NUCLEAR PHYSICS

UNIT III

Particle Accelerators and Detectors

INTRODUCTION

A particle accelerator is a device for increasing the kinetic energy of electrically charged particles.

By the methods of acceleration can be classed into three groups:

- Direct field
- Inductive
- Resonance

According to the shape of the path of the particles, accelerators are classified as

- Linear
- Cyclic

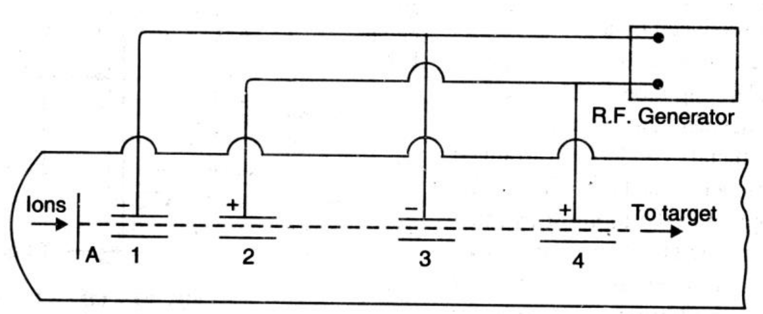
In the linear accelerators, the paths of particles are approximately straight lines; in cyclic accelerators, they are circles or spirals.

(i) In a direct field linear accelerator, a particle passes only once through an electric field with a high p.d. set up by electrostatic generators.

(ii) **Betatron** is the only accelerator of the inductive type.

(iii) In magnetic resonance accelerators, the particle being accelerated repeatedly passes through an alternating electric field along a closed path; its energy is increased in each time. A strong magnetic field is used to control the motion of particles and to return them periodically to the region of the accelerating electric field. The particles pass definite points of the alternating electric field approximately when the field is in the same phase. The simplest resonance accelerator is the **cyclotron.**

LINEAR ACCELERATOR



The Fig. shows the schematic diagram of a linear accelerator. It consists of a series of coaxial hollow metal cylinders or drifts tubes 1, 2, 3, 4, etc. They are arranged linearly in a glass vacuum chamber. The alternate cylinders are connected together, the odd-numbered cylinders being joined to one terminal, and the even-numbered ones to the second terminal of an H.F. oscillator. Thus in one-half cycle, if tubes 1 and 3 are positive, 2 and 4 will be negative. After half a cycle the polarities are reversed i.e., 1 and 3 will be negative and 2 and 4 positive. The ions are accelerated only in the gap between the tubes where they are acted upon by the electric field present in the gaps. The ions travel with constant velocity in the field-free space inside the drift tubes.

Positive ions enter along the axis of the accelerator from an ion source through an aperture A. Suppose a positive ion leaves A and is accelerated during the half-cycle, when the drift tube 1 is negative with respect to A. Let 'e' be the charge and 'm' the mass of the ion and 'V' potential of drift tube 1 with respect to A. Then velocity v_1 of the ion on reaching the drift tube is given by

$$\frac{1}{2}mv_1^2 = Ve$$

$$v_1 = \sqrt{\frac{2Ve}{m}}$$

The length of the tube 1 is so adjusted that as the positive ions come out of it, the tube has a positive potential and the next tube (tube No. 2) has a negative potential, i.e., the potentials change sign. The positive ion is again accelerated in the space between the tubes 1 and 2. On reaching the tube 2, the velocity v_2 of the positive ion is given by

$$\frac{1}{2}mv_2^2 = 2Ve$$

$$v_2 = \sqrt{2}\sqrt{\frac{2Ve}{m}} = \sqrt{2}v_1$$

This shows that v_2 is $\sqrt{2}$ times v_1. In order that this ion, on coming out of tube 2, may find tube 3 just negative and the tube 2 positive, it must take the same time to travel through the tube 2. Since $v_2 = \sqrt{2}\, v_1$, the length of tube 2 must be times the length of tube 1.

For successive accelerations in successive gaps the tubes 1, 2, 3, etc., must have lengths proportional to 1, $\sqrt{2}$, $\sqrt{3}$ etc. i.e., $l_1{:}l_2{:}l_3{:}$etc.= 1 : $\sqrt{2}$, $\sqrt{3}$: etc.

Energy of the ion:

If n = the number of gaps that the ion travels in the accelerator and v_n = the final velocity acquired by the ion, then

Velocity of the ion, as it emerges out of the n^{th} tube = $\sqrt{n}\sqrt{\frac{2Ve}{m}}$

Therefore K.E. acquired by the ion = $\frac{1}{2}mv_n^2 = nVe$

Thus the final energy of the ions depends upon (i) the total number of gaps and (ii) the energy gained in each gap.

The limitations of this accelerator are :

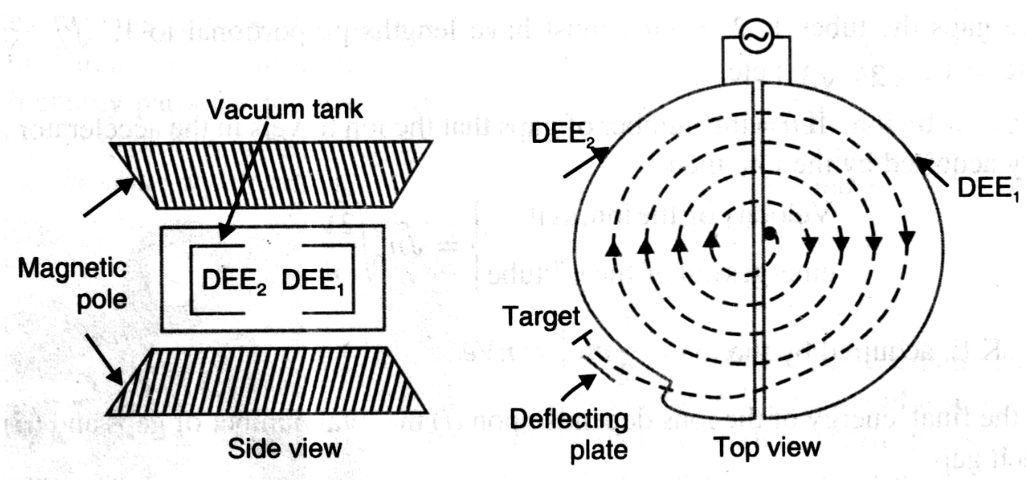
(i) The length of the accelerator becomes inconveniently large and it is difficult to maintain vacuum in a large chamber.

(ii) (ii) The ion current available is in the form of short interval impulses because the ions are injected at an appropriate moment.

CYCLOTRON

Construction

The Figure shows the cyclotron consists of two hollow semicircular metal boxes, D1, D2 called "dees". A source of ions is located near the mid-point of the gap between the "dees" . The "dees" are insulated from each other and are enclosed in another vacuum chamber. The "dees" are connected to a powerful radio-frequency oscillator. The whole apparatus is placed between the pole-pieces of a strong electromagnet. The magnetic field is perpendicular to the plane of the "dees".



Theory

Suppose a positive ion leaves the ion source at the center of the chamber at the instant when the "dees" DI and D2 are at the maximum negative and positive A.C. potentials respectively. The positive ion will be accelerated towards the negative dee DI before entering it. The ions enter the space in-side the dee with a velocity v given by $Ve = \frac{1}{2}mv^2$, where V is the applied voltage, and e and m are the charge and mass of the ion respectively. When the ion is inside the "dee" it is not accelerated since this space is field free. Inside the dee, under the action of the applied magnetic field, the ions travel in a circular path of radius r given by

$$Bev = \frac{mv^2}{r} \quad 1$$

where B = the flux density of the magnetic field. or $r = \frac{mv}{Be}$ 2

The angular velocity of the ion in its circular path = $\omega = \frac{v}{r} = \frac{Be}{m}$ 3

The time is taken by the ion to travel the semicircular path = $t = \frac{\pi}{\omega} = \frac{\pi m}{Be}$ 4

Suppose the strength of the field (B) or the frequency of the oscillator (f) are so adjusted that by the time the ion has described a semicircular path and just enters the space between DI and D2, D2 has become negative with respect to D1. The ion is then accelerated towards D2 and enters the space inside it with a greater velocity. Since the ion is now moving with greater velocity, it will describe a semicircle of the greater radius in the second "dee". But from the equation $t = \frac{\pi m}{Be}$, it is clear that the time taken by the ion to describe a semicircle is independent of both the radius of the path (r) and the velocity of the ion (v). Hence the ion describes all semicircles, whatever be their radii, at exactly the same time. This process continues until the ion reaches the periphery of the dees. The ion thus spirals round in circles of increasing radius and acquires high energy. The ion will finally come out of the dees in the direction indicated, through the window.

The energy of an ion.

Let r_{max}, be the radius of the outermost orbit described by the ion and v, the maximum velocity gained by the ion in its final orbit. Then the equation for the motion of the ion in a magnetic field is

$$Bev_{\max} = \frac{m{v_{\max}}^2}{r_{\max}}$$

or $$v_{\max} = B\frac{e}{m}r_{\max}$$ 5

The energy of the ion $$E = \frac{1}{2}mv_{\max}2 = \frac{B2{r_{\max}}^2}{2}\left[\frac{e^2}{m}\right]$$ 6

The condition for acceleration of the ion in the inter-dee gap is that

The time taken by the ion to travel the semicircular path = Half the time period of oscillation of the applied high frequency voltage

$$\frac{\pi m}{Be} = \frac{T}{2} or T = \frac{2\pi m}{Be}$$

Frequency of the oscillator $f = \frac{Be}{2\pi m}$ 7

Hence the energy of the ion is given by $E = 2\pi^2{r_{\max}}^2 f^2 m$ 8

The particles are ejected out of the cyclotron not continuously but as pulsed streams.

Limitations of the Cyclotron

The energies to which particles can be accelerated in a cyclotron are limited by the relativistic increase of mass with velocity. The mass of a particle, when moving with a velocity v is given by $m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$

where m_0 is the rest mass and c the velocity of light.

According to equation (4),

The time taken by the ion to travel the semicircular path $t = \frac{\pi m}{Be} = \frac{T}{2}$

Frequency of the ion = $n = \frac{1}{T} = \frac{Be}{2\pi m}$ or $n = \frac{Be\sqrt{1 - v^2/c^2}}{2\pi m_0}$

Therefore, the frequency of rotation of the ion decreases with an increase in velocity. The ions take a longer time to describe their semicircular paths than the fixed period of the oscillating electric field. Thus, the ions lag behind the applied potential and finally, they are not accelerated further. Due to this reason, the energy of the ions produced by the cyclotron is limited. This limitation can be overcome in the following two ways.

Now, the frequency of the ion = $\frac{Be\sqrt{1 - v^2/c^2}}{2\pi m_0}$

(i) Field variation.

The frequency of the ion can be kept constant by increasing the magnetic field (B) at such a rate that the product $B\sqrt{1 - v^2/c^2}$ remains constant.

For this purpose, the value of the magnetic field B should increase, as the velocity of the ion increases, so that the product $B\sqrt{1 - v^2/c^2}$ remains unchanged. This type of machine in which the frequency of the electric field is kept constant and the magnetic field is varied is called a synchrotron.

(ii) Frequency modulation.

In another form of apparatus, the frequency of the applied A.C. is varied so that it is always equal to the frequency of rotation of the ion. This type of machine in which the magnetic field is kept constant and the frequency of the applied electric field is varied is called a frequency-modulated cyclotron or synchro-cyclotron.