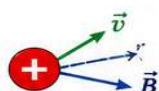


CHAPTER 04



MOVING CHARGES AND MAGNETISM

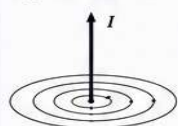
CBSE CLASS 12 PHYSICS – QUICK REVISION SHEET



1. KEY LAWS & PRINCIPLES

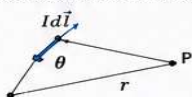
OERSTED'S OBSERVATION

A current-carrying conductor produces a magnetic field around it.



BIOT-SAVART LAW

Magnetic field $d\vec{B}$ at a point due to current element $I d\vec{l}$.



$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2}$$

$\hat{r}$: unit vector from element to point

AMPERE'S CIRCUITAL LAW

Line integral of $\vec{B}$ around any closed path is μ_0 times the current enclosed.

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{encl}}$$

LORENTZ FORCE

Force on a charge q moving with velocity $\vec{v}$ in magnetic field $\vec{B}$.

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

$$F = |q| v B \sin \theta$$

(θ = angle between $\vec{v}$ and $\vec{B}$)

TORQUE ON CURRENT LOOP

A current loop in magnetic field experiences a torque.

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

$$|\tau| = \mu B \sin \theta$$

$$\vec{\mu} = NIA \hat{n}$$

($\hat{n}$: normal to the plane)

2. DIRECTION RULES TOOLKIT

RIGHT HAND THUMB RULE

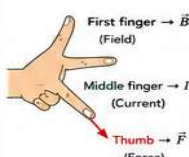
(Magnetic field around a current)



- Thumb $\rightarrow$ Current
- Curled fingers $\rightarrow \vec{B}$

FLEMING'S LEFT HAND RULE

(Force on conductor)



First finger $\rightarrow \vec{B}$
(Field)

Middle finger $\rightarrow I$
(Current)

Thumb $\rightarrow \vec{F}$
(Force)

FORCE DIRECTION FOR CHARGES

Positive charge (+q)



Use $\vec{F} = q(\vec{v} \times \vec{B})$.
For $-q$, force is opposite.

3. MOTION OF CHARGED PARTICLE IN UNIFORM MAGNETIC FIELD

Case	Condition	Path	Key Formulae	Diagram
1.	$\vec{v} \parallel \vec{B}$	Straight line (No deflection)	$F = 0$	
2.	$\vec{v} \perp \vec{B}$	Circular path	$F = qvB$ (centripetal) $r = \frac{mv}{ q B}$ $T = \frac{2\pi m}{ q B}$	
3.	$\vec{v}$ at angle θ to $\vec{B}$	Helical path	$v_{\perp} = v \sin \theta$ $v_{\parallel} = v \cos \theta$ $r = \frac{mv_{\perp}}{ q B}$ Pitch $p = v_{\parallel} T$	

4. APPLICATION BOX – GALVANOMETER & CONVERSIONS

MOVING COIL GALVANOMETER (MCG)



Torque: $\tau = NBAI$

Restoring torque: $\tau_r = k\theta$

At equilibrium: $NBAI = k\theta$

$$\Rightarrow I = \frac{k}{NBA} \theta$$

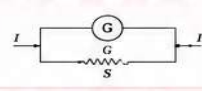
$$\text{Current sensitivity, } S_I = \frac{\theta}{I} = \frac{NBA}{k}$$

$$\text{Voltage sensitivity, } S_V = \frac{\theta}{V} = \frac{NBA}{kG}$$

$$(\text{Figure of merit } K = \frac{\theta}{I} = \frac{k}{NBA})$$

Purpose: Detects small currents / measures current.

CONVERSION TO AMMETER



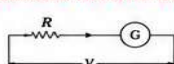
At full scale deflection (I_g):

$$I_g G = (I - I_g) S$$

$$\Rightarrow S = \frac{I_g G}{I - I_g}$$

Purpose: Measure current in a circuit.

CONVERSION TO VOLTMETER



At full scale deflection (V):

$$V = I_g(R + G)$$

$$\Rightarrow R = \frac{V}{I_g} - G$$

Purpose: Measure potential difference.

5. MOST COMMON STUDENT MISTAKES (TOP 6)

1. Magnetic force changes the speed of a charged particle. (False: It only changes direction) ✗
2. Currents in the same direction in parallel wires repel. (False: They attract) ✗
3. Magnetic field is maximum at the centre of a current loop. (False: It is maximum on the axis at the centre, but not at edges) ✗
4. An ammeter is connected in parallel in a circuit. (False: Ammeter is in series) ✗
5. Magnetic field lines intersect each other. (False: they never intersect) ✗
6. Increasing the number of turns always increases voltage sensitivity. (Depends also on resistance) ✗

6. QUICK COMPARISON TABLES

ELECTRIC FORCE vs MAGNETIC FORCE			AMMETER vs VOLTMETER vs GALVANOMETER			
Aspect	Electric Force	Magnetic Force	Feature	Ammeter	Voltmeter	Galvanometer
Acts on	Charge (q)	Moving charge (q) or current (I)	Quantity measured	Current (I)	Potential Difference (V)	Small Current (I)
Expression	$\vec{F}_E = q\vec{E}$	$\vec{F}_B = q(\vec{v} \times \vec{B})$ or $\vec{F} = I(\vec{l} \times \vec{B})$	Connection	Series	Parallel	Usually in measuring circuit
Magnitude	$F_E = q E$	$F_B = q vB\sin\theta$ or $F = I l B \sin\theta$	Resistance	Very low (~ 0)	Very high ($\sim \infty$)	Moderate
Direction	Along $\vec{E}$ for +q (opposite for -)	Perpendicular to both $\vec{v}$ and $\vec{B}$ for $\vec{l}$ and $\vec{B}$)	Purpose	Measure current	Measure voltage	Detect very small current
Work Done	Can do work	Does no work (on charge)	Conversion	—	From galvanometer (with series resistor)	Basic instrument
Effect on speed	Can change speed	Does not change speed (only direction)				

7. EXAM BOOSTER

MOST IMPORTANT DERIVATIONS

- Magnetic field due to a long straight current carrying wire ($B = \frac{\mu_0 I}{2\pi r}$)
- Magnetic field at centre of circular loop ($B = \frac{\mu_0 I}{2R}$)
- Magnetic field inside long solenoid ($B = \mu_0 nI$)
- Force between two parallel current carrying conductors ($\frac{F}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}$)
- Torque on a rectangular current loop ($\tau = NBA \sin \theta$)
- Deflection in moving coil galvanometer ($\theta = \frac{NBA}{k} I$)

FREQUENTLY ASKED CONCEPTS

- Direction of magnetic field around a current carrying conductor
- When is magnetic force zero?
- Why does a charged particle move in a circle in a magnetic field?
- Relation between magnetic field and force on moving charge / current element
- Conversion of galvanometer to ammeter and voltmeter
- Why magnetic force does no work?
- Torque and stable/unstable equilibrium of current loop

HIGH-WEIGHTAGE FORMULAE (MUST MEMORISE)

- $\vec{F} = q(\vec{v} \times \vec{B})$
- $F = |q| v B \sin \theta$
- $B = \frac{\mu_0 I}{2\pi r}$ (straight wire)
- $B = \frac{\mu_0 I}{2R}$ (circular loop)
- $B = \mu_0 nI$ (solenoid)
- $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{encl}}$
- $\frac{F}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}$
- $\vec{\tau} = \vec{\mu} \times \vec{B}$
- $\tau = NBA \sin \theta$
- $S_I = \frac{NBA}{k}$
- $S_V = \frac{NBA}{kG}$

Multiple Choice Questions

1. A metallic rod of mass per unit length 0.5 kg/m is placed horizontally on a smooth plane inclined at 30° to the horizontal. A uniform magnetic field $B = 0.25 \text{ T}$ acts vertically upwards. To prevent the rod from sliding down the incline, the current I required to flow through the rod is:
(a) 7.14 A (b) 11.32 A (c) 14.76 A (d) 5.98 A
2. A particle of charge -2 mC moves with a velocity vector $\mathbf{v} = (2\hat{i} + 3\hat{j}) \times 10^6 \text{ m/s}$ through a region with a uniform magnetic field $B = 2\hat{j} \text{ T}$. The Lorentz force $\mathbf{F}$ acting on the particle is:
(a) $8 \times 10^3 \text{ N}$ along $+\hat{k}$ (b) $4 \times 10^3 \text{ N}$ along $-\hat{k}$
(c) $8 \times 10^3 \text{ N}$ along $-\hat{k}$ (d) $12 \times 10^3 \text{ N}$ along $+\hat{k}$
3. Two long parallel wires are separated by a distance of 10 cm , carrying currents $I_1 = 5 \text{ A}$ and $I_2 = 10 \text{ A}$ in opposite directions. An electron is projected exactly midway between the wires with a velocity of 10^7 m/s parallel to the wires. The magnitude of the net magnetic force on the electron is:
(a) $9.6 \times 10^{-17} \text{ N}$ (b) $1.92 \times 10^{-16} \text{ N}$ (c) $3.2 \times 10^{-16} \text{ N}$ (d) Zero
4. A very long straight wire carries a current I along the positive Y -axis. At a certain instant, a charge $+Q$ at position $(x, 0, 0)$ moves with velocity $\mathbf{v} = v\hat{i}$. The direction of the magnetic force on the charge is:
(a) Along $-Z$ (b) Along $-Y$ (c) Along $+Z$ (d) Along $+Y$
5. A deuteron ($2u, +e$) and a proton ($1u, +e$) enter a magnetic field with the same kinetic energy. If the deuteron describes a circle of radius 0.5 m , the radius of the proton's path is:
(a) $0.5 / \sqrt{2} \text{ m}$ (b) $0.5\sqrt{2} \text{ m}$ (c) 0.25 m (d) 1.0 m
6. Two identical circular coils of radius R and N turns are placed concentrically such that their planes are at right angles. If currents I and $\sqrt{3}I$ flow through them respectively, the resultant magnetic field at the center is:
(a) $\mu_0 NI / 2R$ (b) $2\mu_0 NI / R$ (c) $\mu_0 NI / R$ (d) $\sqrt{2}\mu_0 NI / R$
7. A non-conducting ring of radius R has a total charge Q distributed uniformly. It rotates with an angular velocity ω about its axis. A uniform magnetic field B is applied perpendicular to the axis. The torque on the ring is:
(a) $(1/2)Q\omega R^2 B$ (b) $Q\omega R^2 B$ (c) $(1/4)Q\omega R^2 B$ (d) Zero
8. Three parallel long wires are placed such that they form an equilateral triangle of side d in the cross-sectional plane. Each carries current I in the same direction. The force per unit length on any one wire is:
(a) $\mu_0 I^2 / 2\pi d$ (b) $\sqrt{3}\mu_0 I^2 / 2\pi d$ (c) $\mu_0 I^2 / \pi d$ (d) $2\mu_0 I^2 / \pi d$
9. A square loop of side L carrying current I_2 is placed in the same plane as a long straight wire carrying current I_1 . The side of the loop nearest to the wire is at a distance L . The net force on the loop is:
(a) $\mu_0 I_1 I_2 / 2\pi$ (b) $\mu_0 I_1 I_2 / 4\pi$ (c) $\mu_0 I_1 I_2 / 6\pi$ (d) Zero
10. A circular loop of radius 10 cm carries 5 A current. If it is placed in a uniform field $B = 0.2 \text{ T}$ such that its plane is perpendicular to the field, the net force and torque are respectively:
(a) $0.1 \text{ N}, 0.01 \text{ Nm}$ (b) $0, 0$ (c) $0.5 \text{ N}, 0$ (d) $0, 0.05 \text{ Nm}$

11. A moving coil galvanometer (MCG) has a resistance of $100\ \Omega$. It gives a full-scale deflection for 10 mA . The current sensitivity is 2 div/mA . The voltage sensitivity of the galvanometer is:
 (a) 20 div/V (b) 0.02 div/V (c) 200 div/V (d) 5 div/V
12. A galvanometer of resistance G is shunted by a resistance S . To protect the instrument, a fuse of resistance R_f is added in series only to the galvanometer branch. If the original full-scale deflection current was I_g , the new maximum current I that the ammeter can measure is:
 (a) $I_g [1 + (G + R_f)/S]$ (b) $I_g [1 + G/(S + R_f)]$
 (c) $I_g [(G + S)/S]$ (d) $I_g [1 + S/(G + R_f)]$
13. A moving coil galvanometer has its number of turns increased by 25% to increase its current sensitivity. However, due to the thinner wire used, the internal resistance of the coil increases by 50% . The resulting percentage change in its voltage sensitivity is:
 (a) 25% increase (b) 16.67% decrease (c) 20% decrease (d) 10% decrease
14. A square conducting loop of side a and current I is placed in a uniform magnetic field B . The minimum work required by an external agent to rotate the loop from its most stable equilibrium orientation to its most unstable equilibrium orientation is:
 (a) Zero (b) $I a^2 B$ (c) $2 I a^2 B$ (d) $-I a^2 B$
15. Using Ampere circuital law, magnetic field inside a long solenoid is independent of:
 (a) Current (b) Turn density (c) Core permeability (d) Amperian loop shape
16. Figure of merit of a moving coil galvanometer is the current
 (a) Needed for full scale deflection (b) Needed to just move the needle
 (c) Needed to move the needle by 1 division on scale (d) None of these
17. A charged particle moving along $+x$ enters a region where a uniform magnetic field exists along $+y$. If the particle is negatively charged, initial deflection is toward:
 (a) $+z$ (b) $-z$ (c) $+y$ (d) $-x$
18. A rectangular loop carrying current I is free to rotate in a uniform magnetic field. Stable equilibrium occurs when magnetic moment is:
 (a) Parallel to B (b) Antiparallel to B (c) Perpendicular to B (d) Zero
19. A charged particle enters a magnetic field and continues undeflected. This can occur if:
 (a) $v \parallel B$ only (b) $q = 0$ only (c) $v = 0$ only (d) More than one of these situations
20. At the centre of a regular hexagonal loop carrying current I , magnetic field is B . If current is reversed in three alternate sides only, resultant field is:
 (a) Zero (b) $B/3$ (c) $B/2$ (d) B

1	(b)	2	(c)	3	(a)	4	(d)	5	(a)
6	(c)	7	(a)	8	(b)	9	(b)	10	(b)
11	(a)	12	(a)	13	(b)	14	(c)	15	(d)
16	(c)	17	(b)	18	(a)	19	(d)	20	(a)



ANSWER KEY WITH EXPLANATION

Assertion-Reason Questions

Instructions:

- (a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true but R is NOT the correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

1. **Assertion:** The kinetic energy of a charged particle moving in a uniform magnetic field remains constant.
Reason: A moving charged particle experiences a magnetic force that is directly proportional to its velocity.
2. **Assertion:** A radial magnetic field is essential in a moving coil galvanometer to maintain a linear scale.
Reason: A radial magnetic field makes the magnetic torque on the coil inversely proportional to the current.
3. **Assertion:** Increasing the current sensitivity of a galvanometer by increasing the number of turns always increases its voltage sensitivity.
Reason: Voltage sensitivity is inversely proportional to the resistance of the coil, which increases with the number of turns.
4. **Assertion:** A current-carrying solenoid tends to contract axially when current is passed through it.
Reason: Parallel wires carrying currents in the same direction attract each other.
5. **Assertion:** The magnitude of the magnetic field at the center of a circular current-carrying loop is inversely proportional to its radius.
Reason: The magnetic field lines of a circular loop form closed concentric circles strictly within the same plane as the loop.
6. **Assertion:** An electron and a proton projected with the exact same momentum into a transverse magnetic field will follow circular paths of the same radius.
Reason: The mass of a proton is approximately 1836 times greater than the mass of an electron.
7. **Assertion:** To convert a galvanometer into an ammeter, a high resistance is connected in parallel with it.
Reason: An ideal ammeter should have zero resistance so that it does not alter the main current flowing through the circuit.

ANSWERS

1. B, 2. C, 3.D, 4. A, 5. C, 6. B, 7. D

Two-Mark Questions

1. A circular coil of radius R carries a steady current I . Deduce the distance from the centre of the coil, along its axis, where the magnetic field becomes one-eighth ($1/8$) of its value at the centre.
2. A long straight solid wire carrying current I is placed coaxially inside a long hollow tube carrying an equal current I in the opposite direction. Using Ampere's circuital law, find the magnetic field in the annular region between them and completely outside the tube.
3. A positively charged particle enters a region of mutually perpendicular uniform electric (E) and magnetic (B) fields. If its velocity $v > E/B$, Will the electric force or magnetic force dominate the deflection? Justify your answer.

- An electron enters a uniform magnetic field with velocity v . Show mathematically that its kinetic energy remains constant, even though its linear momentum changes continuously.
- A straight horizontal conducting wire of mass m and length L is placed in a uniform horizontal magnetic field B perpendicular to it. What should be the magnitude and direction of the current in the wire so that it experiences no tension in its supporting wires?
- Two infinitely long straight parallel wires separated by a distance d carry currents I and $3I$ in opposite directions. Locate the exact point on the line joining them where the net magnetic field is zero.
- An electron in a hydrogen atom jumps from the first orbit to the second orbit. How does the ratio of its orbital magnetic moment to its orbital angular momentum change? Give reason.
- A square loop of side a carrying current I lies flat in the X - Y plane. A uniform magnetic field $B = B_0(\hat{i} + \hat{k})$ is applied. Calculate the magnitude of the magnetic torque acting on the loop.
- Why is a radial magnetic field required in a moving coil galvanometer? If flat magnetic poles are used instead, how will the relationship between current (I) and deflection angle (θ) change?
- A student mistakenly connects a laboratory ammeter in parallel with a $10\ \Omega$ resistor in an active circuit. Explain the electrical consequence of this error on the ammeter and the circuit.

Solutions:

- Field on axis: $B_x = (\mu_0 I R^2) / [2(R^2 + x^2)^{3/2}]$. Field at centre: $B_c = \mu_0 I / 2R$.
Given $B_x = B_c / 8$.
 $\Rightarrow (\mu_0 I R^2) / [2(R^2 + x^2)^{3/2}] = 1/8 * (\mu_0 I / 2R) \Rightarrow R^2 / (R^2 + x^2)^{3/2} = 1 / 8R$
 $\Rightarrow 8R^3 = (R^2 + x^2)^{3/2} \Rightarrow 2R = \sqrt{R^2 + x^2} \Rightarrow 4R^2 = R^2 + x^2 \Rightarrow x = \sqrt{3} R$.
- Annular region (radius r): Enclosed current is I .
By Ampere's Law: $B(2\pi r) = \mu_0 I \Rightarrow B = \mu_0 I / (2\pi r)$.
(ii) Outside the tube: Net enclosed current $I_{net} = I - I = 0$. Therefore, $B = 0$.
- It will deflect towards the magnetic field.
Justification: Magnetic force $F_m = qvB$, Electric force $F_e = qE$.
Given $v > E/B \Rightarrow vB > E \Rightarrow qvB > qE$. Since $F_m > F_e$, the magnetic force dominates.
- Magnetic force $F_m = q(v \times B)$.
By properties of cross product, F_m is always perpendicular to velocity v .
Work done $dW = F_m \cdot dx = F_m v dt = 0$ (since $F_m \perp v$).
By Work-Energy Theorem, since $W = 0$, $\Delta K = 0$. Hence, KE is constant.
- For zero tension, magnetic force must balance weight: $F_m = mg \Rightarrow ILB = mg$.
Magnitude of current $I = mg / LB$.
Direction: By Fleming's Left Hand Rule, current must flow such that the force is directed vertically upwards (opposite to gravity).
- Null point lies outside the wires, closer to the weaker current (I). Let distance be x from wire with current I . $\Rightarrow \mu_0 I / (2\pi x) = \mu_0 (3I) / [2\pi(d + x)]$. $\Rightarrow 1/x = 3 / (d + x) \Rightarrow d + x = 3x \Rightarrow x = d/2$. The point is at distance $d/2$ from the weaker wire on the outer side.
- The ratio remains unchanged (1:1). Reason: The ratio of magnetic moment to angular momentum is the gyromagnetic ratio ($e/2m$). It is a universal constant for an electron and is independent of the orbit.

8. Magnetic moment $M = Ia^2 \hat{k}$ (since loop is in X-Y plane). Torque $\tau = M \times B = (Ia^2 \hat{k}) \times B_0(\hat{i} + \hat{k}) = Ia^2 B_0(\hat{k} \times \hat{i}) + Ia^2 B_0(\hat{k} \times \hat{k})$. $\tau = Ia^2 B_0 \hat{j}$. Magnitude of torque $= Ia^2 B_0$.
9. A radial field ensures the plane of the coil is always parallel to the magnetic field (angle is 0), ensuring maximum torque ($\tau = NIAB$) and a linear scale ($I \propto \theta$). If flat poles are used, $\tau = NIAB \sin(\alpha)$. The relation becomes non-linear ($I \propto \theta/\sin(\alpha)$), making the scale uneven and difficult to read.
10. Consequence: An ammeter has very low resistance. Connecting it in parallel creates a short circuit across the resistor. A massive current will flow through the ammeter, which will likely burn out its coil and blow the fuse, potentially damaging the circuit's power supply.

Three-Mark Questions

1. A thin, non-conducting ring of radius R carries a total charge Q uniformly distributed over its circumference. The ring is rotated with a constant angular speed ω about its central axis.
 - (a) Deduce the equivalent electric current constituted by this rotating ring.
 - (b) Obtain the expression for the magnetic field generated exactly at the centre of the ring.
2. A wire carrying a steady current I is bent into the shape of a sine wave $y = A \sin(x)$ from $x = 0$ to $x = \pi$. It is placed in a uniform magnetic field $B = B_0 \hat{j}$ (directed along the positive y-axis). Using the vector properties of magnetic force, deduce the net magnetic force acting on this curved wire.
3. Two infinitely long, insulated straight wires lie in the X-Y plane along the x-axis and y-axis, respectively. Both carry the exact same steady current I in the positive axis directions ($+\hat{i}$ and $+\hat{j}$).
 - (a) Determine the locus of all points in the X-Y plane where the net magnetic field is strictly zero.
 - (b) Briefly describe the direction of the net magnetic field in the first and third quadrants.
4. In a lab expt., a student finds that the 'figure of merit' of a given moving coil galvanometer is 0.005 A/div. The galvanometer scale has exactly 30 divisions, and the internal resistance of the coil is 20 Ω . Calculate the exact value of the resistance that must be connected to this galvanometer to convert it into a voltmeter capable of reading up to 30V.
5. A single point charge q moves with a constant velocity v (where $v \ll c$).
 - (a) Write the expression for the magnetic field B produced by this moving charge at a position vector r .
 - (b) If the charge moves along the x-axis, find the ratio of the magnitude of the magnetic field to the electric field (B/E) it produces at a distance r strictly along the y-axis.
6. An infinitely long, tightly wound solenoid carrying a current I has a uniform magnetic field B_0 well inside its core near the centre. By utilizing simple logical symmetry arguments (without performing complex integration), deduce the exact magnitude of the magnetic field exactly at one of the open ends of this semi-infinite solenoid.
7. A uniform conducting wire of length L carries a current I . It is bent to form a perfect square. Deduce the exact mathematical expression for the magnetic field produced at the geometric centre of this square.

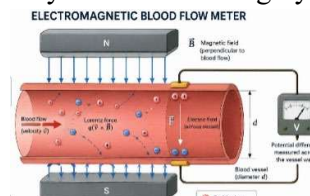
Solutions:

1. The time period of one revolution is $T = 2\pi / \omega$. The equivalent current I is defined as charge passing per unit time: $I = Q / T = Q / (2\pi / \omega) = (Q\omega) / (2\pi)$.
(b) The magnetic field at the centre of a circular current loop is $B = (\mu_0 I) / (2R)$.
Substituting the equivalent current I : $B = (\mu_0) / (2R) * (Q\omega / 2\pi) = (\mu_0 Q\omega) / (4\pi R)$.
2. The magnetic force on any arbitrarily curved wire in a UNIFORM magnetic field depends ONLY on the straight-line displacement vector (L) connecting its starting point to its ending point. $F = I(L \times B)$.
The wire starts at $x = 0$ and ends at $x = \pi$. The displacement vector $L = \pi \hat{i}$.
The magnetic field is $B = B_0 \hat{j}$.
 $F = I (\pi \hat{i} \times B_0 \hat{j}) = I\pi B_0 (\hat{i} \times \hat{j}) = I\pi B_0 \hat{k}$.
The net force is $I\pi B_0$ directed along the positive z -axis.
3. (a) Field due to wire along x -axis at point (x, y) is $B_1 = (\mu_0 I) / (2\pi y) \hat{k}$ (for $y > 0$). Field due to wire along y -axis is $B_2 = -(\mu_0 I) / (2\pi x) \hat{k}$ (for $x > 0$).
For net field to be zero, $B_1 + B_2 = 0 \Rightarrow (\mu_0 I) / (2\pi y) = (\mu_0 I) / (2\pi x)$. Therefore, $y = x$. The locus of null points is the straight line $y = x$.
(b) In the 1st Quadrant ($x > 0, y > 0$): For $y > x$, field is out of page ($+\hat{k}$). For $y < x$, field is into page ($-\hat{k}$). In the 3rd Quadrant ($x < 0, y < 0$): The direction flips due to the signs of x and y , yielding out of page for $|y| > |x|$ and into page for $|y| < |x|$.
4. Figure of merit (k) is current per division. Total full-scale current $I_g = k \times (\text{Total Divisions})$.
 $I_g = 0.005 \text{ A/div} \times 30 \text{ div} = 0.15 \text{ A}$.
Given $G = 20 \Omega$, desired voltage $V = 30 \text{ V}$.
Series resistance required: $R_s = (V / I_g) - G$. $R_s = (30 / 0.15) - 20 = 200 - 20 = 180 \Omega$.
A resistance of 180Ω must be connected in series.
5. (a) Biot-Savart law for a moving charge: $B = (\mu_0 / 4\pi) * [q(v \times r) / r^3]$, where r is the position vector from the charge to the observation point.
(b) Electric field magnitude $E = (1 / 4\pi\epsilon_0) * (q / r^2)$.
Magnetic field magnitude (since v and r are perpendicular, angle is 90°): $B = (\mu_0 / 4\pi) * (qv / r^2)$.
Ratio $B/E = [(\mu_0 / 4\pi) * (qv / r^2)] / [(1 / 4\pi\epsilon_0) * (q / r^2)] = (\mu_0 \epsilon_0) * v$.
Since $\mu_0 \epsilon_0 = 1/c^2$, the ratio $B/E = v/c^2$.
6. Imagine an infinitely long solenoid spanning from $-\infty$ to $+\infty$. The field exactly at its centre (origin) is B_0 . Now, conceptually cut this infinite solenoid into two identical semi-infinite halves at the origin. By the principle of superposition, the field at the origin B_0 is the vector sum of the fields produced by the left semi-infinite half and the right semi-infinite half. Since both halves are perfectly identical, they contribute equally to the field at the cut point. Therefore, $B_{half} + B_{half} = B_0 \Rightarrow 2B_{half} = B_0 \Rightarrow B_{half} = B_0 / 2$. The field at the open end of a semi-infinite solenoid is exactly half the field deep inside.
7. The total length is L , so each side of the square is $a = L/4$. The distance from the centre to any side is $d = a/2 = L/8$. The magnetic field at the centre due to one straight side of length

a is $B_1 = (\mu_0 I / 4\pi d) [\sin(45^\circ) + \sin(45^\circ)]$. $B_1 = [\mu_0 I / 4\pi(L/8)] * (1/\sqrt{2} + 1/\sqrt{2}) = (2\mu_0 I / \pi L) * (2/\sqrt{2}) = (2\sqrt{2} \mu_0 I) / \pi L$. Since there are 4 identical sides and their magnetic fields all point in the same direction (e.g., into the page), the net field is $B_{net} = 4 \times B_1 = 4 * [(2\sqrt{2} \mu_0 I) / \pi L] = (8\sqrt{2} \mu_0 I) / \pi L$.

Case-Based Question

An Electromagnetic Blood Flow Meter measures blood velocity v without surgery. An electromagnet applies a uniform magnetic field B perpendicular to the blood flow. Blood contains free ions. The Lorentz force deflects these ions across the blood vessel of diameter d , creating a transverse electric field. Equilibrium is reached when the electric and magnetic forces balance, producing a steady potential difference V across the vessel walls.



1. Blood flows along $+x$ and the magnetic field B is along $+y$. At steady state, where do the ions accumulate?
 - (a) Positive on $+z$, Negative on $-z$
 - (b) Positive on $-z$, Negative on $+z$
 - (c) Both on $+z$
 - (d) Both on $-y$
2. At equilibrium, what is the measured potential difference V ?
 - (a) $V = vB/d$
 - (b) $V = vBd$
 - (c) $V = B/vd$
 - (d) $V = vd/B$
3. An artery's cross-sectional area halves ($A' = A/2$) due to a blockage. If the volume flow rate (Q) remains constant, the new measured voltage V' is:
 - (a) $V/2$
 - (b) $2V$
 - (c) $\sqrt{2}V$
 - (d) V
4. If pure deionized water is pumped through the meter instead of blood, the voltmeter reading will be:
 - (a) High (water has high permittivity)
 - (b) Low (water is diamagnetic)
 - (c) Zero (no free charge carriers)
 - (d) Zero (magnetic fields block water flow)

Answer Key

1. a, 2. b, 3. c, 4. c.

Five-Mark Questions

1. A beam containing a mixture of two singly ionized isotopes of an element, having masses m_1 and m_2 ($m_1 > m_2$), is accelerated from rest through a potential difference V . The beam then passes completely undeflected through a 'velocity selector' region containing mutually perpendicular uniform electric (E) and magnetic (B_1) fields. Finally, it enters a region containing only a uniform transverse magnetic field B_2 .
 - a) Deduce the relationship between the accelerating potential V and the fields E and B_1 in the first region for the particles to pass undeflected.
 - b) Upon entering the second region (B_2), the isotopes separate and hit a photographic plate. Which isotope (m_1 or m_2) will hit the plate closer to the entry slit? Justify your answer mathematically.
 - c) Write the exact mathematical expression for the spatial separation distance (Δx) between the two marks left by the isotopes on the photographic plate.
2. A student is provided with a moving coil galvanometer of resistance $G = 100 \, \Omega$ having a full-scale deflection current of $I_g = 1 \, \text{mA}$. They are asked to measure the potential difference across a $500 \, \Omega$ resistor connected in series with a $10 \, \text{V}$ ideal battery and another $500 \, \Omega$ resistor.

- a) The student first connects the galvanometer directly across the $500\ \Omega$ resistor. Calculate the voltage reading it displays. Explain physically why this reading is wildly inaccurate compared to the 'true' voltage.
 - b) To fix this, the student converts the galvanometer into a voltmeter of range $0 - 10\text{ V}$. Calculate the exact value of the series resistance required for this conversion.
 - c) The student now uses this newly constructed voltmeter to measure the voltage across the same $500\ \Omega$ resistor. Calculate the percentage error in the measurement compared to the true theoretical voltage.
3. Three infinitely long, straight, parallel wires A, B, and C lie in the same horizontal plane. Wires A and C are rigidly fixed at a separation distance of $2d$ and carry steady currents of I and $4I$ respectively, in the same direction. Wire B, carrying a current I_0 in the opposite direction, is free to move but is currently held in place between them.
- a) Determine the exact geometrical position where Wire B must be placed so that it experiences zero net magnetic force when released.
 - b) If Wire B is displaced slightly from this equilibrium position strictly along the line joining A and C, will it execute oscillatory motion, or will it be pulled entirely towards one of the fixed wires? Justify your answer by analyzing the nature of the magnetic forces.
 - c) Does the equilibrium position of Wire B depend on the magnitude or the direction of the current I_0 flowing through it? Give a reason.
4. Two identical circular coils, C_1 and C_2 , each of radius R and carrying the exact same current I in the same clockwise sense, are placed coaxially with their centers separated by a distance R .
- a) Calculate the exact magnitude and direction of the net magnetic field at the midpoint O on the axis between the two coils.
 - b) A stationary proton is suddenly released at exactly the midpoint O. Describe its subsequent state of motion. Will it accelerate? Justify.
 - c) Now, a highly energetic alpha particle is shot precisely along the central axis of the coils from outside the system, passing through C_1 , midpoint O, and then C_2 . Describe how the kinetic energy and the linear momentum vector of the alpha particle change during this entire journey.

Solutions

1. For undeflected passage, Lorentz force is zero: $qE = qvB_1 \Rightarrow v = E/B_1$. Velocity is acquired by accelerating through V: $\frac{1}{2}mv^2 = qV$. Substituting v : $\frac{1}{2}m(E/B_1)^2 = qV \Rightarrow V = (mE^2) / (2qB_1^2)$.
 - (b) In field B_2 , radius $r = mv / (qB_2)$. Since v , q , B_2 are identical for both, $r \propto m$. Since $m_2 < m_1$, $r_2 < r_1$. The lighter isotope (m_2) hits closer to the entry slit.
 - (c) Separation $\Delta x = \text{diameter}_1 - \text{diameter}_2 = 2r_1 - 2r_2 = (2v / qB_2)(m_1 - m_2)$. Substituting $v = E/B_1$: $\Delta x = (2E / qB_1B_2)(m_1 - m_2)$.
2. (a) True voltage (voltage divider): $V_{\text{true}} = 10 * [500 / (500+500)] = 5\text{ V}$. Parallel resistance of G and $500\ \Omega$: $R_p = (500 * 100) / 600 = 83.33\ \Omega$. Total resistance = $500 + 83.33 = 583.33\ \Omega$. Main current $I = 10 / 583.33 = 0.0171\text{ A}$. Voltage reading = $I * R_p =$

$0.0171 \times 83.33 = 1.42 \text{ V}$. Reason: The low resistance of G draws massive current, altering the circuit's equivalent resistance and severely dropping the measured voltage.

(b) Voltmeter conversion: $R_s = (V / I_g) - G = (10 / 0.001) - 100 = 10000 - 100 = 9900 \Omega$

(c) New voltmeter $R_v = 10000 \Omega$. Parallel with 500Ω : $R'_p = (500 \times 10000) / 10500 = 476.19 \Omega$. Total resistance $= 500 + 476.19 = 976.19 \Omega$. Main $I = 10 / 976.19 = 0.01024 \text{ A}$. Measured Voltage $V_m = I \times R'_p = 0.01024 \times 476.19 = 4.878 \text{ V}$. % Error $= 2.44\%$.

3. Let B be at distance x from A. Distance from C is $(2d - x)$.

Force from A (repulsive, pushing right): $F_A = (\mu_0 I I_0) / (2\pi x)$.

Force from C (repulsive, pushing left): $F_C = (\mu_0 4I I_0) / (2\pi(2d - x))$.

Equilibrium: $F_A = F_C \Rightarrow 1/x = 4/(2d - x) \Rightarrow 2d - x = 4x \Rightarrow 5x = 2d \Rightarrow x = 2d/5$.

(b) Oscillatory motion (Stable equilibrium). If displaced right (towards C), distance from C decreases, so restoring force F_C (pushing left) increases. Distance from A increases, so F_A (pushing right) decreases. Net force is restoring.

No. The equilibrium position ($x = 2d/5$) only depends on the ratio of fixed currents I and $4I$. I_0 cancels out mathematically, and reversing direction makes both forces attractive but they still balance at the exact same point.

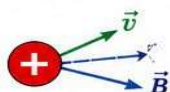
4. (a) Midpoint distance $x = R/2$. Field due to one coil $B_1 = (\mu_0 I R^2) / [2(R^2 + (R/2)^2)^{3/2}] = (4\mu_0 I) / (5\sqrt{5} R)$. Net field $B_{\text{net}} = B_1 + B_2 = 2 \times B_1 = (8\mu_0 I) / (5\sqrt{5} R)$. Direction: Along the common axis.

(b) Proton remains perfectly stationary. Magnetic force $F = q(\mathbf{v} \times \mathbf{B})$. Since initial velocity $\mathbf{v} = 0$, $F = 0$. It will not accelerate.

(c) Kinetic Energy: Remains strictly constant because magnetic force does absolutely zero work. Linear Momentum: The alpha particle's velocity is completely parallel to the magnetic field along the central axis ($\mathbf{v} \parallel \mathbf{B}$). Thus, $F = q(\mathbf{v} \times \mathbf{B}) = 0$. With no transverse or longitudinal forces, linear momentum remains completely unchanged in both magnitude and direction.

CHALLENGE CORNER

1. An electron and an alpha particle, moving with the exact same kinetic energy, enter a uniform magnetic field perpendicularly. Which particle will describe a circular path of a smaller radius?
2. A student is provided with two shunt resistors: $10\ \Omega$ and $0.01\ \Omega$. Which resistor should they choose to convert a moving coil galvanometer into an ammeter, and how should it be connected?
3. A steady electric current flows through a long, hollow copper pipe. Is there a magnetic field produced inside the pipe?
4. A charged particle enters a uniform magnetic field such that its initial velocity makes an angle of 45° with the magnetic field lines. Describe the shape of its resulting trajectory and identify the velocity component responsible for the "pitch".
5. Two infinitely long parallel straight wires carry steady currents in the same direction. What is the physical nature of the magnetic force between them? If the current in the first wire is doubled and the distance separating the two wires is halved, how does the force per unit length change?
6. A bar magnet of magnetic moment M is placed in a uniform magnetic field B . What is the total work required to rotate the magnet from its most stable equilibrium position to its most unstable equilibrium position?
7. Under what exact condition will a charged particle pass completely undeflected through a region with mutually perpendicular electric and magnetic fields? Does this condition depend on the mass or charge of the particle?
8. If doubling the number of turns in a galvanometer coil perfectly doubles its current sensitivity, why does the voltage sensitivity remain completely unchanged?



MOVING CHARGES AND MAGNETISM

CLASS 12 PHYSICS – MOST ESSENTIAL FORMULA SHEET



1. MAGNETIC FIELD

- Biot-Savart Law
$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2}$$
- Magnetic field due to a long straight wire (at distance r)
$$B = \frac{\mu_0 I}{2\pi r}$$
- Magnetic field at centre of circular loop (radius R)
$$B = \frac{\mu_0 I}{2R}$$
- Magnetic field on axis of circular loop (at distance x)
$$B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$
- Magnetic field inside long solenoid
$$B = \mu_0 n I = \mu_0 \frac{N}{\ell} I$$
- Magnetic field inside solenoid (with core of permeability μ_r)
$$B = \mu_0 \mu_r n I$$
- Field due to infinite straight current sheet (surface current density K)
$$B = \frac{\mu_0 K}{2}$$

2. AMPERE'S CIRCUITAL LAW

- Integral form
$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$
- Differential form
$$\nabla \times \vec{B} = \mu_0 \vec{J}$$

3. FORCE ON CHARGED PARTICLE (LORENTZ FORCE)

- Magnetic force
$$\vec{F} = q(\vec{v} \times \vec{B})$$
- Magnitude
$$F = |q| v B \sin \theta$$
- Electric force
$$\vec{F}_E = q\vec{E}, \quad F_E = |q|E$$
- Combined (Electric + Magnetic)
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

4. MOTION OF CHARGED PARTICLE IN MAGNETIC FIELD

- $\vec{v} \perp \vec{B}$ (circular path)
$$F = qvB = \frac{mv^2}{r}$$

$$r = \frac{mv}{|q|B}, \quad T = \frac{2\pi m}{|q|B}, \quad \omega = \frac{|q|B}{m}$$
- $\vec{v} \parallel \vec{B}$: No force, straight line
- $\vec{v}$ at angle θ to $\vec{B}$ (helical path)

$$v_{\perp} = v \sin \theta, \quad v_{\parallel} = v \cos \theta \quad r = \frac{mv \sin \theta}{|q|B}$$

$$\text{Pitch (p)} \quad p = v_{\parallel} T = \frac{2\pi m v \cos \theta}{|q|B}$$

5. FORCE ON CURRENT-CARRYING CONDUCTOR

- Force on straight conductor
$$\vec{F} = I(\vec{l} \times \vec{B})$$

$$F = BIl \sin \theta$$
- Force between two parallel current-carrying conductors
$$\frac{F}{\ell} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

 (attractive if same direction, repulsive if opposite)
- Force on a moving conductor (length l)
$$F = BIl$$

 (when conductor moves perpendicular to B)

6. TORQUE AND MOMENT

- Magnetic dipole moment of a current loop
$$\vec{\mu} = NIA \hat{n} \quad (A = \text{area})$$
- Torque on current loop in uniform field
$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

$$\tau = \mu B \sin \theta$$
- Potential energy of dipole
$$U = -\vec{\mu} \cdot \vec{B} = -\mu B \cos \theta$$
- Work done in rotating dipole (from θ_1 to θ_2)
$$W = \mu B (\cos \theta_1 - \cos \theta_2)$$

7. MOVING COIL GALVANOMETER (MCG)

- Torque
$$\tau = NBAI$$
- Restoring torque
$$\tau_r = k\theta$$
- At equilibrium
$$NBAI = k\theta$$
- Current sensitivity
$$S_I = \frac{\theta}{I} = \frac{NBA}{k}$$
- Voltage sensitivity
$$S_V = \frac{\theta}{V} = \frac{NBA}{kG}$$
- Figure of merit
$$K = \frac{\theta}{I} = \frac{k}{NBA}$$

8. CONVERSION FORMULAE

- Ammeter (shunt S in parallel)
$$S = \frac{I_g G}{I - I_g}$$

 (I_g = full scale current, G = resistance of galvanometer)
- Voltmeter (series resistance R)
$$R = \frac{V - I_g G}{I_g}$$

 (V = required range)

9. INDUCTANCE AND ENERGY

- Self inductance of solenoid
$$L = \mu_0 \mu_r \frac{N^2 A}{\ell}$$
- Magnetic energy stored
$$U = \frac{1}{2} L I^2$$
- Energy density in magnetic field
$$u = \frac{B^2}{2\mu_0}$$

10. IMPORTANT CONSTANTS

- Permeability of free space
$$\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$$
- Charge on electron / proton
$$e = 1.6 \times 10^{-19} \text{ C}$$
- Mass of electron
$$m_e = 9.11 \times 10^{-31} \text{ kg}$$
- Mass of proton
$$m_p = 1.67 \times 10^{-27} \text{ kg}$$
- Electron volt
$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

KEY SYMBOLS: $\vec{B}$: Magnetic field, $\vec{E}$: Electric field, $\vec{v}$: Velocity, q : Charge, I : Current, N : Number of turns, A : Area, θ : Angle between vectors, $n = \frac{N}{\ell}$: Turn density