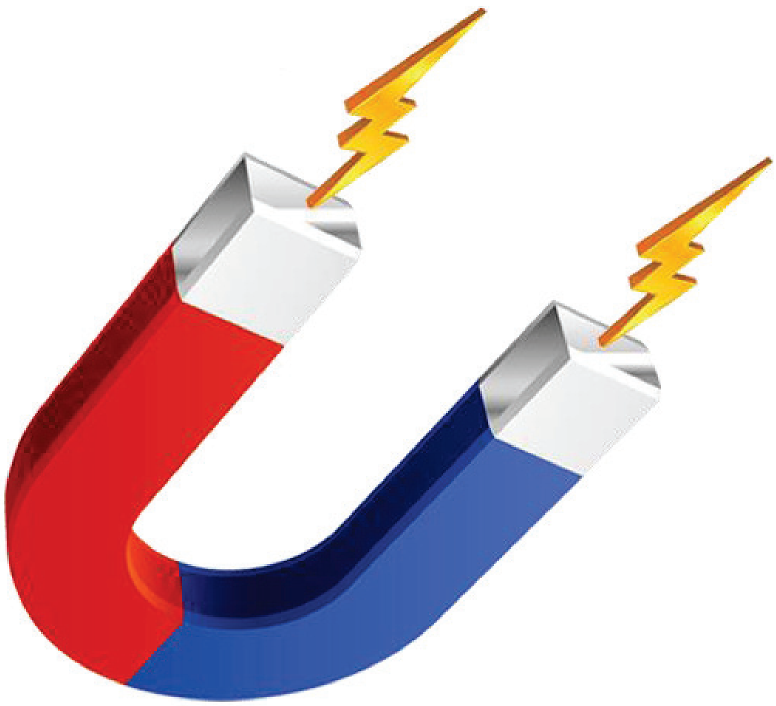
MOVING CHARGES AND MAGNETISM



MOVING CHARGES AND MAGNETISM

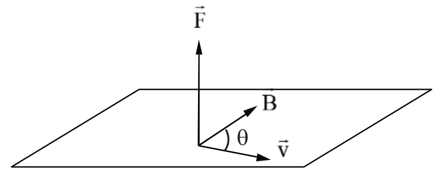
Introduction

A gravitational field is associated with a mass. An electrostatic field is associated with a charge. A magnetic field is in a region surrounding a current carrying conductor.

- An electric charge $\xrightarrow{\text{causes}}$ an electric field $\xrightarrow{\text{affects}}$ an electric charge
- A moving electric charge (electric current) $\xrightarrow{\text{causes}}$ a magnetic field $\xrightarrow{\text{affects}}$ a moving electric charge

Magnetic force on a charged particle moving in a magnetic field

The force exerted by a magnetic field on a moving electric charge or a current carrying conductor is called magnetic force.



Force on a moving charge

A charge q moving with a velocity $\vec{v}$, in a magnetic field $\vec{B}$, experiences a force $\vec{F}$. It is given by

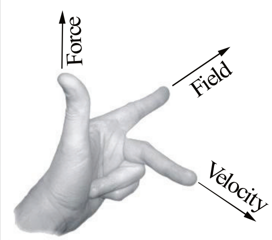
$\vec{\mathbf{F}} = \mathbf{q}\,\vec{\mathbf{v}} \times \vec{\mathbf{B}}$.

- The magnitude of the magnetic force is F = q vB sin θ, where θ is the angle between $\vec{v}$ and $\vec{B}$.
- The direction of $\vec{F}$ is that of $\vec{v} \times \vec{B}$.
- F is zero, when $\vec{v}$ is parallel or anti parallel to $\vec{B}$ (θ = 0 or 180°).
- F is maximum when a charged particle moves in a direction perpendicular to the direction of $\vec{B}$ (θ = 90°). F_{max} = q VB sin 90° = q vB.
- The work by the magnetic force on a charged particle is zero since $\vec{F}$ is perpendicular to $\vec{v}$. Thus, a magnetic field cannot change the speed and kinetic energy of a charged particle.

Fleming's left hand rule

The direction of the force on a charged particle moving perpendicular to a magnetic field is given by Fleming's left hand rule.

Stretch the first three fingers of the left hand such that they are mutually perpendicular. If the forefinger is in the direction of the field, the middle finger in the direction of velocity of the positively charged particle then the thumb gives the direction of the mechanical force.



Fleming's left hand rule

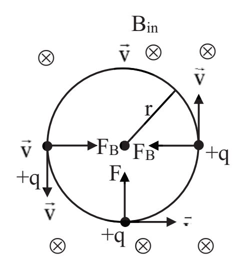
Motion of a charged particle with $\vec{v}$ perpendicular to $\vec{B}$

Consider a positively charged particle moving in a uniform magnetic field. When the initial velocity of the particle is perpendicular to the field, (in the figure, the magnetic field is perpendicular to the plane of the paper and inwards) the particle moves in a circular path whose plane is perpendicular to the magnetic field.

Thus, the centripetal force $\frac{mv^2}{r}$ is provided by the magnetic force qvB,

where r = radius of the circular path.

$\therefore\ \mathbf{r} = \frac{\mathbf{mv}}{\mathbf{qB}}$.



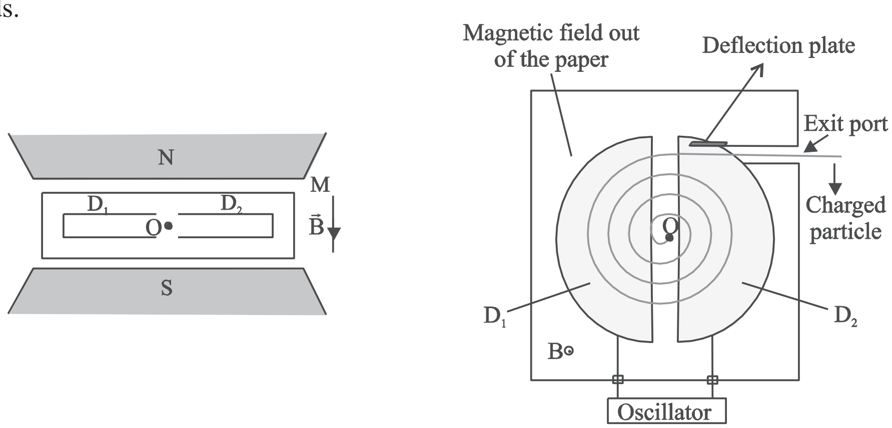
The **angular speed** of the particle, $\boldsymbol{\omega} = \frac{\mathbf{v}}{\mathbf{r}} = \frac{\mathbf{qB}}{\mathbf{m}}$.

The **period** of circular motion, $\mathbf{T} = \frac{\mathbf{2\pi r}}{\mathbf{v}} = \frac{\mathbf{2\pi}}{\boldsymbol{\omega}} = \frac{\mathbf{2\pi m}}{\mathbf{qB}}$ and frequency $f = \frac{qB}{2\pi m}$

Thus, the angular speed of the particle, period of the circular motion and frequencies of rotation do *not* depend on the translational speed of the particle or the radius of the orbit, for a given charged particle in a given uniform magnetic field. This principle is used in the design of a particle accelerator called cyclotron.

Cyclotron

Cyclotron is a device used to accelerate charged particles to very large kinetic energies by applying electric and magnetic fields.



(a) (b)

Schematic diagram of cyclotron

- **Expression for kinetic energy**

  The maximum kinetic energy, of the ion as it emerges from the cyclotron will then be

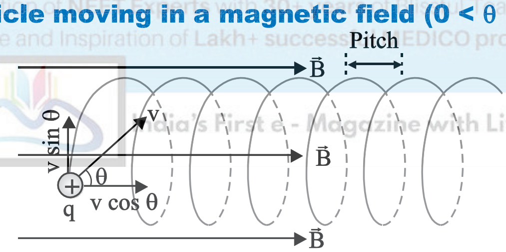
  $(\text{Kinetic energy})_{max}, K_{max} = \dfrac{B^2q^2R^2}{2m} \Rightarrow K_{max} \propto \dfrac{q^2}{m}$.

- **Cyclotron frequency**

  The frequency f, of the oscillator required to keep the ion in phase is the reciprocal of the time in which the particle makes one revolution. This is called the cyclotron frequency given by $f = \dfrac{Bq}{2\pi m}$

  It can be shown that kinetic energy = $2m\pi^2 f^2R^2$

Helical path of a charged particle moving in a magnetic field (0 < θ <90°)



- If a charged particle moves in a uniform magnetic field with its velocity at some arbitrary angle θ $(0 < \theta < 90°)$ with respect to a magnetic field $\vec{B}$, the path is a helix.
- The axis of the helix is along the direction of B.
- The perpendicular component of velocity (v sin θ) determines the radius (r) of the helix.

  Then, $r = \dfrac{mv\sin\theta}{qB}$

- The pitch of the helix $p = (v\cos\theta)T$, where T is the period of the circular motion and is given by $T = \dfrac{2\pi m}{qB}$

  The Pitch of the helical path (p) is the distance travelled by the particle along the direction of the field in one period of revolution of the circular motion.

  $\therefore \quad p = \dfrac{2\pi m v\cos\theta}{qB}$

Motion of a charge in combined electric and magnetic fields

Lorentz force

A charge q moving with a velocity $\vec{v}$ in the presence of an electric field $\vec{E}$ and a magnetic field $\vec{B}$, experiences a force given by $\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B})]$. This force is called the Lorentz force.

This expression for force was deduced by H.A. Lorentz and is based on experimental observations.

Velocity selector

Consider a positively charged particle q, moving with a velocity $\vec{v}$ subjected to uniform electric field $\vec{E}$ and magnetic field $\vec{B}$ acting at right angles to each other, as shown in the figure.

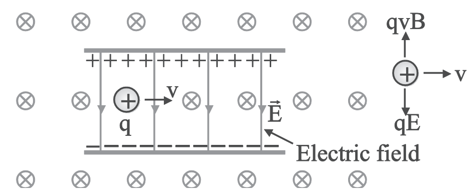
$F_{mag} = qvB$ acting upwards … (1)

$F_{elc} = qE$, … (2)

Let us make $F_{elc} = F_{mag}$

$qE = qvB$

$v = \dfrac{E}{B}$ … (3)



For a given magnitude E and B, v is fixed.

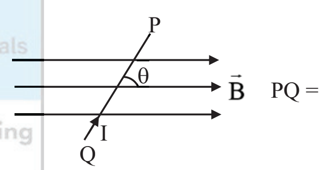
Thus, a particle whose velocity v = E/B alone travels undeflected. Particles whose velocities differ from this value get deflected. Hence, if we inject a stream of particles (each of same charge) with varying velocities into a region of combined fields, we get a fine pencil of particles with a single value of v. In other words this arrangement works as a velocity selector.

Magnetic force on a current carrying wire

The phenomenon in which a current carrying conductor experiences a force in a magnetic field is called the mechanical effect of electric current. This force on the conductor is a manifestation of the force acting on the free electrons in the conductor placed in a magnetic field.

A current carrying conductor placed in a magnetic field experiences a mechanical force. The magnitude of this force given by $F = B I l \sin\theta$

where B is the magnetic field, I is the current, l is the length of the conductor and θ is the angle between the direction of the current and the magnetic field.

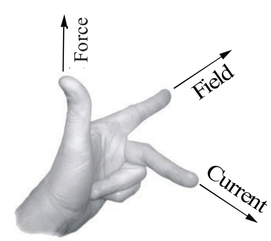


- Vector form : $\vec{F} = I\vec{l} \times \vec{B}$
- The force is maximum when θ = 90°
  i.e., when a current carrying conductor is placed at right angles to the direction of the magnetic field, $F_{max} = B I l$
- The force exerted is zero when θ = 0, or 180° i.e., when a current carrying conductor is placed parallel to the direction of the magnetic field or antiparallel

The direction of the force is given by **Fleming's left hand rule.**

The rule is stated as follows.

Stretch the fore finger, the middle finger and the thumb of the left hand such that they are mutually at right angles. If the fore finger shows the direction of the magnetic field and the middle finger the direction of the current, the thumb shows the direction of the mechanical force on the conductor.



Fleming's left hand rule

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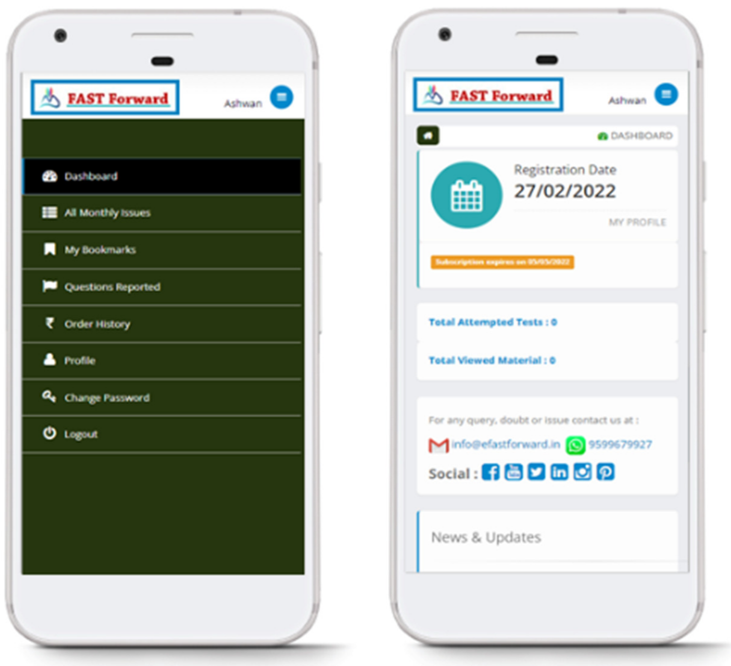

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