Lecture Notes of B.Sc.(HONS.) PHYSICS ,Part-II, Paper -IV

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TOPIC:-------Cyclotron

Introduction:

What are Particle accelerator? -These are the machines that are used to increase the energy of sub-atomic particles and ions by applying electric field that accelerates the particles and magnetic field to control the path of the particles and to focus them.

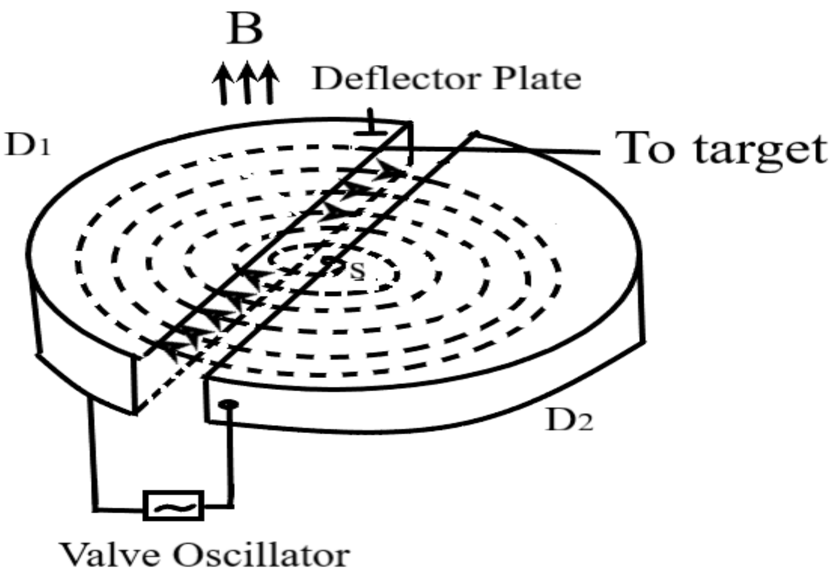
Types of Particle Accelerator :

1. Electrostatic Field Accelerators- It uses static electric field.
2. Oscillating Field Accelerators- It uses radio frequency electromagnetic field.

Oscillating field accelerators comes in the form of straight line or in the form of ring and called as linear accelerator or circular accelerator. In Linear accelerators particles are accelerated in a straight line during the passage of particle beam from one end to other. On the other hand in case of Circular Accelerators particles moves in circle under the influence of magnetic field while they are circulated, eg. Cyclotron for +ve ions, Betatron for electrons.

Cyclotron-It was devised by Lawrence and Livingston in 1932 to accelerate positive ions such as protons , deutrons and $\propto$ particles.

Construction –It consists of two hollow D shaped copper electrodes D_1 and D_2 (called the dees) with a small gap between them as shown in fig.(1).The dees are



Construction of Cyclotron

enclosed in an evacuated steel box placed between poles of a very large magnet. The magnet produces a field of about 15000 gauss perpendicular to the plane of dees. A high frequency alternating potential p.d.($\approx 12 Mc/sec \approx 10^5$ volts)is applied across the dees by means of a powerful valve oscillator.

The ion source consists of a small chamber carrying a heated filament and the gas concerned (hydrogen for protons, heavy hydrogen for deutrons).The electrons emitted by the filament ionise the gas. The ions so produced pass through a capillary tube which ejects them at the centre S of the gap between the dees.

Working: Suppose that a positive ion is ejected at S at a moment when D_2 just acquires a negative potential and D_1 a positive potential. The ions is then accelerated towards D_2 and enters it with increased velocity. Once inside D_2 it becomes free from the electric field and travels with constant speed. Since the ion is moving in a magnetic field perpendicular to the plane of the dees ,it adopts a circular path of radius r given by,

$$\frac{mV^2}{r} = Bqr$$

Where m is the mass ,q the charge and v is the speed of the ion.

$$\therefore \quad v = \frac{Bqr}{m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The time required by the ions to complete one circular revolution is $2\pi r$/v.

$$\therefore T = \frac{2\pi r}{V} = \frac{2\pi m}{Bq}$$

The Frequency of revolution is

$$v = \frac{1}{T} = \frac{Bq}{2\pi m}$$

Thus if B, m and q are constants, the period of revolution T, or the frequency v, is independent if the radius of the path and the speed of the ion. That is all ions take the same time to describe a circle or semicircle irrespective of their speed or energies.

The frequency of the applied p.d.is adjusted to be equal to be equal to the frequency of revolution of the ions. When this is the case ,the positive ion moving in D_2 completes a semicircle and leaves it just at the moment when D_2 becomes positive and D_1 negative. The ion is therefore further accelerated in the gap and enters D_1. Due to its increased speed its semi circular path in D is of greater radius. The time of passage through D is still the same. The process is repeated after every half cycle of of the p.d. and the ion gains speed each time it passes from one dee to the other .Finally the ion reaches the outer edge of one dee where it is pulled out of the system by a a negatively charged deflector plate.

Attained Energy: The velocity and hence the kinetic energy with which the ion leaves the cyclotron can be obtained by putting r=R(radius of dees) in eqn. (1)

$$\text{Thus } v = \frac{BqR}{m}$$

Therefore ,the kinetic energy of the emerging ion is given by,

$$K = \frac{mV^2}{2} = \frac{1}{2}m\left(\frac{BqR}{m}\right)^2 = \frac{1}{2}mB^2R^2\left(\frac{q}{m}\right)^2$$

$$\therefore K = 2\pi^2V^2mR^2$$

This is the expression of energy of particle in terms of the frequency of applied p.d. and the radius of the dees. The frequency depends upon the flux density B. Thus in the nonrelativistic range the limitation on the maximum energy attained by a particular ion is determined by the size of the dees and the pole faces of the magnet.

Limitations of Cyclotron:

1. It cannot accelerate neutral particles.
2. Lighter particles like electrons and positrons cannot be accelerated and requires modification of the device.

The maximum energies of particle attainable in cyclotron cannot be increased indefinitely by increasing the size of the apparatus because of the relativistic increase in mass of the particle in accordance with the eqn.

$$m = \frac{m_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

where m_0 is the rest mass of the particle and m the mass at speed v. As the speed of the particle increases to become comparable with the speed of light c, its mass m increases appreciably. Therefore the frequency of revolution goes on decreasing. Thus the particle transverse each dee too slowly and becomes more and out of step with the applied p.d. until it can no longer be accelerated further.

At 20 Mev the mass of proton is about 2% greater than its rest mass ,but beyond this the increase in mass becomes serious enough to affect the operation of the cyclotron. Thus it is the upper limit of proton energy attainable by a cyclotron.

The electrons due to their very small mass approach the speed of light very quickly so that the relativistic increase in mass becomes appreciable at low enough energies. For example mass of an electron is doubled at an energy of only about 0.5 Mev .Hence the cyclotron cannot be used to accelerate electrons even to moderate energies.