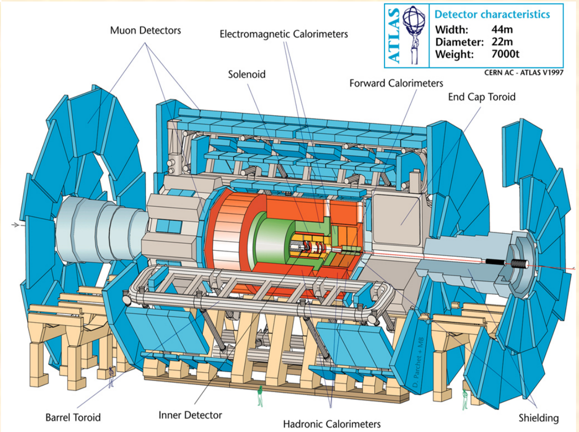
Particle Accelerators I: How to produces protons for the LHC? (or electrons for the ILC)

Nicolas Delerue
delerue@lal.in2p3.fr
LAL (CNRS and Université Paris-Sud)

What is HEP?

- Yuval told us: $\mathcal{L} = ?$
- Alexandre and Maksim
  will suggest to check it with that:



- However you also need another key component: the Accelerator.
- This is what we will cover in the 3 accelerator lecture.

Recommended reading

- "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
- This list will be in the proceedings.

Lectures overview

I. How to produce protons (electrons) for the LHC (ILC)?
   - How to produce protons?
   - How to produce electrons?
   - Antiparticles
   - Particle acceleration

II. How to get protons in the LHC (or electrons in the ILC) ?

III. How to "see" protons (electrons) in the LHC (ILC)? What can you do with a particle accelerator (apart from hunting the Higgs)?

What Physicists want…

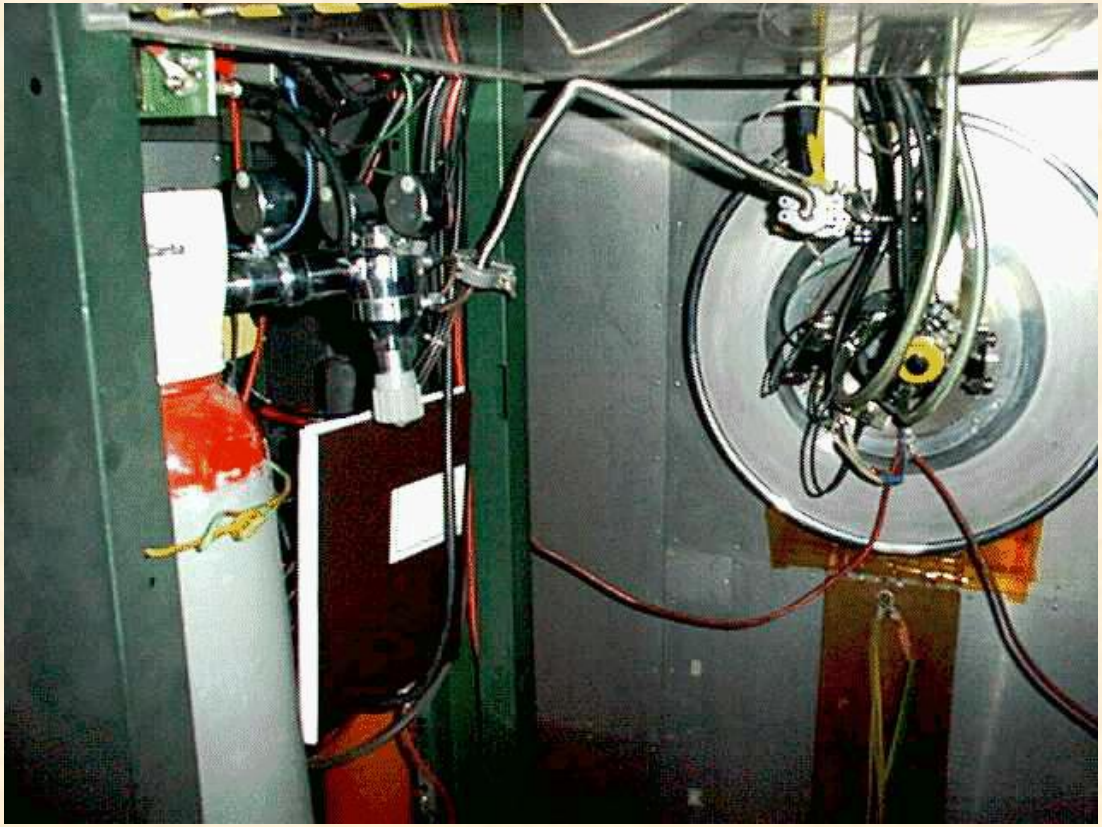
$$\mathcal{L} = ?$$

- We need more luminosity!
- We want to test BSM theory NOW! ☺

- During these lectures we will see some of the limitations of accelerators.

Where do the Higgs bosons come from?

Where do the Higgs bosons come from?



- So far all the Higgs bosons observed on earth came from the bottle above.
- At the LHC the protons (and then the Higgs) are produced by ionizing hydrogen.

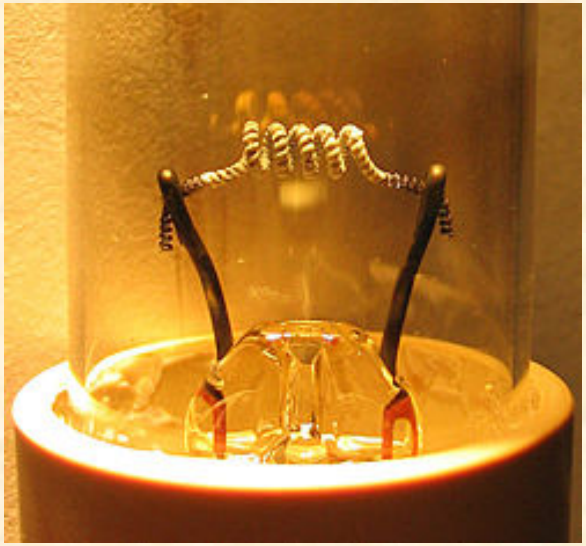
PARTICLE SOURCES

Thermionic effect

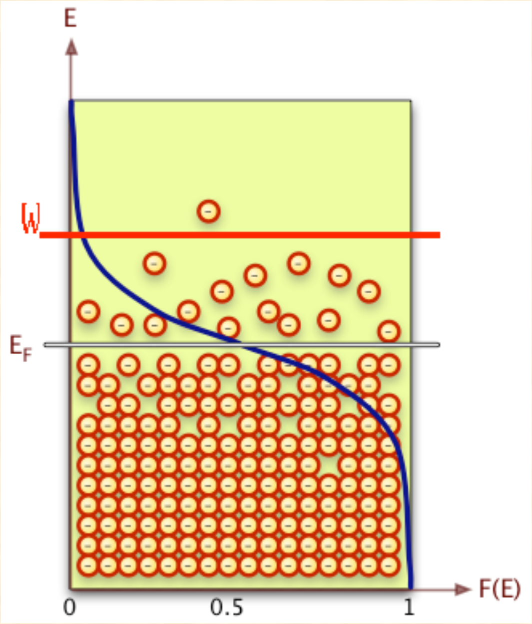
- The thermionic effect as at the heart of particle production in many accelerators, both for electrons and protons.
- Remember the Maxwell-Boltzmann energy distribution:

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

- Electrons (fermions) obey a 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.

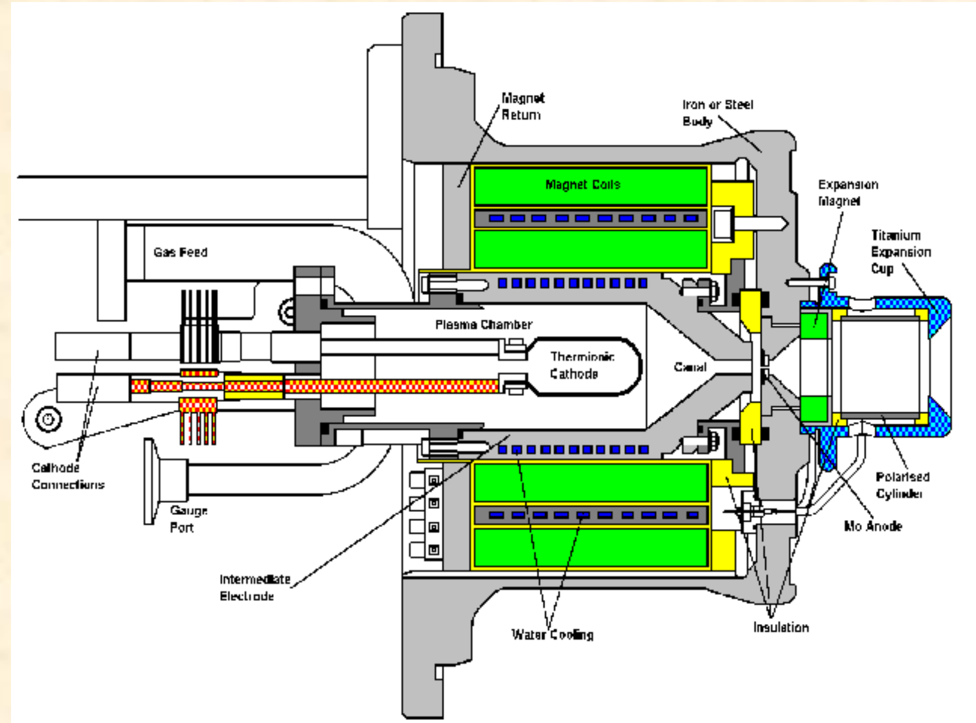


(image source: wikipedia)



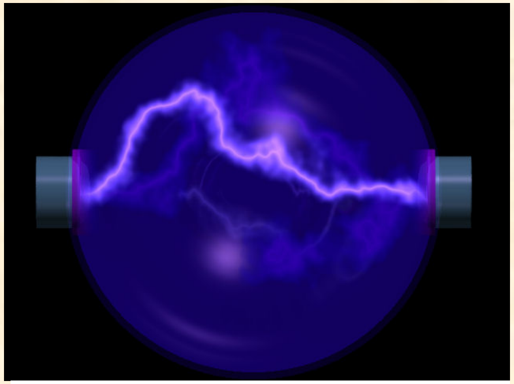
Proton source: the duoplasmotron

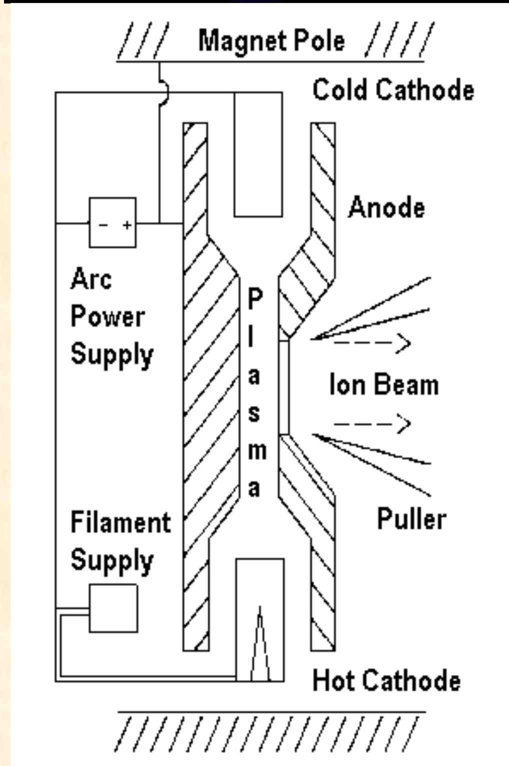
- At CERN the protons are produced in a duoplasmotron source.
- Hydrogen is injected in a plasma chamber at a high electric potential (100kV)
- Inside the plasma chamber a cathode emits electrons.
- These electrons hit the gas atoms and ionise them into protons.
- The protons are attracted toward lower 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.

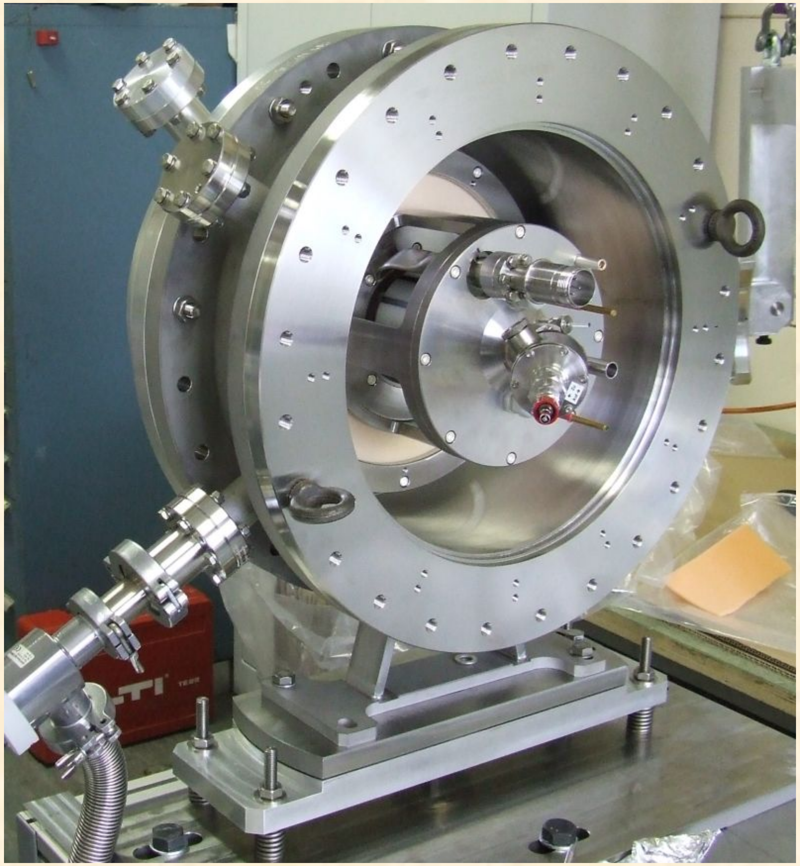




(images source: CERN)

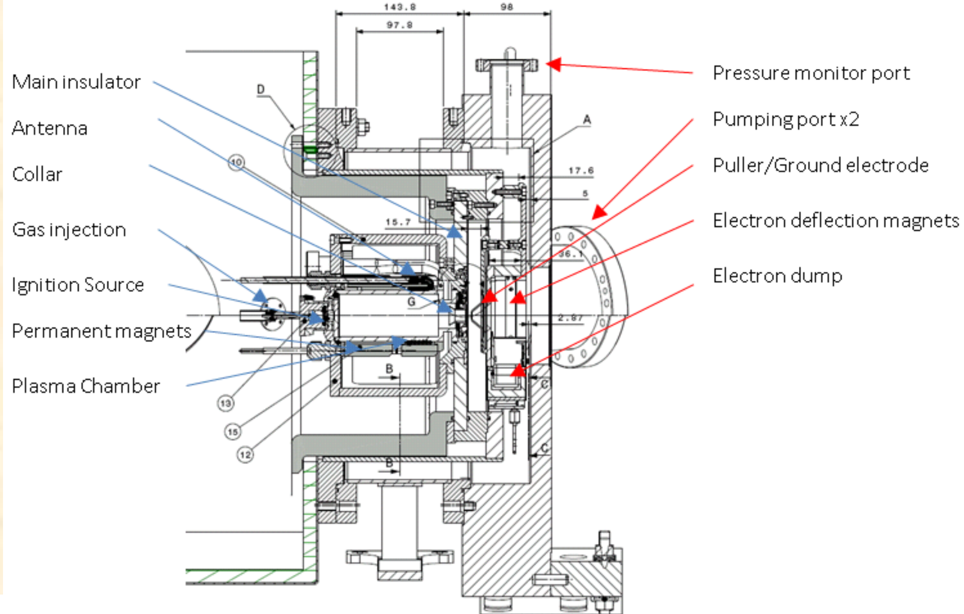
Source upgrade: linac 4 H- source:

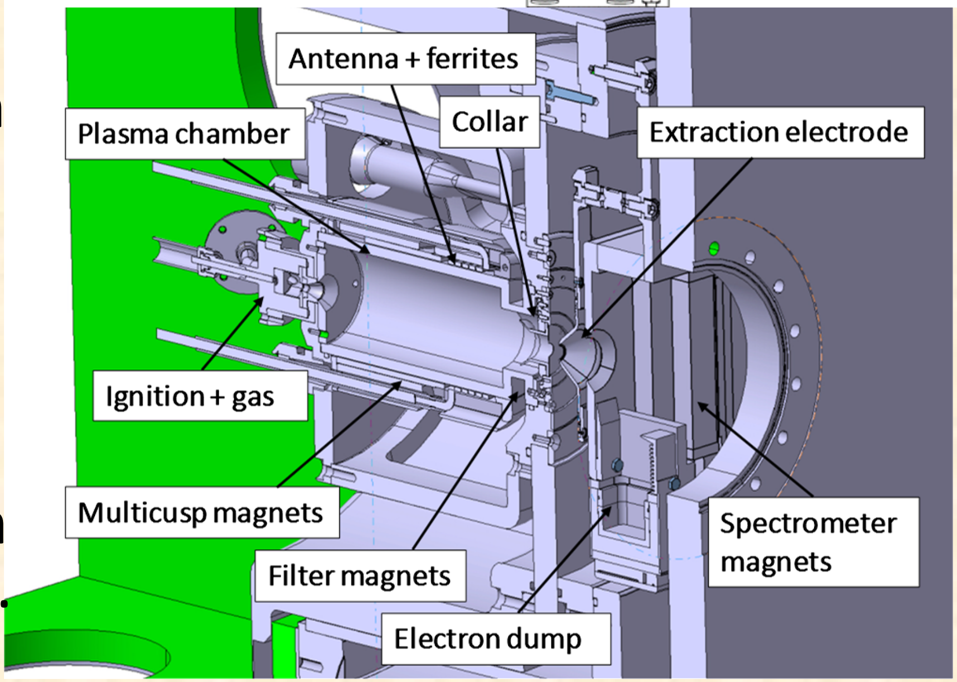
- The current proton source for the LHC was built in 1978.
- It will soon be replaced by a new source based on a different technology: RF ion source.



H- RF source

- In a Radiofrequency ion source an RF field is used to break the gas (hydrogen) into a plasma.
- This RF field is brought in the plasma chamber by an antenna.
- An intense electric field is used to separate the positive ions from the negative ions.
- The negative ions are then extracted and accelerated.



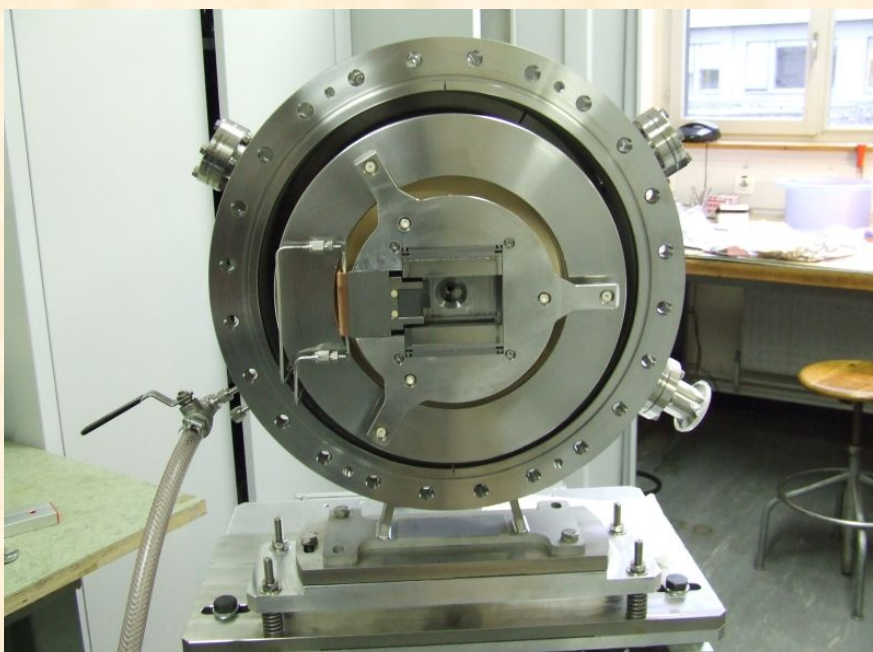


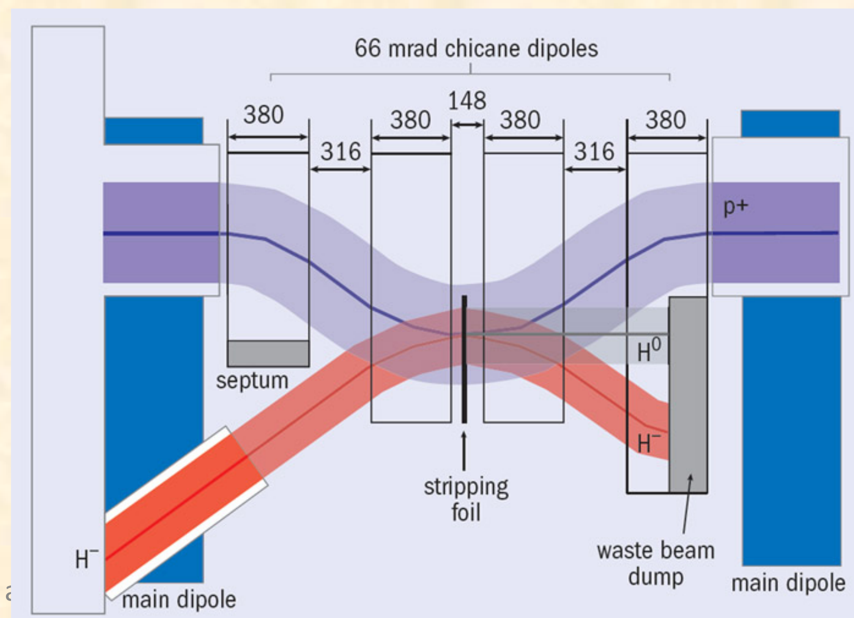
http://linac4ionsource.web.cern.ch/

Courtesy Richard Scrivens, CERN

Why a H- source to produce protons?

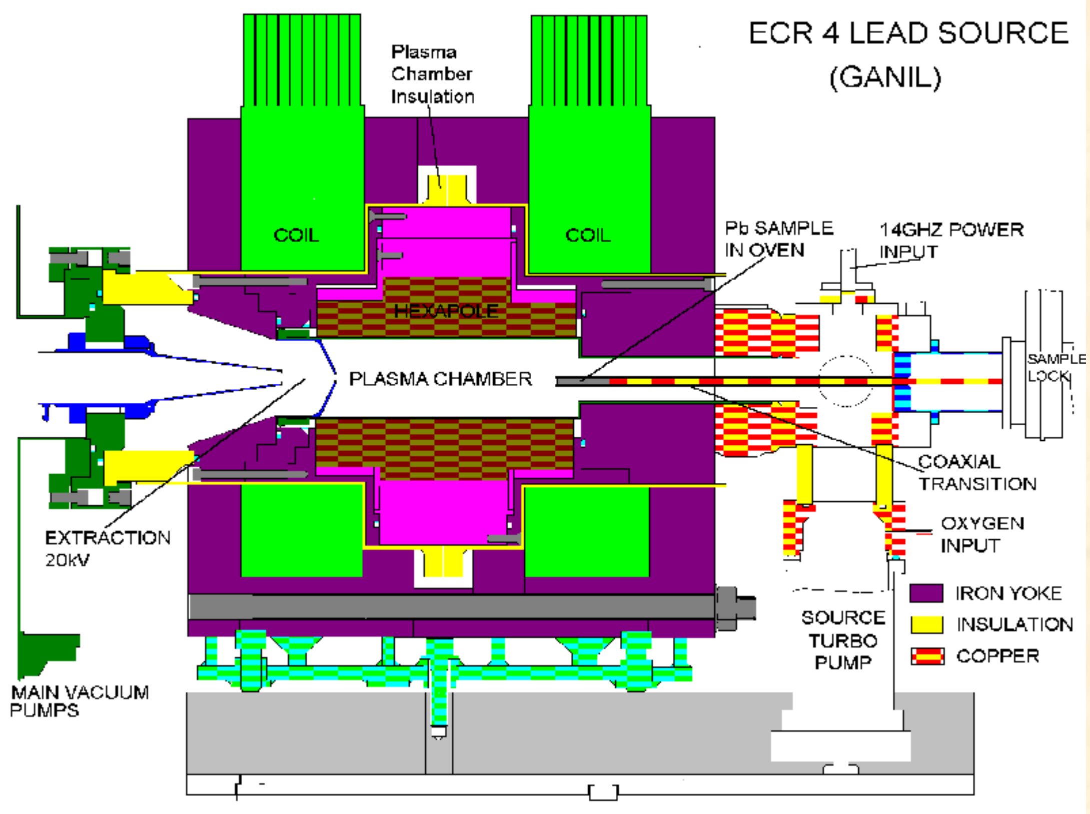
- H- is a proton with 2 electrons
- However the 2 electrons can be stripped easily by sending the H- through a foil.
- Can be injected on already existing proton bunches in a ring more easily by stripping.





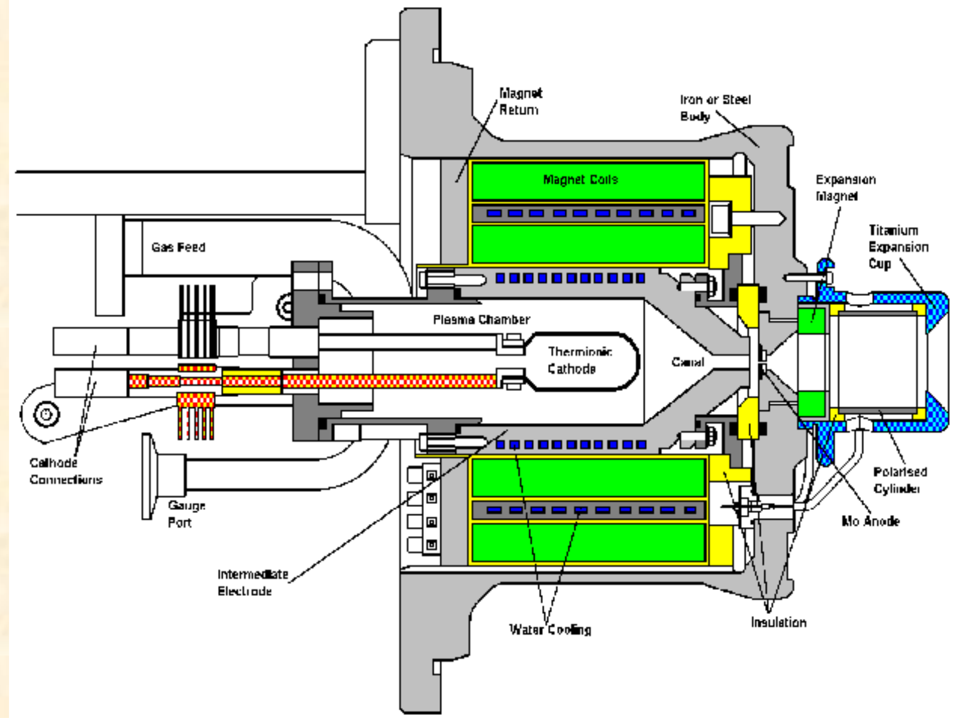
ECR sources

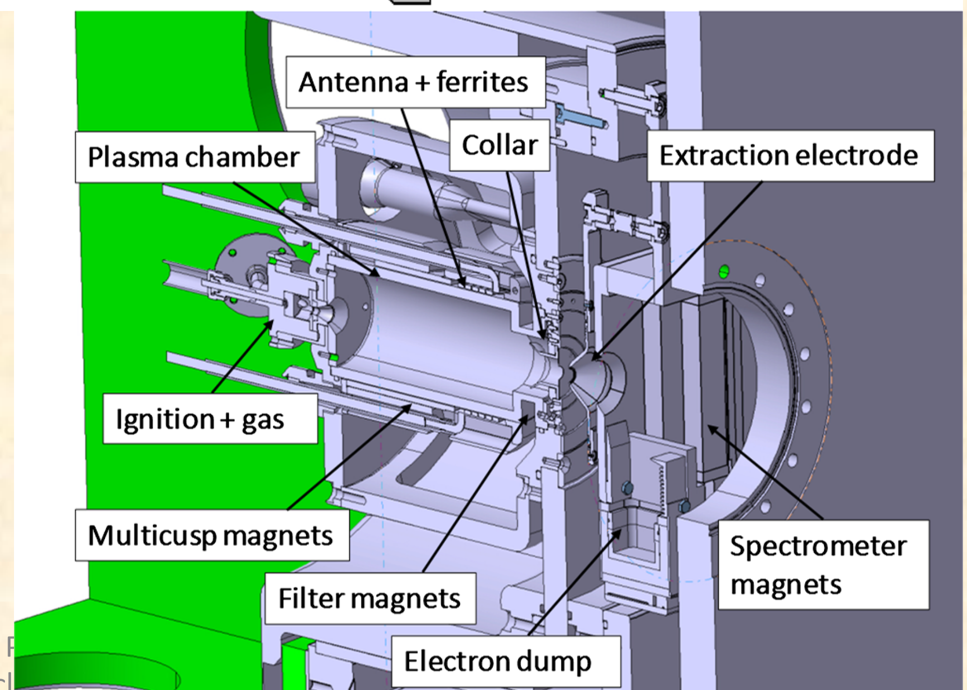
- In addition to pp collisions the LHC will also be used for Pb-Pb collisions.
- The Pb ions are produced in an "Electron Cyclotron Resonance" source.
- Electrons magnetically confined in a plasma chamber are excited by an electric field.
- Lead is heated and brought in the chamber.
- When the electrons collide with the lead they strip it from some of its electrons.
- Under the influence of the electric field the Pb ions are slowly extracted.



Quizz

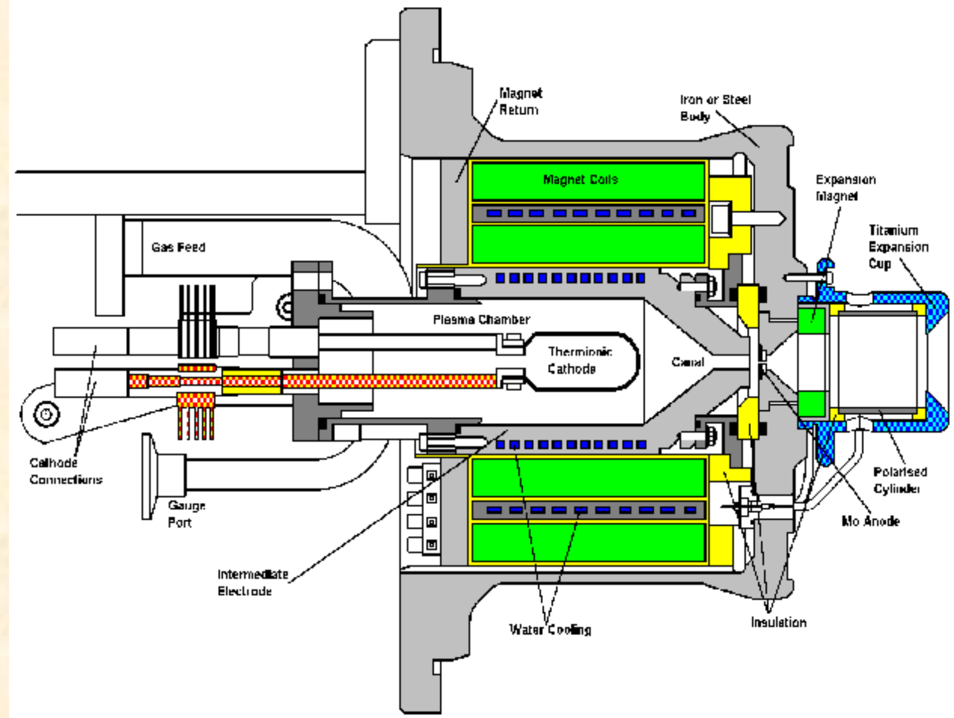
1) We have seen that in a duoplasmotron there is a thermionic electron source. Does that mean that this source produces both protons and electrons? Why?
2) Same question for the H- RF source.

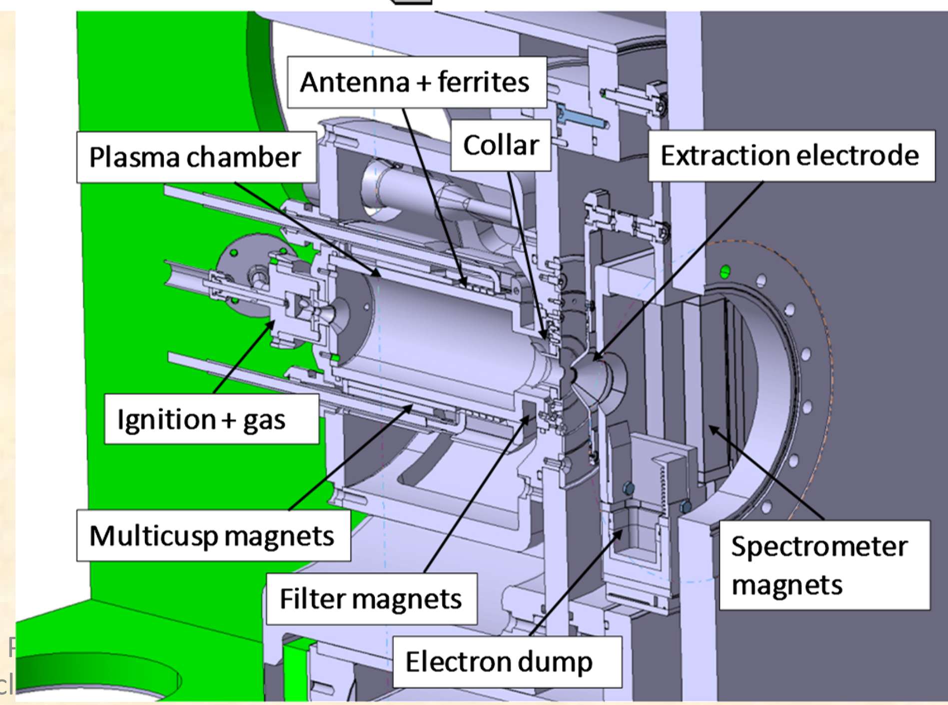




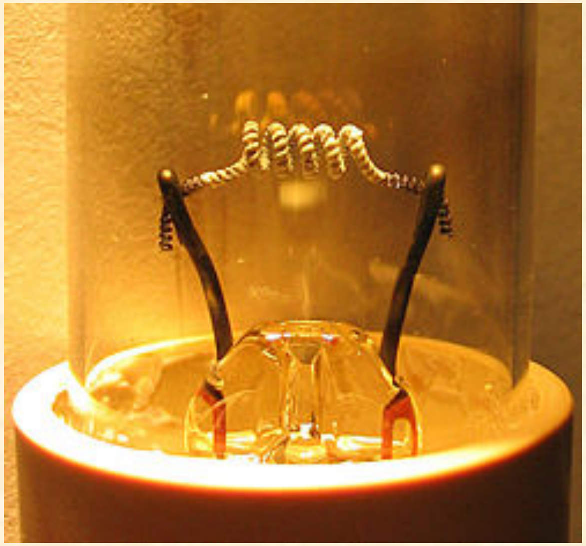
Answer

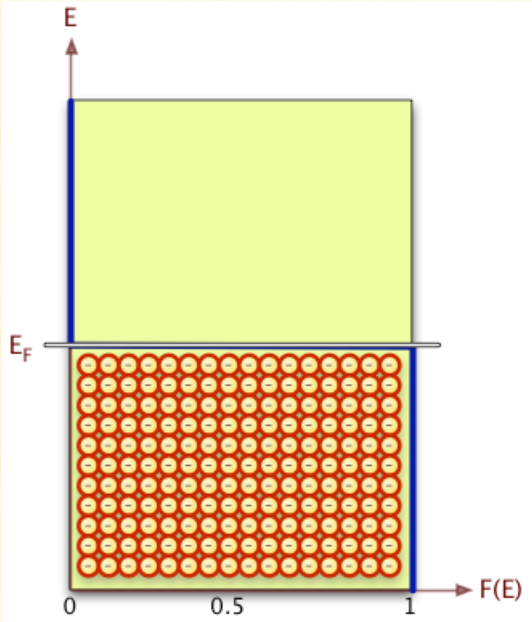
1) In the duoplasmotron the electric field separates the electrons from the proton as they have opposite charge. So only p+ are extracted through the hole.
2) This is not the case in a H- source where the electrons and the ions have the same charge. They must be separated by a magnet at the source exit. This must be done carefully to limit heating of critical components.

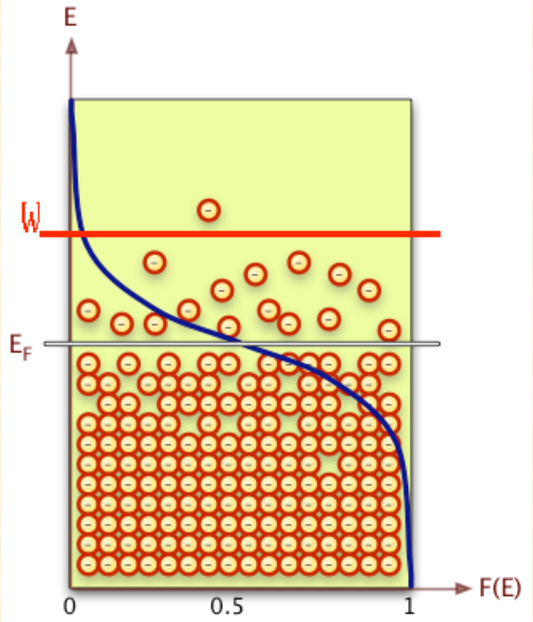




Electrons source: thermionic effect





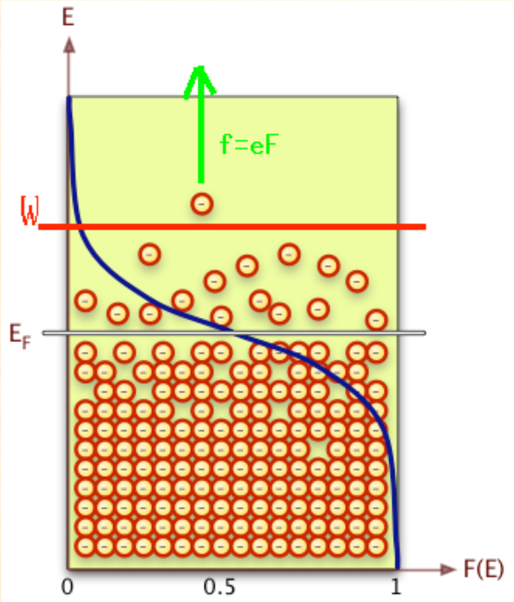


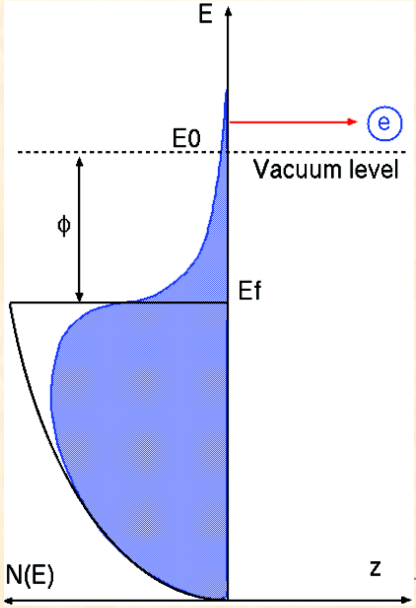
(image source: http://cnx.org/content/m13458/latest/

- We have already seen that electrons can be produced by thermionic effect.
- 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".

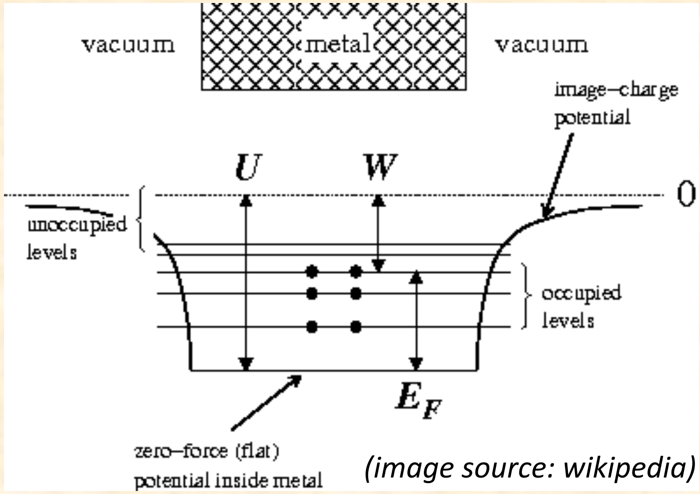




(image source: Masao Kuriki, ILC school)

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, crystalline state, surface roughness,...)

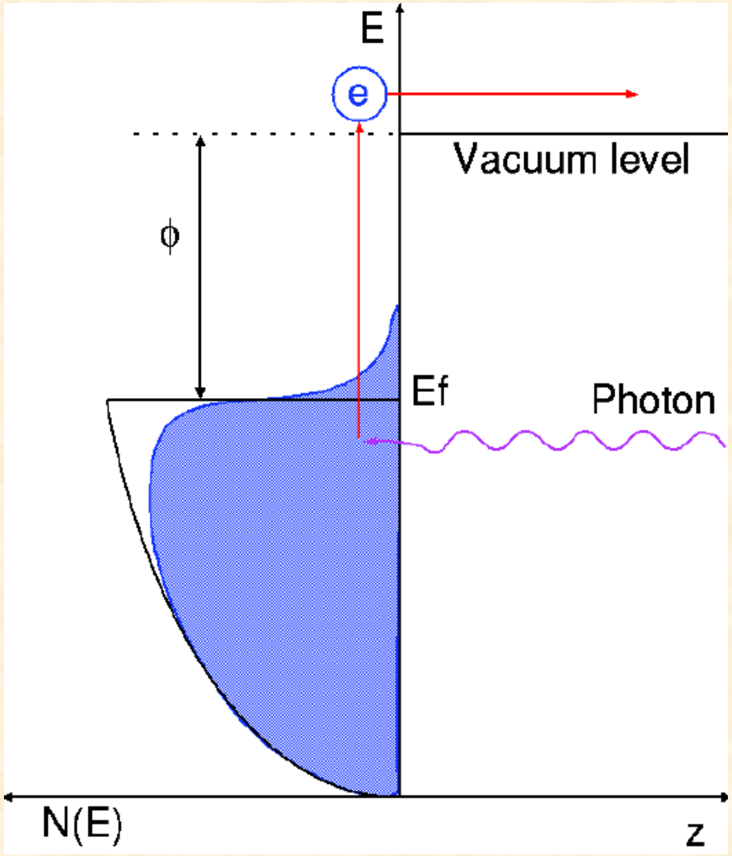


(image source: wikipedia)

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

Other method: 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.

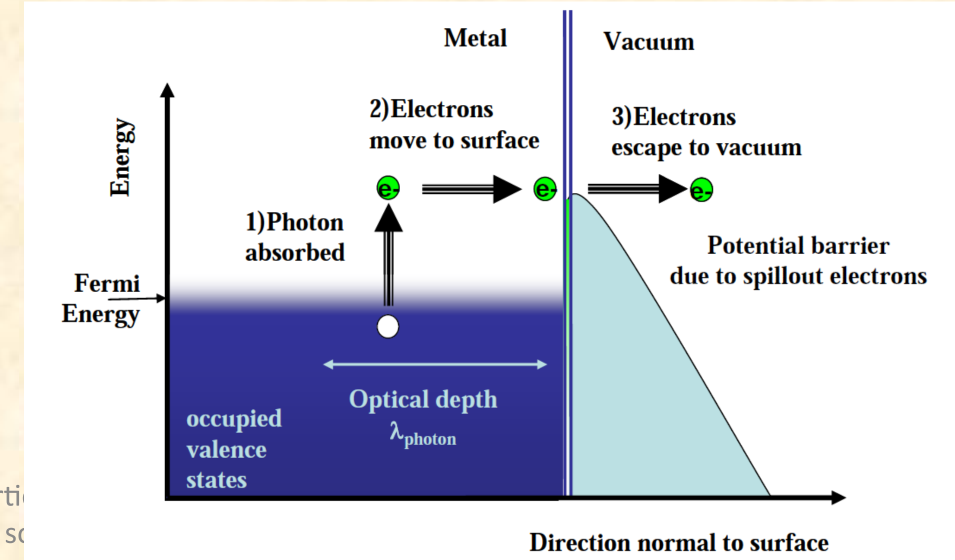


(image source: Masao Kuriki, ILC school)

The 3 steps of photo-electric emission

Photo-electric emission takes place in 3 steps:

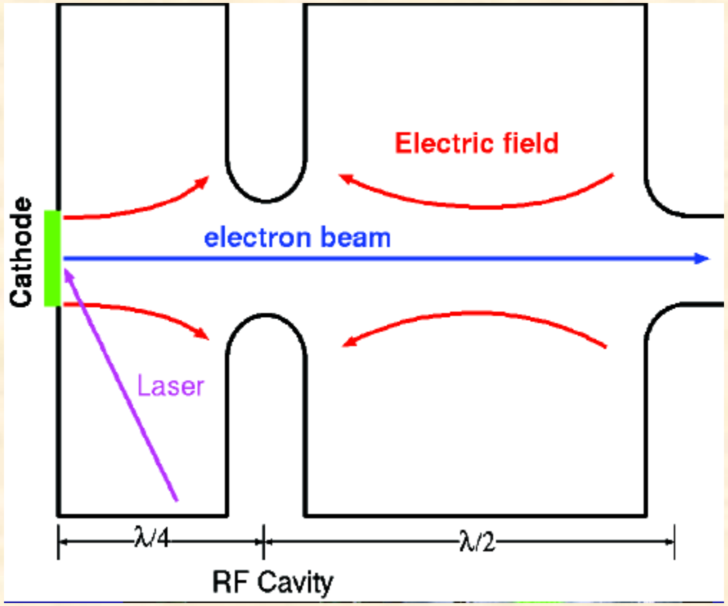
1) Absorption of a photon by an electron inside the metal. The energy transferred is proportional to the photon energy.
2) Transport of the photon to the physical surface of the metal. The electron may loose energy by scattering during this process.
3) Electron emission (if the remaining energy is above the work function; including Schottky effect)



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

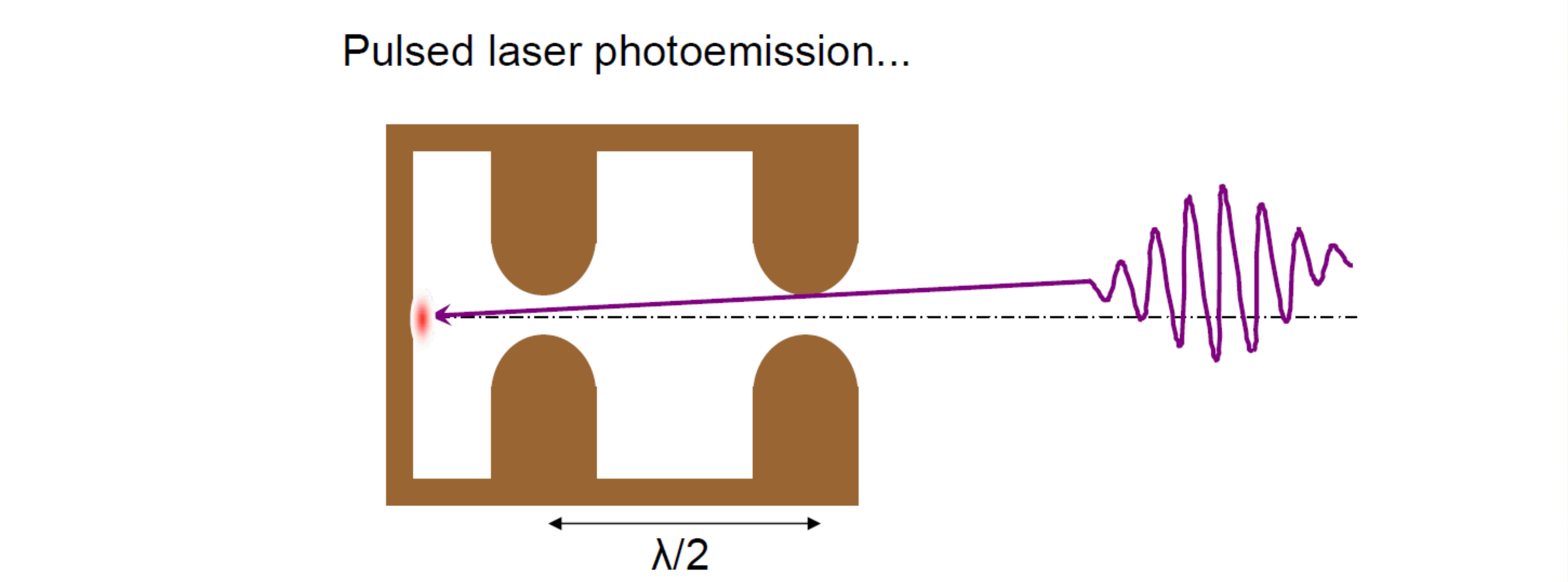
RF Gun

- 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).



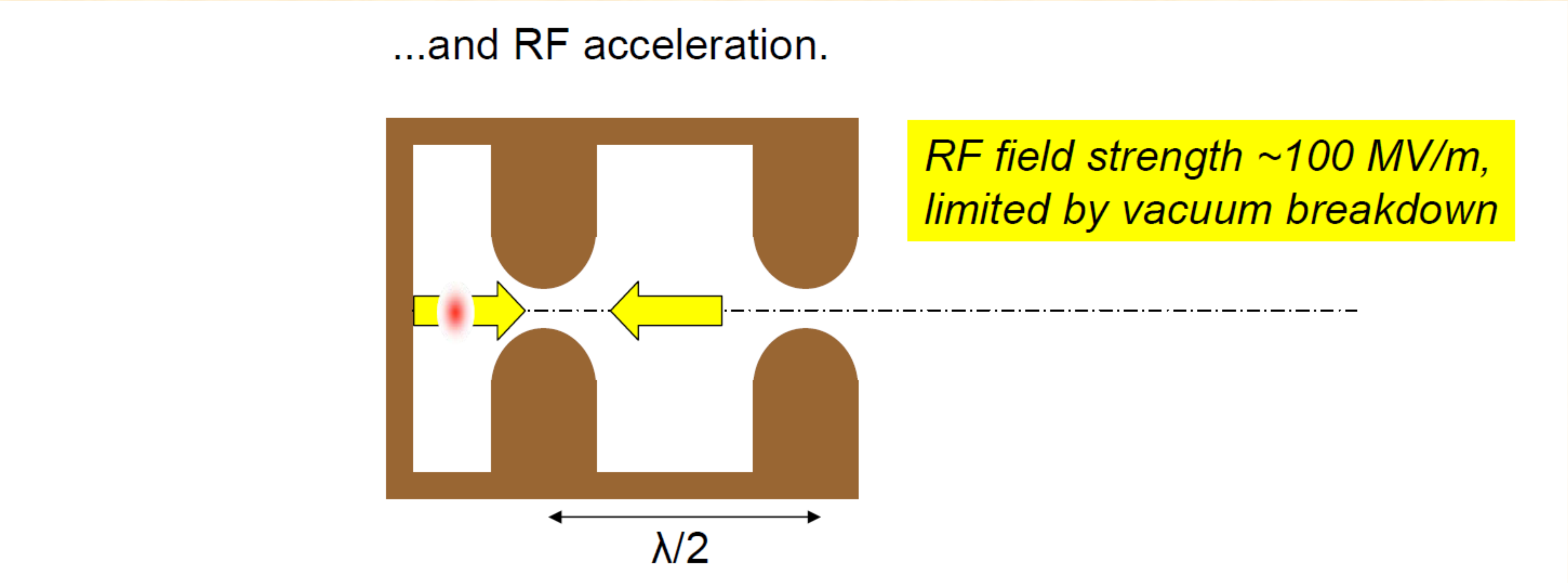
(images source:Masao Kuriki, ILC school)

Principle of a RF Photo-gun



Courtesy Jom Luiten, TUV Eindhoven

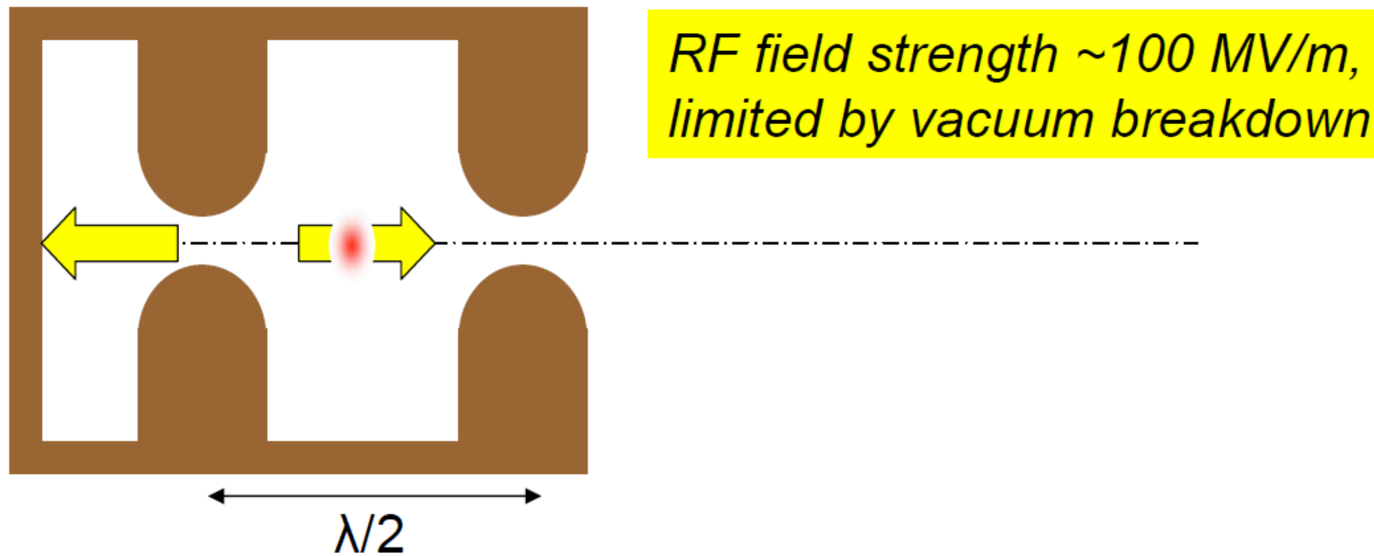
Principle of a RF Photo-gun



Courtesy Jom Luiten, TUV Eindhoven

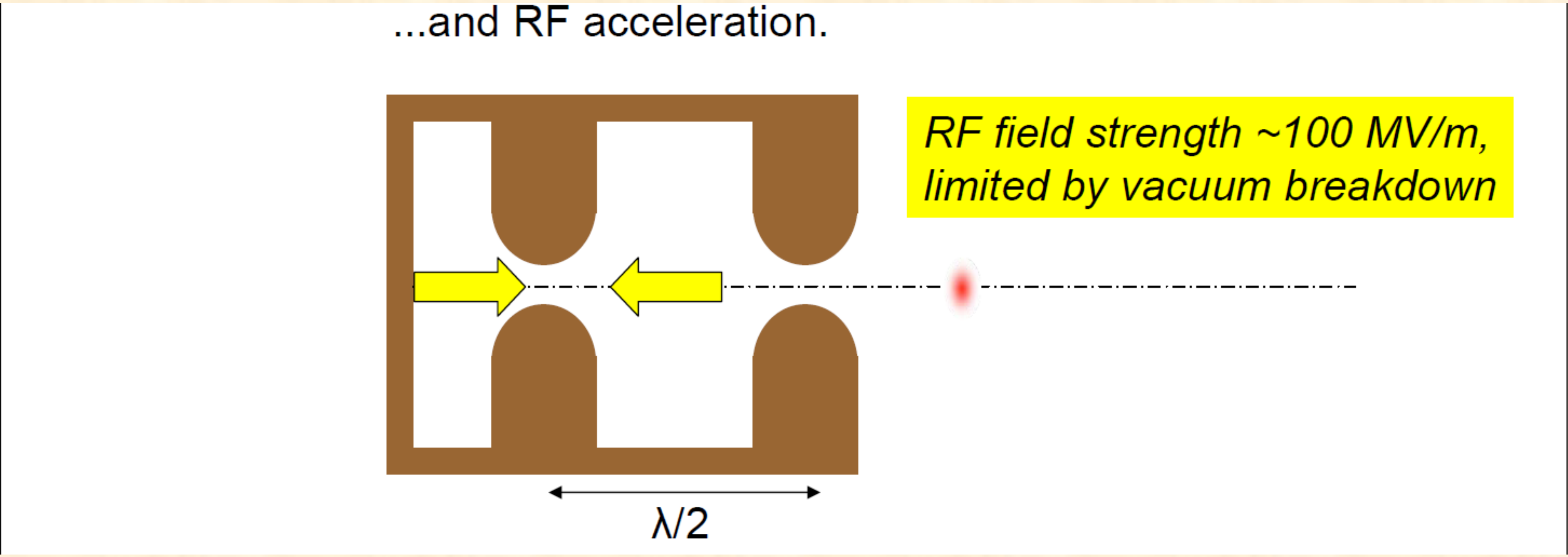
Principle of a RF Photo-gun

...and RF acceleration.



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun



Courtesy Jom Luiten, TUV Eindhoven

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 CO_2 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)

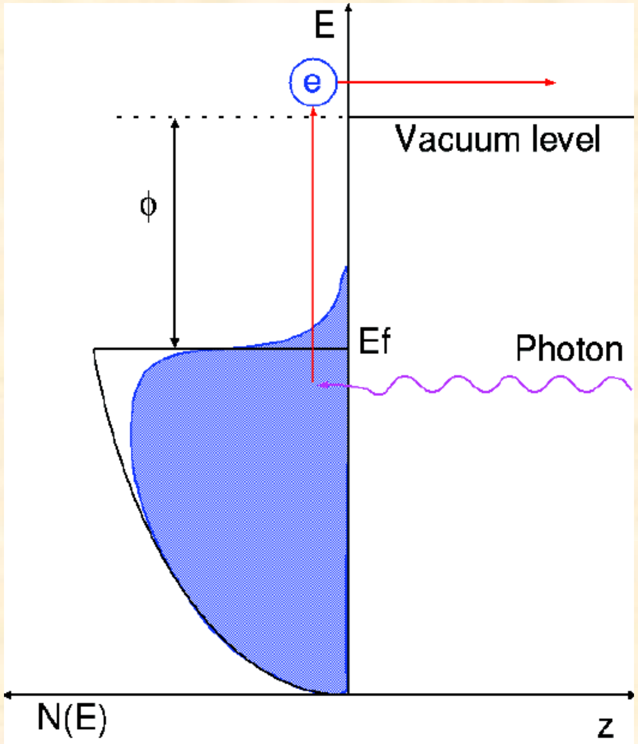
- The lower the work function, the easier it will be for an electron to escape.
  => more electrons will escape
- Gadolinium (b) has the lowest work function and thus it will give a higher current.

Answer 2: (c)

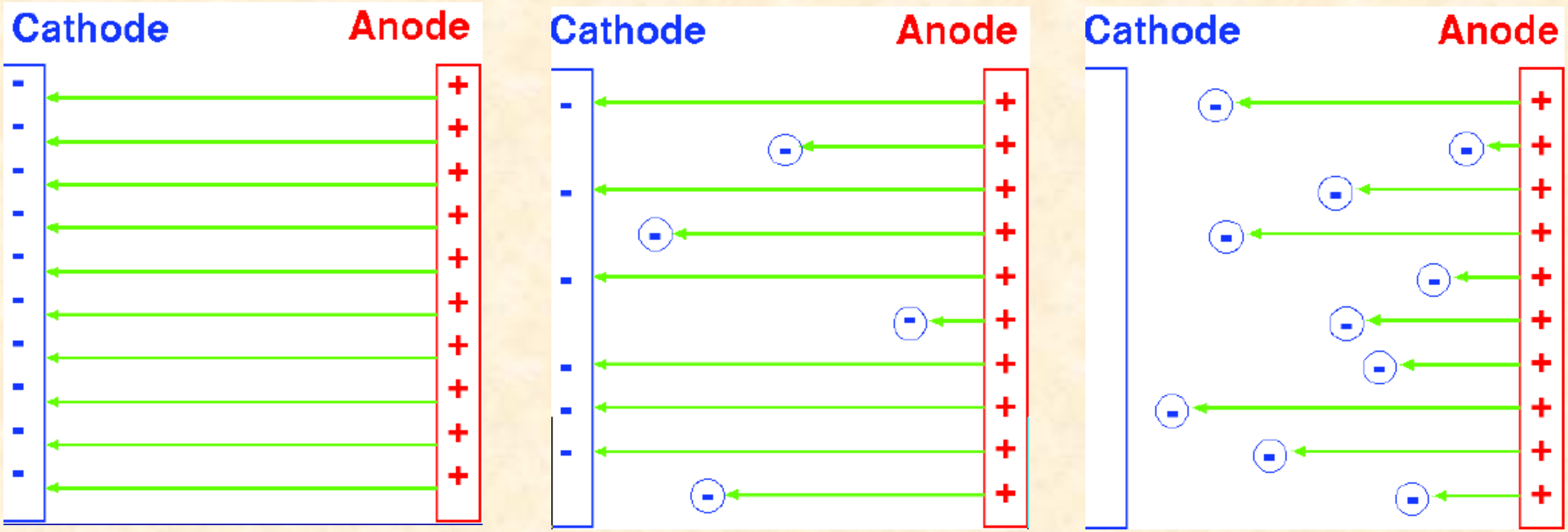
- QE is independent of the laser power: it is the photon energy that matters.
- Remember that

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

- 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 escape by tunnel effect is possible).



Space-charge limitation

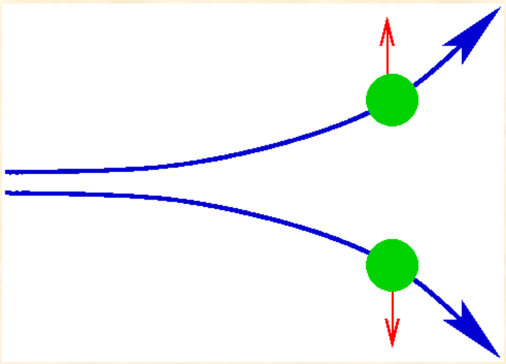


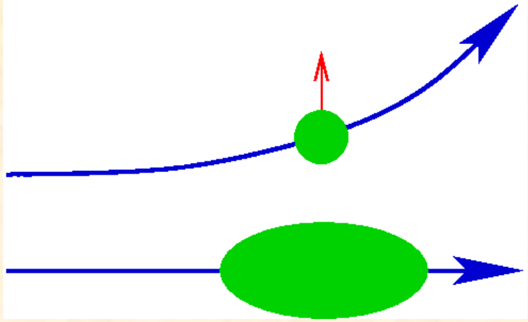
- Emitted electrons shield the cathode from the anode => reduced field
- This limits the intensity of the emission.
  Child-Landmuir law (potential V, area S, distance d)

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

Beam growth due to space charge

- Now let's consider two particles with similar charges travelling in the same direction.
- Due to their charge these particles will push each other away (Coulomb's law).
- What is the intensity of the force with which they repel each other?
- What is the effect of a full bunch?

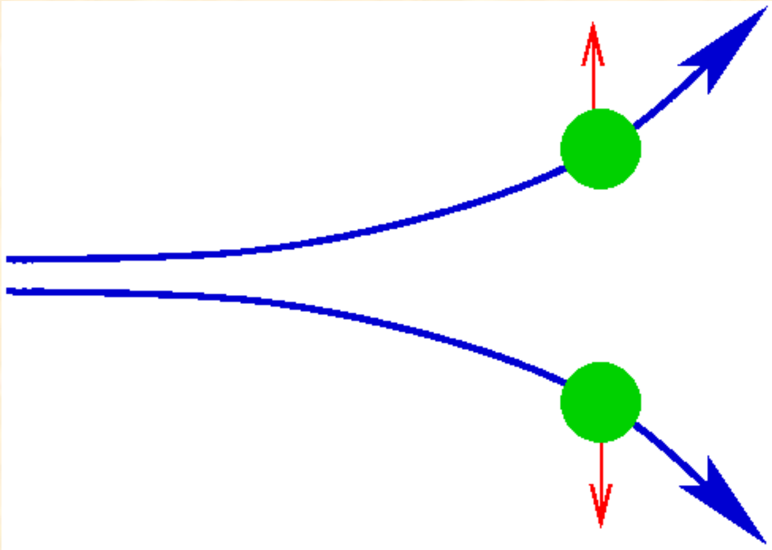


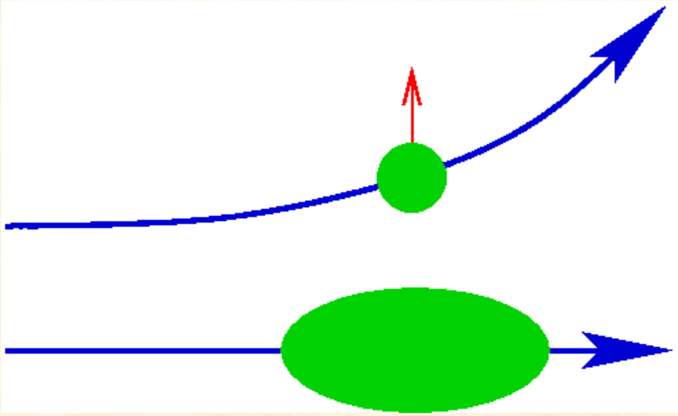


Coulomb force between two electrons

$$f = \frac{1}{4\pi \epsilon_0} \frac{q_1 q_2}{d^2}$$

- Assume d=1micrometre.
- $f=2\ 10^{-16}$N
- This may look small but an electron is not very heavy
- $f/me=2.5\ 10^{14}$N/kg
- This force is very intense on the scale of the electrons.
- Typical charge in a bunch: ~1nC = 1.6 10^{10} electrons

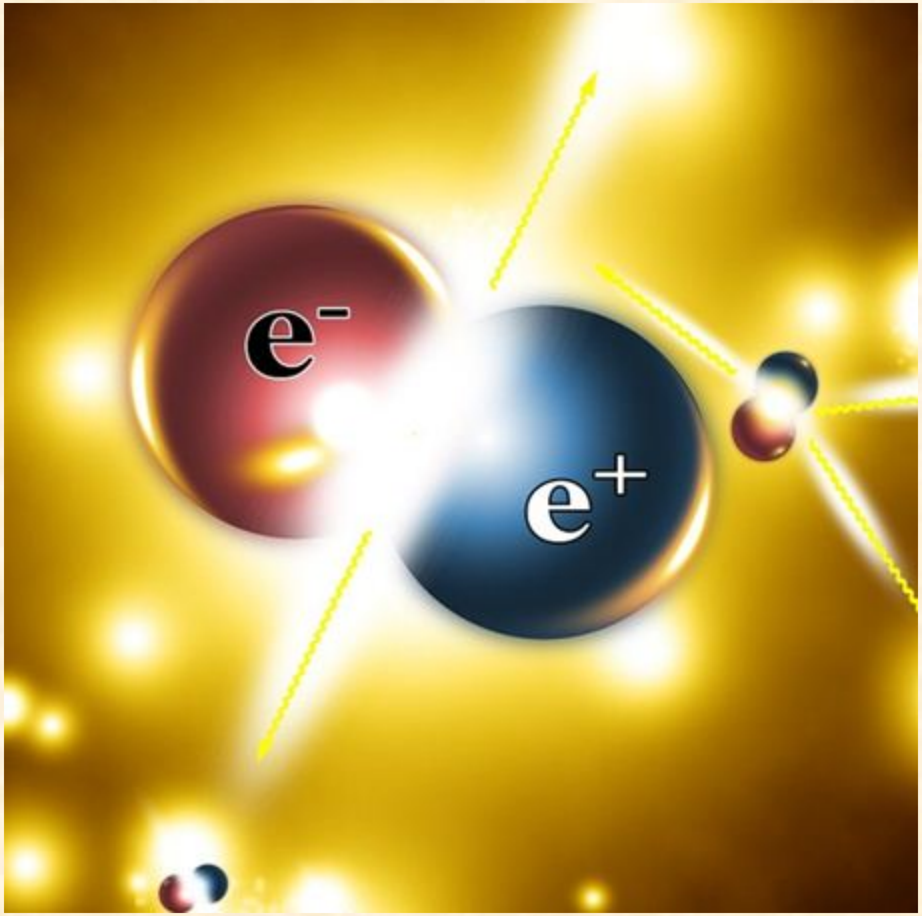




ANTIPARTICLES SOURCES

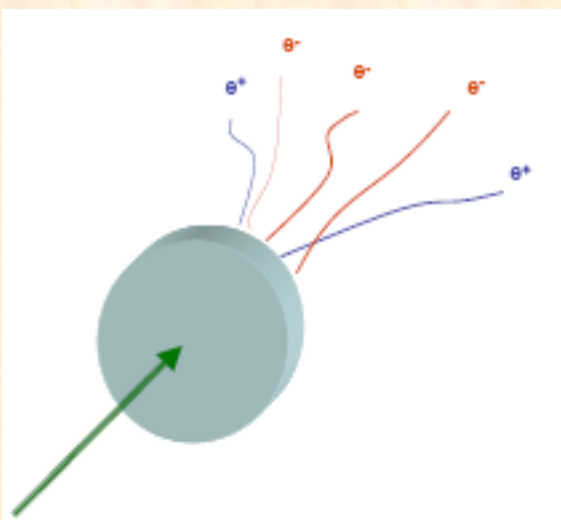
Question

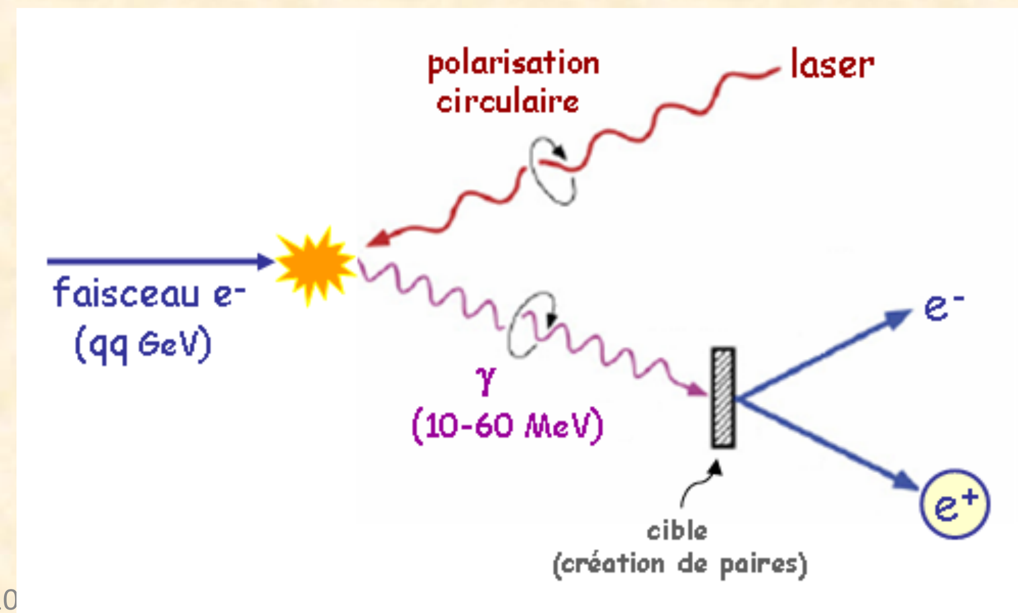
- How can positrons be produced?
- How can antiprotons be produced?



Positron sources

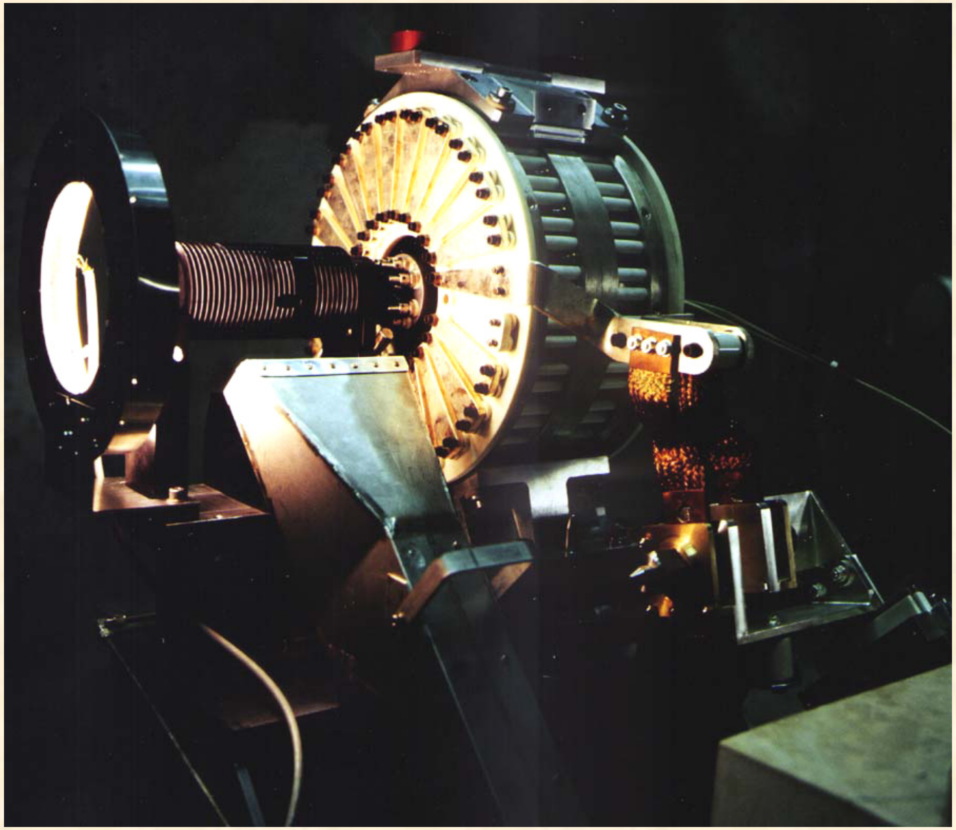
- Electron-Positrons pairs can be produced by high energy (>2xMe) photons.
- These photons can be produced by bremstrahlung of high energy electrons in a target.
- More advanced techniques are being investigated to produce polarised pairs of electron-positrons.





Anti-proton sources

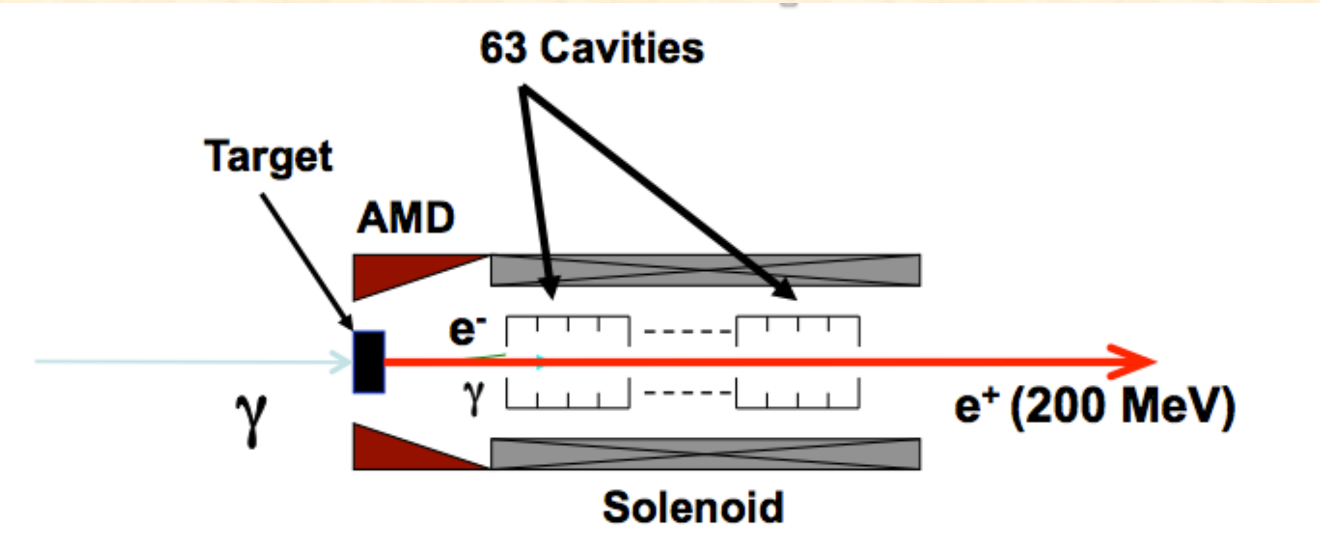
- The creation of anti-protons is similar to that of positrons but at higher energy (>2Mp).
- Typical targets use copper or iridium.
- Anti-protons production is very inefficient so fermilab had built a special ring to “recycle” its anti-protons.
- Big careful to power deposited on target!



CERN antiproton target

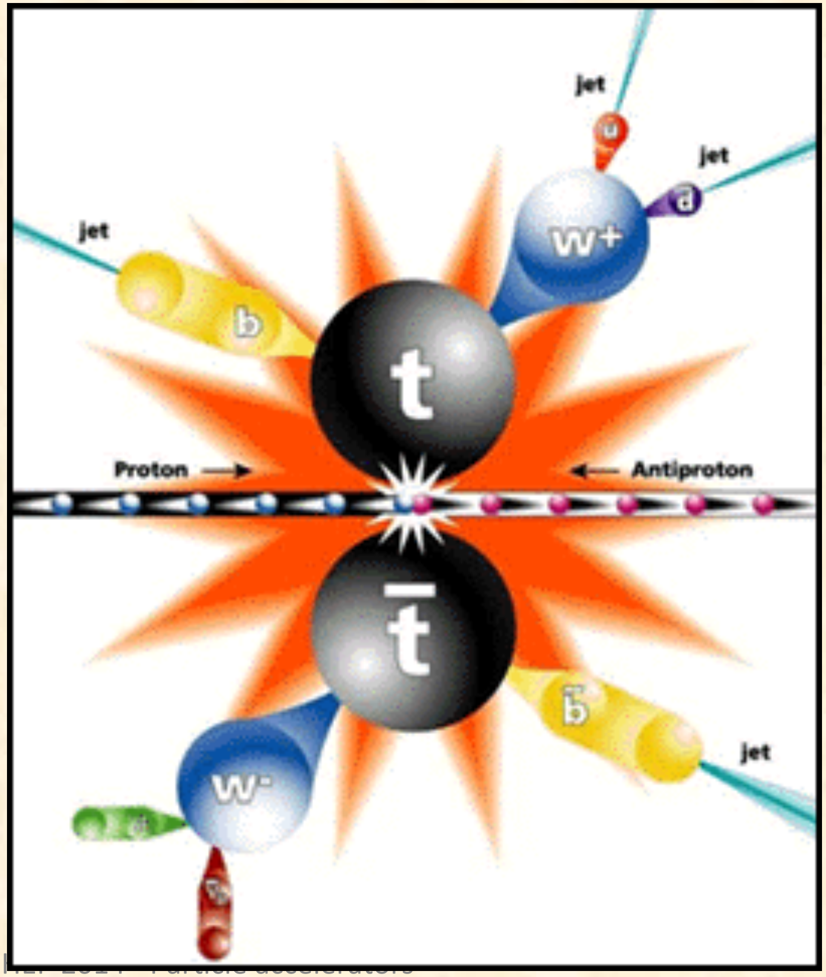
Anti-particles capture

- After the target the anti-particles are emitted from the target with a very large spread.
- They need to be captured by special sections.
- They also need to be "cooled" (for example by radiation damping)
- The whole chain: target/capture/cooling tends to have a low efficiency. That is why in particle vs anti-particles colliders the anti-particles bunches tend to have a lower charge.



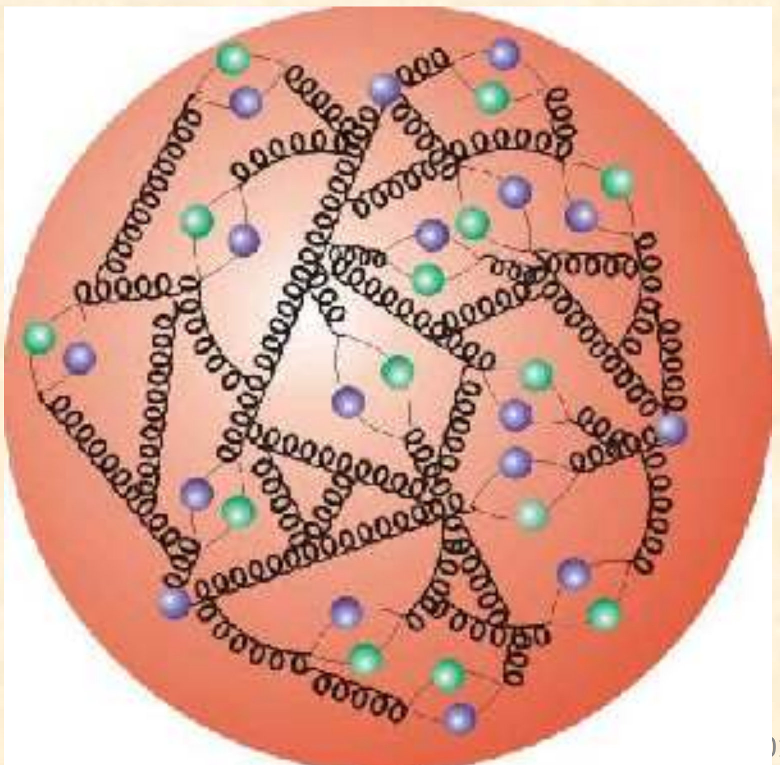
Quizz

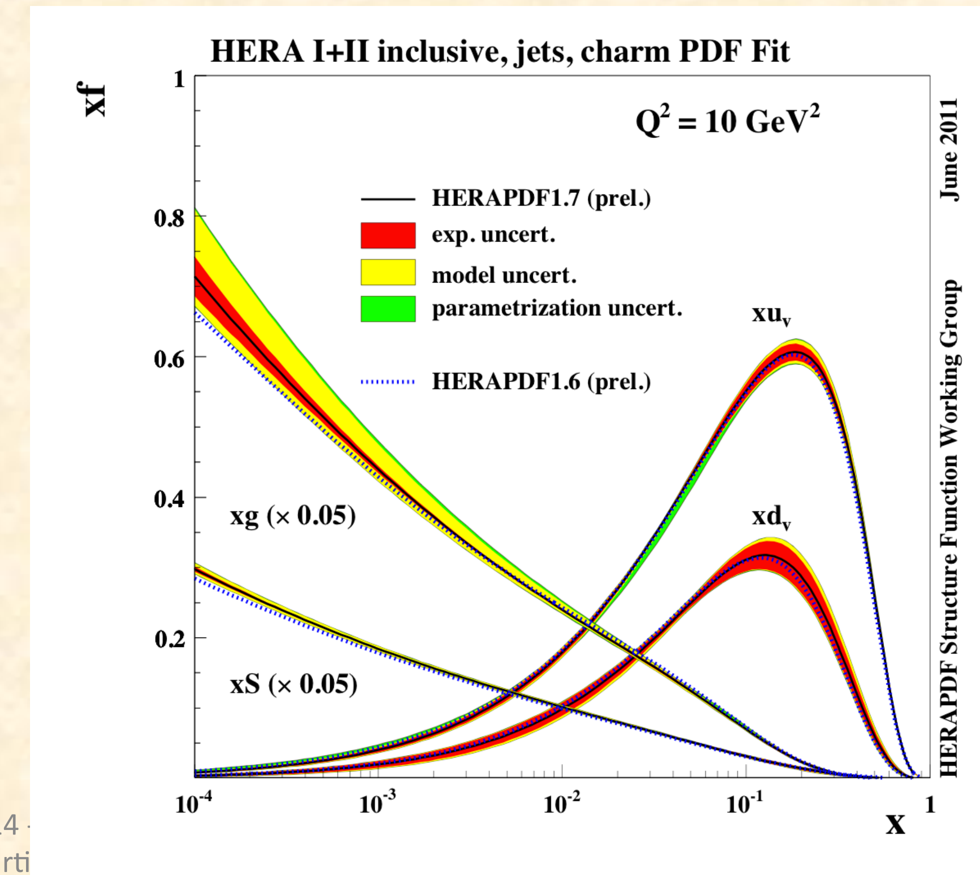
- Why does the LHC not use anti-protons as did the TeVatron?



Answer

- Producing anti-protons is very inefficient.
- QCD tells us that protons at high energy also contain anti-quarks.





PARTICLE ACCELERATION

Special relativity reminder

- In a particle accelerator particles travel at very high speed.
- Special relativity can not be ignored.

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

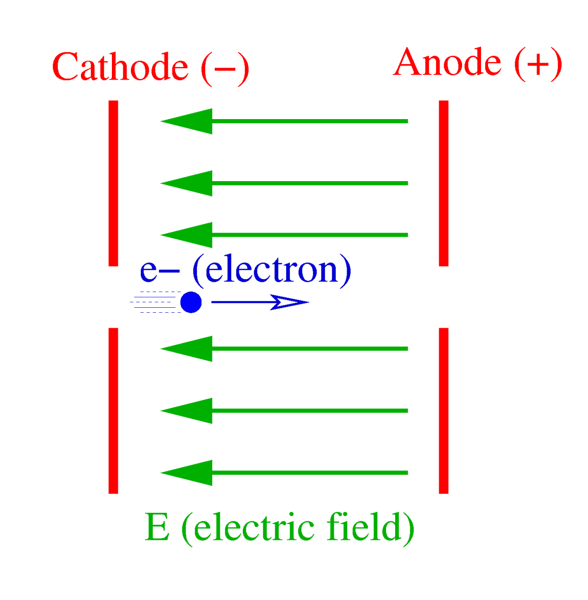
$$E = \gamma m_0 c^2$$

$$\text{Protons: } \gamma = \frac{E}{m_p c^2} \simeq E[GeV]$$

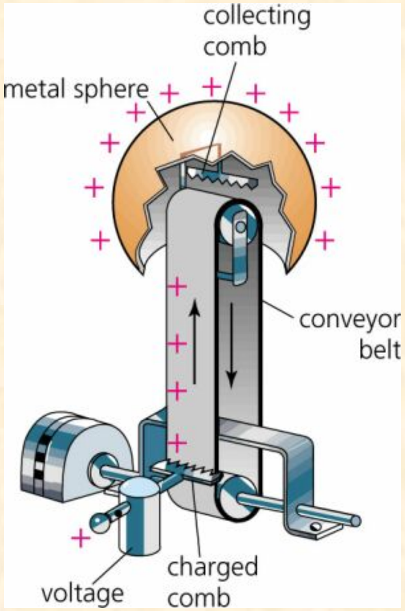
$$\text{Electrons: } \gamma = \frac{E}{m_e c^2} \simeq 2E[\text{MeV}]$$

- Typical RF gun (electrons): few MeV => gamma = 5-10
- Typical proton/H- source: hundred kV => gamma less than 0.001!
- Electrons are very quickly relativistic, protons are not!

- Typical synchrotron light source: 3 GeV => gamma = 6000
- LEP energy 100 GeV/beam => gamma = 200 000.
- LHC Energy (so far) 3.5 TeV/beam => gamma = 3500.
- Relativistic phenomena are much more important in electron accelerators than in proton accelerators.



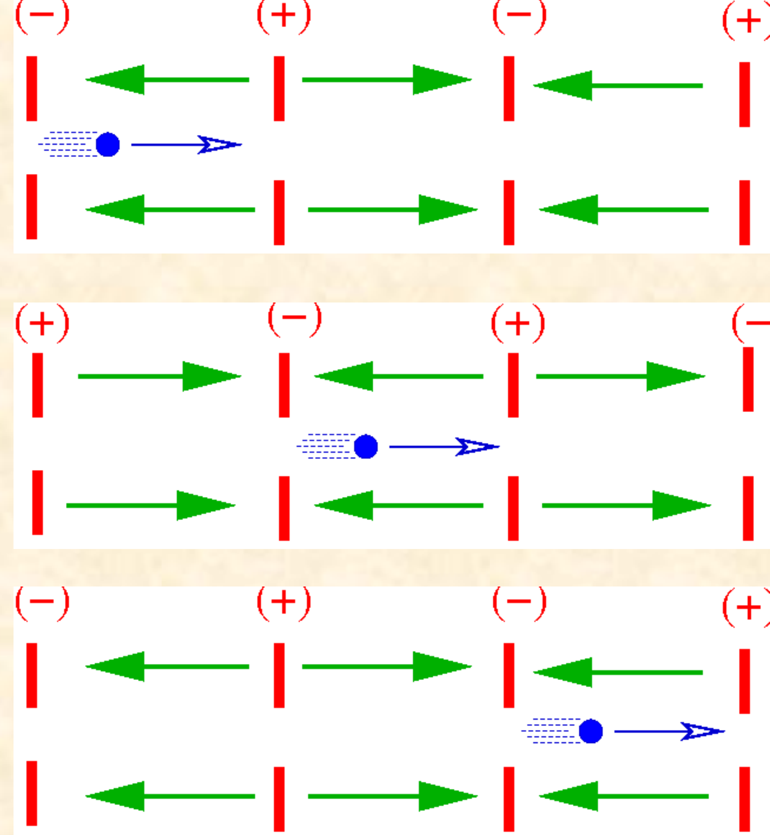
Electrostatic acceleration

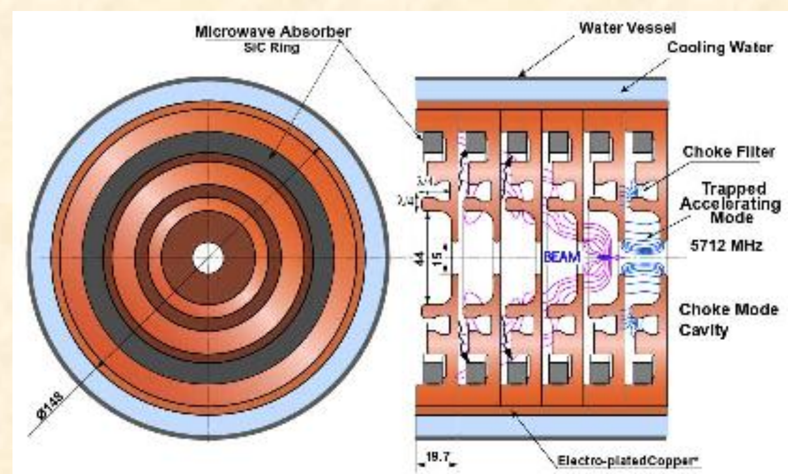


- Charged particles can be accelerated in an electrostatic field.
- This works up to a few MV but we have seen yesterday that intense electric fields can be dangerous.
- To reach more than a few MeV, alternating current accelerators must be used.

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.

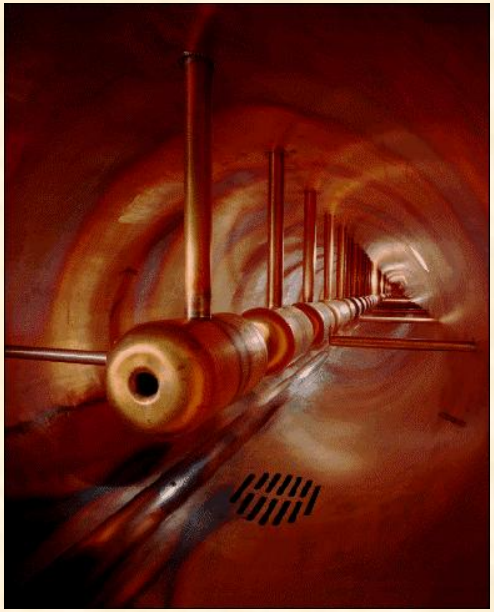




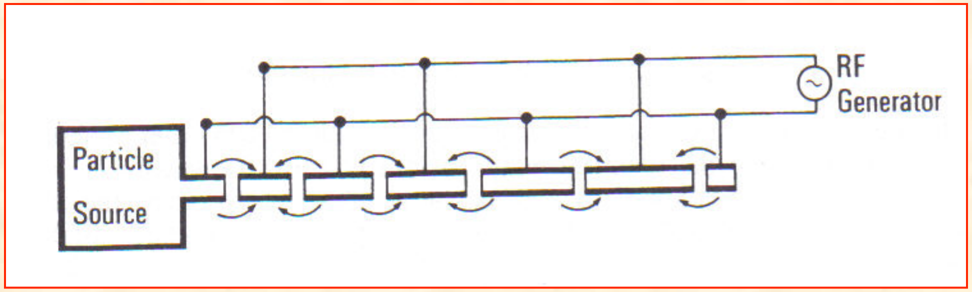
(source: Spring-8, Japan)

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



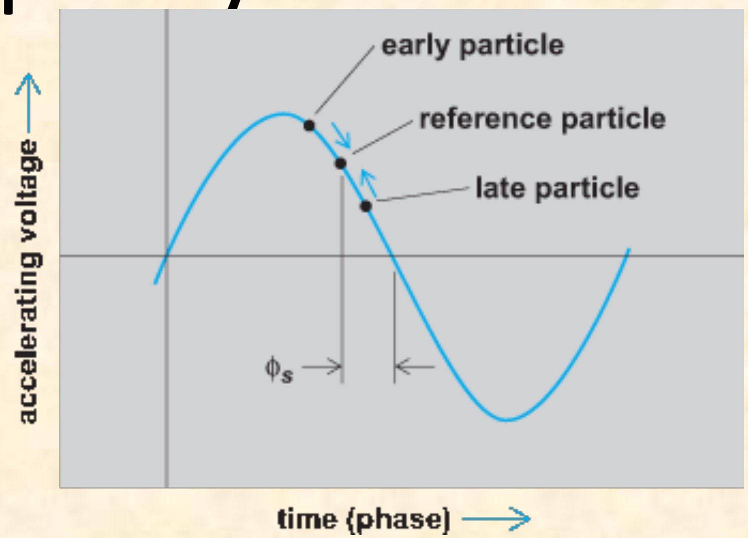
RF accelerators (3)

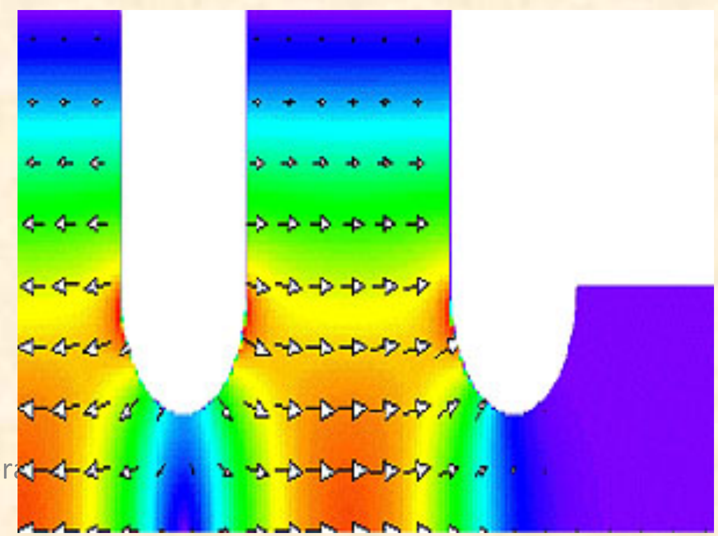
- Because after each cavity the particles return to ground potential there is no theoretical limit on the length of a RF accelerator.
- String of accelerating cavities are usually called “Linac” (Linear Accelerator).
- Linacs are mostly limited by their length: the ILC will accelerate electrons up to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

Artist view of the ILC (source: KEK)

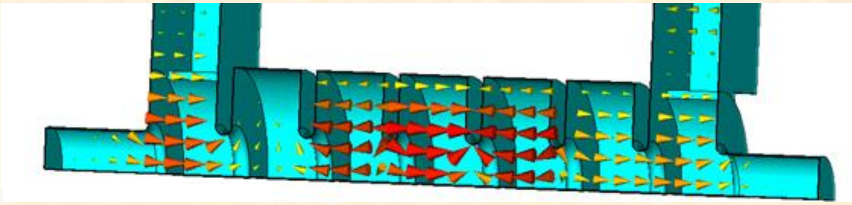
RF: Phase stability and cavity quality

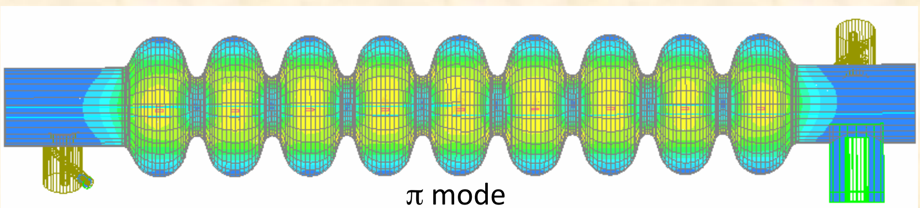
- In an RF accelerator the field felt by the particles depend on the exact phase a which the particle is injected.
- In a linac the phase of all accelerating cavities must be controlled very accurately.
- The shape of the cavity is also very important to ensure a homogeneous field in the center.
- After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

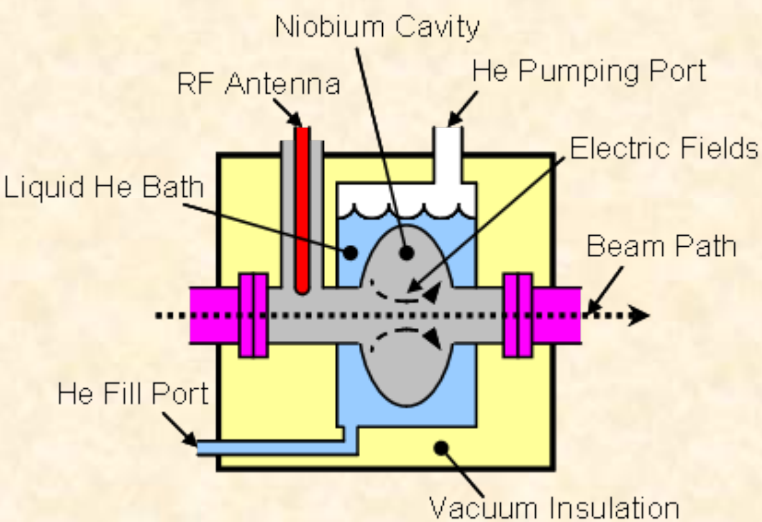




Warm cavities vs cold cavities



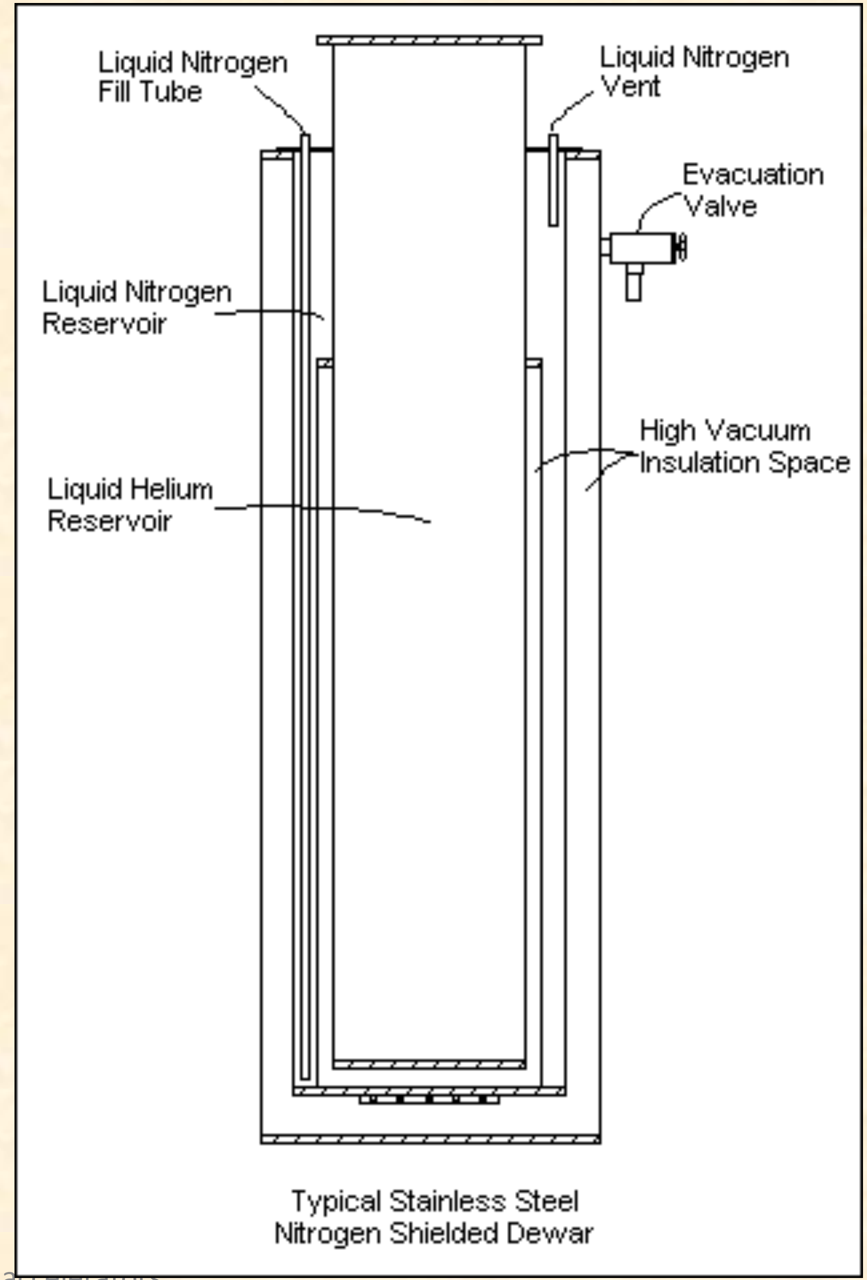




- Two types of technologies exist for accelerating cavities.
- “warm” cavities operate at room temperature.
  - They are easier to install.
  - They have a low quality factor (Q value) so the power injected is dissipated quickly.
- “Cold” cavities work in the superconducting regime (typically 3K).
  - They require an helium cooling plant (expensive)
  - They have a high quality factor and dissipate much less power.
- The most suitable technology depends on the application.
- Modern rings tend to use superconducting cavities.

Cryogenics

- For the LHC it was decided that it would be more economical to use superconducting accelerating cavities and superconducting magnets.
- This requires large amount of cooling down to 2K.
- Thermal radiation depends on T^4. To minimize thermal losses LHE cryostat need an outer LN2 shield.
- Cooling the LHC has its own challenges:
  - During cool down the LHC shrinks by about 80m (over 27km).
  - Warming up/cooling the cold masses takes several weeks per sector.



Summary

- Protons used in the LHC are extracted by ionising hydrogen.
- Electrons can be produced via the thermionic effect or the photoelectric effect.
- Anti-particles are produced by smashing high energy particles on a target.
- RF cavities are used to accelerate the particles. Such cavities can be either at room temperature or superconducting.
- Their frequency and other technological constraints set the bunch pattern.