free space speed of light;

Note : $\frac{F_{magnetic}}{F_{electric}} = \frac{v^2}{c^2}$