Magnetic Effect of Current

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A stationary charge produces only electric field. But charge in motion produces both electric and magnetic field.

Magnetic Field and Biot-Savart's Law

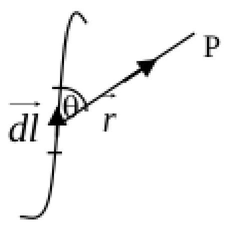
Magnetic Field

It is a region or space around a magnet or current carrying conductor or moving charge in which magnetic effect can be felt.

Biot -Savart's Law

According to this law, the magnetic field induction at a point "P" due to a small piece of current carrying conducer is given by

$$dB = \frac{\mu_0}{4\pi}\frac{Idl\sin\theta}{r^2}$$



In vector form, $\overrightarrow{dB} = \frac{\mu_o}{4\pi}\frac{I(\overrightarrow{di}\times\vec{r})}{r^3}$

Where,

B = magnetic field at any point 'P' at a distance 'r' from the wire.

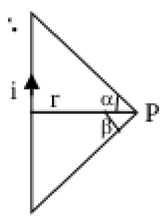
I = Current flowing through the wire.

$\mu_0 = 4\pi\times10^{-7}$ Henry/meter in SI system.

The direction of magnetic field is given with the help of screw rule that is screw is rotated from first vector $(\overrightarrow{dl})$ to 2nd vector $(\vec{r})$ through smaller angle and advancement of screw gives us the direction of magnetic field.

Magnetic field due to flow of current

- **Through a straight conductor:**



Field at point 'p' is given by:

$$\mathrm{B} = \frac{\mu_o}{4\pi}\frac{i}{r}(\sin\alpha+\sin\beta)$$

  - At the end of large conductor.

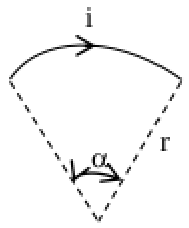
    $A = 0$ and $\beta = \pi/2$

    $$\mathrm{B} = \frac{\mu_0}{4\pi}\frac{i}{r}$$

  - If $\alpha = \pi/2$ and $\beta = \pi/2$ then,

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

- ## Through circular arc:



Magnetic field at the centre is given by:

$$\mathrm{B} = \frac{\mu_o i}{4\pi r} \times \alpha$$

where, α is in radian.

  - For semi circular wire, $\alpha = \pi, \mathrm{B} = \frac{\mu_o i}{4r}$
  - For circular wire, $\alpha = 2\pi; \mathrm{B} = \frac{\mu_o i}{2r}$

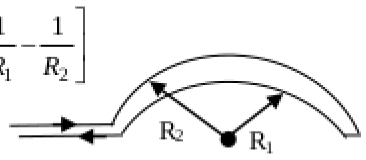
- Magnetic field at the centre of circular coil of N turus carrying current is given by:

$$\mathrm{B} = \frac{\mu_0 N i}{2R}$$

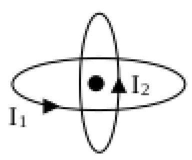
Where N = No. of turn

- Two semi circular loops of radius R_1 and R_2, $(R_2 > R_1)$ are connected to a battery in series. The magnetic field at the centre of coil will be:

$$\mathrm{B} = \frac{\mu_0 \mathrm{i}}{4}\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$



- Two circular coils are placed perpendicularly with their centre coinciding, if current flowing in them, are I_1 and I_2 respectively then magnetic field at their common centre will be:



$$\mathrm{B} = \frac{\mu_0 \mathrm{i}}{4\mathrm{r}}\sqrt{I_1^2 + I_2^2}$$

- A cell is connected across any two points of a uniform circular conductor the magnetic field at the centre of conductor will be zero.
- Magnetic field at a point on the axis of a circular current carrying coil:

$$\mathrm{B} = \frac{\mu_o N I r^2}{2(x^2 + r^2)^{3/2}}$$

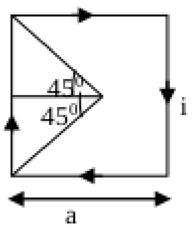
Where,
$r =$ radius of the coil
$x =$ distance of the point from centre of coil

- If $r \gg x$ then $\mathrm{B} = \frac{\mu_o NI}{2r} = \frac{\mu_o}{2\pi} \frac{\mathrm{NIA}}{r^3}$
- If $r \ll x$ then $\mathrm{B} = \frac{\mu_o NIr^2}{x^3}$

- Magneitc field due to moving change in circular orbit at the centre:

$$B = \frac{\mu_o qv}{4\pi r^2}$$

- Magnetic field due to a current carrying square loop of wire:



- due to one side of square of side a at the centre

$$\mathrm{B} = \frac{\mu_o I}{4\pi(a/2)}\left(\sin 45^0 + \sin 45^0\right)$$

- Due to all four sides at the centre

$$B_T = 4B = \frac{2\sqrt{2}\mu_0 I}{\pi a}$$

Ampere's Circuit Law

$\vec{B} \cdot \overrightarrow{dl} = \mu_0 \mu_r \mathrm{NI}$

Where, $N =$ no. of turn

- Magnetic field due to current carrying solenoid:

$$\mathrm{B} = \frac{\mu_o \mu_r NI}{I} = \mu_0 \mu_\mathrm{r} \mathrm{nI}$$

Where,

$\mathrm{N} =$ No. of tum in the solenoid
$l =$ length of solenoid
$\mathrm{n} =$ no. of turn per unit length
$\mathrm{I} =$ Current flowing hrought the solenoid

- Magnetic field due to solenoid is just like bar magnet.
- Magnetic field at a point on the axis of solecoid is:

$$\mathrm{B} = \frac{\mu_0 \mathrm{nI}}{2}[\cos\theta_1 - \cos\theta_2]$$

- If a copper rod carries a direct current, then the magnetic field associated with the current:
  - inside the rod at a rod at a distance 'r' from its axis:

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

- On the surface:

$$\mathrm{B} = \frac{\mu_0 I}{2\pi R}$$

- Outside the rod at a distance x from the the axis:

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

- If a long hollow copper pipe (or thin wall tube) carries a direct current, the magnetic field associated with the cuuent:
  - Zero inside the tube
  - On the surface:

$$\mathrm{B} = \frac{\mu_o I}{2\pi R}$$

  - Outsdie the tube:

$$\mathrm{B} = \frac{\mu_0 I}{2\pi R}$$

Magnetic moment of a carrying coil

a. The magnetic field due to a current carring coil is like as bar magnet:

$$M = NIA$$

b. Magnet moment of moving charge:

$$M = \frac{qvR}{2}$$

$$\mathrm{M} = \frac{qL}{2m}$$

- For electron, $M_e = \dfrac{evR}{2}$
- For α particle, $M_\alpha = evR$

Magnetic flux (ϕ)

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

If $\vec{B} = B_x\vec{i} + B_y\vec{j} + B_z\vec{k}$

And $\vec{A} = A_x\vec{i} + A_y\vec{j} + A_z\vec{k}$

Then, $\phi = \vec{B} \cdot \vec{A} = (A_xB_x + A_yB_y + A_zB_z)$

- If the palne of coil is making an angle 'α' with magniet field then, $\phi = BA\sin\alpha$
- Torque will be maximum when $\theta = 90^\circ,\ T_{max} = BINA$
- Work done to rotate the coil by an anlge 'θ' from equilibrium condition.

$$W = BINA(1 - \cos\theta)$$

- Potential energy of a coil at an angle θ,

$$U = -BINA\cos\theta$$

- Magnetic force will be maximum when $\theta = 90^\circ$

Force due to Magnetic Field

Magnetic force on a current carrying conductor in magnetic field:

$$\overrightarrow{\mathrm{F}} = \mathrm{i}(\overrightarrow{\mathrm{dl}} \times \overrightarrow{\mathrm{B}}) = \mathrm{i}(\overrightarrow{l} \times \overrightarrow{\mathrm{B}})$$
$$\mathrm{F} = Bil \sin\theta$$

Where θ is the angle between magnetic field and direction of current:

i. If $\theta = 0^\circ$ $\quad F_{min} = 0$
ii. If $\theta = 90^\circ$ $\quad F_{max} = Bil$

Magnetic force on a charged particle moving in magnetic field:

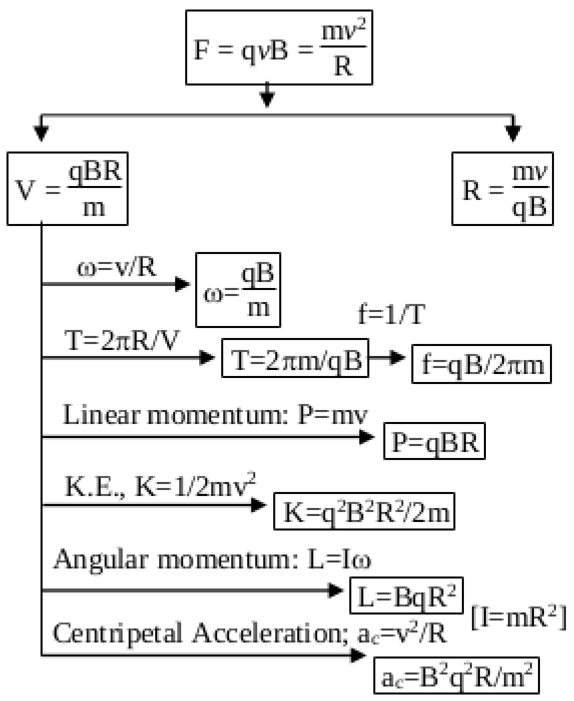
If a charge particle having charge 'q' is moving with velocity 'v' in magnetic field, then force on the charge particle is given by:

$$\overrightarrow{\mathrm{F}} = \mathrm{q}(\overrightarrow{\mathrm{v}} \times \overrightarrow{\mathrm{B}})$$
$$\mathrm{F} = \mathrm{qvB} \sin\theta$$

Force on charge moves parallel to the direction of the magnetic field then force on it is zero.

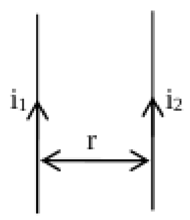
Path of moving charge particle

i. If $\theta = 90^\circ$; the charge particle is thrown perpendicular to B then it moves in a circular path. In the equilibrium condition, the magnetic force = centrifugal force.
ii. If $\vec{v}$ and $\vec{B}$ are parallel to each other, then the charge will continue to move in the same direction (straight line)
iii. If $0 < \theta < 90^\circ$ means the direction of initial velocity is neither along nor perpendicular to the magnetic field then the path of charge particle is helical. (like spring)



i. If the charge on particle is zero (like neutral) then it will experience no force.
ii. The radius of circular path depends upon linear momentum of the particle. The area of the circle depends upon square of the linear momentum.
iii. The time period is independent to the velocity and radius of the path.
iv. Linear velocity, angular velocity and frequency of the particle is directly proportional to specific charge of the particle.
v. Time period and radius are inversely proportional to the specific charge of the particle.
vi. The function of B is only to change the direction of motion. It can not accelerate the charge particle to increase its speed.

Magnetic force per unit length between two parallel current carrying conductors.



$$\mathrm{F} = \frac{\mu_0}{2\pi}\frac{i_1 i_2}{r} \quad \mathrm{N/m}$$

if $\mathrm{i}_1 = \mathrm{i}_2 = \mathrm{i}$ then,

$$\mathrm{F}/l = \frac{\mu_o i^2}{2\pi r}$$

Force between two parallel current elements:

$$\mathrm{d}\vec{F}_2 = -\mathrm{d}\vec{F}_1$$

- When the direction of current in both the conductors is same then they will attract each other. If the direction is opposite to each other they will repel each other.
- Two wires attract each other by magnetic force.

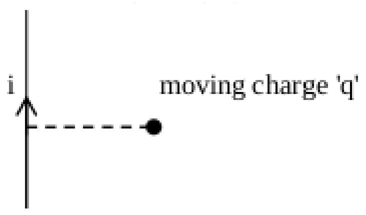
Definition of Ampere:

One Ampere is that current which, when passed in each of two parallel conductors of infinite length and one meter apart in vaccum causes each conductor to experience a force of $2 \times 10^{-7}\, N/m$ of length conductor.

Magnetic force between two moving charge q_1 and q_2 moving with velocity v_1 and v_2 at a distance r parallel to each other:

$$\mathrm{F} = \frac{\mu_o}{4\pi}\frac{\mathrm{q}_1\mathrm{q}_2\mathrm{v}_1\mathrm{v}_2}{\mathrm{r}^2}$$

Force between a current carrying conductor and moving charge parallel to it:



$$\mathrm{B} = \frac{\mu_o i}{2\pi r}$$

$$\mathrm{F} = \mathrm{Bqv} = \frac{\mu_o i q v}{2\pi r}$$

Moving Coil Galvanometer

Moving Coil or Suspended Coil or Darsonval Type Galvanometer:

When a current conductor is placed in magnetic field, it experiences a force in a direction given by Fleming's lest hand rule. It is used to measure D.C. current.

$$\tau = \mathrm{NBIA} = \mathrm{C}\theta$$
$$\mathrm{C} = \text{Spring factor}$$

- **Current Sensivity:**

  The Current sensitivity of a meter is the deflection of the meter per unit current i.e. θ/I. It is given by:

  $$\theta/I = NAB/C$$

- **Voltage Sensivity:**

  Voltage sensitivity of a Galvanometer. It is defined as the deflection of the meter per unit voltage.

  $$\theta/V = \theta/IR = NBA/CR$$

  $R =$ Resistance of the coil.

In Galvanometer the permanent magnets are cylindrically cut to direct the magnet flux to the center and to link the flux always perpendicular the coil.

Advertences

i. The galvanometer can be made extremely sensitive.
ii. Since the magnetic field B is very high therefore the external magnetic field can not appreciably alter the deflection of the coil. So the galvanometer can be used in any position.

iii. Since the deflection of the coil is proportional to current therefore linear scale is used.

Hall effect

The production of transverse e.m.f. in current carrying conductor when a magnetic field is applied perpendicular to the direction of current is known as Hall Effect.

The quantity $1/ne$ is called Hall effect.

Cyclotron

Cyclotron is a device to accelerate ions/charge particle to extremely high voltages. Frequency of cyclotron is given by:

$$f = \frac{Bq}{2\pi m}$$

- Cyclotron frequency is independent of velocity of the particle.
- Maximum kinetic energy of accelerated changed particle in a cyclotron is,

$$\mathrm{K} = \frac{1}{2} m V_{meq}^2 = \frac{1}{2} m \left(\frac{Bqr_{meq}}{m} \right)^2$$

- Radius of charged particle is:

$$\mathrm{r} = \frac{\mathrm{mV}}{\mathrm{Bq}}$$