Curriculum in Electronics and Electrotechnics for Accelerators

M. Migliorati – A. Palmieri

Dipartimento di Scienze
di Base e Applicate
per l'Ingegneria

Sapienza
Università di Roma

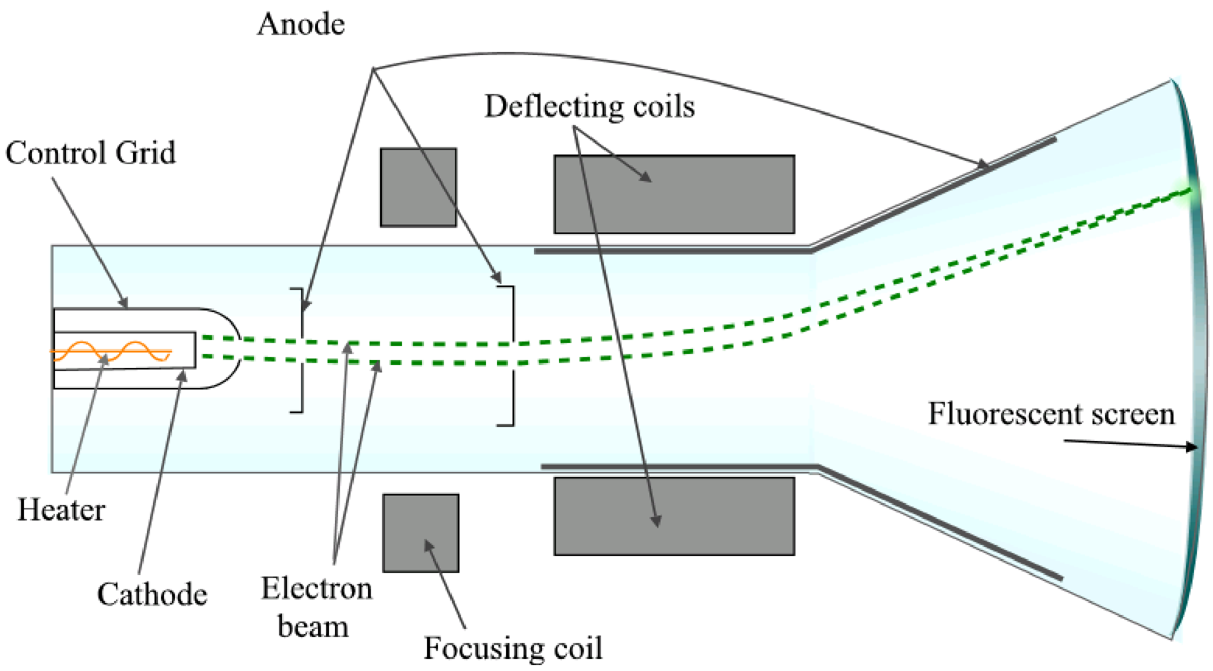
INFN

What is a particle accelerator?

A particle accelerator is a machine that uses electromagnetic fields to accelerate charged particles (electrons, positrons, protons, ions) to very high speeds and energies.

The cathode ray tube of any (old) TV or computer monitor is really a particle accelerator.

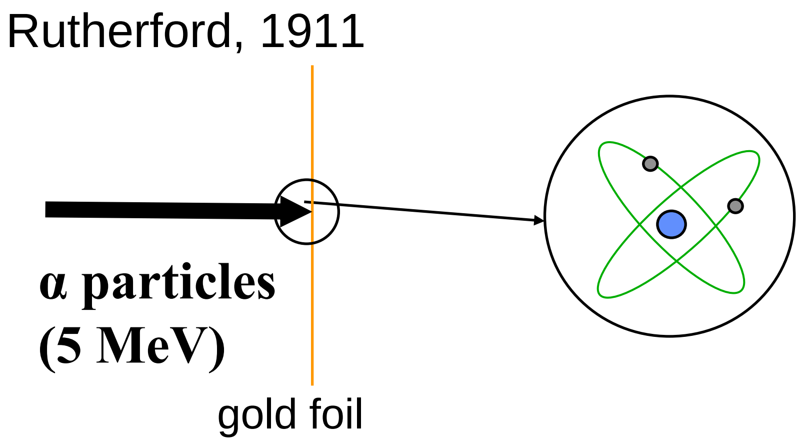
Accelerators can be either giant or tiny, but all have similarities and generally the same subsystems. A giant accelerator, such as CERN LHC circular accelerator and a cathode ray tube TV, have all the main components of a modern accelerator or collider.



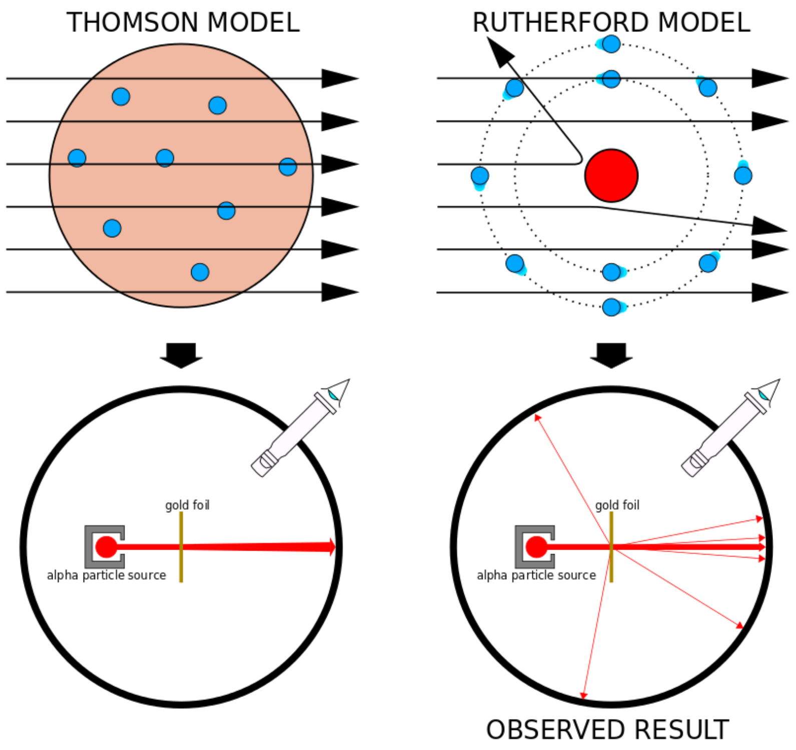
These main components include a source of charged particles, an acceleration area, a drift region with focusing and steering, and a target and a detector (represented in the case of a TV by the phosphorous screen).

A first particle accelerator: Rutherford gold foil experiment

Rutherford wanted to prove the validity of the Thomson model of the atom, in which electrons (discovered by Thomson in 1897) are distributed inside a positive charge as in a 'plum pudding' (a Christmas pudding, from which the name: plum pudding model).



The experiment consisted of bombarding a thin foil of gold with α particles (nuclei of helium, 2p + 2n) and demonstrated that atoms are essentially empty structures.



"What we require is an apparatus to give us a potential of 10 million volts which can be safely accommodated in a reasonably sized room and operated at a few kilowatts of power. We require too an evacuated tube capable of withstanding this voltage... I see no reason why such requirements cannot be made practical" (Rutherford, 1930) [1, p. 444].

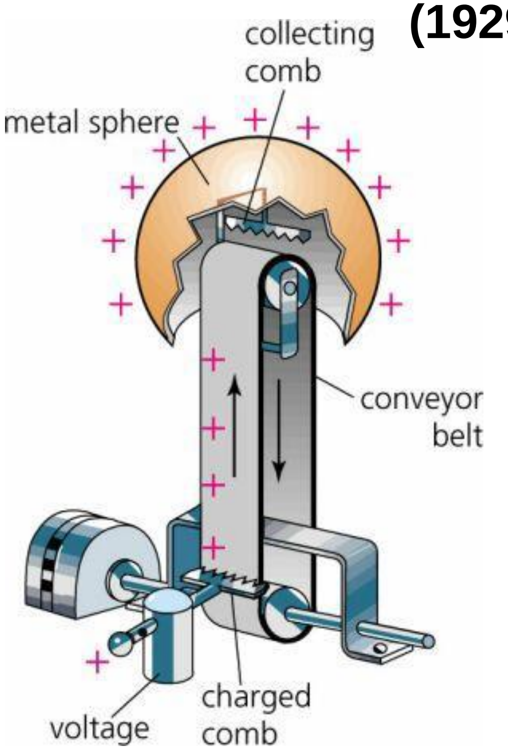
Kinds of particle accelerators: electrostatic linear accelerators

The simplest idea for particle acceleration is to use an electrostatic electric field

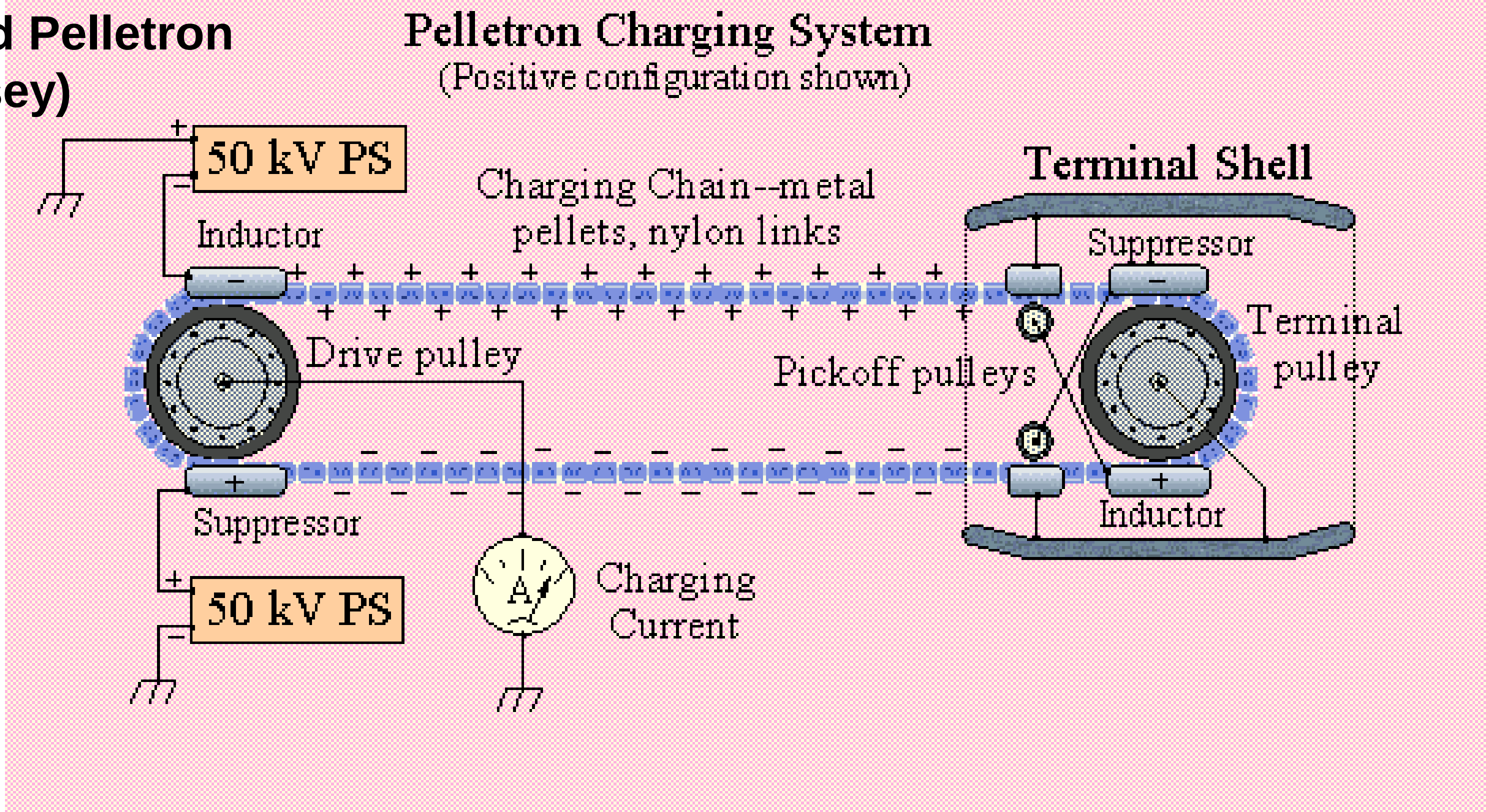
Principle: A static electric field between two electrodes accelerates electrons/ions initially at rest via uniformly accelerated motion.

Van De Graaff … and Pelletron

(1929, Princeton, New Jersey)

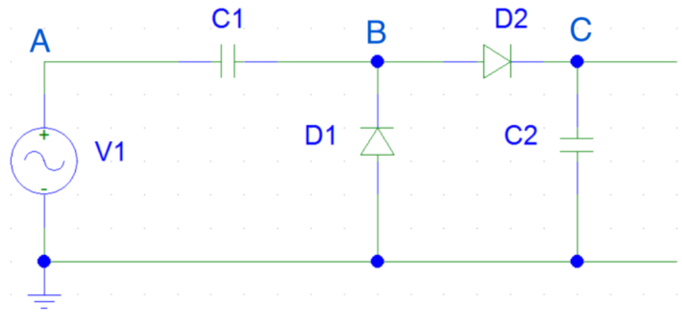


Problem of breakdown → limit in the maximum acceleration



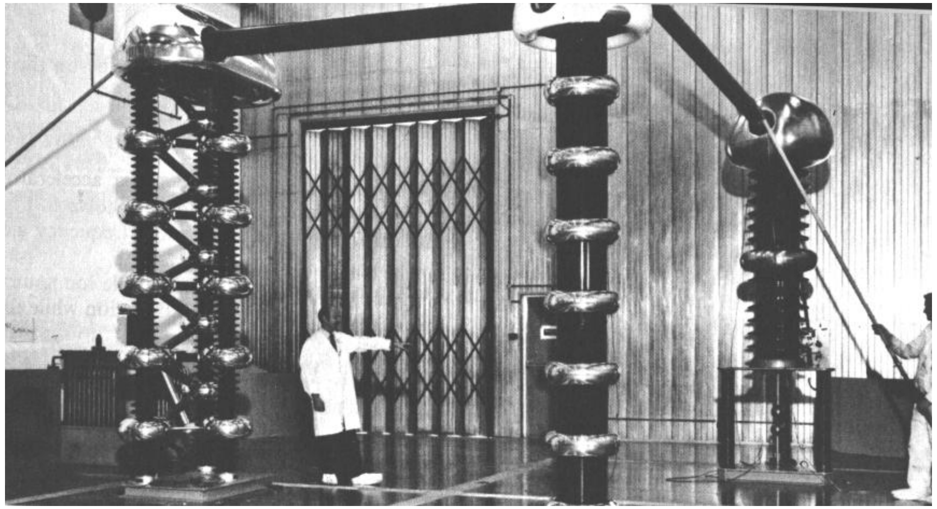
Kinds of particle accelerators: electrostatic linear accelerators

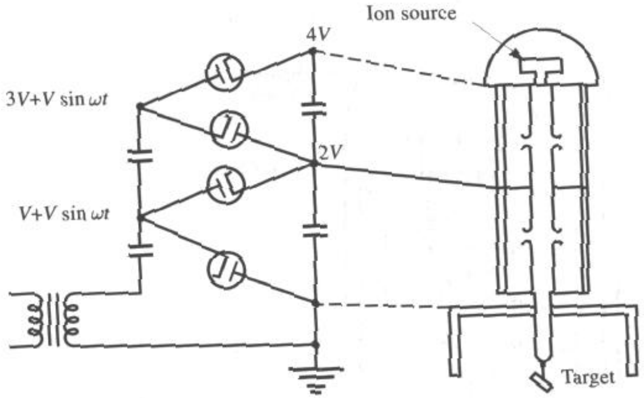
Alternatives: voltage multiplier (rectifier) → Cockcroft & Walton's accelerator



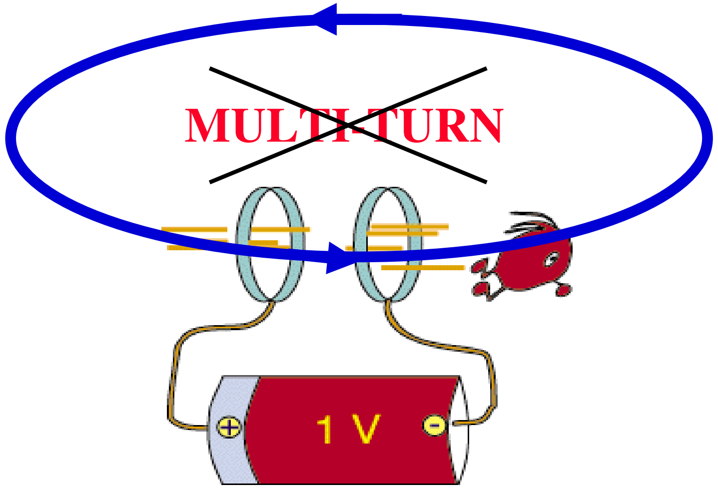
When the AC voltage is negative, the diode D1 allows current to B, filling up the capacitor C1 to a voltage V1, which remains constant if the capacitor is ideal.
When the same AC voltage reverses polarity, current cannot flow back through D1. The voltage across the capacitor C1 remains constant and equal to V1 (rectifier). Since the point A has a voltage oscillating as V1*sin(ωt), then the point B, which must have a voltage V1 higher than A has a total voltage equal to V1+V1*sin(ωt).

The Cockcroft-Walton generator that served the 7 GeV NIMROD synchrotron at Rutherford laboratory.





limits



… however, Tandem Van de Graaff is a clever trick to use the voltage twice …or

Time-varying electric fields

Time-varying electric field:

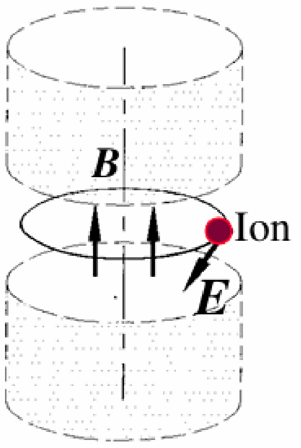
$$F \cdot v = eE \cdot v + \underbrace{e(v \times B) \cdot v}_{=0}$$

Accelerators must use electric fields to transfer energy to charged particles because the force exerted by a magnetic field is always perpendicular to the motion.

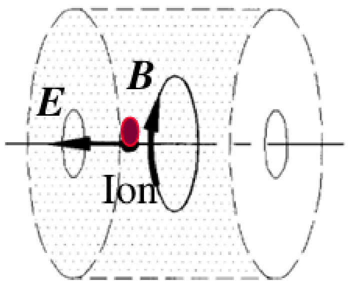
Use of electric field: $E = -\nabla\phi - \partial A/\partial t \rightarrow \nabla \times E = -\partial B/\partial t$

Acceleration by DC voltages:
- Cockcroft & Walton
- Van de Graaff, Tandem …

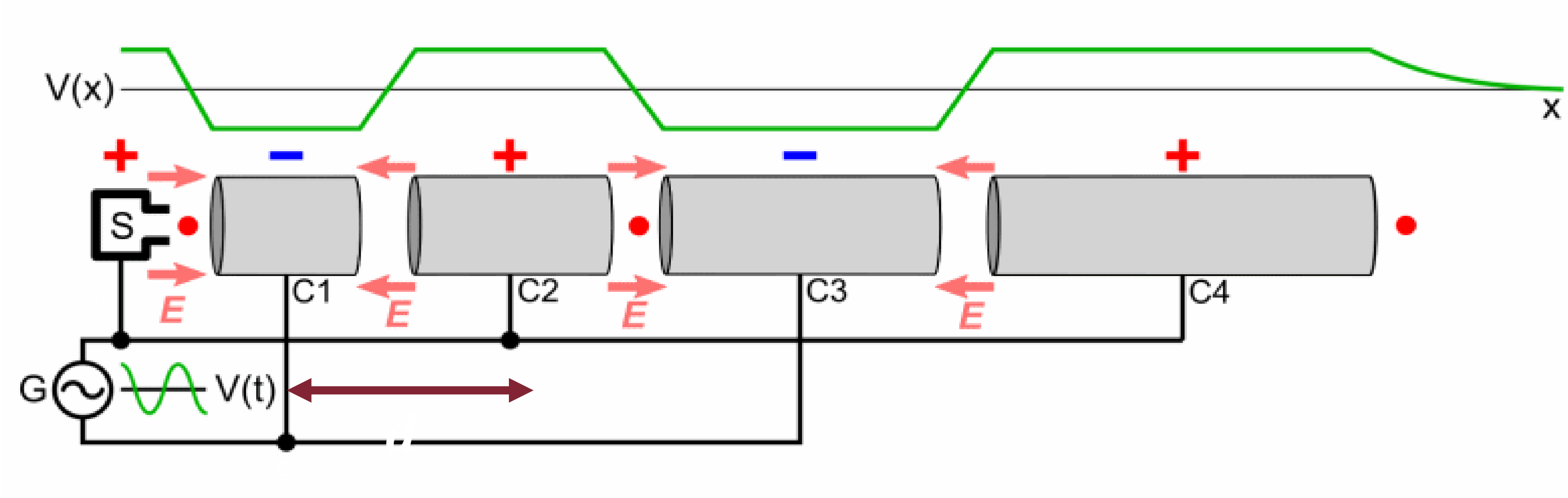
'Betatron' or 'unbunched' acceleration



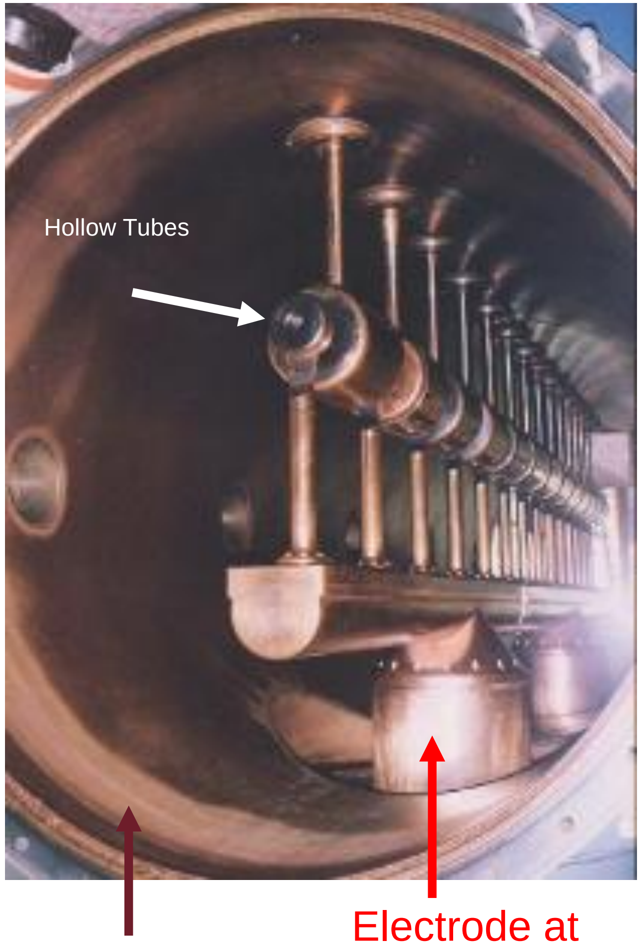
'Resonant' or 'bunched' acceleration
- Linear accelerator (linac).
- Synchrotron.
- Cyclotron



Wideröe Structure

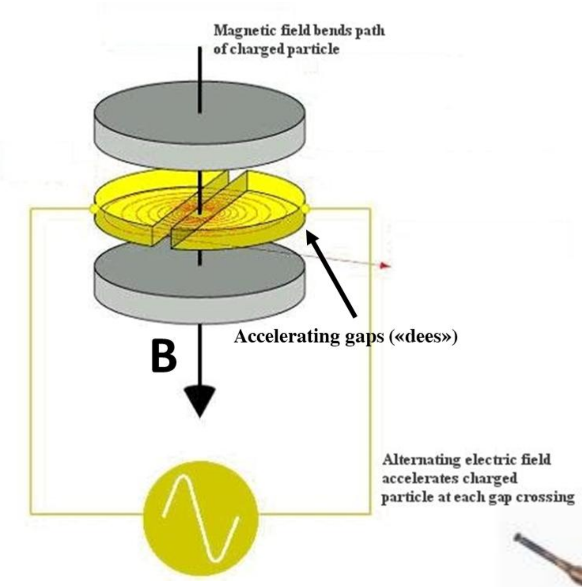


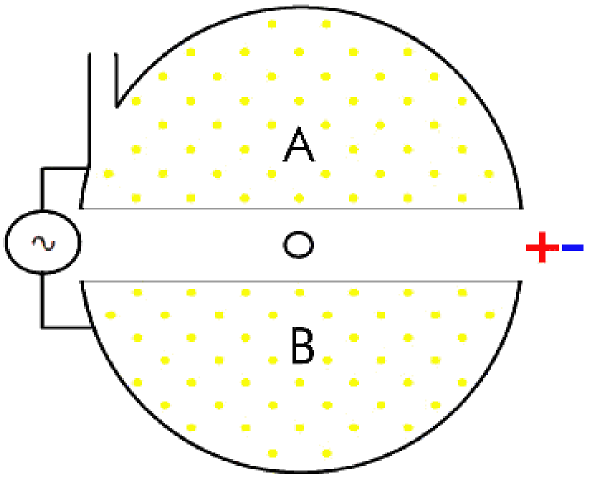
The Wideröe structure (1928) was the first to be proposed to accelerate particles by applying a sinusoidal field. The hollow tubes, C1, C2, C3, C4 etc. are alternately connected to the two ends of a sinusoidal voltage generator. When ions enter an accelerating gap (space between two tubes) with velocity βc, if they have been injected "at the right time", they will find a voltage and therefore a field E that accelerates them. After crossing the gap the particles will enter the hollow tubes which will shield them from the electric field. If now the distance between the centers of two consecutive gaps is equal to $\beta\lambda$ / 2, then the particle, once it has reemerged from the hollow tube, will again find a voltage that accelerates it. On the other hand, the particles of ionized gas, not being in synchrony with the accelerating field, will undergo accelerations and decelerations, so on average they will not gain energy and it will be more difficult for them to create discharges.



The Cyclotron

At the time this solution was considered not very "practical", since only amplifiers capable of delivering power at frequencies up to about 10 MHz were available. The American Physicist D. H. Lawrence realized that if the particles were accelerated in a circular path, the structure would certainly be more compact. For the trajectory to remain circular, the centrifugal force F_C and the Lorenz force F_B had to be equal. The angular velocity $\omega = v / R$ is the number of radians per second that the particle travels.





$$F_c = \frac{mv^2}{R} \qquad F_B = qvB$$

centrifugal force (directed towards the external)

$$F_c = F_B \Rightarrow \frac{v}{R} = \omega = \frac{qB}{m}$$

Lorentz force (directed towards the internal)

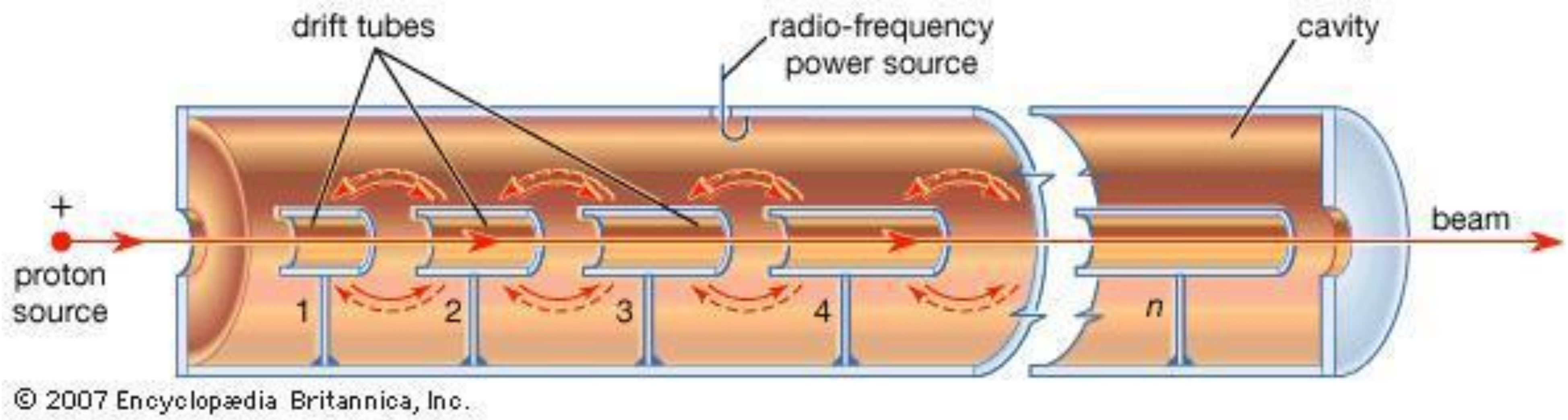
First working Cyclotron Prototype (E.O.Lawrence e M.S.Livingston, 1931, Berkeley, CA)

The cyclotron is limited by relativistic effects, which cause the particles to slow down and lose synchronism with the RF field.

The angular velocity does not depend on the radius, but only on the field B and on the charge/mass ratio. The electric field between points A and B at a frequency equal to $qB/(2\pi m)$ provides the necessary acceleration. This type of machine is called the Cyclotron.

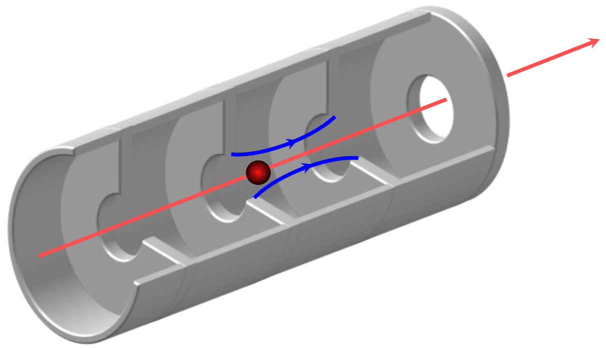
Alvarez DTL

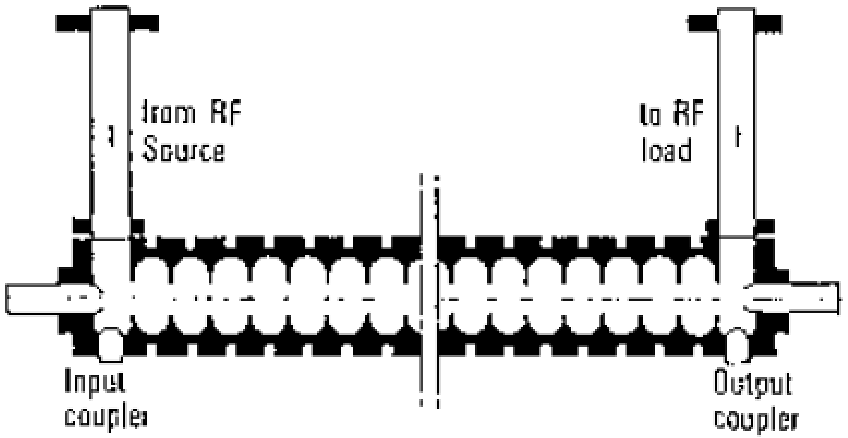
After the end of World War II, some technologies used for radar were de-classified. As a result, new types of high-frequency amplifiers (from 100 MHz to a few GHz) have become available.
Furthermore, in 1946 Luis Alvarez overcame the drawbacks of Wideroe Linac by including the Wideroe structure inside a large metal tube that formed an efficient cavity where the fields were confined and prevented from irradiation. This structure, called DTL (Drift Tube Linac), is widely used as an accelerator for protons and ions.

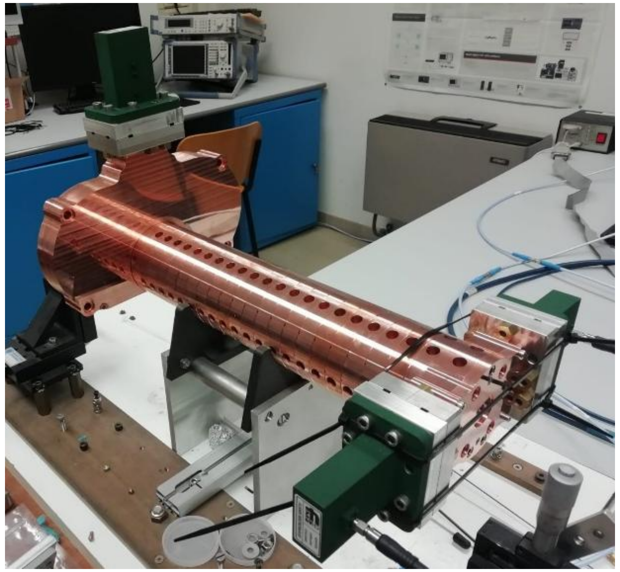


Similarly to Wideroe's machine, the DTL alternates shielded tubes and accelerating gaps and exploits synchronism, but, in Wideroe's machine, the accelerating tubes are directly connected to the RF amplifier, so the machine can behave like an antenna and radiate.
In Alvarez's machine, the RF power injected into the cavity by means of an antenna establishes an electromagnetic field configuration that remains efficiently confined as a standing wave the operating frequency. At different frequencies, the cavity tends to reflect the RF power back.

TW (Travelling Wave) Structures







Another possibility to accelerate particles is using a travelling wave (TW) structure in which the RF wave is co-propagating with the beam with a phase velocity equal to the beam velocity.

Typically, these structures are used for electrons because the phase velocity can be constant all over the structure and equal to the speed of light.

These structures also have relatively high shunt impedance values (tens of MΩ/m) and operate at frequencies in the GHz range (typical value in the S-band is 2.856 GHz). The choice of frequency is a compromise between the compactness of the structure, optimization of Shunt Impedance (which increases with frequency$^{1/2}$) and beam positioning tolerances (which are tighter the smaller the aperture, i.e. the higher the frequency).

We also note that, due to ohmic dissipations, the accelerating field decreases exponentially along the structure. To overcome this inconvenience, one can think of varying the opening of the disks in order to reduce the attenuation coefficient along z: It is possible to have the same acceleration gradient along all the cells (constant gradient structures).

Synchrotron

Cyclotron limitations:

1) Starting from ~ 400MeV the production of cyclotrons becomes inconvenient and expensive

2) High energies => relativistic effects => ω no longer constant (since m increases with v according to Relativity). The particles get out of phase with the accelerating fields, and eventually there is no more acceleration.

Such limitations were overcome by E. McMillan and independently by V. Veksler who discovered the principle of phase stability in 1944 and invented the synchrotron: a bunch of particles, with an energy spread, can be kept bunched throughout the acceleration cycle by simply injecting them at a suitable phase of the RF cycle.

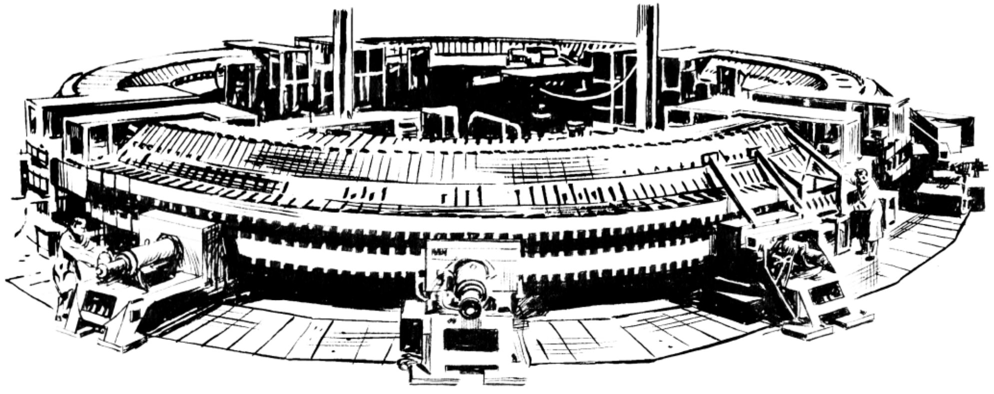
A synchrotron is a particular type of cyclic particle accelerator originating from the cyclotron in which the guiding magnetic field is time-dependent and synchronized to the particle beam of increasing energy.

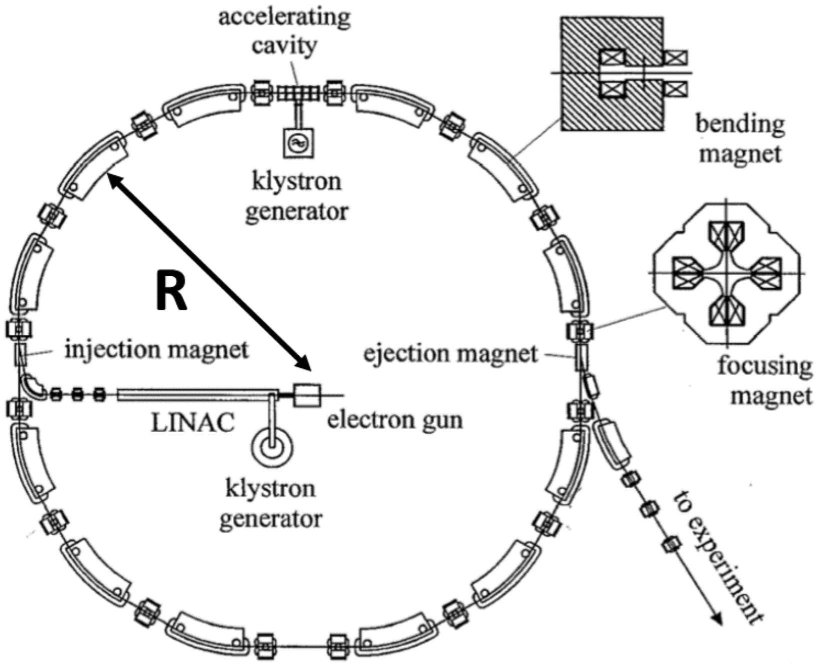
The mechanism used for focusing in the transverse plane was called weak, or constant-gradient focusing: the guide field decreases slightly with increasing radius and its gradient is constant all around the circumference of the machine.

In 1952 Christofilos, and Courant, Livingston and Snyder independently invented strong focusing, also known as alternating-gradient (AG) focusing.

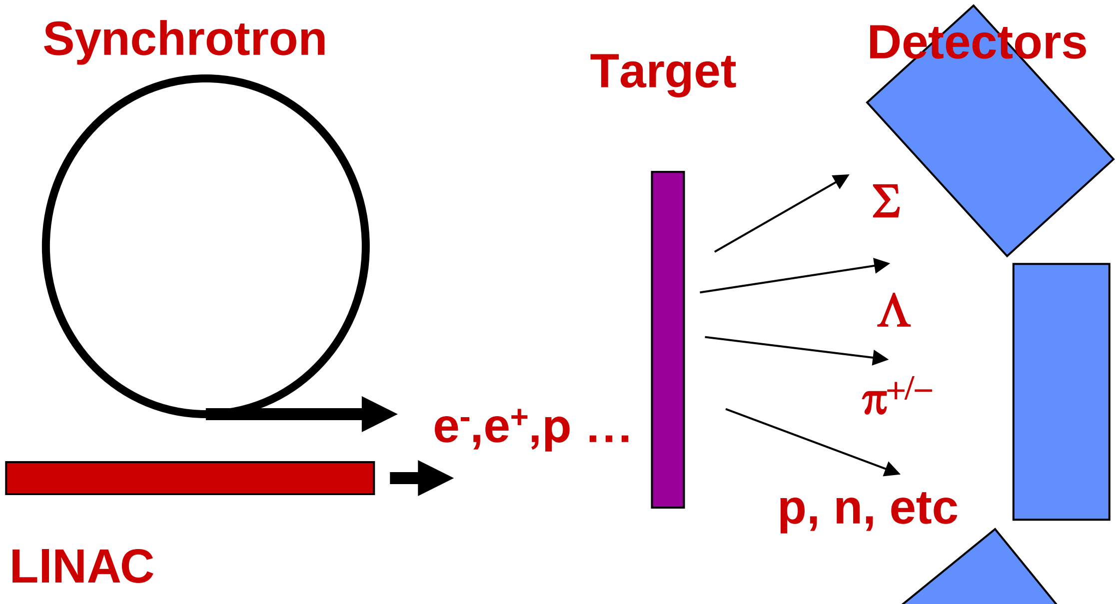
This new principle revolutionized synchrotron design, allowing smaller magnets and higher energies.

weak focusing synchrotron
(0<n<1)



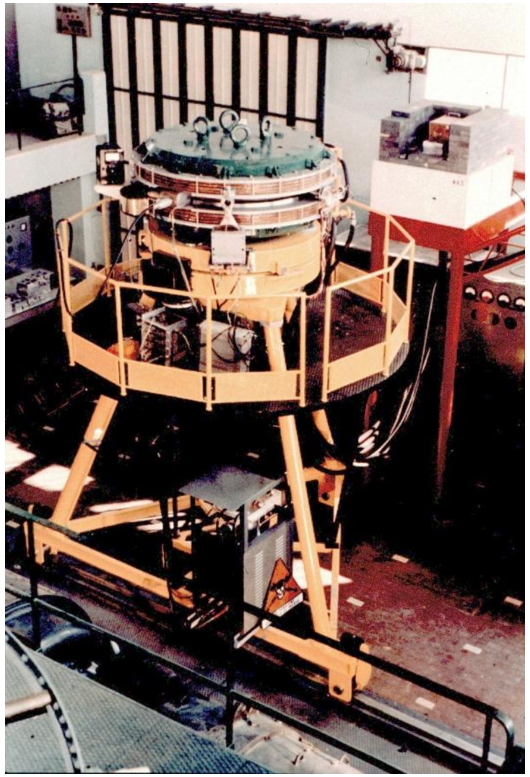


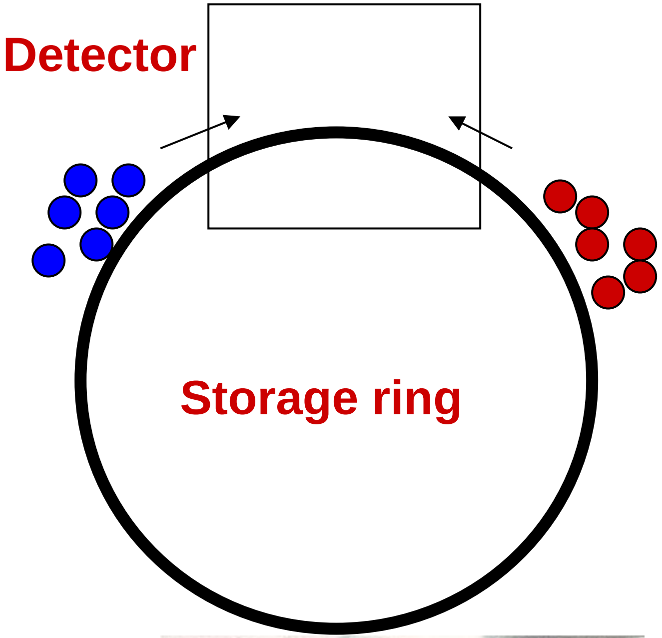
A new concept in particle acceleration: colliding beams



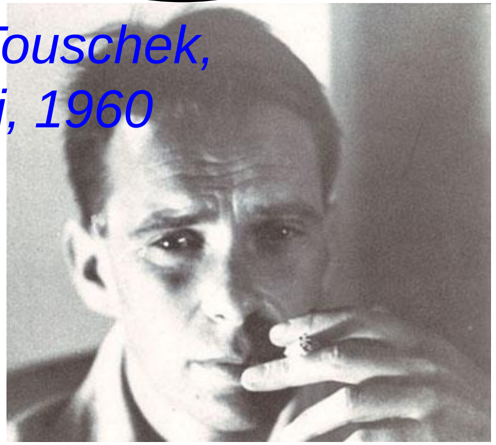
Disadvantages: the atoms are mainly empty, what does not interact is lost, target is composed by complex atoms.

In colliders, the particles which don't interact can be reused at the following turns.
Double energy at the center of the mass collision.
It is possible to use elementary particles (as well as complex ones, as ions).





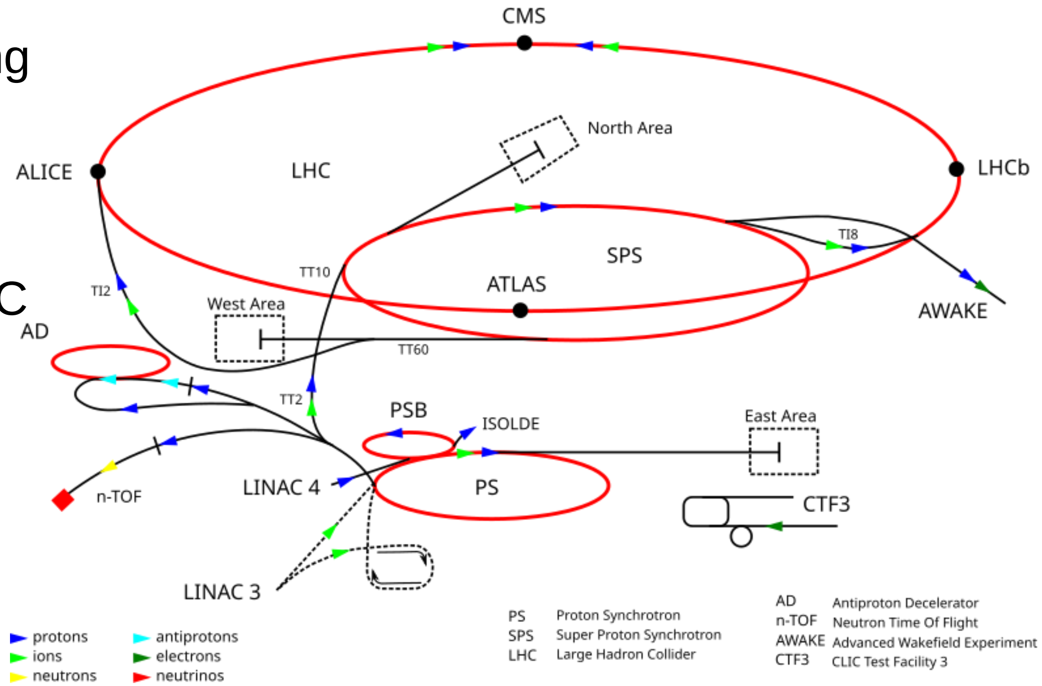
Bruno Touschek, Frascati, 1960

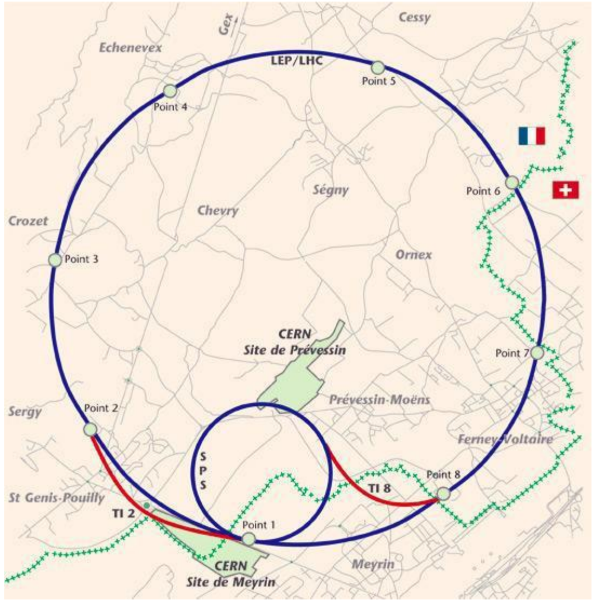


In 1960 AdA (Anello di Accumulazione) was built at LNF Frascati, within a 1.5 m diameter electro-magnet where the radiofrequency field would accelerate the electron-positron beams up to 250 MeV.

The biggest machine: LHC (CERN), 2008

- LHC is responsible for accelerating protons from 450 GeV up to 7000 GeV to collide in the four experimental points
- 450 GeV protons injected into LHC from the SPS
- PS injects into the SPS (Super Proton Synchrotron)
- LINACS injects into the PS

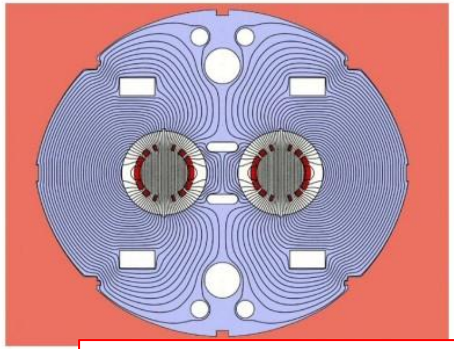




The LHC (Large Hadron Collider) consists of a 27-kilometer ring of SC magnets with a number of SC accelerating structures to boost the energy of the particles along the way. Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets.

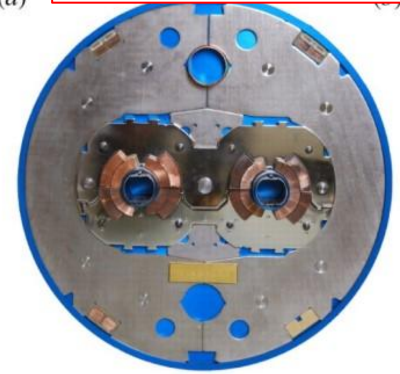
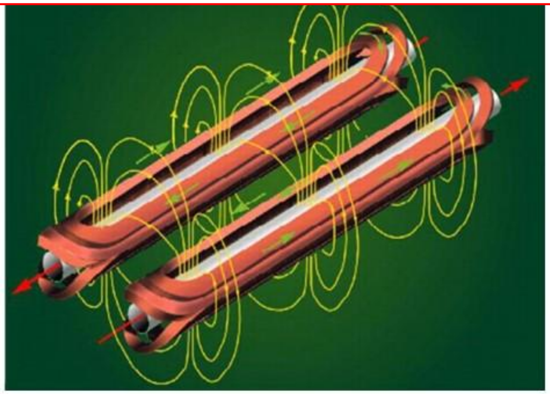
How do we use particle accelerators and what are the needed skills to work with them?

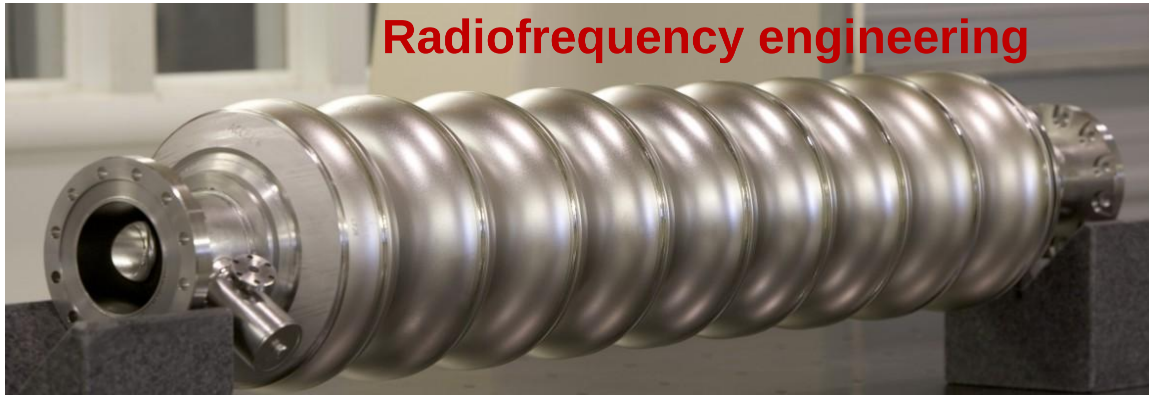
- Accelerators are the most complex machines mankind has ever built. They necessitate competencies from almost every field of engineering and technology:




magnets (normal and superconducting)

(a)

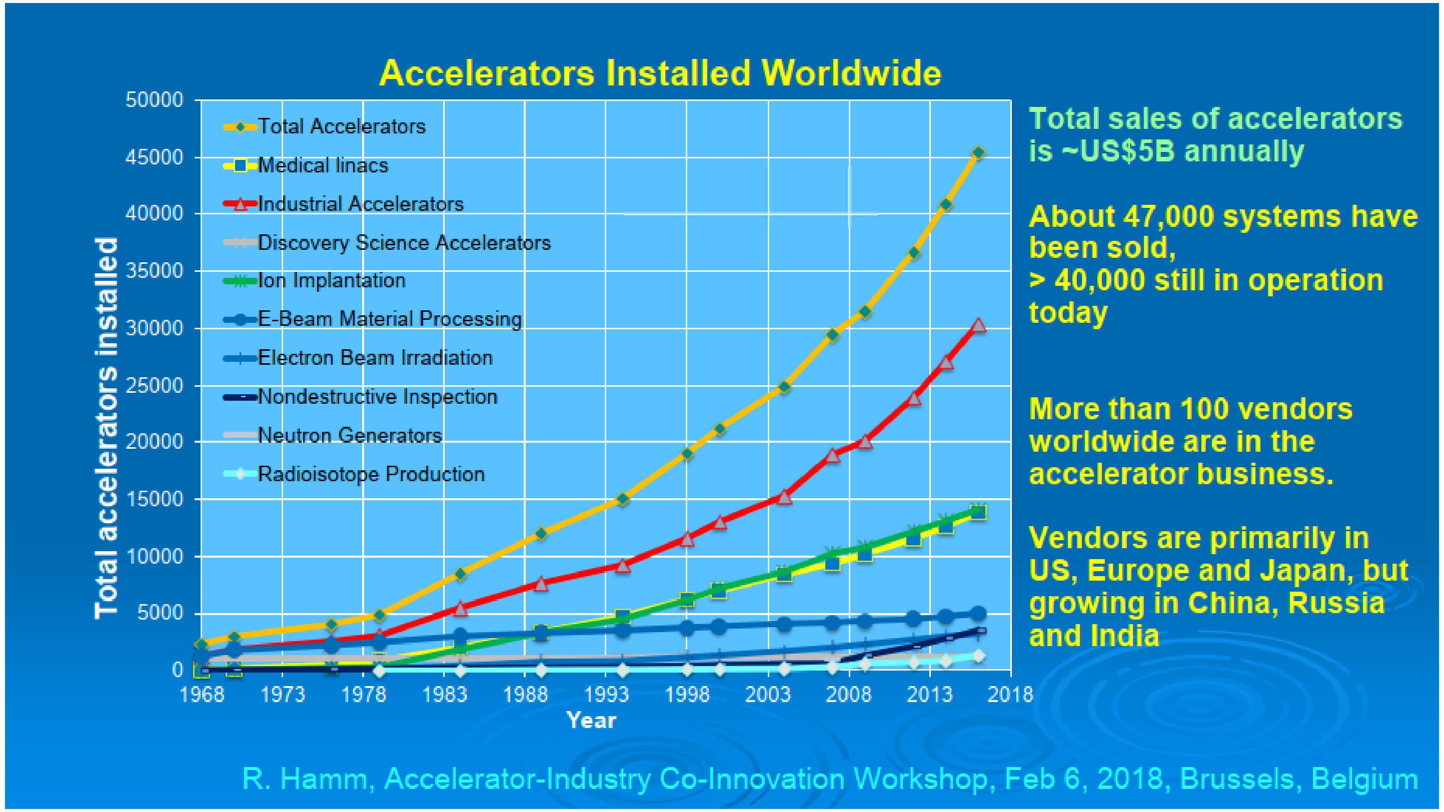


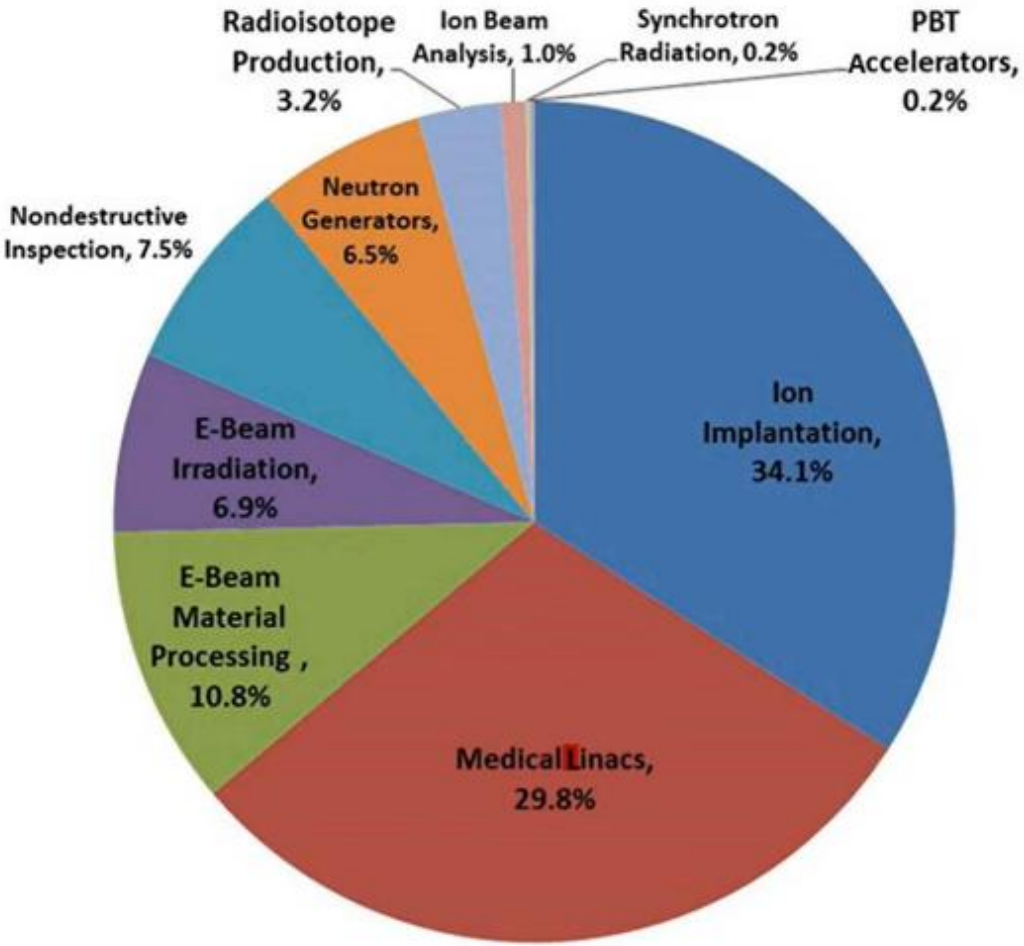
… as well as **vacuum systems**, **cryogenics systems**, **control systems**, **diagnostics**, **electromagnetism**, **radiation safety**, …
Additionally, **computer modelling** (CAD) and **software development are also needed skills**.

Particle accelerators around the world

At present, there are about 40 thousand particle accelerators in the world. They are used in various realms of human activities, including industry, fundamental science, and medicine

PBT=Proton Beam Therapy





Curriculum in Electronics and Electrotechnics for Accelerators

- This CV is focused on technologies applied to the realization of extremely intense electromagnetic fields used in accelerators.

- Examples of fields of research:

  - RF and Microwave Engineering
  - Vacuum Systems
  - Radiation Safety
  - Normal Conducting Magnets
  - Permanent Magnets
  - Accelerators for Industrial and Medical Applications
  - Power Electronics Engineering
  - Cryogenics for Superconducting Devices
  - Accelerator Controls
  - Superconducting RF cavities
  - Superconducting Magnets
  - Beam Instrumentation
  - Life-cycle and Operability of Particle Accelerators

Academic offer

- JUAS (Joint University Accelerators School) courses 1&2
- Collective effects in circular accelerators
- Physics, Technology and Applications of Linear Accelerators
- Physics of High Brightness Accelerators
- Applied Superconductivity: Quantum Phenomena and Quantum Systems
- Machine learning and numerical techniques for inverse problems and design of electrical and electronic systems
- Advanced scientific programming in Matlab
- Additive Manufacturing
- System Engineering and Project Management for Large Scientific Projects
- …

Academic offer

- JUAS (Joint University Accelerators Scho… …urses 1&2
- Collective effects in circular accelera…
- Physics, Technology and Appli… …celerators
- Physics of High Brightnes…
- Applied Supercondu… …nena and Quantum Systems
- Machine learni… …ques for inverse problems and design of electr… …systems
- Advanced scienti… …ning in Matlab
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Thank you for your attention