Introduction to particle accelerators

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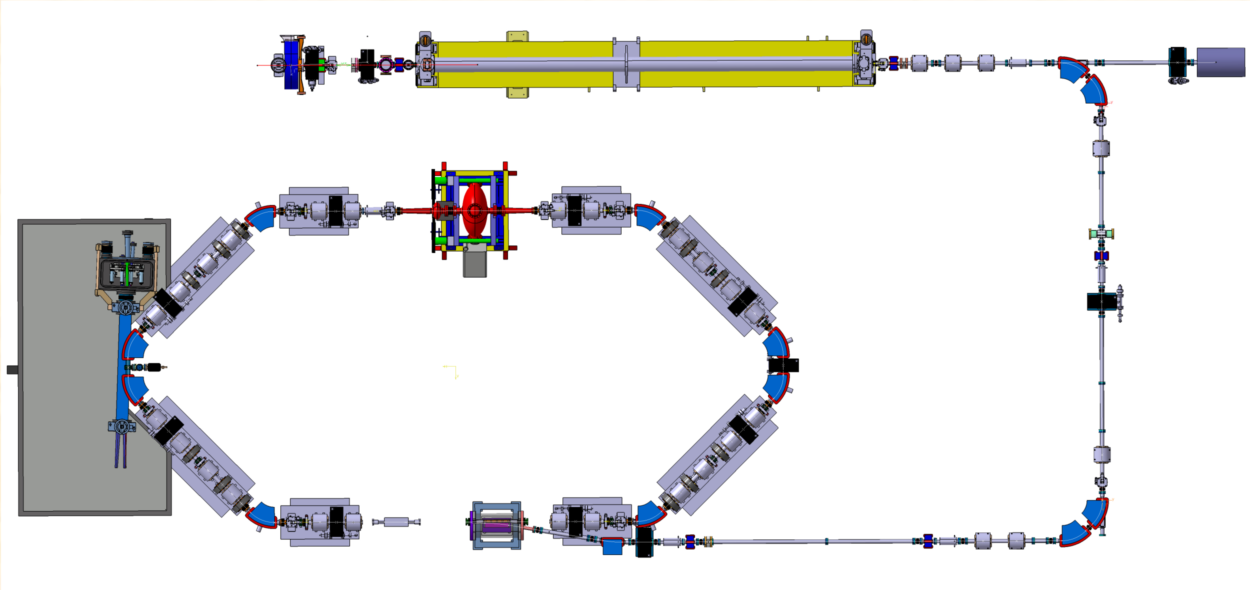
Lectures overview

- Production of particles
  - Electrons (Thermionic and photoelectric effects)
  - Protons and ions
- Acceleration of particles
- Steering the particles, magnets
- Beam dynamics
- The LHC
- Other applications of particle accelerators

Introduction

- We have seen yesterday that to probe matter on smaller scales on needs probes with a higher energy.
- As such probes are not available naturally they have to be produced.
- Particle accelerators take electrons or protons, bring them to high energies and collide them.

How do particle accelerators work?



ThomX, an accelerator being built in Orsay

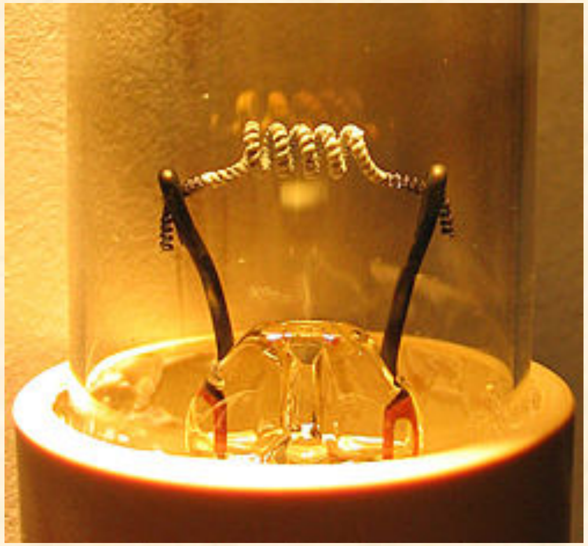
- Particle accelerators are typically made of the following elements:
  - a source
  - an accelerating section
  - a ring
- In a complex accelerator these elements may be repeated.
- We will see how each of them work…

Producing beams of electrons: Thermionic effect

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

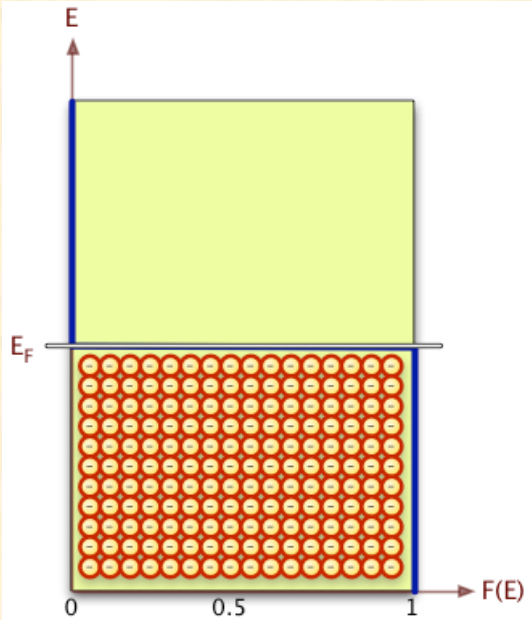
$$f = e^{\frac{-E}{k_B T}}$$

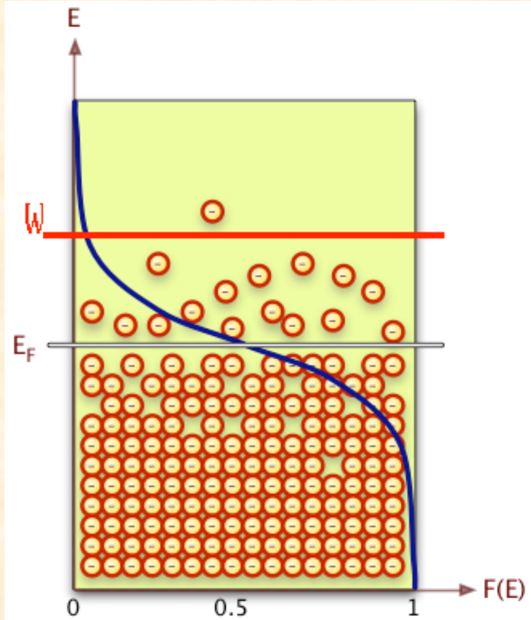
  - Electrons (fermions) obey a different but similar law.
  - When a metal is heated more electrons can populate high energy levels.
  - Above a certain threshold they electrons can break their bound and be emitted:
    This is thermionic emission.



(image source: wikipedia)

Electrons in solids



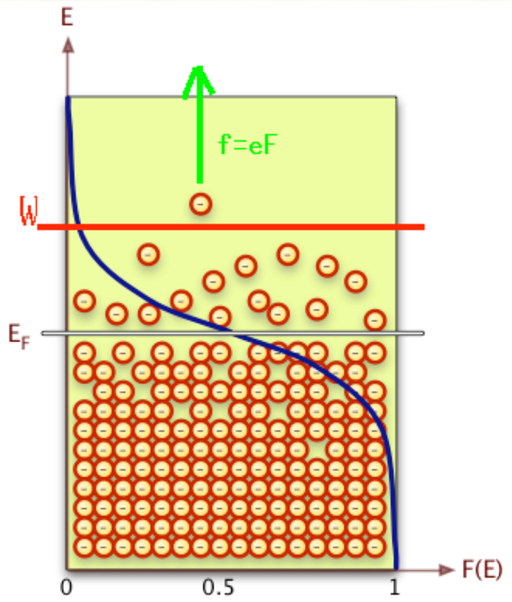


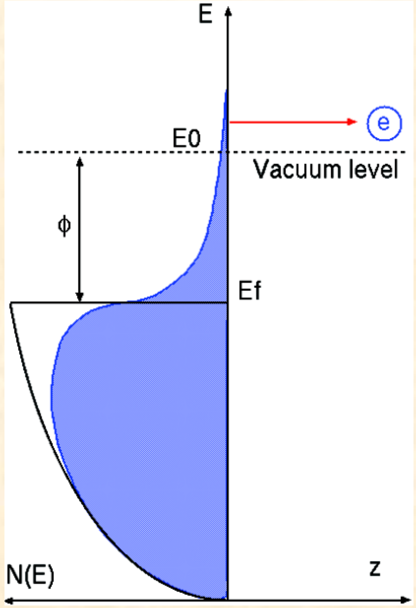
(image source: http://cnx.org/content/m13458/latest/

- At low temperature all electrons are in the lowest possible energy level, below the Fermi level.
- As the temperature increase some electrons will go above the Fermi level.
- But only those with an energy greater than the "work function" are "free".

Electrons extraction

- Once the electrons are free they may fall back on the cathode.
- To avoid this an electric field needs to be applied.
- If a negative potential is applied to the cathode the electrons will be attracted away from the cathode after being emitted.
- The potential the electrons must overcome to escape is called the "work function".



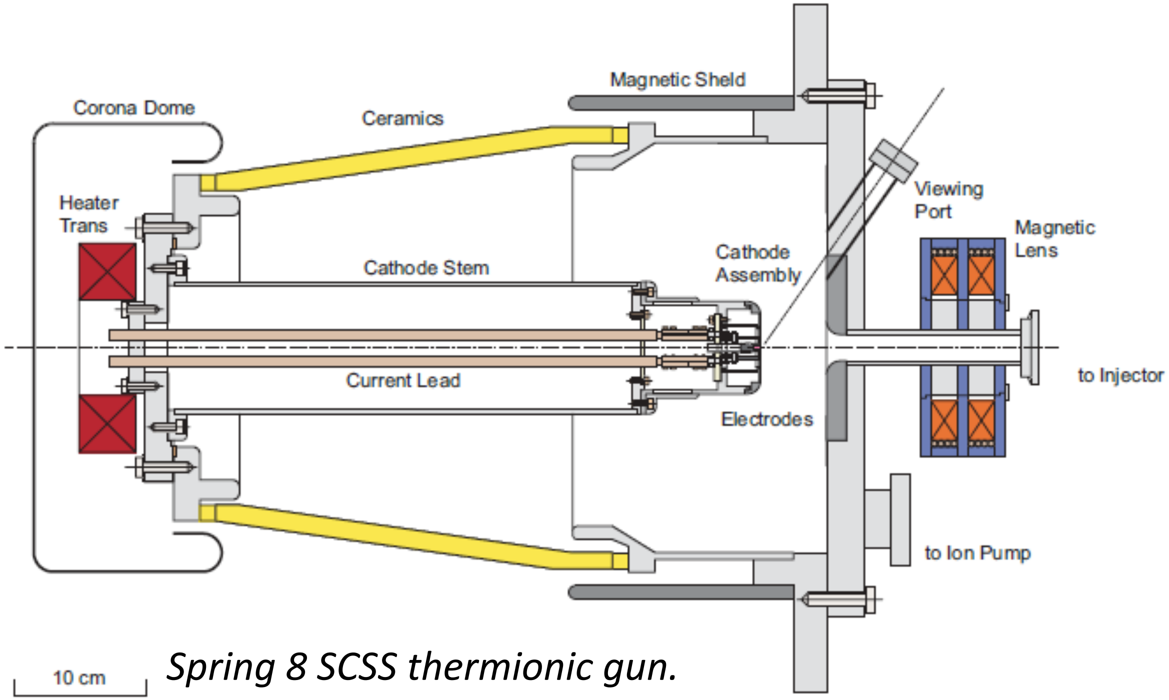


(image source: Masao Kuriki, ILC school)

Example of thermionic gun

SCSS

500kV Electron Gun



Spring 8 SCSS thermionic gun.
(images source: T. Shintake, Spring-8)

Photo-electric emission

Instead of thermionic emission it is possible to shot on the cathode with a laser => photo-electric emission (produces better quality beams)

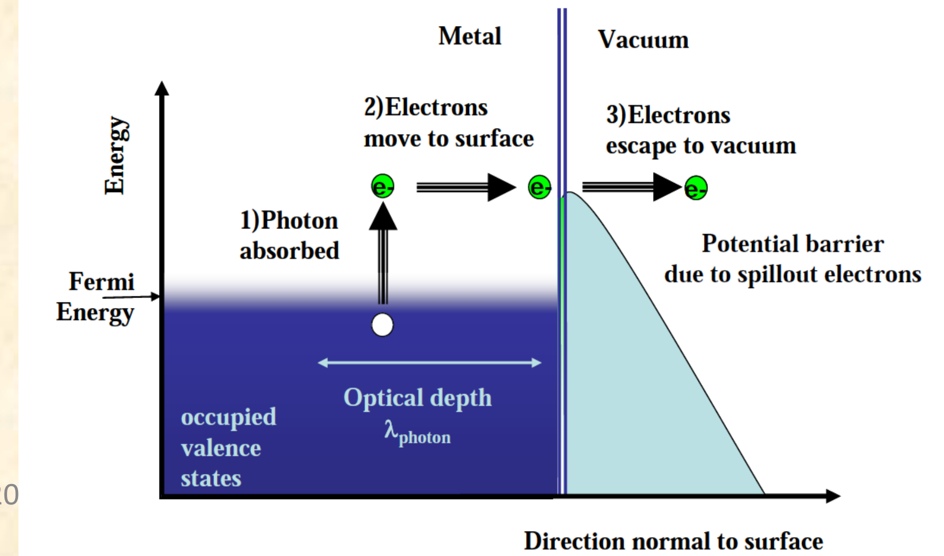
Photo-electric emission takes place in 3 steps:

1) Absorption of a photon by an electron inside the metal. The energy transferred is proportional to the photon energy.

2) Transport of the photon to the physical surface of the metal. The electron may loose energy by scattering during this process.

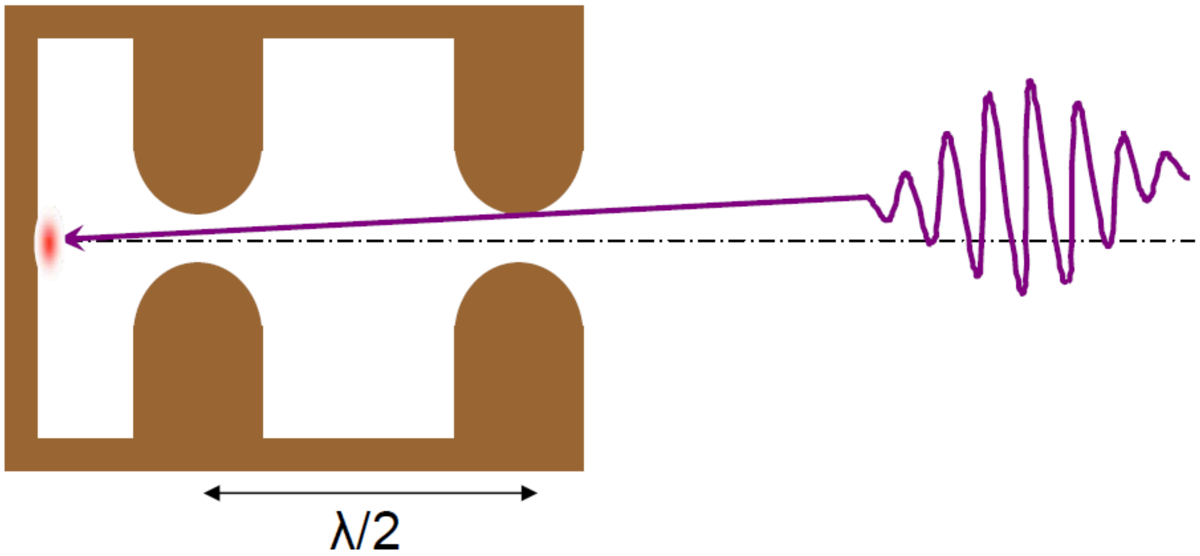
3) Electron emission (if the remaining energy is above the work function; including Schottky effect)

The efficiency of this process is called "quantum efficiency".



Principle of a RF Photo-gun

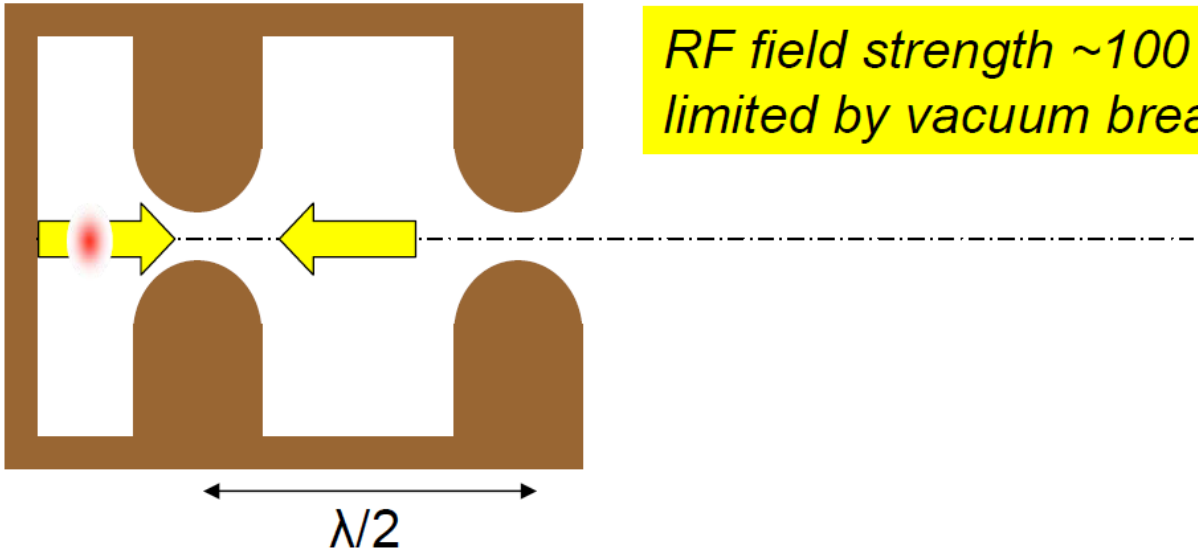
Pulsed laser photoemission...



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

...and RF acceleration.

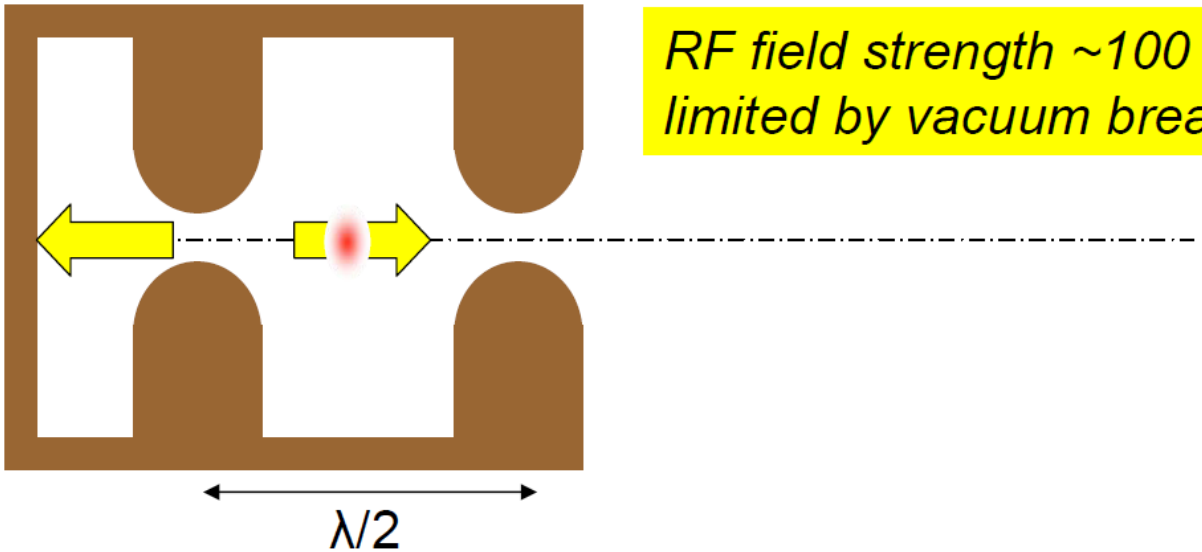


RF field strength ~100 MV/m, limited by vacuum breakdown

Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

...and RF acceleration.



RF field strength ~100 MV/m, limited by vacuum breakdown

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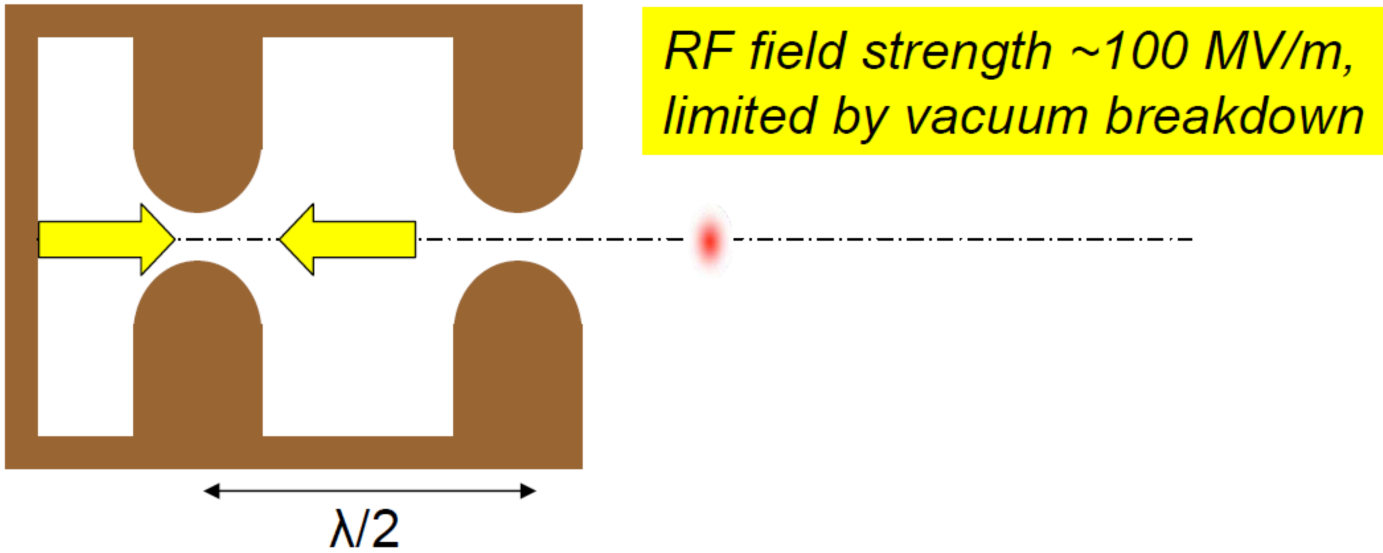
Principle of a RF Photo-gun

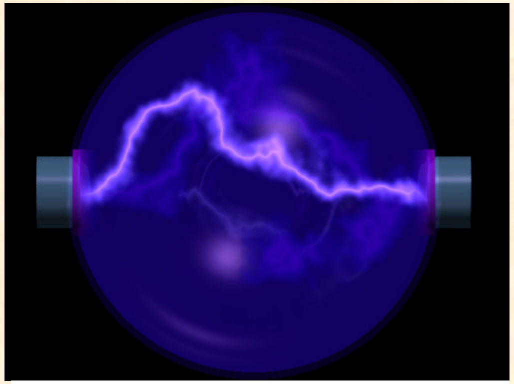
...and RF acceleration.

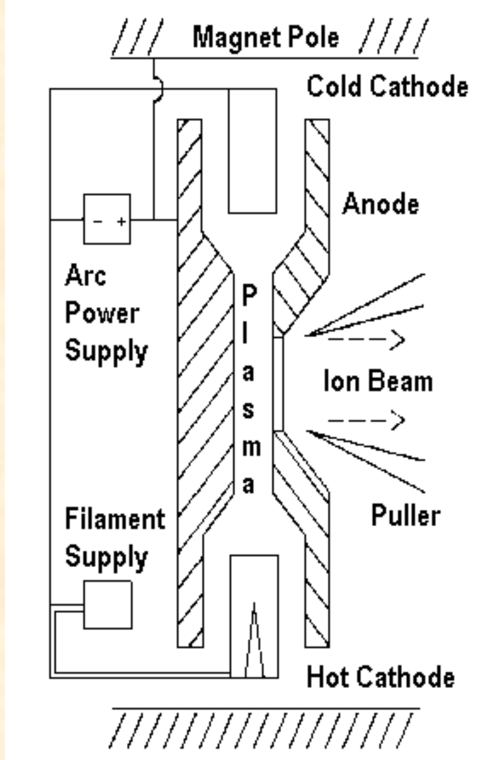


Courtesy Jom Luiten, TUV Eindhoven

Ion (and proton) sources

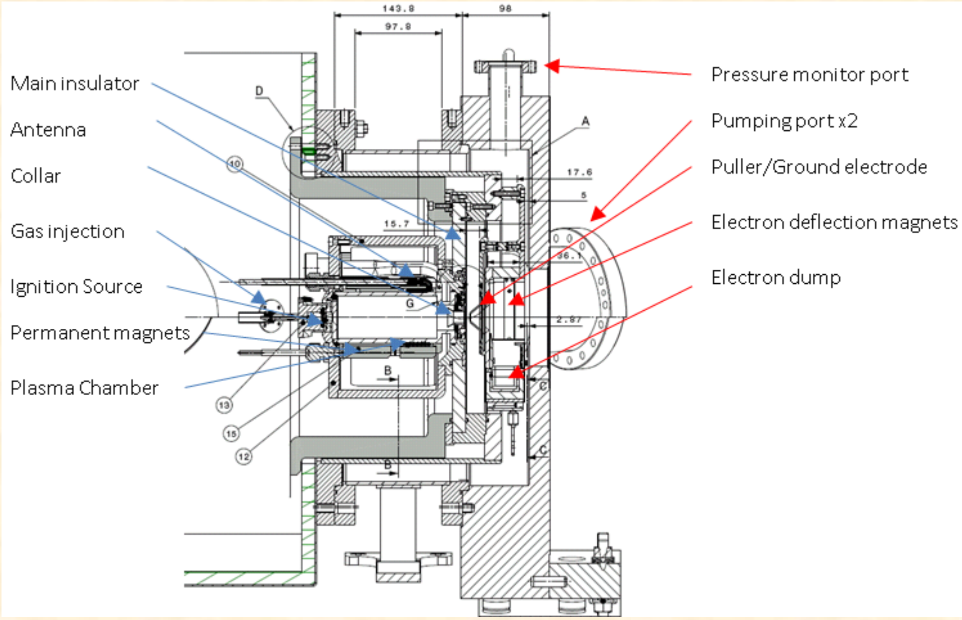
- An electric discharge creates a plasma in which positively and negatively charged ions are present (as well as neutrals).
- If such plasma experiences an intense electric field ions will separate in opposite directions.
- This is a rather crude and inefficient (but very simple) way of producing any sort of ions.
- In a Penning ion source a magnetic field is used to increase the probability the free electron ionize extra neutrals.

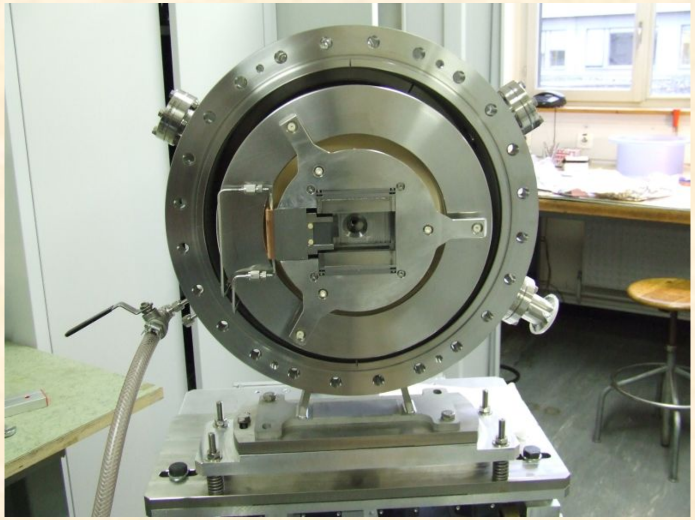


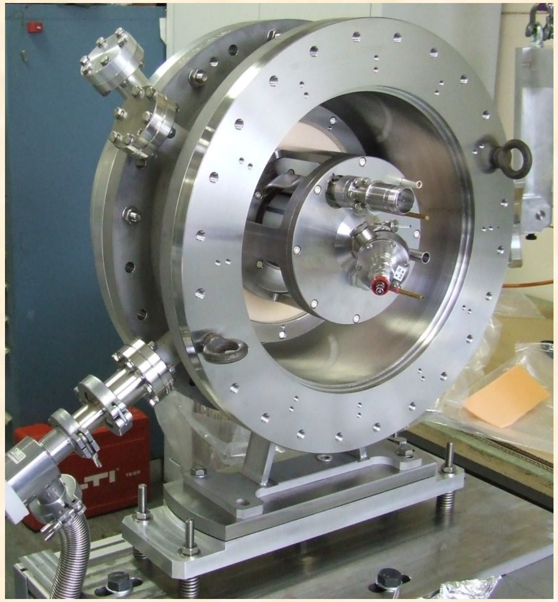


(images source: CERN)

CERN Linac 4 H- source





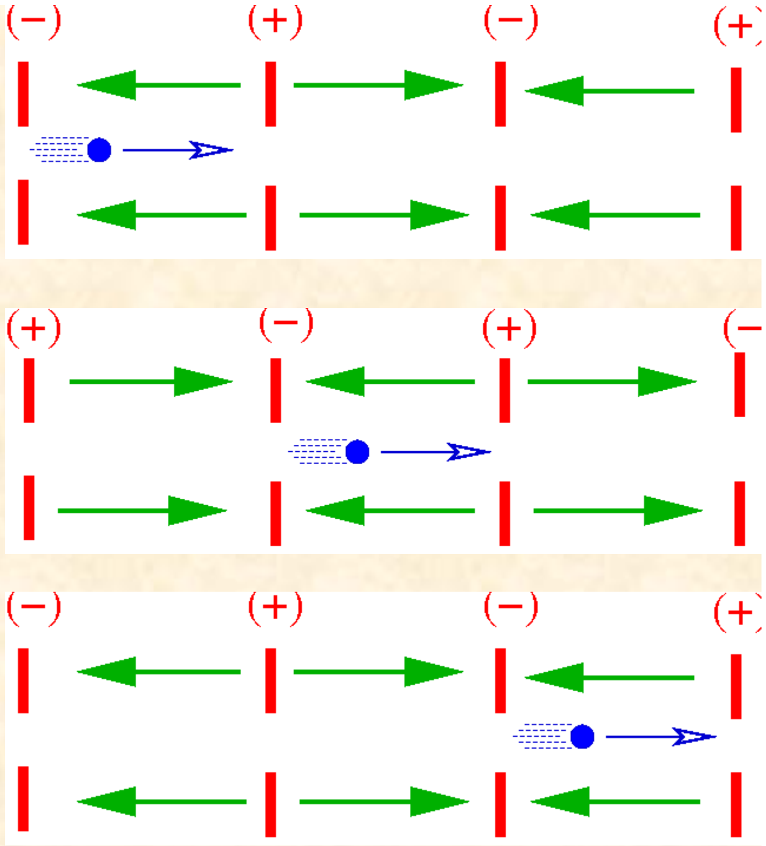


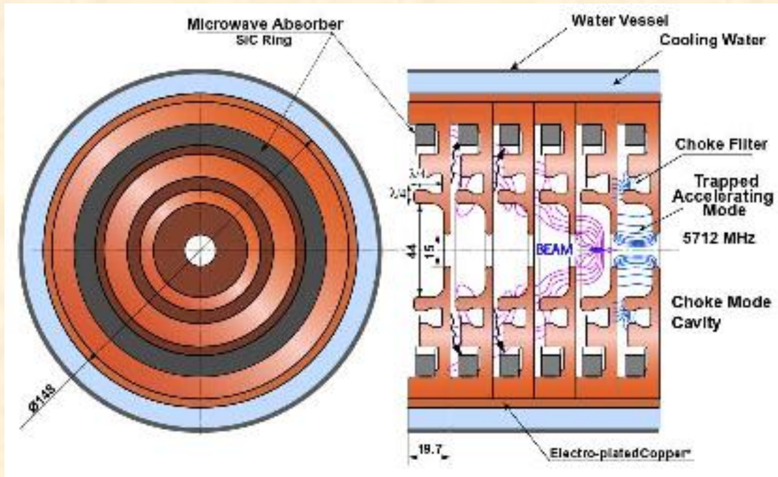
http://linac4ionsource.web.cern.ch/

Courtesy Richard Scrivens, CERN

Particle acceleration

- Van de Graff and Cyclotrons are limited in the energies they can reach.
- 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.

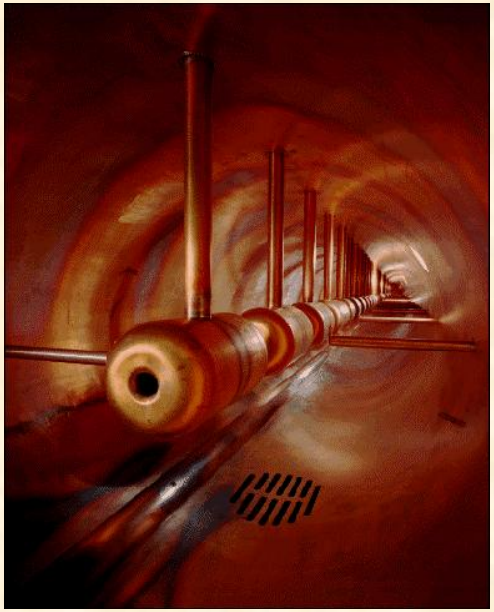


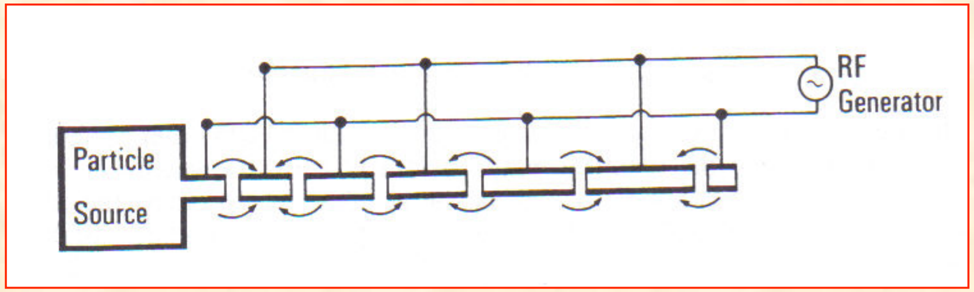


(source: Spring-8, Japan)

RF accelerators (2)

- The first stages of an AC accelerator are quite complicated because the speed of the particles keeps changing and thus the spacing between cavities is changing.
- Once the particles reach the speed of light, the cavities can be evenly spaced.





First stage of a proton RF accelerator

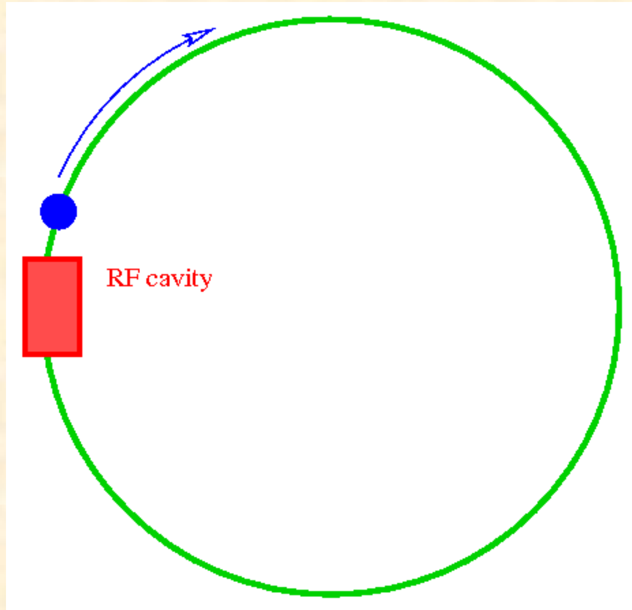
Synchrotrons

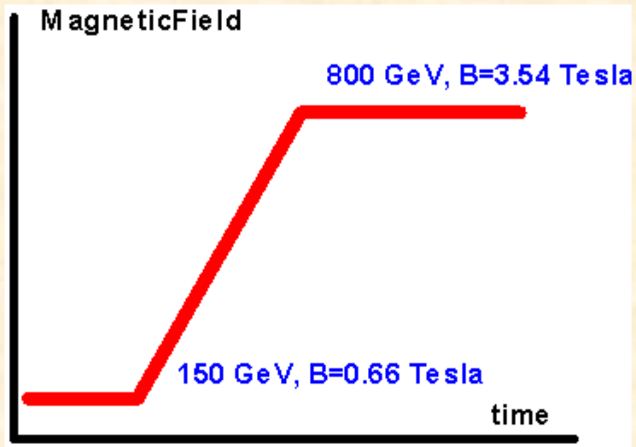
Instead of having a large number of cavities to accelerate the particles, it is also possible to have a single cavity in which the particles pass several times.

Dipole magnets are then used to make the particles follow a circular orbit.

As the particles gain energy the radius of curvature of their orbit in a constant field increases

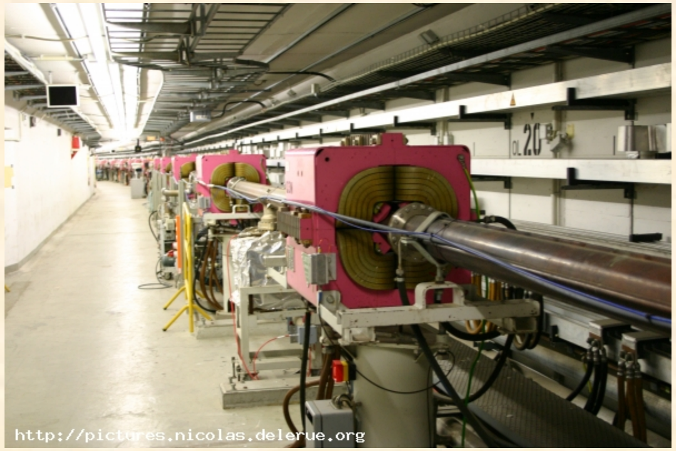
=> The field of the dipoles has to be increased to follow the particles energy gain and keep a constant orbit (synchro-cyclotron).





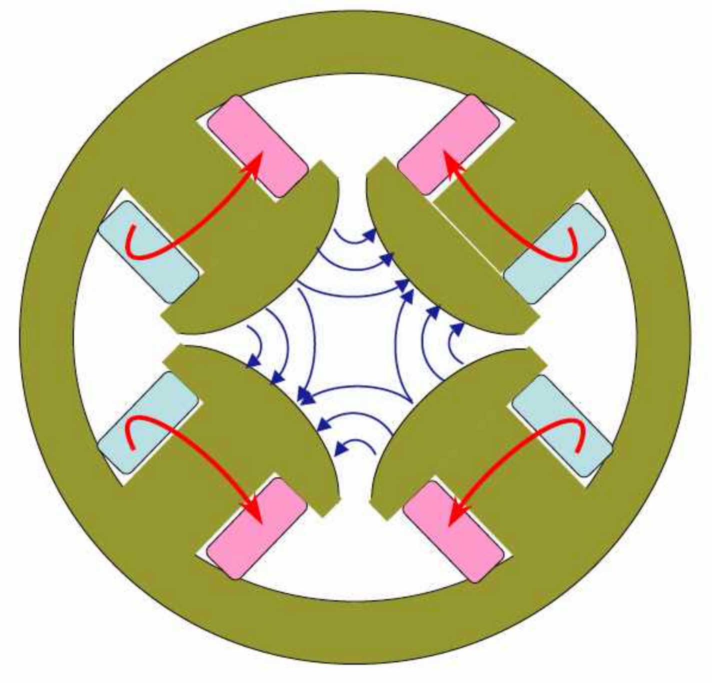
How to control where the particles go?

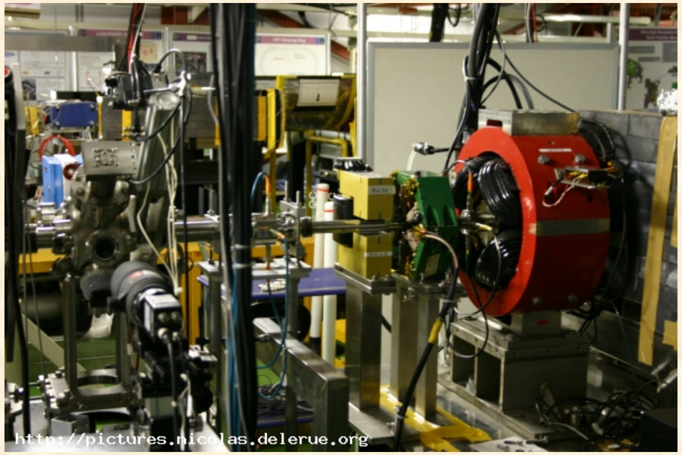
- Electric and magnetic fields can deflect charged particles.
- In an electric field the particles get accelerated.
- In magnetic field the direction of the particles is changed but not their energy.
  => it is preferable to use magnetic field (usually electromagnets) to control a beam.
- Magnets are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



Beam focussing

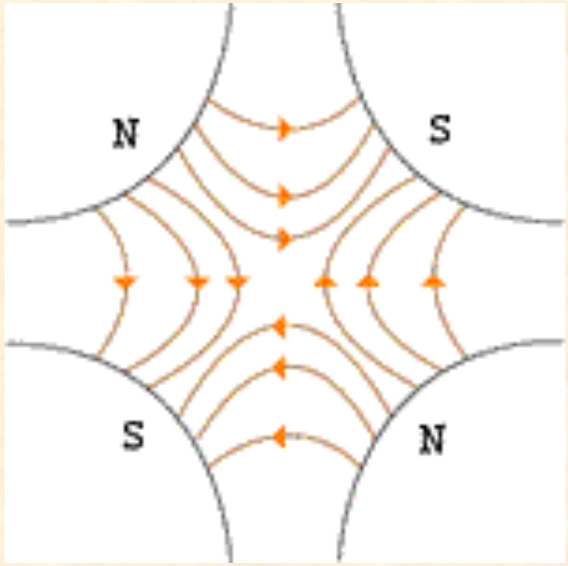
- A regular magnet (dipole) will create a field the will bend the beam in one direction.
- The change the size of the beam a different type of magnets called quadrupoles need to be used.
- Quadrupoles create intense fields for off-axis particles but do not disturb particles on the axis.

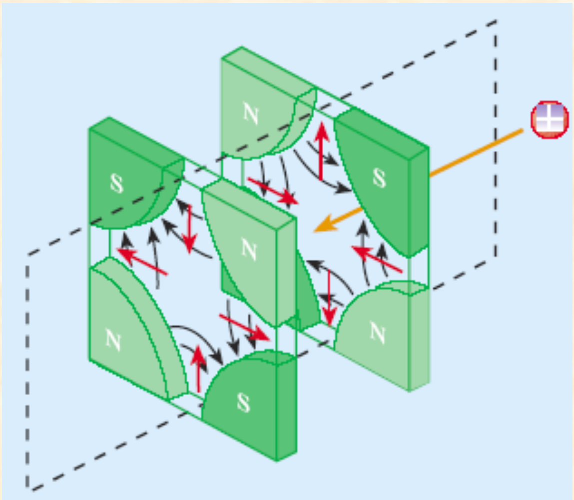


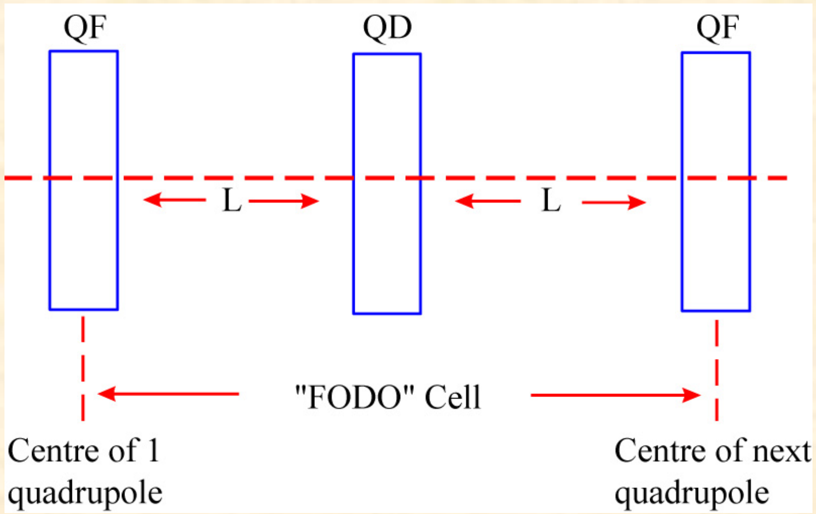


FODO cell

- 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.

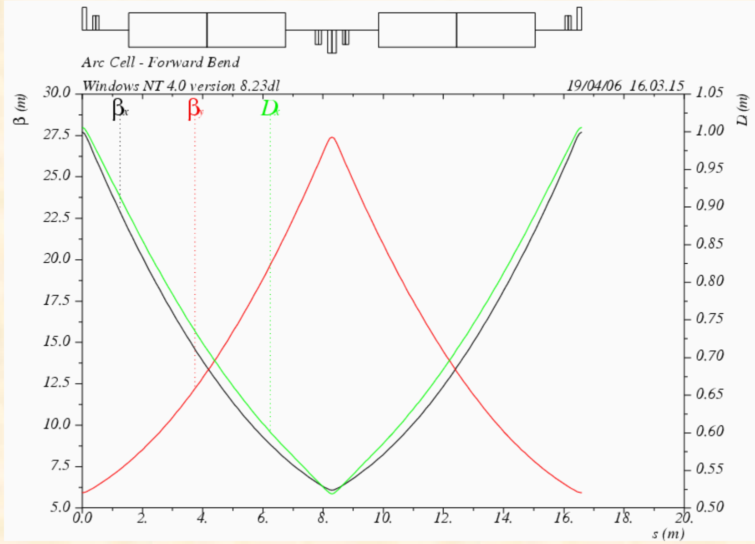


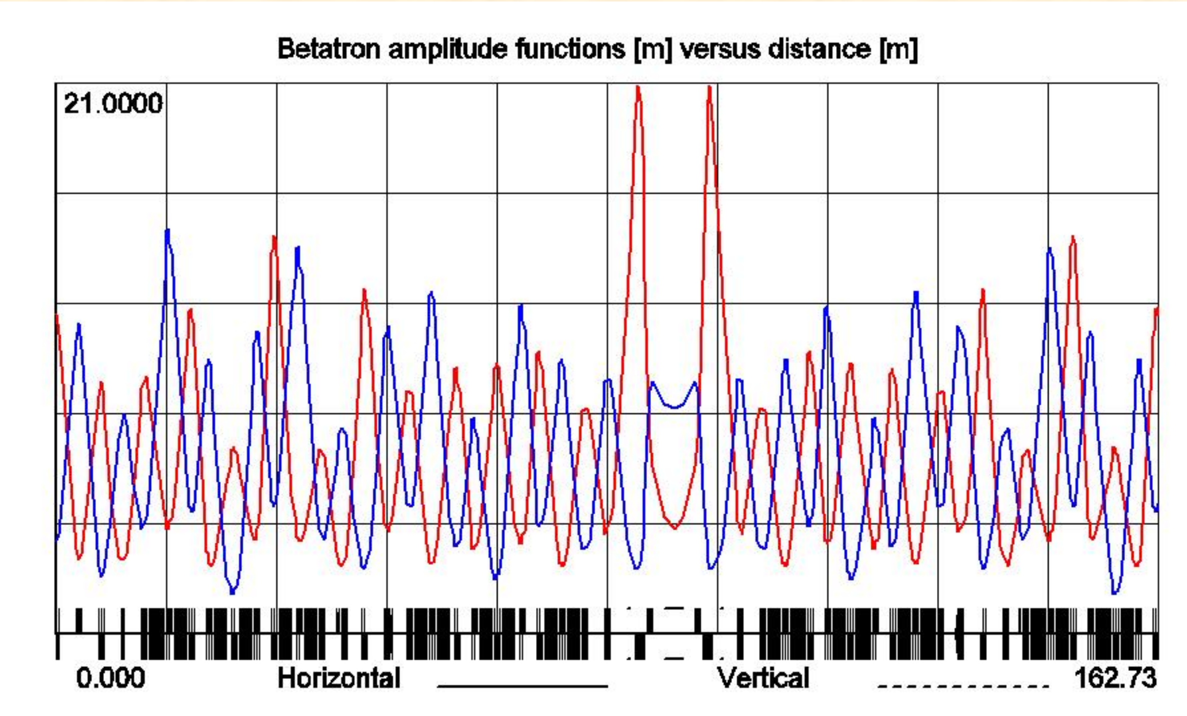


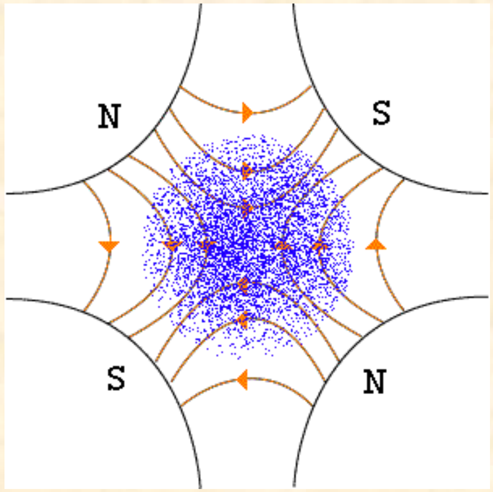


Accelerator lattice

- In an accelerator there is a large number of quadrupoles to keep the beam size under control.
- This is called the lattice of the accelerator.

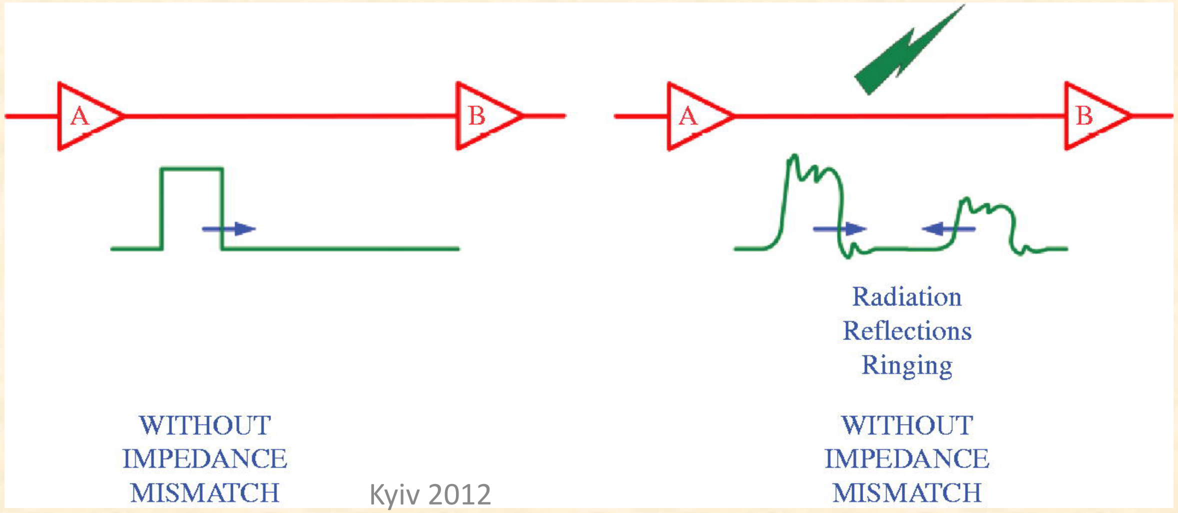






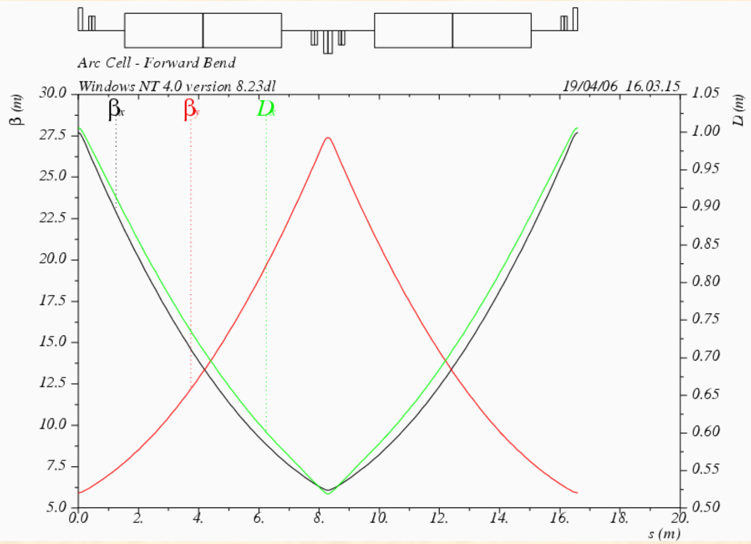
Impedance matching

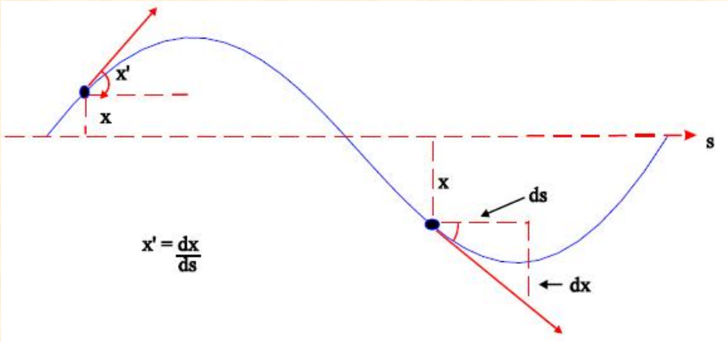
- In a RF circuit an impedance mismatch will result in a reduced transmission at the interface.
- The same is true in an accelerator: an impedance mismatch is likely to induce a reflective wave at the interface.
- This will induce a loss of power and an emittance increase.
- In a synchrotron the impedance of all beam pipe elements is carefully controlled.
- This is less important in a transfer line where the beam passes only once.



Betatron oscillations

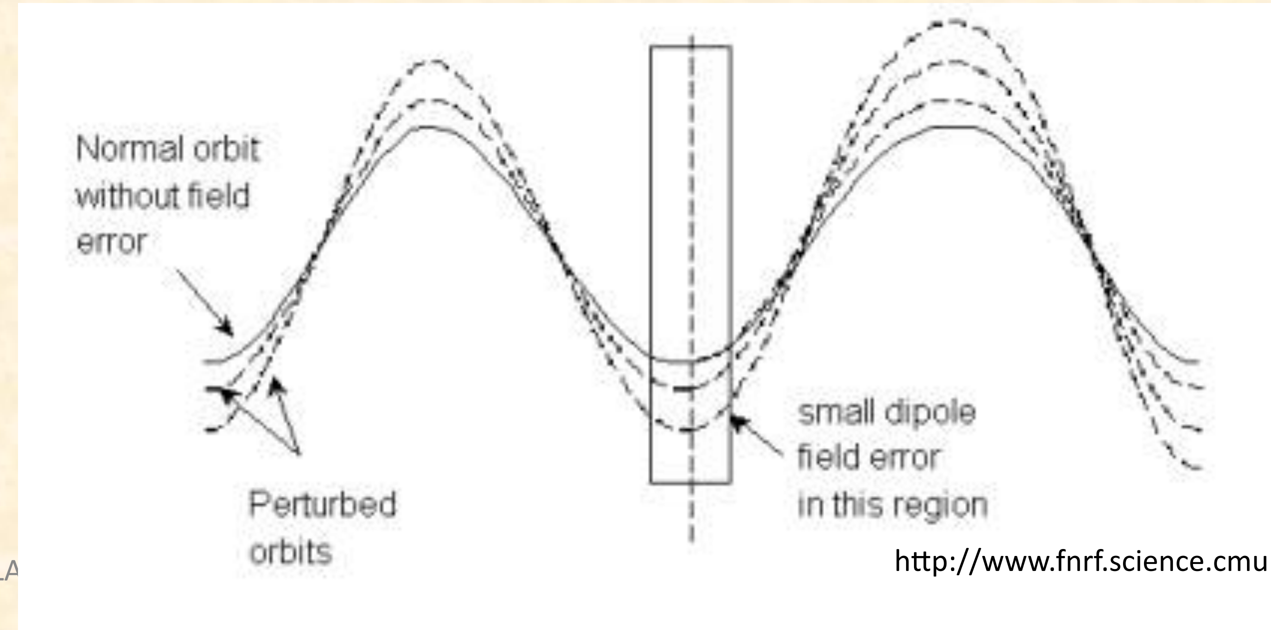
- We have seen that as it travels along the lattice the beam is focussed alternatively in both planes.
- For individual particles this leads to oscillations called "betatron oscillation".
- This occurs in both planes at the same time.
- If the particles perform an integer number of betatron oscillations in one turn, they come back at the same position turn after turn.
- Be careful, you should not confuse the number of lattice periods with the number of betatron oscillations.





Integer betatron oscillations

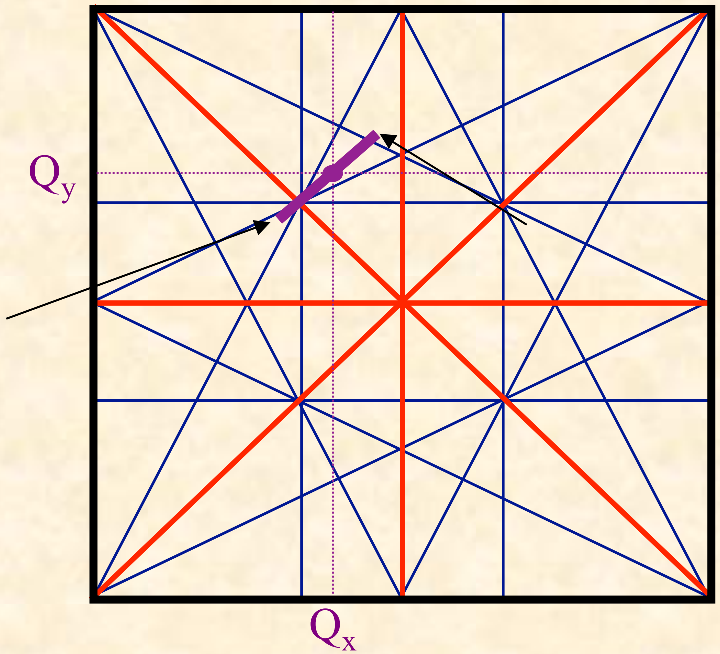
- If one of the magnets in the accelerator has a field error a particle coming turn after turn at the same position will accumulate the effect of this field error.
- After a large number of turns (millions…) what was initially a very small error can lead to large orbit changes and eventually to the loss of the beam.
  => avoid integer betatron oscillations… (avoid half-integers also)



http://www.fnrf.science.cmu.ac.th/

Tune

- To avoid cumulative effects in the accelerator over a large number of turns all rational numbers should be avoid for betatron oscillations in both planes
  => choose an irrational number!
- Choosing an incorrect tune can significantly increase the particle loss rate.

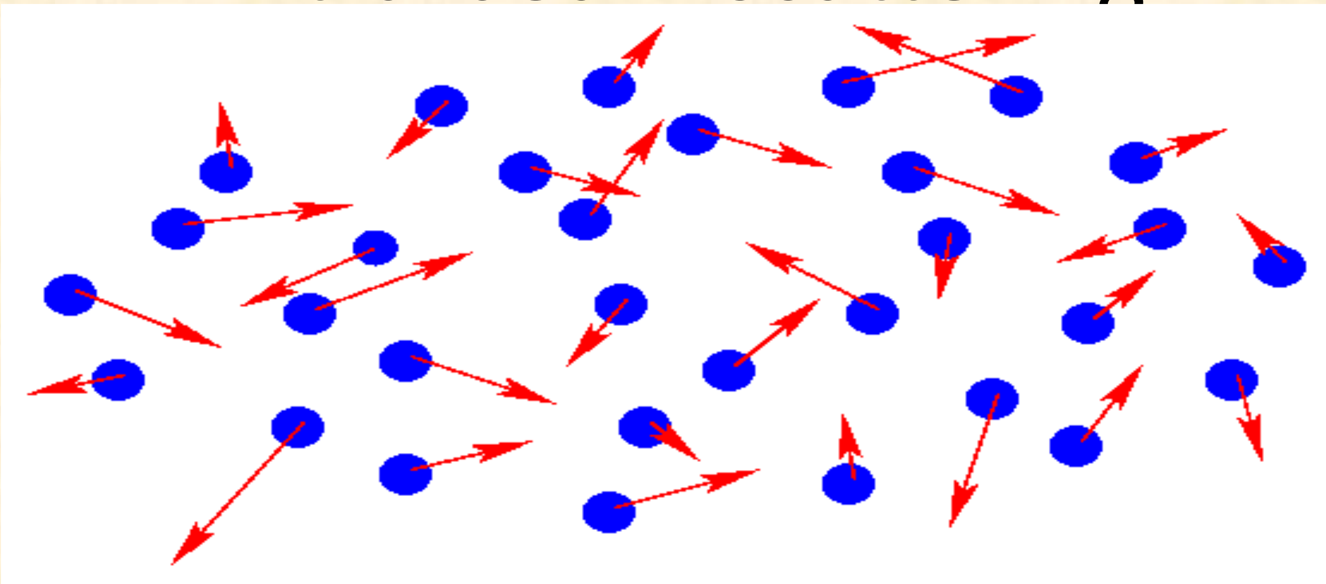


Wakefield issues

- Electrons produce an electromagnetic wave behind them.
- This can be compared the to wake of a boat and is called wakefield.
- Imagine what would happen if there was a second surfer on the picture below...
- How good is the wake for the walls of the canal?
  It is not good for the beam pipe either!

Source: Reuters

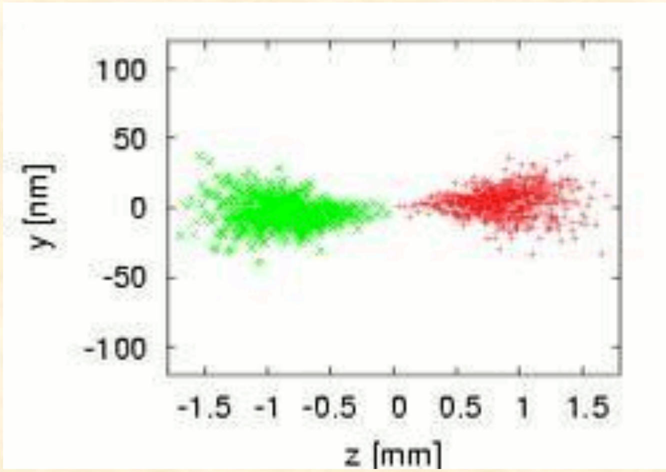
Intra-beam scattering



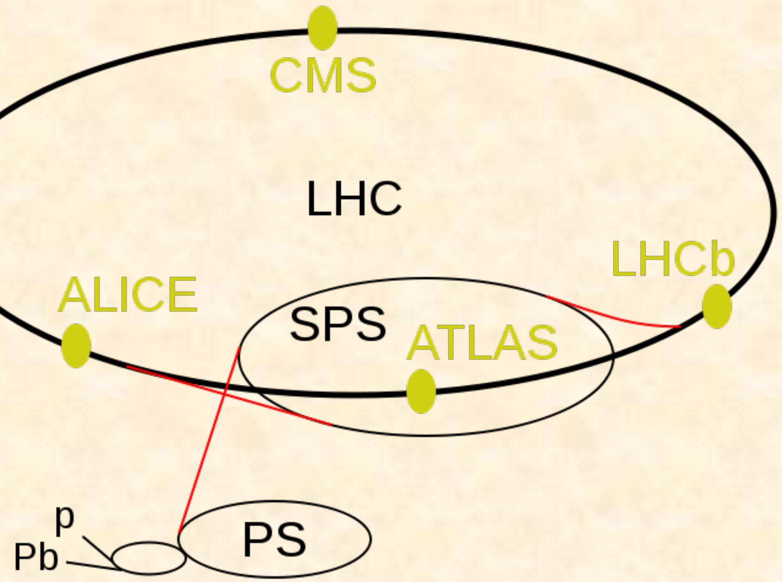
- Inside the beam the particles behave somewhat like a gas.
- Coulomb collisions do occur between the particles leading to momentum transfer between the particles and a degradation of the beam quality.
- In extreme case some particles may be ejected from the beam (Touschek effect).

Beam beam interactions

- When two beams collide they exert intense M forces on each other.
- If the beams are strongly focussed this can lead to severe disruption of the beams.
- In a circular colliders the beam focussing must be kept large enough to minimise the disruption on each turn.



Looking again at an accelerator

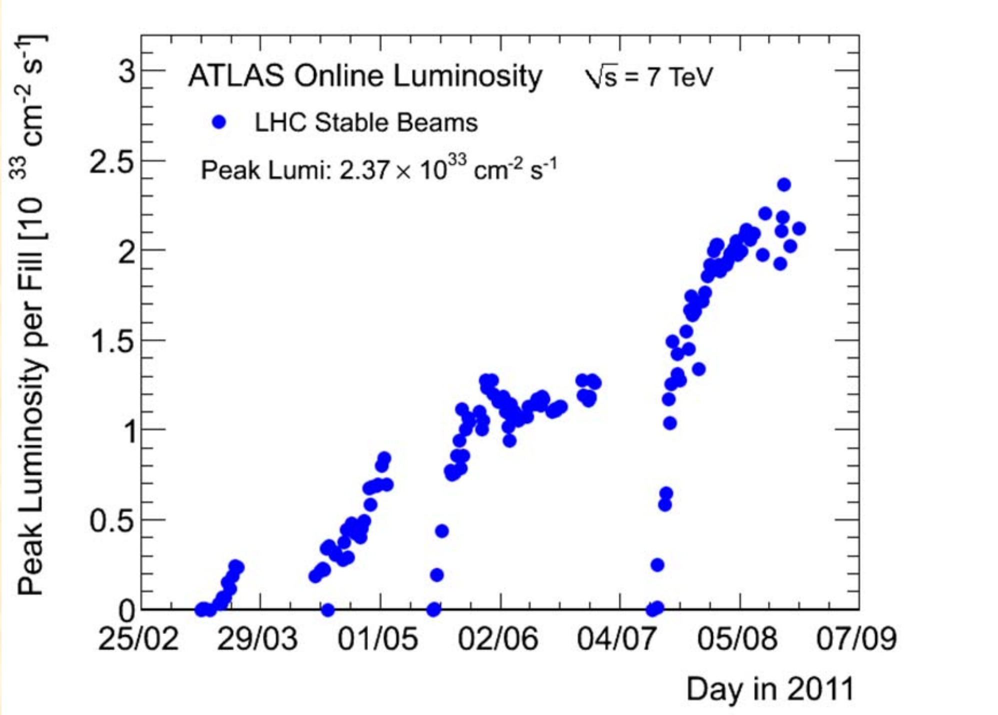


- We can now understand most of the element that make an accelerator, so let's have a look at the largest accelerator in the world: the LHC…

THE LHC

A complex enterprise

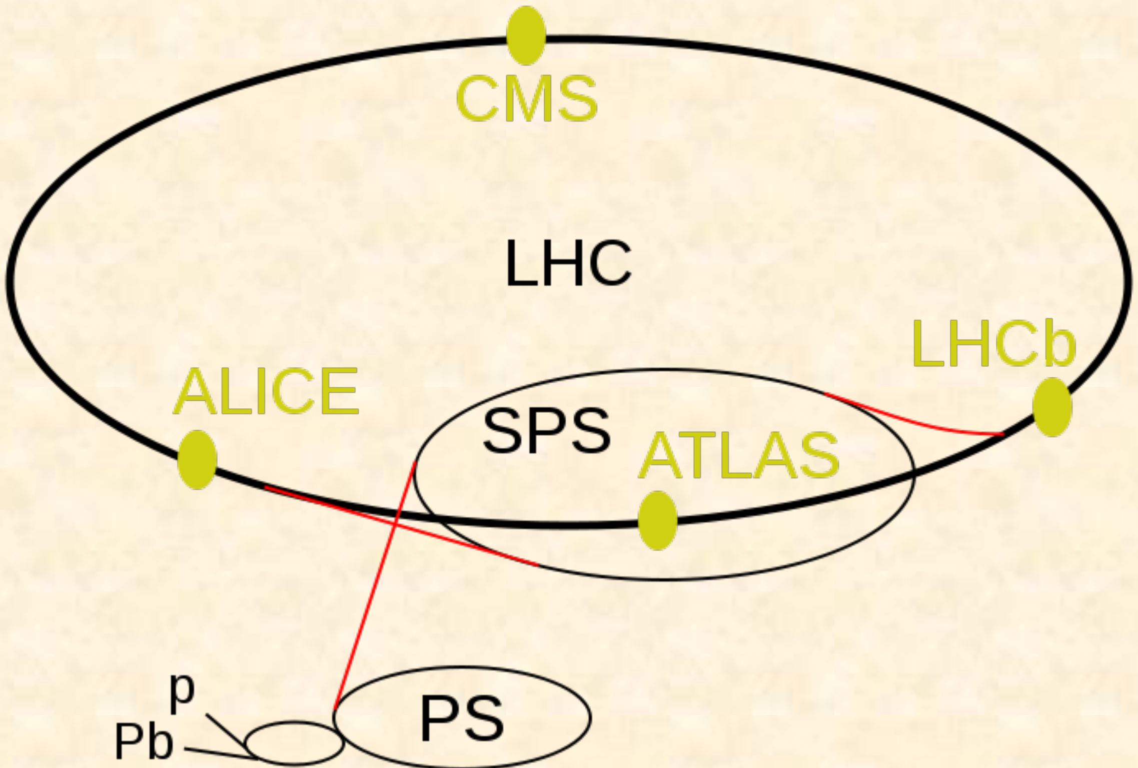
- Beyond the particle physics challenges associated with the construction of the detectors and the analysis of the data, building and operating the LHC machine was also an immense challenge involving a large number of skills.
- The machine has not yet reached its full potential and the engineers running it improve its performance all the time.



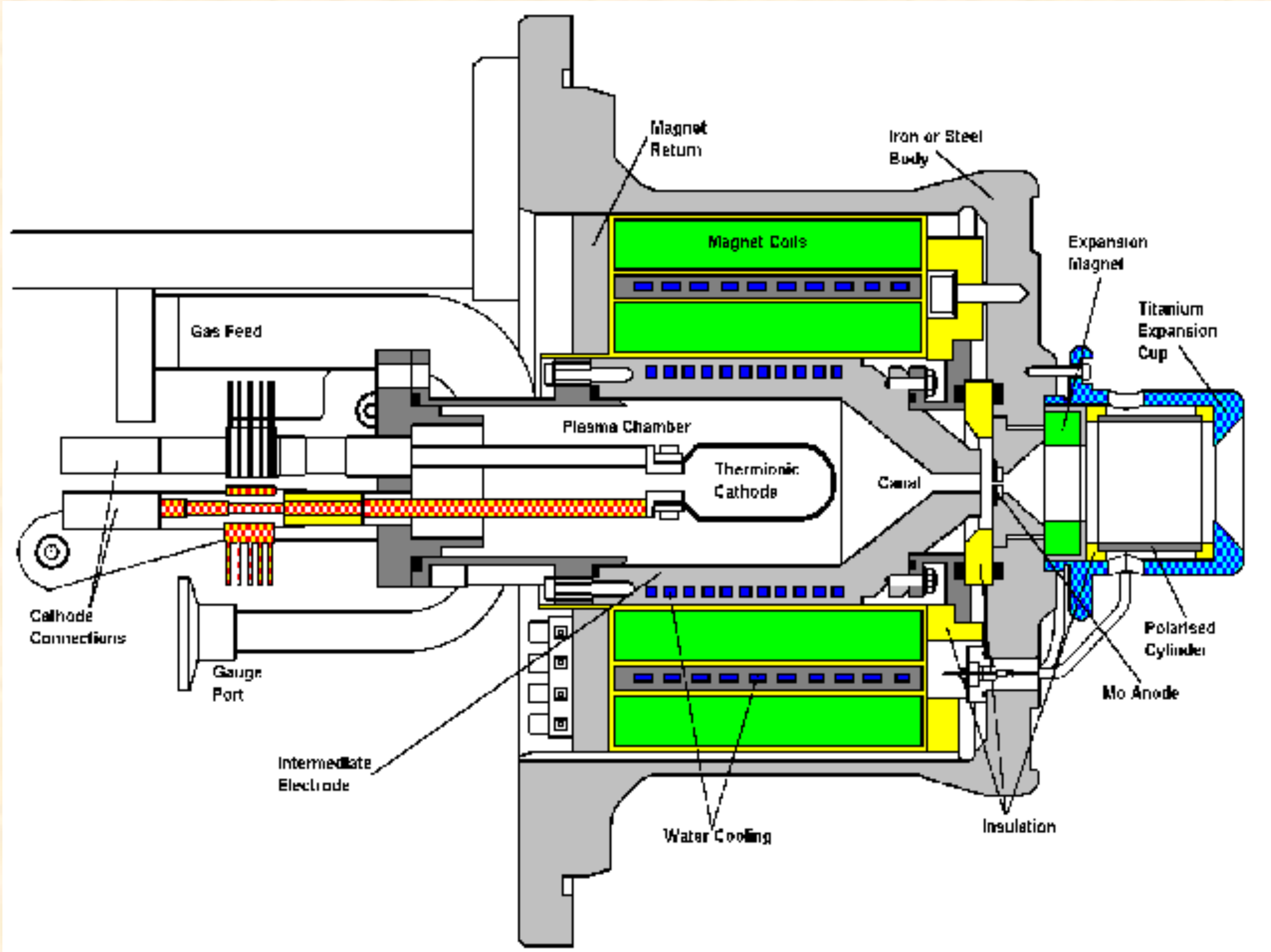
References: http://lhc.web.cern.ch/lhc/LHC-DesignReport.html and
« The LHC Machine, Lyndon Evans and Philip Bryant 2008 *JINST* **3** S08001 doi:10.1088/1748-0221/3/08/S08001 »

The injection chain

- Particles can not directly be produced and accelerated in the LHC, several preliminary steps are necessary.

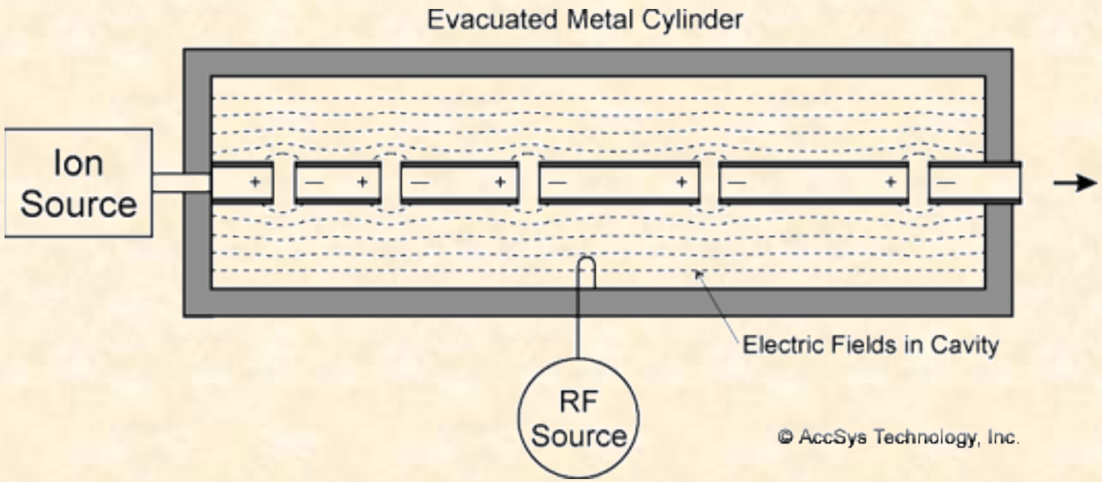


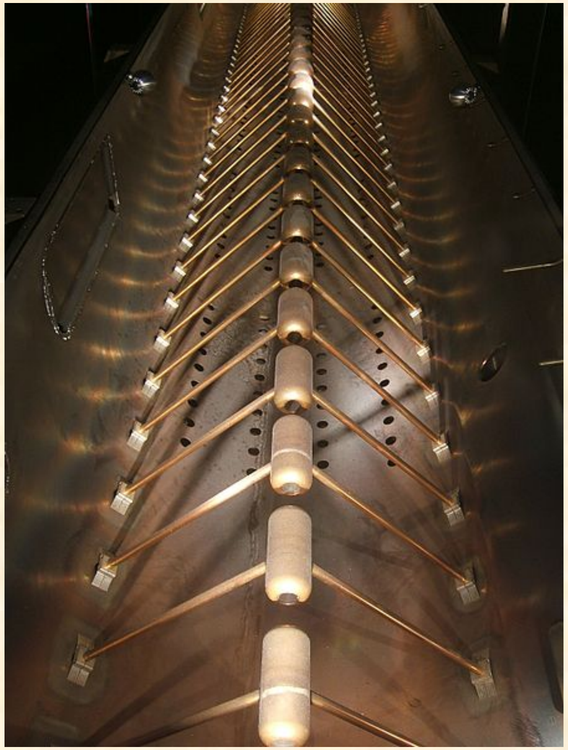
Proton source



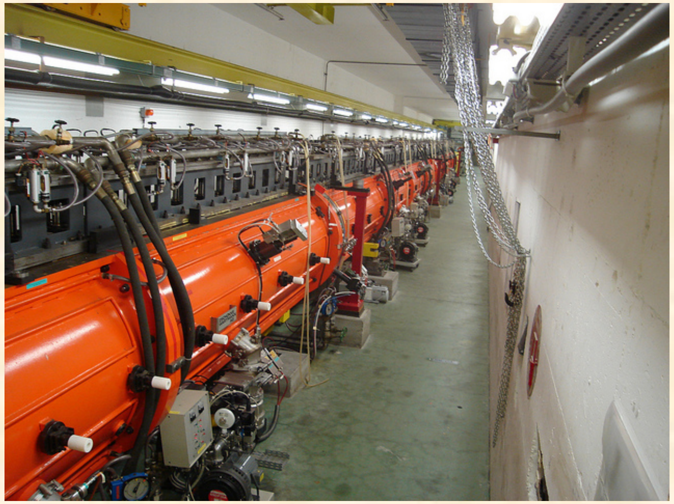
- Particles are extracted by ionisation of hydrogen as in a device called “Duoplasmotron Proton Ion source”

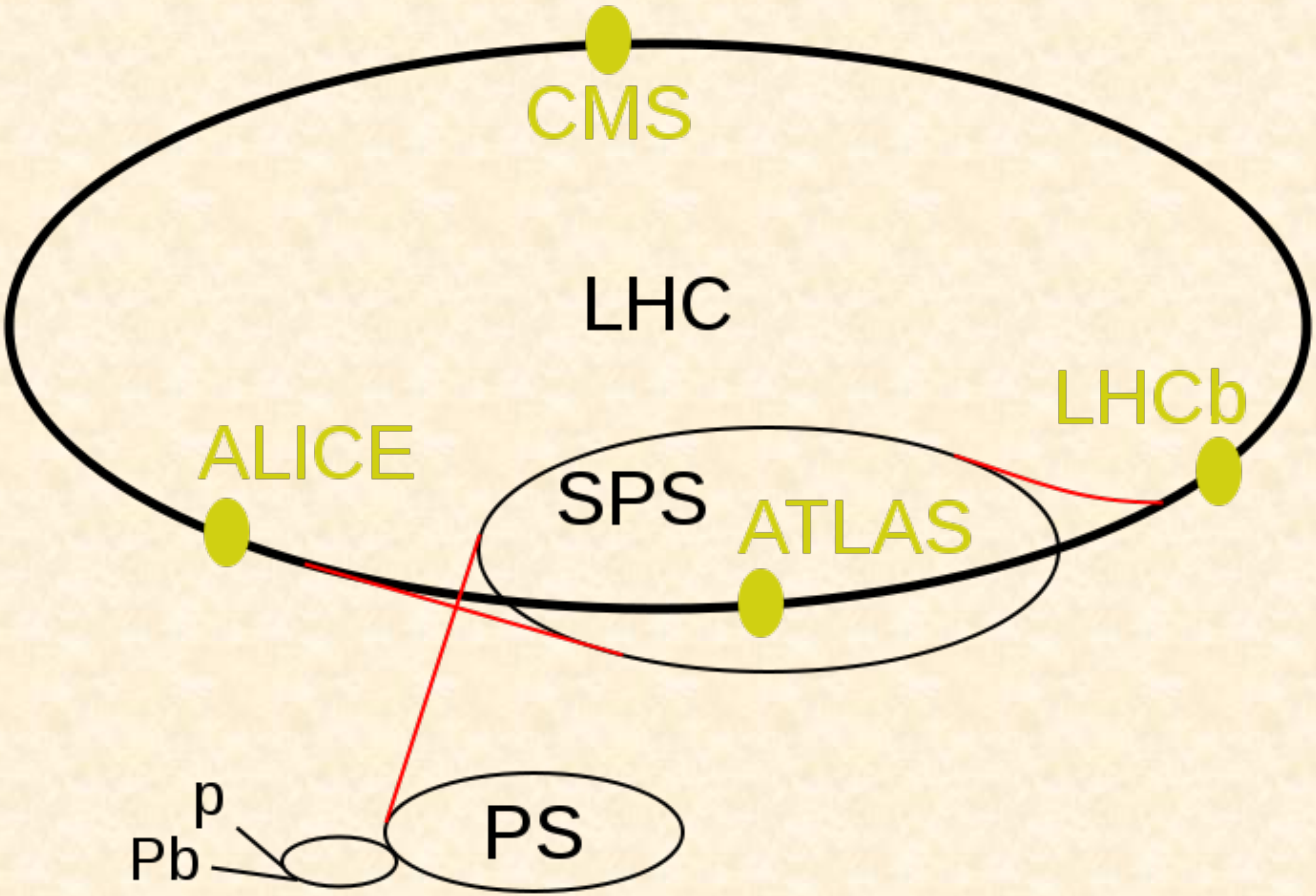
Linac





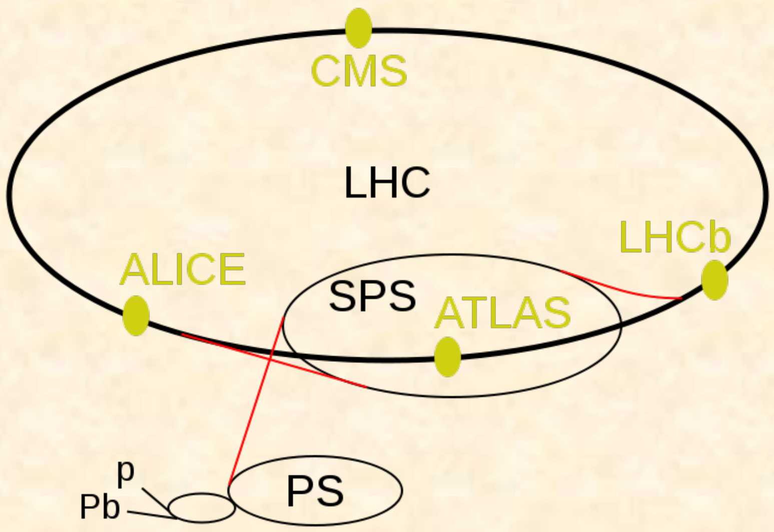
- After the source the protons are accelerated in a linac.
- As the protons gain speed they travel longer distance in a RF cycle and therefore the length of the tubes must be increased.
- At the end of the Linac the protons reach an energy of 50 MeV.

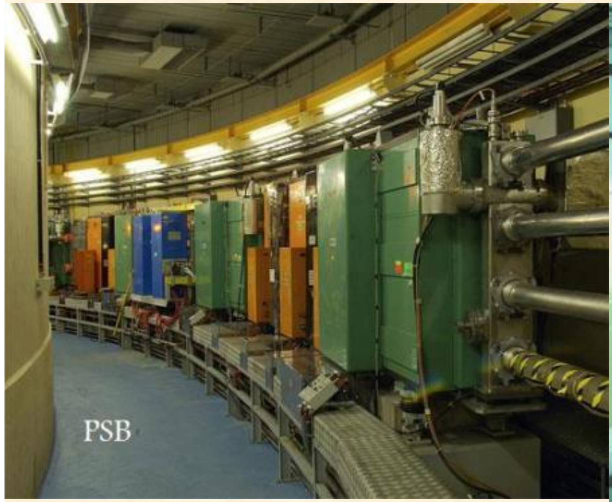


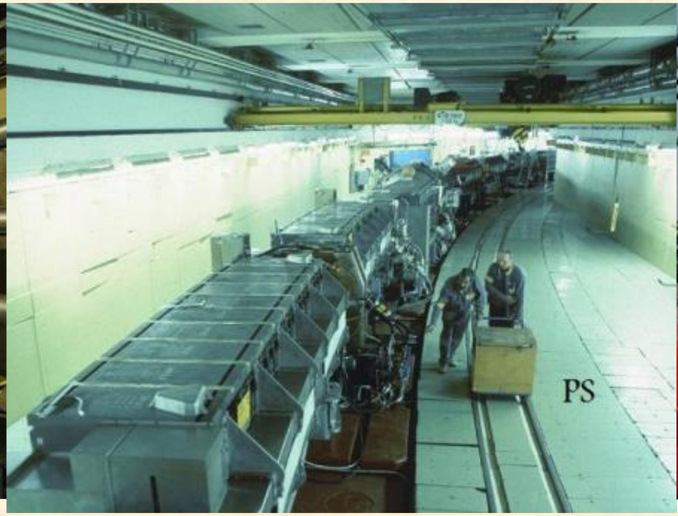

CMS
LHC
LHCb
ALICE
SPS
ATLAS
p
Pb
PS

Pre-acceleration rings

- At 50 MeV the energy of the protons is too low to be injected in the LHC.
- Several intermediate rings are necessary to bring their energy to the LHC injection energy.
- To save space the first of these rings, the PS booster is made of 4 rings stacked on to each other!
- All these rings use pulsed magnets which allow to change the beam configuration very quickly.
- The PS was built in 1959, the PSB in 1972 and the SPS in 1976.

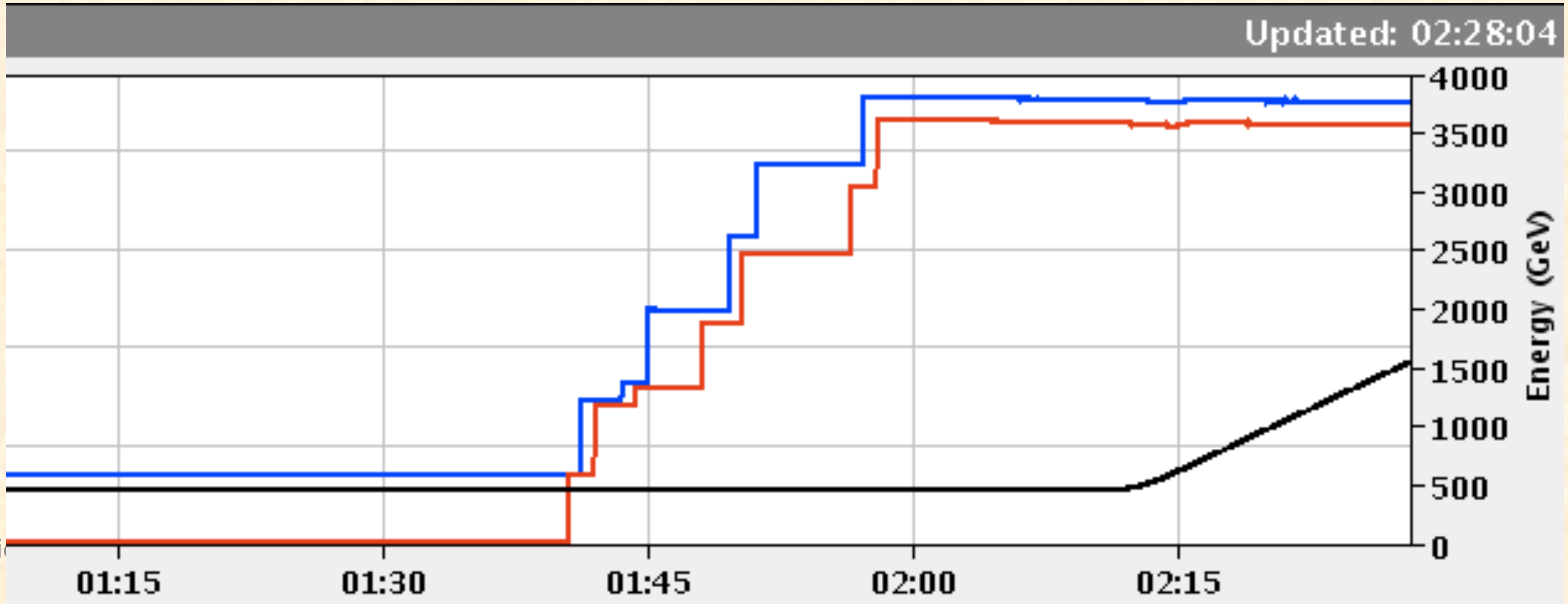






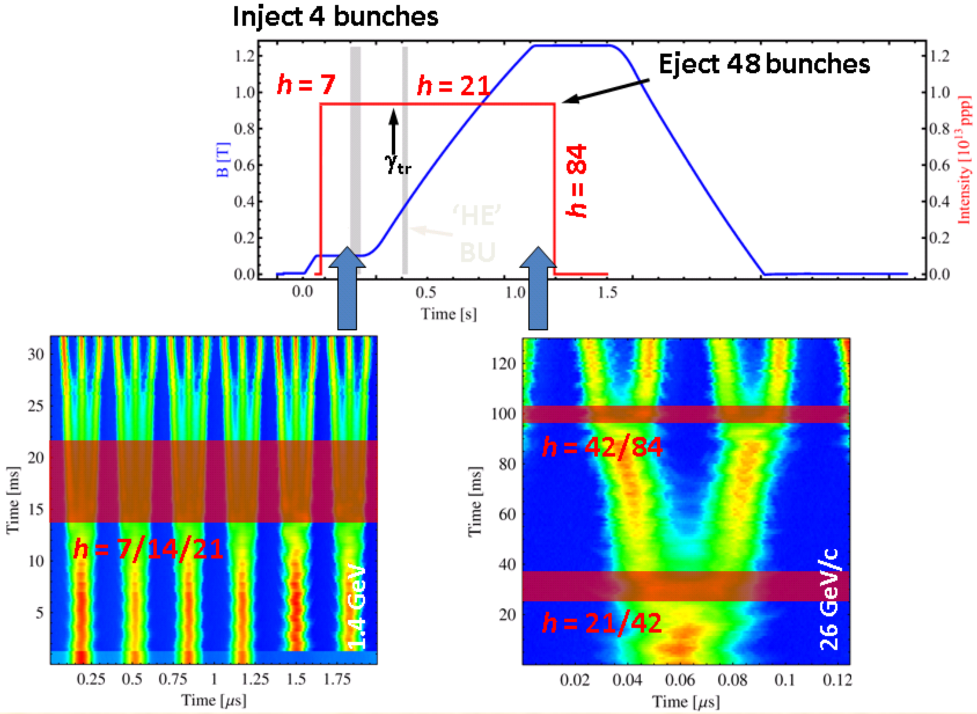
Why pre-acceleration rings?

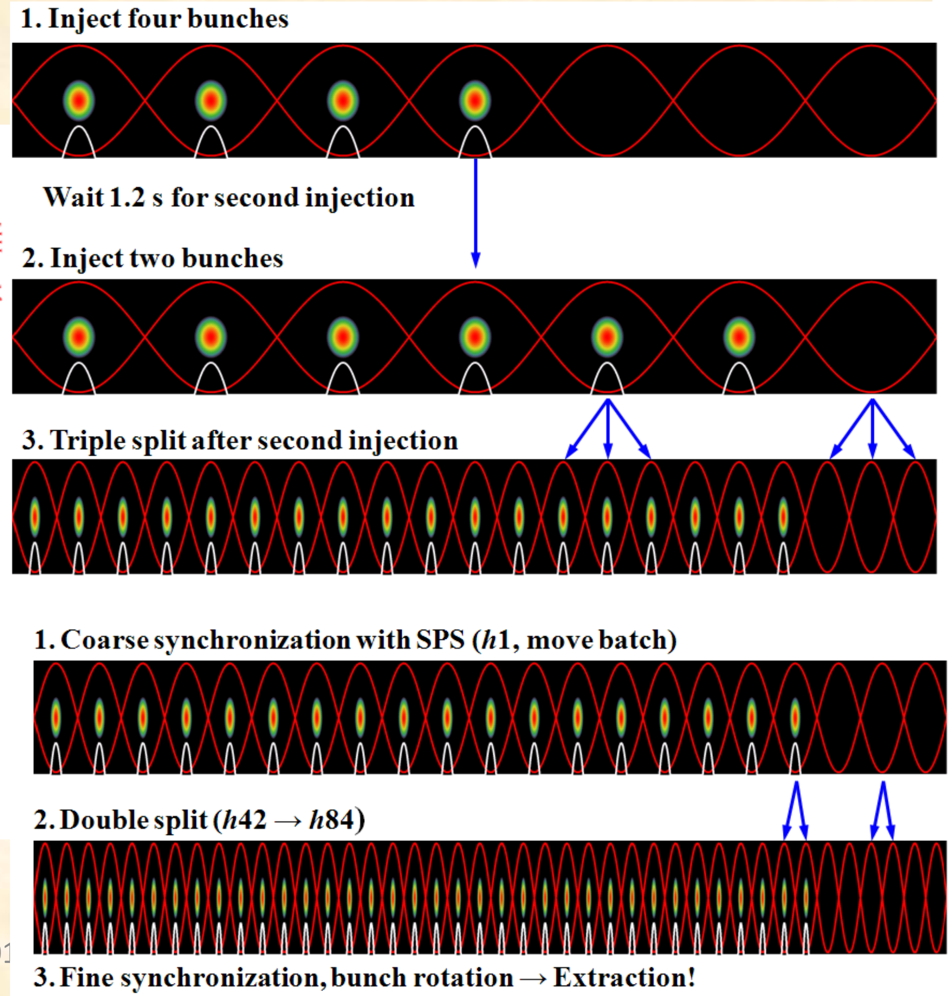
- In a synchrotron the strength of the magnets must be increased when the energy of the particles is increased.
- It is cheaper to have magnets (and power supplies) with a limited dynamic range.
- As the energy of the beam increase its emittance (and therefore its size) decreases.
  Early accelerators in the acceleration chain must have a wide aperture whereas the LHC has a small aperture (a bunch from the Linac would not fit in the LHC.



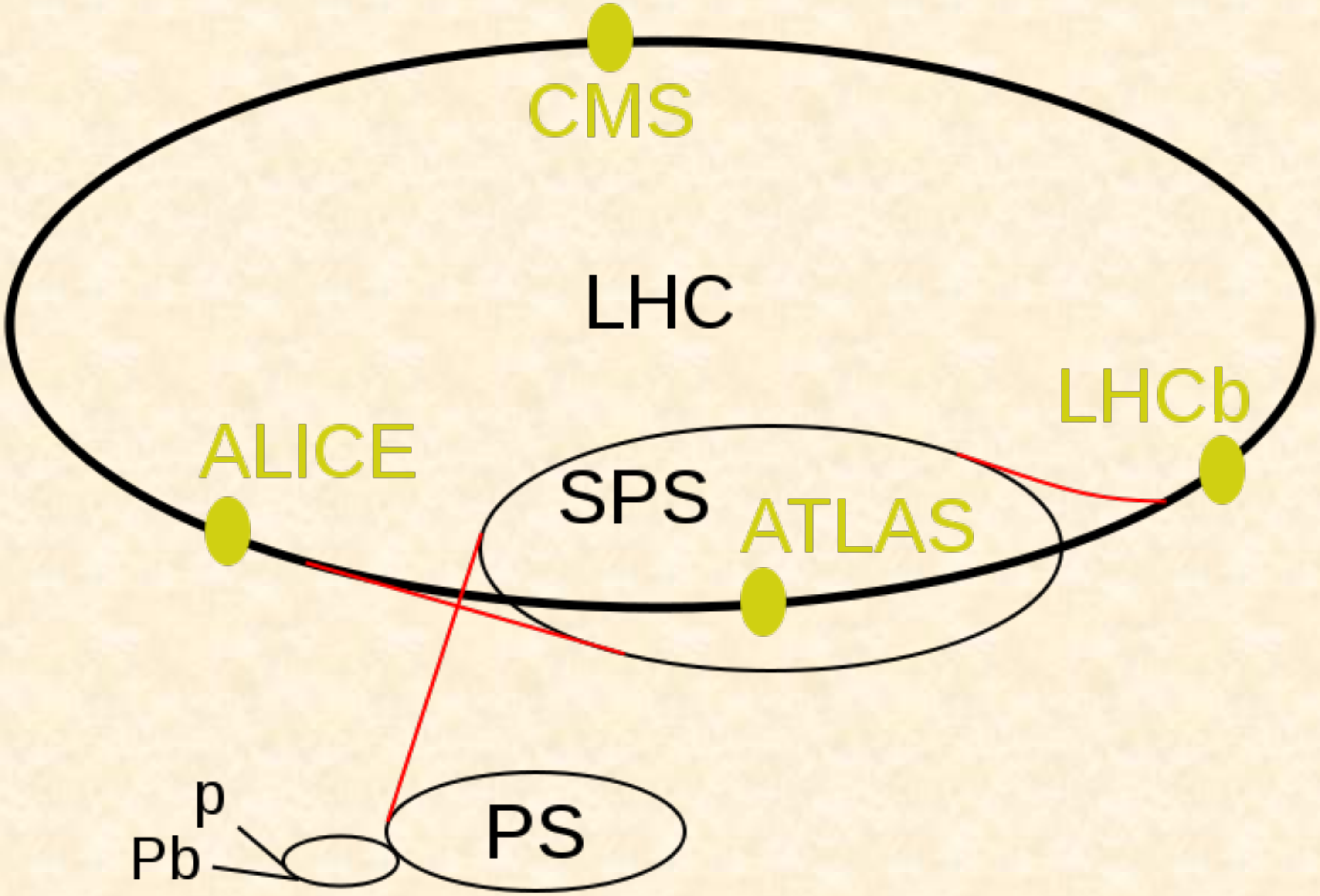
Protons bunch splitting

- Another purpose of the PS is to adapt the bunch structure from the Linac to the requirements of the LHC.
- The RF of the PS is used to split 8 proton bunches into 84 bunches!





The LHC itself



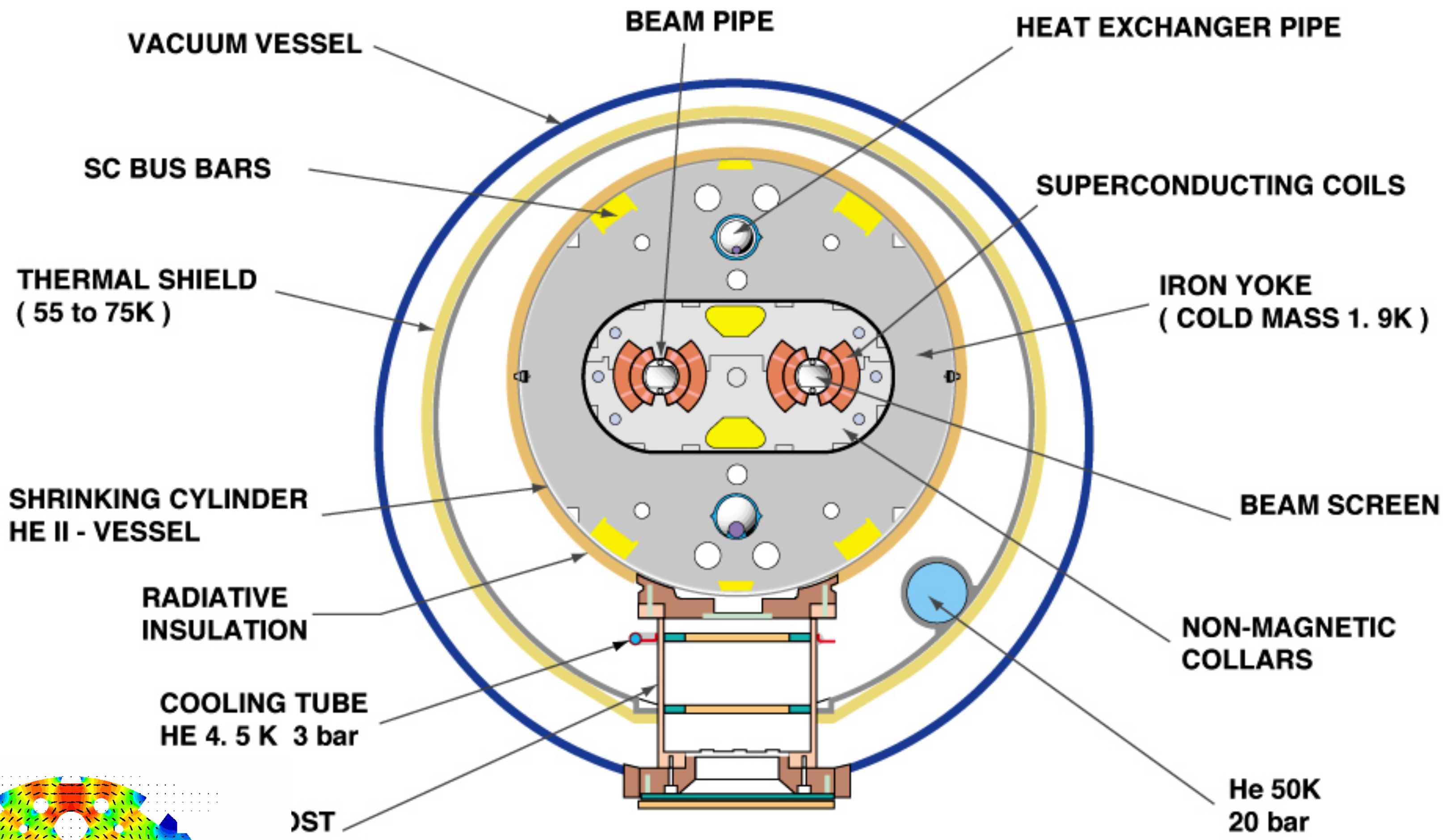
Magnets

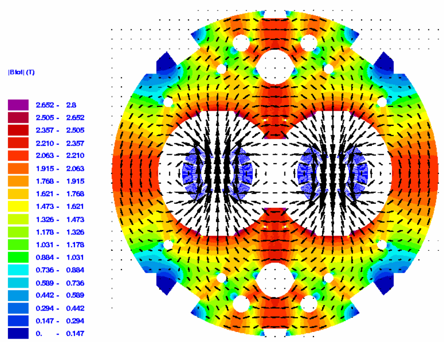
- One of the challenges of the LHC is to give to the 7 TeV protons a circular orbit.
- The magnetic rigidity defines how strong the magnetic field must be to bend particles of a given energy.
- At 7 TeV and with a bending radius of 2.8km this requires a very intense magnetic field: 8.3 Tesla!
- This is a very intense magnetic field.
- To achieve it without using too much power, the coils have to be superconducting.

$$\frac{p}{q} = B\rho$$

$$B\rho = 3.3p(\mathrm{GeV/c})$$

CROSS SECTION OF LHC DIPOLE





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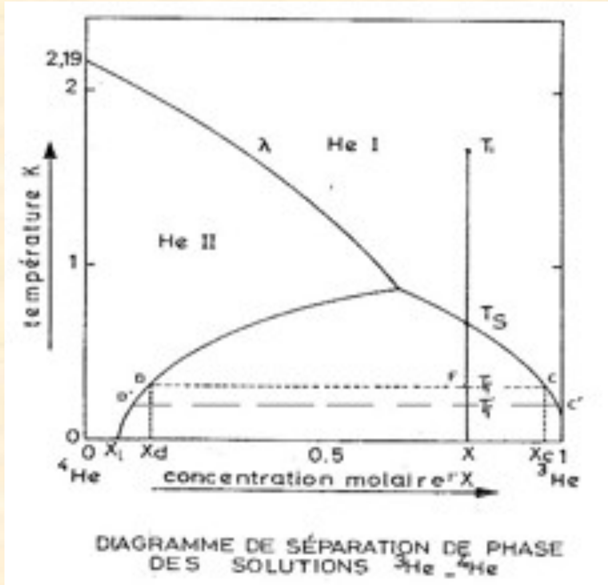
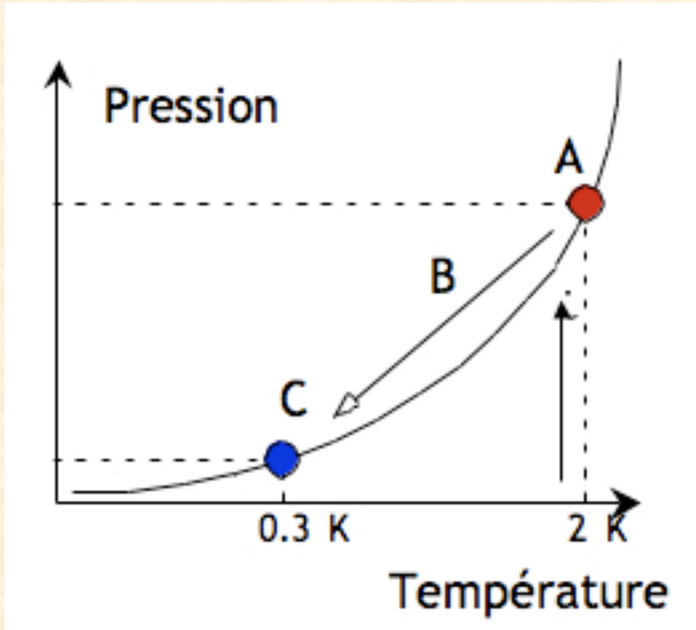
Cryogenics

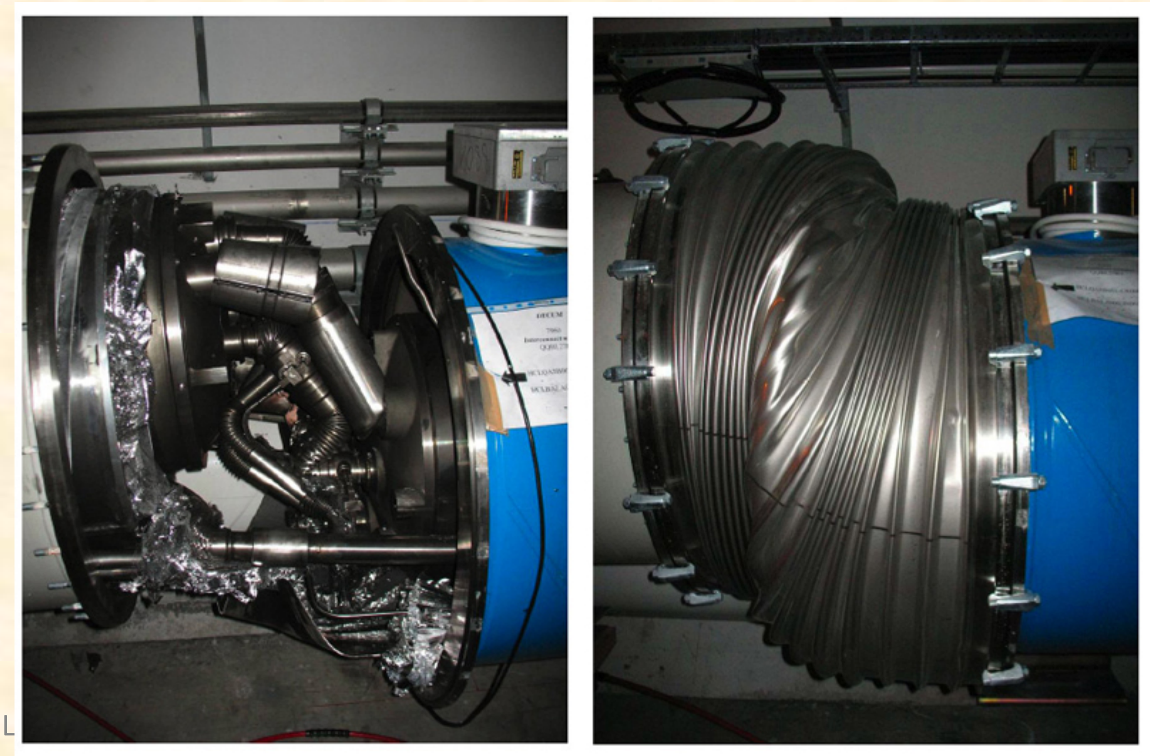
- To keep all the magnets superconducting they must be kept at all time below 4K.
- If a superconducting magnet is suddenly brought back to normal conducting (eg due to heating), the magnetic energy is suddenly released => quench.
- Therefore an important safety margin must be kept to prevent quenches.
- All the LHC magnet are cooled to 1.9K.
- It is not possible to reach such temperature simply by liquefying helium. The phase transition between Helium II and Helium I must used (using a mix of Helium-3 and Helium-4).
- Cooling a large metallic object from room temperature to 1.9K without breaking it is a complex operation that takes several weeks.





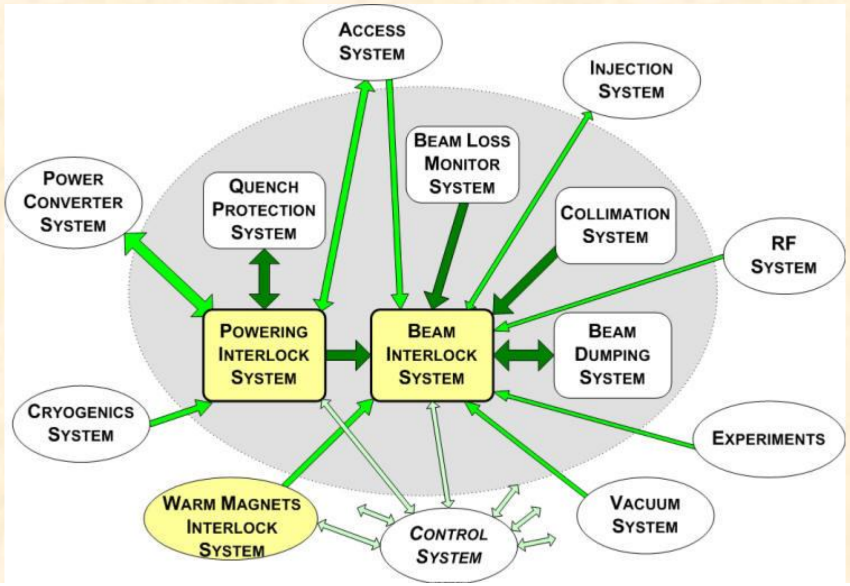
Quench

- Unfortunately a quench occurred in September 2008.
- This was due to the resistance of a busbar (connector) being a few nano-ohms too high.



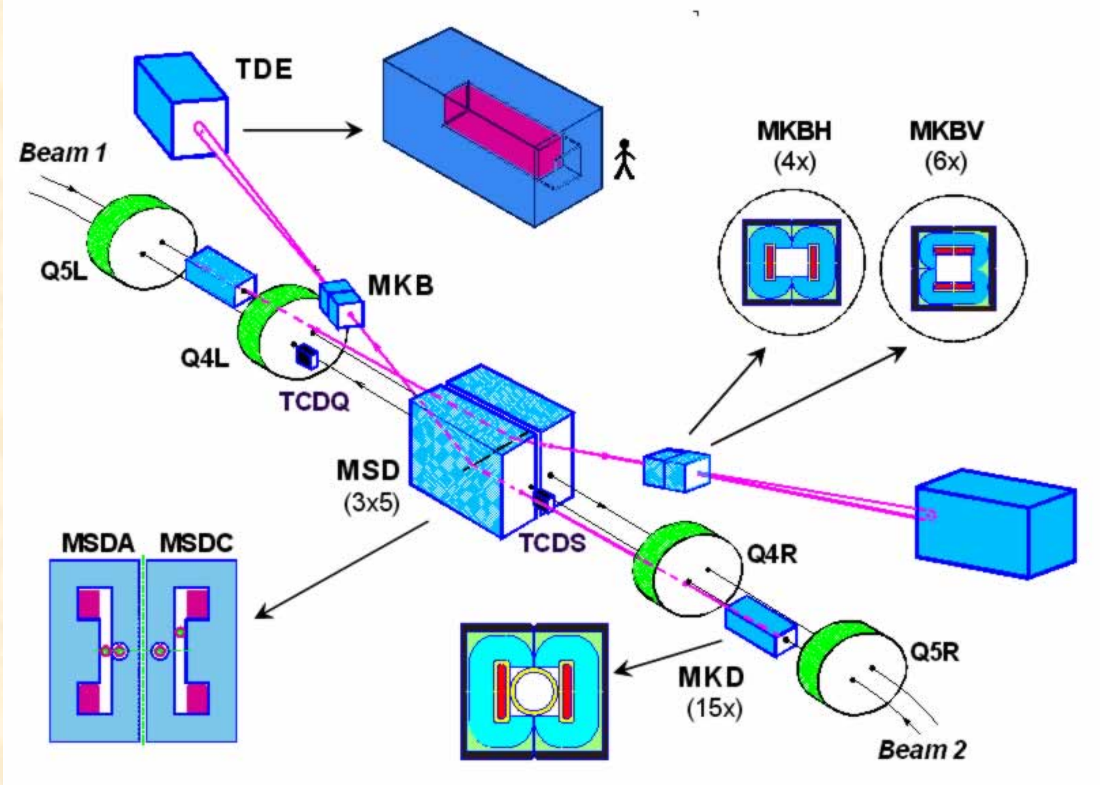
Machine protection system

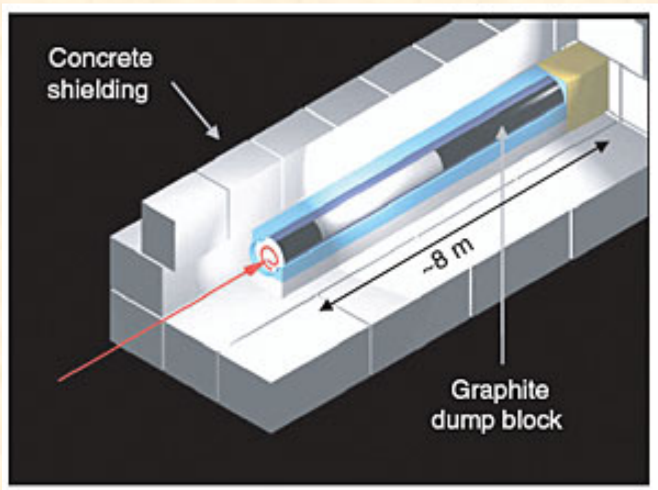
- The LHC beams carry the same amount of energy than a jumbo plane at take-off!
- If a beam is sent on the beam pipe accidentally it could make serious damages!
- A complex "machine protection system" is used to monitor the machine at all time and prevent injection or dump the beam if a fault is detected.

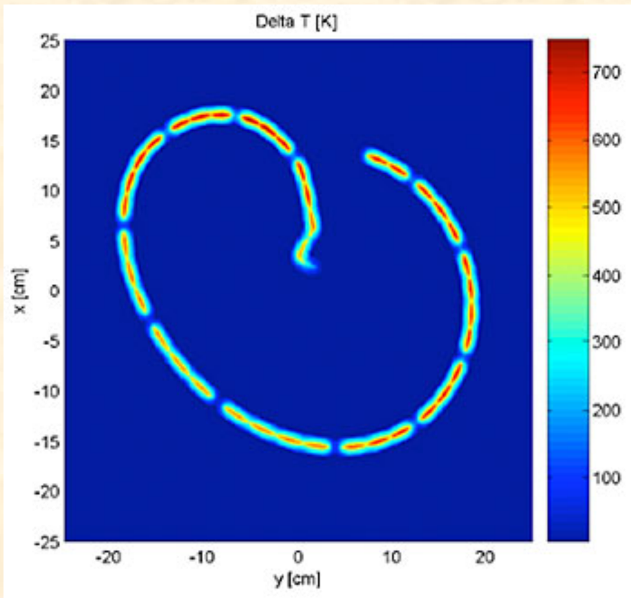


How to get rid of the beams?

- With so much energy stored in the beams they have to be disposed of with care.
- A special area "dumps" has been designated and instrumented for this purpose.





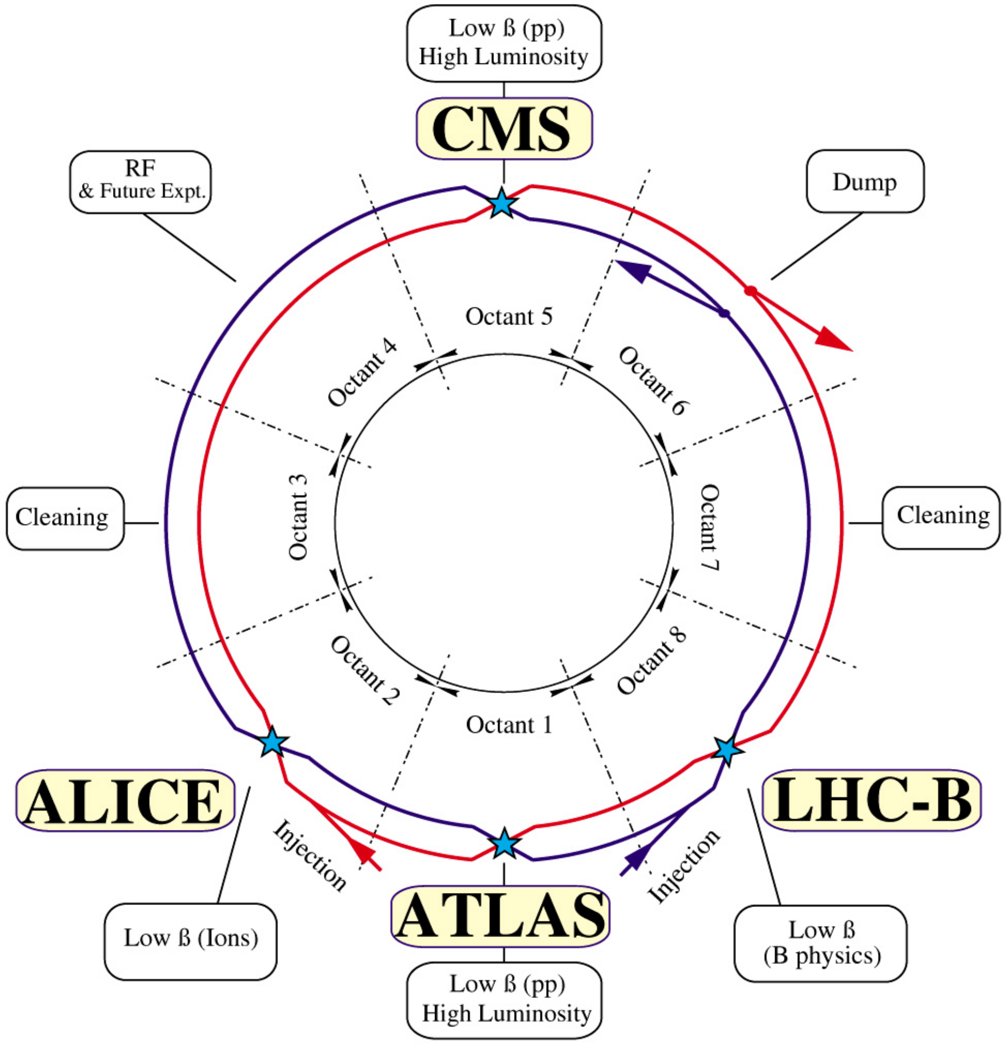


Vacuum

- Collisions between protons and residual gas in the accelerator will reduce the beam's lifetime. => Very stringent requirements (10^{-10} mbar ~ 10^{-8}Pa).
- Use of a special coating (Non Evaporable Getter - NEG) on the beam pipe that "absorbs" residual gas.

GAS	Nuclear scattering cross section(cm^2)	Gas density (m^{-3}) for a 100 hour lifetime	Pressure (Pa) at 5 K, for a 100 hour lifetime
H_2	$9.5\ 10^{-26}$	$9.8\ 10^{14}$	$6.7\ 10^{-8}$
He	$1.26\ 10^{-25}$	$7.4\ 10^{14}$	$5.1\ 10^{-8}$
CH_4	$5.66\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
H_2O	$5.65\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
CO	$8.54\ 10^{-25}$	$1.1\ 10^{14}$	$7.5\ 10^{-9}$
CO_2	$1.32\ 10^{-24}$	$7\ 10^{13}$	$4.9\ 10^{-9}$

LHC LAYOUT



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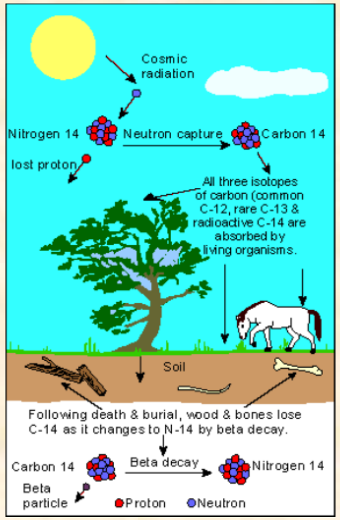
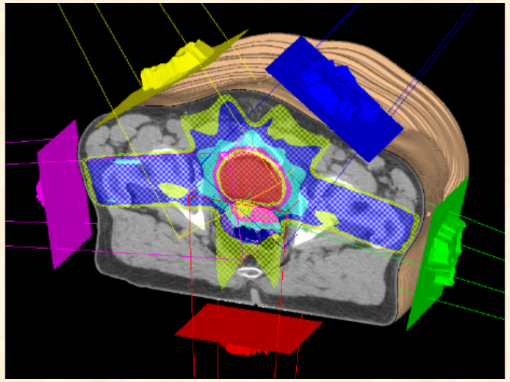
Non HEP applications of particle accelerators

- I discussed mostly of the particle accelerators used for HEP. However most particle accelerators in the world are used for other purposes.
- To treat cancers by radiotherapy or proton therapy.
- To perform Carbon-14 dating on old artefacts.
- As intense sources of light.





Summary

- Particle accelerators are used to produce probes with a very small wavelength and explore matter at a very small scale.
- Electrons can be extracted from cathodes, proton are produced by ionising hydrogen.
- Radiofrequency EM waves are used to accelerate the particles.
- Magnets are used to control the size and direction of the beams.
- The operation of accelerators is very complex and requires skills from different fields.
- Particle accelerators have application many fields such as medicine, material science and even the humanities!

Recommended reading

- 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