OCR A Level Physics

Your notes

Magnetic Fields

Contents

Magnetic Fields

Your notes

Defining Magnetic Fields

- A magnetic field is a **field of force** that is created either by:
  - **Moving** electric charge
  - **Permanent** magnets
- A magnetic field is sometimes referred to as a **B-field**
- Permanent magnets are materials that produce a magnetic field
- A magnetic field is created around a **current carrying wire** due to the movement of electrons
  - A stationary charge will **not** produce a magnetic field
- Although magnetic fields are invisible, they can be observed by the force that pulls on magnetic materials
  - Examples include iron or the movement of a needle in a plotting compass

Representing Magnetic Fields

- Magnetic fields are represented by magnetic field lines
  - These can be shown using iron filings or plotting compasses
- Field lines are best represented on **bar magnets**, which consist of a north pole on one end and south pole on the other
- The magnetic field is produced on a bar magnet by the movement of electrons within the atoms of the magnet
  - This is a result of the electrons circulating around the atoms, representing a tiny current and hence setting up a magnetic field
- The direction of a magnetic field on a bar magnet is always from **north to south**

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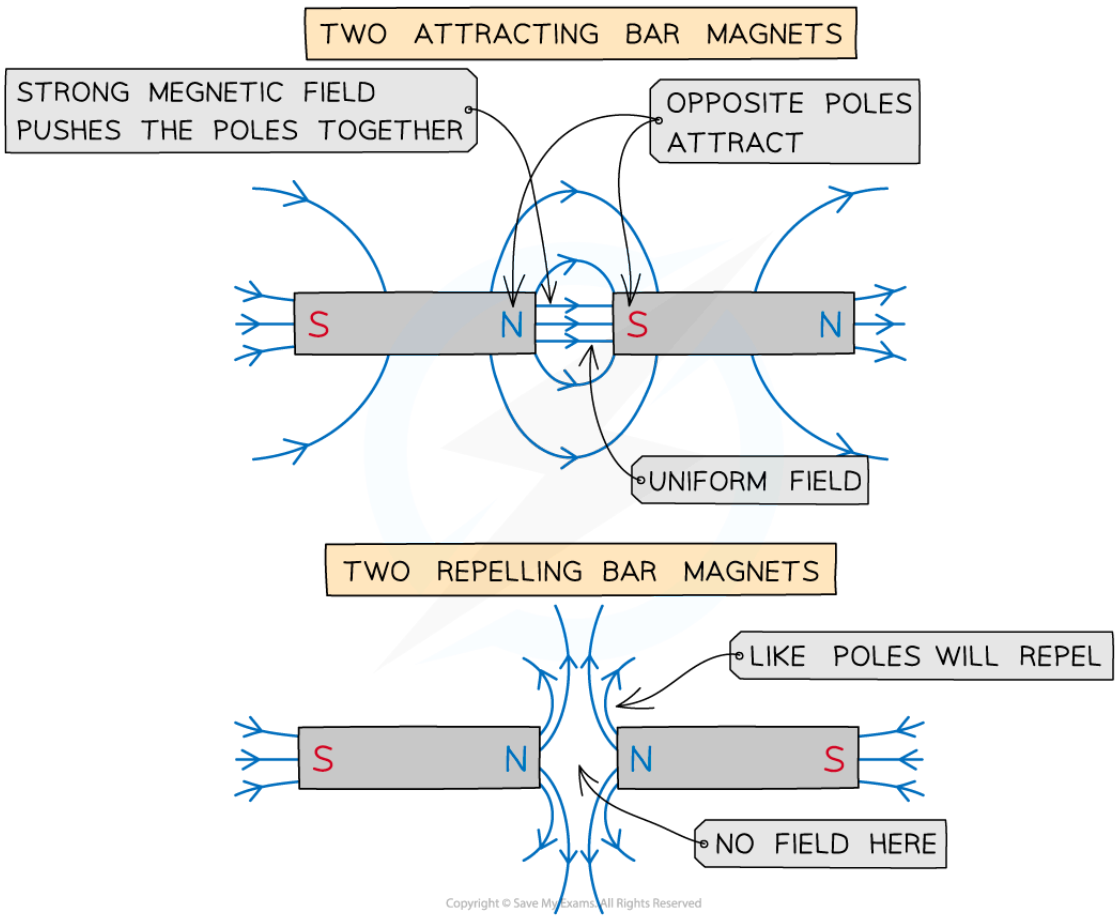
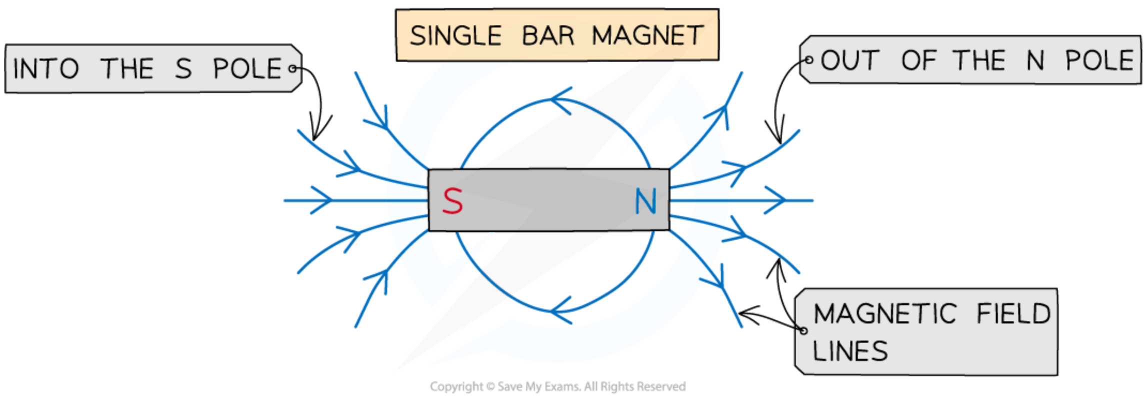


Magnetic field lines are directed from the north pole to the south pole

- When two bar magnets are pushed together, they either attract or repel each other:
  - Two **like** poles (north and north or south and south) **repel** each other
  - Two **opposite** poles (north and south) **attract** each other



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Two opposite poles attract each other and two like poles repel each other

- **The key aspects of drawing magnetic field lines:**
  - The lines come **out** from the north poles and **into** the south poles
  - The direction of the field line shows the direction of the force that a free magnetic north pole would experience at that point
  - The field lines are **stronger** the **closer** the lines are together
  - The field lines are **weaker** the **further apart** the lines are
  - Magnetic field lines **never** cross since the magnetic field is unique at any point
  - Magnetic field lines are **continuous**
- A uniform magnetic field is where the magnetic field strength is the same at all points
  - This is represented by equally spaced parallel lines, just like electric fields

Magnetic Fields Lines

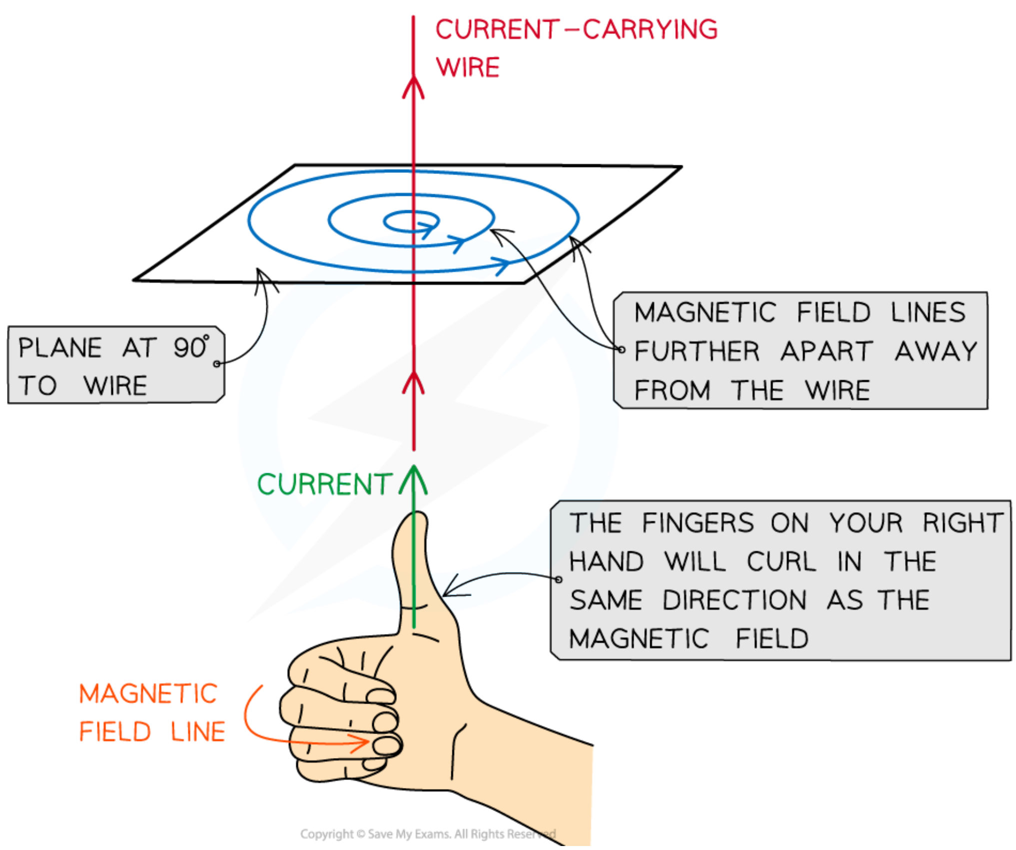
Your notes

Magnetic Field Lines

- Magnetic field patterns are not only observed around bar magnets, magnetic fields are formed wherever current is flowing, such as in:
  - Long straight wires
  - Long solenoids
  - Flat circular coils

Field Lines in a Current-Carrying Wire

- Magnetic field lines in a current carrying wire are circular rings, centered on the wire
- The field lines are strongest near the wire and become further part away from the wire
- Reversing the current reverses the direction of the field



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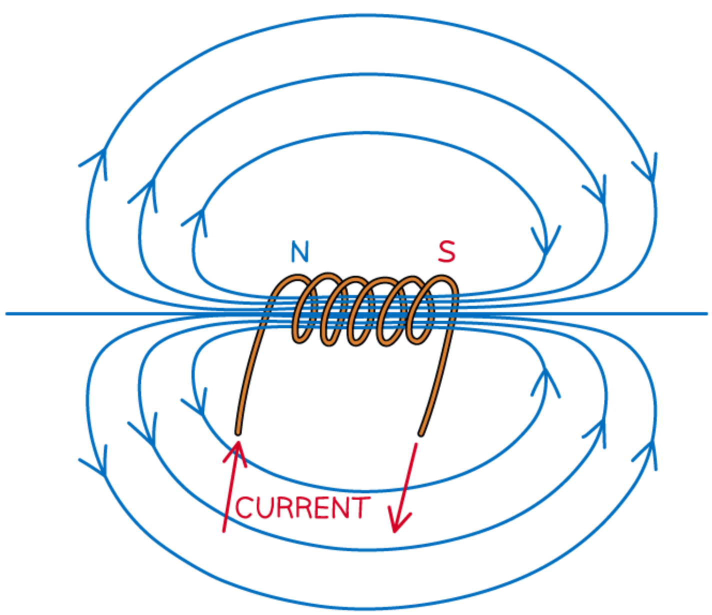
The direction of magnetic field lines on a current carrying wire can be determined by the right hand thumb rule

- The field lines are clockwise or anticlockwise around the wire, depending on the direction of the current
- The direction of the magnetic field is determined by **Maxwell's right hand screw rule**
  - This is determined by pointing the **right-hand** thumb in the direction of the current in the wire and curling the fingers onto the palm
  - The direction of the curled fingers represents the direction of the magnetic field around the wire
  - For example, if the current is travelling vertically upwards, the magnetic field lines will be directed anticlockwise, as seen from directly above the wire
  - **Note:** the direction of the current is taken to be the conventional current ie. from **positive** to **negative**, **not** the direction of electron flow

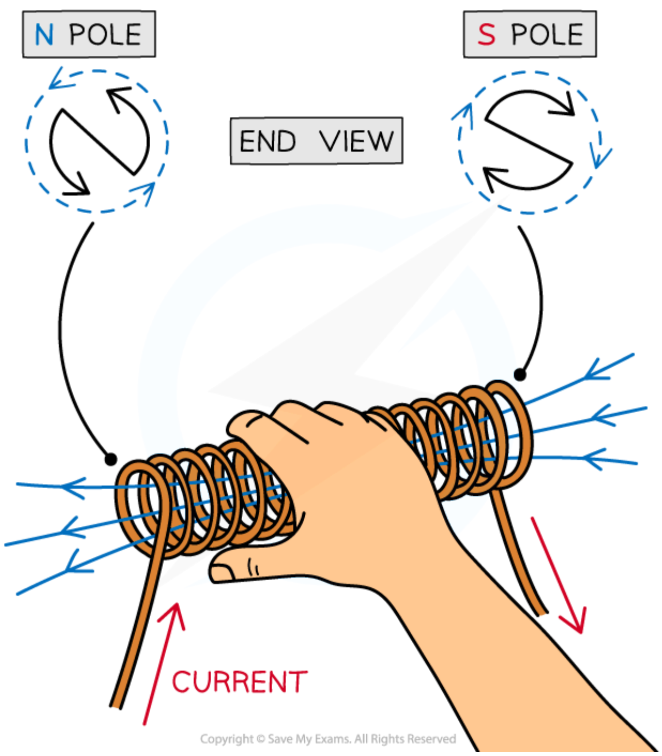
Field Lines in a Solenoid

- As seen from a current-carrying wire, an electric current produces a magnetic field
- An electromagnet makes use of this by using a coil of wire called a solenoid which concentrates the magnetic field
- One end becomes a north pole and the other the south pole



Magnetic field lines around a solenoid are similar to a bar magnet

- Therefore, the magnetic field lines around a solenoid are very similar to a bar magnet
  - The field lines **emerge** from the **north** pole
  - The field lines **return** to the **south** pole
- Which is the north or south pole depends on the direction of the current
  - This can be found by using the **right hand grip rule**



Using the right-hand grip rule to determine the direction of the magnetic field around a solenoid

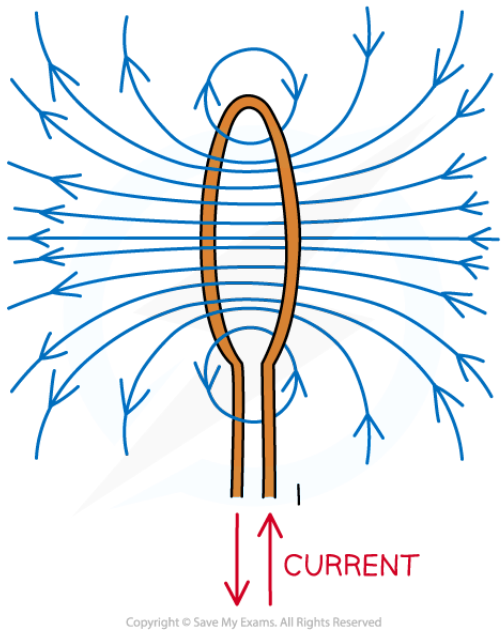
- To determine the direction of the magnetic field around a solenoid:
  - Grip the coil so the fingers represent the direction of the flow of conventional current (i.e. from the **positive** to the **negative** terminal)
  - The thumb points in the direction of the magnetic field lines through the coil from **north** to **south**

Field Lines in a Flat Circular Coil

- A flat circular coil is equal to one of the coils of a solenoid

Your notes

- The field lines will emerge through one side of the circle (north pole) and leave the other (south pole)
- As before, the direction of the north and south poles depends on the direction of the current
  - This can be determined by using the **right-hand thumb rule**
  - It is easier to find the direction of the magnetic field on the straight part of the circular coil to determine which direction the field lines are passing through



Magnetic field lines of a single circular coil are added up together to make to make the field lines of a solenoid

Factors Affecting the Magnetic Field Strength

- The strength of the magnetic field of a solenoid can be increased by:
  - Adding a core made from a **ferrous** (iron-rich) material eg. an iron rod
  - Adding **more turns** in the coil
- When current flows through the solenoid with an iron core, it becomes magnetised, creating an even stronger field
  - The addition of an iron core can strengthen the magnetic field up to a several hundred times more
- When more turns are added to the coil, this concentrates the magnetic field lines, causing the magnetic field strength to increase

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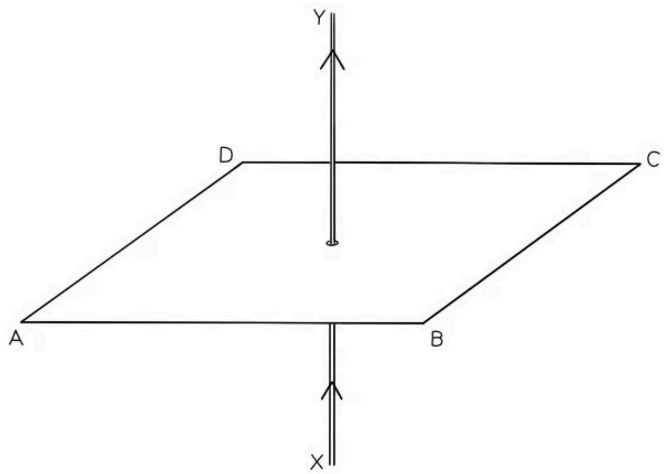
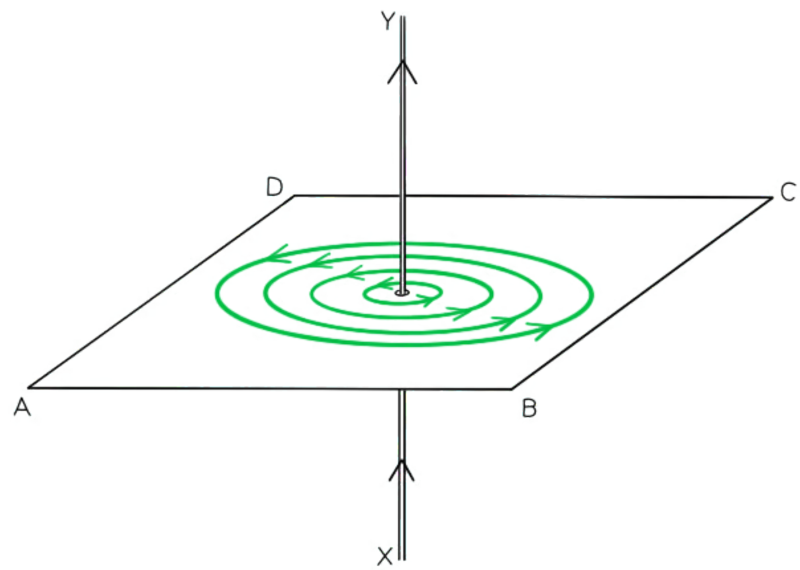
Worked Example

The current in a long, straight vertical wire is in the direction XY, as shown in the diagram.



Sketch the pattern of the magnetic flux in the horizontal plane ABCD due to the current-carrying wire. Draw at least four flux lines.

Answer:



✓ **Concentric circles**

✓ **Increasing separation between each circle**

✓ **Arrows drawn in anticlockwise direction**

Your notes

Examiner Tips and Tricks

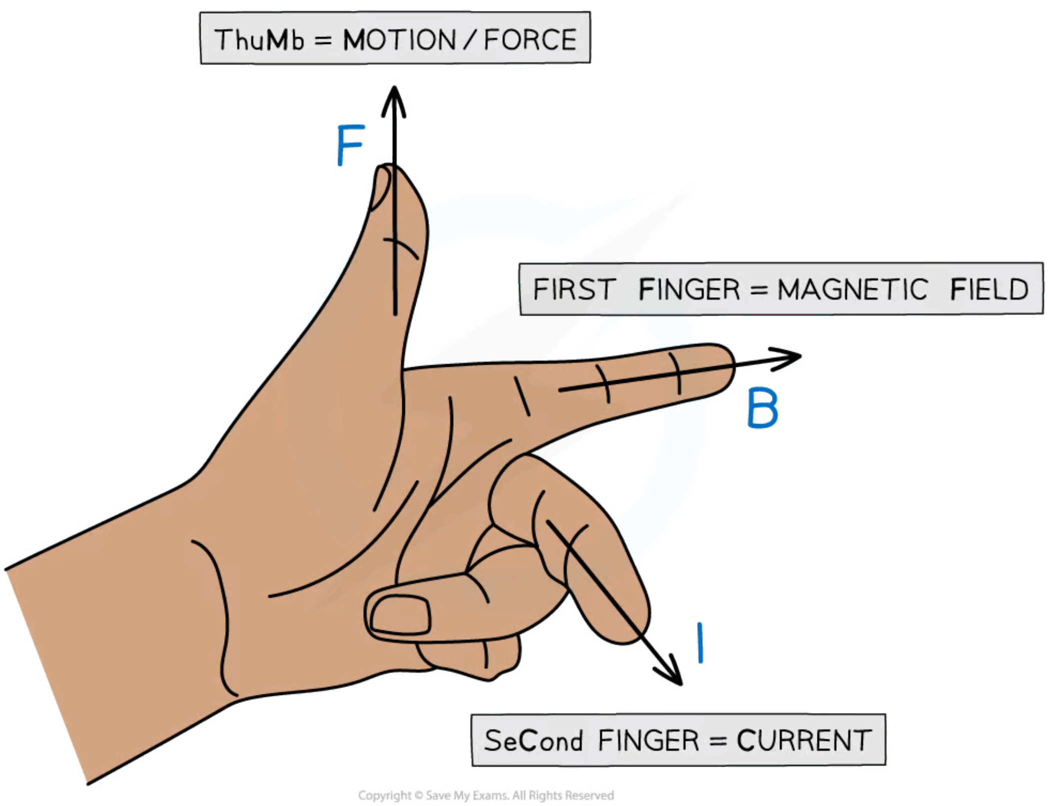
Remember to draw the arrows showing the direction of the field lines on every single field line you draw. Also, ensure that in a uniform magnetic field, the field lines are equally spaced.

Fleming's Left-Hand Rule

Your notes

Fleming's Left-Hand Rule

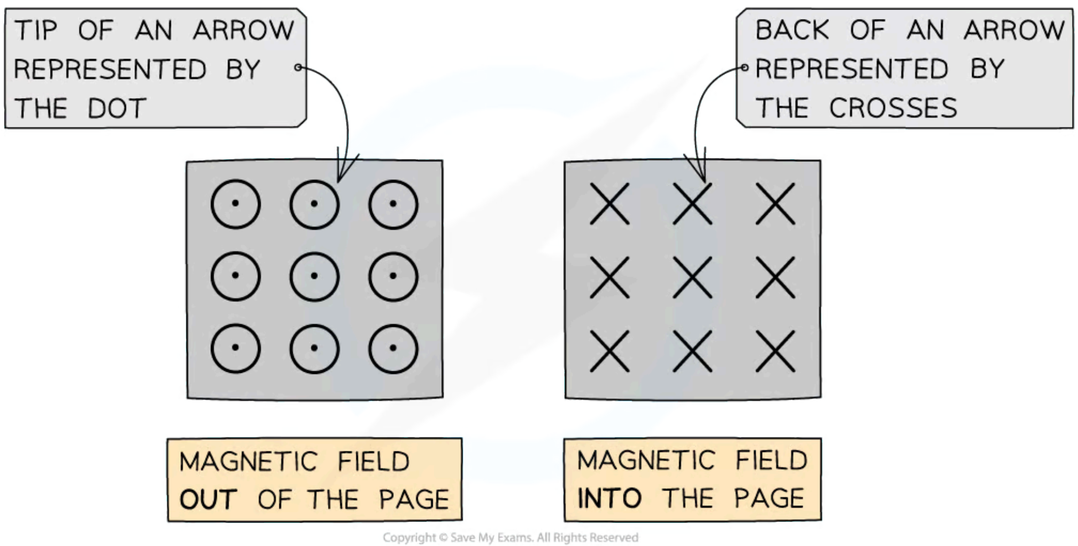
- **Fleming's left hand rule** can be used to determine the direction of the magnetic force on a moving charged particle in a magnetic field
  - The **First Finger** = direction of the magnetic field
  - The **Second Finger** = direction of conventional current (i.e. the velocity of a moving **positive charge**)
  - The **Thumb** = direction of the magnetic force
- Fleming's Left Hand Rule is illustrated in the image below:



Fleming's Left Hand Rule shows the magnetic force, magnetic field and conventional current (flow of positive charge) are all perpendicular to each other

Your notes

- Since this is represented in 3D space, sometimes the flow of charge, magnetic force or magnetic field could be directed into or out of the page, not just left, right, up and down
- The direction of the magnetic field **into** or **out of** the page in 3D is represented by the following symbols:
  - **Dots** (sometimes with a circle around them) represent the magnetic field directed **out** of the plane of the page
  - **Crosses** represent the magnetic field directed **into** the plane of the page



The magnetic field into or out of the page is represented by circles with dots or crosses

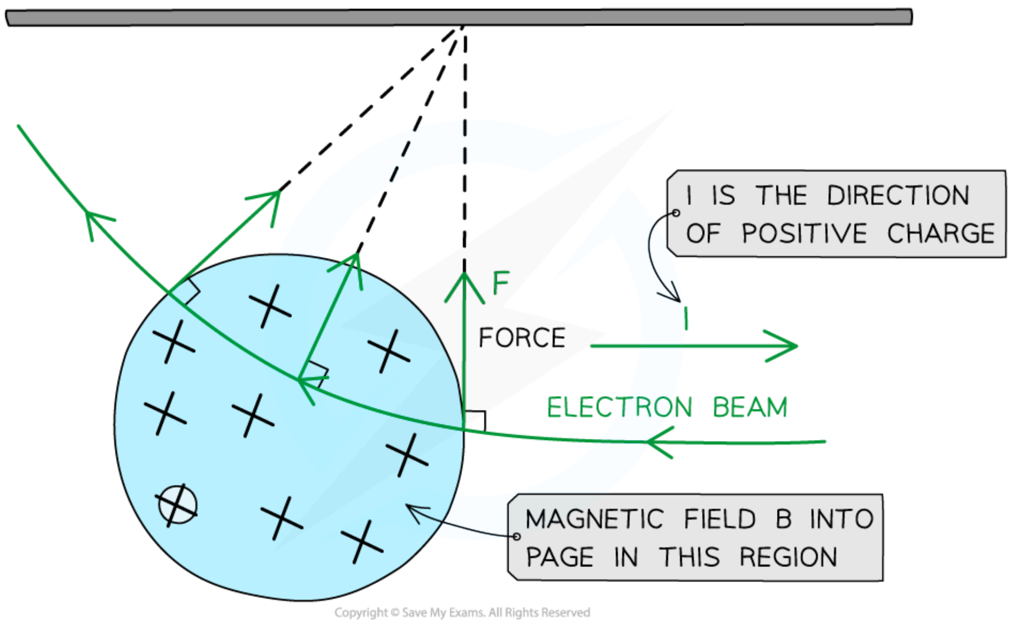
- The way to remember this is by imagining an arrow used in archery or darts:
  - If the arrow is approaching **head-on**, such as out of a page, only the very tip of the arrow can be seen (a dot)
  - When the arrow is **moving away**, such as into a page, only the cross of the feathers at the back can be seen (a cross)

An Electron Moving in a Magnetic Field

- The maximum magnetic force on a moving charged particle is always perpendicular to its velocity
  - This means magnetic forces cause charged particles to move in a **circle**

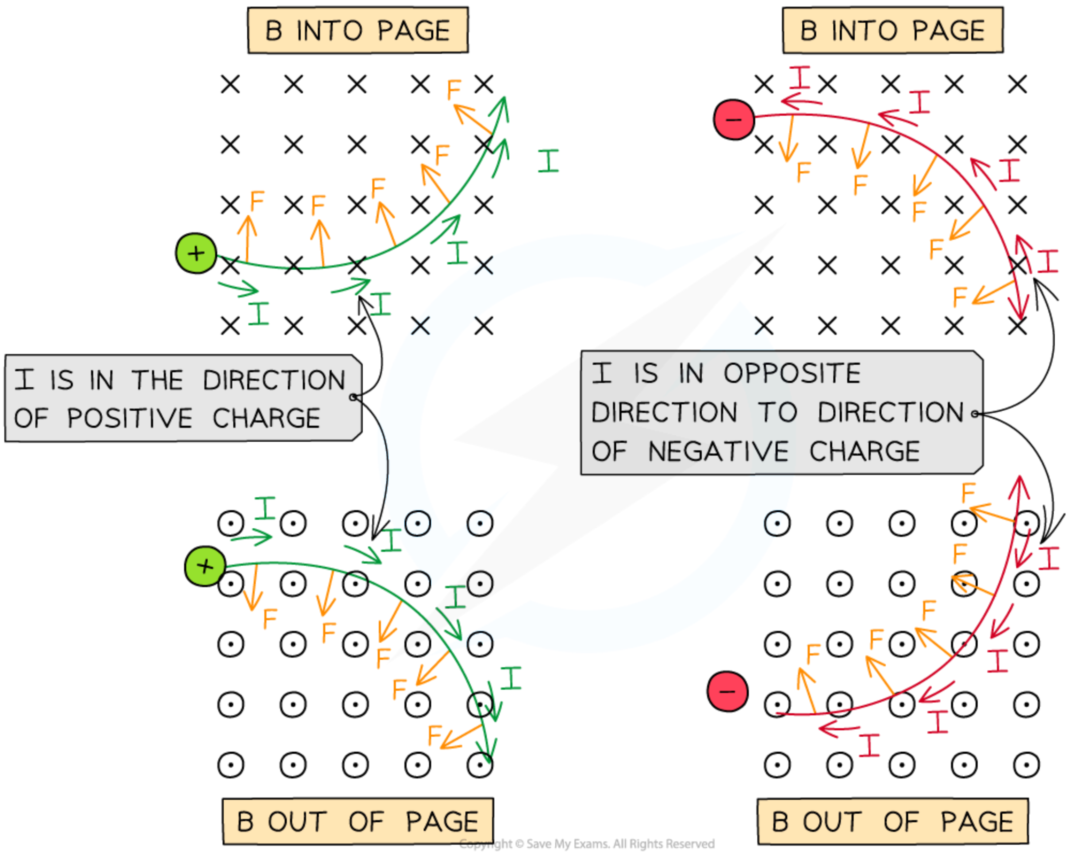
Your notes

- The **direction** of magnetic force on the charged particle can be determined using Fleming's Left Hand Rule
  - The image below shows an electron incident on a uniform magnetic field B directed into the page:



An electron moving to the left as shown is equivalent to a conventional positive charge or current moving to the right. Using Fleming's Left Hand Rule, the direction of the force can be determined

- According to Fleming's Left Hand Rule:
  - B is directed into the page, therefore the first finger should point **into** the page
  - The conventional current (or velocity of a **positive charge**) is directed to the **right** (because an electron is moving to the left), therefore the second finger should point to the **right**
  - Therefore, the force on the electron as shown by the thumb is initially **upwards** as it enters the magnetic field
- The force due to the magnetic field i**s always perpendicular to the velocity** of the electron
  - **Note:** this is equivalent to circular motion
  - Therefore, the magnetic force on a moving charge is a **centripetal force**
- The centripetal force is what keeps moving charges following a **circular** trajectory
- Examples of the direction of the magnetic force on positive and negative particles are:



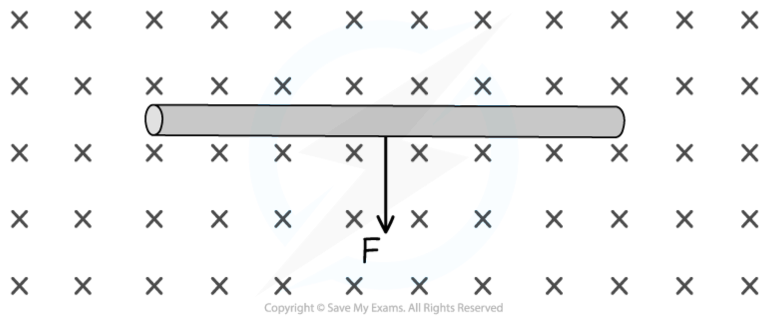
The direction of the magnetic force F on positive and negative particles in a B field in and out of the page

- Fleming's Left Hand Rule can also be used to find the direction of the force, magnetic field and velocity
  - The key difference is that the second finger, representing current *I* (direction of positive charge), can now be used as the **direction of velocity, *v*** of a **positive** charge

Worked Example

A current flows perpendicularly to a uniform magnetic field as shown in the diagram below.

Your notes



As a result, the conductor carrying the current experiences a magnetic force, *F*.

Determine the direction of the current flowing in the conductor.

Answer:

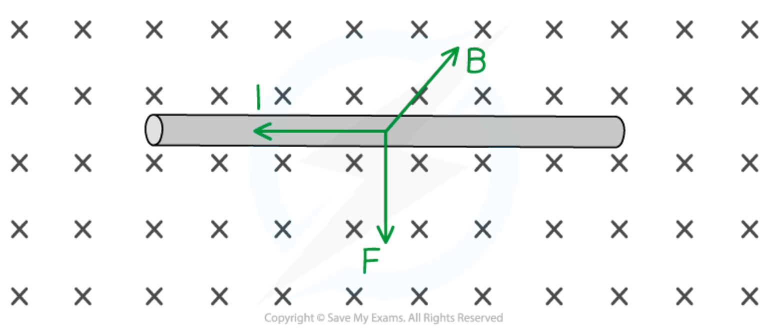
Step 1: Apply the instructions for Fleming's Left Hand Rule

- Using Fleming's Left Hand Rule for the quantities given:
  First finger is the magnetic field, *B* = into the page (or screen!)

  Thumb is the direction of the magnetic force *F* = vertically downwards

Step 2: Determine the direction of the conventional current

- The first finger should be pointing into the page (or screen!) along the direction of the field
  - Rotating the entire hand allows the thumb to point downwards, along the direction of force
- The second finger should be pointing towards the left of the page (or screen!)
- This is the direction of conventional current in the wire, i.e., from **right to left**



Examiner Tips and Tricks

You will certainly need to apply Fleming's Left Hand Rule in your examination, at some point, whenever there is a current or charge flowing in a magnetic field. Remember, it is used to give the **direction** of either the magnetic force *F*, the magnetic field *B*, or the conventional current (or flow of positive charge) *I*.

The most important point when using Fleming's left hand rule is the direction of the **charge** (or **current** flow). This is always the direction of **positive** charge. Therefore, for electrons, or negatively charged ions, you should point your second finger for the current in the **opposite** direction to its motion.

As ever, you will gain more confidence twisting your arm in funny positions with three fingers at right-angles the more questions you practise: the more, the better!

Your notes

Force on a Current-Carrying Conductor

Your notes

Magnetic Flux Density

- The magnetic flux density B is defined as:

  The force acting per unit current per unit length on a current-carrying conductor placed perpendicular to the magnetic field

- Rearranging the equation for magnetic force on a wire, the magnetic flux density is defined by the equation:

$$B = \frac{F}{IL}$$

- Where:
  - B = magnetic flux density (T)
  - F = magnetic force (N)
  - I = current (A)
  - L = length of the wire (m)
- **Note:** this equation is only relevant when the B-field is **perpendicular** to the current
- Magnetic flux density is measured in units of **tesla**, which is defined as:

  A wire carrying a current of 1 A normal to a magnetic field of flux density of 1 T with force per unit length of the conductor of 1 N m^{-1}

- To put this into perspective, the Earth's magnetic flux density is around 0.032 mT and an ordinary fridge magnet is around 5 mT
- The magnetic flux density is sometimes referred to as the **magnetic field strength**

Worked Example

A 15 cm length of wire is placed vertically and at right angles to a magnetic field. When a current of 3.0 A flows in the wire vertically upwards, a force of 0.04 N acts on it to the left.

Your notes

Determine the flux density of the field and its direction.

Answer:

Step 1: Write out the known quantities

- Force on wire, F = 0.04 N
- Current, I = 3.0 A
- Length of wire, L = 15 cm = 15×10^{-2} m

Step 2: Write out the magnetic flux density *B* equation

$$B = \frac{F}{IL}$$

Step 3: Substitute in values

$$B = \frac{0.04}{3 \times (15 \times 10^{-2})} = 0.089 \text{ T (2 s.f.)}$$

Step 4: Determine the direction of the B field

- Using Fleming's left-hand rule :

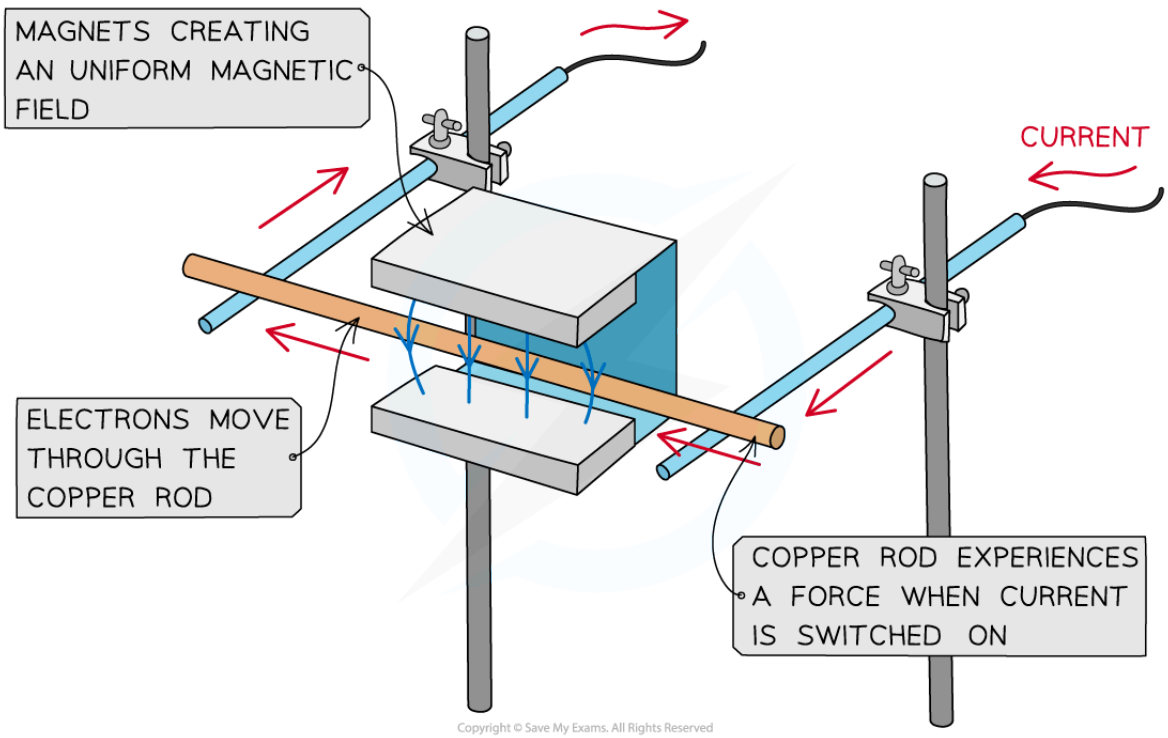
F = to the left

I = vertically upwards

therefore, ***B* = into the page**

Force on a Current-Carrying Conductor

- A current-carrying conductor produces its own **magnetic field**
  - An **external magnetic field** will therefore exert a **magnetic force** on it
- A current-carrying conductor (e.g. a wire) will experience the **maximum** magnetic force if the current through it is **perpendicular** to the direction of the magnetic flux lines
  - A simple situation would be a copper rod placed within a uniform magnetic field
  - When current is passed through the copper rod, it experiences a **force** which makes it accelerate



A copper rod moves within a magnetic field when current is passed through it

- The force F on a conductor carrying current I in a magnetic field with flux density B is defined by the equation

$$F = BIL \sin \theta$$

- Where:
  - F = magnetic force on the current-carrying conductor (N)
  - B = magnetic flux density of external magnetic field (T)
  - I = current in the conductor (A)
  - L = length of the conductor in the field (m)
  - θ = angle between the conductor and external flux lines (degrees)
- This equation shows that the magnitude of the magnetic force F is **proportional** to:
  - Current I
  - Magnetic flux density B

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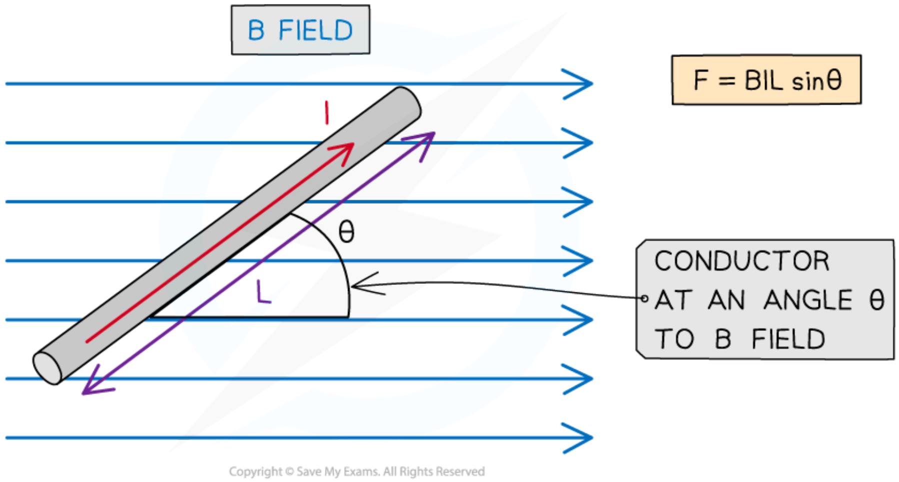
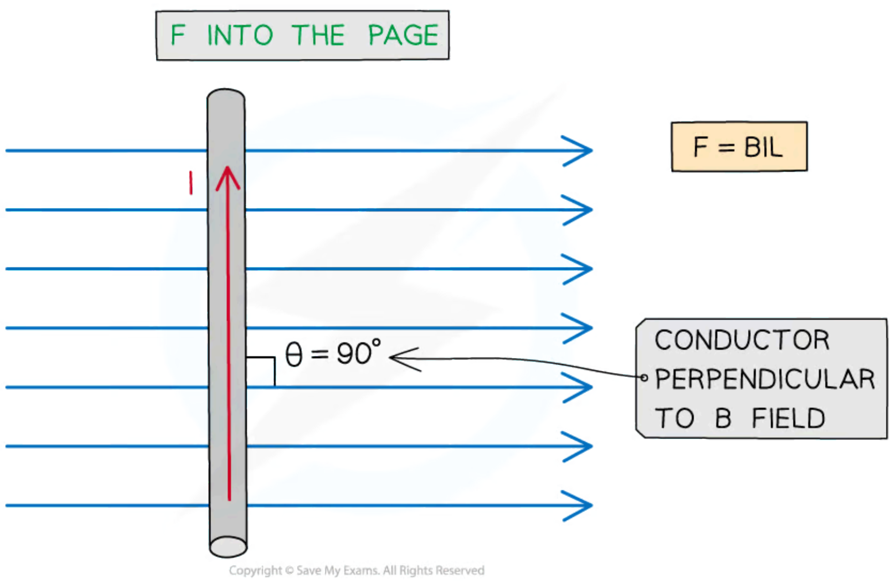
Your notes

- Length of conductor in the field L
- The sine of the angle θ between the conductor and the magnetic flux lines





Magnitude of the force on a current carrying conductor depends on the angle of the conductor to the external B field

- The **maximum** force occurs when $\sin\theta = 1$
  - This means $\theta = 90^\circ$ and the conductor is **perpendicular** to the B field
  - This equation for the magnetic force now becomes:

Your notes

$$F = BIL$$

- The **minimum** force (0) is when sin θ = 0
  - This means θ = 0° and the conductor is **parallel** to the B field
- It is important to note that a current-carrying conductor will experience **no** force if the current in the conductor is parallel to the field

Worked Example

A current of 0.87 A flows in a wire of length 1.4 m placed at 30° to a magnetic field of flux density 80 mT.

Calculate the force on the wire.

Answer:

Step 1: Write down the known quantities

- Magnetic flux density, B = 80 mT = 80×10^{-3} T
- Current, I = 0.87 A
- Length of wire, L = 1.4 m
- Angle between the wire and the magnetic flux lines, θ = 30°

Step 2: Write down the equation for the magnetic force on a current-carrying conductor

$$F = BIL \sin\theta$$

Step 3: Substitute in values and calculate

$$F = (80 \times 10^{-3}) \times (0.87) \times (1.4) \times \sin(30) = 0.04872 = 0.049 \text{ N (2 s.f)}$$

Examiner Tips and Tricks

Remember that the direction of current is the flow of **positive** charge (i.e. conventional current) and this is in the **opposite direction** to the flow of electrons (i.e. electron flow)!

Your notes

Magnetic Flux Density

Determining Magnetic Flux Density

Aims of the Experiment

- The overall aim of this experiment is to calculate the magnetic flux density of a magnet
  - This is done by measuring the force on a current-carrying wire placed perpendicular to the field

Variables

- Independent variable = Current, I
- Dependent variable = mass, m
- Control variables:
  - Length of wire, L
  - Magnetic Flux density, B
  - Potential difference of the power supply

Equipment List

Apparatus	Purpose
Electronic top-pan balance	To measure the mass
Thick copper wire	The object which will experience the magnetic force
Variable Resistor	To vary the current flowing through the wire
DC Power supply	To provide the potential difference through the wire
Ammeter	To measure the current through the wire
2 magnets with opposite poles in a metal cradle	To create the magnetic field
Clamp (retort) stand	To hold the wire in the magnetic field
30 cm ruler	To measure the length of the magnet (which will count as the length of the wire)
Crocodile clips	To hold both ends of the wire in place on the clamp stand

- **Resolution** of measuring equipment:
  - Ammeter = 0.01 A
  - Variable resistor = 0.01 Ω
  - Top-pan balance = 0.01 g
  - Ruler = 1 mm

Method

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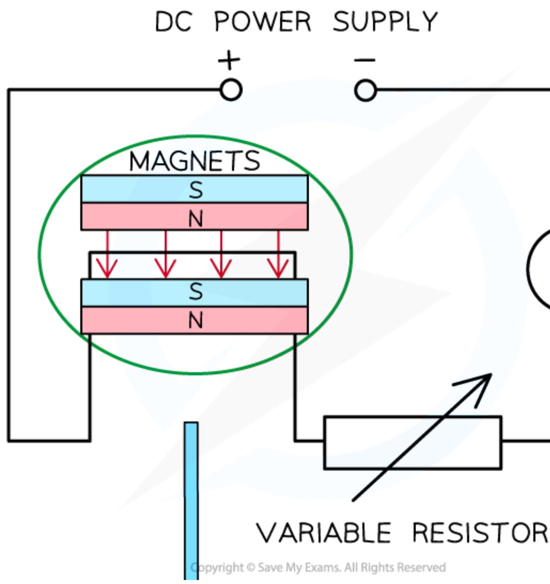
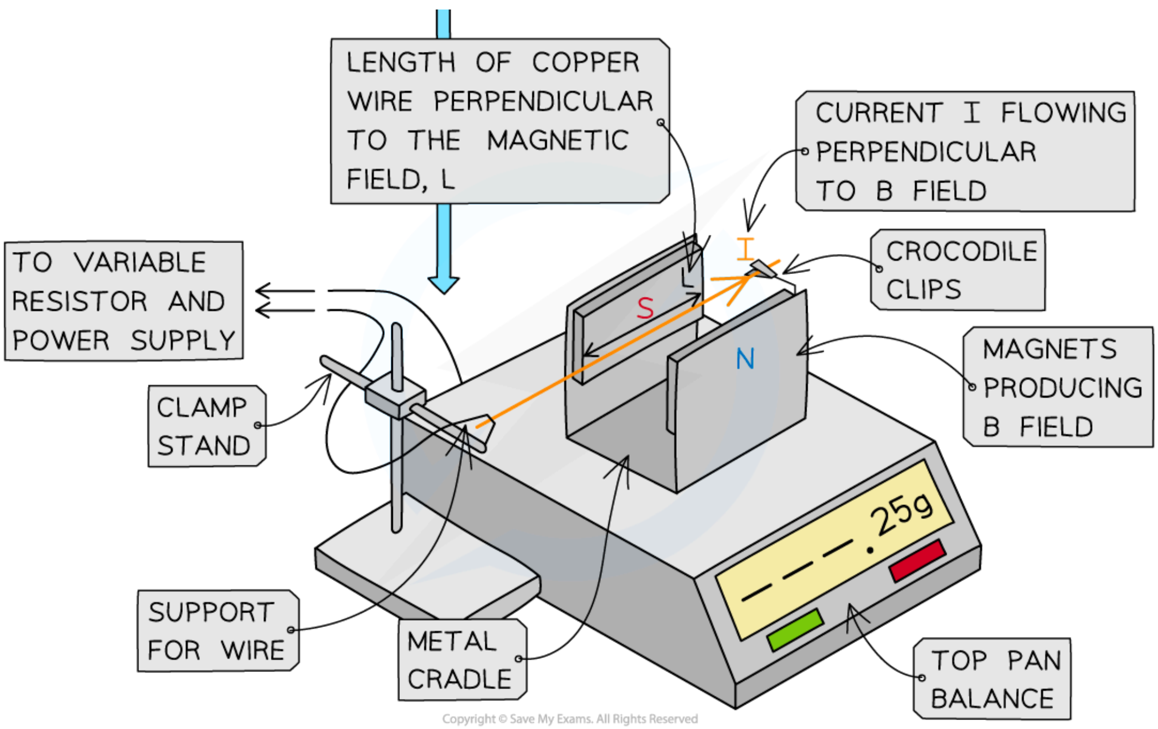




1. Set up the apparatus as shown above
    - Make sure the wire is completely perpendicular in between the magnets

Your notes

2. Measure the length of one of the magnets using the 30 cm ruler
    - This will be the length of the wire L in the magnetic field
3. Once the magnet is placed on the top-pan balance, and whilst there is no current in the wire, reset the top-pan balance to 0 g
4. Adjust the resistance of the variable resistor so that a current of 0.5 A flows through the wire as measured on the ammeter
5. The wire will experience a force upwards.
    - Due to Newton's third law, the force pushing downwards will be the mass on the balance.
    - This movement will be very small, so it may not be completely visible
6. Record the mass on the top-pan balance from this current
7. Repeat the procedure by increasing the current in intervals of 0.5 A between 8–10 readings for the current (not exceeding 6 A)
8. Repeat the experiment at least 3 times, and calculate the mean of the mass readings

- An example table might look like this:

ADJUSTED USING VARIABLE RESISTOR

FROM TOP-PAN BALANCE

$\dfrac{m_1 + m_2 + m_3}{3}$

CURRENT I/A	MASS m_1/g	MASS m_2/g	MASS m_3/g	MEAN MASS m/g
0.50				
1.00				
1.50				
2.00				
2.50				
3.00				
3.50				
4.00				
4.50				
5.00				

Your notes

Analysing the Results

- The magnetic force on the wire is:

$$F = BIL$$

- Where:
  - F = magnetic force (N)
  - B = magnetic flux density (T)
  - I = current (A)
  - L = length of the wire (m)

- Since $F = mg$ where m is the mass in kilograms, equating these gives:

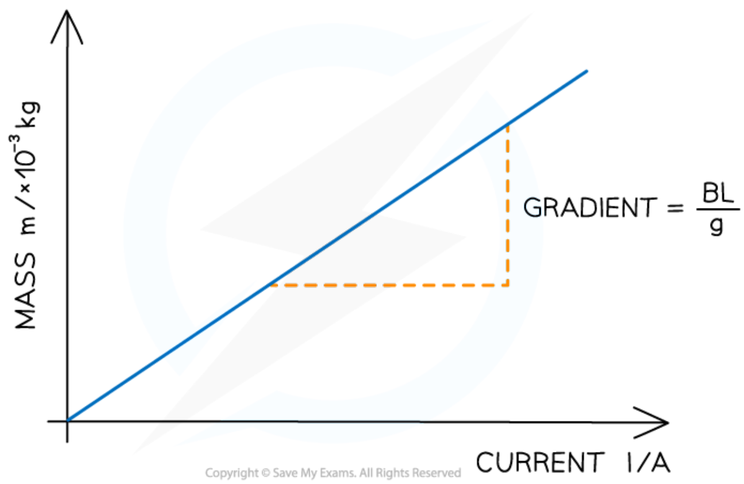
$$mg = BIL$$

- Rearranging for m:

$$m = \frac{BIL}{g}$$

- Comparing this to the straight-line equation: y = mx + c
  - y = m (mass)
  - x = I
  - m = BL / g
  - c = 0
- Plot a graph of m against I and draw a line of best fit
  - Calculate the gradient
- The magnetic flux density B is:

$$B = \frac{g \times \text{gradient}}{L}$$



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Evaluating the Experiment

Systematic Errors:

- Make sure top-pan balance starts at 0 to avoid a zero error

Random Errors:

- Repeat the experiment by turning the magnet in the metal cradle and the wire by 90°
- Make sure no high currents pass through the copper wire,
  - High current will lead to heating, causing the wire's resistance to increase

Safety Considerations

- Keep water or any fluids away from the electrical equipment
- Make sure no wires or connections are damaged and contain appropriate fuses to avoid a short circuit or a fire
- High currents through the wire will cause it to heat up
  - Make sure not to touch the wire when current is flowing through it

Worked Example

A student investigates the relationship between the current and the mass produced from the magnetic force on a current-carrying wire. They obtain the following results:

Your notes

Current I / A	Mass m_1 / × 10^{-3} kg	Mass m_2 / × 10^{-3} kg	Mass m_3 / × 10^{-3} kg
0.50	0.10	0.11	0.11
1.00	0.22	0.23	0.22
1.50	0.34	0.35	0.33
2.00	0.43	0.43	0.43
2.50	0.56	0.57	0.57
3.00	0.64	0.66	0.68
3.50	0.76	0.77	0.78
4.00	0.87	0.86	0.86
4.50	0.99	1.00	0.99
5.00	1.10	1.10	1.09

The mean length of the wire in the magnetic field was found to be 0.05 m. Calculate the magnetic flux density of the magnets from the table.

Answer:

Step 1: Complete the table

- Add an extra column 'Average mass m / × 10^{-3} kg and calculate this for each mass

Your notes

Current I / A	Mass m_1 / × 10^{-3} kg	Mass m_2 / × 10^{-3} kg	Mass m_3 / × 10^{-3} kg	Average Mass m / × 10^{-3} kg
0.50	0.10	0.11	0.11	0.11
1.00	0.22	0.23	0.22	0.22
1.50	0.34	0.35	0.33	0.34
2.00	0.43	0.43	0.43	0.43
2.50	0.56	0.57	0.57	0.57
3.00	0.64	0.66	0.68	0.66
3.50	0.76	0.77	0.78	0.77
4.00	0.87	0.86	0.86	0.86
4.50	0.99	1.00	0.99	0.99
5.00	1.10	1.10	1.09	1.10

Step 2: Plot the graph of average mass *m* against current *I*

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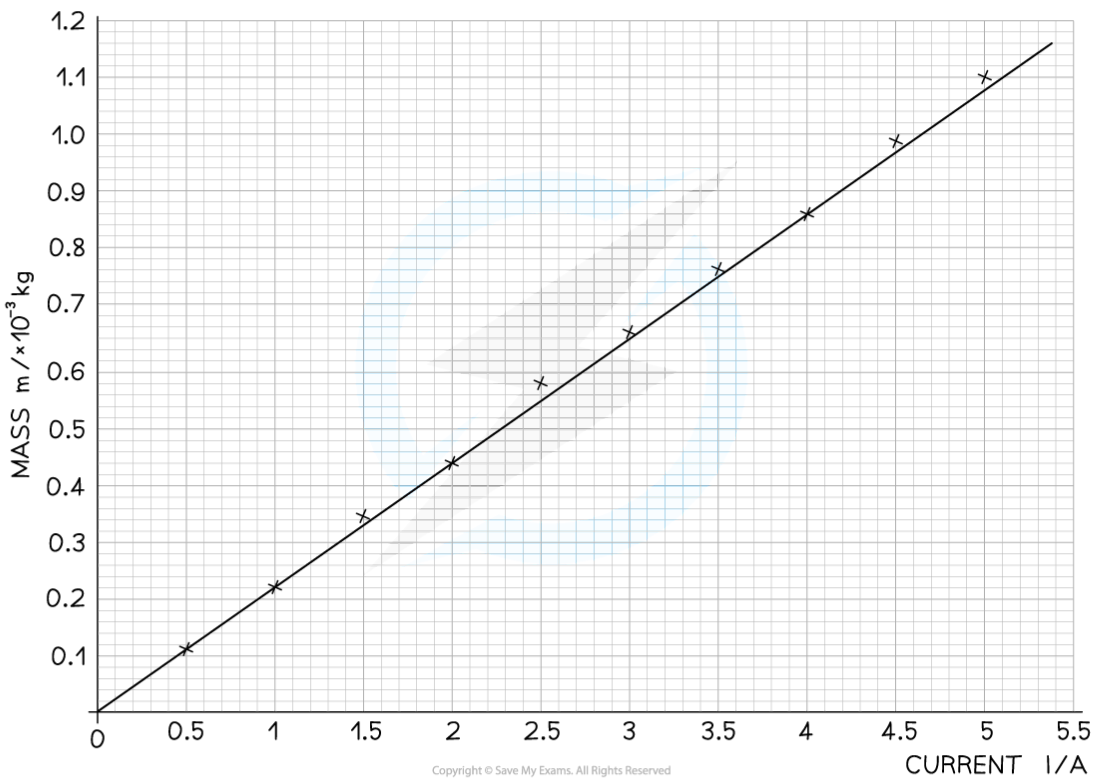
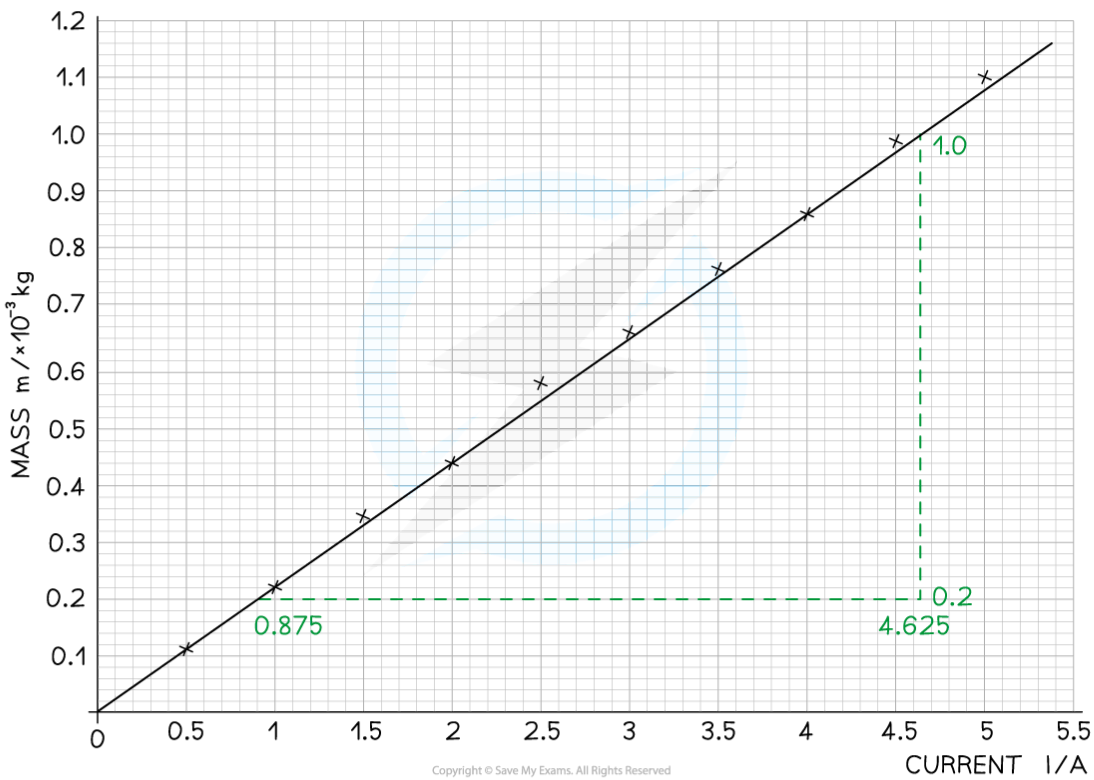


- Make sure the axes are properly labelled and the line of best fit is drawn with a ruler

Step 3: Calculate the gradient of the graph



- The gradient is calculated by:

$$\text{gradient} = \frac{(1.0 - 0.2) \times 10^{-3}}{4.625 - 0.875} = 0.2133 \times 10^{-3}$$

Step 4: Calculate the magnetic flux density, *B*

$$B = \frac{g \times \text{gradient}}{L}$$

$$B = \frac{9.81 \times (0.21333 \times 10^{-3})}{0.05} = 0.041855 = 42 \text{ mT}$$

Force on a Moving Charge

Your notes

Force on a Moving Charge

- The magnetic force on an isolated moving charged particle, such as a proton, is given by the equation:

$$F = BQv$$

- Where:
  - F = magnetic force on the particle (N)
  - B = magnetic flux density (T)
  - Q = charge of the particle (C)
  - v = speed of the particle (m s^{-1})
- This is the maximum force on the charged particle, when F, B and v are mutually perpendicular
  - Therefore if a particle travels **parallel** to a magnetic field, it will not experience a magnetic force

- Current is the rate of flow of **positive** charge
  - This means that the direction of the 'current' for a flow of negative charge (e.g. an electron beam) is in the opposite direction to its motion
- If the charged particle is moving at an angle θ to the magnetic field lines, then the size of the magnetic force F is given by the equation:

$$F = BQv \sin \theta$$

- This equation shows that:
  - The size of the magnetic force is **zero** if the angle θ is **zero** (i.e. the particle moves **parallel** to the field lines)
  - The size of the magnetic force is **maximum** if the angle θ is **90°** (i.e. the particle moves **perpendicular** to field lines)

Worked Example

A beta particle is incident at 70° to a magnetic field of flux density 0.5 mT, travelling at a speed of 1.5 × 10^6 m s^{-1}.

Your notes

Calculate:

a) The magnitude of the magnetic force on the beta particle

b) The magnitude of the maximum possible force on a beta particle in this magnetic field, travelling with the same speed

Answer:

Part (a)

Step 1: Write out the known quantities

- Magnetic flux density $B = 0.5\text{ mT} = 0.5 \times 10^{-3}$ T
- Speed $v = 1.5 \times 10^6$ m s^{-1}
- Angle θ between the flux and the velocity = 70°

Step 2: Substitute quantities into the equation for magnetic force on a charged particle

- A beta particle is an electron
- Therefore, the **magnitude** of electron charge $Q = 1.6 \times 10^{-19}$ C
- Substituting values gives:

$$F = BQv\sin\theta$$

$$F = (0.5 \times 10^{-3}) \times (1.6 \times 10^{-19}) \times (1.5 \times 10^6) \times \sin(70)$$

$$F = 1.1 \times 10^{-16}\text{ N}$$

Part (b)

Step 1: Write out the known quantities

- Magnetic flux density $B = 0.5\text{ mT} = 0.5 \times 10^{-3}$ T
- Speed $v = 1.5 \times 10^6$ m s^{-1}

Step 2: Determine the angle to the flux lines

- Angle θ between the flux and the velocity = 90° if the magnetic force is a maximum

Step 3: Substitute quantities into the equation for magnetic force on a charged particle

- The **magnitude** of electron charge $Q = 1.6 \times 10^{-19}$ C
  - Substituting values gives:

$$F = BQv\sin\theta = BQv \text{ when } \sin 90 = 1$$

$$F = (0.5 \times 10^{-3}) \times (1.6 \times 10^{-19}) \times (1.5 \times 10^6)$$

$$F = 1.2 \times 10^{-16}\text{ N}$$

Examiner Tips and Tricks

Remember not to mix this up with $F = BIL \sin\theta$!

- $\boldsymbol{F = BIL \sin\theta}$ is the force on a current-carrying conductor
- $\boldsymbol{F = BQv \sin\theta}$ is the force on an isolated moving charged particle (which may be inside a conductor)

Another super important fact to remember for typical exam questions is that the magnetic force on a charged particle is **centripetal,** because it **always acts at 90°** to the particle's velocity. You should practise using Fleming's Left Hand Rule to determine the exact direction!

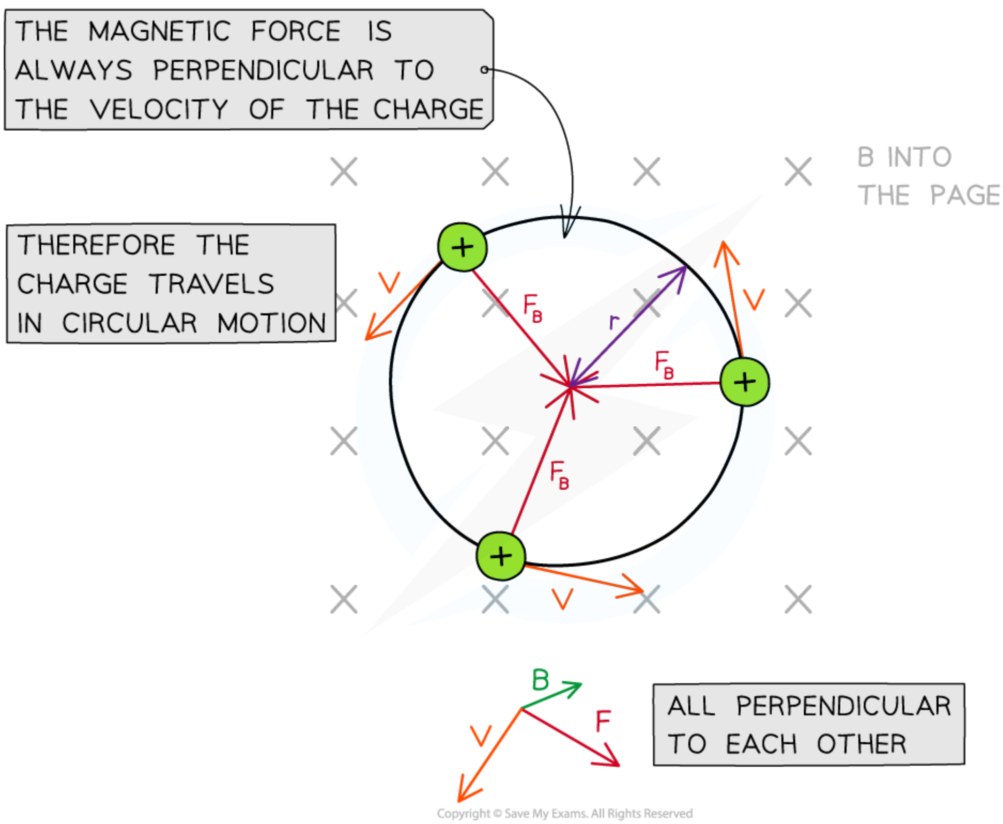
Your notes

Your notes

Motion of Charged Particles in a B Field

Motion of a Charged Particle in a Magnetic Field

- A charged particle in uniform **magnetic field** which is perpendicular to its direction of motion travels in a **circular** path
- This is because the **magnetic force** F will always be perpendicular to its velocity v
  - F will always be directed towards the centre of the path in circular motion



A charged particle moves travels in a circular path in a magnetic field

- The magnetic force F provides the **centripetal force** on the particle
- The equation for centripetal force is:

Your notes

$$F = \frac{mv^2}{r}$$

- Where:
  - F = centripetal force (N)
  - m = mass of the particle (kg)
  - v = linear velocity of the particle (m s^{-1})
  - r = radius of the orbit (m)

- Equating this to the magnetic force on a moving charged particle gives the equation:

$$\frac{mv^2}{r} = Bqv$$

- Rearranging for the radius *r* obtains the equation for the radius of the orbit of a charged particle in a perpendicular magnetic field:

$$r = \frac{mv}{Bq}$$

- This equation shows that:
  - Faster moving particles with speed *v* move in larger circles (larger *r*): $\boldsymbol{r \propto v}$
  - Particles with greater mass *m* move in larger circles: $\boldsymbol{r \propto m}$
  - Particles with greater charge *q* move in smaller circles: $\boldsymbol{r \propto 1 / q}$
  - Particles moving in a strong magnetic field *B* move in smaller circles: $\boldsymbol{r \propto 1 / B}$
- The centripetal acceleration is in the same direction as the centripetal (and magnetic) force
  - This can be found using Newton's second law:

$$\boldsymbol{F = ma}$$

Your notes

Worked Example

An electron with a charge-to-mass ratio of 1.8×10^{11} C kg^{-1} is travelling at right angles to a uniform magnetic field of flux density 6.2 mT. The speed of the electron is 3.0×10^{6} m s^{-1}.

Calculate the radius of the circular path of the electron.

Answer:

Step 1: Write down the known quantities

$$\text{Charge-to-mass ratio} = \frac{q}{m} = 1.8 \times 10^{11} \text{ C kg}^{-1}$$

Magnetic flux density, $B = 6.2$ mT

Electron speed, $v = 3.0 \times 10^{6}$ m s^{-1}

Step 2: Write down the equation for the radius of a charged particle in a perpendicular magnetic field

$$r = \frac{mv}{Bq}$$

Step 3: Substitute in values

$$\frac{m}{q} = \frac{1}{1.8 \times 10^{11}}$$

$$r = \frac{(3.0 \times 10^{6})}{(1.8 \times 10^{11}) \times (6.2 \times 10^{-3})} = 2.688 \times 10^{-3} \text{ m} = \mathbf{2.7 \text{ mm (2 s.f.)}}$$

Examiner Tips and Tricks

Make sure you're comfortable with deriving the equation for the radius of the path of a particle travelling in a magnetic field, as this is a common exam question.

Similar to orbits in a gravitational field, any object moving in circular motion will obey the equations of circular motion. Make sure to refresh your knowledge of these equations.

Your notes

Your notes

Velocity Selector

Charged Particles in a Velocity Selector

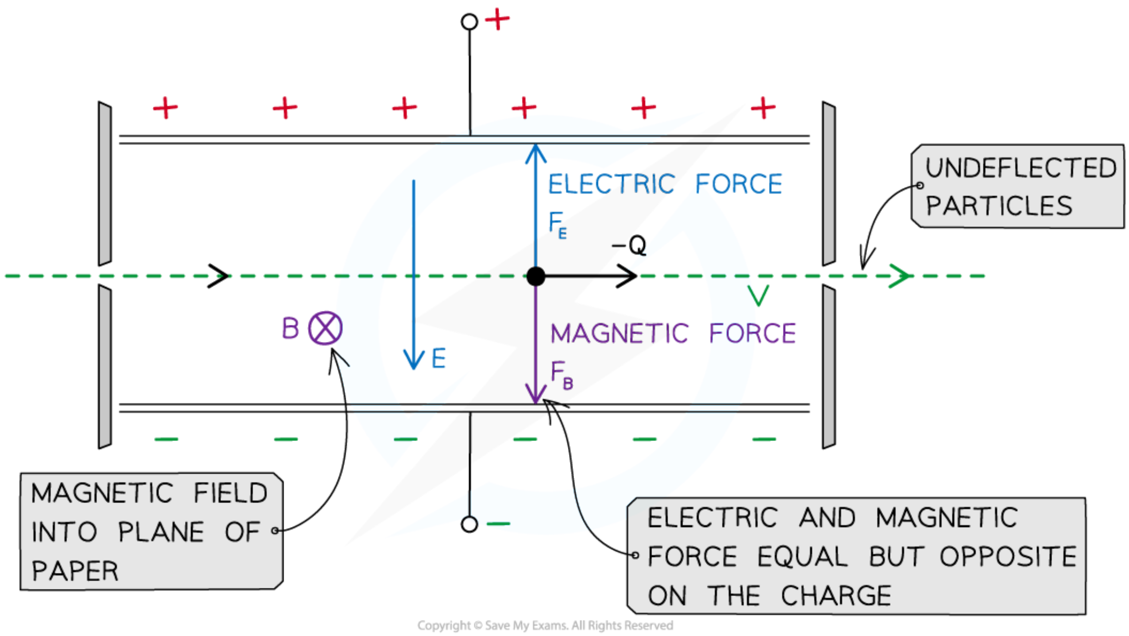
- A velocity selector is defined as:

  A device consisting of perpendicular electric and magnetic fields where charged particles with a specific velocity can be filtered

- Velocity selectors are used in devices, such as mass spectrometers, in order to produce a beam of charged particles all travelling at the same velocity
- The construction of a velocity selector consists of two horizontal oppositely charged plates situated in a vacuum chamber
  - The plates provide a uniform electric field with strength *E* between them
- There is also a uniform magnetic field with flux density *B* applied perpendicular to the electric field
  - If a beam of charged particles enter between the plates, they may all have the same charge but travel at different speeds *v*
- The electric force **does not** depend on the velocity: $F_E = EQ$
- However, the magnetic force **does** depend on the velocity: $F_B = BQv$
  - The magnetic force will be greater for particles which are travelling faster
- To select particles travelling at exactly the desired the speed *v*, the electric and magnetic force must therefore be **equal**, but in **opposite** directions

$$\mathbf{F_E = F_B}$$

Your notes



The particles travelling at the desired speed v will travel through undeflected due to the equal and opposite electric and magnetic forces on them

- The resultant force on the particles at speed *v* will be zero, so they will remain undeflected and pass straight through between the plates
- By equating the electric and magnetic force equations:

$$EQ = BQv$$

- The charge Q will cancel out on both sides to give the selected velocity *v* equation:

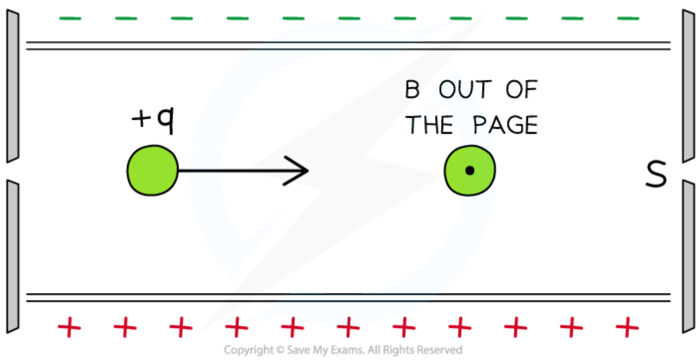
$$v = \frac{E}{B}$$

- Therefore, the speed *v* in which a particle will remain undeflected is found by the **ratio of the electric and magnetic field strength**
  - If a particle has a speed greater or less than *v*, the magnetic force will deflect it and collide with one of the charged plates
  - This would remove the particles in the beam that are not exactly at speed *v*
- **Note:** the gravitational force on the charged particles will be negligible compared to the electric and magnetic forces and therefore can be ignored in these calculations

Your notes

Worked Example

A positive ion travels between two charged plates towards a slit **S**.



a) State the direction of the electric and magnetic fields on the ion.

b) Calculate the speed of the ion emerging from slit S when the magnetic flux density is 0.50 T and the electric field strength is 2.8 kV m^{-1}.

c) Determine which plate the ion will be deflected towards if the speed is greater than the speed in part (b).

Answer:

Part (a)

Step 1: Determine the direction of the E field

- Electric field lines point from the positive to negative to charge
- Therefore, it must be directed **vertically upwards**

Step 2: Determine the direction of the B field

- Using Fleming's left-hand rule:
  - The charge or current *I* is directed to the right
  - *B* must be directed **out of the page / screen** for the magnetic force *F* to act **vertically downwards**

Part (b)

Step 1: List the known quantities

- Electric field strength, $E = 2.8$ kV m^{-1} = 2.8×10^3 V m^{-1}

- Magnetic flux density, $B = 0.50$ T

Step 2: Write down the velocity selector equation

$$v = \frac{E}{B}$$

Step 3: Calculate the speed of the ion at S

$$v = \frac{2.8 \times 10^3}{0.5} = 5600 \text{ m s}^{-1}$$

Part (c)

Step 1: Consider the effect of changing the ion's speed on the electric and magnetic forces

- Electric force is given by:

$$F_E = EQ$$

- Therefore, electric force **does not** depend on the velocity
- Magnetic force is given by:

$$F_B = BQv$$

- Therefore, $F_B \propto v$, so if the speed increases, the magnetic force must increase

Step 2: Determine the net direction of the force

- Since the net magnetic force would direct the ion **downwards** in the direction of the field
- The ion will be deflected **towards the positive plate**

Your notes