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Chapter 4 : Moving Charges and Magnetism (Notes)

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Notes

GSEB and CBSE Board Exam preparation subjective notes · Class 12 Physics · NCERT Chapter 4

Q.1 Describe Oersted's experiment. What conclusion did he draw? (2 Marks)

Oersted's experiment (1820): Hans Christian Oersted noticed that a current in a straight wire caused a noticeable deflection in a nearby magnetic compass needle.

- The needle aligns **tangentially to an imaginary circle** that has the straight wire as its centre and whose plane is perpendicular to the wire (Fig. 4.1(a)).
- Reversing the current** reverses the orientation of the needle (Fig. 4.1(b)).
- The deflection **increases** when the current is increased or the needle is brought closer to the wire.
- Iron filings sprinkled around the wire arrange themselves in **concentric circles** with the wire as centre (Fig. 4.1(c)).

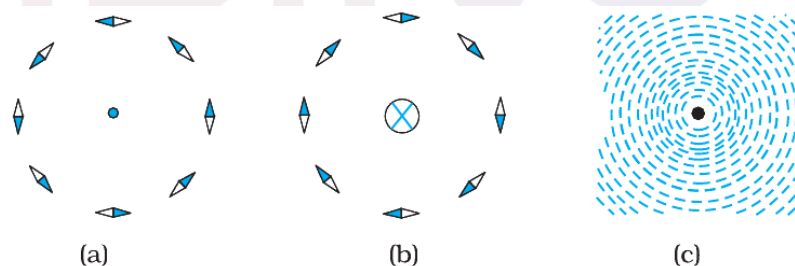


Fig. 4.1: The magnetic field due to a straight long current-carrying wire perpendicular to the plane of the paper. (a) Current coming out of the paper, (b) current going into the paper, (c) arrangement of iron filings around the wire

Conclusion: Moving charges or currents produce a magnetic field in the surrounding space.

Key Examination Points for Full Marks:

- Convention:** a current or field coming **out of** the plane of the paper is shown by a dot ($\odot$); one going **into** the paper is shown by a cross ($\otimes$).
- In 1864, Maxwell unified the laws of electricity and magnetism and realised that light is an electromagnetic wave.

Q.2 What is the Lorentz force? State its features and define the unit of magnetic field. (3 Marks)

Lorentz force: The total force on a point charge q moving with velocity $\vec{v}$ in the presence of an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is

$$\vec{F} = q \left[\vec{E} + \vec{v} \times \vec{B} \right] = \vec{F}_{\text{electric}} + \vec{F}_{\text{magnetic}}$$

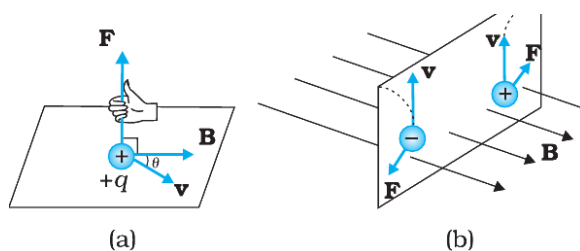


Fig. 4.2: The direction of the magnetic force on a charged particle. (a) The force on a positive charge with velocity $\vec{v}$ at angle θ to $\vec{B}$ is given by the right-hand rule. (b) A moving charge q is deflected in the opposite sense to $-q$

Features of the magnetic force $q(\vec{v} \times \vec{B})$:

- i. It depends on q , $\vec{v}$ and $\vec{B}$. The force on a **negative charge is opposite** to that on a positive charge.
- ii. Its magnitude is $F = qvB \sin \theta$. It is **zero** if $\vec{v}$ is parallel or antiparallel to $\vec{B}$. It acts **perpendicular to both $\vec{v}$ and $\vec{B}$** (screw rule / right-hand rule).
- iii. It is zero if the charge is at rest ($|\vec{v}| = 0$). **Only a moving charge feels the magnetic force.**

Unit of B: From $F = qvB$ (with $\theta = 90^\circ$), the field is **1 tesla** when a charge of 1 C moving at 1 m/s perpendicular to $\vec{B}$ experiences a force of 1 N.

$$1 \text{ T} = 1 \text{ N s C}^{-1} \text{ m}^{-1} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

Key Examination Points for Full Marks:

- Tesla is a large unit. A smaller (non-SI) unit is the **gauss**: $1 \text{ G} = 10^{-4} \text{ T}$. The Earth's magnetic field is about $3.6 \times 10^{-5} \text{ T}$.
- Dimensions of B:** $[M T^{-2} A^{-1}]$.

Q.3 Derive the expression for the force on a current-carrying conductor (2 Marks) in a magnetic field.

Consider a straight rod of uniform cross-section A and length l , with n mobile carriers (charge q) per unit volume moving with drift velocity $\vec{v}_d$. Total number of carriers = nlA .

Force on all carriers in an external field $\vec{B}$:

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

Since $nq\vec{v}_d = \vec{j}$ (current density) and $|nq\vec{v}_d|A = I$:

$$\vec{F} = [(nq\vec{v}_d) lA] \times \vec{B} = [\vec{j}Al] \times \vec{B} \Rightarrow \vec{F} = I \vec{l} \times \vec{B}$$

where $\vec{l}$ is a vector of magnitude l along the direction of the current. Magnitude: $F = IlB \sin \theta$.

Key Examination Points for Full Marks:

- Current is not a vector; the vector sign is transferred from $\vec{j}$ to $\vec{l}$.
- $\vec{B}$ here is the **external** field, not the field of the rod itself.
- For a wire of arbitrary shape: $\vec{F} = \sum_j I d\vec{l}_j \times \vec{B}$.
- Example 4.1:** A wire of mass 200 g and length 1.5 m carrying 2 A is suspended in mid-air by B:

$$mg = IlB \Rightarrow B = \frac{0.2 \times 9.8}{2 \times 1.5} = 0.65 \text{ T}$$

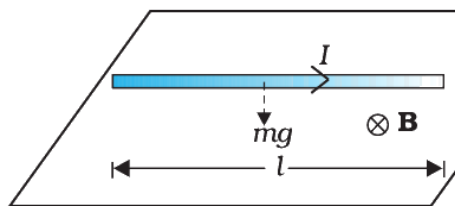


Fig. 4.3: A current-carrying wire suspended in mid-air by a horizontal magnetic field

Q.4 Show that a charged particle moving perpendicular to a uniform magnetic field describes a circle. Derive its radius, frequency and time period. (3 Marks)

The magnetic force $q\vec{v} \times \vec{B}$ is always perpendicular to $\vec{v}$, so it **does no work** and does not change the speed — it only changes the direction of motion. When $\vec{v} \perp \vec{B}$, this force of constant magnitude qvB acts as a **centripetal force**, so the particle moves in a **circle** in a plane perpendicular to $\vec{B}$ (Fig. 4.5).

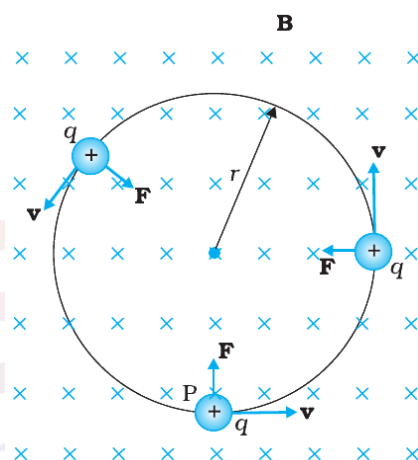


Fig. 4.5: Circular motion of a charged particle in a uniform magnetic field (B into the page)

Radius:

$$\frac{mv^2}{r} = qvB \Rightarrow r = \frac{mv}{qB} = \frac{p}{qB}$$

Angular frequency and frequency: Using $v = \omega r$:

$$\omega = 2\pi\nu = \frac{qB}{m} \Rightarrow \nu = \frac{qB}{2\pi m}$$

Time period:

$$T = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

Key Examination Points for Full Marks:

- The **frequency and time period are independent of speed and energy** of the particle. This fact is used in the **cyclotron**.
- A larger momentum gives a larger radius. In terms of kinetic energy, $r = \frac{\sqrt{2mK}}{qB}$; for a particle accelerated through V , $r = \frac{1}{B} \sqrt{\frac{2mV}{q}}$.
- Example 4.3:** An electron at 3×10^7 m/s in 6×10^{-4} T: $r = 28$ cm, $\nu = 17$ MHz, $E = 2.5$ keV.

Q.5 Explain the helical motion of a charged particle in a magnetic field. (2 Marks)

Define pitch.

If the velocity $\vec{v}$ makes an angle θ with $\vec{B}$, resolve it into:

- $v_{\parallel} = v \cos \theta$ along $\vec{B}$ — **unaffected** by the field, so the particle moves uniformly along $\vec{B}$.
- $v_{\perp} = v \sin \theta$ perpendicular to $\vec{B}$ — gives **circular motion** of radius $r = \frac{mv_{\perp}}{qB}$.

The combination of the two is a **helix** (Fig. 4.6).

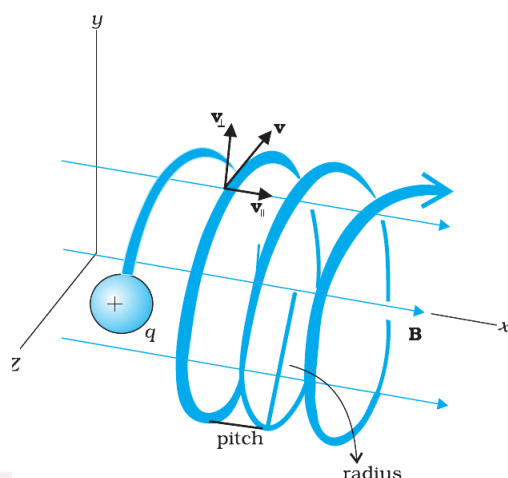


Fig. 4.6: Helical motion of a charged particle in a uniform magnetic field

Pitch: The distance moved along the magnetic field in one rotation:

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

The radius of the circular component of motion is called the **radius of the helix**.

Key Examination Points for Full Marks:

- $\theta = 0^\circ$ or 180° : straight line; $\theta = 90^\circ$: circle; any other angle: helix.
- The time period $T = \frac{2\pi m}{qB}$ is the same as for the circular motion.

Q.6 State the Biot–Savart law. Compare it with Coulomb’s law. (3 Marks)

Biot–Savart law: The magnetic field $d\vec{B}$ due to a current element $I d\vec{l}$ at a point at position vector $\vec{r}$ from it is

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \vec{r}}{r^3} \quad \Rightarrow \quad |d\vec{B}| = \frac{\mu_0}{4\pi} \frac{I dl \sin \theta}{r^2}$$

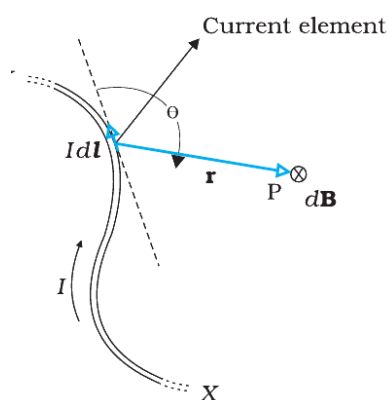


Fig. 4.7: Illustration of the Biot–Savart law. The current element $I dl$ produces a field $d\vec{B}$ at a distance r ; the $\otimes$ sign shows $d\vec{B}$ is into the page

- dB is proportional to the current I and to the element length $|d\vec{l}|$, and inversely proportional to r^2 .
- Its direction is **perpendicular to the plane containing $d\vec{l}$ and $\vec{r}$** (right-hand screw rule).
- $\frac{\mu_0}{4\pi} = 10^{-7} \text{ T m/A}$, where $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$ is the **permeability of free space**.

Similarities with Coulomb's law:

- i. Both are **long range** and follow an **inverse square** dependence on distance.
- ii. Both obey the principle of **superposition**; the field is **linear** in its source.

Differences:

Electrostatic field (Coulomb)	Magnetic field (Biot-Savart)
Produced by a scalar source, the charge q	Produced by a vector source, $I d\vec{l}$
Directed along the displacement vector $\vec{r}$	Perpendicular to the plane of $\vec{r}$ and $I d\vec{l}$
No angle dependence	Depends on $\sin \theta$; zero along the direction of $d\vec{l}$

Key Examination Points for Full Marks:

- $\epsilon_0 \mu_0 = \frac{1}{c^2}$, i.e. $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$.
- **Example 4.4:** $\Delta l = 1 \text{ cm}$, $I = 10 \text{ A}$, at 0.5 m on the y -axis: $dB = \frac{10^{-7} \times 10 \times 10^{-2}}{0.25} = 4 \times 10^{-8} \text{ T}$ along $+z$.

Q.7 Derive the magnetic field on the axis of a circular current loop. (3 Marks)

Consider a loop of radius R carrying current I in the y - z plane, centred at the origin O . P is a point on the axis at distance x from O (Fig. 4.9).

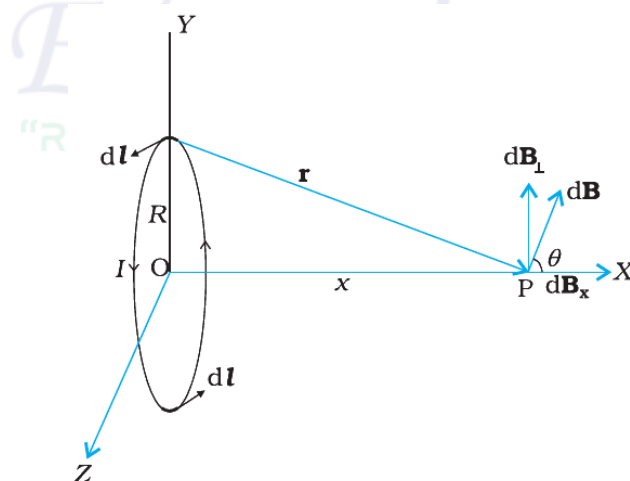


Fig. 4.9: Magnetic field on the axis of a circular current loop of radius R , showing the field dB due to a line element dl and its components

Every element $d\vec{l}$ is perpendicular to the displacement vector $\vec{r}$ to P , so $|d\vec{l} \times \vec{r}| = r dl$ with $r^2 = x^2 + R^2$:

$$dB = \frac{\mu_0}{4\pi} \frac{I dl}{(x^2 + R^2)}$$

$\vec{dB}$ has a component dB_x along the axis and a component $dB_{\perp}$ perpendicular to it. The perpendicular components of **diametrically opposite elements cancel**, so only the x -components add:

$$dB_x = dB \cos \theta, \quad \cos \theta = \frac{R}{(x^2 + R^2)^{1/2}}$$

$$dB_x = \frac{\mu_0 I dl}{4\pi} \frac{R}{(x^2 + R^2)^{3/2}}$$

Summing over the loop, $\oint dl = 2\pi R$:

$$\vec{B} = \frac{\mu_0 IR^2}{2(x^2 + R^2)^{3/2}} \hat{i}$$

At the centre ($x = 0$): $B_0 = \frac{\mu_0 I}{2R}$; for N turns, $B_0 = \frac{\mu_0 NI}{2R}$.

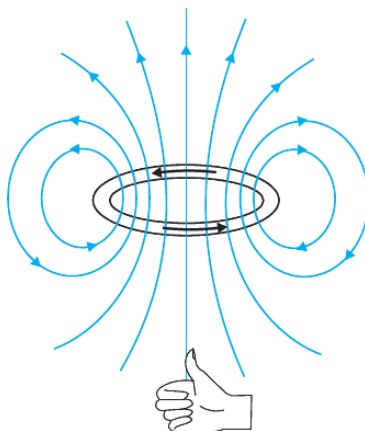


Fig. 4.10: Magnetic field lines of a current loop. The direction is given by the right-hand thumb rule

Right-hand thumb rule: Curl the palm of the right hand around the circular wire with the fingers pointing in the direction of the current; the thumb gives the direction of the field.

Key Examination Points for Full Marks:

- For $x \gg R$: $B \approx \frac{\mu_0 IR^2}{2x^3}$, i.e. $B \propto \frac{1}{x^3}$.
- A circular **arc** subtending angle θ at its centre gives $B = \frac{\mu_0 I \theta}{4\pi R}$; a **semicircle** gives $\frac{\mu_0 I}{4R}$ (Example 4.5: 12 A, $R = 2 \text{ cm} \rightarrow 1.9 \times 10^{-4} \text{ T}$).

Q.8 State Ampere's circuital law. Use it to find the field of a long straight wire.

Ampere's circuital law: The line integral of the magnetic field around any closed loop equals μ_0 times the total current passing through the surface bounded by the loop:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$$

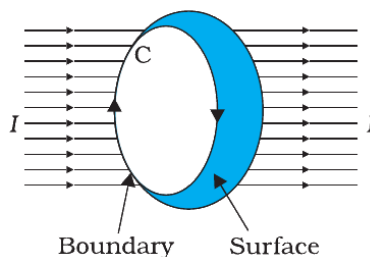


Fig. 4.12: A closed boundary C of a surface through which current I passes

Sign convention: Curl the fingers of the right hand in the sense the boundary is traversed; the thumb gives the direction in which current is taken as positive.

Simplified form: If an **Amperian loop** is chosen so that $\vec{B}$ is tangential and constant in magnitude along a length L of the loop (and zero or normal elsewhere), then $BL = \mu_0 I_e$, where I_e is the enclosed current.

Field of a long straight wire: Take a circle of radius r centred on the wire. B is tangential and constant on it:

$$B (2\pi r) = \mu_0 I \Rightarrow B = \frac{\mu_0 I}{2\pi r}$$

Key Examination Points for Full Marks:

- The field has **cylindrical symmetry**; field lines are **concentric circles** — closed loops, unlike electrostatic field lines.
- Right-hand rule:** grasp the wire with the thumb along the current; the fingers curl in the direction of the field.
- Ampere's law is to the Biot-Savart law what Gauss's law is to Coulomb's law. It holds for **steady currents**.
- Ampere's law cannot easily give $B = \mu_0 I/2R$ at the centre of a loop — it is useful only when there is high symmetry.

Q.9 Find the magnetic field inside and outside a long straight wire of radius a carrying a uniformly distributed current. (3 Marks)

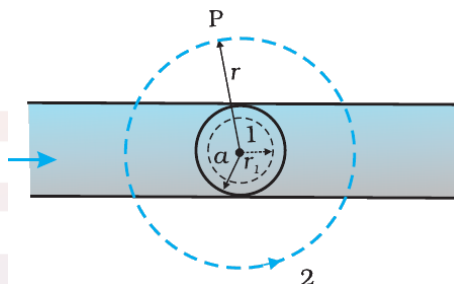


Fig. 4.13: A long straight wire of circular cross-section (radius a) with steady current I ; Amperian loops 1 ($r < a$) and 2 ($r > a$)

(a) **Outside ($r > a$):** Amperian loop 2 encloses the whole current I .

$$B (2\pi r) = \mu_0 I \Rightarrow B = \frac{\mu_0 I}{2\pi r}, \quad B \propto \frac{1}{r}$$

(b) **Inside ($r < a$):** Loop 1 encloses only a fraction of the current:

$$I_e = I \frac{\pi r^2}{\pi a^2} = \frac{I r^2}{a^2}$$

$$B (2\pi r) = \mu_0 \frac{I r^2}{a^2} \Rightarrow B = \left(\frac{\mu_0 I}{2\pi a^2} \right) r, \quad B \propto r$$

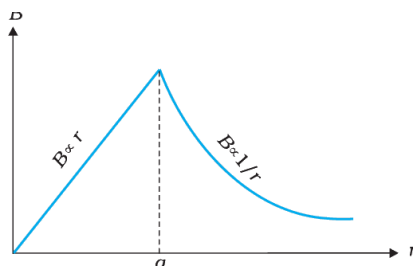


Fig. 4.14: Variation of B with distance r from the centre of the wire

Key Examination Points for Full Marks:

- B is **zero at the axis**, increases linearly to a **maximum at the surface** ($\mu_0 I/2\pi a$) and then decreases as $1/r$.
- For a **hollow pipe** carrying current, $B = 0$ everywhere inside.

Q.10 Using Ampere's law, derive the magnetic field inside a long solenoid. (3 Marks)

A **solenoid** is a long wire wound in the form of a closely spaced helix; each turn is roughly a circular loop. Its length is large compared with its radius.

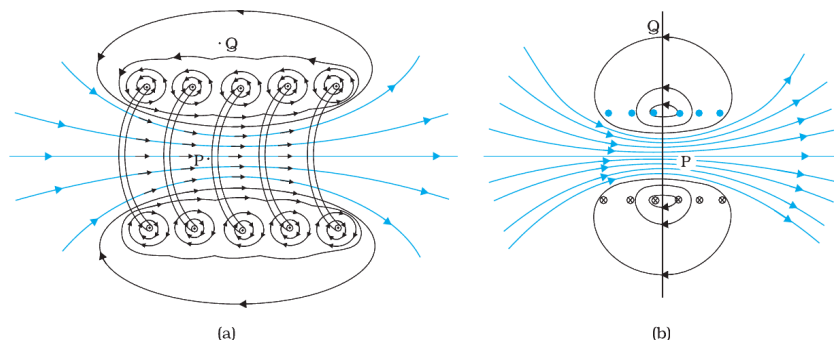


Fig. 4.15: (a) Field of a section of a solenoid stretched out for clarity: the fields between neighbouring turns cancel. (b) Field of a finite solenoid

For a very long solenoid, the field inside is **uniform and parallel to the axis**, and the field outside is nearly **zero**.

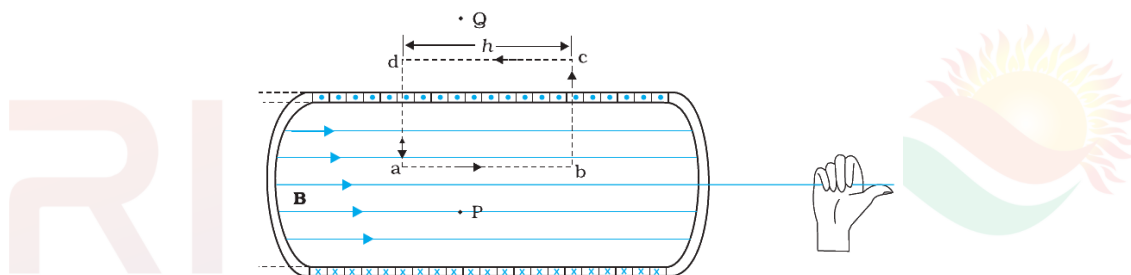


Fig. 4.16: The magnetic field of a very long solenoid, with a rectangular Amperian loop abcd

Take a rectangular Amperian loop abcd (Fig. 4.16), with side ab = h inside:

- Along cd (outside), $B = 0$.
- Along bc and ad, $\vec{B}$ is perpendicular to the path, so they contribute nothing.
- Along ab, B is uniform and tangential: $L = h$.

If n is the number of turns per unit length, the loop encloses nh turns, so $I_e = I (nh)$.

$$BL = \mu_0 I_e \Rightarrow Bh = \mu_0 I (nh) \Rightarrow B = \mu_0 nI$$

Key Examination Points for Full Marks:

- The field is independent of the solenoid's radius and of position inside (uniform).
- At the **ends** of a long solenoid, $B = \frac{\mu_0 nI}{2}$.
- With a soft-iron core of relative permeability μ_r : $B = \mu_0 \mu_r nI$.
- **Example 4.8:** 500 turns over 0.5 m, $I = 5$ A: $n = 1000 \text{ m}^{-1}$, $B = 4\pi \times 10^{-7} \times 10^3 \times 5 = 6.28 \times 10^{-3} \text{ T}$.

Q.11 Derive the force between two parallel current-carrying conductors. (3 Marks)

Define one ampere.

Two long parallel conductors a and b, separated by d, carry currents I_a and I_b (Fig. 4.17). Conductor a produces a field at every point of b:

$$B_a = \frac{\mu_0 I_a}{2\pi d}$$

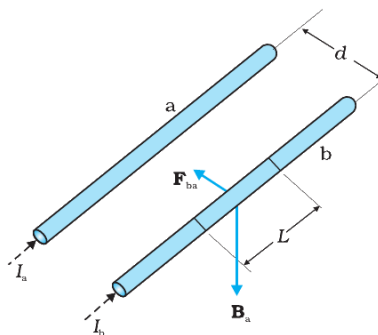


Fig. 4.17: Two long parallel conductors carrying steady currents I_a and I_b , separated by a distance d . B_a is the field set up by a at b

Force on a length L of b due to a (from $F = ILB$):

$$F_{ba} = I_b L B_a = \frac{\mu_0 I_a I_b}{2\pi d} L$$

Force per unit length:

$$f_{ba} = \frac{\mu_0 I_a I_b}{2\pi d}$$

$\vec{F}_{ba} = -\vec{F}_{ab}$, consistent with Newton's third law.

Parallel currents attract, and antiparallel currents repel — the opposite of electrostatics, where like charges repel.

Definition of ampere: One ampere is the steady current which, when maintained in each of two very long, straight, parallel conductors of negligible cross-section placed **1 m apart in vacuum**, produces on each a force of 2×10^{-7} N per metre of length.

Key Examination Points for Full Marks:

- 1 coulomb is the charge that flows through a cross-section in 1 s when a steady current of 1 A flows.
- **Example 4.9:** For 1 A in the Earth's field 3×10^{-5} T, $f = 3 \times 10^{-5}$ N/m (east to west), which exceeds 2×10^{-7} N/m — so stray fields must be eliminated when standardising the ampere. For current along the field (south to north), $f = 0$.

Q.12 Derive the torque on a rectangular current loop in a uniform magnetic field. Define magnetic moment. (3 Marks)

Case 1 — field in the plane of the loop (Fig. 4.18): A rectangular loop ABCD (sides a and b) carries current I .

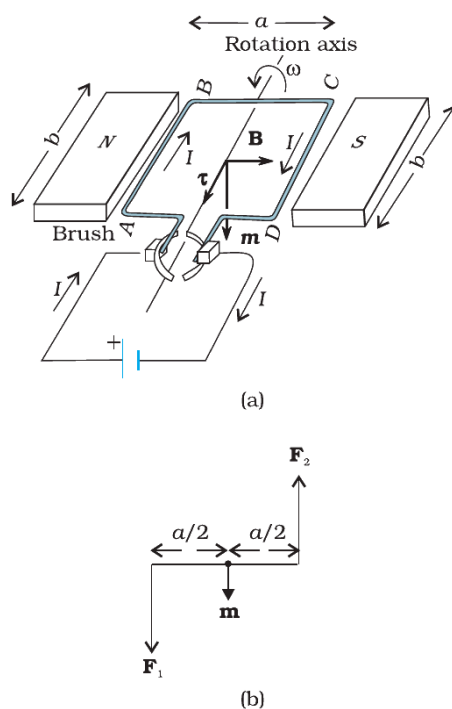


Fig. 4.18: (a) A rectangular current-carrying coil in a uniform magnetic field. (b) The couple acting on the coil, seen from the AD end

- Arms AD and BC are parallel to $\vec{B}$: no force.
- Arm AB experiences $F_1 = IbB$ into the plane; arm CD experiences $F_2 = IbB$ out of the plane.
- Net force is zero**, but the two forces form a couple:

$$\tau = F_1 \frac{a}{2} + F_2 \frac{a}{2} = IbB a = IAB, \quad A = ab$$

Case 2 — normal to the loop at angle θ to $\vec{B}$ (Fig. 4.19): Forces on BC and DA are equal, opposite and collinear (cancel). Forces on AB and CD are still IbB but the perpendicular distance between them is $a \sin \theta$:

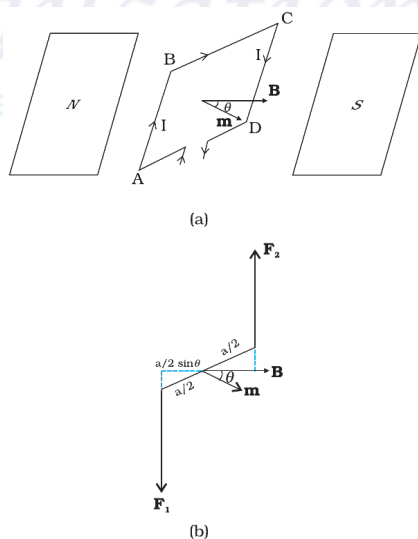


Fig. 4.19: (a) The area vector of loop ABCD at an arbitrary angle θ with $\vec{B}$. (b) Top view showing the forces F_1 and F_2 on arms AB and CD

$$\tau = F_1 \frac{a}{2} \sin \theta + F_2 \frac{a}{2} \sin \theta = IAB \sin \theta$$

Magnetic moment: $\vec{m} = I\vec{A}$, with $\vec{A}$ given by the right-hand thumb rule. For N turns, $\vec{m} = N I \vec{A}$. Then

$$\vec{\tau} = \vec{m} \times \vec{B}$$

Key Examination Points for Full Marks:

- Unit of m : $A \, m^2$ ($= J/T$); dimensions $[L^2 A]$.

- Analogous to an electric dipole: $\vec{\tau} = \vec{p}_e \times \vec{E}$.
- $\vec{m} \parallel \vec{B}$: **stable** equilibrium; $\vec{m}$ antiparallel to $\vec{B}$: **unstable** equilibrium. Torque is maximum (mB) when $\vec{m} \perp \vec{B}$.
- **Net force on a closed loop in a uniform field is always zero.**

Q.13 Show that a circular current loop behaves as a magnetic dipole. (2 Marks)

The field on the axis of a loop is $B = \frac{\mu_0 IR^2}{2(x^2 + R^2)^{3/2}}$. For $x \gg R$:

$$B = \frac{\mu_0 IR^2}{2x^3} = \frac{\mu_0 IA}{2\pi x^3} \quad (A = \pi R^2)$$

With $m = IA$:

$$\vec{B} = \frac{\mu_0 2\vec{m}}{4\pi x^3} \quad (\text{on the axis}), \quad \vec{B} = -\frac{\mu_0 \vec{m}}{4\pi x^3} \quad (\text{in the plane of the loop})$$

These have the same form as the electric dipole fields $\vec{E} = \frac{2\vec{p}_e}{4\pi\epsilon_0 x^3}$ and $\frac{-\vec{p}_e}{4\pi\epsilon_0 x^3}$, with the substitutions $\mu_0 \rightarrow 1/\epsilon_0$, $\vec{m} \rightarrow \vec{p}_e$, $\vec{B} \rightarrow \vec{E}$.

Key Examination Points for Full Marks:

- Any planar current loop is equivalent to a magnetic dipole of moment $\vec{m} = I\vec{A}$.
- **Fundamental difference:** an electric dipole is made of two monopoles (charges); **magnetic monopoles are not known to exist.** The current loop is the most elementary magnetic element.
- Electrons and protons also carry an **intrinsic** magnetic moment.

Q.14 Describe the principle, construction and working of a moving coil galvanometer. Define current sensitivity. (3 Marks)

Principle: A current-carrying coil placed in a magnetic field experiences a torque.

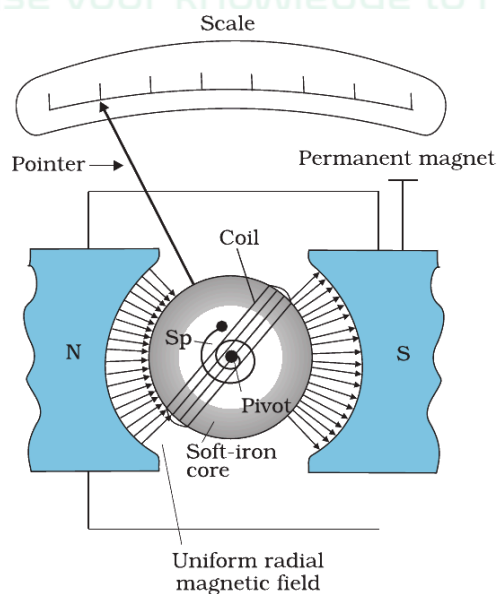


Fig. 4.20: The moving coil galvanometer

Construction:

- A coil of many turns, free to rotate about a fixed axis, in a **uniform radial magnetic field** produced by concave pole pieces of a permanent magnet.
- A cylindrical **soft-iron core** makes the field radial and also increases its strength.
- A spring S_p provides a restoring torque; a pointer attached to the coil moves over a scale.

Working: With a radial field, the plane of the coil is always parallel to $\vec{B}$ ($\sin \theta = 1$), so the magnetic torque is $\tau = NIAB$. The spring gives a restoring torque $k\phi$ (k = torsional constant). In equilibrium:

$$k\phi = NIAB \Rightarrow \phi = \left(\frac{NAB}{k} \right) I$$

So the deflection is proportional to the current and the scale is linear.

Current sensitivity: The deflection per unit current:

$$\frac{\phi}{I} = \frac{NAB}{k}$$

Voltage sensitivity: The deflection per unit voltage:

$$\frac{\phi}{V} = \left(\frac{NAB}{k} \right) \frac{1}{R}$$

Key Examination Points for Full Marks:

- Sensitivity can be increased by increasing N , A or B , or decreasing k .
- A galvanometer used as a **null detector** (e.g. in a Wheatstone bridge) has its zero at the centre of the scale.

Q.15 How is a galvanometer converted into (a) an ammeter (b) a voltmeter? (3 Marks)

A galvanometer cannot directly measure current because (i) it is very sensitive — full-scale deflection for a current of the order of μA , and (ii) its large resistance changes the circuit current.

(a) Ammeter: Connect a **small resistance r_s (shunt) in parallel** with the galvanometer (Fig. 4.21). Most of the current passes through the shunt.

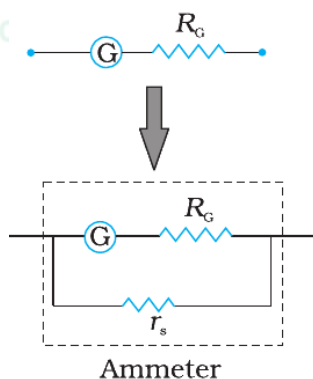


Fig. 4.21: Conversion of a galvanometer (G) to an ammeter by a shunt resistance r_s of very small value in parallel

$$R_{\text{ammeter}} = \frac{R_G r_s}{R_G + r_s} \approx r_s \quad (R_G \gg r_s)$$

Required shunt for range I : $I_g G = (I - I_g) S \Rightarrow S = \frac{I_g G}{I - I_g}$

(b) Voltmeter: Connect a **large resistance R in series** with the galvanometer (Fig. 4.22). It is connected in parallel with the section of the circuit, and draws very little current.

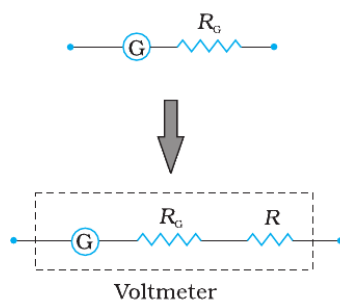


Fig. 4.22: Conversion of a galvanometer (G) to a voltmeter by a resistance R of large value in series

$$R_{\text{voltmeter}} = R_G + R \approx R \text{ (large)}; \quad R = \frac{V}{I_g} - G$$

Key Examination Points for Full Marks:

- An ideal ammeter has **zero** resistance; an ideal voltmeter has **infinite** resistance.
- Example 4.12:** With a $3\ \Omega$ resistor and $3\ \text{V}$ battery: galvanometer ($60\ \Omega$) reads $0.048\ \text{A}$; converted ammeter (shunt $0.02\ \Omega$) reads $0.99\ \text{A}$; ideal ammeter $1.00\ \text{A}$.

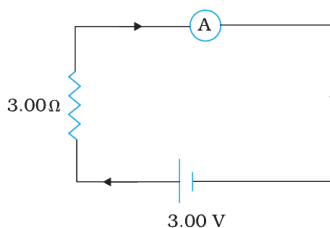


Fig. 4.23: Circuit for Example 4.12

Q.16 Why does increasing the current sensitivity not necessarily increase the voltage sensitivity? (2 Marks)

Current sensitivity: $\frac{\phi}{I} = \frac{NAB}{k}$. Voltage sensitivity: $\frac{\phi}{V} = \frac{NAB}{k} \cdot \frac{1}{R}$.

If the number of turns is doubled ($N \rightarrow 2N$):

- Current sensitivity **doubles**: $\frac{\phi}{I} \rightarrow 2\frac{\phi}{I}$.
- But the wire length — and so the resistance — also doubles ($R \rightarrow 2R$). Hence

$$\frac{\phi}{V} \rightarrow \frac{2NAB}{k} \cdot \frac{1}{2R} = \frac{\phi}{V} \text{ (unchanged)}$$

Key Examination Points for Full Marks:

- The modification needed for an ammeter (small shunt in parallel) is different from that for a voltmeter (large resistance in series).
- Current sensitivity unit: rad A^{-1} (or div A^{-1}); voltage sensitivity: rad V^{-1} (or div V^{-1}).

Formula Sheet — Moving Charges and Magnetism

Quantity	Formula	SI Unit
Lorentz force	$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$	N
Magnetic force on a charge	$F = qvB \sin \theta$	N
Force on a conductor	$\vec{F} = I\vec{l} \times \vec{B}$; $F = IlB \sin \theta$	N
Radius of circular path	$r = \frac{mv}{qB} = \frac{\sqrt{2mK}}{qB}$	m
Cyclotron frequency	$\nu = \frac{qB}{2\pi m}$; $T = \frac{2\pi m}{qB}$	Hz, s
Pitch of helix	$p = \frac{2\pi m v \cos \theta}{qB}$	m
Biot-Savart law	$dB = \frac{\mu_0 I dl \sin \theta}{4\pi r^2}$	T
Field on axis of loop	$B = \frac{\mu_0 N I R^2}{2(x^2 + R^2)^{3/2}}$	T
Field at centre of loop	$B = \frac{\mu_0 N I}{2R}$; arc: $\frac{\mu_0 I \theta}{4\pi R}$	T
Ampere's circuital law	$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$	T m
Long straight wire	$B = \frac{\mu_0 I}{2\pi r}$	T
Finite straight wire	$B = \frac{\mu_0 I}{4\pi d} (\sin \phi_1 + \sin \phi_2)$	T
Inside a thick wire	$B = \frac{\mu_0 I r}{2\pi a^2}$	T
Long solenoid	$B = \mu_0 n I$; at the end $\frac{\mu_0 n I}{2}$	T
Force between parallel wires	$f = \frac{\mu_0 I_1 I_2}{2\pi d}$	N m ⁻¹
Magnetic moment	$\vec{m} = N I \vec{A}$	A m ²
Torque on a loop	$\vec{\tau} = \vec{m} \times \vec{B}$; $\tau = N I A B \sin \theta$	N m
Dipole field (axis)	$B = \frac{\mu_0 2m}{4\pi x^3}$	T
Galvanometer	$k\phi = N I A B$; $\frac{\phi}{I} = \frac{N A B}{k}$	—
Shunt (ammeter)	$S = \frac{I_g G}{I - I_g}$	Ω
Series resistance (voltmeter)	$R = \frac{V}{I_g} - G$	Ω

Constants: $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$; $\frac{\mu_0}{4\pi} = 10^{-7} \text{ T m A}^{-1}$; $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$; $1 \text{ G} = 10^{-4} \text{ T}$.

Dimensions: B [M T⁻² A⁻¹]; μ_0 [M L T⁻² A⁻²]; magnetic moment [L² A]; torsion constant [M L² T⁻²].

NEET / JEE Quick Points and Tricks

- Magnetic force does no work:** speed and kinetic energy are constant; only the direction of velocity (and so momentum) changes.

2. **Same momentum** → same radius for equal charges. **Same KE** → $r \propto \sqrt{m/q}$. **Same accelerating voltage** → $r \propto \sqrt{m/q}$.
3. For p, d, α with the **same KE**: $r_p : r_d : r_\alpha = 1 : \sqrt{2} : 1$. With the **same V**: $1 : \sqrt{2} : \sqrt{2}$.
4. **Undelected (velocity selector)**: crossed $\vec{E}$ and $\vec{B}$ with $v = E/B$, independent of charge and mass.
5. **E || B and particle released from rest** → straight line with increasing speed. v at an angle to B → helix.
6. **Rewinding a wire** of fixed length from N_1 to N_2 turns: $B_{\text{centre}} \propto N^2$ (since $R \propto 1/N$).
7. **Arcs**: each straight segment pointing towards the centre gives zero field. A **semi-infinite** wire ending at the foot of the perpendicular gives $\frac{\mu_0 I}{4\pi d}$.
8. **Polygon of n sides** (side's distance d from centre): $B = n \frac{\mu_0 I}{4\pi d} \cdot 2 \sin \frac{\pi}{n}$. Equilateral triangle of side l: $B = \frac{9\mu_0 I}{2\pi l}$; square of side l: $B = \frac{2\sqrt{2} \mu_0 I}{\pi l}$.
9. **Axial point**: $\frac{B_{\text{axis}}}{B_{\text{centre}}} = \left(1 + \frac{x^2}{R^2}\right)^{-3/2}$. At $x = R$: $B_c/2\sqrt{2}$.
10. **Parallel currents attract, antiparallel repel**. For two wires with opposite currents, fields **add** at the midpoint; with the same currents, they cancel there.
11. **Net force on any closed loop in a uniform B is zero**, but torque may not be. Torque is zero when the plane of the loop is perpendicular to B.
12. **Magnetic moment and angular momentum**: for an orbiting electron, $\vec{\mu} = -\frac{e}{2m} \vec{L}$ (gyromagnetic ratio $e/2m$).
13. **Bending a magnet/wire**: into a semicircle, $m' = \frac{2m}{\pi}$; into an arc of angle θ , $m' = m \frac{2 \sin (\theta/2)}{\theta}$.
14. **Galvanometer conversions**: ammeter — small shunt **in parallel**; voltmeter — large resistance **in series**.
 $G = \frac{\text{current sensitivity}}{\text{voltage sensitivity}}$.

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