Synchrotron

A **synchrotron** is a particular type of cyclic particle accelerator, descended from the cyclotron, in which the accelerating particle beam travels around a fixed closed-loop path. The magnetic field which bends the particle beam into its closed path increases with time during the accelerating process, being *synchronized* to the increasing kinetic energy of the particles. The synchrotron is one of the first accelerator concepts to enable the construction of large-scale facilities, since bending, beam focusing and acceleration can be separated into different components. The most powerful modern particle accelerators use versions of the synchrotron design. The largest synchrotron-type accelerator is the 27-kilometre-circumference (17 mi) Large Hadron Collider (LHC) near Geneva, Switzerland, built in 2008 by the European Organization for Nuclear Research (CERN).

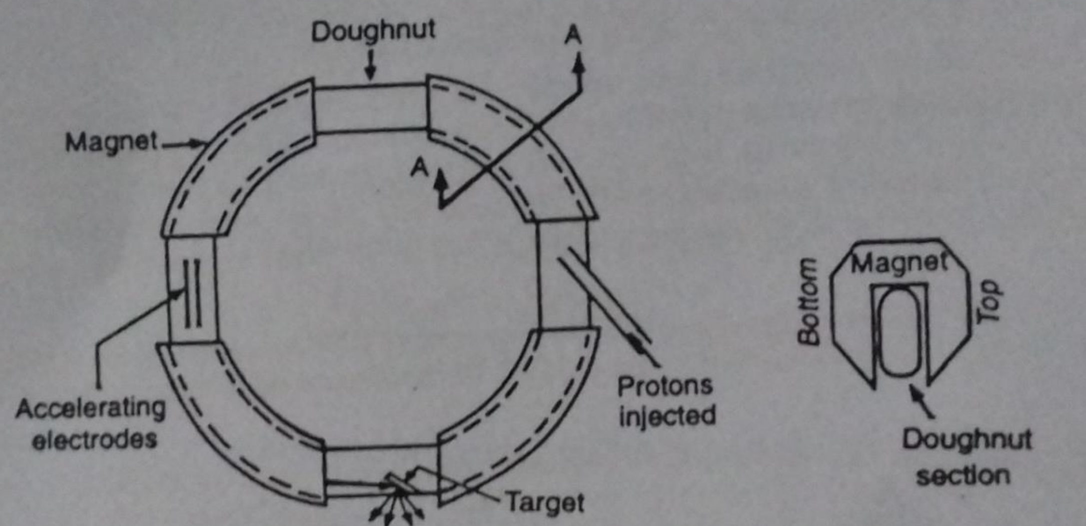
The synchrotron principle was invented by Vladimir Veksler in 1944. Edwin McMillan constructed the first electron synchrotron in 1945, arriving at the idea independently, having missed Veksler's publication (which was only available in a Soviet journal, although in English). The first proton synchrotron was designed by Sir Marcus Oliphant and built in 1952.

Proton Synchrotron or Bevatron

Billions of eV. (**B**illions of **eV** Synchro**tron**.)

14.10 Proton synchrotron or Bevatron

The *proton synchrotron*, also called the *bevatron*, essentially follows the same principle of construction and operation as the electron synchrotron except that it is designed to accelerate protons or heavy positive ions. It has a race track design. The proton revolves in *stable orbits* of constant radius in a *doughnut shaped vacuum chamber*. It has also *no solid magnetic core*. A ring-shaped magnet around the periphery produces a magnetic field normal to the chamber to bend the path of the particles. The magnet has four quadrants covering the doughnut as shown in Fig.14.12.



(a) Plan

(b) Section through AA

Fig.14.12 Bevatron or proton synchrotron

The protons to be accelerated are produced by an ion-source and are injected into the synchrotron orbit in the doughnut at low energy either from a linear accelerator or a van de Graaff generator, in the form of periodic pulses. The protons are accelerated by applying an alternating rf-electric field, and the magnetic field, as already indicated, is applied normal to the chamber from the ring-shaped magnet that can be excited periodically. In one of the field-free straight parts, a high frequency resonator cavity is used with an increasing frequency corresponding to the increasing speed of protons.

Just as with electrons, the guide magnetic field must steadily increase for each pulse of protons to prevent them from spiralling outward. The frequency of the electric field cannot however be kept constant as in electron synchrotron. The frequency of the electric field is to be simultaneously increased suitably so as to have a resonance with the orbital frequency of the ions. Thus the protons get accelerated in a circular trajectory of constant radius in successive steps during the time when the magnetic field is increasing until the maximum energy is acquired. The frequency of the rf-field is suddenly changed, the orbit expands and the protons are ejected so as to hit a specific target.

Calculation of frequency, energy and orbit radius — If the straight section were absent, the circulation frequency of protons of energy W_k in equilibrium orbit of radius r_0 in a magnetic field B would be given by

$$\frac{Bec^2}{2\pi(m_pc^2 + W_k)}$$

where m_p is the rest mass of proton and e its charge.

Because of the straight section, the circulation frequency f' would be modified as

$$f' = \frac{Bec^2}{2\pi(m_pc^2 + W_k)} \cdot \frac{2\pi r_0}{2\pi r_0 + 4L}$$

$$= \frac{Bec^2}{m_pc^2 + W_k} \cdot \frac{r_0}{2\pi r_0 + 4L} \qquad \text{(i)}$$

where L is the length of each of the four straight sections.

The kinetic energy W_k of a proton of momentum $\vec{p}$ may be written as

$$E = W_k + m_p c^2 = \sqrt{p^2c^2 + m_p^2 c^4} = \sqrt{(Ber_0c)^2 + m_p^2 c^4}$$

where E is the total energy and $p = Ber_0$.

$$\therefore \quad W_k^2 + 2W_k m_p c^2 = (Ber_0c)^2$$

$$\text{or,} \quad W_k(W_k + 2m_p c^2) = (Ber_0c)^2 \qquad \text{(ii)}$$

$$\Rightarrow \quad r_0 = \frac{\{W_k(W_k + 2m_p c^2)\}^{\frac{1}{2}}}{Bec}. \qquad \text{(iii)}$$

If B be in tesla, and W_k and $m_p c^2$ in GeV, then r above is in m.

Then, from (iii)

$$r_0 = \frac{\{W_k(W_k + 2m_p c^2\}^{\frac{1}{2}}}{0.3B} \text{ m.} \qquad \text{(iv)}$$

From (iii),

$$B = \frac{\{W_k(W_k + 2m_p c^2)\}^{\frac{1}{2}}}{ecr_0} \qquad \text{(v)}$$

This shows how to increase the magnetic field B at the equilibrium orbit with increase in proton energy W_k as it circulates in the orbit.

Substituting for B in (i), we obtain

$$f' = \frac{c\{W_k(W_k + 2m_pc^2)\}^{\frac{1}{2}}}{(m_pc^2 + W_k)(2\pi r_0 + 4L)}. \quad \text{(vi)}$$

If the accelerating voltage is to be in phase with f', its rf-value should always match f' and vary according to the variation of f' with W_k.

A proton synchrotron can energise protons to values as high as 10 BeV. In 1952, the protons were accelerated to an energy of 3 BeV in the proton synchrotron at Brookehaven National Laboratory. In 1954, the energy attained was 6 BeV in the bevatron at the Radiation Laboratory of the University of California. The Russian proton synchrotron at Dubna could produce protons of energy 10 BeV in 1957. As the machine is capable of energising particles of the order of BeV, it is termed a *bevatron*. It is also called a *cosmotron*.