- ***Candidates should be able to*** *:*
  - *Describe the magnetic field patterns of a* ***long, straight, current-carrying conductor*** *and a* ***long solenoid.***
  - ***State*** *and* ***use Fleming's left-hand rule*** *to determine the force on a conductor placed at right angles to a magnetic field.*
  - ***Select*** *and* ***use*** *the equations :*

$$F = BIL \quad \text{and} \quad F = BIL\sin\theta$$

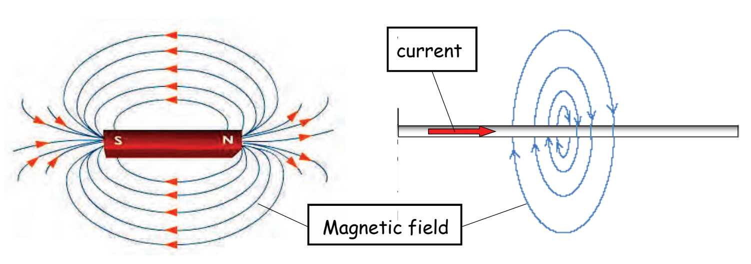
  - ***Define magnetic flux density*** *and the* ***tesla.***
  - ***Select*** *and* ***use*** *the equation for the* ***force*** *on a charged particle travelling at right angles to a uniform magnetic field :*

$$F = BQv$$

  - ***Analyse*** *the circular orbits of charged particles moving in a plane perpendicular to a uniform magnetic field, by relating the* ***magnetic force*** *to the* ***centripetal acceleration*** *it causes.*
  - ***Analyse*** *the motion of charged particles in both* ***electric*** *and* ***magnetic*** *fields.*
  - ***Explain*** *the use of deflection of charged particles in the electric and magnetic fields of a* ***mass spectrometer.***

MAGNETIC FIELDS

A ***MAGNETIC FIELD*** *is a region in which a piece of* ***ferromagnetic material OR*** *a* ***magnet OR*** *a* ***current-carrying conductor OR*** *a* ***moving electric charge****, will experience a* ***force.***



- *Magnetic fields exist around* ***permanent magnets*** *or* ***current-carrying conductors.***
- *Magnetic fields are represented by* ***magnetic field lines*** *which show the* ***direction of the force that a magnetic north-pole*** *would experience at a given point in the field.*
- *The* ***relative density (i.e. the number of lines per unit area)*** *of the field lines is a measure of the* ***magnetic field strength*** *in a particular region.*
  - ***Parallel*** *field lines indicate* ***constant field strength*** *which means a* ***uniform*** *magnetic field.*
  - ***Converging*** *field lines indicate a* ***strengthening*** *magnetic field and* ***diverging*** *field lines indicate a* ***weakening*** *magnetic field.*
- *In 1820,* ***Hans Christian Oersted*** *discovered that* ***electric currents produce magnetic fields*** *and, a short time later,* ***James Clark Maxwell*** *proved that* ***all magnetic fields have their origins in the movement of electric charges.***

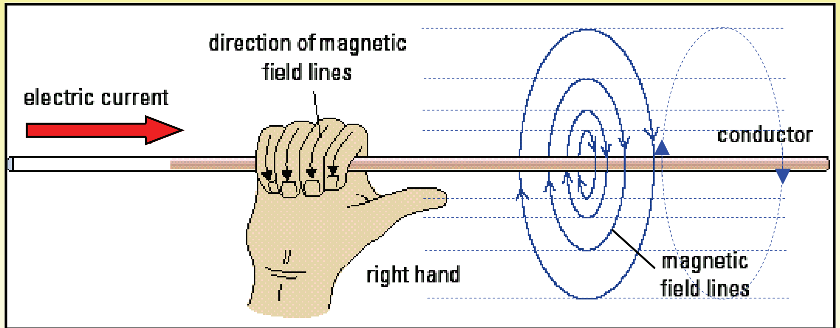
MAGNETIC FIELD PATTERNS AROUND CURRENT-CARRYING WIRES

- *Since **an electric current is a flow of charged particles,** it follows that **a magnetic field will be produced around any current-carrying conductor.***

  *The shape and magnitude of the field depends on the **size of the current, the arrangement of the conductor and the medium in which it is situated.***

LONG, STRAIGHT CURRENT-CARRYING CONDUCTOR

This is the simplest arrangement for producing a magnetic field from an electric current. The field which is generated from a straight, current-carrying wire forms a set of concentric cylinders, centred on the wire as shown in the diagram below.

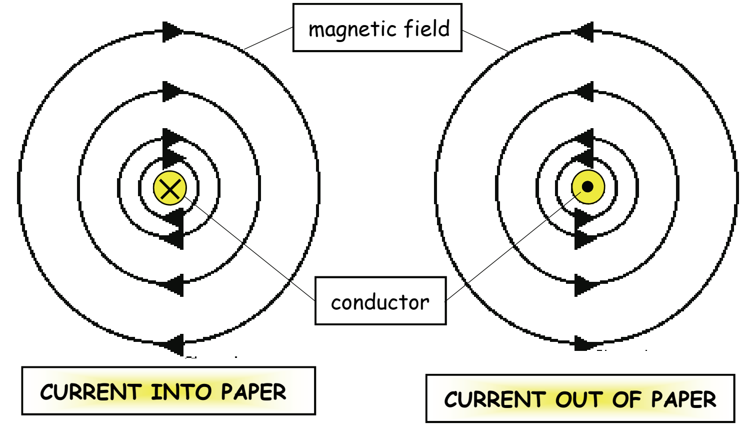


- *The **direction of the magnetic field** can be predicted using the :*

RIGHT-HAND GRIP RULE.

If you imagine gripping the wire in your right hand, with the thumb pointing in the current direction, the direction of the field is given by the way the fingers would curl around the wire.

- *Although **magnetic fields are 3-dimensional,** it is usually more convenient in diagrams to represent the directions of currents and fields **2-dimensionally** as shown below. The current direction is shown by a **dot or a cross** in the centre of the conductor (Think about the appearance of a dart - **going away from you,** all you see is the flight at the back, hence the **cross - coming towards you,** all you see is the point, hence the **dot**).*



- *Note that the field lines are **further apart** as we move away from The wire, which shows that **the field weakens with distance.***

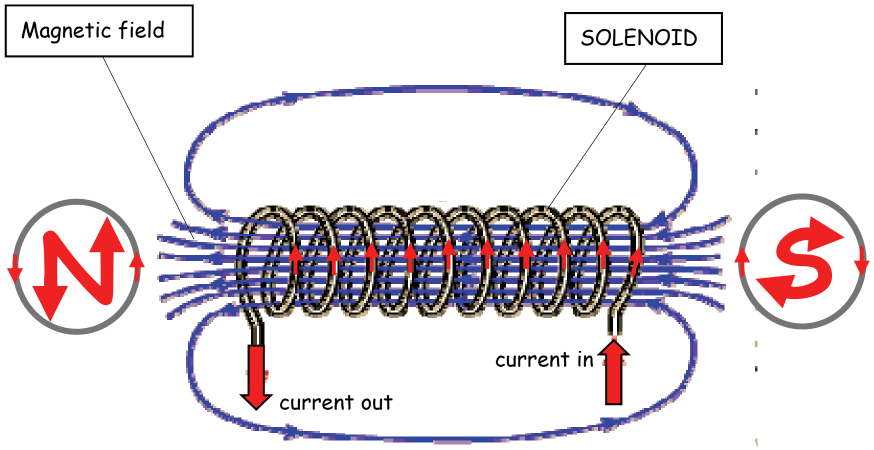
- *We model the magnetic field by thinking of it as being filled with **MAGNETIC FLUX,** represented by field lines in diagrams. The concept of magnetic flux provides a useful means of measuring field strength in terms of flux concentration.*

- *Measurement of the **FLUX DENSITY (the flux per unit area)** around a current-carrying wire shows that it is :*
  - ***Directly proportional to the current in the wire.***
  - ***Inversely proportional to the distance from the centre of the wire.***

LONG SOLENOID

- *A **SOLENOID** consists of many turns of insulated wire wound on a hollow, insulating tube. Most solenoids are cylindrical, but there are also square and flat rectangular prism types.*

- *When there is a **current** in the windings, the magnetic field pattern obtained is very similar to that of a bar magnet as shown in the diagram below.*

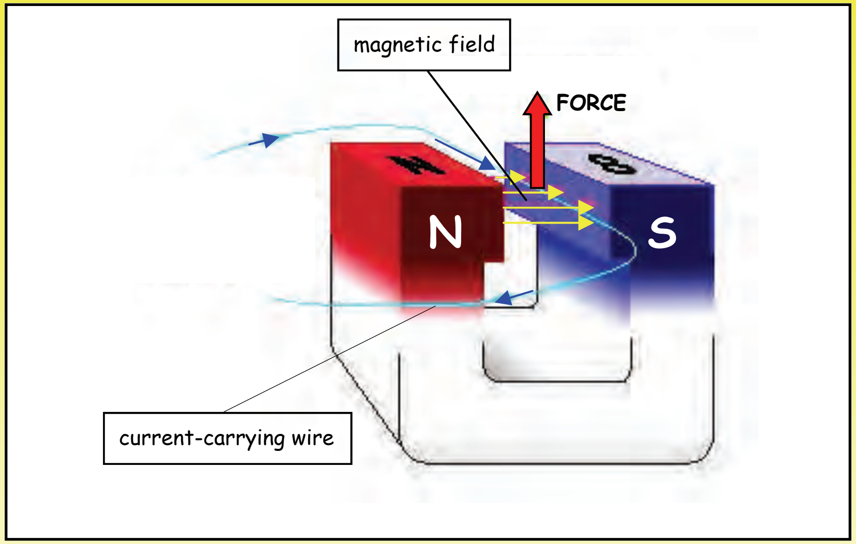


- ***Inside** the solenoid, the field lines are **close together, parallel and equally spaced.** This tells us that the field is **strong and uniform.***

- *The **polarity** of the solenoid ends may be identified in the following way. Imagine turning the solenoid so that the end is facing you. If the current at the end you have turned is **CLOCKWISE**, that end is a **S-POLE** and if it is **ANTI-CLOCKWISE**, that end is a **N-POLE**.*

- *An electromagnet is really **a solenoid wound on a soft iron core.** The soft iron core dramatically increases the strength of the magnetic field.*

FORCE ON A CURRENT-CARRYING CONDUCTOR IN A MAGNETIC FIELD



- *A current-carrying wire placed in the magnetic field between two magnet poles experiences a **force** as shown in the diagram above. The **current, magnetic field and force directions** are **mutually perpendicular.***

- *The **size of the FORCE (F)** acting on the wire is increased by increasing :*
  - *The size of the **CURRENT (I)** in the wire.*
  - *The **MAGNETIC FIELD STRENGTH** or **MAGNETIC FLUX DENSITY (B).***
  - *The **LENGTH (L)** of wire which is in the field.*

- *For a wire of **LENGTH (L)**, carrying a **CURRENT (I)** at right angles to a magnetic field of **STRENGTH** or **FLUX DENSITY (B)**, the **FORCE (F)** on the wire is given by :*

$$F = BIL$$

(N) (T or WB m^{-2}) (A) (m)

- *The unit of **MAGNETIC FIELD STRENGTH** or **MAGNETIC FLUX DENSITY (B)** is the :*

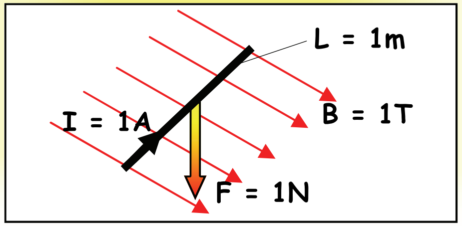
WEBER PER METRE^2 (Wb m^{-2}) which is called the **TESLA (T)**.

$$1\ T = 1\ Wb\ m^{-2}$$

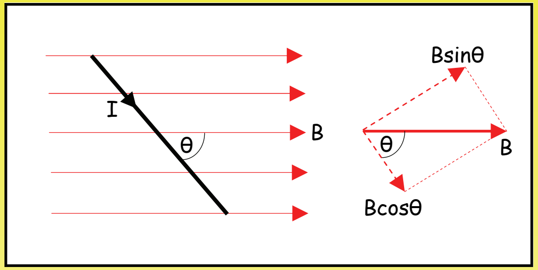
- *Since $B = F/IL$:*

<u>MAGNETIC FIELD STRENGTH or FLUX DENSITY (B)</u> is defined as: **the force acting per unit current, in a wire of unit length which is at right angles to the field.**

<u>1 TESLA (T)</u> is the flux density of a magnetic field in which a wire of length **1 METRE**, carrying a current of **1 AMPERE** at right angles to the field, experiences a force of **1 NEWTON** in a direction which is at right angles to both the field and the current.



- *For a wire which is at An angle **(θ)** to the Magnetic field lines, The force on the wire Due to the field is Determined using the Component of the field At 90° to the wire **(Bsinθ)**.*

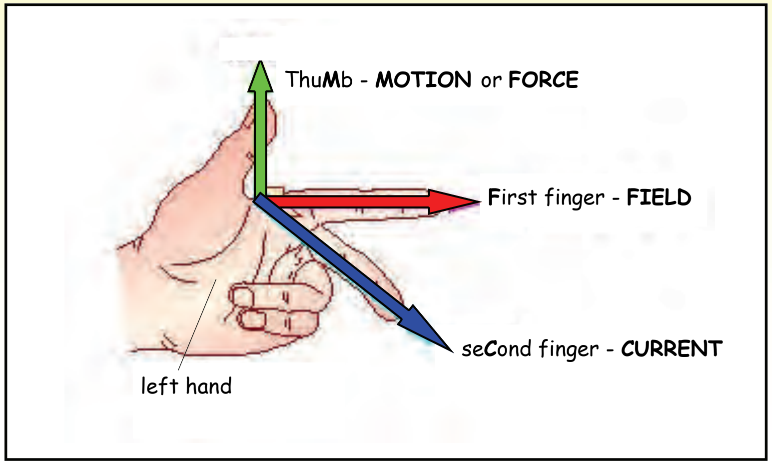


*So the **FORCE (F)** acting on a wire of **LENGTH (L)** which carries a **CURRENT (I)** at an **ANGLE (θ)** to a uniform magnetic field of **FLUX DENSITY (B)** is given by :*

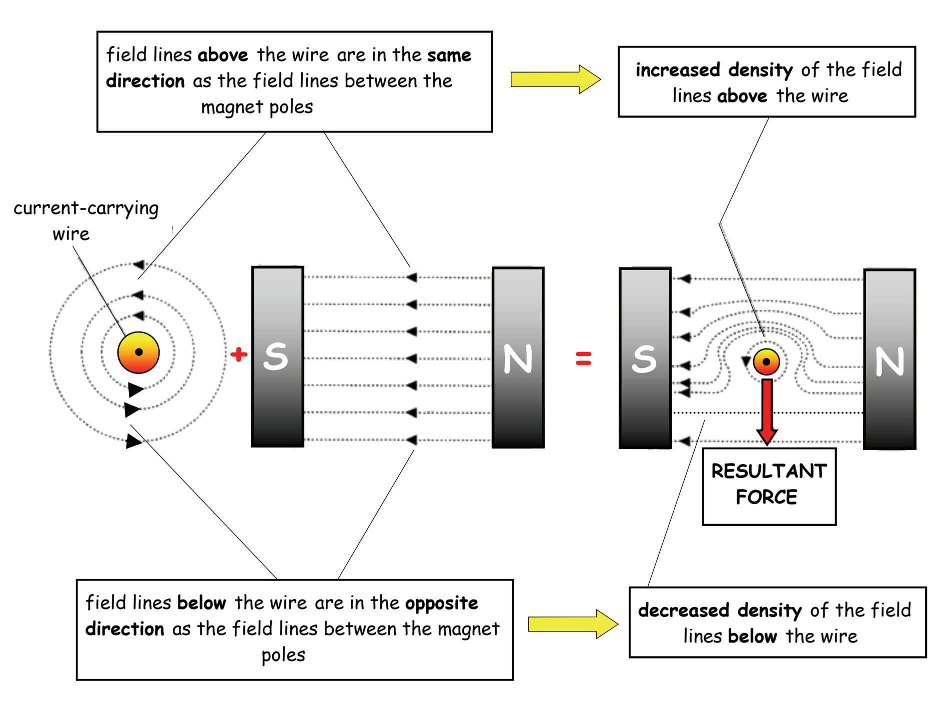
$$F = BIL \sin\theta$$

- ***When the wire is at 90° to the magnetic field :***
  *θ = 90°, so sin θ = sin 90° = 1 and **F = BIL***

- ***When the wire is parallel to the magnetic field :***
  *θ = 0°, so sin θ = sin 0° = 0 and **F = 0***



FORCE ON A CURRENT-CARRYING WIRE IN A MAGNETIC FIELD - EXPLANATION



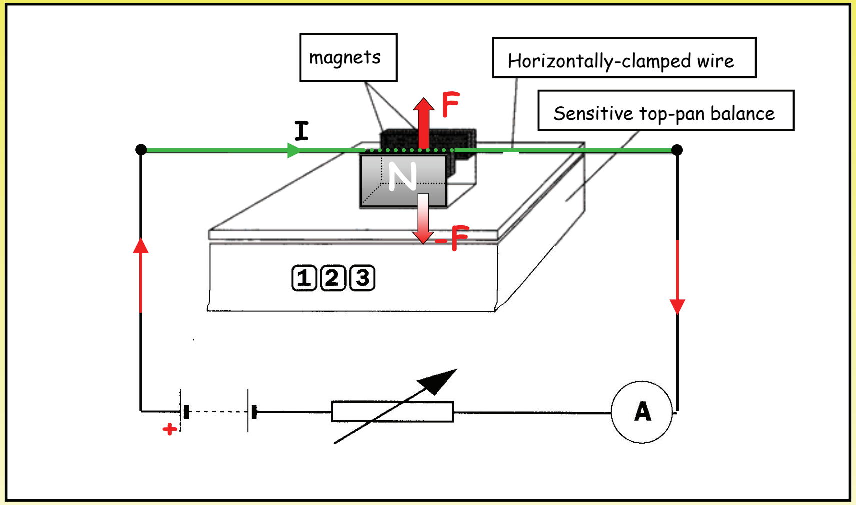
- *The diagram shown above illustrates why a current-carrying wire placed in the uniform magnetic field between two magnet poles experiences a **resultant force**.*

- *The interaction of the field around the wire with that between the poles gives rise to a **resultant** magnetic field whose flux density is **greater** in the region **above** the wire. This is because in the region above the wire, the field due to the current is in the **same direction** as that between the poles and so they reinforce to give an **increased flux density**. Whereas **below** the wire, the fields are **oppositely directed** and so give a **decreased flux density**.*

- *The overall effect of the distorted field is that a resultant force acts on the wire which will then move if it is free to do so.*

MEASURING THE FORCE ON A CURRENT-CARRYING WIRE IN A MAGNETIC FIELD

- *The diagram below shows an arrangement which can be used to measure the size of the force acting on a current-carrying wire placed in a uniform magnetic field.*



- *The magnets are attached to the soft-iron yoke with opposite poles facing each other, so that a strong magnetic field is created in the space between. The top-pan balance is set to read **zero** when the yoke and magnets are placed on the pan. When a **current (I)** flows through the clamped wire, an **Upward force (F)** is exerted on the wire.*

- *According to **Newton's third law**, there is then an **equal and opposite force (F)** on the yoke + magnets and this pushes down on the pan to give a reading on the balance. The size of the force exerted can then be calculated by multiplying the balance reading in kg by **g = 9.81 N kg^{-1}**.*

- *By varying the **current (I)** using the variable resistor and measured by the ammeter, its effect on the **size of the force** exerted on the wire may be investigated.*

- **PRACTICE QUESTIONS (1)**

1 (a) Sketch the magnetic field pattern around a **long, straight wire** which is carrying an **electric current, I** and next to this, sketch the field pattern when the current is increased to **2I** and its direction is **reversed**. Use the conventional **end-on view** of the wire and field in each case, indicating current and magnetic field directions.

(b) Sketch the magnetic field pattern obtain in and around a **long solenoid** which is carrying an **electric current, I.** Clearly show the current and magnetic field directions and **explain** how the polarity of the solenoid ends can be predicted from the current direction.

2 A superconducting wire of length **20 mm** carries a current of **1200 A**. It is situated in a magnetic field of flux density **25 mT**.

Calculate the **force** acting on the wire when it is :

(a) **Perpendicular,** (b) **Parallel,** (c) **At an angle of 60°**

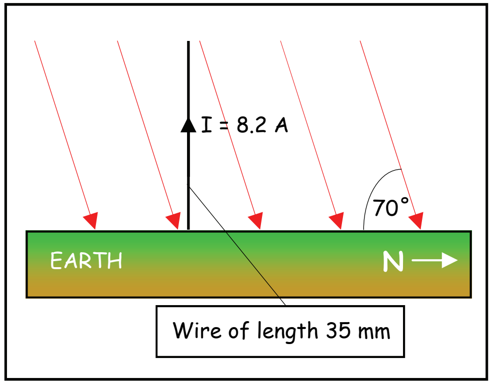
to the magnetic field direction.

3 A supercoducting wire has a radius of **1.5 mm** and a density of **8600 kg m^{-3}**.

Calculate the **current** in the wire which would make it 'float' without any visible support when it is placed at right angles to a horizontal magnetic field of flux density **5.0 x 10^{-4} T**.

> **HINT** : Mass **(m)** = density x volume
> Volume = **π r^{2}L**
> There must be an upward force (= **BIL**) to balance the wire weight (= **mg**)

4 The Earth's magnetic field at a certain place has a flux density of **0.070 mT** in a direction **due North** at an angle of **70°** to the surface, as shown in the diagram.

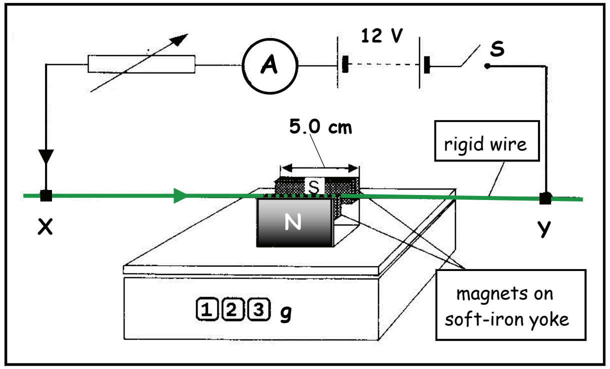


A straight wire of length **35 mm** carrying a current of **8.2 A upwards** is placed vertically in the field.

(a) Show that the wire experiences a **force** of **6.9 x 10^{-6} N.**

(b) Determine the **force direction.**

5 The diagram shows an arrangement used to measure the force on a current-carrying wire **XY** in a magnetic field. The reading on the balance is **272.0 g** when switch **S** is **open**. When **S** is **closed** and the variable resistor is adjusted so that the total circuit resistance is **6.0 Ω,** the balance reads **274.0 g.**



(a) Briefly **explain** why the reading on the balance changes when there is a current through the wire.

(b) If the length of wire which is in the magnetic field is **5.0 cm,** calculate :

(i) The **extra force** acting on the balance pan when **S is closed.**

(ii) The **magnetic flux density** between the magnets at right angles to the wire.

(iii) The **new balance reading** which would be obtained if the connections to the 12 V supply were **reversed.**

FORCE ON MOVING CHARGES IN A MAGNETIC FIELD

- *A **moving electric charge** constitutes an **electric current** and so it will create a **magnetic field** around itself. Therefore, when an electric charge moves through a magnetic field, there is an interaction between the two fields and the charge will experience a **force**.*

- *The size of the **FORCE (F)** on a moving charge in a magnetic field depends on :*

  - *The **MAGNETIC FLUX DENSITY (B)** of the field.*
  - *The **SIZE OF THE CHARGE (Q)**.*
  - *The **SPEED (v)** of the moving charge.*
  - *The **ANGLE (θ)** between the direction of motion and the field.*

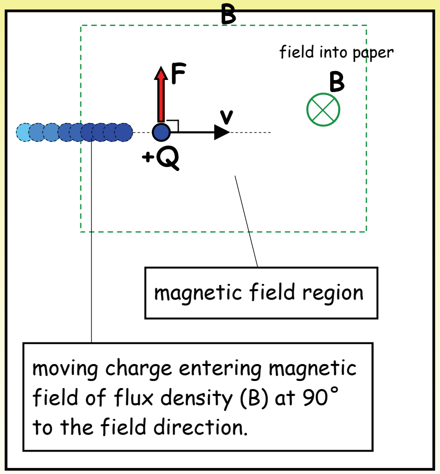
- *Consider a charge, **+Q** moving with speed, **v** at right angles to a magnetic field of flux density, **B**.*

  In time, t, the charge moves through distance, **L = vt**.

  The current due to the moving charge, **I = Q/t**.

  *Then the **FORCE (F)** acting on the charge is given by :*

  $F = BIL = B \times Q/t \times vt$

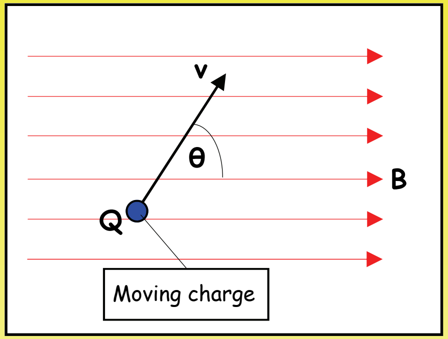


$$F = BQv$$

(N) (T) (C) (m s^{-1})

- *The **FORCE (F)** on a **CHARGE (Q)** moving with a **SPEED (v)** at an **ANGLE (θ)** to a magnetic field of **FLUX DENSITY (B)** is given by :*

$$F = BQv \sin\theta$$



When the charge is moving at 90° to the magnetic field **:**

$\sin\theta = \sin 90° = 1$ ………….. so ………… $F = BQv$

When the charge is moving parallel to the magnetic field **:**

$\sin\theta = \sin 0° = 0$ ………….. so ………… $F = 0$

POINTS TO NOTE

- *There is **NO FORCE** on the charge when :*

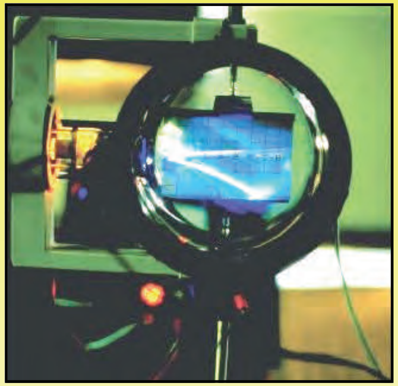
  - *It is **STATIONARY** (i.e. F = 0 when v = 0).*
  - *It moves **PARALLEL** to the field (i.e. F = 0 when θ = 0).*

- *The **DIRECTION** of the force can be predicted using **FLEMING'S LEFT-HAND RULE**, but you must bear in mind that the current direction is that of **CONVENTIONAL CURRENT** (which is opposite to that of electrons).*

- *The **FORCE (F)** on the moving charge is always at **right-angles** to the direction of motion.*

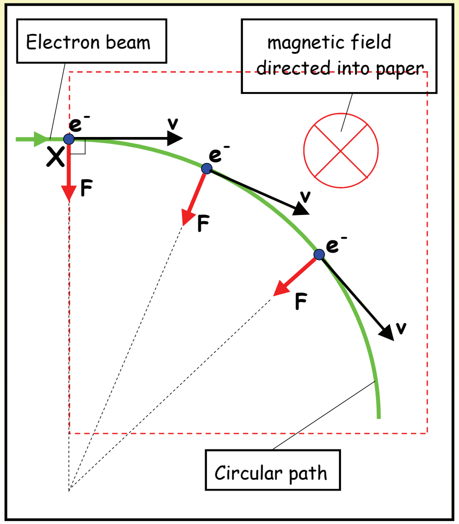
ELECTRON BEAM TUBE DEMONSTRATION OF PATH OF CHARGED PARTICLES IN A MAGNETIC FIELD

- *An **ELECTRON BEAM TUBE** can be used to show the effect of a magnetic field on moving electric charges.*

  A fine beam of electrons is produced by an 'electron gun' consisting of a heated filament cathode and an anode. The electrons are then accelerated towards and through the anode which is at a high positive potential with respect to the cathode.
  The electron beam then enters a magnetic field (produced by magnets or coils) which is directed at right angles to the electron path.
  The circular path followed by the beam can then be seen where the beam passes over the fluorescent screen. The deflection of the beam may be reversed by reversing the magnetic field direction.

- *The direction of the force on the electrons as they pass through the magnetic field is given by **Fleming's Left hand rule.***

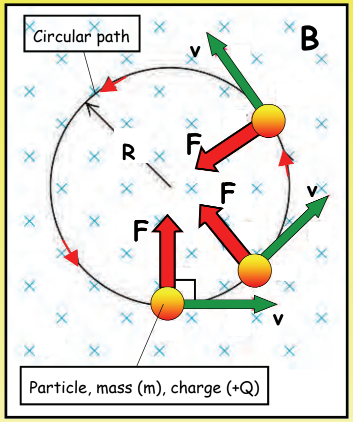
  

  *Since electrons have a **negative** charge, an electron beam moving to the **right** is seen as **conventional current** moving to the **left**. Thus at point **X** the force **(F)** on an electron is **downwards**, so the beam is deflected in that direction.*
  As the beam direction changes, so too does the force direction.

The force is always <u>AT RIGHT ANGLES</u> to the direction of motion.

ANALYSIS OF THE CIRCULAR ORBITS OF CHARGED PARTICLES AS THEY MOVE IN A PLANE PERPENDICULAR TO A UNIFORM MAGNETIC FIELD

- When a charged particle moves at right angles to a uniform magnetic field, the **constant force (F= BQv)** exerted on it is **perpendicular** to both the **particle motion** and the **field direction.**

  Thus, although the force continually changes the particle's direction of motion, it has **no effect** on its **speed (and hence on its kinetic energy).**

  The result is that the particle moves in a <u>**CIRCULAR PATH**</u> while it is in the magnetic field.

- The <u>**CENTRIPETAL FORCE**</u> needed for the charged particle to move in a circular path is provided by the <u>**ELECTROMAGNETIC FORCE**</u> which acts on it due to its interaction with the magnetic field.

- The diagram above shows a particle of **mass (m)** and **charge (Q)** which moves with **speed (v)** in a perpendicularly directed magnetic field of **flux density (B).**

  The magnetic force acting on the particle causes it to move in a circular path of **radius (R).** Then :

magnetic force = centripetal force

$$BQv = \frac{mv^2}{R}$$

$$R = \frac{mv}{BQ}$$

R (m), m (kg), v (m s^{-1}), B (T), Q (C)

POINTS TO NOTE

- From the equation for the **radius (R)** of the path we deduce that :

  - **R decreases** if **B is increased** *(stronger field - tighter circle).*
  - **R decreases** if **Q is increased** *(Greater charge - tighter circle).*
  - **R increases** if **m is increased** *(Greater mass- wider circle).*
  - **R increases** if **v is increased** *(Greater speed - wider circle).*

- **NO WORK IS DONE by the magnetic field on the particle.**
  *This is because the magnetic force acts **at right angles** to the particle's motion, and **work done = force x distance moved in the force direction.***

- **Magnetic fields** are used to control charged particle beams in :

  - Television and cathode-ray tubes.
  - High energy particle accelerators (cyclotron and synchrotron).
  - Mass spectrographs.

- Because of their motion, charged particles can get 'trapped' within magnetic fields.
  This is the case in certain regions around the Earth, called the '**Van Allen radiation belts'**, where the Earth's magnetic field causes large numbers of charged particles from space to become trapped in a great spiralling motion from one pole to the other.

The spectacular **Aurora Borealis (or Northern Lights)** glow in the Northern Hemisphere (shown in the above photo) is produced when charged particles from the radiation belts enter the Earth's atmosphere.

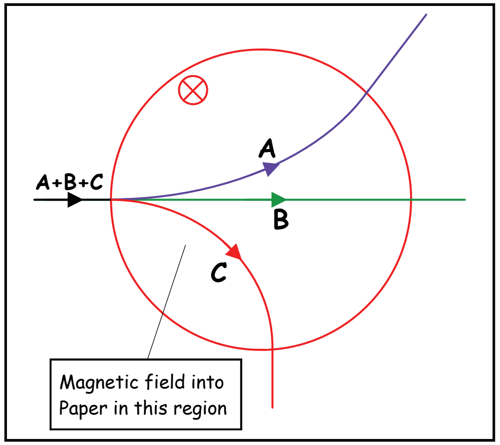
- PRACTICE QUESTIONS (2)

1 A beam of electrons moving at $\mathbf{2.0 \times 10^{6}\ m\ s^{-1}}$, is directed through a magnetic field of flux density **0.50 T**. Calculate the **force** on each electron if the beam is :

(a) At **right angles**, and (b) **at 45°** to the magnetic field lines.

(electron charge, **e** = **1.6 x** 10^{-19} **C**).

2 The diagram opposite shows radiation from a radioactive source passing through a uniform magnetic field.



Which of the tracks, **A, B** or **C** are those of **alpha particles (+ve charge), beta particles (-ve charge)** and **gamma rays (0 charge).**

3 A beam of electrons in a uniform magnetic field of flux Density **3.6 mT** moves in a circular path of radius **55 mm.**

(a) **Explain** why the electrons travel at a **constant speed** in the field.

(b) Calculate the **speed** of the electrons.

(Given that **Q/m for an electron = 1.76 x** 10^{11} **C kg**$^{-1}$).

4 An electron beam in a vacuum tube is directed **at right angles** to a magnetic field so that it travels along a **circular** path. Predict the effect on the **size** and **shape** of the path which is produced (separately) by each of the following changes :

(a) **Increasing the strength** of the magnetic field.
(b) **Reversing the direction** of the magnetic field.
(c) **Decreasing the speed** of the electrons in the beam
(d) Replacing the electron beam with a **beam of protons.**

5 **Positrons** are the **anti-particles** of electrons. Except for the fact that their charge is **positive,** they are identical to electrons in all other respects.

Explain how a magnetic field could be used to separate a charged particle beam which consists of a mixture of positrons and electrons.

6 A beam of electrons moving at a speed of **3.2 x 10^{7} m s^{-1}** is directed at right angles to a magnetic field having a flux density of **8.5 mT.** The electrons move in a **circular path** in the field.

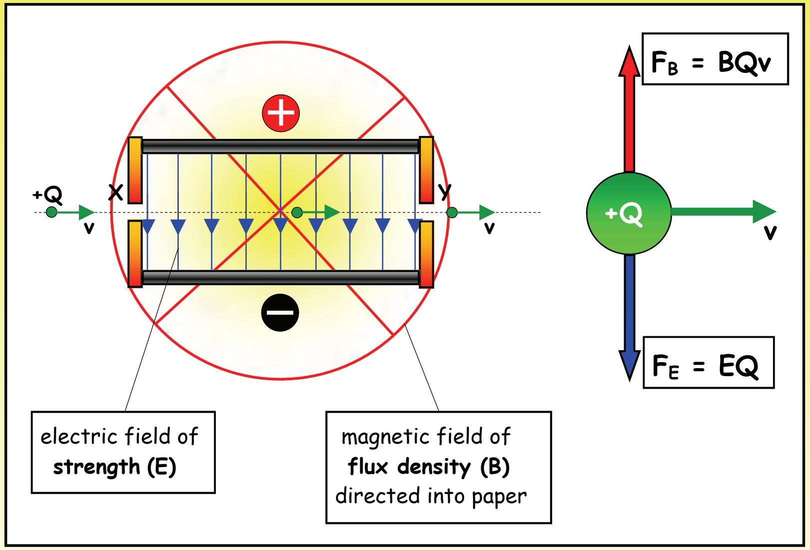
(a) (i) **Explain** why the electrons move in a **circular path.**

(ii) Calculate the **radius** of the circular path.

(b) The flux density is adjusted until the radius of the path is **65 mm.** Calculate the value of the **flux density** for this new radius.

MOTION OF CHARGED PARTICLES IN COMBINED ELECTRIC AND MAGNETIC FIELDS

- *Combined **ELECTRIC** and **MAGNETIC** fields are used in a device called a **VELOCITY SELECTOR,** which only allows charged particles of a specific, chosen velocity to pass through it.*



- *A cross-sectional view of a velocity selector is shown in the diagram above. When charged particles enter the device, they pass through a region in which there is an **electric field of strength (E)** acting **vertically downwards** and a **magnetic field of flux density (B)** which is **perpendicular** to the electric field.*

- *A particle of velocity **(v)** and charge **(+Q)** entering at **X** is simultaneously subjected to oppositely acting forces due to the two fields.*

- *The **ELECTRIC FIELD FORCE (FE = EQ)** acts **vertically downwards** on the particle and the **MAGNETIC FIELD FORCE (FB = BQv)** acts **vertically upwards** (This direction is given by **Fleming's left-hand rule**).*