Unit 13

ELECTROMAGNETISM

Major Concepts **(18 PERIODS)**

- Magnetic field of current – carrying conductor
- Magnetic force on a current-carrying conductor
- Magnetic flux density
- Ampere's law and its application in solenoid
- Force on a moving charged particle in a magnetic field
- e/m of an electron
- Torque on a current carrying coil in a magnetic field
- Electro-mechanical instruments

Conceptual Linkage

This chapter is built on Electromagnetism Physics X

Students Learning Outcomes

After studying this unit, the students will be able to:

- explain that magnetic field is an example of field of force produced either by current-carrying conductors or by permanent magnets.
- describe magnetic effect of current.
- describe and sketch field lines pattern due to a long straight wire.
- explain that a force might act on a current-carrying conductor placed in a magnetic field.
- investigate the factors affecting the force on a current carrying conductor in a magnetic field.
- solve problems involving the use of $F = BIL \sin\theta$.
- define magnetic flux density and its units.
- describe the concept of magnetic flux (ϕ_B) as scalar product of magnetic field (B) and area (A) using the relation $\phi_B = B_{\perp}A = B \cdot A$.
- state Ampere's law.
- apply Ampere's law to find magnetic flux density around a wire and inside a solenoid.
- describe quantitatively the path followed by a charged particle shot into a magnetic field in a direction perpendicular to the field.
- explain that a force may act on a charged particle in a uniform magnetic field.

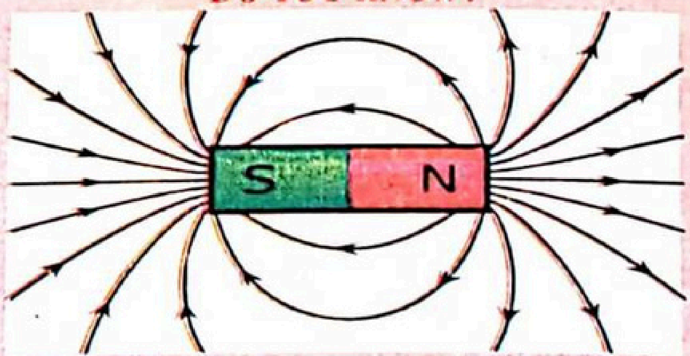
- describe a method to measure the e/m of an electron by applying magnetic field and electric field on a beam of electrons.
- predict the turning effect on a current carrying coil in a magnetic field and use this principle to understand the construction and working of a galvanometer.
- explain how a given galvanometer can be converted into a voltmeter or ammeter of a specified range.
- describe the use of avometer / multimeter (analogue and digital)

INTRODUCTION

A naturally occurring Lodestone was first mined at magnesia, Anatolia in Turkey. It was named as magnetite, Fe_3O_4. It has a property to attract iron pieces. If a bar-shaped of this permanent magnet is suspended from its midpoint by a piece of string so that it can swing freely, it will rotate until its one end points to the earth's geographic north pole. This end is called north (N) pole of bar magnet. The other end points to the earth's geographic south Pole called south (S) pole. The same idea is being used to construct a simple compass. Like electric charges, the like or similar poles repel, and the unlike or opposite poles attract each other with a force called magnetic force.

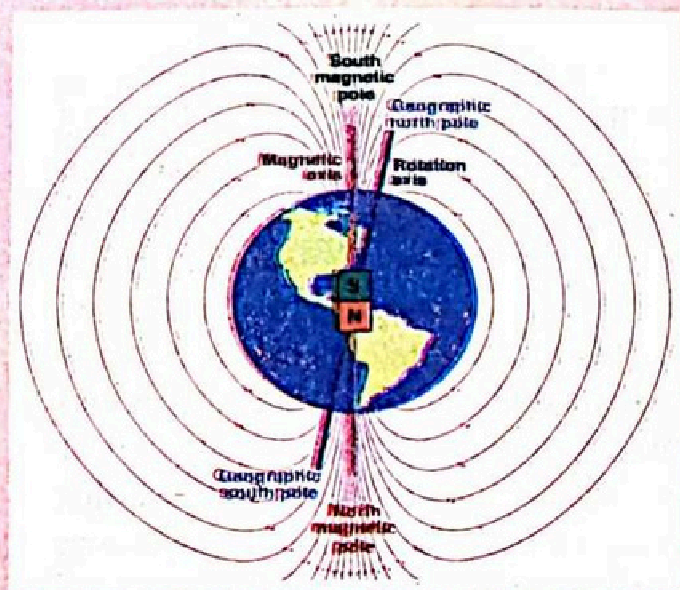
In 1820, Oersted discovered the relationship between magnetism and electricity. He observed that a compass needle was deflected by a current carrying wire. A few years later, Michelson Faraday discovered that an electric current can be produced in a circuit by moving a magnet near the circuit. These

DO YOU KNOW?



Like electric dipole, a magnetic dipole consist of a south pole and a north pole.

INTERESTED INFORMATION



The Earth's magnetic field is approximately that of a dipole, like that of the fictitious bar magnetic. Where the south magnetic pole is towards the geographic north pole and the north magnetic pole is towards the geographic south pole.

observations show that an electric field creates a magnetic field. Such interaction, or production of magnetism due to electricity implies to electromagnetism. Magnetism and electromagnetism are being used in several fields of daily life, such as in electric motors, loud speaker, TV picture tubes, microwaves oven, tapes, disk drives, computer printer, MRI (magnetic resonance imaging) etc.

INTERESTING INFORMATION

When you insert your credit, debit or ATM card into the Automated Teller Machine (ATM). A magnetic strip on a card contains millions of tiny magnetic domains held together by a resin binder. The machine reads the information encoded on the magnetic strip and it makes your access to your account.

In this unit we will determine the magnetic field, magnetic flux and magnetic force that acts on a moving charge as well as on a current carrying wire which is placed in the applied magnetic field. Similarly, we also explain the construction, principle and working of some electromagnetic instruments, such as: galvanometer, voltmeter, ammeter and Avometer.

POINT TO PONDER

Does every magnetic material have a north and south pole?

13.1 MAGNETIC FIELD

An iron ore called lodestone is a naturally occurring magnetic rock found near the ancient city of 'Magnesia' (in western Turkey). This is a reason that why this lodestone is named as a 'Magnet'. If a suspended bar-shaped magnet is free to rotate its one end points north, called north pole, and its other end points towards south and is called south pole. The like poles repel and unlike poles attract each other with a force, as shown in Fig.13.1. Such force of attraction or repulsion between unlike or like poles is known as magnetic force. Since each pole produces a magnetic field around it, so the field of one pole exerts a force on the nearby other pole and vice versa. Like electric field, magnetic field is represented by

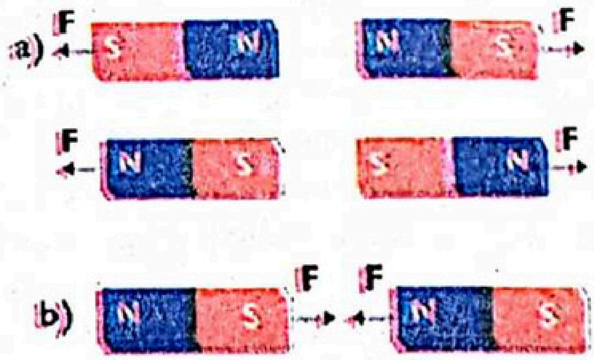


Fig.13.1(a) Like poles repel each other (b) Unlike poles attract to each other.

DO YOU KNOW

Like electric field lines, magnetic field lines also never cross each other but instead push apart of each other.

magnetic lines of force $\vec{B}$ which provides both magnitude and direction of the field. The magnetic field vector $\vec{B}$ at any point is tangent to the field line as shown in Fig.13.2.

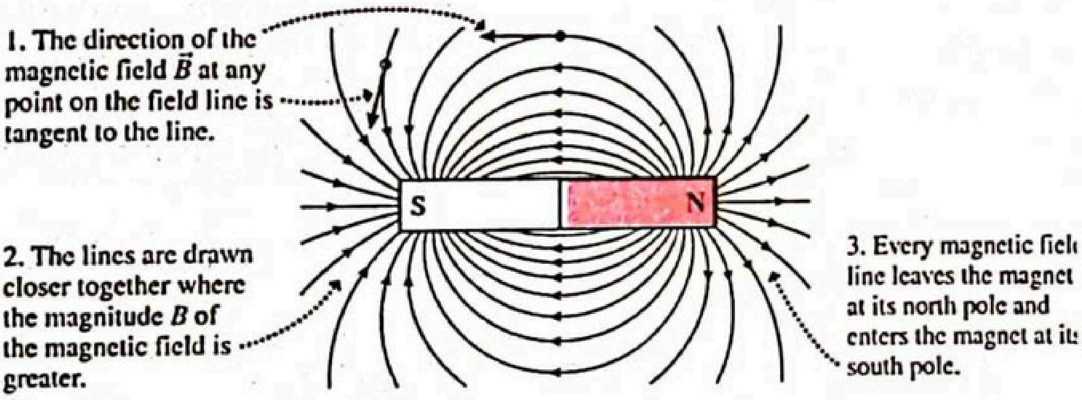


Fig.13.2 Magnetic field vector 'B' is tangent to the field line.

H.C. Orested was the first person who discovered the magnetic effect of electric current in 1820. According to him, a current carrying-conductor can also produces magnetic effect. He verified his notion by performing a simple experiment. The experimental setup consists of a wire AB which is connected across the source of e.m.f. and a compass needle placed parallel to wire as shown Fig.13.3(a). If the switch S is opened and there is no current in the wire, the needle remains parallel to the wire i.e., the needle does not deflect. However, when the switch is closed and the current starts to flow in the wire, the needle deflects as shown in Fig.13.3(b). Thus, this deflection shows that a current carrying wire produces a magnetic field around it. The strength of the magnetic field depends upon the magnitude of current.

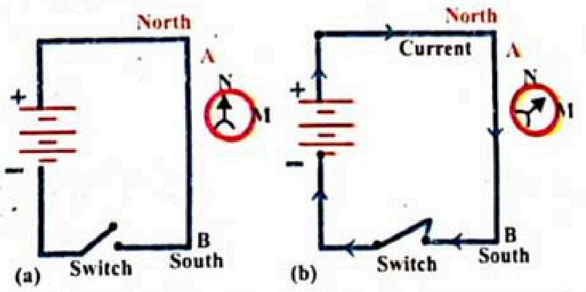


Fig.13.3(a) No deflection, when the wire carries no current (b) There is deflection, when the wire carries a current.

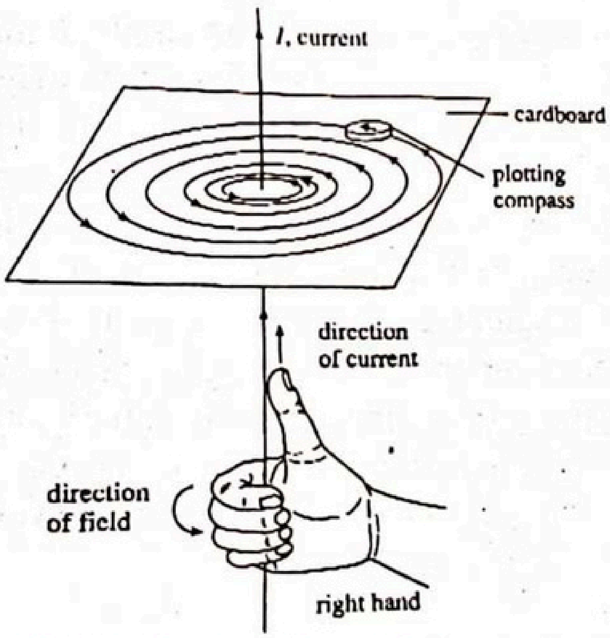


Fig.13.4(a) Magnetic lines of force in form of concentric circles due to a current carrying a wire, which is detected by plotting compass.

Magnetic field due to current carrying a long straight wire

Consider a current carrying long straight wire, according to Orested a magnetic field is produced around it. The pattern of such magnetic field is in form of closed concentric circles in a plane which is perpendicular to the wire. It can be detected by using a small plotting compass placed near the wire as shown in Fig.13.4(a). The experiments show that the strength of such field depends upon current, medium and distance from the wire. Similarly, the direction of magnetic lines of force can be determined by "right hand rule".

Right hand rule

The direction of magnetic lines of force due to a current carrying long wire can be determined by "right hand rule". According to this rule, the wire is grasped in the right hand such that if the thumb is pointing in the direction of current, then the curved fingers of the hand will give the direction of magnetic field as shown in Fig. 13.4(b).

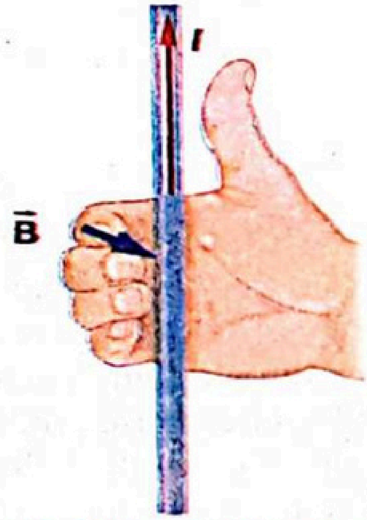


Fig.13.4(b) Right hand rule shows the direction of magnetic lines of force.

13.2 FORCE ON A CURRENT CARRYING CONDUCTOR IN UNIFORM MAGNETIC FIELD

We have studied that a current carrying conductor produces a magnetic field around it. Now if such conductor is placed in an applied magnetic field, as shown in Fig.13.5, then these two magnetic fields i.e., the magnetic field due to a current carrying conductor and the applied magnetic field interact with each other, as a result, a force is exerted on the conductor. The observations show that the magnitude of such magnetic force depends upon the following four factors.

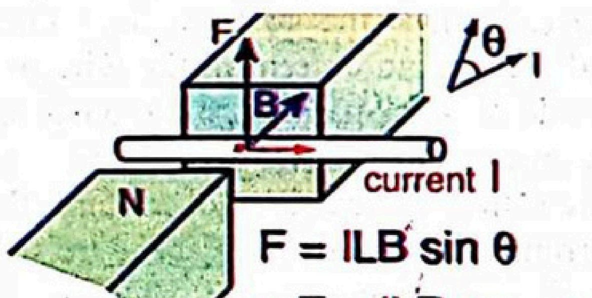


Fig.13.5 A current carrying conductor in an applied magnetic field experiences a magnetic force.

i. Current: The magnitude of force exerts on the conductor is directly proportional to the magnitude of current flowing through the conductor.

$$F_m \propto I$$

ii. Length of the conductor: The magnitude of magnetic force is also directly proportional to the length of the conductor within the applied external magnetic field

$$F_m \propto \ell$$

iii. Strength of the field: The magnitude of the magnetic force is directly proportional to the magnitude of the applied magnetic field B.

$$F_m \propto B$$

iv. Directions: If the length of the conductor is perpendicular to the direction of the applied field then a maximum force acts on the conductor. However, if the length is parallel to the direction of field, the conductor experiences no force. It means, the magnitude of force is also depends upon the factor of $\sin\theta$. That is,

$$F_m \propto \sin\theta$$

Combining all the above results we may write;

$$F_m \propto I\ell B\sin\theta$$
$$F_m = kI\ell B\sin\theta$$

where 'k' is constant of proportionality. It is dimensionless and if its value is 1 in SI units then

$$F_m = I\ell B\sin\theta \quad ......(13.1)$$

In vectors form

$$\vec{F}_m = I(\vec{\ell}\times\vec{B}) \quad ......(13.2)$$

If the length of the conductor is perpendicular to direction of magnetic field and angle 'θ' between them is 90^0 then magnetic force on the conductor is maximum. It is given by

$$F_m = I\ell B \qquad \therefore \sin 90^\circ = 1$$

$$B = \frac{F_m}{I\ell} \quad ......(13.3)$$

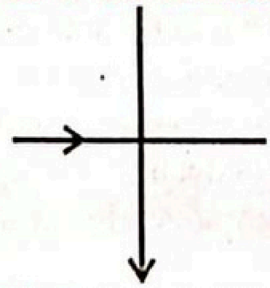
Magnetic field is a vector quantity and its SI unit is Tesla (T) i.e., **the strength of the magnetic field is said to be one tesla if it exerts a force of one newton on a conductor of length one metre through which current of one ampere is passing through it.** Mathematically, it is expressed as;

$$1T = \frac{1N}{1A - 1m}$$

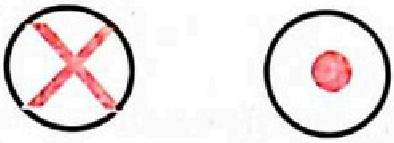
POINT TO PONDER

Why does a picture become distorted when a magnetic bar is brought near to the screen of TV, Computer Monitor or Oscilloscope?

POINT TO PONDER



Two conductors are at right angle in form of a plane carry equal currents. At what point in the plane that their magnetic field is zero?



Current into the page **Current coming out ofthe page**

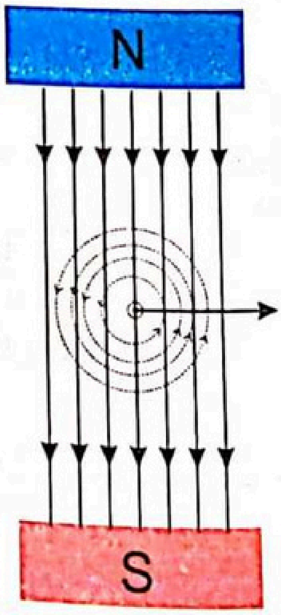


Fig.13.6(a) A magnetic force due to a current carrying a conductor in uniform magnetic field.

The magnetic field $\vec{B}$ can also be measured in terms of Gauss (G) where,

$$1\ \text{Tesla(T)} = 10^4\ \text{Gauss(G)}$$

In order to determine the direction of force, we have a current carrying conductor perpendicularly in uniform magnetic field, if the current flow is out of the page then it is represented by symbol dot (•), as shown in Fig.13.6(a). Similarly, if the flow of current is into the page then it is represented by symbol cross (X).

Due to the interaction these two fields reinforce each other on the left side of the conductor and give a strong magnetic field while cancel each other on the right side of the conductor and give a weak magnetic field. Thus, the direction of the force on the conductor will be directed from stronger to weaker side at right angle to both the length of conductor and magnetic field.

The direction of force on the conductor can further be explained by Fleming's left hand rule. **According to this rule, stretched the thumb, forefinger and middle finger of the left hand perpendicularly in such a way that the forefinger is along the magnetic field, middle finger is along the current flow then thumb indicates the direction of force as shown in Fig.13.6(b).**

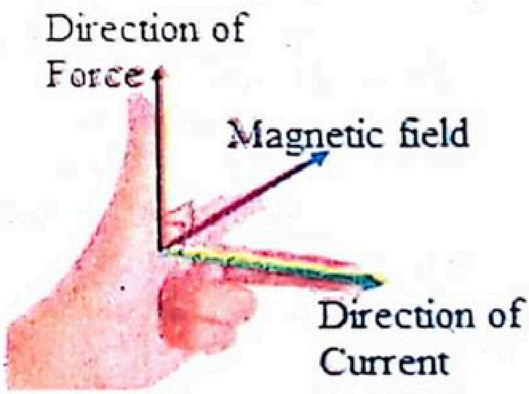


Fig.13.6(b) Flaming left hand rule explaining the directions of force, magnetic field and current.

Example 13.1

A straight conductor of length 20cm carrying a current of 10A in a uniform magnetic field of strength 0.4T. What is the force on the wire when it is (a) at right angles to the field and (b) at 45^0 to the field.

Solution:

Length of the conductor = ℓ = 20cm = 0.2m

Current = I = 10A

Strength of the field = B = 0.4T

(a) Force = F_1 = ?

$\theta_1 = 90^\circ$

(b) Force = F_2 = ?

$\theta_2 = 45^\circ$

By definition of force on a current carrying a conductor,

(a)

$$F_1 = I\ell B \sin\theta_1$$

$$F_1 = (10A)(0.2m)(0.4T)\sin 90^\circ$$

$$F_1 = 0.8N$$

(b)

$$F_2 = I\ell B\sin\theta_2$$
$$F_2 = (10A)(0.2m)(0.4T)\sin 45^o$$
$$F_2 = (0.8)(0.707)$$
$$F_2 = 0.57N$$

13.3 MAGNETIC FLUX AND MAGNETIC FLUX DENSITY

A magnetic field can be represented by imaginary lines of force called magnetic field lines. Like electric flux, the magnetic flux is also defined as, **the number of magnetic field lines passing through a certain area held perpendicular to the direction of field** as shown in Fig.13.7. Magnetic flux is represented by ϕ_B. Quantitatively, it is equal to the scalar product of magnetic field strength '$\vec{B}$' and vector area $\vec{A}$. i.e.,

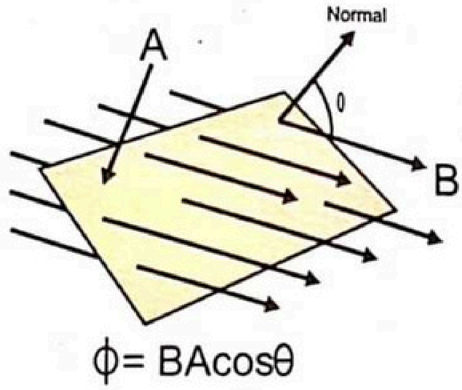


Fig.13.7 The magnetic field lines passing through area.

$$\phi_B = \vec{B}\cdot\vec{A}$$
$$\phi_B = BA\cos\theta \quad ......(13.4)$$

Magnetic flux is a scalar quantity and it can be studied under the following two cases:

<u>Case I:</u> If area is held perpendicular to the direction of field B then the direction of vector area $\vec{A}$ is parallel to the direction of $\vec{B}$ and angle 'θ' between them is zero as shown in Fig.13.8. Thus Eq.13.4 becomes

$$\phi_B = BA\cos 0^o$$
$$\phi_B = BA \quad ......(13.5)$$

This is the maximum flux.

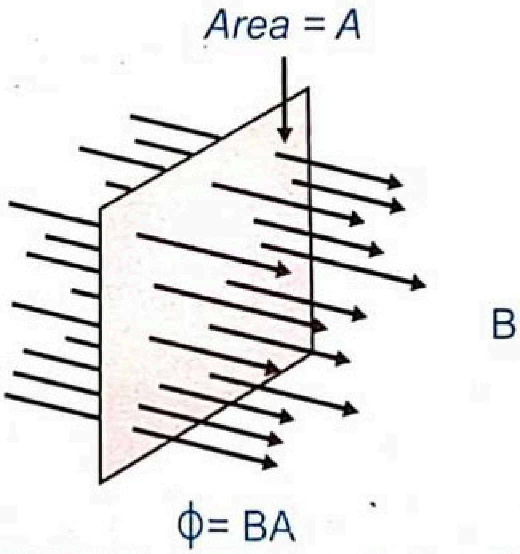


Fig.13.8 Area held perpendicular and angle θ between B and A is 0^0.

<u>Case II:</u> Similarly, if the area A is placed parallel to the direction of field B then the direction of vector area $\vec{A}$ is perpendicular to the direction of $\vec{B}$ and angle 'θ' between them is 90° as shown in Fig.13.9, then Eq.13.4 becomes

$$\phi_B = BA\cos 90^o$$
$$\phi_B = 0$$

This is the minimum flux.

The SI unit of magnetic flux is Weber (Wb), which can be derived by using Eq.13.5.

$$\phi_B = BA$$

$$1\ Wb = 1T \cdot 1m^2$$

or $$1\ Wb = \frac{1N}{A \cdot m} \cdot m^2$$

$$1\ Wb = 1N \cdot m \cdot A^{-1}$$

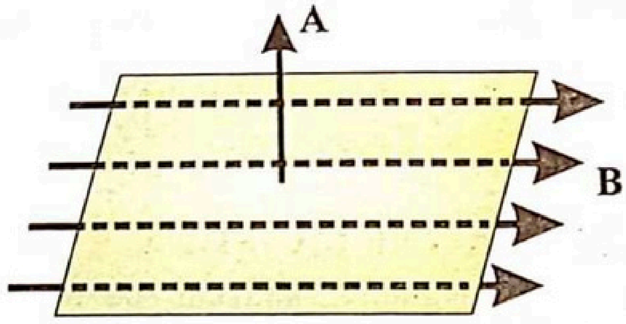


Fig.13.9 Area held parallel and angle θ between B and A is 90^0.

Magnetic flux density

Magnetic flux density is defined as **the magnetic flux per unit area held perpendicular to the direction of field strength 'B'.** It is measured in terms of ratio between magnetic flux ϕ_B and unit area 'A' by using Eq.13.5

$$B = \frac{\phi_B}{A} \quad ......(13.6)$$

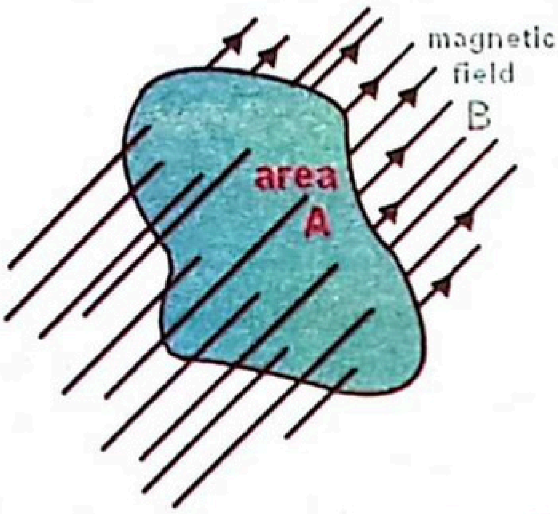
The unit of magnetic flux density is Wbm^{-2} and it is equal to tesla. i.e.,

$$Wbm^{-2} = \left(\frac{N \cdot m}{A}\right) m^{-2}$$

$$Wbm^{-2} = \frac{N \cdot m^{-1}}{A}$$

$$Wbm^{-2} = \frac{N}{A \cdot m}$$

$$Wbm^{-2} = T$$

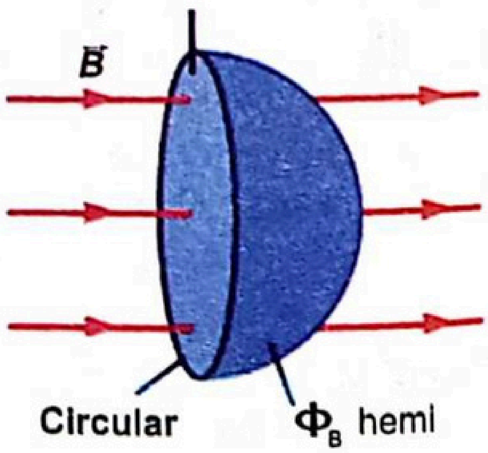


Magnetic lines of force passing through a unit area.

This shows that magnetic field strength and magnetic flux density both have same unit.

Example 13.2

A hemispherical surface of radius 5cm is placed in a magnetic field of strength 0.6T. If the direction of the surface is along the direction of the field then calculate the flux through the hemispherical surface.



Solution:

Radius of hemisphere = R = 5cm = 0.05m

Magnetic field strength = B = 0.6T

Angle between B and A = $\theta = 0^o$

Magnetic flux = ϕ_B = ?

By definition of magnetic flux

$$\phi_B = \vec{B}\cdot\vec{A} = BA\cos\theta$$
$$\phi_B = BA\cos 0$$
$$\phi_B = BA$$

But area of hemispherical surface $= \pi R^2$

$$\phi_B = B\pi R^2$$
$$\phi_B = (0.6T)(3.14)(0.05m)^2$$
$$\phi_B = 4.7\times 10^{-3}\ Wb$$

13.4 AMPERE'S LAW

We have studied that a current carrying conductor produces a magnetic field around it in the form of a closed circular loop of radius 'r' as shown in Fig.13.10. The experiment shows that the direction of the magnetic field is tangent at each point of the circular loop and its strength is directly proportional to the current flowing through the wire and inversely proportional to the distance from the wire. Mathematically, these two results can be expressed as,

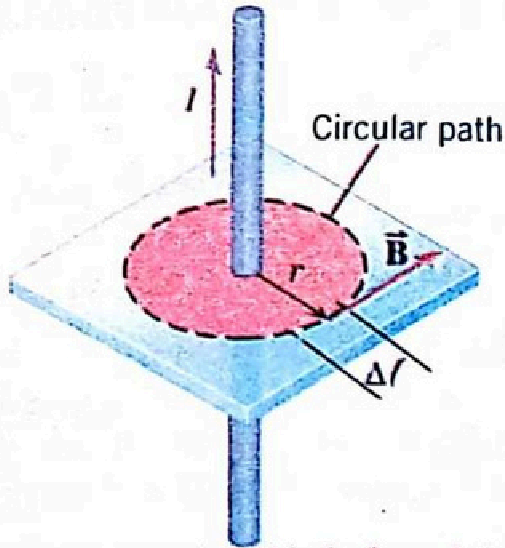


Fig.13.10 A magnetic field in the form of circular loop of constant radius r around steady current carrying a conductor.

$$B \propto \frac{I}{r}$$

$$B = \frac{\mu_0 I}{2\pi r} \quad ......(13.7)$$

Here $\frac{\mu_0}{2\pi}$ is the constant of proportionality. The parameter 'μ_0' is called the permeability of free space and its value is $4\pi\times10^{-7}\ TmA^{-1}$.

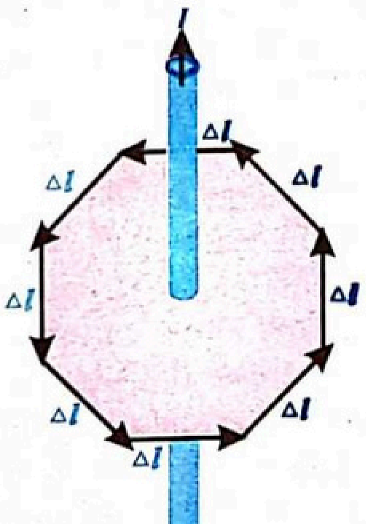


Fig.13.11 An arbitrary closed path around a current carrying a conductor

Equation 13.7 was derived for the magnetic field in form of a close circular loop around a steady current-carrying conductor. However, when the magnetic field is along an arbitrary closed path called 'amperean path' around the current-carrying conductor as show in Fig.13.11, then we cannot use Eq. 13.7 directly. For this Ampere has expressed a general relation between current and magnetic field along an arbitrary closed path.

Consider the arbitrary path around the current-carrying conductor which consists of 'n' number of small segments, such that each segment has same length equals to $\Delta\ell$ and is parallel to the magnetic field B, where

$$\vec{B}\cdot\Delta\vec{\ell} = B\Delta\ell\cos\theta = B\Delta\ell \qquad \therefore \theta = 0^{\circ}$$

According to Ampere, **the sum of all such product, $(B\cdot\Delta\ell)$ over the closed path is equal to μ_0 times of the total current that passes through the surface bounded by the closed path.** This statement is called Ampere's circuital law and it can be expressed as,

$$(B\cdot\Delta\ell)_1 + (B\cdot\Delta\ell)_2 + \cdots + (B\cdot\Delta\ell)_n = \mu_0 I$$

$$\sum_{i=1}^{n}(B\cdot\Delta\ell)_i = \mu_0 I \qquad \ldots\ldots(13.8)$$

This is the mathematical form of Ampere's circuital law.

13.4.1 Magnetic field due to a current carrying solenoid

A solenoid is a long coil of conducting wire with many turns. When current is passed through a solenoid then a uniform magnetic field is produced in it as shown in Fig.13.12. The solenoid acts as a bar magnet when it carries current i.e., it becomes a strong electromagnet. The magnetic field lines are entering at its one end and emerging from the other end. The lines emerging end of the solenoid acts as a north pole and the line entering end acts as a south pole as shown in Fig.13.13. The magnetic field inside the solenoid is not only uniform but also stronger. Whereas, the field outside the solenoid is weaker and negligible.

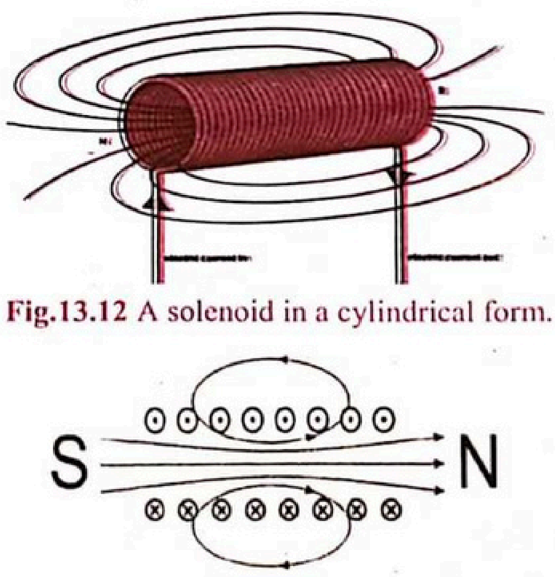


Fig.13.12 A solenoid in a cylindrical form.

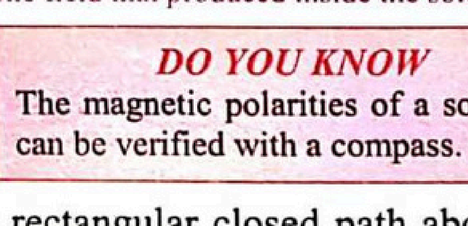


Fig.13.13 Polarities of uniform and strong magnetic field that produced inside the solenoid.

Consider a current-carrying solenoid of length 'ℓ'. Here we assume that magnetic field outside the solenoid is zero. To calculate the value of magnetic field B inside the solenoid using Ampere's law, we consider a rectangular closed path abcd such

> ***DO YOU KNOW***
> **The magnetic polarities of a solenoid can be verified with a compass.**

that ab=l_1, bc=l_2, cd=l_3 and da=l_4, as shown in Fig.13.14. The sum of the products of magnetic field B and lengths of rectangular closed path is expressed as,

$$\sum \vec{B}\cdot\Delta\vec{\ell} = \vec{B}\cdot\vec{\ell}_1 + \vec{B}\cdot\vec{\ell}_2 + \vec{B}\cdot\vec{\ell}_3 + \vec{B}\cdot\vec{\ell}_4$$

$$\sum \vec{B}\cdot\Delta\vec{\ell} = B\ell_1\cos 0^\circ + B\ell_2\cos 90^\circ$$

$$+(0)(\ell_3)\cos 180^\circ + B\ell_4\cos 270^\circ$$

$$\sum \vec{B}\cdot\Delta\vec{\ell} = B\ell_1 + 0 + 0 + 0$$

$$\sum \vec{B}\cdot\Delta\vec{\ell} = B\ell_1 \quad ......(13.9)$$

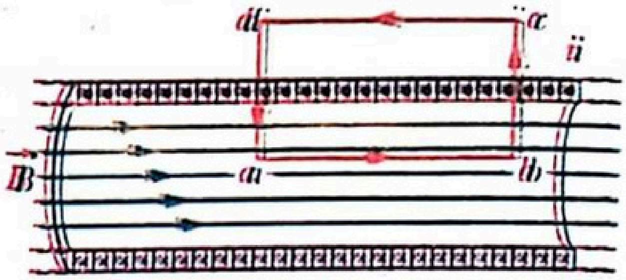


Fig.13.14 To calculate magnetic field B considering a closed rectangular path abcd on a solenoid.

If the number of turns per unit length is 'n' then total number of turns of solenoid of length 'ℓ' is $N = n\ell$ and total number of turns in length ℓ_1 is $n\ell_1$.

Thus, total current in closed path abcda = $n\ell_1 I$

According to Ampere's Law.

$\Sigma B\cdot\Delta\ell = \mu_0$ (total current enclosed)

$$\sum \vec{B}\cdot\Delta\vec{\ell} = \mu_0 n\ell_1 I \qquad ......(13.10)$$

POINT TO PONDER

By what factor will the magnetic field inside a solenoid increase if both the number of turns and the current are doubled?

Comparing the left-hand sides of Eq.13.9 and Eq.13.10

$$B\ell_1 = \mu_0 n\ell_1 I$$

$$\Rightarrow \qquad B = \mu_0 nI \quad ......(13.11)$$

The direction of field B is along the axis of solenoid. The result of Eq. 13.11 shows that magnetic field B is independent of the position within the solenoid. It means the field is uniform within a long solenoid. Eq. 13.11 is also valid to the solenoid which has more than one layer of windings because B does not depend on the radius of the solenoid. A much stronger magnetic field can be produced if windings of solenoid are made on magnetic material that is use of an iron core.

Example 13.3

A 10cm long solenoid has 400 turns of wire and carries a current of 2A. Calculate the magnetic field inside the solenoid.

Solution:

Length of the solenoid = ℓ = 10cm = 0.1m

Total number of turns of solenoid = N = 400

Current through the solenoid = I = 2A

Magnetic field inside the solenoid = B = ?

Number of turns in length per unit length= $n = \frac{N}{l}$

$$n = \frac{400}{0.1} = 4000 \text{ turns/m}$$

The magnetic field inside the solenoid is given by

$$B = \mu_o nI$$

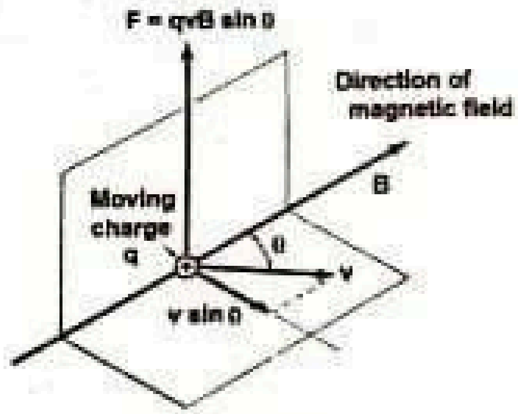
$$B = 4\pi \times 10^{-7} \times 4000 \times 2$$

$$B = 0.01 \text{ T}$$

$$B = 10^{-2} \text{ T}$$

13.5 FORCE ON A MOVING CHARGED PARTICLE IN A MAGNETIC FIELD

As we know the rate of flow of charges through a conductor is known as current. We have already studied that when current-carrying conductor is placed in a uniform magnetic field, it experiences a magnetic force. Indeed, the magnetic force acts on the moving charges because a beam of charged particles which are moving with uniform velocity equals to a steady current in the direction of their motion. The magnetic force on the charge is due to interaction between the applied magnetic field and the induced magnetic field around the moving charges.



The magnetic force F acting on a charge q moving with velocity v

$\vec{F} = q\vec{v} \times \vec{B}$

Consider a charge particle **q** is moving with velocity **v** in a uniform magnetic field **B**, it experiences a magnetic force. The magnitude of this force depends upon the following factors;

i. **Charge:** The magnitude of magnetic force is directly proportional to the magnitude of charge.

$$F_m \propto q$$

ii. **Magnetic Field:** The force is directly proportional to the strength of the magnetic field.

$$F_m \propto B$$

iii. **Velocity:** The magnetic force also directly proportional to the velocity of the charge particle.

$$F_m \propto v$$

iv. **<u>Direction:</u>** It is found experimentally that when a charge particle is moving perpendicular to the direction of magnetic field, a maximum force exerts on it. However, when its motion is along the direction of the field, it experiences no force. This shows that the magnitude of the magnetic force is directly proportional to $\sin\theta$

$$F_m \propto \sin\theta$$

Combining all the above results, we get a relation,

$$F_m \propto qBv\sin\theta$$

$$F_m = kqBv\sin\theta$$

where 'k' is a constant of proportionality. In SI units its value is one and is dimensionless,

$$F_m = qvB\sin\theta$$

> *POINT TO PONDER*
>
> A force exerts on a moving charged particle in a magnetic field, but in what direction it moves that the force does not exert on it?

In vector form

$$\vec{F}_m = q(\vec{v}\times\vec{B}) \quad \ldots\ldots(13.12)$$

This result is applied for both types of charges i.e. positive and negative charges. The direction of the magnetic force can be determined by using right hand rule as; place or draw the vectors $\vec{v}$ and $\vec{B}$ with their tail together. Imagine rotating $\vec{v}$ towards $\vec{B}$ through the smaller angle between them by curl of fingers of right hand in the direction of rotation. The erected thumb points in the direction of force on moving charge as shown in Fig.13.15. In this case we have considered a positively charged particle (proton). i.e., when the proton enters into a magnetic field, it experiences a force in the upward direction as given by the vector $\vec{v}\times\vec{B}$. Hence, the proton is deflected in the upward direction as shown in Fig.13.16(a). If the moving particle is negatively charged such as an electron then the direction of force will be opposite to that of positive charge. When the electron enters into a magnetic field, a magnetic force acts on it in the

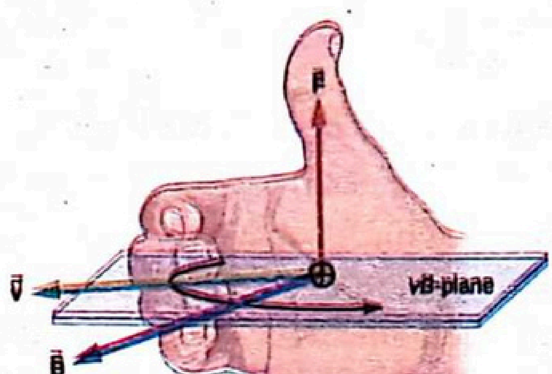


Fig.13.15 Right hand rule showing a direction of force.

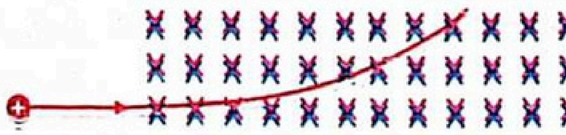


Fig.13.16(a) The proton is deflected upward under the action of magnetic force.

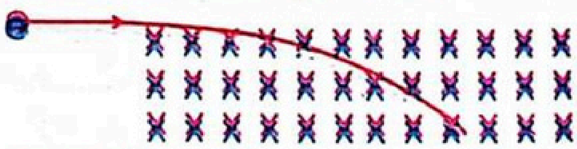


Fig.13.16(b) The electron is deflected downward under the action of magnetic force.

downward direction. As a result, the electron is deflected in the downward direction, as shown in Fig.13.16(b).

Example 13.4

An ion (q = +2e) enters into a magnetic field of strength 1.2T with a velocity 2.5×10^5 m s^{-1} perpendicular to the field. Determine the force that acts on the ion.

Solution:

Charge on an ion = q = +2e

$$q = 2.(1.6 \times 10^{-19})C$$

$$q = 3.2 \times 10^{-19}\ C$$

Magnetic field strength = B = 1.2T

Velocity of ions = v = 2.5×10^5 m s^{-1}

Angle between field and velocity = $\theta = 90^\circ$

The force on a the given ion is given by

$$F = qvB\sin\theta$$

$$F = (3.2 \times 10^{-19}C)(2.5 \times 10^5 m\ s^{-1})(1.2T)\sin 90^\circ$$

$$F = 9.6 \times 10^{-14}\ N$$

13.6 DETERMINATION OF e/m OF AN ELECTRON

Consider an electron which is moving with a constant velocity $\vec{v}$ and enters in a uniform magnetic field $\vec{B}$ such that the direction of its motion is perpendicular to direction of the field $\vec{B}$. It is to be noted that the direction of the magnetic field is into the page as shown in Fig.13.17. Thus, the force acting on the moving electron through $\vec{B}$ is given by:

$$\vec{F}_m = -e\left(\vec{v}\times\vec{B}\right) \quad ......(13.13)$$

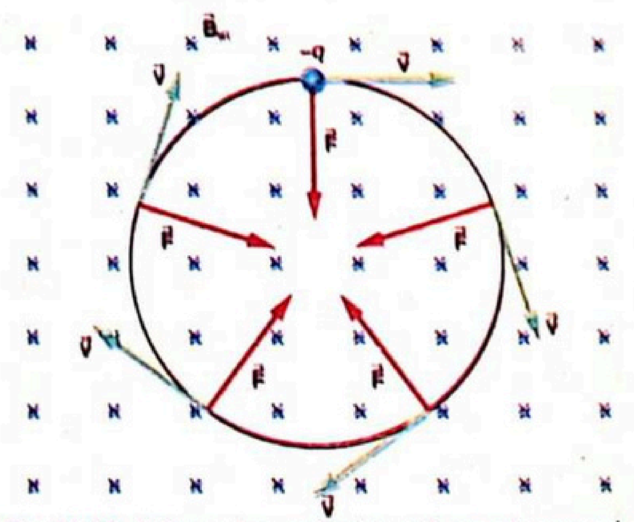


Fig.13.17 When the velocity of an electron is perpendicular to the magnetic field then the magnetic force acting on it equals to the centripetal force.

This magnetic force is perpendicular to both $\vec{v}$ and $\vec{B}$. So, it changes the direction of velocity of electron, but the magnitude of the velocity remains same. Thus, under the action of this constant force the electron will move along a circular path as shown in Fig.13.17. The magnitude of magnetic force on electron is given by

$$F_m = evB\sin\theta = evB \qquad \therefore \theta = 90^\circ$$

According to right hand rule, the magnetic force is always directed towards the centre of the circle. Therefore, it provides the necessary centripetal force to the electron of mass m to move it along a circular path of radius r. Thus, we have;

$$F_m = F_c$$

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

$$\frac{e}{m} = \frac{v}{Br} \quad ......(13.14)$$

If the values of v, B and r are known then we could determine the e/m i.e., charge to mass ratio. In this regard, the radius 'r' can be measured by making circular path of electron visible. It is taken place by using gas (hydrogen or helium) filled tube at a low pressure placed in the magnetic field. The molecules of the gas are excited by the elastic collision of electrons with them. Now during deexcitation, the molecules emit light and hence the circular path of electron becomes visible as shown in Fig.13.18. In this way, the radius of the ring can be determined easily.

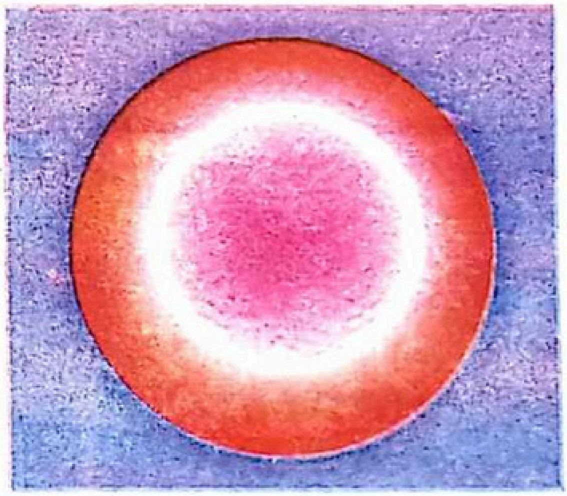


Fig.13.18 A visible circular path of electrons.

Similarly, the velocity of electrons can be determines when they are accelerated before entering into the magnetic field by applying potential difference 'V_o'. These accelerated electrons gain kinetic energy $\left(\frac{1}{2}mv^2\right)$ which equals to eV_o.

That is,

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

$$v = \sqrt{\frac{eV_0}{m}}$$

Substituting the value of e in eq. 13.14.

$$\frac{e}{m} = \frac{1}{Br}\sqrt{\frac{2eV_2}{m}}$$

$$\frac{e^2}{m^2} = \frac{1}{B^2r^2}\frac{2eV_o}{m}$$

$$\frac{e}{m} = \frac{2V_o}{B^2r^2} \quad ......(13.15)$$

The velocity of electron can also be determined by velocity selector method. The arrangement of such method consists of the applied electric and magnetic fields at right angle between the two plates as shown in Fig.13.19.

When an electron of mass 'm' charge 'e' enters perpendicularly with velocity 'v' in the region occupied by mutually perpendicular electric and magnetic fields, it experiences both electric force (+eE) and magnetic force (−evB). Negative sign shows that the magnetic force has same magnitude as that of electric force but in opposite direction. Hence, under the action of these two equal forces, the electron is in the state of equilibrium. i.e.,

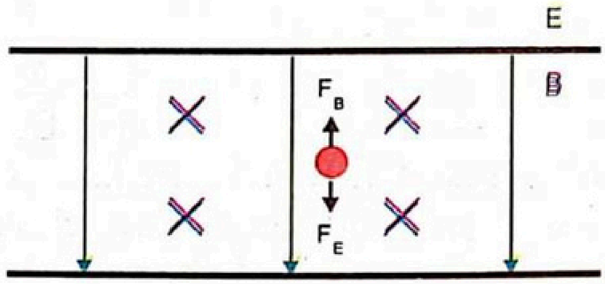


Fig.13.19 When an electron enters in the region occupied by electric and magnetic fields at right angle. It experiences electric and magnetic forces which are same in magnitude but in opposite direction.

$$F_e + F_B = 0$$
$$eE - evB = 0$$
$$vB = E$$
$$v = \frac{E}{B}$$

Substituting the value of v in Eq.13.14. We get

$$\frac{e}{m} = \frac{E}{B^2r} \quad ......(13.16)$$

Example 13.5

A proton of mass 1.67×10^{-27} kg and charge 1.6×10^{-19}C is moving in a circle of radius 0.4m in a magnetic field of strength 1.2T. Find (i) speed and (ii) kinetic energy of proton.

Solution:

Mass of proton = m = 1.67×10^{-27}kg

Charge on a proton = e = 1.6×10^{-19}c

Radius of the circular path of proton = r = 0.4m

Magnetic field strength = B = 1.2T

(i) Speed of proton = v = ?

(ii) K.E. of proton = ?

i. To find the speed of proton in uniform magnetic field along a circular path, we use the following equation

$$v = \frac{eBr}{m}$$

$$v = \frac{(1.6\times10^{-19}\,C)(1.2T)(0.4m)}{1.67\times10^{-27}\,kg}$$

$$v = 4.6 \times 10^{7}\ m\,s^{-1}$$

ii

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

$$K.E. = \frac{1}{2}(1.67\times10^{-27}\,kg)(4.6\times10^{7}\,m s^{-1})^2$$

$$K.E. = 17.7\times10^{-13}\,J = \frac{17.7\times10^{-13}}{1.6\times10^{-19}}eV = 1.1\times10^{6}eV$$

$$K.E. = 11MeV$$

13.7 TORQUE ON A CURRENT CARRYING COIL IN A MAGNETIC FIELD

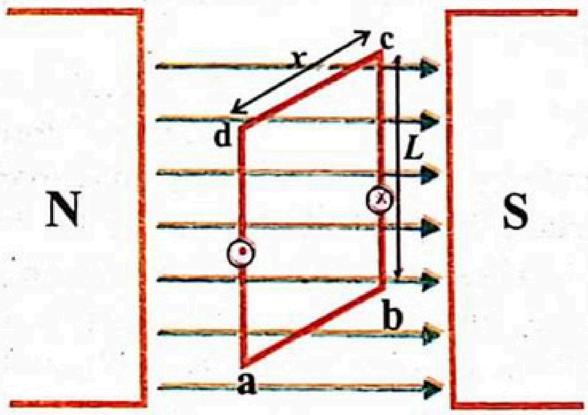


Fig.13.20 Torque on a current carrying a rectangular coil in a uniform magnetic field.

Consider a current-carrying rectangular coil 'abcd' of length L and width x which is placed in a uniform magnetic field such that the direction of field is parallel to the direction of the plane of the rectangular coil as shown in Fig.13.20. Also, the coil is capable to rotate about its axis. We have studied in the previous section that when a current carrying conductor is placed in a magnetic field, such that the length of the conductor is perpendicular to the direction of field then it experiences a magnetic force, $\vec{F} = I\left(\vec{L}\times\vec{B}\right) = ILB\sin\theta\,\hat{n}$. Where $\hat{n}$ is a unit vector perpendicular to the plane containing $\vec{L}$ and $\vec{B}$ and it indicates the direction of force. In case of rectangular coil, no forces act on its side 'ab' and 'cd' because these two lengths are parallel to the field and angle between B and these two sides is zero. Therefore, $\vec{F}_2 = \vec{F}_4 = I(\vec{L} \times \vec{B}) = 0$. On the other hand, the magnetic forces act on the sides bc and ad because these two sides are perpendicular to the field. Thus, the magnitude of these forces is given by

$$F_1 = F_2 = ILB \qquad \therefore \theta = 90^\circ$$

Where the force F_1 is directed out of the plane (page), while the force F_2 is directed into the plane. These two forces are same in magnitude but in opposite directions, Therefore, they produce the rotation in the coil about an axis which is known as torque, as $\frac{x}{2}$ is the moment arm of each force, the magnitude of the net torque is given by

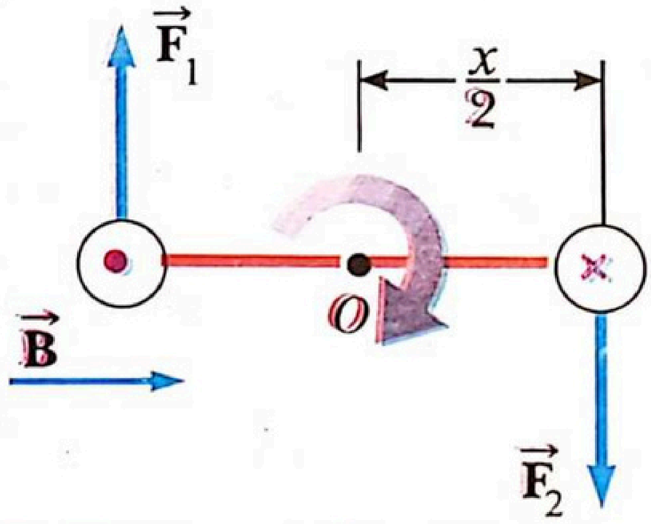


Fig.13.21(a) A magnetic field parallel to the plane of the loop, where F_1 and F_2 act perpendicularly on moment arm x/2 and produce maximum torque.

$$\tau = F_1\frac{x}{2} + F_2\frac{x}{2}$$

$$\tau = ILB\frac{x}{2} + ILB\frac{x}{2}$$

$$\tau = xLIB$$

where xL is the vector area of the rectangular coil and its magnitude is A. Therefore,

$$\tau = IAB \qquad \ldots(13.16)$$

This is the maximum torque produced by a current-carrying rectangular coil. Equation 13.16 hold only when the field is parallel to the plane of the coil as shown in Fig. 13.21(a). Now if there is some angle 'θ' between the field and area 'A' of the coil as shown in Fig.13.21(b) then the torque will be due to the vertical component of moment arm $\frac{x}{2}\sin$ as shown in Fig.13.21(b). In this case, the magnitude of the resultant torque is given as

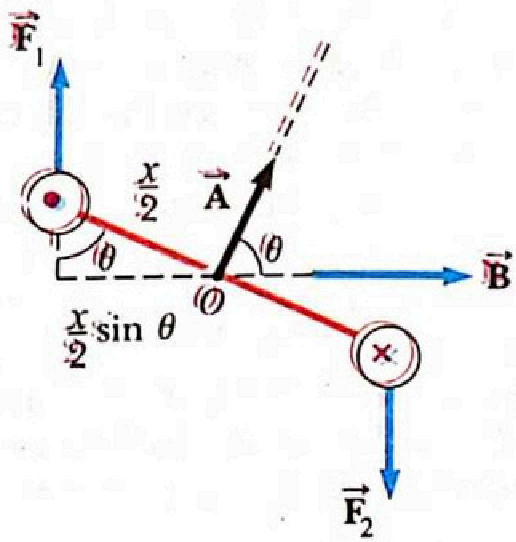


Fig.13.21(b) There is some angle between field $\vec{B}$ and area $\vec{A}$ of the loop and torque is due to the forces F_1 and F_2 and vertical components of moment arm (x/2 sinθ)

$$\tau = F_1 \frac{x}{2} \sin\theta + F_2 \frac{x}{2} \sin\theta$$

$$\tau = IAB \sin\theta$$

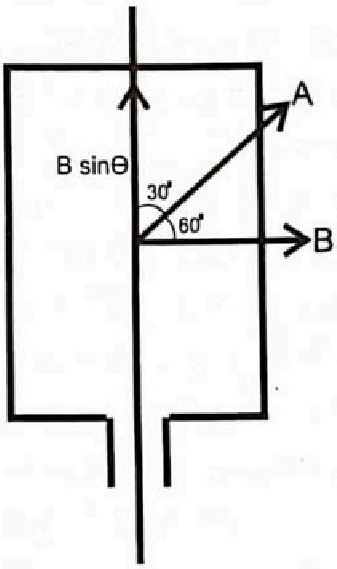
If the rectangular coil has 'N' number of turns. Then

$$\tau = INAB \sin\theta \quad ......(13.17)$$

This result shows that the rotation (torque) due to current carrying coil in magnetic field depends upon the magnitude of current, number of turns of the coil, magnetic field strength, area 'A' of the coil and the angle 'θ' between the field B and plane area 'A' of the coil.

Example 13.6

The plane of a rectangular coil makes an angle of 60° with the direction of a uniform magnetic field of strength 0.9T. The coil has 50 turns and the magnitude of its plane area is $0.12m^2$. If it carries a current of 10A then calculate the torque acting on the coil.



Solution:

Current through the coil = I = 10A

Strength of field = B = 0.9T

Number of turns of coil = N = 50

Angle between area and field = $\theta = 90^\circ - 60^\circ = 30^\circ$

Area of the plane of the coil = $0.12m^2$

Torque = τ = ?

The torque on a current carrying a coil is given by

$$\tau = INAB \sin\theta$$

$$\tau = (10A)(50)(0.12m^2)(0.9T)\sin 30^\circ$$

$$\tau = 27Nm$$

13.8 GALVANOMETER

A galvanometer is a sensitive electrical instrument used to detect or measure a small electric current. The most commonly used type of galvanometer is the moving-coil galvanometer. The working principle of galvanometer is based upon the fact that when a current-carrying coil is placed in a uniform magnetic field, it is acted upon by forces on its both end sides which produces a deflecting torque given as:

$$\tau = INAB\sin\theta$$

where I is the current in the rectangular coil, N is the number of turns of the coil, 'A' area of coil, 'B' is the uniform applied magnetic field, θ is the angle between the field and direction of plane of the coil.

Construction

A moving coil galvanometer consists of a rectangular coil 'abcd' which contains 'N' number of turns of insulated copper wire wounded on a non-magnetic light frame. The coil is suspended with the help of a phosphor bronze wire x between the curved N and S poles of a powerful U-shaped permanent magnet, such that it is free to rotate as shown in Fig.13.22(a). Inside the coil, a soft iron cylinder is fixed between the curved faces of the poles. Its function is to make the field radial, uniform and stronger. The suspension phosphor-bronze wire x is also serves as one current lead of the coil. The other terminal of the coil is connected to a spring 'y' of phosphor-bonze having a few turns. It is used as the second current lead. A small plane mirror is also attached to the top suspension wire. It helps to measure the deflection of the coil by lamp and scale arrangement.

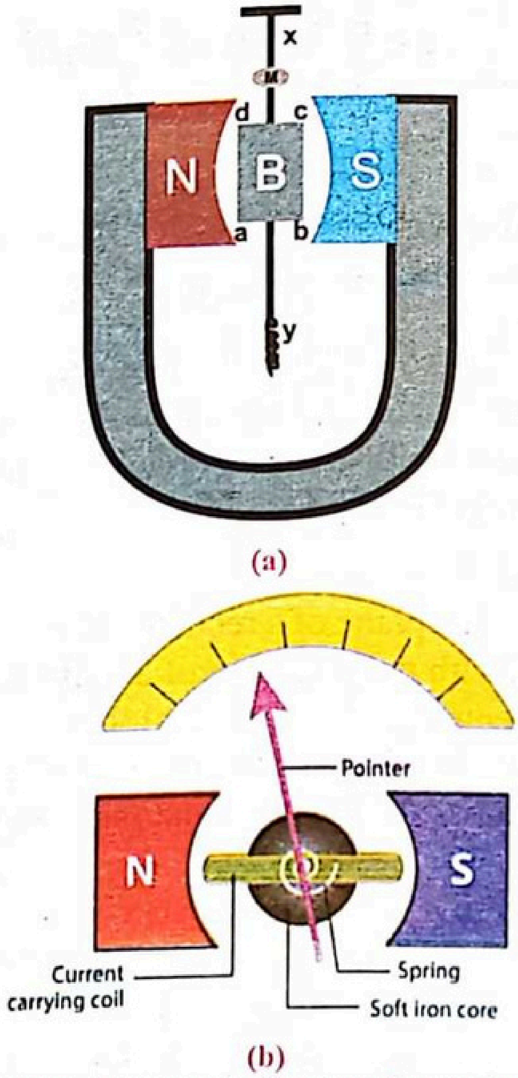


Fig.13.22 A schematic diagram of a moving coil galvanometer.

Working

When a current is passed through the coil, two forces of the same magnitude but in opposite direction act on the two sides of the coil called a couple. This couple produces a deflecting torque τ_d which is given by;

$$\tau_d = INAB\sin\theta$$

Since the coil is placed in a radial magnetic field, where angle 'θ' between the field and the direction of the plane of the coil is 90°. Therefore, the coil experiences a maximum torque. i.e.,

$$\tau_d = INAB \ldots\ldots(13.18)$$

Due to this maximum deflection torque, the coil rotates, and this rotation of coil produces a twist in the phosphor-bronze wire which causes the restoring torque. This restoring torque is directly proportional to the angle 'θ' through which the wire is twisted. i.e.,

$$\tau_r \propto \theta$$

$$\tau_r = c\theta \ldots\ldots(13.19)$$

where 'c' is a constant of proportionality called torsion constant of the suspension wire. Its unit is Nm per degree. The coil rotates until the restoring torque becomes equal to the deflection torque. i.e., when the coil is at the state of equilibrium, i.e.,

$$\tau_d = \tau_r$$

$$INAB = c\theta$$

$$I = \frac{c}{NAB}\theta \ldots\ldots(13.20)$$

As all the terms of $\frac{c}{NAB}$ are constant so,

$$I \propto \theta$$

This shows that the deflection of the coil is directly proportional to the current passing through it. Also, this result leads to the development of a linear scale of a galvanometer. Usually, there are two methods of observing the angle of deflection of the coil, which are explained as under:

In a sensitive galvanometer, if a small current passes through a coil, it produces a large deflection. Such deflection is observed by means of a small plane mirror

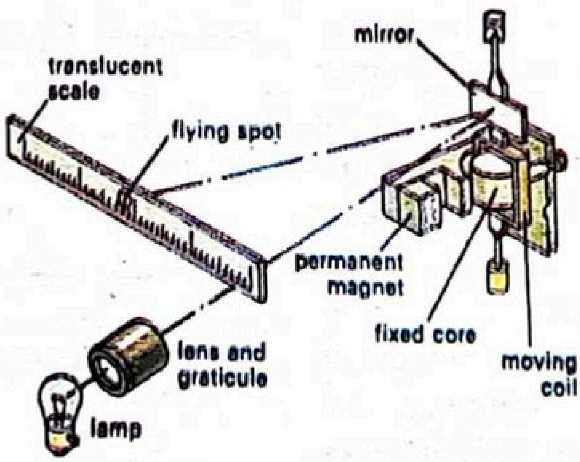


Fig.13.23 Observing of deflection by lamp and scale arrangement.

attached to the suspension wire along with a lamp and scale arrangement as shown in Fig.13.23. A beam of light from the lamp is focused on the mirror of the galvanometer. It is reflected from mirror and produces a spot on a scale placed at a distance of one metre from the galvanometer. Now when the coil rotates, the mirror also rotates with the coil and the spot of light moves along the scale. The displacement of the spot of light on the scale is proportional to the angle of deflection.

The second type of galvanometer is a pivoted coil galvanometer which is being used in the laboratories of school, colleges and other educational institutions. Such type of galvanometer is a less sensitive, where the coil is pivoted between two jeweled bearings. The restoring torque is provided by two hair springs which also work as current leads. A light aluminum pointer is attached to the coil which moves over the calibrated scale as shown in Fig.13.24. This moment of the pointer provides the measurement of the angle of deflection of the coil.

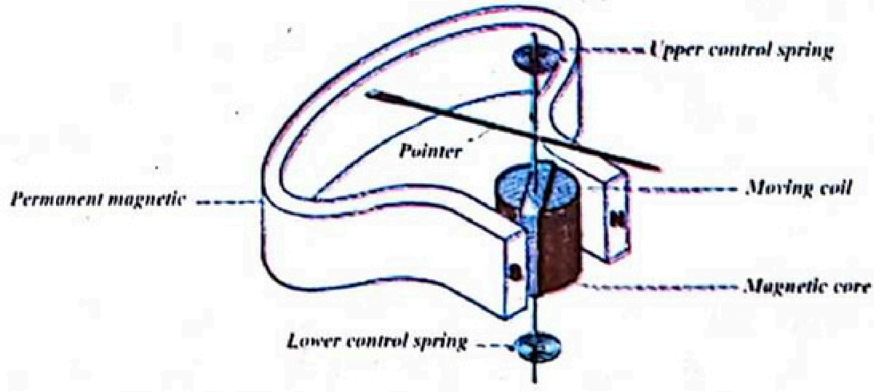


Fig.13.24 A schematic diagram of a pivoted type galvanometer.

13.8.1 Ammeter

An ammeter is an electrical device used to measure the electric current passing through a circuit. A galvanometer is a sensitive instrument and its pointer shows full scale deflection for a very small current even for current of milli ampere. Thus, in practice, an ordinary galvanometer cannot be used for large current and its measurement. To overcome this problem, we convert a galvanometer into an ammeter by connecting a suitable low resistance in parallel with it as shown in Fig.13.25. Such low resistance diverts (by passes) the

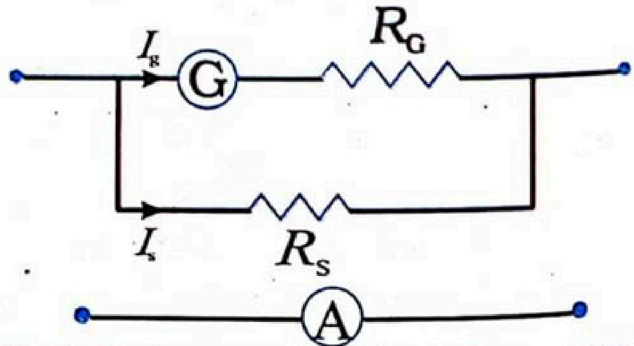


Fig.13.25 An equivalent circuit for ammeter, where a shunt resistance is connected parallel with a galvanometer.

extra current and hence it is named as shunt resistance R_s. This shunted galvanometer is called an ammeter.

To find the required value of shunt resistance R_S for a given range of ammeter, we allow flow of current I across the circuit of ammeter. A fraction of this current of value I_g passes through a galvanometer of resistance R_g, while the remaining large amount of current of value $(I - I_g)$ passes through the shunt resistance. As shunt resistance is parallel to the galvanometer so there is same potential difference across both shunt resistance and galvanometer thus, we have;

$$V_s = V_g$$

$$(I - I_g)R_s = I_g R_g$$

$$R_s = \left(\frac{I_g}{I - I_g}\right) R_g \quad \ldots\ldots(13.21)$$

The above equation can be used to calculate the required shunt resistance for given galvanometer in order to convert it for any range of ammeter.

Since ammeter is being used to measure the current, so it should always be connected in series and the current flow through the component of a circuit can be calculated by using the following relation:

$$I = I_g\left(\frac{R_g}{R_S} + 1\right) \quad \ldots\ldots(13.22)$$

13.8.2 Voltmeter

A voltmeter is an electrical device used to measure the potential difference between two points in an electric circuit. As we have discussed that a galvanometer can measure a current only in milliampere due its very low resistance. It means that the potential difference can also be applied across the galvanometer in millivolts. But in practice, our requirement is to measure the high potential difference. To overcome this problem, we convert a galvanometer into voltmeter by connecting a suitable high resistance R_x in series with it as shown in Fig.13.26.

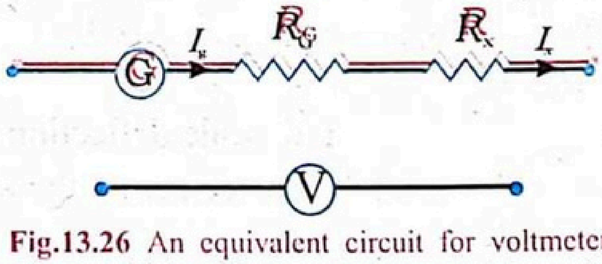


Fig.13.26 An equivalent circuit for voltmeter, where a high resistance is connected in series with a galvanometer

Now when a potential difference 'V' is applied across the voltmeter, then only a fraction of volts V_g drops across the galvanometer and the remaining high voltage $(V - V_g)$ drops across the high resistance R_x. Since the deflection of galvanometer is proportional to the current I_g flowing through it and I_g is proportional to the potential difference. Therefore, the scale is calibrated to indicate the voltage across the voltmeter.

Suppose we want to measure the applied potential difference in volts by using a galvanometer of resistance R_g having full scale deflection current I_g, we connect a high resistance R_x in series with the galvanometer. It may be noted that the same amount of current is passed through both high resistance and galvanometer but the value of the potential difference across each is different. Thus, their resultant potential difference 'V' is given as;

$$V = V_g + V_x$$
$$V = I_gR_g + I_gR_x$$
$$V = I_g(R_g + R_x)$$
$$\frac{V}{I_g} = R_g + R_x$$
$$R_x = \frac{V}{I_g} - R_g \quad ......(13.23)$$

The high resistance R_x obtained by Eq. 13.23 has to be connected in series with galvanometer to provide the potential difference of desired range. Since voltmeter is being used for measurement of potential difference between two points of the given circuit, it should always be connected in parallel.

Example 13.7

A galvanometer gives full-scale reading of 25mA when potential difference across its terminals is 75mV. How it can be used (i) as an ammeter of range 100A and (ii) as a voltmeter of range 750V?

Solution:

Full scale deflection current = $I_g = 25\text{mA} = 25 \times 10^{-3}\text{A}$

Potential difference across the terminal = $V_g = 75\text{mV} = 75 \times 10^{-3}\text{V}$

Shunt resistance = R_s = ?

(i)

$I = 100\text{A}$

If

High resistance = R_x = ?

(ii)

$V = 750\text{V}$

If

$$\text{Resistance of galvanometer} = R_g = \frac{V_g}{I_g} = \frac{75 \times 10^{-3}}{25 \times 10^{-3}} = 3\Omega$$

(i)

$$\text{Shunt resistance} = R_s = \frac{I_gR_g}{I - I_g} = \frac{25 \times 10^{-3} \times 3}{100 - 0.025}$$

$$R_s = \frac{75 \times 10^{-3}}{99.975}$$

$$R_s = 0.00075\,\Omega$$

(ii) High resistance $= R_h = \frac{V}{I_g} - R_g$

$$R_x = \frac{750}{25 \times 10^{-3}} - 3$$

$$R_x = 30000 - 3$$

$$R_x = 29997\,\Omega$$

13.9 AVOMETER (MULTIMETER)

An Avometer is a multipurpose electrical device for measuring alternating/direct current, voltages and resistance. The name Avometer comes from AVO and meter which means ampere meter, voltmeter and ohmmeter.

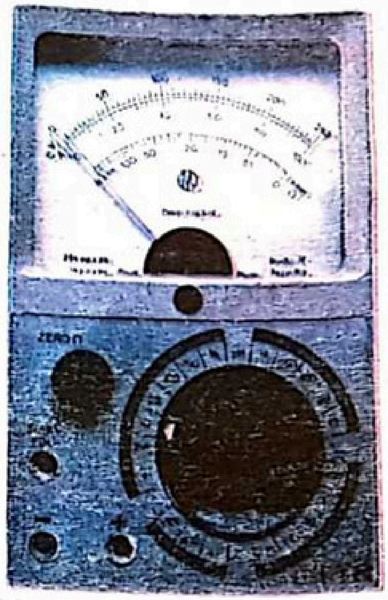


Fig.13.27 An Analogue Avometer

An Avometer may be of analogue or digital type. The analog type has the pointer and scale system as shown in Fig.13.27. However, digital multimeter has a numerical display screen as shown in Fig.13.28, where the digital values in terms of amperes, volts and ohms are displayed automatically with decimal point on it. Such meter also eliminates the human error.

An Avometer is basically a sensitive moving coil galvanometer which is arranged with a necessary network of resistances, a battery and switching system as shown in Fig.13.29. It has four terminals. When one terminal of X and the other of terminal of Y is selected, then the required quantity can be measured. Now all the three parts of Avometer circuit are explained as;

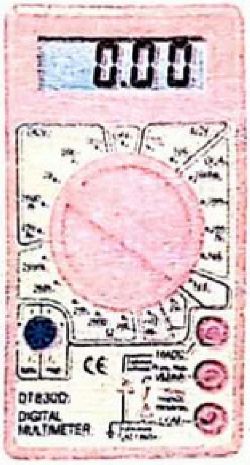


Fig.13.28 A digital Avometer

I The current measurement part

As we know, when a low shunt resistance is connected in parallel to a galvanometer then such arrangement converts a galvanometer into ammeter. The range of such meter can be extended when series combination of low resistance R_1, R_2 and R_3 are connected in parallel with a galvanometer as shown in Fig.13.30. Such arrangement provides the measurement of current in the range from milli amperes to amperes. Alternating current (A.C.) can also be measured by Avometer when a diode is connected with it. Here the diode is used as a rectifier, i.e. a diode converts A.C. into D.C.

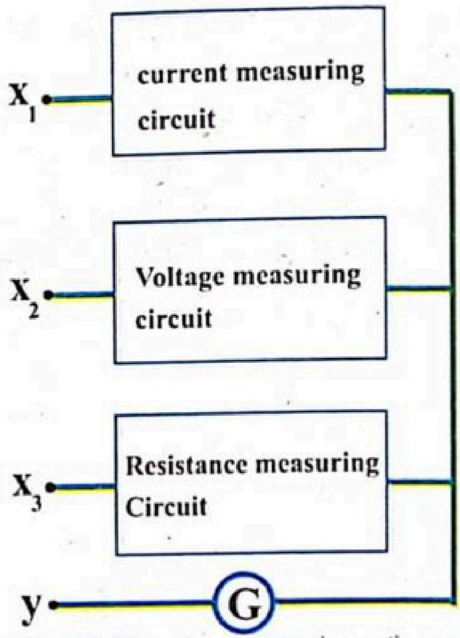


Fig.13.29 A network of an avometer.

II The voltage measurement part

We have already explained that when a high resistance is connected in series with a galvanometer, then such arrangement converts a galvanometer into voltmeter. The range of this instrument can further be increased, when a number of high resistances R_1, R_2, and R_3, are connected in series with a galvanometer as shown in Fig.13.31. This network gives the measurement of potential difference in different range such as 10V, 50V and 250V etc.

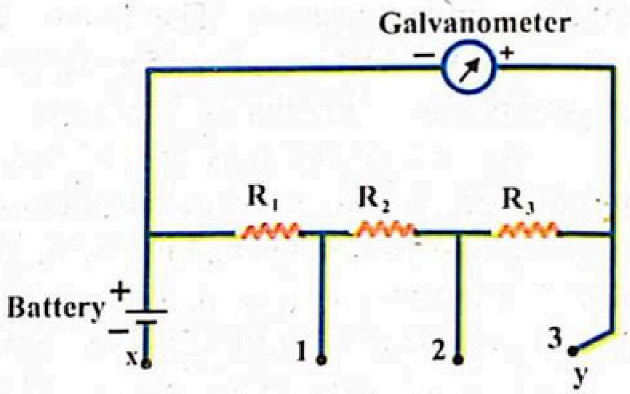


Fig.13.30 A circuit diagram for current measuring of an Avometer.

Avometer can also be used to measure the A.C. voltage when a diode is connected with it. Where A.C. voltage is first converted into DC voltage by the diode then the measurement of voltage is taken place.

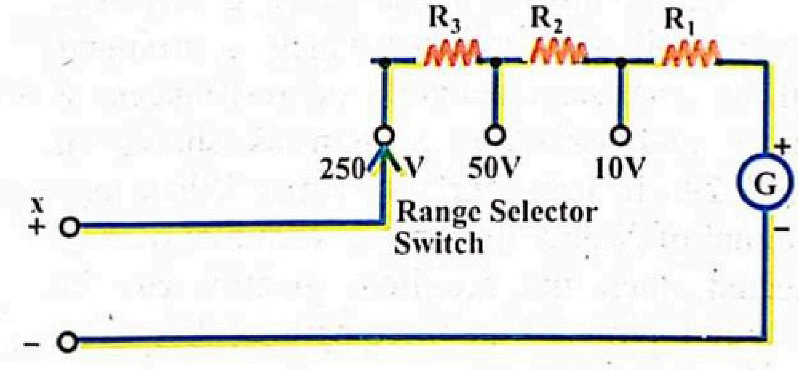


Fig.13.31 A circuit diagram for voltage measuring of an avometer.

III The resistance measurement part

A circuit for an ohmmeter in a Avometer consists of a galvanometer, a variable resistance R_v and a source of e.m.f. E connected in series as shown in Fig.13.32. The resistance 'R' to be measured is connected between terminals x and y.

First, the variable resistance R_v is adjusted so that when the terminals x and y are short circuited, that is, when R = 0, the galvanometer deflects full scale. Then the circuit is opened, i.e., nothing is connected between the terminals x and y, so resistance is infinity and current is zero. Thus, the deflection of the meter is also zero. Finally, when a resistance 'R_n' (n = 1, 2, 3, …) is connected between the terminals x and y, the galvanometer deflects to some intermediate point. This point is calibrated as a resistance. The range of ohmmeter can further be extended by introducing different resistances of different values such R_1, R_2, R_3 and so on.

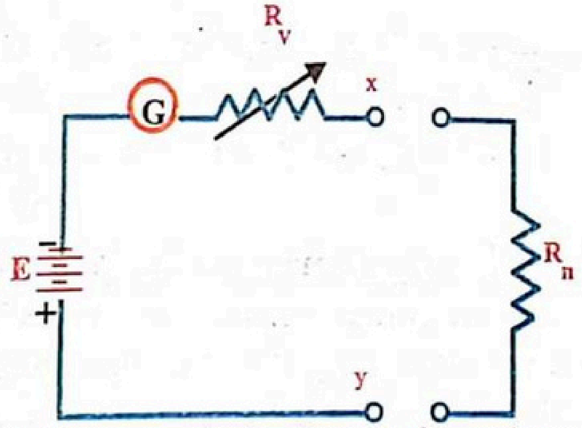


Fig.13.32 A circuit diagram for resistance measuring of an avometer.

SUMMARY

- **Magnetic Field:** The region around the magnetic or the current carrying conductor in which a magnetic effect or force can be experienced is called magnetic field.
- **Magnetic Force on Current Carrying Conductor:** When a current carrying conductor of length 'ℓ' is placed perpendicularly in uniform magnetic field B, it is acted upon by a magnetic force given as;

$$\vec{F} = I(\vec{\ell} \times \vec{B})$$

- **Magnetic Flux:** The number of magnetic lines of force passing through certain element of an area is called magnetic flux. It is equal to the dot product of field strength 'B' and vector area A.

$$\phi_m = \vec{B} \cdot \vec{A}$$

- **Magnetic Flux Density:** The magnetic flux per unit area held perpendicular to field lines is called magnetic flux density.
- **Tesla:** Tesla is the unit of magnetic field strength or magnetic flux density. The strength of the magnetic field is said to be 1T, if it exerts a force of 1N on a conductor when flow of current through it is 1A, also

$$1T = 10^4 G$$

- **Ampere's Law:** The sum of the dot product of B and $\Delta\ell$, i.e., $(\vec{B} \cdot \Delta\vec{\ell})$ over the closed loop around the current-carrying conductor is equal to μ_0 times of the total current surrounded by the closed loop. i.e.,

$$\sum \vec{B} \cdot \Delta\vec{\ell} = \mu_0 I$$

- **Solenoid** A solenoid is a long coil of conducting wire wounded in many turns which produces a uniform magnetic field inside it when current is passed through it. The magnetic field due to current-carrying solenoid is given by

$$\vec{B} = \mu_0 n I$$

- **Force on a charge particle moving through magnetic field:** When a charged particle is moving with velocity 'v' in a magnetic field experiences a force. The force on a charged particle is perpendicular to both the direction of the field and direction of the motion of charged particle. The magnetic force is given as;

$$F = q(\vec{v} \times \vec{B})$$

- **Torque on a current carrying coil:** When a current carrying rectangular coil is placed in a uniform magnetic field, the coil experiences a torque given by;

$$\tau = INAB \sin\theta$$

- **Galvanometer:** It is an electrical device used to detect a small electric current.
- **Ammeter:** It is a device used to measure the large current passing through a circuit.
- **Voltmeter:** It is an electrical instrument used to measure the potential difference between two point in an electric circuit.
- **Avometer:** It is a multimeter used to measure current, voltage and resistance in an electric circuit.

EXERCISE

Multiple choice questions.

1. A maximum force that acts on a current carrying conductor placed in a magnetic field, when angle between the field and length of the conductor is
   (a) 0^0 (b) 45^0 (c) 90^0 (d) 180^0
2. Tesla in terms of base units is equal to
   (a) kg $m^{-1}A^{-1}$ (b) kg mA (c) kg $s^{-1}A^{-1}$ (d) kg $s^{-2}A^{-1}$
3. One Gauss is equal to
   (a) 1T (b) 10^2T (c) 10^{-4}T (d) 10^4T
4. The unit of magnetic flux is
   (a) Tesla (b) Weber (c) Gauss (d) Henry
5. The magnetic flux is maximum when angle between magnetic field and vector area is
   (a) 0^0 (b) 30^0 (c) 60^0 (d) 90^0
6. Magnetic flux density is defined in terms of
   (a) Tesla (b) wb m^{-2} (c) $NA^{-1}m^{-1}$ (d) All of them
7. A charged particle is moving along X-axis in a magnetic field along the Y-axis. The direction of magnetic force acting on it is

(a) along x-axis (b) along y-axis (c) along z-axis (d) in xy-plane

8. Ampere's Law gives us the relationship between
(a) Force and velocity of charge (b) Force and magnitude field
(c) Current and force (d) Current and magnetic field

9. The value of permeability of free space is
(a) $10^{-7} T.m.A^{-1}$ (b) $2\pi \times 10^{-7} T.m.A^{-1}$
(c) $4\pi \times 10^{-7} T.m.A^{-1}$ (d) $4\pi \times 10^{7} T.m.A^{-1}$

10. The magnetic field due to a current-carrying solenoid which has 'n' number of turns per unit length is
(a) $B = \mu_0 n I$ (b) $B = \mu_0 n^2 I$ (c) $B = \frac{\mu_0 n I}{\ell}$ (d) $B = \frac{\mu_0 n^2 I}{\ell}$

11. The magnetic field inside the solenoid is independent of one of the following quantities
(a) Permeability (b) Position vector
(c) Number of turns (d) Flow of current

12. What is the magnetic force on a stationery charged particle in a uniform magnetic field?
(a) Zero (b) $F = q(v \times B)$ (c) $F = qvB$ (d) $F = ILB \sin\theta$

13. An electron is moving horizontally towards east. If it enters in magnetic field directed upward then the electron will be deflected in the direction of
(a) East (b) West (c) North (d) South

14. When the direction of motion of a charged particle is perpendicular to the direction of magnetic field, then the particle follows the path of a
(a) Straight line (b) helix (c) ellipse (d) circle

15. The torque due to a current carrying rectangular coil placed in a uniform magnetic field is
(a) $\tau = IBA \sin\theta$ (b) $\tau = IAN \sin\theta$ (c) $\tau = IBN \sin\theta$ (d) $\tau = NAIB \sin\theta$

16. The working principle of a galvanometer is based upon
(a) Momentum (b) Torque (c) Force (d) Impulse

17. The current passing through the coil of a galvanometer is directly proportional to the
(a) Resistance (b) Conductance (c) Reactance (d) Angle of deflection

18. A shunted galvanometer is called
(a) Voltmeter (b) Ammeter (c) Ohmmeter (d) Potentiometer

19. A galvanometer can be converted into voltmeter by connecting it with
(a) Low resistance in parallel (b) Low resistance in series
(c) High resistance in parallel (d) High resistance in series

20. Which one of the following quantity is not measured by Avometer
(a) Charge (b) Current (c) Resistance (d) Potential difference

SHORT QUESTIONS

1. How can you determine the direction of the magnetic field due to a current carrying a conductor?
2. What is tesla and what is the relation between Tesla and Gauss?
3. Distinguish between Tesla and Weber.
4. How can you differentiate the flow of current into the page and out of the page?
5. Under what condition the magnetic flux is minimum and maximum?
6. Differentiate between magnetic flux and magnetic flux density.
7. What do you know about the magnetic force on a stationary charged particle in a uniform magnetic field?
8. Why Ampere's law is true only for a steady current?
9. What do you know about the amperean path?
10. What are the values of the magnetic field inside and outside of a current-carrying solenoid?
11. State the Fleming's left-hand rule to determine the direction of force that acts on a charged particle moving perpendicular to the magnetic field.
12. Explain the path of deflection of an electron and a proton when they enters perpendicularly in a uniform magnetic field.
13. How does an electron come under the centripetal force when its motion is perpendicular to a uniform magnetic field?
14. How can you determine $\frac{e}{m}$ by velocity selector method?
15. How can we increase the magnitude of torque due to a current carrying rectangular coil placed in a uniform magnetic field?
16. How does radial magnetic field produce in a moving coil galvanometer?
17. Why low resistance in an ammeter is called shunt resistance? Why it is connected parallel to a galvanometer?
18. How can you convert a moving galvanometer into a voltmeter?
19. Explain the method of measurement of resistance by using ohmmeter.
20. Distinguish between analogue and digital Avometer.

COMPREHENSIVE QUESTIONS

1. What is magnetic field? Explain the magnetic field produced around a current carrying conductor.
2. Define magnetic force and derive a relation for a magnetic force that is exerted on a current-carrying a conductor placed in uniform applied magnetic field.

3. What do you know about Flemming left hand rule? How can you determine the direction of magnetic force by using flaming left-hand rule?
4. Define magnetic flux, magnetic flux density and their SI units.
5. State and explain Ampere's circuital law and calculate magnetic field due to a current carrying solenoid using Ampere's law.
6. How can you determine the force that acts on a moving charged particle (proton and electron) in a uniform magnetic field?
7. Explain the torque on a current carrying rectangular coil placed in a uniform magnetic field.
8. Define and explain galvanometer, its construction and working principle.
9. How can you develop an ammeter and a voltmeter by using a galvanometer?
10. Define and explain an Avometer, its functions and its various parts.

NUMERICAL PROBLEMS

1. A current of 10A carrying conductor of length 20cm is placed in uniform magnetic field 2T. If the length is at 60^0 to the field, then calculate the magnitude of the force acting on the conductor. **(3.5N)**
2. A maximum magnetic force of 0.3N exerts on a 15cm long conductor carrying a current of 10A in a uniform magnetic field. Find the magnitude of the magnetic field. **(0.2T)**
3. Calculate the value of magnetic flux density and magnetic flux within an air core solenoid of radius 2cm and 4000 turns per unit length carrying a current of 5A. **(2.51×10^{-2}T, 3.15×10^{-5}wb)**
4. A solenoid 10cm long has 500 turns. Find the magnetic field inside the solenoid if it carries a current of 10A. **(6.28×10^{-2}T)**
5. What will be the speed of an electron if it moves at right angle to the magnetic field of 0.2T and it experiences a magnetic force of 2×10^{-12}N. **($6.25 \times 10^{17}ms^{-1}$)**
6. A proton enters a magnetic field of flux density $1.5wbm^{-2}$ with a velocity of $2 \times 10^7ms^{-1}$ at an angle of 45^0 with the field. Compute the force on the proton. **(3.4×10^{-12}N)**
7. A velocity selector has a magnetic field of 0.3T. If a perpendicular electric field of 10^4Vm^{-1} is applied, what will be the speed of the particle when it passes through the selector? **($3.3 \times 10^4ms^{-1}$)**
8. A rectangular coil of sides 10cm and 6cm having 2000 turns and carrying a current of 5A is placed in a uniform magnetic field of 0.5T. Calculate the maximum torque that experiences by the coil. **(30Nm)**

9. Find the value of shunt resistance required to convert a galvanometer into ammeter of range 5A. Where the galvanometer has internal resistance 50Ω and it gives full deflection with a current of 10mA. (0.1Ω)

10. A galvanometer has an internal resistance 40Ω and deflects full scale for 4mA current. Calculate the high resistance that should be connected in series with galvanometer, in order to convert the galvanometer into voltmeter of range 100volt. (24960Ω)