18

MAGNETIC EFFECT OF ELECTRIC CURRENT

18.1 INTRODUCTION

In everyday situations one hardly thinks of the connection between electricity and magnetism. In 1820, Oersted by a series of experiments established an important result that moving charges exert forces, which are different from electrostatic forces due to charges at rest. This principle is used in many modern day gadgets like electric meters, motors, and generators.

In the previous lesson you have studied about the thermal and chemical effects of electric current. In the present lesson you will study about the magnetic effect of current and their applications in our day to day life. You will also study the principle of working of current measuring and detecting devices like galvanometer, ammeters and voltmeter.

18.2 OBJECTIVES

After studying this lesson, you should be able to:

- *visualize magnetic effect of electric current;*
- *difine Biot Savart's law and understand its applications;*
- *explain Ampere's circuital law and its applioation to find the magnetic field due to current in solenoids and toroids;*
- *difine ampere in terms of magnetic field;*
- *explain the motion of a charged particle in a magnetic field and undurstand Lorentz force;*
- *describe the behaviour of a current loop in a magnetic field; and*
- *explain the principle of working of current measuring and detecting instruments such as galvanometers, ammeters and voltmeters.*

18.3 ELECTRICITY AND MAGNETISM - CORE CONCEPTS

You have studied earlier that the flow of electrons in a conductor, due to a potential difference across it, is called ***electric current.*** The current flowing in the conductor exerts force on a free magnetic needle in a region, this region is known a magnetic field. The ***magnetic field*** is characterised by the magnitude and direction of the field given by ***magnetic induction*** vector B or ***magnetic intensity.*** The field is visualised by ***magnetic field lines*** which give the direction of the field at a point in the space. You will learn about these and more term, such as magnetic permieability, susceptibility etc. at the appropriate place in this lesson.

18.3.1 Magnetic Field Around an Electric Current

We will do a simple experiment. For this, you will require a 1.5 volt battery, a wire about 1m long, a campass needle and a match box. Take the match box base and wrap the electric wire on it about 10-15 times. See Fig. 18.1.

Place the campass needle at its base. Turn the match box so as to have the wires running along the North - South direction. Connect the free ends of the wire to the battery. Watch what happens to the needle.

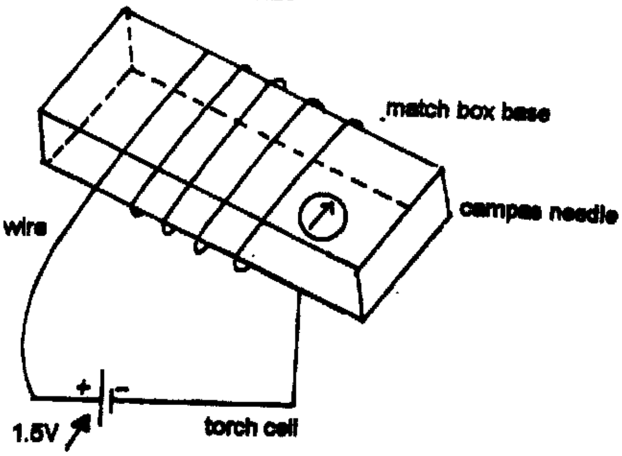


Fig. 18.1: *Demonstration of magnetic field due to the electric current*

The needle deflects, this means there is a magnetic force around the coiled up wire. The deflection reverses if you change the direction of current by changing the terminals of the bettary. When there is no current in the wire the campass needle points in the North - South direction.Fig.18.2(a,b & c). Fig. 18.2 (d) shows concentric circles around the wire.

In 1820 ***Hans Christian Oersted***, Professor of Physics at Copenhager in Denmark performed similar experiments and established that there is a magnetic field around a current carrying conductor.

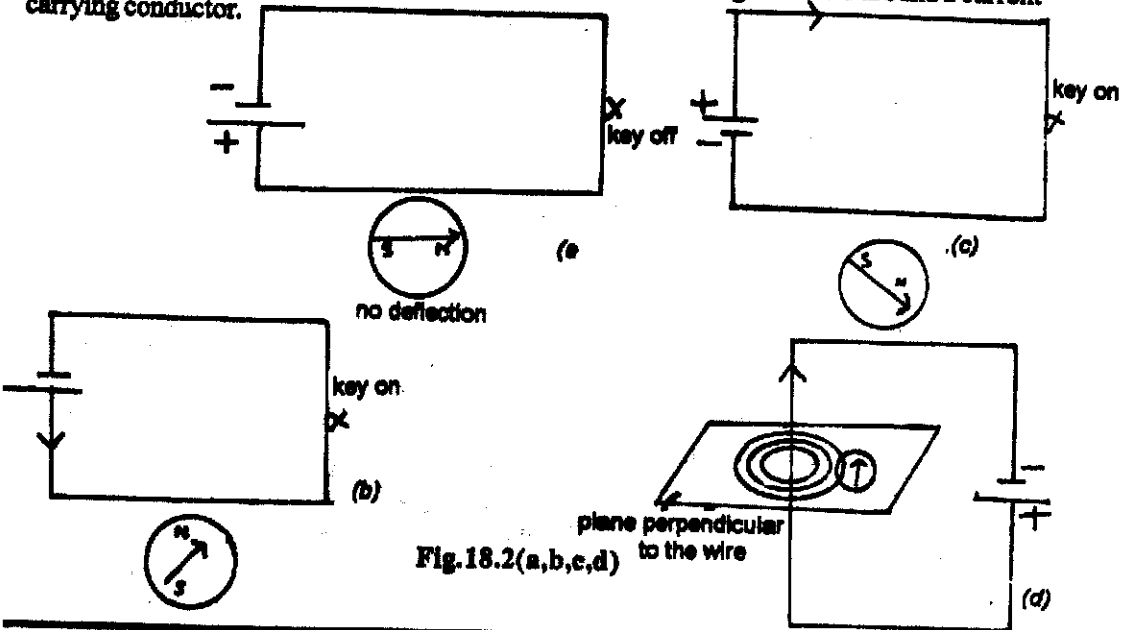


Fig.18.2(a,b,c,d)

18.3.2 Biot Savart's Law

We now present a law that gives a quantitative relationship between the current in any conductor and the resulting magnetic field at a point in the space around it.

Each part of the conductor contributes towards a magnetic field. The net value of **B** at a point is the combined effect of all the individual parts of the conductor. According to the experiment as shown in Fig. 18.3 we can say that the magnetic field due to any current carrying conductor is the vector sum of the contribution due to the current in each minute element of length Δl.

The field ΔB due to an element Δl depends upon

(a) I : current through the conductor;
(b) Δl : length of the element;
(c) $\frac{1}{r^2}$: r is the distance of point P where the field is to be calculated from the element Δl
(d) θ : θ is the angle between the element and the line joing the element to the point P.

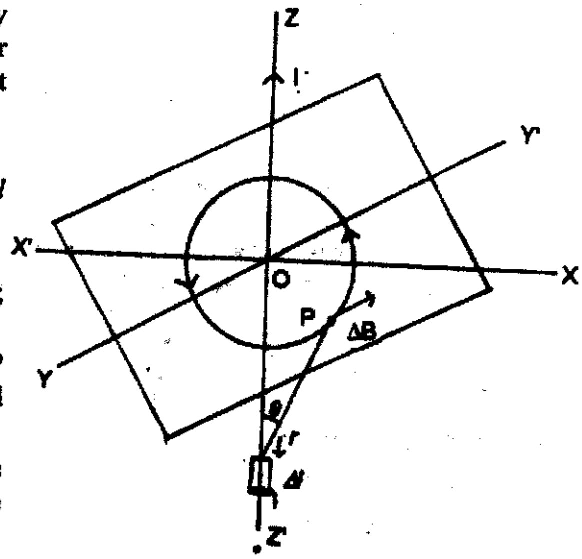


Fig. 18.3:

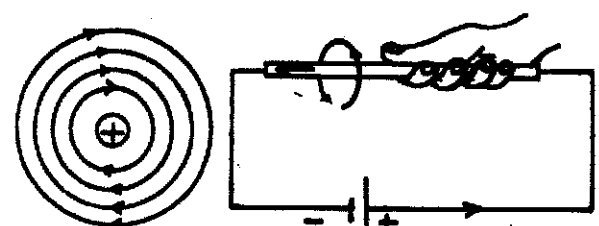
$$\Delta \mathbf{B} \propto \frac{I \Delta l \sin\theta}{r^2}$$

$$= \frac{\mu_o}{4\pi} \frac{I \Delta l \sin\theta}{r^2} \qquad ...(18.1)$$

This is an imperical result and μ_o is the permeability of vacuums or air. Its value is $4\pi \times 10^{-7}$ Wb A^{-1} m^{-1}

If the conductor is surrounded by a medium then the value of the field is altered and it becomes $\mathbf{B} = \mu\, \mathbf{B}_o$ Here, μ represents, the permeabilty of the medium which is different from μ_o $\mathbf{B}_o$ = magnetic field at a point in vacuum, and $\mathbf{B}$ = magnetic field at a point with a mentioned medium of permeability μ.

Direction of B : Magnetic field is a vector. Let us consider the direction of the field produced in some simple cases. As shown in the Fig. 18.4, with your hand grasp the wire, so that the thumb points



(b) current into the plane of the paper. (a)

Fig. 18.4 : Direction of magnetic field

in the directoin of the current, the curled fingers of the hand point in the direction of the magnetic field. In Fig. 18.4(b) check if the direction of magnetic field matches this description.

In Fig. 18.5, the thumb is along I i.e. the plane containing OP, **B** is perpendicular to it along the direction of the curl of the fingers of the right hand. This is called the ***right hand grip rule.***

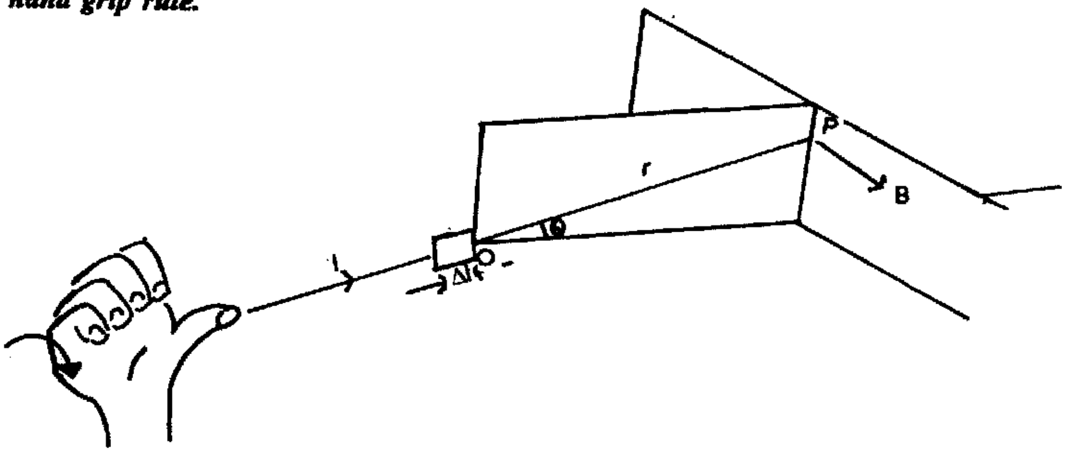


Fig. 18.5 : Right hand grip rule

18.3.3 Applications of Biot Savart's Law

As Biot Savart's law gives the magnitude of the magnetic field, it can be used to find the field around different shapes of conductors. However, to find the net field due to different segments of the conductor we add up the Δ **B** contribution due to each one of them. Calulus makes it very easy. A few applications of Biot Savart's law are given below.

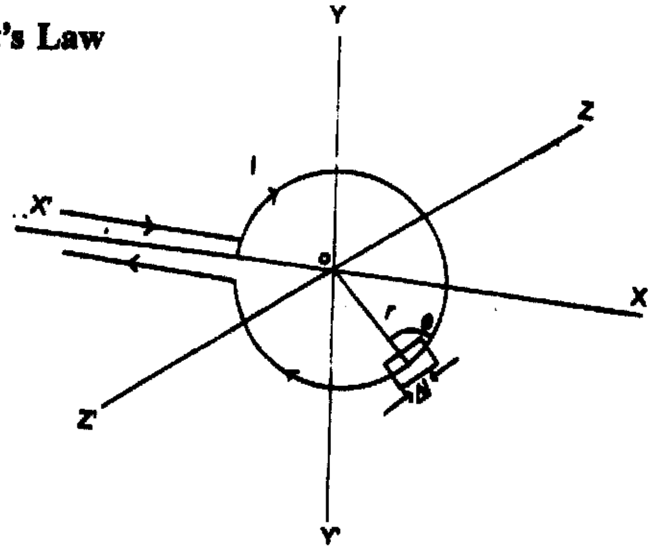


Fig. 18.6 : Circular coil carrying current

Megnetic field at the centre of a circular coil carrying current. Consider a wire stiff enough to form a circular loop like a steel bangle. This would look like Fig. 18.6

To find the field at O due to current element Δl of the circular coil. This element as well as any other are at a distance r from the centre O. The angle made by l with r is $\theta = 90^{\circ}$.

Using Biot Savart's law, the field at the centre O due to Δl is,

$$\Delta B = \frac{\mu_o}{4\pi} I \frac{\Delta l}{r^2} \sin\theta$$

$$= \frac{\mu_o}{4\pi} I \frac{\Delta l}{r^2}$$

The direction of ΔB is perpendicular to the xy plane along Z– axis. Since the field due to every element of the circular coil is in the same direction, the resultant is found by adding all the ΔB contributions at the centre of the loop.

Therefor,

$$\mathbf{B} = \sum \Delta \mathbf{B} = \frac{\mu_o I}{4\pi r^2} \sum \Delta \ell$$

$$= \frac{\mu_o I}{4\pi r^2} 2\pi r$$

or **B** at the centre of coil of radius *r* having a current *I* in it is ,

$$\boxed{\mathbf{B} = \frac{\mu_o I}{2r}} \qquad ...(18.2\ )$$

In case there are more then one loop of wire, say there are n turns

$$\mathbf{B} = \frac{\mu_o I}{2r} n \qquad ...(18.3\ )$$

B is measured in tesla (T); $1T = 1N\ A^{-1}\ m^{-1}$

You can cleck the direction of the net field using Fig. 18.4. You can use reght hand rule in any segment of the coil and obtain the same result.

(Another simple quick rule to find the direction of magnetic field due to a coil is as thown in Fig. 18.7 (a,b).

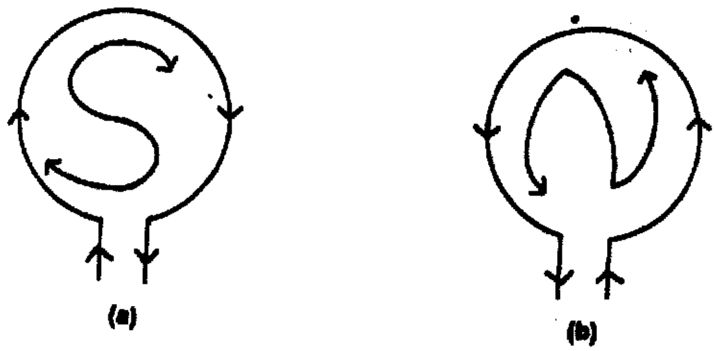


Fig. 18.7: Finding the direction of magnetic field

When an observer looking at the circular coil, finds the current to be flowing in the *clock wise* sense than face of the coil behaves like the *South pole* of the equivalent magnet, or **B** is directed in wards. On the other hand if the current is seen to flow in the *anticlock wise* sense the face of the coil behaves like the *North pole* of the equivalent magnet or the field is directed towards yourself.

Examples 18.1: *At what distance from a long straight wire carying a current of 12 Amp will the magnetic field be equal to 3×10^{-5} Tesla.*

Solution :

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

$$\mathbf{B} = 3 \times 10^{-5}\,\text{T}$$

$I = 12$ Amp

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

$r = ?$

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

$$= \frac{4\pi \times 10^{-7} \times 12}{2\pi \times 3 \times 10^{-5}}$$

$= 0.25$m

INTEXT QUESTIONS 18.1

1. *What is the nature of the field developed by ?*
   (i) a stationary electron?
   (ii) a moving electron?

   ....

2. *Electrons in a conductor are in constant motion due to temperature, why do they not show the property of magnetism unless a potential difference to applied across it ?*

   ....

3. *A current is flowing in a long wire. It is first shaped as a circular coil of one turn, and then into a coil of two turns of smaller radius. In which case is the magnetic field at the centre stronger and by how much?*

   ....

4. *On what factors does the field around a current carrying conductor depend upon ? Use Biot Savarts Law.*

   ....

18.4 AMPERE'S CIRCUITAL LAW

Ampere's circuital law is another property of magnetic field around a current carrying conductor. This can be used to find the field in some simple situations.

Ampere's circuital law states that the line integral of the magnetic field **B** around any closed path or circuit is equal to μ_o times the total current I threading this closed circuit

$$\oint \mathbf{B}.d\ell = \mu_o I$$

This is independent of the size or shape of the closed path or ciruit. ...(18.4)

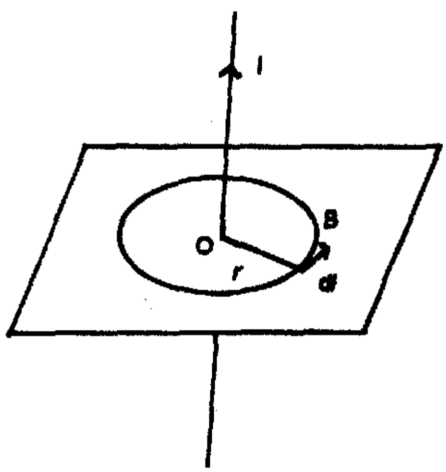


Fig. 18.8: Infinitely long straight conductor

In order to understand this consider an infinitely long straight conductor carrying a current I Fig. 18.8.

Consider a circular loops of radius r. We have already seen that the lines of **B** also form circles around the wire. Then magnetic field is parellel to $d\ell$ every where on the loop. Further the magnitude of **B** is also same at all points of the loop.

$$\oint \mathbf{B}.\, d\ell \;= \oint \mathbf{B}\, d\ell \cos\theta \qquad (\theta = 0)$$
$$= \oint \mathbf{B}\, d\ell$$

Now $\oint \mathbf{B}.d\ell$ along the circular loop will be = $\mathbf{B}.2\,\pi\, r$
But **B** from Biot savart's law

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

$$\oint \mathbf{B}.dl = \frac{\mu_o I}{2\pi r}\; 2^{10}\hat{r}$$

$$= \mu_o \hat{I} \qquad \text{...(18.5)}$$

Thus, Ampere's law is derived using Biot Savart's law.

In case, the imagined loop in not circular, we can cansider dot product of B.dl at every point, where **B** and $d\ell$ may not be along the same line.
But, $d\ell = r\,\theta$

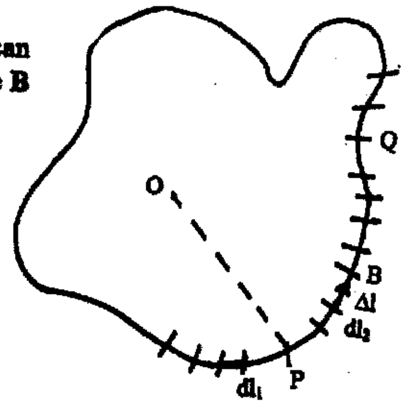


Fig. 18.9: Irregular loop

The Fig. 18.9 shows any imagined shape of closed loop. The wire passes through O. Dividing the closed loop into many small elements dl,

$$\oint \mathbf{B}.dl = \oint \mathbf{B}.dl \cos\theta$$

$$\mathbf{B}_1 \cdot dl_1 + \mathbf{B}_2 \cdot dl_2 + \text{---------} = \mathbf{B}_1 . dl_2$$

Since **B** is parallel to dl at each small segment, $\cos\theta = 1$

$$\oint \mathbf{B}.dl = \frac{\mu_o I}{2\pi r}\; r\theta \;\; \{\because dl = r\,\theta\}$$

$$= \frac{\mu_o I}{2\pi r}\, \theta$$

But θ at the centre O = 2 π, so to trace the entire loop
This law is valid for any assembly of current and for any arbitary closed loop

$$\oint \mathbf{B}.\, d\ell \;=\; \frac{\mu_o I}{2\pi}\; 2\pi$$

$$= \mu o\, I$$

Therefore, this law is valid for any assembly of current and for any arbitrary closed loop.

18.4. 1 Applications of Ampere's Circuital Law

The Ampere's law enables us to obtain the magnetic field in two situations in a very simple manner. Both these results are of practical value and are otherwise difficult to obtain.

(a) Magnetic field due to an infinitely long conductor carrying current

Fig. 18.10 shows a conductor POQ carrying a current I. Take a circular loop of radius r around it in the plane as shown.

$$\sum \mathbf{B}.dl = \mathbf{B}.2\pi r$$
$$= \mu_o I \quad \text{by the law}$$
$$\therefore \mathbf{B}.2\pi r = \mu_o I$$
$$\text{or } \mathbf{B} = \frac{\mu_o I}{2\pi r}$$

This gives the field around a straight conductor as

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

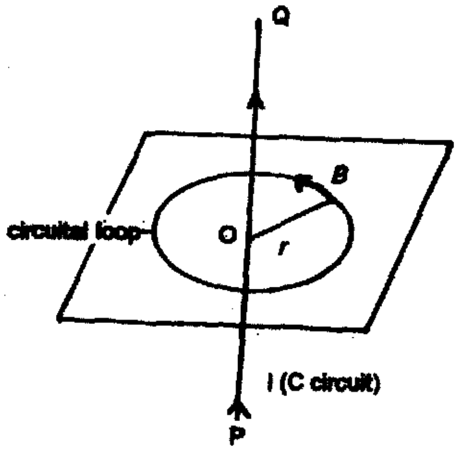


Fig. 18.10: Infinitely long current carrying conductor

(b) **Toroidal Solenoid :** Take a large solenoid. Bring together its ends A & B. This can also be picturised by taking a bangle and wrapping a wire on it all along its circumference. It would look like Fig. 18.11.

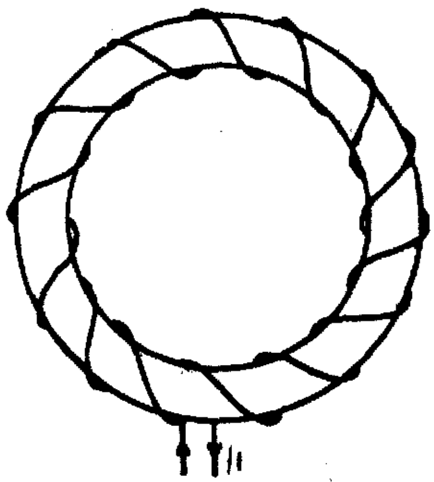


Fig. 18.11: Toroid

Magnetic Field Inside a Toroid : Consider a section or cut of the toroid in the plane of the paper. The current loops go out of the plane of the paper at the outer rim, and into the plane of the paper at the inner rim Fig. 18.12. PQR, and P'Q'R' are two amperian loops one inside the toroid and the other outside it.

If I is the current through the toroid and if there are N number of turns, a total of NI current flows in the inner ring.

We have

$$\oint \mathbf{B}.dl = \mu_o I$$

B & dl are along the same direction.

$$\mathbf{B}.2\pi r = \mu_o NI$$

$$\text{or} \quad \mathbf{B} = \frac{\mu_o NI}{2\pi r}$$

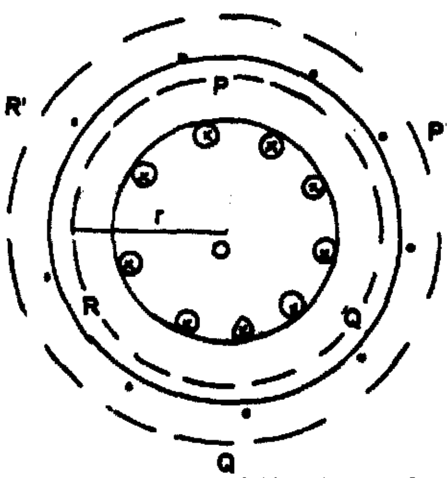


Fig. 18.12 : Magnetic field inside a toroid

If r is the radius of toroid ; then

or $\quad \mathbf{B} = \mu_o nI$ ..(18.6)

where $n = \frac{N}{2\pi r}$ or number of turns per unit length.

The magnetic field B depends upon

(a) current (I)

(b) number of turn per unit length (n)

What about the field outside the toroid ? We can take another amperian corcuit P'Q'R' out side the toroid ; but with centre O.

The net current passing within this circular disc is zero. Since NI passes in and out at the inner and outer rims of the toroids. Thus, B is zero.

What will be the direction of B ? This will be tangential to the circle.

(c) Magnetic field due to a solenoid

Solenoid is a straight coil having large number of loops set in a straight line with a common axis as shown in Fig. 18.13.

If a current I flows through the wire a magnetic field sets up around it. A and B are two ends of the solenoid of length l having N number of turns.

To find magnetic field inside, along the axis in Fig. 18.13, we can consider it to be a section of a toroidal solenoid of a very large radius.

$$\mathbf{B} = \mu_o IN$$

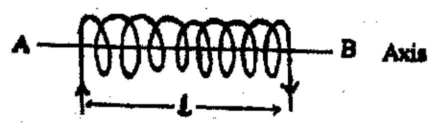


Fig. 18.13 : Solenoid

The direction of the field is along the axis of the solenoid. A straight solenoid is finite, it has ends. Therefore,

$$\mathbf{B} = \mu_o IN,$$

should be correct well inside the solenoid, near its centre and at points close to the axis.

It can be seen mathematically that for solenoids of small radius, B at the ends is approximately

$$= \frac{B}{2} = \frac{\mu_o IN}{2} \quad .....(18.7)$$

The solenoid behaves like a bar magnet and the magnetic field due to a solenoid is much like the bar magnet as shown in Fig.18.14.

Solenoids and Toroids are widely used in motors, generators, toys, fan windings, transformers, electromagnets etc. They are used to provide uniform magnetic fields. Sometimes to increase **B** different materials may be placed within the windings.

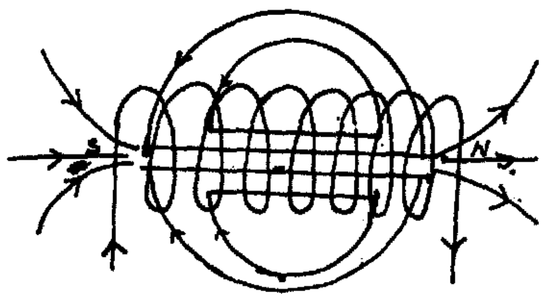


Fig. 18.14: Solenoid field is much like the bar magnet

Example 18.2:. *A solenoid 50cm long has 3 layers of windings of 250 turns each. The radius of the lowest layer is 2cm. If the current through it is 4.0 A. Estimate the magnitute of* **B**,

(a) near the centre of the solenoid on and about the axis.

(b) near the ends on its axis.

(c) outside the solenoid near the middle.

Solution :

(a) at the centre or near it

$$\mathbf{B} = \mu_o nI$$

to find n

$$n = \frac{250}{50} \quad \text{for 1 layer}$$

$\therefore$ for 3 layers it would be $3n$

or for 3 layer total number of turns, $= \frac{250}{50} \times 3 = 15 \text{ cm}^{-1}$

$= 1500 \text{ m}^{-1}$

$$\mathbf{B} = 4\pi \times 10^{-7} \times 1500 \times 4$$
$$= 16 \times 15\pi \times 10^{5} \quad \text{Tesla}$$

Same about the axis also.

(b) at the ends $\mathbf{B}_{ends} = \frac{\mathbf{B}_{Centre}}{2}$

$= 8 \times 15\,\pi \times 10^{5}$ Tesla

(c) Outside the solenoid the field is negtigible.

INTEXT QUESTIONS 18.2

1. *A drawing of the lines of force of a magnetic field provides information on*
   (a) direction of field only
   (b) magnitude of field only
   (c) both the direction and magnitude of the field
   (d) the force of the field.

   . . . .

2. *What is common between Biot Savart's law and Ampere's circuital law ?*

   . . . .

3. *In the following drawing of line of force of a non-uniform magnetic field at which point is the field*
   (i) uniform?
   (ii) weakest?
   (iii) strongest?

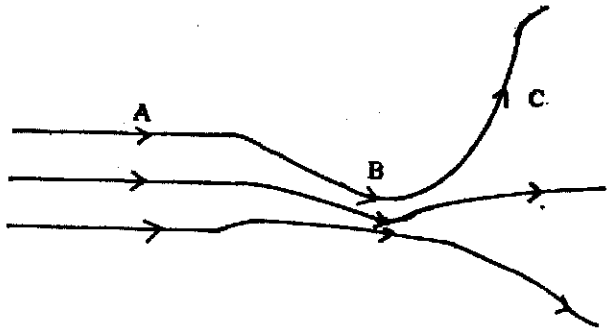


Fig. 18.15

. . . .

4. *A solenoid 10cm long is meant to have a magnetic field 0.002T inside it, when a current of 3A flows through it. Fing the required turns.*

. . . .

18.5 INTERACTION BETWEEN A CONDUCTOR CARRYING CURRENT AND A MAGNETIC FIELD

We have understood that a current carrying cinductor generates a magnetic field around it. we are now going to see what happens if a magnet is brought close to such a conductor. You can make your guesses. To support your imagination we can perform a simple experiment. For this you need a pencil, 25cm of flexible connecting wire, a jhora pin U-clip (or a piece of copper or aluminium wire about 15cm long), a battery, two glasses of equal size. See the set up as shown in Fig. 18.16.

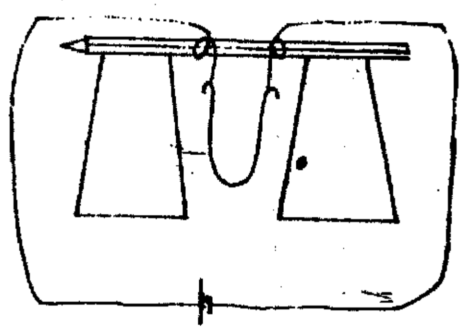


***Fig. 18.16** : Experimental set up*

Bend the stiff wire into a "U"shape and slightly bend its ends. Now tie one end of one of the flexible wires to the "U". Connect the other wire to the other end of the U. Loop the wire over the pencil, U is suspended from the pencil like a swing. Pass current through the wire.

Next take the magnet and bring it close to the U. The U- wire swings. What do you think is the reason for this? Stop the current and see if the swing again takes place. The reason is that like the interaction between two magnets here also field due to the magnet and the one produceded by the current in the U interact - creating an attraction or repulsion. It is like exerting a mechanical force on it.

If the U wire was fixed, the force would have been there but its effect unseen.

Right hand palm rule : The direction of force on a conductor carrying current when placed in a magnetic field is given in a simple way by right hand rule (Fig. 18.17).

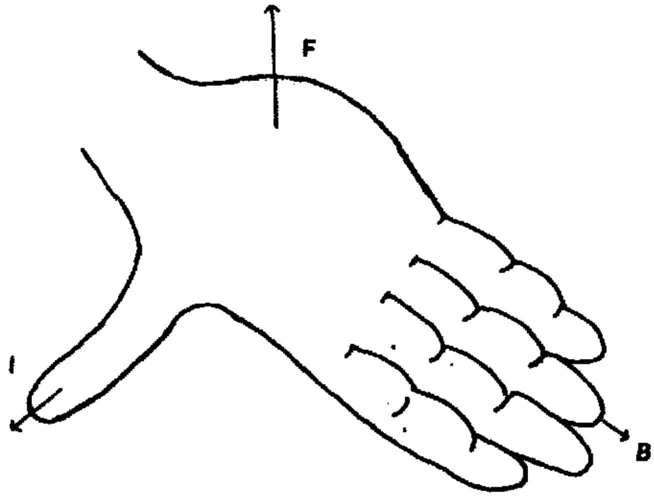


Fig. 18.17 : Right hand palm rule

Stretch the right hand palm such that the thumb is perpendicular to the fingers and points in the direction of current *I*, the fingers point in the direction of external magnetic field **B**. Then the force **F** on the conductor will be perpendicular to the palm in the direction of pushing by the palm.

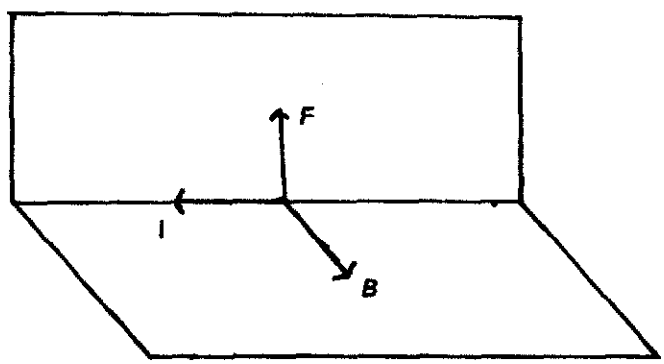


Fig. 18.18 : Direction of force on a current carrying conductor

Take a paper and fold it, mark *I* along the fold ; **B** along the edge of the lower fold then the direction of '**F** is along the edge of the upper fold (Fig. 18.18).

18.5.1 Force on a Moving Charge in a Magnetic Field

When a charged body is moved in a magnetic field, it experiences a force. Such a force experienced by a moving charge is called the ***Lorentz force.***

You might wonder that we have been talking about currents and now suddenly we are saying a 'moving charge'. Well, since the Lorentz force and its magnitude was determined for moving charges, we consider it and later extend the idea to the currents.

According to this the Lorentz force on a particle with a charge $+q$ moving with a velocity 'v in a magnetic field **B** is given by,

$$\mathbf{F} = q(v \times \mathbf{B}) \qquad ...(18.8)$$

$$\text{or } |\mathbf{F}| = q\, v\, \mathbf{B} \sin\theta \qquad ...(18.9)$$

where θ is the angle between the direction of v and **B** the direction of **F** is given by right hand palm rule.

Some important points

1. *F is a mechanical force resulting in a pull or a push.*
2. *The direction of force is given by the right hand rule.*
3. *In case of negative charge moving, the direction of its motion is considered opposite to F.*
4. *If the charge stops, the force stops instantly.*
5. *Force is zero if the charge moves along the field* **B**.
6. *Force is maximum if charge moves perpendicular to the field given by* $\mathbf{F} = Bqv$

18.5.2 Force on a Conductor Carrying Current in a Magnetic Field

The idea in the above section can be extended to current carrying conductors for force on a charge q moving with velocity 'v' perpendicular to '**B**' is,

$$|\mathbf{F}| = qv\mathbf{B}$$

Suppose the charge 'q' travels a distance 'Δl' in time 'Δt'

$$v = \frac{\Delta \ell}{\Delta t}$$

or $$\mathbf{F} = q\,\frac{\Delta \ell}{\Delta t}\mathbf{B}$$

$\Rightarrow$ $$\mathbf{F} = \frac{q}{\Delta t}\,\Delta \ell\,\mathbf{B} \qquad \left\{I = \frac{q}{\Delta t},\ \text{rate of flow of charge}\right\}$$

$\Rightarrow$ $$\boxed{\mathbf{F} = I\,\Delta \ell\,\mathbf{B}}$$

If conductor makes an angle θ with **B** the n $\mathbf{F} = I\Delta l\,\mathbf{B}\sin\theta$ ...(18.10)

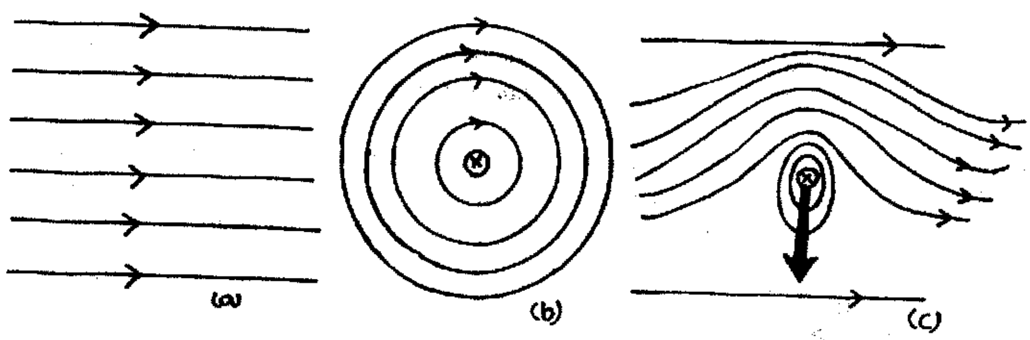


***Fig. 18.19**: (a) Uniform magnetic field, (b) field of current, (c) force on current conductor*

The direction of the force on a current carrying conductor in a magnetic field is from the region of strong field to the region of weak field.

The unit of magnetic field 'B' can be expressed as the force experienced by a current carrying conductor in the field. From equ. 18.10.

$$\mathbf{B} = \frac{\mathbf{F}}{I \Delta \ell}$$

F is taken in newton, I in ampere and Δl in metre, then the unit of **B** will be $NA^{-1}\ m^{-1}$.

If 1 m long conductor, carrying 1 ampere current is placed perpendicular to the magnetic field, experiences a force of 1newton then the magnetic field is 1 tesla.

1 tesla = 1 newton × $(\text{ampere})^{-1}$ × $(\text{metre})^{-1}$

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

18.5.3 Force Between two Parallel Wires Carrying Current

Every current carrying conducter is surrounded by a magnetic field, and because of this, nearby exert forces upon nearby current carrying conducter. The force is mutual. The forces are magnetic is origin ; a current carrying wire has no net electric charge, and hence cannot interact electricoty with another such wire.

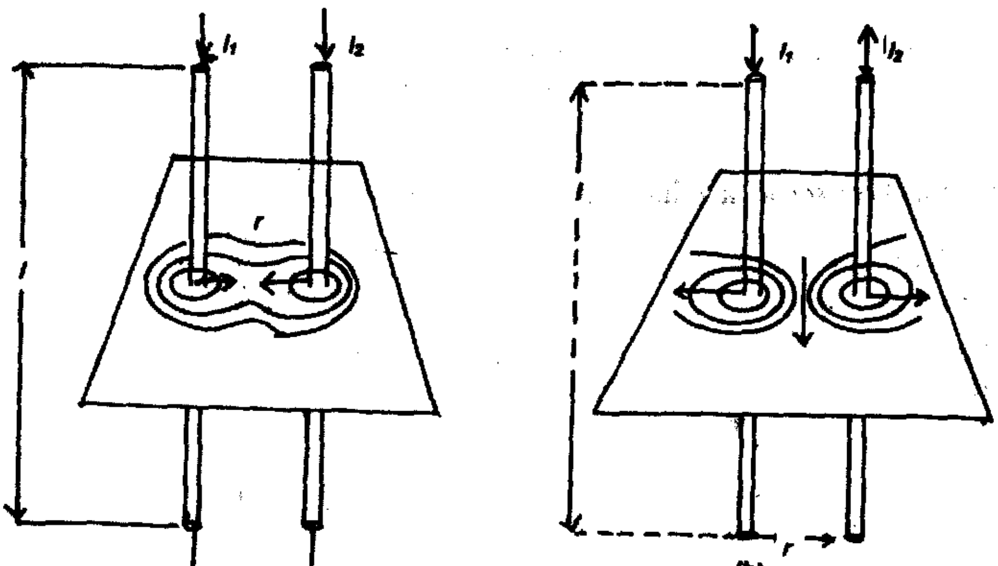


Fig. 18.20 : Experimental demonstration of force between two parallel wires carrying current

Fig 18.20 shows two parallel wires separated by distance r and carrying current I_1 and I_2 respectively. The magnetic fields due to each wire at distance r are

$$\mathbf{B}_1 = \frac{\mu_0 I_1}{2\pi r}; \qquad \mathbf{B}_2 = \frac{\mu_0 I_2}{2\pi r}$$

The fields are perpendicular to the length of the wires and therefore the force on a lenght L of current is,

$$\mathbf{F} = \mathbf{B}IL \Rightarrow \frac{\mu_0 I_1}{2\pi r} I_2 L$$

or Force per unit length $= \dfrac{\mu_0 I_1 I_2}{2\pi r}$

i.e. $$\boxed{\frac{\mathbf{F}}{L} = \frac{\mu_0 I_1 I_2}{2\pi r}} \quad ...(18.11)$$

The forces are *attractive* when the currents are in the *same* direction and repulsive when they are in *opposite* directions.

Definition of ampere : We know that

$$\mathbf{F} = \frac{\mu_0 I_1 I_2}{2\pi r} I_2 \ell$$

if $I_1 = I_2 = 1\text{A}, \ \mu_o = 4\pi \times 10^{-7} \text{ Wb A}^{-1}\text{ m}^{-1}$
$l = 1\text{m}$, and $r = 1\text{m}$

then, $$\mathbf{F} = \frac{\mu_o}{2\pi} = \frac{4\pi \times 10^{-7}}{2\pi} = 2 \times 10^{-7}\text{N}$$

Thus, if two parallel wires carrying equal currents are placed 1m apart in vacuum or air experience a mutual force of 2×10^{-7} N m^{-1}, then the current in each wire is one ampere.

18.5.4 Motion of a Charged Particle in a Uniform Magnetic Field

We can now think of various situations in which a charged particle or current carrying conductor, when placed in a magnetic field, moves due to *Lorentz force.*

The force on the particle of charge 'q' moving with velocity 'v' in a magnetic field **B** has the magnitude

$$\boxed{\mathbf{F} = qv\mathbf{B} \sin \theta}$$

θ being the angle between 'v' and '**B**'. The direction of the force '**F**' is given by the right hand rule.

The work done by a force on a body depends on the components of the force in the direction the body moves. When the force on a charged particle *in a magnetic field is perpendicular to its direction of motion, the force does no work on it.* Hence, the particle keeps the same speed v and energy it had when it entered the field, even though it is deflected. On the other hand, the speed and energy of charged particle in an electrical field are always affected by the interaction between the field and particle, when v is perpendicular to **E**. A charged particle moving perpendicular to a magnetic field follows a circular path as shown in Fig. 18.21.

To find the radius R of the circular path of the charged particle, we note that the magnetic force $qv\mathbf{B}$ provides the particle with the centripetal force $\frac{mv^2}{R}$ that keeps it moving in a circle. Equating the magnetic and centripetal forces we have,

$$q\,v\,\mathbf{B} = \frac{mv^2}{R}$$

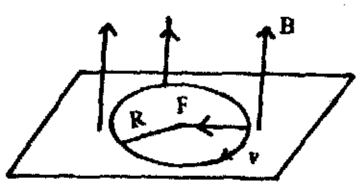


Fig. 18.21 : Path of a charged particle

Solving for R we have

$$R = \frac{mv^2}{q\,B} \qquad ...(18.12)$$

The *radius* of the charged particle's orbit in a uniform magnetic field is directly proportional to its momentum (mv) and inversely proportional to its charge and to the magnetic field.

$R \propto v$, if m, $\mathbf{B}$, q are constant

The greater the momentum, the larger the circle, and the stronger the field, the smaller the circle. The time period of rotation of the particle in circular path is given by,

$$T = \frac{2\pi R}{v} = \frac{2\pi\, mv}{v\,\mathbf{B}q} = \frac{2\pi m}{\mathbf{B}q}$$

$$\boxed{T = \frac{2\pi m}{\mathbf{B}q}} \qquad ...(18.13)$$

We see that the time period is independent of velocity and radius which means once the particle is in the magnetic field it would go round and round in a circle. If m, $\mathbf{B}$, q, are same this T remains constant even if v and R are different.

Now think, what happens to R and T if the following changes are made ?
(a) field B is made stronger,
(b) field B is made weaker,
(c) field B ceases to exist,
(d) direction of B is changed,
(e) the particle in made to enter the magnetic field at a higher speed,
(f) the particle enters at an angle to B,
(g) the charged particle looses its charge.

Example 18.4 : *Using the figure given below calculate the force acting over a length of 5 m of the wires. What is the nature of this force?*

Solution: When currents flow in two long parallel wires in the same directions, the wires exert a force of attraction on each other,

$$\frac{\mathbf{F}}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

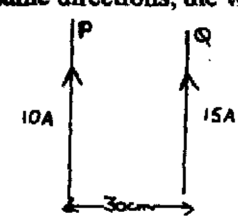


Fig. 18.22

$$= 2\times 10^{-7} \cdot \frac{10\times 15}{0.3}$$

$$= 10^{-4}\ N\,m^{-1}$$

for 5m length. $F = 5\times10^{-4}$ N

Example 18.5: *An electron with velocity 3×10^7 m s^{-1} describes a circular path in a magnetic field of 0.2T. perpendicular to it. What is the radius of the path?*

Solution : $m_e = 9 \times 10^{-31}$ kg

$e = 1.6 \times 10^{-19}$C

$$R = \frac{mv}{Bq}$$

$$= \frac{9\times10^{-31} \times 3\times10^7}{0.2 \times 1.6 \times 10^{-19}}$$

$$= 75 \times 10^{-5}\text{m}$$

INTEXT-QUESTION 18.3

1. *A stream of protons is moving parallel to a stream of electrons what is the nature of force between them ?*

   ....

2. *Both the elect[illegible] and magnetic field can deflect an electron. What is the difference between them ?*

   ....

3. *A body in suspended from the lower end of a vertical spring. What shall be the effect on the position of the body when a current is sent through the spring. Does it depend upon the direction of current in the spring ?*

   ....

4. *Two long, parallel wires are hanging freely. If they are connected to a battery (a) in series, (b) in parallel, what would be the effect on their positions ?*

   ....

18.6 CURRENT LOOP AS A DIPOLE

In section 18.3.3, we had considered the field at the centre of a coil. It was given by

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

This also means that a current carrying coil behaves like a magnetic dipole having north and south poles. One face of the loop becomes as North pole while the other as South pole.

Cansider a simple exerecise say a bar magnet is suspended by a thread between the horse shoe magnete as shown in Fig. 18.23.

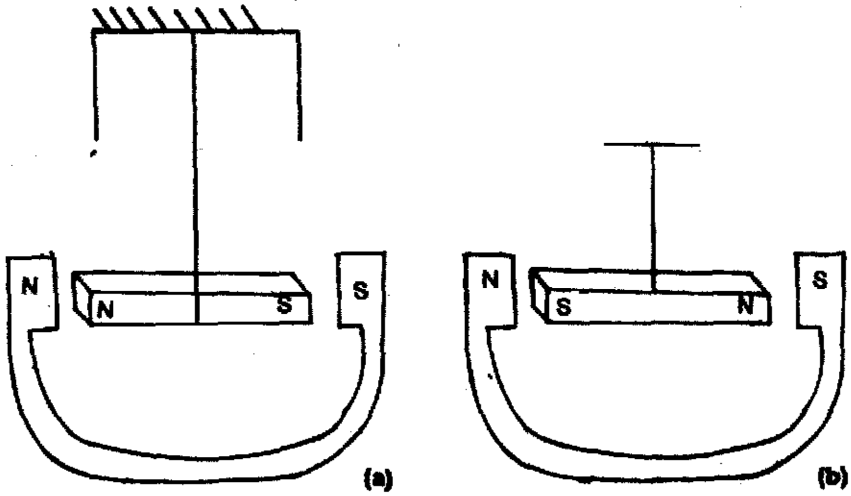


Fig 18.23 (a) (b) : A bar magnet suspended between a horse shoe magnet.

What do you think will happen and why? There is a repulsion between like poles hence the bar magnet will rotate and turn through 180° to align like in Fig. 18.23 (b).

Similarly a current carrying coil will rotate to align its dipole in the external field.

18.6.1 Magnetic Moment of a Dipole

This is defined as the moment of the couple which acts on the dipole when it is kept perpendicular to uniform magnetic field of unit strength (Fig. 18.24). A couple is a pair of equal and opposite forces for which the line of action is not the same. Moment of the couple = force × perpendicular distance between the line of action of the force.

$$F_1 = F_2 = F$$

Moment of the couple = $F \times b$

This is also called torque (τ).

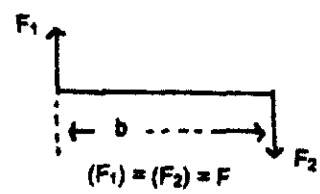


Fig 18.24 : Equal and opposite forces acting on a dipole

18.6.2 Torque on a Current Loop

A loop of current in a uniform magnetic field (**B**) experiences no net force but instead a torque acts on it. This tends to rotate the loop or coil to bring its plane perpendicular to **B**. This is the principle that underlines the operation of all electric motors, meters etc.

Let us examine the force on each side of a rectangular current carrying loop where plane is parallel to a uniform magnetic field **B**.Fig. 18.25 (a).

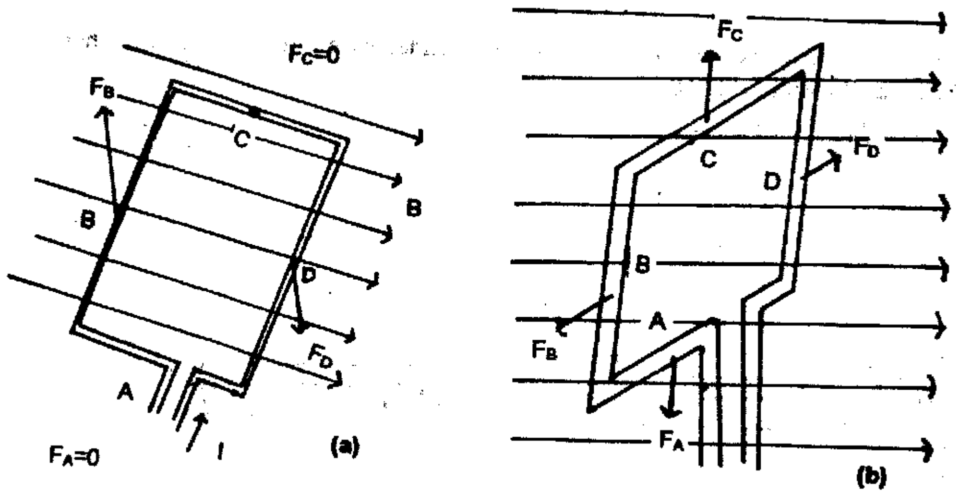


Fig. 18.25 : (a) (b)

The sides A and C of the loop are parallel to B hence there is no force on them. Side B and D are perpendicular to B, however, and each therefore experiences a force. We can find the directions of the force on B and D.

$F_B = F_D$ - so there is no net force on the loop. But F_B and F_D do not act along the same line and hence they exert a torque on the loop that tends to turn it. This holds good for a current loop of any shape in a magnetic field.

In case the plane of the loop is perpendicular to the magnetic field instead of parallel to it, there is neither a net force nor a net torque on it. See Fig.18.25(b).

A current carrying loop in a magnetic field always tends to turn so that its plane becomes perpendicular to the field.

Tarque = force × perpendicular distance between the forces

$\tau = \mathbf{B}\, IL\, .b \sin\theta$

Consider Fig. 18.26 ABCD is a loop with current I,

θ is the angle between the magnetic field **B** and the normal to the plane of the coil **n**. The torque is then,

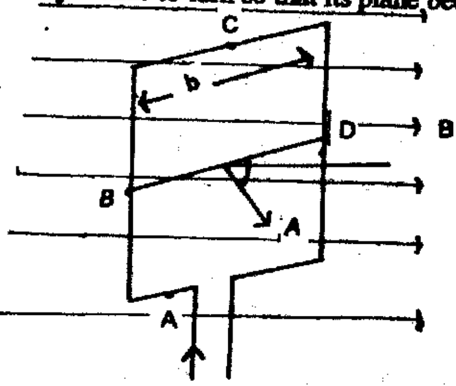


Fig. 18.26 : Current carrying loop

$\tau = N\mathbf{B}IL\, \text{b} \sin\theta$

N is the number of turns of the coil

$\tau = N\mathbf{B}I\,A \sin\theta$ ...(18.14)

A is area of the coil $= L \times b$

$\tau = N\mathbf{B}\, \text{m} \sin\theta$ ...(18.15)

Where $m = IA$ is known as the magnetic moment of the magnetic loop (coil).

Thus, we see that the torque τ is directly proportional to **B**, θ, A, I, and N.

18.6.3 Keeping the Torque Constant

If a uniform rotation of the loop is desired in a magnetic field, we need to have a constant torque. The couple would be approximately constant if the plane of the coil were always parallel to the magnetic field. This is achieved by making the pole pieces of the magnet curved to give a radial field.

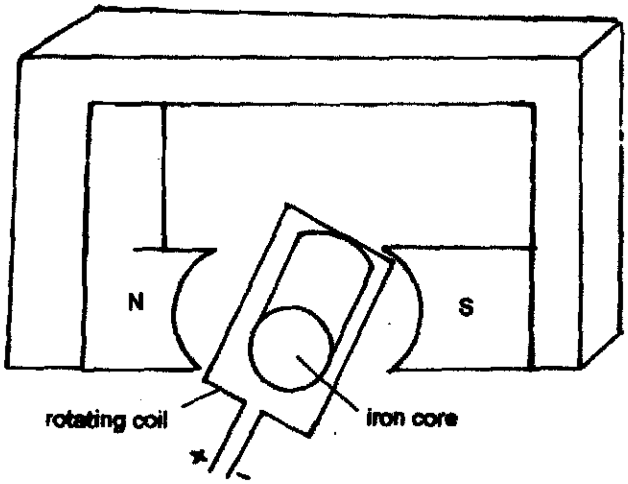


Fig 18.27 : Constant torque on a coil.

If inside the loop or a coil a soft iron core in placed, this would make the magnetic field stronger, hence make the torque greater (Fig. 10.27).

Perhaps, a more simple way of understanding the rotation of a coil in a magnetic field is to remember that as soon as the current flows through the coil, it becomes a magnet. If it is free to move it rotates until the S - pole of the coil is opposite to the N-pole of the magnet and vice versa.

18.6.4 Galvanometer

From what we have learnt so far, we can think of an instrument to detect and measure current in any circuit. A divice doing precisely this is called a galvanomenter.

The principle of a galvanometer is that when a *current carrying coil is placed in a magnetic field it experiences a torque.*

Construction : It consists of a coil wound on a soft iron frame. A soft iron cylinder is placed inside the coil. The assembly is supported on two pivots attached to springs with a pointer. This is placed between the radial poles of a horse shoe magnet, see Fig. 18.28.

Theory : When current is passed through the coil, it rotates due to the torque acting on it. The spring sets up a restoring force and hence, a restoring torque.

If α is the angle of twist and k in the restoring torque per unit twist or *torseonal constant.*

$$NBIA \sin\theta = K\alpha \qquad \{\theta = 90° \text{ for radial field}\}$$

$$NBIA = K\alpha \qquad ...(18.16)$$

or $$\frac{INBA}{K} = \alpha$$

$$I = \frac{K}{NBA}\alpha = G\alpha\,; \quad \text{Where, } G = \frac{K}{NBA} \text{ is called the } \textit{galvanometer constant}$$

or $\alpha \times I$ ....(18.17)

i.e α is proportional to I

Deflection produced in a galvanometer is proportional to the current flowing through it provided N, **B**, A and K are constant.

$$\frac{\alpha}{I}$$ is known as current sensitivity.

It is defined as the diflection of the coil per unit current. The more the current, stronger the torque and the coil turns more.

Galvanometers can be constructed to respond to very small current of the order of 0.1 microampere (10^{-7} A).

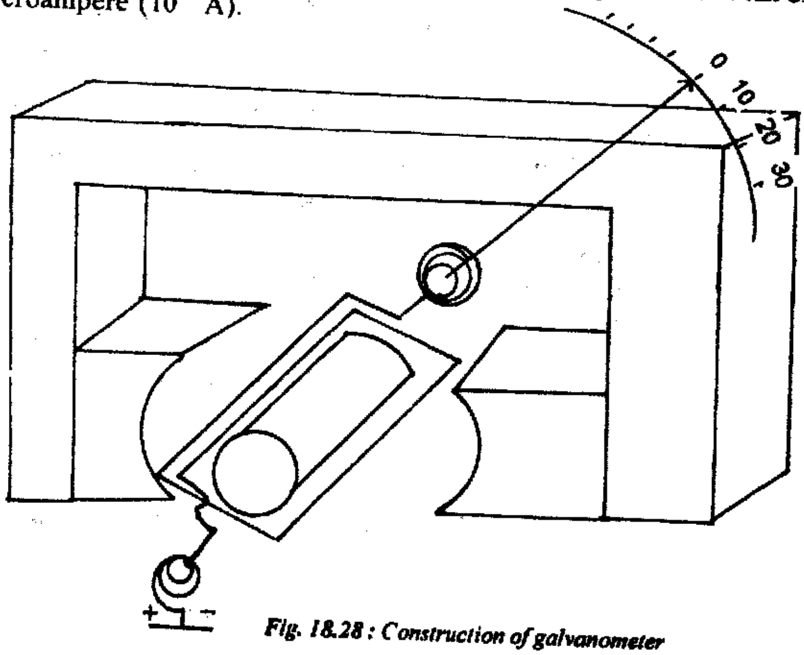


Fig. 18.28 : Construction of galvanometer

Condition for a sensitive galvanometer: In order to have a more sensitive galvanometer,

1. *N should be large,*
2. ***B** should be large and uniform,*
3. *face area A of the coild should be large,*
4. *K should be small.*

The values of N and A cannot be increased beyond a certain limit. Large values of N and A will increase the electrical and inertial resistance and the size of the galvanometer. **B** can be increased using a strong horse shoe magnet and by mounting the coil on a soft iron core.

The value of K can be decreased by the material such as quartz or phospher bronze.

Shunt : *Shunt is a low resistance connected in parallel with the galvanometer.* It is used to protect the galvanometer from strong

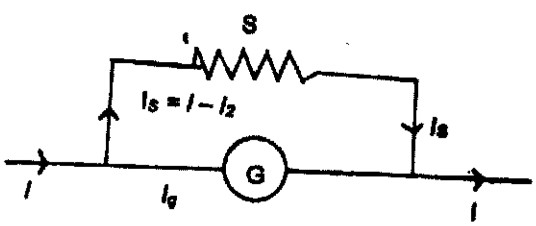


Fig. 18.29 : Shunt resistance connected to a galvanometer

currents. A strong current may damage the galvanometer by producing a large torque. To over come this, a low resistance (i.e. shunt) is connected in parallel with the coil. The major portion of the current passes through this low resistance (i.e. shunt) and only a small portion passes through the instrument. Due to this the coil remains safe.(See Fig. 18.29).

Current through the galvanometer circuit

Let I is the total current in the circuit, G_i is resistance of the galvanometer, S is resistance of the shunt, I_g is current through galvanometer, and I_s current through the shunt. From your knowledge in the lesson 16, we have,

$$I = I_s + I_g$$

$$I_g G = I_s S$$

$$I_g G = (I - I_g) S$$

$$\text{or, } I_g = \frac{(I - I_g)S}{G_i} \qquad \text{...(18.17)}$$

$$\text{or, } I_s = \frac{I_g . G}{S} = I\{\frac{G}{G + S}\} \qquad \text{....(18.18)}$$

16.6.5 Ammenter and voltmeter

(a) Ammeter : An Ammeter is a low resistance galvanometer. Its scale is calibrated to give the value of current in the circuit. A galvanometer can be converted into an ammeter by shunting it. For this a low resistance wire is connected in parallel with the galvanometer. The resistance of the shunt depends on the range of the ammeter and can be calculated as follows,

Let, m = resistance of galvanometer.
N = number of scale divisions in the galvanometer.
K = figure of merit or current for one scale deflection in the galvanometer.

Then, current which produces full scale deflection in the galvanometer is,

$$I_g = NK.$$

Let I be the maximum current to be measured by the galvanometer.

Refer to Fig. 18.29 and using eq. (18.17) we can get,

$$S = \frac{I_g G}{(I - I_g)} \qquad \text{...(18.19)}$$

Where S is the shunt resistance which can be calculated using eq. (18.18).

As G and S are in parallel to each other, therefore the effective resistance R_A of the ammeter,

$$\frac{1}{R_A} = \frac{1}{G} + \frac{1}{S}$$

$$= \frac{S + G}{GS}$$

$$R_A = \frac{S + G}{GS}$$

As *the shunt resistance is small, the combined resistance of the galvanometer and the shunt is very low and, hence, ammeter resistance is lower than the galvanometer.* An ideal ammeter has zero resistaance. It is always connected in series with the circuit so that all the current passes through it without increasing the circuit resistance.

(b) Voltmeter : A voltmeter is a high resistance galvanometer. It is used to measure the potential difference between two points in a circuit.

A galvanometer can be converted into a voltmeter by connecting a suitable high resistance in series with the galvanometer as shown in Fig 18.30. The value of the resistance depends upon the range of voltmeter and can be calculated as follows.

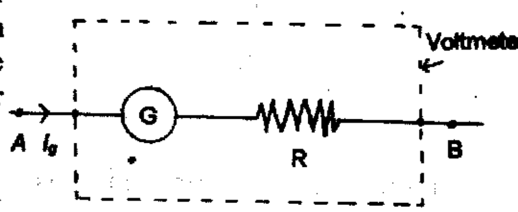


Fig. 18.30 : Galvanometer as a voltmeter

A high resistance, say R is connected in series with the galvanomter coil.
If the potential difference across AB is V volt,

Total resistance of the voltmeter = $G + R$

From Ohm's law

$$I_g\,(G + R) = V$$

$$G + R = \frac{V}{I_g}$$

$$\Rightarrow \boxed{R = \frac{V}{I_g} - G} \qquad ...(18.21)$$

This means, if a resistance of R is connected in series with the coil of the galvanometer, it works as a voltmeter of range 0-V volts.

Now, the same scale of the galvanometer which was recording the maximum potential $I_g G$ before conversion will record the potential V after conversion into voltmeter. The scale can be calibrated accordingly. The resistance of the voltmeter is higher than the galvanometer. Effective resistance of the voltmeter,

$$\boxed{R_{eff} = G + R}$$

The resistance of an ideal voltmeter is infinity, it is connected is parralel across the points, whose potential difference is to be found in a circuit. It is then expected not to draw any current and yet the galvanometer coil to deflect. Seems quite impossible? Think about it.

Example 18.6 : *A circular coil of 30 turns and radius 8.0 cm. carrying a current of 6.0A is suspended vertically in a uniform horizontal magnetic field of magnitude 1.0 T. The field lines make an angle of 90⁰ with the normal to the coil. Calculate the magnitude of the counter torque that must be applied to prevent the coil from turning.*

Solution : $N = 30$, $I = 6.0$ A, $B = 1.0$ T,
$\theta = 90^0$ $r = 8.0$ cm $= 8 \times 10^{-2}$ m

Area (A) of the coil $= \pi r^2 = \frac{22}{7} \times (8 \times 10^{-2})^2$
$= 2.01 \times 10^{-2}$ m^2

Torque $= N I B A \sin\theta$

$= 30 \times 6 \times 1.0 \times (2.01 \times 10^{-2}) \times \sin 90°$

$= 30 \times 6 \times (2.01 \times 10^{-2})$

$= 3.61$ Nm

Example 18.7: *A galvanometer with a coil of resistance 12.0 Ω shows a full scale deflection for a current of 2.5 mA. How will you convert the meter into*
(a) an ammeter of range 0 - 2A?
(b) voltmeter of range 0 - 10 volt?

Solution : (a) $G = 12.0\ \Omega$. $I_g = 2.5$ mA $= 2.5 \times 10^{-3}$ A,
$I = 2$ A, $S = ?$

$$S = \left(\frac{I_g}{I - I_g}\right) G$$

$$= \frac{2.5 \times 10^{-3}}{2 - 2.5 \times 10^{-3}} \times 12$$

$$= 15 \times 10^{-3}\ \Omega$$

Thus, for converting a galvanometer, a shunt of 15×10^{-3} Ω resistance should be connected in parallel to the coil.

(b) For conversion into voltmeter, let R be the resistance to be connected in series.

$$R = \frac{V}{I_g} - G$$

$$= \frac{10}{2.5 \times 10^{-3}} - 12$$

$$= 4000 - 12\ \Omega$$

$$= 3988\ \Omega$$

Thus, a resistance of 3988 Ω should be connected in series to convert into voltmeter.

INTEXT QUESTIONS 18.4

1. *What is radial magnetic field?*

   ....

2. *What is the main function of a soft iron core used in a moving coil galvanometer?*

   ....

3. *Which one has the lowest resistance – ammeter, voltmeter and galvanometer, explain?*

   ....

4. *A galvanometer having a coil of resistance 20 Ω needs 20 mA current for full scale deflection. In order to pass a maximum of 3A through the galvanometer, what resistance should be added and how?*

   ....

18.7 WHAT YOU HAVE LEARNT

- Every current carrying conductor has a magnetic field around it.
- The value of magnetic field strength is given by Biot Savart's Law.

  $$\Delta \mathbf{B} = \frac{\mu_o I}{4\pi} \frac{\Delta l \sin\theta}{r^2}$$

  The direction of magnetic field is given by right hand grip rule.
- Unit of magnetic field is tesla and $1T = 1NA^{1} m^{-1}$.

  Field at the centre for a flat coil is

  $$\mathbf{B} = \frac{\mu_o I}{r^2}$$

- Ampere's circuital law also gives the magnitude of the magnetic field around a conductor.

  $$\oint \mathbf{B}.dl = \mu_o I$$

  using. this **B** due to a toroid and solenoid are calculated $= \mu_o nI$

  n = number of turns per unit lenght for a long $\{l > r\}$ solenoid

  The field at the edges is $= \frac{\mu_o nI}{2}$
- Moving charges have a magnetic field around them.
- A mechanised force acts on a current carrrying conductor in a magnetic field.
- The Lorentz force on a moving charge q is $\mathbf{F}=q(v \times \mathbf{B})$ and its direction is given by right hand palm rule.
- The mechanical force on a wire of lenght L and carrying a current of I in a magetic field $\mathbf{B}$ is $\mathbf{F} = BIL$
- Mutual force per unit length between parallel striaght conductors with currents I_1 I_2 is given by

  $$\frac{\mathbf{F}}{L} = \frac{\mu_o I_1 I_2}{2\pi r}$$

- A charged particle traces a circular path if it enters a magnetic field at right angles

  Radius of the path $R = \frac{mv}{q\mathbf{B}}$

- A current loop behaves like a magnetic dipole.
- A current carrying coil placed in magnetic field expriences a torque given by

$$\tau = N\,\mathbf{B}IA\sin\theta$$
$$\tau = N\,\mathbf{B}IA,\ \text{if}\ \theta = 90^{\circ}$$

- Galvanometer is an instrument used to detect electric current in a circuit.
- An ammeter is a sunted galvanometer and voltmeter is a galvanometer with a high resistance in series. Current is measured by an ammeter and potential difference by voltmeter.

18.8 TERMINAL QUESTIONS

1. How will you show that a current carrying conductor has a magnetic field arround it? How will you find its magnitude and direction at a particular place?
2. A force acts upon a charged particle moving in a magnetic field, but this force does not change the speed of the particle. Why ?
3. At any instant a charged particle is moving parallel to a long, straight current carrying wire. Does it experience any force?
4. A current of 10 ampere is flowing through a wire. It is kept perpendicular to a magnetic field of 5T. Find the force on its 1/10 m length.
5. A long straight wire carries a current of 12 amperes. Calculate the intensity of the magnetic field at a distance of 48 cm from it.
6. Two parallel wires, each 3m long, are situated at a distance of 0.05m from each other. A current of 5A flows in each of the wires in the same direction. How much force will act on the wires? What will be its nature?
7. The magnetic field at the centre of a 50cm long solenoid is 4.0×10^{-2} $NA^{-1}\,m^{-1}$ when a current of 8.0A flows through it, find the number of turns in the solenoid.
8. Of the two identical galvanometers one is to be converted into an ammeter and the other into a milli - ammter. Which of the shunts will be of a larger resistance?
9. The resistance of a galvanometer is 20Ω and gives a full scale deflction for 0.005A. Find the value of shunt required to change it into an ammeter to measure 1A. What is the resistance of the ammeter?
10. An electron is moving in a circular orbit of radius 5×10^{-11} m at the rate of 7.0×10^{15} revolutions per sec. Calculate the magnetic field B at the centre of the orbit.
11. Calculate the magnetic field at the centre of a flat circular coil containing 200 turns, of radius 0.16m and carrying a current of 4.8 ampere.
12. See the following Fig. 18.31 and calculate the magnetic field at A, B and C.

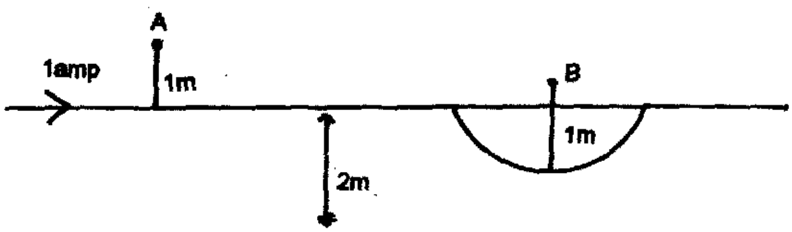


Fig. 18.31

CHECK YOUR ANSWERS

Intext questions 18.1

1. (i) electrical (ii) magnetic
2. Conducters are neutral and have no net electrical field. The thermal electrons cancel the magnetic effect produced by them due to random motion, hence no net magnetic field.
3. In first case length of wire $\ell_1 = 2\pi r_1$ In second case length of wire $\ell_2 = 2(2\pi r_2)$

   But $\ell_1 = \ell_2 \therefore r_1 = r_2$

   $\therefore$ Using $B = \frac{\mu_o I}{2r}$

   $$\frac{B_1}{B_2} = \frac{r_2}{r_1} = \frac{r_2}{2(2r_2)} = \frac{1}{4}$$

   Hence, $B_2 = 4B_1$

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

   $B \ \alpha \ \mu o$ (material)

   $\alpha \ I$ (current)

   $\alpha \ \frac{1}{r}$ (– distance from the wire)

5. Field at C due to straight wire $B = \frac{\mu_o I}{2\pi r}$

   $$= \frac{4\pi \times 10^{-7} \times 8}{2\pi \times 10 \times 10^{-2}}$$

   $$= 16 \times 10^{-6}\ NA^{-1}m^{-1}$$

   Field due to the coil $B = \frac{\mu_o I}{2r}$

   $$= 16\pi \times 10^{-6} NA^{-1}m^{-1}$$

   Net field = B1 – B

   $$= (\frac{22}{7} - 1)(16 \times 10^{-6})$$

   $$= 34.3 \times 10^{-6} T$$

Intext questions 18.2

1. C
2. Both give B value due to current in conductors.
3. (i) A, (ii) C, (iii) B.
4. $B = \frac{\mu_o N}{l} I$, Therefore, putting the given values we get $N = 5.3 \times 10^{-3}$ T

Intext questions 18.3

1 $+p \uparrow \quad \downarrow e^-$ therefore repulsion

2. The force exerted by a magnetic field on a moving charge is perpendicular to the motion of the charge, hence the work done by the force on the charge is = 0. So the KE of the charge does not change. In an electric field the deflection is in the direction of the field, hance, accelerates on a straight track.
3. The direction of current in each turn of the spring is the same. Since parrallel currents in the same direction exert force of attraction, the turns will come closer and the body shall be lifted upward, whatever be the direction of the current in the spring.
4. In series, the current in them will be in opposite directions, hence they repel each other moving farther apart. In parrallel, the currents in them will be in the same direction. Hence they will attract each other and come closer.

Intext Question 18.4

1. Radial magnetic field is one in which **B** remains constant for the plane of the coil always lies in the direction of the magnetic field.
2. (i) This makes the magnetic field radial. In such a magnetic field the plane of the coil is always parallel to the direction of magnetic field.
   (ii) This increases the strength of magnetic field due to the crowding of the magnetic lines of force through the soft iron core, which in turn increases the sensitivity of the glavanometer.
3. Ammeter has the lowest resistance where as voltmeter has the highest resistance.
4. Using, $I_g = \dfrac{S}{S+G} I$

   S = 0.3