CIE International A Level Physics

Topic 20

Magnetic Fields

Revision Booklet

This booklet covers:

- Magnetic Fields and Field Lines
- Force on a Current-Carrying Conductor
- Force on a Moving Charge
- Hall Effect and Velocity Selector
- Magnetic Fields due to Currents
- Electromagnetic Induction

Magnetic Fields

Magnetic Field

A **magnetic field** is a region of space in which a moving charge, or a current-carrying conductor, experiences a force.

- Magnetic fields are produced by **moving charges** (electric currents) or by **permanent magnets**.
- The field is represented by **field lines** (flux lines); the direction is the direction of the force on a north pole.
- Field lines never cross; closer lines indicate a stronger field.
- Crosses ($\times$) represent field into the page; dots ($\bullet$) represent field out of the page.

Force on a Current-Carrying Conductor

Force on a Conductor

$$F = BIL\sin\theta$$

F = force on the conductor (N)
B = magnetic flux density (T)
I = current in the conductor (A)
L = length of conductor in the field (m)
θ = angle between the conductor and the field direction

Force is **maximum** when $\theta = 90°$ (conductor perpendicular to field): $F = BIL$.
Force is **zero** when $\theta = 0°$ (conductor parallel to field).

Magnetic Flux Density B

Magnetic flux density is defined as the force per unit current per unit length acting on a wire placed **at right angles** to the field.

$$B = \frac{F}{IL} \qquad \text{units: T (tesla)} \equiv \text{N A}^{-1}\text{m}^{-1}$$

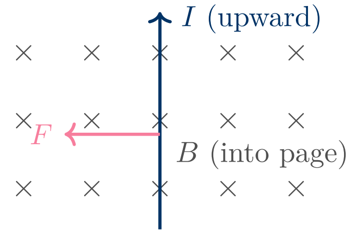
B is a vector quantity. 1 T is a strong field; Earth's field is $\approx 50\ \mu$T.

Fleming's Left-Hand Rule

For a **conventional current** in a magnetic field:

- **Thumb**: direction of force (motion) F
- **First finger**: direction of magnetic field B
- **Second finger**: direction of conventional current I

Remember: the rule gives the force on *positive* charges / conventional current. For electrons, reverse the direction.



Force on a Moving Charge

Force on a Moving Charge

$$F = BQv\sin\theta$$

F = magnetic force (N)
B = magnetic flux density (T)
Q = charge (C)
v = speed of the charge (m s^{-1})
θ = angle between velocity and field

For $\theta = 90°$: $F = BQv$, directed perpendicular to both v and B.

Circular Motion in a Magnetic Field

When a charged particle moves **perpendicular** to a uniform magnetic field, the magnetic force is always perpendicular to the velocity, so no work is done and the **speed is constant**. The particle moves in a **circle**:

$$BQv = \frac{mv^2}{r} \quad \Rightarrow \quad r = \frac{mv}{BQ}$$

A larger momentum or smaller B gives a larger radius.

The Hall Effect

Hall Voltage

When a current-carrying conductor is placed in a magnetic field perpendicular to the current, charge carriers experience a sideways force. They accumulate on one face until the electric force balances the magnetic force, producing the **Hall voltage**:

$$V_H = \frac{BI}{ntq}$$

V_H = Hall voltage (V)
B = magnetic flux density (T)
I = current through the conductor (A)
n = number density of charge carriers (m^{-3})
t = thickness of the conductor in the direction of B (m)
q = charge on each carrier (C)

A **Hall probe** uses this effect to measure B: since $V_H \propto B$ at constant I.

Velocity Selector

Velocity Selector

A velocity selector uses **crossed** electric and magnetic fields so that only particles with a specific speed pass through undeflected:

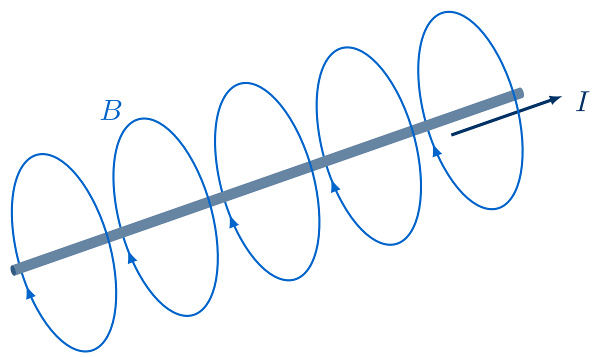
$$qE = BQv \quad \Rightarrow \quad v = \frac{E}{B}$$

- Electric force qE and magnetic force BQv act in **opposite** directions.
- Only particles where these forces balance travel in a straight line.
- Faster particles are deflected one way; slower particles the other.

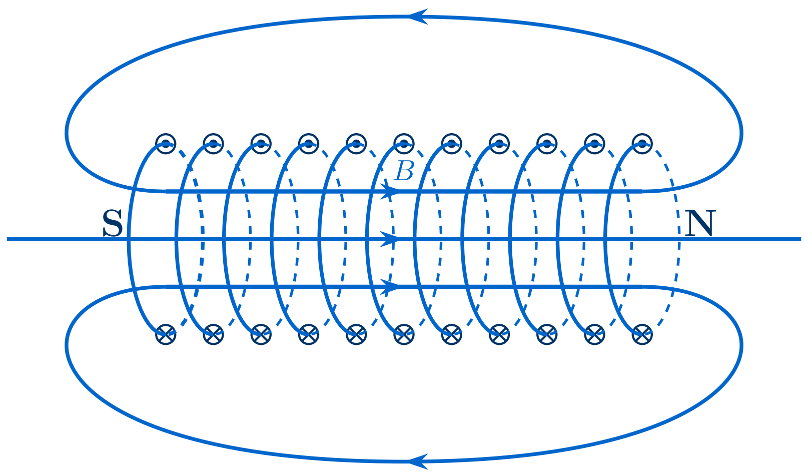
Magnetic Fields due to Currents

Field Patterns

- **Long straight wire**: concentric circles centred on the wire. Direction given by the **right-hand grip rule** — thumb points in direction of current, fingers curl in direction of field.
- **Flat circular coil**: field lines pass through the centre of the coil. Field at the centre is approximately uniform over a small region.
- **Long solenoid**: nearly uniform field inside, similar to a bar magnet outside. A **ferrous (iron) core** greatly increases the field strength.



Magnetic field around a straight wire



Magnetic field around a Solenoid

Forces Between Parallel Conductors

- **Same direction currents**: conductors **attract** each other.
- **Opposite direction currents**: conductors **repel** each other.
- Each conductor sits in the magnetic field produced by the other; the force is given by $F = BIL$.

Electromagnetic Induction

Magnetic Flux

Magnetic flux Φ is the product of the magnetic flux density and the cross-sectional area perpendicular to the field:

$$\Phi = BA\cos\theta \qquad \text{units: Wb (weber)} \equiv \text{T m}^2$$

When B is perpendicular to the area: $\Phi = BA$.

Flux linkage $N\Phi$ is the flux through a single turn multiplied by the number of turns N of the coil: units Wb-turns.

Faraday's Law and Lenz's Law

$$\mathcal{E} = -\frac{\Delta(N\Phi)}{\Delta t}$$

Faraday's Law: the induced e.m.f. is proportional to the rate of change of flux linkage.

Lenz's Law: the induced e.m.f. (and hence current) acts in a direction that **opposes** the change in flux that caused it (the minus sign above).

$\mathcal{E}$ = induced e.m.f. (V)
N = number of turns
$\Delta\Phi/\Delta t$ = rate of change of flux (Wb $s^{-1} \equiv$ V)

Factors Affecting the Induced E.M.F.

- **Rate of change** of flux: faster change $\Rightarrow$ larger e.m.f.
- **Number of turns** N: more turns $\Rightarrow$ larger e.m.f.
- **Strength of field** B: stronger field $\Rightarrow$ larger flux change.
- **Area** of coil: larger area $\Rightarrow$ more flux.

Lenz's law is a consequence of conservation of energy — the induced current creates a force that opposes the motion causing induction.

Common Mistake

An e.m.f. is induced only when the flux is **changing**. A conductor stationary in a steady field has zero induced e.m.f., even if the field is strong.

Formula Summary Sheet

Formula	Quantity	Units
$F = BIL\sin\theta$	Force on current-carrying conductor	N
$F = BQv\sin\theta$	Force on moving charge	N
$r = mv/(BQ)$	Radius of circular orbit in B field	m
$V_H = BI/(ntq)$	Hall voltage	V
$v = E/B$	Velocity selector condition	m s^{-1}
$\Phi = BA\cos\theta$	Magnetic flux	Wb
$\mathcal{E} = -\Delta(N\Phi)/\Delta t$	Faraday's / Lenz's law	V

Units: 1 T = 1 N A^{-1}m^{-1}; 1 Wb = 1 T m^2 = 1 V s
Right-hand grip rule: thumb ∥ current, fingers curl in direction of B field.

Worked Examples

Example 1 — Force on a Conductor

Question: A wire of length 0.15 m carries a current of 3.0 A at 60° to a uniform field of 0.25 T. Calculate the force on the wire.

Solution

$$F = BIL\sin\theta = 0.25 \times 3.0 \times 0.15 \times \sin 60^\circ$$
$$F = 0.25 \times 3.0 \times 0.15 \times 0.866 = \mathbf{9.7 \times 10^{-2}}\ \text{N}$$

Example 2 — Circular Motion of a Charged Particle

Question: A proton (mass 1.67×10^{-27} kg, charge 1.6×10^{-19} C) moves at 2.0×10^6 m s^{-1} perpendicular to a field of 0.15 T. Calculate the radius of its circular path.

Solution

$$r = \frac{mv}{BQ} = \frac{1.67 \times 10^{-27} \times 2.0 \times 10^6}{0.15 \times 1.6 \times 10^{-19}} = \frac{3.34 \times 10^{-21}}{2.40 \times 10^{-20}} = \mathbf{0.14}\ \text{m}$$

Example 3 — Induced E.M.F.

Question: A coil of 200 turns and area 50 cm^2 is in a field of 0.30 T perpendicular to the plane of the coil. The field drops to zero in 0.040 s. Calculate the induced e.m.f.

Solution

$$\Delta\Phi = B \times A = 0.30 \times 50 \times 10^{-4} = 1.5 \times 10^{-3}\ \text{Wb}$$
$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t} = 200 \times \frac{1.5 \times 10^{-3}}{0.040} = \mathbf{7.5}\ \text{V}$$

Practice Exam Questions

Section A — Short Answer Questions

Q1. Define magnetic flux density and state its SI unit.

[2 marks]

Q2. A wire of length 8.0 cm is placed perpendicular to a field of flux density 0.40 T and carries a current of 2.5 A. Calculate the force on the wire.

[2 marks]

Q3. State Faraday's Law and Lenz's Law of electromagnetic induction.

[3 marks]

Q4. Explain why the speed of a charged particle moving perpendicular to a uniform magnetic field remains constant.

[2 marks]

Q5. A Hall probe gives a voltage of 3.2 mV when a current of 50 mA passes through a slice of thickness 2.0 mm in a field B. Given $n = 8.5 \times 10^{28}$ m^{-3} and $q = 1.6 \times 10^{-19}$ C, calculate B.

[3 marks]

Section B — Longer Structured Questions

Q6. An electron (mass 9.11×10^{-31} kg, charge 1.6×10^{-19} C) enters a uniform magnetic field of 2.0×10^{-3} T perpendicular to the field with speed 5.0×10^{6} m s^{-1}.

(a) Calculate the radius of the circular path followed by the electron.

[2 marks]

(b) The field strength is doubled. State and explain the effect on the radius.

[2 marks]

(c) An electric field is now applied perpendicular to B so that the electron travels in a straight line. Calculate the electric field strength required.

[2 marks]

Q7. A rectangular coil of 80 turns and dimensions 4.0 cm × 6.0 cm is placed with its plane perpendicular to a uniform field of 0.50 T.

(a) Calculate the flux linkage through the coil.

[2 marks]

(b) The coil is rotated so that its plane becomes parallel to the field in 0.030 s. Calculate the mean induced e.m.f.

[2 marks]

(c) State and explain the direction of the induced current using Lenz's law.

[2 marks]

Mark Scheme and Answers

Q1. Magnetic flux density is the force per unit current per unit length on a wire placed at right angles to the field [1]; unit: tesla (T) or N A^{-1} m^{-1} [1].

Q2. $F = BIL \sin 90° = 0.40 \times 2.5 \times 0.080 = \mathbf{0.080}$ N [2].

Q3. Faraday's Law: the induced e.m.f. is proportional to the rate of change of flux linkage [1]; $\mathcal{E} = -\Delta(N\Phi)/\Delta t$ [1]. Lenz's Law: the induced e.m.f. acts in a direction to oppose the change in flux that caused it [1].

Q4. The magnetic force is always perpendicular to the velocity [1]; a perpendicular force does no work, so kinetic energy and hence speed remain unchanged [1].

Q5. $B = V_H ntq/I = (3.2 \times 10^{-3} \times 8.5 \times 10^{28} \times 2.0 \times 10^{-3} \times 1.6 \times 10^{-19})/(50 \times 10^{-3})$ [2] $= \mathbf{0.174}$ T [1].

Q6(a). $r = mv/(BQ) = (9.11 \times 10^{-31} \times 5.0 \times 10^{6})/(2.0 \times 10^{-3} \times 1.6 \times 10^{-19})$ [1] $= \mathbf{1.4 \times 10^{-2}}$ m [1].

Q6(b). Radius halves [1]; $r = mv/BQ$, so $r \propto 1/B$; doubling B halves r [1].

Q6(c). For straight-line motion: $qE = BQv$; $E = Bv = 2.0 \times 10^{-3} \times 5.0 \times 10^{6} = \mathbf{1.0 \times 10^{4}}$ V m^{-1} [2].

Q7(a). $\Phi = BA = 0.50 \times (0.040 \times 0.060) = 1.2 \times 10^{-3}$ Wb [1]; flux linkage $= N\Phi = 80 \times 1.2 \times 10^{-3} = \mathbf{9.6 \times 10^{-2}}$ Wb-turns [1].

Q7(b). $\Delta(N\Phi) = 9.6 \times 10^{-2}$ Wb-turns (falls to zero) [1]; $\mathcal{E} = 9.6 \times 10^{-2}/0.030 = \mathbf{3.2}$ V [1].

Q7(c). By Lenz's law the induced current opposes the decrease in flux [1]; the current flows in the direction that would create a field to oppose the rotation / maintain the flux through the coil [1].

Revision Checklist

Use this checklist to track your understanding. Tick each box when you are confident:

	Learning Objective	Confidence (1–3)
☐	Define magnetic flux density; use $F = BIL\sin\theta$	
☐	Apply Fleming's left-hand rule to find force directions	
☐	Use $F = BQv\sin\theta$ for force on a moving charge	
☐	Derive and use $r = mv/(BQ)$ for circular orbit radius	
☐	Explain and use the Hall effect; use $V_H = BI/(ntq)$	
☐	Explain the velocity selector condition $v = E/B$	
☐	Sketch field patterns for straight wire, circular coil and solenoid	
☐	Apply the right-hand grip rule for field direction around a wire	
☐	Explain forces between parallel current-carrying conductors	
☐	Define magnetic flux $\Phi = BA\cos\theta$ and flux linkage $N\Phi$	
☐	State and apply Faraday's and Lenz's laws	
☐	Identify factors that affect the magnitude of induced e.m.f.	

Key: 1 = Need more work 2 = Getting there 3 = Confident

Good luck with your revision!

Faraday's law — one equation — explains the generator, the transformer, and the electric motor. Master flux linkage and you understand how almost all electrical power is generated.