Unit - 3 : Magnetic Effects of Current and Magnetism

Magnetic Effects of Current and Magnetism

Magnetic phenomena are universal, permeating everything from distant galaxies to the atoms within our own bodies. This unit explores the relationship between electricity and magnetism, beginning with the discovery that moving charges generate magnetic fields.

I. Concept of Magnetic Field and Oersted's Experiment

The connection between electricity and magnetism was first established in 1820 by **Hans Christian Oersted**. He observed that an electric current in a straight wire caused a magnetic compass needle to deflect, aligning itself tangentially to a circle centered on the wire.

- **Oersted's Conclusion:** Moving charges or currents produce a magnetic field ($\vec{B}$) in the surrounding space.
- **Magnetic Field ($\vec{B}$):** A vector field defined at every point in space. It obeys the **principle of superposition**, meaning the field from multiple sources is the vector sum of individual fields.
- **Units:** The SI unit of magnetic field is the **tesla (T)**. A smaller non-SI unit is the **gauss (G)**, where $1\ \mathrm{G} = 10^{-4}\ \mathrm{T}$.
- **Convention:** A dot ($\odot$) represents a field emerging out of the plane of paper, while a cross ($\otimes$) represents a field going into the paper.

II. Biot-Savart Law and Applications

The **Biot-Savart Law** provides a quantitative relationship between a current element and the magnetic field it produces. For an infinitesimal element $d\vec{l}$ carrying current I, the magnetic field $d\vec{B}$ at a point $\vec{r}$ is: $d\vec{B} = \frac{\mu_0}{4\pi}\frac{I(d\vec{l} \times \vec{r})}{r^3}$ where $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T\ m\ A^{-1}}$ is the **permeability of free space**.

Application: Current-Carrying Circular Loop For a circular loop of radius R carrying current I:

- **Magnetic field at the center ($x = 0$):** $B = \frac{\mu_0 I}{2R}$
- **Magnetic field on the axis at distance x from the center:** $B = \frac{\mu_0 I R^2}{2(x^2 + R^2)^{3/2}}$
- **At large distances ($x \gg R$):** The field falls off as $1/x^3$, behaving like an electric dipole.

III. Ampere's Circuital Law and Applications

Ampere's Law relates the integrated magnetic field around a closed loop (Amperian loop) to the total current passing through the surface bounded by that loop. $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$

Applications:

1. **Infinitely Long Straight Wire:** At a distance r from the wire, the field is tangential and its magnitude is: $B = \frac{\mu_0 I}{2\pi r}$
2. **Solenoid:** A long solenoid consists of a wire wound into a helix. Inside a long solenoid, the field is uniform and parallel to the axis: $B = \mu_0 n I$ where n is the number of turns per unit length.

IV. Force on Charges and Conductors

1. Lorentz Force

The total force on a charge q moving with velocity $\vec{v}$ in both electric ($\vec{E}$) and magnetic ($\vec{B}$) fields is: $\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$

- **Magnetic Force Features:** It is zero if the charge is stationary ($v = 0$) or if $\vec{v}$ is parallel/anti-parallel to $\vec{B}$. The force is always perpendicular to both $\vec{v}$ and $\vec{B}$, so the magnetic field does **no work** on the charge.
- **Motion in B-field:** If $\vec{v} \perp \vec{B}$, the charge follows a circular path with radius $r = mv/qB$. The **cyclotron frequency** is $v_c = qB/2\pi m$.

2. Force on a Current-Carrying Conductor

A straight rod of length l carrying current I in an external field $\vec{B}$ experiences a force: $\vec{F} = I(\vec{l} \times \vec{B})$

3. Force between Two Parallel Conductors

Two parallel wires a and b separated by distance d carrying currents I_a and I_b exert forces on each other. The force per unit length f_{ba} is: $f_{ba} = \dfrac{\mu_0 I_a I_b}{2\pi d}$

- **Parallel currents attract**; anti-parallel currents repel.
- **Definition of Ampere:** 1 Ampere is the steady current which, in two infinitely long parallel conductors 1 meter apart in vacuum, produces a force of 2×10^{-7} N/m on each.

V. Current Loop as a Magnetic Dipole

A planar current loop acts as a magnetic dipole.

- **Magnetic Dipole Moment ($\vec{m}$):** For a loop with N turns, area A, and current I: $\vec{m} = NI\vec{A}$ Its direction is given by the **right-hand thumb rule**.
- **Torque in Uniform Field:** A loop experiences a torque but no net force: $\vec{\tau} = \vec{m} \times \vec{B}$
- **Potential Energy:** The energy of a dipole in a field is: $U = -\vec{m} \cdot \vec{B}$ Equilibrium is **stable** when $\vec{m} \parallel \vec{B}$ $(U = -mB)$ and **unstable** when $\vec{m}$ is anti-parallel ($U = +mB$).

VI. Moving Coil Galvanometer (MCG)

The MCG is a device used to detect or measure small currents.

- **Principle:** A current-carrying coil in a radial magnetic field experiences a torque $NIAB$ which is balanced by a restoring torque $k\phi$ from a spring.
- **Deflection (ϕ):** $\phi = \left(\dfrac{NAB}{k}\right) I$.
- **Current Sensitivity:** $\phi/I = NAB/k$.
- **Conversions:**
  - **To Ammeter:** Connect a small resistance (**shunt** r_s) in parallel with the galvanometer.

- ○ **To Voltmeter:** Connect a **large resistance** R in series with the galvanometer.

VII. Bar Magnet and Magnetism

A bar magnet is a magnetic dipole.

- **Equivalent Solenoid:** The field lines of a bar magnet resemble those of a finite solenoid. At large distances, its axial field is $\frac{\mu_0}{4\pi}\frac{2m}{r^3}$.
- **Field Lines:** Form continuous **closed loops** (unlike electric field lines). The tangent gives field direction, and density represents field strength.
- **Gauss's Law for Magnetism:** The net magnetic flux through any closed surface is always **zero** ($\oint \vec{B} \cdot d\vec{S} = 0$). This implies that **magnetic monopoles do not exist**.
- **Magnetic Intensity Axial and Equatorial (for $r \gg l$):**
  - ○ **Axial:** $\vec{B}_A = \frac{\mu_0}{4\pi}\frac{2\vec{m}}{r^3}$.
  - ○ **Equatorial:** $\vec{B}_E = -\frac{\mu_0}{4\pi}\frac{\vec{m}}{r^3}$.

VIII. Magnetic Properties of Materials

Materials are classified based on their response to an external field, defined by **Magnetisation** ($\vec{M}$, magnetic moment per unit volume) and **Magnetic Intensity** ($\vec{H}$).

- **Relations:** $\vec{B} = \mu_0(\vec{H} + \vec{M})$. For linear materials, $\vec{M} = \chi\vec{H}$, where χ is **magnetic susceptibility**.
- **Permeability:** $\mu = \mu_0\mu_r = \mu_0(1 + \chi)$.

Material	Susceptibility (χ)	Permeability (μ_r)	Examples
Diamagnetic	Small, Negative	$0 \leq \mu_r < 1$	Copper, Water, Bismuth
Paramagnetic	Small, Positive	$1 < \mu_r < 1 +$	Aluminum, Oxygen (STP)
Ferromagnetic	Large, Positive	$\mu_r \gg 1$	Iron, Cobalt, Nickel

- **Magnetisation Mechanisms:**
  - ○ **Diamagnetism:** Induced current (Lenz's Law) in atoms with zero net moment opposes the applied field. Superconductors show perfect diamagnetism (**Meissner effect**, $\chi = -1$).
  - ○ **Paramagnetism:** Randomly oriented permanent dipoles align with the field.
  - ○ **Ferromagnetism:** Atoms interact to form **domains**—regions of spontaneous alignment. Hard ferromagnets (e.g., Alnico) retain magnetisation; soft ones (e.g., Soft Iron) lose it.
- **Temperature Effects:** Paramagnetic χ depends on temperature. At high temperatures, ferromagnetic materials lose domain structure and become paramagnetic.