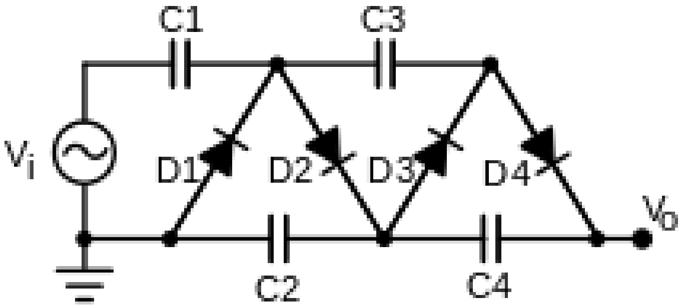
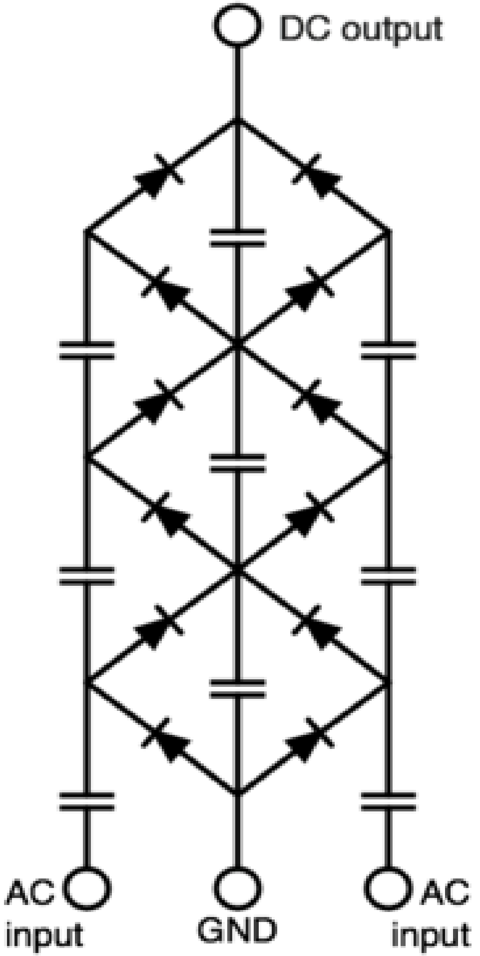
Cockcroft–Walton (CW) generator

- The **Cockcroft–Walton** (**CW**) **generator**, or **multiplier**, is an electric circuit that generates a high DC voltage from a low-voltage AC or pulsing DC input.

- It was named after the British and Irish physicists John Douglas Cockcroft and Ernest Thomas Sinton Walton, who in 1932 used this circuit design to power their particle accelerator, performing the first artificial nuclear disintegration in history. They used this voltage multiplier cascade for most of their research, which in 1951 won them the Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles".

- The circuit was discovered in 1919, by Heinrich Greinacher, a Swiss physicist. For this reason, this doubler cascade is sometimes also referred to as the **Greinacher multiplier**. Cockcroft–Walton circuits are still used in particle accelerators. They also are used in everyday electronic devices that require high voltages, such as X-ray machines, cathode ray tube television sets, microwave ovens and photocopiers.





A three-stage full-wave CW multiplier

- The CW generator is a voltage multiplier that converts AC or pulsing DC electrical power from a low voltage level to a higher DC voltage level. It is made up of a voltage multiplier ladder network of capacitors and diodes to generate high voltages.

- Unlike transformers, this method eliminates the requirement for the heavy core and the bulk of insulation/potting required. Using only capacitors and diodes, these voltage multipliers can step up relatively low voltages to extremely high values, while at the same time being far lighter and cheaper than transformers.

- The biggest advantage of such circuits is that the voltage across each stage of the cascade is equal to only twice the peak input voltage in a half-wave rectifier. In a full-wave rectifier it is three times the input voltage. It has the advantage of requiring relatively low-cost components and being easy to insulate. One can also tap the output from any stage, like in a multitapped transformer.

To understand the circuit operation, see the diagram of the two-stage version at right. Assume the circuit is powered by an alternating voltage $\boldsymbol{V}_\mathbf{i}$ with a peak value of V_p, and initially the capacitors are uncharged. After the input voltage is turned on

- When the input voltage $\boldsymbol{V}_\mathbf{i}$ reaches its negative peak $-V_\mathrm{p}$, current flows through diode *D1* to charge capacitor *C1* to a voltage of V_p.
- When $\boldsymbol{V}_\mathbf{i}$ reverses polarity and reaches its positive peak $+V_\mathrm{p}$, it adds to the capacitor's voltage to produce a voltage of $2V_\mathrm{p}$ on *C1s* righthand plate. Since *D1* is reverse-biased, current flows from *C1* through diode *D2*, charging capacitor *C2* to a voltage of $2V_\mathrm{p}$.
- When $\boldsymbol{V}_\mathbf{i}$ reverses polarity again, current from *C2* flows through diode *D3*, charging capacitor *C3* also to a voltage of $2V_\mathrm{p}$.
- When $\boldsymbol{V}_\mathbf{i}$ reverses polarity again, current from *C3* flows through diode *D4*, charging capacitor *C4* also to a voltage of $2V_\mathrm{p}$.

With each change in input polarity, current flows up the "stack" of capacitors through the diodes, until they are all charged. All the capacitors are charged to a voltage of $2V_\mathrm{p}$, except for *C1*, which is charged to V_p. The key to the voltage multiplication is that while the capacitors are charged in parallel, they are connected to the load in series. Since *C2* and *C4* are in series between the output and ground, the total output voltage (under no-load conditions) is $\boldsymbol{V}_\mathbf{o} = 4V_\mathrm{p}$.

With each change in input polarity, current flows up the "stack" of capacitors through the diodes, until they are all charged. All the capacitors are charged to a voltage of $2V_p$, except for *C1*, which is charged to V_p. The key to the voltage multiplication is that while the capacitors are charged in parallel, they are connected to the load in series. Since *C2* and *C4* are in series between the output and ground, the total output voltage (under no-load conditions) is $\boldsymbol{V_o} = 4V_p$.

This circuit can be extended to any number of stages. The no-load output voltage is twice the peak input voltage multiplied by the number of stages ***N*** or equivalently the peak-to-peak input voltage swing (V_{pp}) times the number of stages.

$$V_0 = 2NV_p = NV_{PP}$$

The number of stages is equal to the number of capacitors in series between the output and ground.

One way to look at the circuit is that it functions as a charge "pump", pumping electric charge in one direction, up the stack of capacitors. The CW circuit, along with other similar capacitor circuits, is often called charge pump. For substantial loads, the charge on the capacitors is partially depleted, and the output voltage drops according to the output current divided by the capacitance.

The number of stages of voltage doubling may be increased by adding more rectifiers and condensers. Therefore for a number of $2n$ of each component, the circuit is an n-stage voltage doubler which gives no-load output of voltage $2nV$ i.e. $2 \times 2V = 4V$. for Fig. shown here.

Now if the frequency of transformers main supply is f Hz and i current is drawn from high voltage terminal P_4 then in one cycle the condenser C_4 drops in voltage which is $\frac{i}{fC}$. A ripple $\delta v'$ of supply main frequency appears in the output as given as

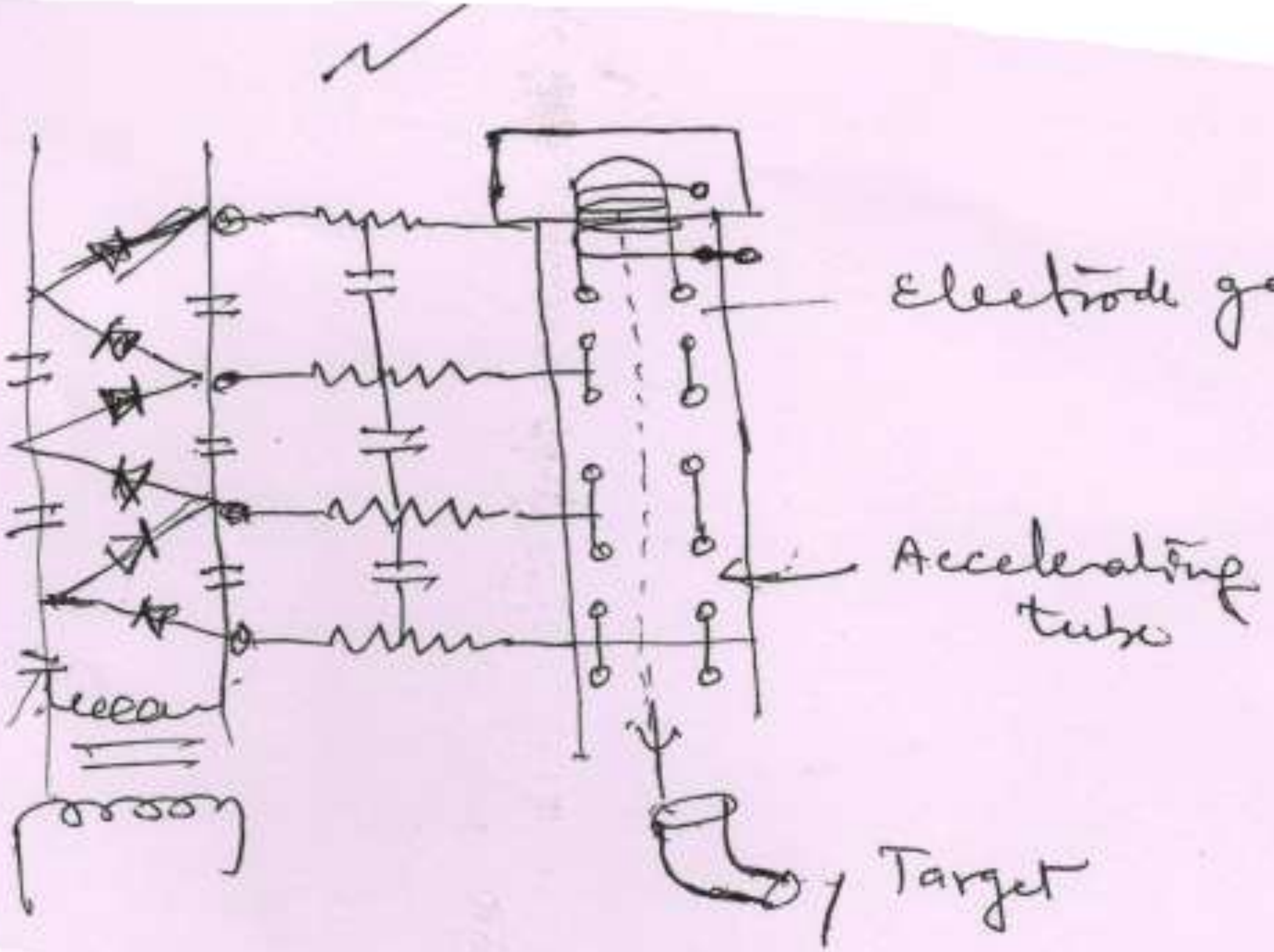
$$\delta v = \frac{n(n+1)}{2} \frac{i}{fC}$$

and the voltage drop from no-load value will be

$$\Delta V = \left(\frac{2}{3}n^3 + \frac{1}{2}n^2 \pm \frac{1}{3}n\right)\frac{i}{fC}$$

~~From~~ To get negligible δv or Δv, we require

(a) smallest possible number of stages
(b) highest possible capacities
(c) highest possible frequencies.


Electrode gap
Accelerating tube
Target

The Modern cascade is shown in above Fig. In this case the cascade generator is connected to a continuous pumped accelerating tube having 10^{-5} mm Hg pressure through high resistance. These are accelerating gaps in series and constitute successive electrostatic lense. The focussed beam of ions is delivered from the ion source through a small canal kept at high +ve potential. The beam emerges at ground potential with a velocity correspond to accelerating voltage. The pressure in the ion source is much higher than the accelerating tube. The power to the ion source is conveyed to the high voltage terminal ~~neither~~ by high frequency circulating in the condenser stacks.

The cascade generator has the following advantages

1– uses standard components
2. gives large output
3. It has high current ≃ 10mA of +ve ions.
4. It is possible to obtain energy upto 4 MeV

These generators in the range of 200 to 300 KV are used in the production of neutrons by reactions

$$^{3}_{1}H + ^{2}_{1}H \rightarrow {}_{2}He^{4} + n + 17.58\ MeV$$

1.2.2 Synchrotron Radiation:

All electromagnetic radiations emitted by charged particles in circular motion are called Synchrotron Radiations. Synchrotron radiation can be generated continuously by circulating e^+ or e^- beam in the storage ring. The orbit of the beam consists of straight and arc sections. Dipole magnets called "bending magnets" (BM) are installed in the arc sections to bend the beam for generation of synchrotron radiation. Quadrupole magnet (QM), RF accelerating cavities, insertion devices (ID) and many other devices are installed in straight sections. The beam runs in ultra-high vacuum duct to minimise scattering due to collisions with any remaining gas molecules in the duct. Such collisions cause the stored beam to decay. The classical picture for the geometry of synchrotron radiation source is shown in Fig. 1.8. One of the most important characteristics of synchrotron radiation produced by bending magnets or insertion devices (e.g. wigglers placed in the straight sections of the electron beam path, between successive bending magnets) is *critical frequency* ω_c, and the *critical energy* E_c:

$$\omega_c = \frac{1}{\delta t} = \frac{3c\gamma^3}{2\rho} \qquad \text{..... (1.21)}$$

where δt is time during which radiation is received, γ is $1/\sqrt{(1-v^2/c^2)}$ and ρ is bending magnet curvature.

$$E_c = \hbar\omega_c = \frac{3\hbar e}{2m_o\left(m_o c^2\right)^2} E^2 B \qquad \text{..... (1.22)}$$

where E is the revolving particle energy, and B is the field strength of bending magnets. The critical photon energy divides the spectrum into two parts of equal power, one half of the total power is irradiated at lower photon energies and the other half at higher ones. In practical units

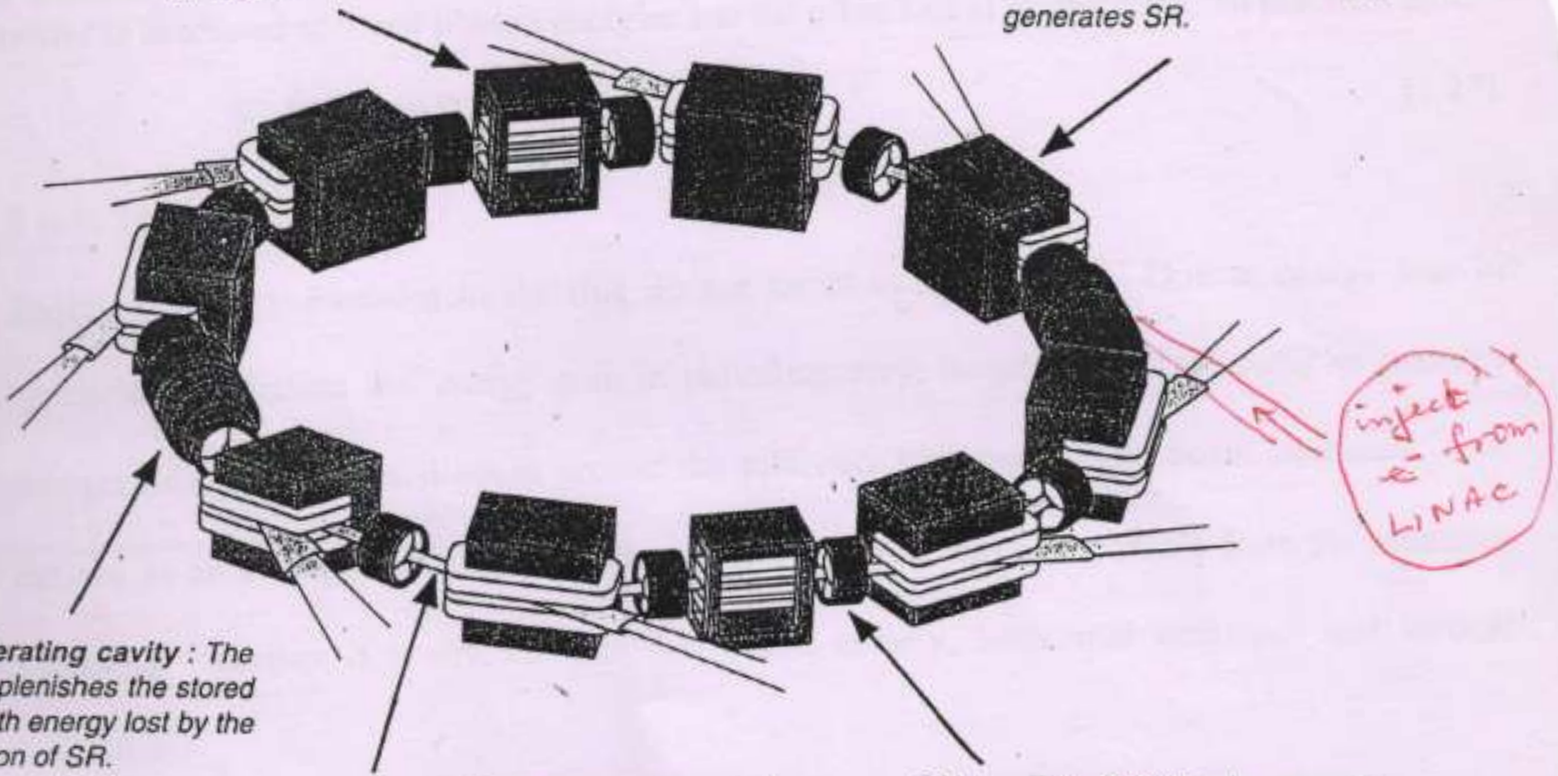
$$E_c\,(\text{keV}) = 0.665E^2B \qquad \text{..... (1.23)}$$

B is in Tesla and E in GeV.

(a)

ID : The insertion device generates various characteristic types of SR.

BM : The bending magnet bends the beam and generates SR.



rf accelerating cavity : *The cavity replenishes the stored beam with energy lost by the generation of SR.*

Vacuum Duct : *The pressure in the duct is kept below 10^{-10} Torr in order to reduce beam decay caused by collisions with residual gas.*

QM : The quadrupole magnet works as a lens to focus the beam.

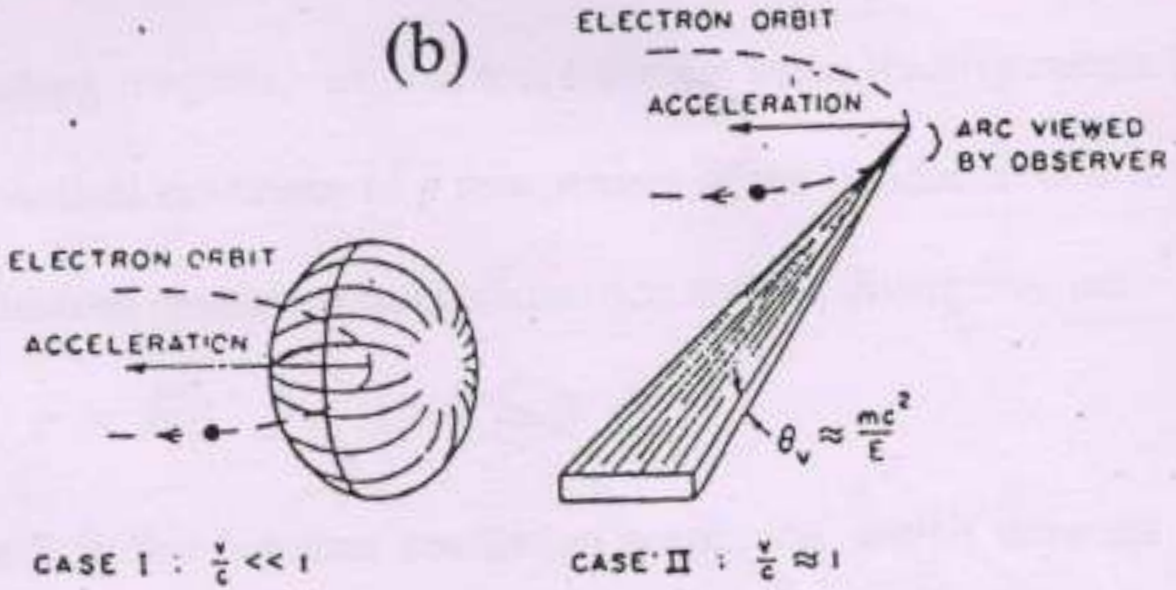


Fig. 1.8 (a) Schematic geometry of synchrotron radiation source. (b) Radiation emission pattern of electrons in circular motion: Case I, non-relativistic electrons. Case II, relativistic electrons.

Beam emittance: Particles in the ring do not travel in ideal orbits. Due to energy loss in synchrotron radiation and energy gain in radiofrequency, longitudinal field particles undergo non-periodic betatron oscillations around the reference trajectory. The *beam emittance*, ε, is defined as an average value $\varepsilon=\langle r^2\rangle$, where r is a displacement of a particle from the reference trajectory. Further it is divided into two kinds, namely, horizontal emittance and vertical emittance.

The *horizontal emittance* can be estimated as

$$\varepsilon = 94.7E^2\theta^3 \text{ [nm.rad]} \qquad \text{..... (1.24)}$$

where θ is the deflection angle of the bending magnet $\theta = 2\pi/N$ (N is twice the number of bending magnets).

In principle, there should not be any vertical emittance since there are only horizontal bending magnets. In practice, there are some misalignments in the directions of the field and the vertical emittance of a few percent of the horizontal one is observed. The vertical ~~(horizontal)~~ electron ~~(positron)~~ beam dimension and the divergence are

$$\sigma = \sqrt{\varepsilon\beta}, \qquad \cancel{\sigma' = \sqrt{\varepsilon/\beta}} \qquad \text{.....} (1.25)$$

where β is the betatron oscillation amplitude, which depends on synchrotron source characteristics. It can also be defined as the product of the source size and the source divergence. Typical synchrotron radiation source sizes are in the range 0.1 - 1 mm.

Brightness: Brightness is one of the most important characteristics of Synchrotron Radiation. The spectral brightness can be defined as the photon flux (the number of photons radiated per second into a 1 mrad orbital fan in an energy bandwidth $d\omega/\omega = 10^{-3}$) per solid angle, which can be expressed in practical units as

$$\text{Brightness} = 1.3 \times 10^{13} E^2 I \, f\left(\frac{\omega}{\omega_c}\right) \qquad \text{.....} \quad (1.26)$$

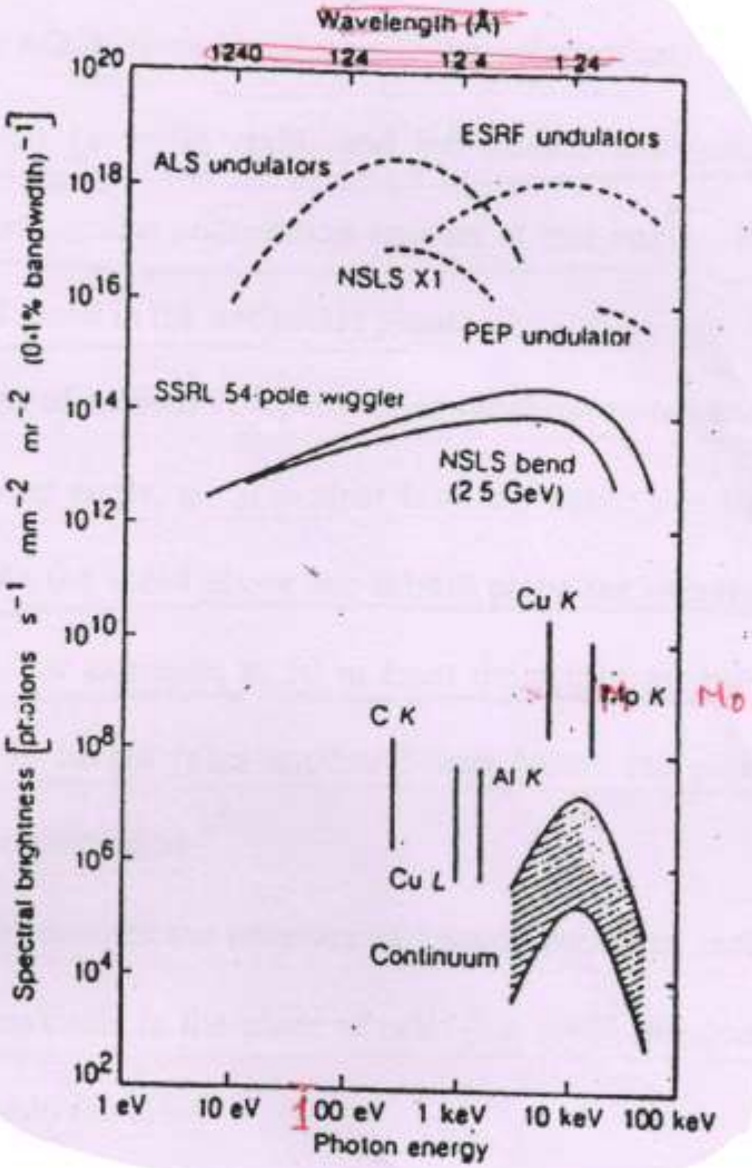
where E is given in GeV and I in amperes. $f(\omega/\omega_c)$ is a function describing the spectral dependence of brightness expressed in the reduced variable of photon energy with respect to the critical energy. The spectral brightness for several SR sources and conventional sources is shown in Fig. 1.9.

Brilliance: The brilliance is the brightness per transverse area of the optical source of synchrotron radiation determined by its horizontal and vertical emittances ε_x, ε_z;

$$\text{Brilliance} = (\text{Brightness}/\varepsilon_x\varepsilon_z) \qquad \text{..... (1.27)}$$

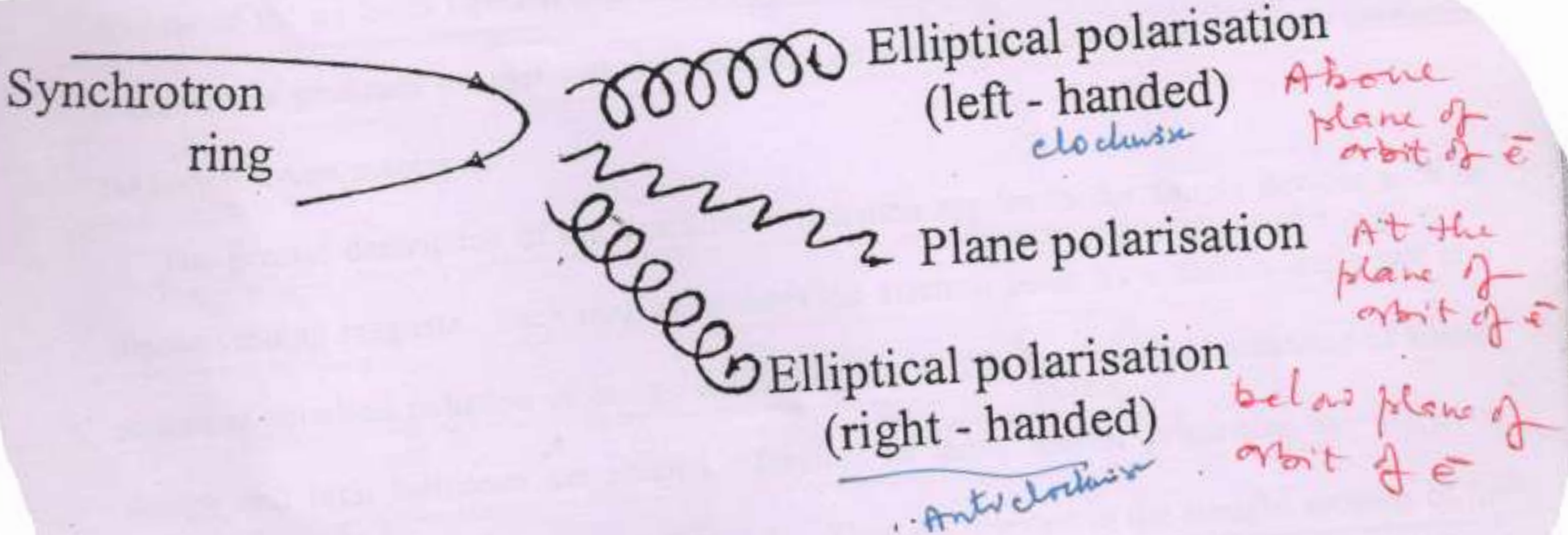
It defines the surface density of the radiation from the source and practically depends on the transverse size of the electron beam passing through a particular device. This is a very important parameter for the experiments with focused photon beam. It defines the possibility of using very intense photon flux in a spot of area related to the area of the source. Less diffused source gives higher brilliance and smaller size of the focused beam.

Including all electrons travelling in bunches in the synchrotron ring (simple summation without wave interference effects due to large spatial separation of two particles, which is of order of a few thousand Å), one gets B_σ and B_π [21], two-component relation for spatial (angular) distribution of the brightness of synchrotron radiation. Brightness B_σ is related to the



The spectral brightness for several synchrotron radiation sources and conventional sources. The indicated two orders of magnitude ranges show the approximate variation that can be expected among stationary anode tube (lower end of range), rotating anode tube (middle) and rotating anode tubes with microfocussing (upper end of range). Clearly synchrotron radiation sources are several orders of magnitude brighter than the conventional sources.

linear polarisation of the radiation in the plane of rotation of the particle (horizontal plane, σ polarisation state) and B_{π} is related to the linear polarisation of the radiation in the plane perpendicular to the first one (π polarisation state). Because these two polarisation states are phase shifted by $\pi/2$, they can produce circular polarisation. When the beam is observed in the plane of the orbit ($\psi = 0$), right- and left-handed polarisation have the same brightness. Therefore, no net circular polarisation appears at that angle. Radiation in the orbital plane is fully linearly polarised in the horizontal plane.

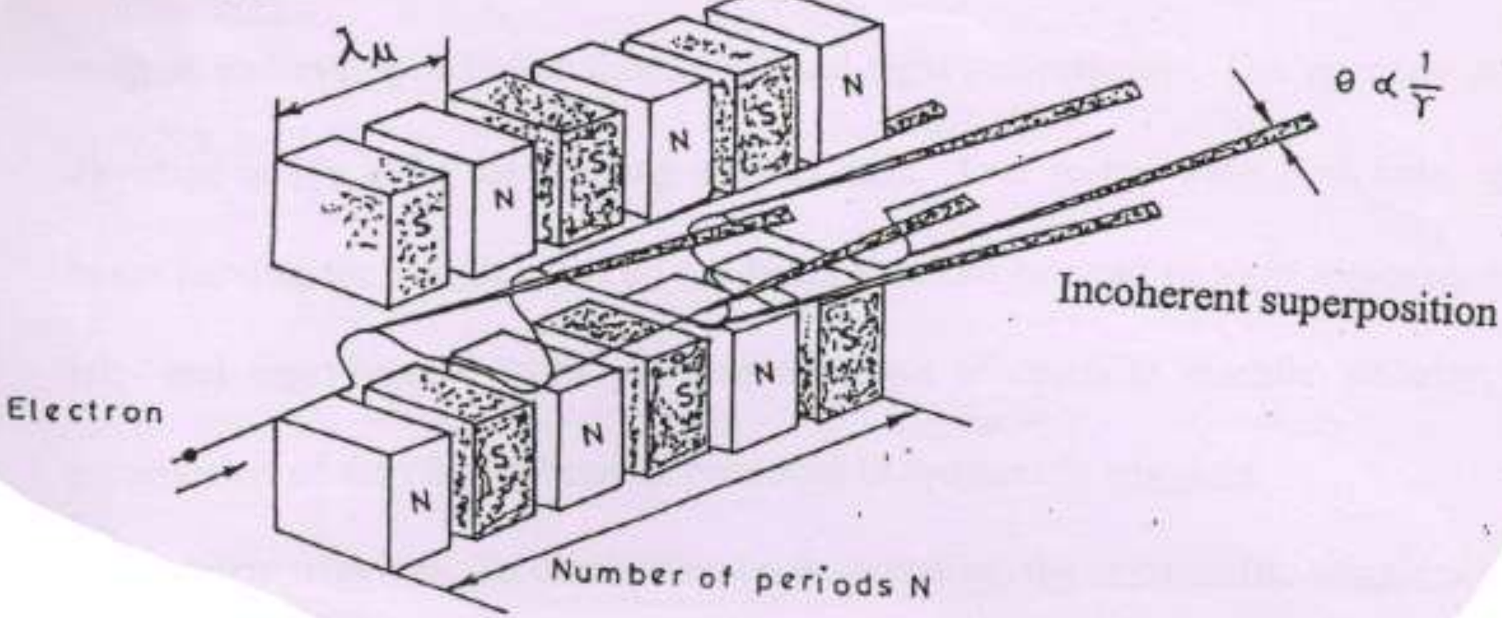


Extraction of circularly polarised photons from a synchrotron using the inclined view method. The handedness or helicity of the photon beam is determined by the apparent motion of the circulating electron beam.

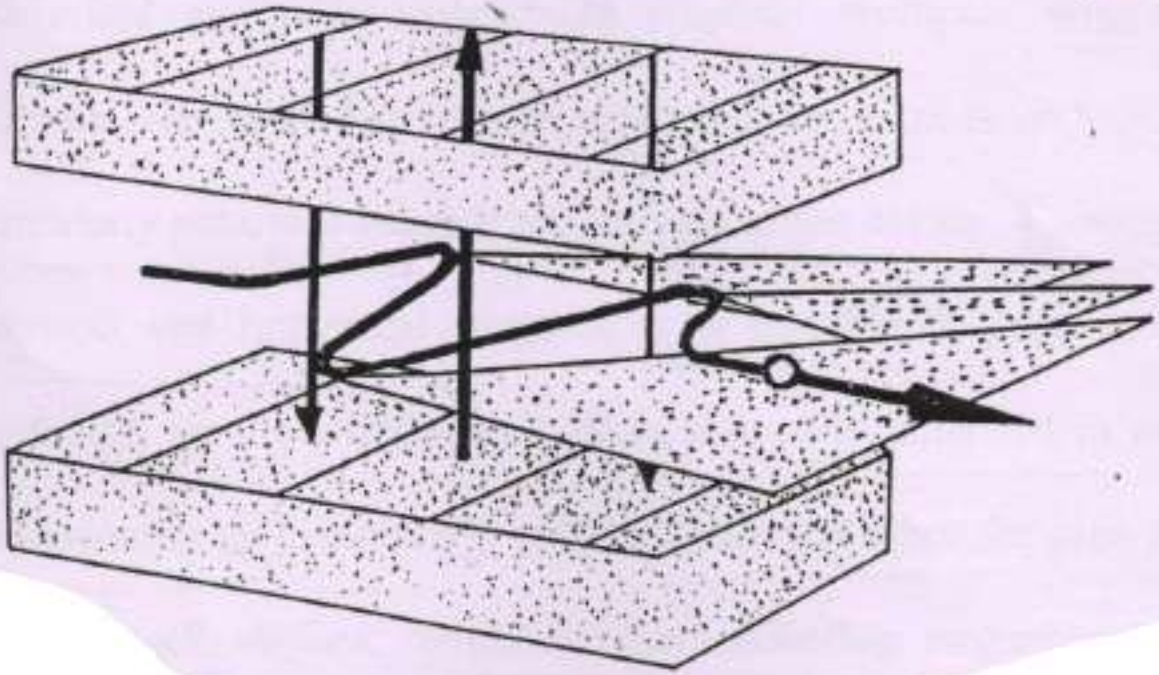
Devices of these special properties are wigglers, undulators, waveshifters as shown in Fig. 1.13. They are inserted in the straight sections of the ring between two bending magnets. Brief characteristics of some special insertion devices are as follows:

- *Symmetric wiggler:* As shown in Fig. 1.13, in case of symmetric wiggler, electrons or positrons oscillate passing through the vertical magnetic field of alternate polarity and the same strength. Each individual "wiggler" produces radiation exactly as the bending magnet. Output photon flux is the incoherent sum of all wiggles, just increased by factor 2N, where N is the number of periods of magnetic field.

(a) Symmetric wiggler



(b) Asymmetric wiggler



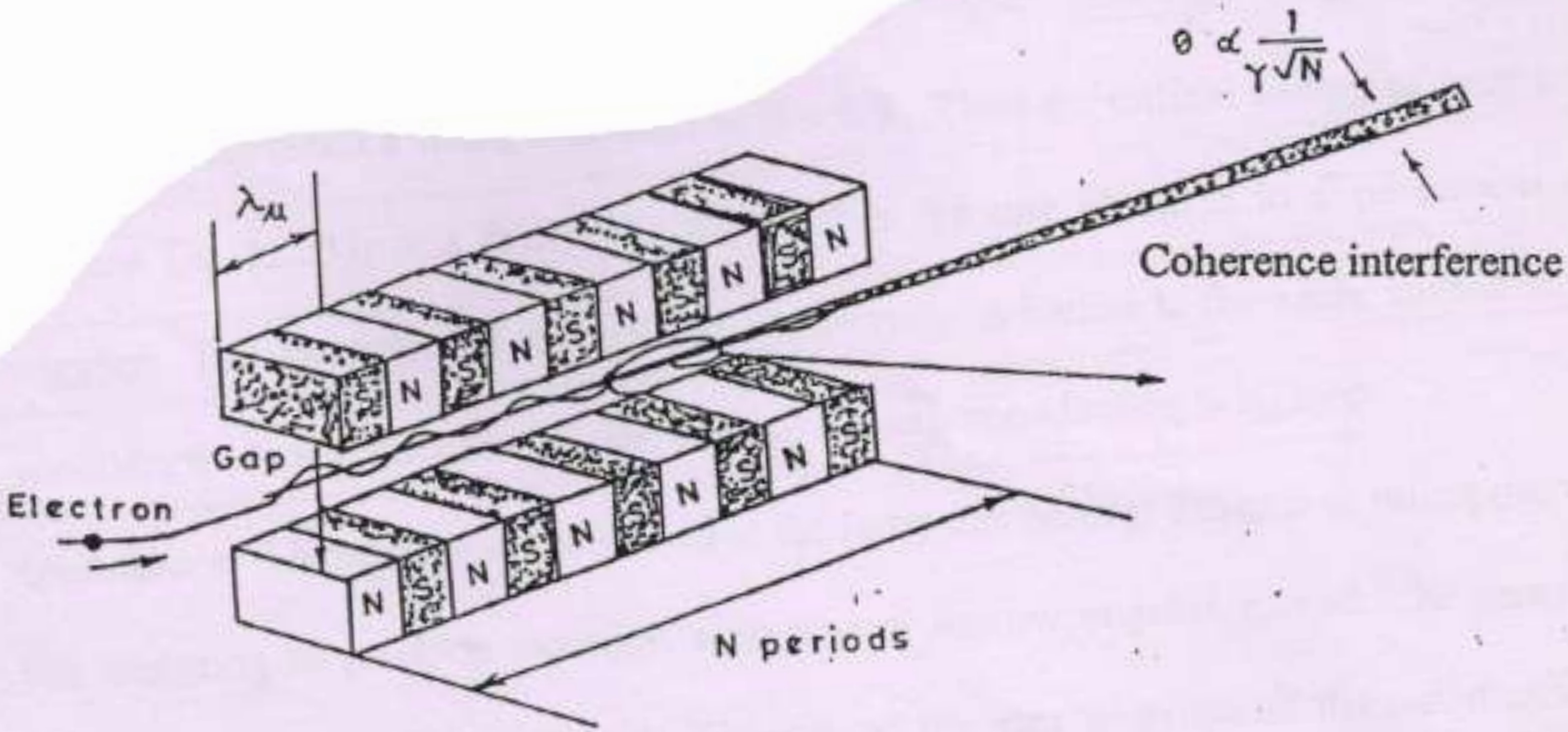


Fig. 1.13 Schematic of different type of insertion devices used in synchrotron sources.

- *Asymmetric wigglers:* To obtain circular polarisation, the asymmetric wigglers with different magnetic fields are used. This is shown in Fig. 1.13. Moving the observation point above or below the orbital plane, one observes the net circular polarisation of the photon beam.
- *Elliptical multipole wiggler*: In elliptical multipole wiggler, the magnetic poles are alternatively rotated so that the charged particles move on helical trajectory, which produces circularly polarised beam along the axis of the device. Changing the gap width between the vertical and horizontal magnets, it is possible to produce different kinds of polarised radiation on the wiggler axis, from a linearly polarised in one plane, through an elliptic polarisation up to circularly polarised radiation when the gaps are equal.

- *Wavelength shifters*: When a superconducting magnet produces magnetic field in the wiggler, it can reach a strength as high as $B \approx 6$ T. Then the critical energy of such a device, E_c, (see Eq. (1.23)) is a few times higher than the one obtained in a permanent magnet wiggler. The spectrum of the emitted synchrotron radiation is therefore shifted to shorter wavelength, hence the name of that class of the superconducting wigglers.

Typical brilliance (in photons/sec/mrad^2/mm^2/0.1% BW) of an X-ray tube is of order 10^7; bending magnets of third generation synchrotrons can reach a value of 10^{15}, wigglers - 10^{17}, whereas brilliance 10^{19} can be reached from undulators. The maximum energy of radiation from the undulators is, however, at least one order of magnitude smaller than the highest energy of wiggler radiation.