24 Magnetic Fields

24.1 Current Carrying Conductors in a Magnetic Field

A **magnetic field** is a force field surrounding a **magnet** or **current-carrying wire** which acts on any other magnets or current-carrying wire placed in the field.

- The magnetic field of a bar magnet is **strongest at its ends** referred to as north-seeking and south-seeking poles.
- A **magnetic field line** of a magnetic field is a line along which a **north pole would move** in the field.

The **Earth's magnetic field** is caused by circulation currents in the molten iron core.

The Motor Effect

A current-carrying wire placed at a **non-zero angle** to the field lines of an external magnetic field experiences a force due to the field, this effect is known as the **motor effect**.

The force is perpendicular to the wire and the field lines.

The magnitude of the force depends on the

- Current
- Magnetic flux density
- Length of the wire
- The angle between the field lines and the current direction.

  The force is greatest when the wire is at right angles to the magnetic field, zero when the wire is parallel to the magnetic field.

Observations show that the force F on the wire is proportional to the **current** and the **length of the wire**.

- The **magnetic flux density** of the magnetic field is defined as the force per metre length per unit current on a current-carrying conductor at **right angles** to the magnetic field lines.
- For a wire of length l carrying a current I in a uniform magnetic field B at **90 deg to the field lines**.

$$F = BIl$$

The unit of B is the **tesla**, equal to $1\text{Nm}^{-1}\text{A}^{-1}$.

For a straight wire at angle θ to the magnetic field lines, the force on the wire is due to the **component of magnetic field perpendicular to the wire**.

$$F = BIl \sin\theta$$

Couple on a Coil

Consider a **rectangular current-carrying coil** of n turns, and can rotate about a vertical axis.

- The long sides of the coil are vertical, each experiences a force $F = n(BIl)$.
- The pair of forces acting **forms a couple** as they are not directed along the same line.

$$\tau = Fd$$

  where d is the **perpendicular distance** between the line of action of forces.
- If the plane of coil is at angle α to the field lines, $d = w \cos \alpha$ where w is the width of the coil.
- Therefore, $\tau = Fw \cos \alpha = nBIlw \cos \alpha = nBIA \cos \alpha$.

24.2 Moving Charges in a Magnetic Field

- Each electron in the beam experiences a force due to the magnetic field.
- The beam **follows a circular path** because the direction of the force on each electron is **perpendicular to the motion** of the electron.

A current-carrying wire in a magnetic field experiences a force is that the electrons moving along the wire are **pushed to one side** by the force of the field.

Magnetic fields are used in particle physics detectors to **separate different charged particles** out, and measure their momentum from the curvature of the tracks they create.

For a charge moving in a magnetic field

- In time t, it travels distance $l = vt$.
- Its passage is equivalent to current $I = \dfrac{Q}{t}$

$$F = BIl = B\left(\frac{Q}{t}\right)(vt) = BQv$$

If the direction of motion of a charged particle in a magnetic field is at angle θ to the lines of the field, then the component of B perpendicular to the motion of the charged particle is $B \sin \theta$, giving

$$F = BQv \sin \theta$$

The Hall Probe

Hall probes are used to **measure magnetic flux density**. Consists of

- A slice of semiconducting material.
- A magnetic field **perpendicular to the flat side** of the semiconductor.
- A **constant current** passes through the slice.

The charge carriers are deflected by the field, creating a potential difference between the top and bottom edges of the slice. This is known as the **Hall effect**.

The **Hall's voltage** is proportional to magnetic flux density.

Once the voltage is created,

$$\begin{aligned} F_{\text{mag}} &= BQv \\ F_{\text{elec}} &= \frac{QV_h}{d} \\ \frac{QV_h}{d} &= BQv \\ V_h &= BQd \end{aligned}$$

which is proportional to B.

24.3 Charged Particles in Circular Orbits

The force of the magnetic field on a moving charged particle is **at right angles** to the direction of motion of the particle.

- **No work is done** by the magnetic field on the particle, as the force **always acts at right angles** to the velocity of the particle.
- The force causes a **centripetal acceleration** because it is perpendicular to the velocity. The path is a **complete circle** because the magnetic field is uniform and the particle remains in the field.

$$\begin{aligned} BQv &= \frac{mv^2}{r} \\ r &= \frac{mv}{BQ} \end{aligned}$$

- r decreases if B is increased or if v is decreased.
- If particles with a **larger specific charge** $\frac{Q}{m}$ are used.

The Cyclotron

A cyclotron is used to **produce high-energy beams**.

- Two hollow **D-shaped electrodes** in a vacuum chamber.
- A **uniform magnetic field** applied perpendicular to the plane of the electrodes.
- A **high-frequency alternating voltage** is applied between the electrodes.

Charged particles are directed into one of the electrodes near the centre of the cyclotron.

1. The charged particles are **forced on a circular path** by the magnetic field, causing them to emerge from the electrode they were directed into.

2. As they cross into the other electrode, the alternating voltage reverses so they are **accelerated into the other electrode** where they were once again forced on a circular path by the magnetic field.

This occurs because the time taken by a particle to move around its semi-circular path in each electrode **does not depend on the particle speed**.

$$\begin{aligned} r &= \frac{mv}{BQ} \\ T_{\text{semi-circle}} &= \frac{\pi r}{v} \\ &= \frac{m\pi}{BQ} \\ T &= \frac{2m\pi}{BQ} \end{aligned}$$

The Mass Spectrometer

A mass spectrometer is used to analyse the **type of atoms present** in a sample.

1. The atoms of the sample are **ionised** and directed in a narrow beam **at the same velocity** into a **uniform magnetic field**.
2. Each ion is **deflected in a semi-circle** my the magnetic field onto a detector.
3. The radius of curvature **depends on the specific charge** of the ion in accordance with $r = \dfrac{mv}{BQ}$.
4. The detector is linked to a computer to show the **relative abundance** of each type of ion in the sample.