Introduction to particle accelerators
I. Basic principles and overview

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Lectures overview

I. Basic principles and overview

- Designs of early accelerators
- How does an accelerator work?
  - How are the particles produced?
  - How are they accelerated?
  - How are they kept where they should be?
- Example of modern accelerators

II. Beam dynamics

III. Diagnostics and applications

Personal experience

- Physicist at LAL (Orsay, France):
  - New acceleration techniques
  - Design of compact accelerator-based sources of X-rays
  - Experiment in Japan on the production of X-rays at an Accelerator
- Previously at Oxford and in Japan:
  - New acceleration techniques
  - Laser-electrons interactions
  - Beam diagnostics
  - Ultra fast feedback systems to stabilize the position of the beams within a few nanoseconds.

Recommended reading

- An introduction to particle accelerators, Edmund Wilson
- The physics of Particle accelerators, Klaus Wille

If you want to learn much more:

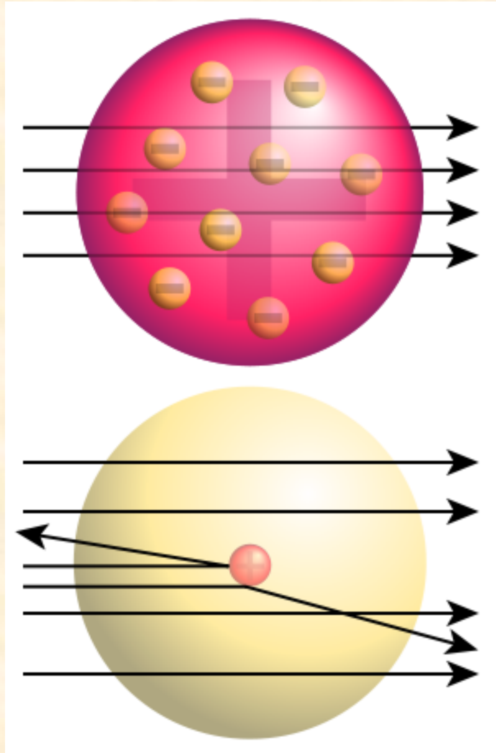
- Handbook of Accelerator Physics and Engineering,
  by Alex Chao and Maury Tigner ISBN-10: 9810235003
- Charged Particle Beams, by Stanley Humphries http://www.fieldp.com/cpb/cpb.html
- Principles of Charged Particle Acceleration by Stanley Humphries, http://www.fieldp.com/cpa/cpa.html

Rutherford scattering experiment

- In 1909 Rutherford studied the scattering of alpha particle on a gold foil.
- 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.
- This experiment shown that by using an appropriate probe it was possible to study very small objects.
- The smaller the object the higher the energy of the probe.

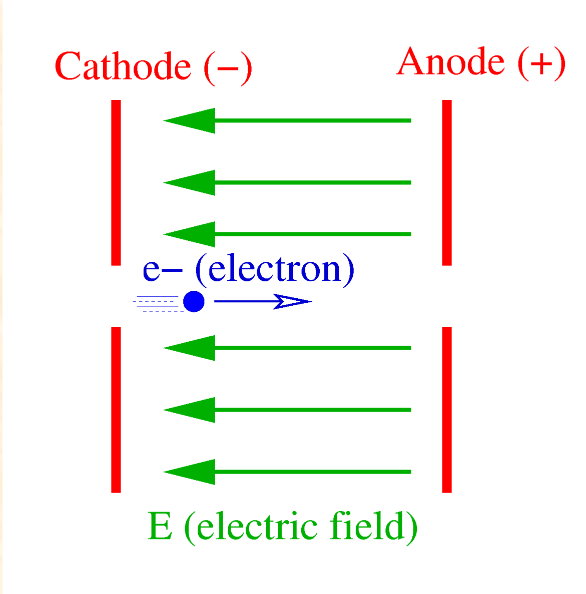
$$\lambda = \frac{h}{p}$$

=> basis for modern accelerators

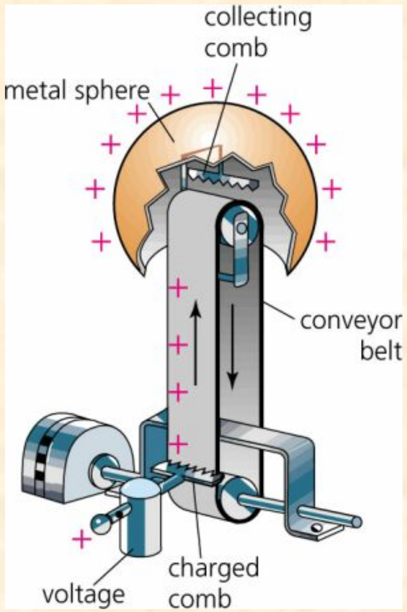


Trajectory of alpha particles in a uniformly charged sphere (top) and in a real gold nucleus (bottom) (image source: wikipedia)

Van de Graaff generator



- To reach high particle energies an electric field is necessary to accelerate them.
- 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 in DC accelerators.

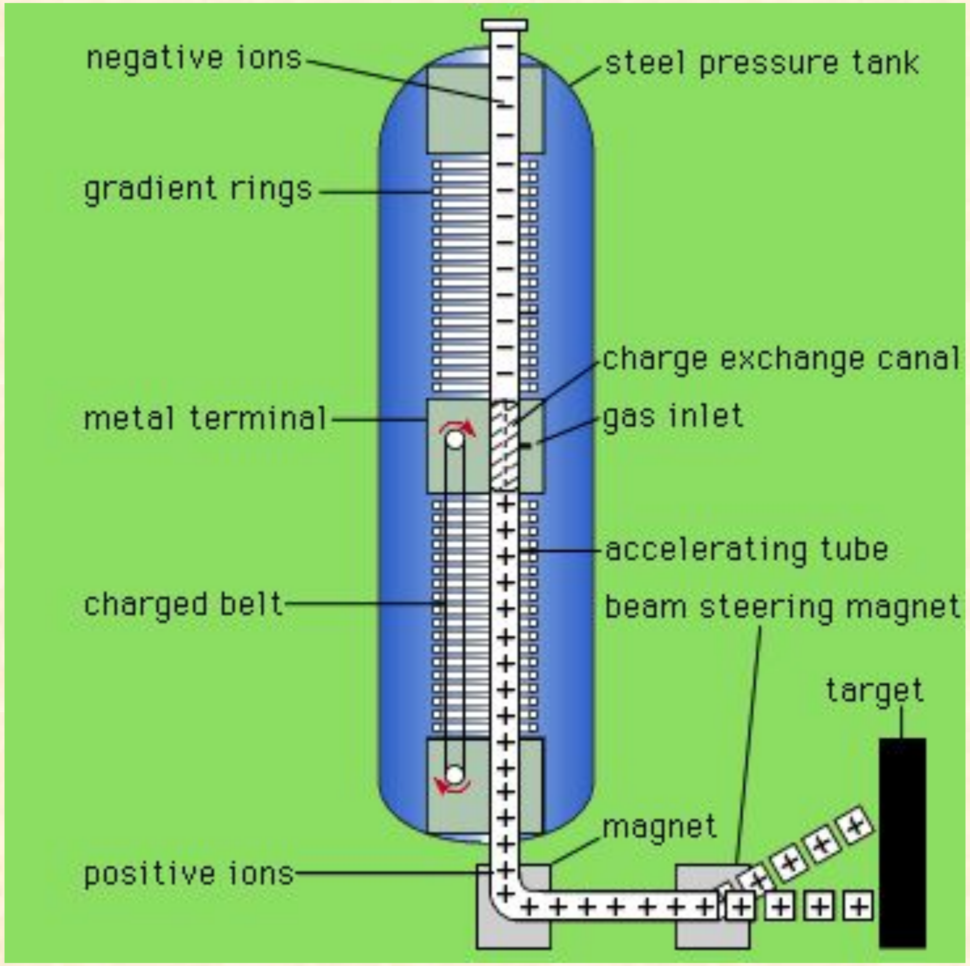


Images courtesy:

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.

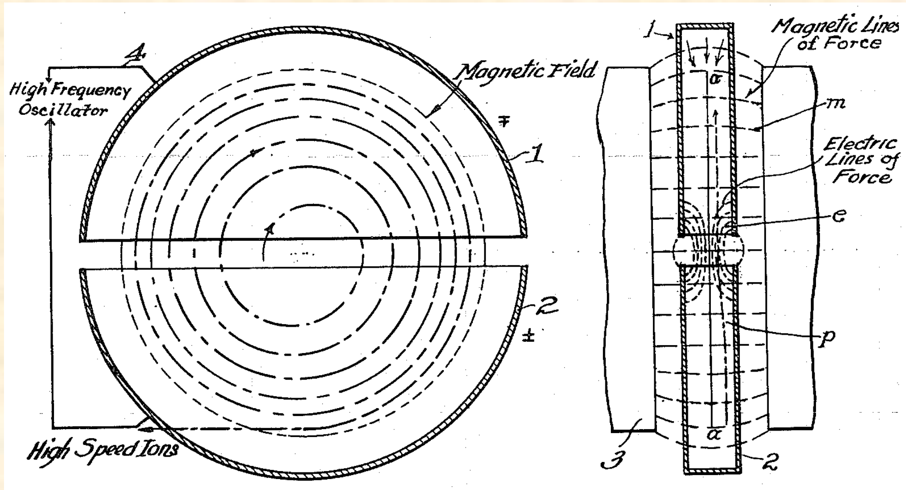


Example: 10MV Van de Graaff can accelerate C^- to 10 MeV and then C^{2+} to 30 MeV.

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

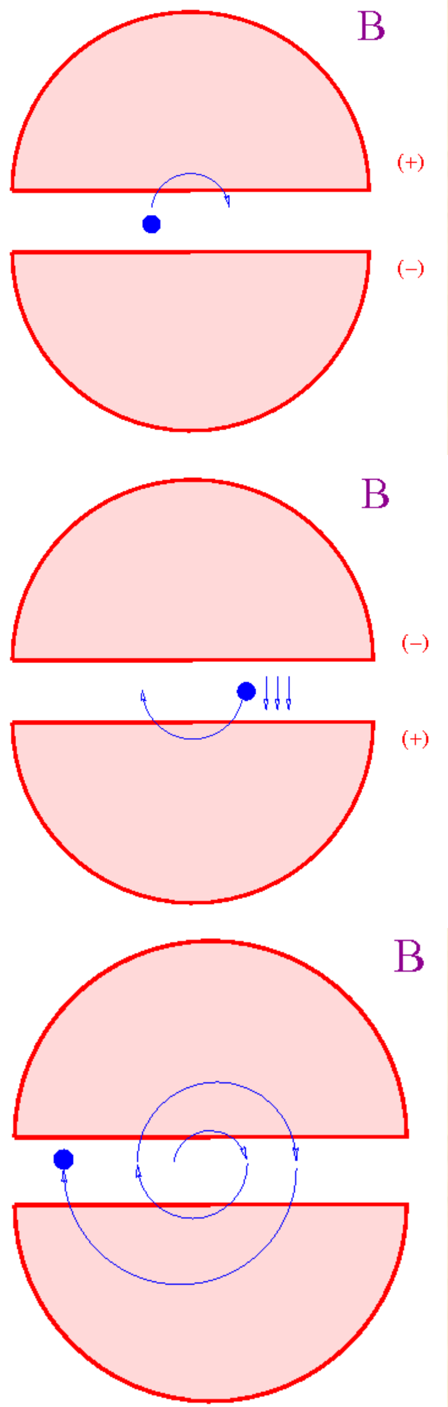
Cyclotron

- 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.



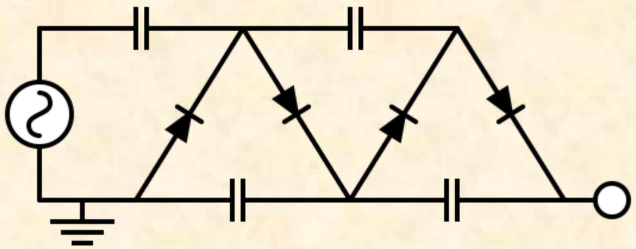
Cyclotron (2)

- 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.

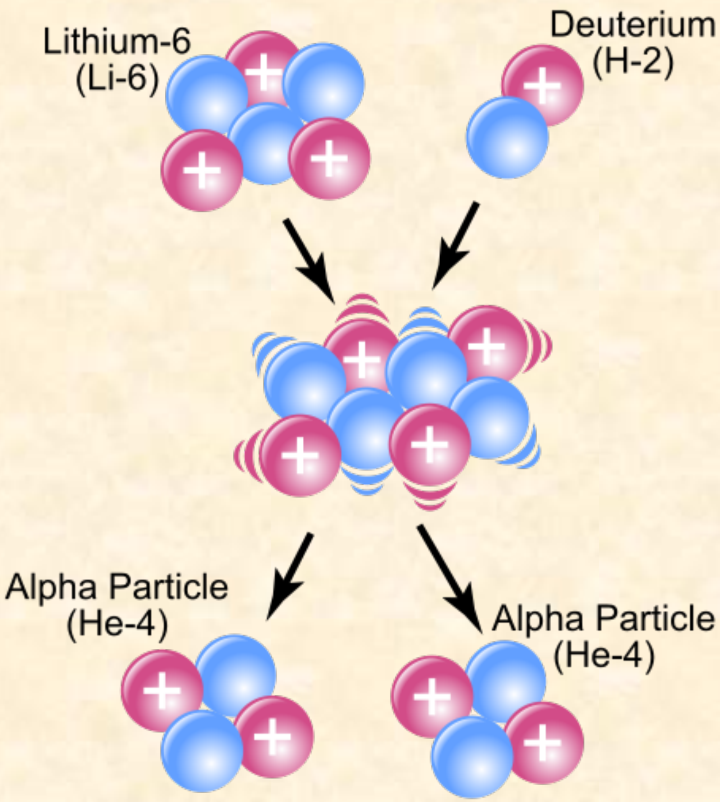


- The first half-cycle will load the first capacitor to its peak voltage. The second half-cycle loads the second capacitor and so on...
  => high voltage pulses

A Cockroft-Walton generator

(image source: wikipedia)

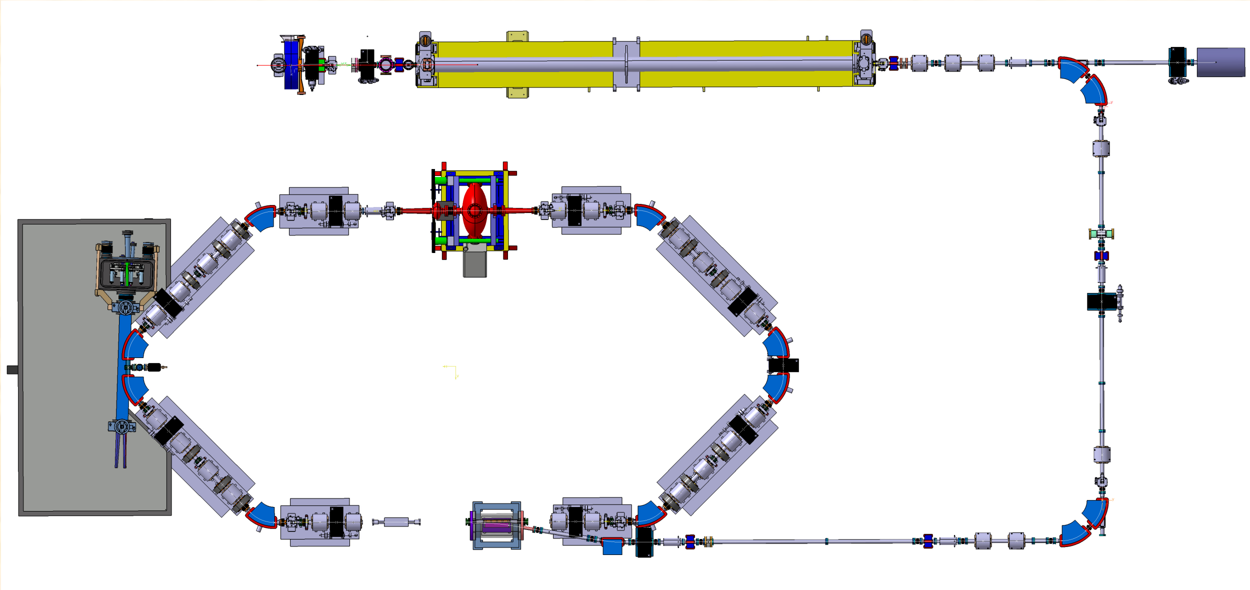
Splitting the atom



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.

How do particle accelerators work?



ThomX, an accelerator being built in Orsay

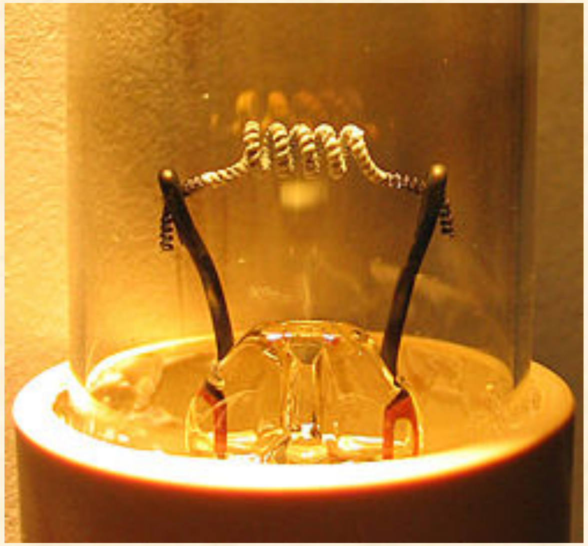
- Particle accelerators are typically made of the following elements:
  - a source
  - an accelerating section
  - a ring
- In a complex accelerator these elements may be repeated.
- We will see how each of them work…

Producing beams of electrons: Thermionic effect

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

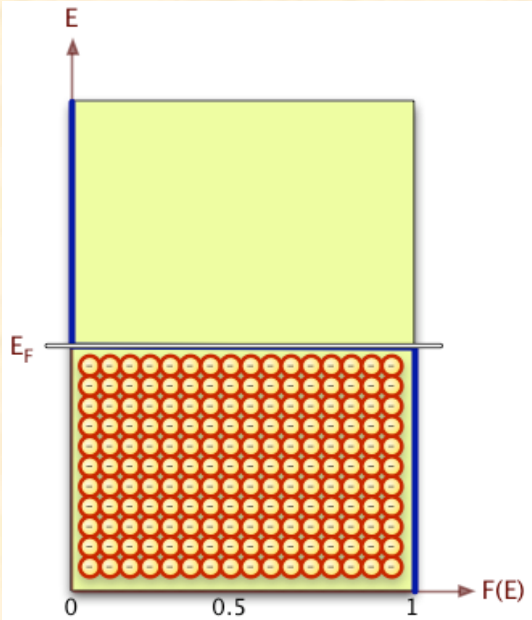
$$f = e^{\frac{-E}{k_B T}}$$

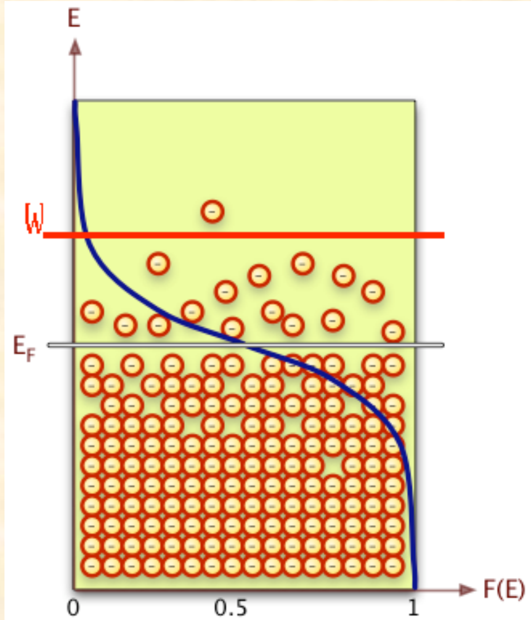
  - Electrons (fermions) obey a different but similar law.
  - When a metal is heated more electrons can populate high energy levels.
  - Above a certain threshold they electrons can break their bound and be emitted:
    This is thermionic emission.



(image source: wikipedia)

Electrons in solids



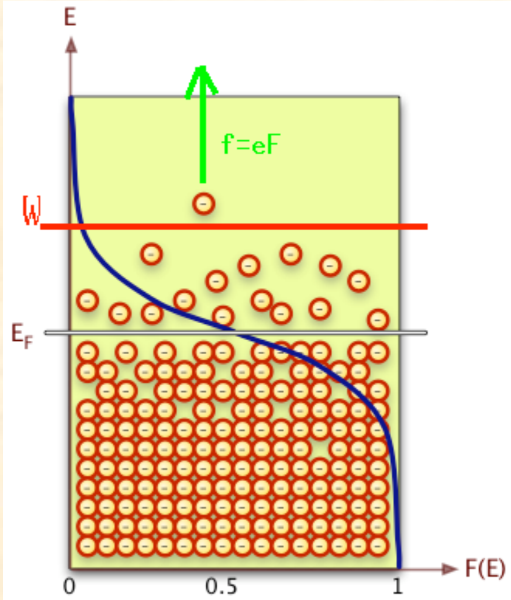


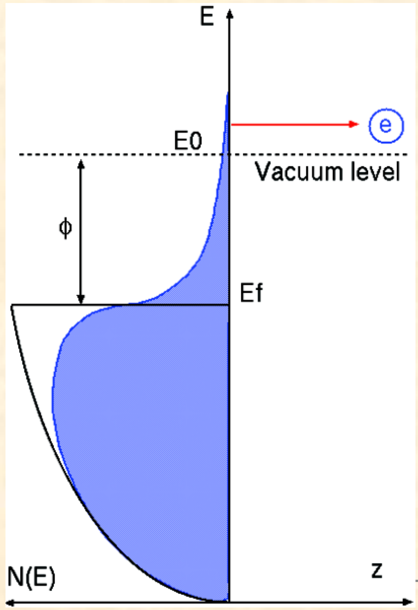
(image source: http://cnx.org/content/m13458/latest/

- 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".

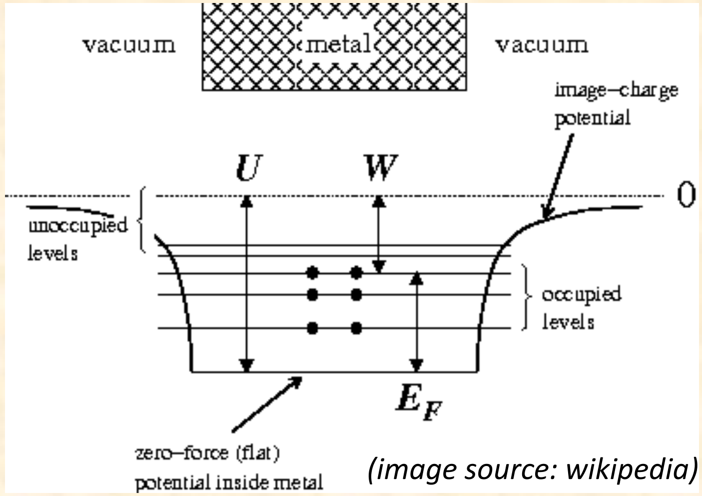




(image source: Masao Kuriki, ILC school)

Work function

- To escape from the metal the electrons must reach an energy greater than the edge of the potential well.
- The energy that must be gained above the Fermi energy is called the “work function” of the metal.
- The work function is a property specific to a given metal. It can be affected by many parameters (eg: doping, crystaline state, surface roughness,...)



(image source: wikipedia)

- Example values:
  Fe: 4.7 eV ; Cu: ~5eV; Al: ~4.1 eV; **Cs: ~2 eV**

Schottky emission

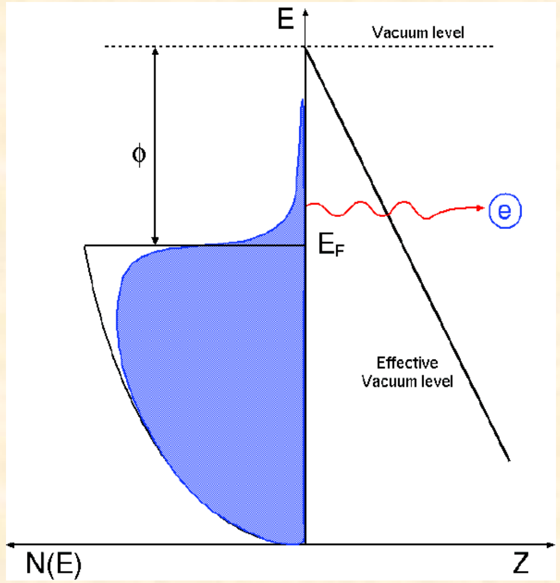
- The application of an electric field F to a material modifies the work function, this is called the Schottky effect:

$$\Delta W = \sqrt{\frac{e3F}{4\pi \in_0}}$$

- This will lead to a reduction of the work function. The higher the field the lower the work function. The Richardson-Dushman equation becomes:

$$J = AT^2 e^{\frac{-W - \Delta W}{k_B T}}$$

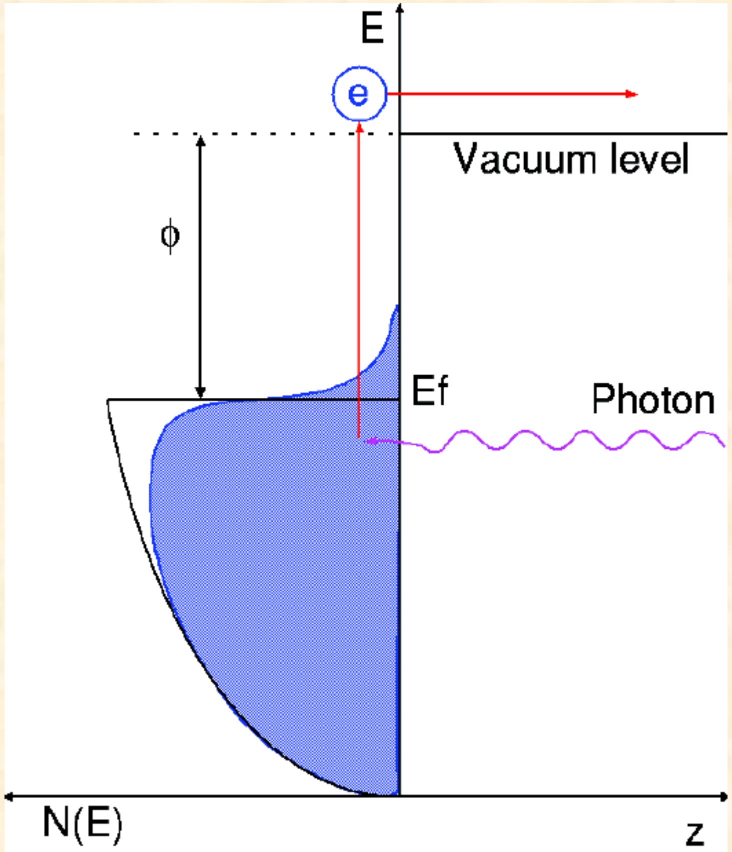
- This formula is valid only up to 10^8V/m. For more intense fields additional phenomena happen.



(image source: Masao Kuriki, ILC school)

Photo-electric emission

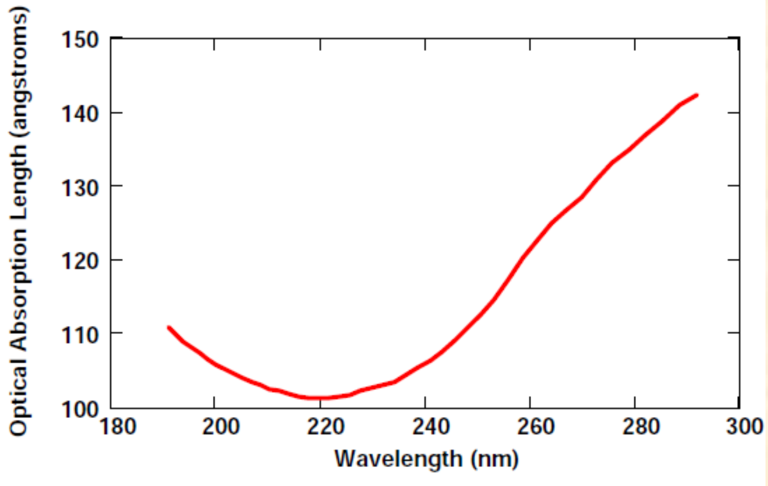
- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.



(image source: Masao Kuriki, ILC school)

Photo-electric emission (2)

- A UV photon at 200nm carries an energy of about 6 eV, this is enough to “jump” over the work function of most metals.
- As seen in electromagnetism, electromagnetic waves (photons) can penetrate inside a metal.
- The photo-electric emission may thus take place away from the surface.

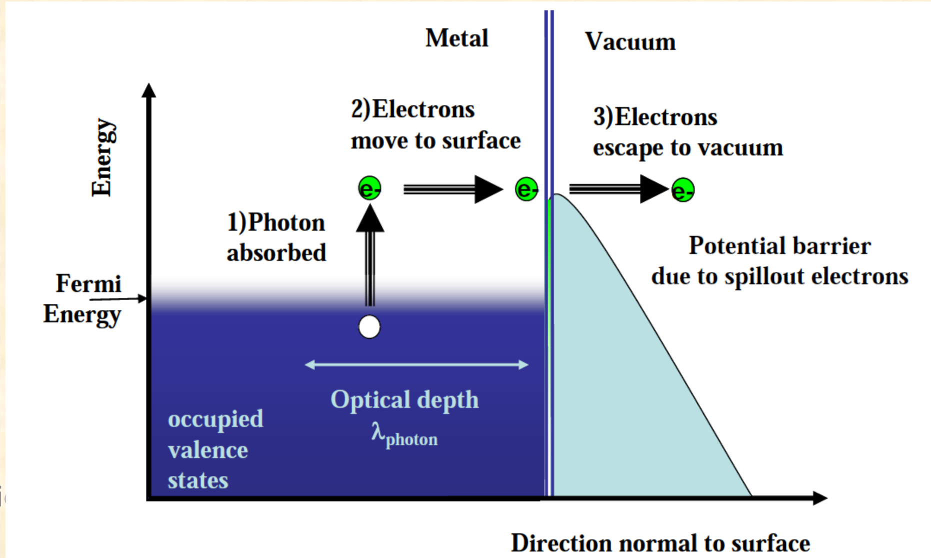


(image source: Dowell et al., Photoinjectors lectures)

The 3 steps of photo-electric emission

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".

Quizz

1) Which of these materials would give the highest thermionic emission current (at the same temperature)?
   (a) Iron (Fe); W=4.7 eV
   (b) Gadolinium (Gd); W=2.90 eV
   (c) Cobalt (Co); W=5 eV
2) Which laser would give the best Quantum efficiency on a Copper-based photo-cathode (W=5 eV)
   (a) A 5GW CO2 laser (wavelength=10 micrometers)
   (b) A 10 kW frequency doubled Nd:YAG laser (wavelength=532nm)
   (c)A 3MW frequency quadrupled Ti-Sapphire laser (wavelength=200nm)

Answer 1: (b)

- The lower the work function, the easier it will be for an electron to escape.
  => more electrons will escape
- Gadolinium (b) has the lowest work function and thus it will give a higher current.

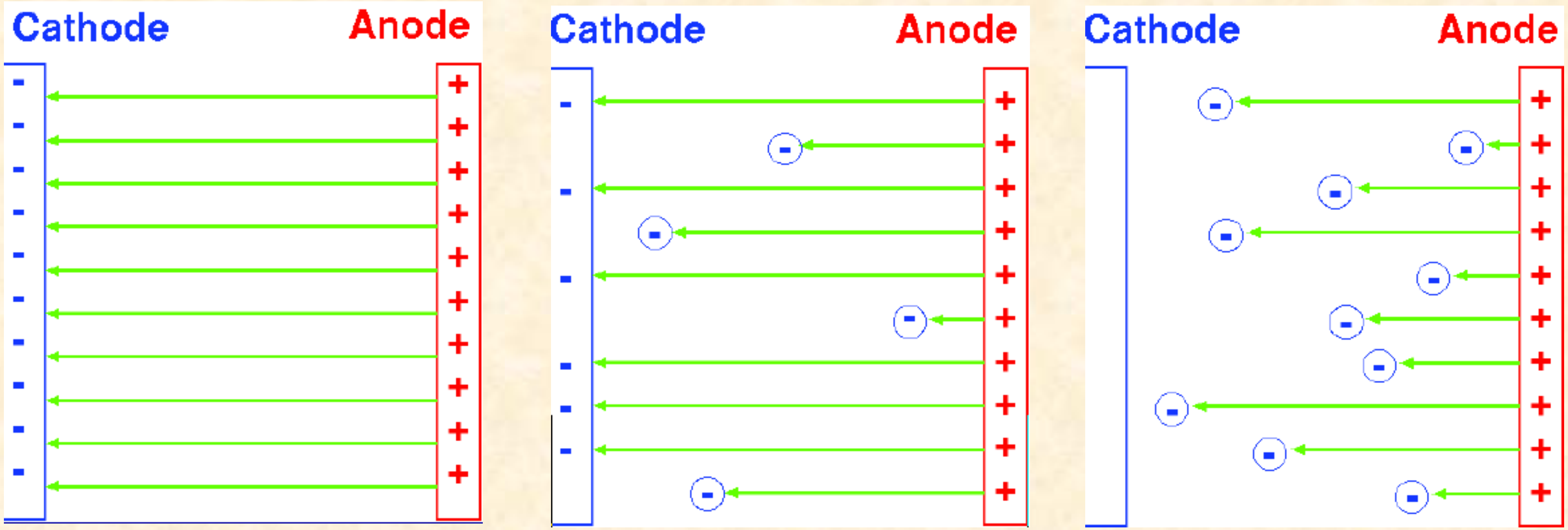
Answer 2: (c)

- QE is independent of the laser power:
  it is the photon energy that matters.
- Remember that

$$E = h\nu = \frac{hc}{\lambda}$$

- The shortest the wavelength, the highest the energy. At 200nm a photon carries ~6 eV, so a 400nm photon carries ~3eV.
- Note: photons with a wavelength of 532nm (2.33eV) or 10 micrometer (~0.1eV) will have less energy than the work function of the photo-cathode (but escapes by tunnel effect are possible).

Space-charge limitation



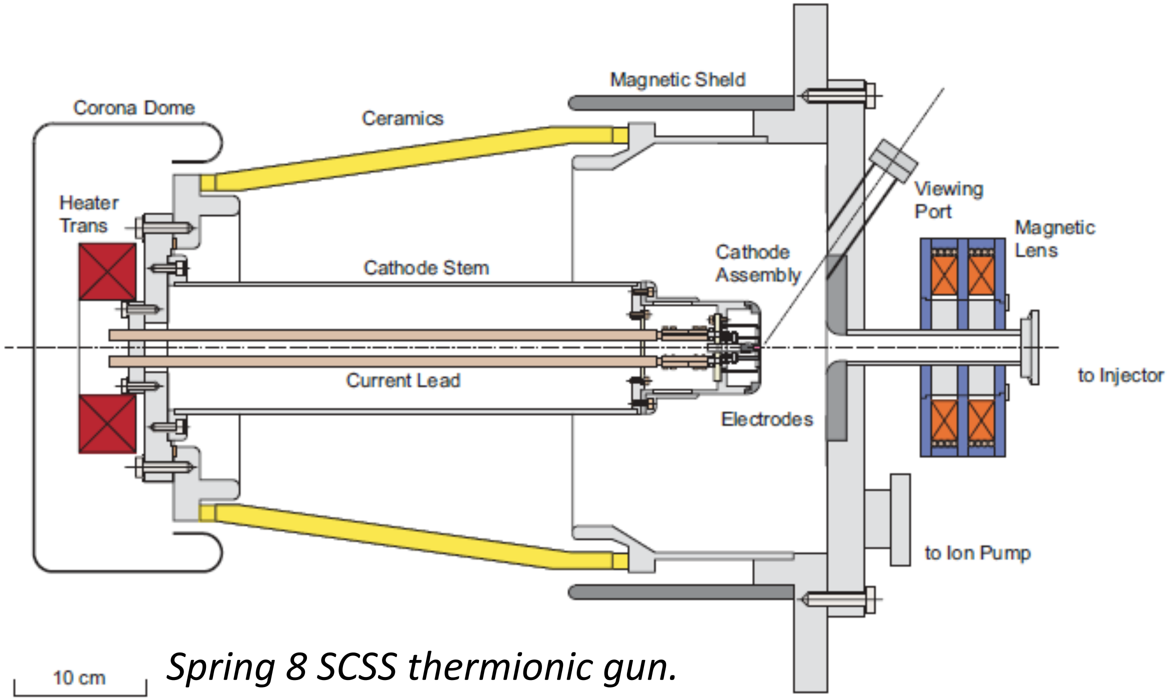
- Emitted electrons shield the cathode from the anode => reduced field
- This limits the intensity of the emission.
  Child-Landmuir law (potential V, area S, distance d)

$$J = 2.33 x 10^{-6} S \frac{V^{3/2}}{d^2}$$

Example of thermionic gun

SCSS

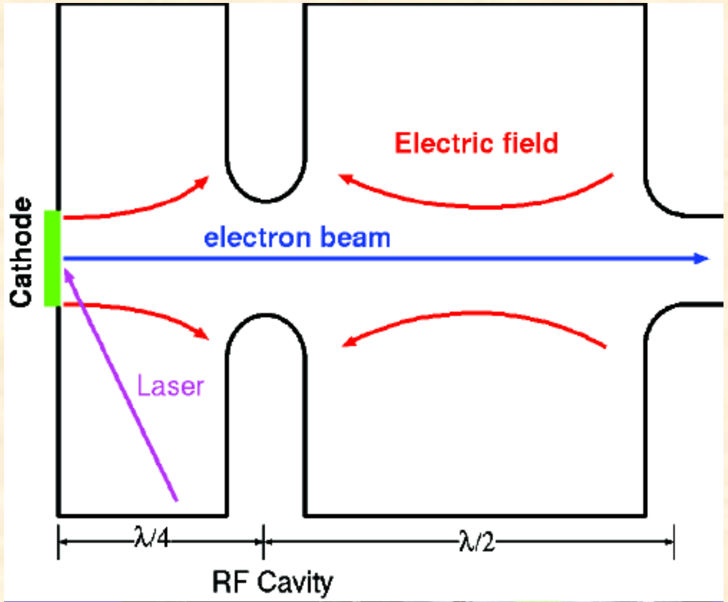
500kV Electron Gun



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

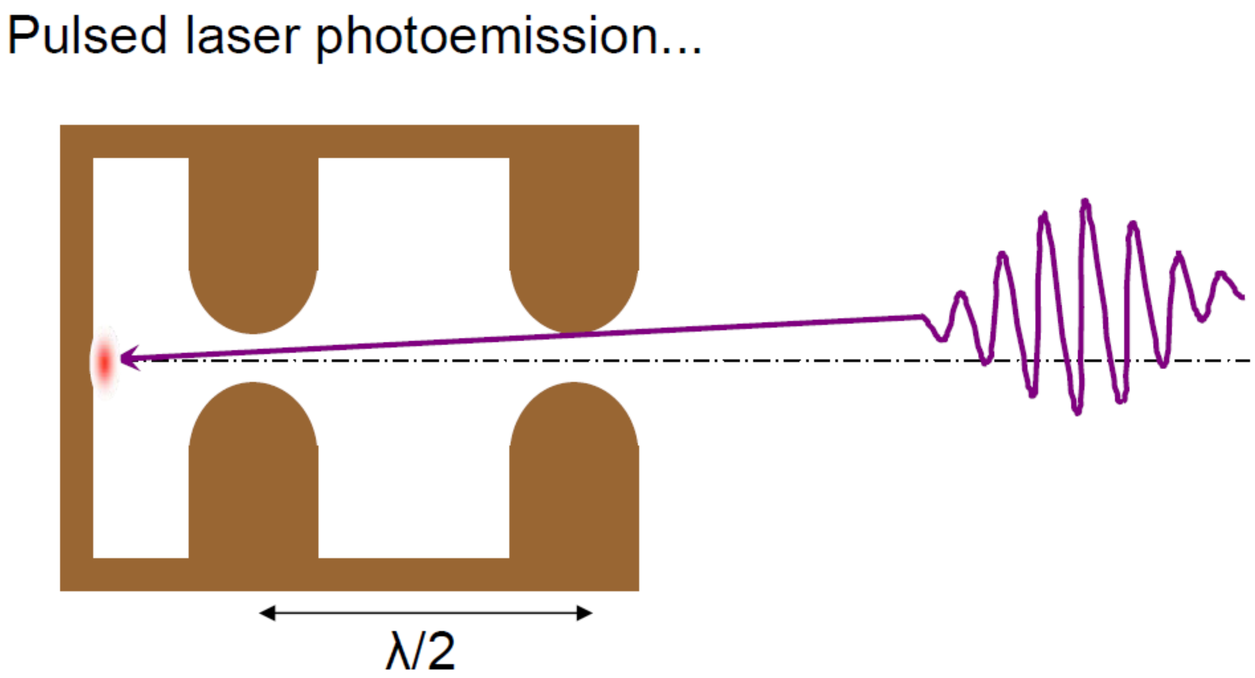
RF Gun

- The high voltage of a DC gun can be replaced by a RF cavity.
- This can provide much higher accelerating gradients and hence limit the space charge.
- RF guns are often coupled with a photo-cathode.
- RF gun can generate shorter bunches (using short laser pulses).



(images source:Masao Kuriki, ILC school)

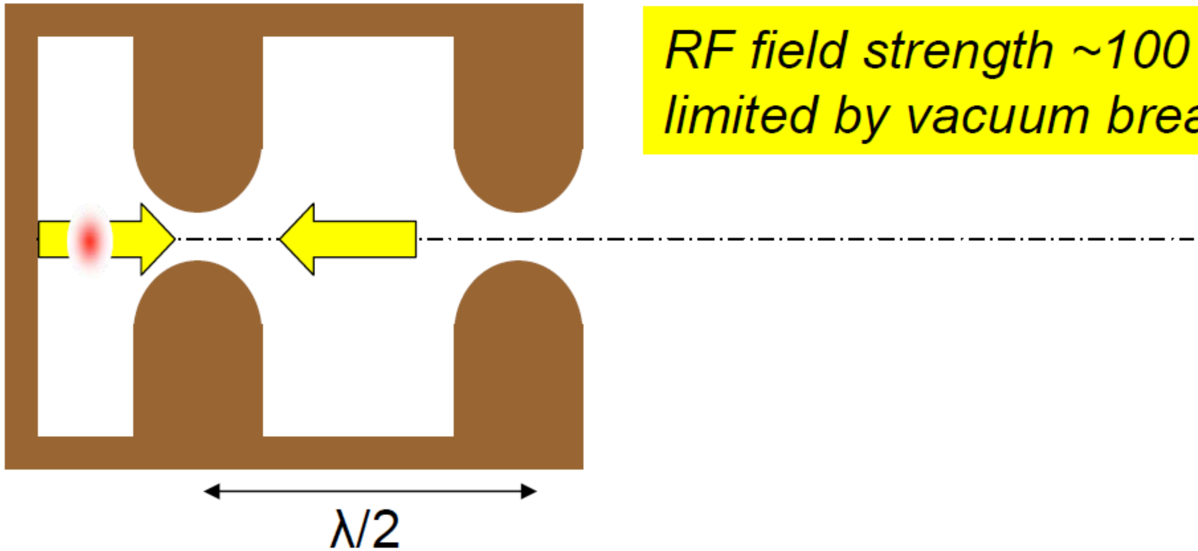
Principle of a RF Photo-gun



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

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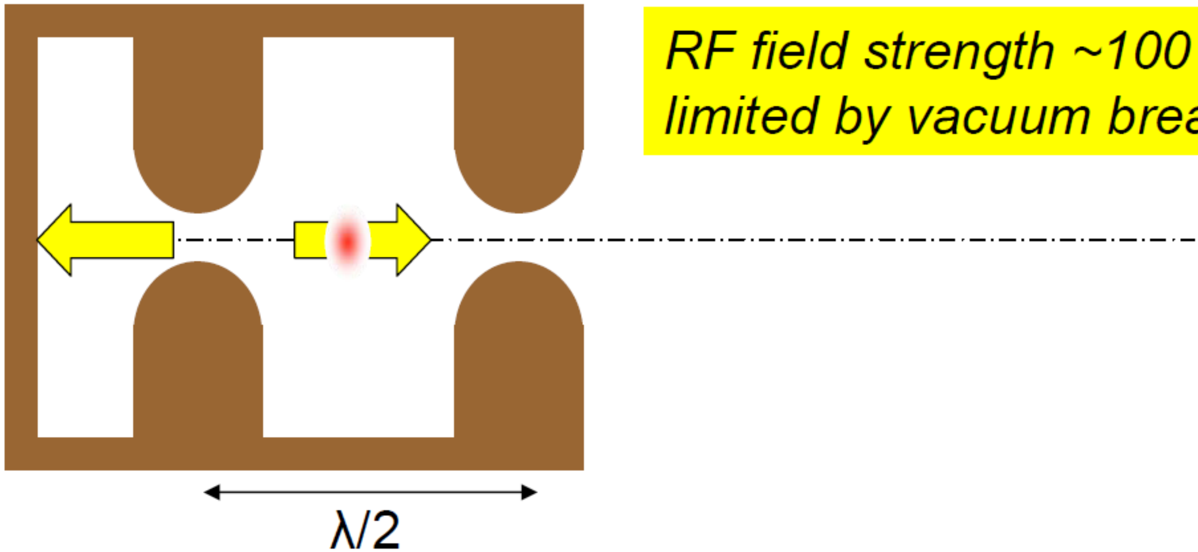

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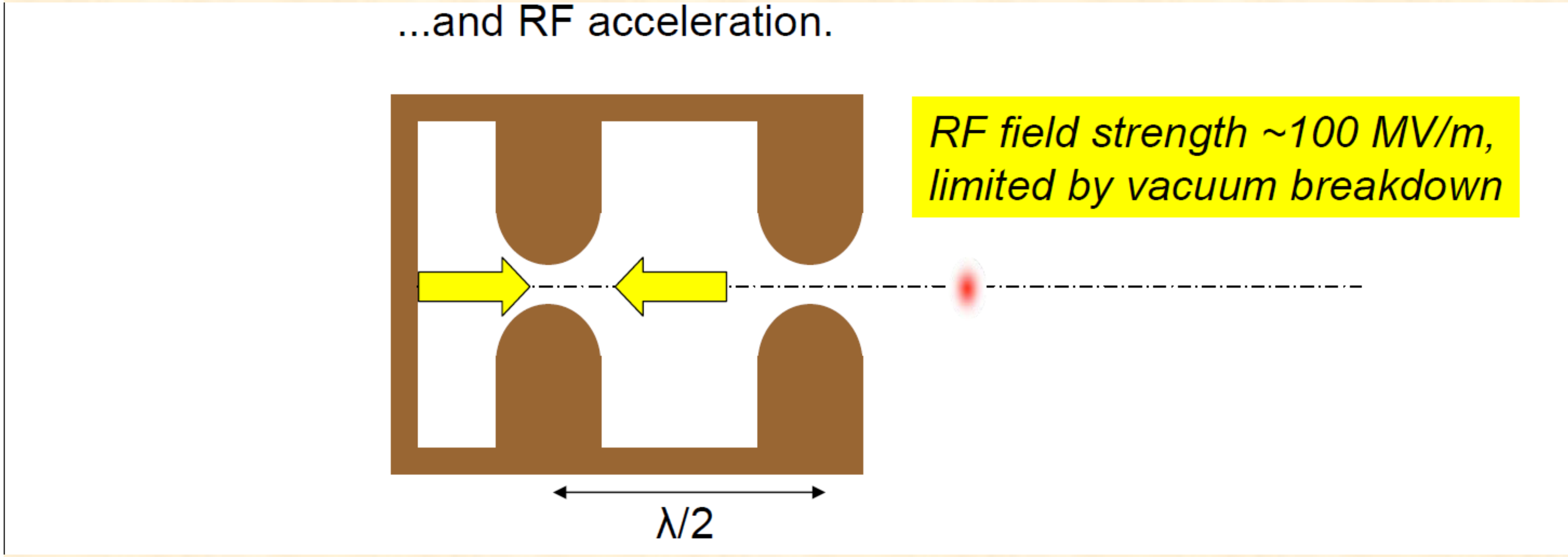
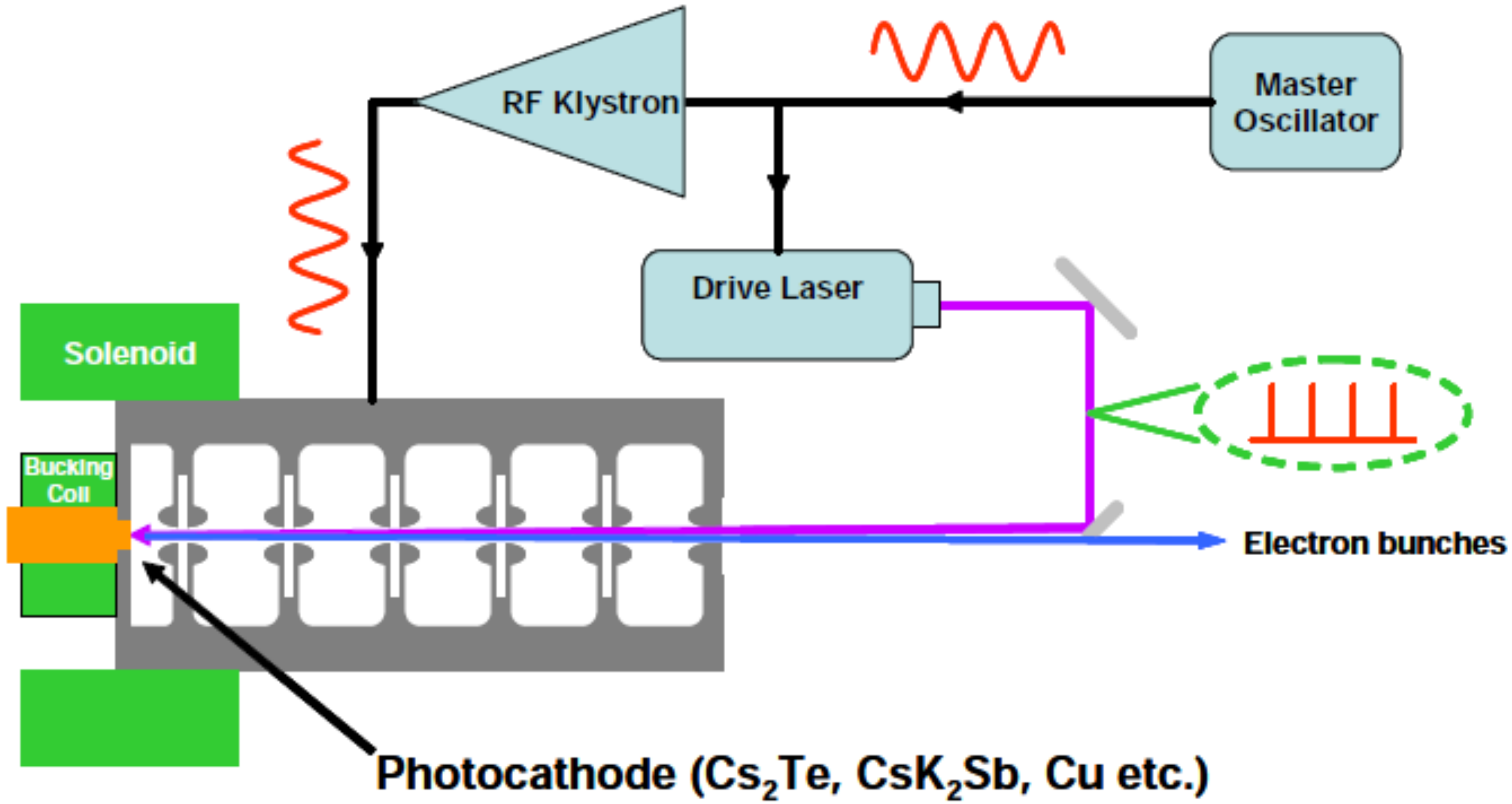
Principle of a RF Photo-gun



Courtesy Jom Luiten, TUV Eindhoven

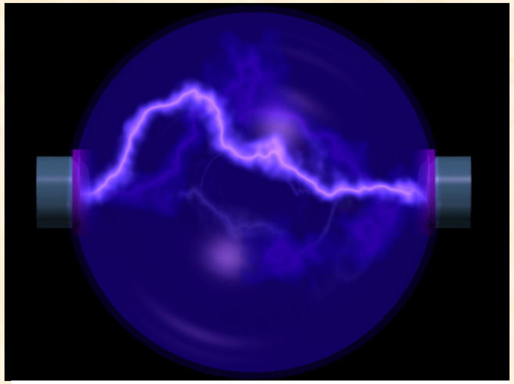
RF photocathode gun

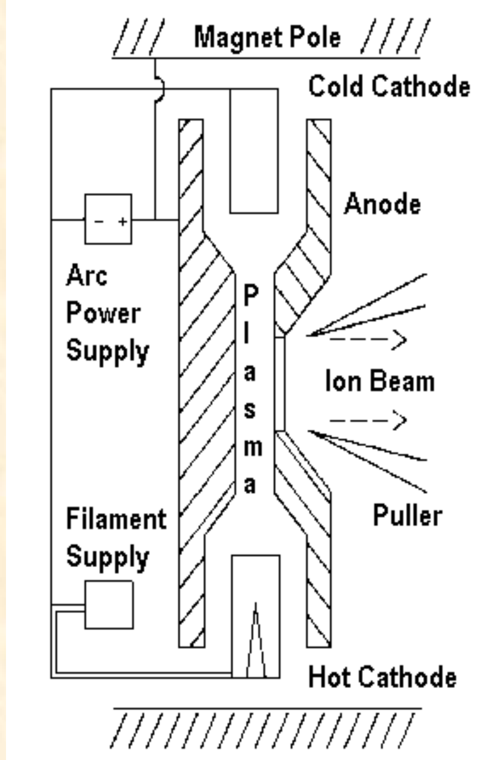


Slide compliments of P. O'Shea, UMd

Ion (and proton) sources

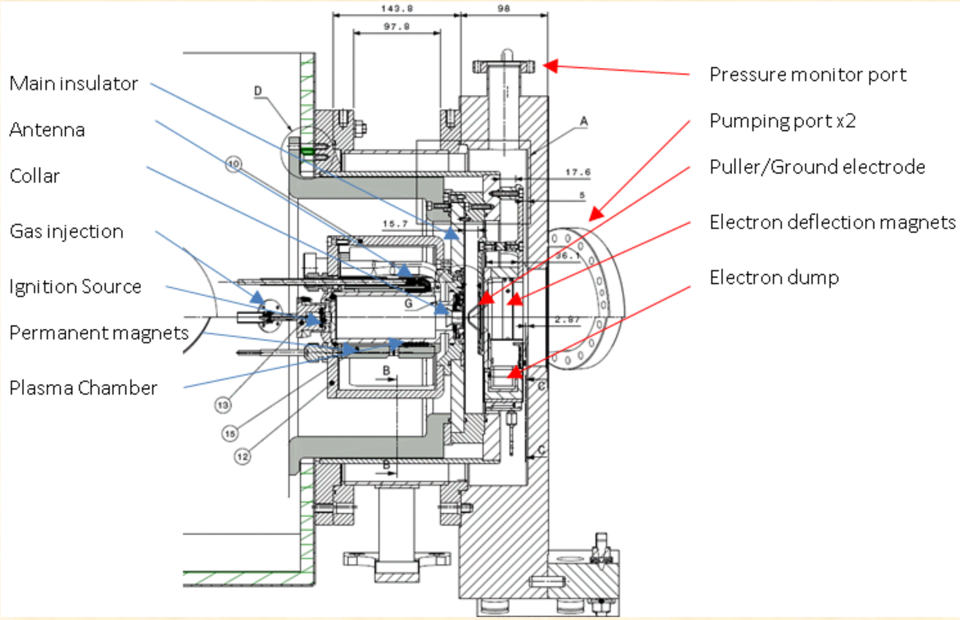
- An electric discharge creates a plasma in which positively and negatively charged ions are present (as well as neutrals).
- If such plasma experiences an intense electric field ions will separate in opposite directions.
- This is a rather crude and inefficient (but very simple) way of producing any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

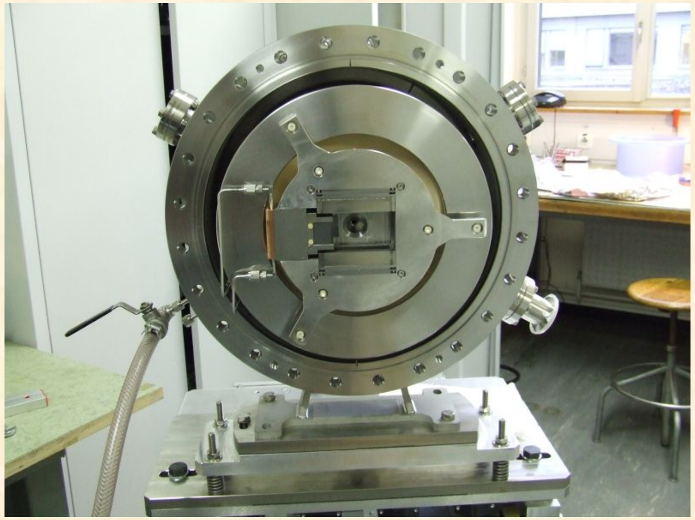




(images source: CERN)

CERN Linac 4 H- source



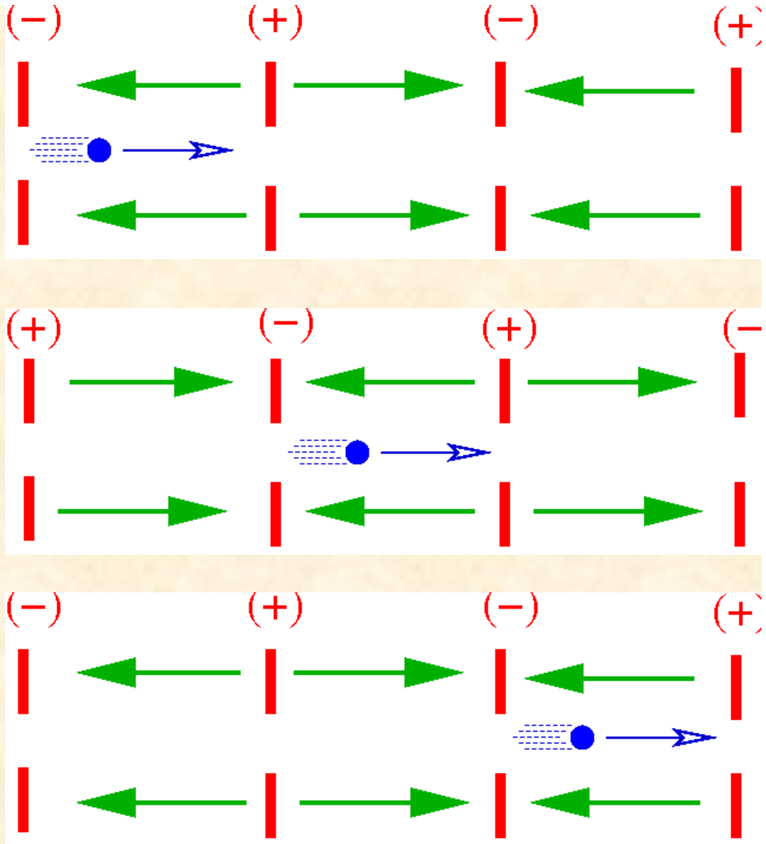


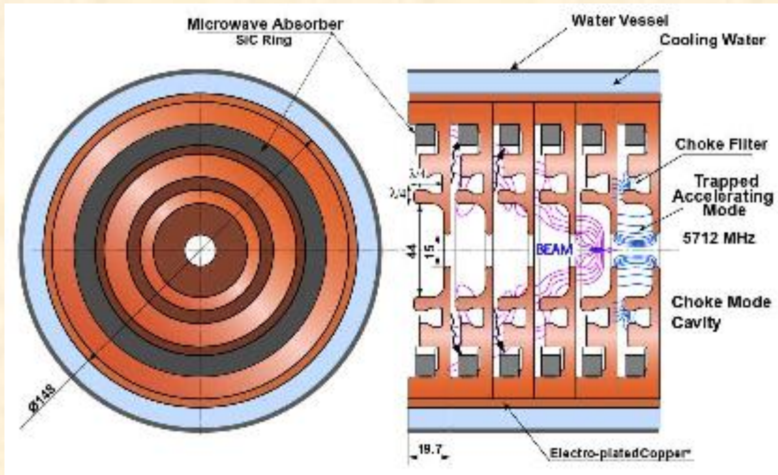
http://linac4ionsource.web.cern.ch/

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.

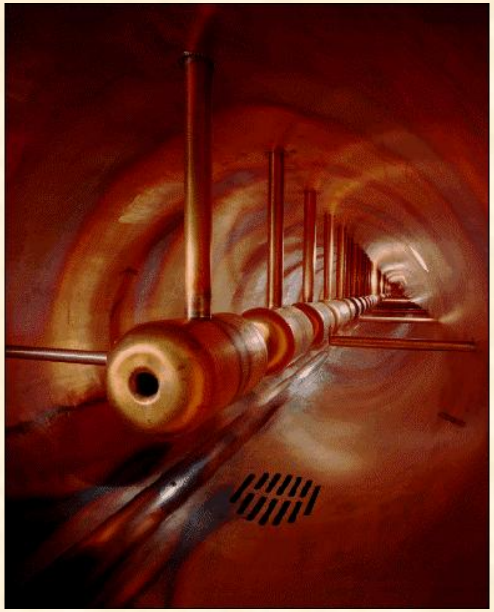




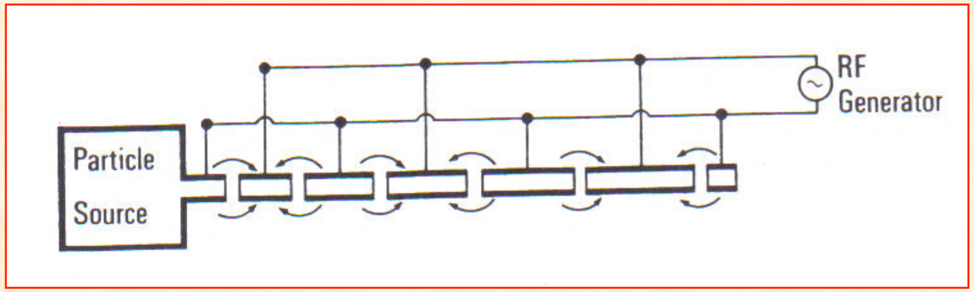
(source: Spring-8, Japan)

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



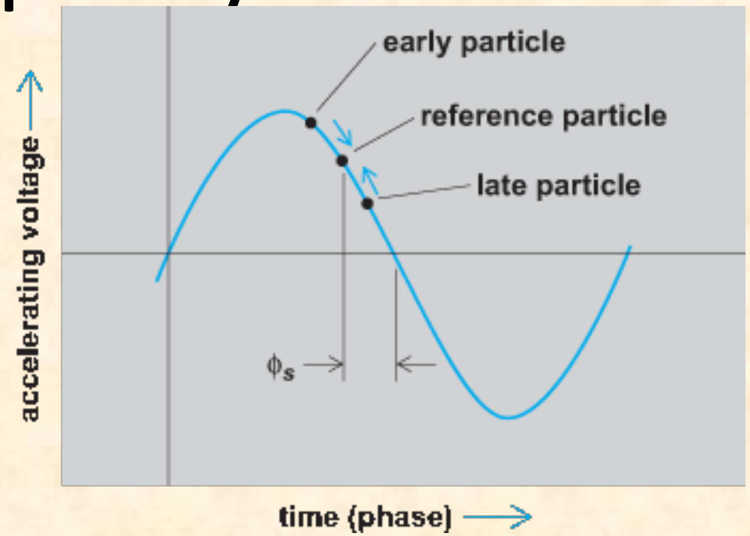
RF accelerators (3)

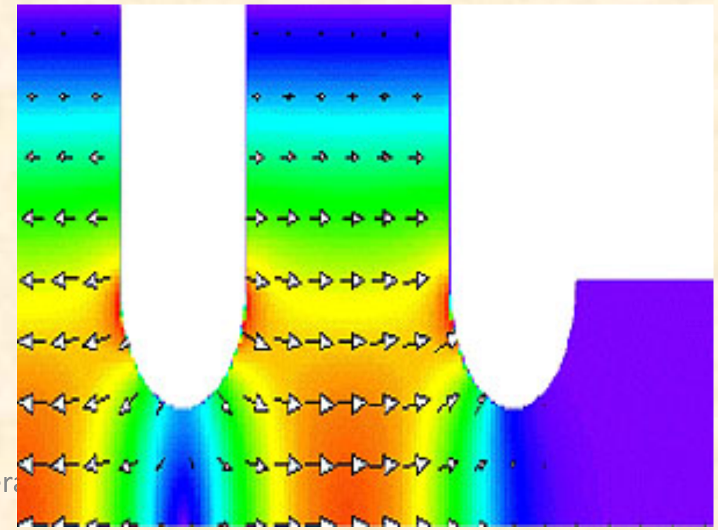
- Because after each cavity the particles return to ground potential there is no theoretical limit on the length of a RF accelerator.
- String of accelerating cavities are usually called “Linac” (Linear Accelerator).
- Linacs are mostly limited by their length: the ILC will accelerate electrons up to 1 TeV, each linac will be ~20km long!

Artist view of the ILC (source: KEK)

RF: Phase stability and cavity quality

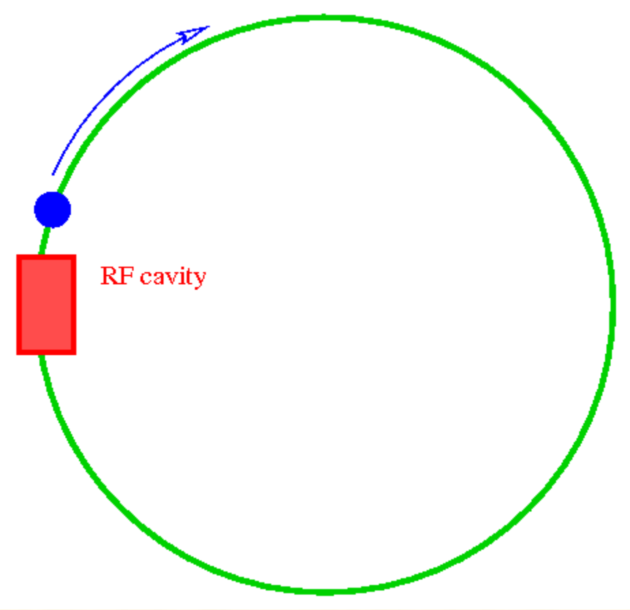
- In an RF accelerator the field felt by the particles depend on the exact phase a which the particle is injected.
- In a linac the phase of all accelerating cavities must be controlled very accurately.
- The shape of the cavity is also very important to ensure a homogeneous field in the center.
- After a while cavities dissipate the energy they store
  => the design must optimise the Q factor.





Synchrotrons

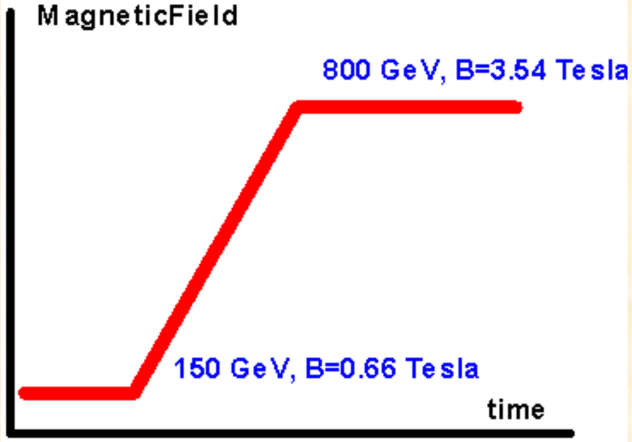
Instead of having a large number of cavities to accelerate the particles, it is also possible to have a single cavity in which the particles pass several times.



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

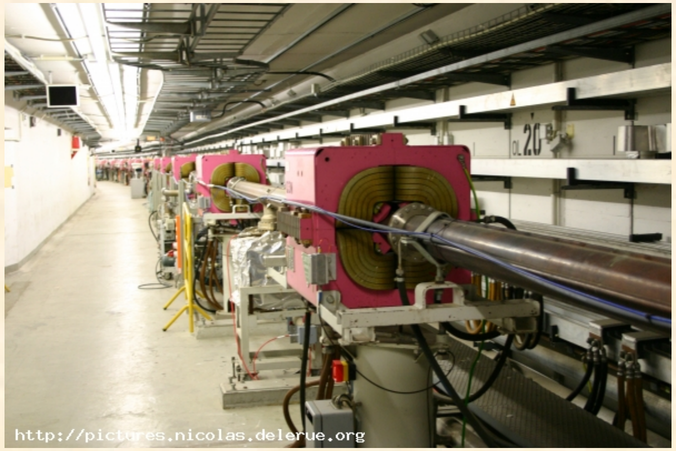
As the particles gain energy the radius of curvature of their orbit in a constant field increases

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



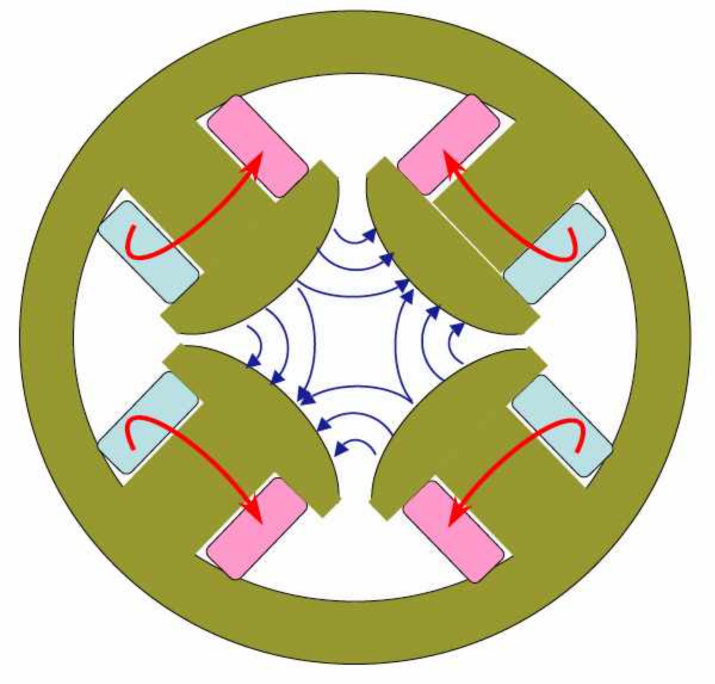
How to control where the particles go?

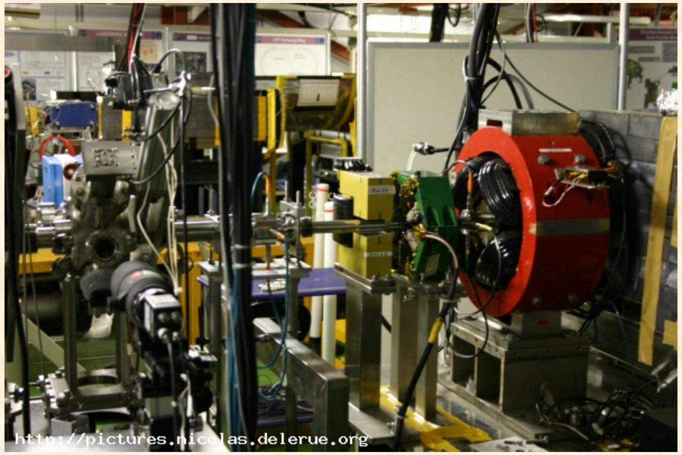
- Electric and magnetic fields can deflect charged particles.
- In an electric field the particles get accelerated.
- In magnetic field the direction of the particles is changed but not their energy.
  => it is preferable to use magnetic field (usually electromagnets) to control a beam.
- Magnets are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



Beam focussing

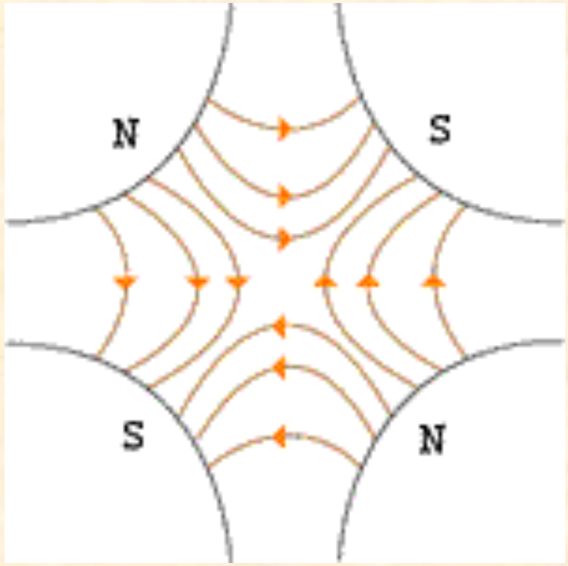
- A regular magnet (dipole) will create a field the will bend the beam in one direction.
- The change the size of the beam a different type of magnets called quadrupoles need to be used.
- Quadrupoles create intense fields for off-axis particles but do not disturb particles on the axis.

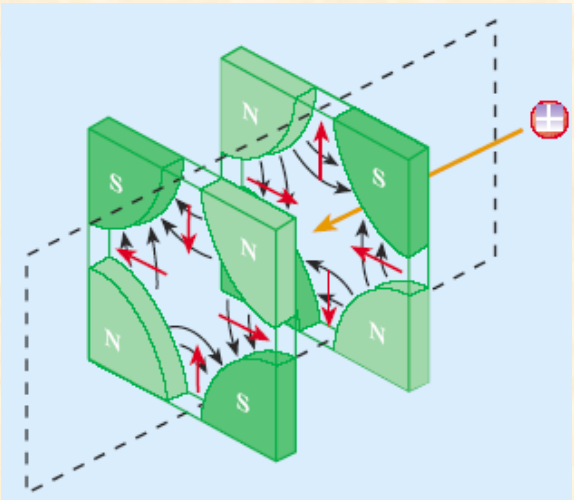


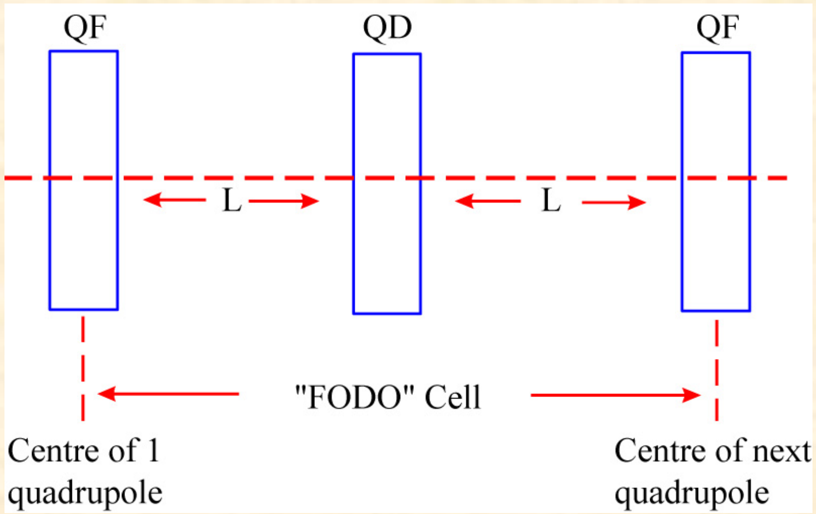


FODO cell

- 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.

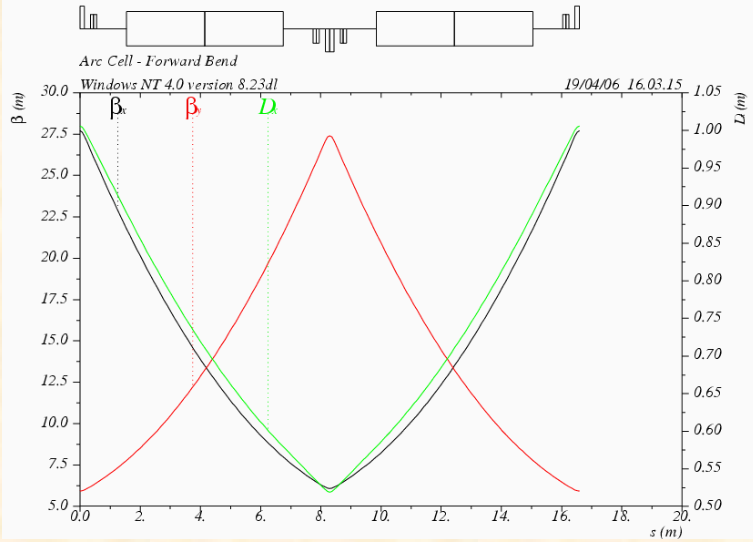


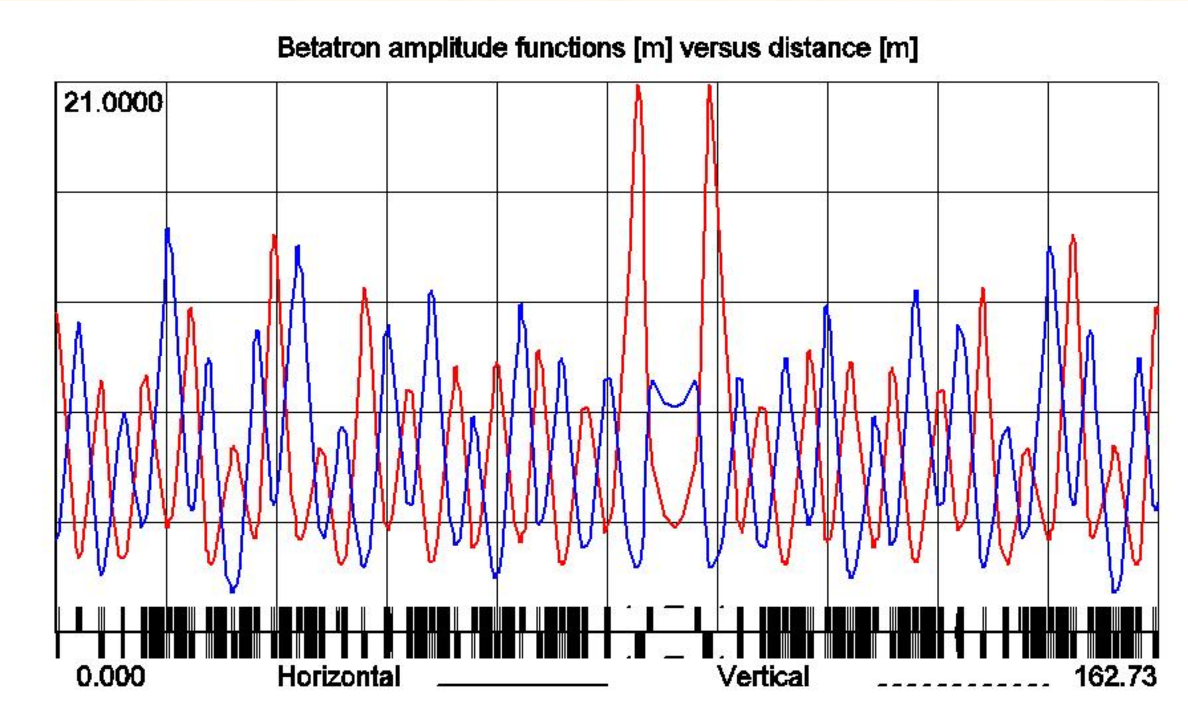


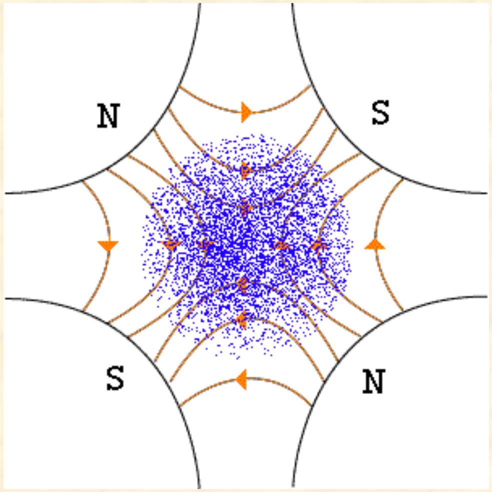


Accelerator lattice

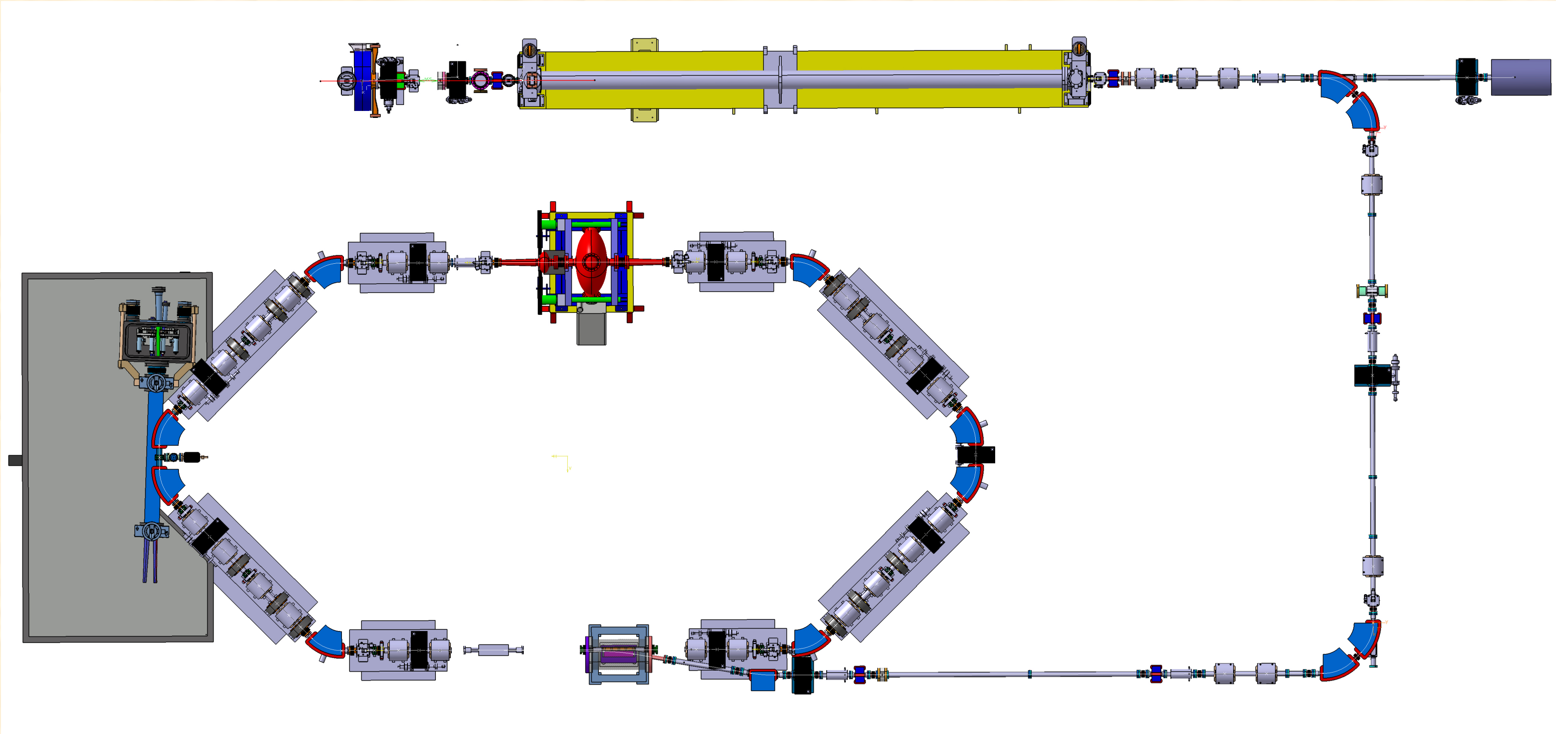
- In an accelerator there is a large number of quadrupoles to keep the beam size under control.
- This is called the lattice of the accelerator.



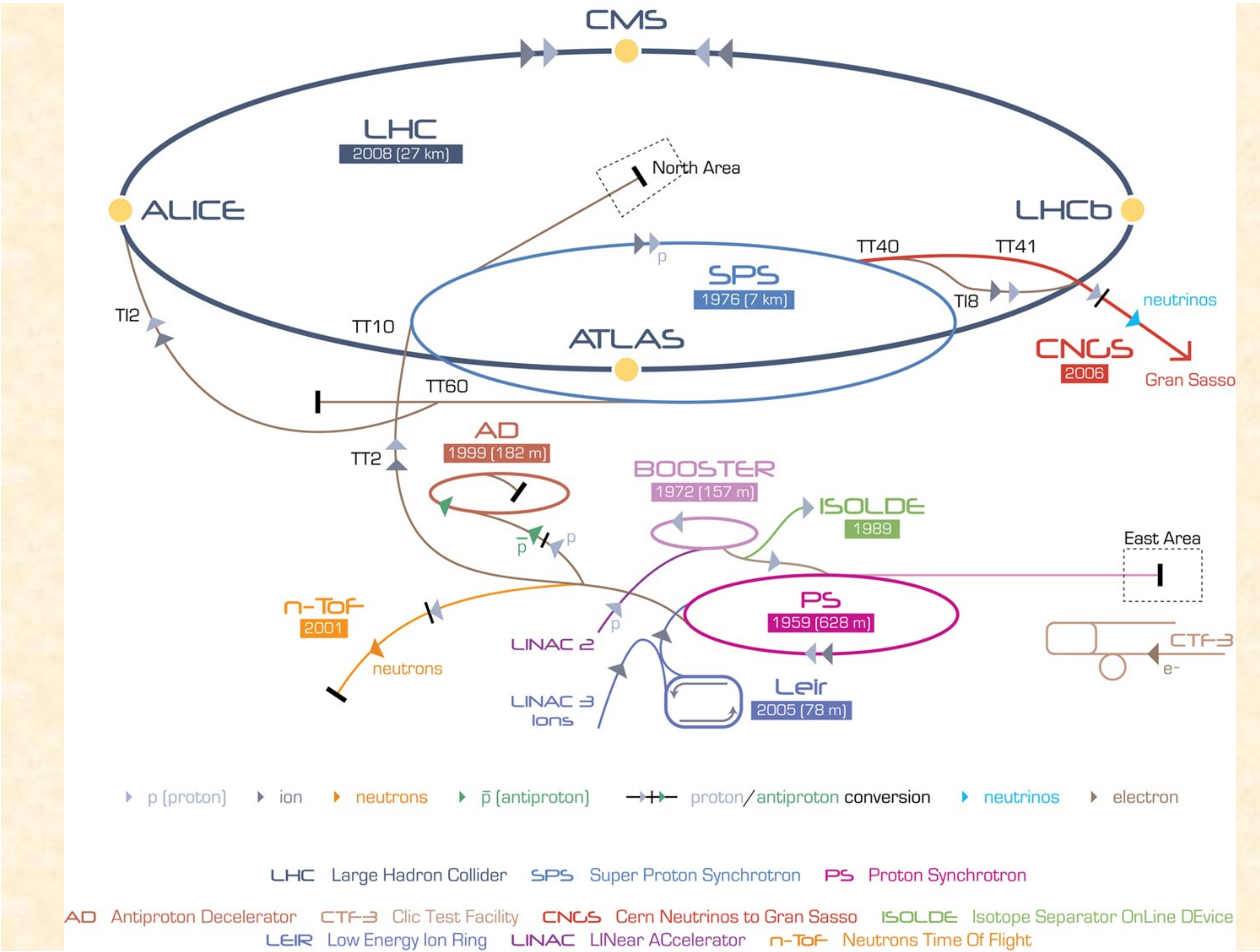




Looking again at an accelerator



- We can now understand most of the element that make this accelerator…


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
p
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
LINAC 2
p
CTF3
e–
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

Summary

- We have seen what are the main types of accelerators: Van de Graaff, Cyclotrons, Linacs, synchrotrons…
- To produce electrons they must be extracted from a cathode. This can be done by heating it or by shooting at it with a laser.
- To produce ions they must be extracted from a plasma.
- To reach high energies RF acceleration is required.
- Magnets are used to keep the particles in the right orbit.

However…

- We ignored:
  - That particles have the same charge and they repel each other
  - If they are packed too close from each other they may hit each other
  - Some particles may have the wrong phase…
- Charged particles undergoing an acceleration should emit radiations…

  We will attempt to answer these questions in the next lecture…