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CUET · PHYSICS · CLASS XII · CODE 322

Moving Charges and Magnetism

CUET unit: Moving Charges and Magnetism

By **UniDrill** · NCERT-grounded study material

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📌 Snapshot

- Establishes the link between currents (moving charges) and magnetic fields, beginning with Oersted's observation that a current-carrying wire deflects a compass needle.
- Develops the Lorentz force F = q(E + v × B), motion of a charged particle in a magnetic field (circular and helical paths) and the cyclotron principle.
- Introduces the Biot–Savart law and Ampere's circuital law as the two basic tools for computing magnetic fields of steady currents, applied to a long straight wire, a circular loop, a solenoid and a toroid.
- Derives the force on a current-carrying conductor (F = I l × B), the force between two parallel currents (which defines the ampere), and the torque on a current loop (τ = m × B, m = NIA).
- Closes with the moving-coil galvanometer and its conversion to an ammeter (low-R shunt in parallel) and a voltmeter (high-R in series) — a recurring CUET application area.

📖 Detailed Notes

2.1 Core concepts

For most of human history electricity and magnetism were thought to be unrelated. The decisive experimental link came in 1820 when Hans Christian **Oersted** noticed that a compass needle placed near a wire was deflected the moment a current flowed through the wire (NCERT §4.1, p. 108). The deflection traced out a tangential pattern: the needle aligned itself along circles concentric with the wire, with the sense given by the right-hand rule. The conclusion was inescapable — moving charges (currents) produce magnetic fields in the space around them. This single observation triggered the development, over the next half-century, of the entire classical electromagnetic theory of Ampere, Faraday and Maxwell.

The complete force on a point charge q moving with velocity v through a region carrying simultaneously an electric field E and a magnetic field B is the **Lorentz force**:

F = q[E + v × B] (NCERT Eq. 4.3, §4.2.2, p. 109).

Three features of the magnetic part F_mag = q(v × B) deserve particular attention. (i) It is perpendicular to both v and B; it can change the direction of motion but never the magnitude of the velocity, so **the magnetic force does no work**. (ii) It vanishes whenever v is parallel (or anti-parallel) to B — only the component of v perpendicular to B contributes. (iii) It is zero for a stationary charge (v = 0). The SI unit of B is the **tesla** (T); 1 T = 1 N·s/(C·m). A handy non-SI unit is the gauss ($1\ G = 10^{-4}$ T); Earth's magnetic field at the surface is about 3×10^{-5} T = 0.3 G.

The same formula applied to a macroscopic current gives the force on a current-carrying conductor. A straight wire of length l carrying current I in an external uniform field B experiences the **Laplace force**

F = I l × B (NCERT Eq. 4.4, §4.2.3, p. 110),

where the direction of l is taken along the current. This is just the Lorentz force on the drifting charge carriers, summed over the wire's cross-section and length.

Motion of a charged particle in a magnetic field (NCERT §4.3, p. 112). When v is perpendicular to a uniform B, the magnetic force qvB acts always at right angles to v, providing exactly the centripetal force for circular motion of radius r:

$qvB = mv^2/r \Rightarrow$ **$r = mv/(qB)$**.

The angular speed is **$\omega = qB/m$**, independent of v, and the period is $T = 2\pi/\omega = 2\pi m/(qB)$. The **cyclotron frequency** $\nu_c = \omega/(2\pi) = qB/(2\pi m)$ is the rate at which the particle circles the field line; remarkably, it depends only on the charge-to-mass ratio and B, not on the particle's speed or orbital radius. This is precisely the feature that makes the cyclotron particle accelerator work: a fixed-frequency oscillating electric field stays in resonance with the orbiting particle even as it gains energy.

If v has a component $v_{\parallel}$ along B, the parallel component is unaffected by the magnetic force, so the particle drifts steadily along B while spiralling around it — a **helical** trajectory. The pitch of the helix (distance advanced along B per revolution) is

$p = v_{\parallel} T = 2\pi m v_{\parallel}/(qB)$ (NCERT Eq. 4.6b, p. 113).

This is the basic mechanism behind aurora, magnetic mirror traps and the curving particle tracks seen in cloud chambers.

Biot–Savart law (NCERT §4.4, p. 113–114). The fundamental law relating a current element to the field it produces was inferred by Jean-Baptiste Biot and Félix Savart in 1820. For a current element I dl at position vector r from the field point P,

$dB = (\mu_0/4\pi)\,(I\,dl \times \hat{r})/r^2$ (NCERT Eq. 4.7a),

with magnitude $|dB| = (\mu_0/4\pi)(I\,dl \sin\theta)/r^2$ where θ is the angle between dl and $\hat{r}$. The proportionality constant is

$\mu_0/(4\pi) = 10^{-7}$ T m A^{-1}, so $\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1},

the **permeability of free space**. Several immediate observations: the field is perpendicular to the plane containing dl and $\hat{r}$; it vanishes along the direction of dl itself (sin 0 = 0); and superposition lets us build up the field of any current by integrating over all the elements.

Field on the axis of a circular loop (NCERT §4.5, p. 116). For a single circular loop of radius R carrying current I, the field at axial distance x from the loop's centre is

$B(x) = \mu_0 I R^2/[2(x^2 + R^2)^{3/2}]$ (NCERT Eq. 4.11),

directed along the axis. At the centre (x = 0):

$\mathbf{B_0 = \mu_0 I/(2R)}$.

For N tightly-wound turns the field at the centre is $B = \mu_0 N I/(2R)$. Far from the loop ($x \gg R$) the field falls off as $1/x^3$ — the loop behaves like a magnetic dipole of moment $m = IA = \pi R^2 I$.

Ampere's circuital law (NCERT §4.6, p. 118). Although the Biot–Savart law solves every problem in principle, the integration is usually messy. For configurations with enough symmetry, Ampere's law is much easier. It states:

$\oint \mathbf{B \cdot dl = \mu_0 I_{enc}}$

around any closed loop, where I_{enc} is the total steady current passing through any surface bounded by the loop. Three classic applications:

- **Long straight wire**: a coaxial circular Amperian loop of radius r gives $B(2\pi r) = \mu_0 I$ ⇒ $\mathbf{B = \mu_0 I/(2\pi r)}$ (NCERT Eq. 4.14, p. 119). The field forms tangential circles, as Oersted first observed.
- **Thick wire with uniform current density**: for r > a (outside), the result is the same as a thin wire ($\propto 1/r$); for r < a (inside), the enclosed current scales as r^2/a^2, giving $B = \mu_0 I r / (2\pi a^2)$ — a linear growth from zero at the axis to B_{max} at the surface (NCERT Example 4.7, p. 120).
- **Long solenoid**: a rectangular Amperian loop with one side parallel to the axis inside the solenoid and the opposite side far outside (where $B \approx 0$) gives $\mathbf{B = \mu_0 n I}$ inside, where n is the number of turns per unit length (NCERT Eq. 4.16, §4.7, p. 122). The field is uniform throughout the bulk of a long solenoid and is the workhorse field for laboratory experiments. A **toroid** is a closed solenoid bent into a ring; by the same Amperian argument $B = \mu_0 n I$ inside the core and zero outside (NCERT p. 122).

Force between two parallel currents (NCERT §4.8, p. 123–124). Two long parallel wires a distance d apart carrying currents I_a and I_b exert magnetic forces on each other. The first wire creates a field $B_a = \mu_0 I_a/(2\pi d)$ at the position of the second; the second wire then experiences a force per unit length

$\mathbf{f = \mu_0 I_a I_b / (2\pi d)}$ (NCERT Eq. 4.19, p. 123).

Parallel currents attract (the opposite of the rule for like electric charges!); **antiparallel currents repel**. This very effect defines the SI unit of current: the **ampere** is the steady current that, flowing in each of two long parallel wires 1 m apart in vacuum, produces a force of **2×10^{-7} N per metre of length** on each.

Torque on a current loop (NCERT §4.9.1, p. 124–126). Place a rectangular loop of N turns carrying current I in a uniform magnetic field B. Its area vector A makes angle θ with B. The forces on opposite arms cancel, so the **net force is zero**, but a couple acts producing a torque

$\tau = N I A B \sin\theta$, or in vector form $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$, with magnetic moment $\mathbf{m} = N I A$ (NCERT Eq. 4.23).

The moment m is taken along the area-vector normal (right-hand rule). The torque tries to align m with B; it is zero in stable equilibrium (m ∥ B), zero in unstable equilibrium (m ∥ −B), and maximum when m ⊥ B.

Magnetic dipole equivalence (NCERT §4.9.2, p. 128–129). A planar current loop behaves exactly like a magnetic dipole of moment m = NIA. At large axial distance x ≫ R, $B_{axial} = (\mu_0/4\pi)(2m/x^3)$; on the equatorial line, $B_{equ} = (\mu_0/4\pi)(m/x^3)$. These have exactly the same form as the electric dipole field with the replacement $(1/4\pi\varepsilon_0) \rightarrow (\mu_0/4\pi)$ and p → m — the deep electrostatic-magnetic analogy.

Moving-coil galvanometer (MCG) (NCERT §4.10, p. 130–131). A rectangular coil of N turns of area A is suspended in a **radial** magnetic field (a soft-iron core curves the field so that B is always tangential to the coil's motion). The magnetic torque NIAB is balanced by the elastic torque $k\phi$ of a spring, giving deflection ϕ proportional to current:

$\phi = (NAB/k)\, I$.

The **current sensitivity** is $d\phi/dI = NAB/k$; the **voltage sensitivity** is $d\phi/dV = NAB/(kR)$, where R is the coil's resistance.

A galvanometer is converted to an **ammeter** by connecting a **small shunt resistance** r_s in parallel: most of the circuit current bypasses the meter through the shunt, and the parallel combination $R_G r_s/(R_G + r_s) \approx r_s$ is much smaller than R_G, so the ammeter has very low resistance and barely disturbs the circuit. It is converted to a **voltmeter** by connecting a **large resistance** R in series, so the meter draws negligible current; the voltmeter has very high resistance and is connected across the element whose voltage is being measured.

2.2 Definitions to memorise

Term	Definition	Page
Magnetic field (B)	Vector field due to currents/moving charges; magnetic part of the Lorentz force on q is $q(v \times B)$	109
Lorentz force	$F = q(E + v \times B)$; total EM force on a moving charge	109
Tesla (T)	SI unit of B; $1\ T = 1\ N\ s\ C^{-1}\ m^{-1}$; $1\ G = 10^{-4}\ T$	110
Force on current element	$dF = I\, dl \times B$	110

Term	Definition	Page
Cyclotron radius	$r = mv/(qB)$ for $v \perp B$	112
Cyclotron frequency	$\nu_c = qB/(2\pi m)$; independent of speed and radius	112
Pitch of helix	$p = 2\pi\, m\, v_{\parallel}/(qB)$	113
Biot–Savart law	$dB = (\mu_0/4\pi)(I\, dl \times \hat{r})/r^2$	113
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1}	114
Field at centre of loop	$B_0 = \mu_0 I/(2R)$	116
Axial field of loop	$B(x) = \mu_0 I R^2/[2(x^2 + R^2)^{3/2}]$	116
Ampere's circuital law	$\oint B \cdot dl = \mu_0 I_{enc}$	118
Field of long straight wire	$B = \mu_0 I/(2\pi r)$	119
Field of long solenoid	$B = \mu_0 n I$	122
Field of toroid	$B = \mu_0 n I$ inside, 0 outside	122
Force between parallel currents	$f = \mu_0 I_a I_b/(2\pi d)$, attractive if parallel	123
Ampere (A)	Current in each of two long parallel wires 1 m apart producing 2×10^{-7} N/m	124
Magnetic moment of a loop	$m = NIA$; right-hand-rule direction	126
Torque on dipole	$\tau = m \times B$, magnitude $NIAB \sin\theta$	126
Magnetic dipole field (axial)	$B = (\mu_0/4\pi)(2m/x^3)$	128
Magnetic dipole field (equatorial)	$B = (\mu_0/4\pi)(m/x^3)$	129
Current sensitivity (MCG)	NAB/k	130
Voltage sensitivity (MCG)	$NAB/(kR)$	131
Ammeter	Galvanometer + low shunt in parallel	130
Voltmeter	Galvanometer + high resistance in series	131

2.3 Diagrams / processes to remember

- **Fig. 4.1 (p. 108):** Magnetic field lines around a long straight current as concentric circles; iron-filing pattern that Oersted observed.
- **Fig. 4.2 (p. 109):** Right-hand rule for direction of $v \times B$ for positive and negative charges.

- **Fig. 4.5 / 4.6 (p. 112):** Circular motion of a charge perpendicular to B; helical motion when v has a component along B.
- **Fig. 4.7 (p. 113):** Geometry of the Biot–Savart law showing dl, r and the dB direction perpendicular to their plane.
- **Fig. 4.9 / 4.10 (p. 115–116):** Axial field of a circular current loop; the closed-loop magnetic field-line pattern that makes a current loop look like a tiny bar magnet.
- **Fig. 4.13 / 4.14 (p. 119–120):** Amperian loops for a thick wire ($r < a$ and $r > a$), and B vs r plot showing linear growth inside, 1/r decay outside.
- **Fig. 4.15 / 4.16 (p. 121):** Solenoid — stretched-out side view showing inter-turn cancellation; rectangular Amperian loop abcd used to derive $B = \mu_0 n I$.
- **Fig. 4.17 (p. 122):** Two parallel wires with their mutual force, the basis of the ampere definition.
- **Fig. 4.18 / 4.19 (p. 125):** Rectangular loop in B with torque from a couple on opposite arms.
- **Fig. 4.20 (p. 130):** MCG with radial field, soft-iron core and restoring spring; Figs. 4.21–4.22 — shunt for ammeter, series R for voltmeter.

2.4 Common confusions / NTA trap points

- Cyclotron frequency $\nu_c = qB/(2\pi m)$ is independent of speed v and radius r — distractors often insert v or r. Note $\omega = qB/m$, while $\nu_c = \omega/(2\pi)$.
- Field at the centre of a circular loop is $B = \mu_0 I/(2R)$ (not $\mu_0 n I$, which is the solenoid result, and not $\mu_0 I/(2\pi R)$, which is the straight-wire result). The factor of π distinguishes them.
- $B = \mu_0 I/(2\pi r)$ is for a long straight wire; the same formula does NOT apply at the centre of a loop.
- For a thick wire, inside ($r < a$) B grows linearly with r; outside ($r > a$) B falls as 1/r. Students often invert this.
- **Parallel currents attract, antiparallel currents repel** — the opposite of the rule for like/unlike electric charges.
- The magnetic force does no work because it is always perpendicular to v; kinetic energy and speed are unchanged, only direction of momentum changes.
- For a loop in a uniform field, net force is zero but torque is non-zero (unless $m \parallel B$ or $m \parallel -B$). Stable equilibrium is $m \parallel B$; unstable is $m \parallel -B$.
- Doubling N in a galvanometer doubles current sensitivity but leaves voltage sensitivity unchanged (because the coil resistance also doubles).
- Ammeter: low shunt **in parallel**; voltmeter: high resistance **in series**. Reversing these gives wrong meters that disturb the circuit.
- Biot–Savart involves a cross product; the field is perpendicular to both dl and $\hat{r}$, never along dl itself.

- The Lorentz force vector form has E + v × B (with a plus), not E − v × B.
- In a uniform field a current loop experiences zero net force but a torque; in a non-uniform field both force and torque can be non-zero.

2.5 Key formulas table

Symbol	Formula	Meaning	NCERT page
Lorentz force	$F = q(E + v \times B)$	Total EM force	109, Eq. 4.3
Force on wire	$F = I\, l \times B$	Straight wire of length l	110, Eq. 4.4
Cyclotron radius	$r = mv/(qB)$	$v \perp B$ circular motion	112, Eq. 4.5
Cyclotron angular freq	$\omega = qB/m$	Independent of v	112, Eq. 4.6a
Cyclotron frequency	$\nu_c = qB/(2\pi m)$	Hz	112
Helix pitch	$p = 2\pi\, m v_{\parallel}/(qB)$	When v has parallel component	113, Eq. 4.6b
Biot–Savart	$dB = (\mu_0/4\pi)(I\, dl \times \hat{r})/r^2$	Vector form	113, Eq. 4.7a
μ_0	$4\pi \times 10^{-7}$ T m A^{-1}	Vacuum permeability	114
Loop axial field	$B = \mu_0 I R^2/[2(x^2 + R^2)^{3/2}]$	Single turn	116, Eq. 4.11
Loop centre field	$B = \mu_0 N I/(2R)$	N turns at x = 0	116, Eq. 4.12
Ampere's law	$\oint B\cdot dl = \mu_0 I_{enc}$	Around closed loop	118, Eq. 4.13
Straight wire	$B = \mu_0 I/(2\pi r)$	At distance r	119, Eq. 4.14
Thick wire (inside)	$B = \mu_0 I r/(2\pi a^2)$	$r < a$	120, Eq. 4.15
Solenoid	$B = \mu_0 n I$	Inside long solenoid	122, Eq. 4.16
Toroid	$B = \mu_0 n I$	Inside, 0 outside	122
Parallel-wire force/length	$f = \mu_0 I_a I_b/(2\pi d)$	Attractive if parallel	123, Eq. 4.19
Magnetic moment	$m = N I A$	Area-vector convention	126
Loop torque	$\tau = m \times B$	Magnitude NIAB sin θ	126, Eq. 4.23
Dipole axial B	$B = (\mu_0/4\pi)(2m/x^3)$	$x \gg R$	128

Symbol	Formula	Meaning	NCERT page
Dipole equatorial B	$B = (\mu_0/4\pi)(m/x^3)$	x ≫ R	129
MCG deflection	$\phi = (NAB/k)\ I$	Linear with I	130, Eq. 4.26
Current sensitivity	NAB/k	$d\phi/dI$	130
Voltage sensitivity	NAB/(kR)	$d\phi/dV$	131

🎯 Practice MCQs

📊 PYQ Alignment

This chapter is consistently among the highest-weighted units in CUET (UG) Physics, typically contributing 12–15 MCQs per year across 2023–2025. Recurring question types include: numerical use of $B = \mu_0 I/(2\pi r)$, $B = \mu_0 nI$ and $B = \mu_0 NI/(2R)$; cyclotron-frequency and radius calculations ($r = mv/qB$, $\nu\_c = qB/(2\pi m)$); force per unit length between parallel currents and the ampere definition; torque on a current loop and magnetic moment m = NIA; and the conversion of a galvanometer into an ammeter/voltmeter via shunt vs series resistance.

CUET 2025 — Actual PYQs from this chapter

Q.18 (CUET 2025) A current element 1 cm carrying 10 A current along x-axis. Magnetic field on y-axis at 0.5 m distance is:

- A) 4×10^{-8} T B) 5×10^{-8} T C) 6×10^{-8} T D) 2×10^{-8} T Tests: Biot–Savart law — field of a current element on perpendicular axis Answer: Not in extracted key

Q.19 (CUET 2025) A conductor carrying current along z-axis placed in magnetic field along y-axis. Direction of magnetic force will be:

- A) +x-axis B) +z-axis C) −x-axis D) −z-axis Tests: Force on a current-carrying conductor $F = IL \times B$ Answer: Not in extracted key

Q.20 (CUET 2025) A galvanometer of resistance 520 Ω is shunted with 20 Ω to convert into ammeter. Resistance of ammeter is:

- A) 16.8 Ω B) 540 Ω C) 19.3 Ω D) 18 Ω Tests: Conversion of galvanometer to ammeter — shunt Answer: Not in extracted key

Q.21 (CUET 2025) Magnetic field inside solenoid: Length 0.3 m, turns 800, current 6 A

- A) 2.03 T B) 0.03 mT C) 20 mT D) 6.03 T Tests: Magnetic field inside a solenoid $B = \mu_0 nI$ Answer: Not in extracted key

Q.22 (CUET 2025) A charged particle accelerated by V volts acquires speed u. When moving perpendicular to magnetic field B, radius of path ∝

- A) √V B) V C) √V² D) 1/V Tests: Charged particle in magnetic field — radius r = mv/qB ∝ √V Answer: Not in extracted key

CUET 2024 — Actual PYQs from this chapter

Q.9 (CUET 2024) Force between two parallel current-carrying wires is proportional to:

- A) L only B) I_1I_2 only C) I_1I_2L D) $L/(I_1I_2)$ Tests: Force per unit length between parallel current-carrying wires Answer: Not in extracted key

Q.10 (CUET 2024) Magnetic field at center of circular loop with two semicircular resistances 2R and R carrying current 3I:

- A) $\mu_0 I/4r$ (out of plane) B) $\mu_0 I/4r$ (into plane) C) $\mu_0(3I)/4r$ (out of plane) D) $\mu_0(3I)/4r$ (into plane) Tests: Magnetic field at centre of a circular loop with split semicircular resistors Answer: Not in extracted key

Q.11 (CUET 2024) Square loop side 1 cm, current 10 A, magnetic field 0.2 T parallel to plane. Torque:

- A) 0 B) 2×10^{-4} Nm C) 2×10^{-2} Nm D) 2 Nm Tests: Torque on a current loop in a magnetic field τ = NIAB sinθ Answer: Not in extracted key

Q.31 (CUET 2024) A wire carrying current I is bent as shown and placed in a uniform magnetic field B coming out of the plane. The force on the wire is:

- A) 4BIR, vertically downward B) 3BIR, vertically upward C) BI(2R + πR), vertically downward D) 2πBIR, from P to Q Tests: Force on a bent current-carrying wire in a uniform magnetic field Answer: Not in extracted key

CUET 2023 — Actual PYQs from this chapter

Q.13 (CUET 2023) To protect a galvanometer from large current, which should be connected?

- A) Low resistance in series B) High resistance in series C) High resistance in parallel D) Low resistance in parallel Tests: Conversion of galvanometer to ammeter — shunt resistance Answer: Not in extracted key

Q.14 (CUET 2023) The charge which is a source of electric field but not magnetic field is:

- A) Charge moving in straight line B) Charge at rest C) Charge moving in circular path D) Oscillating charge Tests: Source of magnetic field — current vs static charge Answer: Not in extracted key

Q.15 (CUET 2023) In a thin conducting wire carrying current, magnetic field induction along the conductor should be:

- A) Zero B) Constant C) Positive D) Negative Tests: Magnetic field along the axis of a current-carrying straight wire Answer: Not in extracted key

Q.17 (CUET 2023) Magnetic field at point P in the given current-carrying wire arrangement is:

- A) μ0I4πR(3π)\frac{\mu_0 I}{4\pi R}(3\pi)4πRμ0 I (3π) B) μ0I4πR(2π+2)\frac{\mu_0 I}{4\pi R}(2\pi+2)4πRμ0 I (2π+2) C) μ0I4πR(2π−2)\frac{\mu_0 I}{4\pi R}(2\pi-2)4πRμ0 I (2π−2) D) 3μ0I2R\frac{3\mu_0 I}{2R}2R3μ0 I **Tests:** Biot–Savart law / magnetic field of composite current paths **Answer:** Not in extracted key