FREE NOTES · NCERT + JEE/NEET LEVEL

Moving Charges & Magnetism

Lorentz force, circular and helical paths of charges in a magnetic field, the cyclotron, Biot-Savart, Ampere's law, solenoids, force between wires, torque on a current loop and the galvanometer.

01 Magnetic force (Lorentz force)
02 Motion of a charge in a magnetic field
03 Velocity selector & cyclotron
04 Force on a current-carrying wire
05 Biot-Savart law
06 Field of a circular loop
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01 Magnetic force (Lorentz force)

Oersted saw a compass needle turn near a current-carrying wire. So **moving charges create a magnetic field**, and a magnetic field exerts a force on **moving** charges.

$$\mathrm{F} = \mathrm{q}\,(\mathrm{v} \times \mathrm{B}),\ |\mathrm{F}| = \mathrm{q}\,\mathrm{v}\,\mathrm{B}\,\sin\theta$$

Unit of B: tesla (T) = N/(A·m). 1 gauss = 10^{-4} T. Earth's field ≈ 0.4 gauss. With an electric field too: $\mathrm{F} = \mathrm{q}(\mathrm{E} + \mathrm{v} \times \mathrm{B})$.

- No magnetic force on a charge at rest (v = 0).
- No force if v ∥ B.
- The force is always ⊥ to v ⇒ **the magnetic force does no work**; speed doesn't change, only direction.

DIRECTION: FLEMING'S LEFT-HAND RULE

On the left hand, Forefinger = Field, Middle finger = current (velocity of a positive charge), thumb = force. Reverse for an electron.

02 Motion of a charge in a magnetic field

V ⊥ B: A CIRCLE

$$r = m\,v\,/\,(q\,B)$$

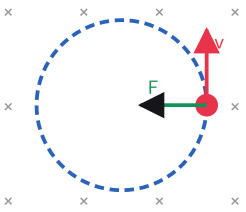
$T = 2\pi\,m\,/\,(q\,B)$, $f = qB/(2\pi m)$

The period and frequency **don't depend on speed** (the cyclotron relies on this). r = p/(qB) = √(2mK)/(qB).

ANGLE Θ BETWEEN V AND B: A HELIX

$r = m\,v\sin\theta/(qB)$

$\text{Pitch} = v\cos\theta \times T = 2\pi m\,v\cos\theta/(qB)$



B into the page (×)

Force toward the centre ⇒ circular path

03 Velocity selector & cyclotron

VELOCITY SELECTOR

E and B perpendicular, their forces opposite. Only charges with $v = E/B$ pass straight through (independent of mass and charge).

CYCLOTRON

AC voltage between two "dees", with B across them. The particle gains energy every half-turn and its radius grows. $f_c = qB/(2\pi m)$ = oscillator frequency (resonance). Max KE = $q^2B^2R^2/(2m)$. It doesn't work for electrons (too light, relativistic).

04 Force on a current-carrying wire

$$F = I\,(L \times B),\ |F| = B\,I\,L\sin\theta$$

Zero if the wire is parallel to B. Any closed loop in a uniform B: net force 0.

05 Biot-Savart law

$$dB = (\mu_0/4\pi)\, I\, (dl \times \hat{r})/r^2\,,\ |dB| = (\mu_0/4\pi)\, I\, dl \sin\theta\ /\ r^2$$

$\mu_o = 4\pi \times 10^{-7}$ T·m/A (permeability of free space). Like Coulomb's law for E, but the direction comes from a cross product.

Wire	Field
Infinite straight wire, distance r	$B = \mu_0 I/(2\pi r)$
Finite wire (angles α, β)	$B = \mu_0 I(\sin\alpha + \sin\beta)/(4\pi r)$
Semi-infinite, opposite its end	$\mu_0 I/(4\pi r)$

DIRECTION: RIGHT-HAND THUMB RULE

Point the right thumb along the current; the curled fingers give the field direction (circles around the wire).

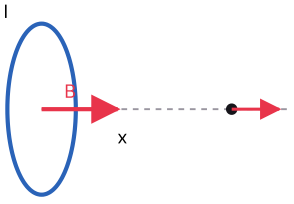
06 Field of a circular loop

At the centre: $B = \mu_0\, I\ /\ (2R)$

N turns: $B = \mu_0\, N\, I\ /\ (2R)$

On the axis at x: $B = \mu_0\, I\, R^2\ /\ (2(R^2 + x^2)\text{^}(3/2))$

At the centre of an arc (angle θ): $B = \mu_0 I\theta/(4\pi R)$



On the axis the field is perpendicular to the loop

A loop behaves like a **magnetic dipole**: one face North, the other South. The face where the current appears anticlockwise is North.

07 Ampere's circuital law

STATEMENT

$\oint B \cdot dl = \mu_o I_{enclosed}$

The line integral of B around any closed loop (Amperian loop) = μ_o × net current through the loop. Like Gauss's law: easy when there is symmetry.

Case	Inside (r < R)	Outside (r > R)
Thick solid cylindrical wire (uniform I)	$B = \mu_0 Ir/(2\pi R^2)$	$\mu_0 I/(2\pi r)$
Hollow pipe conductor	0	$\mu_0 I/(2\pi r)$

08 Solenoid & toroid

LONG SOLENOID

$$B = \mu_0 \, n \, I$$

n = turns per metre. Uniform inside, ≈ 0 outside. Half the field at the ends ($\mu_o nI/2$). Behaves like a bar magnet. With an iron core ⇒ electromagnet.

TOROID

$$B = \mu_0 \, N \, I \, / \, (2\pi r)$$

A circular (doughnut) solenoid. The field is only inside the core; zero in the open space inside and completely outside.

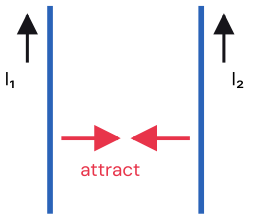
09 Force between two parallel wires

$$F/L = \mu_0 I_1 I_2 / (2\pi d)$$

Currents in the same direction: **attract**. Opposite: **repel**. (The reverse of charges!)

DEFINITION OF THE AMPERE

If two long parallel wires 1 m apart carry equal currents and the force is 2×10^{-7} N/m, each current is 1 A.



Same-direction currents ⇒ pulled together

10 Torque on a current loop

$$\tau = m \times B, \quad |\tau| = N I A B \sin\theta$$

Magnetic moment $m = N I A$ ($A \cdot m^2$), direction by the right-hand rule

Potential energy $U = -m \cdot B$

θ = angle between the loop's normal (m) and B. Maximum torque when the plane of the loop is parallel to B. Electric motors work on this.

ORBITING ELECTRON (BOHR)

An orbiting electron is a tiny current loop: $\mu = evr/2$. Bohr magneton $\mu_B = eh/(4\pi m) = 9.27 \times 10^{-24}$ $A \cdot m^2$.

11 Moving coil galvanometer

A coil in a radial magnetic field; current produces a torque, balanced by a spring's counter-torque. At balance: $NIAB = k\varphi \Rightarrow \varphi \propto I$.

$$\text{Current sensitivity} = \varphi/I = NAB/k$$

$$\text{Voltage sensitivity} = \varphi/V = NAB/(kR_G)$$

Doubling the turns doubles current sensitivity, but resistance also doubles ⇒ voltage sensitivity unchanged.

GALVANOMETER → AMMETER

A **small shunt** in parallel: $S = I_g G/(I - I_g)$. An ammeter has very low resistance and is connected in series.

GALVANOMETER → VOLTMETER

A **large resistance** in series: $R = V/I_g - G$. A voltmeter has very high resistance and is connected in parallel.

12 JEE Extra + Tricks

JEE LEVEL

- Charge in B: radius $r = mv/(qB) = \sqrt{(2mK)}/(qB)$; time period $2\pi m/(qB)$ (independent of speed); helix pitch $= 2\pi m\, v\cos\theta/(qB)$.
- Field at centre of an arc of angle θ: $B = \mu_0 I\theta/(4\pi R)$; full loop $\mu_0 I/2R$; semicircle $\mu_0 I/4R$.
- Finite straight wire: $B = (\mu_0 I/4\pi d)(\sin\alpha + \sin\beta)$.
- Parallel wires: force per length $\mu_0 I_1 I_2/(2\pi d)$; like currents attract.
- Galvanometer → ammeter: small shunt $S = I_g G/(I - I_g)$ in parallel; → voltmeter: large $R = V/I_g - G$ in series.

13 Solved numericals ($\mu_0 = 4\pi \times 10^{-7}$)

Q1. A proton (1.6×10^{-19} C) moves at 10^6 m/s ⊥ to a 0.5 T field. Force?
$F = qvB = 1.6 \times 10^{-19} \times 10^6 \times 0.5 = 8 \times 10^{-14}$ N. **Ans: 8×10^{-14} N**

Q2. An electron ($m = 9.1 \times 10^{-31}$ kg) at 3×10^7 m/s ⊥ to 10^{-3} T. Radius?
$r = mv/(qB) = 9.1 \times 10^{-31} \times 3 \times 10^7/(1.6 \times 10^{-19} \times 10^{-3}) \approx 0.17$ m. **Ans: ≈ 17 cm**

Q3. A long straight wire carries 10 A. B at 5 cm?
$B = 2 \times 10^{-7} \times 10/0.05 = 4 \times 10^{-5}$ T. **Ans: 4×10^{-5} T**

Q4. A coil of 100 turns, radius 10 cm, carries 1 A. B at the centre?
$B = \mu_0 NI/(2R) = 4\pi \times 10^{-7} \times 100/0.2 = 2\pi \times 10^{-4} \approx 6.28 \times 10^{-4}$ T. **Ans: ≈ 6.3×10^{-4} T**

Q5. Solenoid: 50 cm long, 500 turns, 2 A. B inside?
$n = 1000$/m. $B = 4\pi \times 10^{-7} \times 1000 \times 2 \approx 2.51 \times 10^{-3}$ T. **Ans: ≈ 2.5 mT**

Q6. Galvanometer G = 50 Ω, full scale 5 mA. Shunt for a 5 A ammeter?
$S = 0.005 \times 50/(5 - 0.005) \approx 0.05$ Ω. **Ans: ≈ 0.05 Ω in parallel**

Q7. Using the same galvanometer for a 10 V voltmeter?
$R = 10/0.005 - 50 = 1950$ Ω. **Ans: 1950 Ω in series**

14 Common mistakes

- Thinking the magnetic force does work (speed doesn't change).
- Forgetting to reverse the force direction for an electron.
- Applying "like repel" to parallel currents (same-direction currents attract).
- Thinking cyclotron frequency depends on speed.
- Putting a series resistance in an ammeter and a shunt in a voltmeter (reversed).
- Using total N instead of n for a solenoid.

15 Formula sheet

Lorentz force	$F = q(v \times B)$, $F = qvB \sin\theta$
Circular motion	$r = mv/qB$, $T = 2\pi m/qB$
Velocity selector	$v = E/B$
Force on a wire	$F = BIL \sin\theta$
Straight wire	$B = \mu_0 I/2\pi r$
Loop centre / axis	$\mu_0 NI/2R$ / $\mu_0 IR^2/2(R^2 + x^2)\text{^}(3/2)$
Solenoid / toroid	$\mu_0 nI$ / $\mu_0 NI/2\pi r$
Parallel wires	$F/L = \mu_0 I_1 I_2/2\pi d$
Torque on a loop	$\tau = NIAB \sin\theta$, $m = NIA$
Shunt / series R	$S = I_g G/(I - I_g)$, $R = V/I_g - G$

16 Practice questions

1. A proton and an alpha particle move with the same speed $\perp$ to B. Ratio of radii?
2. Two wires 10 cm apart each carry 5 A in the same direction. Force per metre?
3. A loop's radius is doubled (same current). B at the centre?
4. A charge moves parallel to B. Its path?
5. Resistance of an ideal ammeter and an ideal voltmeter?

ANSWERS

1) $r \propto m/q \Rightarrow 1:2$ · 2) $2 \times 10^{-7} \times 25/0.1 = 5 \times 10^{-5}$ N/m (attractive) · 3) Halved · 4) Straight line (no force) · 5) 0 and ∞

17 Quick revision: 5 minutes before the exam

FORCE

- F = qvB sin θ; no work.
- r = mv/qB; T independent of speed.
- Velocity selector v = E/B.

FIELDS

- Wire $\mu_o I/2\pi r$; loop $\mu_o I/2R$.
- Solenoid $\mu_o nI$; toroid $\mu_o NI/2\pi r$.
- $\oint B \cdot dl = \mu_o I$.

WIRES & LOOPS

- Same current direction ⇒ attract.
- τ = NIAB sin θ; m = NIA.

GALVANOMETER

- Ammeter: small shunt in parallel.
- Voltmeter: large R in series.
- $\varphi \propto I$ (radial field).

Have a doubt? Ask the AI Doubt Solver at padhaiadda.netlify.app, or take the mock test on this chapter.