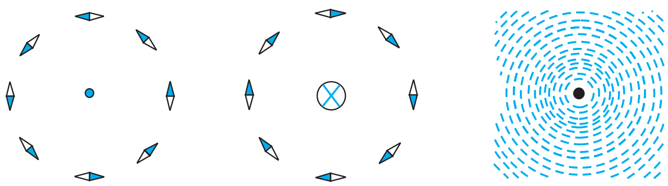
James Maxwell who then realised that light was electromagnetic waves. Radio waves were discovered by Hertz, and produced by J.C.Bose and G. Marconi by the end of the 19th century. A remarkable scientific and technological progress has taken place in the 20th century. This is due to our increased understanding of electromagnetism and the invention of devices for production, amplification, transmission and detection of electromagnetic waves.



(a) (b) (c)

FIGURE 4.1 The magnetic field due to a straight long current-carrying wire. The wire is perpendicular to the plane of the paper. A ring of compass needles surrounds the wire. The orientation of the needles is shown when (a) the current emerges out of the plane of the paper, (b) the current moves into the plane of the paper. (c) The arrangement of iron filings around the wire. The darkened ends of the needle represent north poles. The effect of the earth's magnetic field is neglected.

In this chapter, we will see how magnetic field exerts forces on moving charged particles, like electrons, protons, and current-carrying wires. We shall also learn how currents produce magnetic fields. We shall see how particles can be accelerated to very high energies in a cyclotron. We shall study how currents and voltages are detected by a galvanometer.

In this and subsequent Chapter on magnetism, we adopt the following convention: A current or a field (electric or magnetic) emerging out of the plane of the paper is depicted by a dot (⊙). A current or a field going into the plane of the paper is depicted by a cross (⊗)*. Figures. 4.1(a) and 4.1(b) correspond to these two situations, respectively.

HANS CHRISTIAN OERSTED (1777–1851)

Hans Christian Oersted (1777–1851) Danish physicist and chemist, professor at Copenhagen. He observed that a compass needle suffers a deflection when placed near a wire carrying an electric current. This discovery gave the first empirical evidence of a connection between electric and magnetic phenomena.

4.2 Magnetic Force

4.2.1 Sources and fields

Before we introduce the concept of a magnetic field **B**, we shall recapitulate what we have learnt in Chapter 1 about the electric field **E.** We have seen that the interaction between two charges can be considered in two stages. The charge Q, the source of the field, produces an electric field **E**, where

* A dot appears like the tip of an arrow pointed at you, a cross is like the feathered tail of an arrow moving away from you.

HENDRIK ANTOON LORENTZ (1853 – 1928)

Hendrik Antoon Lorentz (1853 – 1928) Dutch theoretical physicist, professor at Leiden. He investigated the relationship between electricity, magnetism, and mechanics. In order to explain the observed effect of magnetic fields on emitters of light (Zeeman effect), he postulated the existence of electric charges in the atom, for which he was awarded the Nobel Prize in 1902. He derived a set of transformation equations (known after him, as Lorentz transformation equations) by some tangled mathematical arguments, but he was not aware that these equations hinge on a new concept of space and time.

$$\mathbf{E} = Q\ \hat{\mathbf{r}} \,/\, (4\pi\varepsilon_0)r^2 \tag{4.1}$$

where $\hat{\mathbf{r}}$ is unit vector along **r**, and the field **E** is a vector field. A charge q interacts with this field and experiences a force **F** given by

$$\mathbf{F} = q\ \mathbf{E} = q\,Q\ \hat{\mathbf{r}} \,/\, (4\pi\varepsilon_0)\ r^2 \tag{4.2}$$

As pointed out in the Chapter 1, the field **E** is not just an artefact but has a physical role. It can convey energy and momentum and is not established instantaneously but takes finite time to propagate. The concept of a field was specially stressed by Faraday and was incorporated by Maxwell in his unification of electricity and magnetism. In addition to depending on each point in space, it can also vary with time, i.e., be a function of time. In our discussions in this chapter, we will assume that the fields do not change with time.

The field at a particular point can be due to one or more charges. If there are more charges the fields add vectorially. You have already learnt in Chapter 1 that this is called the principle of superposition. Once the field is known, the force on a test charge is given by Eq. (4.2).

Just as static charges produce an electric field, the currents or moving charges produce (in addition) a magnetic field, denoted by **B (r)**, again a vector field. It has several basic properties identical to the electric field. It is defined at each point in space (and can in addition depend on time). Experimentally, it is found to obey the principle of superposition: *the magnetic field of several sources is the vector addition of magnetic field of each individual source.*

4.2.2 Magnetic Field, Lorentz Force

Let us suppose that there is a point charge q (moving with a velocity **v** and, located at **r** at a given time t) in presence of both the electric field **E (r)** and the magnetic field **B (r)**. The force on an electric charge q due to both of them can be written as

$$\mathbf{F} = q\,[\,\mathbf{E}\,(\mathbf{r}) + \mathbf{v} \times \mathbf{B}\,(\mathbf{r})] \equiv \mathbf{F}_{electric} + \mathbf{F}_{magnetic} \tag{4.3}$$

This force was given first by H.A. Lorentz based on the extensive experiments of Ampere and others. It is called the *Lorentz force*. You have already studied in detail the force due to the electric field. If we look at the interaction with the magnetic field, we find the following features.

(i) It depends on q, **v** and **B** (charge of the particle, the velocity and the magnetic field). *Force on a negative charge is opposite to that on a positive charge.*

(ii) The magnetic force $q\,[\,\mathbf{v} \times \mathbf{B}\,]$ includes a vector product of velocity and magnetic field. The vector product makes the force due to magnetic field vanish (become zero) if velocity and magnetic field are parallel or anti-parallel. The force acts in a (sideways) direction perpendicular to both the velocity and the magnetic field. Its direction is given by the screw rule or right hand rule for vector (or cross) product as illustrated in Fig. 4.2.

(iii) The magnetic force is zero if charge is not moving (as then $|\mathbf{v}| = 0$). Only a moving charge feels the magnetic force.

The expression for the magnetic force helps us to define the unit of the magnetic field, if one takes q, $\mathbf{F}$ and $\mathbf{v}$, all to be unity in the force equation $\mathbf{F} = q\,[\,\mathbf{v} \times \mathbf{B}] = q\,v\,B \sin\theta\ \hat{\mathbf{n}}$, where θ is the angle between $\mathbf{v}$ and $\mathbf{B}$ [see Fig. 4.2 (a)]. The magnitude of magnetic field B is 1 SI unit, when the force acting on a unit charge (1 C), moving perpendicular to $\mathbf{B}$ with a speed 1m/s, is one newton.

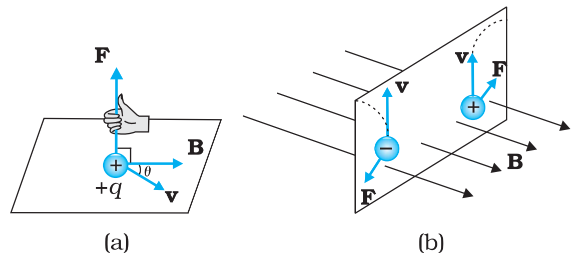


FIGURE 4.2 The direction of the magnetic force acting on a charged particle. (a) The force on a positively charged particle with velocity **v** and making an angle θ with the magnetic field **B** is given by the right-hand rule. (b) A moving charged particle q is deflected in an opposite sense to $-q$ in the presence of magnetic field.

Dimensionally, we have $[B] = [F/qv]$ and the unit of **B** are Newton second / (coulomb metre). This unit is called *tesla* (T) named after Nikola Tesla (1856 – 1943). Tesla is a rather large unit. A smaller unit (non-SI) called *gauss* ($=10^{-4}$ tesla) is also often used. The earth's magnetic field is about 3.6×10^{-5} T. Table 4.1 lists magnetic fields over a wide range in the universe.

TABLE 4.1 ORDER OF MAGNITUDES OF MAGNETIC FIELDS IN A VARIETY OF PHYSICAL SITUATIONS

Physical situation	Magnitude of B (in tesla)
Surface of a neutron star	10^{8}
Typical large field in a laboratory	1
Near a small bar magnet	10^{-2}
On the earth's surface	10^{-5}
Human nerve fibre	10^{-10}
Interstellar space	10^{-12}

4.2.3 Magnetic force on a current-carrying conductor

We can extend the analysis for force due to magnetic field on a single moving charge to a straight rod carrying current. Consider a rod of a uniform cross-sectional area A and length l. We shall assume one kind of mobile carriers as in a conductor (here electrons). Let the number density of these mobile charge carriers in it be n. Then the total number of mobile charge carriers in it is nAl. For a steady current I in this conducting rod, we may assume that each mobile carrier has an average drift velocity $\mathbf{v}_d$ (see Chapter 3). In the presence of an external magnetic field $\mathbf{B}$, the force on these carriers is:

$$\mathbf{F} = (nAl)q\,\mathbf{v}_d \times \mathbf{B}$$

where q is the value of the charge on a carrier. Now $nq\mathbf{v}_d$ is the current density $\mathbf{j}$ and $|(nq\,\mathbf{v}_d)|A$ is the current I (see Chapter 3 for the discussion of current and current density). Thus,

$$\mathbf{F} = [(nqe\mathbf{v}_d)Al] \times \mathbf{B} = [\,\mathbf{j}Al\,] \times \mathbf{B}$$

$$= I\mathbf{l} \times \mathbf{B} \qquad (4.4)$$

where $\mathbf{l}$ is a vector of magnitude l, the length of the rod, and with a direction identical to the current I. Note that the current I is not a vector. In the last step leading to Eq. (4.4), we have transferred the vector sign from $\mathbf{j}$ to $\mathbf{l}$.

Equation (4.4) holds for a straight rod. In this equation, $\mathbf{B}$ is the external magnetic field. It is not the field produced by the current-carrying rod. If the wire has an arbitrary shape we can calculate the Lorentz force on it by considering it as a collection of linear strips $\mathrm{d}\mathbf{l}_j$ and summing

$$\mathbf{F} = \sum_j I\mathrm{d}\mathbf{l}_j \times \mathbf{B}$$

This summation can be converted to an integral in most cases.

ON PERMITTIVITY AND PERMEABILITY

In the universal law of gravitation, we say that any two point masses exert a force on each other which is proportional to the product of the masses m_1, m_2 and inversely proportional to the square of the distance r between them. We write it as $F = Gm_1m_2/r^2$ where G is the universal constant of gravitation. Similarly in Coulomb's law of electrostatics we write the force between two point charges q_1, q_2, separated by a distance r as $F = kq_1q_2/r^2$ where k is a constant of proportionality. In SI units, k is taken as $1/4\pi\varepsilon$ where ε is the permittivity of the medium. Also in magnetism, we get another constant, which in SI units, is taken as $\propto/4\pi$ where $\propto$ is the permeability of the medium.

Although G, ε and $\propto$ arise as proportionality constants, there is a difference between gravitational force and electromagnetic force. While the gravitational force does not depend on the intervening medium, the electromagnetic force depends on the medium between the two charges or magnets. Hence while G is a universal constant, ε and $\propto$ depend on the medium. They have different values for different media. The product $\varepsilon\propto$ turns out to be related to the speed v of electromagnetic radiation in the medium through $\varepsilon\propto = 1/\,v^2$.

Electric permittivity ε is a physical quantity that describes how an electric field affects and is affected by a medium. It is determined by the ability of a material to polarise in response to an applied field, and thereby to cancel, partially, the field inside the material. Similarly, magnetic permeability $\propto$ is the ability of a substance to acquire magnetisation in magnetic fields. It is a measure of the extent to which magnetic field can penetrate matter.

EXAMPLE 4.1

Example 4.1 A straight wire of mass 200 g and length 1.5 m carries a current of 2 A. It is suspended in mid-air by a uniform horizontal magnetic field **B** (Fig. 4.3). What is the magnitude of the magnetic field?

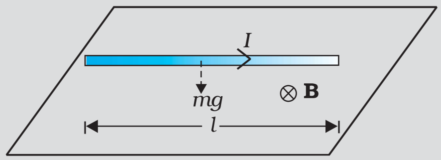


FIGURE 4.3

Solution From Eq. (4.4), we find that there is an upward force **F**, of magnitude IlB,. For mid-air suspension, this must be balanced by the force due to gravity:

$$m\,g = I\,lB$$

$$B = \frac{m\,g}{I\,l}$$

$$= \frac{0.2 \cdot 9.8}{2 \cdot 1.5} = 0.65 \text{ T}$$

Note that it would have been sufficient to specify m/l, the mass per unit length of the wire. The earth's magnetic field is approximately 4×10^{-5} T and we have ignored it.

EXAMPLE 4.1

Example 4.2 If the magnetic field is parallel to the positive y-axis and the charged particle is moving along the positive x-axis (Fig. 4.4), which way would the Lorentz force be for (a) an electron (negative charge), (b) a proton (positive charge).

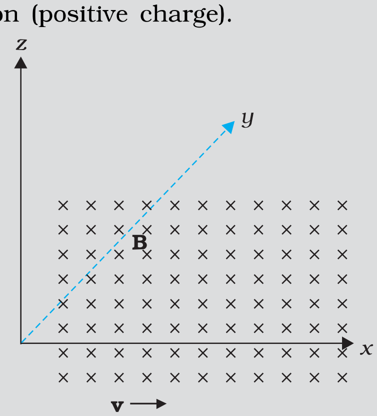


FIGURE 4.4

Solution The velocity **v** of particle is along the x-axis, while **B**, the magnetic field is along the y-axis, so **v × B** is along the z-axis (screw rule or right-hand thumb rule). So, (a) for electron it will be along $-z$ axis. (b) for a positive charge (proton) the force is along $+z$ axis.

EXAMPLE 4.2

PHYSICS

Charged particles moving in a magnetic field.
Interactive demonstration:
http://www.phys.hawaii.edu/~teb/optics/java/partmagn/index.html

4.3 Motion in a Magnetic Field

We will now consider, in greater detail, the motion of a charge moving in a magnetic field. We have learnt in Mechanics (see Class XI book, Chapter 6) that a force on a particle does work if the force has a component along (or opposed to) the direction of motion of the particle. In the case of motion

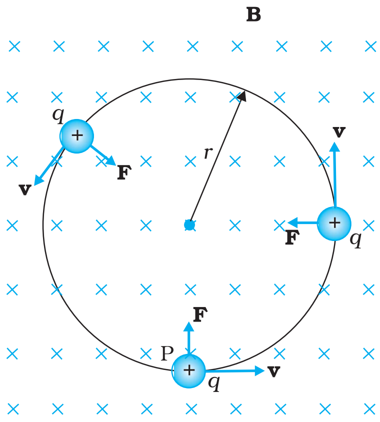


FIGURE 4.5 Circular motion

of a charge in a magnetic field, the magnetic force is perpendicular to the velocity of the particle. So no work is done and no change in the magnitude of the velocity is produced (though the direction of momentum may be changed). [Notice that this is unlike the force due to an electric field, $q\mathbf{E}$, which *can* have a component parallel (or antiparallel) to motion and thus can transfer energy in addition to momentum.]

We shall consider motion of a charged particle in a *uniform* magnetic field. First consider the case of $\mathbf{v}$ perpendicular to $\mathbf{B}$. The perpendicular force, $q\,\mathbf{v} \times \mathbf{B}$, acts as a centripetal force and produces a circular motion perpendicular to the magnetic field. *The particle will describe a circle if* $\mathbf{v}$ *and* $\mathbf{B}$ *are perpendicular to each other* (Fig. 4.5).

If velocity has a component along $\mathbf{B}$, this component remains unchanged as the motion along the magnetic field will not be affected by the magnetic field. The motion in a plane perpendicular to $\mathbf{B}$ is as before a circular one, thereby producing a *helical motion* (Fig. 4.6).

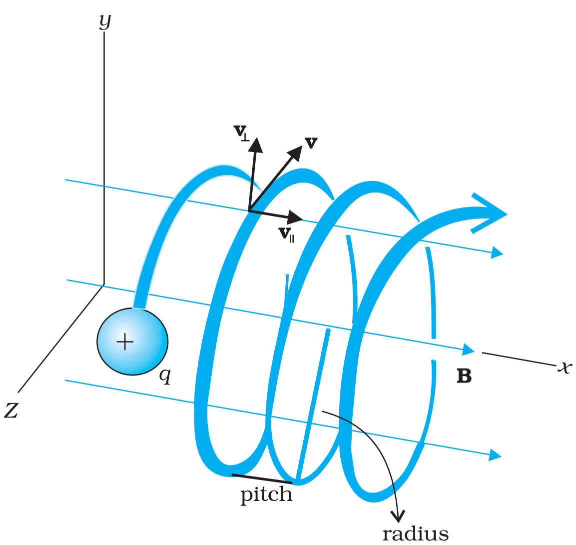


FIGURE 4.6 Helical motion

You have already learnt in earlier classes (See Class XI, Chapter 4) that if r is the radius of the circular path of a particle, then a force of $m\,v^2 / r$, acts perpendicular to the path towards the centre of the circle, and is called the centripetal force. If the velocity $\mathbf{v}$ is perpendicular to the magnetic field $\mathbf{B}$, the magnetic force is perpendicular to both $\mathbf{v}$ and $\mathbf{B}$ and acts like a centripetal force. It has a magnitude $q\,v\,B$. Equating the two expressions for centripetal force,

$$m\,v^2/r = q\,v\,B, \text{ which gives}$$

$$r = m\,v\,/\,qB \qquad (4.5)$$

for the radius of the circle described by the charged particle. The larger the momentum, the larger is the radius and bigger the circle described. If ω is the angular frequency, then $v = \omega\, r$. So,

$$\omega = 2\pi\,\nu = q\,B/\,m \qquad [4.6(a)]$$

which is independent of the velocity or energy . Here ν is the frequency of rotation. The independence of ν from energy has important application in the design of a cyclotron (see Section 4.4.2).

The time taken for one revolution is $T = 2\pi/\omega \equiv 1/\nu$. If there is a component of the velocity parallel to the magnetic field (denoted by $v_{||}$), it will make the particle move along the field and the path of the particle would be a helical one (Fig. 4.6). The distance moved along the magnetic field in one rotation is called pitch p. Using Eq. [4.6 (a)], we have

$$p = v_{||}T = 2\pi m\,v_{||}\,/\,q\,B \qquad [4.6(b)]$$

The radius of the circular component of motion is called the *radius* of the *helix*.

Example 4.3 What is the radius of the path of an electron (mass 9×10^{-31} kg and charge 1.6×10^{-19} C) moving at a speed of 3×10^{7} m/s in a magnetic field of 6×10^{-4} T perpendicular to it? What is its frequency? Calculate its energy in keV. (1 eV = 1.6×10^{-19} J).

Solution Using Eq. (4.5) we find

$r = mv / (qB) = 9 \times 10^{-31}\ \text{kg} \times 3 \times 10^{7}\ \text{m s}^{-1} / (1.6 \times 10^{-19}\ \text{C} \times 6 \times 10^{-4}\ \text{T})$

$= 26 \times 10^{-2}\ \text{m} = 26\ \text{cm}$

$\nu = v / (2\pi r) = 2\times10^{6}\ \text{s}^{-1} = 2\times10^{6}\ \text{Hz} = 2\ \text{MHz}.$

$E = (½)mv^{2} = (½)\ 9 \times 10^{-31}\ \text{kg} \times 9 \times 10^{14}\ \text{m}^2/\text{s}^2 = 40.5 \times 10^{-17}\ \text{J}$

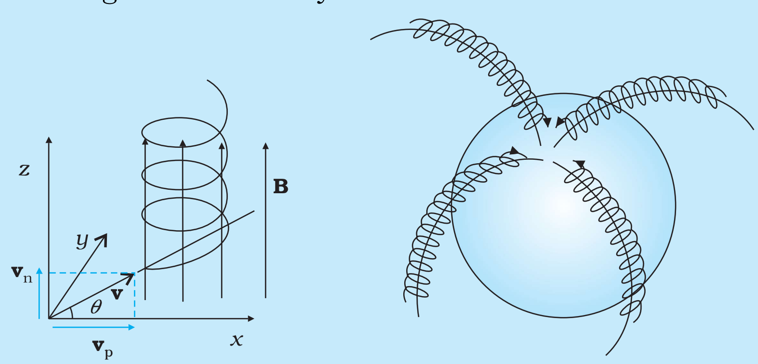
$\approx 4\times10^{-16}\ \text{J} = 2.5\ \text{keV}.$

EXAMPLE 4.3

HELICAL MOTION OF CHARGED PARTICLES AND AURORA BORIOLIS

In polar regions like Alaska and Northern Canada, a splendid display of colours is seen in the sky. The appearance of dancing green pink lights is fascinating, and equally puzzling. An explanation of this natural phenomenon is now found in physics, in terms of what we have studied here.

Consider a charged particle of mass m and charge q, entering a region of magnetic field **B** with an initial velocity **v**. Let this velocity have a component $\mathbf{v}_p$ parallel to the magnetic field and a component $\mathbf{v}_n$ normal to it. There is no force on a charged particle in the direction of the field. Hence the particle continues to travel with the velocity $\mathbf{v}_p$ parallel to the field. The normal component $\mathbf{v}_n$ of the particle results in a Lorentz force ($\mathbf{v}_n \times \mathbf{B}$) which is perpendicular to both $\mathbf{v}_n$ and **B**. As seen in Section 4.3.1 the particle thus has a tendency to perform a circular motion in a plane perpendicular to the magnetic field. When this is coupled with the velocity parallel to the field, the resulting trajectory will be a helix along the magnetic field line, as shown in Figure (a) here. Even if the field line bends, the helically moving particle is trapped and guided to move around the field line. Since the Lorentz force is normal to the velocity of each point, the field does no work on the particle and the magnitude of velocity remains the same.



(a) (b)

During a solar flare, a large number of electrons and protons are ejected from the sun. Some of them get trapped in the earth's magnetic field and move in helical paths along the field lines. The field lines come closer to each other near the magnetic poles; see figure (b). Hence the density of charges increases near the poles. These particles collide with atoms and molecules of the atmosphere. Excited oxygen atoms emit green light and excited nitrogen atoms emits pink light. This phenomenon is called *Aurora Boriolis* in physics.

4.4 Motion in Combined Electric and Magnetic Fields

4.4.1 Velocity selector

You know that a charge q moving with velocity $\mathbf{v}$ in presence of both electric and magnetic fields experiences a force given by Eq. (4.3), that is,

$$\mathbf{F} = q\,(\mathbf{E} + \boldsymbol{v} \times \mathbf{B}) = \mathbf{F}_E + \mathbf{F}_B$$

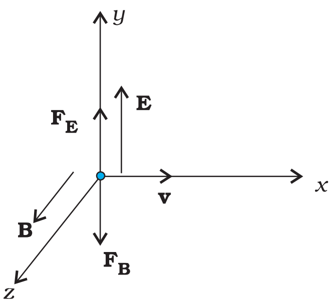


FIGURE 4.7

We shall consider the simple case in which electric and magnetic fields are perpendicular to each other and also perpendicular to the velocity of the particle, as shown in Fig. 4.7. We have,

$$\mathbf{E} = E\,\hat{\mathbf{j}},\ \mathbf{B} = B\,\hat{\mathbf{k}},\ \mathbf{v} = v\,\hat{\mathbf{i}}$$

$$\mathbf{F}_E = q\mathbf{E} = qE\,\hat{\mathbf{j}},\ \mathbf{F}_B = q\mathbf{v} \times \mathbf{B}, = q\left(v\,\hat{\mathbf{i}} \times B\hat{\mathbf{k}}\right) = -qB\,\hat{\mathbf{j}}$$

Therefore, $\mathbf{F} = q\left(E - vB\right)\hat{\mathbf{j}}$.

Thus, electric and magnetic forces are in opposite directions as shown in the figure. Suppose, we adjust the value of $\mathbf{E}$ and $\mathbf{B}$ such that magnitude of the two forces are equal. Then, total force on the charge is zero and the charge will move in the fields undeflected. This happens when,

$$qE = qvB \quad \text{or} \quad v = \frac{E}{B} \tag{4.7}$$

This condition can be used to select charged particles of a particular velocity out of a beam containing charges moving with different speeds (irrespective of their charge and mass). The crossed E and B fields, therefore, serve as a *velocity selector*. Only particles with speed E/B pass undeflected through the region of crossed fields. This method was employed by J. J. Thomson in 1897 to measure the charge to mass ratio (e/m) of an electron. The principle is also employed in Mass Spectrometer – a device that separates charged particles, usually ions, according to their charge to mass ratio.

4.4.2 Cyclotron

Cyclotron
Interactive demonstration:
http://www.phy.ntnu.edu.tw/ntnujava/viewtopic.php?t=50

The cyclotron is a machine to accelerate charged particles or ions to high energies. It was invented by E.O. Lawrence and M.S. Livingston in 1934 to investigate nuclear structure. The cyclotron uses both electric and magnetic fields in combination to increase the energy of charged particles. As the fields are perpendicular to each other they are called *crossed fields*. Cyclotron uses the fact that the frequency of revolution of the charged particle in a magnetic field is independent of its energy. The particles move most of the time inside two semicircular disc-like metal containers, D_1 and D_2, which are called *dees* as they look like the letter D. Figure 4.8 shows a schematic view of the cyclotron. Inside the metal boxes the particle is shielded and is not acted on by the electric field. The magnetic field, however, acts on the particle and makes it go round in a circular path inside a dee. Every time the particle moves from one dee to another it is acted upon by the electric field. The sign of the electric field is changed alternately in tune with the circular motion of the particle. This ensures that the particle is always accelerated by the electric field. Each time the acceleration increases the energy of the particle. As energy increases, the radius of the circular path increases. So the path is a spiral one.

The whole assembly is evacuated to minimise collisions between the ions and the air molecules. A high frequency alternating voltage is applied to the dees. In the sketch shown in Fig. 4.8, positive ions or positively charged particles (e.g., protons) are released at the centre P. They move in a semi-circular path in one of the dees and arrive in the gap between the dees in a time interval $T/2$; where T, the period of revolution, is given by Eq. (4.6),

$$T = \frac{1}{\nu_c} = \frac{2\pi m}{qB}$$

$$\text{or } \nu_c = \frac{qB}{2\pi m} \quad (4.8)$$

This frequency is called the *cyclotron frequency* for obvious reasons and is denoted by ν_c.

The frequency ν_a of the applied voltage is adjusted so that the polarity of the dees is reversed in the same time that it takes the ions to complete one half of the revolution. The requirement $\nu_a = \nu_c$ is called the *resonance condition*. The phase of the supply is adjusted so that when the positive ions arrive at the edge of D_1, D_2 is at a lower potential and the ions are accelerated across the gap. Inside the dees the particles travel in a region free of the electric field. The increase in their kinetic energy is qV each time they cross from one dee to another (V refers to the voltage across the dees at that time). From Eq. (4.5), it is clear that the radius of their path goes on increasing each time their kinetic energy increases. The ions are repeatedly accelerated across the dees until they have the required energy to have a radius approximately that of the dees. They are then deflected by a magnetic field and leave the system via an exit slit. From Eq. (4.5) we have,

$$v = \frac{qBR}{m} \quad (4.9)$$

where R is the radius of the trajectory at exit, and equals the radius of a dee.

Hence, the kinetic energy of the ions is,

$$\frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m} \quad (4.10)$$

The operation of the cyclotron is based on the fact that the time for one revolution of an ion is independent of its speed or radius of its orbit. The cyclotron is used to bombard nuclei with energetic particles, so accelerated by it, and study

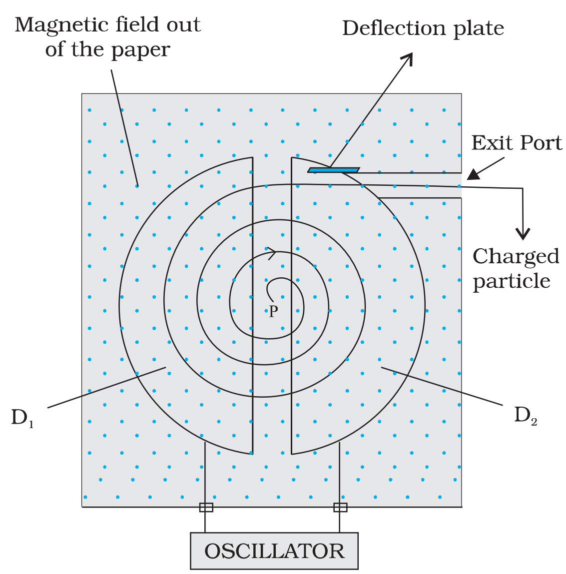


FIGURE 4.8 A schematic sketch of the cyclotron. There is a source of charged particles or ions at P which move in a circular fashion in the dees, D_1 and D_2, on account of a uniform perpendicular magnetic field B. An alternating voltage source accelerates these ions to high speeds. The ions are eventually 'extracted' at the exit port.

the resulting nuclear reactions. It is also used to implant ions into solids and modify their properties or even synthesise new materials. It is used in hospitals to produce radioactive substances which can be used in diagnosis and treatment.

EXAMPLE 4.4

Example 4.4 A cyclotron's oscillator frequency is 10 MHz. What should be the operating magnetic field for accelerating protons? If the radius of its 'dees' is 60 cm, what is the kinetic energy (in MeV) of the proton beam produced by the accelerator.

(e =1.60 × 10^{-19} C, m_p = 1.67 × 10^{-27} kg, 1 MeV = 1.6 × 10^{-13} J).

Solution The oscillator frequency should be same as proton's cyclotron frequency.

Using Eqs. (4.5) and [4.6(a)] we have

$B = 2\pi\, m\, \nu/q = 6.3 \times 1.67 \times 10^{-27} \times 10^{7} / (1.6 \times 10^{-19}) = 0.66$ T

Final velocity of protons is

$v = r \times 2\pi\, \nu = 0.6 \text{ m} \times 6.3 \times 10^{7} = 3.78 \times 10^{7}$ m/s.

$E = ½\, mv^{2} = 1.67 \times 10^{-27} \times 14.3 \times 10^{14} / (2 \times 1.6 \times 10^{-13}) = 7$ MeV.

ACCELERATORS IN INDIA

India has been an early entrant in the area of accelerator- based research. The vision of Dr. Meghnath Saha created a 37" Cyclotron in the Saha Institute of Nuclear Physics in Kolkata in 1953. This was soon followed by a series of Cockroft-Walton type of accelerators established in Tata Institute of Fundamental Research (TIFR), Mumbai, Aligarh Muslim University (AMU), Aligarh, Bose Institute, Kolkata and Andhra University, Waltair.

The sixties saw the commissioning of a number of Van de Graaff accelerators: a 5.5 MV terminal machine in Bhabha Atomic Research Centre (BARC), Mumbai (1963); a 2 MV terminal machine in Indian Institute of Technology (IIT), Kanpur; a 400 kV terminal machine in Banaras Hindu University (BHU), Varanasi; and Punjabi University, Patiala. One 66 cm Cyclotron donated by the Rochester University of USA was commissioned in Panjab University, Chandigarh. A small electron accelerator was also established in University of Pune, Pune.

In a major initiative taken in the seventies and eighties, a Variable Energy Cyclotron was built indigenously in Variable Energy Cyclotron Centre (VECC), Kolkata; 2 MV Tandem Van de Graaff accelerator was developed and built in BARC and a 14 MV Tandem Pelletron accelerator was installed in TIFR.

This was soon followed by a 15 MV Tandem Pelletron established by University Grants Commission (UGC), as an inter-university facility in Inter-University Accelerator Centre (IUAC), New Delhi; a 3 MV Tandem Pelletron in Institute of Physics, Bhubaneshwar; and two 1.7 MV Tandetrons in Atomic Minerals Directorate for Exploration and Research, Hyderabad and Indira Gandhi Centre for Atomic Research, Kalpakkam. Both TIFR and IUAC are augmenting their facilities with the addition of superconducting LINAC modules to accelerate the ions to higher energies.

Besides these ion accelerators, the Department of Atomic Energy (DAE) has developed many electron accelerators. A 2 GeV Synchrotron Radiation Source is being built in Raja Ramanna Centre for Advanced Technologies, Indore.

The Department of Atomic Energy is considering Accelerator Driven Systems (ADS) for power production and fissile material breeding as future options.