

THEME D · FIELDS

SL & HL

≈ 30 min read

IB Physics D.3 Motion in Electromagnetic Fields — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). D.3 is the same for SL and HL — there is no additional higher level content — so every section on this page is examinable for all students.



SL D.3 questions



HL D.3 questions



Flashcards



Charge in a magnetic field simulation

What this page covers

- ✓ How a charged particle moves in a uniform electric field — along the field lines and when it enters at right angles to them
- ✓ How a charged particle moves in a uniform magnetic field, and why its kinetic energy stays constant
- ✓ Motion in uniform electric and magnetic fields at right angles to each other (crossed fields and the velocity selector)
- ✓ The size and direction of the magnetic force on a moving charge,
 $F = qvB \sin \theta$
- ✓ The size and direction of the force that a magnetic field exerts on a wire carrying a current, $F = BIL \sin \theta$
- ✓ The force per unit length between parallel current-carrying wires,
 $\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$, and when it is attractive or repulsive
- ✓ Finding the charge-to-mass ratio of a particle from its circular path in a magnetic field

- ✓ Finding the direction of the magnetic field around a straight current-carrying wire

In one minute

- **Electric field:** force $F = qE$, the same everywhere in a uniform field. Along the field the particle accelerates uniformly and gains kinetic energy qV ; entering at right angles it follows a **parabola**, like a projectile.
- **Magnetic field:** force $F = qvB \sin \theta$, always **perpendicular to the velocity**, so it does no work: the speed and kinetic energy stay constant and, for motion perpendicular to the field, the path is a **circle** of radius $r = \frac{mv}{qB}$.
- **Direction:** Fleming's left-hand rule, with the second finger along the velocity of a *positive* charge. For a negative charge, reverse the force.
- **Crossed fields:** a particle passes straight through when $qE = qvB$, i.e. $v = E/B$, whatever its charge or mass.
- **Wires:** $F = BIL \sin \theta$ on a conductor; parallel wires attract if the currents are in the same direction and repel if opposite, with $\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$.

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How does a charged particle move in a uniform electric field?

Between two parallel plates with a potential difference V across a separation d , the electric field is uniform (D.2): the field lines are parallel, equally spaced and point from the positive plate to the negative plate. A charge q in the field feels the same force at every point.

In a uniform electric field a charged particle experiences a constant force $F = qE$ parallel to the field lines — in the direction of the field for a positive charge and opposite to it for a negative charge — so it has a constant acceleration $a = \frac{qE}{m}$.

$$F = qE \qquad E = \frac{V}{d} \qquad a = \frac{qE}{m} = \frac{qV}{md}$$

- F = electric force (N), q = charge (C), E = electric field strength (N C^{-1} or V m^{-1}), V = potential difference between the plates (V), d = plate separation (m), m = mass (kg). $E = F/q$ and $E = V/d$ are in the data booklet (D.2); $a = F/m$ is Newton's second law (A.2).
- Because the acceleration is constant, the **suvat equations** (A.1) apply.
- For electrons and ions the electric force is so much larger than the weight that **gravity can be neglected** — check this by comparing qE with mg if asked.

Moving along the field lines

A particle released from rest (or moving parallel to the field) accelerates in a straight line. The work done on it by the field equals the gain in kinetic energy. Since $V = W/q$ (B.5), moving through a potential difference V gives:

$$\Delta E_k = qV \qquad \Rightarrow \qquad \frac{1}{2}mv^2 = qV \text{ (from rest)}$$

- This is how an **electron gun** works: electrons are accelerated from a hot cathode through a potential difference of a few kilovolts. The result does not depend on the plate separation — only on V .

- A kinetic energy of qV for $q = e$ and $V = 1 \text{ V}$ is 1 electronvolt ($1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$).

WORKED EXAMPLE 1 Easy · Calculate

Two parallel plates 4.0 cm apart have a potential difference of 800 V between them. A proton is released from rest next to the positive plate.

(a) Calculate the electric field strength and the force on the proton. (b) Calculate the acceleration of the proton. (c) Determine the speed of the proton when it reaches the negative plate.

$$\text{(a)} \quad E = \frac{V}{d} = \frac{800}{0.040} = 2.0 \times 10^4 \text{ V m}^{-1}; \quad F = qE = 1.60 \times 10^{-19} \times 2.0 \times 10^4 = 3.2 \times 10^{-15} \text{ N}$$

$$\text{(b)} \quad a = \frac{F}{m} = \frac{3.2 \times 10^{-15}}{1.673 \times 10^{-27}} = 1.9 \times 10^{12} \text{ m s}^{-2} \quad (1.91 \times 10^{12} \text{ m s}^{-2}) \text{ — about } 2 \times 10^{11} \text{ times } g, \text{ so the weight is negligible.}$$

$$\text{(c)} \quad \text{Energy: } \frac{1}{2}mv^2 = qV \Rightarrow v = \sqrt{\frac{2qV}{m}} = \sqrt{\frac{2 \times 1.60 \times 10^{-19} \times 800}{1.673 \times 10^{-27}}} = 3.9 \times 10^5 \text{ m s}^{-1} \quad (3.91 \times 10^5 \text{ m s}^{-1})$$

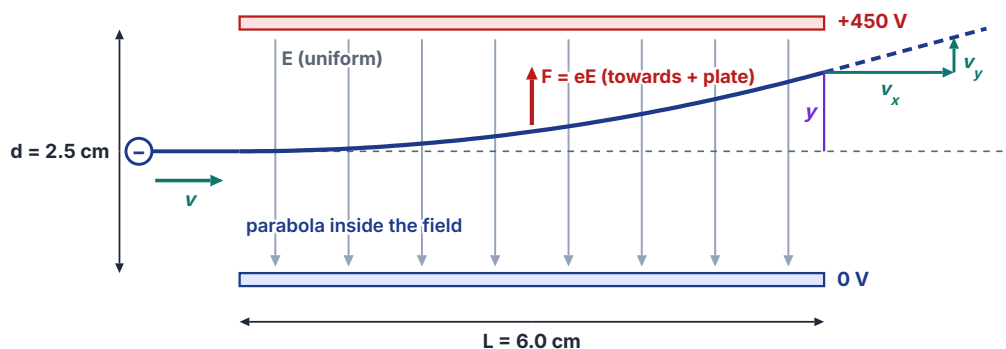
Check with kinematics: $v = \sqrt{2ad} = \sqrt{2 \times 1.913 \times 10^{12} \times 0.040} = 3.91 \times 10^5 \text{ m s}^{-1}$ — the same, as it must be.

Entering at right angles to the field

When a charged particle enters the field moving **perpendicular** to the field lines, treat the two directions separately, exactly as for a projectile (A.1):

- **Parallel to the plates:** no force, so the velocity component v_x is constant: $x = v_x t$.
- **Perpendicular to the plates:** constant acceleration $a = qE/m$ from rest in that direction: $y = \frac{1}{2}at^2$, $v_y = at$.
- Eliminating t gives $y \propto x^2$: the path is a **parabola**. Once the particle leaves the plates there is no force, and it continues in a straight line.

- The time spent between plates of length L is $t = L/v_x$. A faster particle spends less time in the field and is deflected less.



An electron accelerated through 2.0 kV enters the field between plates 6.0 cm long and 2.5 cm apart with 450 V across them (the set-up of worked example 2), drawn to scale. The force eE is constant and towards the positive plate, so the path is a parabola, with deflection y at the exit; the velocity components at exit are drawn to scale.

WORKED EXAMPLE 2 Medium · Show that / Determine

Electrons are accelerated from rest through a potential difference of 2.0 kV. They then enter, midway between them and parallel to them, the region between two horizontal plates 6.0 cm long and 2.5 cm apart. The potential difference between the plates is 450 V.

- (a) Show that the speed of the electrons is about $2.7 \times 10^7 \text{ m s}^{-1}$. (b) Determine the vertical deflection of an electron as it leaves the plates. (c) Determine the angle between the electron's velocity and the plates as it leaves. (d) Determine the smallest potential difference between the plates for which the electrons strike a plate.

$$\text{(a)} \quad \frac{1}{2}m_e v^2 = eV \Rightarrow v = \sqrt{\frac{2 \times 1.60 \times 10^{-19} \times 2000}{9.110 \times 10^{-31}}} = 2.65 \times 10^7 \text{ m s}^{-1}$$

$$\approx 2.7 \times 10^7 \text{ m s}^{-1}$$

$$\text{(b)} \quad E = \frac{450}{0.025} = 1.8 \times 10^4 \text{ V m}^{-1}; a = \frac{eE}{m_e} = \frac{1.60 \times 10^{-19} \times 1.8 \times 10^4}{9.110 \times 10^{-31}} = 3.16 \times 10^{15} \text{ m s}^{-2}$$

$$\text{Time between plates } t = \frac{L}{v} = \frac{0.060}{2.65 \times 10^7} = 2.26 \times 10^{-9} \text{ s}$$

$y = \frac{1}{2}at^2 = \frac{1}{2} \times 3.16 \times 10^{15} \times (2.26 \times 10^{-9})^2 = \mathbf{8.1 \text{ mm}}$ ($8.10 \times 10^{-3} \text{ m}$),
towards the positive plate

(c) $v_y = at = 3.16 \times 10^{15} \times 2.26 \times 10^{-9} = 7.16 \times 10^6 \text{ m s}^{-1}$

$\tan \alpha = \frac{v_y}{v_x} = \frac{7.16 \times 10^6}{2.65 \times 10^7} \Rightarrow \alpha = \mathbf{15^\circ}$ (15.1°)

(d) The electron hits a plate if y reaches $d/2 = 12.5 \text{ mm}$. Since $y \propto a \propto$

$V_{\text{plates}}: V = 450 \times \frac{12.5}{8.10} = \mathbf{690 \text{ V}}$ (694 V)

Note: combining the steps gives $y = \frac{V_{\text{plates}} L^2}{4dV_{\text{acc}}}$ — the charge and mass cancel, so any charged particle accelerated from rest through the same potential difference is deflected by the same distance (towards the positive plate for a negative particle, towards the negative plate for a positive one).

What force does a magnetic field exert on a moving charge?

A magnetic field exerts a force on a charge only when the charge is **moving**, and only if its velocity has a component perpendicular to the field.

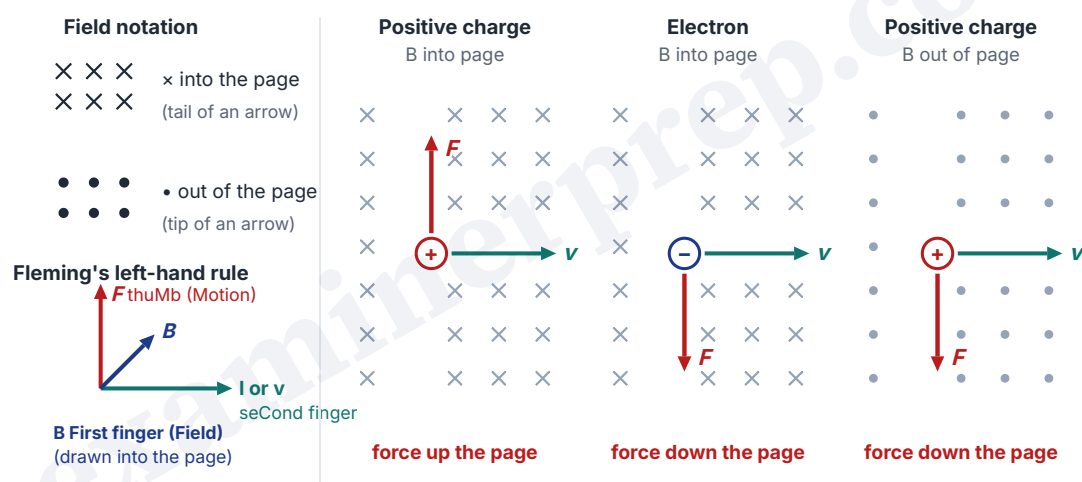
The magnetic force on a charge q moving with speed v at angle θ to a magnetic field of flux density B has magnitude $F = qvB \sin \theta$ and acts perpendicular to both the velocity and the field.

$$F = qvB \sin \theta$$

- F = magnetic force (N), q = charge (C), v = speed (m s^{-1}), B = magnetic flux density or magnetic field strength (T), θ = angle between the velocity and the field. In the data booklet.
- $\theta = 90^\circ$: maximum force, $F = qvB$. $\theta = 0$ or 180° (moving along the field lines): **no force**. A charge at rest feels no magnetic force at all.
- The equation defines the tesla: 1 T is the field in which a charge of 1 C moving at 1 m s^{-1} perpendicular to the field feels a force of 1 N ($1 \text{ T} = 1 \text{ N s C}^{-1} \text{ m}^{-1} = 1 \text{ N A}^{-1} \text{ m}^{-1}$).

Finding the direction

- **Fleming's left-hand rule:** hold the thumb, first finger and second finger of the left hand mutually at right angles. **F**irst finger = **F**ield (N to S); **sE**Cond finger = **C**urrent; **thU**Mb = **M**otion (force).
- A moving **positive** charge is a conventional current in the direction of its velocity. A moving **negative** charge (e.g. an electron) is a conventional current *opposite* to its velocity — so point the second finger backwards, or find the force for a positive charge and reverse it.
- Diagrams are two-dimensional, so fields at right angles to the page use a standard notation: **x** = into the page (you see the tail of the arrow), **•** = out of the page (you see its tip).



Left: the dot and cross notation and Fleming's left-hand rule. Right: three cases with the velocity to the right. Reversing either the sign of the charge or the direction of the field reverses the force; reversing both leaves it unchanged.

Quick example. An alpha particle (charge $+2e$) moves at $1.5 \times 10^7 \text{ m s}^{-1}$ perpendicular to a 0.40 T field. $F = qvB = 2 \times 1.60 \times 10^{-19} \times 1.5 \times 10^7 \times 0.40 = 1.9 \times 10^{-12} \text{ N}$. At 30° to the field the force would be half this.

TRY IT YOURSELF

D.3 Charge in a magnetic field simulation: change the sign of the charge, its speed and the field direction, and predict the direction of the force before you run it.

Why does a charged particle move in a circle in a magnetic field?

Consider a particle moving perpendicular to a uniform magnetic field. The magnetic force is always at right angles to the velocity, and its magnitude qvB is constant. A force of constant size that is always perpendicular to the velocity is exactly the condition for **uniform circular motion** (A.2): the magnetic force provides the centripetal force.

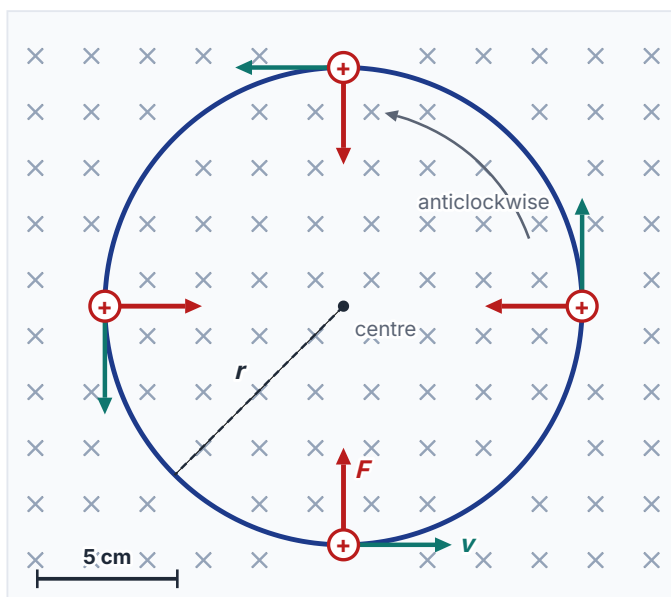
A charged particle moving perpendicular to a uniform magnetic field moves in a circle at constant speed, because the magnetic force is always perpendicular to its velocity and so acts as the centripetal force.

$$qvB = \frac{mv^2}{r} \quad \Rightarrow \quad r = \frac{mv}{qB} \quad T = \frac{2\pi r}{v} = \frac{2\pi m}{qB}$$

- r = radius of the path (m), m = mass (kg), T = time for one revolution (s). Neither result is in the data booklet: derive them from $F = qvB$, $F = ma$ and $a = v^2/r$, all of which are.
- $r \propto v$: a faster particle moves in a larger circle. $r \propto m/q$: heavier particles curve less; more highly charged ones curve more. A stronger field gives a tighter circle.
- The **period does not depend on the speed**: a faster particle travels a bigger circle in the same time.

The kinetic energy stays constant

The magnetic force is perpendicular to the displacement at every instant, so the work it does is $W = Fs \cos 90^\circ = 0$ (A.3). **The magnetic force changes the direction of the velocity but never its magnitude**, so the speed and the kinetic energy of the particle remain constant. Only an electric field can change a charged particle's kinetic energy.



Proton accelerated through 5.0 kV

$B = 0.12 \text{ T}$ into the page

$F = qvB$, always $\perp v$

$\rightarrow$ centripetal force

speed and E_k constant

(F does no work)

An electron would circle

clockwise

A proton accelerated through 5.0 kV moving in a 0.12 T field into the page (the set-up of worked example 3), drawn to scale. At every point the force (red) is perpendicular to the velocity (green) and points to the centre. Fleming's left-hand rule gives an anticlockwise path for a positive charge here.

If the velocity is at an angle to the field, only the perpendicular component $v \sin \theta$ is affected; the component along the field is unchanged. The particle then circles while drifting along the field lines — a helical path (for interest only — not required by the guide).

WORKED EXAMPLE 3 Medium · Calculate / Determine / Explain

A proton is accelerated from rest through a potential difference of 5.0 kV and then enters a region of uniform magnetic field of strength 0.12 T, directed into the page, moving perpendicular to the field.

- Calculate the speed of the proton.
- Determine the radius of its path.
- Calculate the time the proton takes to complete half a circle.
- State its kinetic energy after half a circle, and explain your answer.
- The accelerating potential difference is increased to 20 kV. Determine the new radius.

$$\text{(a) } v = \sqrt{\frac{2eV}{m_p}} = \sqrt{\frac{2 \times 1.60 \times 10^{-19} \times 5000}{1.673 \times 10^{-27}}} = 9.8 \times 10^5 \text{ m s}^{-1} \text{ (} 9.78 \times 10^5 \text{ m s}^{-1} \text{)}$$

$$(b) r = \frac{m_p v}{eB} = \frac{1.673 \times 10^{-27} \times 9.78 \times 10^5}{1.60 \times 10^{-19} \times 0.12} = \mathbf{0.085 \text{ m}} \text{ (8.52 cm)}$$

$$(c) T = \frac{2\pi m_p}{eB} = \frac{2\pi \times 1.673 \times 10^{-27}}{1.60 \times 10^{-19} \times 0.12} = 5.47 \times 10^{-7} \text{ s, so half a circle takes } \mathbf{2.7 \times 10^{-7} \text{ s}} \text{ (} 2.74 \times 10^{-7} \text{ s)}$$

(d) $\mathbf{5.0 \text{ keV} = 8.0 \times 10^{-16} \text{ J}}$, unchanged. The magnetic force is always perpendicular to the velocity, so it does no work on the proton; the speed (and therefore E_k) is constant, only the direction of motion changes.

(e) $v \propto \sqrt{V}$, so four times the potential difference doubles the speed, and $r \propto v$: $r = 2 \times 0.0852 = \mathbf{0.17 \text{ m}}$

How can the path of a particle reveal its charge-to-mass ratio?

Rearranging $r = mv/(qB)$ gives the **specific charge** (charge-to-mass ratio) of the particle:

$$\frac{q}{m} = \frac{v}{rB}$$

If the particles were accelerated from rest through a potential difference V , then $\frac{1}{2}mv^2 = qV$, so $v = \sqrt{2qV/m}$. Substituting and squaring:

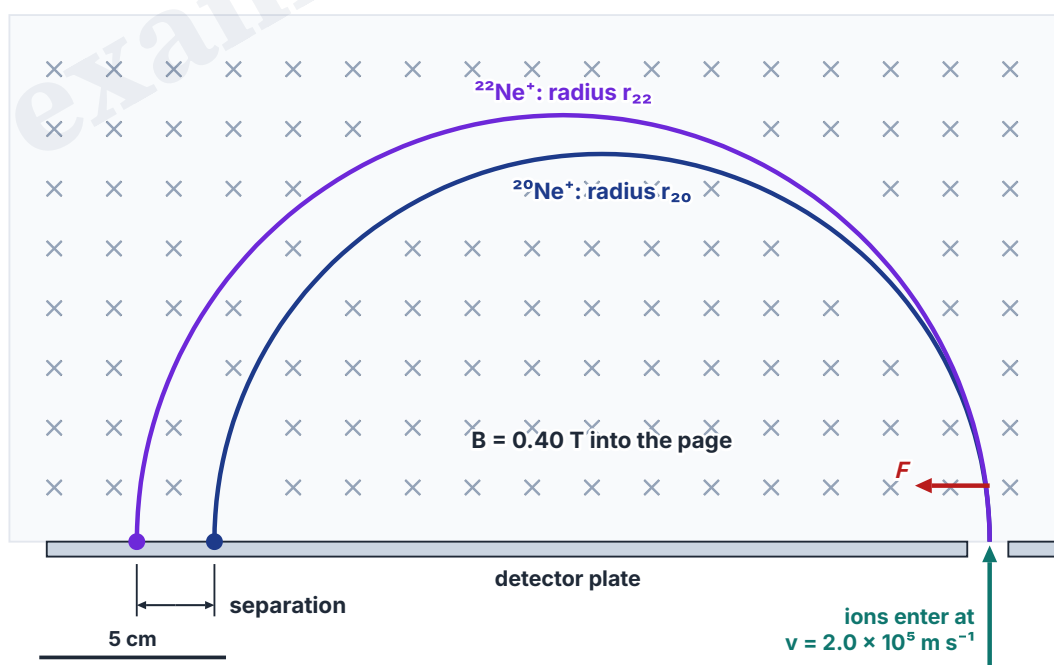
$$r^2 = \frac{2m}{qB^2} V \quad \Rightarrow \quad \frac{q}{m} = \frac{2V}{r^2 B^2}$$

- Neither result is in the data booklet; both follow in two lines from $qvB = mv^2/r$ and $\frac{1}{2}mv^2 = qV$. Expect to derive them.
- A graph of r^2 against V (at constant B) is a straight line through the origin with gradient $\frac{2m}{qB^2}$, so $\frac{q}{m} = \frac{2}{\text{gradient} \times B^2}$.
- For electrons this is the classic **fine-beam tube** experiment: a beam of electrons passes through a low-pressure gas, which glows along the beam, so the circular path can be seen and its diameter measured against a scale.

Deducing the nature of a particle

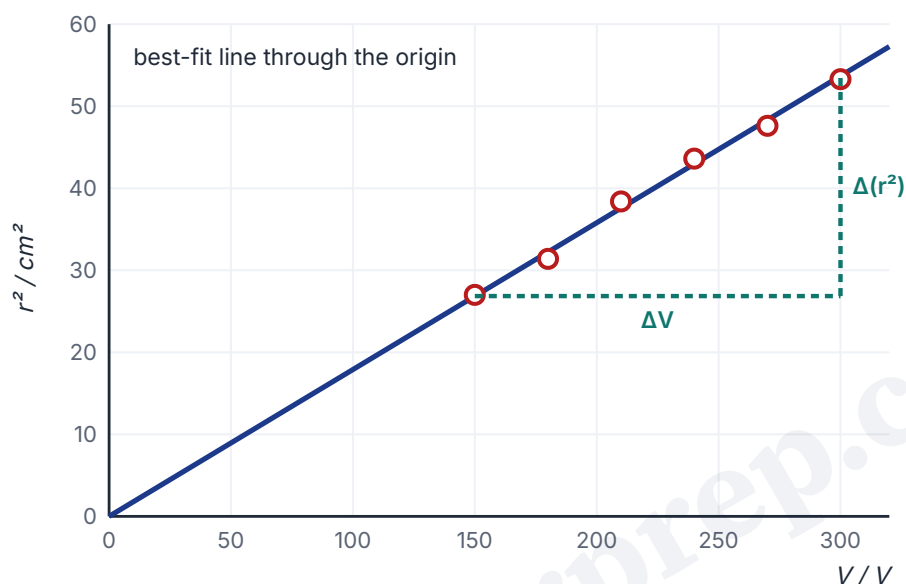
Observation	What it tells you
Sense of curving (clockwise or anticlockwise) in a known field	the sign of the charge (use the left-hand rule; a negative charge curves the opposite way to a positive one)
Radius at a known speed and field	the ratio q/m — not q and m separately
No deflection at all	the particle is uncharged (e.g. a neutron or a gamma photon) or moving along the field
Same speed, same field: proton, alpha particle ($q = 2e$, $m \approx 4\text{ u}$), electron	$r_\alpha \approx 2r_p$; $r_e = r_p/1836$, curving the other way

Because the radius depends only on m/q , particles with the same speed and the same m/q — for example an alpha particle and a deuteron ($q = e$, $m \approx 2\text{ u}$) — follow identical paths. Ions of the same element but different mass (isotopes) can be separated, which is the principle of a mass spectrometer.



Singly charged neon-20 and neon-22 ions, all moving at $2.0 \times 10^5 \text{ m s}^{-1}$, enter a 0.40 T field (the set-up of worked example 5), drawn to scale. The heavier ions move in a larger semicircle and land further from the entrance slit.

V / V	150	180	210	240	270	300
r / cm	5.2	5.6	6.2	6.6	6.9	7.3
r^2 / cm^2	27.0	31.4	38.4	43.6	47.6	53.3



r^2 against V for the electron beam in worked example 4 ($B = 0.80 \text{ mT}$). The data lie close to a straight line through the origin; the gradient triangle is drawn on the best-fit line, not between data points.

WORKED EXAMPLE 4 Medium · Determine (graph) / Explain

In a fine-beam tube, electrons are accelerated from rest through a potential difference V and enter a uniform magnetic field of 0.80 mT perpendicular to their velocity. The radius r of the circular beam is measured for six values of V (table above).

- (a) Show that a graph of r^2 against V should be a straight line through the origin. (b) Use the graph to determine the charge-to-mass ratio of the electron. (c) The magnetic field was in fact 5% smaller than the value used in the calculation. Explain the effect on the value found in (b).

$$\text{(a)} \quad eV = \frac{1}{2}m_e v^2 \text{ and } r = \frac{m_e v}{eB} \Rightarrow r^2 = \frac{m_e^2 v^2}{e^2 B^2} = \frac{m_e^2}{e^2 B^2} \times \frac{2eV}{m_e} = \frac{2m_e}{eB^2} V.$$

With B constant, $r^2 \propto V$: a straight line through the origin with gradient $\frac{2m_e}{eB^2}$.

(b) Using the triangle on the best-fit line from $V = 150 \text{ V}$ to $V = 300 \text{ V}$, where $\Delta(r^2) = 26.9 \text{ cm}^2$: $\text{gradient} = \frac{26.9}{150} = 0.179 \text{ cm}^2 \text{ V}^{-1} = 1.79 \times 10^{-5} \text{ m}^2 \text{ V}^{-1}$

$$\frac{e}{m_e} = \frac{2}{\text{gradient} \times B^2} = \frac{2}{1.79 \times 10^{-5} \times (0.80 \times 10^{-3})^2} = 1.7 \times 10^{11} \text{ C kg}^{-1} \text{ (} 1.75 \times 10^{11} \text{ C kg}^{-1} \text{)}$$

Data-booklet value: $1.60 \times 10^{-19} / 9.110 \times 10^{-31} = 1.76 \times 10^{11} \text{ C kg}^{-1}$.

(c) $\frac{e}{m_e} \propto \frac{1}{B^2}$. The value of B used was too large, so the calculated e/m_e is too **small**, by a factor $0.95^2 = 0.90$ — about 10 %. This is a systematic error: it does not change the straightness of the graph, only the value deduced from its gradient.

What happens in perpendicular electric and magnetic fields?

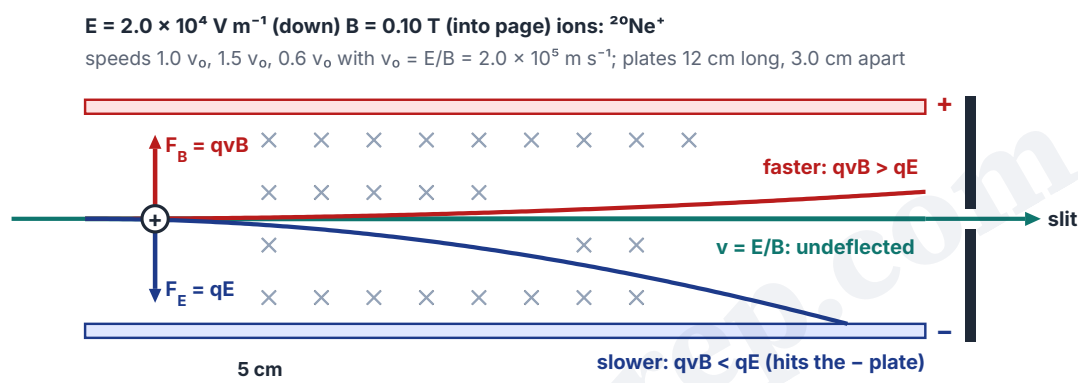
Now combine the two fields: a uniform electric field between parallel plates and a uniform magnetic field at right angles to it, both perpendicular to the particle's velocity. The fields are arranged so that the electric and magnetic forces are in **opposite directions**.

In perpendicular uniform electric and magnetic fields, a charged particle passes through undeflected when the electric and magnetic forces on it are equal and opposite, $qE = qvB$, which happens only for particles with speed $v = E/B$.

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

- Not in the data booklet: derive it by equating $F = qE$ and $F = qvB$.
- The charge cancels, so the selected speed is the same for **any** charge and mass, positive or negative: for a negative particle both forces reverse and still balance.

- **Faster** particles: $qvB > qE$, deflected in the direction of the magnetic force.
Slower particles: deflected in the direction of the electric force. Only particles at $v = E/B$ emerge through a slit in line with the entrance — a **velocity selector**.
- Inside the selector a deflected particle's path is neither a parabola nor a circle, because the magnetic force changes as the velocity changes. You only need to explain qualitatively which way it goes.



A velocity selector with $E = 2.0 \times 10^4 \text{ V m}^{-1}$ and $B = 0.10 \text{ T}$. Paths of neon-20 ions were computed from the forces and are drawn to scale. Ions at $v_0 = E/B$ go straight through; at $1.5 v_0$ the magnetic force wins and the ions miss the slit; at $0.6 v_0$ the electric force wins and they hit the negative plate.

TRY IT YOURSELF

D.3 Velocity selector simulation: adjust E and B and find the one speed that passes straight through. Then change the charge and mass and check that the selected speed does not change.

WORKED EXAMPLE 5 Hard · Determine / Explain

A beam of singly charged neon ions moving to the right passes through a velocity selector and then into a separate region of uniform magnetic field of 0.40 T (as in the diagram of section 4). The selector has a magnetic field of 0.080 T directed out of the page and parallel plates 1.5 cm apart. Only ions of speed $2.0 \times 10^5 \text{ m s}^{-1}$ are to pass through. The masses of the two isotopes are 20.0 u and 22.0 u .

(a) Determine the potential difference needed between the plates of the selector, and state which plate must be positive. (b) Explain why ions of both isotopes leave the selector with the same speed. (c) Determine the distance between the points where the two isotopes strike the detector after a semicircle.

(a) $E = vB = 2.0 \times 10^5 \times 0.080 = 1.6 \times 10^4 \text{ V m}^{-1}$; $V = Ed = 1.6 \times 10^4 \times 0.015 = \mathbf{240 \text{ V}}$

Direction: for a positive ion moving right in a field out of the page, the left-hand rule gives a magnetic force **down the page**. The electric force must act up, so the field points up: the **lower plate is positive**.

(b) The condition $qE = qvB$ does not contain the mass (and the charge cancels), so every ion that passes undeflected has $v = E/B$, whatever its mass.

(c) $r = \frac{mv}{qB}$: $r_{20} = \frac{20.0 \times 1.661 \times 10^{-27} \times 2.0 \times 10^5}{1.60 \times 10^{-19} \times 0.40} = 0.104 \text{ m}$; $r_{22} = \frac{22.0}{20.0} \times 0.104 = 0.114 \text{ m}$

Each lands a diameter from the slit, so the separation is $2(r_{22} - r_{20}) = 2 \times (0.1142 - 0.1038) = \mathbf{0.021 \text{ m} = 2.1 \text{ cm}}$

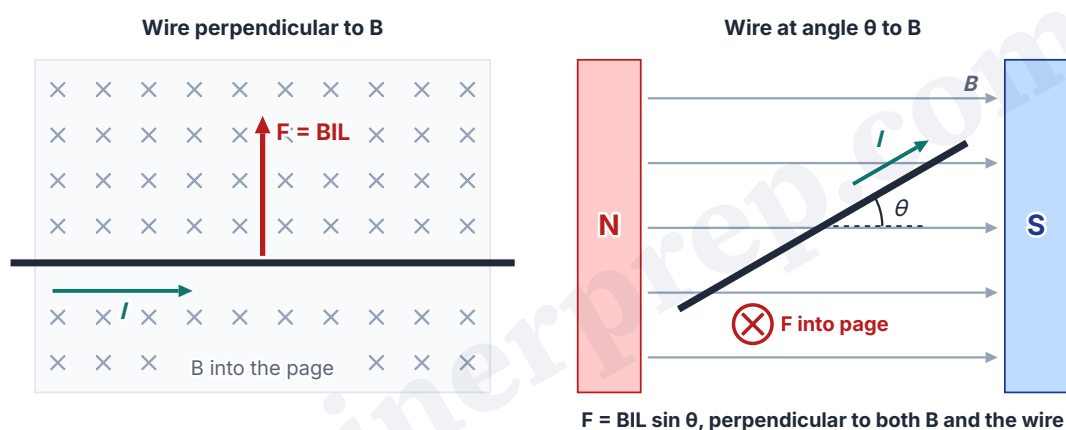
What force acts on a current-carrying wire in a magnetic field?

A current is a flow of charge, so a wire carrying a current in a magnetic field has a magnetic force on every moving charge carrier. These forces add up to a force on the wire itself — the **motor effect**.

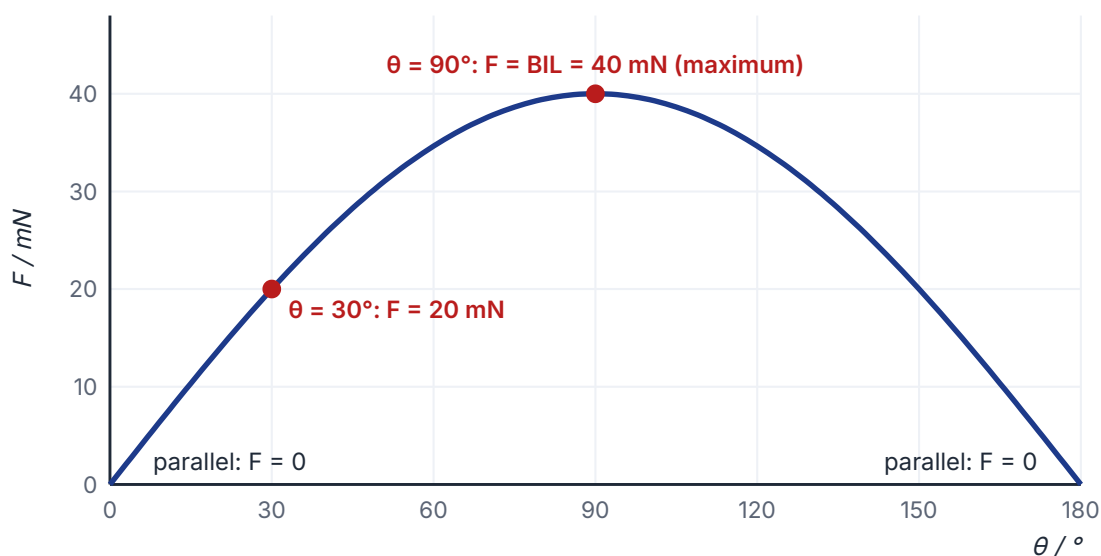
A conductor of length L carrying a current I at angle θ to a uniform magnetic field B experiences a force $F = BIL \sin \theta$, perpendicular to both the conductor and the field.

$$F = BIL \sin \theta$$

- F = force on the conductor (N), B = magnetic flux density (T), I = current (A), L = length of conductor in the field (m), θ = angle between the conductor (current) and the field. In the data booklet.
- Link with $F = qvB \sin \theta$: in a time t , a charge $q = It$ moves a distance $L = vt$, so $qv = ItL/t = IL$ and $qvB \sin \theta = BIL \sin \theta$.
- Direction: Fleming's left-hand rule, with the second finger along the **conventional current**. Reversing the current or the field reverses the force.
- A wire parallel to the field ($\theta = 0$) feels no force. The force is largest when the wire is perpendicular to the field.



Left: a wire carrying a current to the right in a field into the page is pushed up the page with $F = BIL$. Right: viewed from above, a wire at θ to the field between N and S poles; only the component of B perpendicular to the wire, $B \sin \theta$, contributes, and the force is into the page.



Force on a 0.20 m wire carrying 4.0 A in a 0.050 T field against the angle between the wire and the field. $F = BIL \sin \theta$: zero when the wire is parallel to the field and a maximum of 40 mN when it is perpendicular.

Quick example. A 0.20 m wire carrying 4.0 A lies at 30° to a 0.050 T field: $F = 0.050 \times 4.0 \times 0.20 \times \sin 30^\circ = 0.020 \text{ N}$.

TRY IT YOURSELF

D.3 Magnetic force on a wire simulation: change the current, field and angle and watch the force change as $BIL \sin \theta$.

Why do parallel current-carrying wires attract or repel?

The field around a straight wire

A current in a long straight wire produces a magnetic field whose lines are **concentric circles** centred on the wire, in planes perpendicular to it (D.2). The field is stronger close to the wire and weaker further away (the field strength is proportional to I/r).

Right-hand grip rule: grip the wire with the right hand, thumb pointing along the conventional current; the curled fingers give the direction of the magnetic field lines around the wire.

- Current **out of the page** ($\bullet$): field lines circle **anticlockwise**. Current **into the page** ($\times$): field lines circle **clockwise**.

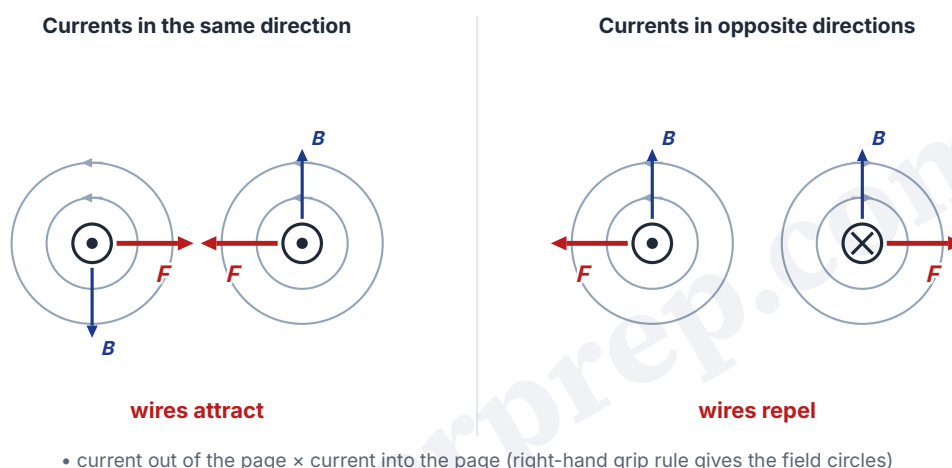
The force between two wires

Each wire sits in the magnetic field of the other, so each carries a current in a magnetic field and feels a force $F = BIL$. Applying the right-hand grip rule and then the left-hand rule:

- Currents in the **same direction**: the wires **attract**.
- Currents in **opposite directions**: the wires **repel**.

$$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$$

- F/L = force per unit length on each wire (N m^{-1}), μ_0 = permeability of free space = $4\pi \times 10^{-7} \text{ T m A}^{-1}$ (data booklet), I_1, I_2 = the two currents (A), r = separation of the wires (m). In the data booklet.
- The forces on the two wires are a **Newton's third law pair**: equal in size and opposite in direction, even if the currents are different. Both depend on the product $I_1 I_2$.
- $F/L \propto 1/r$: doubling the separation halves the force.



Two long parallel wires seen end-on. Grey circles: the field of each wire (right-hand grip rule). Blue: the field at each wire due to the other. Red: the force on each wire from the left-hand rule — towards each other for currents in the same direction, apart for opposite currents.

WORKED EXAMPLE 6 Medium · Calculate / Determine / State

In a battery pack, two straight parallel copper bars, each 0.80 m long and 2.0 cm apart (centre to centre), carry currents of 250 A in opposite directions.

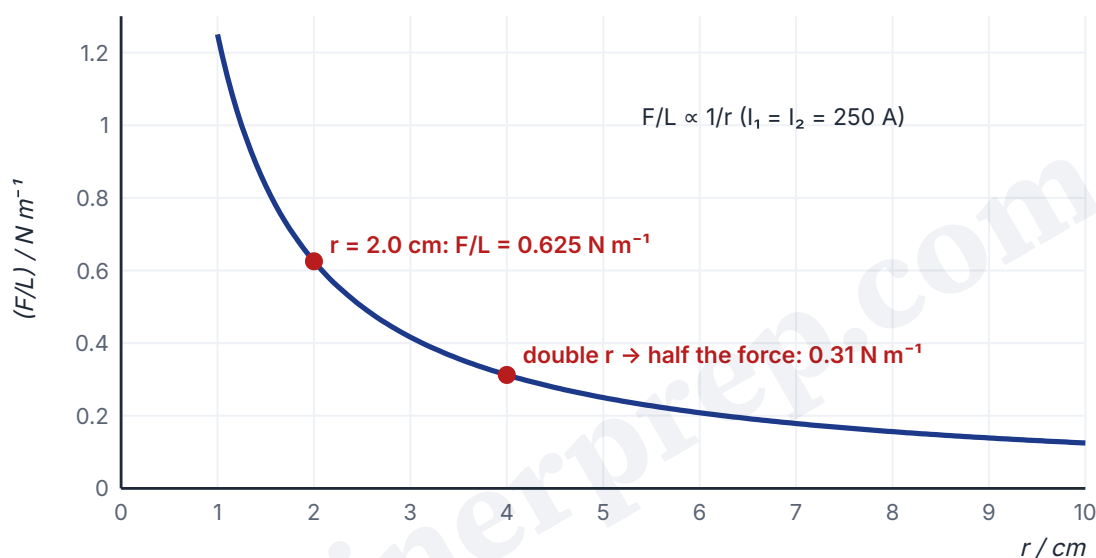
(a) Calculate the force on each bar and state whether the bars attract or repel. (b) Determine the magnetic flux density produced by one bar at the position of the other. (c) The current in one bar is halved. State the force on each bar now.

$$\text{(a)} \quad \frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r} = \frac{4\pi \times 10^{-7} \times 250 \times 250}{2\pi \times 0.020} = 0.625 \text{ N m}^{-1}$$

$F = 0.625 \times 0.80 = \mathbf{0.50 \text{ N}}$; the currents are opposite, so the bars **repel**.

(b) The force on the second bar is $F = BIL$ with B the field of the first bar: $B = \frac{F}{IL} = \frac{0.50}{250 \times 0.80} = 2.5 \times 10^{-3} \text{ T}$ (2.5 mT)

(c) $F \propto I_1 I_2$, so the force halves to **0.25 N on each bar**. The forces on the two bars are a Newton's third law pair, so they are still equal in size even though the currents are different.



Force per unit length between two parallel wires, each carrying 250 A, against their separation (the bars of worked example 6). F/L is inversely proportional to r .

Exam tips for D.3

EXAM TIP 1 — ELECTRONS ARE NEGATIVE

The most common lost mark in D.3 is a force direction given for a positive charge when the particle is an electron. Find the direction with the left-hand rule for conventional current and then **reverse it for a negative charge**. Say which way in words ("into the page", "towards the top of the page"), not just "downwards" when the diagram is a plan view.

EXAM TIP 2 — WHY THE KINETIC ENERGY IS CONSTANT

For "explain why the speed (or kinetic energy) is constant", the answer needs the link: the magnetic force is **perpendicular to the velocity**, so it

does no work on the particle. "The force is centripetal" on its own is not enough — say what that implies for the work done.

EXAM TIP 3 — DERIVE, DON'T QUOTE

$r = mv/(qB)$, $T = 2\pi m/(qB)$, $v = E/B$ and $q/m = 2V/(r^2 B^2)$ are not in the data booklet. In "show that" and "determine" questions start from the data-booklet equations: write $qvB = mv^2/r$ or $qE = qvB$ first. That line usually carries a mark on its own.

EXAM TIP 4 — PARABOLA VERSUS CIRCLE

An electric field gives a **parabolic** path (constant force in a fixed direction); a magnetic field gives a **circular** arc (constant-size force always perpendicular to the velocity). When sketching, the path in an electric field must leave the plates as a straight line, and a path in a magnetic field must be curved by the same amount everywhere inside a uniform field.

EXAM TIP 5 — JUSTIFY NEGLECTING GRAVITY

If asked why the weight of an electron or ion can be ignored, give numbers: compare qE (or qvB) with mg , or compare the acceleration with g . For the proton in worked example 1, $a \approx 2 \times 10^{11}g$. A bare statement such as "electrons are very light" earns little.

Common misconceptions

Misconception	Why it is wrong	Correct idea
A magnetic field speeds up a charged particle.	The force is perpendicular to the velocity, so no work is done.	A magnetic field changes only the direction of motion; an electric field can change the speed.
A stationary charge in a magnetic field feels a force.	$F = qvB \sin \theta$ is zero when $v = 0$.	Only moving charges (with a velocity component across the field) feel a magnetic force.
The magnetic force acts along the field lines, like the electric force.	The electric force is parallel to E ; the magnetic force is perpendicular to B .	F is perpendicular to both v and B .
A faster particle in a magnetic field goes round in a shorter time.	Its circle is larger in proportion to its speed.	$T = 2\pi m/(qB)$ is independent of speed.
The wire with the larger current feels the larger force.	Each force depends on the product $I_1 I_2$, and they form a Newton's third law pair.	The forces on two parallel wires are always equal and opposite.
A velocity selector only works for particles of one charge or mass.	The charge cancels in $qE = qvB$, and the mass does not appear.	It selects speed $v = E/B$ only, for any charge (either sign) and any mass.

How this topic connects

A magnetic force as the centripetal force: why charges move in circles

Circular motion needs a force of constant size directed towards a centre, always perpendicular to the velocity (A.2). The magnetic force qvB on a charge moving perpendicular to a uniform field has exactly these properties, so it acts as the centripetal force and $qvB = mv^2/r$. Gravity (D.1) and the electric force (D.2) can also give circular orbits — a planet round a star, or (in the Bohr model of E.1) an

electron round a nucleus — but there the force points towards a central body. The uniform electric field between plates cannot produce circular motion, because its force has a fixed direction.

Identifying a particle from the radius of its path

The radius $r = mv/(qB)$ gives the charge-to-mass ratio once v and B are known, and the sense of rotation gives the sign of the charge. Thomson's measurement of e/m for cathode rays showed that they were particles with a specific charge more than a thousand times that of the hydrogen ion (the modern ratio is about 1840) — the discovery of the electron. In particle detectors, tracks curving opposite ways reveal opposite charges, and tracks of particles with the same speed but different radii reveal different masses, as with the neon isotopes in worked example 5.

Energy bookkeeping for charges in electric and magnetic fields

In an electric field, the work done by the field on a charge moving through a potential difference V becomes kinetic energy: $\Delta E_k = qV$. This is how speeds are found for particles from an electron gun or an ion accelerator (worked examples 1–3). In a magnetic field, no work is done, so the kinetic energy is conserved on its own — which is why the radius of a circular path stays constant. In crossed fields only the electric force does work: a particle deflected towards the negative plate (for a positive charge) speeds up, one deflected the other way slows down.

Tools & inquiry — measuring in fields (NOS: representing fields)

- **Fine-beam tube:** measure the diameter of the glowing circle rather than the radius, reading both sides against a scale while looking perpendicular to it to avoid parallax. The uniform field is usually produced by a pair of coils, with B proportional to the coil current.
- **Linearise:** plot r^2 against V (gradient $2m/(qB^2)$), or $1/r$ against B at constant V , rather than using a single reading.
- **Current balance:** a wire on a sensitive balance in the field of a magnet; the change in balance reading against current is a straight line with

gradient BL/g (in kg A^{-1}), giving B .

- **NOS — representing fields:** field lines, the dot-and-cross convention and left/right-hand rules are human conventions for showing three-dimensional vector fields on a flat page. They are models: no “line” exists in space, but the representation lets us predict forces correctly.
- **NOS — defining units:** the force between parallel wires was once used to define the ampere. Since 2019 the ampere has been defined by fixing the value of the elementary charge e , and μ_0 is now a measured quantity (still very close to $4\pi \times 10^{-7} \text{ T m A}^{-1}$).

Key equations

Equation	Use	In data booklet?
$F = qE, E = \frac{V}{d}$	force on a charge in a uniform electric field between plates	yes (D.2)
$\Delta E_k = qV$	energy gained moving through a potential difference	no — from $V = W/q$ (B.5)
$F = qvB \sin \theta$	magnetic force on a moving charge	yes
$r = \frac{mv}{qB}$	radius of circular path in a magnetic field	no — from $qvB = mv^2/r$
$T = \frac{2\pi m}{qB}$	period of circular motion (independent of v)	no — from $T = 2\pi r/v$
$\frac{q}{m} = \frac{v}{rB} = \frac{2V}{r^2 B^2}$	charge-to-mass ratio	no — derive
$v = \frac{E}{B}$	velocity selector (crossed fields)	no — from $qE = qvB$
$F = BIL \sin \theta$	force on a current-carrying conductor	yes
$\frac{F}{L} = \mu_0 \frac{I_1 I_2}{2\pi r}$	force per unit length between parallel wires	yes

Check your understanding

1. A wire of length 0.15 m carries a current of 3.0 A at 50° to a uniform magnetic field of 0.040 T. Calculate the force on the wire.

$F = BIL \sin \theta = 0.040 \times 3.0 \times 0.15 \times \sin 50^\circ = 1.4 \times 10^{-2}$ N (0.0138 N), perpendicular to both the wire and the field.

2. An alpha particle moves in a circle in a uniform magnetic field. Explain why the field does no work on it, and state what happens to its kinetic energy.

The magnetic force is always perpendicular to the velocity, and so to the displacement at every instant; $\text{work} = F s \cos 90^\circ = 0$. The kinetic energy (and the speed) therefore stays constant; only the direction of motion changes.

3. An electron and a proton enter the same uniform magnetic field with the same velocity, perpendicular to the field. Compare their paths.

Both move in circles, but in **opposite senses** because their charges are opposite. Their charges have the same magnitude, so $r \propto m$: $\frac{r_p}{r_e} = \frac{1.673 \times 10^{-27}}{9.110 \times 10^{-31}} = 1.84 \times 10^3$ — the proton's circle is about 1840 times larger.

4. Calculate the time taken for a proton to complete one circle in a uniform field of 0.50 T. How does this change if the proton's speed is doubled?

$T = \frac{2\pi m_p}{eB} = \frac{2\pi \times 1.673 \times 10^{-27}}{1.60 \times 10^{-19} \times 0.50} = 1.3 \times 10^{-7} \text{ s}$ ($1.31 \times 10^{-7} \text{ s}$, a frequency of 7.6 MHz). Doubling the speed doubles the radius but leaves the period **unchanged**.

5. A velocity selector has an electric field of $3.0 \times 10^4 \text{ V m}^{-1}$ and a magnetic field of 0.020 T. Determine the speed of the particles that pass undeflected. Would an electron with this speed also pass undeflected?

$v = \frac{E}{B} = \frac{3.0 \times 10^4}{0.020} = 1.5 \times 10^6 \text{ m s}^{-1}$. Yes: for an electron both the electric and the magnetic force reverse direction, and their magnitudes eE and evB are still equal, so they still balance.

Practise D.3 with exam-style questions

Original Paper 1A, 1B and 2 questions on motion in electromagnetic fields, with full mark schemes. Tick the questions you want and print them as your

own test.

SL D.3 questions

HL D.3 questions

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