CHAPTER 18

Magnetic Effect of Current and Magnetism

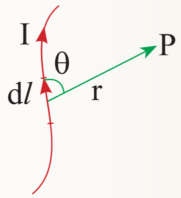
A static charge produces only electric field. A moving charge produces both electric field and magnetic field. A current carrying conductor produces only magnetic field.

MAGNETIC FIELD 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:

$$dB = \frac{\mu_0\mu_r}{4\pi}\frac{I\,dl\sin\theta}{r^2} \Rightarrow \vec{dB} = \frac{\mu_o\mu_r}{4\pi}\frac{I\left(d\vec{l}\times\vec{r}\right)}{r^3}$$

here the quantity Idl is called as current element.



μ = permeability of the medium = $\mu_0\mu_r$

μ_0= permeability of free space

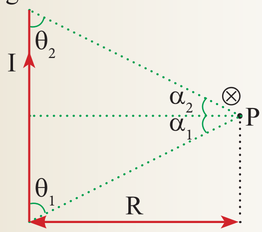
μ_r= relative permeability of the medium (Dimensionless quantity)

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 Straight Current Conductor

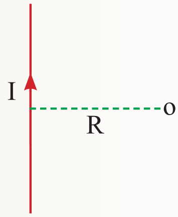
Magnetic induction due to a current carrying straight wire



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

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

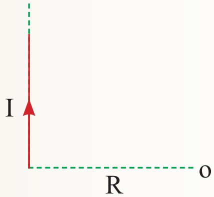
$$\alpha_1 = 90^\circ;\ \alpha_2 = 90^\circ$$



Magnetic induction due to semi infinite straight conductor

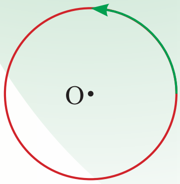
$$B = \frac{\mu_0 I}{4\pi R} \otimes$$

$$\alpha_1 = 0^\circ;\ \alpha_2 = 90^\circ$$



- Magnetic field due to a flat circular coil carrying a current:

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



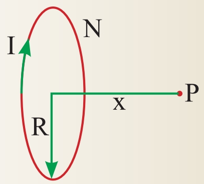
where

N = total number of turns in the coil

I = current in the coil

R = Radius of the coil

(*ii*) On the axis $B = \dfrac{\mu_0 N I R^2}{2\left(x^2 + R^2\right)^{3/2}}$

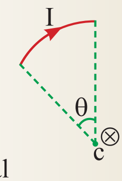


Where x = distance of the point from the centre.

It is maximum at the centre $B_C = \dfrac{\mu_0 N I}{2R}$

(*iii*) Magnetic field due to flat circular ARC :

$$B = \frac{\mu_0 I \theta}{4\pi R}$$



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

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

Magnetic Induction Due to Solenoid

$B = \mu_0 n I$, direction along axis.

where n $\rightarrow$ number of turns per meter;

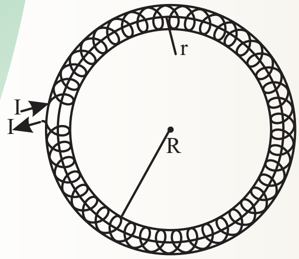
I $\rightarrow$ current

Magnetic Induction Due To Toroid :

$B = \mu_0 n I$

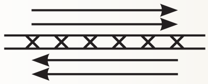
where $n = \dfrac{N}{2\pi R}$ (no. of turns per m)

N = total turns and $R \gg r$



Magnetic Induction Due To Current Carrying Sheet

$B \; \frac{1}{2} \mu_0 \lambda$ where λ = Linear current density (A/m)



Earth's Magnetic Field

(a) 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 poles 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 in $\vec{B}$ in the magnetic meridian plane $= B \sin\theta$

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

and $\tan\theta = \dfrac{B_v}{B_H}$

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

AMPERES CIRCUITAL LAW

$\oint \vec{B}.\vec{d}l = \mu\Sigma I$ where Σ I = algebraic sum of all the current.

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

(c) When $\vec{V}$ is at $\angle\,\theta$ to $\vec{B}$: Motion will be helical with radius $R_k = \dfrac{mv\sin\theta}{qB}$ and pitch $P_H = \dfrac{2\pi mv\cos\theta}{qB}$ and $F = qvB\sin\theta$.

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 $\vec{F} = q\vec{v}\times\vec{B}$. There fore, 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 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 will move 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 $\vec{F} = \int I\left(d\vec{l} \times \vec{B}\right)$

Magnetic Interaction Force Between Two Parallel Long Straight Currents:

The interactive force between 2 parallel long straight wires is:

(i) Repulsive if the currents are anti-parallel.

(ii) Attractive if the currents are parallel.

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

Where r = perpendicular distance between the parallel conductors

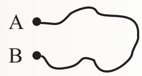
Magnetic Torque On a Closed current Circuit :

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 $\vec{\tau} = NI\vec{A}\times\vec{B} = \vec{M}\times\vec{B} = BINA\sin\theta$

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 = $NI\vec{A}$

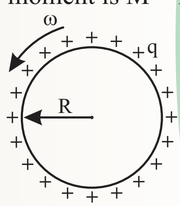
FORCE ON A RANDOM SHAPED CONDUCTOR IN A UNIFORM MAGNETIC FIELD



- 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 $M = I\pi R^2 = \frac{1}{2}q\omega R^2$.



NOTES

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 M/L = 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 $\vec{B} = \frac{\mu_0}{4\pi}\frac{2\vec{M}}{r^3}$
  - Magnetic field at equatorial position (Broad-on) of dipole

    $= \vec{B} = \frac{\mu_0}{4\pi}\frac{\left(-\vec{M}\right)}{r^3}$

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

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

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

- Torque on dipole placed in uniform magnetic field $\vec{\tau} = \vec{M} \times \vec{B}$
- Potential energy of dipole placed in an uniform field $U = -\vec{M} \cdot \vec{B}$
- Intensity of magnetisation $I = M/V$
- Magnetic induction $B = \mu H = \mu_0(H + I)$
- Magnetic permeability $\mu = \dfrac{B}{H}$
- Magnetic susceptibility $\chi_m = \dfrac{1}{H} = \mu - 1$
- Curie Law
  For paramagnetic materials $\chi_m \propto \dfrac{1}{T}$
- Curie Wiess law
  For Ferromagnetic materials $\chi_m \propto \dfrac{1}{T - T_C}$
  Where T_C = Curie temperature

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