MAGNETIC EFFECT OF CURRENT & MAGNETISM

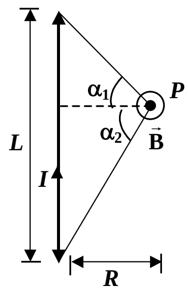
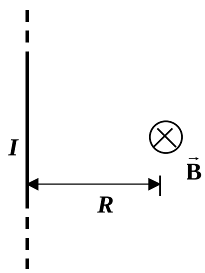
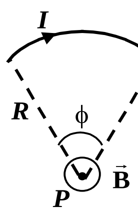
BIOT- SAVART LAW

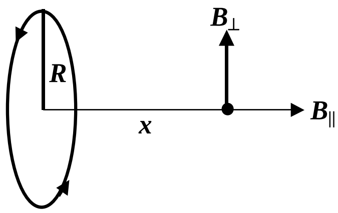
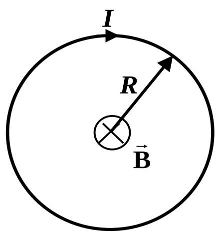
The direction of the magnetic field element dB as given by Biot Savart law is shown in the figure.

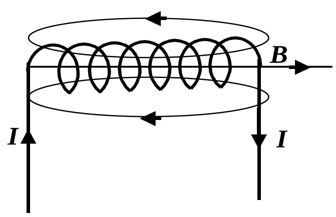
$$dB = \frac{\mu_o}{4\pi} \frac{Idl \sin\theta}{r^2}$$

The direction of $\vec{\mathbf{B}}$ can be obtained by applying right hand on $Id\vec{l} \times \vec{r}$.

Table 1 *Magnetic field due to different current systems*

1. A straight wire of finite length 	$B = \frac{\mu_o I}{4\pi R}(\sin\alpha_1 + \sin\alpha_2)$
2. ***An infinitely long straight wire*** 	$B = \frac{\mu_o I}{2\pi R}$
3. ***An arc of a circle*** 	$B = \frac{\mu_o I\phi}{4\pi R}$

4. ***On the axis of a Ring*** 	$B_\perp = 0$ $B_\parallel = \frac{\mu_o I R^2}{2\left(R^2 + x^2\right)^{3/2}}$
5. At the centre of a Ring 	$B = \frac{\mu_o I}{2R}$

6. On the axis of a solenoid 	$B = \mu_o n I = \mu_o \frac{N}{l} I$ where N is the total number of turns and n is the number of turns per unit length. Assuming that radius of the loop is very small compared to its length.

MAGNETIC FORCE

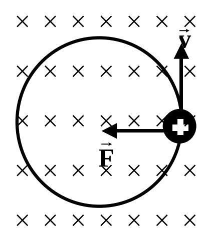
The magnitude of the force is given by $F = qvB\sin$□

where θ is the angle between the vectors v and B.

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

Motion of a charged particle in a Uniform Magnetic Field

Consider the motion of a positively charged particle moving with an initial velocity $\vec{v}$ perpendicular to a uniform magnetic field $\vec{B}$ as shown in figure. Since $\vec{v}$ and $\vec{B}$ are perpendicular, the particle experiences a force $F = qvB$ of constant magnitude directed perpendicular to $\vec{v}$.



Motion of a charged particle perpendicular to a uniform magnetic field.

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

Where, r is the ***radius*** of the circular path.

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

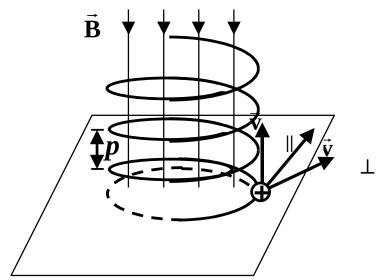
The radius of the orbit is directly proportional to the linear momentum of the particle and inversely proportional to the magnetic field strength.

The ***time period*** is given by

$$T = \frac{2\pi r}{v} = \frac{2\pi m}{qB}$$

Helical Motion

Let us consider the motion of a positive charged particle whose velocity $\vec{v}$ is not perpendicular to the uniform magnetic field $\vec{\mathbf{B}}$. The velocity $\vec{v}$ can be resolved into two components:



When a charged particle moves at an angle to the field it travels in a helical path.

$\vec{v}$□, perpendicular to $\vec{\mathbf{B}}$, and $\vec{v}_{||}$, parallel to $\vec{\mathbf{B}}$. The perpendicular component $\vec{v}_{\perp}$ gives rise to a force $qv_{\perp}B$ that produces circular motion.

The parallel component $v_{\|}$ is unaffected by the magnetic field $\vec{B}$, therefore, the particle moves with constant velocity parallel to the field. *The resultant motion is a uniform circular motion perpendicular to field lines and a constant linear motion along the field lines*. This is called a circular ***helical path***.

Radius of helix $r = \frac{mv_{\perp}}{qB}$

The ***pitch*** of a helix is defined as *the linear distance moved by the particle in one revolution.*

$$p = v_{\|}T = \frac{2\pi m v_{\|}}{qB}$$

Lorentz Force

When a particle is subjected to both electric and magnetic fields in the same region, the total force on it is called the ***Lorentz force***.

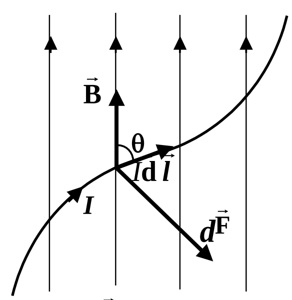
$$\vec{F} = q\,(\vec{\mathbf{E}} + \vec{v} \times \vec{\mathbf{B}})$$

FORCE ON A CURRENT CARRYING CONDUCTOR

When a wire is placed in a magnetic field, it experiences no force. The thermal velocities of the free electrons are randomly oriented and so net force on them is zero. However, when a current flows, the electrons as a whole acquire a velocity in a definite direction and experience a magnetic force which is then transmitted to the wire.

The force experienced by an infinitesimal current element $Id\vec{l}$ placed in a magnetic field $\vec{B}$ is given by

$$d\vec{F} = Id\vec{l} \times \vec{B} \qquad \textbf{(8)}$$



Force $d\vec{F}$ acting on a small current element $Id\vec{l}$

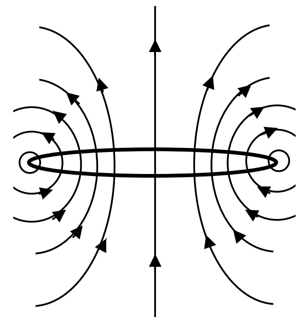
The total force on a wire is the vector sum (*integral*) of the forces on all current elements.

$$\int d\vec{F} = \int (Id\vec{l} \times \vec{B})$$

MAGNETIC DIPOLE

A small current carrying loop acts like a ***magnetic dipole***. The magnitude of a ***magnetic dipole moment or magnetic moment*** $\vec{p}_m$. *It is defined as the product of the current in a flat current - carrying loop and the area enclosed by it.*

Thus, $\vec{p}_m = I\vec{A}$



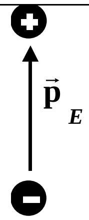
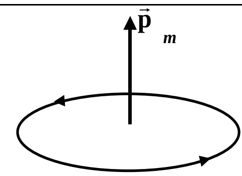
The magnetic field lines of a current loop. Close to the current the lines approach circles.
Far from the loop the *B*-field lines are identical to those of a magnetic dipole.

The *direction* of magnetic moment coincides with the direction of the *area vector* (which is the direction of the magnetic field).

If the loop contains *N* number of turns, the magnetic moment is given by

$$\vec{p}_m = NI\vec{A} \quad \textbf{(9)}$$

1.	Electric Dipole	Magnetic Dipole

		
2.	Electric Field along the axis $\vec{E}_{\parallel} = \frac{1}{2\pi\varepsilon_o}\frac{\vec{p}_E}{x^3}$	Magnetic Field along the axis $\vec{B}_{\parallel} = \frac{\mu_o\vec{p}_m}{2\pi x^3}$
3.	Torque $\vec{\tau} = \vec{p}_E \times \vec{E}$	Torque $\vec{\tau} = \vec{p}_m \times \vec{B}$ **(20)**
4.	Potential Energy $U = -\vec{p}_E \cdot \vec{E}$	Potential Energy $U = -\vec{p}_m \cdot \vec{B}$ **(21)**

AMPERE'S LAW

The integral of the quantity $\vec{B} \cdot d\vec{l}$ around loop is related to the current flowing through the surface bounded by the loop.

$$\oint \vec{B} \cdot d\vec{l} = \mu_o I$$

MAGNETOSTATICS

Magnetic Field / Magnetic Induction or Flux Density (B)

The total number of lines of force per unit area due to magnetizing field and due to the field induced in the substance is called flux density (B), the unit in which B is measured is Wb/m^2.

The magnetic field intensity is given by

$$\vec{B} = \frac{\mu}{4\pi}\frac{m}{r^2}\hat{r} \quad Wb/m^2$$

Where, μ is the absolute permeability of the medium and is expressed as $\mu = \mu_o \times \mu_r$

Where, μ_r is relative permeability of the material and μ_o is the permeability of the free space or air and is taken as

$4\pi \times 10^{-7}$ Wb/A.m.

Magnetic field strength or Magnetizing field

The magnetic field strength or magnetizing field is given by

$$\vec{H} = \frac{\vec{B}}{\mu}$$ A/m and is independent of the medium.

Intensity of Magnetization (I or J)

The measure of the magnetization of a magnetized specimen is called intensity of magnetization. It is defined as the magnetic moment per unit volume.

Thus $I = \frac{\text{magnetic moment}}{\text{volume}}$

Magnetic Susceptibility

The magnetic susceptibility (χ) of a specimen measures the ease with which the specimen can be magnetized and can be defined as the ratio of the intensity of magnetization induced in it and the magnetizing field i.e.

$$\chi = \frac{I}{H}$$

Magnetic Permeability

The permeability is defined as the ratio of the magnetic induction B in the medium to the magnetizing field H i.e.

$$\mu_\alpha = \mu_o \mu_\rho = B/H$$

Paramagnetic Substances

The substances which when placed in a magnetic field acquires a feeble magnetization in the same sense as the applied field are called paramagnetic substances. The examples are platinum, aluminum, manganese, chromium, copper sulphate, iron or nickel salt solutions and crown glass.

Their properties can be summarized as

(i) Such substances in non-uniform magnetic field, experience an attractive force towards the stronger part of the field.

(ii) The permeability μ for a paramagnetic substance is slightly greater than one.

(iii) The magnetic susceptibility is small positive value.

(iv) For a given temperature χ does not change with variation in H.

(v) The susceptibility varies inversely as the absolute temperature and at higher temperature its value becomes negative.

Diamagnetic substances

1. Diamagnetism is universal property of the substances.
2. χ_m is small and negative
3. $\mu_r < 1$.

4. As $\Rightarrow I$ is small and opposite to H.

$\therefore$ They are magnetized weakly and opposite to applied magnetic field.

5. Magnetic field lines do not cross through diamagnetic materials.

Some examples of diamagnetic substances are Cu, Zn, Bi, Ag, Au, Glass, NaCl.

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Paramagnetic and Ferromagnetic Substances

1. for paramagnetic, χ_m is small and positive, $\mu_r > 1$.
2. for ferromagnetic, χ_m is large and positive, $\mu_r >> 1$.
3. Both get magnetized in the direction of applied field.
4. Magnetic field lines cross through them.

Some examples are given below:

(a) Paramagnetic - Al, Na, Sb, Pt.

(b) Ferromagnetic - Fe, Ni, Co

Ferromagnetic Substance

Such substances acquire high degree of magnetization in the same sense as the applied magnetic field. The example are: iron, steel, nickel and cobalt. Ferromagnetic substances exhibit the following properties:

(i) They have permeability of the order of hundreds and thousands.

(ii) Susceptibility is also very large and positive.

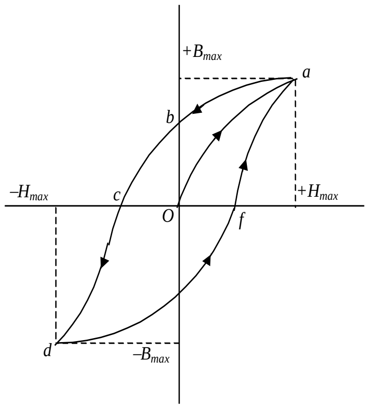
(iii) For small values of *H* susceptibility, remains constant and for moderate value of *H* increases rapidly with *H* and for large value attains a constant value.

(iv) They are attracted even by weak magnet.

(v) As temperature increases the value of χ decreases. Above certain temperature ferromagnetic become ordinary paramagnetics and this temperature is called curie temperature ($\chi \propto 1/T$ is called curie law). For iron, steel and nickel the curie point is $1000^{o}C$, $770^{o}C$ and $360^{o}C$ respectively.

Hysteresis Loop

If we take a ferromagnetic material in completely demagnetized state and make it to undergo through a cycle of magnetization in which H is increased from zero to a maximum value H_{max}, then decreases to zero, then reversed and again taken to $-H_{max}$, and finally brought back to zero.

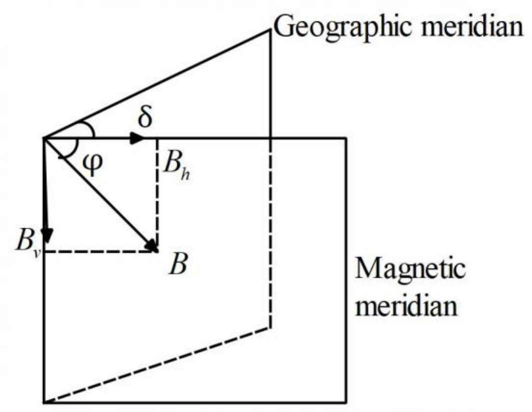


Energy Loss Due to Hysteresis

When a magnetic material is taken round cycle, there is an energy loss per unit volume of the material given by the area B-H curve.

Components of Earth's Magnetic Field

The main components of the Earth's magnetic field at one place are shown in figure below:



1. δ = Angle of declination
2. ϕ = Angle of dip
3. $B_H = B \cos\phi$
4. $B_V = B \sin\phi$
5. $B_H^2 + B_V^2 = B^2$

Angle of Dip or Inclination (δ)

The total intensity of the Earth's magnetic field varies from-direction with the magnitude. An angle that is drawn with the horizontal line in the magnetic meridian in the Earth's magnetic field, known as magnetic or tilt. We use dip circles and poles to measure this angle. Thus,

$\delta = 90^o$ and at equator $\delta = 0$.

Horizontal Component

The resulting magnetic field due to Earth can be resolved into two components.

(i) Horizontal component (H),

(ii) Vertical component (V).

From the figure, we get, horizontal component of the Earth's magnetic field is the total intensity of the components of the Earth's magnetic field in the horizontal direction of the magnetic meridian. That is,

$$H = B_e \cos \delta \text{ and } V = B_e \sin \delta$$

BAR MAGNET

Field on an axial line of Bar magnets (ending at position).

Magnetic dipole moment is given by *m*,

$$B = \frac{\mu_o}{4\pi}\frac{2md}{\left(d^2 - l^2\right)^2} \quad \text{if } l^2 << d^2, \quad B = \frac{\mu_o}{4\pi}\frac{2m}{d^3}$$

At a Point on Equatorial Line (Broad side on Position)

Magnetic dipole moment is given by *m*,

$$B = \frac{\mu_o}{4\pi}\frac{m}{\left(d^2 + l^2\right)^{3/2}} \text{ If } l^2 << d^2, \; B = \frac{\mu_o}{4\pi}\frac{m}{d^3}$$

Tangent Law

When a magnet is suspended in the two mutually pending zones of an intensity field B and H, the magnet shifts to a resting position by making an angle θ along the direction of H such that,

$$B = H \tan\theta$$

This is known as the tangent method.

TANGENT GALVANOMETER

The tangent galvanometer is an electric current measuring instrument.

$$B_H \tan\theta = \frac{\mu_o in}{2r}$$

Or $i = \frac{2rB_H}{\mu_o n}\tan\theta$ or $i = K\tan\theta$

Where, $K = \frac{2rB_H}{\mu_o n}$ is a constant for the given galvanometer at a given place.