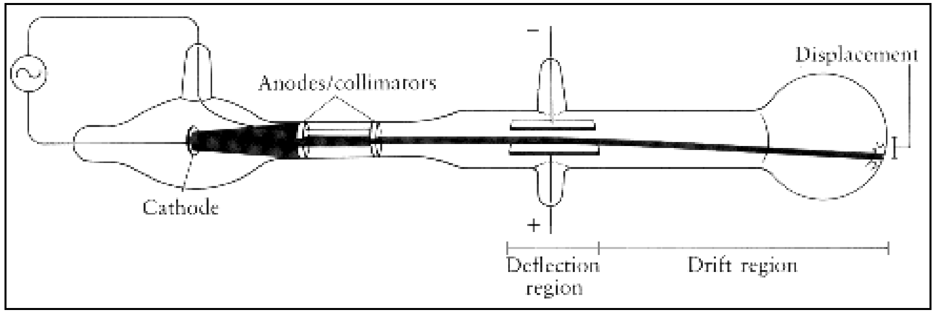
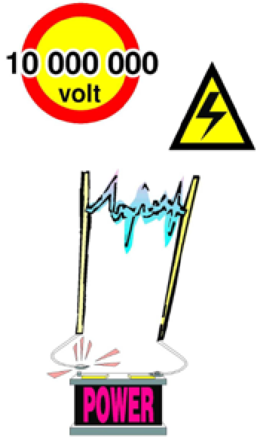
2025 가속기 여름학교
Introduction

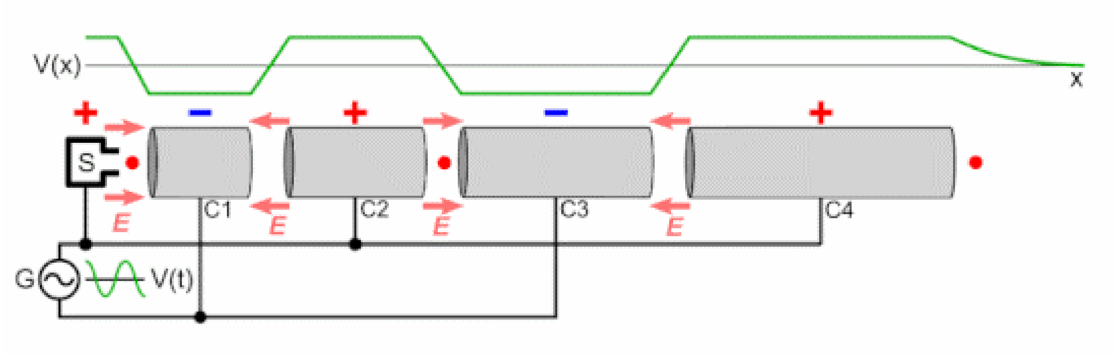
(Part 1)



The components of a cathode ray tube perform all the essential functions of the components in a modern accelerator and include: a particle source, vacuum, some means of acceleration, components for controlling the trajectory of particles, and a way of detecting or observing the particles.

Nearly 30 years elapsed between the development of the first cathode ray tubes by William Crookes and others, around 1869, and the discovery of the electron by J J Thomson in 1897.

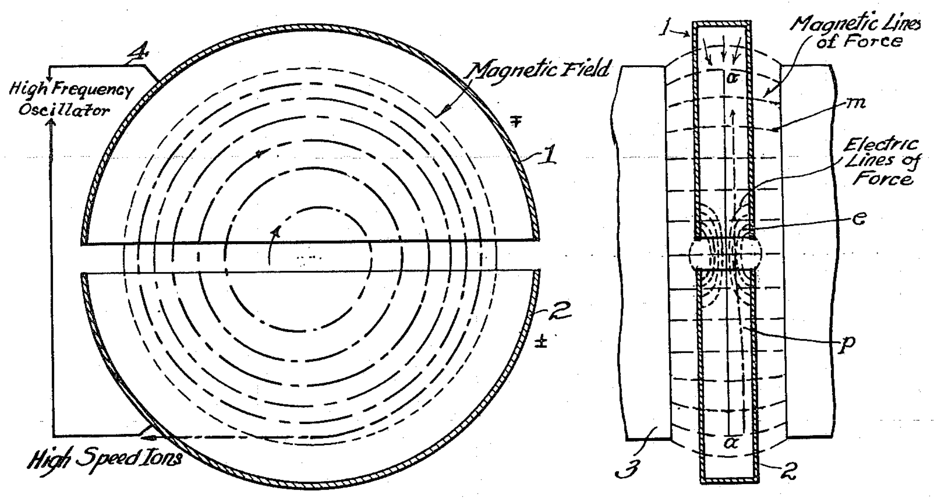




The desire to understand the physical properties of materials, and the laws of nature, at ever more fundamental levels required increases in beam energy and intensity, and improvements in the quality and stability of the beams.

The strength of a static electric field is limited by the fact that any material will break down once the field reaches a certain value.

By using oscillating fields, it is possible to arrange for particles always to see accelerating fields, and for their energy then to increase over the entire length of the linac (linear accelerator).



The invention of the cyclotron by Ernest O Lawrence in 1934 was a major step for achieving high energy (by 'reusing' the same field).

However, the energy that can be reached by particles in a cyclotron is limited by the size and strength of the magnets needed to maintain the spiral trajectory.

Furthermore, as the energy of an electron increases, the radius of its trajectory in a magnetic field increases; however, its speed approaches a limit, the speed of light (relativistic effects).

Already in the first half of the twentieth century, it was realised that the limitations from relativity on electron beam energy could be overcome if particles could be kept on a circular, rather than spiral, trajectory as they were accelerated.

Betatron:

- The strengths of the magnetic fields controlling the trajectory to be increased in proportion to the momentum of the particles; conveniently, increasing the magnetic field created (by electromagnetic induction) an electric field that would accelerate the particles.

- Although the concept dates back to 1922, the first successful machine was not demonstrated until 1940.

- Using betatrons, it became possible to accelerate electrons to tens of MeV; but the concept was soon superseded by the synchrotron.

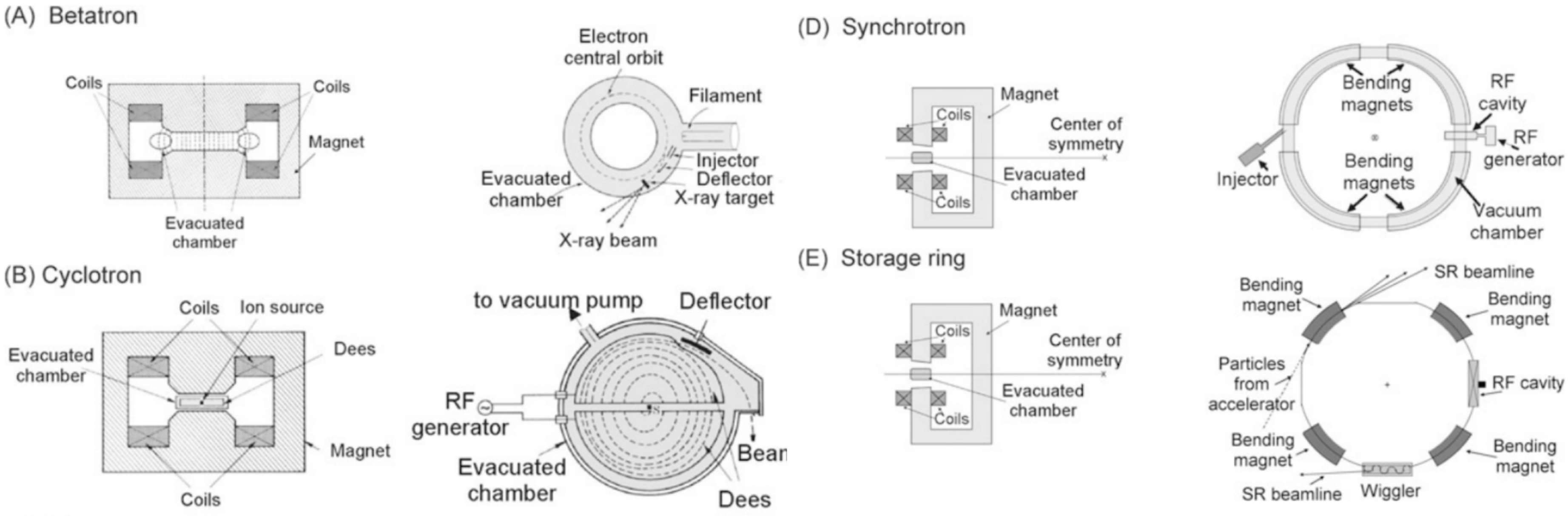
Synchrotron:

- The magnetic fields used to guide the electrons are increased with beam energy, in the same way as in a betatron.

- However, rather than using electromagnetic induction to accelerate the particles, a synchrotron uses oscillating electric fields, in a similar way to a cyclotron.

- To compensate for changes in the speed of the electrons as they increase in energy, the oscillation frequency of the accelerating field is varied. In other words, the accelerating field oscillation is synchronised with the revolution frequency of the particles travelling around the ring: hence, the name 'synchrotron'.

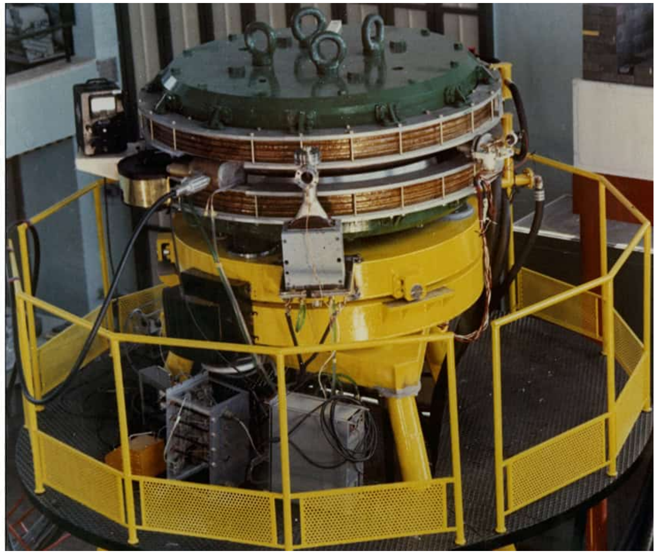
- The first synchrotron was constructed (from a modified betatron) in the late 1940s at UK.


(A) Betatron
Coils
Coils
Magnet
Evacuated chamber
Electron central orbit
Filament
Injector
Deflector
X-ray target
Evacuated chamber
X-ray beam
(B) Cyclotron
Coils
Ion source
Evacuated chamber
Dees
Magnet
Coils
to vacuum pump
Deflector
RF generator
Evacuated chamber
Dees
(D) Synchrotron
Magnet
Coils
Center of symmetry
Evacuated chamber
Coils
Bending magnets
RF cavity
RF generator
Injector
Bending magnets
Vacuum chamber
(E) Storage ring
Magnet
Coils
Center of symmetry
Evacuated chamber
Coils
SR beamline
Bending magnet
Bending magnet
Particles from accelerator
RF cavity
Bending magnet
Bending magnet
SR beamline
Wiggler

After the first electron synchrotrons, a number of proton synchrotrons were developed with the aim of achieving beam energies of several GeV, motivated by the production of beams of high-energy particles for studies in nuclear physics.

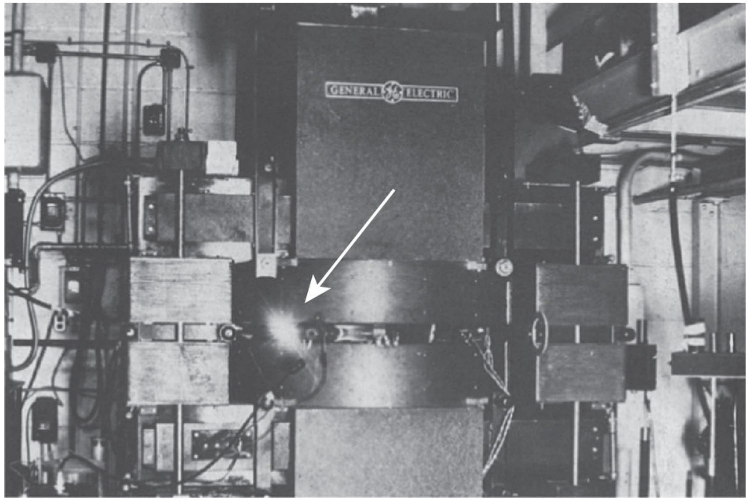
It was soon realised that there were applications for high-energy beams (of protons or electrons) stored in synchrotrons for long periods. In principle, to operate the synchrotron as a storage ring all that was needed was to maintain the magnetic field strengths at constant values once the desired energy was reached.

The use of synchrotron storage rings made it possible to perform collider experiments, in which two colliding particles' total momentum is zero so all the energy is available for producing new states (a significant advantage over fixed-target experiments).

Colliders began to be developed in the 1960s. The first machine to be completed, AdA (Anello di Accumulazione, 이탈리아어로 저장링) was an electron–positron collider constructed in Frascati, Italy in 1961, by a team led by Bruno Touschek. The storage ring had a diameter of about 1.3 m and stored beams with energy 250 MeV.

Numerous colliders have since been built, aiming for higher energy and/or luminosity, with colliding different combinations of lepton (electron or positron) and hadron (proton, antiproton, or ion) beams.



It has been known since the late 19th century that any charged particle will radiate energy in the form of electromagnetic waves when undergoing a change in speed or direction.

The radiation from a beam of relativistic electrons is known as synchrotron radiation, and was observed for the first time in 1946, at the General Electric Company synchrotron in Schenectady.

Despite a growing interest in synchrotron radiation as a tool for scientific investigation, the use of synchrotron radiation was for many years ‘parasitic’(기생충처럼) on machines built for high-energy physics.

In 1968, Tantalus, a 240 MeV electron storage ring at the University of Wisconsin, became the first machine constructed specifically for light source.

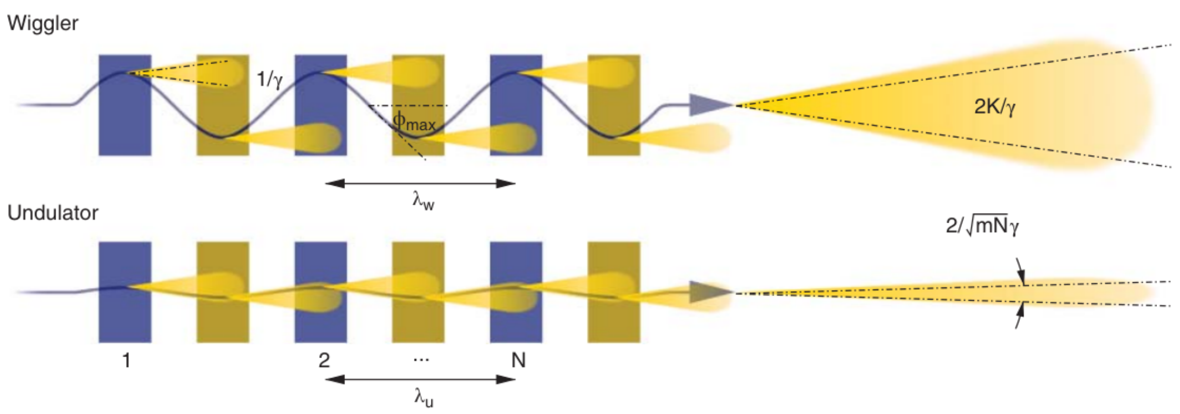
- 1st generation: Although the colliding beams are tightly focused at the interaction point to generate high luminosity, the beam size in the rest of the ring tends to be relatively large: this limits the brightness of the synchrotron radiation produced from the electron beams in the dipole magnets.

- 2nd generation: The beam size in a 2nd-generation light source can be smaller than that in a collider, with the radiation coming principally from the dipole magnets used to steer the beam around the storage ring.

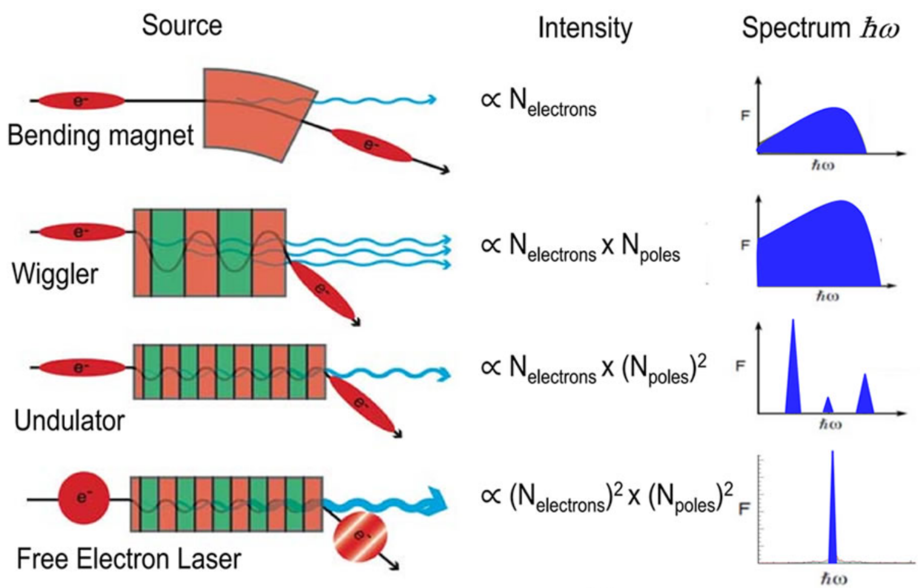
- 3rd generation:

  From detailed studies of the effects of synchrotron radiation on the electron beam, advances in the design of the magnetic lattice were possible, allowing an improvement in brightness by several orders of magnitude.

  At the same time, magnets were developed specifically for generating synchrotron radiation with desirable properties for light source users. These insertion devices (undulators and wigglers) consist of sequences of short dipole magnets of alternating polarity.



Particles passing through dipoles and IDs in storage rings generally produce radiation independently of other particles in the beam, so that the intensity of the radiation is proportional to the number of particles (of order 10^9 or more).



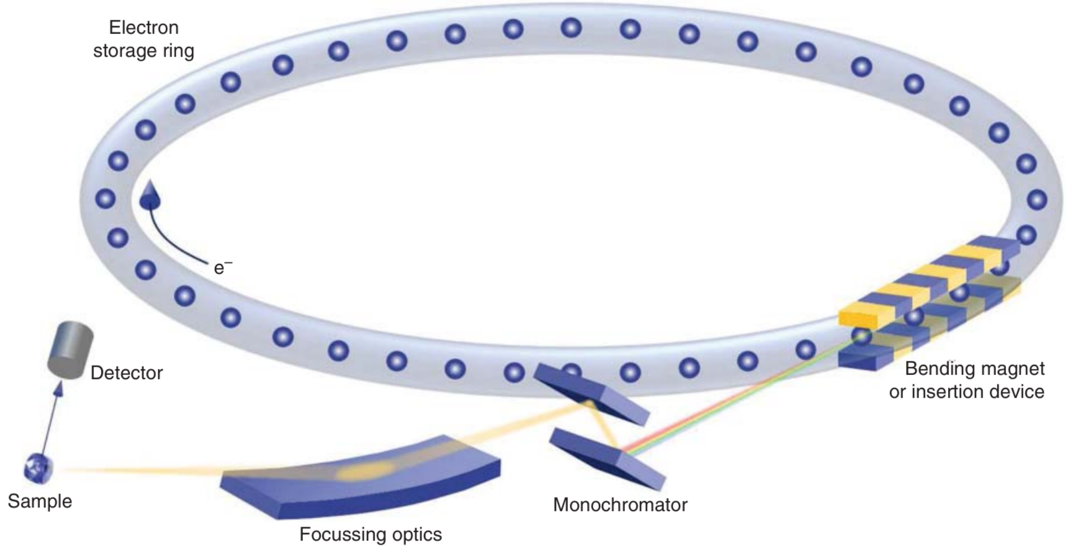
If the size of a bunch of particles is small compared to the wavelength of the radiation being produced, then the particles can radiate coherently, i.e. acting as effectively a single particle. The intensity of the radiation in that case is proportional to the square of the number of particles.

Since bunches in an electron storage ring are typically several millimetres in length (of order of 10 ps), any coherent radiation from an entire bunch has a large wavelength and does not propagate efficiently through the vacuum chamber (cut-off).

However, it is possible in some circumstances for substructures to develop within a bunch (e.g., microbunching), leading to coherent radiation at wavelengths below a millimetre.

A free electron laser (FEL) is an accelerator designed to produce coherent synchrotron radiation, either from an electron storage ring, or from a linear accelerator delivering the beam for a long undulator.

Short-wavelength (extreme ultra-violet or x-ray) FELs are based on linacs rather than storage rings, producing extremely intense and short pulses of radiation (sometimes below 1 fs); but with limited number of beamliines. Sometimes, and confusingly, FELs are referred to as 4th-generation (linear-type) light sources.



Instruments are required to steer and focus high-intensity and short wavelength radiation, to select particular wavelengths and polarisations, and to detect the response after interaction with a sample.

- Diffraction and scattering techniques
- Spectroscopic techniques
- Imaging techniques
- Time-resolved experiments (e.g., pump-probe)

The value of synchrotron light sources for fields as diverse as materials science, information technology, engineering, biology, and medicine is such that about fifty facilities are currently in operation around the world, with several new (including 4GSR) facilities either proposed, under construction or being commissioned. (as of 2018)

[1] Introduction to Beam Dynamics in High-Energy Electron Storage Rings, Andrzej Wolski.

[2] Beam Dynamics In High Energy Particle Accelerators, Andrzej Wolski.

[3] An Introduction to Synchrotron Radiation: Techniques and Applications, Philip Willmott.