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7.8 Magnetic Field

PHYSICS

AQA A Level Revision Notes

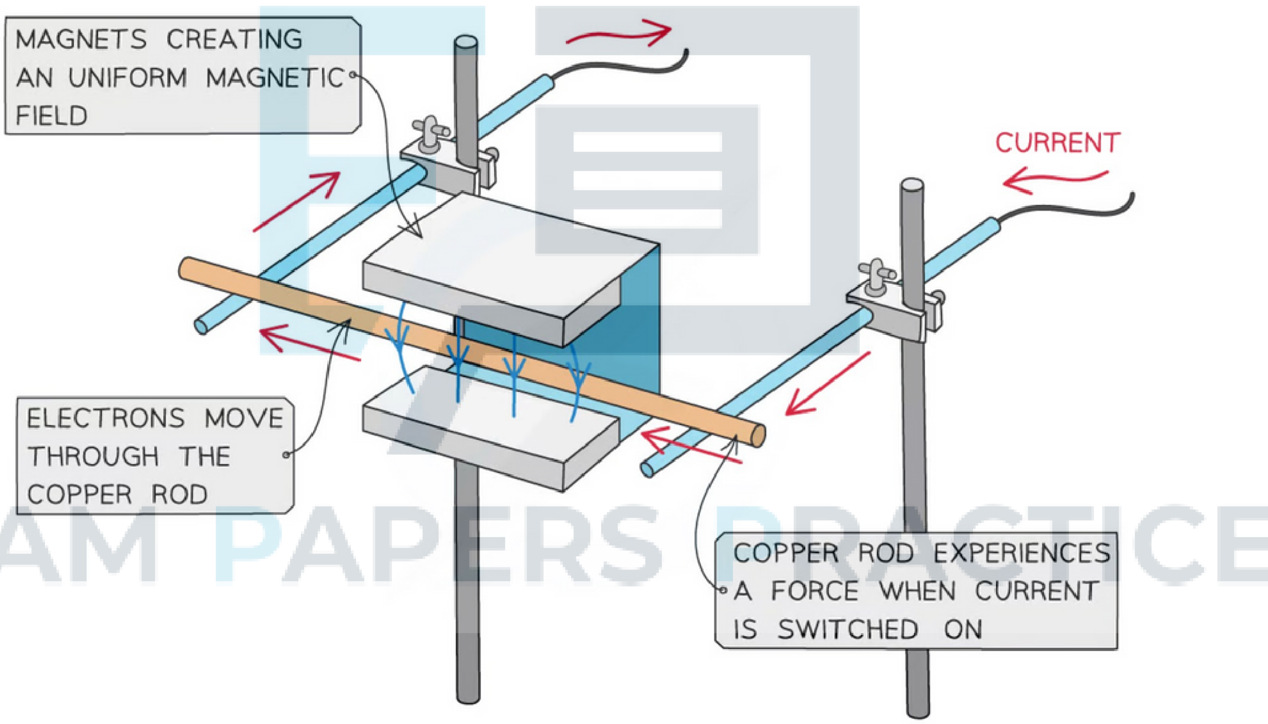
A Level Physics AQA

7.8 Magnetic Fields

CONTENTS

Magnetic Force on a Current-Carrying Conductor

- A current-carrying conductor produces its own **magnetic field**
  - When interacting with an external magnetic field, it will experience a **force**
- A current-carrying conductor (eg. a wire) will experience the **maximum** magnetic force if the current through it is **perpendicular** to the direction of the magnetic field lines
  - It experiences no force if it is parallel to magnetic field 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

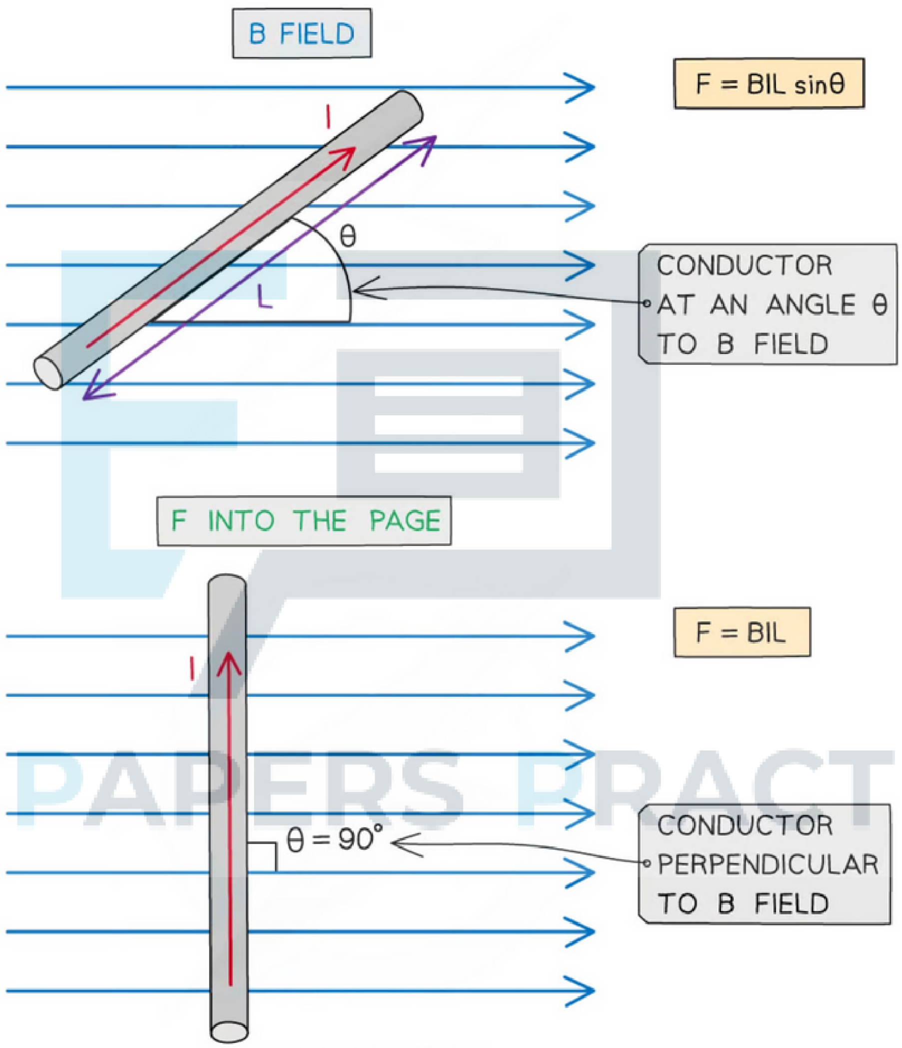
- The strength of a magnetic field is known as the **magnetic flux density, B**
  - This is also known as the magnetic field strength
  - It is measured in units of **Tesla (T)**
- The force *F* on a conductor carrying current *I* at right angles to a magnetic field with flux density *B* is defined by the equation

$$F = BIL\sin\theta$$

- Where:
  - F = force on a current carrying conductor in a B field (N)
  - B = magnetic flux density of external B field (T)

- I = current in the conductor (A)
- L = length of the conductor (m)
- θ = angle between the conductor and external B field (degrees)

- This equation shows that the greater the current or the magnetic field strength, the greater the force on the conductor
- The length of the conductor, *L* in this equation is only the length that is **within** the field



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 $\theta = 90°$ and the conductor is **perpendicular** to the B field
  - This equation for the magnetic force now becomes:

$$F = BIL$$

- The **minimum** force (0) is when $\sin\theta = 0$
  - This means $\theta = 0°$ 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
  - This is because the *F*, *B* and *I* must be **perpendicular** to each other

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.

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 field, θ = 30°

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

$$F = BIL \sin\theta$$

Step 3: Substitute in values and calculate

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

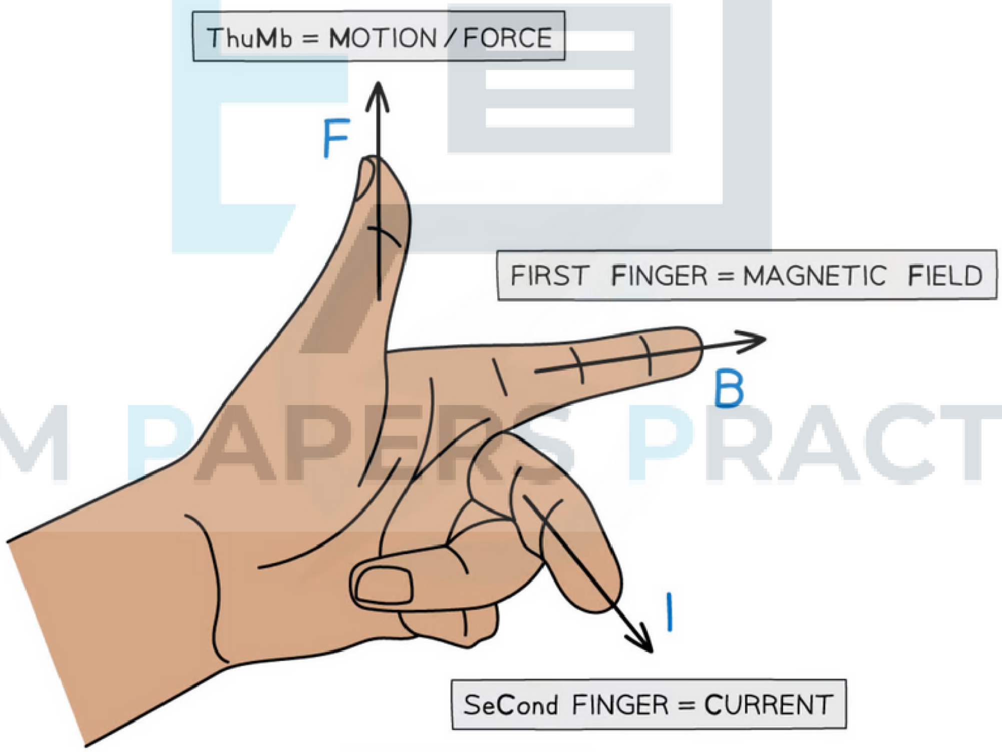
Exam Tip

Remember that the direction of current flow is the flow of **positive** charge (positive to negative), and this is in the **opposite direction** to the flow of electrons

Fleming's Left Hand Rule

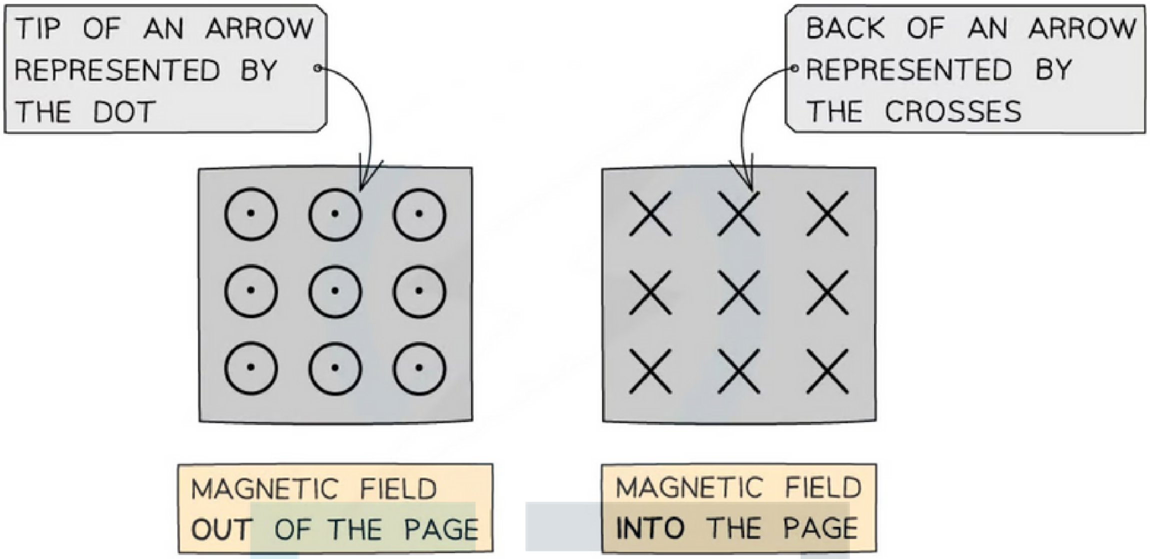
- The **direction** of the force on a charge moving in a **magnetic field** is determined by the direction of the magnetic field and the current
  - Recall that the direction of the current is in the direction of **conventional** current flow (positive to negative)

- When the force, the magnetic field and the current are all mutually perpendicular to each other, the directions of each can be interpreted by **Fleming's left-hand rule**
- On the left hand, with the thumb pointed upwards, first finger forwards and the second finger to the right, ie. all three are perpendicular to each other
  - The **thumb** points in the direction of **motion** of the rod (or the direction of the force) (*F*)
  - The **first** finger points in the direction of the external **magnetic field** (*B*)
  - The **second** finger points in the direction of conventional **current** flow (*I*)



Fleming's left hand rule

- Since this is represented in 3D space, sometimes the current, 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

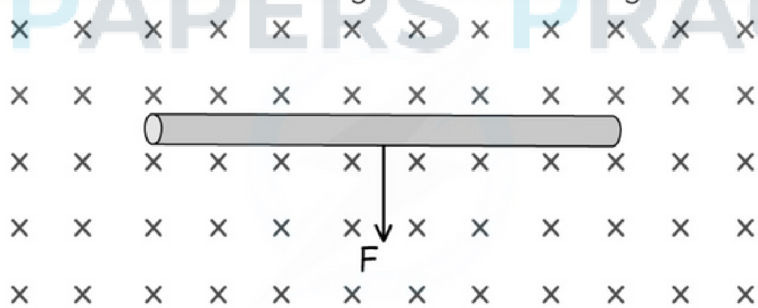


The magnetic field into or out of the page is represented by circles with dots or crosses

- 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 **receding away**, such as into a page, only the cross of the feathers at the back can be seen (a cross)

Worked Example

State the direction of the current flowing in the wire in the diagram below.

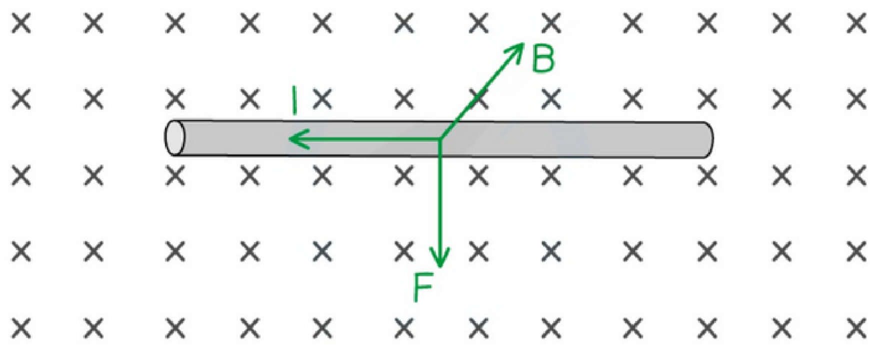


Using Fleming's left-hand rule:

B **= into the page**

F **= vertically downwards**

I **= from right to left**

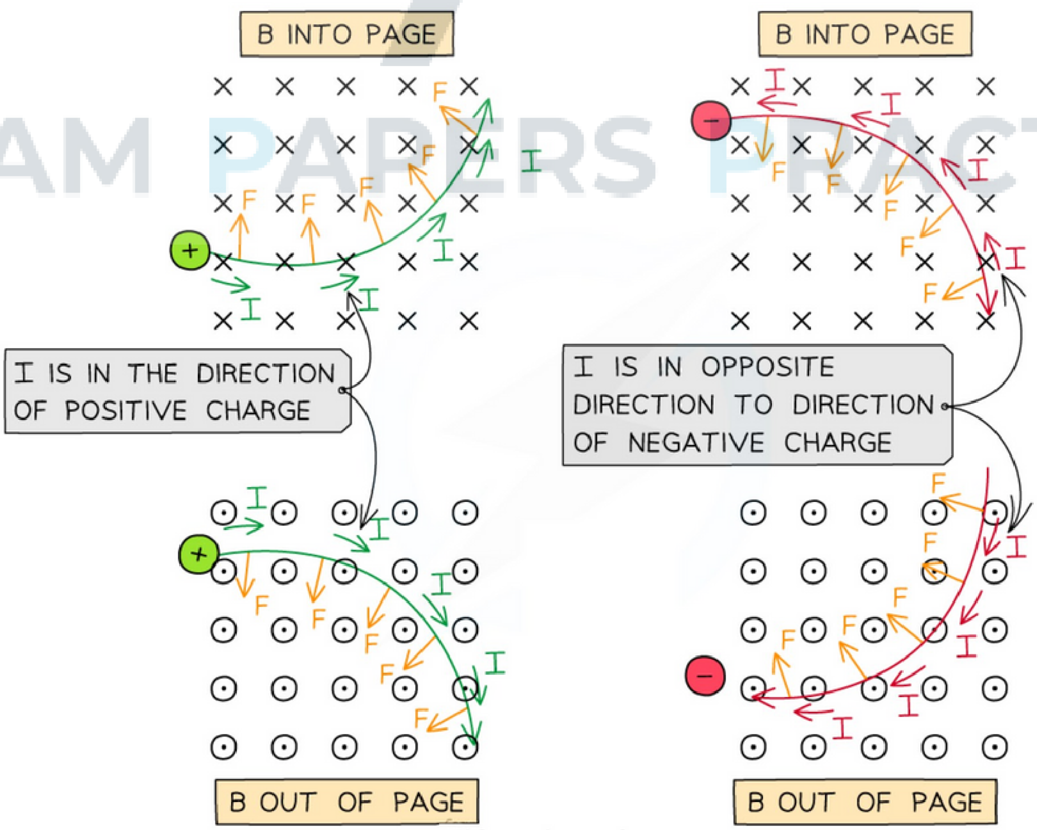


Exam Tip

Don't be afraid to use Fleming's left-hand rule during an exam. Although, it is best to do it subtly in order not to give the answer away to other students!

Direction of the Magnetic Force

- The direction of the magnetic force on positive and negative charged particles depends on
  - The direction of flow of the charged particles
  - The direction of the magnetic field
- This can be found using Fleming's left-hand rule by remembering that the second finger represents the **current** flow or the flow of **positive** charge
  - This means that for negative charges, such as electrons, their flow will be in the opposite direction to which the second finger points
  - Therefore, if a particle carries a negative charge, the second finger should be pointed in the **opposite** direction to its motion
- For example, when a **positively** charged particle enters a magnetic field **into** the page from **left to right**:
  - Using Fleming's left-hand rule, the first finger points into the page and the second finger (current) points to the right
  - This means the force is upwards
  - The particle is then pulled in the direction of this force (upwards). This means the direction of the current also changes direction slightly (slanting upwards)
  - This means the force will **also** change direction since it still needs to keep perpendicular to the current and the field
- Therefore, the moving charges will follow 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

Exam Tip

Remember not to get this mixed up with Fleming's right-hand rule. That is used for a dynamo, where a current is **induced** in the **conductor** (not following through it initially). Fleming's left-hand rule is sometimes referred to as the 'Fleming's left-hand rule for motors'.

7.8.3 Magnetic Flux Density

Magnetic Flux Density Definition

- 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.

Determine the flux density of the field and its direction.

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**

7.8.4 Force on a Moving Charge

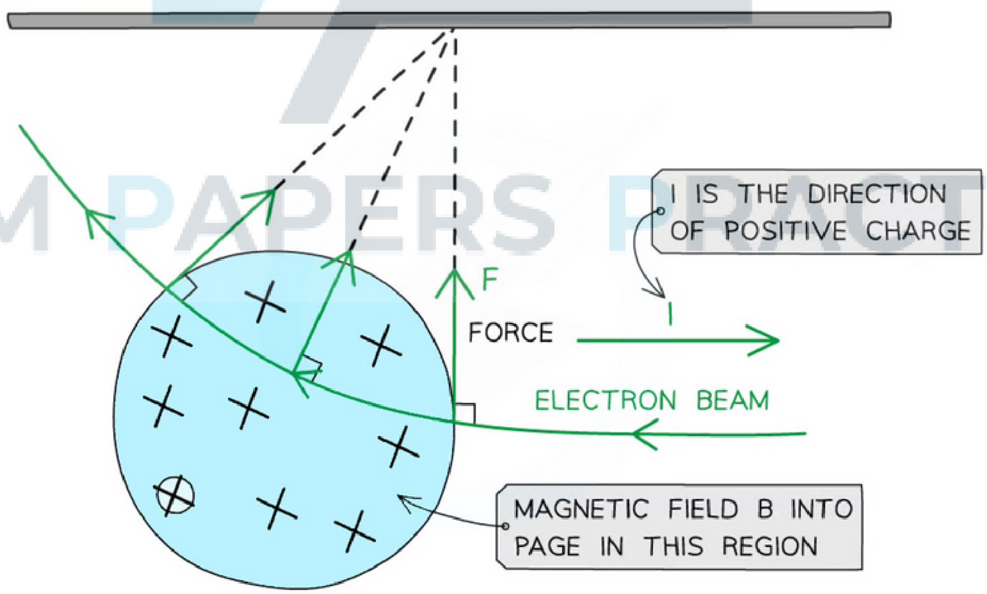
Calculating Magnetic Force on a Moving Charge

- The magnetic force on an isolating moving charged particle, such as an electron, 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})

- Current is the rate of flow of **positive** charge
  - This means that the direction of the current for a flow of negative charge (eg. an electron beam) is in the opposite direction to its motion
- F, B and v are mutually perpendicular
  - Therefore if a particle travels **parallel** to a magnetic field, it will not experience a magnetic force



The force on an isolated moving charge is perpendicular to its motion and the magnetic field B

- According to **Fleming's left hand rule**:
  - B is directed into the page, and current I (or speed v) is directed to the right
  - When an electron enters a magnetic field from the **left**, and if the magnetic field is directed **into the page**, then the force on it will be directed **upwards**

- The equation shows:
  - If the direction of the electron changes, the magnitude of the force will change too
- The force due to the magnetic field is always perpendicular to the velocity of the electron
  - **Note:** this is equivalent to circular motion
- Fleming's left-hand rule can be used again 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

An electron is moving at 5.3×10^7 m s^{-1} in a uniform magnetic field of flux density 0.2 T.

Calculate the force on the electron when it is moving perpendicular to the field.

Step 1: Write out the known quantities

- Speed of the electron, $v = 5.3 \times 10^7$ m s^{-1}
- Charge of an electron, $Q = 1.60 \times 10^{-19}$ C
- Magnetic flux density, $B = 0.2$ T

Step 2: Write down the equation for the magnetic force on an isolated particle

$$F = BQv$$

Step 3: Substitute in values, and calculate the force on the electron

$$F = (0.2) \times (1.60 \times 10^{-19}) \times (5.3 \times 10^7) = 1.696 \times 10^{-12} \text{ N}$$

Exam Tip

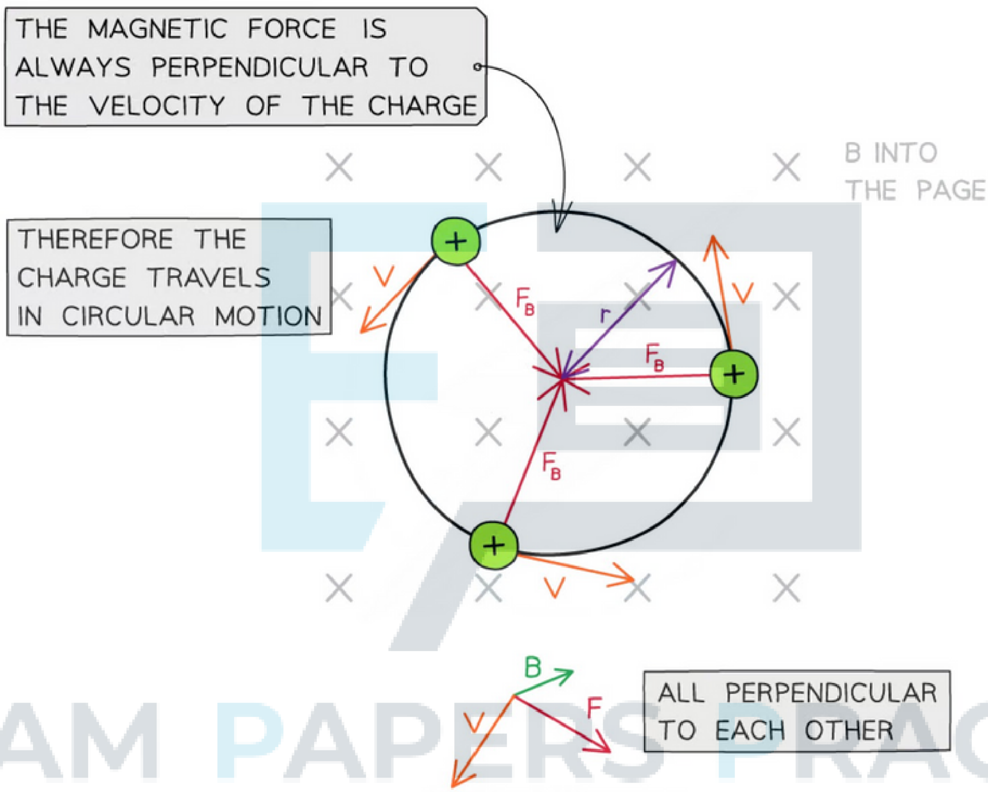
Remember not to mix this up with $F = BIL$!

- ***F* = *BIL*** is for a current-carrying conductor
- ***F* = *BQv*** is for an isolated moving charge (which may be inside a conductor)

7.8.5 Circular Path of Particles

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:

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

- 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:

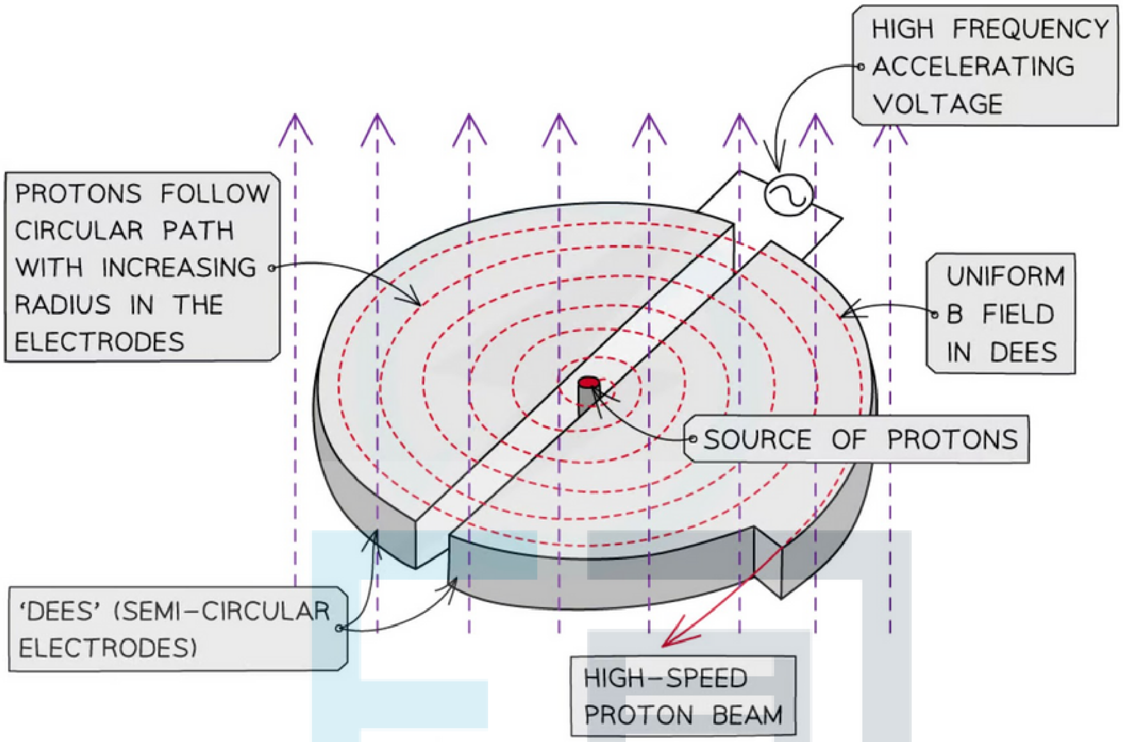
$$r = \frac{mv}{Bq}$$

- 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:

$$F = ma$$

Cyclotrons

- Cyclotrons are a type of particle accelerator that accelerates charged particles (eg. protons) from their centre along a spiral path
- They are used for medical research such as:
  - Producing medical isotopes (**tracers**)
  - Creating high-energy beams of radiation for **radiotherapy**
- Cyclotrons make use of the circular trajectory of charged particles in a magnetic field to create the spiral path
- Cyclotrons are made up of:
  - Two hollow semicircular electrodes called '**dees**'
  - A uniform **magnetic field** applied **perpendicular** to the electrodes
  - An alternating potential difference is also applied between the electrodes, which creates an **electric field** between them



A cyclotron is a type of particle accelerator that creates a high energy proton beam by accelerating protons in circular motion

- The process of accelerating a particle in a cyclotron is:
    - A source of charged particles is placed at the **centre** of the cyclotron and they are fired into one of the electrodes
    - The magnetic field in the electrode makes them follow a **semi-circular path**, since it is perpendicular to their motion until they eventually leave the electrode
    - The potential difference applied between the electrode **accelerates** the particles across the gap to the next electrode (since there is an **electric field** in the gap)
    - Since the speed of the particles is now higher, they will follow a circular path with a **larger radius** (since $r \propto v$) before leaving the electrode again
    - The potential difference is then reversed so the particles accelerate towards the opposite electrode
    - This process is repeated as the particles spiral outwards and eventually have a speed large enough to exit the cyclotron

- The alternating potential difference is needed to accelerate the particles across the gap between opposite electrodes
    - Otherwise, the particles will only accelerate in one direction

Worked Example

An electron with 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 circle path of the electron.

Step 1: Write down the known quantities

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

Magnetic flux density, B = 6.2 mT

Electron speed, v = 3.0×10^{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

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

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

Exam Tip

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 on these equations. They will be in the 'Circular Motion' section of the data sheet, and not under 'Magnetic Fields'.

Required Practical: Investigating Magnetic Fields in Wires

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
  - This is just one example of how this required practical might be carried out

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

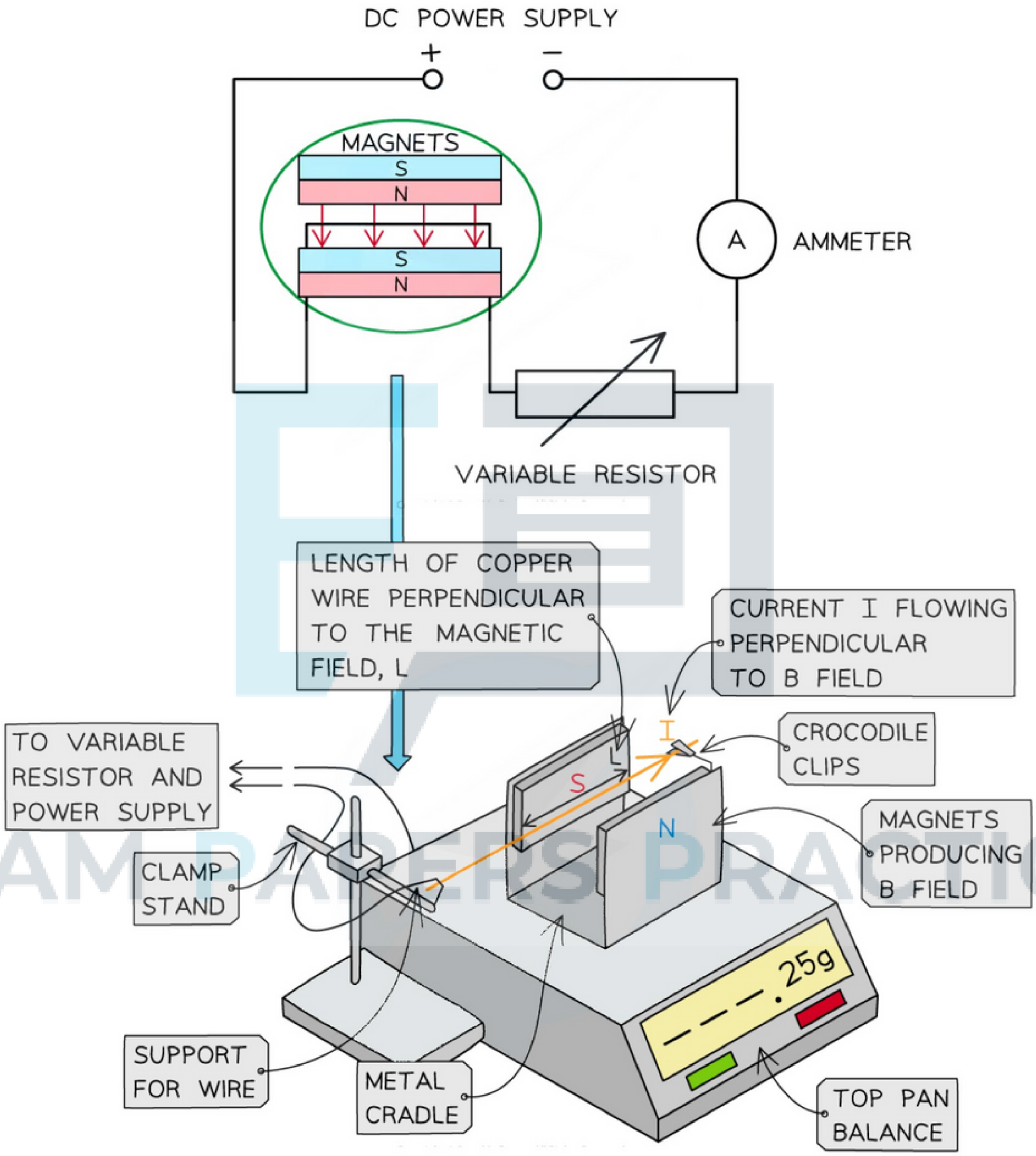
Equipment List

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



1. Set up the apparatus as shown above. Make sure the wire is completely perpendicular in between the magnets
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 (current)
FROM TOP-PAN BALANCE (masses m_1, m_2, m_3)
$\frac{m_1 + m_2 + m_3}{3}$ (mean mass)

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				

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:

$$mg = BIL$$

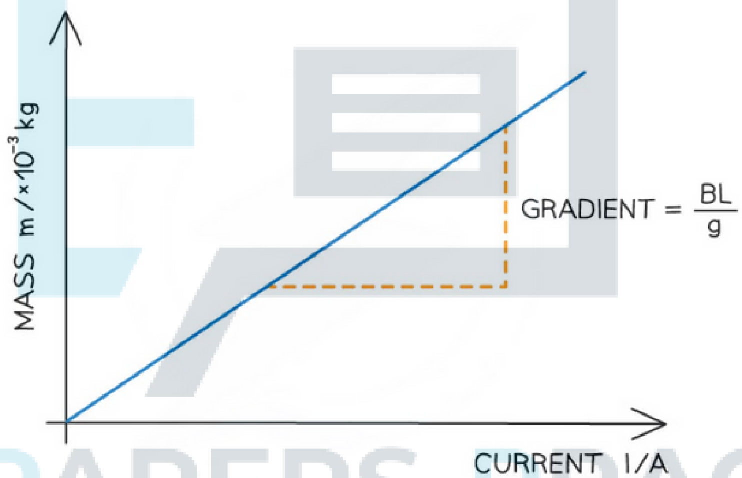
- Rearranging for m:

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

- Comparing this to the straight-line equation: $y = mx + c$
  - $y = m$ (mass)
  - $x = I$
  - $m = BL / g$
  - $c = 0$

1. Plot a graph of *m* against *I* and draw a line of best fit
2. Calculate the gradient
3. The magnetic flux density *B* is:

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



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 (up to 6 A) pass through the copper wire, otherwise the wire's resistance will increase and affect the experiment

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:

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

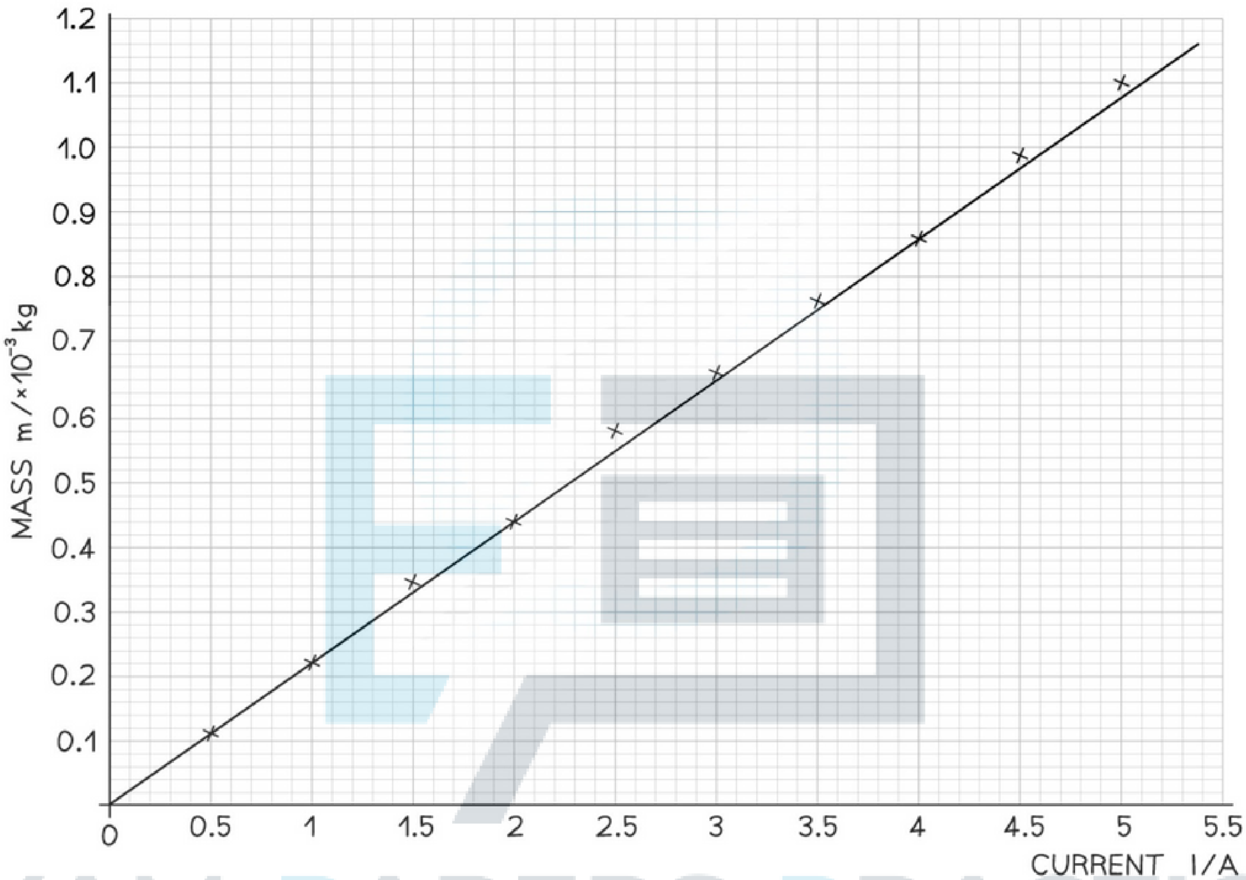
The mean length of the wire in the magnetic field was found to be 0.05 m. Calculate the magnetic flux density of the magnets from the table.

Step 1: Complete the table

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

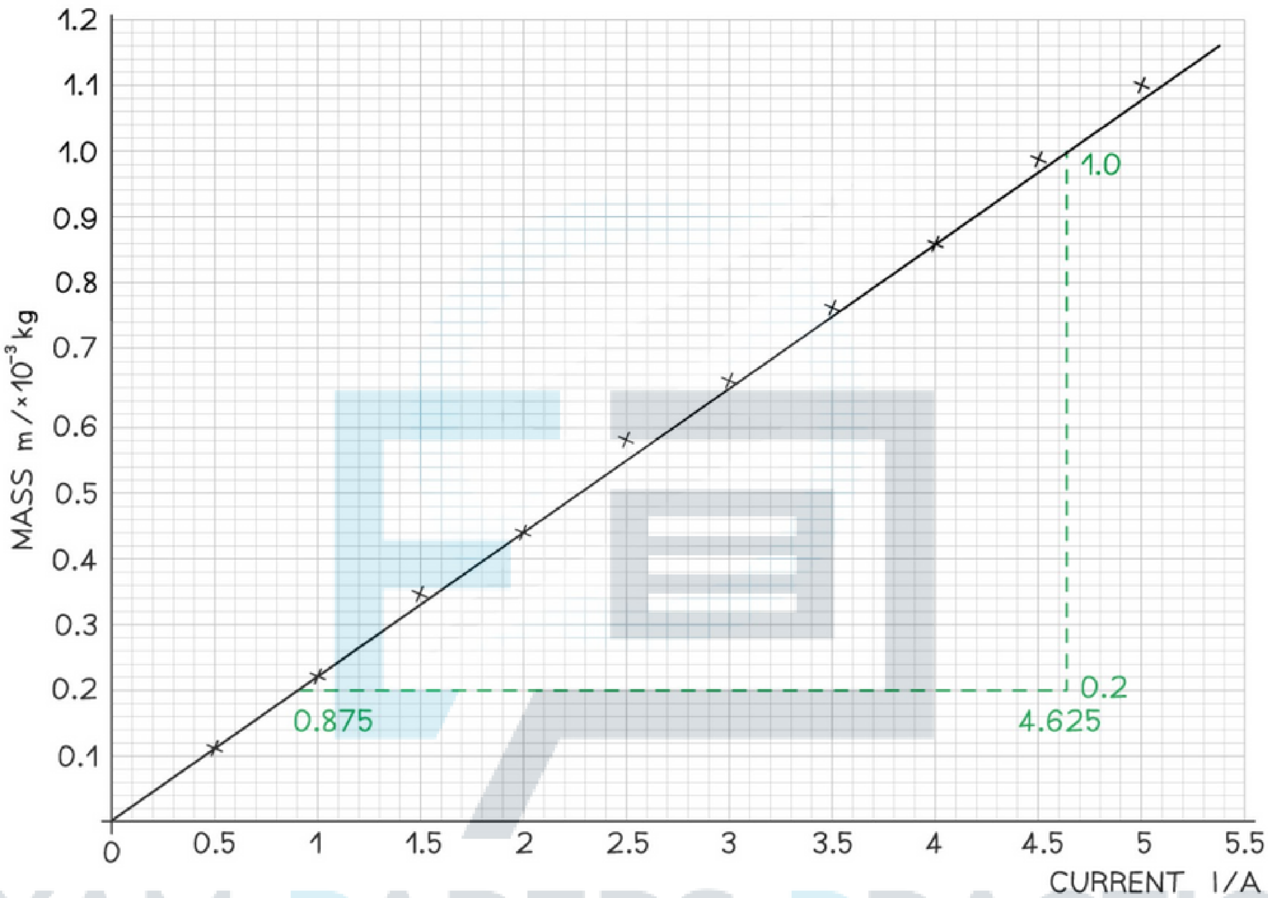
Current I / A	Mass m_1 / × 10^{-3} kg	Mass m_2 / × 10^{-3} kg	Mass m_3 / × 10^{-3} kg	Average Mass m / × 10^{-3} kg
0.50	0.10	0.11	0.11	0.11
1.00	0.22	0.23	0.22	0.22
1.50	0.34	0.35	0.33	0.34
2.00	0.43	0.43	0.43	0.43
2.50	0.56	0.57	0.57	0.57
3.00	0.64	0.66	0.68	0.66
3.50	0.76	0.77	0.78	0.77
4.00	0.87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



- 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*

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

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