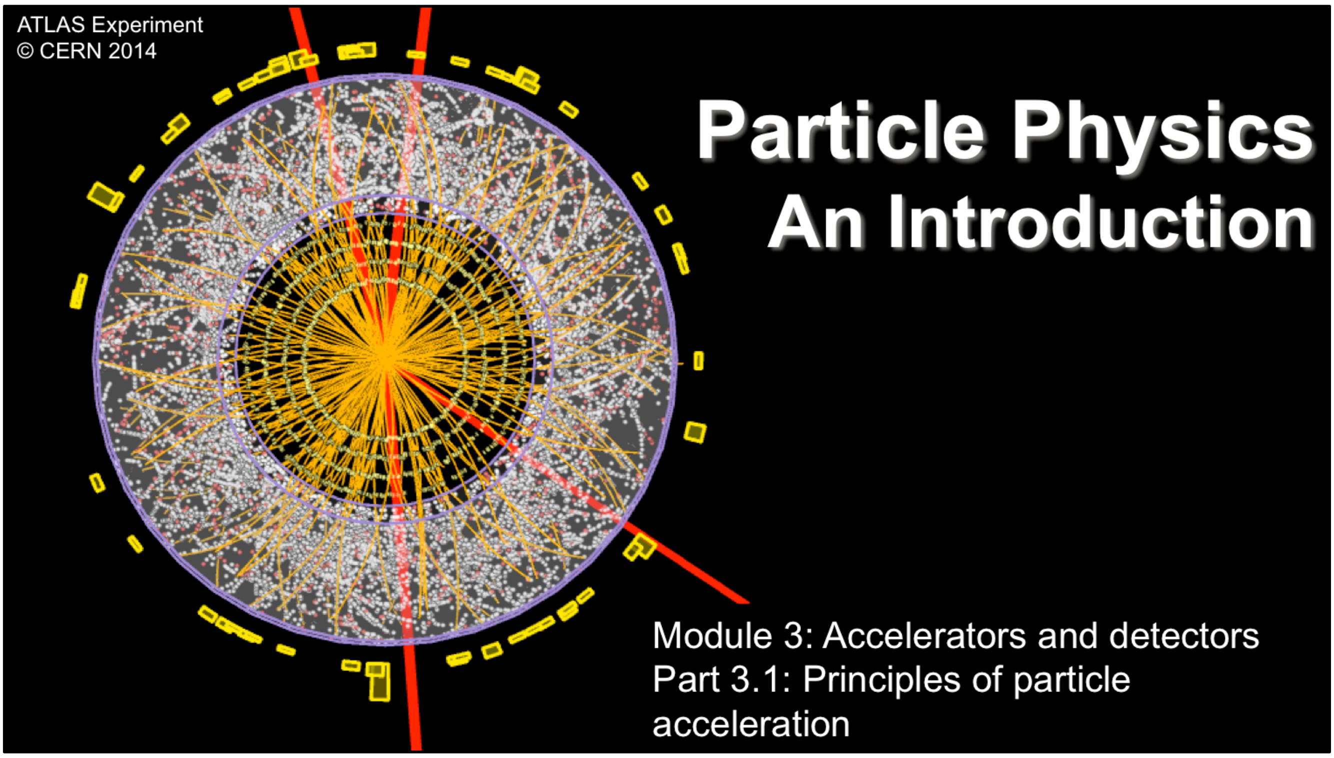
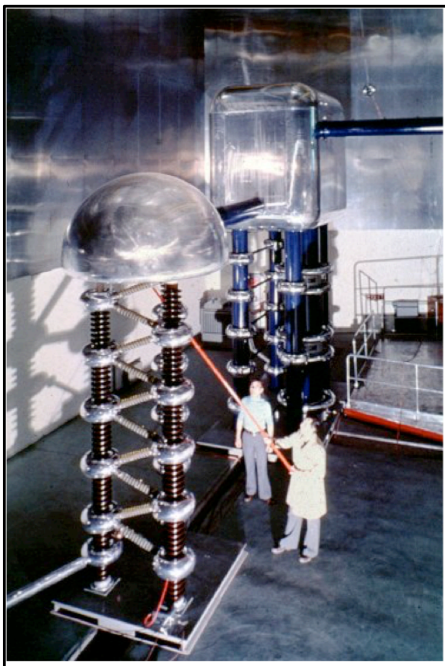


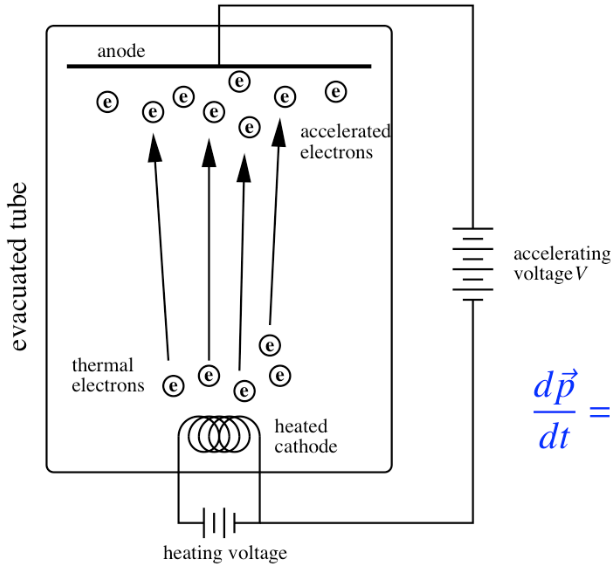
In this module, we will touch the basics of particle acceleration and detection methods.

In this video we will explain the physical principles of linear and circular accelerators.

Afterwards you will be able to answer the following questions:

- What are the principles of particle acceleration by electromagnetic fields?
- How does an electrostatic accelerator work?
- How do cyclotrons and synchrotrons work?



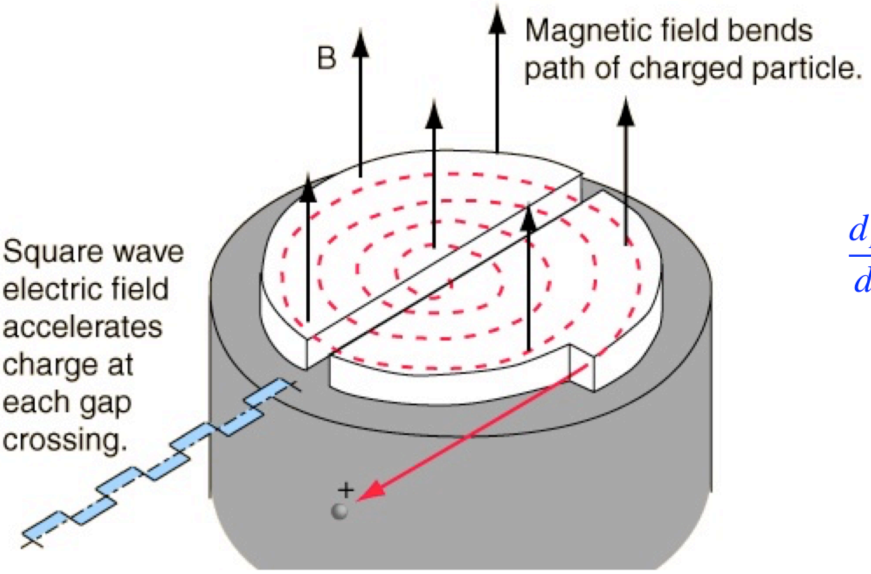


$$\frac{d\vec{p}}{dt} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

- The force acting on a particle of charge *e* in an electric field *E* and magnetic field *B* is given by the **Lorentz** force.
- Electric **fields** are used to **accelerate** particles by increasing their momentum. Magnetic **fields** serve to **deflect** them from their original direction, to store them in a ring, or to focus a beam of particles.

- The simplest accelerator for electrons is the **Cathod Ray Tube**. An electron emerging from a heated filament is accelerated by a potential *V*. The energy of the outgoing electron corresponds to *V* eV.

- Electrostatic **accelerators** chain together stages of this type. Their energy is limited by the stability of the high-voltage insulation, thus it does not exceed **a few MeV**. To reach a higher energy requires that the projectile passes several times by an accelerating potential.



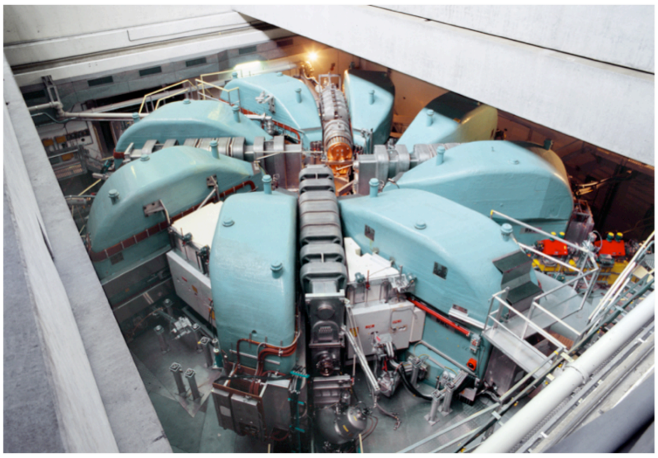
$$\frac{d\vec{p}}{dt} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$\omega_c = \frac{eB}{m}$$

- The simplest **circular accelerator** is the cyclotron. In a uniform and constant magnetic field *B,* a particle of charge *e* moves on a circle of radius $\rho = p/(e\,B)$, where *p* is the momentum. The angular frequency of this movement is called **cyclotron frequency** $\boldsymbol{\omega_{c.}}$ It is proportional to the **ratio** ***e/m*** of the particle charge and mass, and the magnetic field intensity *B*.

- The particle is accelerated by **the electric field** present in the space between the two **D-shaped cavities.** This field is provided by a **radio frequency generator** such that its frequency is equal to the cyclotron frequency. In the non-relativistic domain, this frequency is constant, because **the circumference of the orbit increases proportional to the velocity** of the particle. Thus we can inject particles in a quasi-continuous manner if the accelerating RF frequency is high and an even multiple of the cyclotron frequency.

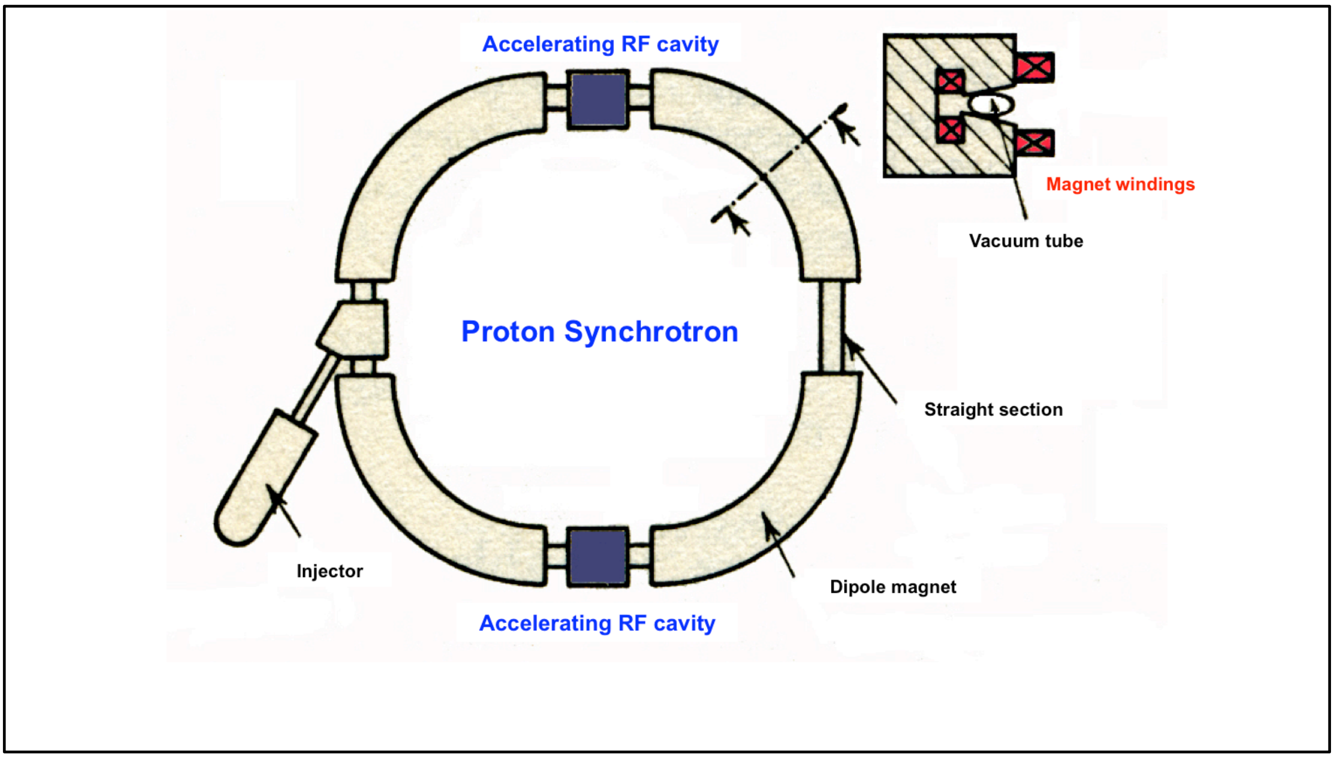
- You find a calculation of the cyclotron frequency in video **3.1a**.



http://www.psi.ch/media/the-psi-proton-accelerator

$$v = \sqrt{1 - \frac{m^2}{E^2}}$$

- The cyclotron has its limits in that the velocity of the particle does not remain proportional to the momentum but approaches **the speed of light** in a saturation process.
- In the relativistic limit, the velocity barely increases despite a steady increase in energy. Acceleration radiofrequency and the particle revolution frequency dephase quickly at an energy of some tens of MeV for protons.
- One must thus adjust the radio frequency to the relativistic velocity. For example, the **proton cyclotron at the Paul Scherrer Institute** in Villigen, Switzerland, accelerates protons to nearly 80% of the speed of light.

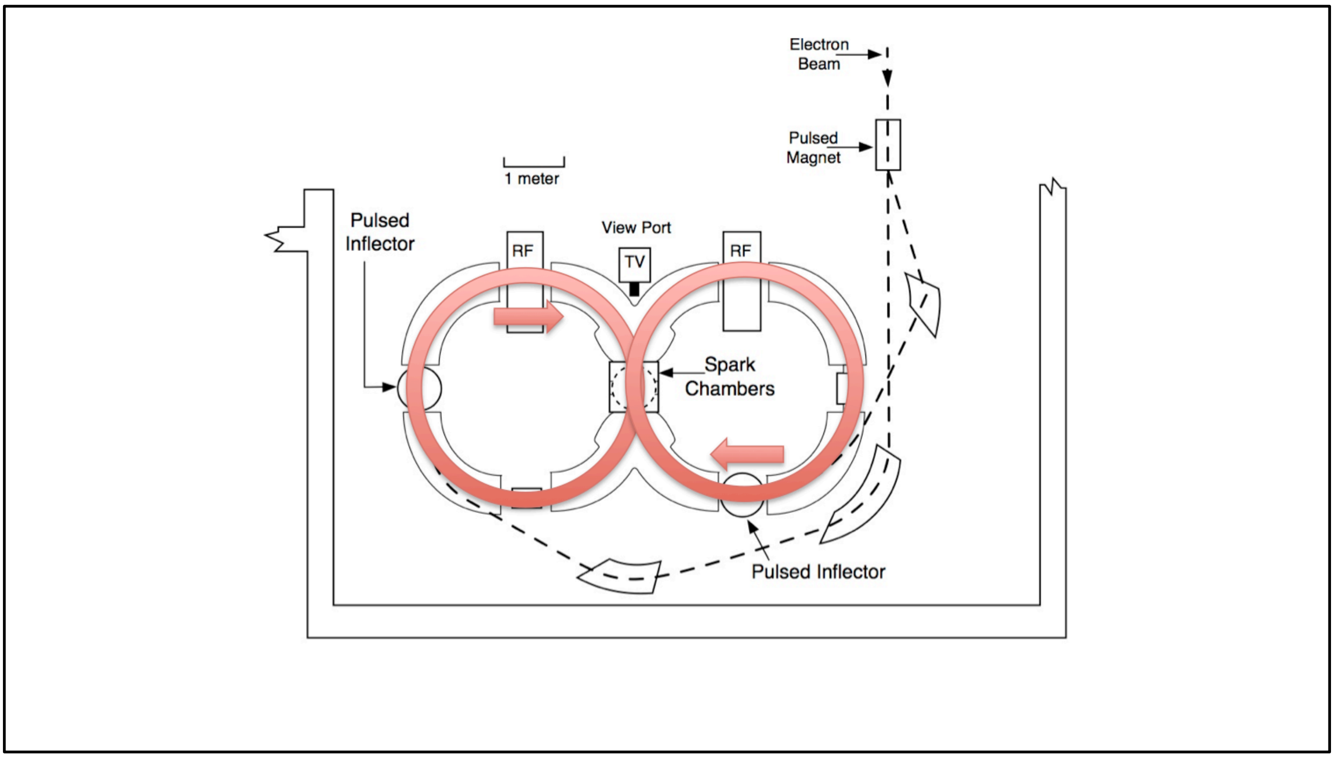


- The **asymptotic saturation** of the speed to the speed of light is on the contrary very useful, provided that the **radius of curvature** is held constant. In this case, the rotational frequency is again independent of energy.

- This is the principle of the **synchrotron**. By increasing the magnetic field proportional to the momentum of the particle, the radius of curvature remains constant. One does not have to fill a large volume with the magnetic field, but can concentrate it inside a vacuum chamber whose shape approximates a ring.

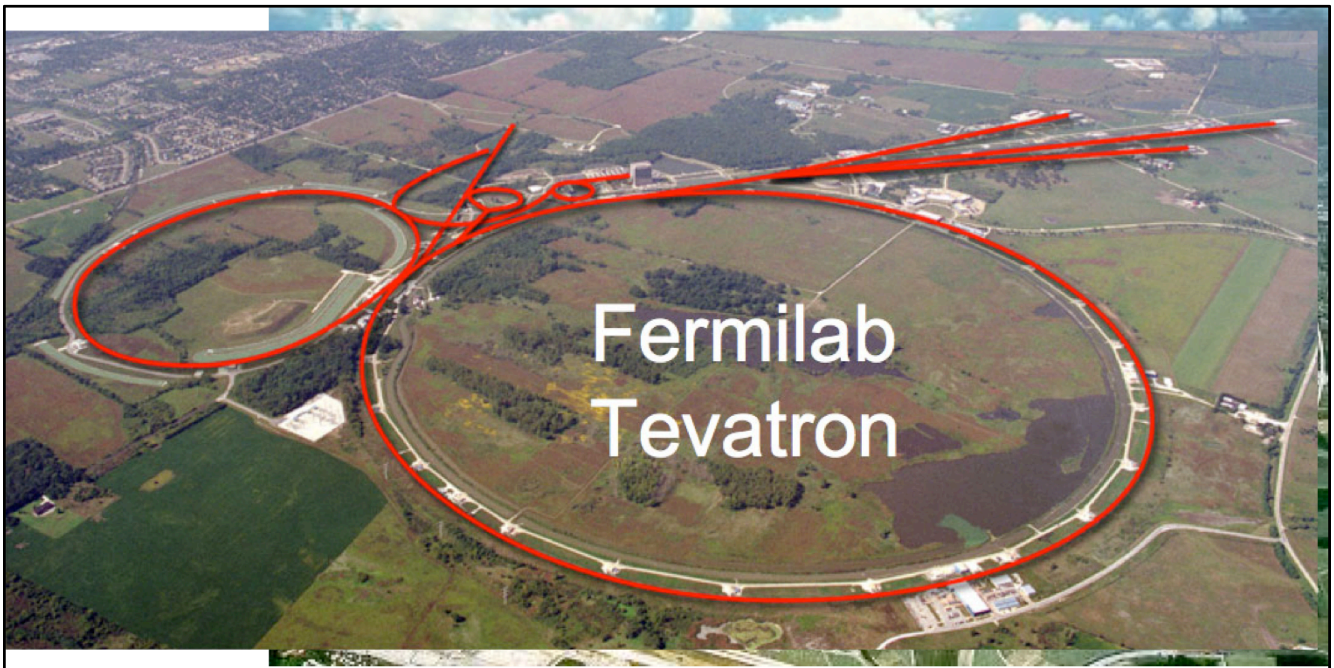
- The cyclotron frequency becomes constant at high energies if the **field *B* is kept proportional to the momentum**. We can then work with a constant accelerating radio frequency. The RF field is transmitted to the beam by **resonant cavities**.

- The synchrotron principle requires a **certain initial velocity,** sufficiently close to the speed of light. The beam is thus pre-accelerated before injection, usually by a linear accelerator. The acceleration process must stop when one reaches the **maximum field of the dipole magnets**.



- One then extracts the beam or converts the accelerator into a **storage ring**. In this operational mode, it provides at each turn just the energy lost by the beam via bremsstrahlung. This loss of energy will be introduced in the next section of the module, video 3.2.

- The separation of functions and the concentration of the components around a ring allows to combine two rings to construct a **collider**. A historical example is **the Princeton-Stanford storage ring** an early example of a particle collider. It worked with electrons in the two rings, which interact in the middle, where the two storage rings touch. The detector was rather primitive, a spark chamber, but it allowed to determine the scattering angle.



- Obviously you can also **fold the two accelerators** onto each other, or **even combine them** if you want to **collide particles and antiparticles**. Examples of the latter type of colliders are:
    - The **Tevatron** at the Fermi National Laboratory close to Chicago, which collided protons and antiprotons until 2011;
    - and the **Large Electron-Positron collider LEP at** CERN **,** which collided electrons and positrons.

- The latter was in operation between 1989 and 2000 in the tunnel which now houses the **Large Hadron Collider LHC** at CERN. We will return to the LHC in the next video of this module.