Question 4.1:

A circular coil of wire consisting of 100 turns, each of radius 8.0 cm carries a current of 0.40 A. What is the magnitude of the magnetic field **B** at the centre of the coil?

Answer

Number of turns on the circular coil, n = 100

Radius of each turn, r = 8.0 cm = 0.08 m

Current flowing in the coil, I = 0.4 A

Magnitude of the magnetic field at the centre of the coil is given by the relation,

$$|\mathbf{B}| = \frac{\mu_0}{4\pi}\frac{2\pi nI}{r}$$

Where,

μ_0 = Permeability of free space

= $4\pi \times 10^{-7}$ T m A^{-1}

$$|\mathbf{B}| = \frac{4\pi\times 10^{-7}}{4\pi}\times\frac{2\pi\times 100\times 0.4}{0.08}$$

$$= 3.14 \times 10^{-4}\ \text{T}$$

Hence, the magnitude of the magnetic field is 3.14×10^{-4} T.

Question 4.2:

A long straight wire carries a current of 35 A. What is the magnitude of the field **B** at a point 20 cm from the wire?

Answer

Current in the wire, I = 35 A

Distance of a point from the wire, r = 20 cm = 0.2 m

Magnitude of the magnetic field at this point is given as:

$$B = \frac{\mu_0}{4\pi}\frac{2I}{r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

$$B = \frac{4\pi \times 10^{-7} \times 2 \times 35}{4\pi \times 0.2}$$
$$= 3.5 \times 10^{-5}\ \text{T}$$

Hence, the magnitude of the magnetic field at a point 20 cm from the wire is 3.5×10^{-5} T.

Question 4.3:

A long straight wire in the horizontal plane carries a current of 50 A in north to south direction. Give the magnitude and direction of **B** at a point 2.5 m east of the wire.

Answer

Current in the wire, I = 50 A

A point is 2.5 m away from the East of the wire.

∴ Magnitude of the distance of the point from the wire, r = 2.5 m.

Magnitude of the magnetic field at that point is given by the relation, $B = \frac{\mu_0 2I}{4\pi r}$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

$$B = \frac{4\pi \times 10^{-7} \times 2 \times 50}{4\pi \times 2.5}$$
$$= 4 \times 10^{-6}\ \text{T}$$

The point is located normal to the wire length at a distance of 2.5 m. The direction of the current in the wire is vertically downward. Hence, according to the Maxwell's right hand thumb rule, the direction of the magnetic field at the given point is vertically upward.

Question 4.4:

A horizontal overhead power line carries a current of 90 A in east to west direction. What is the magnitude and direction of the magnetic field due to the current 1.5 m below the line?

Answer

Current in the power line, I = 90 A

Point is located below the power line at distance, r = 1.5 m

Hence, magnetic field at that point is given by the relation,

$$B = \frac{\mu_0 2I}{4\pi r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

$$B = \frac{4\pi \times 10^{-7} \times 2 \times 90}{4\pi \times 1.5} = 1.2 \times 10^{-5}\ \text{T}$$

The current is flowing from East to West. The point is below the power line. Hence, according to Maxwell's right hand thumb rule, the direction of the magnetic field is towards the South.

Question 4.5:

What is the magnitude of magnetic force per unit length on a wire carrying a current of 8 A and making an angle of 30º with the direction of a uniform magnetic field of 0.15 T?

Answer

Current in the wire, I = 8 A

Magnitude of the uniform magnetic field, B = 0.15 T

Angle between the wire and magnetic field, θ = 30°.

Magnetic force per unit length on the wire is given as:

$f = BI \sin\theta$

$= 0.15 \times 8 \times 1 \times \sin 30°$

$= 0.6$ N m^{-1}

Hence, the magnetic force per unit length on the wire is 0.6 N m^{-1}.

Question 4.6:

A 3.0 cm wire carrying a current of 10 A is placed inside a solenoid perpendicular to its axis. The magnetic field inside the solenoid is given to be 0.27 T. What is the magnetic force on the wire?

Answer

Length of the wire, l = 3 cm = 0.03 m

Current flowing in the wire, I = 10 A

Magnetic field, B = 0.27 T

Angle between the current and magnetic field, θ = 90°

Magnetic force exerted on the wire is given as:

$F = BIl\sin\theta$

$= 0.27 \times 10 \times 0.03 \sin 90°$

$= 8.1 \times 10^{-2}$ N

Hence, the magnetic force on the wire is 8.1×10^{-2} N. The direction of the force can be obtained from Fleming's left hand rule.

Question 4.7:

Two long and parallel straight wires A and B carrying currents of 8.0 A and 5.0 A in the same direction are separated by a distance of 4.0 cm. Estimate the force on a 10 cm section of wire A.

Answer

Current flowing in wire A, $I_A = 8.0$ A

Current flowing in wire B, $I_B = 5.0$ A

Distance between the two wires, $r = 4.0$ cm $= 0.04$ m

Length of a section of wire A, $l = 10$ cm $= 0.1$ m

Force exerted on length l due to the magnetic field is given as:

$$B = \frac{\mu_0 2\, I_A I_B l}{4\pi r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

$$B = \frac{4\pi \times 10^{-7} \times 2 \times 8 \times 5 \times 0.1}{4\pi \times 0.04}$$

$$= 2 \times 10^{-5} \text{ N}$$

The magnitude of force is 2×10^{-5} N. This is an attractive force normal to A towards B because the direction of the currents in the wires is the same.

Question 4.8:

A closely wound solenoid 80 cm long has 5 layers of windings of 400 turns each. The diameter of the solenoid is 1.8 cm. If the current carried is 8.0 A, estimate the magnitude of **B** inside the solenoid near its centre.

Answer

Length of the solenoid, l = 80 cm = 0.8 m

There are five layers of windings of 400 turns each on the solenoid.

∴ Total number of turns on the solenoid, $N = 5 \times 400 = 2000$

Diameter of the solenoid, D = 1.8 cm = 0.018 m

Current carried by the solenoid, I = 8.0 A

Magnitude of the magnetic field inside the solenoid near its centre is given by the relation,

$$B = \frac{\mu_0 N I}{l}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

$$B = \frac{4\pi \times 10^{-7} \times 2000 \times 8}{0.8}$$

$$= 8\pi \times 10^{-3} = 2.512 \times 10^{-2} \text{ T}$$

Hence, the magnitude of the magnetic field inside the solenoid near its centre is 2.512×10^{-2} T.

Question 4.9:

A square coil of side 10 cm consists of 20 turns and carries a current of 12 A. The coil is suspended vertically and the normal to the plane of the coil makes an angle of 30º with the direction of a uniform horizontal magnetic field of magnitude 0.80 T. What is the magnitude of torque experienced by the coil?

Answer

Length of a side of the square coil, l = 10 cm = 0.1 m

Current flowing in the coil, I = 12 A

Number of turns on the coil, n = 20

Angle made by the plane of the coil with magnetic field, $\theta = 30°$

Strength of magnetic field, B = 0.80 T

Magnitude of the magnetic torque experienced by the coil in the magnetic field is given by the relation,

$\tau = n BIA \sin\theta$

Where,

A = Area of the square coil

$\Rightarrow l \times l = 0.1 \times 0.1 = 0.01\ m^2$

$\therefore \tau = 20 \times 0.8 \times 12 \times 0.01 \times \sin 30°$

= 0.96 N m

Hence, the magnitude of the torque experienced by the coil is 0.96 N m.

Question 4.10:

Two moving coil meters, M_1 and M_2 have the following particulars:

$R_1 = 10\ \Omega$, $N_1 = 30$,

$A_1 = 3.6 \times 10^{-3}\ m^2$, $B_1 = 0.25$ T

$R_2 = 14\ \Omega$, $N_2 = 42$,

$A_2 = 1.8 \times 10^{-3}\ m^2$, $B_2 = 0.50$ T

(The spring constants are identical for the two meters).

Determine the ratio of (a) current sensitivity and (b) voltage sensitivity of M_2 and M_1.

Answer

For moving coil meter M_1:

Resistance, $R_1 = 10\ \Omega$

Number of turns, $N_1 = 30$

Area of cross-section, $A_1 = 3.6 \times 10^{-3}\ m^2$

Magnetic field strength, $B_1 = 0.25$ T

Spring constant $K_1 = K$

For moving coil meter M_2:

Resistance, $R_2 = 14\ \Omega$

Number of turns, $N_2 = 42$

Area of cross-section, $A_2 = 1.8 \times 10^{-3}\ m^2$

Magnetic field strength, $B_2 = 0.50$ T

Spring constant, $K_2 = K$

(a) Current sensitivity of M_1 is given as:

$$I_{s1} = \frac{N_1 \ B_1 \ A_1}{K_1}$$

And, current sensitivity of M_2 is given as:

$$I_{s2} = \frac{N_2 \ B_2 \ A_2}{K_2}$$

$$\therefore \text{Ratio } \frac{I_{s2}}{I_{s1}} = \frac{N_2 \ B_2 \ A_2 K_1}{K_2 N_1 \ B_1 \ A_1}$$

$$= \frac{42 \times 0.5 \times 1.8 \times 10^{-3} \times K}{K \times 30 \times 0.25 \times 3.6 \times 10^{-3}} = 1.4$$

Hence, the ratio of current sensitivity of M_2 to M_1 is 1.4.

(b) Voltage sensitivity for M_2 is given as:

$$V_{s2} = \frac{N_2 \ B_2 \ A_2}{K_2 \ R_2}$$

And, voltage sensitivity for M_1 is given as:

$$V_{s1} = \frac{N_1 \ B_1 \ A_1}{K_1}$$

$$\therefore \text{Ratio } \frac{V_{s2}}{Vs1} = \frac{N_2 \ B_2 \ A_2 K_1 R_1}{K_2 R_2 \ N_1 \ B_1 \ A_1}$$

$$= \frac{42 \times 0.5 \times 1.8 \times 10^{-3} \times 10 \times K}{K \times 14 \times 30 \times 0.25 \times 3.6 \times 10^{-3}} = 1$$

Hence, the ratio of voltage sensitivity of M_2 to M_1 is 1.

Question 4.11:

In a chamber, a uniform magnetic field of 6.5 G (1 G = 10^{-4} T) is maintained. An electron is shot into the field with a speed of 4.8 × 10^6 m s^{-1} normal to the field. Explain why the path of the electron is a circle. Determine the radius of the circular orbit. (e = 1.6 × 10^{-19} C, m_e= 9.1×10^{-31} kg)

Answer

Magnetic field strength, B = 6.5 G = 6.5 × 10^{-4} T

Speed of the electron, v = 4.8 × 10^6 m/s

Charge on the electron, e = 1.6 × 10^{-19} C

Mass of the electron, m_e = 9.1 × 10^{-31} kg

Angle between the shot electron and magnetic field, θ = 90°

Magnetic force exerted on the electron in the magnetic field is given as:

$F = evB \sin\theta$

This force provides centripetal force to the moving electron. Hence, the electron starts moving in a circular path of radius r.

Hence, centripetal force exerted on the electron,

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

In equilibrium, the centripetal force exerted on the electron is equal to the magnetic force i.e.,

$$F_c = F$$

$$\frac{mv^2}{r} = evB \sin\theta$$

$$r = \frac{mv}{Be\sin\theta}$$

$$= \frac{9.1\times10^{-31}\times4.8\times10^{6}}{6.5\times10^{-4}\times1.6\times10^{-19}\times\sin 90°}$$

$$= 4.2\times10^{-2} \text{ m } = 4.2 \text{ cm}$$

Hence, the radius of the circular orbit of the electron is 4.2 cm.

Question 4.12:

In Exercise 4.11 obtain the frequency of revolution of the electron in its circular orbit. Does the answer depend on the speed of the electron? Explain.

Answer

Magnetic field strength, B = 6.5 × 10^{-4} T

Charge of the electron, e = 1.6 × 10^{-19} C

Mass of the electron, m_e = 9.1 × 10^{-31} kg

Velocity of the electron, v = 4.8 × 10^{6} m/s

Radius of the orbit, r = 4.2 cm = 0.042 m

Frequency of revolution of the electron = ν

Angular frequency of the electron = ω = 2πν

Velocity of the electron is related to the angular frequency as:

$v = r\omega$

In the circular orbit, the magnetic force on the electron is balanced by the centripetal force. Hence, we can write:

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

$$eB = \frac{m}{r}(r\omega) = \frac{m}{r}(r2\pi\nu)$$

$$\nu = \frac{Be}{2\pi m}$$

This expression for frequency is independent of the speed of the electron.

On substituting the known values in this expression, we get the frequency as:

$$\nu = \frac{6.5\times10^{-4}\times1.6\times10^{-19}}{2\times3.14\times9.1\times10^{-31}}$$

$$= 18.2 \times 10^6 \text{ Hz}$$

$$\approx 18 \text{ MHz}$$

Hence, the frequency of the electron is around 18 MHz and is independent of the speed of the electron.

Question 4.13:

(a) A circular coil of 30 turns and radius 8.0 cm carrying a current of 6.0 A is suspended vertically in a uniform horizontal magnetic field of magnitude 1.0 T. The field lines make an angle of 60º with the normal of the coil. Calculate the magnitude of the counter torque that must be applied to prevent the coil from turning.

(b) Would your answer change, if the circular coil in (a) were replaced by a planar coil of some irregular shape that encloses the same area? (All other particulars are also unaltered.)

Answer

(a) Number of turns on the circular coil, n = 30

Radius of the coil, r = 8.0 cm = 0.08 m

Area of the coil $= \pi r^2 = \pi(0.08)^2 = 0.0201 \text{ m}^2$

Current flowing in the coil, I = 6.0 A

Magnetic field strength, B = 1 T

Angle between the field lines and normal with the coil surface,

θ = 60°

The coil experiences a torque in the magnetic field. Hence, it turns. The counter torque applied to prevent the coil from turning is given by the relation,

$\tau = n\, IBA \sin\theta$ … (i)

= 30 × 6 × 1 × 0.0201 × sin60°

= 3.133 N m

(b) It can be inferred from relation (i) that the magnitude of the applied torque is not dependent on the shape of the coil. It depends on the area of the coil. Hence, the answer would not change if the circular coil in the above case is replaced by a planar coil of some irregular shape that encloses the same area.

Question 4.14:

Two concentric circular coils X and Y of radii 16 cm and 10 cm, respectively, lie in the same vertical plane containing the north to south direction. Coil X has 20 turns and carries a current of 16 A; coil Y has 25 turns and carries a current of 18 A. The sense of the current in X is anticlockwise, and clockwise in Y, for an observer looking at the coils facing west. Give the magnitude and direction of the net magnetic field due to the coils at their centre.

Answer

Radius of coil X, r_1 = 16 cm = 0.16 m

Radius of coil Y, r_2 = 10 cm = 0.1 m

Number of turns of on coil X, n_1 = 20

Number of turns of on coil Y, n_2 = 25

Current in coil X, I_1 = 16 A

Current in coil Y, I_2 = 18 A

Magnetic field due to coil X at their centre is given by the relation,

$$B_1 = \frac{\mu_0 n_1 I_1}{2r_1}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}\ \mathrm{T\,m\,A^{-1}}$

$$\therefore B_1 = \frac{4\pi \times 10^{-7} \times 20 \times 16}{2 \times 0.16}$$
$$= 4\pi \times 10^{-4}\ \text{T (towards East)}$$

Magnetic field due to coil Y at their centre is given by the relation,

$$B_2 = \frac{\mu_0 n_2 I_2}{2r_2}$$
$$= \frac{4\pi \times 10^{-7} \times 25 \times 18}{2 \times 0.10}$$
$$= 9\pi \times 10^{-4}\ \text{T (towards West)}$$

Hence, net magnetic field can be obtained as:

$$B = B_2 - B_1$$
$$= 9\pi \times 10^{-4} - 4\pi \times 10^{-4}$$
$$= 5\pi \times 10^{-4}\ \text{T}$$
$$= 1.57 \times 10^{-3}\ \text{T (towards West)}$$

Question 4.15:

A magnetic field of 100 G (1 G = 10^{-4} T) is required which is uniform in a region of linear dimension about 10 cm and area of cross-section about 10^{-3} m^2. The maximum current-carrying capacity of a given coil of wire is 15 A and the number of turns per unit length that can be wound round a core is at most 1000 turns m^{-1}. Suggest some appropriate design particulars of a solenoid for the required purpose. Assume the core is not ferromagnetic

Answer

Magnetic field strength, B = 100 G = 100 × 10^{-4} T

Number of turns per unit length, n = 1000 turns m^{-1}

Current flowing in the coil, I = 15 A

Permeability of free space, $\mu_0 = 4\pi \times 10^{-7}\ \text{T m A}^{-1}$

Magnetic field is given by the relation,

$$B = \mu_0 n I$$

$$\therefore nI = \frac{B}{\mu_0}$$

$$= \frac{100 \times 10^{-4}}{4\pi \times 10^{-7}} = 7957.74$$

$$\approx 8000 \text{ A/m}$$

If the length of the coil is taken as 50 cm, radius 4 cm, number of turns 400, and current 10 A, then these values are not unique for the given purpose. There is always a possibility of some adjustments with limits.

Question 4.16:

For a circular coil of radius *R* and *N* turns carrying current *I*, the magnitude of the magnetic field at a point on its axis at a distance *x* from its centre is given by,

$$B = \frac{\mu_0 I R^2 N}{2\left(x^2 + R^2\right)^{\frac{3}{2}}}$$

(a) Show that this reduces to the familiar result for field at the centre of the coil.
(b) Consider two parallel co-axial circular coils of equal radius *R*, and number of turns *N*, carrying equal currents in the same direction, and separated by a distance *R*. Show that the field on the axis around the mid-point between the coils is uniform over a distance that is small as compared to *R*, and is given by,

$$B = 0.72 - \frac{\mu_0 BNI}{R}$$, approximately.

[Such an arrangement to produce a nearly uniform magnetic field over a small region is known as *Helmholtz coils*.]

Answer

Radius of circular coil = *R*

Number of turns on the coil = *N*

Current in the coil = *I*

Magnetic field at a point on its axis at distance *x* is given by the relation,

$$B = \frac{\mu_0 I R^2 N}{2\left(x^2 + R^2\right)^{\frac{3}{2}}}$$

Where,

μ_0 = Permeability of free space

(a) If the magnetic field at the centre of the coil is considered, then *x* = 0.

$$\therefore B = \frac{\mu_0 I R^2 N}{2R^3} = \frac{\mu_0 I N}{2R}$$

This is the familiar result for magnetic field at the centre of the coil.

(b) Radii of two parallel co-axial circular coils = *R*

Number of turns on each coil = *N*

Current in both coils = *I*

Distance between both the coils = *R*

Let us consider point Q at distance *d* from the centre.

Then, one coil is at a distance of $\frac{R}{2}+d$ from point Q.

∴ Magnetic field at point Q is given as:

$$B_1 = \frac{\mu_0 N I R^2}{2\left[\left(\frac{R}{2}+d\right)^2 + R^2\right]^{\frac{3}{2}}}$$

Also, the other coil is at a distance of $\frac{R}{2}-d$ from point Q.

∴ Magnetic field due to this coil is given as:

$$B_2 = \frac{\mu_0 N I R^2}{2\left[\left(\frac{R}{2}-d\right)^2 + R^2\right]^{\frac{3}{2}}}$$

Total magnetic field,

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$$B = B_1 + B_2$$

$$= \frac{\mu_0 I R^2}{2}\left[\left\{\left(\frac{R}{2}-d\right)^2 + R^2\right\}^{-\frac{3}{2}} + \left\{\left(\frac{R}{2}+d\right)^2 + R^2\right\}^{-\frac{3}{2}}\right]$$

$$= \frac{\mu_0 I R^2}{2}\left[\left(\frac{5R^2}{4} + d^2 - Rd\right)^{-\frac{3}{2}} + \left(\frac{5R^2}{4} + d^2 + Rd\right)^{-\frac{3}{2}}\right]$$

$$= \frac{\mu_0 I R^2}{2} \times \left(\frac{5R^2}{4}\right)^{-\frac{3}{2}}\left[\left(1 + \frac{4}{5}\frac{d^2}{R^2} - \frac{4}{5}\frac{d}{R}\right)^{-\frac{3}{2}} + \left(1 + \frac{4}{5}\frac{d^2}{R^2} + \frac{4}{5}\frac{d}{R}\right)^{-\frac{3}{2}}\right]$$

For $d << R$, neglecting the factor $\frac{d^2}{R^2}$, we get:

$$\approx \frac{\mu_0 I R^2}{2} \times \left(\frac{5R^2}{4}\right)^{-\frac{3}{2}} \times \left[\left(1 - \frac{4d}{5R}\right)^{-\frac{3}{2}} + \left(1 + \frac{4d}{5R}\right)^{-\frac{3}{2}}\right]$$

$$\approx \frac{\mu_0 I R^2 N}{2R^3} \times \left(\frac{4}{5}\right)^{\frac{3}{2}}\left[1 - \frac{6d}{5R} + 1 + \frac{6d}{5R}\right]$$

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 I N}{R} = 0.72\left(\frac{\mu_0 I N}{R}\right)$$

Hence, it is proved that the field on the axis around the mid-point between the coils is uniform.

Question 4.17:

A toroid has a core (non-ferromagnetic) of inner radius 25 cm and outer radius 26 cm, around which 3500 turns of a wire are wound. If the current in the wire is 11 A, what is the magnetic field (a) outside the toroid, (b) inside the core of the toroid, and (c) in the empty space surrounded by the toroid.

Answer

Inner radius of the toroid, r_1 = 25 cm = 0.25 m

Outer radius of the toroid, r_2 = 26 cm = 0.26 m

Number of turns on the coil, N = 3500

Current in the coil, I = 11 A

(a) Magnetic field outside a toroid is zero. It is non-zero only inside the core of a toroid.

(b) Magnetic field inside the core of a toroid is given by the relation,

$B = \frac{\mu_0 NI}{l}$

Where,

μ_0 = Permeability of free space = $4\pi\times10^{-7}\ \mathrm{T\,m\,A^{-1}}$

l = length of toroid

$$= 2\pi\left[\frac{r_1+r_2}{2}\right]$$

$$= \pi(0.25+0.26)$$

$$= 0.51\pi$$

$$\therefore B = \frac{4\pi\times10^{-7}\times3500\times11}{0.51\pi}$$

$$\approx 3.0\times10^{-2}\ \mathrm{T}$$

(c) Magnetic field in the empty space surrounded by the toroid is zero.

Question 4.18:

Answer the following questions:

(a) A magnetic field that varies in magnitude from point to point but has a constant direction (east to west) is set up in a chamber. A charged particle enters the chamber and travels undeflected along a straight path with constant speed. What can you say about the initial velocity of the particle?

(b) A charged particle enters an environment of a strong and non-uniform magnetic field varying from point to point both in magnitude and direction, and comes out of it following a complicated trajectory. Would its final speed equal the initial speed if it suffered no collisions with the environment?

(c) An electron travelling west to east enters a chamber having a uniform electrostatic field in north to south direction. Specify the direction in which a uniform magnetic field should be set up to prevent the electron from deflecting from its straight line path.

Answer

(a) The initial velocity of the particle is either parallel or anti-parallel to the magnetic field. Hence, it travels along a straight path without suffering any deflection in the field.

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(b) Yes, the final speed of the charged particle will be equal to its initial speed. This is because magnetic force can change the direction of velocity, but not its magnitude.

(c) An electron travelling from West to East enters a chamber having a uniform electrostatic field in the North-South direction. This moving electron can remain undeflected if the electric force acting on it is equal and opposite of magnetic field. Magnetic force is directed towards the South. According to Fleming's left hand rule, magnetic field should be applied in a vertically downward direction.

Question 4.19:

An electron emitted by a heated cathode and accelerated through a potential difference of 2.0 kV, enters a region with uniform magnetic field of 0.15 T. Determine the trajectory of the electron if the field (a) is transverse to its initial velocity, (b) makes an angle of 30º with the initial velocity.

Answer

Magnetic field strength, B = 0.15 T

Charge on the electron, $e = 1.6 \times 10^{-19}$ C

Mass of the electron, $m = 9.1 \times 10^{-31}$ kg

Potential difference, V = 2.0 kV = 2×10^{3} V

Thus, kinetic energy of the electron = eV

$$\Rightarrow eV = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2eV}{m}} \qquad \ldots (1)$$

Where,

v = velocity of the electron

(a) Magnetic force on the electron provides the required centripetal force of the electron. Hence, the electron traces a circular path of radius r.

Magnetic force on the electron is given by the relation,

$B\,ev$

Centripetal force $= \frac{mv^2}{r}$

$$\therefore Bev = \frac{mv^2}{r}$$

$$r = \frac{mv}{Be} \qquad \dots(2)$$

From equations (1) and (2), we get

$$r = \frac{m}{Be}\left[\frac{2eV}{m}\right]^{\frac{1}{2}}$$

$$= \frac{9.1\times10^{-31}}{0.15\times1.6\times10^{-19}}\times\left(\frac{2\times1.6\times10^{-19}\times2\times10^{3}}{9.1\times10^{-31}}\right)^{\frac{1}{2}}$$

$$= 100.55\times10^{-5}$$

$$= 1.01\times10^{-3}\text{ m}$$

$$= 1\text{ mm}$$

Hence, the electron has a circular trajectory of radius 1.0 mm normal to the magnetic field.

(b) When the field makes an angle θ of 30° with initial velocity, the initial velocity will be,

$$v_1 = v\sin\theta$$

From equation (2), we can write the expression for new radius as:

$$r_{1,} = \frac{mv_1}{Be}$$

$$= \frac{mv\sin\theta}{Be}$$

$$= \frac{9.1\times10^{-31}}{0.15\times1.6\times10^{-19}}\times\left[\frac{2\times1.6\times10^{-19}\times2\times10^{3}}{9\times10^{-31}}\right]^{\frac{1}{2}}\times\sin30^\circ$$

$$= 0.5\times10^{-3}\text{ m}$$

$$= 0.5\text{ mm}$$

Hence, the electron has a helical trajectory of radius 0.5 mm along the magnetic field direction.

Question 4.20:

A magnetic field set up using Helmholtz coils (described in Exercise 4.16) is uniform in a small region and has a magnitude of 0.75 T. In the same region, a uniform electrostatic field is maintained in a direction normal to the common axis of the coils. A narrow beam of (single species) charged particles all accelerated through 15 kV enters this region in a direction perpendicular to both the axis of the coils and the electrostatic field. If the beam remains undeflected when the electrostatic field is 9.0×10^{-5} V m^{-1}, make a simple guess as to what the beam contains. Why is the answer not unique?

Answer

Magnetic field, B = 0.75 T

Accelerating voltage, V = 15 kV = 15×10^3 V

Electrostatic field, $E = 9 \times 10^5$ V m^{-1}

Mass of the electron = m

Charge of the electron = e

Velocity of the electron = v

Kinetic energy of the electron = eV

$$\Rightarrow \frac{1}{2}mv^2 = eV$$

$$\therefore \frac{e}{m} = \frac{v^2}{2V} \qquad \ldots (1)$$

Since the particle remains undeflected by electric and magnetic fields, we can infer that the electric field is balancing the magnetic field.

$$\therefore eE = evB$$

$$v = \frac{E}{B} \qquad \ldots (2)$$

Putting equation (2) in equation (1), we get

$$\frac{e}{m} = \frac{1}{2}\frac{\left(\frac{E}{B}\right)^2}{V} = \frac{E^2}{2VB^2}$$

$$= \frac{\left(9.0\times10^5\right)^2}{2\times15000\times\left(0.75\right)^2} = 4.8\times10^7 \text{ C/kg}$$

This value of specific charge e/m is equal to the value of deuteron or deuterium ions. This is not a unique answer. Other possible answers are He^{++}, Li^{++}, etc.

Question 4.21:

A straight horizontal conducting rod of length 0.45 m and mass 60 g is suspended by two vertical wires at its ends. A current of 5.0 A is set up in the rod through the wires.

(a) What magnetic field should be set up normal to the conductor in order that the tension in the wires is zero?

(b) What will be the total tension in the wires if the direction of current is reversed keeping the magnetic field same as before? (Ignore the mass of the wires.) g = 9.8 m s^{-2}.

Answer

Length of the rod, l = 0.45 m

Mass suspended by the wires, m = 60 g = 60 × 10^{-3} kg

Acceleration due to gravity, g = 9.8 m/s^2

Current in the rod flowing through the wire, I = 5 A

(a) Magnetic field (B) is equal and opposite to the weight of the wire i.e.,

$$BIl = mg$$

$$\therefore B = \frac{mg}{Il}$$

$$= \frac{60\times10^{-3}\times9.8}{5\times0.45} = 0.26 \text{ T}$$

A horizontal magnetic field of 0.26 T normal to the length of the conductor should be set up in order to get zero tension in the wire. The magnetic field should be such that Fleming's left hand rule gives an upward magnetic force.

(b) If the direction of the current is revered, then the force due to magnetic field and the weight of the wire acts in a vertically downward direction.

∴Total tension in the wire = $BIl + m$g

$$= 0.26 \times 5 \times 0.45 + \left(60 \times 10^{-3}\right) \times 9.8$$
$$= 1.176 \text{ N}$$

Question 4.22:

The wires which connect the battery of an automobile to its starting motor carry a current of 300 A (for a short time). What is the force per unit length between the wires if they are 70 cm long and 1.5 cm apart? Is the force attractive or repulsive?

Answer

Current in both wires, I = 300 A

Distance between the wires, r = 1.5 cm = 0.015 m

Length of the two wires, l = 70 cm = 0.7 m

Force between the two wires is given by the relation,

$$F = \frac{\mu_0 I^2}{2\pi r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7} \text{ T m A}^{-1}$

$$\therefore F = \frac{4\pi \times 10^{-7} \times (300)^2}{2\pi \times 0.015}$$
$$= 1.2 \text{ N/m}$$

Since the direction of the current in the wires is opposite, a repulsive force exists between them.

Question 4.23:

A uniform magnetic field of 1.5 T exists in a cylindrical region of radius10.0 cm, its direction parallel to the axis along east to west. A wire carrying current of 7.0 A in the north to south direction passes through this region. What is the magnitude and direction of the force on the wire if,

(a) the wire intersects the axis,

(b) the wire is turned from N-S to northeast-northwest direction,

(c) the wire in the N-S direction is lowered from the axis by a distance of 6.0 cm?

Answer

Magnetic field strength, B = 1.5 T

Radius of the cylindrical region, r = 10 cm = 0.1 m

Current in the wire passing through the cylindrical region, I = 7 A

(a) If the wire intersects the axis, then the length of the wire is the diameter of the cylindrical region.

Thus, $l = 2r = 0.2$ m

Angle between magnetic field and current, $\theta = 90°$

Magnetic force acting on the wire is given by the relation,

$F = BIl \sin\theta$

$= 1.5 \times 7 \times 0.2 \times \sin 90°$

$= 2.1$ N

Hence, a force of 2.1 N acts on the wire in a vertically downward direction.

(b) New length of the wire after turning it to the Northeast-Northwest direction can be given as: :

$$l_1 = \frac{l}{\sin\theta}$$

Angle between magnetic field and current, $\theta = 45°$

Force on the wire,

$F = BIl_1 \sin\theta$

$$= BIl$$
$$= 1.5 \times 7 \times 0.2$$
$$= 2.1 \text{ N}$$

Hence, a force of 2.1 N acts vertically downward on the wire. This is independent of angleθbecause $l \sin\theta$ is fixed.

(c) The wire is lowered from the axis by distance, d = 6.0 cm

Let l_2 be the new length of the wire.

$$\therefore \left(\frac{l_2}{2}\right)^2 = 4(d+r)$$
$$= 4(10+6) = 4(16)$$
$$\therefore l_2 = 8 \times 2 = 16 \text{ cm} = 0.16 \text{ m}$$

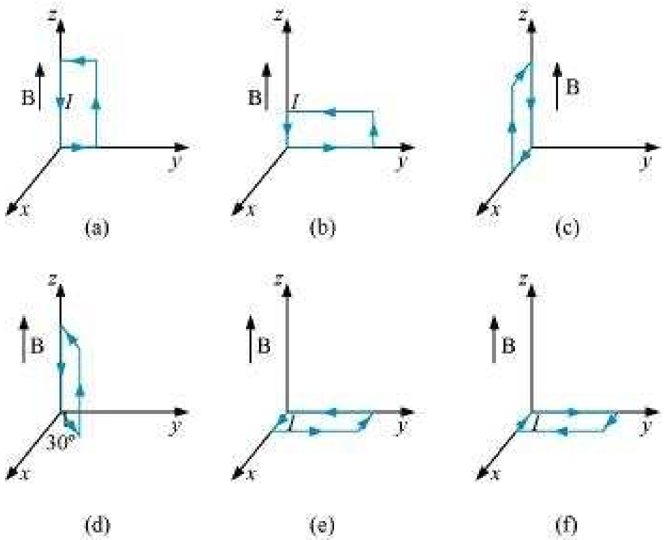
Magnetic force exerted on the wire,

$$F_2 = BIl_2$$
$$= 1.5 \times 7 \times 0.16$$
$$= 1.68 \text{ N}$$

Hence, a force of 1.68 N acts in a vertically downward direction on the wire.

Question 4.24:

A uniform magnetic field of 3000 G is established along the positive *z*-direction. A rectangular loop of sides 10 cm and 5 cm carries a current of 12 A. What is the torque on the loop in the different cases shown in Fig. 4.28? What is the force on each case? Which case corresponds to stable equilibrium?



Answer

Magnetic field strength, B = 3000 G = 3000 × 10^{-4} T = 0.3 T

Length of the rectangular loop, l = 10 cm

Width of the rectangular loop, b = 5 cm

Area of the loop,

$A = l \times b = 10 \times 5 = 50 \text{ cm}^2 = 50 \times 10^{-4} \text{ m}^2$

Current in the loop, I = 12 A

Now, taking the anti-clockwise direction of the current as positive and vise-versa:

(a) Torque, $\vec{\tau} = I\vec{A} \times \vec{B}$

From the given figure, it can be observed that *A* is normal to the *y*-*z* plane and *B* is directed along the *z*-axis.

$$\therefore \tau = 12\times\left(50\times10^{-4}\right)\hat{i}\times0.3\hat{k}$$
$$= -1.8\times10^{-2}\,\hat{j}\ \text{N m}$$

The torque is 1.8×10^{-2} N m along the negative *y*-direction. The force on the loop is zero because the angle between *A* and *B* is zero.

(b) This case is similar to case (a). Hence, the answer is the same as (a).

(c) Torque $\tau = I\vec{A}\times\vec{B}$

From the given figure, it can be observed that *A* is normal to the *x*-*z* plane and *B* is directed along the *z*-axis.

$$\therefore \tau = -12\times\left(50\times10^{-4}\right)\hat{j}\times0.3\hat{k}$$
$$= -1.8\times10^{-2}\hat{i}\ \text{N m}$$

The torque is 1.8×10^{-2} N m along the negative *x* direction and the force is zero.

(d) Magnitude of torque is given as:

$$|\tau| = IAB$$
$$= 12\times50\times10^{-4}\times0.3$$
$$= 1.8\times10^{-2}\,\text{N m}$$

Torque is 1.8×10^{-2} N m at an angle of 240° with positive *x* direction. The force is zero.

(e) Torque $\tau = I\vec{A}\times\vec{B}$

$$= \left(50\times10^{-4}\times12\right)\hat{k}\times0.3\hat{k}$$
$$= 0$$

Hence, the torque is zero. The force is also zero.

(f) Torque $\tau = I\vec{A}\times\vec{B}$

$$= \left(50\times10^{-4}\times12\right)\hat{k}\times0.3\hat{k}$$
$$= 0$$

Hence, the torque is zero. The force is also zero.

In case (e), the direction of $I\vec{A}$ and $\vec{B}$ is the same and the angle between them is zero. If displaced, they come back to an equilibrium. Hence, its equilibrium is stable.

Whereas, in case (f), the direction of $I\vec{A}$ and $\vec{B}$ is opposite. The angle between them is 180°. If disturbed, it does not come back to its original position. Hence, its equilibrium is unstable.

Question 4.25:

A circular coil of 20 turns and radius 10 cm is placed in a uniform magnetic field of 0.10 T normal to the plane of the coil. If the current in the coil is 5.0 A, what is the

(a) total torque on the coil,

(b) total force on the coil,

(c) average force on each electron in the coil due to the magnetic field?

(The coil is made of copper wire of cross-sectional area 10^{-5} m^2, and the free electron density in copper is given to be about 10^{29} m^{-3}.)

Answer

Number of turns on the circular coil, n = 20

Radius of the coil, r = 10 cm = 0.1 m

Magnetic field strength, B = 0.10 T

Current in the coil, I = 5.0 A

(a) The total torque on the coil is zero because the field is uniform.

(b) The total force on the coil is zero because the field is uniform.

(c) Cross-sectional area of copper coil, $A = 10^{-5}$ m^2

Number of free electrons per cubic meter in copper, $N = 10^{29}$ /m^3

Charge on the electron, $e = 1.6 \times 10^{-19}$ C

Magnetic force, $F = Bev_d$

Where,

v_d = Drift velocity of electrons

$$= \frac{I}{NeA}$$

$$\therefore F = \frac{BeI}{NeA}$$

$$= \frac{0.10 \times 5.0}{10^{29} \times 10^{-5}} = 5 \times 10^{-25} \text{ N}$$

Hence, the average force on each electron is 5×10^{-25} N.

Question 4.26:

A solenoid 60 cm long and of radius 4.0 cm has 3 layers of windings of 300 turns each. A 2.0 cm long wire of mass 2.5 g lies inside the solenoid (near its centre) normal to its axis; both the wire and the axis of the solenoid are in the horizontal plane. The wire is connected through two leads parallel to the axis of the solenoid to an external battery which supplies a current of 6.0 A in the wire. What value of current (with appropriate sense of circulation) in the windings of the solenoid can support the weight of the wire? *g* = 9.8 m s^{-2}

Answer

Length of the solenoid, *L* = 60 cm = 0.6 m

Radius of the solenoid, *r* = 4.0 cm = 0.04 m

It is given that there are 3 layers of windings of 300 turns each.

$\therefore$ Total number of turns, *n* = 3 × 300 = 900

Length of the wire, *l* = 2 cm = 0.02 m

Mass of the wire, *m* = 2.5 g = 2.5 × 10^{-3} kg

Current flowing through the wire, *i* = 6 A

Acceleration due to gravity, g = 9.8 m/s^2

Magnetic field produced inside the solenoid, $B = \frac{\mu_0 n I}{L}$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ T m A^{-1}

I = Current flowing through the windings of the solenoid

Magnetic force is given by the relation,

$$F = Bil$$
$$= \frac{\mu_0 nI}{L} il$$

Also, the force on the wire is equal to the weight of the wire.

$$\therefore mg = \frac{\mu_0 nIil}{L}$$
$$I = \frac{mgL}{\mu_0 nil}$$
$$= \frac{2.5\times10^{-3}\times9.8\times0.6}{4\pi\times10^{-7}\times900\times0.02\times6} = 108 \text{ A}$$

Hence, the current flowing through the solenoid is 108 A.

Question 4.27:

A galvanometer coil has a resistance of 12 Ω and the metre shows full scale deflection for a current of 3 mA. How will you convert the metre into a voltmeter of range 0 to 18 V?

Answer

Resistance of the galvanometer coil, G = 12 Ω

Current for which there is full scale deflection, I_g = 3 mA = 3 × 10^{-3} A

Range of the voltmeter is 0, which needs to be converted to 18 V.

$\therefore V$ = 18 V

Let a resistor of resistance R be connected in series with the galvanometer to convert it into a voltmeter. This resistance is given as:

$$R = \frac{V}{I_g} - G$$
$$= \frac{18}{3\times10^{-3}} - 12 = 6000 - 12 = 5988\ \Omega$$

Hence, a resistor of resistance $5988\ \Omega$ is to be connected in series with the galvanometer.

Question 4.28:

A galvanometer coil has a resistance of 15 Ω and the metre shows full scale deflection for a current of 4 mA. How will you convert the metre into an ammeter of range 0 to 6 A?

Answer

Resistance of the galvanometer coil, G = 15 Ω

Current for which the galvanometer shows full scale deflection,

$I_g = 4\text{ mA} = 4 \times 10^{-3}\text{ A}$

Range of the ammeter is 0, which needs to be converted to 6 A.

$\therefore$ Current, I = 6 A

A shunt resistor of resistance S is to be connected in parallel with the galvanometer to convert it into an ammeter. The value of S is given as:

$$S = \frac{I_g G}{I - I_g}$$

$$= \frac{4 \times 10^{-3} \times 15}{6 - 4 \times 10^{-3}}$$

$$S = \frac{6 \times 10^{-2}}{6 - 0.004} = \frac{0.06}{5.996}$$

$$\approx 0.01\ \Omega = 10\ \text{m}\Omega$$

Hence, a $10\ \text{m}\Omega$ shunt resistor is to be connected in parallel with the galvanometer.

Question 5.1:

Answer the following questions regarding earth's magnetism:

(a) A vector needs three quantities for its specification. Name the three independent quantities conventionally used to specify the earth's magnetic field.

(b) The angle of dip at a location in southern India is about 18º.

Would you expect a greater or smaller dip angle in Britain?

(c) If you made a map of magnetic field lines at Melbourne in Australia, would the lines seem to go into the ground or come out of the ground?

(d) In which direction would a compass free to move in the vertical plane point to, if located right on the geomagnetic north or south pole?

(e) The earth's field, it is claimed, roughly approximates the field due to a dipole of magnetic moment 8 × 1022 J T^{-1} located at its centre. Check the order of magnitude of this number in some way.

(f) Geologists claim that besides the main magnetic N-S poles, there are several local poles on the earth's surface oriented in different directions. How is such a thing possible at all?

Answer

(a) The three independent quantities conventionally used for specifying earth's magnetic field are:

(i) Magnetic declination,

(ii) Angle of dip, and

(iii) Horizontal component of earth's magnetic field

(b) The angle of dip at a point depends on how far the point is located with respect to the North Pole or the South Pole. The angle of dip would be greater in Britain (it is about 70°) than in southern India because the location of Britain on the globe is closer to the magnetic North Pole.

(c) It is hypothetically considered that a huge bar magnet is dipped inside earth with its north pole near the geographic South Pole and its south pole near the geographic North Pole.

Magnetic field lines emanate from a magnetic north pole and terminate at a magnetic south pole. Hence, in a map depicting earth's magnetic field lines, the field lines at Melbourne, Australia would seem to come out of the ground.

(d) If a compass is located on the geomagnetic North Pole or South Pole, then the compass will be free to move in the horizontal plane while earth's field is exactly vertical to the magnetic poles. In such a case, the compass can point in any direction.

(e) Magnetic moment, $M = 8 \times 10^{22}$ J T^{-1}

Radius of earth, $r = 6.4 \times 10^{6}$ m

Magnetic field strength, $B = \frac{\mu_0 M}{4\pi r^3}$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ Tm A^{-1}

$$\therefore B = \frac{4\pi \times 10^{-7} \times 8 \times 10^{22}}{4\pi \times (6.4 \times 10^{6})^3} = 0.3 \text{ G}$$

This quantity is of the order of magnitude of the observed field on earth.

(f) Yes, there are several local poles on earth's surface oriented in different directions. A magnetised mineral deposit is an example of a local N-S pole.

Question 5.2:

Answer the following questions:

(a) The earth's magnetic field varies from point to point in space.

Does it also change with time? If so, on what time scale does it change appreciably?

(b) The earth's core is known to contain iron. Yet geologists do not regard this as a source of the earth's magnetism. Why?

(c) The charged currents in the outer conducting regions of the earth's core are thought to be responsible for earth's magnetism. What might be the 'battery' (i.e., the source of energy) to sustain these currents?

(d) The earth may have even reversed the direction of its field several times during its history of 4 to 5 billion years. How can geologists know about the earth's field in such distant past?

(e) The earth's field departs from its dipole shape substantially at large distances (greater than about 30,000 km). What agencies may be responsible for this distortion?

(f) Interstellar space has an extremely weak magnetic field of the order of 10−12 T. Can such a weak field be of any significant consequence? Explain.

[**Note:** Exercise 5.2 is meant mainly to arouse your curiosity. Answers to some questions above are tentative or unknown. Brief answers wherever possible are given at the end. For details, you should consult a good text on geomagnetism.]

Answer

(a) Earth's magnetic field changes with time. It takes a few hundred years to change by an appreciable amount. The variation in earth's magnetic field with the time cannot be neglected.

(b) Earth's core contains molten iron. This form of iron is not ferromagnetic. Hence, this is not considered as a source of earth's magnetism.

(c) Theradioactivity in earth's interior is the source of energy that sustains the currents in the outer conducting regions of earth's core. These charged currents are considered to be responsible for earth's magnetism.

(d) Earth reversed the direction of its field several times during its history of 4 to 5 billion years. These magnetic fields got weakly recorded in rocks during their solidification. One can get clues about the geomagnetic history from the analysis of this rock magnetism.

(e) Earth's field departs from its dipole shape substantially at large distances (greater than about 30,000 km) because of the presence of the ionosphere. In this region, earth's field gets modified because of the field of single ions. While in motion, these ions produce the magnetic field associated with them.

(f) An extremely weak magnetic field can bend charged particles moving in a circle. This may not be noticeable for a large radius path. With reference to the gigantic interstellar space, the deflection can affect the passage of charged particles.

Question 5.3:

A short bar magnet placed with its axis at 30º with a uniform external magnetic field of 0.25 T experiences a torque of magnitude equal to 4.5×10^{-2} J. What is the magnitude of magnetic moment of the magnet?

Answer

Magnetic field strength, $B = 0.25$ T

Torque on the bar magnet, $T = 4.5 \times 10^{-2}$ J

Angle between the bar magnet and the external magnetic field, $\theta = 30°$

Torque is related to magnetic moment (M) as:

$T = MB \sin \theta$

$\therefore M = \frac{T}{B\sin\theta}$

$$= \frac{4.5 \times 10^{-2}}{0.25 \times \sin 30°} = 0.36 \text{ J T}^{-1}$$

Hence, the magnetic moment of the magnet is 0.36 J T^{-1}.

Question 5.4:

A short bar magnet of magnetic moment m = 0.32 J T^{-1} is placed in a uniform magnetic field of 0.15 T. If the bar is free to rotate in the plane of the field, which orientation would correspond to its (a) stable, and (b) unstable equilibrium? What is the potential energy of the magnet in each case?

Answer

Moment of the bar magnet, M = 0.32 J T^{-1}

External magnetic field, B = 0.15 T

(a) The bar magnet is aligned along the magnetic field. This system is considered as being in stable equilibrium. Hence, the angle θ, between the bar magnet and the magnetic field is 0°.

Potential energy of the system $= -MB\cos\theta$

$= -0.32 \times 0.15\cos 0°$

$= -4.8 \times 10^{-2}$ J

(b) The bar magnet is oriented 180° to the magnetic field. Hence, it is in unstable equilibrium.

θ = 180°

Potential energy = − MB cos θ

$= -0.32 \times 0.15\cos 180°$

$= 4.8 \times 10^{-2}$ J

Question 5.5:

A closely wound solenoid of 800 turns and area of cross section 2.5×10^{-4} m^2 carries a current of 3.0 A. Explain the sense in which the solenoid acts like a bar magnet. What is its associated magnetic moment?

Answer

Number of turns in the solenoid, $n = 800$

Area of cross-section, $A = 2.5 \times 10^{-4}$ m^2

Current in the solenoid, $I = 3.0$ A

A current-carrying solenoid behaves as a bar magnet because a magnetic field develops along its axis, i.e., along its length.

The magnetic moment associated with the given current-carrying solenoid is calculated as:

$M = n I A$

$= 800 \times 3 \times 2.5 \times 10^{-4}$

$= 0.6$ J T^{-1}

Question 5.6:

If the solenoid in Exercise 5.5 is free to turn about the vertical direction and a uniform horizontal magnetic field of 0.25 T is applied, what is the magnitude of torque on the solenoid when its axis makes an angle of 30° with the direction of applied field?

Answer

Magnetic field strength, $B = 0.25$ T

Magnetic moment, $M = 0.6$ T^{-1}

The angle θ, between the axis of the solenoid and the direction of the applied field is 30°.

Therefore, the torque acting on the solenoid is given as:

$$\tau = MB\sin\theta$$
$$= 0.6 \times 0.25 \sin 30^\circ$$
$$= 7.5 \times 10^{-2} \text{ J}$$

Question 5.7:

A bar magnet of magnetic moment 1.5 J T^{-1} lies aligned with the direction of a uniform magnetic field of 0.22 T.

(a) What is the amount of work required by an external torque to turn the magnet so as to align its magnetic moment: (i) normal to the field direction, (ii) opposite to the field direction?

(b) What is the torque on the magnet in cases (i) and (ii)?

Answer

(a) Magnetic moment, M = 1.5 J T^{-1}

Magnetic field strength, B = 0.22 T

(i) Initial angle between the axis and the magnetic field, θ_1 = 0°

Final angle between the axis and the magnetic field, θ_2 = 90°

The work required to make the magnetic moment normal to the direction of magnetic field is given as:

$$\begin{aligned}W &= -MB\left(\cos\theta_2 - \cos\theta_1\right)\\ &= -1.5 \times 0.22\left(\cos 90° - \cos 0°\right)\\ &= -0.33\left(0-1\right)\\ &= 0.33\text{ J}\end{aligned}$$

(ii) Initial angle between the axis and the magnetic field, θ_1 = 0°

Final angle between the axis and the magnetic field, θ_2 = 180°

The work required to make the magnetic moment opposite to the direction of magnetic field is given as:

$$\begin{aligned}W &= -MB\left(\cos\theta_2 - \cos\theta_1\right)\\ &= -1.5 \times 0.22\left(\cos 180 - \cos 0°\right)\\ &= -0.33\left(-1-1\right)\\ &= 0.66\text{ J}\end{aligned}$$

(b)<u>For case (i):</u> $\theta = \theta_2 = 90°$

∴Torque, $\tau = MB\sin\theta$

$$\begin{aligned}&= 1.5 \times 0.22 \sin 90°\\ &= 0.33\text{ J}\end{aligned}$$

<u>For case (ii):</u> $\theta = \theta_2 = 180°$

∴Torque, $\tau = MB\sin\theta$

$= MB\sin 180° = 0$ J

Question 5.8:

A closely wound solenoid of 2000 turns and area of cross-section 1.6×10^{-4} m^2, carrying a current of 4.0 A, is suspended through its centre allowing it to turn in a horizontal plane.

(a) What is the magnetic moment associated with the solenoid?

(b) What is the force and torque on the solenoid if a uniform horizontal magnetic field of 7.5×10^{-2} T is set up at an angle of 30º with the axis of the solenoid?

Answer

Number of turns on the solenoid, n = 2000

Area of cross-section of the solenoid, $A = 1.6 \times 10^{-4}$ m^2

Current in the solenoid, I = 4 A

(a) The magnetic moment along the axis of the solenoid is calculated as:

$M = nAI$

$= 2000 \times 1.6 \times 10^{-4} \times 4$

= 1.28 Am^2

(b) Magnetic field, $B = 7.5 \times 10^{-2}$ T

Angle between the magnetic field and the axis of the solenoid, θ = 30°

Torque, $\tau = MB\sin\theta$

$= 1.28 \times 7.5 \times 10^{-2} \sin 30°$

$= 4.8 \times 10^{-2}$ Nm

Since the magnetic field is uniform, the force on the solenoid is zero. The torque on the solenoid is 4.8×10^{-2} Nm.

Question 5.9:

A circular coil of 16 turns and radius 10 cm carrying a current of 0.75 A rests with its plane normal to an external field of magnitude 5.0×10^{-2} T. The coil is free to turn about an axis in its plane perpendicular to the field direction. When the coil is turned slightly and released, it oscillates about its stable equilibrium with a frequency of $2.0\ s^{-1}$. What is the moment of inertia of the coil about its axis of rotation?

Answer

Number of turns in the circular coil, $N = 16$

Radius of the coil, $r = 10$ cm $= 0.1$ m

Cross-section of the coil, $A = \pi r^2 = \pi \times (0.1)^2\ m^2$

Current in the coil, $I = 0.75$ A

Magnetic field strength, $B = 5.0 \times 10^{-2}$ T

Frequency of oscillations of the coil, $\nu = 2.0\ s^{-1}$

$\therefore$Magnetic moment, $M = NIA = NI\pi r^2$

$= 16 \times 0.75 \times \pi \times (0.1)^2$

$= 0.377\ J\ T^{-1}$

Frequency is given by the relation:

$$\nu = \frac{1}{2\pi}\sqrt{\frac{MB}{I}}$$

Where,

I = Moment of inertia of the coil

$$\therefore I = \frac{MB}{4\pi^2\nu^2}$$

$$= \frac{0.377 \times 5 \times 10^{-2}}{4\pi^2 \times (2)^2}$$

$$= 1.19 \times 10^{-4}\ \text{kg m}^2$$

Hence, the moment of inertia of the coil about its axis of rotation is 1.19×10^{-4} kg m^2.

Question 5.10:

A magnetic needle free to rotate in a vertical plane parallel to the magnetic meridian has its north tip pointing down at 22º with the horizontal. The horizontal component of the earth's magnetic field at the place is known to be 0.35 G. Determine the magnitude of the earth's magnetic field at the place.

Answer

Horizontal component of earth's magnetic field, B_H = 0.35 G

Angle made by the needle with the horizontal plane = Angle of dip = $\delta = 22°$

Earth's magnetic field strength = B

We can relate B and $B_H$as:

$$B_H = B\cos\theta$$

$$\therefore B = \frac{B_H}{\cos\delta}$$

$$= \frac{0.35}{\cos 22°} = 0.377 \text{ G}$$

Hence, the strength of earth's magnetic field at the given location is 0.377 G.

Question 5.11:

At a certain location in Africa, a compass points 12º west of the geographic north. The north tip of the magnetic needle of a dip circle placed in the plane of magnetic meridian points 60º above the horizontal. The horizontal component of the earth's field is measured to be 0.16 G. Specify the direction and magnitude of the earth's field at the location.

Answer

Angle of declination,θ = 12°

Angle of dip, $\delta = 60°$

Horizontal component of earth's magnetic field, B_H = 0.16 G

Earth's magnetic field at the given location = B

We can relate B and B_H as:

$$B_H = B\cos\delta$$

$$\therefore B = \frac{B_H}{\cos\delta}$$

$$= \frac{0.16}{\cos 60^\circ} = 0.32 \text{ G}$$

Earth's magnetic field lies in the vertical plane, 12° West of the geographic meridian, making an angle of 60° (upward) with the horizontal direction. Its magnitude is 0.32 G.

Question 5.12:

A short bar magnet has a magnetic moment of 0.48 J T^{-1}. Give the direction and magnitude of the magnetic field produced by the magnet at a distance of 10 cm from the centre of the magnet on (a) the axis, (b) the equatorial lines (normal bisector) of the magnet.

Answer

Magnetic moment of the bar magnet, M = 0.48 J T^{-1}

(a) Distance, d = 10 cm = 0.1 m

The magnetic field at distance d, from the centre of the magnet on the axis is given by the relation:

$$B = \frac{\mu_0}{4\pi}\frac{2M}{d^3}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ Tm A^{-1}

$$\therefore B = \frac{4\pi \times 10^{-7} \times 2 \times 0.48}{4\pi \times (0.1)^3}$$

$$= 0.96 \times 10^{-4} \text{ T} = 0.96 \text{ G}$$

The magnetic field is along the S − N direction.

(b) The magnetic field at a distance of 10 cm (i.e., d = 0.1 m) on the equatorial line of the magnet is given as:

$$B = \frac{\mu_0 \times M}{4\pi \times d^3}$$

$$= \frac{4\pi \times 10^{-7} \times 0.48}{4\pi (0.1)^3}$$

$$= 0.48 \text{ G}$$

The magnetic field is along the N − S direction.

Question 5.13:

A short bar magnet placed in a horizontal plane has its axis aligned along the magnetic north-south direction. Null points are found on the axis of the magnet at 14 cm from the centre of the magnet. The earth's magnetic field at the place is 0.36 G and the angle of dip is zero. What is the total magnetic field on the normal bisector of the magnet at the same distance as the null−point (i.e., 14 cm) from the centre of the magnet? (At *null points*, field due to a magnet is equal and opposite to the horizontal component of earth's magnetic field.)

Answer

Earth's magnetic field at the given place, H = 0.36 G

The magnetic field at a distance d, on the axis of the magnet is given as:

$$B_1 = \frac{\mu_0}{4\pi}\frac{2M}{d^3} = H \qquad \dots(i)$$

Where,

μ_0 = Permeability of free space

M = Magnetic moment

The magnetic field at the same distance d, on the equatorial line of the magnet is given as:

$$B_2 = \frac{\mu_0 M}{4\pi d^3} = \frac{H}{2} \qquad \text{[Using equation } (i)]$$

Total magnetic field, $B = B_1 + B_2$

$$= H + \frac{H}{2}$$

$$= 0.36 + 0.18 = 0.54 \text{ G}$$

Hence, the magnetic field is 0.54 G in the direction of earth's magnetic field.

Question 5.14:

If the bar magnet in exercise 5.13 is turned around by 180º, where will the new null points be located?

Answer

The magnetic field on the axis of the magnet at a distance d_1 = 14 cm, can be written as:

$$B_1 = \frac{\mu_0 2M}{4\pi (d_1)^3} = H \qquad \dots (1)$$

Where,

M = Magnetic moment

μ_0 = Permeability of free space

H = Horizontal component of the magnetic field at d_1

If the bar magnet is turned through 180°, then the neutral point will lie on the equatorial line.

Hence, the magnetic field at a distance d_2, on the equatorial line of the magnet can be written as:

$$B_2 = \frac{\mu_0 M}{4\pi (d_2)^3} = H \qquad \dots (2)$$

Equating equations (1) and (2), we get:

$$\frac{2}{(d_1)^3} = \frac{1}{(d_2)^3}$$

$$\left(\frac{d_2}{d_1}\right)^3 = \frac{1}{2}$$

$$\therefore d_2 = d_1 \times \left(\frac{1}{2}\right)^{\frac{1}{3}}$$

$$= 14 \times 0.794 = 11.1 \text{ cm}$$

The new null points will be located 11.1 cm on the normal bisector.

Question 5.15:

A short bar magnet of magnetic moment 5.25×10^{-2} J T^{-1} is placed with its axis perpendicular to the earth's field direction. At what distance from the centre of the magnet, the resultant field is inclined at 45º with earth's field on

(a) its normal bisector and (b) its axis. Magnitude of the earth's field at the place is given to be 0.42 G. Ignore the length of the magnet in comparison to the distances involved.

Answer

Magnetic moment of the bar magnet, $M = 5.25 \times 10^{-2}$ J T^{-1}

Magnitude of earth's magnetic field at a place, H = 0.42 G = 0.42×10^{-4} T

(a) The magnetic field at a distance R from the centre of the magnet on the normal bisector is given by the relation:

$$B = \frac{\mu_0 M}{4\pi R^3}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ Tm A^{-1}

When the resultant field is inclined at 45° with earth's field, $B = H$

$$\therefore \frac{\mu_0 M}{4\pi R^3} = H = 0.42 \times 10^{-4}$$

$$R^3 = \frac{\mu_0 M}{0.42 \times 10^{-4} \times 4\pi}$$

$$= \frac{4\pi \times 10^{-7} \times 5.25 \times 10^{-2}}{4\pi \times 0.42 \times 10^{-4}} = 12.5 \times 10^{-5}$$

$$\therefore R = 0.05 \text{ m} = 5 \text{ cm}$$

(b) The magnetic field at a distanced R' from the centre of the magnet on its axis is given as:

$$B' = \frac{\mu_0 2M}{4\pi R^3}$$

The resultant field is inclined at 45° with earth's field.

$$\therefore B' = H$$

$$\frac{\mu_0 2M}{4\pi (R')^3} = H$$

$$(R')^3 = \frac{\mu_0 2M}{4\pi \times H}$$

$$= \frac{4\pi \times 10^{-7} \times 2 \times 5.25 \times 10^{-2}}{4\pi \times 0.42 \times 10^{-4}} = 25 \times 10^{-5}$$

$$\therefore R' = 0.063 \text{ m} = 6.3 \text{ cm}$$

Question 5.16:

Answer the following questions:

(a) Why does a paramagnetic sample display greater magnetisation (for the same magnetising field) when cooled?

(b) Why is diamagnetism, in contrast, almost independent of temperature?

(c) If a toroid uses bismuth for its core, will the field in the core be (slightly) greater or (slightly) less than when the core is empty?

(d) Is the permeability of a ferromagnetic material independent of the magnetic field? If not, is it more for lower or higher fields?

(e) Magnetic field lines are always nearly normal to the surface of a ferromagnet at every point. (This fact is analogous to the static electric field lines being normal to the surface of a conductor at every point.) Why?

(f) Would the maximum possible magnetisation of a paramagnetic sample be of the same order of magnitude as the magnetization of a ferromagnet?

Answer

(a) Owing to therandom thermal motion of molecules, the alignments of dipoles get disrupted at high temperatures. On cooling, this disruption is reduced. Hence, a paramagnetic sample displays greater magnetisation when cooled.

(b) The induced dipole moment in a diamagnetic substance is always opposite to the magnetising field. Hence, the internal motion of the atoms (which is related to the temperature) does not affect the diamagnetism of a material.

(c) Bismuth is a diamagnetic substance. Hence, a toroid with a bismuth core has a magnetic field slightly greater than a toroid whose core is empty.

(d) The permeability of ferromagnetic materials is not independent of the applied magnetic field. It is greater for a lower field and vice versa.

(e) The permeability of a ferromagnetic material is not less than one. It is always greater than one. Hence, magnetic field lines are always nearly normal to the surface of such materials at every point.

(f) The maximum possible magnetisation of a paramagnetic sample can be of the same order of magnitude as the magnetisation of a ferromagnet. This requires high magnetising fields for saturation.

Question 5.17:

Answer the following questions:

(a) Explain qualitatively on the basis of domain picture the irreversibility in the magnetisation curve of a ferromagnet.

(b) The hysteresis loop of a soft iron piece has a much smaller area than that of a carbon steel piece. If the material is to go through repeated cycles of magnetisation, which piece will dissipate greater heat energy?

(c) 'A system displaying a hysteresis loop such as a ferromagnet, is a device for storing memory?' Explain the meaning of this statement.

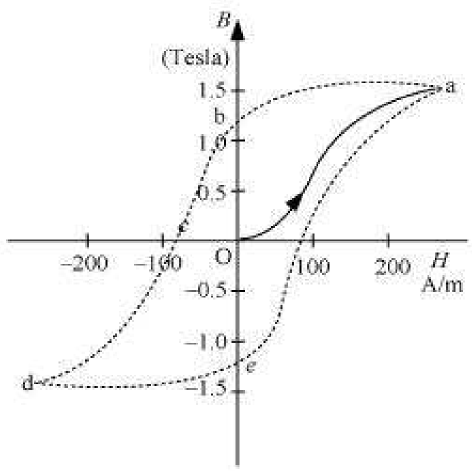
(d) What kind of ferromagnetic material is used for coating magnetic tapes in a cassette player, or for building 'memory stores' in a modern computer?

(e) A certain region of space is to be shielded from magnetic fields.

Suggest a method.

Answer

The hysteresis curve (*B*-*H* curve) of a ferromagnetic material is shown in the following figure.



(a) It can be observed from the given curve that magnetisation persists even when the external field is removed. This reflects the irreversibility of a ferromagnet.

(b) The dissipated heat energy is directly proportional to the area of a hysteresis loop. A carbon steel piece has a greater hysteresis curve area. Hence, it dissipates greater heat energy.

(c) The value of magnetisation is memory or record of hysteresis loop cycles of magnetisation. These bits of information correspond to the cycle of magnetisation. Hysteresis loops can be used for storing information.

(d) Ceramic is used for coating magnetic tapes in cassette players and for building memory stores in modern computers.

(e)A certain region of space can be shielded from magnetic fields if it is surrounded by soft iron rings. In such arrangements, the magnetic lines are drawn out of the region.

Question 5.18:

A long straight horizontal cable carries a current of 2.5 A in the direction 10º south of west to 10° north of east. The magnetic meridian of the place happens to be 10º west of the geographic meridian. The earth's magnetic field at the location is 0.33 G, and the angle of dip is zero. Locate the line of neutral points (ignore the thickness of the cable). (At *neutral points*, magnetic field due to a current-carrying cable is equal and opposite to the horizontal component of earth's magnetic field.)

Answer

Current in the wire, I = 2.5 A

Angle of dip at the given location on earth, δ = 0°

Earth's magnetic field, H = 0.33 G = 0.33×10^{-4} T

The horizontal component of earth's magnetic field is given as:

$H_H = H \cos \delta$

$= 0.33 \times 10^{-4} \times \cos 0° = 0.33 \times 10^{-4}\ \text{T}$

The magnetic field at the neutral point at a distance R from the cable is given by the relation:

$$H_H = \frac{\mu_0 I}{2\pi R}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}\ \text{Tm A}^{-1}$

$$\therefore R = \frac{\mu_0 I}{2\pi H_H}$$

$$= \frac{4\pi \times 10^{-7} \times 2.5}{2\pi \times 0.33 \times 10^{-4}} = 15.15 \times 10^{-3}\ \text{m} = 1.51\ \text{cm}$$

Hence, a set of neutral points parallel to and above the cable are located at a normal distance of 1.51 cm.

Question 5.19:

A telephone cable at a place has four long straight horizontal wires carrying a current of 1.0 A in the same direction east to west. The earth's magnetic field at the place is 0.39 G, and the angle of dip is 35º. The magnetic declination is nearly zero. What are the resultant magnetic fields at points 4.0 cm below the cable?

Answer

Number of horizontal wires in the telephone cable, $n = 4$

Current in each wire, $I = 1.0$ A

Earth's magnetic field at a location, $H = 0.39$ G $= 0.39 \times 10^{-4}$ T

Angle of dip at the location, $\delta = 35°$

Angle of declination, $\theta \sim 0°$

<u>For a point 4 cm below the cable:</u>

Distance, $r = 4$ cm $= 0.04$ m

The horizontal component of earth's magnetic field can be written as:

$H_h = H\cos\delta - B$

Where,

B = Magnetic field at 4 cm due to current I in the four wires

$= 4 \times \dfrac{\mu_0 I}{2\pi r}$

μ_0 = Permeability of free space $= 4\pi \times 10^{-7}$ Tm A^{-1}

$\therefore B = 4 \times \dfrac{4\pi \times 10^{-7} \times 1}{2\pi \times 0.04}$

$= 0.2 \times 10^{-4}$ T $= 0.2$ G

$\therefore H_h = 0.39 \cos 35° - 0.2$

$= 0.39 \times 0.819 - 0.2 \approx 0.12$ G

The vertical component of earth's magnetic field is given as:

$H_v = H\sin\delta$

$= 0.39 \sin 35° = 0.22$ G

The angle made by the field with its horizontal component is given as:

$$\theta = \tan^{-1}\frac{H_v}{H_h}$$

$$= \tan^{-1}\frac{0.22}{0.12} = 61.39°$$

The resultant field at the point is given as:

$$H_1 = \sqrt{(H_v)^2 + (H_h)^2}$$

$$= \sqrt{(0.22)^2 + (0.12)^2} = 0.25 \text{ G}$$

For a point 4 cm above the cable:

Horizontal component of earth's magnetic field:

$H_h = H\cos\delta + B$

$= 0.39 \cos 35° + 0.2 = 0.52$ G

Vertical component of earth's magnetic field:

$H_v = H\sin\delta$

$= 0.39 \sin 35° = 0.22$ G

Angle, $\theta = \tan^{-1}\frac{H_v}{H_h} = \tan^{-1}\frac{0.22}{0.52} = 22.9°$

And resultant field:

$$H_2 = \sqrt{(H_v)^2 + (H_h)^2}$$

$$= \sqrt{(0.22)^2 + (0.52)^2} = 0.56 \text{ T}$$

Question 5.20:

A compass needle free to turn in a horizontal plane is placed at the centre of circular coil of 30 turns and radius 12 cm. The coil is in a vertical plane making an angle of 45º with the magnetic meridian. When the current in the coil is 0.35 A, the needle points west to east.

(a) Determine the horizontal component of the earth's magnetic field at the location.

(b) The current in the coil is reversed, and the coil is rotated about its vertical axis by an angle of 90º in the anticlockwise sense looking from above. Predict the direction of the needle. Take the magnetic declination at the places to be zero.

Answer

Number of turns in the circular coil, $N = 30$

Radius of the circular coil, $r = 12$ cm $= 0.12$ m

Current in the coil, $I = 0.35$ A

Angle of dip, $\delta = 45°$

(a) The magnetic field due to current I, at a distance r, is given as:

$$B = \frac{\mu_0 2\pi NI}{4\pi r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ Tm A^{-1}

$$\therefore B = \frac{4\pi \times 10^{-7} \times 2\pi \times 30 \times 0.35}{4\pi \times 0.12}$$

$= 5.49 \times 10^{-5}$ T

The compass needle points from West to East. Hence, the horizontal component of earth's magnetic field is given as:

$B_H = B\sin\delta$

$= 5.49 \times 10^{-5} \sin 45° = 3.88 \times 10^{-5}$ T $= 0.388$ G

(b) When the current in the coil is reversed and the coil is rotated about its vertical axis by an angle of 90 º, the needle will reverse its original direction. In this case, the needle will point from East to West.

Question 5.21:

A magnetic dipole is under the influence of two magnetic fields. The angle between the field directions is 60º, and one of the fields has a magnitude of 1.2×10^{-2} T. If the dipole comes to stable equilibrium at an angle of 15º with this field, what is the magnitude of the other field?

Answer

Magnitude of one of the magnetic fields, $B_1 = 1.2 \times 10^{-2}$ T

Magnitude of the other magnetic field = B_2

Angle between the two fields, $\theta = 60°$

At stable equilibrium, the angle between the dipole and field B_1, $\theta_1 = 15°$

Angle between the dipole and field B_2, $\theta_2 = \theta - \theta_1 = 60° - 15° = 45°$

At rotational equilibrium, the torques between both the fields must balance each other.

∴Torque due to field B_1 = Torque due to field B_2

$MB_1 \sin\theta_1 = MB_2 \sin\theta_2$

Where,

M = Magnetic moment of the dipole

$$\therefore B_2 = \frac{B_1 \sin\theta_1}{\sin\theta_2}$$

$$= \frac{1.2 \times 10^{-2} \times \sin 15°}{\sin 45°} = 4.39 \times 10^{-3} \text{ T}$$

Hence, the magnitude of the other magnetic field is 4.39×10^{-3} T.

Question 5.22:

A monoenergetic (18 keV) electron beam initially in the horizontal direction is subjected to a horizontal magnetic field of 0.04 G normal to the initial direction. Estimate the up or down deflection of the beam over a distance of 30 cm (m_e= 9.11×10^{-19} C). [**Note:** *Data* in this exercise are so chosen that the answer will give you an idea of the effect of earth's magnetic field on the motion of the electron beam from the electron gun to the screen in a TV set.]

Answer

Energy of an electron beam, E = 18 keV = 18×10^3 eV

Charge on an electron, $e = 1.6 \times 10^{-19}$ C

$E = 18 \times 10^3 \times 1.6 \times 10^{-19}$ J

Magnetic field, B = 0.04 G

Mass of an electron, $m_e = 9.11 \times 10^{-19}$ kg

Distance up to which the electron beam travels, d = 30 cm = 0.3 m

We can write the kinetic energy of the electron beam as:

$$E = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E}{m}}$$

$$= \sqrt{\frac{2 \times 18 \times 10^3 \times 1.6 \times 10^{-19} \times 10^{-15}}{9.11 \times 10^{-31}}} = 0.795 \times 10^8 \text{ m/s}$$

The electron beam deflects along a circular path of radius, *r*.

The force due to the magnetic field balances the centripetal force of the path.

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

$$\therefore r = \frac{mv}{Be}$$

$$= \frac{9.11 \times 10^{-31} \times 0.795 \times 10^8}{0.4 \times 10^{-4} \times 1.6 \times 10^{-19}} = 11.3 \text{ m}$$

Let the up and down deflection of the electron beam be $x = r(1 - \cos\theta)$

Where,

θ = Angle of declination

$$\sin\theta = \frac{d}{r}$$

$$= \frac{0.3}{11.3}$$

$$\theta = \sin^{-1}\frac{0.3}{11.3} = 1.521°$$

$$\text{And } x = 11.3(1 - \cos 1.521°)$$

$$= 0.0039 \text{ m} = 3.9 \text{ mm}$$

Therefore, the up and down deflection of the beam is 3.9 mm.

Question 5.23:

A sample of paramagnetic salt contains 2.0×10^{24} atomic dipoles each of dipole moment 1.5×10^{-23} J T^{-1}. The sample is placed under a homogeneous magnetic field of 0.64 T, and cooled to a temperature of 4.2 K. The degree of magnetic saturation achieved is equal to 15%. What is the total dipole moment of the sample for a magnetic field of 0.98 T and a temperature of 2.8 K? (Assume Curie's law)

Answer

Number of atomic dipoles, $n = 2.0 \times 10^{24}$

Dipole moment of each atomic dipole, $M = 1.5 \times 10^{-23}$ J T^{-1}

When the magnetic field, $B_1 = 0.64$ T

The sample is cooled to a temperature, $T_1 = 4.2°K$

Total dipole moment of the atomic dipole, $M_{tot} = n \times M$

$= 2 \times 10^{24} \times 1.5 \times 10^{-23}$

$= 30$ J T^{-1}

Magnetic saturation is achieved at 15%.

Hence, effective dipole moment, $M_1 = \frac{15}{100} \times 30 = 4.5 \text{ J T}^{-1}$

When the magnetic field, $B_2 = 0.98$ T

Temperature, $T_2 = 2.8°K$

Its total dipole moment = M_2

According to Curie's law, we have the ratio of two magnetic dipoles as:

$$\frac{M_2}{M_1} = \frac{B_2}{B_1} \times \frac{T_1}{T_2}$$

$$\therefore M_2 = \frac{B_2 T_1 M_1}{B_1 T_2}$$

$$= \frac{0.98 \times 4.2 \times 4.5}{2.8 \times 0.64} = 10.336 \text{ J T}^{-1}$$

Therefore, 10.336 J T^{-1} is the total dipole moment of the sample for a magnetic field of 0.98 T and a temperature of 2.8 K.

Question 5.24:

A Rowland ring of mean radius 15 cm has 3500 turns of wire wound on a ferromagnetic core of relative permeability 800. What is the magnetic field **B** in the core for a magnetising current of 1.2 A?

Answer

Mean radius of a Rowland ring, r = 15 cm = 0.15 m

Number of turns on a ferromagnetic core, N = 3500

Relative permeability of the core material, $\mu_r = 800$

Magnetising current, I = 1.2 A

The magnetic field is given by the relation:

$$B = \frac{\mu_r \mu_0 IN}{2\pi r}$$

Where,

μ_0 = Permeability of free space = $4\pi \times 10^{-7}$ Tm A^{-1}

$$B = \frac{800 \times 4\pi \times 10^{-7} \times 1.2 \times 3500}{2\pi \times 0.15} = 4.48 \text{ T}$$

Therefore, the magnetic field in the core is 4.48 T.

Question 5.25:

The magnetic moment vectors μ_s and μ_l associated with the intrinsic spin angular momentum **S** and orbital angular momentum **l**, respectively, of an electron are predicted by quantum theory (and verified experimentally to a high accuracy) to be given by:

$\mu_s = -(e/m)$ **S**,

$\mu_l = -(e/2m)$**l**

Which of these relations is in accordance with the result expected *classically*? Outline the derivation of the classical result.

Answer

The magnetic moment associated with the intrinsic spin angular momentum ( ) is given as

The magnetic moment associated with the orbital angular momentum ( ) is given as

For current *i* and area of cross-section *A*, we have the relation:

Where,

e = Charge of the electron

r = Radius of the circular orbit

T = Time taken to complete one rotation around the circular orbit of radius r

Angular momentum, $l = mvr$

Where,

m = Mass of the electron

v = Velocity of the electron

Dividing equation (1) by equation (2), we get:

Therefore, of the two relations, is in accordance with classical physics.

4.* An electric bulb rated for 500W at 100V is used in circuit having a 200V supply. Calculate the resistance R that must be put in series with the bulb, so that the bulb delivers 500W. (2)

Ans: Resistance of bulb=V^2/P = 20Ω, I = 5A, for the same power dissipation, current should be 5A when the bulb is connected to a 200V supply. The safe resistance R' = V'/I = 40Ω. Therefore, 20Ω resistor should be connected in series.

5. Two bulbs are marked 220V-100W and 220V-50W. They are connected in series to 220V mains. Find the ratio of heat generated in them. (2)

Ans: $H_1/H_2 = I^2R_1/I^2R_2 = R_1/R_2 = ½$

6.* Can a 30W, 6V bulb be connected supply of 120V? If not what will have to be done for it? (3)

Ans: Resistance of bulb R= V^2/P = 36/30 = 1.2Ω Current capacity of the bulb I = P/V = 5A

A resistance R' to be added in series with the bulb to have current of 5 A, I = V'/R + R' =5, R' = 22.8Ω

3.MAGNETIC EFFECTS OF CURRENT AND MAGNETISM

GIST

MAGNETIC EFFECTS OF CURRENT AND MAGNETISM:

1. Magnetic field:
   It is a region around a magnet or current carrying conductor in which its magnetic influence can be felt by a magnetic needle.
2. Biot-Savart Law
   $dB = \mu_0 \mathbf{I} dl \sin\theta / 4\pi r^2$
   $\mu_0 = 4\pi \times 10^{-7}$ Tm/A
   [Direction of dB can be found by using Maxwell's Right hand thumb rule.]
3. Applications :
   Magnetic field at a centre of a current carrying circular coil $B= \mu_0 I/2a$
   Magnetic field at a point on the axis of current carrying coil. $B= \mu_0 N i a^2/2(a^2+x^2)^{3/2}$ (N=no. of turns in the coil)
4. Ampere's circuital law
   It states that the line integral of magnetic field around any closed path in vacuum/air is μ_0 times the total current threading the closed path.
   $\oint B.\, dl= \mu_0 \mathbf{I}$
5. Applications
   i) Magnetic field due to straight infinitely long current carrying straight conductor.
   $B= \mu_0 \mathbf{I}/2\pi r$
   ii) Magnetic field due to a straight solenoid carrying current
   $B= \mu_0 n \mathbf{I}$
   n= no. of turns per unit length
   iii) Magnetic field due to toroidal solenoid carrying current.
   $B= \mu_0 N \mathbf{I} / 2\pi r$
   N= Total no. of turns.
6. Force on a moving charge [Lorentz Force]
   (i) In magnetic field F=q(V x B)
   (ii) In magnetic and electric field F=q[E+(v x B)] Lorentz force
7. Cyclotron
   (i) Principle
   (a) When a charged particle moves at right angle to a uniform magnetic field it describes circular path.

(b) An ion can acquire sufficiently large energy with a low ac voltage making it to cross the same electric field repeatedly under a strong magnetic field.

(ii) Cyclotron frequency or magnetic resonance frequency
$\nu = qB/2\pi m$, $T = 2\pi m/Bq$; $\omega = Bq/m$
(iii) Maximum velocity and maximum kinetic energy of charged particle.

$V_m = Bqr_m/m$

$E_m = B^2q^2r_m^2 / 2m$

8. Force on a current carrying conductor in uniform
   $F = (I\, l \times B)$
   l=length of conductor
   Direction of force can be found out using Fleming's left hand rule.
9. Force per unit length between parallel infinitely long current carrying straight conductors.
   $F/l = \mu_0 I_1 I_2 / 2\pi d$
   (a) If currents are in same direction the wires will attract each other.
   (b) If currents are in opposite directions they will repel each other.
10. 1 Ampere – One ampere is that current, which when flowing through each of the two parallel straight conductors of infinite length and placed in free space at a distance of 1m from each other, produces between them a force of 2×10^{-7} N/m of their length.
11. Torque experienced by a current loop in a uniform B.

    $\tau = NIBA \sin\theta$

    $\tau = M \times B$

    Where M=NIA

12. Motion of a charge in
    (a) Perpendicular magnetic field $F = q(v \times B)$, $F = qvB\sin 90 = qvB$ (circular path)
    (b) Parallel or antiparallel field $F = qvB\sin 0$ (or) $qvB\sin 180 = 0$ (Straight-line path)

    If $0 < \theta < 90$, the path is helix

    $v\cos\theta$ is responsible for linear motion v, $v\sin\theta$ is responsible for circular motion

    Hence trajectory is a helical path

13. Moving coil galvanometer

It is a sensitive instrument used for detecting small electric Currents.

Principle: When a current carrying coil is placed in a magnetic field, it experiences a torque.

$I \alpha \theta$ and $I = K\theta$ where $K = NAB / C$

Current sensitivity, $I_s = \theta / I = NBA/K$
voltage sensitivity, $V_s = \theta / V = NBA/KR$

Changing N -> Current sensitivity changes but Voltage Sensitivity does not change

(a) Conversion of galvanometer into ammeter

A small resistance S is connected in parallel to the galvanometer coil

$S = I_gG/(I - I_g)$; $R_A = GS/(G+S)$

(b) Conversion of galvanometer into a voltmeter.

A high resistance R is connected in series with the galvanometer coil.

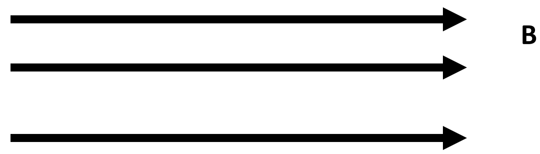
$R = (V/I_g) - G$; $R_v = G + R$

Current loop as a magnetic dipole

Magnetic dipole moment $M = \frac{evr}{2}$

$$M = n(eh / 4\pi m_e)$$

14. Representation of uniform magnetic field.



15. Magnetic dipole moment of a magnetic dipole.

M=m (2l) SI unit of M -> ampere metre m= pole strength.

16. Work done in rotating a magnetic dipole in a magnetic field.

$$W = MB(\cos\theta_1 - \cos\theta_2)$$

$$W = -\vec{M}.\vec{B}$$

17. Magnetic field due to magnetic dipole

a) at any point on axial line (P)

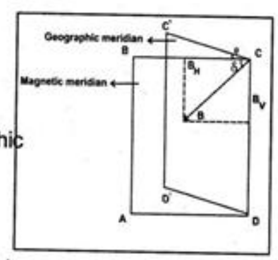
$$B = \frac{\mu_0 2M}{4\pi(r^2 - l^2)^2} \quad 2$$

b) at any point on equatorial line

$$B = \frac{\mu_0 M}{4\pi(r^2 + l^2)^{3/2}}$$

Torque experienced by a magnetic diploe in uniform magnetic field

$$\tau = MXB$$



18. Elements of earth's magnetic field

a) Declination (θ)

It is the angle between the magnetic meridian and geographic meridian

b) Inclination (or) Dip (δ)

It is the angle between the direction of total intensity of earth's magnetic field and its horizontal component.

c) Horizontal component of earths magnetic field (B_H)

It is the component of total intensity of earth's magnetic field along the horizontal.

$$\tan\delta = B_V / B_H \quad B = \sqrt{B_V^2 + B_H^2}$$

19. a) Intensity of magnetisation I

$$I = \frac{M}{V} = \frac{Magnetic\ moment}{Volume}$$

$I = \frac{m}{a}$ where m is pole strength

b) Magnetic induction B

$$B = \mu_0 (H + I)$$

H = strength of the magnetising field

c) Permeability

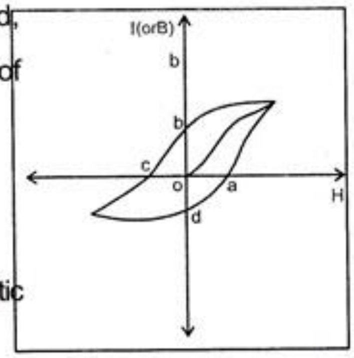
The magnetic permeability of a material may be defined as the ration of magnetic induction B to the magnetic intensity H

$\mu = B/H$

d) Susceptibility

$$\chi = \frac{I}{H}$$

20. Hysteresis



Intensity of magnetisation lags behind the magnetising field, when a magnetic substance is taken through a complete cycle of magnetisation.

a) Retentivity or remanance

ob (or) od

It is the value of magnetic field intensity retained by the magnetic substance when the magnetising field is reduced to zero.

b) Coercivity:- (oc (or) oa):- It is the value of magnetizing field required to reduce the residual intensity of magnetisation of sample to zero.

c) Hysteresis loss:- It is the loss of energy which takes place when a magnetic substance is taken over a complete cycle of magnetisation.

21. a) Electromagnet:- It is a magnet whose magnetism is due to current flowing through a coil wound over a soft iron. It maintains **magnetic** strength till the current is on in the coil. (eg) Soft iron

b) Permanent magnet:- It is a magnet which owes its strength due to the alignment of its molecules.

eg. steel

Properties to make

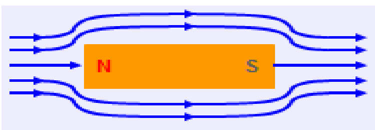
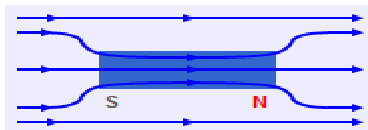
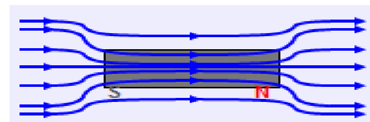
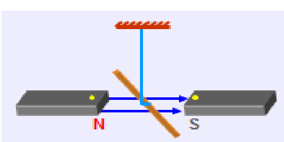
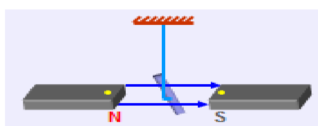
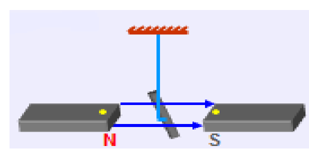
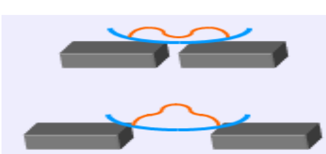
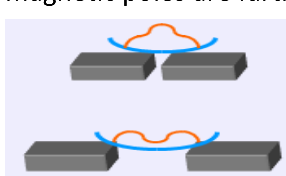
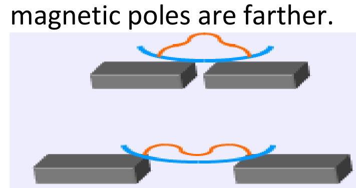
1) Electro magnet

High retentivity and low coercivity

2) Permanent magnet

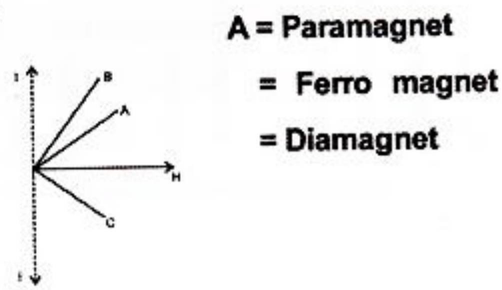
High retentivity and high coercivity

22. Properties of magnetic substances

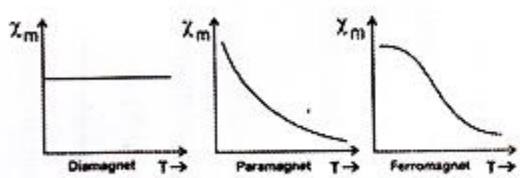
DIA	PARA	FERRO
1. Diamagnetic substances are those substances which are feebly repelled by a magnet. Eg. Antimony, Bismuth, Copper, Gold, Silver, Quartz, Mercury, Alcohol, water, Hydrogen, Air, Argon, etc.	Paramagnetic substances are those substances which are feebly attracted by a magnet. Eg. Aluminium, Chromium, Alkali and Alkaline earth metals, Platinum, Oxygen, etc.	Ferromagnetic substances are those substances which are strongly attracted by a magnet. Eg. Iron, Cobalt, Nickel, Gadolinium, Dysprosium, etc.
2. When placed in magnetic field, the lines of force tend to avoid the substance. 	The lines of force prefer to pass through the substance rather than air. 	The lines of force tend to crowd into the specimen. 
3. When placed in non-uniform magnetic field, it moves from stronger to weaker field (feeble repulsion).	When placed in non-uniform magnetic field, it moves from weaker to stronger field (feeble attraction).	When placed in non-uniform magnetic field, it moves from weaker to stronger field (strong attraction).
4. When a diamagnetic rod is freely suspended in a uniform magnetic field, it aligns itself in a direction perpendicular to the field. 	When a paramagnetic rod is freely suspended in a uniform magnetic field, it aligns itself in a direction parallel to the field. 	When a paramagnetic rod is freely suspended in a uniform magnetic field, it aligns itself in a direction parallel to the field very quickly. 
5. If diamagnetic liquid taken in a watch glass is placed in uniform magnetic field, it collects away from the centre when the magnetic poles are closer and collects at the centre when the magnetic poles are farther. 	If paramagnetic liquid taken in a watch glass is placed in uniform magnetic field, it collects at the centre when the magnetic poles are closer and collects away from the centre when the magnetic poles are farther. 	If ferromagnetic liquid taken in a watch glass is placed in uniform magnetic field, it collects at the centre when the magnetic poles are closer and collects away from the centre when the magnetic poles are farther. 
6. Induced Dipole Moment (M) is a small – ve value.	Induced Dipole Moment (M) is a small + ve value.	Induced Dipole Moment (M) is a large + ve value.

7. Intensity of Magnetisation (I) has a small – ve value.	Intensity of Magnetisation (I) has a small + ve value.	Intensity of Magnetisation (I) has a large + ve value.
8. Intensity of Magnetisation (I) has a small – ve value.	Intensity of Magnetisation (I) has a small + ve value.	Intensity of Magnetisation (I) has a large + ve value.
9. Magnetic permeability μ is always less than unity.	Magnetic permeability μ is more than unity.	Magnetic permeability μ is large i.e. much more than unity.
10. Magnetic susceptibility c_m has a small – ve value.	Magnetic susceptibility c_m has a small + ve value.	Magnetic susceptibility c_m has a large + ve value.
11. They do not obey Curie's Law. i.e. their properties do not change with temperature.	They obey Curie's Law. They lose their magnetic properties with rise in temperature.	They obey Curie's Law. At a certain temperature called Curie Point, they lose ferromagnetic properties and behave like paramagnetic substances.

Graph between H and I

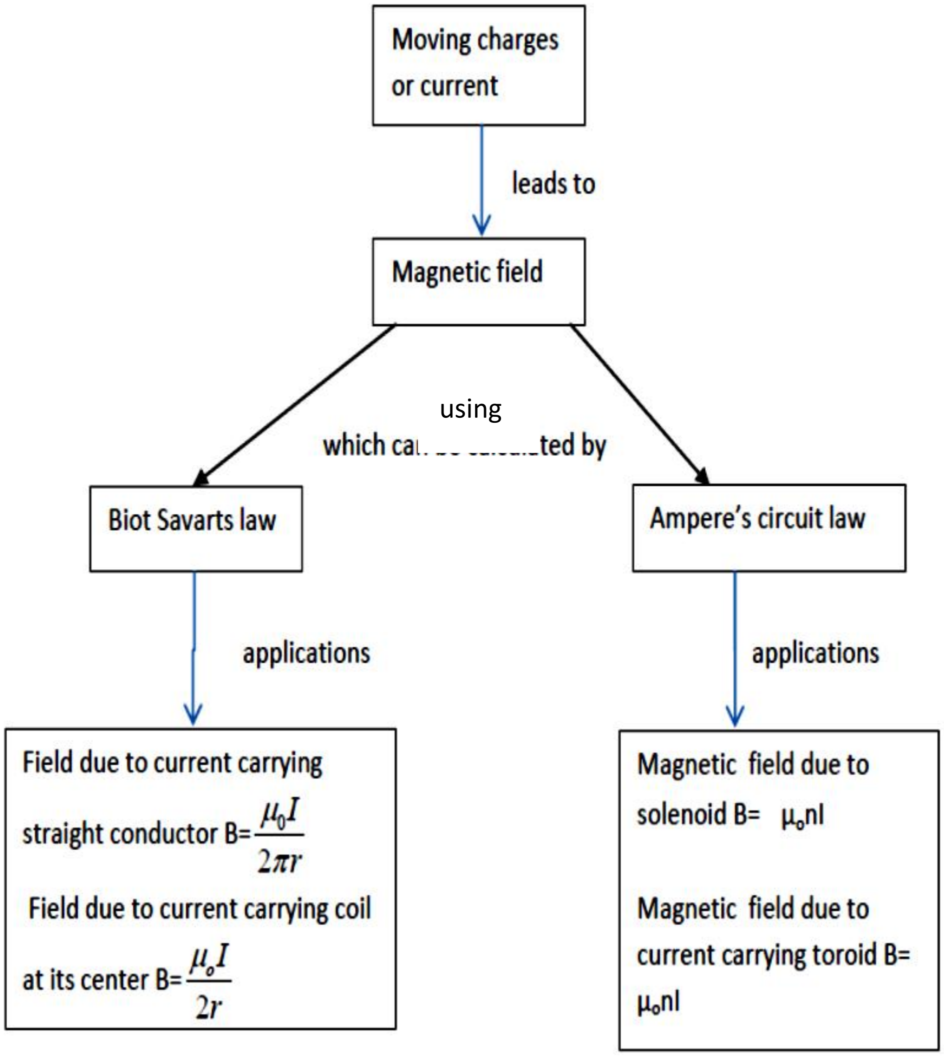


. Graph between χm and Temperature

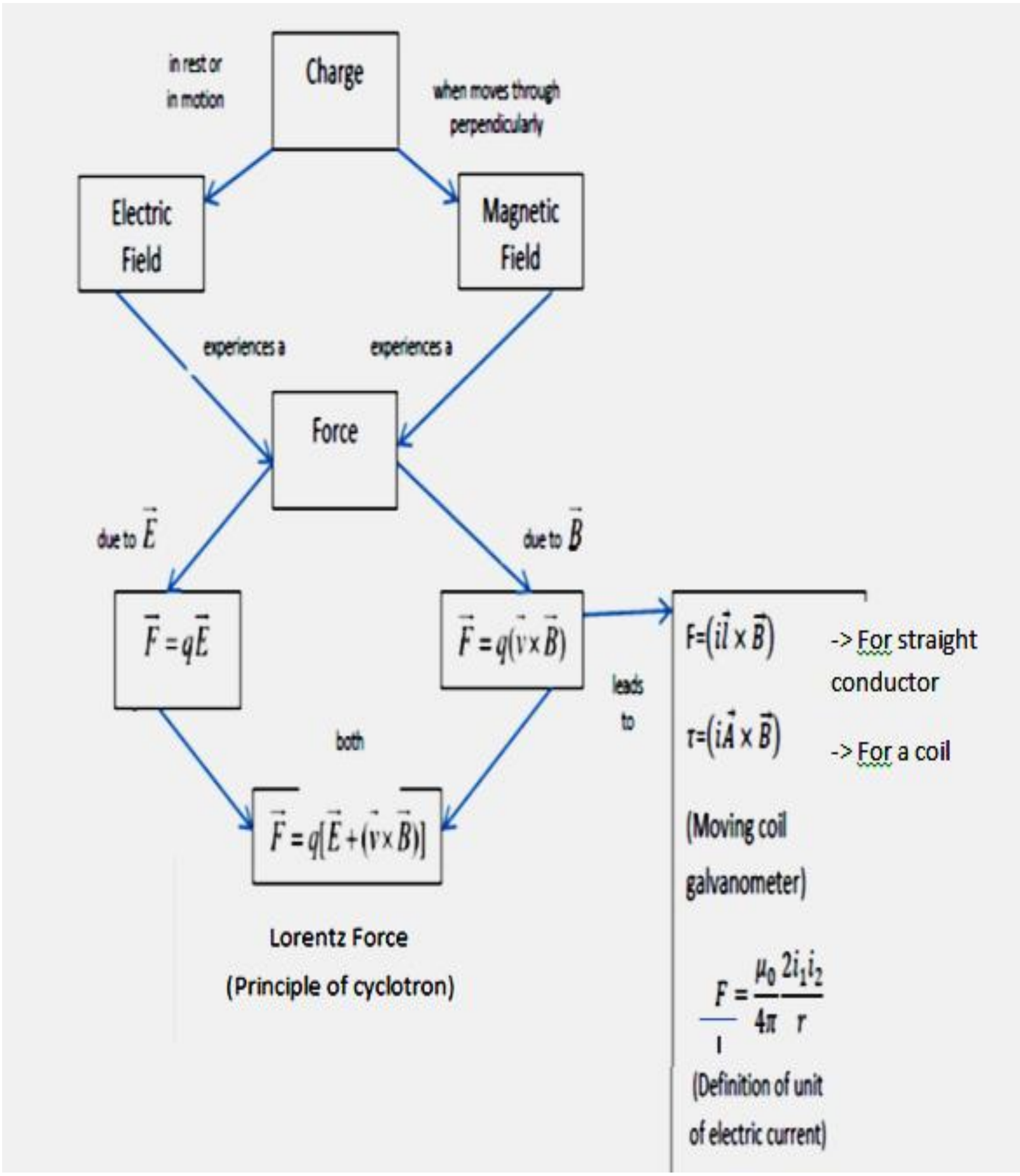


CONCEPT MAP

Moving Charges



Moving Charge and Force



QUESTIONS

MAGNETIC FORCE

1* In a certain arrangement, a proton does not get deflected while passing through a magnetic field region. State the condition under which it is possible. 1

Ans: **v** is parallel or antiparallel to **B**

2 An electron beam is moving vertically upwards. If it passes through a magnetic field directed from South to North in a horizontal plane, in what direction will the beam be deflected? 1

Ans:-Towards geographical East in the horizontal plane

3 What is the work done by the magnetic force on a charged particle moving perpendicular to the magnetic field? 1

Ans: Zero

4 A wire of length 0.04m carrying a current of 12 A is placed inside a solenoid, making an angle of 30^0 with its axis. The field due to the solenoid is 0.25 T. Find the force on the wire. 2

Ans; 0.06N

5 A circular loop of radius 0.1 m carries a current of 1A and is placed in a uniform magnetic field of 0.5T. The magnetic field is perpendicular to the plane of the loop. What is the force experienced by the loop? 2

Ans: The magnetic dipole does not experience any force in a uniform magnetic field.
Hence, the current carrying loop (dipole) does not experience any net force.

6* A proton, alpha particle and deuteron are moving in circular paths with same kinetic energies in the same magnetic fields. Find the ratio of their radii and time periods.

Ans: $R_p: R_\alpha : R_d = 1:1:\sqrt{2}$ 2

$T_p: T_\alpha : T_d = 1:2:2$

7 An electron moving with Kinetic Energy 25 keV moves perpendicular to a uniform magnetic field of 0.2 mT. Calculate the time period of rotation of electron in the magnetic field. 2

Ans: $T = 1.79 \times 10^{-7}$ S

8 A charged particle of mass 'm' charge 'q' moving at a uniform velocity 'v' enters a uniform magnetic field 'B' normal to the field direction. Deduce an expression for Kinetic Energy of the particle. Why does the Kinetic Energy of the charged particle not change when moving through the magnetic field? 3

9 An electron is revolving around the nucleus of an atom in an orbit of radius 0.53 Å. Calculate the equivalent magnetic moment, if the frequency of revolution of the electron is 6.8×10^{9} MHz.

Ans: $p_m = 9.6 \times 10^{-24}$ A m^2 3

BIOT-SAVART LAW AND ITS APPLICATIONS

1 A current is set up in a long copper pipe. What is the magnetic field inside the pipe?

Ans: Zero 1

2 A wire placed along north south direction carries a current of 5 A from South to North. Find the magnetic field due to a 1 cm piece of wire at a point 200 cm North East from the piece. 2

Ans: 8.8×10^{-10} T, acting vertically downwards.

3 How will the magnetic filed intensity at the centre of a circular coil carrying current change if the current through the coil is doubled and the radius of the coil is halved. 2

Ans: $B = \mu_0 n \times 2I / 2 \times (R/2) = 4B$

4 A circular coil of 500 turns has a radius of 2 m, and carries a current of 2 A. What is the magnetic field at a point on the axis of the coil at a distance equal to radius of the coil from the center? 2

Ans: $B = 1.11 \times 10^{-4}$ T

5* The strength of magnetic induction at the center of a current carrying circular coil is B_1 and at a point on its axis at a distance equal to its radius from the center is B_2. Find B_1/B_2. 2

Ans: $2\sqrt{2}$

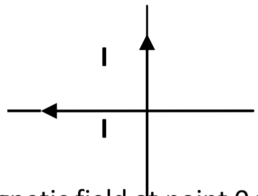
6* A current is flowing in a circular coil of radius 'r' and magnetic field at its center is B_0. At what distance from the center on the axis of the coil, the magnetic field will be $B_0/8$? 2

Ans: $x = \sqrt{3}r$

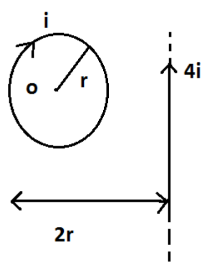
7* A straight wire of length' $\frac{\pi}{2}$'m, is bent into a circular shape. if the wire were to carry a current of 5 A, calculate the magnetic field due to it, before bending, at a point 0.01 times the radius of the circle formed from it. Also calculate the magnetic field at the center of the circular loop formed, for the same value of current. 3

Ans: $B_1 = 4 \times 10^{-4}$ T, $B_2 = 1.256 \times 10^{-5}$ T

8 Two insulated wires perpendicular to each other in the same plane carry equal currents as shown in figure. Is there a region where the magnetic field is zero? If so, where is the region? If not, explain why the field is not zero? 3



9 What is the net magnetic field at point 0 for the current distribution shown here?



ans $(\mu_0 I / 2r) = (\mu_o i/\pi r)$

AMPERE'S CIRCUITAL LAW AND APPLICATIONS

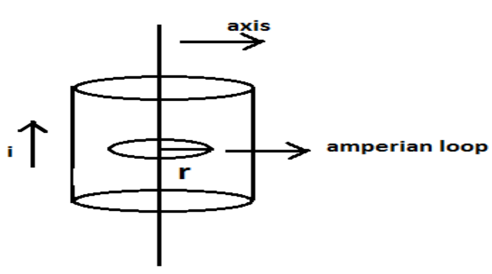
1 A long straight solid metal wire of radius 'R' carries a current 'I', uniformly distributed over its circular cross section. Find the magnetic field at a distance 'r' from the axis of the wire (a) inside and (b) outside the wire 2

Ans; (a) $\mu_0\mu_r Ir/2\pi R^2$ (b) $\mu_0 2I/ 4\pi r$

2 A solenoid is 1m long and 3 cm in mean diameter. It has 5 layers of windings of 800 turns each and carries a current of 5 A. Find Magnetic Field Induction at the center of the solenoid. 2

Ans: 2.5×10^{-2} T, parallel to the axis of the solenoid.

3 Find the value of magnetic field inside a hollow straight current carrying conductor at a distance r from axis of the loop. 2

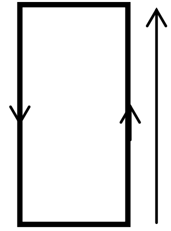


Ans B=0

FORCE BETWEEN TWO PARALLEL CURRENTS, TORQUE ON A CURRENT LOOP, MOVING COIL GALVANOMETER

1* A rectangular loop of size 25 cm x 10 cm carrying a current of 15A is placed 2 cm away from a long, straight conductor carrying a current of 25 A. What is the direction and magnitude of the net Force acting on the loop?

Ans: $F = 7.8175 \times 10^{-4}$ N



2* A long straight conductor PQ , carrying a current of 60 A, is fixed horizontally. Another long conductor XY is kept parallel to PQ at a distance of 4 mm, in air. Conductor XY is free to move and carries a current 'I' . Calculate the magnitude and direction of current 'I' for which the magnetic repulsion just balances the weight of the conductor XY. 2

Ans: I = 32. 67 A, The current in XY must flow opposite to that in PQ, because only then the force will be repulsive.

3 A circular coil of 200 turns, radius 5 cm carries a current of 2.5 A. It is suspended vertically in a uniform horizontal magnetic field of 0.25 T, with the plane of the coil making an angle of 60^0 with the field lines. Calculate the magnitude of the torque that must be applied on it to prevent it from turning. 2

Ans: 0.49Nm

4* A Galvanometer of resistance 3663 ohm gives full scale deflection for a certain current I_g.Calculate the value of the resistance of the shunt which when joined to the galvanometer coil will result in 1/34 of the total current passing through the galvanometer. Also find the total resistance of the Galvanometer and shunt. 3

Ans: 111 ohm, 107.7 A.

MAGNETISM AND MATTER

BAR MAGNET

1 A short bar magnet has magnetic moment of 50 A m^2. Calculate the magnetic field intensity at a distance of 0.2 m from its centre on (1) its axial line (2) its equitorial line. 2

Ans: $B_1 = 1.25 \times 10^{-3}$ T , $B_2 = 0.625 \times 10^{-3}$ T.

2 Calculate the torque acting on a magnet of length 20 cm and pole strength 2×10^{-5} Am, placed in the earth's magnetic field of flux density 2×10^{-5} T, when (a) magnet is parallel to the field (b) magnet is perpendicular to the field. 2

Ans: (a) Zero (b) 0.8×10^{-10} Nm

MAGNETISM AND GAUSS LAW

1 What is the significance of Gauss's law in magnetism? 1

Ans: Magnetic monopoles do not exist.

THE EARTH'S MAGNETISM

1 How the value of angle of dip varies on moving from equator to Poles? 1

2 A compass needle in a horizontal plane is taken to geographic north / south poles. In what direction does the needle align? 1

3 The horizontal component of earth's magnetic field is 0.2 G and total magnetic field is 0.4 G. Find the angle of Dip. 1

Ans: 60. 25^0

4* A long straight horizontal table carries a current of 2.5 A in the direction 10^0 south of west to $10^{\ 0}$ north of east. The ,magnetic meridian of the place happens to be $10^{\ 0}$ west of the geographic meridian. The earth's magnetic field at the locations 0.33G and the angle of dip is zero. Ignoring the thickness of the cable, locate the line of neutral points.

Ans: r = 1.5 cm ($B_H = B \cos \delta$, $B_H = \mu_0 I / 2\pi r$) 2

5 The vertical component of earth's magnetic field at a place is √3 times the horizontal component. What is the value of angle of dip at this place? 2

Ans: 60^0

6* A ship is sailing due west according to mariner's compass. If the declination of the place is

15^0east, what is the true direction of the ship? 2
Ans: 75^0 west of north.

IMPORTANT TERMS IN MAGNETISM

1 A magnetising field of 1600 A/m produces a magnetic flux of 2.4×10^{-5} Wb in a bar of iron of cross section 0.2 cm^2. Calculate permeability and susceptibility of the bar.
Ans: Permeability = 7.5×10^{-4} T A^{-1} m, Susceptibility =596.1 2

2 The maximum value of permeability of μ-metal is 0.126 Tm/A. Find the maximum relative permeability and susceptibility.
Ans: 10^5 each. 2

MAGNETIC PROPERTIES OF MATERIALS

1 The susceptibility of para magnetic material at 300K is 1.2×10^5. At what temperature will the susceptibility be equal to 1.44×10^{-5} . 1
Ans: 250 K

2 An iron bar magnet is heated to 1000^0C and then cooled in a magnetic field free space. Will it retain its magnetism? Ans: No it is above curie temperature. 1

3 What is the net magnetic moment of an atom of a diamagnetic material? 1
Ans : Zero

4 Which materials have negative value of magnetic susceptibility? 1
Ans : Diamagnetic materials.

5 Why permanent magnets are made of steel while the core of the transformer is made of soft iron? 1

6* An iron rod of volume 10^{-4} m^3 and relative permeability 1000 is placed inside a long solenoid wound with 5 turns/cm. If a current of 0.5A is passed through the solenoid , find the magnetic moment of the rod. 2

7* The susceptibility of a magntic mateial is 0.9853. Identify the type of the magnetic material.Draw the modification of the field pattern on keeping a piece of this material in a uniform magnetic field. 2
Ans : paramagnetic

8 Two similar bars, made from two different materials P and Q are placed one by one in a non uniform magnetic field. It is observed that (a) the bar P tends to move from the weak to the strong field region. (b) the bar Q tends to move from the strong to the weak field region. What is the nature of the magnetic materials used for making these two bars? 2

4. ELECTROMAGNETIC INDUCTION AND ALTERNATING CURRENTS

GIST

1 The phenomenon in which electric current is generated by varying magnetic fields is called electromagnetic induction.

2 Magnetic flux through a surface of area A placed in a uniform magnetic field B is defined as
$\Phi_B = B.A = BACos\theta$ where θ is the angle between B and A.

3 Magnetic flux is a scalar quantity and its SI unit is weber (Wb). Its dimensional formula is $[\Phi] = ML^2T^{-2}A^{-1}$.

4 Faraday's laws of induction states that the magnitude of the induced e.m.f in a circuit is equal to the time rate of change of magnitude flux through the circuit.