History and basic principles of particle accelerators

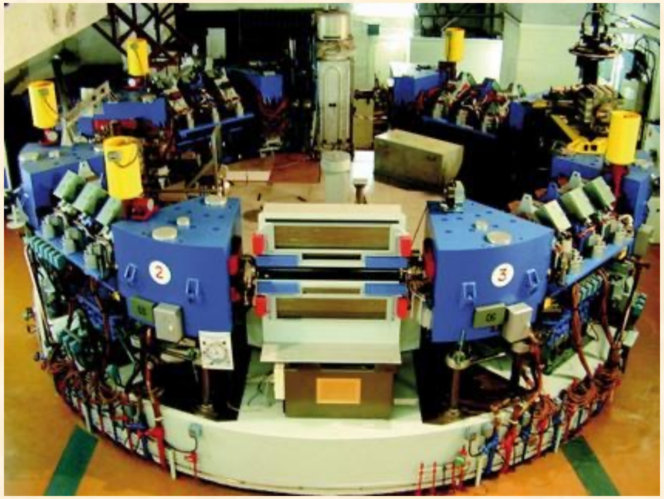
Nicolas Delerue
LAL (CNRS and Université Paris-Saclay)

About myself

- Researcher at IJClab in the direction team of the Accelerator Department
- Working on:
  - beam instrumentation and diagnostics (how to measure what happens in an accelerator) and
  - new acceleration techniques (how to reach higher energy over shorter distances)
  - how to apply accelerators to address societal issues.

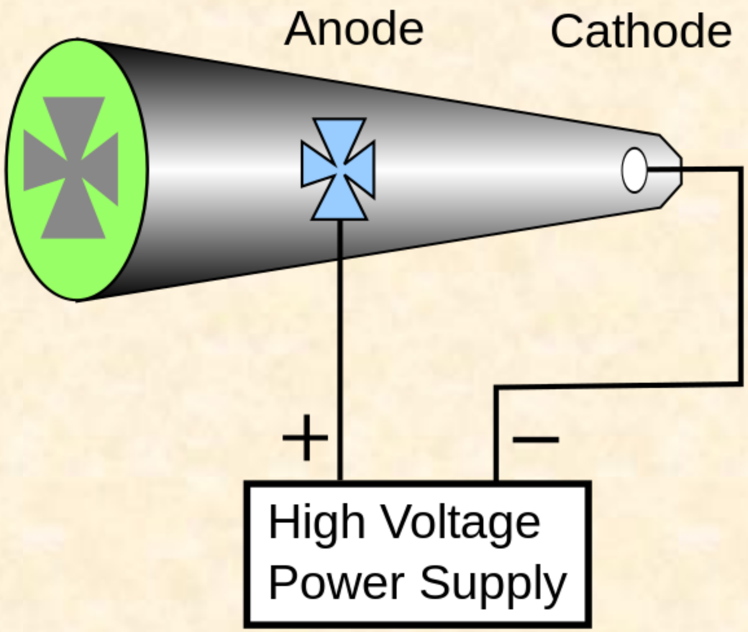
Lecture content

- **History of particle accelerators**
- Basic principles:
  - Particle sources
  - Particle acceleration
  - Magnets



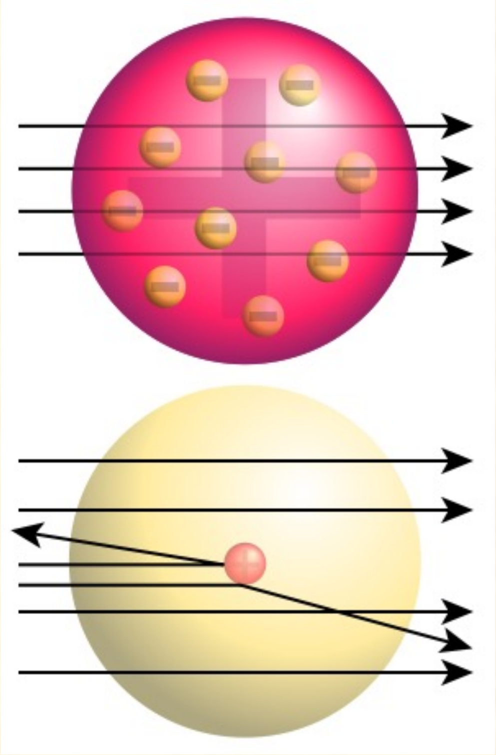
The first accelerator: Crookes tubes

- First ever particle accelerator:
Crookes (1869) – Cathode Ray tubes.
- Discovery of the electron:
J. J. Thomson (1897).
- X-rays Roengten (1895) – The first accelerator was already used a source of X-rays!



Rutherford scattering experiment (1)

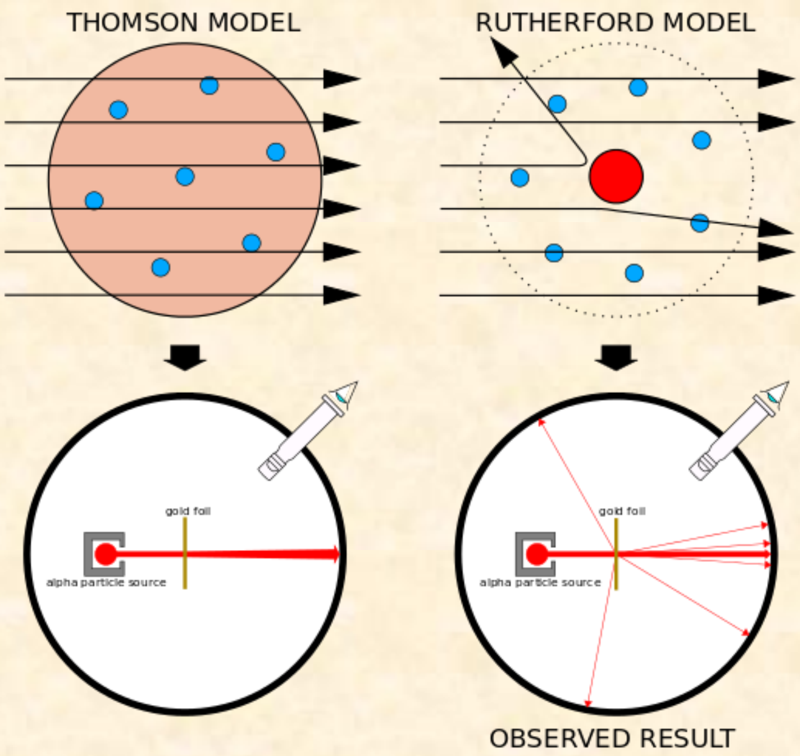
- In the early 20th century the structure of the atoms
- In 1909 Rutherford was studying the structure of the atom.
- He proposed to use alpha particles on a gold foils to probe the structure of the atom.
- This experiment shows that by using an appropriate probe it was possible to study very small objects.



Trajectory of alpha particles in a uniformly charged sphere (top) and in a real gold nucleus (bottom) (image source: wikipedia)

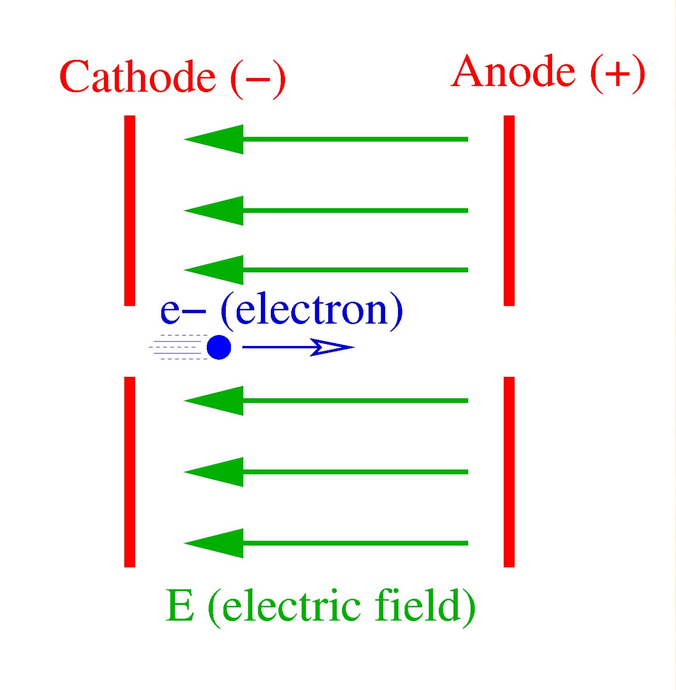
Rutherford scattering experiment (2)

- Geiger and Marsden carried out the experiment proposed by Rutherford and recorded the scattering pattern.
- The best explanation of the scattering pattern observed was that gold atoms were made of a hard core (now known as the nucleus) surrounded by a cloud of electrons.
- The idea of using « small »probes to study the structure of particles is the basis of many accelerator.
- The resolution depends on the probe size which is inversely proportional to its energy.



Beyond the Geiger-Marsden experiment

- The Geiger-Marsden experiment used alpha particles that were not accelerated.
- To get a better resolution one needs a higher energy .
- To go beyond what is available naturally it is necessary to accelerate the particles.
- Charged particles can accelerated with an electric field (as was done in the Crookes tubes).
- However the electric fields needed to study sub-nuclear matter are in the Megavolt range or beyond!



Van de Graaff generator

- In 1929 Van de Graaff proposed a generator capable of producing such high voltages.
- In a Van de Graaff generator charges are mechanically carried by a conveyor belt from a low potential source to a high potential collector.
- Van de Graaff generators can reach several MV and are still used as static accelerators especially for ions.
- An improvement to Van de Graaff generators uses a pellet chain instead of a belt. It is called a Pelletron.

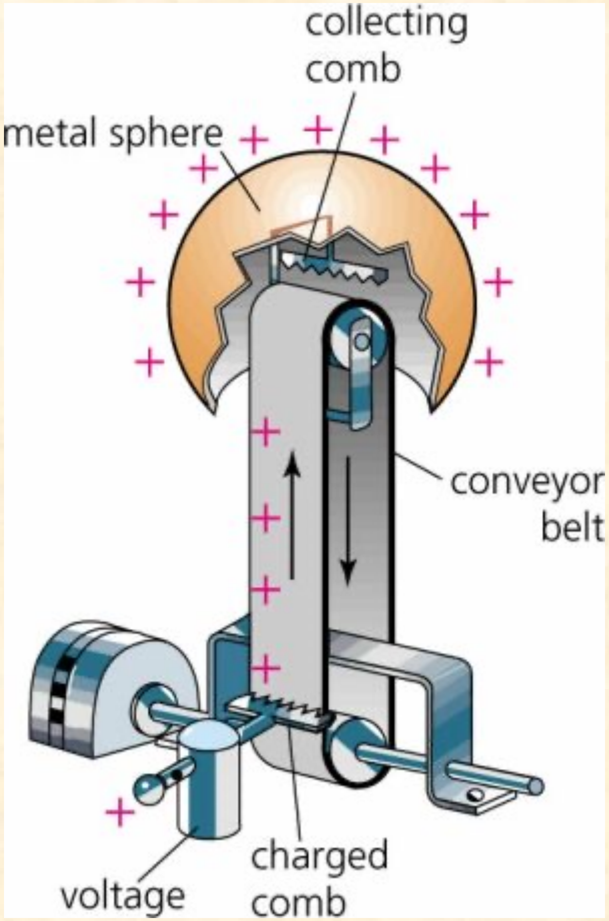
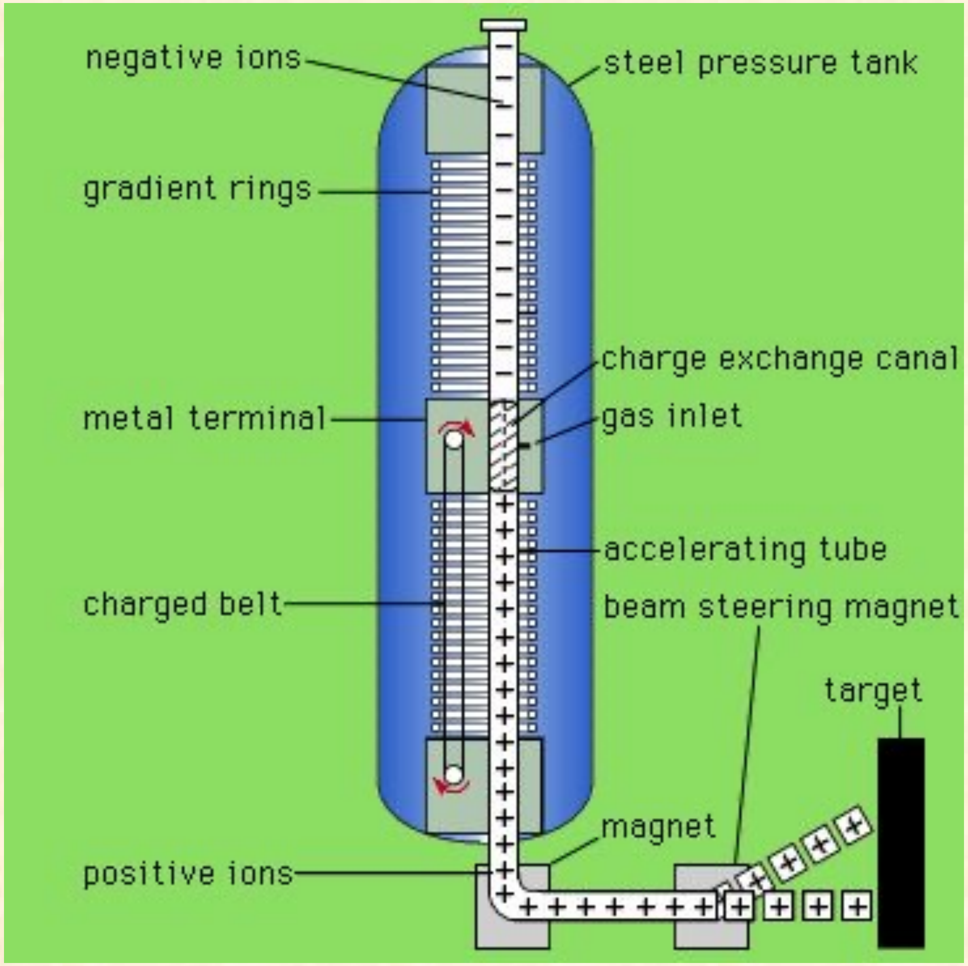


Image courtesy of http://people.clarkson.edu/~ekatz/scientists/graaff.html

Tandem accelerators

- It is possible to increase the energy reach of a Van de Graaff accelerators by using a “tandem” accelerator.
- Such accelerator has two stage:
  - In the first stage negative ions (with extra e-) are accelerated from ground to a positive high voltage.
  - These ions are then stripped of 2-3 electrons in a stripper and become negative.
  - They are then accelerated further by going from the positive high voltage to DC.

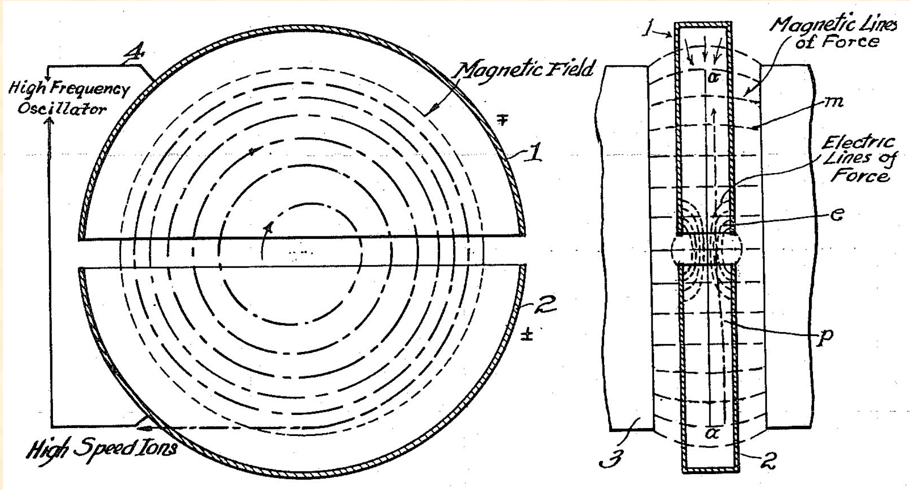


Example: 10MV Van de Graaff can accelerate C^- to 10 MeV and then C^{2+} to 30 MeV.

Image source: http://people.clarkson.edu/~ekatz/scientists/graaff.html

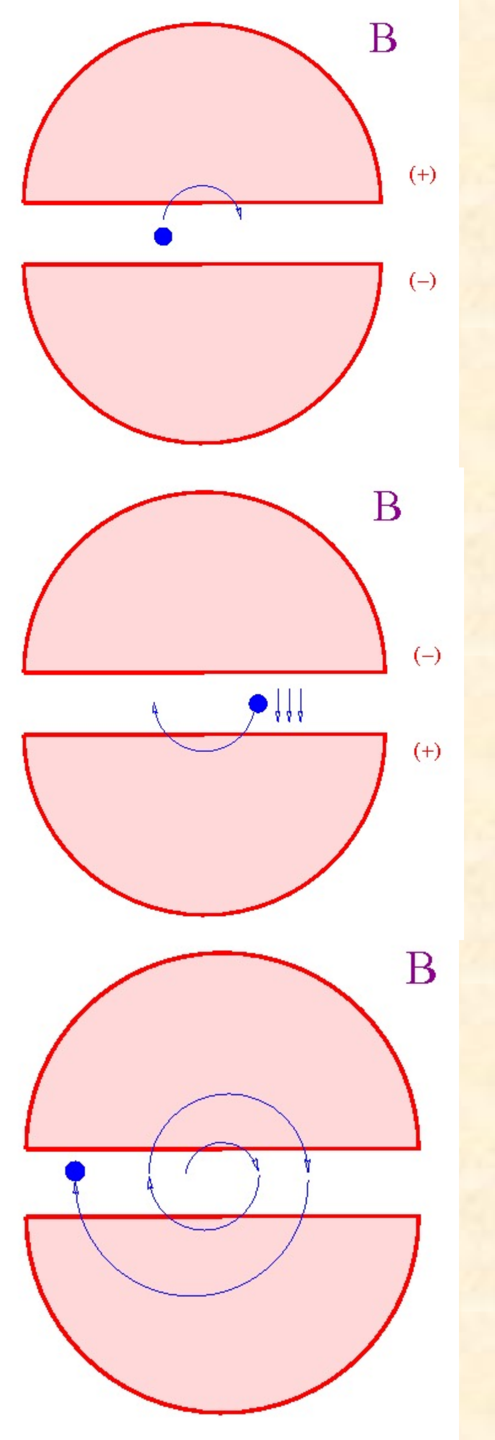
Cyclotron

- DC electric fields beyond 20MV are very difficult to achieve.
- Above 20MV, it is easier to use an electric field created by an alternating current (AC).
- In 1931 Lawrence designed a “cyclotron”, a circular device made of two electrodes placed in a magnetic field that used AC field to accelerate the particles.



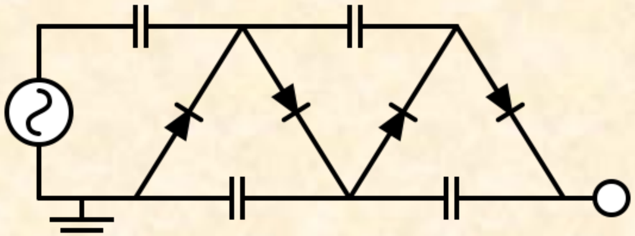
Cyclotron (2)

- The particle source is located in the middle of the cyclotron.
- Due to the magnetic field the particles follow a circular trajectory
- By reversing the electric field of the electrode between two gap crossing it is possible to accelerate the particles.
- With an AC potential of only 2000V Lawrence accelerated protons to 80kV!
- Lawrence received the Nobel prize in 1939 for this work.
- However, Cyclotrons can only accelerate non-relativistic particles…



Cockroft-walton generator

- To reach higher energies, the particles can be accelerated in an electric field.
- Cockroft and Walton used a voltage multiplier made of diodes and capacitors.

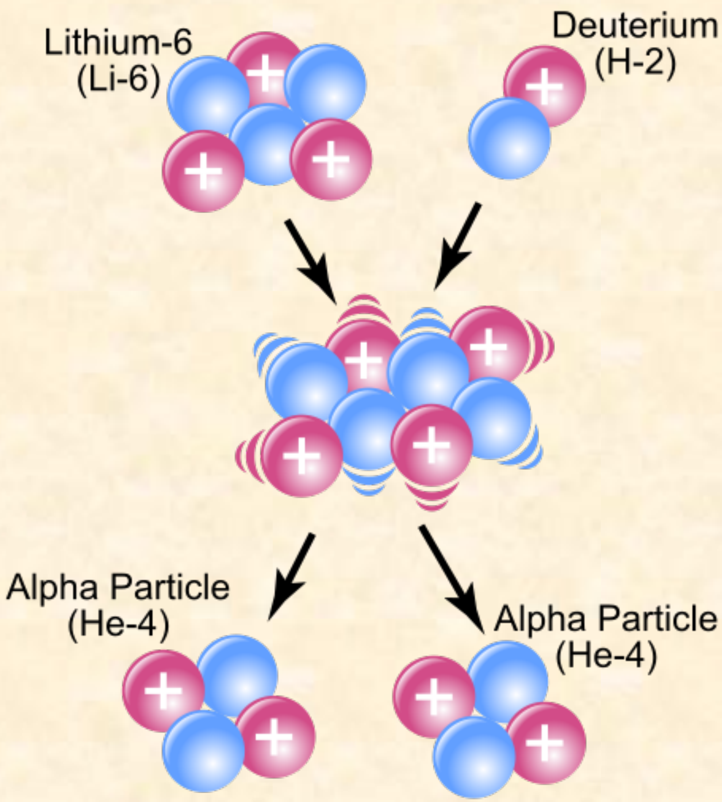


- The first half-cycle will load the first capacitor to its peak voltage. The second half-cycle loads the second capacitor and so on...
  => high voltage pulses

A Cockroft-Walton generator

(image source: wikipedia)

Splitting the atom



Lithium-6 – Deuterium Reaction

- By using their generator Cockroft and Walton were able to accelerate protons to hundreds of keV.
- In 1932 they bombarded Lithium with 700 keV hydrogen nuclei and transmuted it into Helium and other elements.
- This was the first time that a particle accelerator had been use to trigger a nuclear reaction.
- Cockroft and Walton were awarded the Nobel prize for this work in 1951.

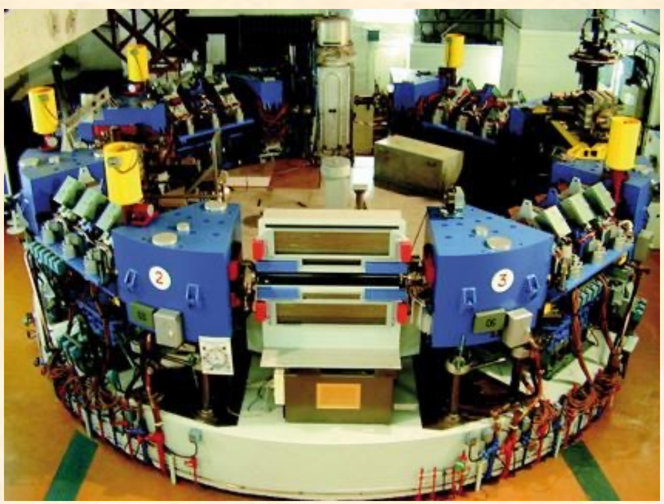
AdA

- Most work in new accelerators stopped during WWII.
- After the war the work resumed and in 1961 Bruno Touschek suggested the concept of “collider”.
- To test it, he built AdA which was succesfully tested at LAL in Orsay in 1962.

AdA in a glass case at Frascati National Laboratory

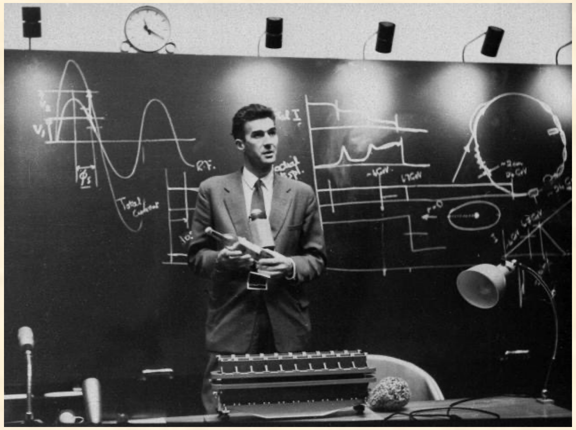
L'Anneau de Collision d'Orsay

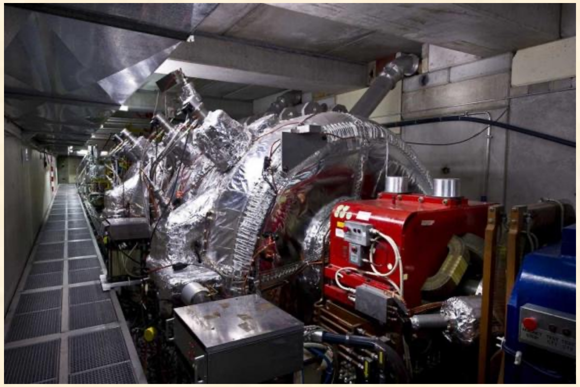
- The AdA success led to the construction of the first French collider, ACO in 1963 (first collision in 1965).
- ACO was decommissioned as a collider in 1975. After it served as a light source until 1988.
- Another collider, DCI (Dispositif de Collision dans l'Igloo), was used on site from 1975 until 1985 (and as synchrotron source until 2001).



ACO is now a museum in Orsay that can be visited.

Accelerators at CERN

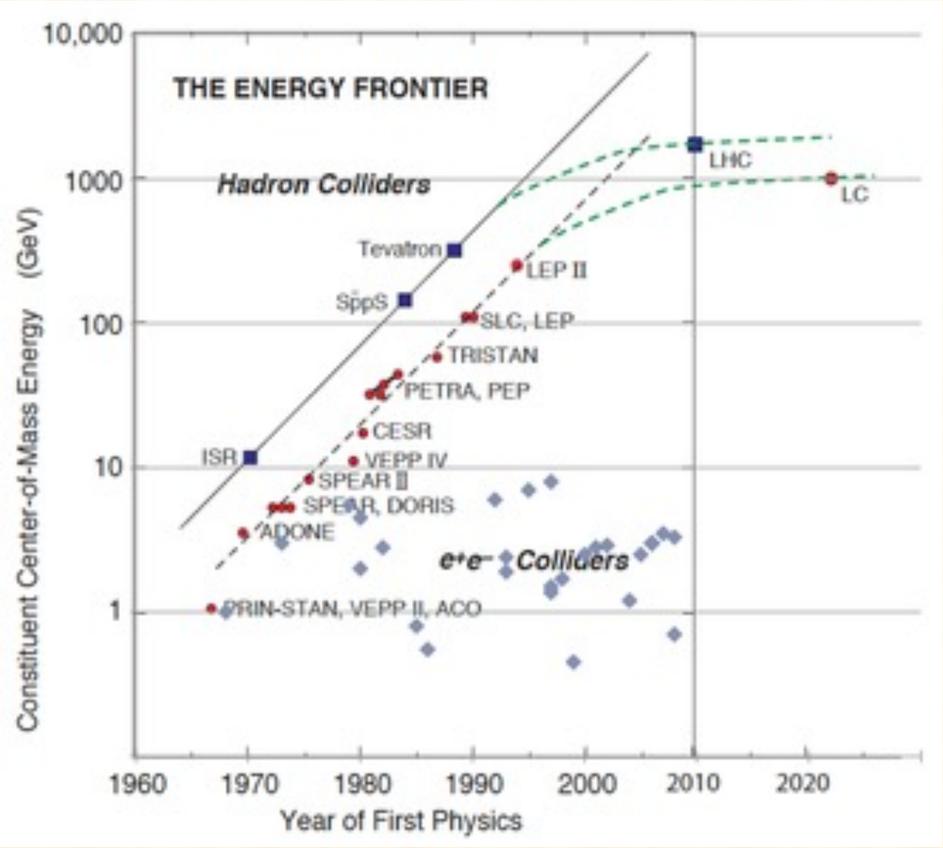




- 1957: Synchrocyclotron (SC), 600 MeV, protons/ions (closed in 1990).
- 1959: Proton Synchrotron (PS), 28 GeV, still in use!
- 1971: Intersecting Storage Ring (ISR), first CERN collider, 62 GeV protons (closed 1984)
- 1976: Super Proton Synchroton (SPS), 7km,
  up to 400 GeV (now 450 GeV).
  {Discovery of neutral currents and the Z boson in 1983}
- 1989: Large Electron Positron collider (LEP), 27 km,
  up to 209 GeV e- (stopped in 2000)
- 1997: Antiproton Decelarator (down to 100MeV/c) for antimatter studies.
- 2008: Large Hadron Collider (LHC), 7 TeV protons…

- Source: http://timeline.web.cern.ch/timelines/CERN-accelerators

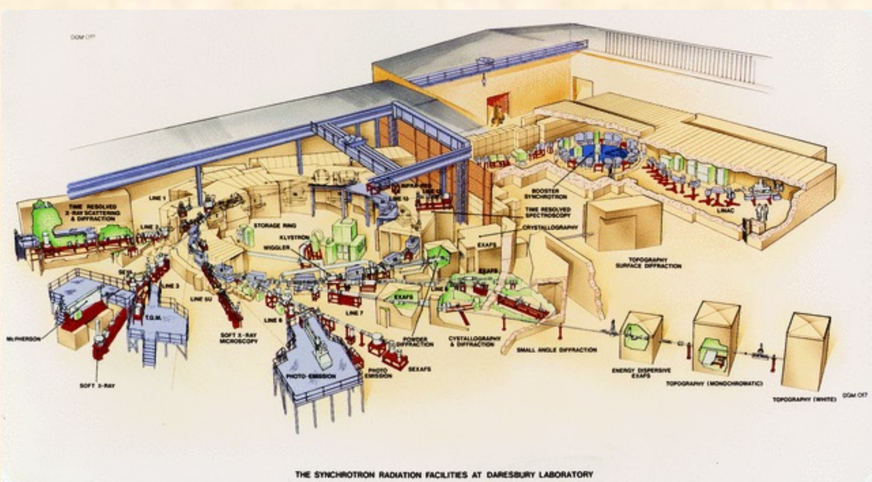
Livingston chart



- Note: did not mention all accelerators for high energy physics or nuclear physics.
- Since 1962 there has been a constant progress in c.m. energy.
- However in the recent years this progress has slowed down…

Light sources

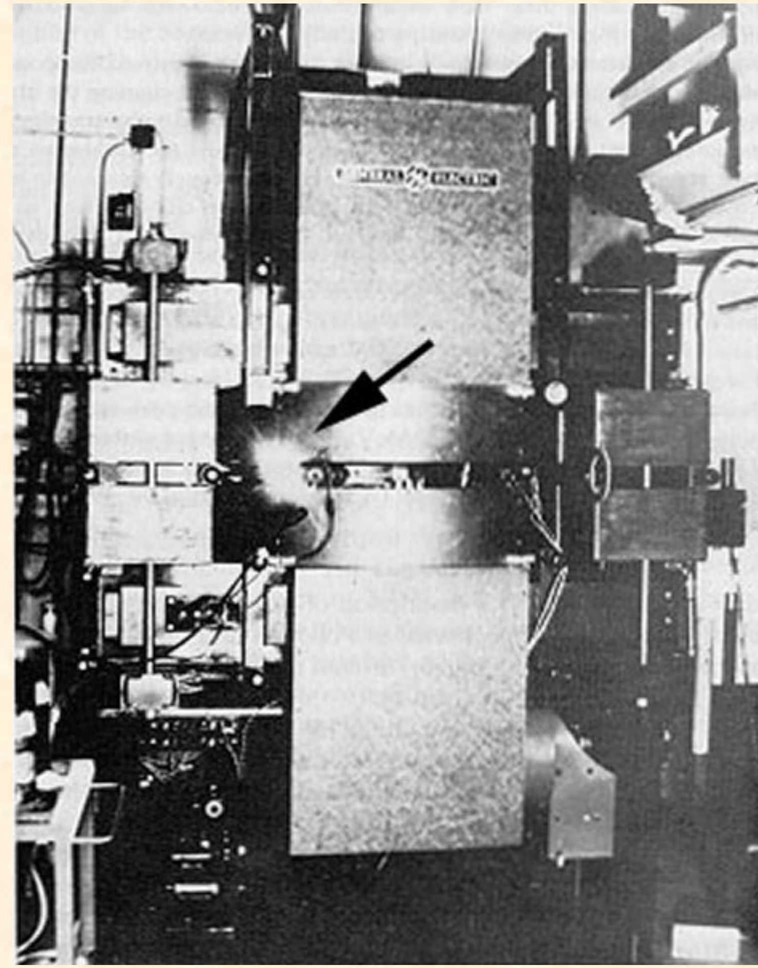
- Circular accelerators emit radiation.
- With some tuning it is possible to make them emit an intense flux of radiation at a useful wavelength.
- Some machines have been built entirely for this purpose, including several in the area
  - Super-ACO (now decommissioned)
  - SOLEIL near SACLAY



Source: SOLEIL

1st generation light source

- Synchrotron radiation was discovered in 1946.
- It was first seen as a nuisance as it makes the beam loose energy.
- In the 1960 it was recognised that it could be used as a powerful source of radiation (X-rays)
- Some accelerators started to make this radiation available to other users.



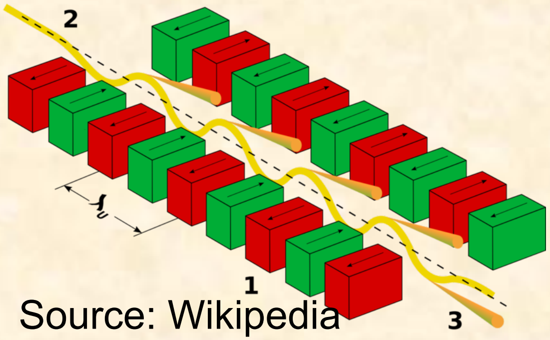
Discovery of Synchrotron radiation in 1946. Source: wikipedia

2nd generation light sources

- In the 1980s machine dedicated to the production of light were built.
- The first one in France was Super-ACO.
- In these machines the light is extracted from the bending magnets and delivered to users.

3rd generation light sources

- With the increasing need for synchrotron radiation extracting the light from bending magnets was not enough.
- Special arrays of magnets called “wigglers” or “undulators” can be used to improve the radiation produced by a light source.
- 3rd generation light source were also design with brilliance optimisation in mind (smaller beams, large rings...).
- SOLEIL (in Saint-Aubin, near Saclay) is a 3rd generation light source.



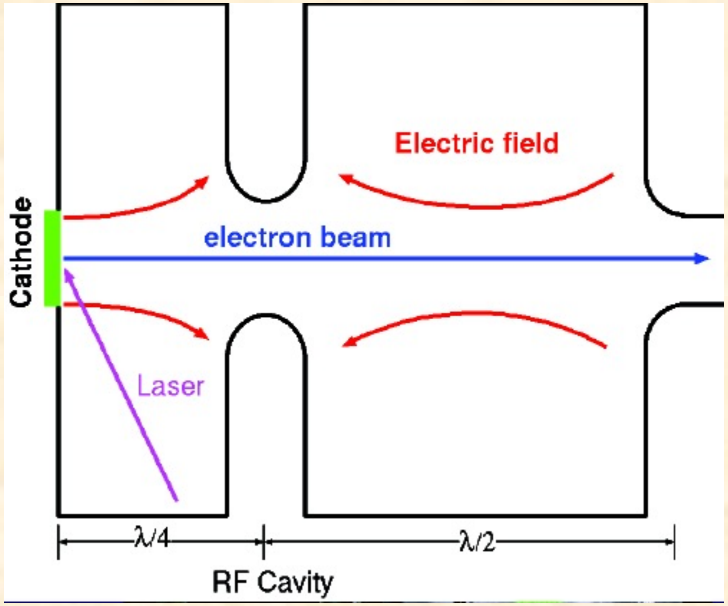
Source: Wikipedia

Undulator, *Source: Diamond*


Source: Diamond

Lecture content

- *History of particle accelerators*
- Basic principles:
  - Particle sources
  - Particle acceleration
  - Magnets



Particle sources

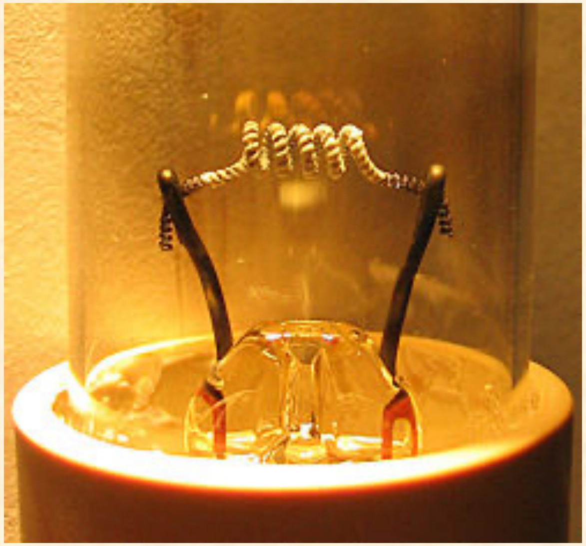
- How particles are first produced?
- How to extract particles with the right properties?
- What are the limitations of the sources?
- *The quality of the source is very important. If the particles emitted by the source do not have the right properties, it will be very difficult and/or expensive to rectify it later.*

Producing beams of electrons: Thermionic effect

- Most particle accelerators in the world accelerate electrons.
  - Remember the Maxwell-Boltzmann energy distribution:

$$f = e^{\frac{-E}{k_B T}}$$

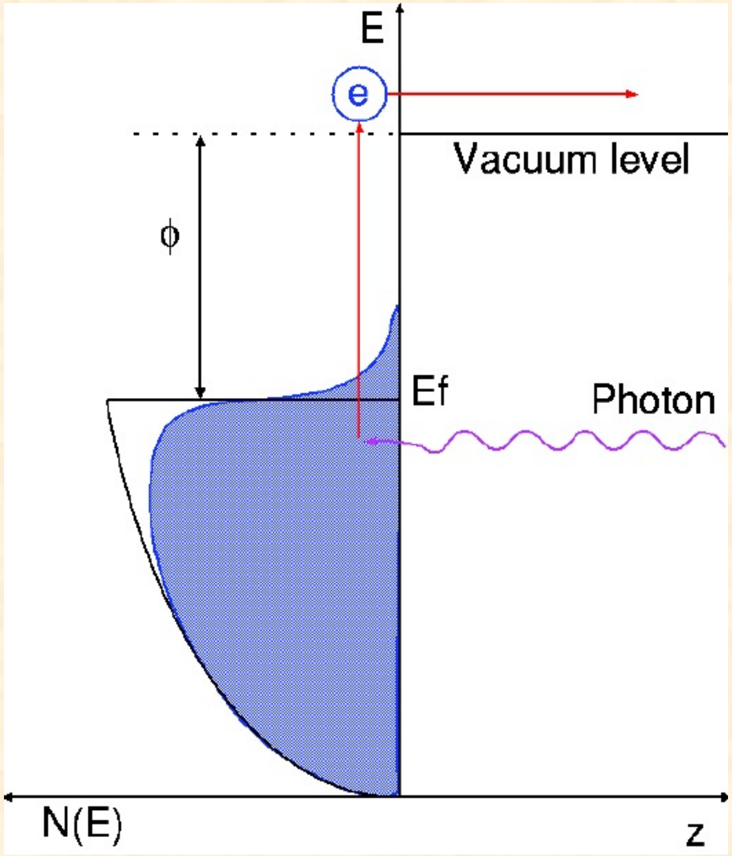
  - Electrons (fermions) obey a different but similar law.
  - When a metal is heated more electrons can populate high energy levels.
  - Above a certain threshold they electrons can break their bound and be emitted:
    This is thermionic emission.



(image source: wikipedia)

Photo-electric emission

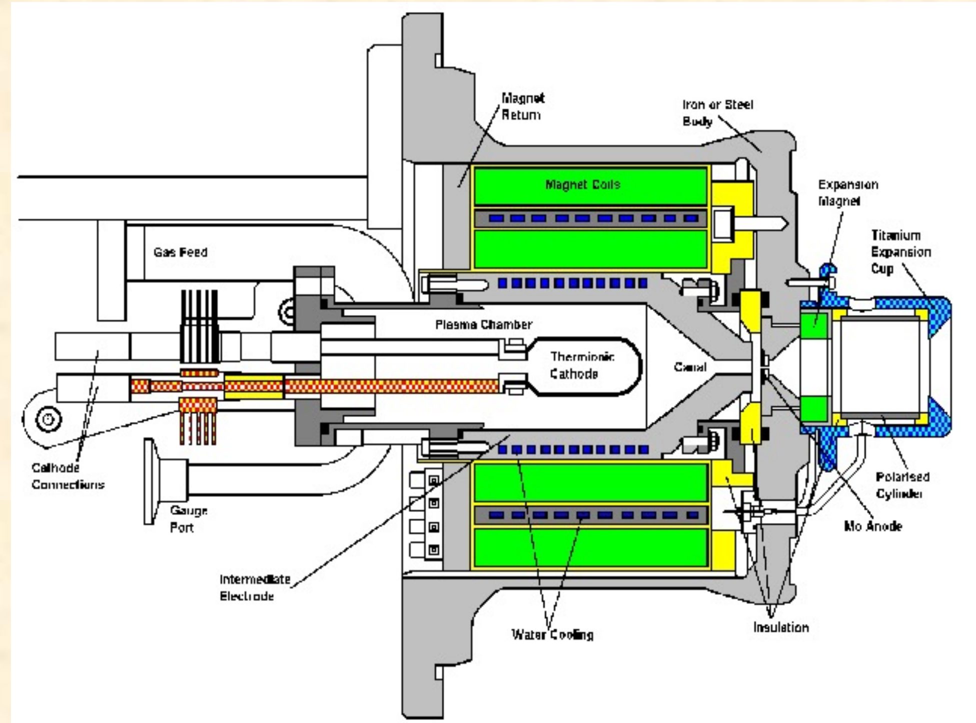
- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.



(image source: Masao Kuriki, ILC school)

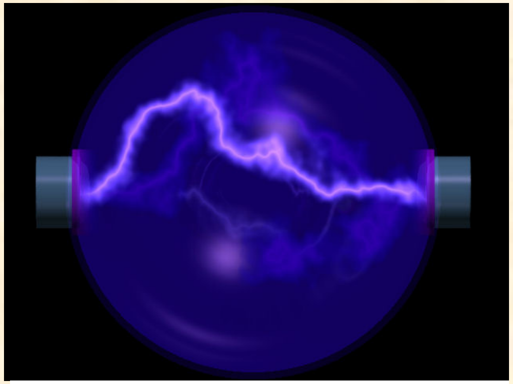
Proton source: the duoplasmotron

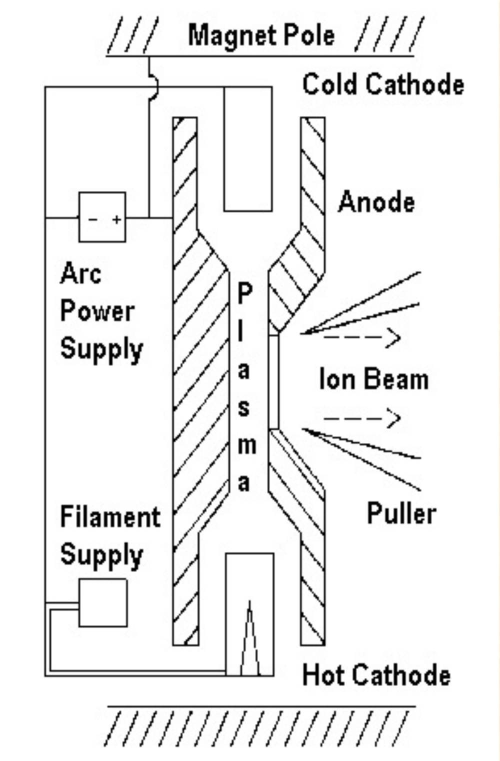
- At CERN the protons are produced in a duoplasmotron source.
- Hydrogen is injected in a plasma chamber at a high electric potential (100kV)
- Inside the plasma chamber a cathode emits electrons.
- These electrons hit the gas atoms and ionise them into protons.
- The protons are attracted toward lower potential areas and are ejected from the source.
- Magnets are used to minimise transverse momentum of the particles and focus them at the exit.



Other proton and ion sources

- An electric discharge creates a plasma in which positively and negatively charged ions are present (as well as neutrals).
- If such plasma experiences an intense electric field ions will separate in opposite directions.
- This is a rather crude and inefficient (but very simple) way of producing any sort of ions.

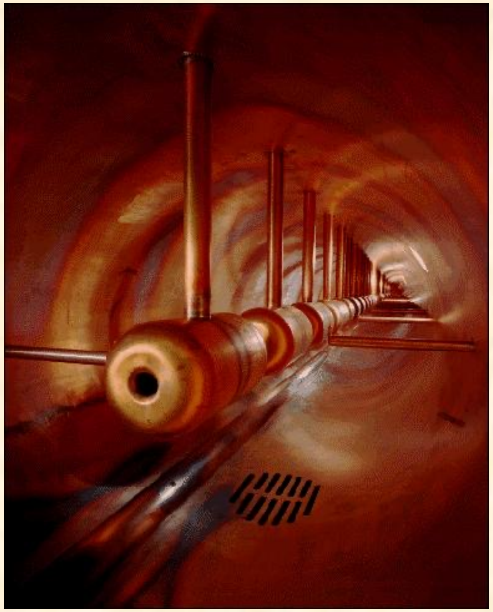




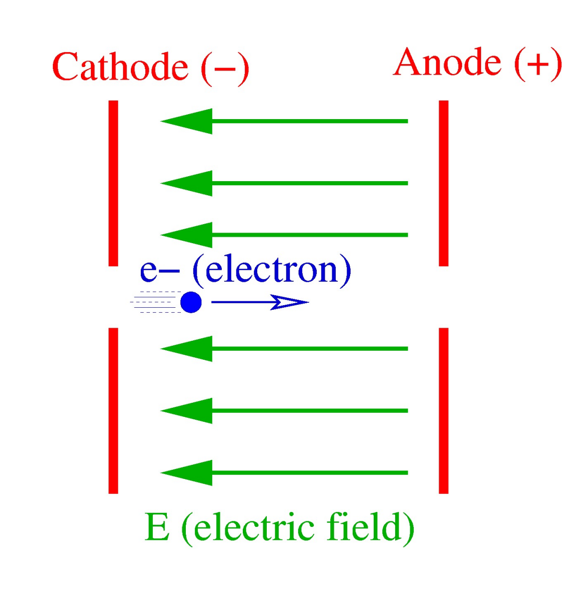
(images source: CERN)

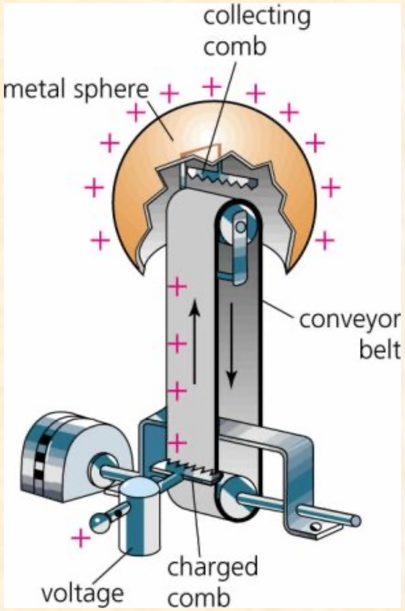
Lecture content

- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - **Particle acceleration**
  - Magnets



Electrostatic acceleration

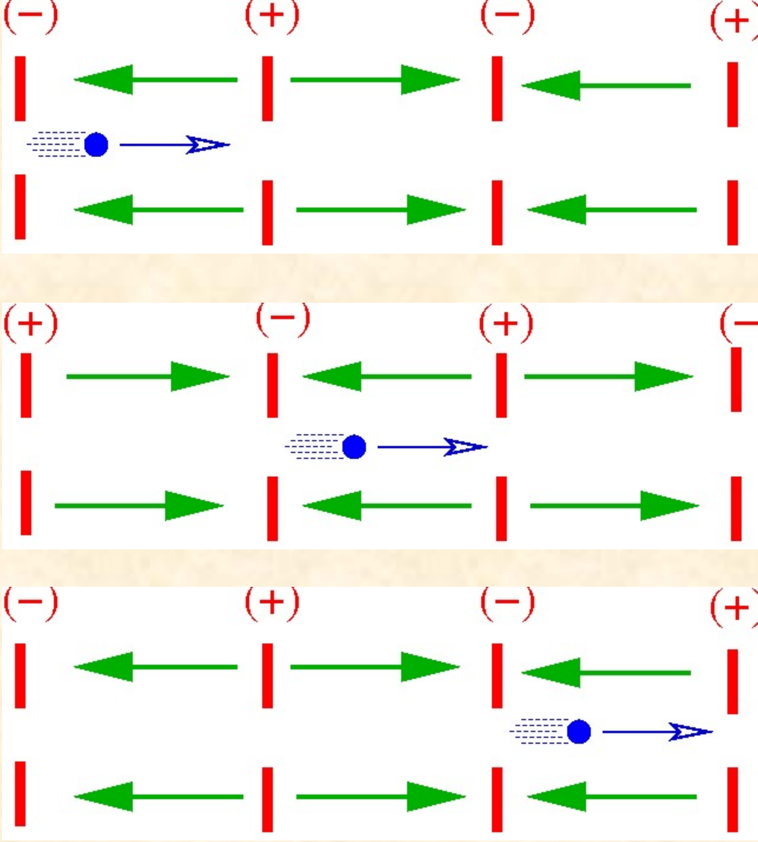


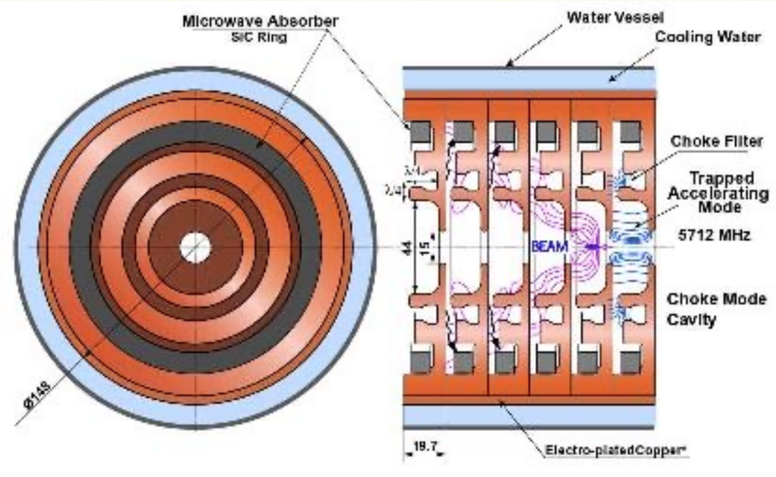


- Charged particles can be accelerated in an electrostatic field.
- This works up to a few MV but we have seen yesterday that intense electric fields can be dangerous.
- To reach more than a few MeV, alternating current accelerators must be used.

Particle acceleration

- Particles can be accelerated in a static electric field, however such fields are limited to a few megavolts.
- To go beyond these limits it is necessary to use cavities in which the fields is alternatively accelerating and decelerating. Radio-frequency (RF) cavities use such AC field to accelerate particles to very high energies.
- In a RF cavity the particles "surf" on an electromagnetic wave that travels in the cavity.

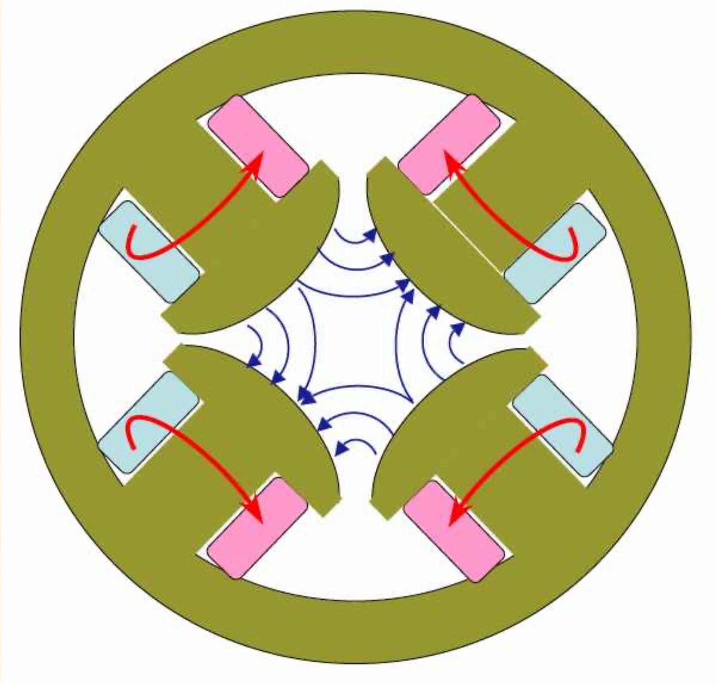




(source: Spring-8, Japan)

Lecture content

- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - *Particle acceleration*
  - **- Magnets**

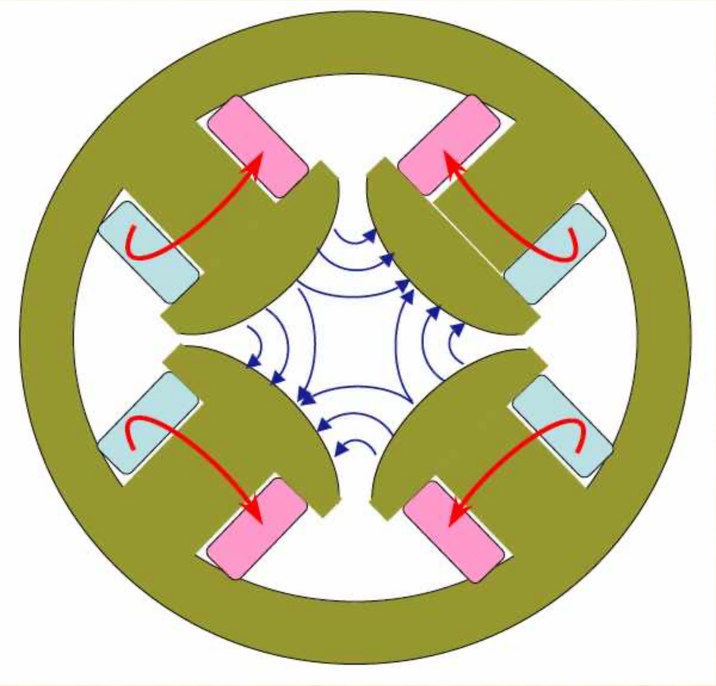


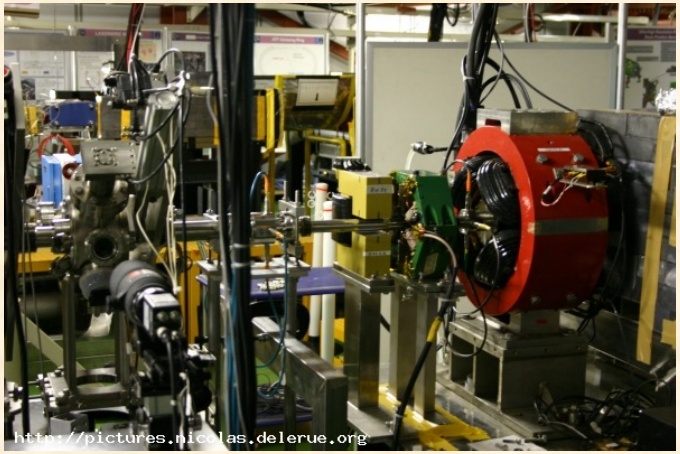
How to control where the particles go?

- Electric and magnetic fields can deflect charged particles.
- In an electric field the particles get accelerated.
- In magnetic field the direction of the particles is changed but not their energy.
  => it is preferable to use magnetic field (usually electromagnets) to control a beam.
- Magnets are also more efficient.

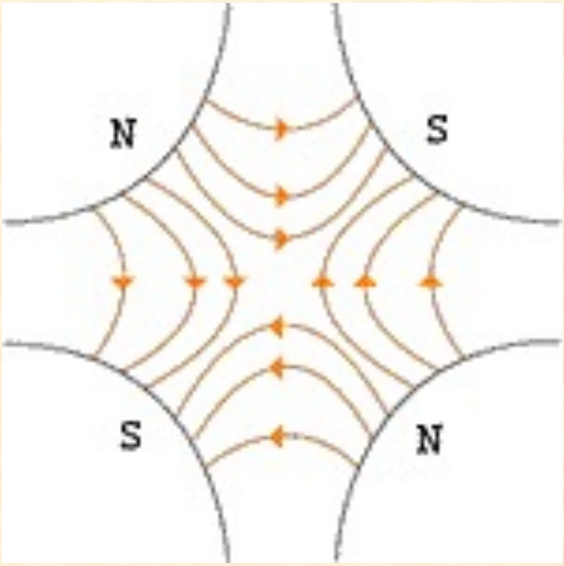
Beam focussing

- A regular magnet (dipole) will create a field that will bend the beam in one direction.
- To change the size of the beam a different type of magnets called quadrupoles need to be used.
- Quadrupoles create intense fields for off-axis particles but do not disturb particles on the axis.

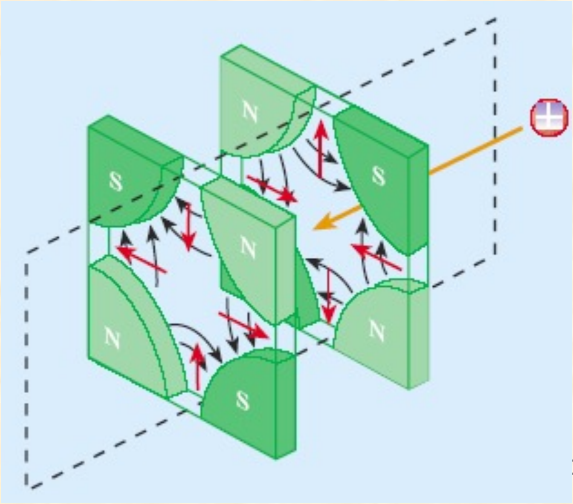


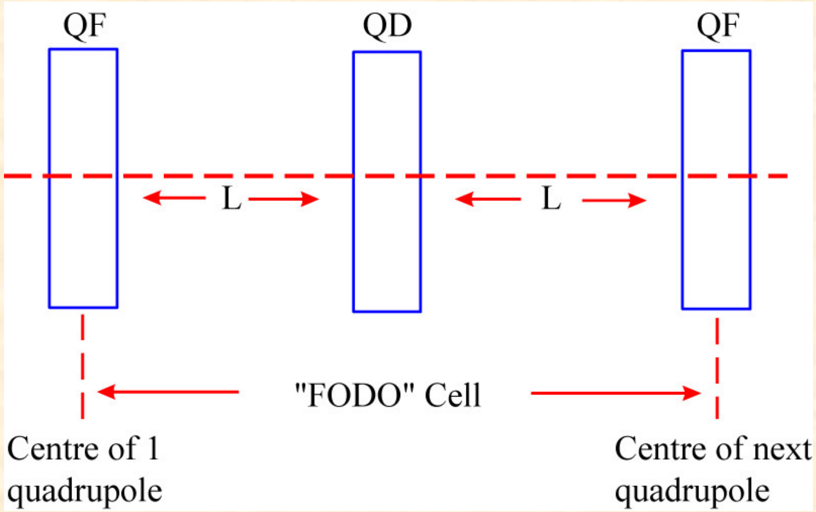


FODO cell



- A quadrupole will focus the beam in one plane but defocus it in the other plane.
- To have a net focussing effect, 2 quadrupoles are used, one focussing in one plane and the other one focussing in the other plane.





Summary

- The first particle accelerators were invented about 150 years ago.
- There are several different architectures for accelerators: Van de Graaff, Tandem, Cyclotron, RF accelerator…
- The main components of accelerators are: particle source, accelerating section (electrostatic or RF) and magnets to control the beam.

Recommended reading

- Slides of this lecture are available at
  http://lal.delerue.org/teaching/2022_France_Ghana/202203_introduction_accelerators.pdf

- « Accelerators for pedestrians » CERN-AB-Note-2007-014
  Available for free online at http://cdsweb.cern.ch/record/1017689

- An introduction to particle accelerators, Edmund Wilson

- The physics of Particle accelerators, Klaus Wille

If you want to learn much more:

- Handbook of Accelerator Physics and Engineering,
  by Alex Chao and Maury Tigner ISBN-10: 9810235003

- Charged Particle Beams, by Stanley Humphries
  http://www.fieldp.com/cpb/cpb.html

- Principles of Charged Particle Acceleration by Stanley Humphries,
  http://www.fieldp.com/cpa/cpa.html