Magnetic fields

Magnetic fields and field lines, the force on a current and on a moving charge, Fleming's left-hand rule, the Hall voltage, circular paths and velocity selection, field patterns of currents, forces between conductors, and electromagnetic induction with Faraday's and Lenz's laws.

20.1 Concept of a magnetic field

A **magnetic field** is a field of force, produced either by **moving charges** (currents) or by **permanent magnets**. Field lines point from north to south outside a magnet. They show the direction of the force on a north pole, and closer lines mean a stronger field.

20.2 Force on a current-carrying conductor

A wire carrying a current in a magnetic field may feel a force:

$$F = BIL \sin\theta$$

where θ is the angle between the current and the field. The force is greatest at 90° and zero when the wire is parallel to the field.

Fleming's left-hand rule

Hold your left hand with the thumb, first finger and second finger all at right angles:

- **F**irst finger: **F**ield (north to south).
- Se**C**ond finger: **C**urrent (conventional, positive to negative).
- Thu**M**b: **M**otion, that is, the force.

Magnetic flux density

Magnetic flux density B is the force acting per unit current per unit length on a wire placed at right angles to the magnetic field. Its unit is the **tesla**, where 1 T = 1 N A^{-1} m^{-1}.

20.3 Force on a moving charge

$$F = BQv \sin\theta$$

Find the direction with the left-hand rule, with the second finger along the direction of **conventional current**. For a negative charge such as an electron, the current direction is **opposite** to its motion.

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Circular motion in a magnetic field

For a charge moving at right angles to a uniform field, the force is always perpendicular to the velocity. So the speed stays constant and the path is a **circle**. The magnetic force provides the centripetal force:

$$BQv = \frac{mv^2}{r} \quad \Rightarrow \quad r = \frac{mv}{BQ}$$

A bigger momentum means a bigger circle, and a stronger field means a smaller circle. The force does no work, so the kinetic energy does not change.

Velocity selection

Put an electric field and a magnetic field at right angles, so that the forces on a charge are opposite. For an undeflected particle:

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

Only particles of this speed pass straight through, whatever their charge or mass.

The Hall effect

When a current flows through a thin slice of conductor with a magnetic field at right angles to it, the charge carriers are pushed to one side. Charge builds up until the electric force balances the magnetic force. This gives a p.d. across the slice, the **Hall voltage**.

Balance gives $qV_H/d = Bqv$, where d is the width. Substituting $I = nAvq$ with $A = dt$ gives:

$$V_H = \frac{BI}{ntq}$$

where t is the thickness and n is the number density of carriers. **Semiconductors** give a much larger Hall voltage than metals, because their n is much smaller. A **Hall probe** measures B: with a constant current, $V_H \propto B$, and the probe must be perpendicular to the field to read its full value.

20.4 Magnetic fields due to currents

- **Long straight wire:** concentric circles, more widely spaced further away. Use the right-hand grip rule: thumb along the current, and your fingers curl along the field.
- **Flat circular coil:** the field runs through the middle of the coil and loops round outside.
- **Long solenoid:** a strong, uniform field inside, and outside like a bar magnet's field. Putting a **ferrous core** (soft iron) inside greatly increases the field.

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Forces between conductors

Each wire sits in the field of the other, so each feels a force. **Currents in the same direction attract**, and currents in opposite directions repel. The forces are equal and opposite, by Newton's third law.

20.5 Electromagnetic induction

Flux and flux linkage

Magnetic flux is the flux density × the cross-sectional area perpendicular to the flux density:

$$\Phi = BA$$

The unit is the **weber** (Wb). For a coil of N turns, the **flux linkage** is $N\Phi$. If the field is at an angle θ to the normal, $\Phi = BA\cos\theta$.

Faraday's and Lenz's laws

> **Faraday's law: the magnitude of the induced e.m.f. is proportional to the rate of change of magnetic flux linkage. Lenz's law: the direction of the induced e.m.f. is such as to oppose the change producing it.**

$$E = -\frac{\Delta(N\Phi)}{\Delta t}$$

The minus sign is Lenz's law, which is a consequence of conservation of energy. If the induced current helped the change, you would get energy from nothing.

Experiments

- Moving a magnet into a coil connected to a sensitive meter gives a reading only while it moves.
- Reversing the direction reverses the reading.
- The e.m.f. is larger with a faster movement, a stronger magnet or more turns. This shows the factors that affect its size.
- A moving magnet's north pole approaching a coil makes the near end of the coil a north pole, which **repels** the magnet, so you must do work to push it in.

> **TRY IT**

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A 100-turn coil of area 2.0×10^{-3} m² is at right angles to a 0.50 T field. The field falls to zero in 0.20 s. Find the average e.m.f. $\Delta(N\Phi) = 100 \times 0.50 \times 2.0 \times 10^{-3} = 0.10$ Wb. $E = 0.10/0.20 = 0.50$ V.

NOTE

Exam tip: a straight wire of length L moving at speed v at right angles to a field sweeps area Lv per second, so $E = BLv$. There must be a **change** in flux linkage to induce an e.m.f.; a steady field through a stationary coil gives none.

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