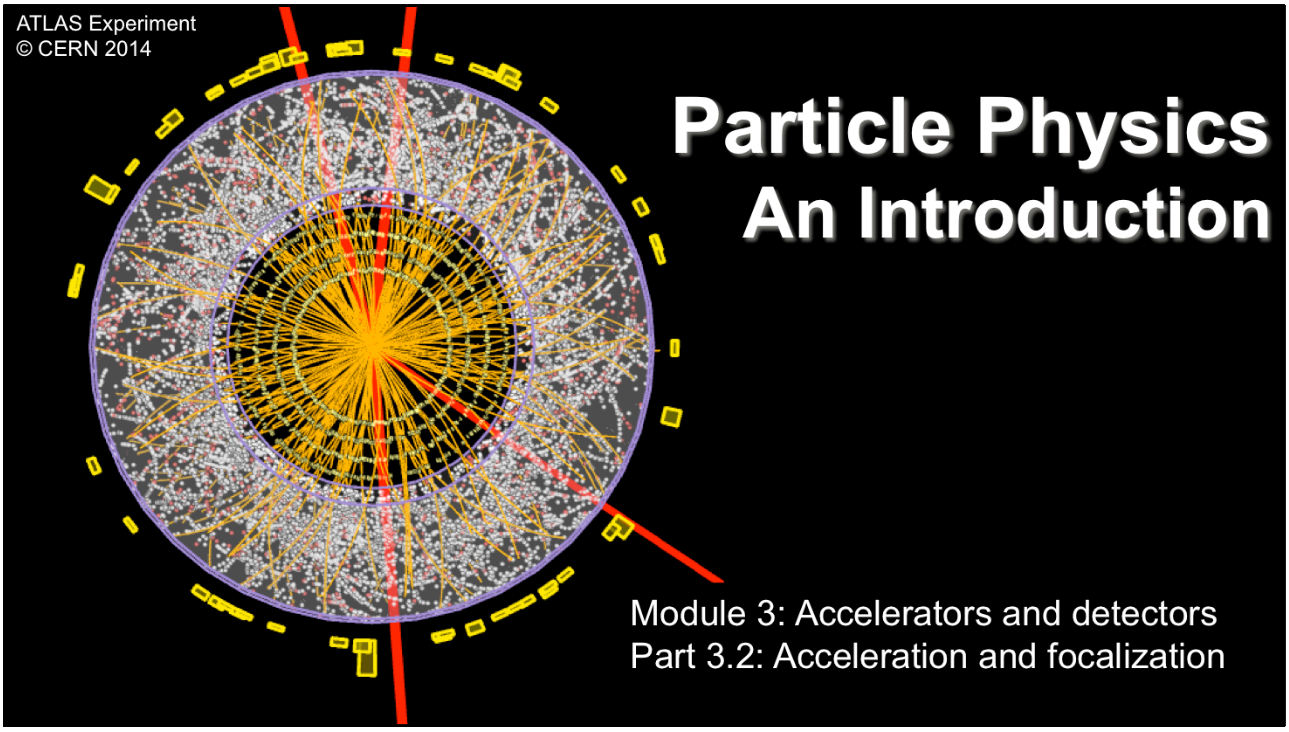
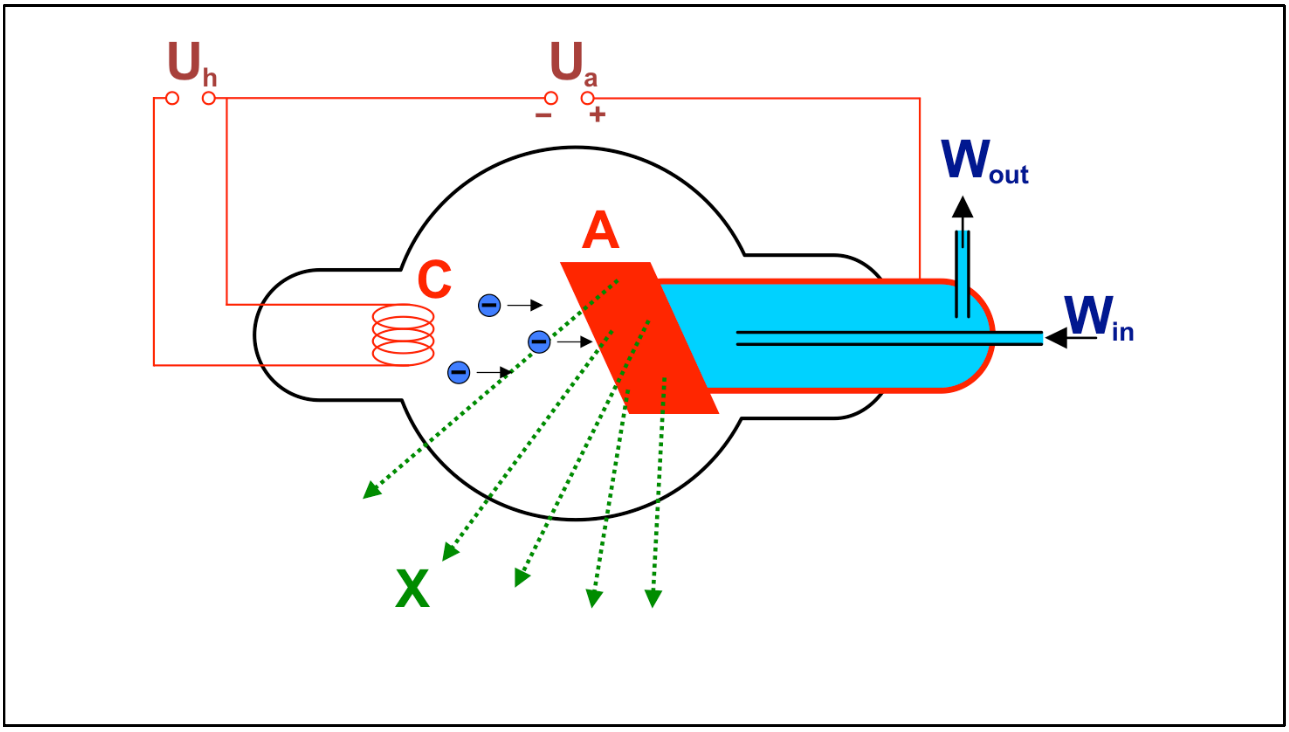


In this module, we will touch the basics of particle acceleration and detection methods.

In this second video we treat the acceleration and focusing mechanisms at work inside accelerators.

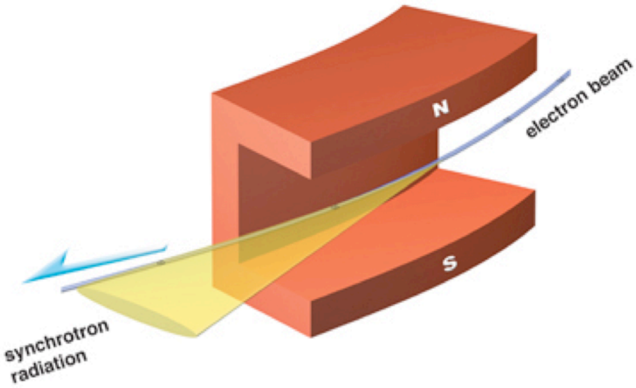
At the end, you will be able to answer the following questions:

- What are the main components of an accelerator and how do they work?
- How does a complex of accelerators like that at CERN work together to achieve the highest energies and highest intensities?



- Inside an accelerator particles obviously move in **an evacuated** tube. This is to prevent them from interacting with air molecules and lose energy or be transformed.
- Even if they don't, we still need to supply radiofrequency acceleration in a storage ring if we want to keep the beam energy constant. This is because an **accelerated charged particle** loses some fraction of its energy in the form of radiation, by emitting photons.

- This process is called **bremsstrahlung**. The same process produces photons in a X-ray tube. In such a tube, the electron cathode ray beam is stopped by an inclined water-cooled target. The energy of the electrons is typically ten keV, they thus yield X-ray photons of a comparable energy.



Power lost per turn :

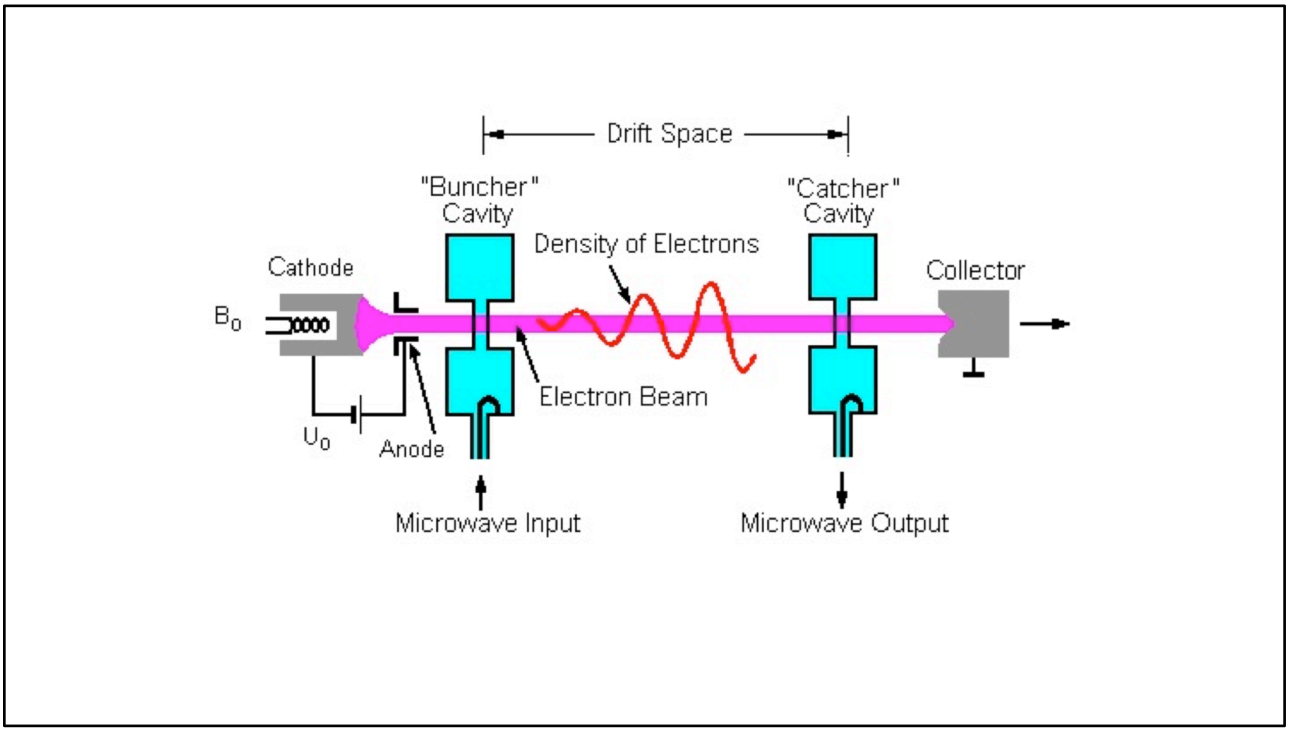
$$P \sim \frac{\gamma^4}{\rho} \sim \frac{E^4}{m^4 \rho} \quad (\beta \simeq 1)$$

http://www.synchrotron-soleil.fr

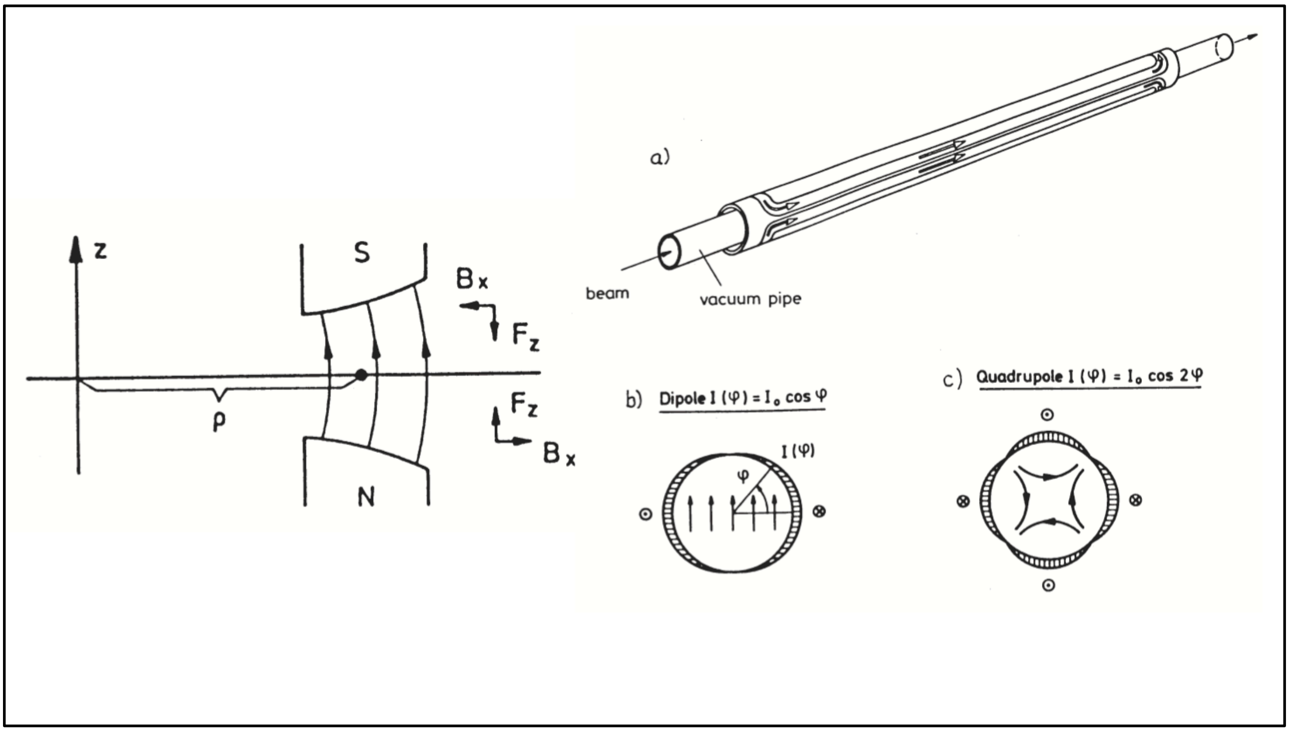
- But also **lateral acceleration** creates bremsstrahlung, namely **synchrotron** radiation. For relativistic particles, the **lost power per turn *P*** is proportional to the 4th power of the relativistic factor γ, and inversely proportional to the radius of curvature ρ. It is **large for light particles circulating in small orbits**. This loss must be **replaced constantly** to get a stable beam in an **orbit of constant** radius.

https://www.psi.ch/sls/about-sls

- But synchrotron radiation is more than a nuisance. One uses it to produce **monochromatic photons**.
- The **Swiss Light Source** (SLS) at the Paul Scherrer Institute in Villigen is a source of high-brightness light, based on an electron synchrotron of 2.4 GeV. Its beam lines are used for research in materials science, biology and chemistry.



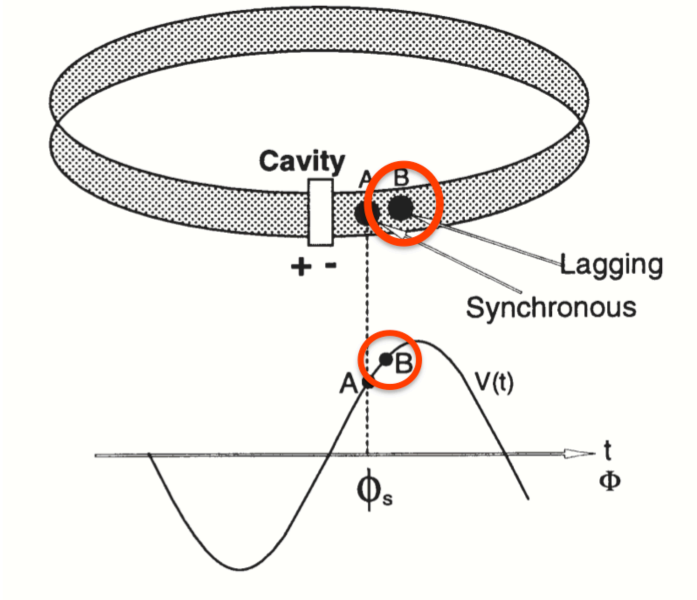
- The **accelerating electric field** is generated by a vacuum tube amplifier, the **klystron**. An intense electron beam is **accelerated,** then **bunched** in a resonant cavity. In a **second resonant cavity,** the electron kinetic energy is extracted in the form of a **radio frequency** wave. Modern klystrons have normally several such amplification stages.



- The beam is held on a **circular path** by **dipole** magnets.

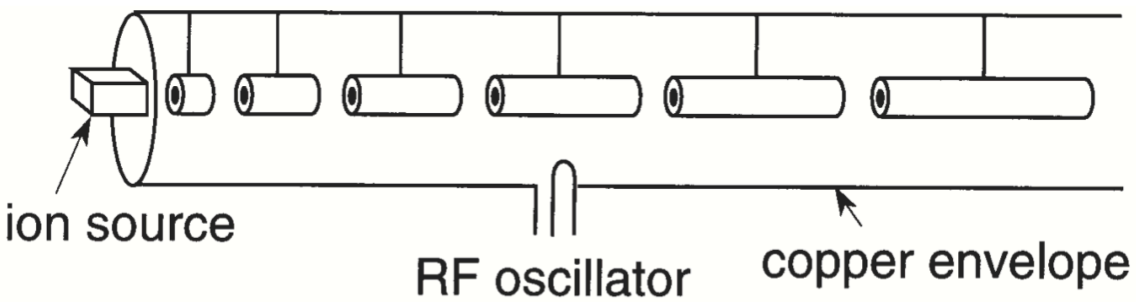
- **The transverse focusing** of the beam is done by **quadrupole magnetic fields**. A low quadrupole component is normally present even in dipole magnets. The focalizing forces come from a slight horizontal component of the magnetic field, which changes sign as one passes from below to above the orbital plane. By alternating this quadrupole configuration with one which is rotated 90^o, a focalization is obtained in both horizontal and vertical directions transverse to the beam.

- Magnets with dipolar and quadrupole fields thus accompany the accelerator ring. **Two coils create a dipole field, four create a quadrupole field as shown**. Today these coils are normally **superconducting** to minimize resistive losses.

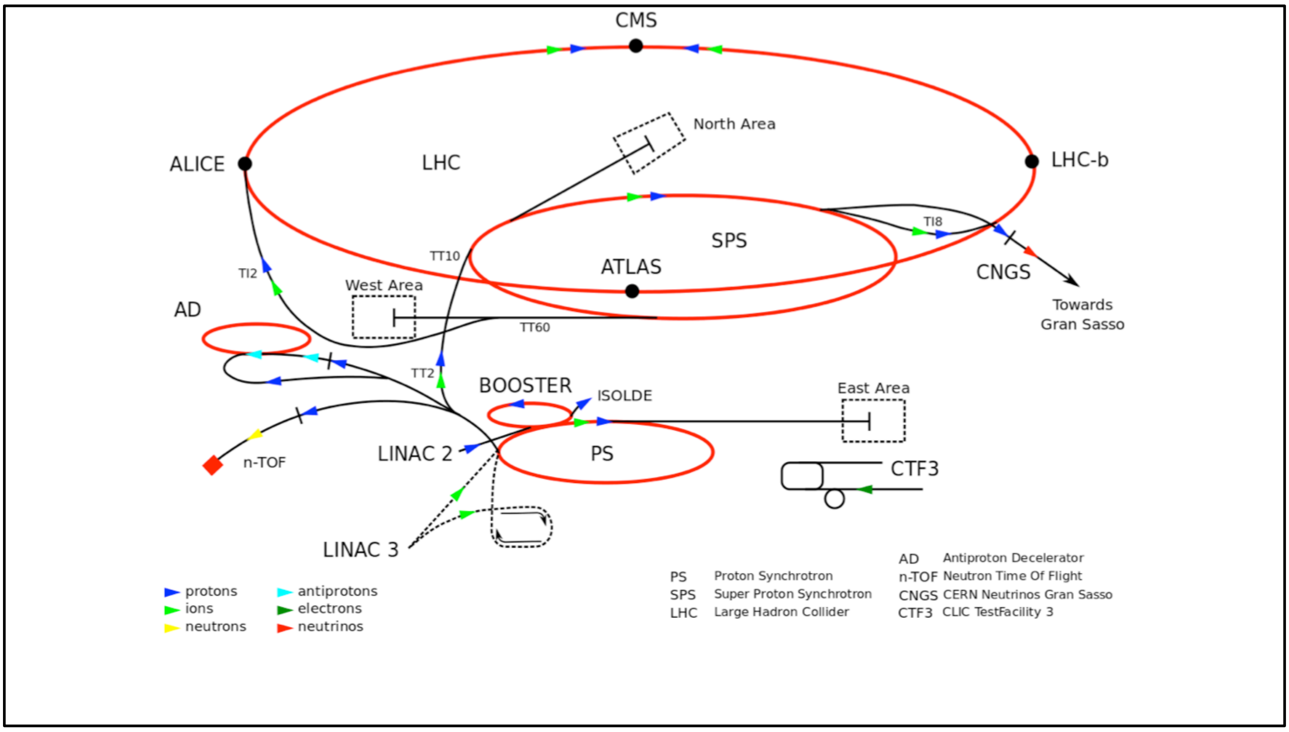


- But **focalization** is also needed in the **longitudinal** direction. The reason is that the particles must arrive **synchronously** to acceleration points. Thus they are injected in **short packets called bunches**. If they arrive at radio frequency resonators on the **increasing slope** of the electric field, their phase remains stable.

- A particle arriving with a **slight delay** compared to the ideal phase will see a field that is **stronger** than the average field. A particle with a **slight advance** will on the contrary see less accelerating field. In this way, the particles will automatically oscillate around the **ideal phase.**



- We can lower energy loss from synchrotron radiation by **increasing the radius of curvature ρ**, weakening at the same time the dipole field. Asymptotically, we can let ρ tend to infinity, resulting in a **linear** accelerator. Almost every accelerator complex begins with such a device.
- Much of the **vacuum tube** which contains the beam itself is a **resonant structure of radio frequency with a travelling electromagnetic wave**. Between the resonant cavities, there are spacers made of conductive tubes. Inside these, the electric field is zero. Their length must follow the velocity of the accelerated particles, such that it is $v \times T/2$, where T is the period of the radio frequency.
- It is also necessary that when passing in a non-shielded portion of the cavity, the **electric field** has the **desired sign and value**. Once the velocity of the particle is sufficiently close to *c*, the spacing becomes constant.



- Today's powerful accelerators are mainly working in **synchrotron mode**. The most powerful, the Large Hadron Collider (LHC), has been in operation since 2008. It is part of a **complex of accelerators** to obtain maximum energy luminosity. In 2011/12, the energy per proton beam was 3.5 TeV, in 2012 it was 4 TeV. After a technical interruption that started in February 2013, the operation resumed in 2015 with 7 TeV per beam. This corresponds to the impressive energy of 1.12 μJ.

- The path of particles through the complex is shown in the short **CERN video 3.2a.**

In the next video, we will visit CERN to discuss the key components of the LHC with Prof. Tobias Golling of University of Geneva.