UNIT 13

.....Electromagnetism......

After studying this chapter students will be able to:

- explain that magnetic field is an example of a 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) as scalar product of magnetic field (B) and area (A) using the relation $\Phi_B = B.A = B\perp A$.
- 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).

A magnet (from Greek "Magnesian stone") is a material that produces a magnetic field. This magnetic field is invisible but is responsible for the most notable property of a magnet: a force that pulls on other ferromagnetic materials, such as iron, and attracts or repels other magnets. A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. An everyday example is a refrigerator magnet used to hold notes on a refrigerator door.

For your information

Magnetic recording media: VHS (Video Home System) tapes contain a reel of magnetic tape. The information that makes up the video and sound is encoded on the magnetic coating on the tape. Common audio cassettes also rely on magnetic tape. Similarly, in computers, floppy disks and hard disks record data on a thin magnetic coating.

Credit, debit, and ATM cards: All of these cards have a magnetic strip on one side. This strip encodes the information to contact an individual's financial institution and connect with their account(s).

13.1 Magnetic Field

The study of magnetism started with the discovery of the mineral called loadstone, which was found to attract iron and other magnetic materials. Today, much is known of this mineral, also called magnetic iron ore, or iron oxide. From these early discoveries, interest was developed in the study of the properties of magnetism.

By the end of the nineteenth century, scientists had tested all the known elements and compounds for their magnetic properties. As a result, these materials were grouped into categories based on their magnetic behavior. With the discovery of electricity it was soon realized that a steady current through a conducting wire creates a magnetic field around the wire as shown in figure 13.1. The direction of such field is determined by right hand rule.

Curl of the fingers show the direction of magnetic field while thumb indicates the direction of the current *I*. The direction of the magnetic field can be verified by placing compasses on a card near a current carrying wire and observing their direction. The magnetic field is the region around a magnet or a current carrying wire in which it can attract or repel other magnetic materials. Magnetic field is a vector quantity and represented by a vector **B** called magnetic induction.

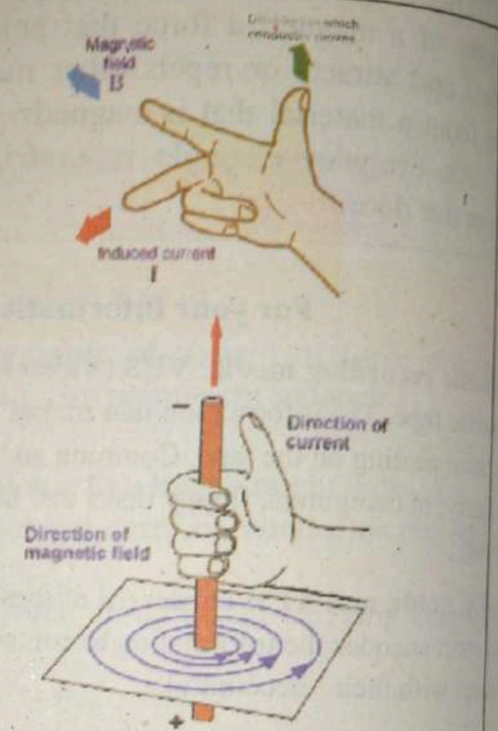


Figure 13.1 : direction of current

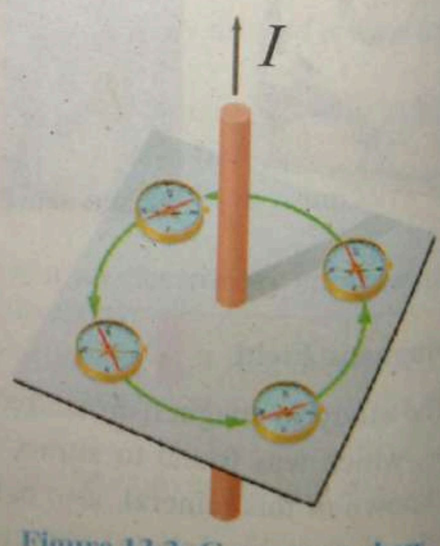


Figure 13.2: Compasses show direction of magnetic field.

13.2 Force on a current carrying conductor

When a current carrying wire is placed at right angles to a uniform magnetic field, the magnetic field of the wire and external uniform field interact, resulting in a force F on the wire. This force depends on the current I in the wire, and the length L of the wire that lies in the field figure 13.3.

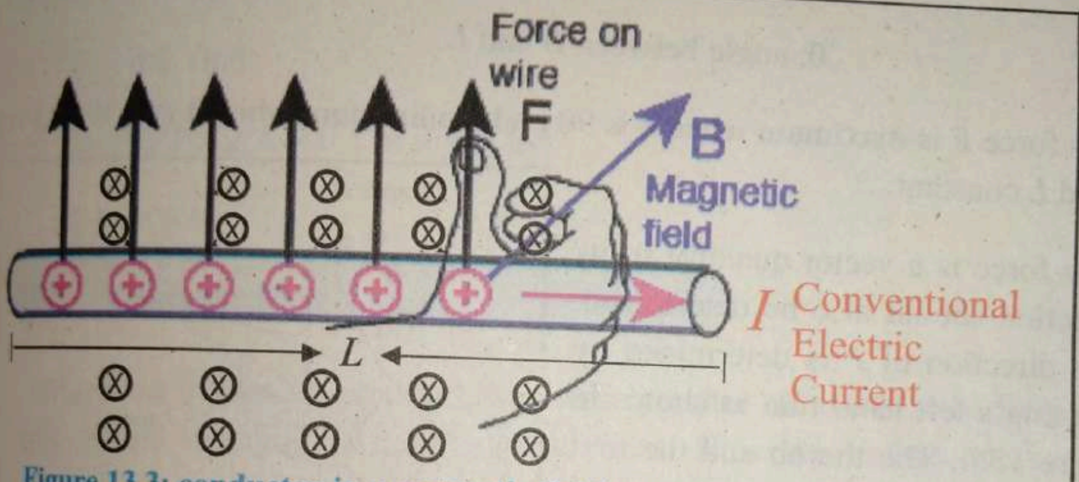


Figure 13.3: conductor in a magnetic field

$$F \propto IL$$

The strength of the uniform field, which is called magnetic induction (or magnetic flux density and will be defined later) B, is the constant of proportionality.

$$F = BIL$$

If the wire is place in the field B at some angle θ with it, then the force is given by the relation

$$F = BIL \sin\theta \qquad (13.1)$$

Or in vector form

$$\mathbf{F} = I\,(\mathbf{L} \times \mathbf{B}) \qquad (13.2)$$

Equation 13.1 shows that the magnitude of the force F on a current carrying wire of length L depends upon the following factors.

B: Magnitude of magnetic induction

I: amount of current flowing in the wire

L: Length of the wire lying in the field

θ: angle between B and L

This force F is maximum when θ is 90 and is minimum when θ is 0, if we keep B, I and L constant.

As force is a vector quantity so its direction should also be determined. The direction of F is determined by Fleming's left hand rule as shown in figure 13.4. The thumb and the first two fingers of the left hand are set at right angles to each other.

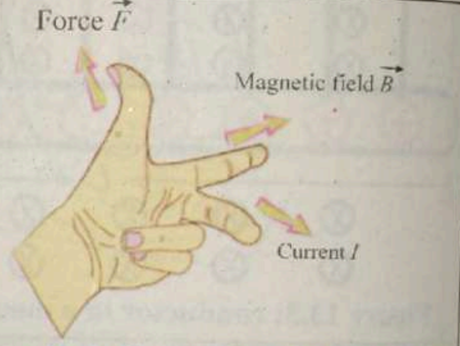


Figure 13.4: Fleming's left hand rule

With the first finger pointing in the direction of the field and second finger pointing in the direction of current, the thumb gives the direction of the force. The S.I. unit for magnetic induction B is tesla (T) and it can be defined as

$$B = \frac{F}{IL}$$

$$1\text{ T} = 1\text{ N A}^{-1}\text{m}^{-1}$$

If the force experienced by 1 m of a wire carrying 1 A current placed perpendicularly in magnetic field is one newton, then the magnetic induction is one tesla.

Another unit used for B is Gauss, which is given by

$$1\text{ G} = 10^{-4}\text{ T}$$

Or $$1\text{ T} = 10^{4}\text{ G}$$

Example 13.1:

A wire carrying 2 A current and has length of 10 cm between the poles of a magnet is kept at an angle of 30^0 to the uniform field of 0.6 T. Find the force acting on the wire?

Solution:

Using equation 13.1

$$F = BIL \sin\theta$$

$$F = 0.6\ \text{T} \times 2\ \text{A} \times 0.1\ \text{m} \times \sin 30^0$$

$$F = 0.06\ \text{N}$$

13.3 Magnetic Flux

Magnetic induction tells us how close together magnetic field lines are, as it tells us the strength of the magnetic field. Now we define another quantity magnetic flux which is the dot product of magnetic induction B and vector area element ΔA.

Magnetic flux denoted by symbol Φ, is given by

$$\Delta\Phi = B \cdot \Delta A \qquad (13.3)$$

$$= B\,\Delta A \cos\theta$$

Where $\Delta\Phi$ represents the magnetic field lines passing through the vector area element ΔA placed perpendicular to the field. Direction of the vector area element ΔA is normal to the surface area.

The total flux through surface area A is given by

$$\Phi = \sum B \cdot \Delta A$$

$$= B \cdot A$$

$$= B\,A \cos\theta$$

The flux Φ through the area A will be maximum if the surface is perpendicular to the field, because in this case normal to the surface will be parallel to B as shown in Fig 13.5 (b). Similarly the flux will be zero when normal to the surface become perpendicular to B Fig 13.5 (c).

The unit of magnetic flux is weber. One weber is given by

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

Magnetic Flux Density

Using equation 13.3 we can see that

$$B = \frac{\Phi}{A}$$

So magnetic induction B can also be defined as *magnetic flux per unit area, and it is called magnetic flux density.* So

$$1\,T = 1\,Wb\,m^{-2}$$

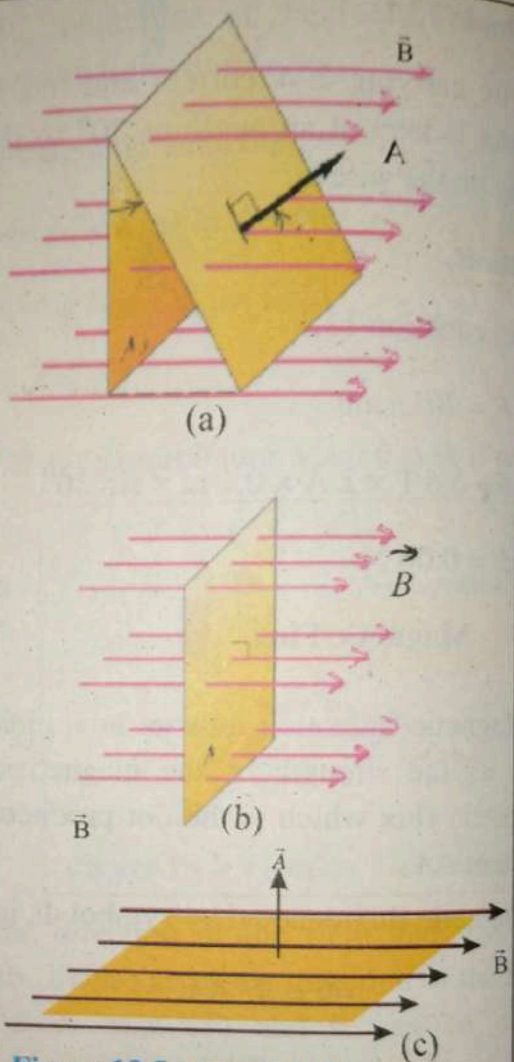


Figure 13.5: magnetic flux

Quiz?

Can you explain how bullet train and a circuit breaker work on the magnetic effect of a current?

13.4 Ampere's Law

Ampere's circuital law, discovered by Andre Marie Ampere in 1826, relates the integrated magnetic field in a loop around a current carrying wire to the current passing through the wire. We know that there is a magnetic field around a current carrying wire. If we consider a closed path around the wire in the form of a circle having the wire at the center, then the magnitude of magnetic flux density B changes with the current I in the wire and the distance r from the wire figure 13.6.

So

$$B \propto I$$

$$\& \; B \propto \frac{1}{r}$$

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

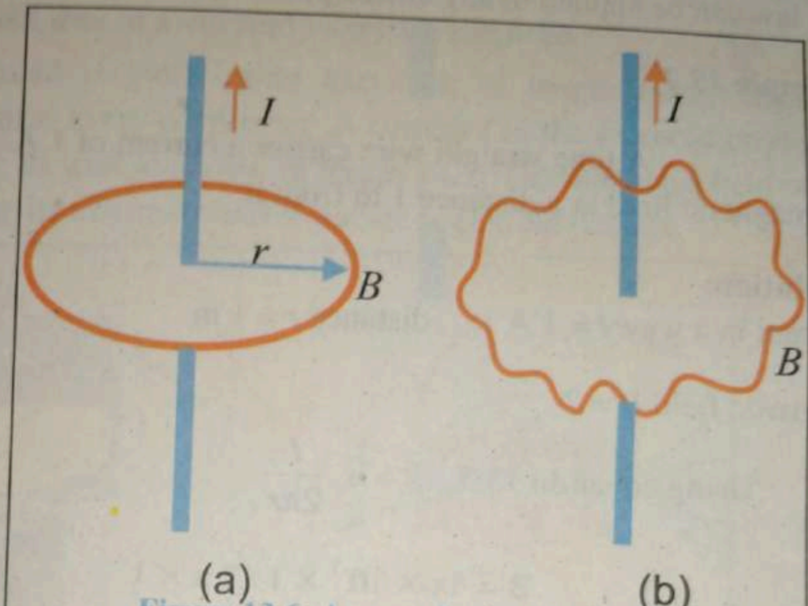


Figure 13.6: Ampere's circuital law

Summing up all around the circular path

$$B = \mu_o \frac{I}{2\pi r}$$

μ_o = Permeability of free space ($4\pi \times 10^{-7}$ Wb A^{-1} m^{-1})

$$B\, 2\pi r = \mu_o I \qquad (13.4)$$

Now consider a closed path around the wire figure 13.8. For any path element ΔL we can write

$$B \cdot \Delta L = \mu_o I$$

As B and ΔL are parallel, so $B \cdot \Delta L = B\Delta L = \mu_o I$

Now summing over the entire closed path,

$$\sum B \cdot \Delta L = \mu_o I, \qquad (13.5)$$

which is Ampere's Law. The closed path is called the amperian path. In general this law can be applied to any closed path around a uniform magnetic field.

Example *13.2*

A long straight wire carries a current of 1 A. Find the magnitude of the magnetic field at a distance 1 m from it.

Solution:

Current in a wire $I = 1$ A distance $r = 1$ m

Magnetic field $B = ?$

Using equation 13.5, $B = \mu_o \dfrac{I}{2\pi r}$

$$B = 4\pi \times 10^{-7} \times 1 / 2\pi \times 1$$

$$B = 2 \times 10^{-7}\ T$$

Example 13.3

Two long parallel wires 6cm apart carry current of 8 A and 2 A. What is magnitude of magnetic field midway between them?

Solution:

current due to 1st wire $= I_1 = 8$ A

current due to 2nd wire $= I_2 = 2$ A

The midway between wires is $= r_1 = r_2 = 3\text{cm} = 3 \times 10^{-2}\text{m}$

$$B_{net} = B_1 + B_2$$

$$= \mu_o \frac{I_1}{2\pi r_1} - \mu_o \frac{I_2}{2\pi r_2}$$

negative sign is there as fields are opposite in the middle,

$$B = 4\pi \times 10^{-7}\left(\frac{8-2}{2\pi \times 3 \times 10^{-2}}\right) = 4 \times 10^{-5}\,T$$

$$B = 4 \times 10^{-5}\,T$$

13.5 Magnetic Field due to a current carrying solenoid

A solenoid is long spring like coil, of length many times its diameter, with many turns every centimeter. A current I in the solenoid produce a magnetic field B along its axis as shown in figure 13.7. The magnetic field of the solenoid is strong along its axis and weaker, rather negligible outside.

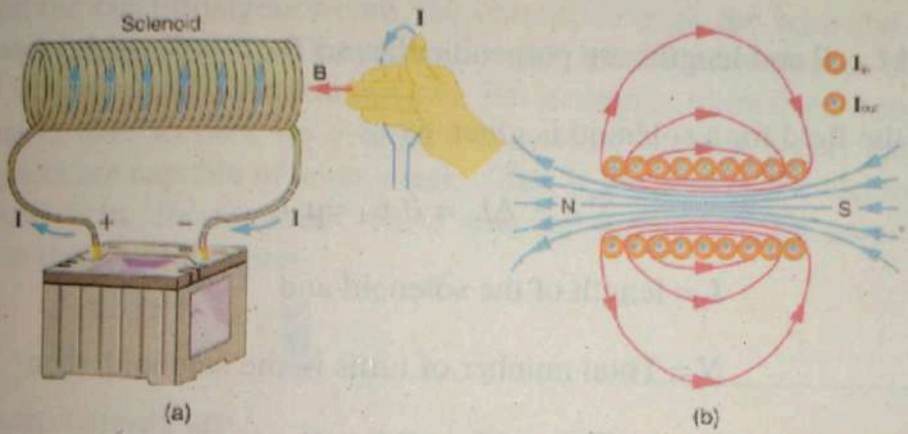


Figure 13.7 : Magnetic Field due to a current carrying solenoid

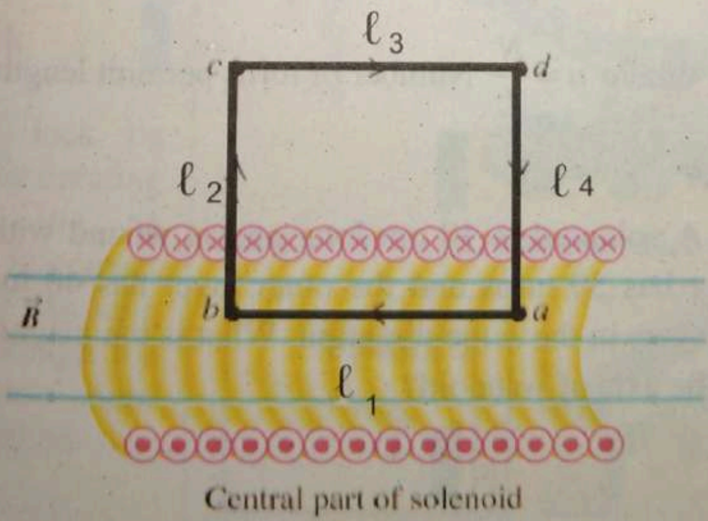


Figure 13.7(c): amperian loop in a solenoid

To determine the value of B of a solenoid let us consider an amperian path abcd with lengths ℓ_1 and ℓ_3 much longer as compare to other two lengths. Now applying Ampere's law

$$\sum B \cdot \Delta L = \mu_o I,$$

$$B \cdot \ell_1 + B \cdot \ell_2 + B \cdot \ell_3 + B \cdot \ell_4 = \mu_o I$$

Now inside the solenoid, B and l_1 are parallel, so $B \cdot \ell_1 = B\,\ell_1$

Outside $B = 0$, so $B \cdot \ell_3 = 0$

For ℓ_2 and ℓ_4, B and lengths are perpendicular, so $B \cdot \ell_2 = 0$ and $B \cdot \ell_4 = 0$

Therefore the field for a solenoid is given by

$$\sum B \cdot \Delta L = B\,\ell_1 = \mu_o I,$$

Now if L = length of the solenoid and

N = Total number of turns in the solenoid, then

$$\sum B \cdot \Delta L = B\,L = N\mu_o I,$$

So

$$B = n\,\mu_o I, \qquad (13.6)$$

Where $n = \frac{N}{L}$ Number of turns per unit length.

Example 13.4

A solenoid is 10 cm long and is wound with two layers of wire. The inner layer has 50 turns and the outer layer has 40 turns. A current of 3A flows in both layers in the same direction. What is the magnitude of magnetic flux density along the axis of solenoid?

Solution:

Length of a solenoid is = L= 10 cm

Inner layer = n_1 = 50 turns
Outer layer = n_2 = 40 turns
Flow of current = I = 3A
magnetic flux density = B = ?

$$B = n_1 \mu_o I_1 + n_2 \mu_o I_2$$
$$= 3.4 \times 10^{-3}\ T$$

13.5.1 Applications of magnetic field

The magnetic strength of an electromagnet depends on the number of turns of wire around the electromagnet's core, the current through the wire and the size of the iron core. Increasing these factors can result in an electromagnet that is much larger and stronger than a natural magnet. For example, there is no known natural magnet that is able to pick up a large steel object such as a car, but industrial electromagnets are capable of such a task. Also, if the core of the electromagnet is made of soft iron, its magnetic force can be turned off by turning off the electricity to the electromagnet.

Cranes

Strong electromagnets are often used in cranes to move large pieces of iron or steel.

Figure 13.8(a) : Crane uses electromagnet

Electromagnetic lock

An electromagnetic lock be used to lock a door by creating a strong field in an electromagnet that is in contact with a magnetic plate. As long as there is current through the electromagnet, the door remains closed and locked.

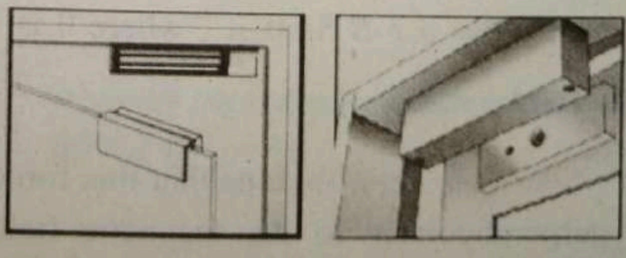


Figure 13.8(b) : electromagnetic door lock

Another type of electromagnetic lock uses an electromagnet to extend a plunger between the doors, making it nearly impossible to open the door until the electromagnet releases the plunger.

Doorbell ringer:

An old-fashioned doorbell used an electromagnet that was rapidly turned on and off to pull a clangor against a bell.

Quiz?

1. Why wheat flour is usually passed near a magnet before being packed?
2. Why a steel ship becomes magnetized as it is constructed?

13.6 Motion of a charged particle in uniform magnetic field

In our study of electrostatics, we saw that a charged particle in an electric field experiences a force in the direction of the field, or against the field, depending on the sign of the charge. Similarly, a charged particle in a magnetic field would experience a force. In case of the magnetic field, however the charge must be moving. The force acting on the charged particle results from the interaction of the external magnetic field and the magnetic field created by the moving charge.

For a positive charge q moving with velocity v in a magnetic field of flux density B, the force acting on the charge is given by the expression

$$\vec{F} = q(\vec{v}\times\vec{B}) \qquad (13.7)$$

$= q\,v\,B\,\text{Sin}\theta\,\hat{n}$ where θ is the angle between the velocity and magnetic field.

It is very obvious that this force is maximum when charge particle moves perpendicularly to the magnetic field and minimum when the charge moves parallel to the field.

$F_{max} = qvB$ $\qquad \theta = 90^0$

$F_{min} = 0$ $\qquad \theta = 0^0$

The direction of this force is determined by Fleming's left hand rule as shown in figure 13.9. The thumb and the first two fingers of the left hand are set at right angles to each other. With the first finger pointing in the direction of the field and second finger pointing in the direction of velocity of the charged particle, the thumb gives the direction of the force.

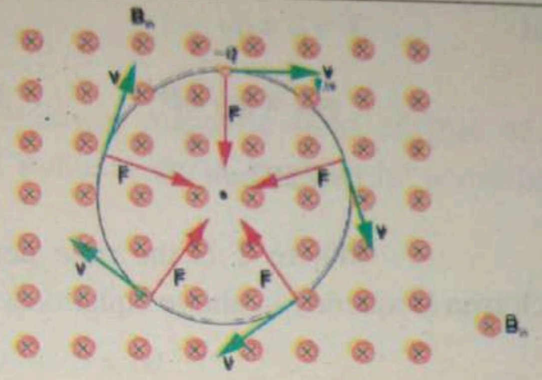


Figure 13.9: a charged particle in uniform magnetic field

Now as the force is always perpendicular to the direction of velocity, so the charged particle follows a circular path as shown in figure 13.10. The symbol ⊗ shows that the magnetic field is acting into the plane of the paper.
Fig 13.10 shows that charge particle move on spiral path when angle θ is between 0 & 90°.
So the centripetal force provided for this motion of a charged particle entering perpendicularly to the magnetic field is given by

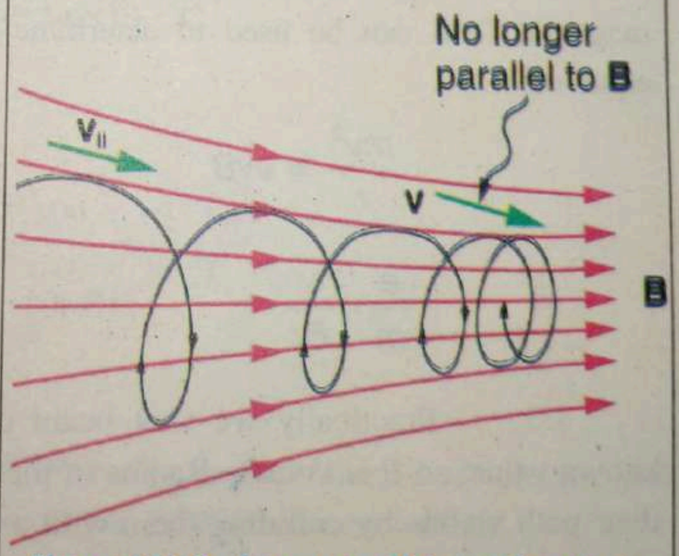


Figure 13.10: charges particle motion on a spiral path

$$\frac{mv^2}{r} = mr\omega^2 = qvB \qquad \therefore\ F_c = qvB$$

As $v = r\omega$ so,

$$\omega = qB/m \qquad (13.8)$$

and $$T = 2\pi/\omega$$

$$= 2\pi m/qB \qquad (13.9)$$

And $$f = qB/2\pi m$$

Where T is the time period of the charged particle and f is the cyclotron frequency in above equations.

Determination of e/m for an electron

The circular motion of an electron shot perpendicularly into a magnetic field can be used to determine its charge to mass ratio. Using the equation

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

$$\frac{e}{m} = \frac{v}{Br} \qquad (13.10)$$

Practically we shot beam of electrons into a magnetic field of known value, so B is known. Radius of the electrons can be measured by making their path visible by colliding them with a gas like hydrogen or helium in a tube place in uniform magnetic field. Electrons excite the atoms of the gas and their de-excitation causes emission of visible blue light. So the path is visible. For the velocity of the electrons their kinetic energy is measured by passing them through a potential difference of known value.

So $\frac{1}{2}mv^2 = eV$, (13.11)

Using equations 13.10 and 13.11

$$\frac{e}{m} = \frac{2V}{B^2 r^2} \quad (13.12)$$

Example 13.5

The path of an electron in a uniform magnetic field of flux density 1.0×10^{-2} T in a vacuum is a circle of radius 1 cm. Calculate the period of its orbit?

Solution:

Magnetic field density= $B = 1.0 \times 10^{-2}$ T
Radius of circle = r = 1 cm
Period of circular orbit = T= ?
Mass of electron= m_e=9.109×10^{-31} kg
Charge on electron = e=1.6×10^{-19}C

Using equation $T = \frac{2\pi m}{qB}$

Putting values

$$= \frac{2\times3.14\times9.109 \times 10^{-31}\text{kg}}{1.6\times10^{-19}\times1.0 \times 10^{-2}\text{T}}$$

$$T = 3.57 \times 10^{-9} \text{ s}$$

Velocity Selector:

If a charged particle is passed through a region where both electric and magnetic fields are acting such that two forces may balance each other,

$$F_E = F_M$$

$$qE = qvB$$

$$v = \frac{E}{B}$$

Such arrangement is called velocity selector because charges with velocity in the ratio of E to B will come out un-deflected as shown in figure 13.11.

In a beam all charged particles do not move with same velocity so we can separate charges with desired velocity.

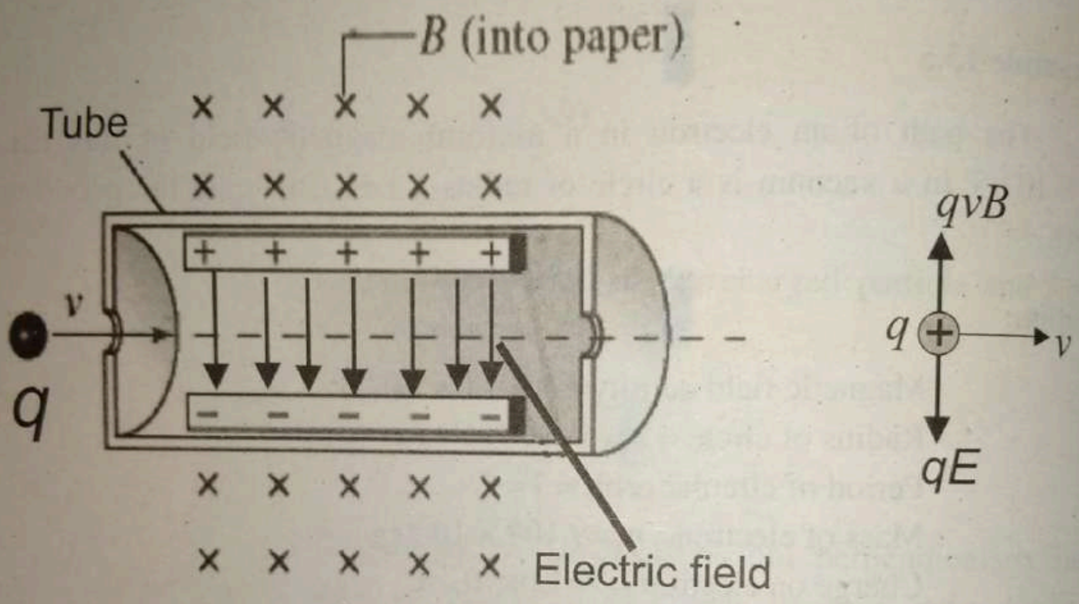


Figure 13.11: charge particle motion in both electric and magnetic fields

13.7 Torque on a current carrying loop / coil

If a current carrying rectangular coil is placed in a uniform magnetic field, it experience force and torque. Let us consider a rectangular coil having N turns carrying current I in a uniform magnetic field of flux density B. Each side PS and QR of the coil experiences a force $\vec{F}$ as shown in figure 13.12. The effect of these forces is to try to compress the coil. Since the coil is rigid, no distortion of the coil occurs. The force F acting on the sides PQ and RS due to the magnetic field are in opposite directions and normal to the magnetic field and the sides PQ and RS.

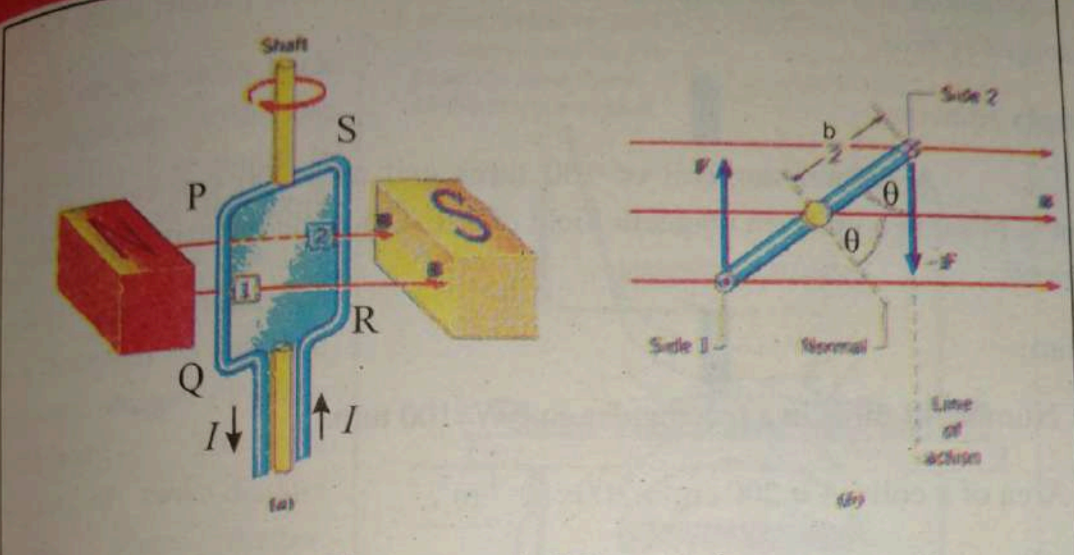


Figure 13.12(a) : a coil in a magnetic field (b): torque on a coil

The magnitude of this force on sides PQ and RS is

$$F_1 = F_2 = F = N\,B\,I\,a \qquad ...(13.13)a$$

Where, 'a' is the length of sides PQ and RS. Fig:13.12(b) shows the directions of the two forces as seen from the top. The effect of this pair of forces is a couple which has a torque, given by

$$\tau = F\,(\,b\cos\theta) \qquad ...(13.13)b$$

where θ = angle between the plane of the coil and the magnetic field, and 'b' is the moment arm of the couple. From equation 13.13, we have

$$\tau = N\,B\,I\,a\,(\,b\cos\theta)$$

$$= NBI(ab)\cos\theta$$

$$= NBIA\cos\theta, \qquad ...(13.14)$$

where A= area of the coil. The maximum torque is $BINA$ it occurs when the angle θ = 0, that is when the plane of the coil is parallel to the magnetic field or normal to the plane is perpendicular to the field as shown in Fig:13.12. When the plane of the coil is perpendicular to the magnetic field, or normal to it is parallel to the field then torque is zero.

coil is perpendicular to the magnetic field, or normal to it is parallel to the field then torque is zero.

Example 13.6

A rectangular coil of 100 turns and area 200 cm^2 carrying 2A current is place in a uniform magnetic field of 2 T. Calculate the maximum torque on the coil.

Solution:

Number of turns in a rectangular coil=N=100 turns

Area of a coil= $A = 200\ cm^2 = 200\times10^{-4}\ m^2$,

Current = I = 2A

Torque on the coil= τ =?

For maximum torque, $\theta = 0$

Using equation, $\tau = NBIA\cos\theta$,

$$\tau = 100\times2\times2\times200\times10^{-4} = 8\ Nm$$

MRI

Magnetic Resonance Imaging (MRI) is one of the most advanced diagnostic tools available. MRI uses a combination of a strong magnetic field and radio waves to produce detailed high resolution images of the inside of the body.

Principle:

Magnetic Resonance Imaging (MRI) systems are able to generate high-quality diagnostic images through the use of magnetic field. The human body is composed primarily of fat and water, it is made up mostly of hydrogen atoms. By applying short radio frequency (RF) pulses to a specific anatomical slice, the protons in the slice absorb energy at this resonant frequency, causing them to spin perpendicular to the magnetic field.

As the protons relax back into alignment with the magnetic field, a signal is received by an RF coil. This signal acts as an antenna, and is processed by a computer to produce diagnostic images of areas of the body. The brain consists of two distinct regions: white matter, which is composed of myelinated nerve fibres, and grey matter, which consists of nerve cell bodies.

These two regions interact to perform critical information processing and damage to either region causes brain dysfunction. Notably, the white matter is referred to as being 'white' due to the light colour of the myelin insulation covering the nerve fibres. Now, magnetic resonance imaging (MRI) is used widely to study brain function, where damage to the white matter is seen as bright areas.

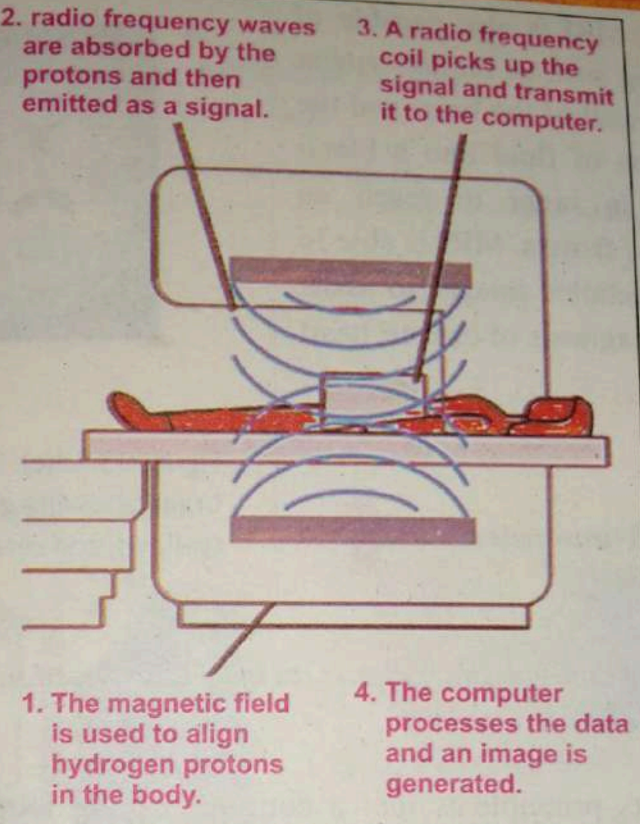


Figure 13.13(a).MRI Scanning process

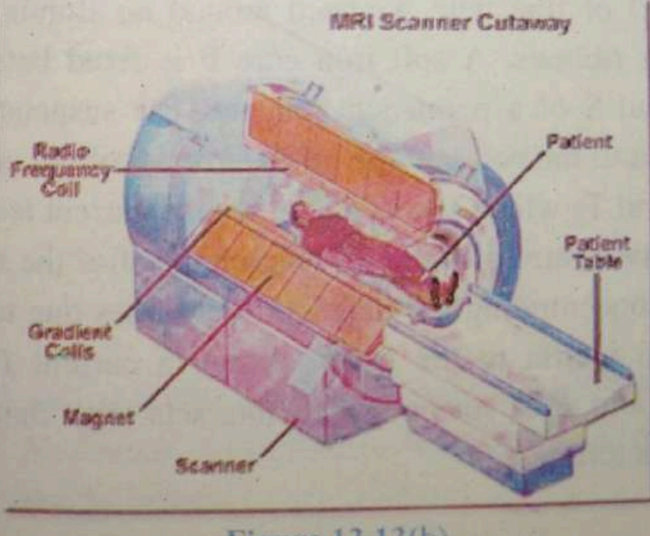


Figure 13.13(b).

MRI is also capable of imaging such as the movement of the wall of the heart and the injection of fluid into a blood vessel in order to reach an organ or tissues. MRI is able to create detailed images to assist in the diagnosis of cancer, heart disease.

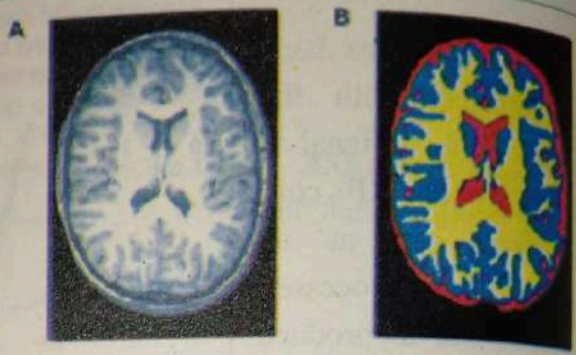


Figure 13.13(c). Example of an MRI image of the brain, showing gray matter (blue), white matter (yellow), and cerebral spinal fluid (red).

13.8 Galvanometer

A moving coil galvanometer is an instrument used for detection and measurement of small electric currents.

Its principle is that a current carrying loop placed in a magnetic field experiences a torque. A simplified version of a galvanometer is shown schematically in figure 13.14. Most modern galvanometers are of the moving-coil type and are called d'Arsonval galvanometers. It mainly consists of a rectangular coil ABCD of fine wire wrapped around an aluminum frame is suspended by conducting ribbons. A soft iron core F is fixed between cylindrically concave poles N and S of a permanent magnet. The suspension wire T_1 is used as one current lead to the coil and the other terminal of the coil is connected to a loosely wound spiral T_2 which serves as the second current lead. A cylinder of soft iron is placed at the centre of the coil which intensifies the magnetic field and makes it radial by concentrating the magnetic field lines due to its high permeability (and gives more inertia to the coil). When a current I flows through the coil, a magnetic field B is set up which interacts with that of the permanent magnet producing a torque τ.

$$=NIAB\cos\alpha$$

In this expression,

N = number of turns in the coil, A = area per turn of the coil,

B = magnetic induction of the radial magnetic field,

α= angle between the plane of coil and the direction of $\vec{B}$.

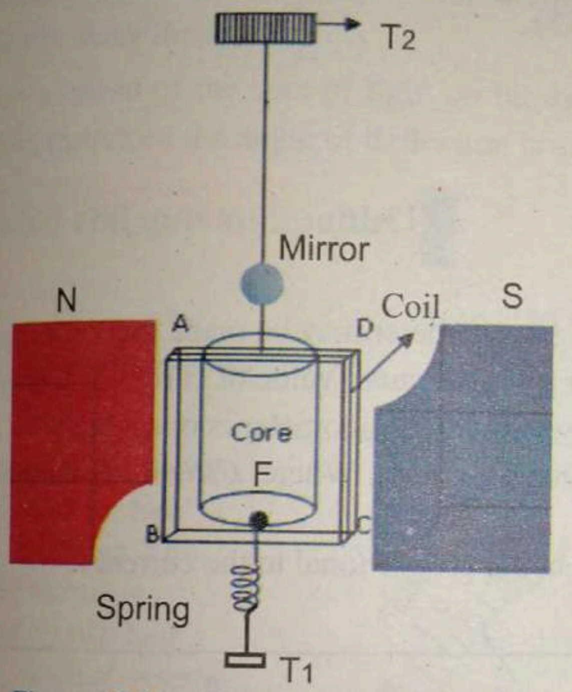
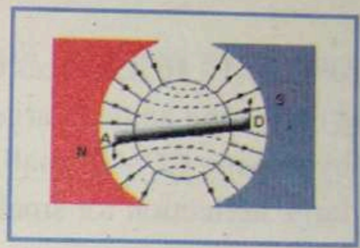


Figure 13.14 : (a) galvanometer-



13.14 (b) radial field

Since the magnetic field is radial the plane of the coil is parallel to the magnetic field B, so

$$\tau = NBIA \qquad \text{...(13.14)}$$

The torque rotates the coil and twists the suspension ribbon, until it is fully resisted by the suspension. As a result a restoring torque comes into play trying to restore the coil back to original position.

If θ be the twist produced in the strip and C be the restoring torque per unit twist then:

$$\text{Restoring torque} = \tau = C\,\theta. \qquad \ldots(13.15)$$

When the coil is in equilibrium then the deflecting torque is equal to the restoring torque. Then from Eq: (13.14) & (13.15)

$$NBIA = C\,\theta$$

$$\text{Or } I = \frac{C\theta}{NAB} \qquad \ldots(13.16)$$

From Eq: 13.16 it is clear that galvanometer may be made more sensitive by making deflecting angle θ large for a certain small value of current I. It may be achieved by making C/NAB small. A sensitive galvanometer is one which produces large deflection for small value of current. Where, C/NAB is a constant.

The angular displacement θ produced being proportional to the current I.

$$I \propto \theta$$

The result is read from a scale onto which a light beam is reflected from a mirror M carried on the suspension ribbons. There are two methods of observing the angle of deflection of the coil.

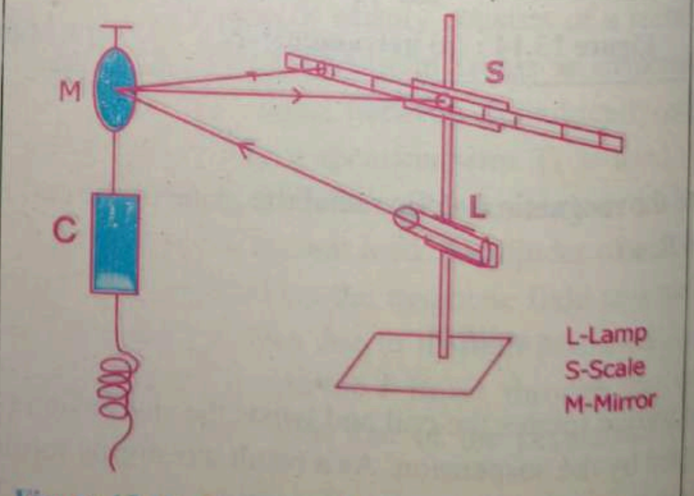


Figure 13.15 : Lamp and scale arrangement for measuring the angle of deflection.

1) Lamp Scale method:

In sensitive galvanometer the large angle is observed by means of small mirror attached with coil along with lamp and scale arrangement. A beam of light from the lamp is directed towards the mirror of the galvanometer. After reflection from the mirror it produces a spot on a translucent scale placed at a distance of one meter from the galvanometer. As the coil along with the mirror rotates 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 (provided the angle of deflection is small).

2) Pivoted coil galvanometer:

In second type of observing angle θ is used in the pivoted coil galvanometer.

In less sensitive galvanometer the coil is pivoted between two jeweled bearings. The restoring torque is provided by two hair springs which also serves as current lead.

A light aluminum pointer is attached to the coil which moves over the scale thus giving the angle of deflection of the coil.

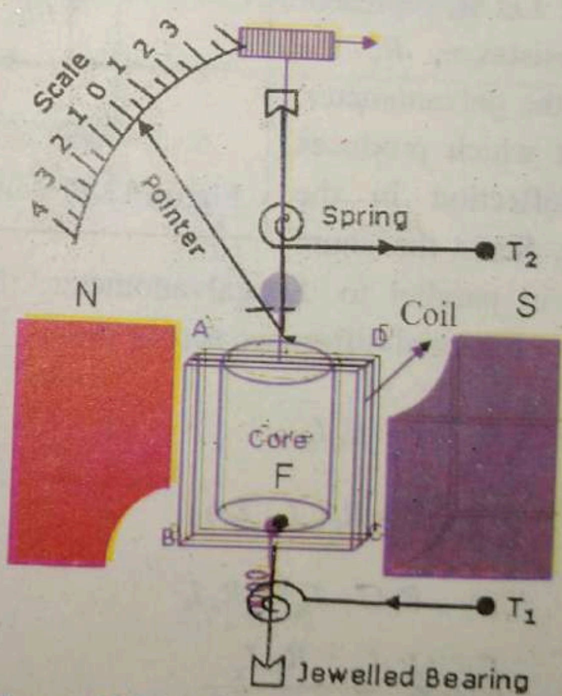


Figure 13.16 : pivoted type moving coil galvanometer.

13.9 Conversion of Galvanometer into Ammeter

Galvanometer very sensitive instrument, a large current cannot be passed through it, as it may damage the coil. The conversion of a galvanometer into an ammeter is done by connecting a low resistance in parallel with it. As a result, when large current flows in a circuit, only a small fraction of the current passes through the galvanometer and the remaining larger portion of the current passes through the low resistance. The low resistance connected in parallel with the galvanometer is called shunt resistance. The scale is marked in ampere.

An ammeter is a measuring instrument used to measure the electric current in a circuit.

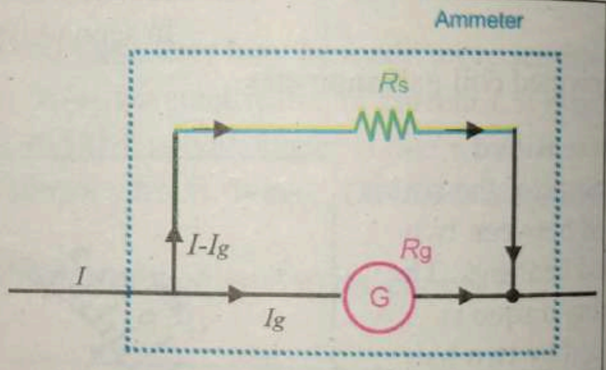


Figure 13.17 : ammeter circuit

The value of shunt resistance depends on the fraction of the total current required to be passes through the galvanometer. Let R_s represent the shunt resistance, R_g the resistance of the galvanometer, I_g the current which produces full scale deflection in the galvanometer. Since the shunt is connected in parallel to the galvanometer, the potential difference across galvanometer = potential difference across shunt.

$$V = R_g I_g$$

And $$V = R_s(I - I_g) \qquad ...(13.17)$$

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

$$R_s = \frac{R_g I_g}{(I - I_g)} \qquad ...(13.18)$$

An ideal ammeter has a zero resistance.

13.10 Conversion of Galvanometer to Voltmeter

A Galvanometer can be converted into a voltmeter by connecting a high resistance in series with a galvanometer as shown in fig: 13.18.

The value of this resistance depends upon the range of the voltmeter. In series connection the current through the galvanometer is same as that due to the resistance.

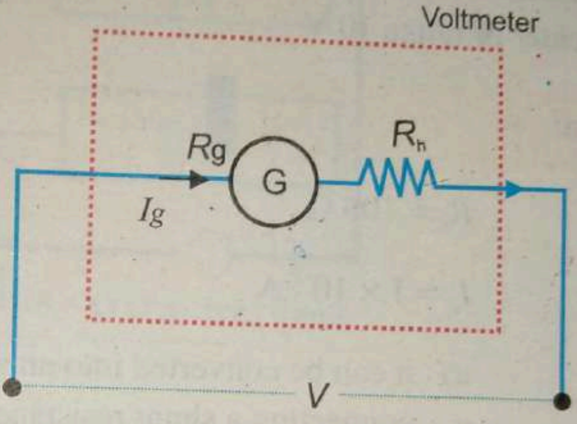


Figure 13.18: voltmeter circuit

Suppose a galvanometer has resistance "R_g" and current "I_g" is passing through it of potential "V_g" across it. And the high resistance also draws same current "I_g", and potential "V_h" across resistor "R_h".

The desired potential "V" is to be determined.

Hence,
$$V = V_g + V_h$$

$$V = R_g I_g + R_h I_g$$

$$V = I_g (R_g + R_h)$$

$$\frac{V}{I_g} = (R_g + R_h)$$

$$R_h = \frac{V}{I_g} - R_g \qquad \ldots(13.19)$$

This works as a voltmeter of range 0 to V volt. Since the value of R_h is high, the effective resistance also has a higher value. Voltmeters have a high resistance. The reason is that the voltmeter must not draw current from the circuit otherwise; the P.D. which the voltmeter is required to measure will change. An ideal voltmeter has an infinite resistance.

Example 13.7

A galvanometer has a resistance of 100 ohms and gives full scale deflection on 1 mA current. How it can be converted into a) an ammeter of range 10 A , b) voltmeter of range 10 V

Solution:

$R_g = 100\ \Omega$

$I_g = 1 \times 10^{-3}\ A$

a) it can be converted into an ammeter of range I =10A by connecting a shunt resistance in parallel

$$R_s = \frac{R_g\ I_g}{(I - I_g)}$$

$R_S = 0.010\ \Omega$

b) it can be converted into a voltmeter of range $V = 10$ V by connecting a high resistance R in series

$$R_h = \frac{V}{I_g} - R_g$$

$R = 9900\ \Omega$

13.11 AVOMETER-MULTIMETER

It is an instrument to measure current, voltage and resistance. So it is Amperemeter, Voltmeter and Ohmmeter (AVO). It can measure direct as well as alternating current and voltage. It is a galvanometer having a series of combination of resistors, all enclosed in a box. It has different scales graduated in such a manner that all the three quantities can be measured. It has its own battery for its function and for operating the electrical circuits.

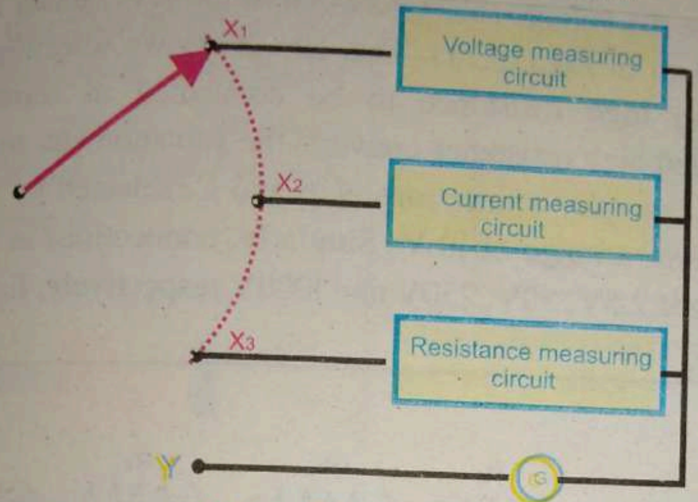


Figure 13.19 : AVO meter circuit

The quantity to be measured and its range can be selected by a selector switch which connects the particular electrical circuit to the galvanometer.

Current Measurement

For the measurement of current the selector switch is turned to X_2. The proper scale is selected. This circuit is a series combination of shunt resistances R_1, R_2, and R_3 is called Universal shunt as shown in Fig:(13.20). Any one of the shunts can be used for measurement of current in different ranges. This circuit provides a safe method of switching between current ranges without any danger of excessive current through the meter.

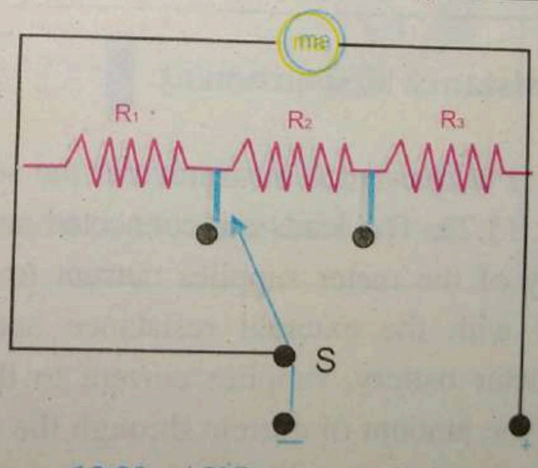


Figure 13.20 : AVO meter switch turned to current measurement

Voltage Measurement

For measuring voltage the voltage selector switch of the AVO meter changes the circuit to the type shown in Fig:(13.21). This circuit allows selecting any range and the corresponding high resistance to be connected in series with the galvanometer. The added high resistance converts the galvanometer to a voltmeter of specific range. For example, connections at A and C, selected by the multiple switch arrangement gives a range of 10-V. Similarly, connections at A and at B, D, E or F give the ranges 2.5V, 50V, 250V and 1000V respectively, Fig.(13.21).

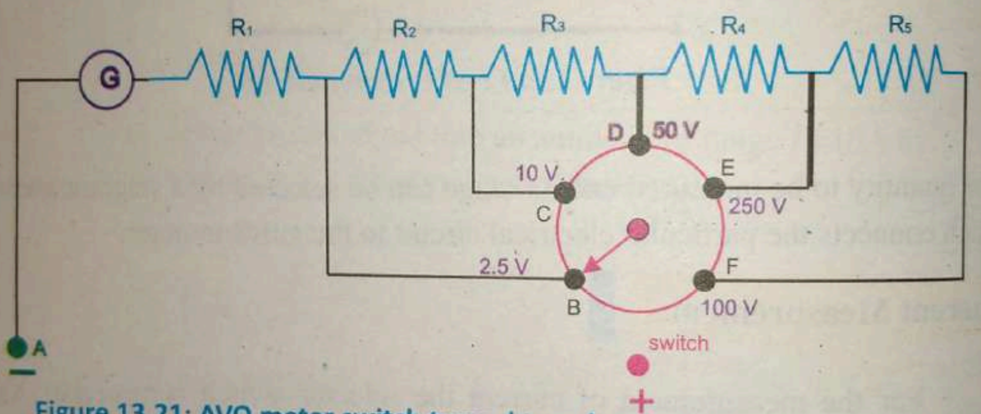


Figure 13.21: AVO meter switch turned to voltage measurement

Resistance Measurement:

For resistance measurement the selector switch uses the circuit as shown in fig: 13.22. The leads are connected across the resistance to be measured. The battery of the meter supplies current to the meter for deflection which in turn varies with the external resistance and can be calibrated. In this case the ohmmeter battery, supplies current to the galvanometer for deflecting its coil. Since the amount of current through the galvanometer depends upon the external resistance, we can calibrate the scale in ohms. The amount of deflection on the ohms scale indicates directly the magnitude of the resistance.

The ohmmeter reads up-scale regardless of the polarity of the leads because the polarity of the internal battery determines the direction of the current through the galvanometer. Commercial AVO meters provide resistance measurements from less than one ohm up to many megaohms.

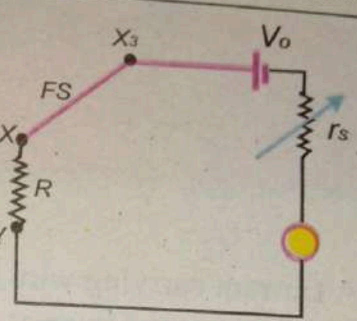


Figure 13.22 : AVO meter switch turned to resistance measurement

Digital Multimeters

Modern multimeters are often digital due to their accuracy, durability and extra features. In a digital multimeter the signal under test is converted to a voltage and an amplifier with electronically controlled gain preconditions the signal. A digital multimeter displays the quantity measured as a number, which eliminates parallax errors.

Modern digital multimeters may have an embedded computer, which provides a variety of convenience features.

Figure 13.23 : digital Multimeters

KEY POINTS

- A Current carrying wire has a magnetic field around it.
- The force on the current carrying wire in a uniform magnetic field is given by $\boldsymbol{F} = I\,\boldsymbol{L} \times \boldsymbol{B}$
- The magnetic flux is defined as $\Phi = B \cdot \Delta A$
- Ampere's law relates the integrated magnetic field in a loop around a current carrying wire to the current passing through the wire.

$$B \cdot \Delta L = \mu_0 I$$

- The magnetic field of a solenoid is given by $B = n\,\mu_0 I$
- The force on a charged particle shot at right angles to the magnetic field is $F = qvB$
- Torque on a current carrying coil is $\tau = NIAB \cos\theta$
- The shunt resistance for an ammeter is

$$R_s = \frac{R_g\, I_g}{(I - I_g)}$$

- The high resistance for a voltmeter is

$$R_h = \frac{V}{I_g} - R_g$$

Exercise ?

Multiple choice questions:

Each of the following questions is followed by four answers. Select the correct answer in each case.

1 A moving charge is surrounded by
- a) 2 fields
- b) 3 fields
- c) 4 fields
- d) None of these

2 A photon while passing through a magnetic field are deflected towards
- a) North pole
- b) South pole
- c) Are ionized
- d) None of these

3 Magnetism is related to
- a) Stationary charges
- b) Moving charges
- c) Stationary and moving charge
- d) Law of motion

4 when charge particle enter perpendicular to magnetic field, the path followed by it is
- a) A helix
- b) A circle
- c) Straight line
- d) Ellipse

5 The torque in the coil can be increased by increasing
- a) No, of turns
- b) Current and magnetic field
- c) Area of coil
- d) All of above

6 The magnetic flux will be max, for an angle of
   a) 0^{o}
   b) 60^{o}
   c) 90^{o}
   d) 180^{o}

7 The Weber is unit of measure of
   a) Conductance
   b) Electric current
   c) Magnetic flux
   d) Electric flux

8 One weber is equal to
   a) $N.A^{2}/m$
   b) $N.m^{2}/A$
   c) N.A/m
   d) N.m/A

9 An electron moves at 2×10^{2}m/sec perpendicular to magnetic field of 2T what is the magnitude of magnetic force
   a) 1×10^{-6}N
   b) 6.4×10^{-17}N
   c) 3.6×10^{-24}N
   d) 4×10^{6}N

10 The force on a charge particle moving parallel to magnetic field is
   a) Maximum
   b) Minimum
   c) Zero
   d) None of these

11 Ampere's law is applicable to
a) Circular path
b) Rectangular path
c) To any closed path
d) None of these

12 The unit of permiability of free space is
a) T.m/A
b) $T.m^2/A$
c) $T.m/A^2$
d) None of these

CONCEPTUAL QUESTIONS

1. What is the force that a conductor of length L carrying a current I, experiences when placed in a magnetic field B? What is the direction of this force?
2. What is the nature of force between two parallel current carrying wires (in same direction)?
3. What is the magnitude of the force on a charge q moving with a velocity **v** in a magnetic field **B**?
4. In a uniform magnetic field **B**, an electron beam enters with velocity **v**. Write the expression for the force experienced by the electrons.
5. What will be the path of a charged particle moving in a uniform magnetic field at any arbitrary angle with the field?
6. An electron does not suffer any deflection while passing through a region. Are you sure that there is no magnetic field?
7. An electron beam passes through a region of crossed electric and magnetic fields of intensity E and B respectively. For what value of the electron speed the beam will remain un-deflected?
8. Uniform electric and magnetic fields are produced pointing in the same direction. An electron is projected in the direction of the fields. What will be the effect on the kinetic energy of the electron due to the two fields?
9. What is the cyclotron frequency of a charged particle of mass m, charge q moving in a magnetic field B?
10. Can neutrons be accelerated in a cyclotron? Give reason.

11. A current carrying loop, free to turn, is placed in a uniform magnetic field **B**. What will be its orientation relative to **B**, in the equilibrium state?
12. How does a current carrying coil behave like a bar magnet?

Comprehensive Questions

1. Derive an expression for the force acting on a current carrying conductor in a uniform magnetic field.
2. A current carrying loop is placed in a uniform magnetic field. Derive an equation for the torque acting on it?
3. Does a moving charge experiences a force in magnetic field? Explain.
4. How *e/m* ratio for electron is determined using magnetic field?
5. Define and explain magnetic flux?
6. State Ampere's law and use it to derive an expression for the magnetic field of a solenoid?
7. What is galvanometer? How it is converted into an ammeter and a voltmeter?

Numerical Problems

1. At what distance from a long straight wire carrying a current of 10 A is the magnetic field is equal to the earth's magnetic field of 5×10^{-5} T?

   [0.04 m]
2. A long solenoid having 1000 turns uniformly distributed over a length of 0.5 m produces a magnetic field of 2.5×10^{-3} T at the center. Find the current in the solenoid?

   [1 A]
3. A proton moving at right angles to a magnetic field of 0.1 T experiences a force of 2×10^{-12} N. What is the speed of the proton?

   [1.3×10^{8} m/s]
4. An 8 MeV proton enters perpendicularly into a uniform magnetic field of 2.5 T. Find (a) the force on the electron (b) what will be the radius of the path of proton?

   ((a) 1.6×10^{-11} N (b) 0.17 m)

5. A wire carrying current 10 mA experiences a force of 2 N in a uniform magnetic field. What is the force on it when current rises to 30 mA?

[6 N]

6. What is the time period of an electron projected into a uniform magnetic field of 10 mT and moves in a circle of radius 6 cm?

[3.6 ns]

7. A 0.2 m wire is bent into a circular shape and is placed in uniform magnetic field of 2 T, .If the current in the wire is 20 mA then find the maximum torque acting on the loop?

[1.27×10^{-5} Nm]

8. The full scale deflection for a galvanometer is 10 mA. Its resistance is 100 ohms. How can it be converted into an ammeter of range 100 A?

[$R_S = 0.01\,\Omega$]

9. How a 5 mA, 100 ohms galvanometer is converted into 20 V voltmeter ?

[$R = 3900\ \Omega$]

10. Two parallel wire 10 cm apart carry currents in opposite directions of 8 A. What is the magnetic field halfway between them?

(6.4×10^{-5}T)

11.