ED PHENIICS
Understanding basic principles of particle accelerators

History and basic principles of particle accelerators

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Slides are available at http://lal.delerue.org/teaching/202206_PHENIICS/

Lecture series overview

- Monday (today): History and basic principles
  of particle accelerators.
- Tuesday: Zoom on the LHC and
  Machine detector interface and applications.
- Wednesday: Optics and beam dynamics.
- Thursday: Zoom SPIRAL2 and (in french) Ultra-vide
- Friday: Related technologies: Radiofrequency and Cryogenics.

- + Visits of accelerators facilities:
- Monday: ThomX
- Tuesday: ACO (Collider)
- Thursday: SCALP (Low energy accelerator)
- Friday: Supratech (Superconducting RF test facility)

Today’s lecture content

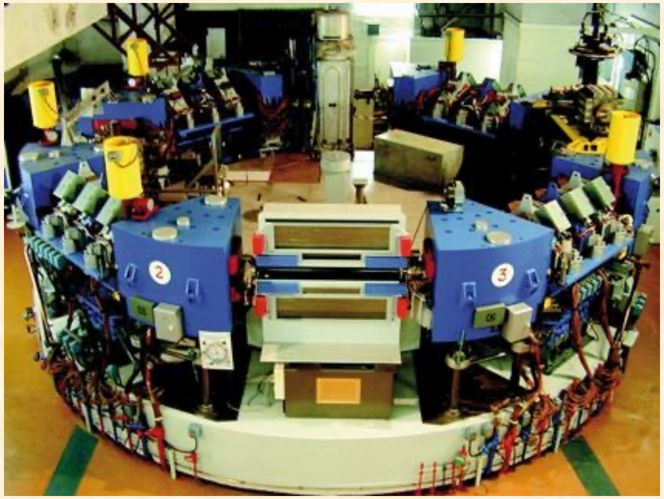
- History of particle accelerators
- Basic principles:
  - Particle sources
  - Particle acceleration
  - Magnets
  - Emittance and beam dynamics
  - Beam diagnostics
- Challenges for present and future accelerators

About myself

- Researcher at IJCLab in 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).

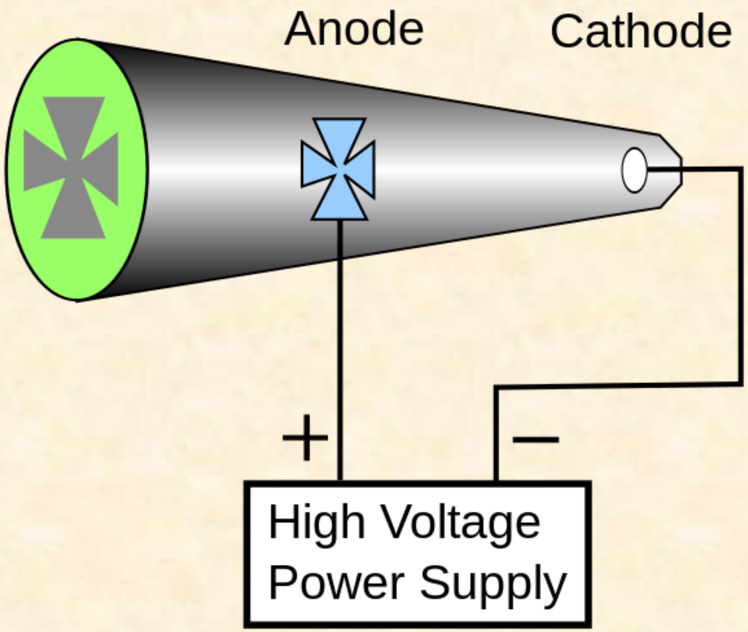
Lecture content

- **History of particle accelerators**
- Basic principles:
  - Particle sources
  - Particle acceleration
  - Magnets
  - Emittance and beam dynamics
  - Beam diagnostics
- Challenges for present and future accelerators



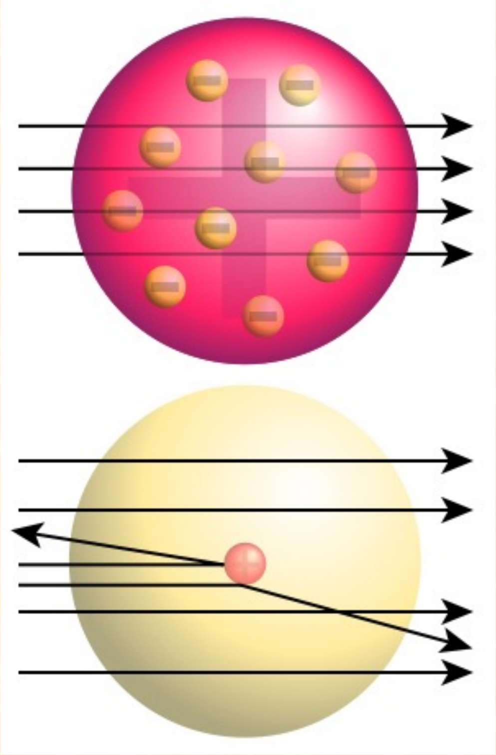
The first accelerator: Crookes tubes

- 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)

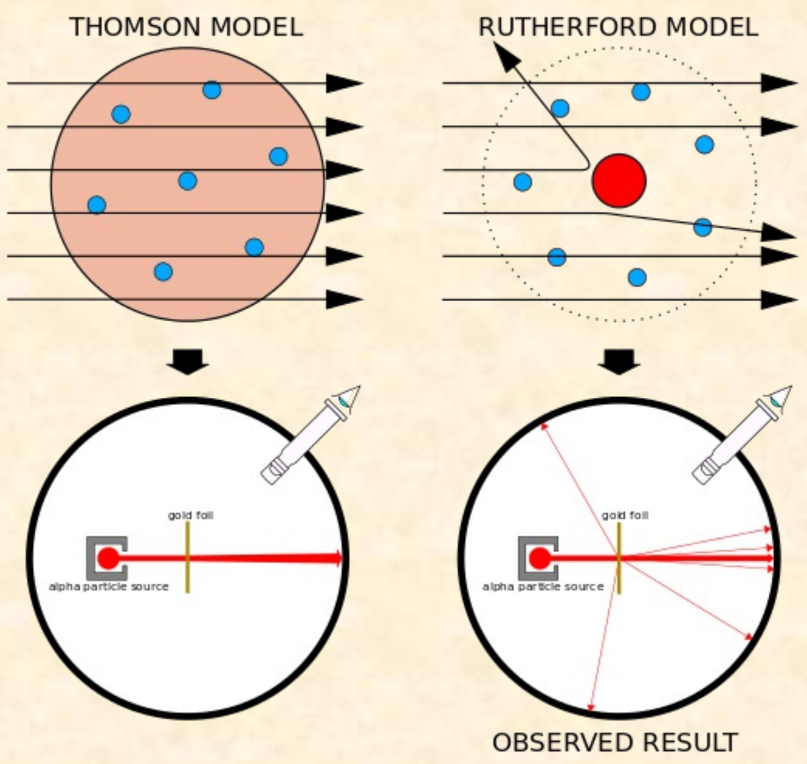
- In the early 20th century the structure of the atoms
- In 1909 Rutherford was studying the structure of the atom.
- He proposed to use alpha particles on a gold foils to probe the structure of the atom.
- This experiment shows that by using an appropriate probe it was possible to study very small objects.



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

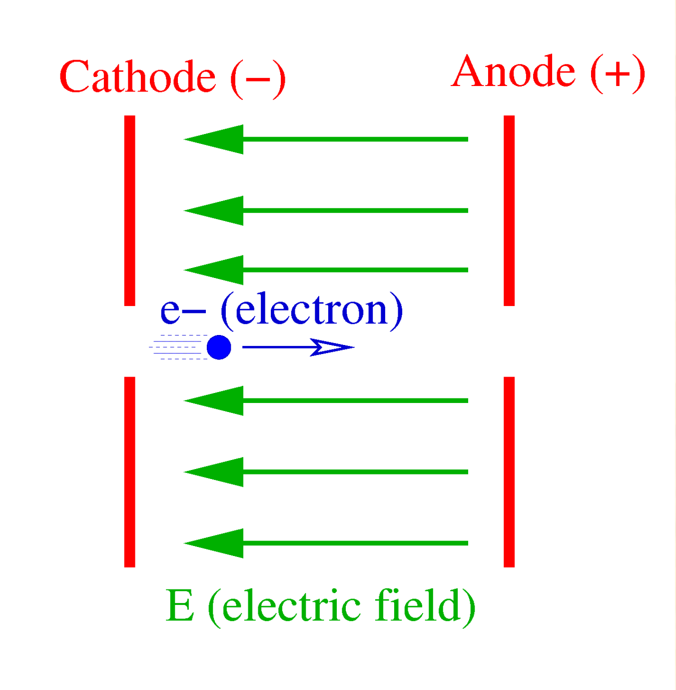
Rutherford scattering experiment (2)

- 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.

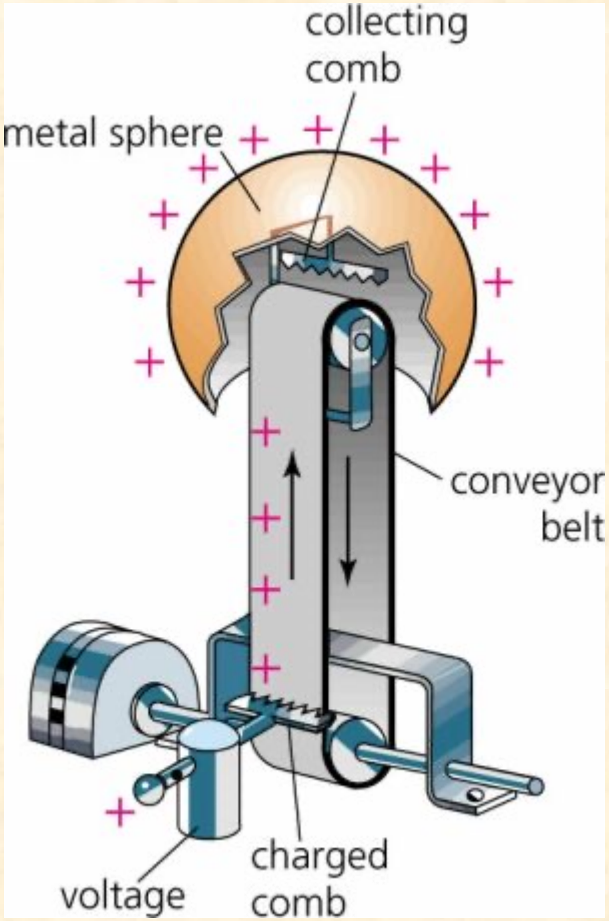
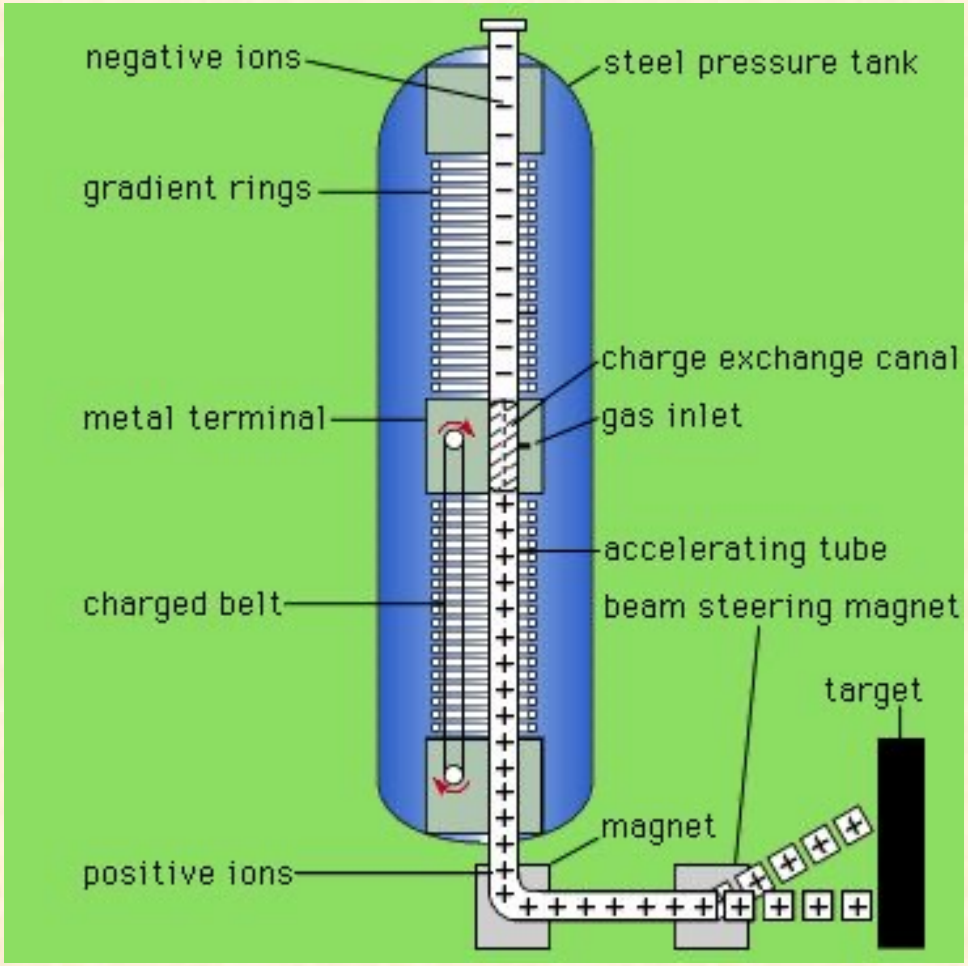


Image courtesy of http://people.clarkson.edu/~ekatz/scientists/graaff.html

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.
- There is a Tandem Van de Graaff at IPN Orsay (you will visit it Thursday).

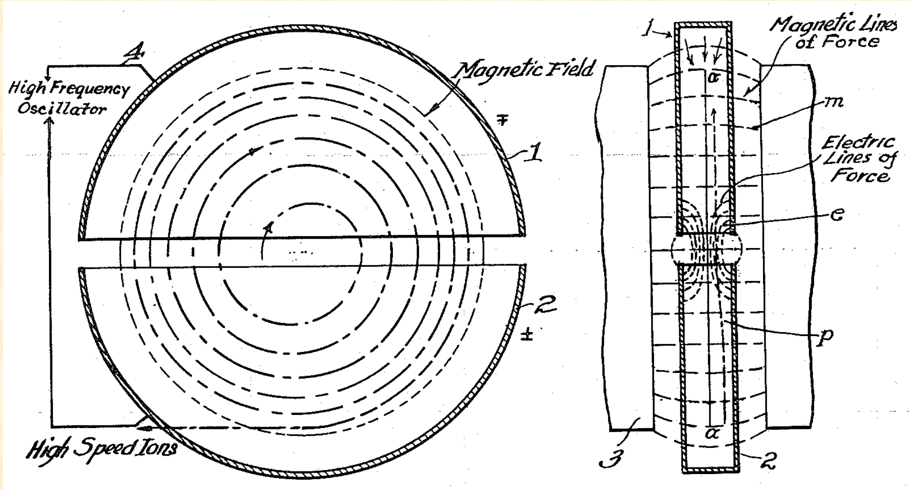


Example: 10MV Van de Graaff can accelerate C^- to 10 MeV and then C^{2+} to 30 MeV.

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

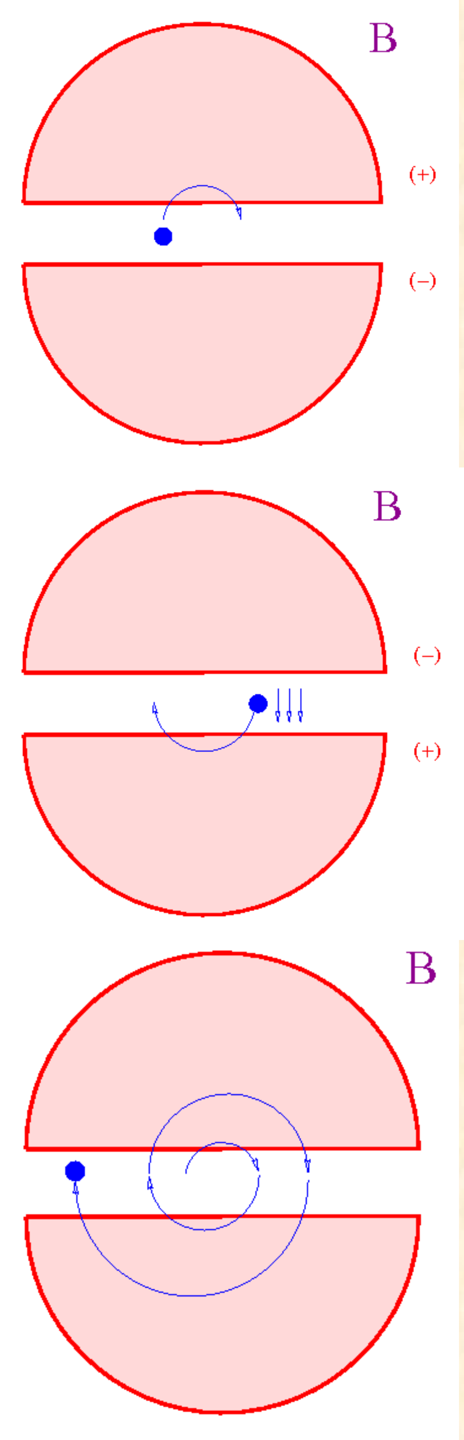
Cyclotron

- 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.



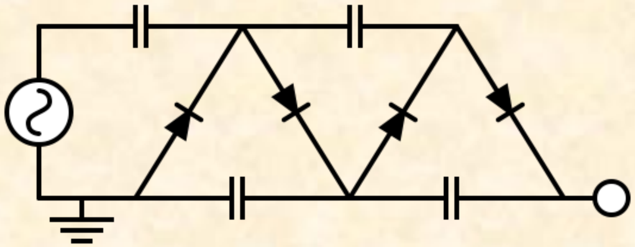
Cyclotron (2)

- 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.

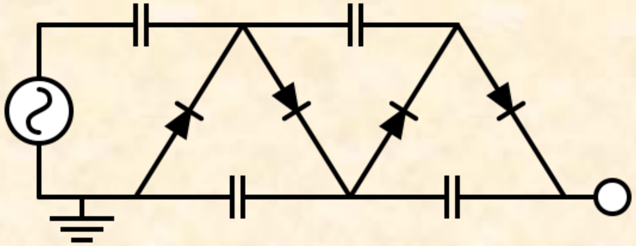


- The first half-cycle will load the first capacitor to its peak voltage. The second half-cycle loads the second capacitor and so on...
  => high voltage pulses

A Cockroft-Walton generator

(image source: wikipedia)

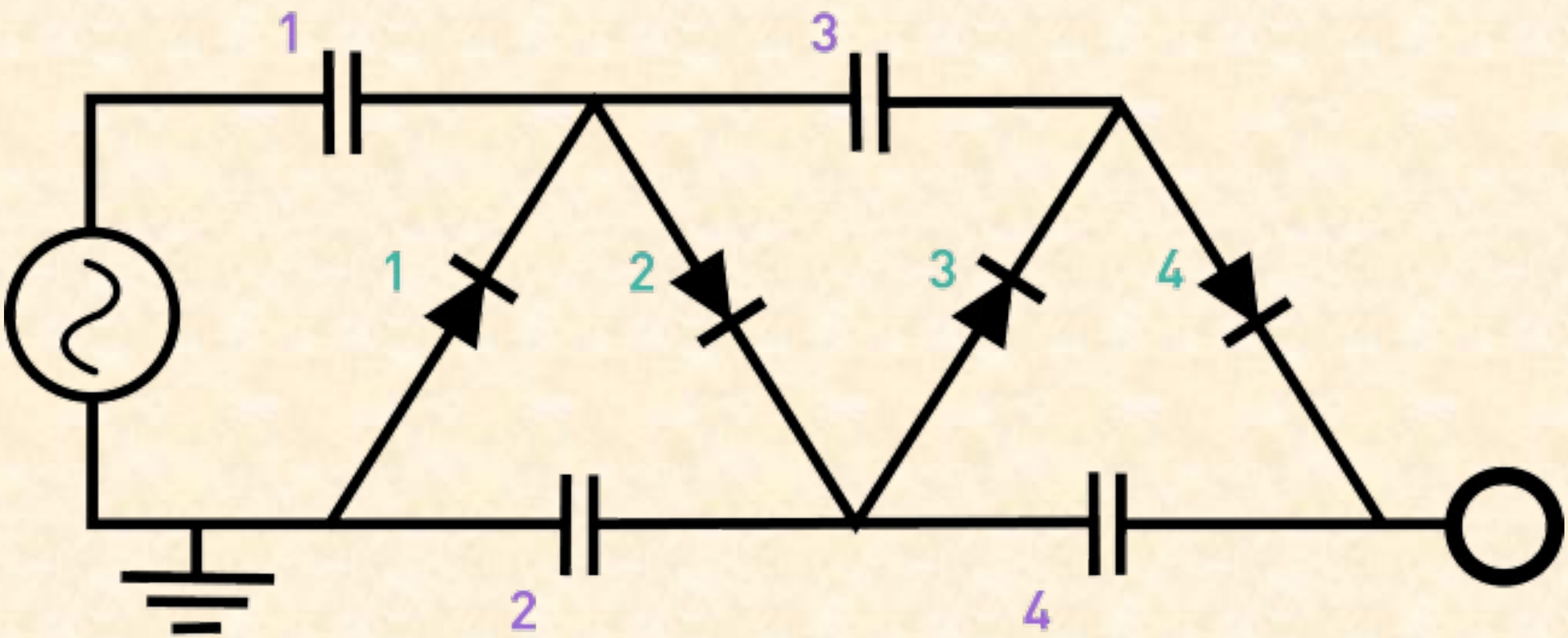
Quizz



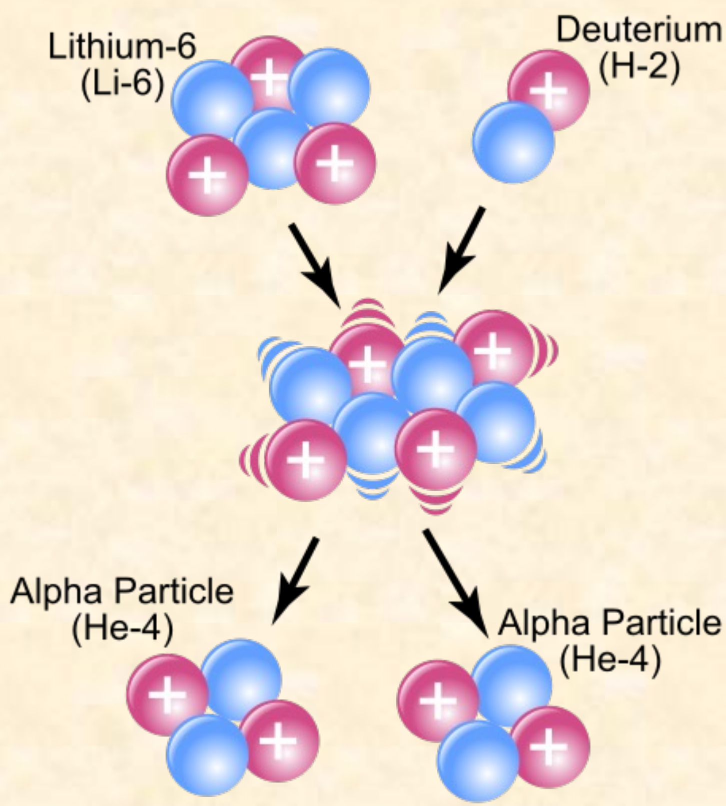
- Explain how a Cockroft-Walton generator works.

Answer

- Each cell is loaded in turn at each half period.
- Voltage on even side twice greater than on odd side.



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.

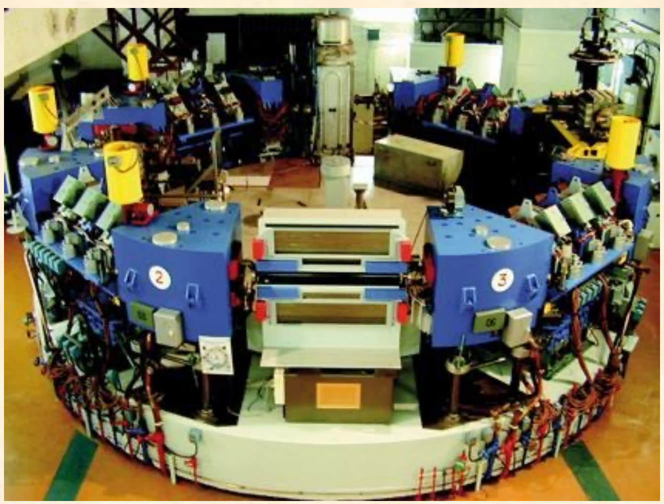
AdA

- 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).

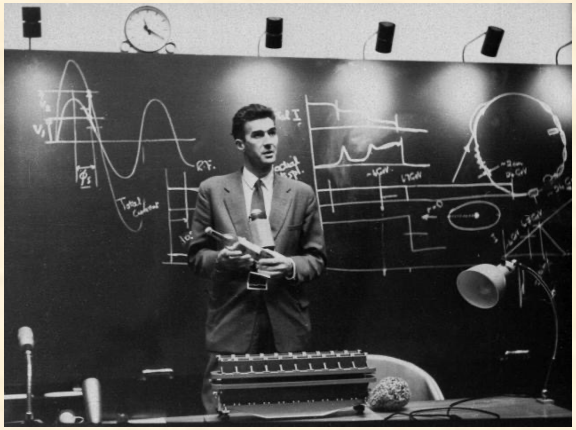


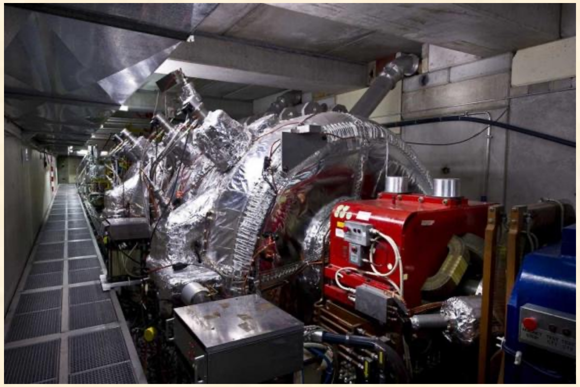
ACO is now a museum that can be visited.
We will visit it tomorrow.

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





Quizz

- Why CERN built a 200 GeV electron position collider after building a 400 GeV proton collider?

(a) Because of budget cuts: they could no longer afford to go to 400 GeV

(b) Stability (and hence luminosity) is better at 200 GeV than at 400 GeV

(c) The physics potential of a 200 GeV lepton collider is higher than that of a 400 GeV proton collider.

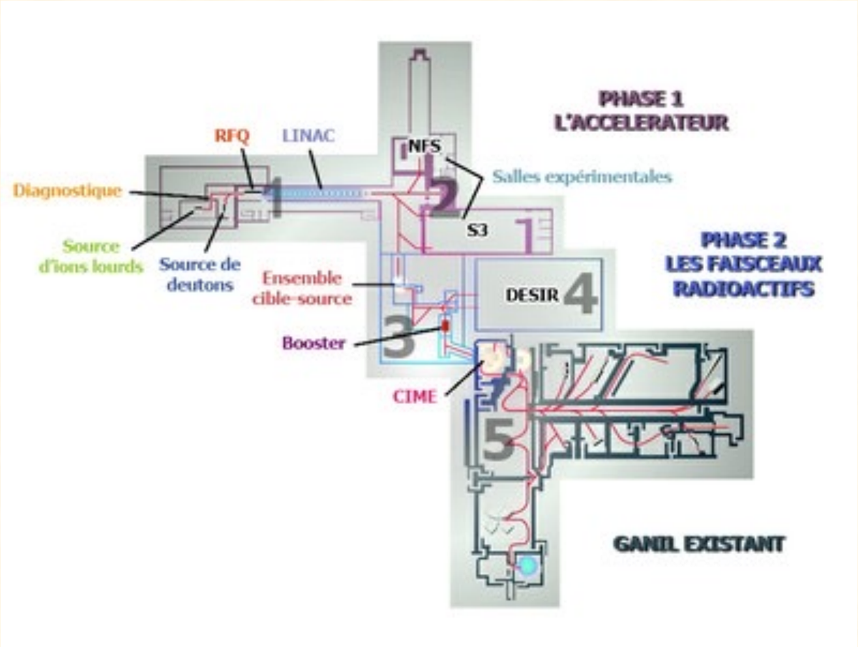
Answer (c)

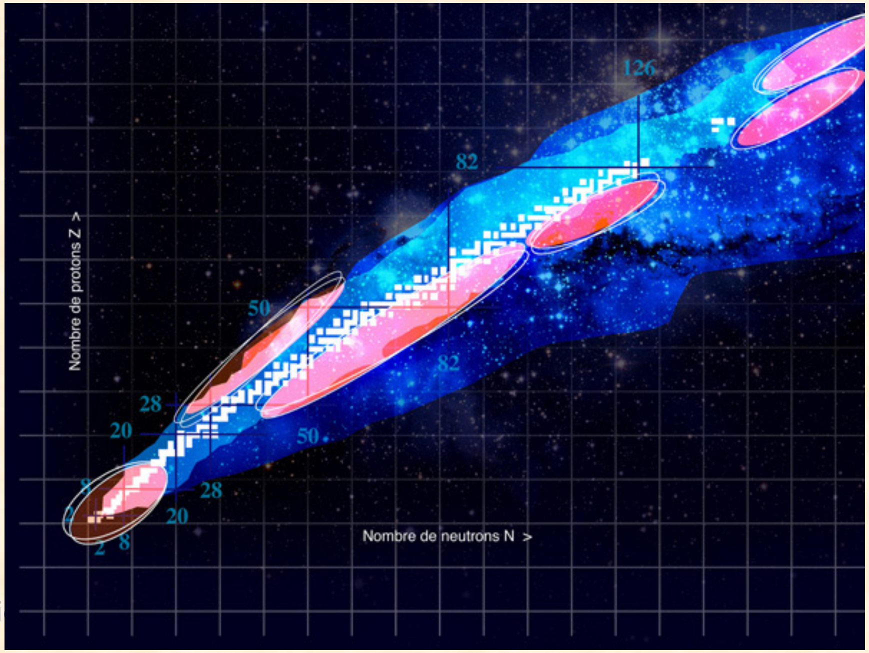
- The physics potential of a 200 GeV lepton collider is higher than that of a 400 GeV proton collider.

- For example to discover the Higgs only twice the Higgs mass was need in the cm with leptons (but they did not reach that energy).

GANIL and SPIRAL2

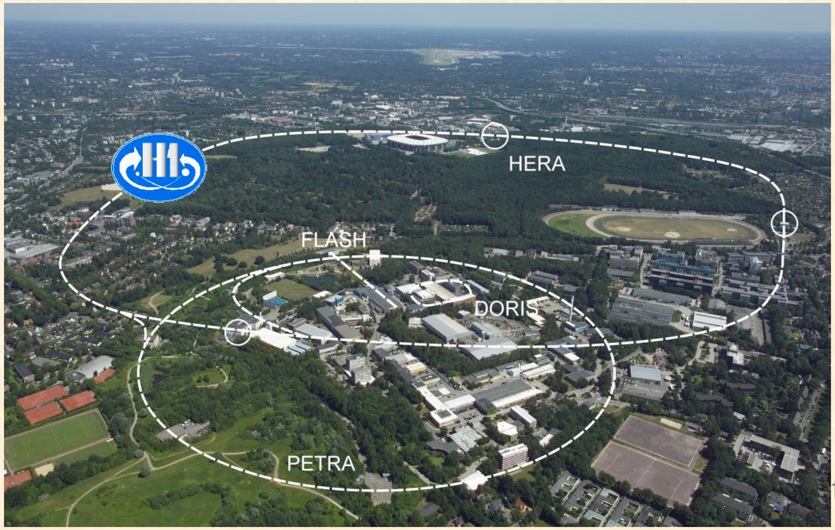
- GANIL is a laboratory dedicated to radioactive ions.
- An upgrade, SPIRAL2 will increase its physics reach.
- More about during the dedicated lecture on Thursday.

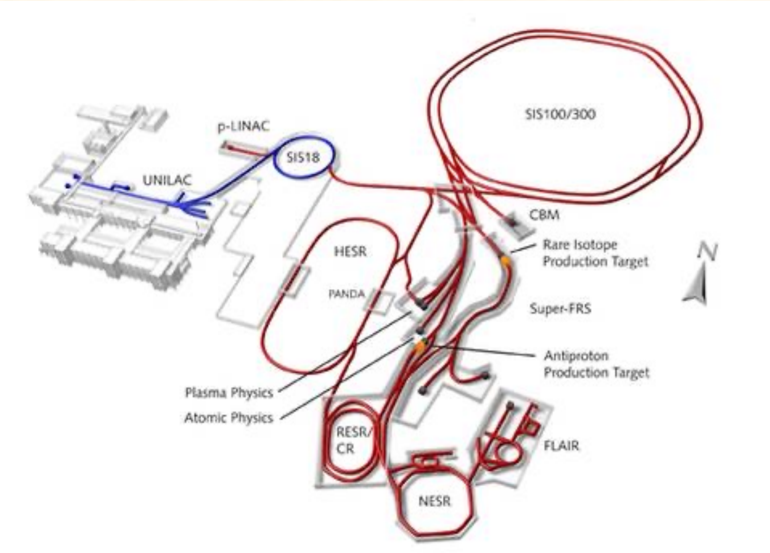




Other HEP accelerators in Europe

- Frascati (near Rome, Italy):
  ADONE: e+/e- collider (1969-1993) 1.5 GeV
  DAFNE (since 1999): e+/e- collider; 1 GeV, Kaon studies.
- DESY (Hambourg Germany):
  e+/e- collider (1960-1980)
  Electron-proton collider (HERA; 1990-2007) up to 920 GeV protons on 27 GeV electrons.
- GSI/FAIR:
  GSI is a heavy ions accelerator in Darmstadt, Germany (11.4 MeV/nucl.) since 1975. It is being upgraded as FAIR (start: 2018).





Accelerators at SLAC

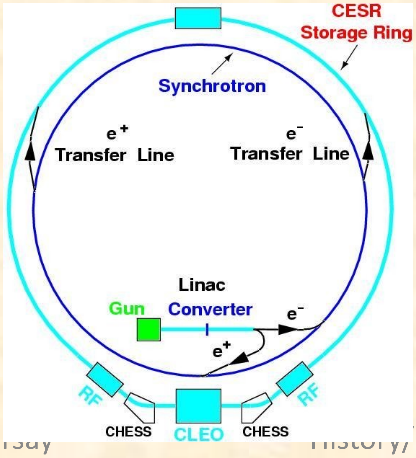
- 1962: Construction of the « 2 miles accelerator », the Stanford Linear Accelerator at SLAC (for e+/e- up to 45 GeV). {1968: Evidence for quarks}
- 1980: PEP: Positron-Electron Project at 29 GeV until 1990.
- 1989: Stanford Linear Collider (90 GeV cm) until 1998 (Detector: SLD).
- 1999: PEP-II, ~10 GeV B-Factory until 2008 (Detector: BaBar).

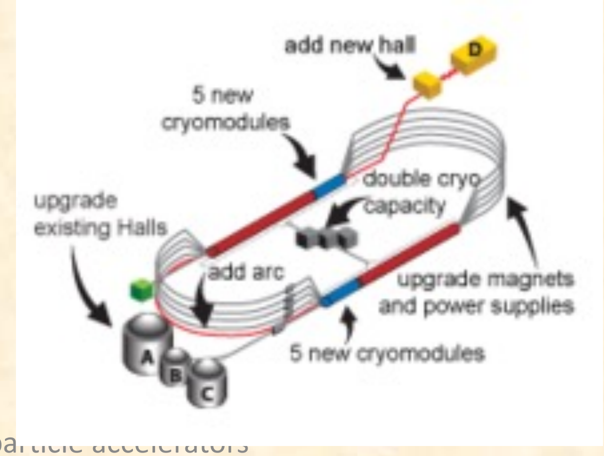
Other HEP accelerators in North America: Proton/ions

- 1969: Proton Linac at Fermilab near Chicago (200 MeV)
- 1974: TRIUMF, H- cyclotron (500MeV) in Vacouver, Canada
- 1976: 500 GeV ring at Fermilab.
- 1989: Tevatron (1 TeV cm then 2 TeV cm) @ FNAL.
  {Discovery of the top quark in 1995}
- 1983-1993: Superconducting Super Collider: attempt to build a 20 TeV collider in Texas (aborted in 1993 due to budget problems).
- 2001: RHIC, Brookhaven, heavy ions, up to 100GeV/nucleon

Other HEP accelerators in North America: CSER and JLAB

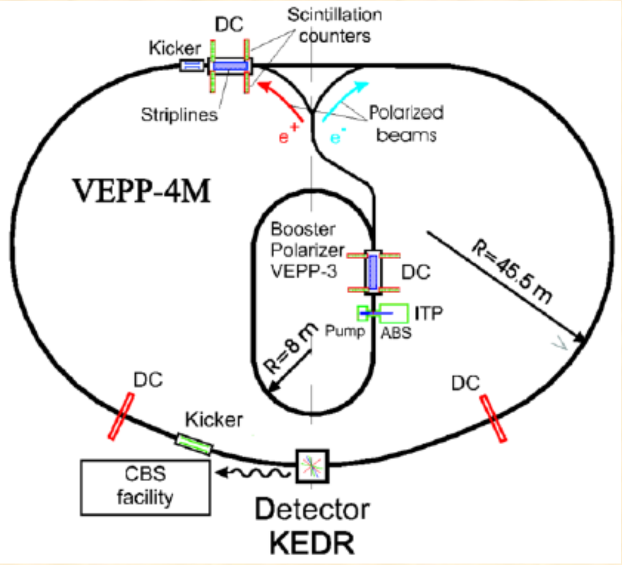
- Cornell (NY state):
  1979 CESR 3.5-12 GeV ring; B and C physics
  CESR has been converted into a test facility for rings.
  Cornell is also working (with other labs) on a new kind of accelerators called “Energy recovery Linacs”).
- Jefferson Lab (Virginia):
  1984: CEBAF Up to 6 GeV electrons; fixed target experiments; high intensity (still in operation).

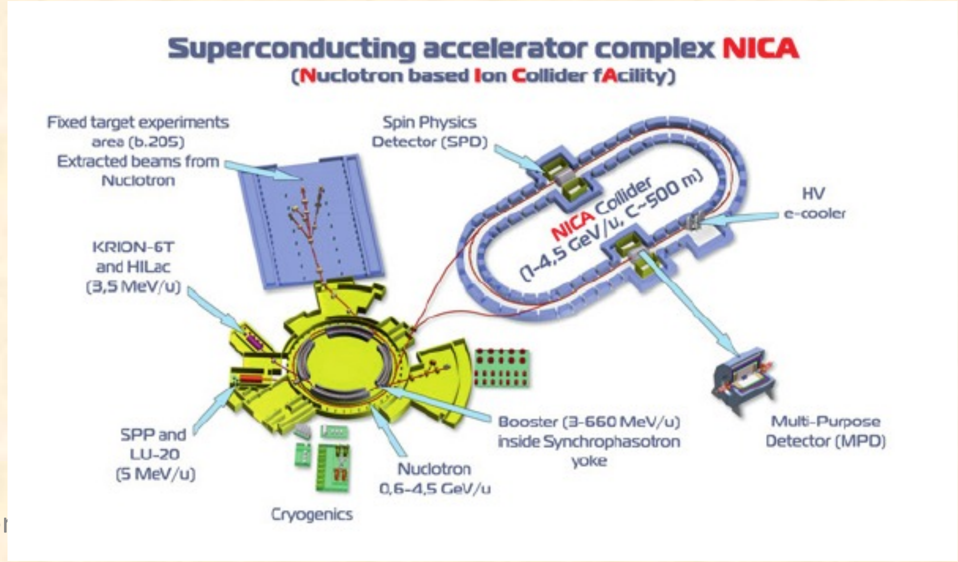




HEP Accelerators in (former) Soviet Union

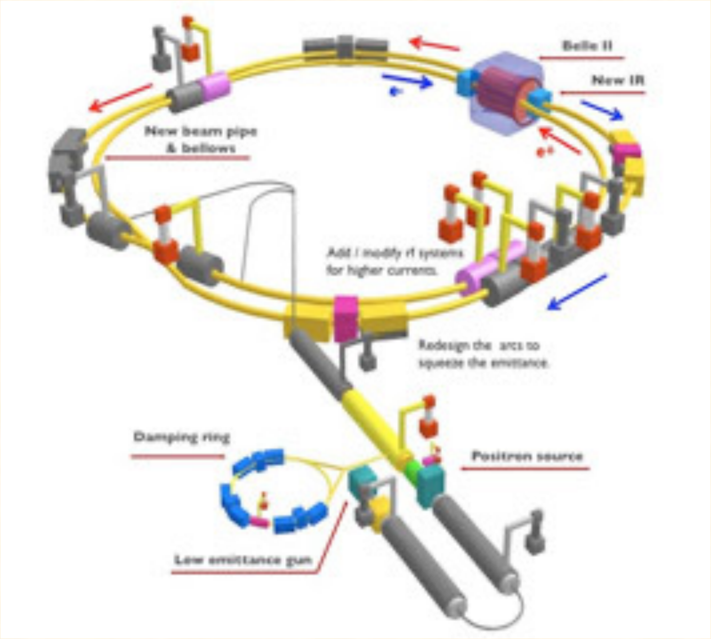
- Novosibirsk, Budker institute:
  - 1964: VEP, e+/e-, 130 MeV in Novosibirsk
  - …
  - 1994: VEPP-4M, e+/e-, 6 GeV, Meson physics
- Dubna, JINR:
  - 1957: 10 GeV protons (closed 2003)
  - NICA: Nuclotron Based Ion Collider Facility. Commissioning expected 2020.





HEP Accelerators in Asia

- KEK (Tsukuba, Japan):
  Proton synchroton (1976-2005), 12 GeV
  TRISTAN (1986-1995): e+/e- collider at 26 GeV
  KEKB (1998-2010): e+/e- collider 8 GeV on 3.5GeV
  SuperKEKB (2016+): e+/e- collider: 7GeV on 4 GeV.
- BEPC-II:
  Beijing Electron Positron Collider (started 2008) 4.6 GeV; charm quark studies.



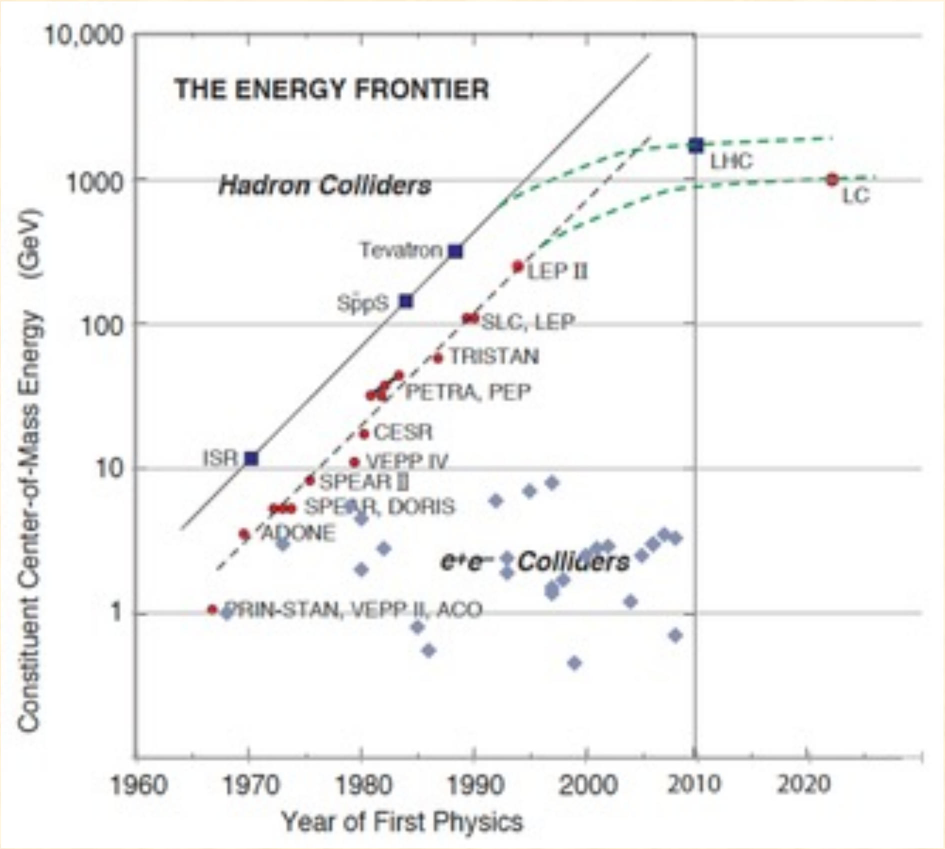
Quizz

- Why did KEK downgrade its TRISTAN collider from 26 GeV to 8 on 3.5 GeV?
  (a) Because of budget cuts
  (b) Because the physics is more interesting at low energy
  (c) Energy is not the only interesting parameter, luminosity is more important and they could reach a high luminosity at lower energy.

Answer (c)

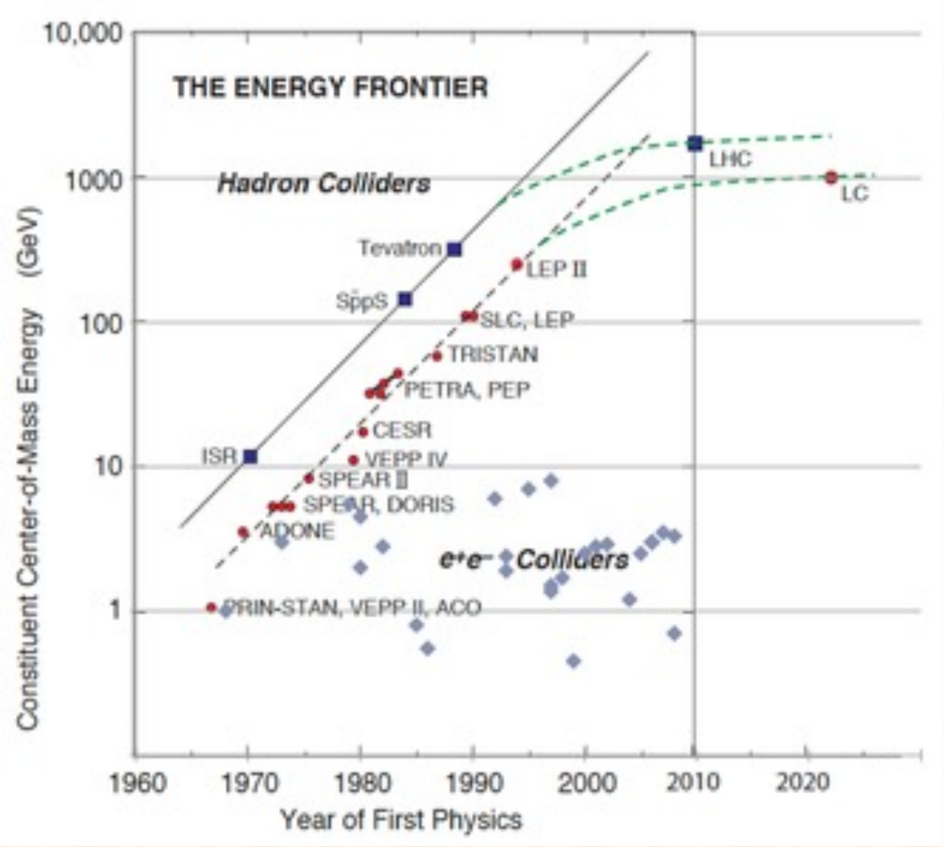
- To reach a high energy the peak current in the accelerator has to be reduced.
- There is a case for high energy accelerators to discover new particles.
- However lower energy accelerators can do “precision” physics by studying some rare particle with a very large statistics and studying more accurately their properties.
- KEKB (and SuperKEKB) study CP violation.

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…

Quizz



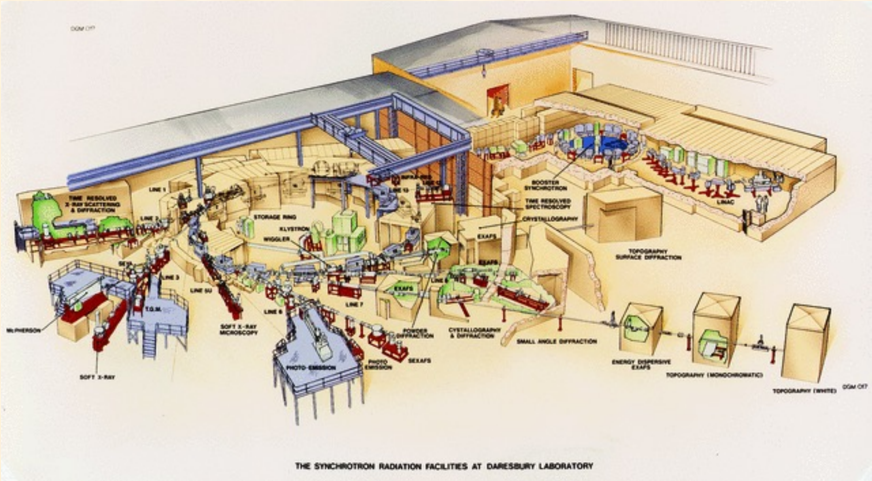
- On the livingston chart:
  1) Give the name of proton accelerator with an energy > 100 GeV
  2) What was the highest energy reached to date by an electron accelerator?

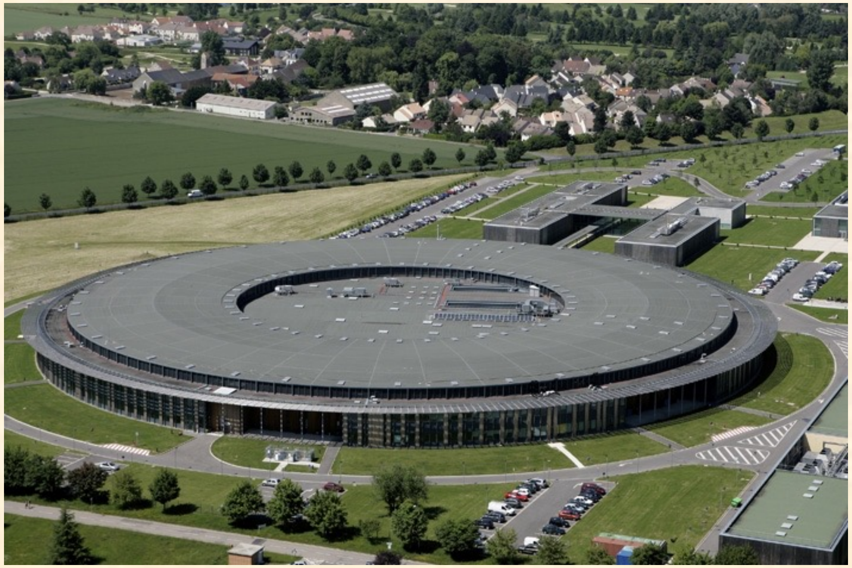
Light sources

- 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

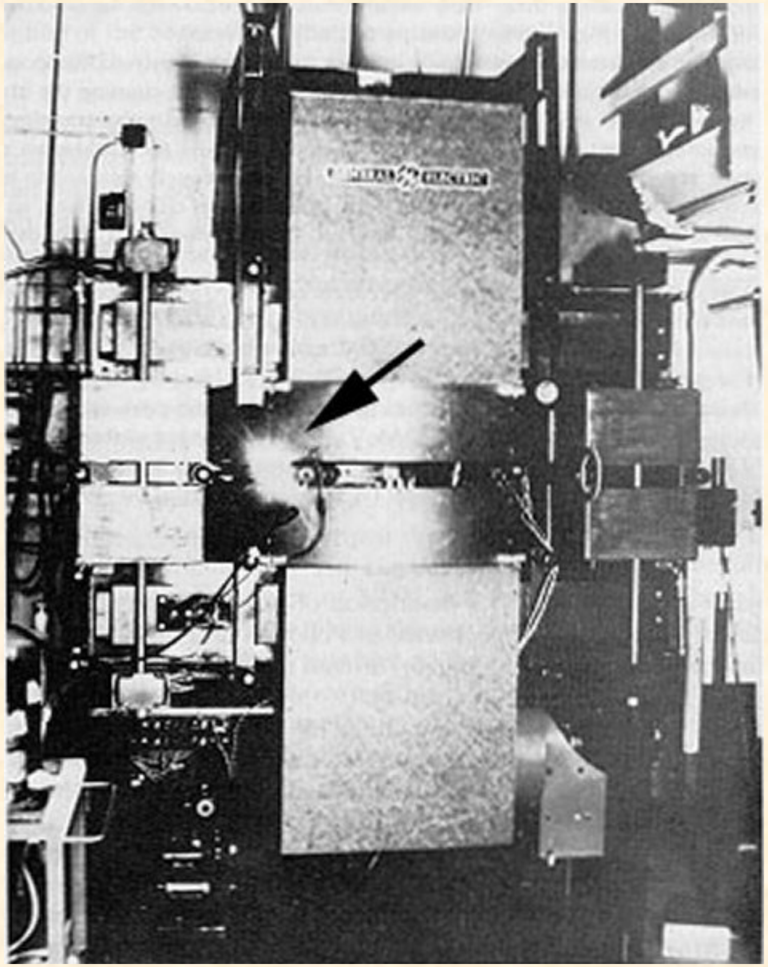




Source: SOLEIL

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.



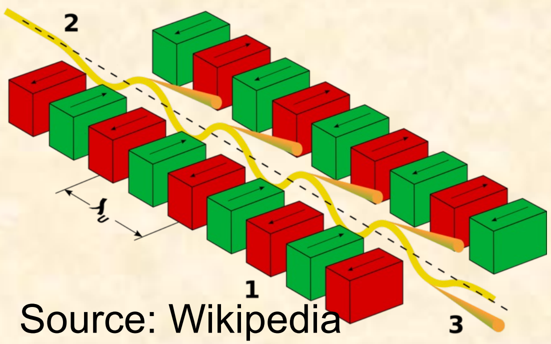
Discovery of Synchrotron radiation in 1946. Source: wikipedia

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.



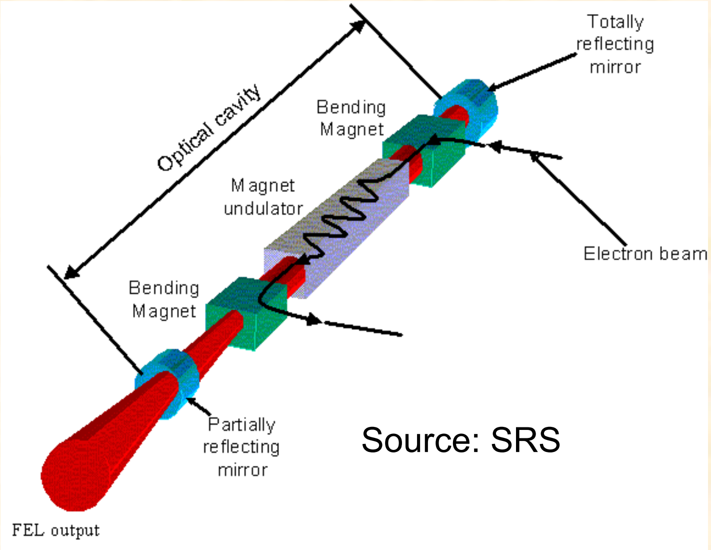
Source: Wikipedia

Undulator, *Source: Diamond*

Source: Diamond

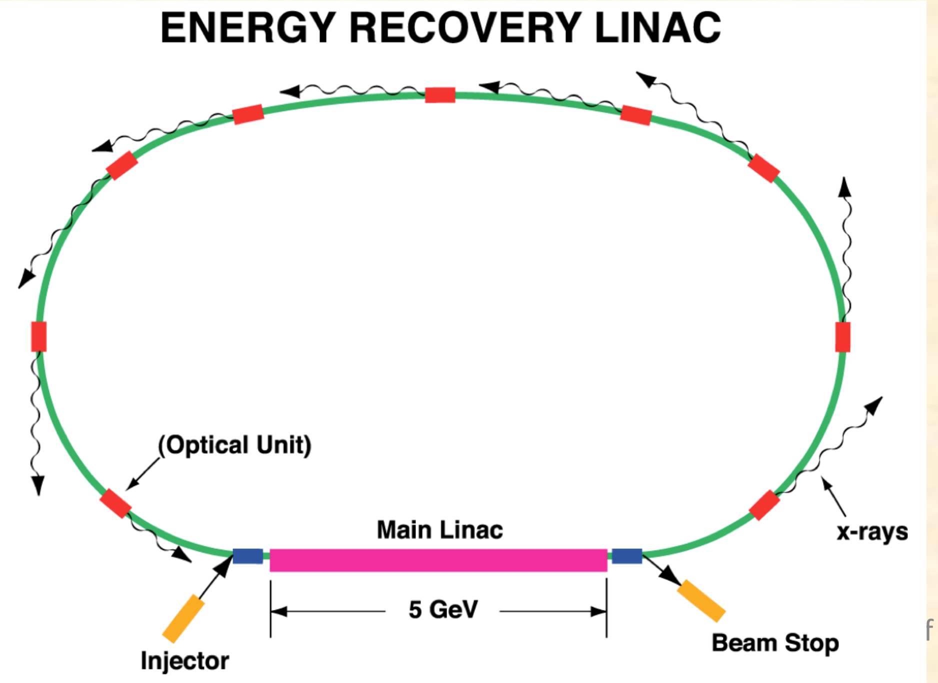
4^{th} generation light sources: Free electron lasers

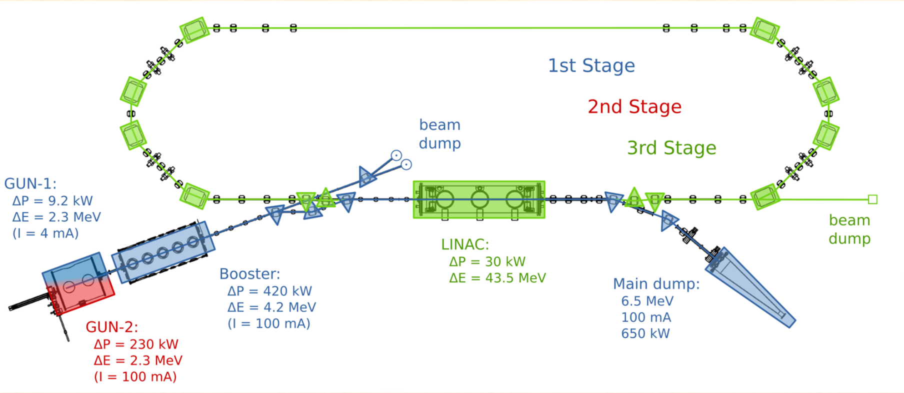
- The photons emitted in an undulator can stimulate the emission of more photons from the bunch.
- Free electron lasers (FEL) use this phenomena to generate photon beams with an even higher brilliance.
- FEL form the 4^{th} generation of light source. Some have started to operate in the past few years.
- FEL use a linac (not a storage ring, unlike synchrotrons).



Energy Recovery Linacs

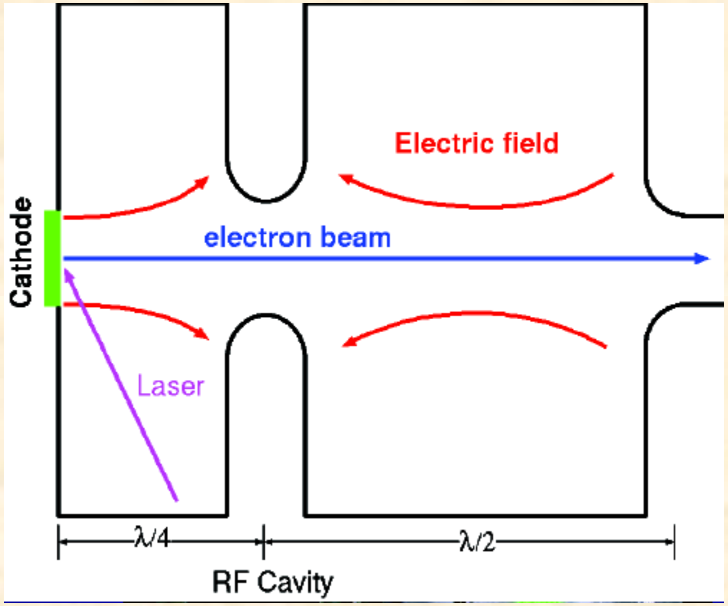
- Rings have the advantage of recycling the particles turn after turn => High efficiency
- FEL produce ultra-short light pulses => Interesting physics potential
- To combine the advantages of rings and FEL the concept of « Energy Recovery Linac »has been invented: after being used to produce light the particles are decelerated and the energy recycled to accelerate other particles.



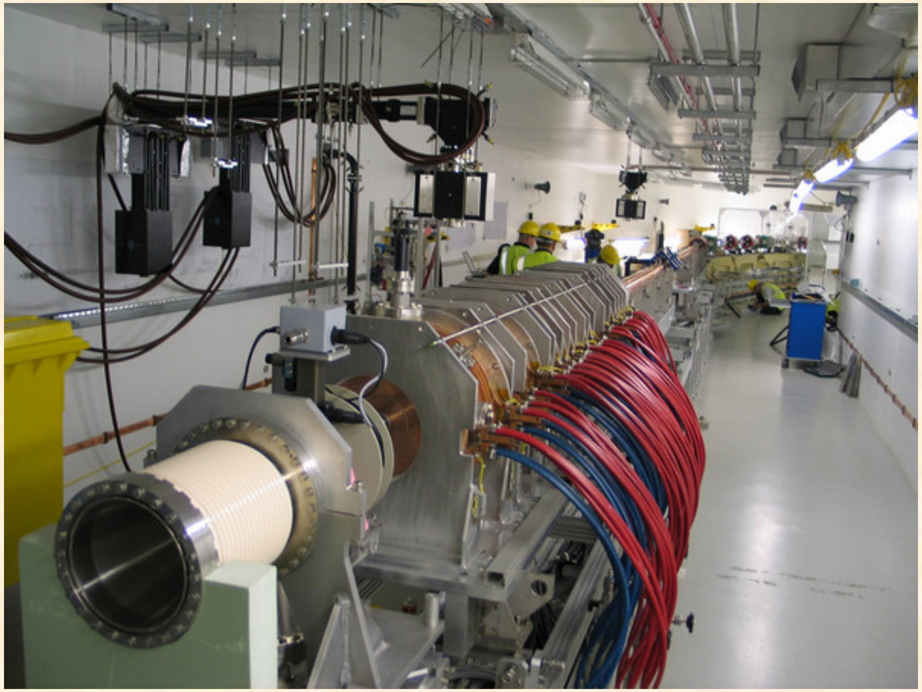


Lecture content

- *History of particle accelerators*
- Basic principles:
  - Particle sources
  - Particle acceleration
  - Magnets
  - Emittance and beam dynamics
  - Beam diagnostics
- Challenges for present and future accelerators



Particle sources



- Electrons
  - Thermionic emission
  - Field emission
  - Photo-emission
  - Beam quality
  - Space-charge
- Protons and ions

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.*

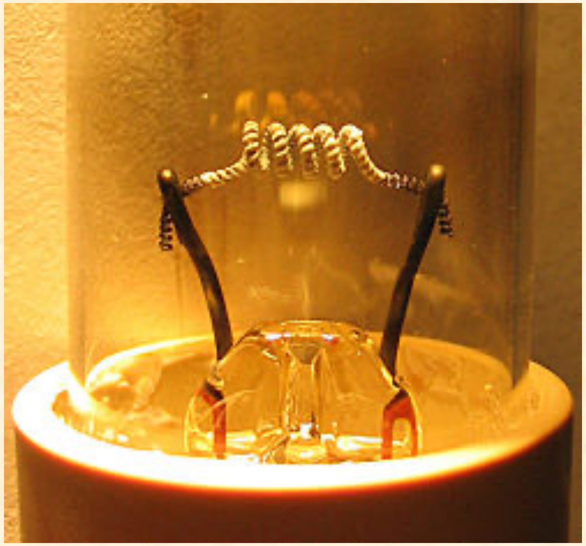
Producing beams of electrons: Thermionic effect

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

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

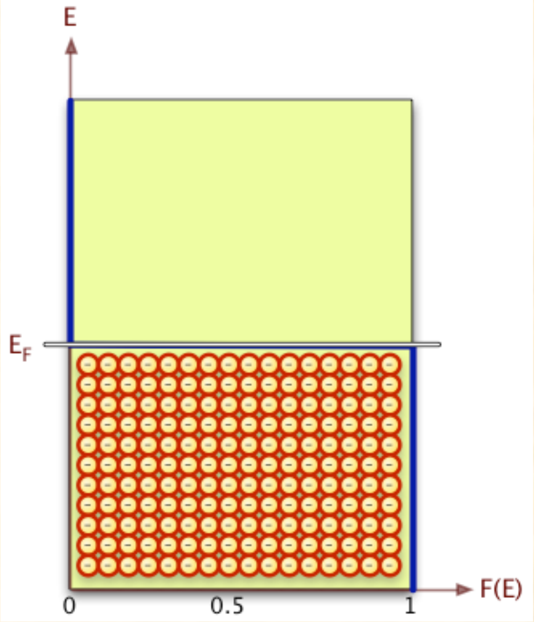
  - Electrons (fermions) obey a different but similar law.
  - When a metal is heated more electrons can populate high energy levels.
  - Above a certain threshold they electrons can break their bound and be emitted:

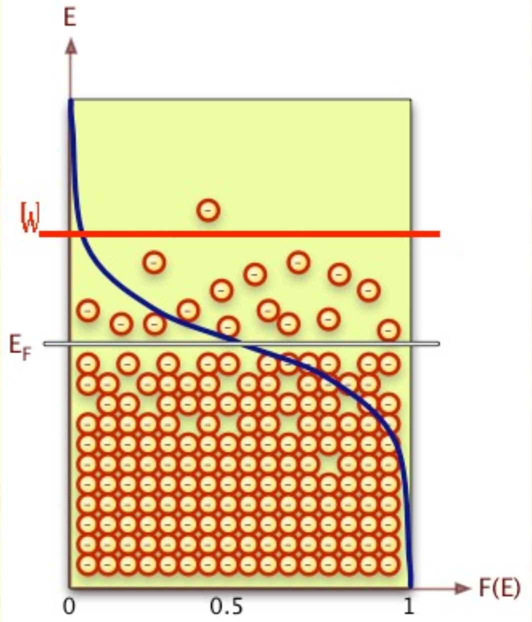
    This is thermionic emission.



(image source: wikipedia)

Electrons in solids



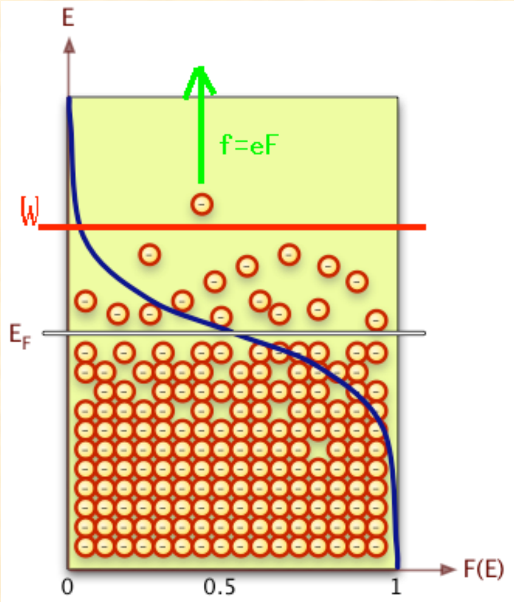


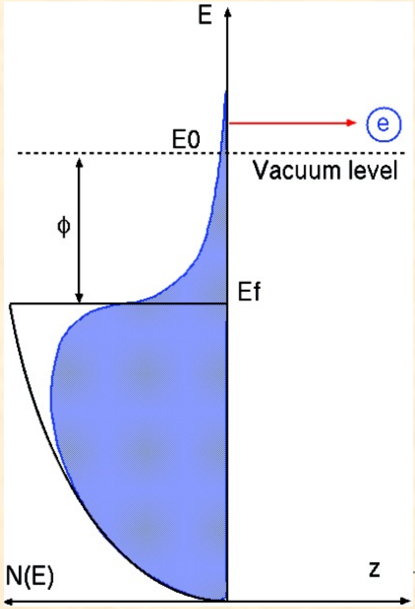
(image source: http://cnx.org/content/m13458/latest/

- 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".

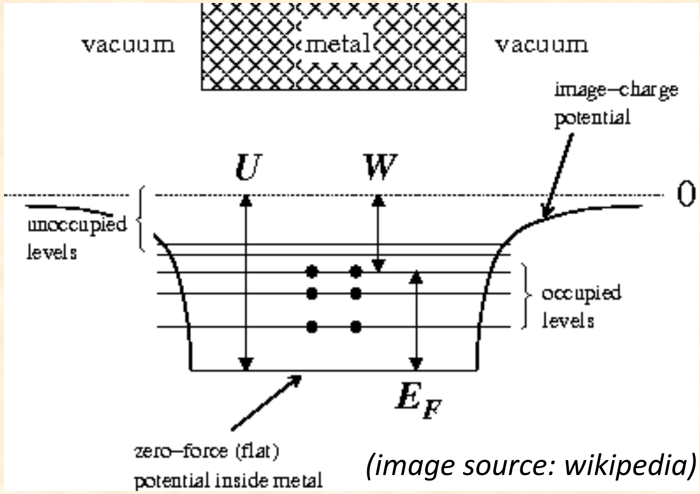




(image source: Masao Kuriki, ILC school)

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

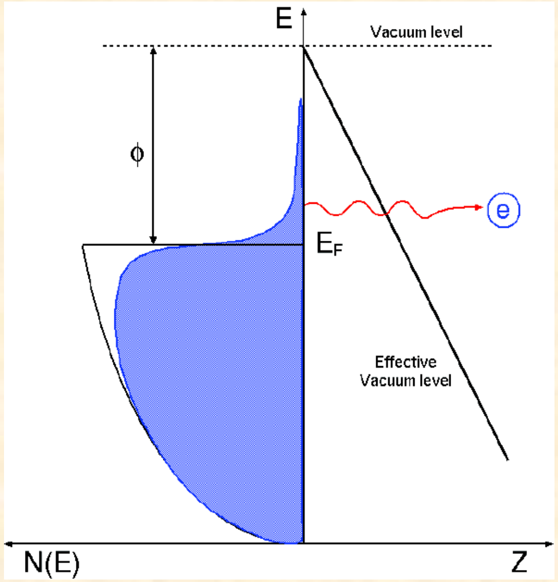
- The application of an electric field F to a material modifies the work function, this is called the Schottky effect:

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

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

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

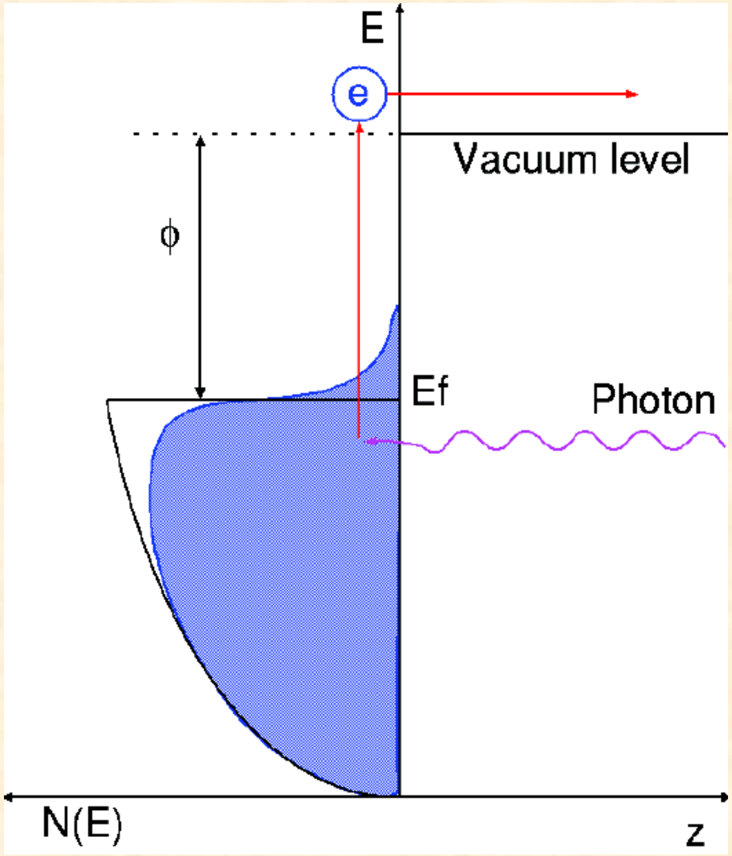
- This formula is valid only up to 10^8V/m. For more intense fields additional phenomena happen.



(image source: Masao Kuriki, ILC school)

Photo-electric emission

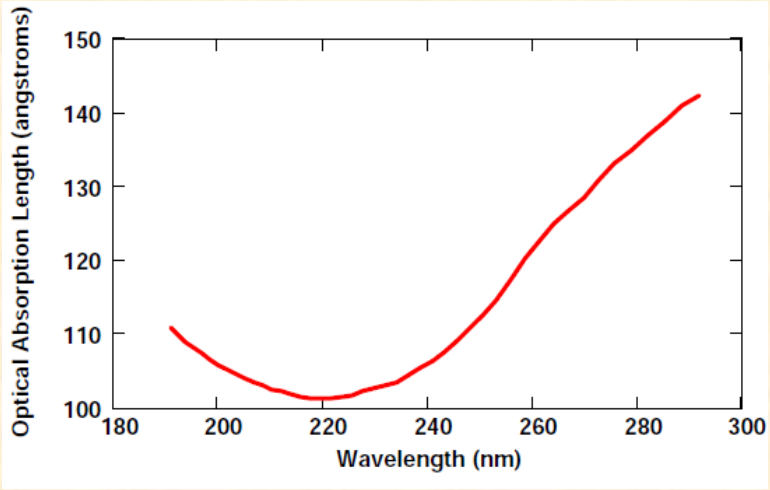
- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.



(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.

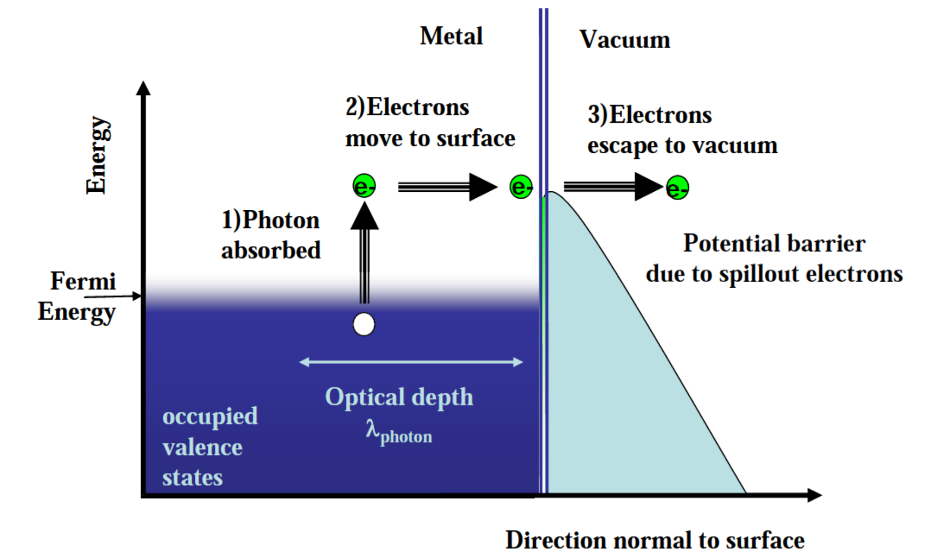


(image source: Dowell et al., Photoinjectors lectures)

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 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

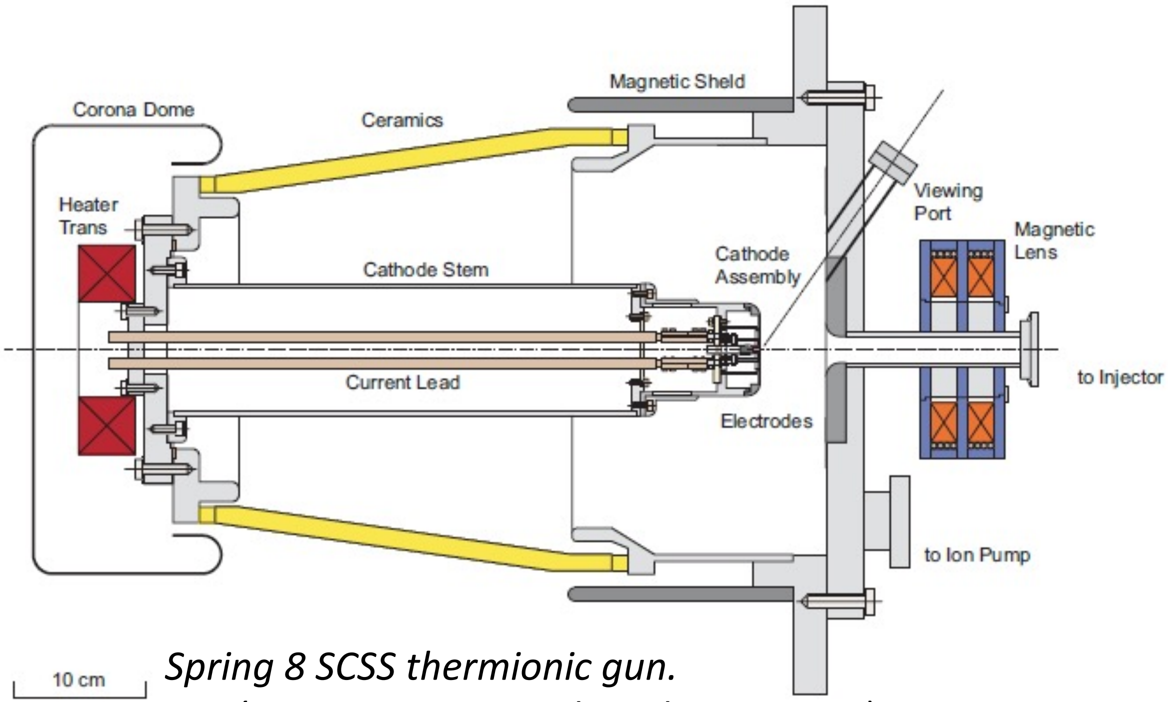
$$E = h\nu = \frac{hc}{\lambda}$$

- 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 escapes by tunnel effect are possible).

Example of thermionic gun

SCSS

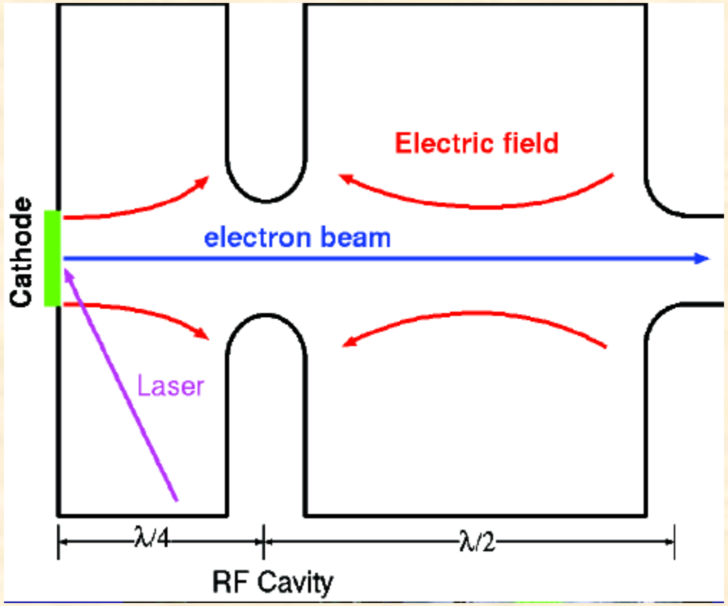
500kV Electron Gun



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

RF Gun

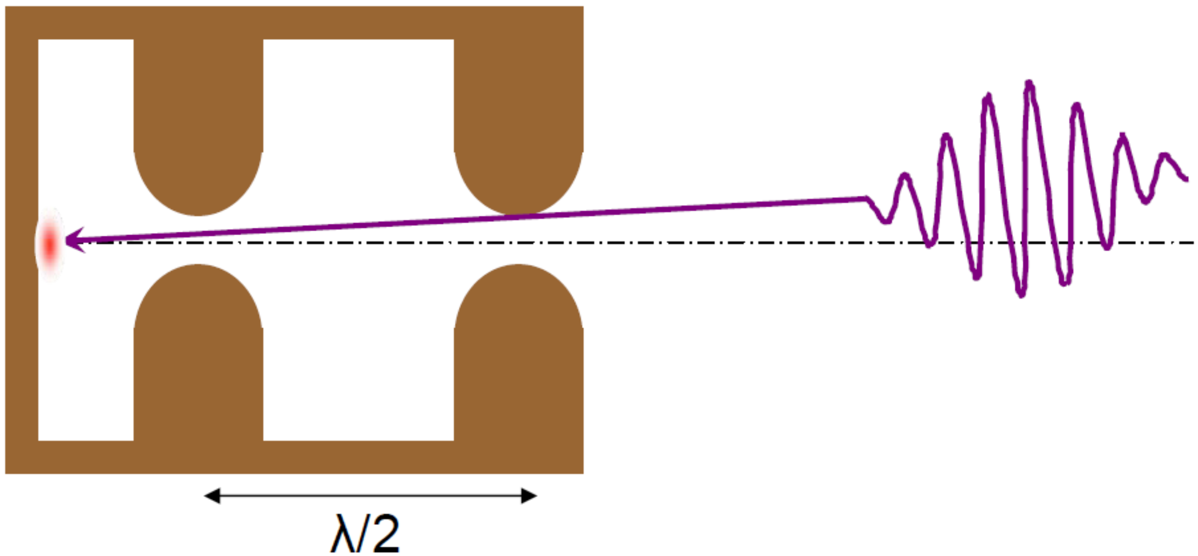
- The high voltage of a DC gun can be replaced by a RF cavity.
- This can provide much higher accelerating gradients and hence limit the space charge.
- RF guns are often coupled with a photo-cathode.
- RF gun can generate shorter bunches (using short laser pulses).



(images source:Masao Kuriki, ILC school)

Principle of a RF Photo-gun

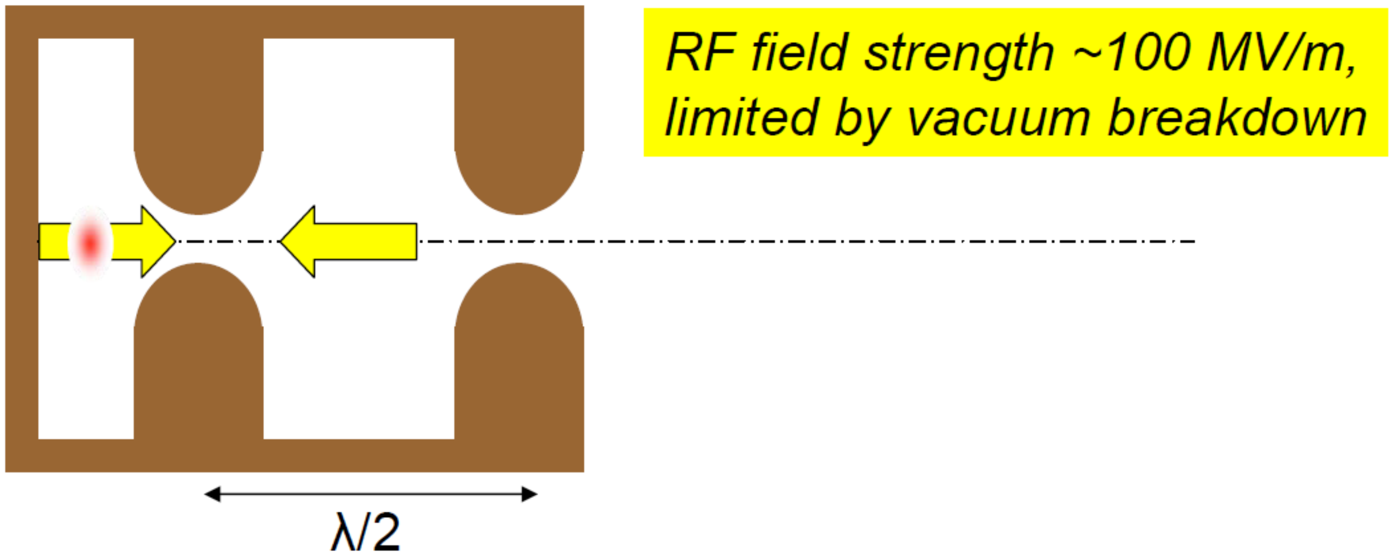
Pulsed laser photoemission...



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

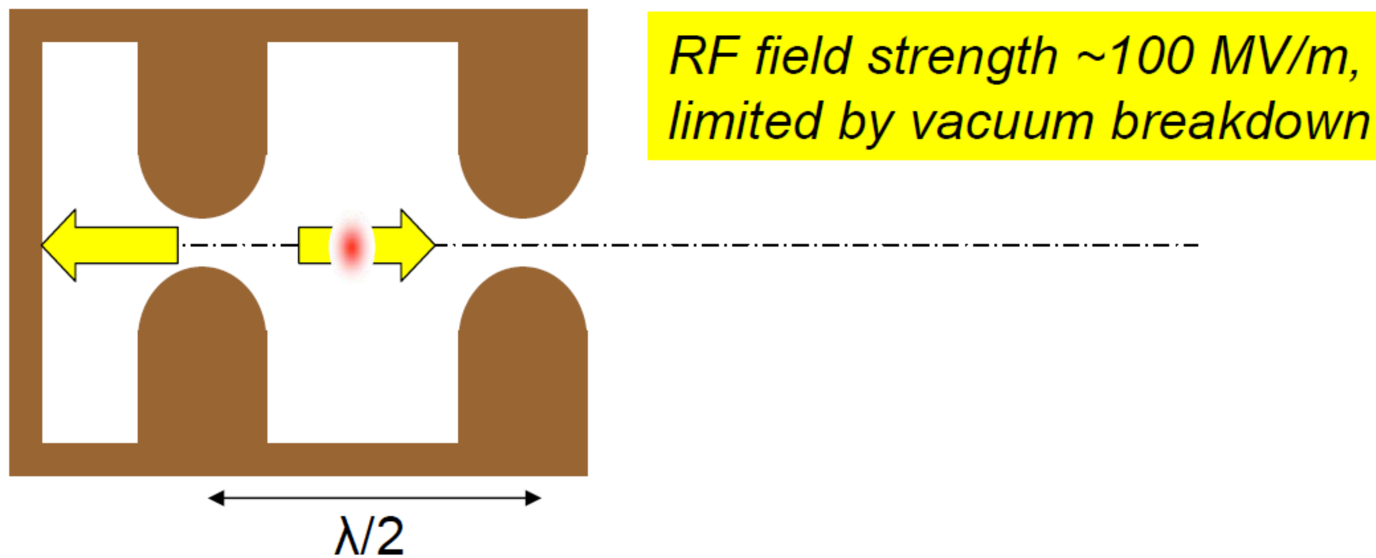
...and RF acceleration.



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

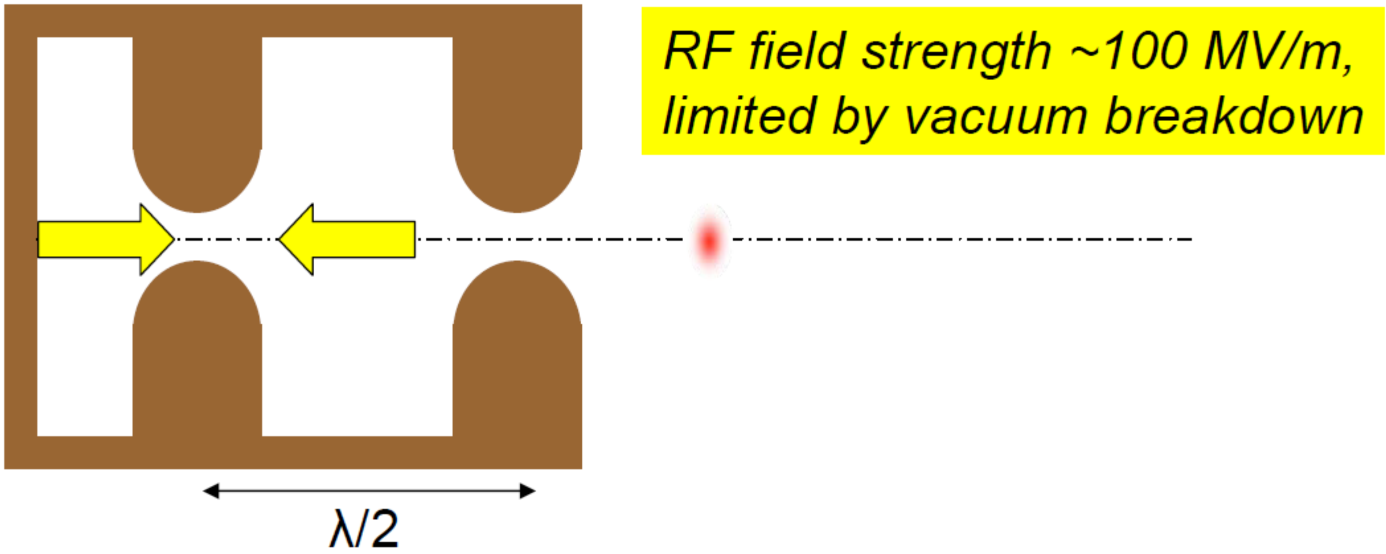
...and RF acceleration.



Courtesy Jom Luiten, TUV Eindhoven

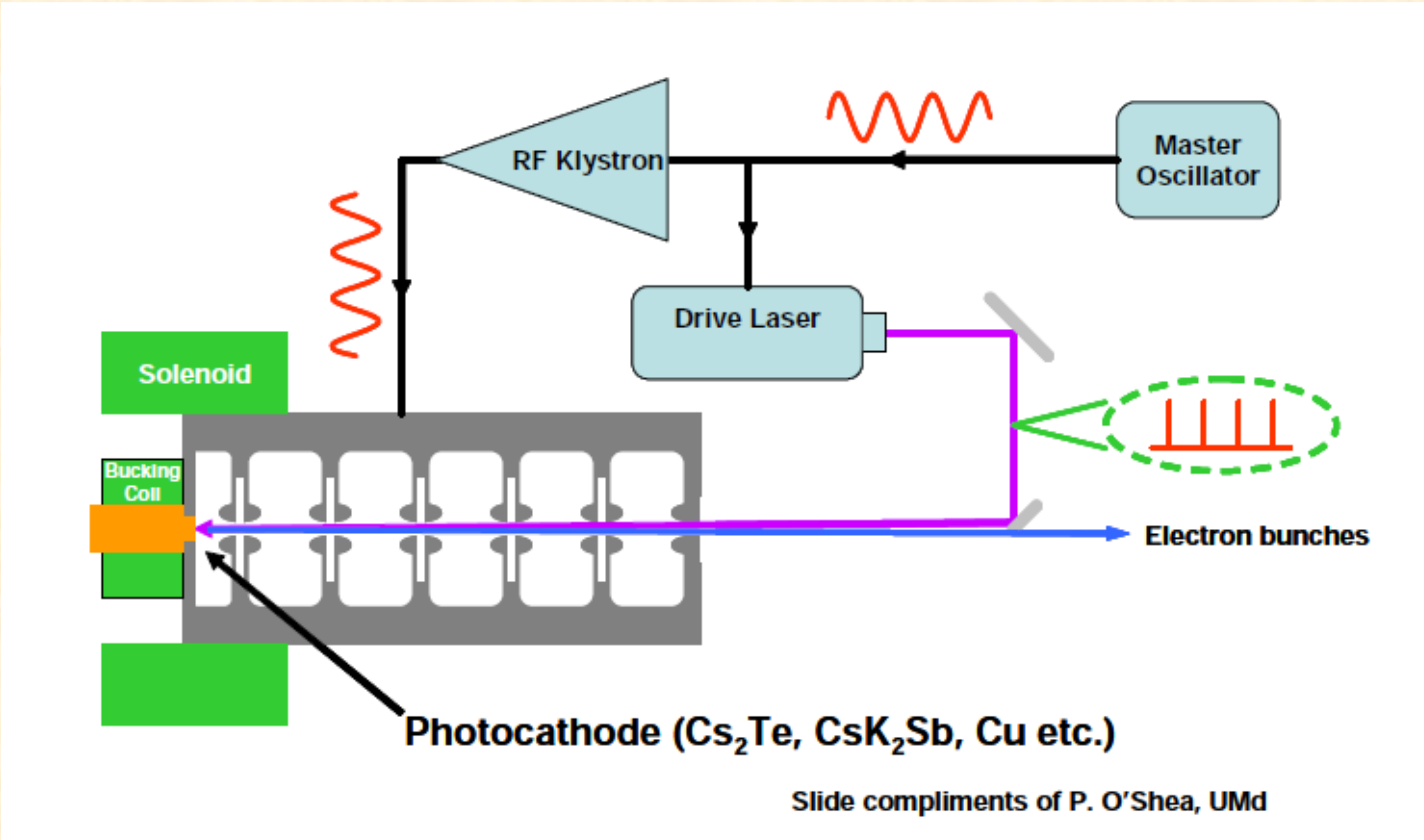
Principle of a RF Photo-gun

...and RF acceleration.

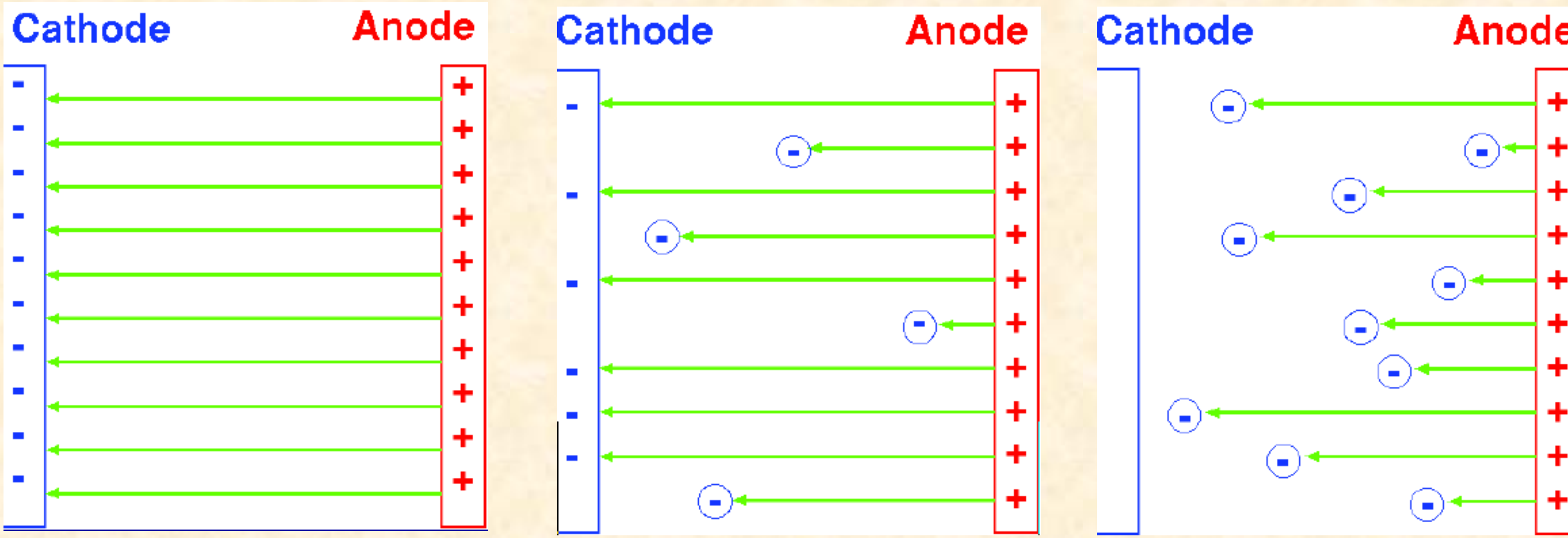


Courtesy Jom Luiten, TUV Eindhoven

RF photocathode gun



Space-charge limitation

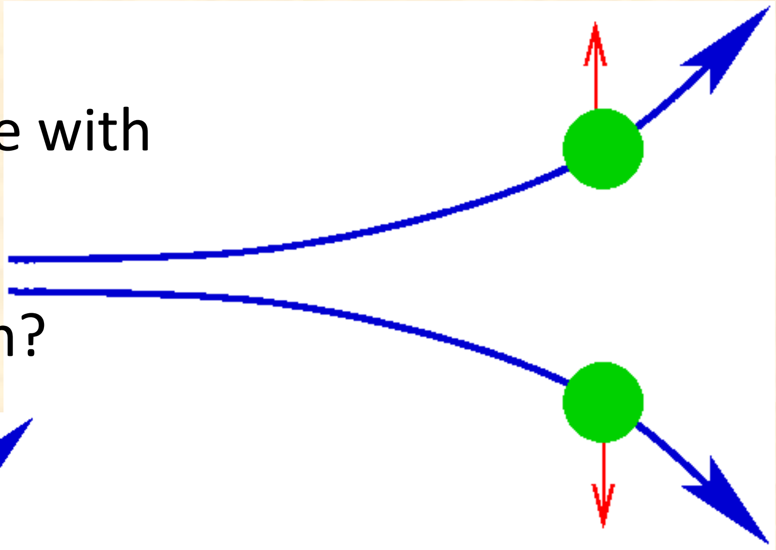


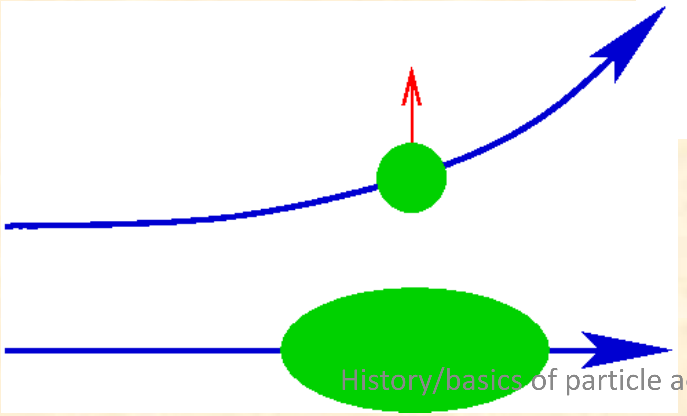
- Emitted electrons shield the cathode from the anode => reduced field
- This limits the intensity of the emission.
  Child-Landmuir law (potential V, area S, distance d)

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

Space-charge effect

- 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?

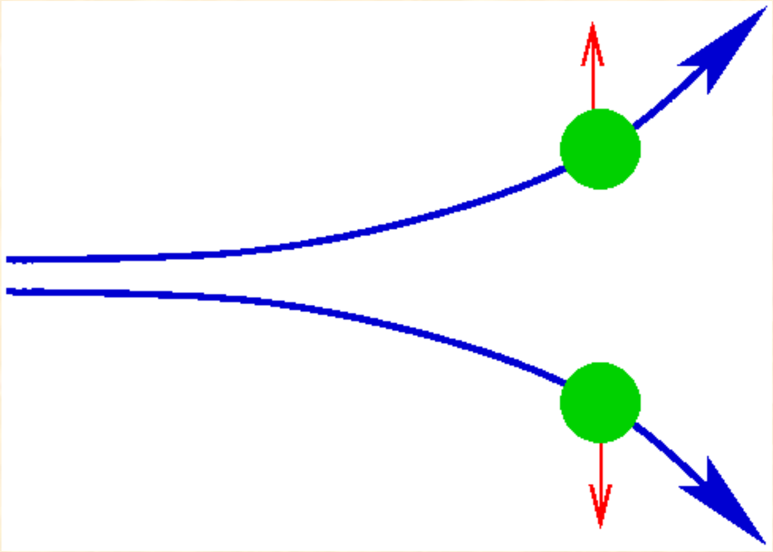


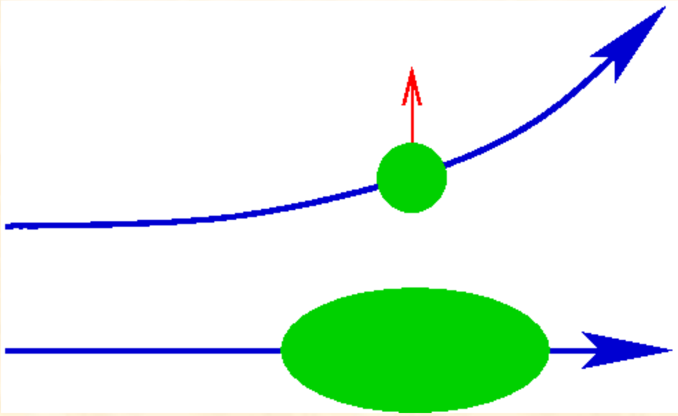


Coulomb force between two electrons

$$f = \frac{1}{4\pi \in_0} \frac{q_1 q_2}{d^2}$$

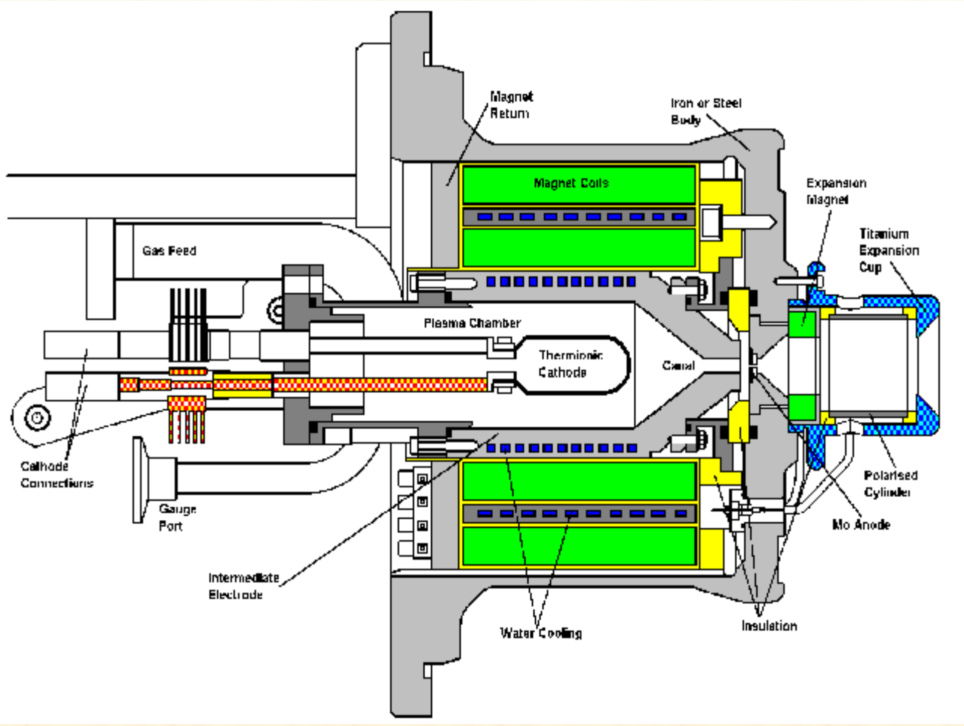
- Assume d=1micrometre.
- $f=2\ 10^{-16}$N
- This may look small but an electron is not very heavy
- $f/me=2.5\ 10^{14}$N/kg
- This force is very intense on the scale of the electrons.
- Typical charge in a bunch: ~1nC = $1.6\ 10^{10}$ electrons
- This force has to be taken into account to mitigate beam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





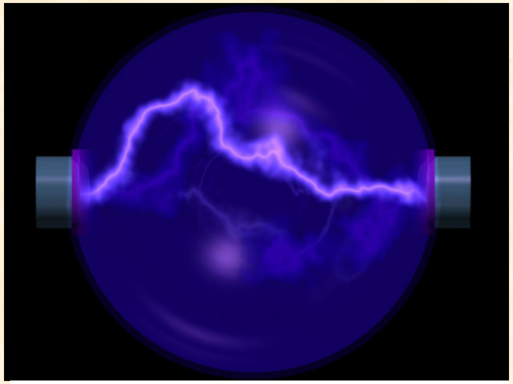
Proton source: the duoplasmotron

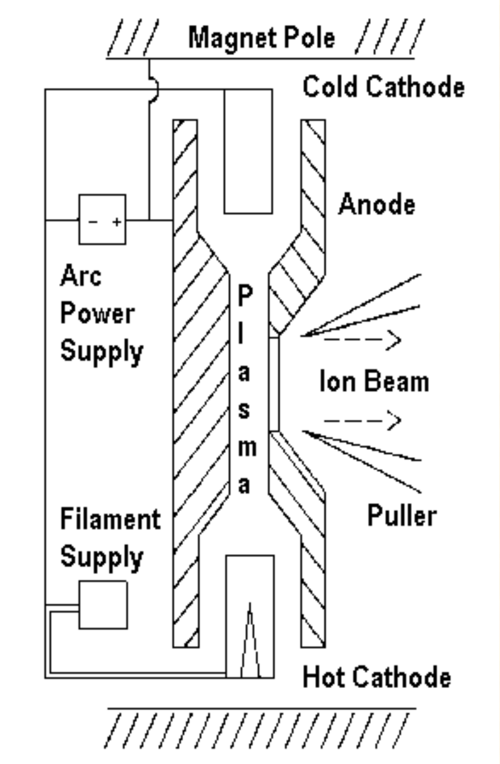
- At CERN the protons are produced in a duoplasmotron source.
- Hydrogen is injected in a plasma chamber at a high electric potential (100kV)
- Inside the plasma chamber a cathode emits electrons.
- These electrons hit the gas atoms and ionise them into protons.
- The protons are attracted toward lower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

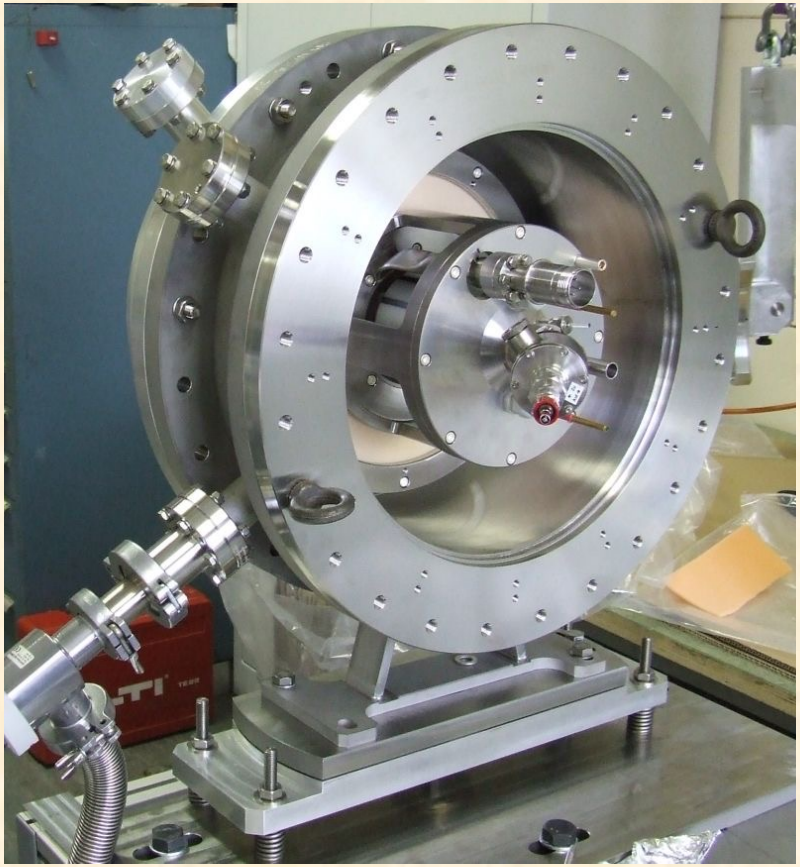




(images source: CERN)

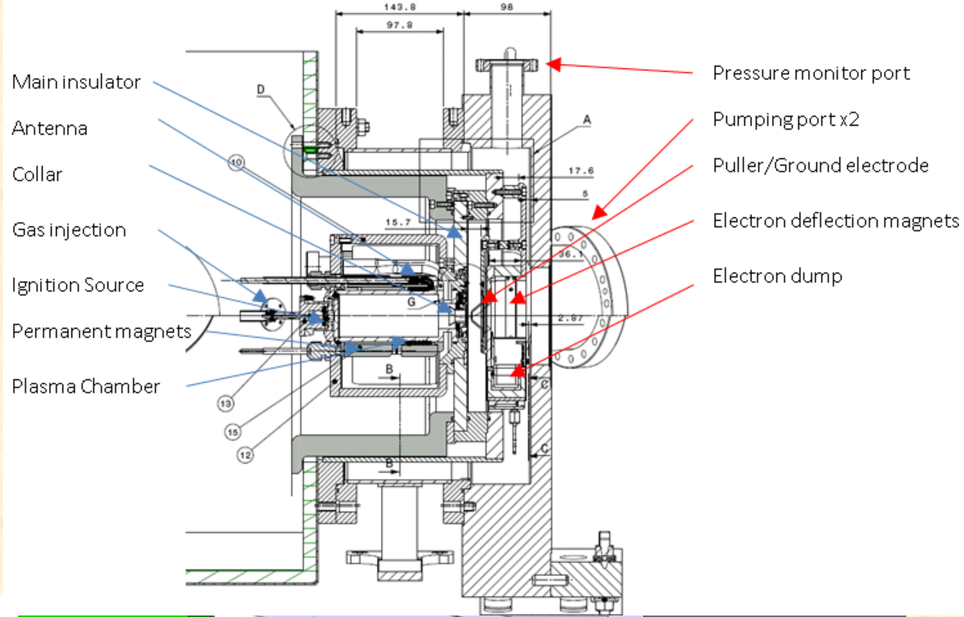
Source upgrade: linac 4 H- source:

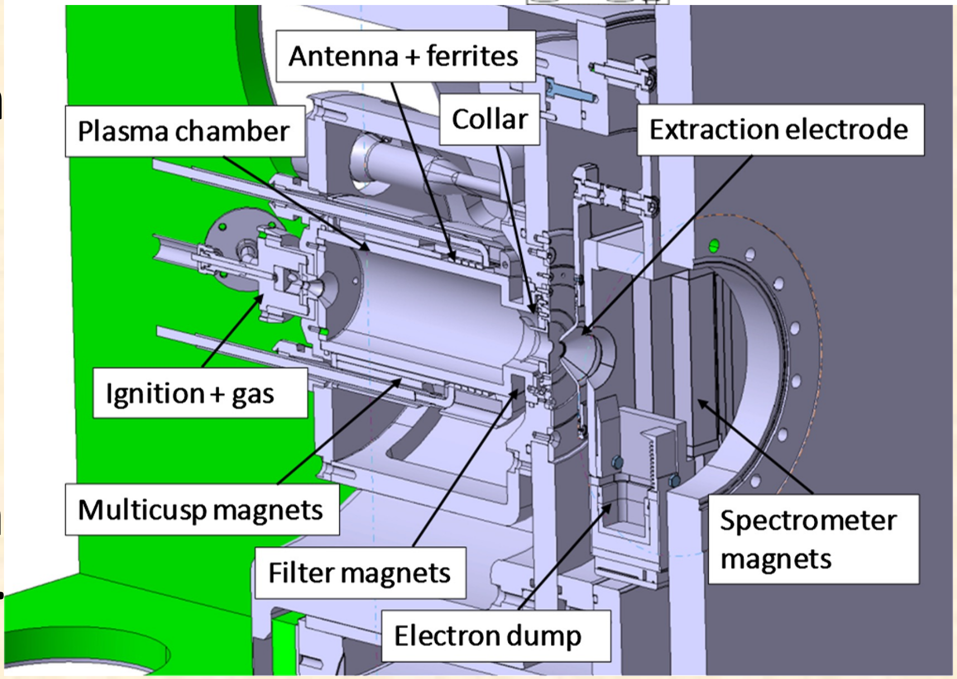
- The current proton source for the LHC was built in 1978.
- It will soon be replaced by a new source based on a different technology: RF ion source.



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.



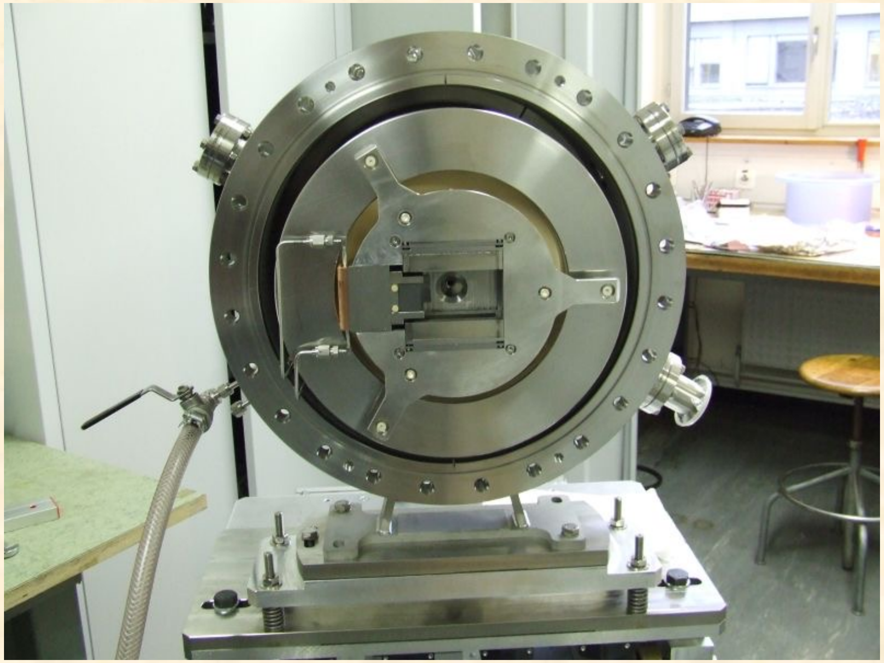


http://linac4ionsource.web.cern.ch/

Courtesy Richard Scrivens, CERN

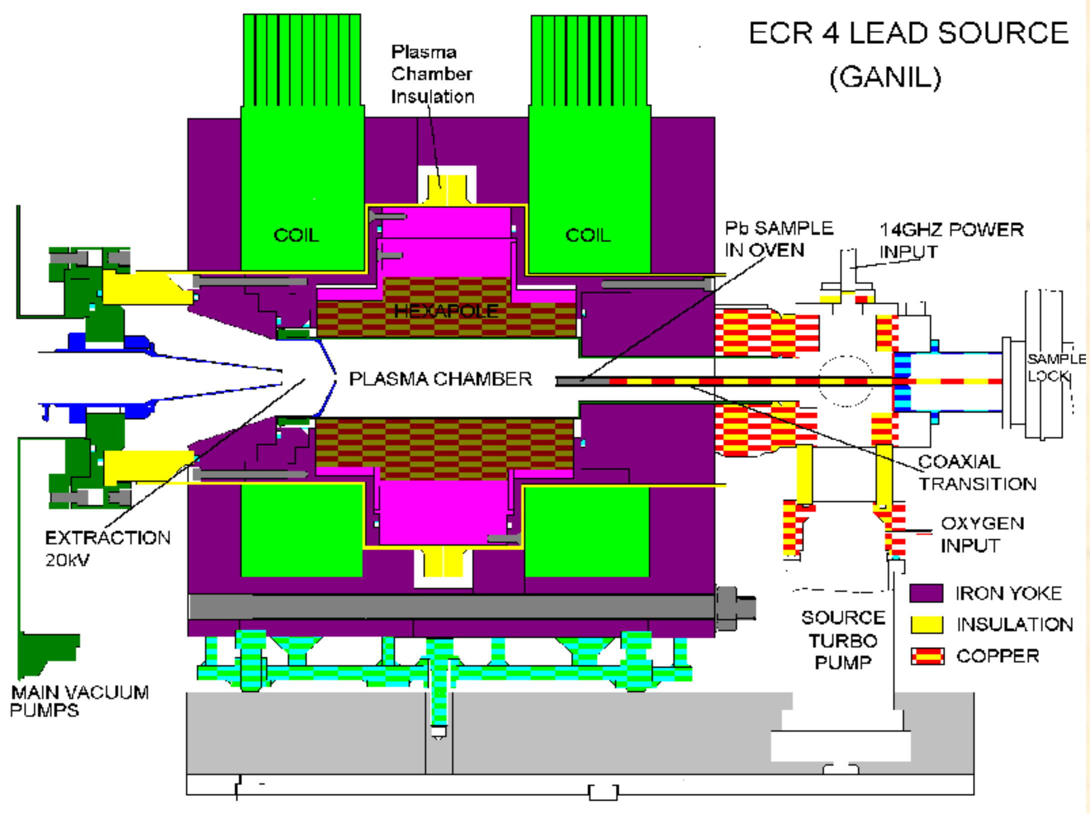
Why a H- source to produce protons?

- 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 (we will see why later).



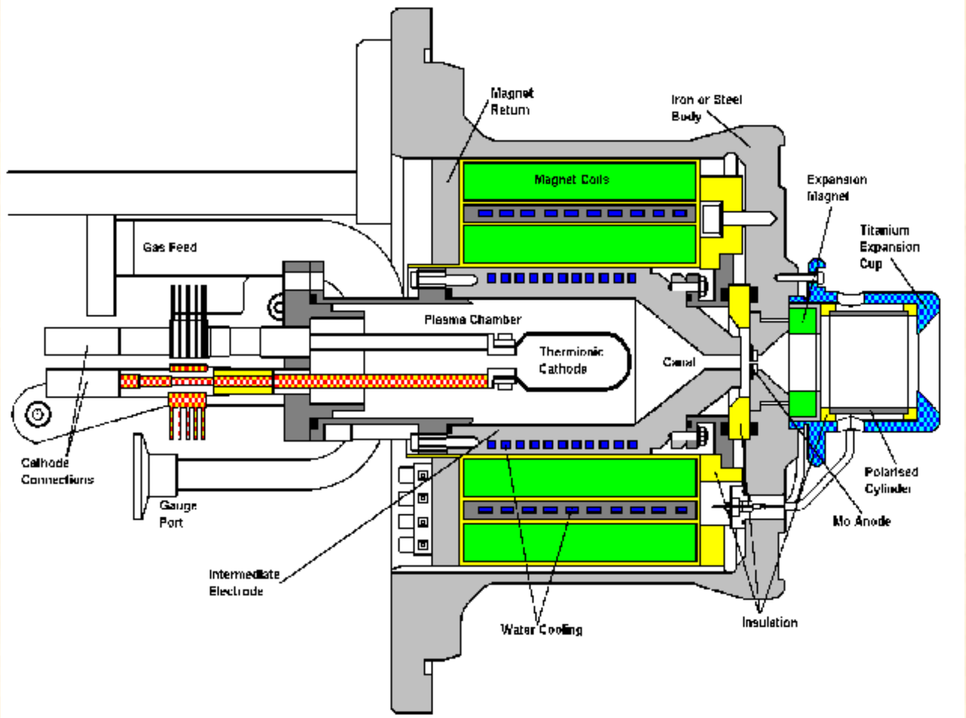
ECR sources

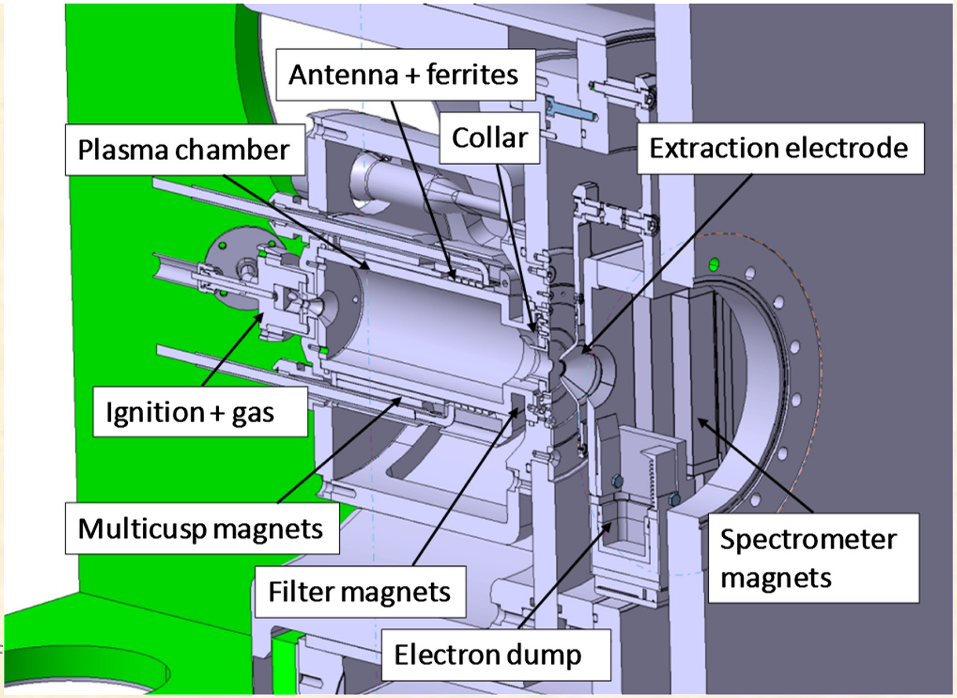
- In addition to pp collisions the LHC will also be used for Pb-Pb collisions.
- The Pb ions are produced in an “Electron Cyclotron Resonance” source.
- Electrons magnetically confined in a plasma chamber are excited by an electric field.
- Lead is heated and brought in the chamber.
- When the electrons 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

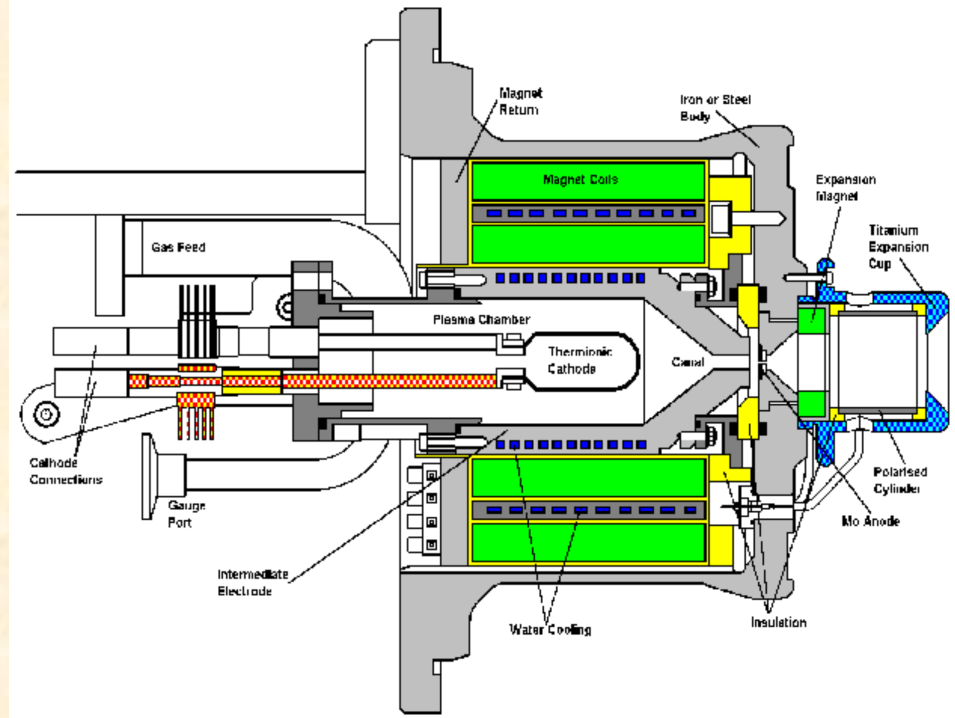
1) We have seen that in a duoplasmotron there is a thermionic electron source. Does that mean that this source produces both protons and electrons? Why?
2) Same question for the H- RF source.

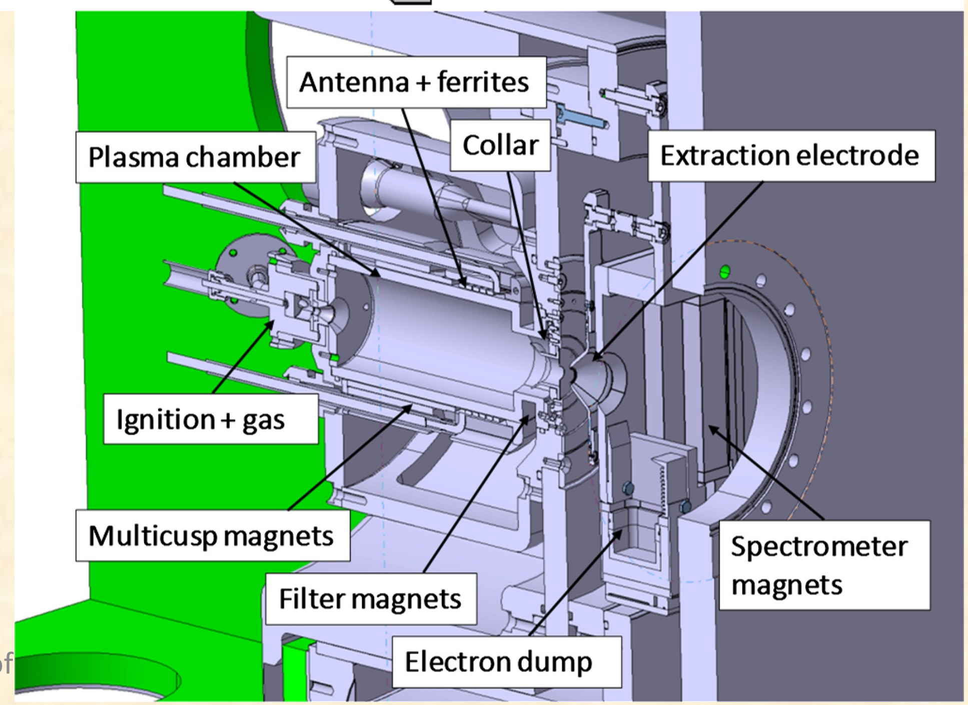




Answer

1) In the duoplasmotron the electric field separates the electrons from the proton as they have opposite charge. So only p+ are extracted.
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 done carefully to limit heating of critical components.





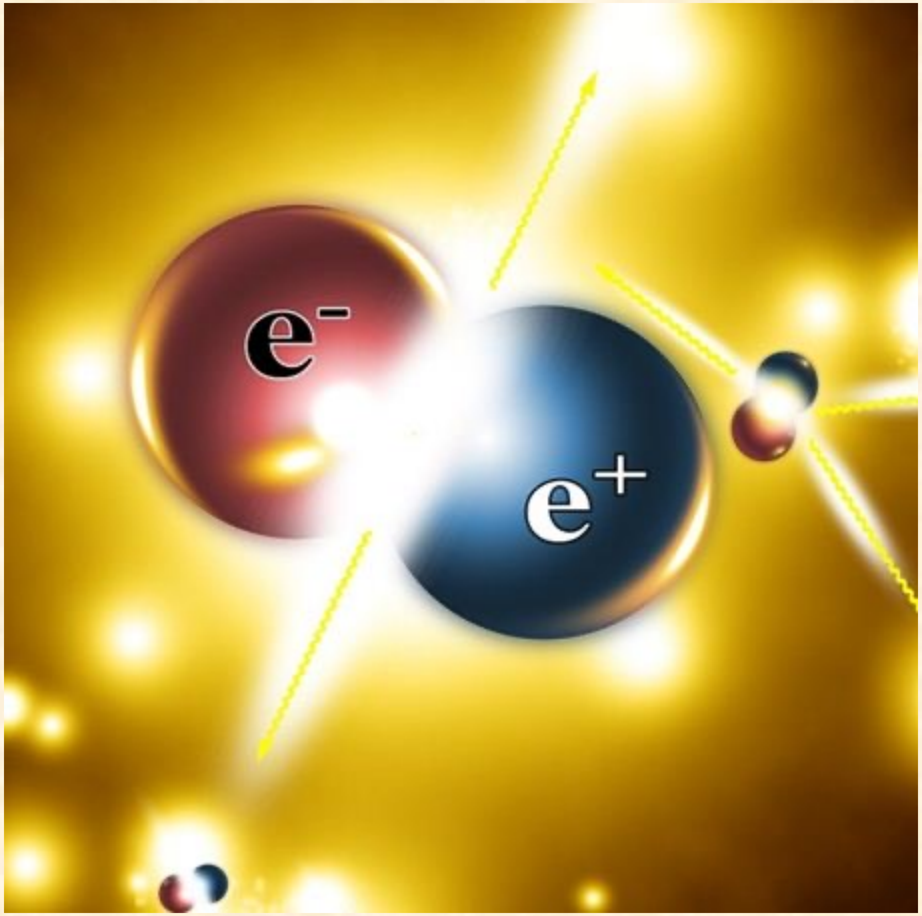
… Particle sources

- We have discussed how to produce the particles used in accelerators.
- The requirement of the next generation of electron accelerators impose strong constraint on the quality of the beam produced by electron sources. Several recent development aim at improving this quality.
- Ion machine are limited by the beam intensity that can reliably be extracted form the source.
- For both electrons and ions the quality of the particle source has a strong impact on the overall accelerator performance.

ANTIPARTICLES SOURCES

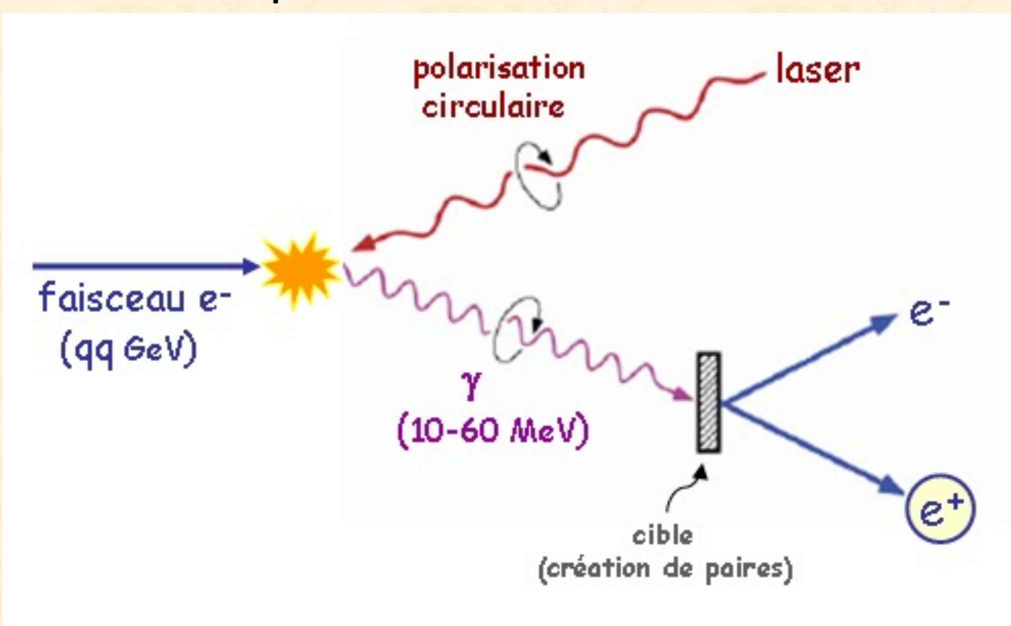
Question

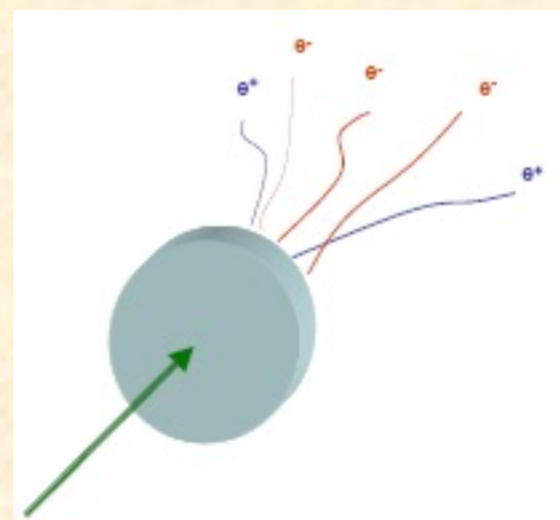
- How can positrons be produced?
- How can antiprotons be produced?



Positron sources

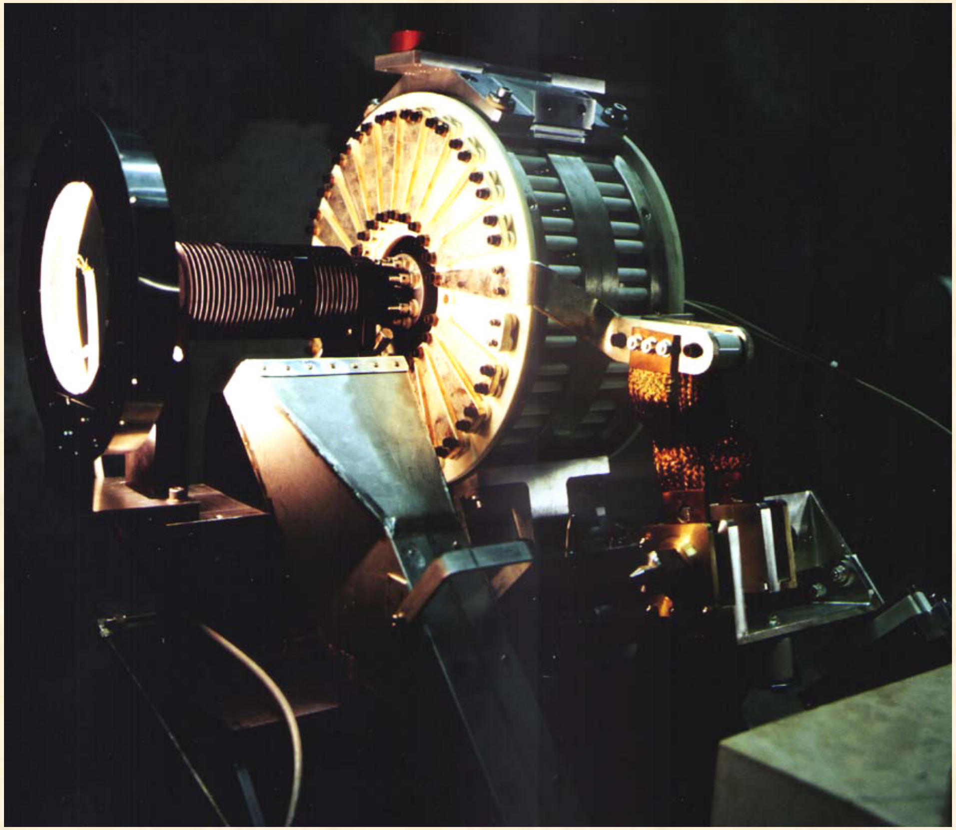
- Electron-Positrons pairs can be produced by high energy (>2xMe) photons.
- These photons can be produced by bremstrahlung of high energy electrons in a target.
- More advanced techniques are being investigated to produce polarised pairs of electron-positrons.





Anti-proton sources

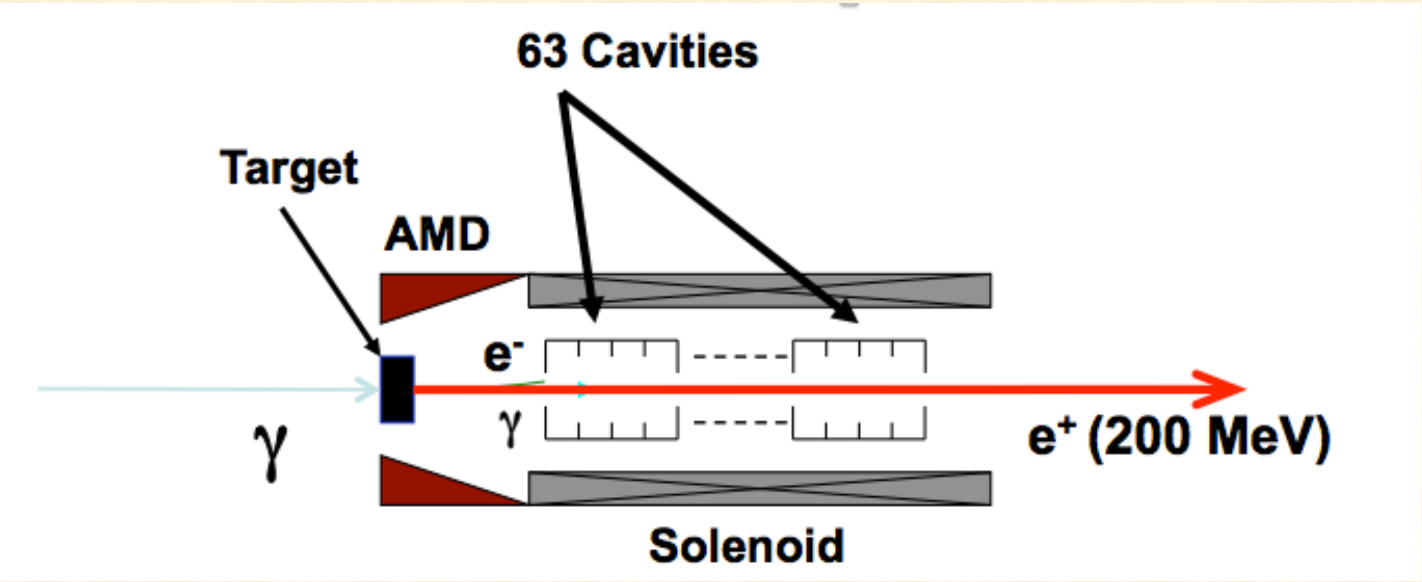
- The creation of anti-protons is similar to that of positrons but at higher energy (>2Mp).
- Typical targets use copper or iridium.
- Anti-protons production is very inefficient so fermilab had built a special ring to “recycle” its anti-protons.



CERN antiproton target

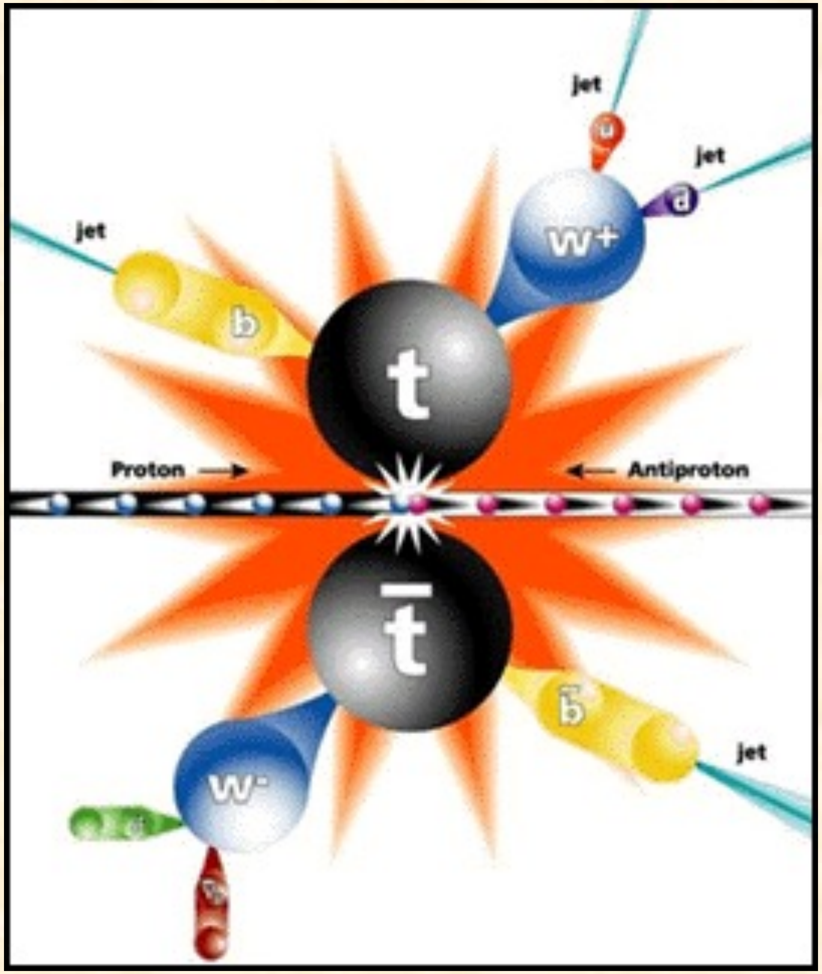
Anti-particles capture

- 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”.
- 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.



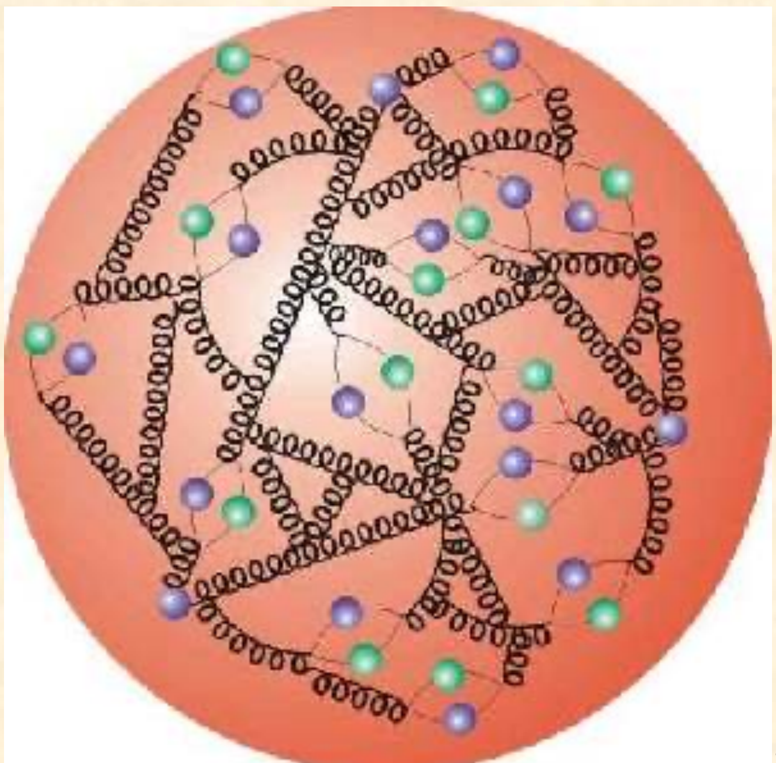
Quizz

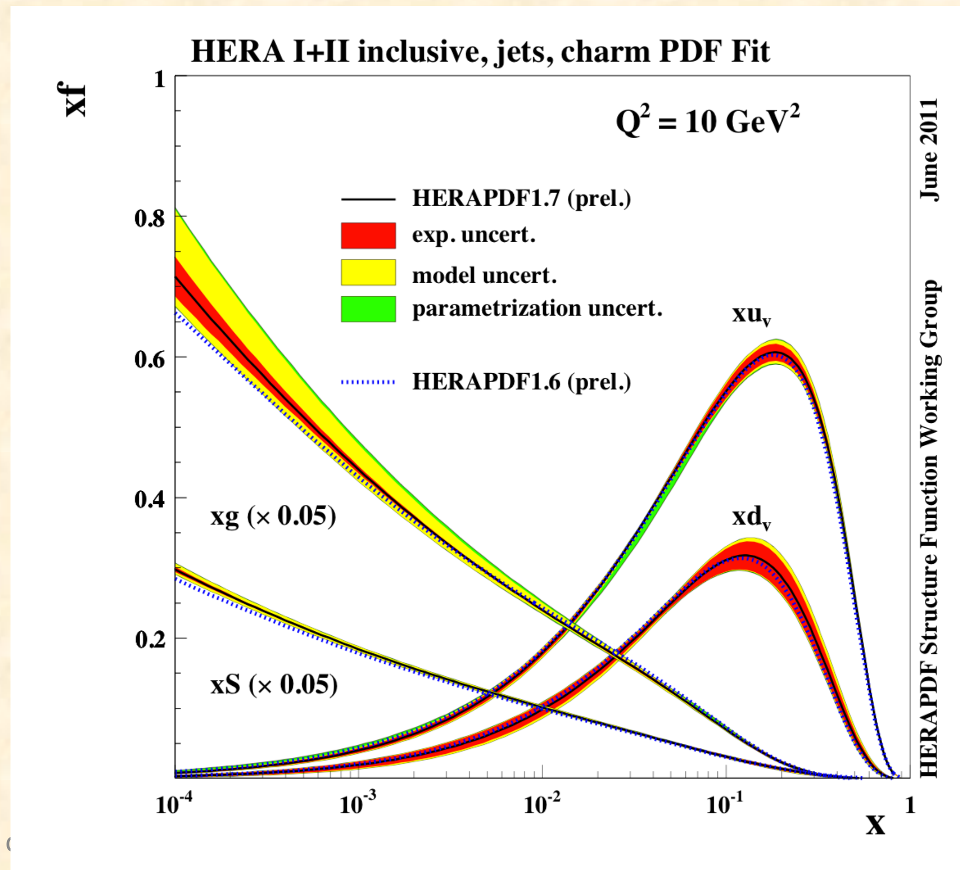
- Why does the LHC not use anti-protons as did Fermilab?



Answer

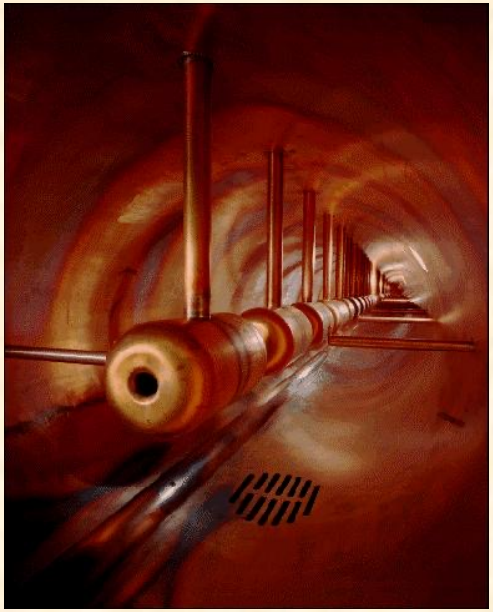
- Producing anti-protons is very inefficient.
- QCD tells us that protons at high energy also contain anti-quarks.





Lecture content

- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - **Particle acceleration**
  - Magnets
  - Emittance and beam dynamics
  - Beam diagnostics
- Challenges for present and future accelerators



Special relativity reminder

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

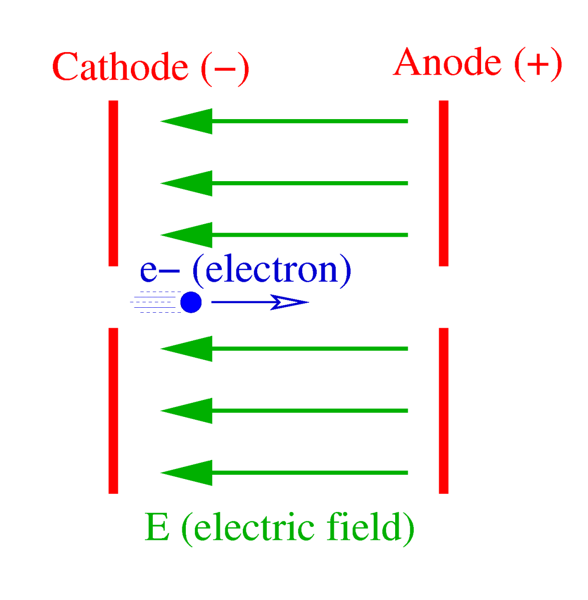
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

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

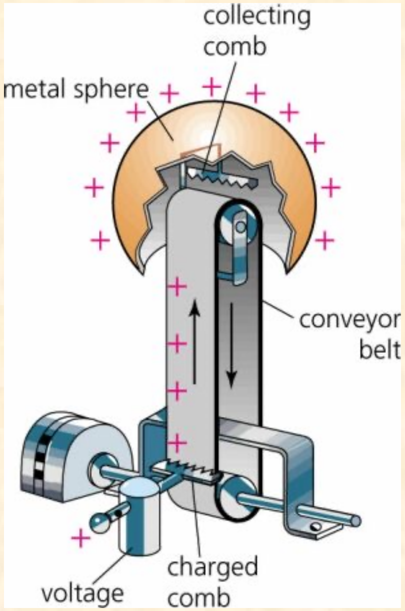
$$\text{Protons: } \gamma = \frac{E}{m_p c^2} \simeq E[GeV] \quad \text{Electrons: } \gamma = \frac{E}{m_e c^2} \simeq 2E[MeV]$$

- Typical RF gun (electrons): few MeV => gamma = 5-10
- Typical proton/H- source: hundred kV => gamma ~ 1!
- 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 7 TeV/beam => gamma = 7000.
- Relativistic phenomena are much more important in electron accelerators than in proton accelerators.



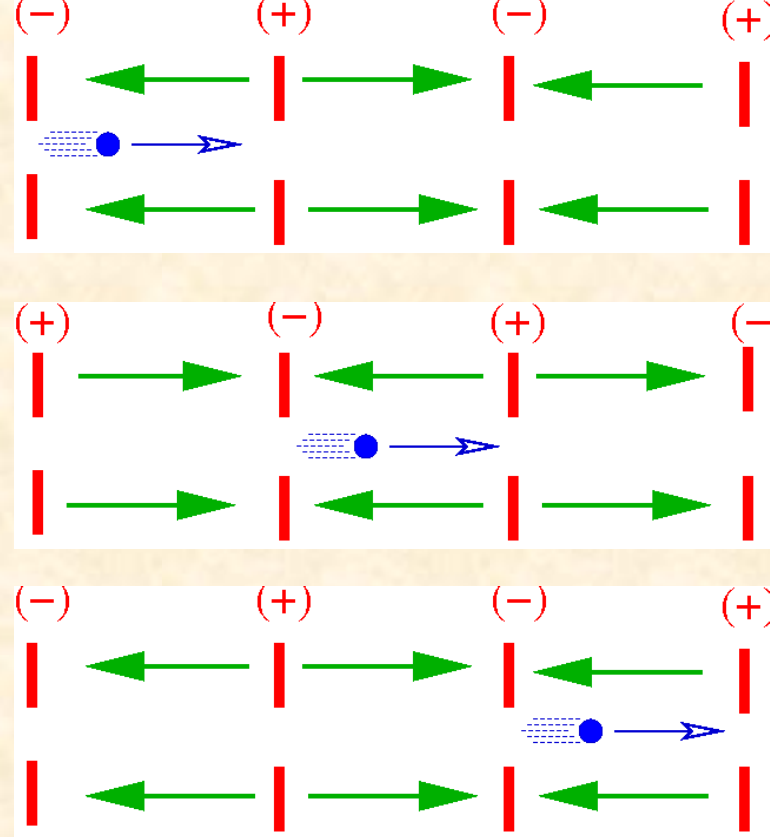
Electrostatic acceleration

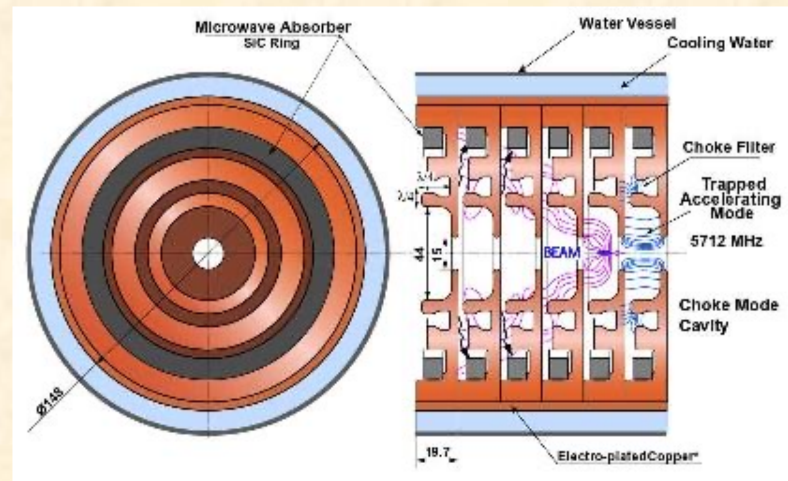


- Charged particles can be accelerated in an electrostatic field.
- This works up to a few MV but we have seen yesterday that intense electric fields can be dangerous.
- To reach more than a few MeV, alternating current accelerators must be used.

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.

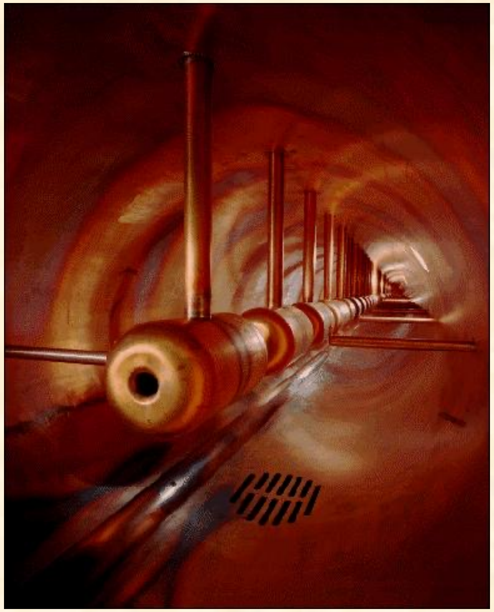




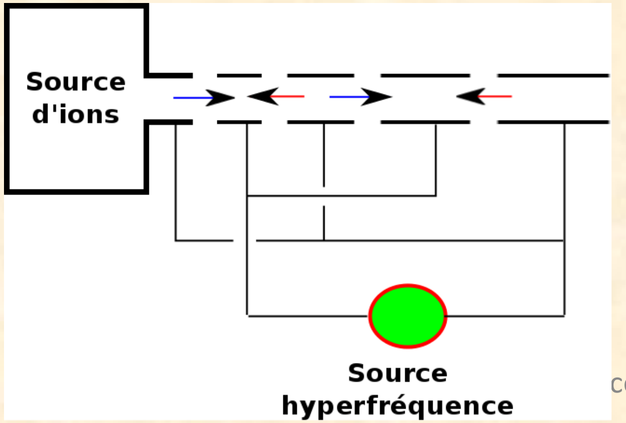
(source: Spring-8, Japan)

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



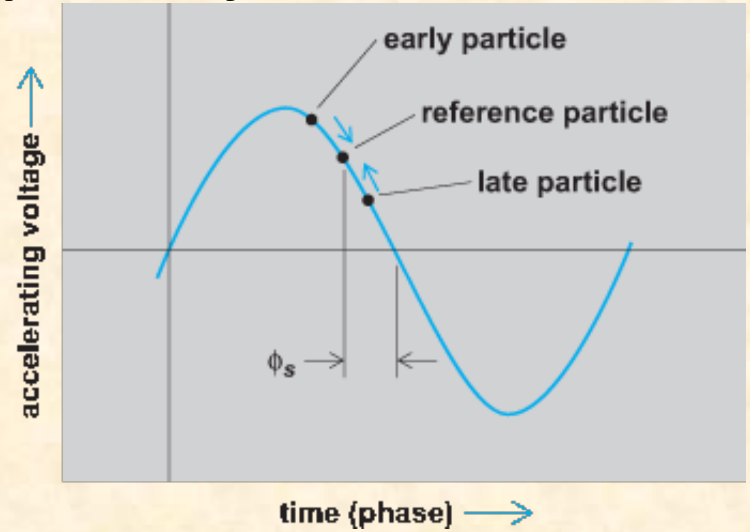
RF accelerators (3)

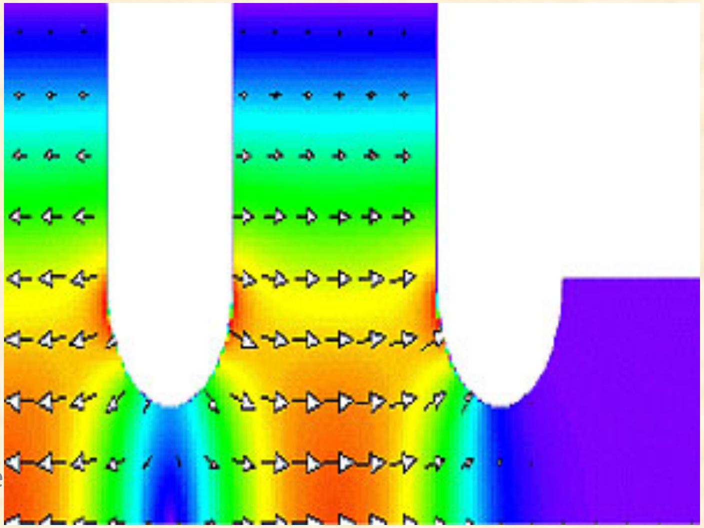
- Because after each cavity the particles return to ground potential there is no theoretical limit on the length of a RF accelerator.
- String of accelerating cavities are usually called “Linac” (Linear Accelerator).
- Linacs are mostly limited by their length: the ILC will accelerate electrons up to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

Artist view of the ILC (source: KEK)

RF: Phase stability and cavity quality

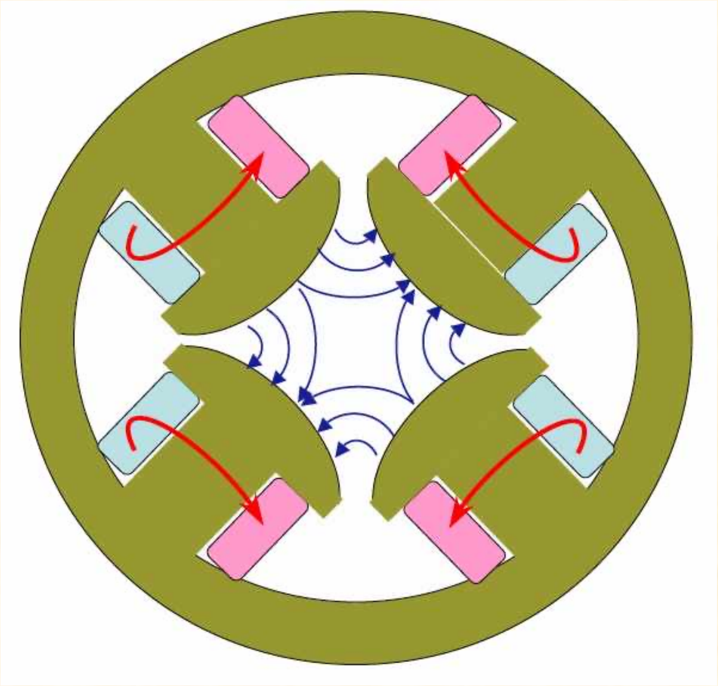
- In an RF accelerator the field felt by the particles depend on the exact phase a which the particle is injected.
- In a linac the phase of all accelerating cavities must be controlled very accurately.
- The shape of the cavity is also very important to ensure a homogeneous field in the center.
- After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





Lecture content

- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - *Particle acceleration*
  - **- Magnets**
  - Emittance and beam dynamics
  - Beam diagnostics
- Challenges for present and future accelerators

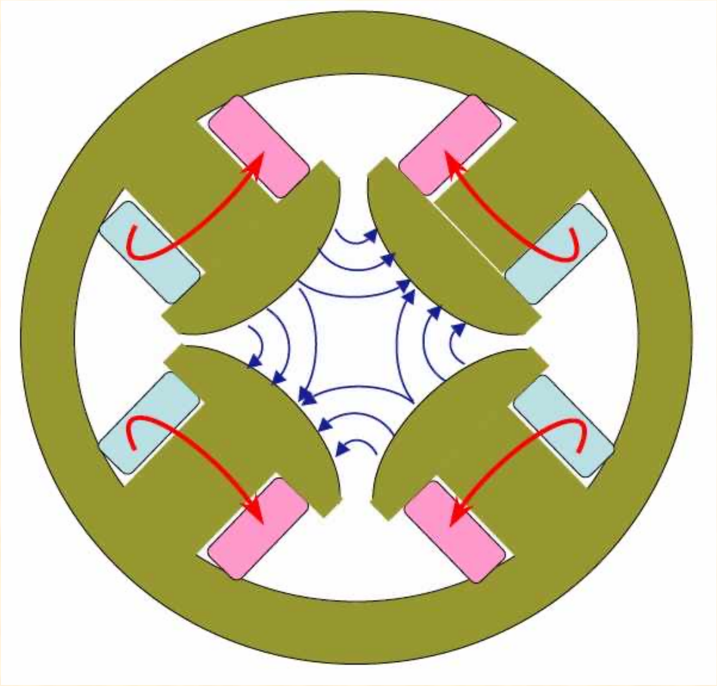


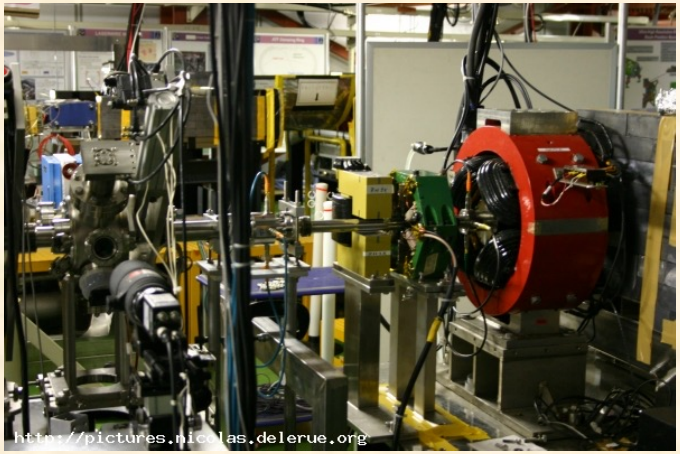
How to control where the particles go?

- 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.

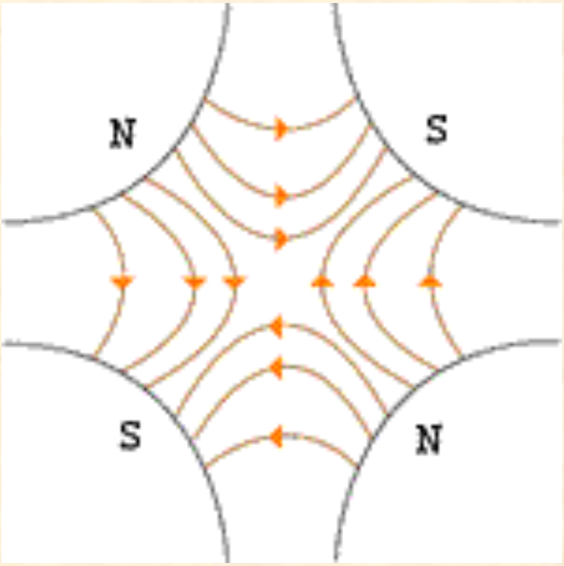
Beam focussing

- 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.

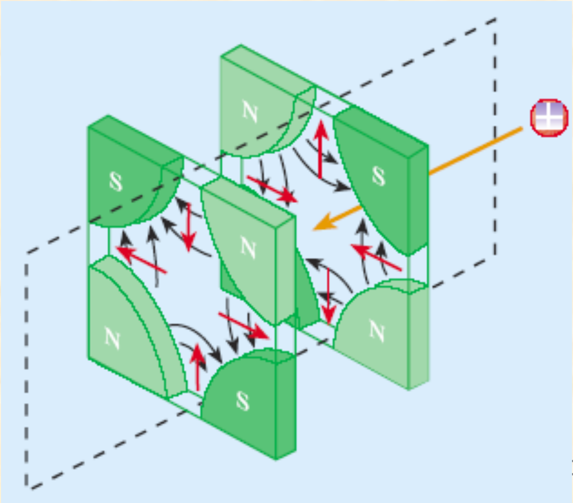


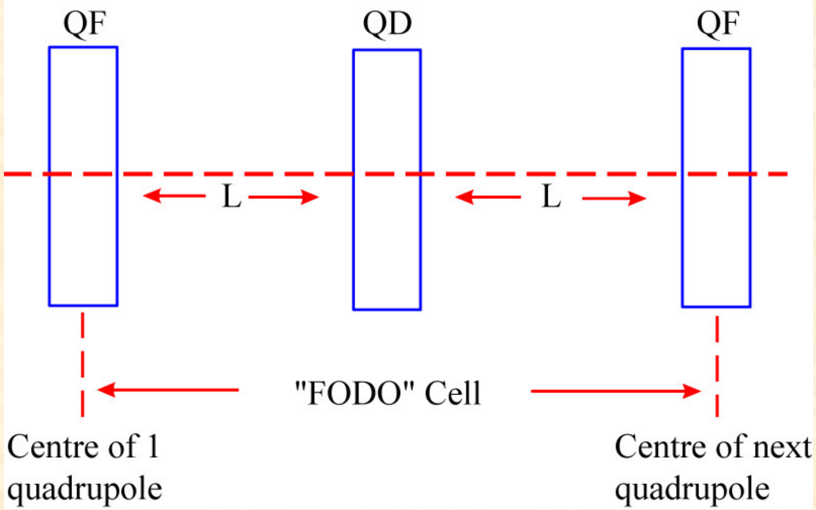


FODO cell



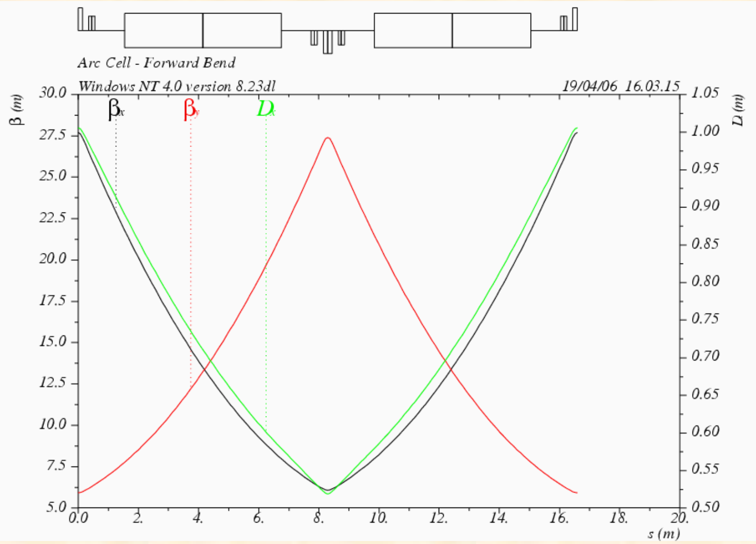
- A quadrupole will focus the beam in one plane but defocus it in the other plane.
- To have a net focussing effect, 2 quadrupoles are used, one focussing in one plane and the other one focussing in the other plane.

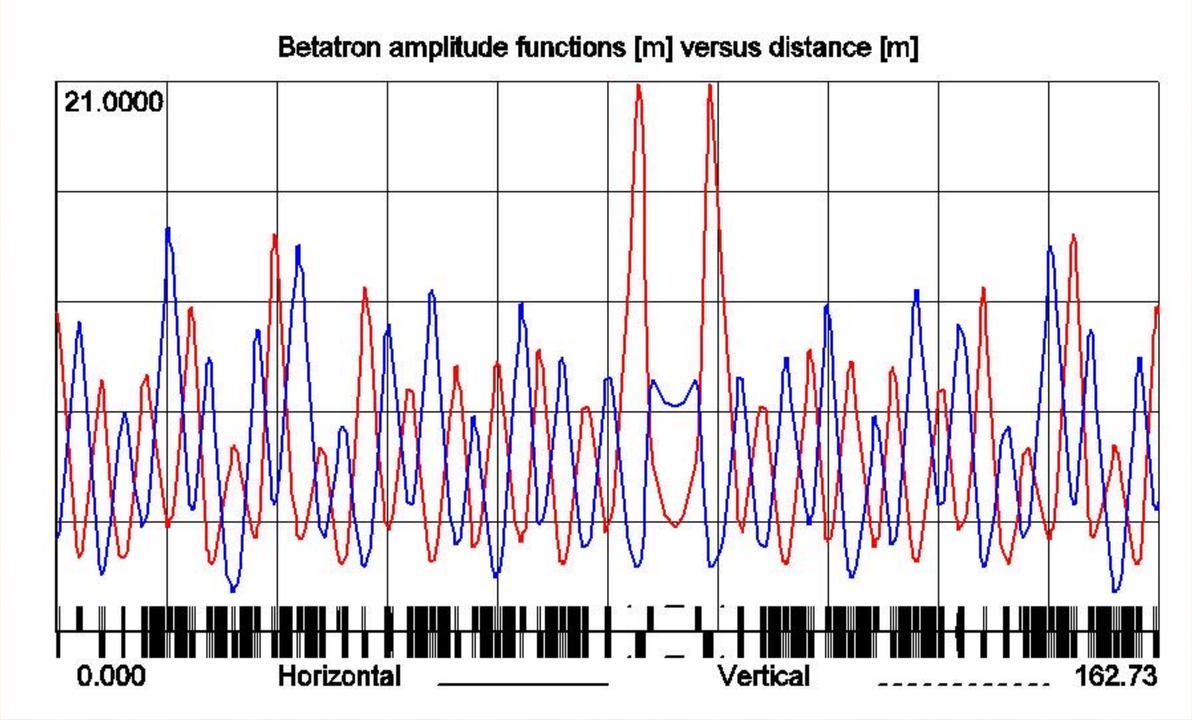


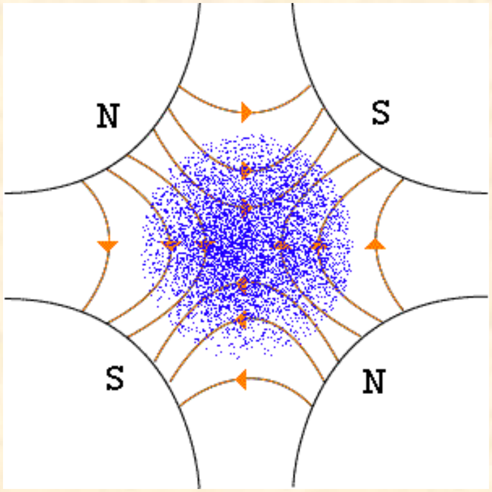


Accelerator lattice

- An even better effect is reached with 3 quadrupoles. This is called a “triplet”.
- 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.
- The magnet strength are characterised by a “beta” function.

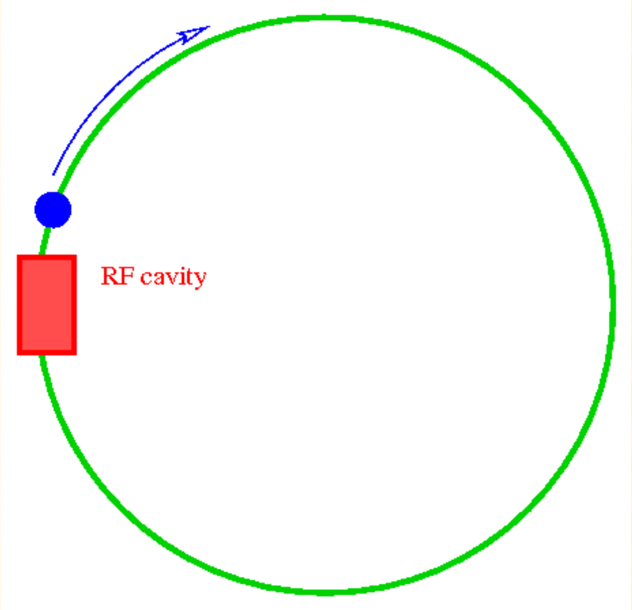






Synchrotrons

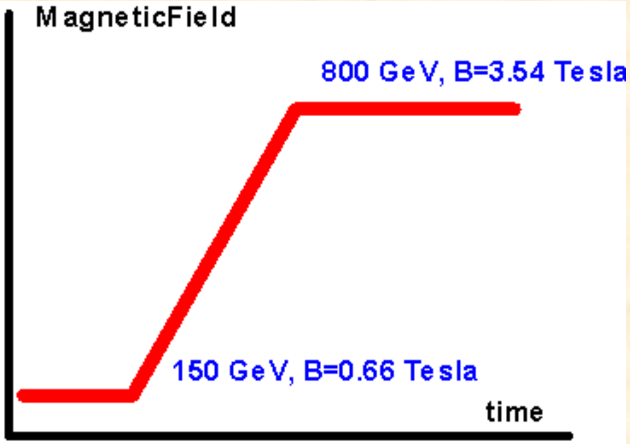
Dipole magnets are then used to make the particles follow a circular orbit.



This can be used instead of having a large number of cavities to accelerate the particles, by using a single cavity in which the particles pass several times.

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.



Magnetic rigidity

- The bending power of a magnet depends on the beam energy.
- It is often useful to use the “magnetic rigidity” of a beam.
- One should note that rings often have straight section. So the magnetic radius of an accelerator is smaller than its geometrical radius.
- The LHC has a magnetic radius of 2804m.

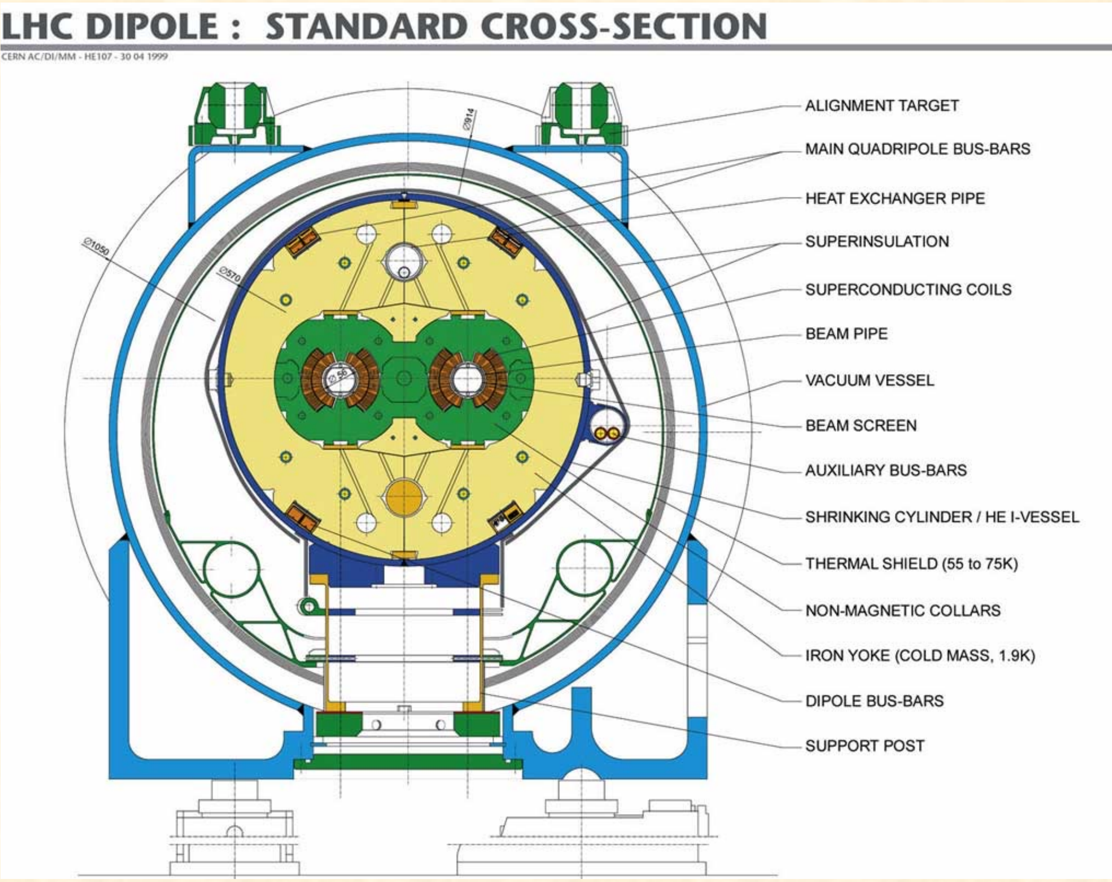
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

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

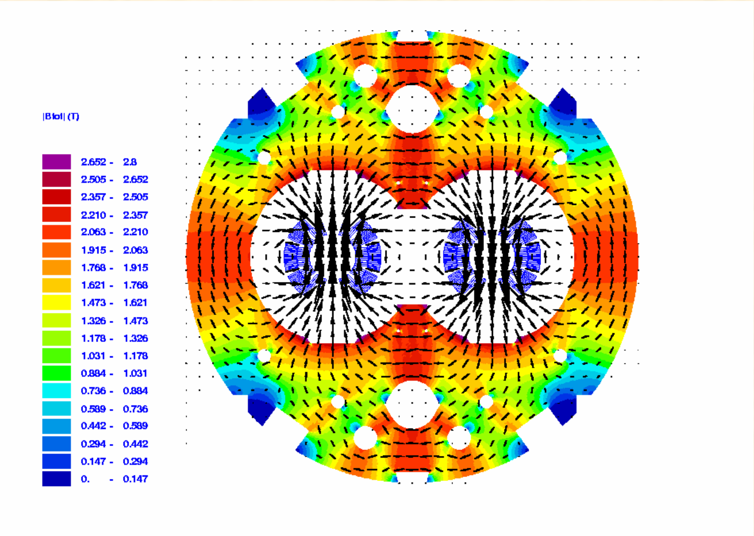
$$B[T]\rho[m] = 3.34p[GeV/c]$$

$$B[T] = \frac{3.34 * 4000[GeV/c]}{2804[m]} = 4.8[T]$$

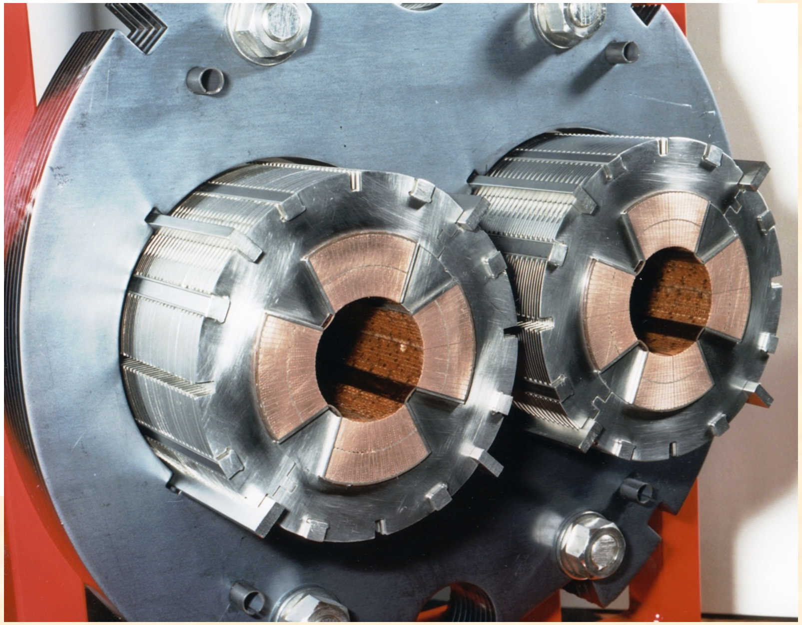
LHC Magnets



LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST

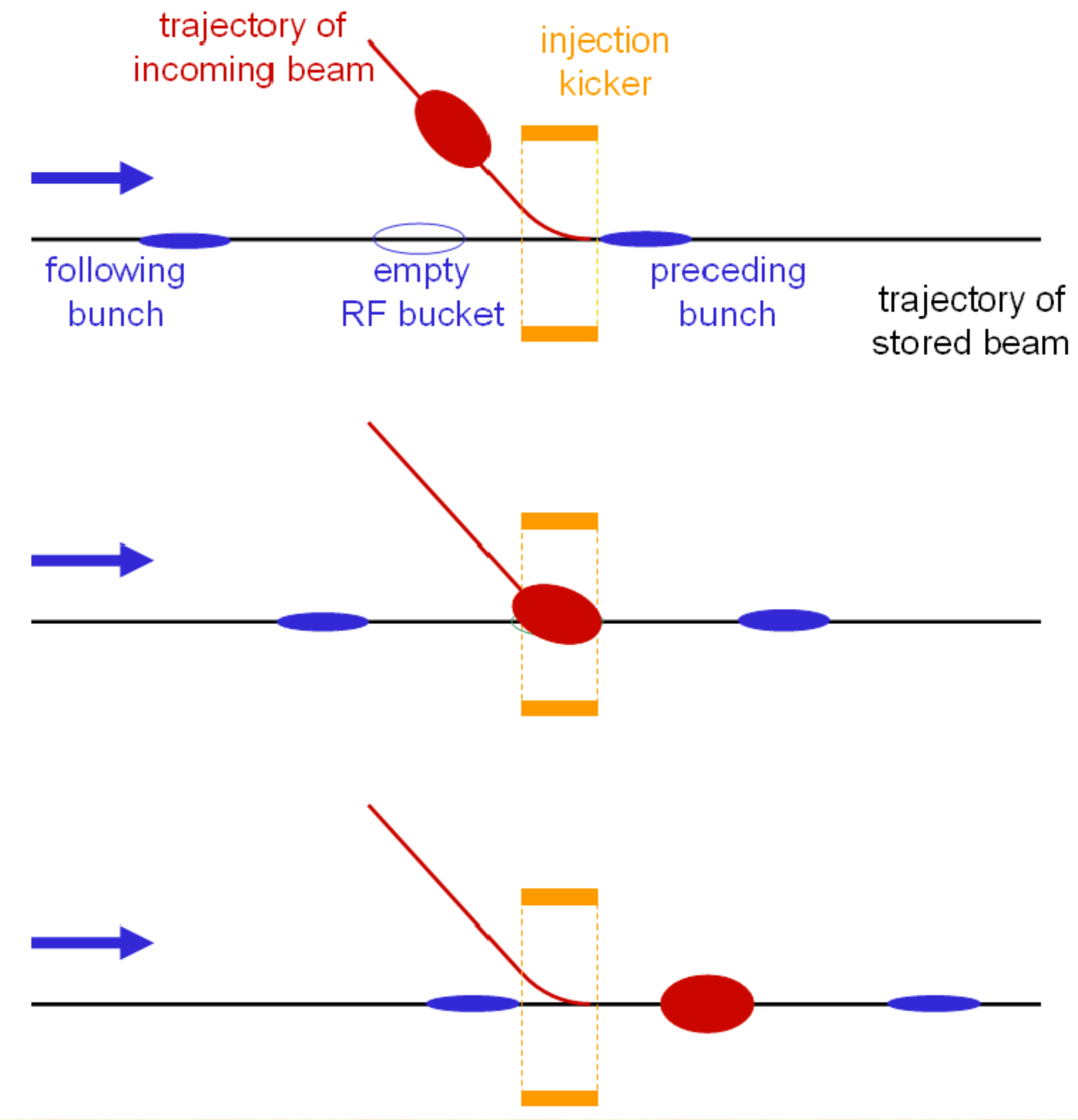


|Btot| (T)
2.652 - 2.8
2.505 - 2.652
2.357 - 2.505
2.210 - 2.357
2.063 - 2.210
1.915 - 2.063
1.768 - 1.915
1.621 - 1.768
1.473 - 1.621
1.326 - 1.473
1.178 - 1.326
1.031 - 1.178
0.884 - 1.031
0.736 - 0.884
0.589 - 0.736
0.442 - 0.589
0.294 - 0.442
0.147 - 0.294
0. - 0.147



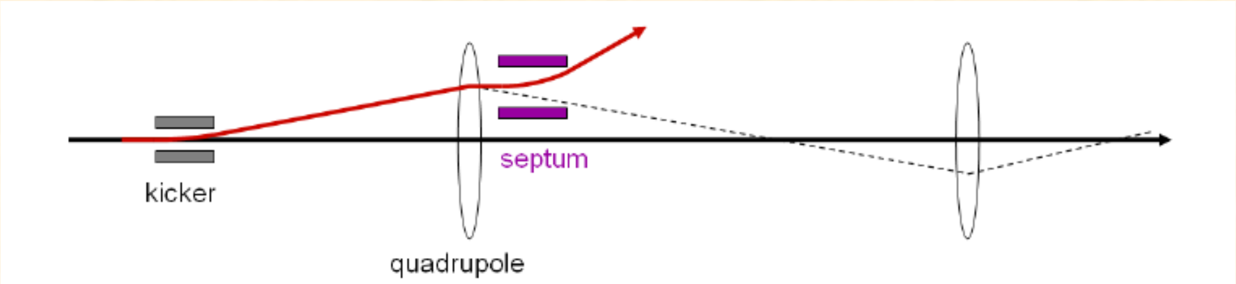
Beam injection/extraction

- Injecting (or extracting) particles from a ring is not easy.
- The particles must be inserted on the correct orbit.
- However the deflector must not affect the trajectory of other bunches in the ring (or of the same bunch after one turn).

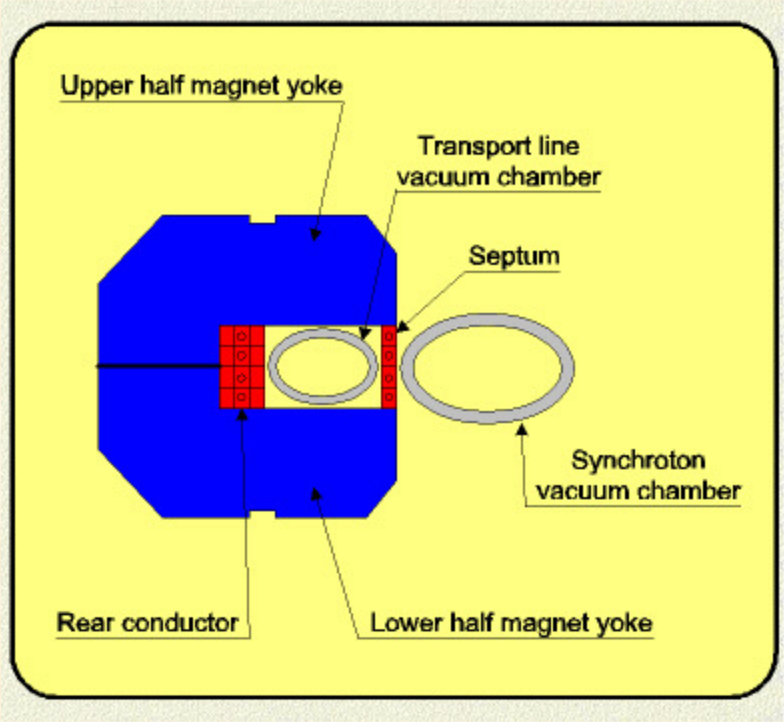


Courtesy of Andy Wolski

Septum magnets

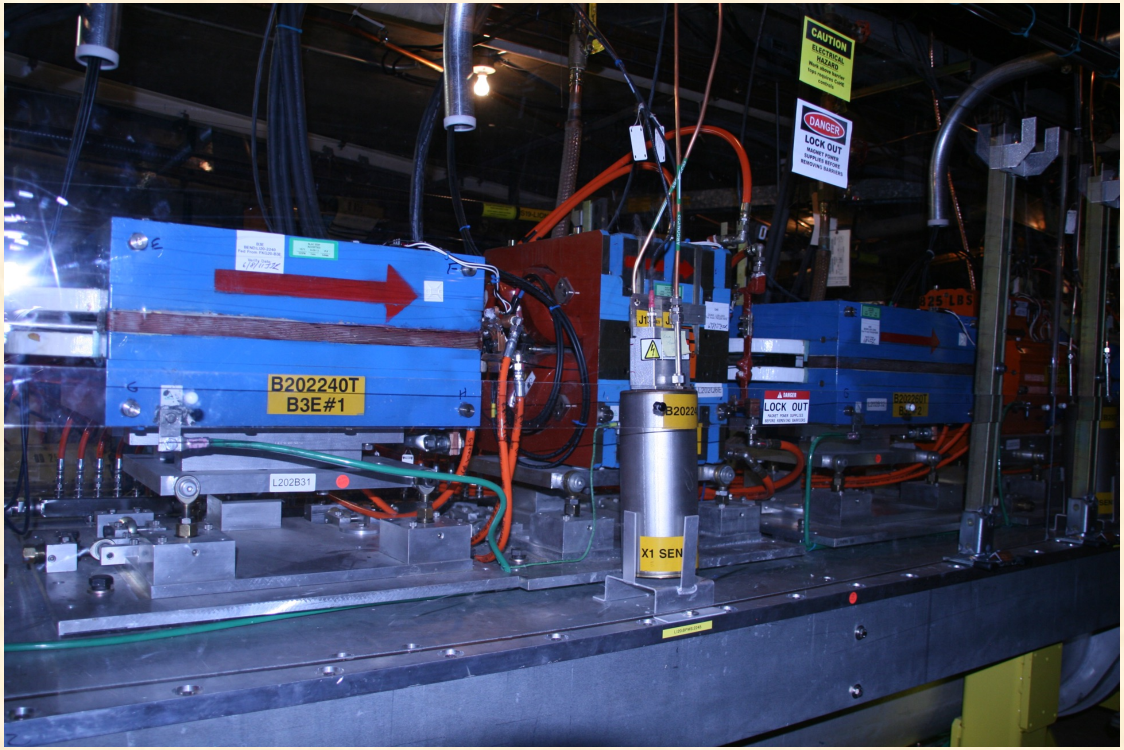


- Insertion/extraction are usually done by combining 2 types of deflectors:
  - Ultra fast kickers use an intense electric field to deflect the particles (but beware to ripples)
  - A septum magnet is used to separate neighbouring trajectories (thanks to a magnetic shield).
- This explain why producing H- ions to store protons is interesting.



Magnets summary

- Magnets are used to control particles in an accelerator.
- Dipole magnets are used to change the direction of the beam.
- Quadrupoles are used to control the size of the beam.
- Septum magnets are used to inject extract the beam.



Lecture content

- *History of particle accelerators*
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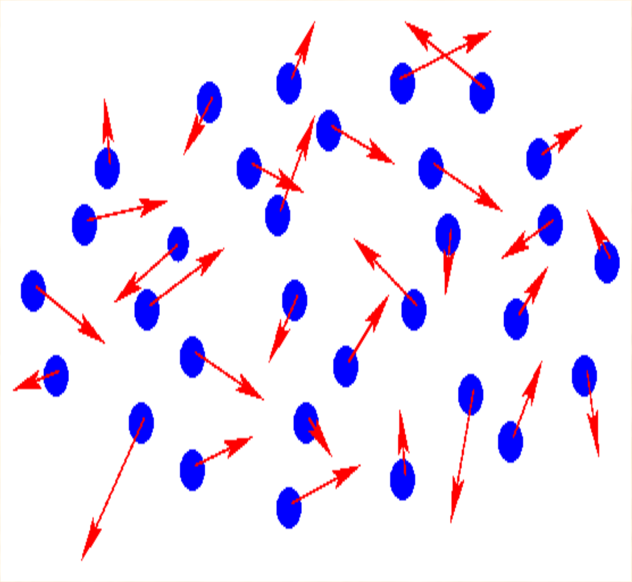
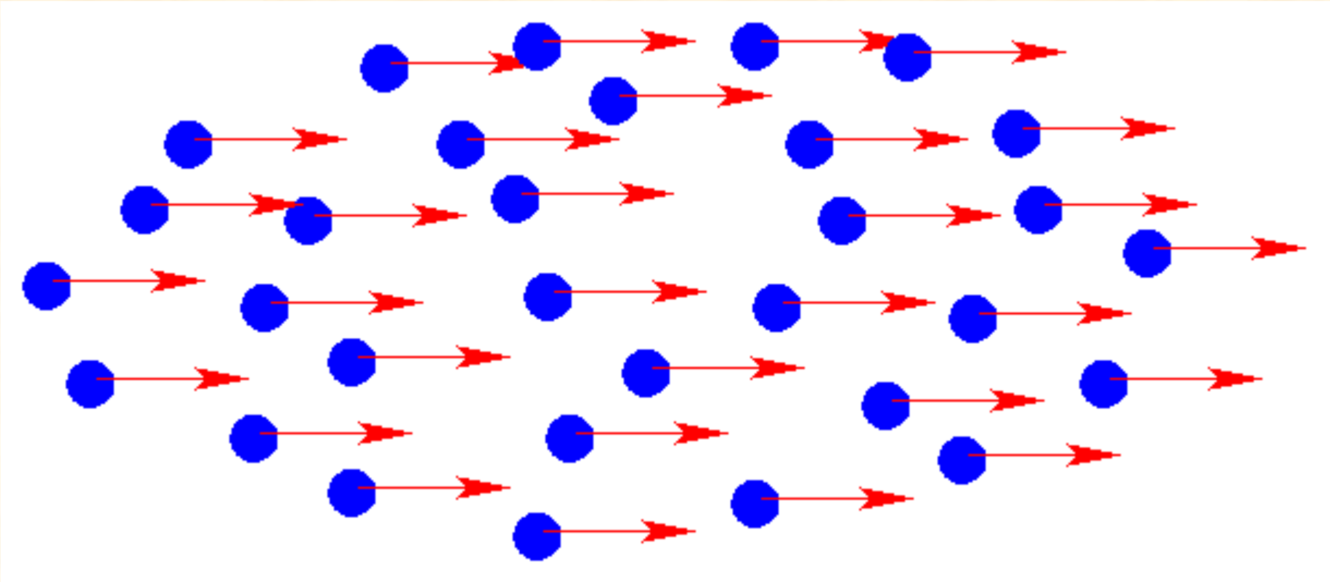


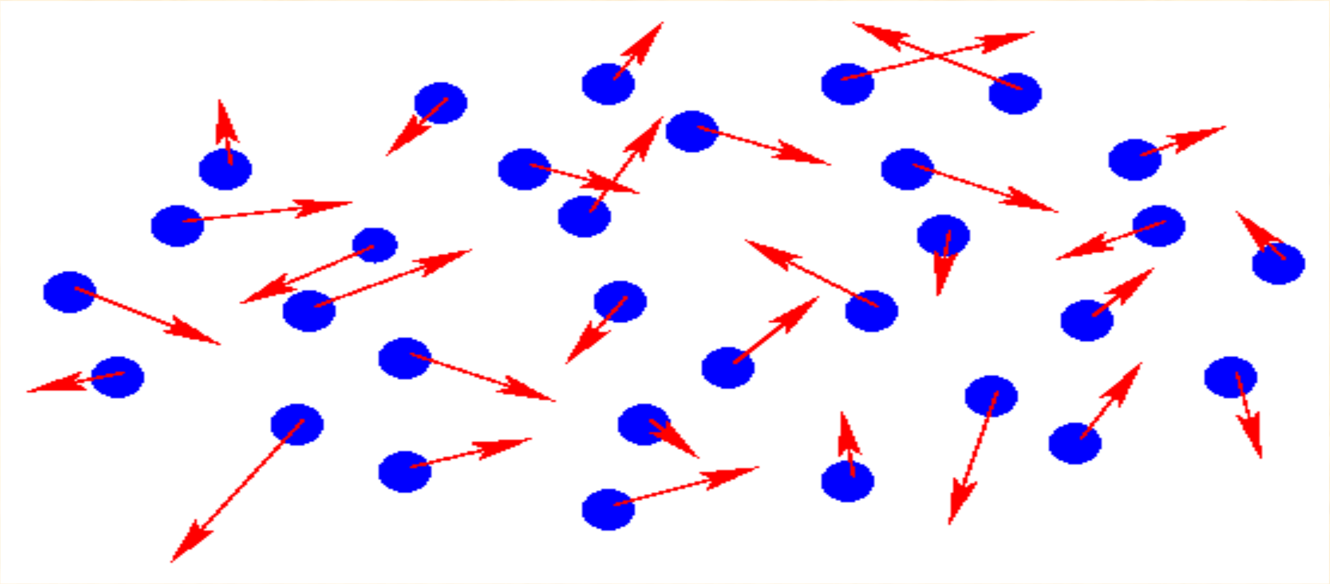
Let's look at a particle bunch



An observer in the laboratory frame looking at a particle bunch will only see particles travelling at the speed of light, apparently all in the same direction.

It is very different if one looks in the bunch's centre of mass frame...

Let's look at a particle bunch



In the centre of mass of the bunch, the particles do not look so well organised...

This should remind you other statistical systems that you have already studied: Gases!

Perfect gas law

- You have studied earlier that a perfect gas obeys the law: PV=nRT
- V is the volume term (V=xyz)
- P is a dynamic term: P, the pressure is proportional to the amount of scattering experienced by atoms as they travel in the volume. It is proportional to the momentum of the gas atoms (P~x'y'z').
- Hence it is possible to write that for gas atoms the product of their position by their momentum is expressed by their temperature *(times a constant).*
- We have seen that in the CoM particles look like a perfect gas. The product of their position by their momentum is called the “emittance” of the beam.

6D Trace space

- The position-momentum 6D space is called the trace space.
- To help visualisation the trace space can be decomposed in 3 orthogonal position-momentum planes:

$$xyzx'y'z' = xx'*yy'*zz'$$

- It is also often useful to look separately at the transverse and longitudinal planes.

Liouville's theorem

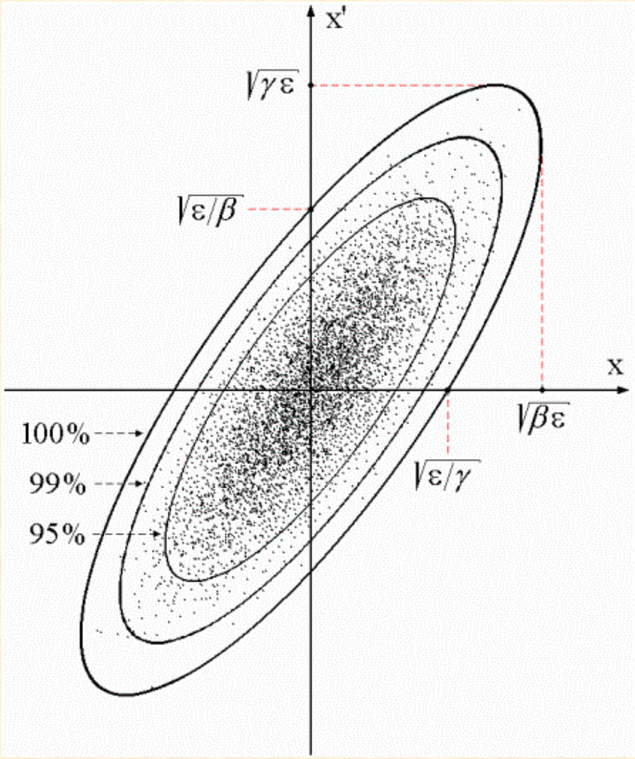
$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + \sum_{i=1}^{d} \left(\frac{\partial \rho}{\partial q^i} \dot{q}^i + \frac{\partial \rho}{\partial p_i} \dot{p}_i \right) = 0.$$

- The volume occupied in the phase space by a system of particles is constant.
- This is a general physics theorem, not limited to accelerators.
- The application of external forces or the emission of radiation needs to be treated carefully.

Joseph Liouville
1809-1882
(source: wikipedia)

Emittance

- We have defined the emittance as the volume occupied by the beam in the trace space.
- Liouville's theorem tells us that such volume must be constant.
- Hence the emittance of a beam is constant (unless external forces are applied).



- The total volume occupied by the bunch in trace-space is usually dominated by a few far-outlying particles.
- Instead of giving the volume occupied by all the particles, it is common to give the volume occupied by 90% or 60% of the particles or to give the RMS emittance.
- The fraction of particles included in the emittance is usually quoted.

$\in_{90}$ $\in_{RMS}$

Quizz: Gun emittance

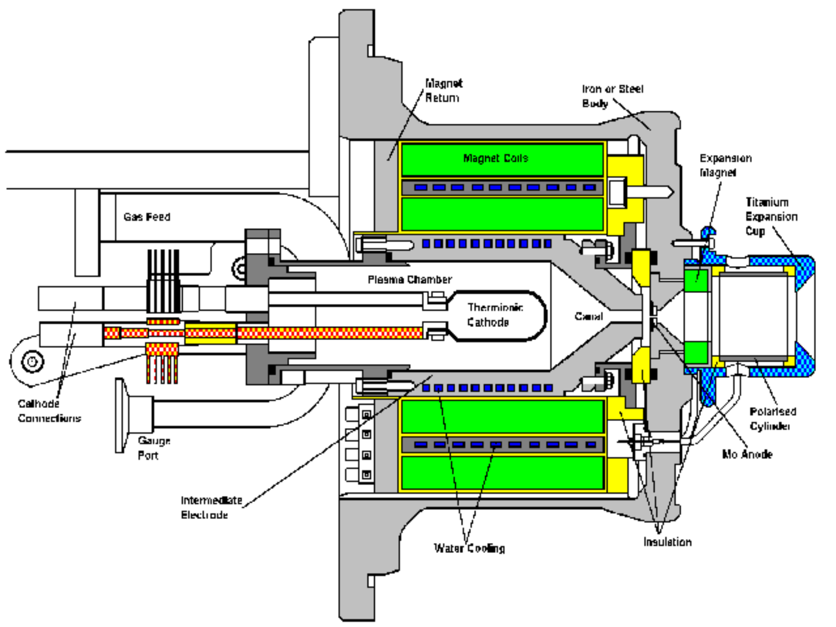
- A particle gun emits particles with a x divergence of 0.5mrad.
- It is fitted with an exit collimator with a hole with a dimension of 1mm in x.
- What is the geometrical x-emittance of the bunch produced by this gun?

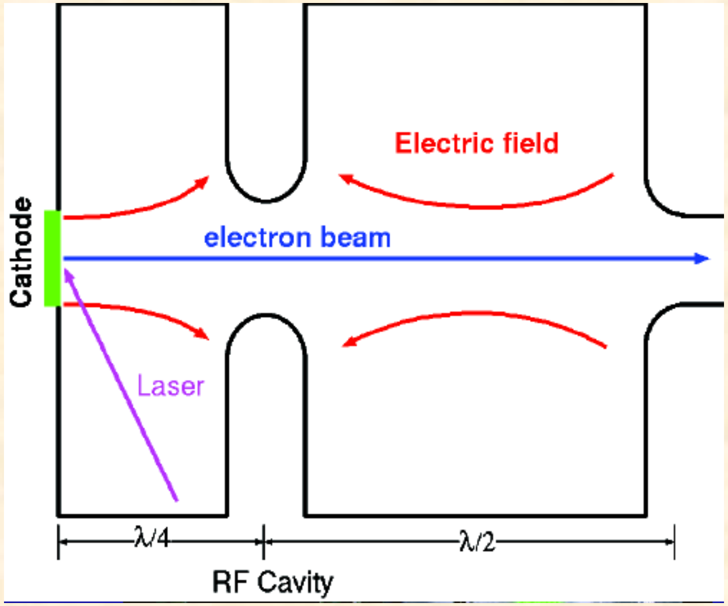
(A) 5mm.mrad

(B) 1mm. rad

(C) 500m.nrad

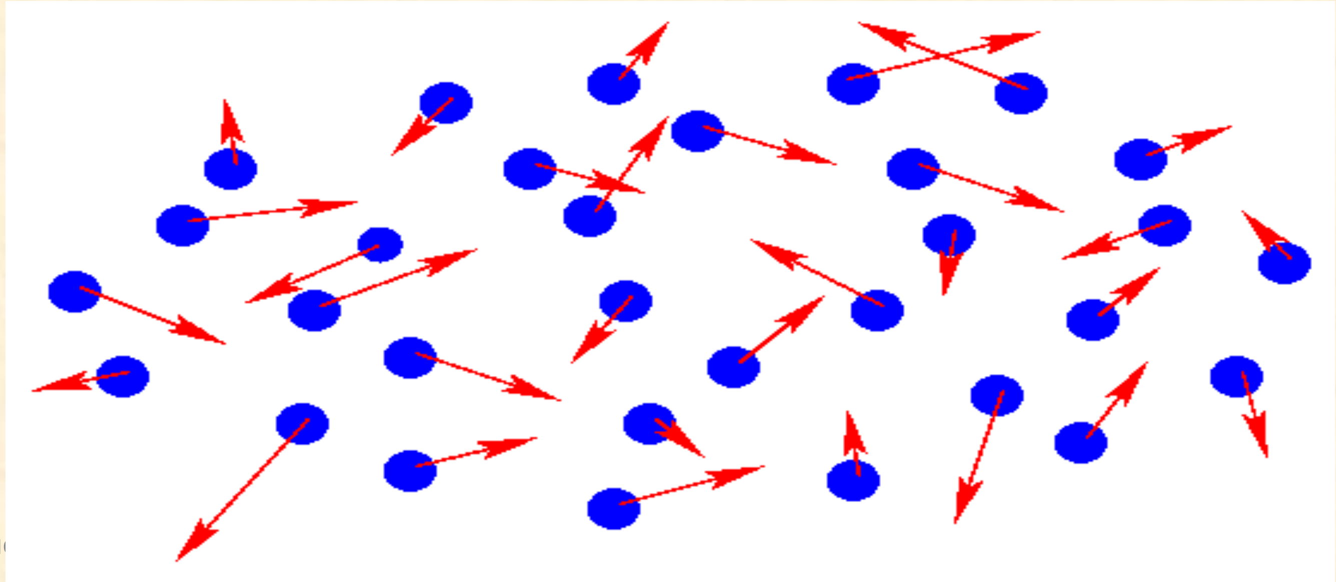
(D) 50mm.urad





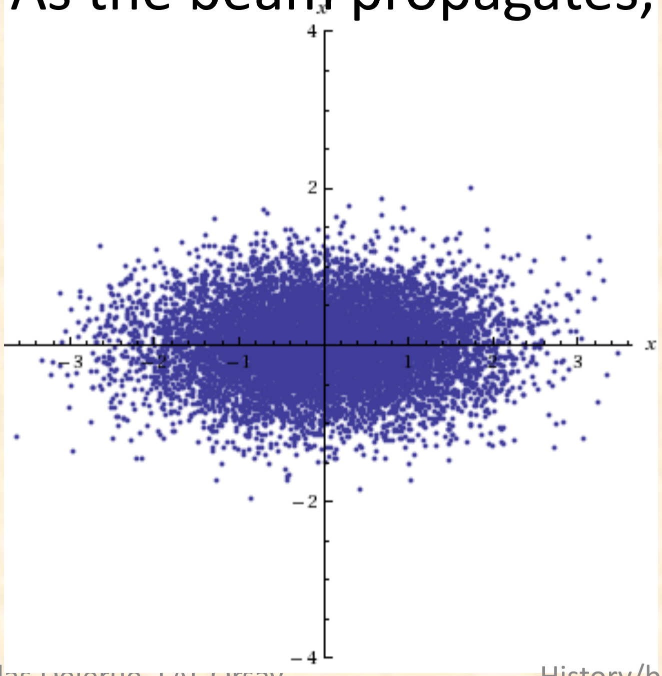
Answer (c)

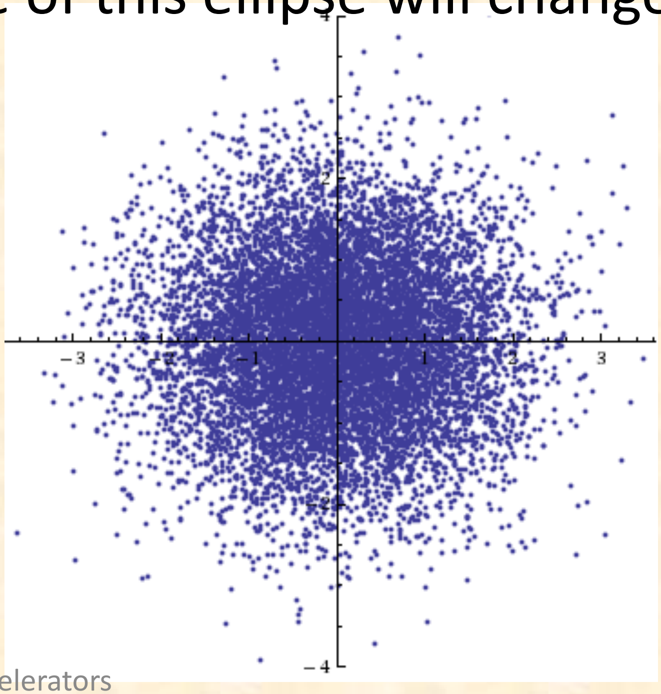
- The x-emittance at a waist is given by x*x'.
- Here we have x=1mm, x'=0.5mm
- That is:
  0.5 mm.mrad or 500mm.urad or 500m.nrad.



Emittance ellipse

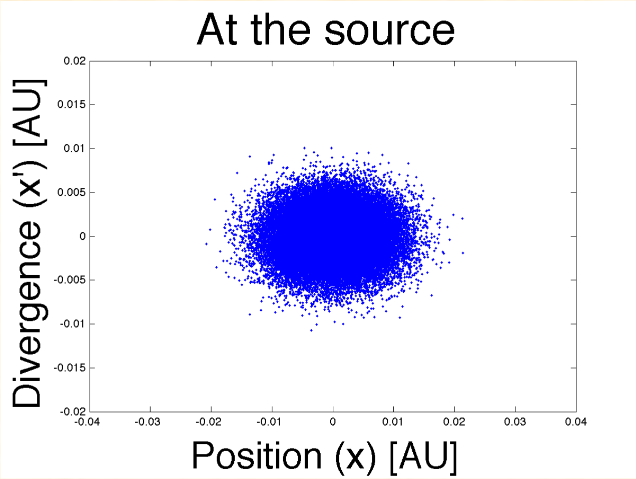
- A random Gaussian distribution of particles forms a straight ellipse.
- By choosing the right set of coordinates this ellipse can be transformed in a circle (do not forget that the two axis are orthogonal!).
- As the beam propagates, the shape of this ellipse will change.





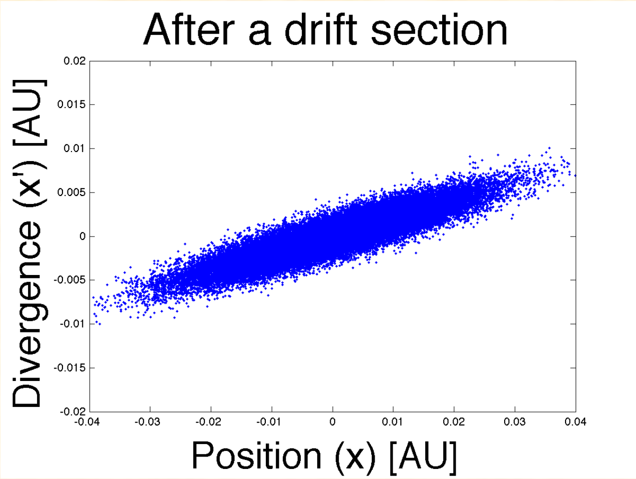
Beam drift

- When the beam "drifts" that is, propagates in space, over a length L with no external forces applied:
  - The momentum of the particles is constant
  - The position changes by the momentum times L.
- Hence, the emittance ellipse is sheared.



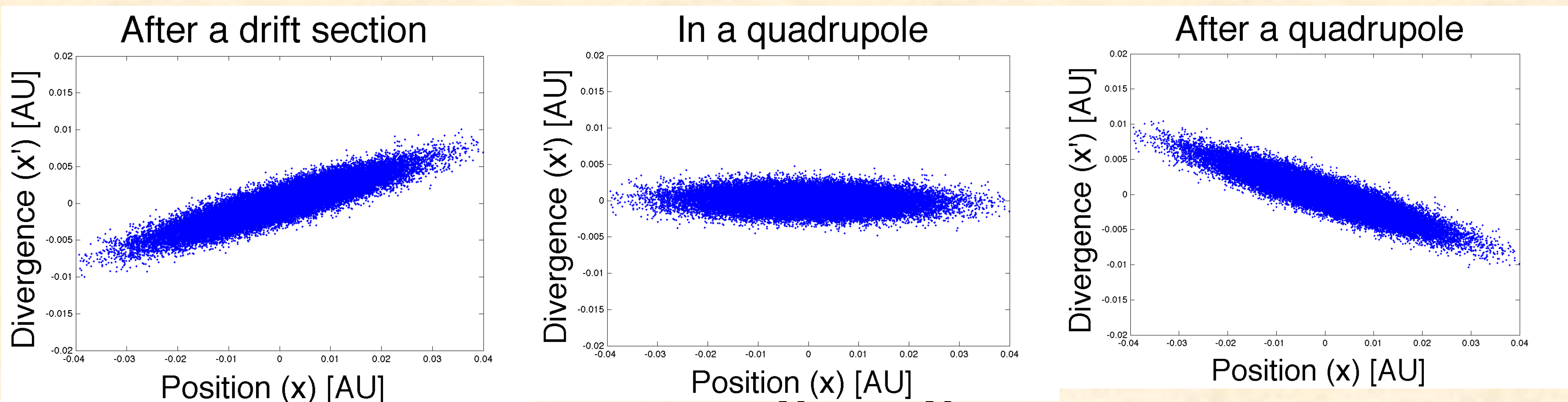
$$x'_2 = x'_1$$

$$x_2 = x_1 + Lx'_1$$



Focussing

- In a focussing section (typically a quadrupole), in the thin lens approximation:
  - The position of the particles is not affected
  - The momentums are reversed, hence a waist (at which all x'=0) is formed.
- The ellipse is unsheared and then sheared in the other direction

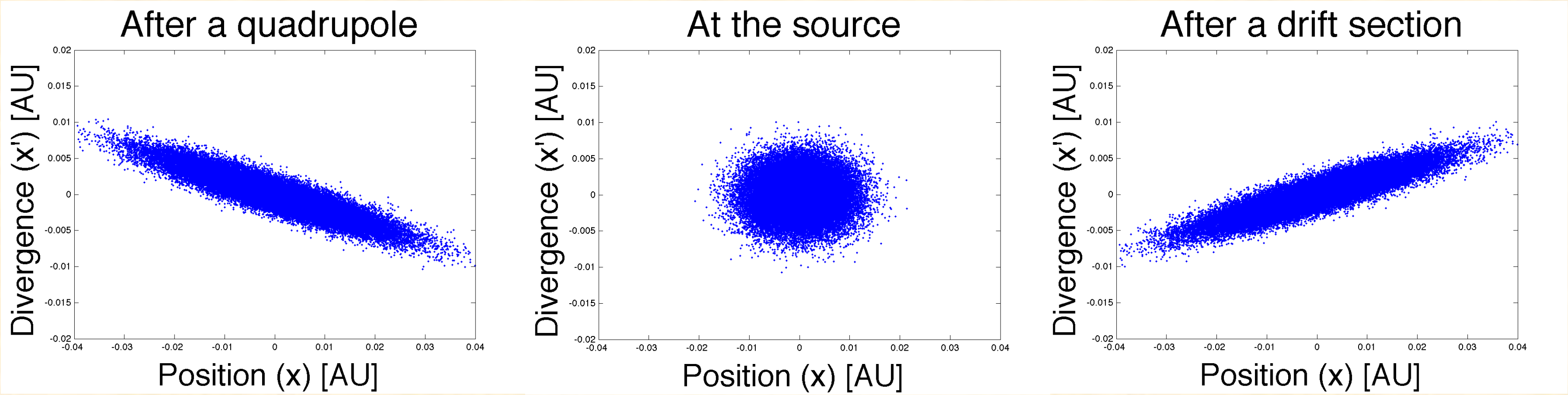


$$x_2 = x_1$$
$$x'_2 = 0$$

$$x'_3 = -x'_1$$
$$x_3 = x_1$$

Beam waist

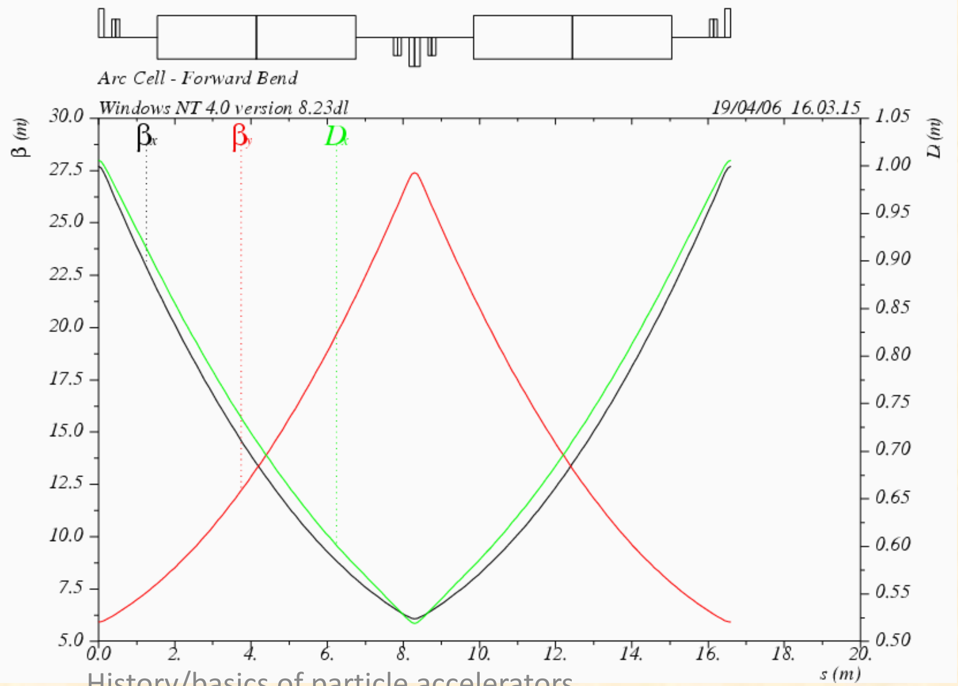
- After the focussing section the beam will drift again, decreasing the shearing of the emittance ellipse.
- At some point the momentums will again average to 0, the beam will be forming a waist.
- At the waist the shearing of the emittance ellipse flips and starts increasing again.
- The beam size is the smallest at the waist.



Beta function

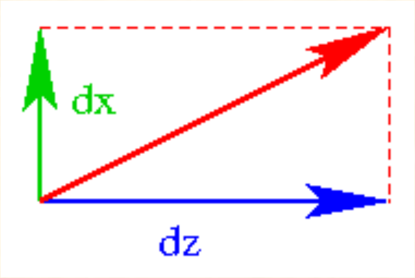
It is convenient to define the "beta function" to relate the beam size to the emittance.

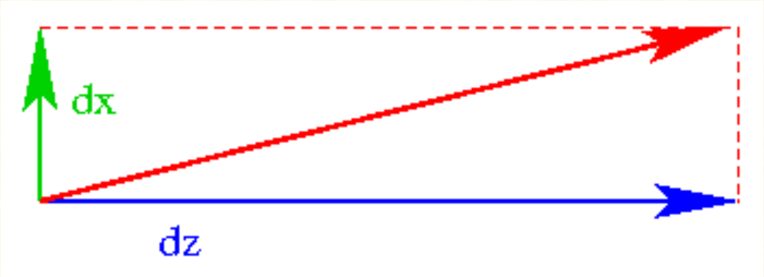
$$\beta = \frac{\sigma^2}{\in} \qquad \sigma = \sqrt{\beta \in} \qquad \sigma_{RMS} = \sqrt{\beta \in_{RMS}}$$



Acceleration

- When the beam is accelerated, its longitudinal momentum is increased,
- But the transverse momentum remains the same.
- Hence the beam divergence decreases.





- Accelerating the beam leads to a reduction the volume occupied in phase space.
- This reduction is proportional to the increase of the relativistic gamma.
  => The beam size is reduced when the beam is accelerated!

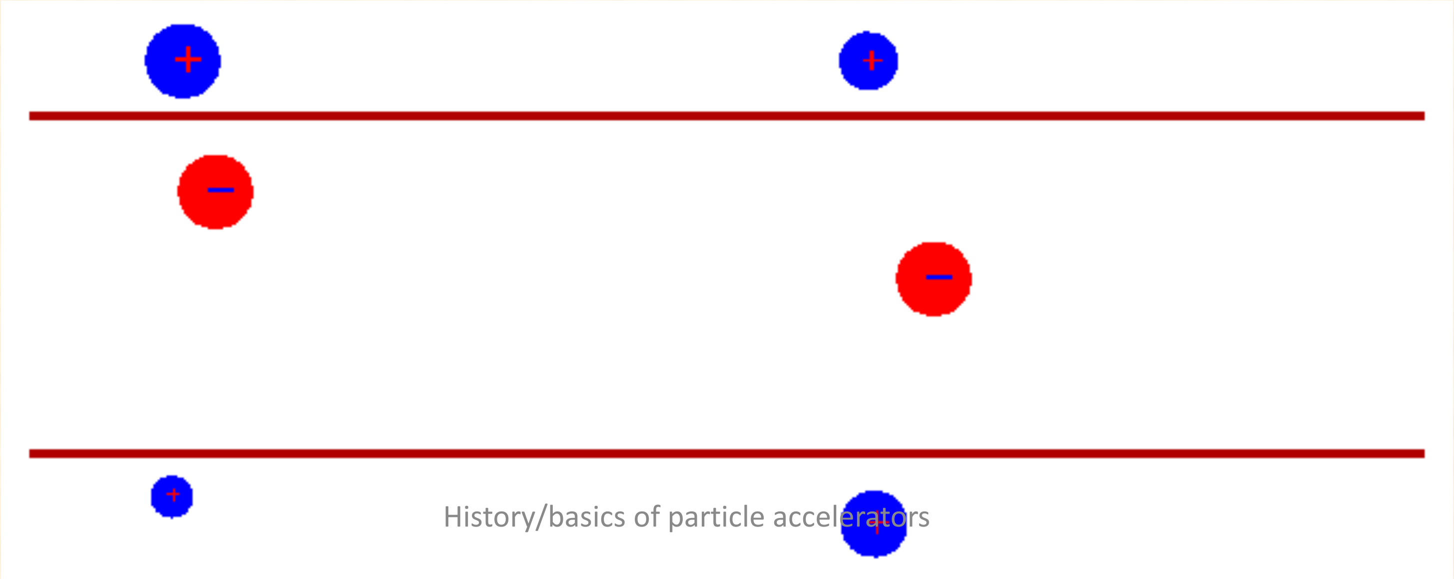
Normalised emittance

- It is convenient to define the normalised emittance of a beam: it is the volume of phase space occupied by the beam multiplied by gamma.
- The actual volume of phase space occupied by the beam is called the geometric emittance.
- The normalised emittance of a beam is constant under acceleration.

$$\in_N = \gamma \in_{Geometric}$$

Impedance issues

- Charged particles travelling near a conductor induce image charges (induced current).
- This image current dissipate power in the beam pipe (Joule effect).
- The smaller the beam pipe, the higher the induced charge and thus the highest the losses.
- The impedance of a beam pipe must be carefully controlled!



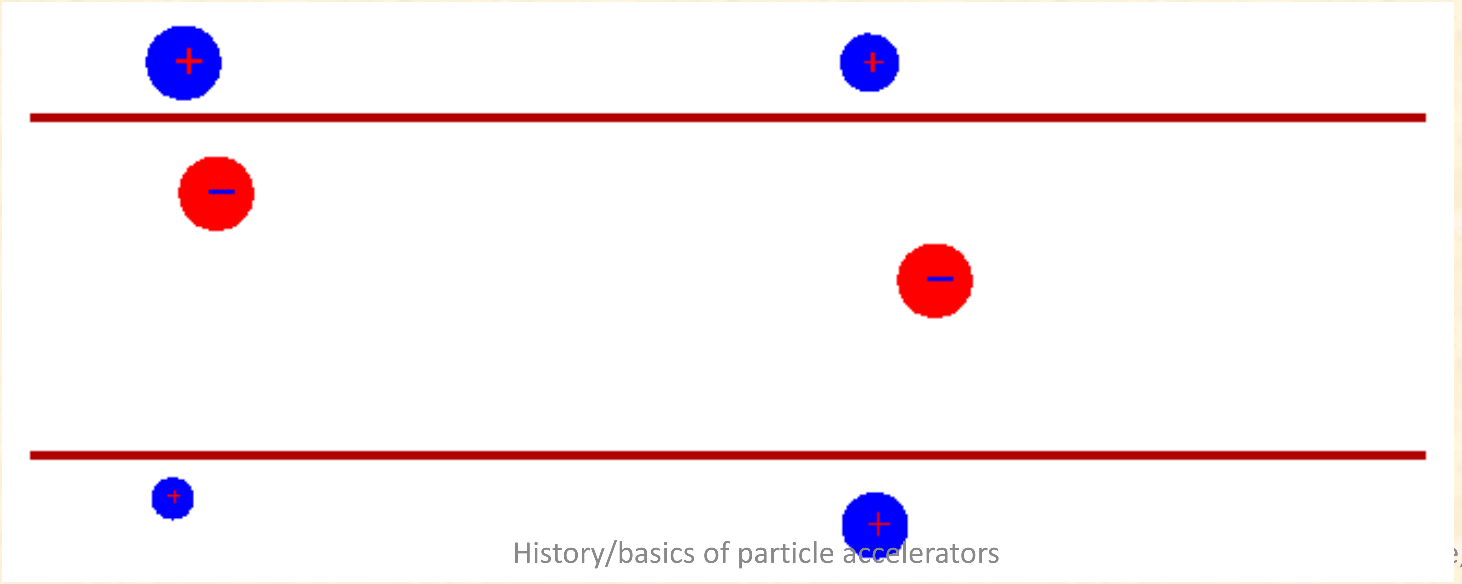
Quiz

- In the example below, which particle will create the more induced current on the beam pipe?

a) The particle on the left hand-side

b) The particle on the right hand-side

c) Both will induce the same current



Answer (c)

- Apply Gauss's law: $$\oint_{\partial\Omega} E.dS = \frac{Q(V)}{\epsilon_0}$$
- The total charge going through the beam pipe is the same for both particles.
- Hence the total current induced on the beam pipe by both particles will be the same.

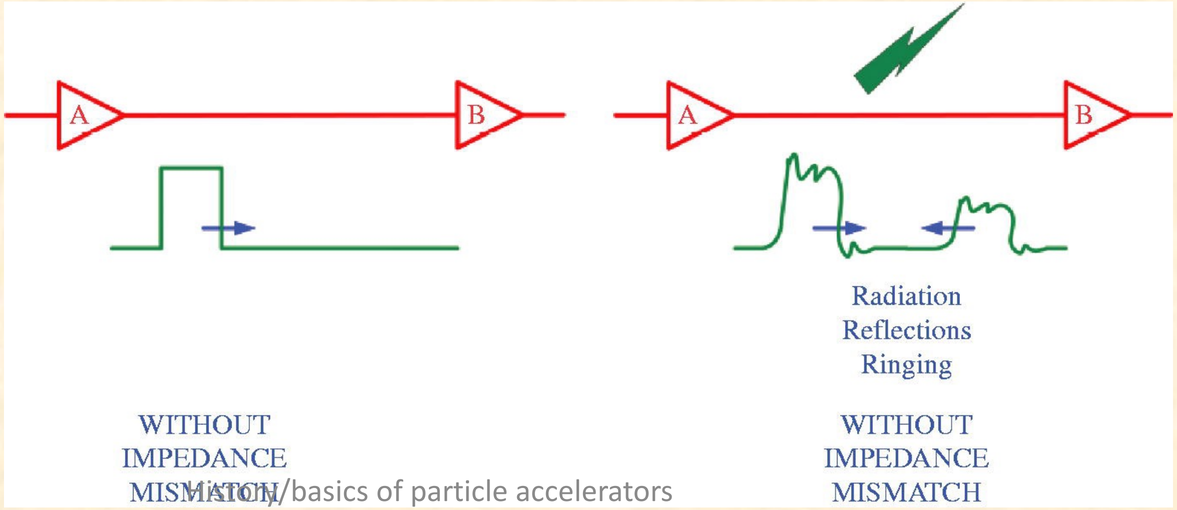
Wake field issues

- Electrons produce an electromagnetic wave behind them.
- This can be compared the to wake of a boat and is called wake field.
- 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

Impedance matching

- In a electronic 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.

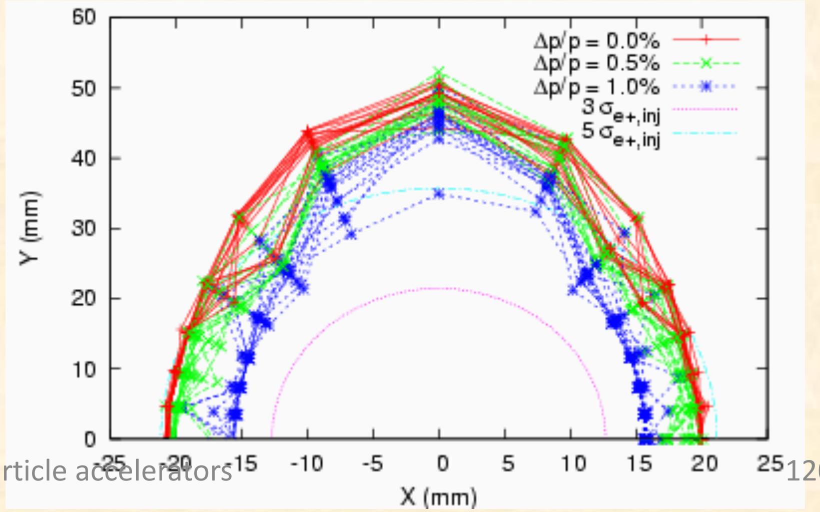


Beam size and magnet aperture

- One of the motivations for keeping the beam small is that magnets have a limited aperture.
- The larger the aperture the more difficult it is to keep a uniform field (and the bigger/more expensive the magnet is).
- It is recommended to have a beam pipe 5 times larger than the RMS size of the beam.

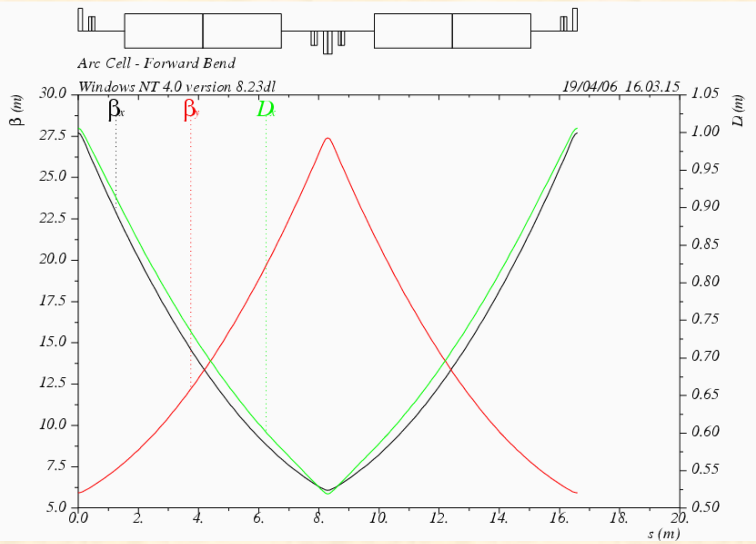
Magnet aperture

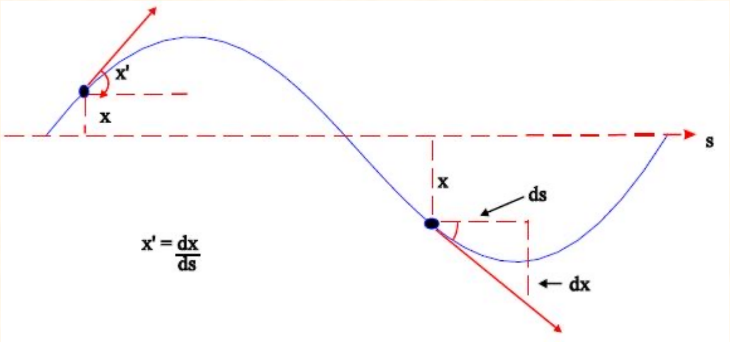
- Clipping, wake field and impedances issues lead to poor accelerator performances.
- To avoid these effects the trajectory of the beam in the accelerator must be simulated.
- Tracking software are used to do this: they study how particles move from one location to the next.
- Instead of tracking each particle individually it is enough to track the envelope of the beam.



Betatron oscillations

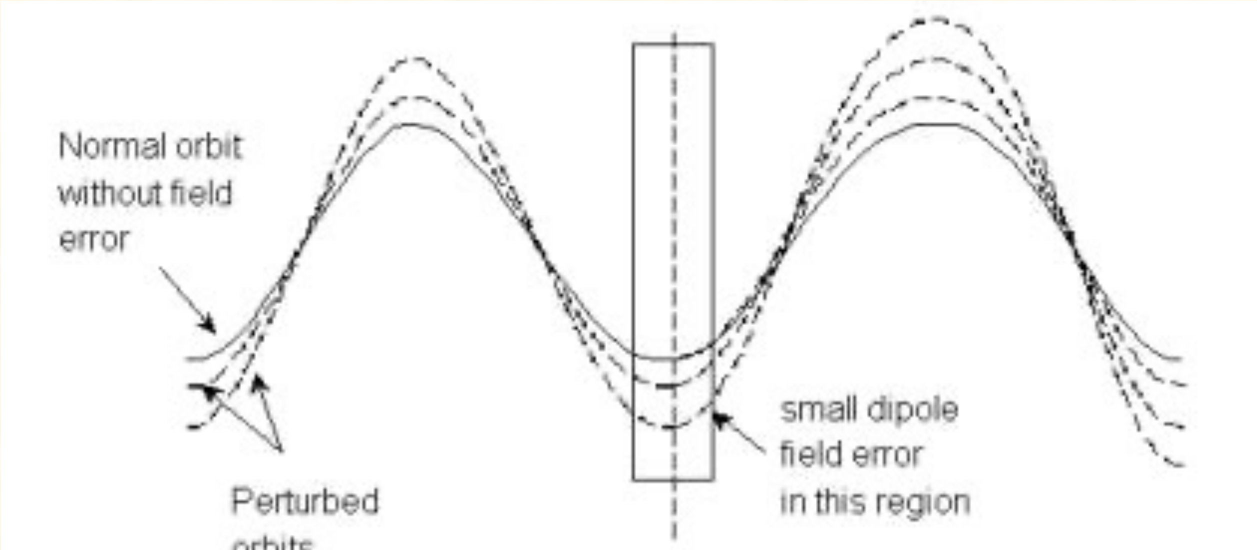
- We have seen that as it travels along the lattice the beam is focussed alternatively in both planes.
- For individual particles this leads to oscillations called "betatron oscillation".
- This occurs in both planes at the same time.
- If the particles perform an integer number of betatron oscillations 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

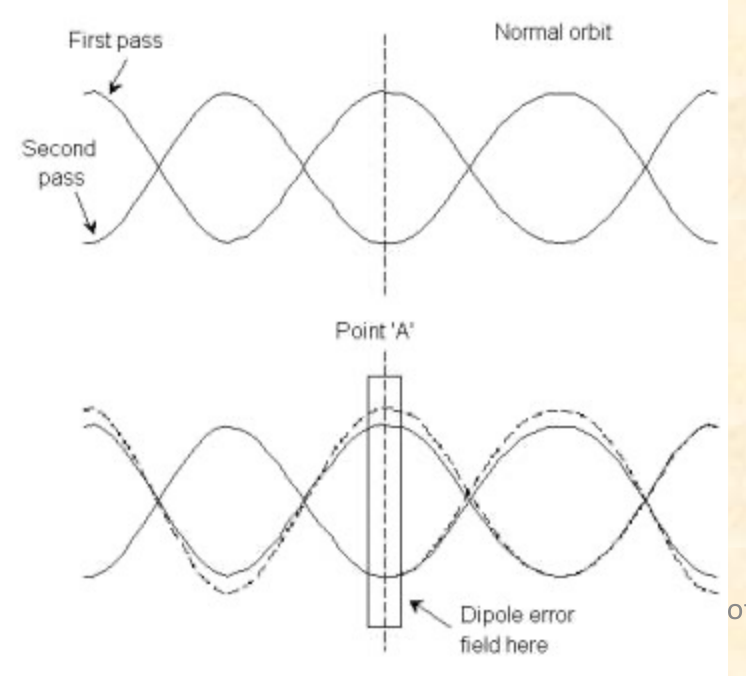
- If one of the magnets in the accelerator has a field error a particle coming turn after turn at the same position will accumulate the effect of this field error.
- After a large number of turns (millions…) what was initially a very small error can lead to large orbit changes and eventually to the loss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

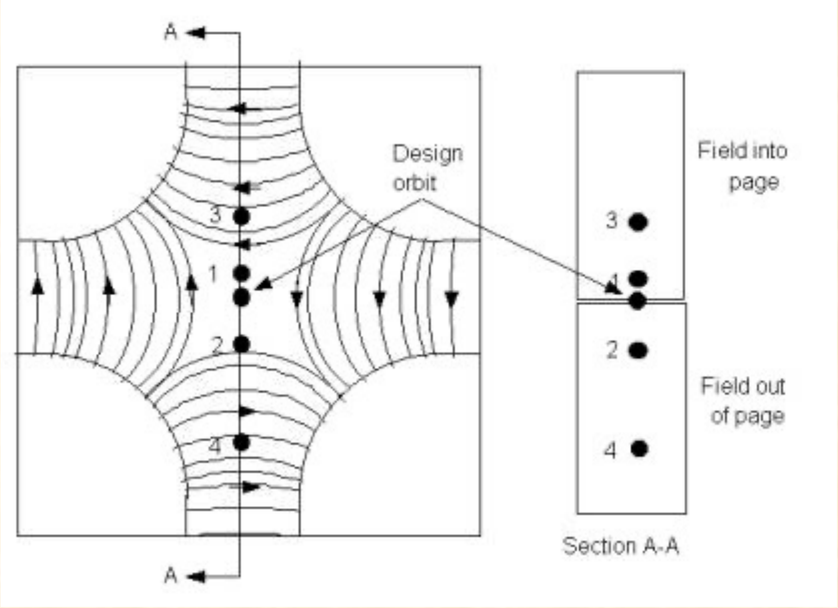


http://www.fnrf.science.cmu.ac.th/

Half-integer betatron oscillations

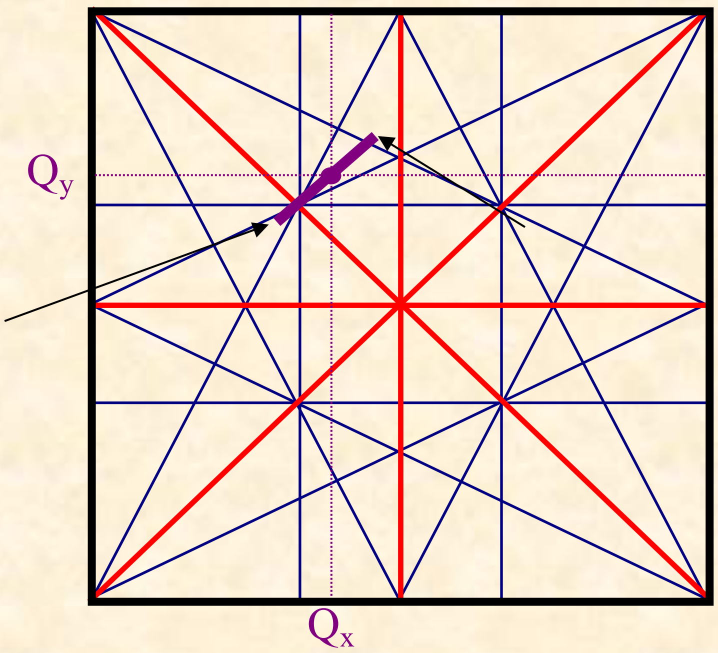
- Using an optic with an half-integer number of oscillations avoids first order problems.
- However a similar effect may accumulate every other turn…



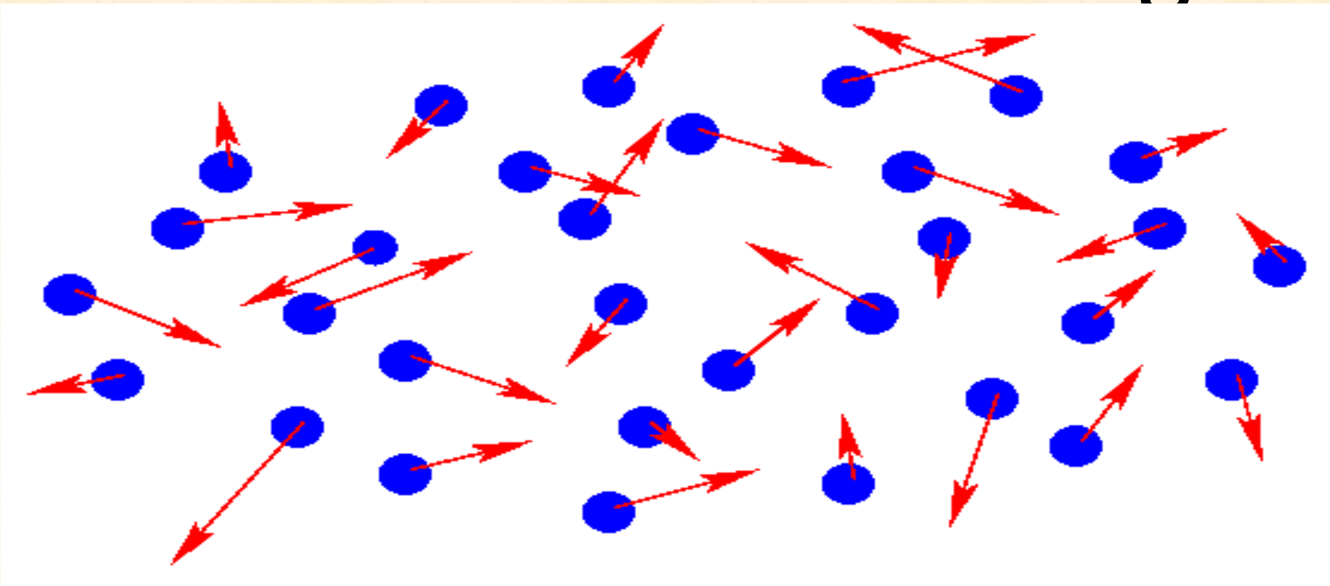


Tune

- 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.



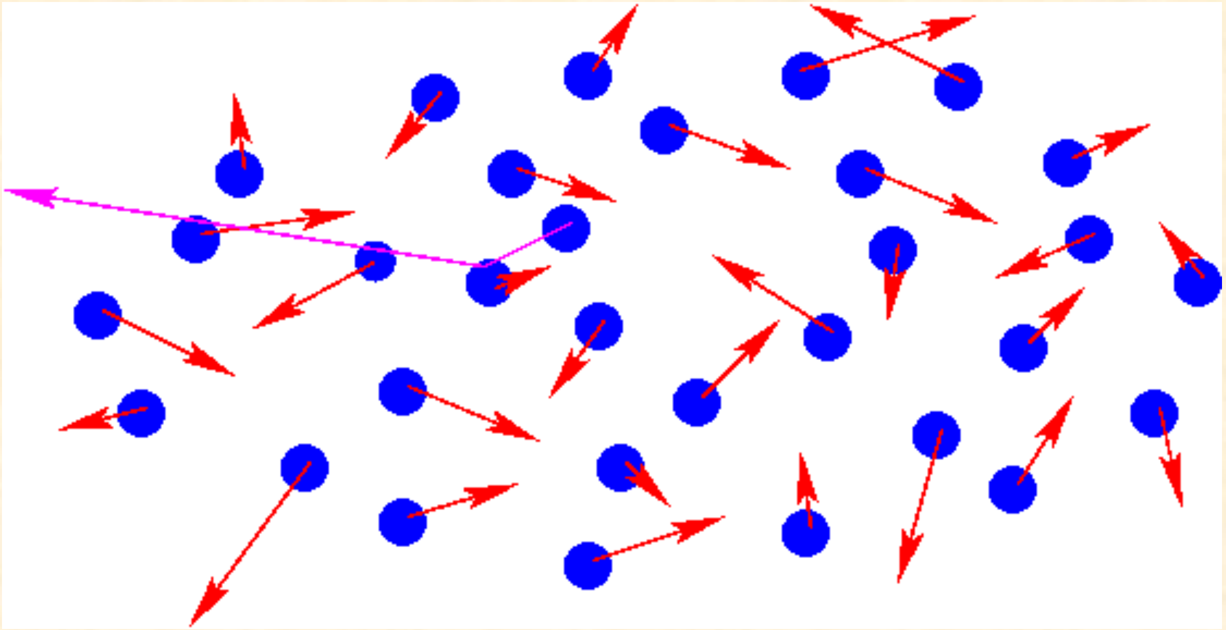
Intra-beam scattering



- We have seen that inside the beam the particles behave somewhat like a gas.
- Coulomb collisions do occur between the particles.
- These collisions lead to a momentum transfer between the particles and thus an emittance coupling and emittance growth.
- Beams with a larger emittance will experience more IBS.

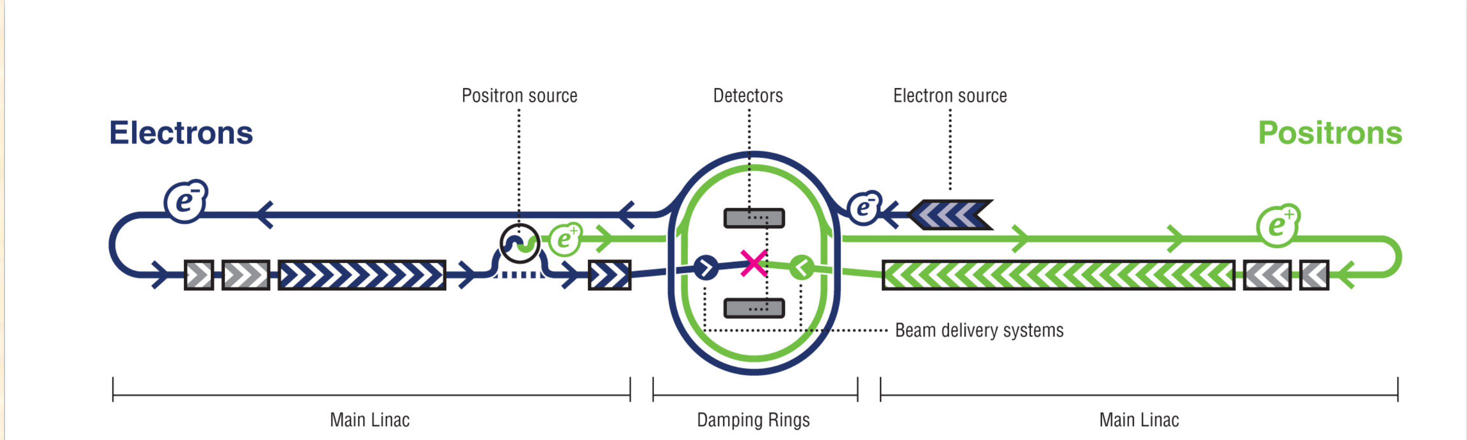
Touschek effect

- In addition to Coulomb scattering, hard scattering can also occur.
- In most cases this will lead to one particle being pushed out of the acceptable beam orbit and thus being lost soon after.
- Touschek scattering occurs in high current beams.



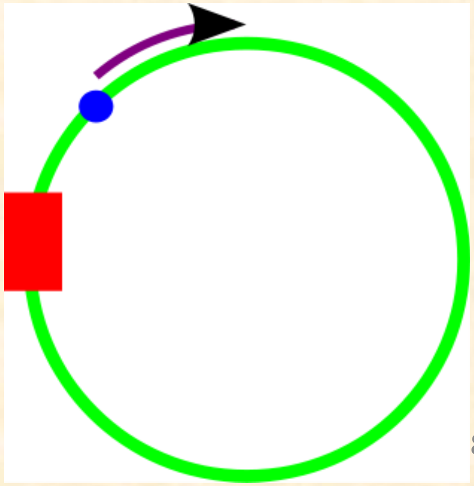
Radiation damping

- The energy lost du to synchrotron radiation emission has to be compensated by a RF cavity that tops-up the energy of the beam at each turn.
- This additional acceleration at each turns results in a decrease of the beam transverse emittance.
- By storing a beam in a ring for several milliseconds it is possible to significantly reduce its transverse emittance.
- The reduction of emittance in a ring due to SR emission is called “radiation damping”.
- As the radiation is emitted in the plane of the accelerator, radiation damping is faster in the direction orthogonal to the accelerator. => very flat beams



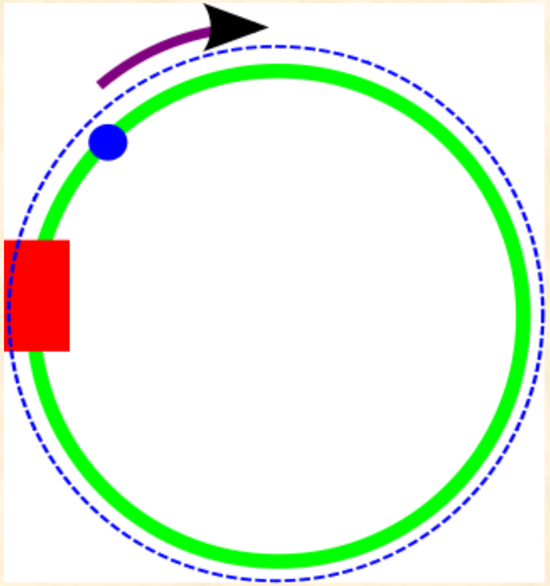
Quizz

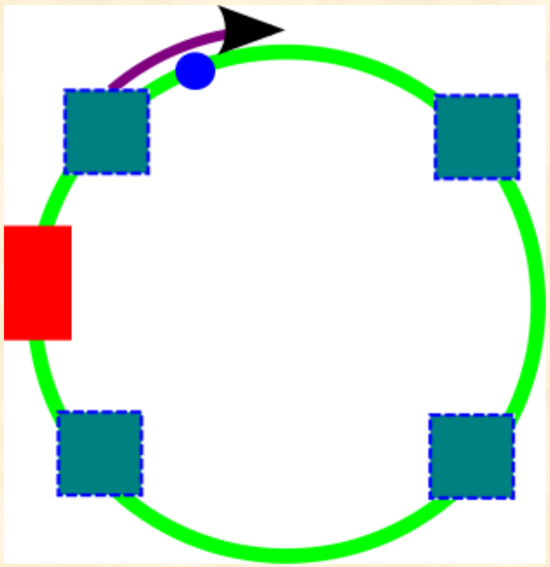
- The particles in the beam do not all have the same energy. This is the “energy spread” of the beam.
- Let’s consider a ring with no focusing element (only dipoles).
- (1) How will the trajectory of the particle with more energy compare to that of particles with less energy?
  (a) they will have a larger orbit
  (b) they will have a narrower orbit
  (c) their orbit will be similar
  (d) can not tell



Answer (1a)

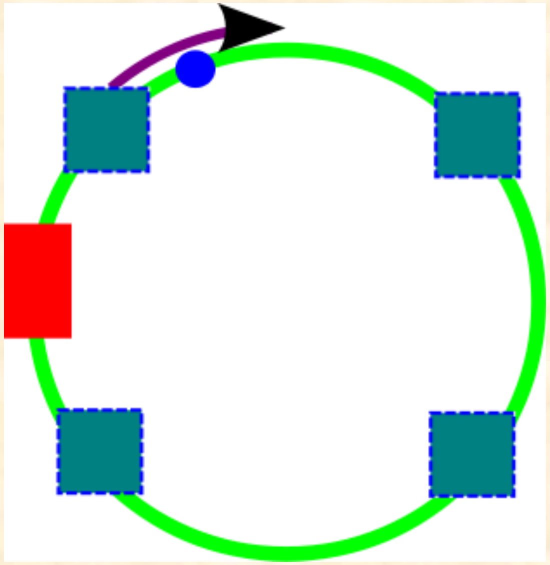
- Particles with a higher energy will be less deflected by the dipole magnets so they will have a larger orbit.
- (2) How is this result changed if there are 4 quadrupoles in the ring?
  (a) they will have a larger orbit
  (b) they will have a narrower orbit
  (c) their orbit will be similar
  (d) Can not tell





Answer (2d): Can not tell

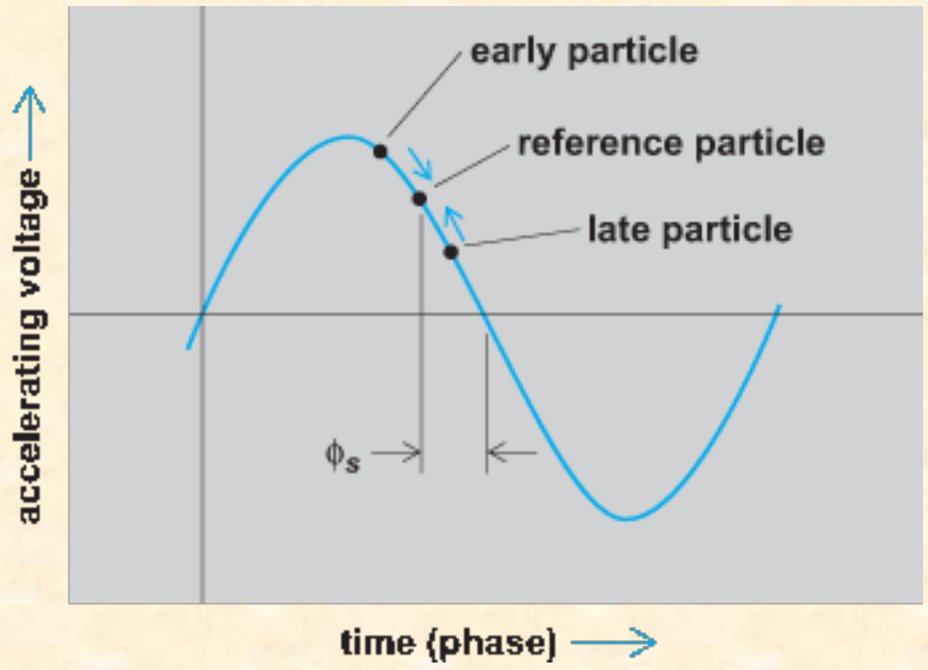
- To know which particles have a larger orbit and which particles have a narrower orbit the lattice must be taken into account.
- The momentum compaction factor gives the relation between momentum and orbit radius.
- It is dependant on the beam optics.

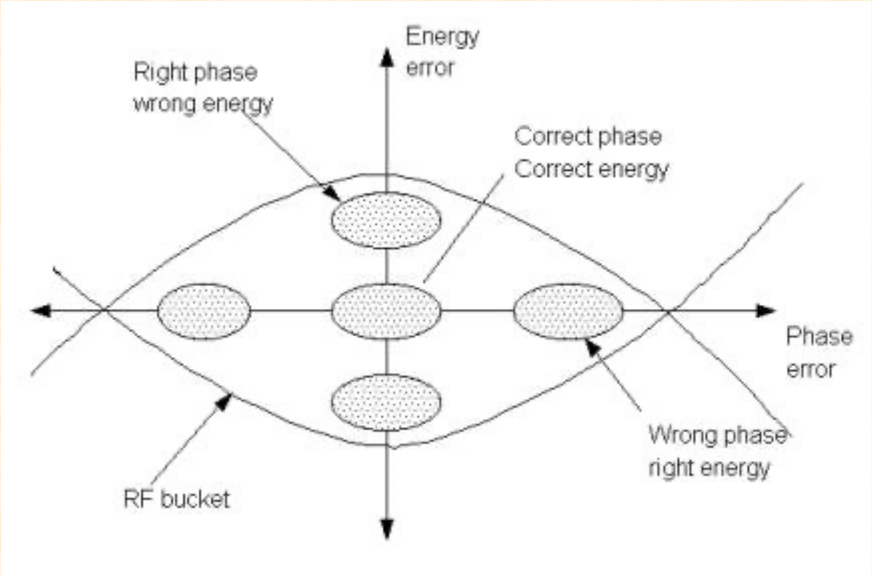


$$\frac{\Delta r}{r} = \alpha p \frac{\Delta p}{p}$$

Longitudinal dynamics

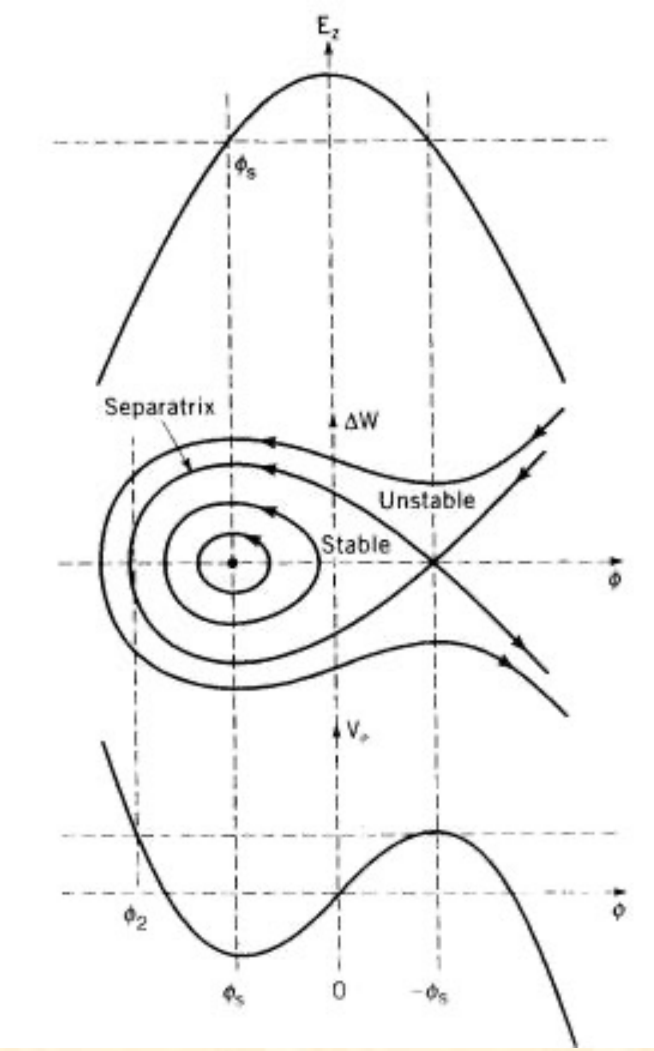
- As there is a relation between momentum and orbit, the particles that do not have the correct momentum will experience a phase slippage.
- This will in turn induce a change in their energy.





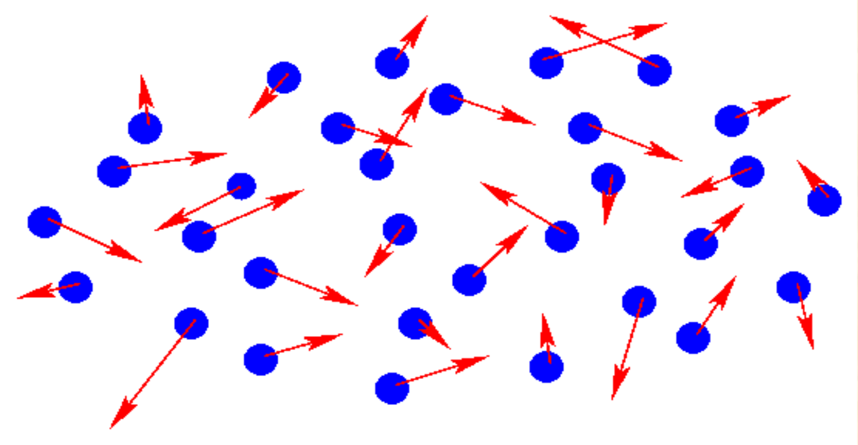
Longitudinal dynamics (2)

- Only a certain area of the phase vs energy plan is stable.
- Particles outside this stable area will drift away and eventually get lost.
- The position and size of this area will depend on the RF cavity voltage, the energy lost per turn (SR) and momentum compaction factor.

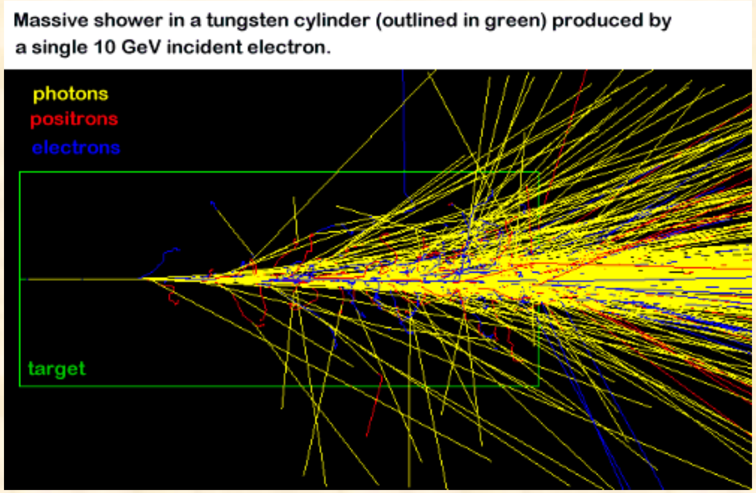


Summary emittance and beams dynamics

- The behavior of the beam is very important to understand what happens in the accelerator.
- Many phenomena can disrupt the beam, reducing its quality and hence the luminosity produced.

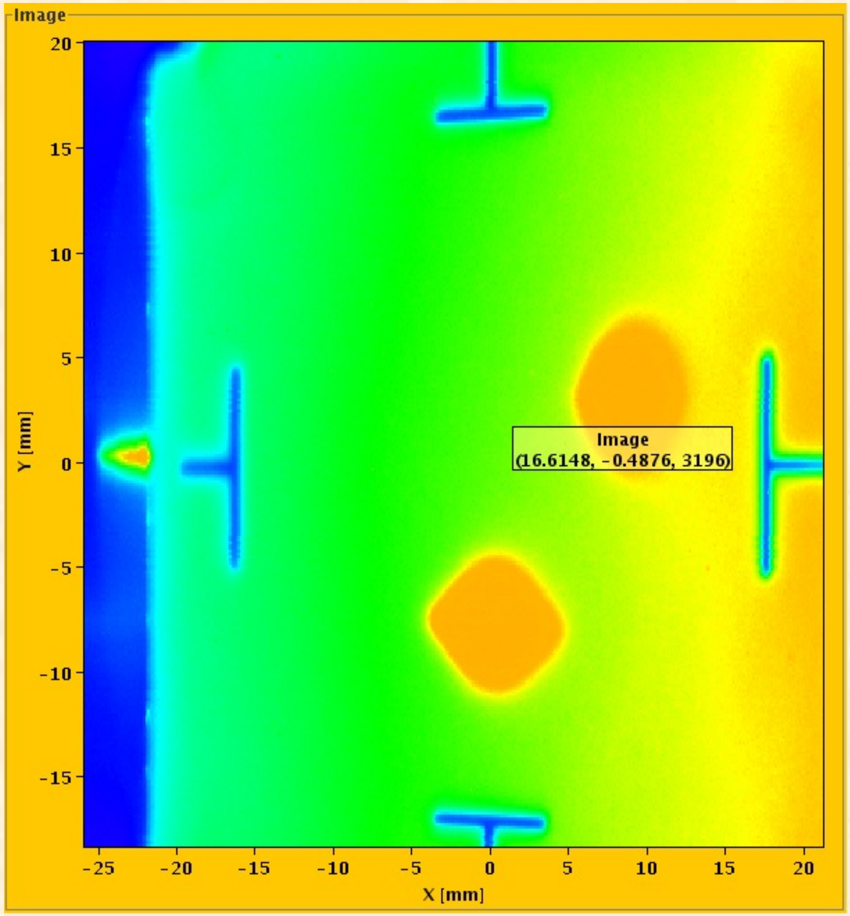


Lecture content



- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - *Particle acceleration*
  - *Magnets*
  - *Emittance and beam dynamics*
  - **Beam diagnostics**
- Challenges for present and future accelerators

Diagnostics



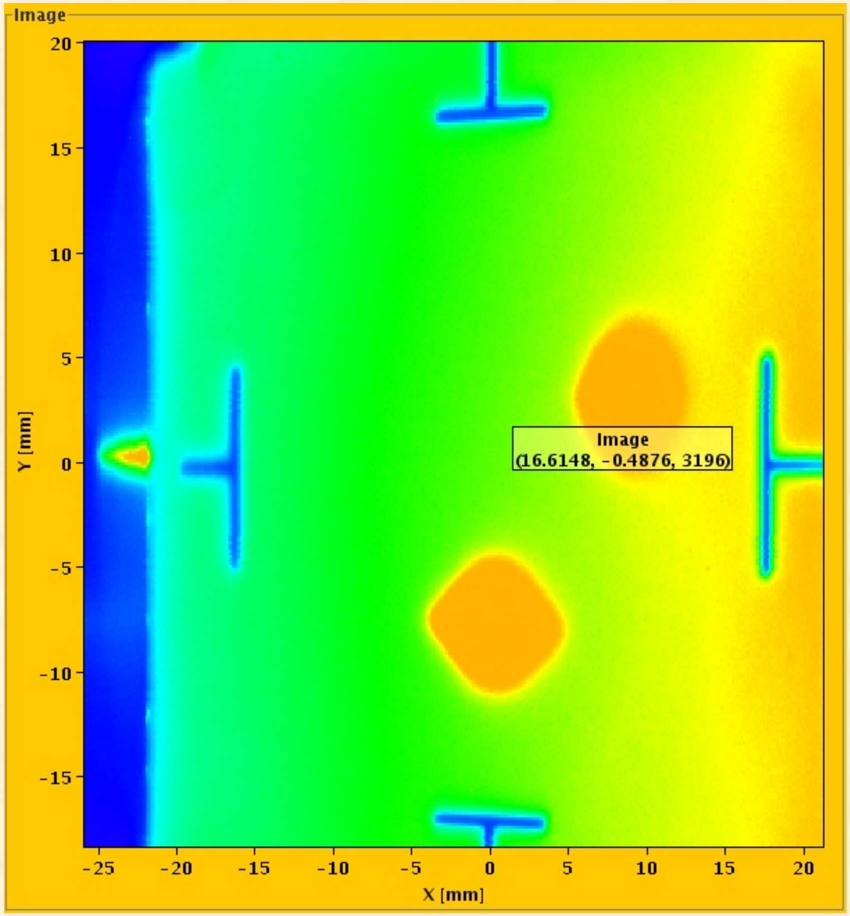
- Which diagnostics do we need?
- Particles interactions with matter
- Charged particles detection

What do **you** want to know about the beam?

?

What do you want to know about the beam?

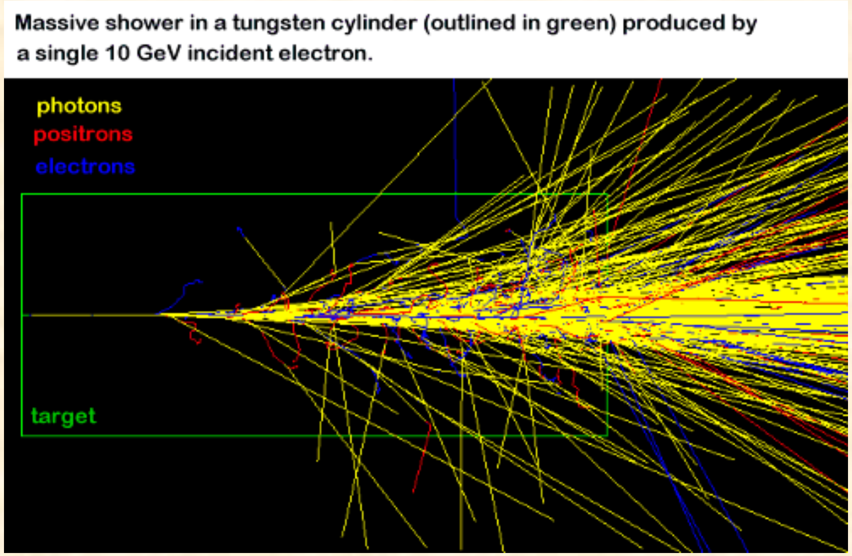
- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses

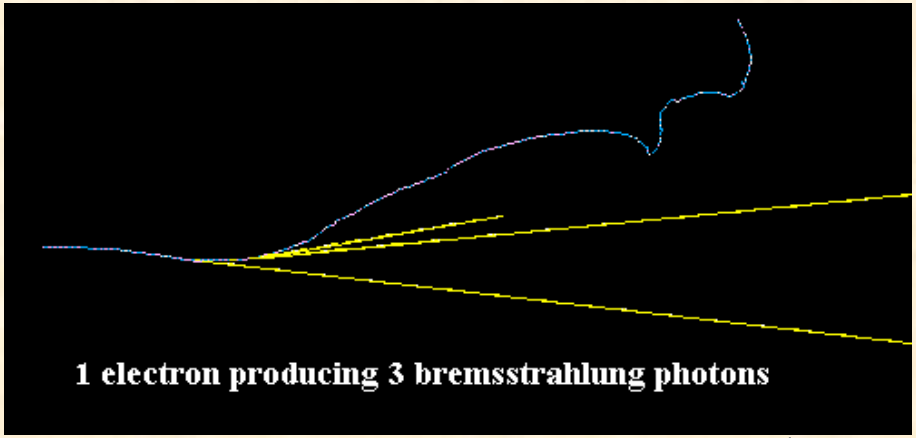


Properties of a charged beam

- Almost all accelerators accelerate
  charged particles which interact with matter.
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

Particles interact with matter

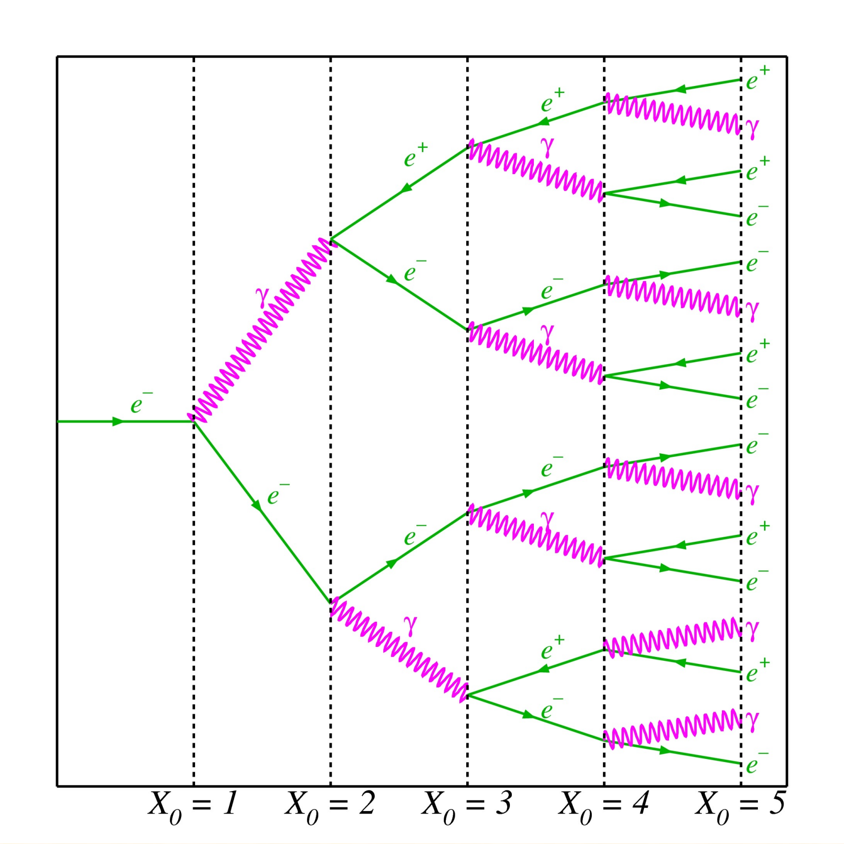




- When a particle enters (nuclear) matter, it loses energy.
- It will scatter off the nuclei that form the nuclear matter.
- Particles produced when such scattering occur will carry a significant energy and scatter themselves.

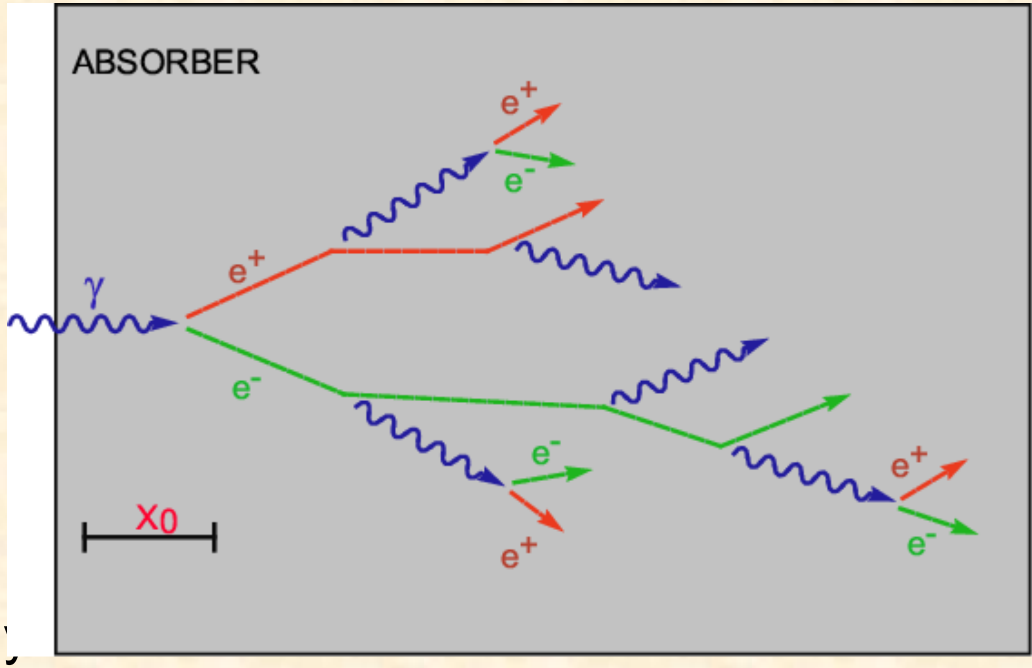
Example: Electron shower (1)

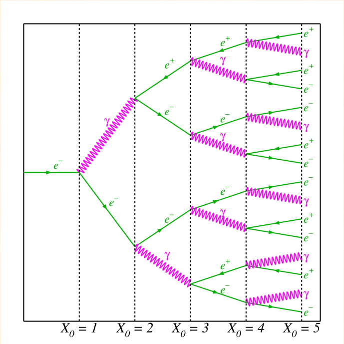
- The distance after which an electron or a photon interacts is called the "radiation length"
- Radiation length vary from material to material and can be found in tables.
- X_0(Pb)= 0.56cm
  X_0(Ta)= 0.41cm
  X_0(Cu)= 1.44cm
  X_0(Fe)= 1.76cm
  X_0(C graphite)= 19.32cm



Example: Electron shower (2)

- Particles loose 1/e of their energy after each radiation length.
- The reality is a bit more complex but statistically this picture is true...
- Heavy particles such as protons will loose some energy as they travel in matter and suddenly stop when their energy slow enough.





Example: Electron showers (3)

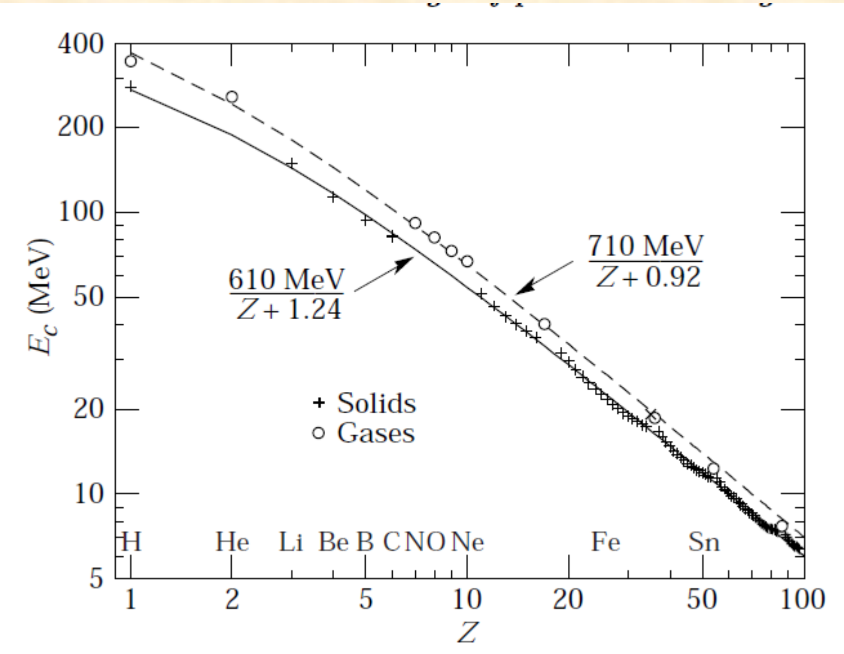


Image source: Particle Data Group

- After loosing enough energy the electrons are finally absorbed.
- The energy at which they are absorbed depends on the absorber (see Particle Data Group booklet for more details).

Quiz: shower depth

- A 1 GeV electron hits a 4.1cm thick plate of Tantalum.
- X_0(Ta)= 0.41cm
- How many particles (approximately) will be present in the shower at the exit of the plate?

a) 10

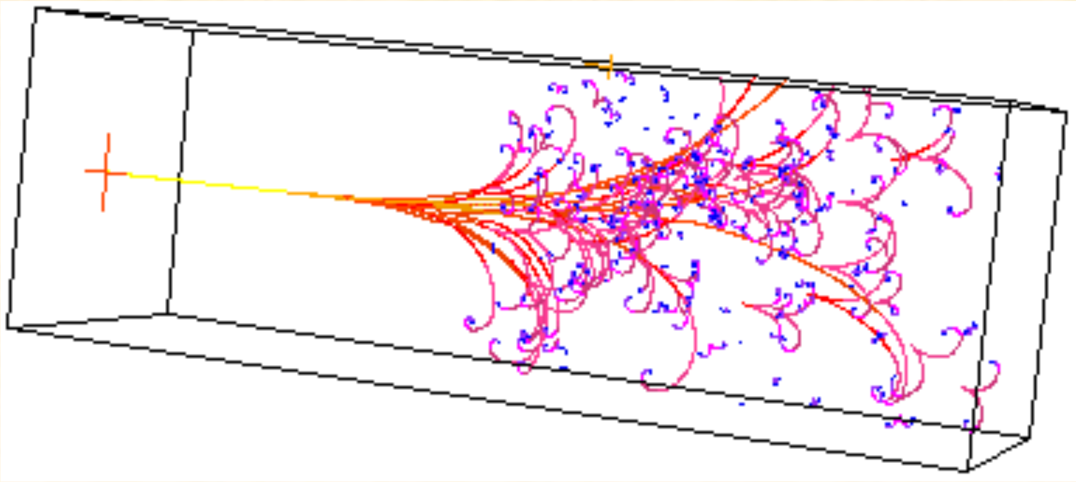
b) 10*10

c) 2^{10}

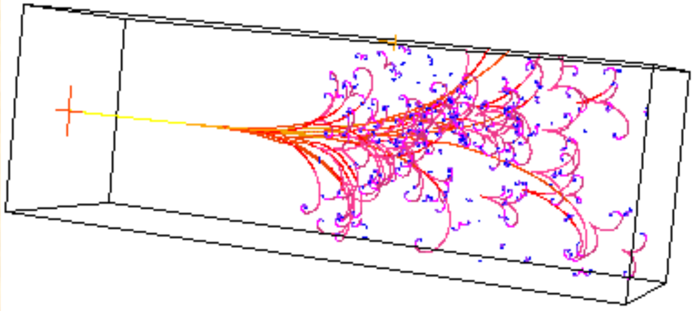
d) 1 (the original electron)

Answer: (c)

- The number of particles double after each radiation length.
- There are 4.1cm/0.41=10 radiation length
- So there will be approximately 2^{10} particles after the plate.

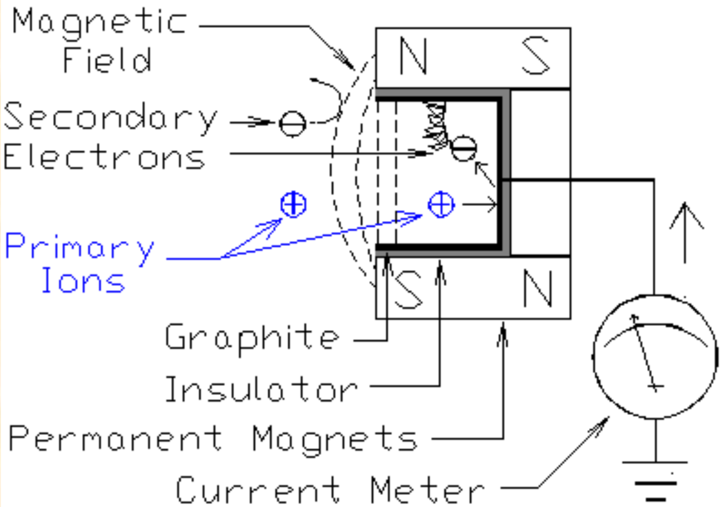


Faraday cup (1)



- Let's send the beam on a piece of copper.
- What information can be measured after the beam has hit the copper?

Faraday cup (2)



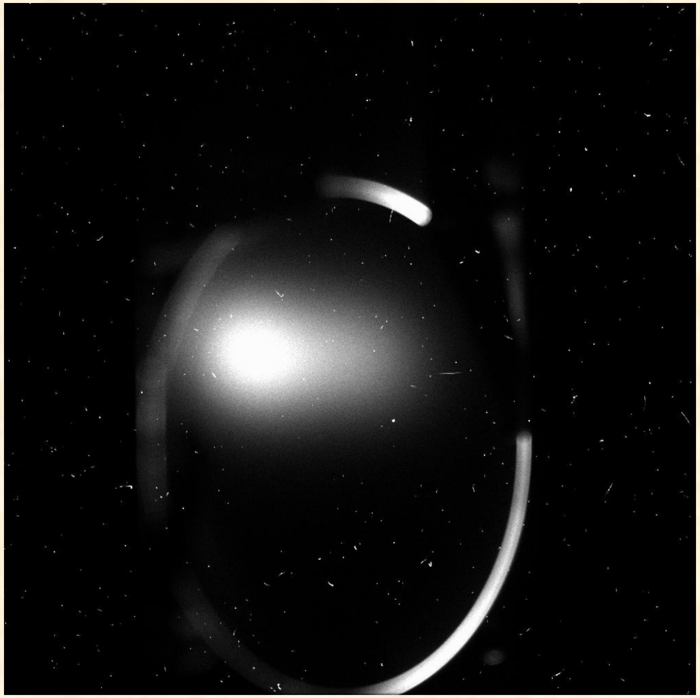
- Two properties can be measured:
  - Beam total energy
  - Beam total charge
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large:
  More than 1m at Diamond for a 3 GeV electron beam.

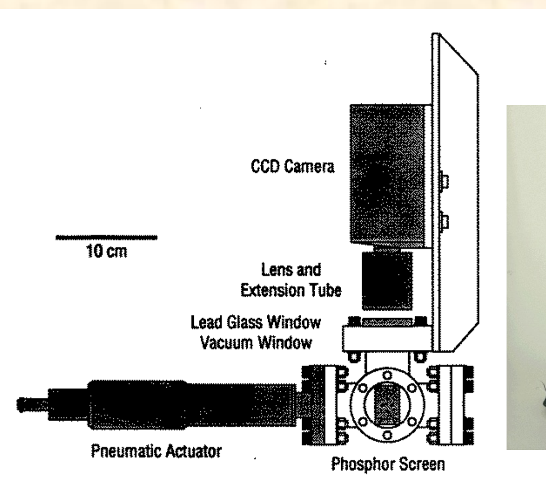
Image source: Pelletron.com

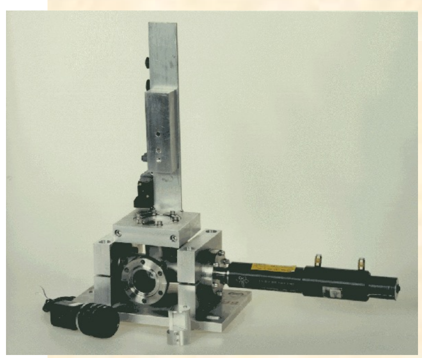
Screen (1)

- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

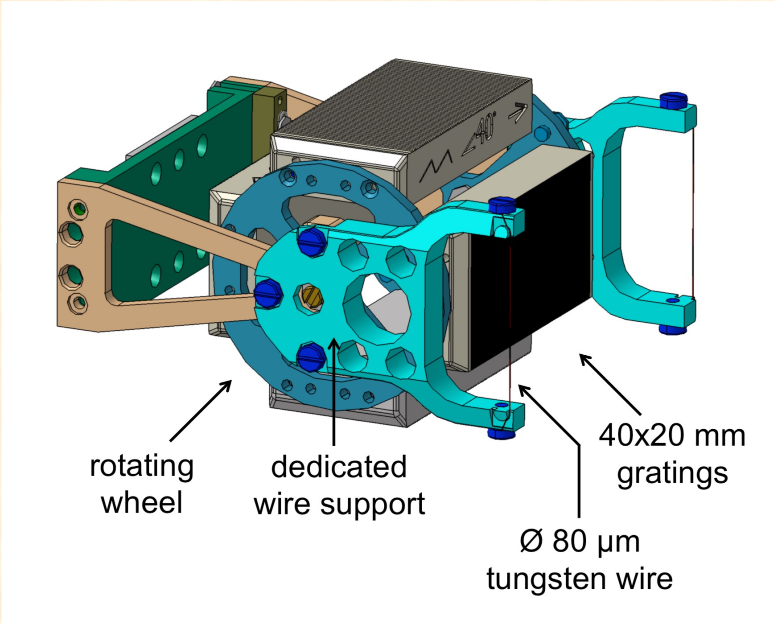
Screen (2)

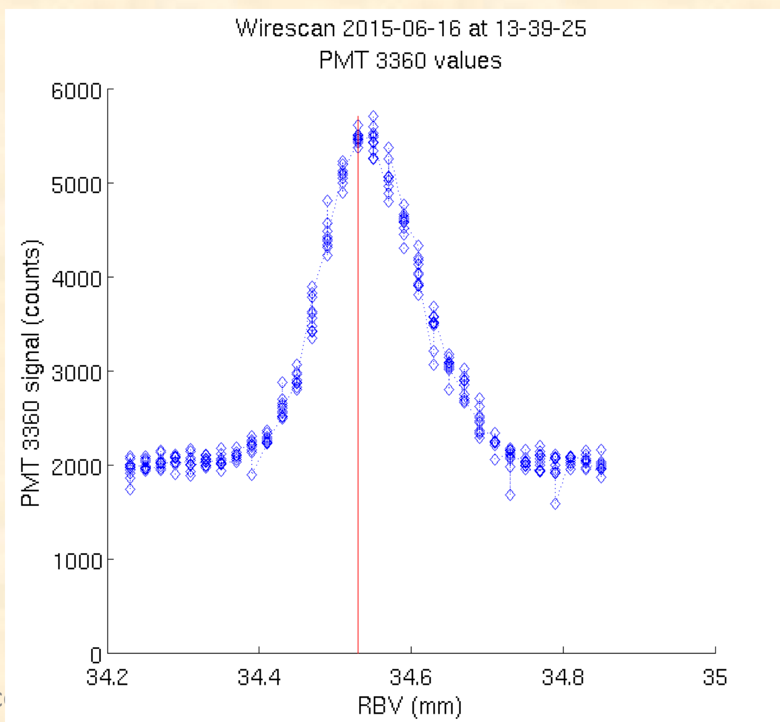






- It is not possible for the operators to stay in the accelerator while the beam is on so the screen must be monitored by a camera.
- To avoid damaging the camera the screen is at
  45 degrees.
- On this screen you can see both the position of the beam and its shape.
- Note the snow on the image.

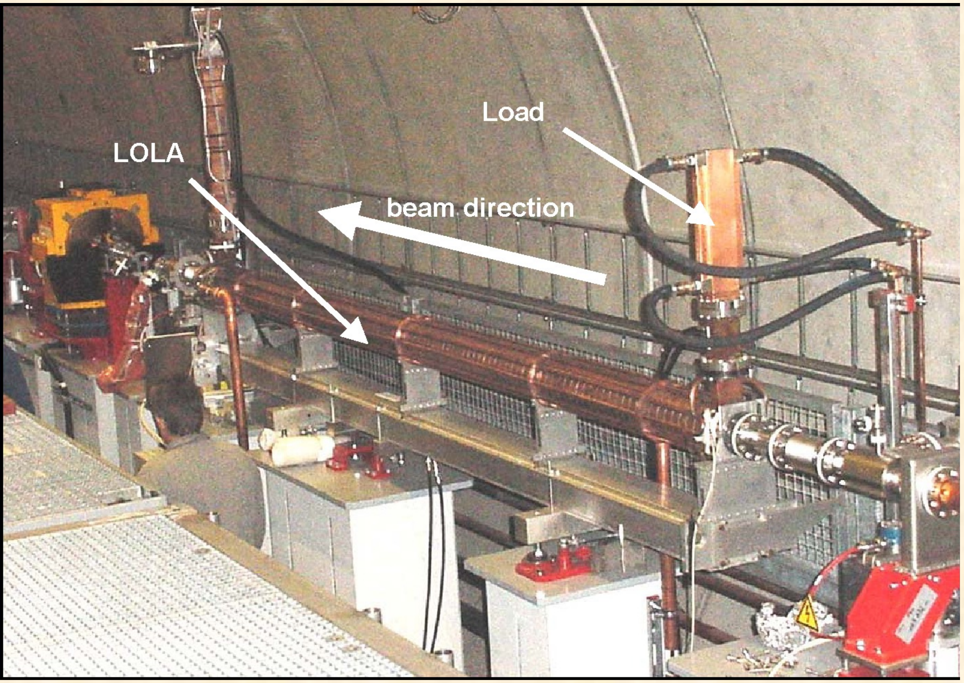




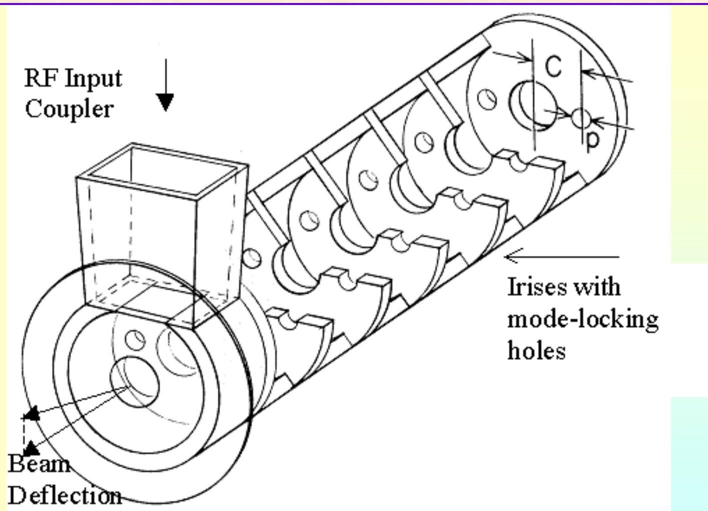
Wire-scanner

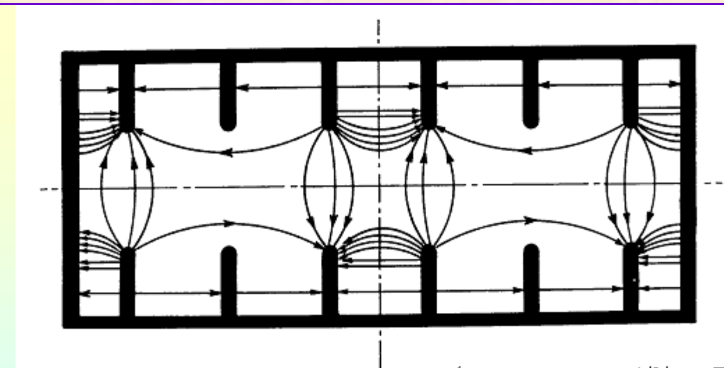
- By inserting a thin wire in the beam trajectory (instead of a full screen) it is possible to sample parts of the beam.
- By moving the wire in the transverse direction one can get a profile of the beam.
- It is possible to use wire diameters of just a few micrometres.
- However, a too strong beam current can lead to damages to the wire (requiring replacement of the wire).

Longitudinal properties



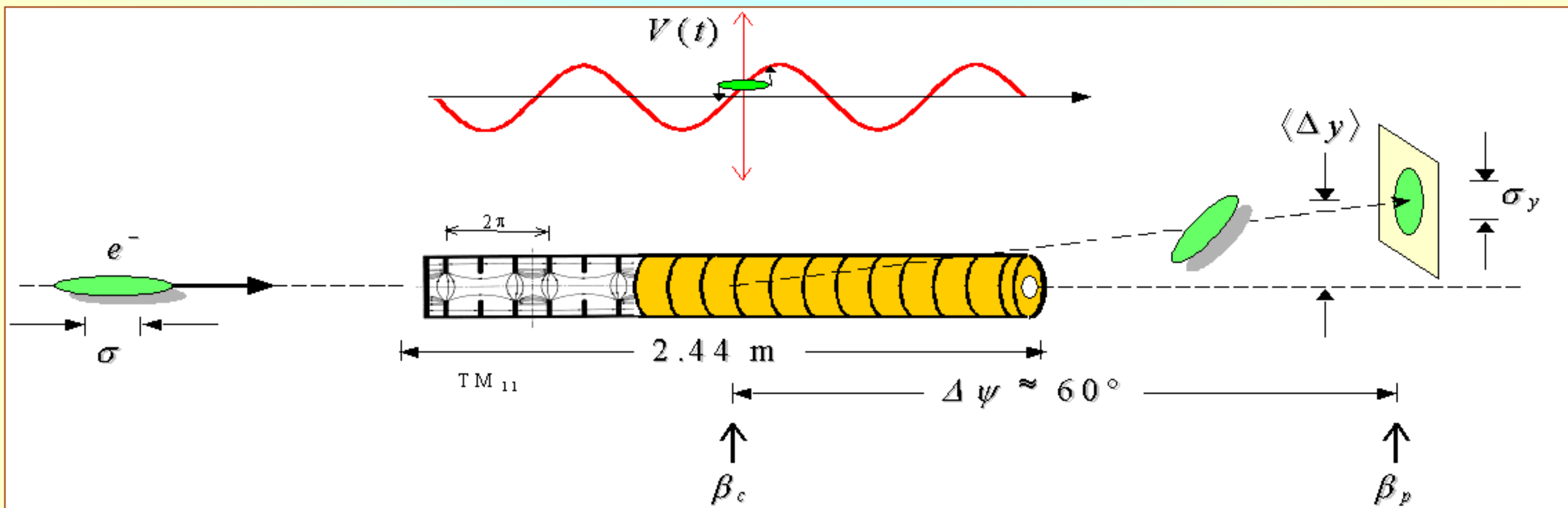
- It is not possible to directly image the longitudinal profile of a bunch.
- By giving longitudinal impulsion to the beam it is possible to make it rotate and observe its longitudinal profile.



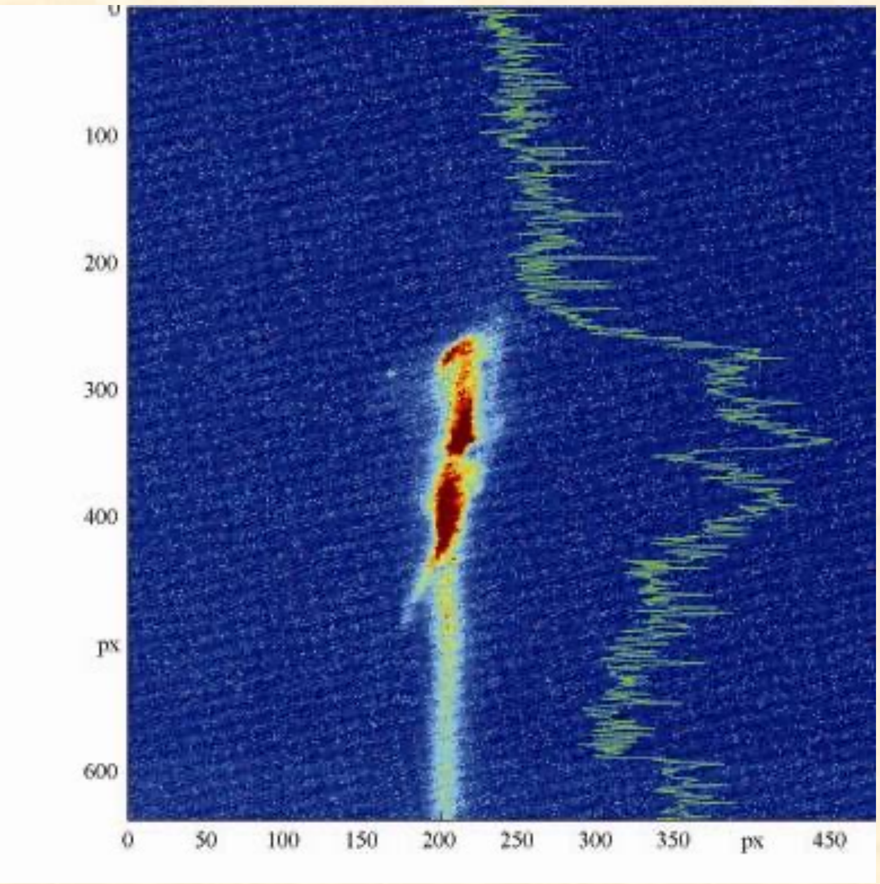


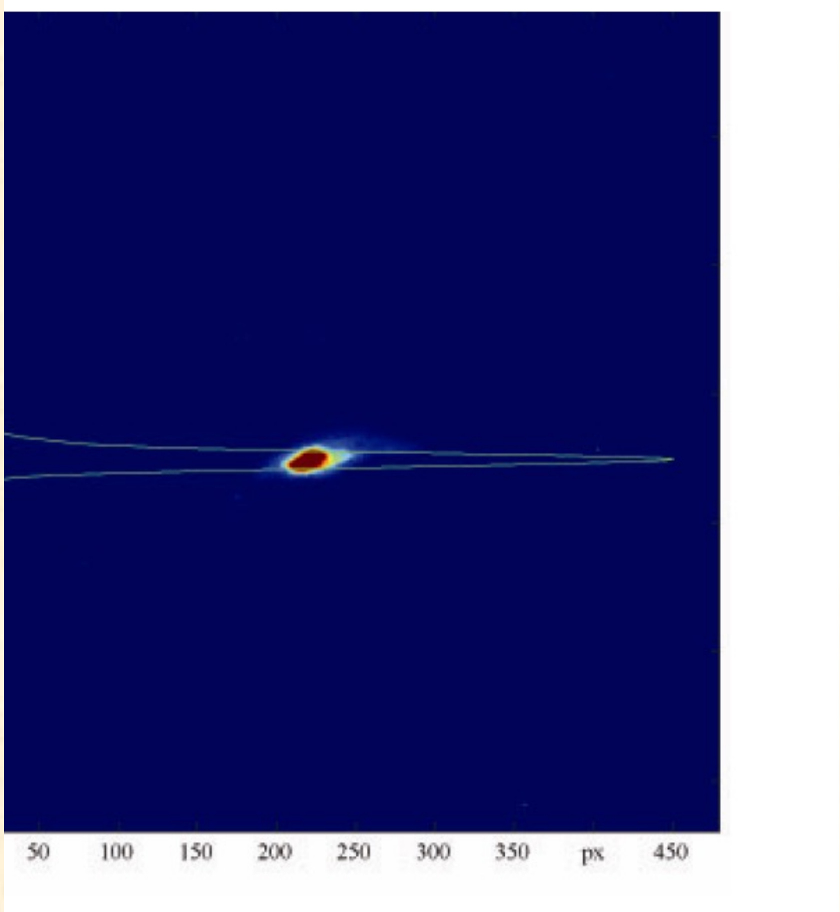
$$V_0 \approx \left(1.6\ \mathrm{MV/m/MW}^{1/2}\right) L\sqrt{P_0}$$

$$bunchlenght, \sigma_z \approx \frac{\lambda_{rf}}{2\pi}\frac{E_s}{\left|eV_0 \sin\Delta\psi \cos\varphi\right|}\sqrt{\frac{\left(\sigma_y^2-\sigma_{y0}^2\right)}{\beta_d\beta_s}}$$



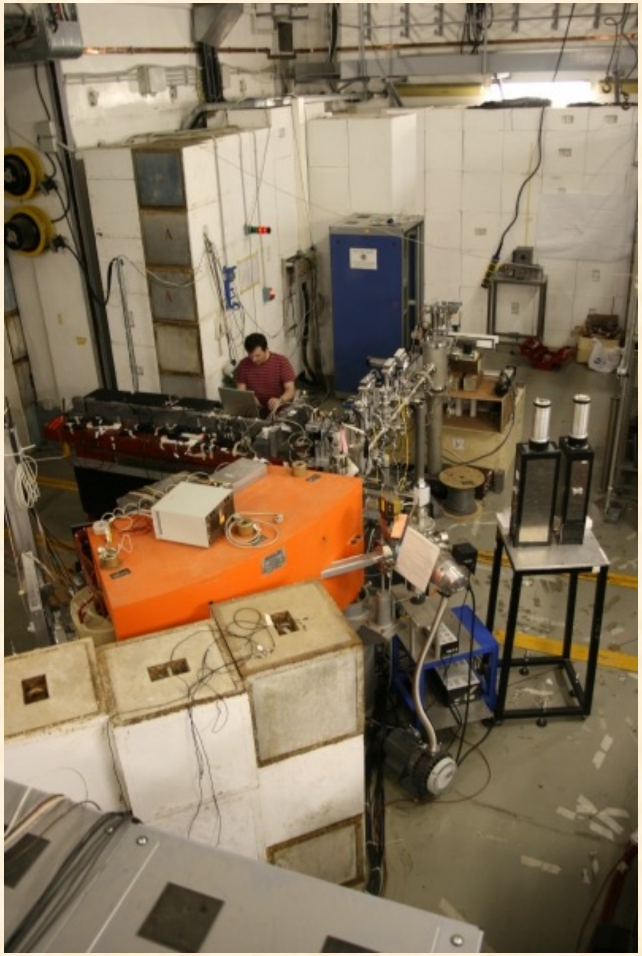
RF deflector off and on



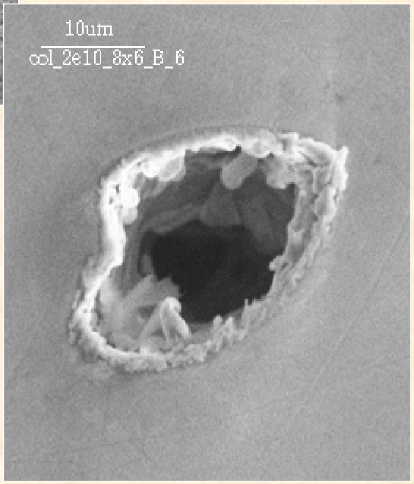


Beam losses

- It is important to monitor the beam losses directly:
- Small beam losses may not be detected by other systems
- Beam losses are a source of radiation and activation
- Most beam losses indicate that there is a problem somewhere.

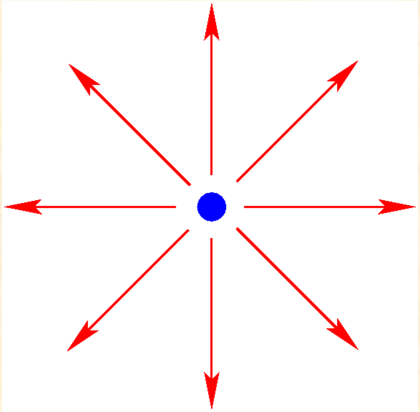


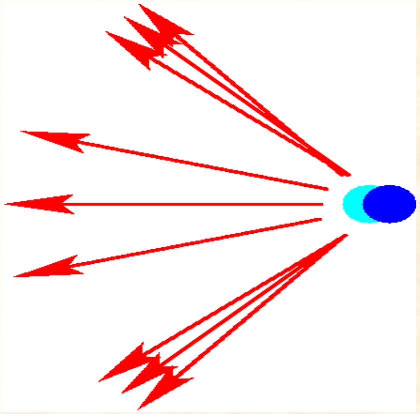
Limitation of these monitors



- Monitors in which the matter interacts are prone to damage.
- With high energy high intensity colliders such damages are more likely to occur.
- To the left: hole punched by a 30 GeV beam into a scintillating screen.

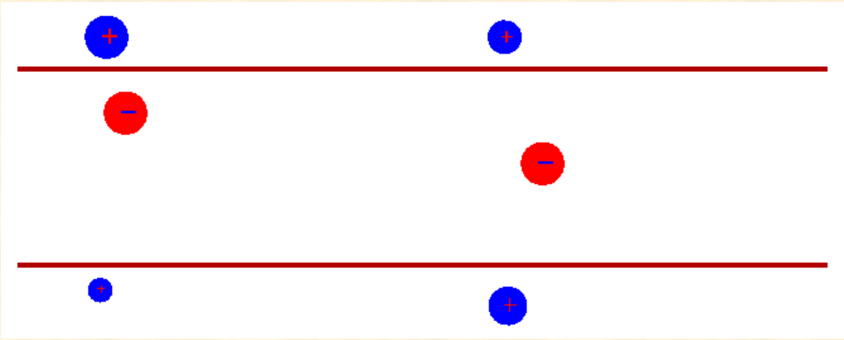
Charged particle

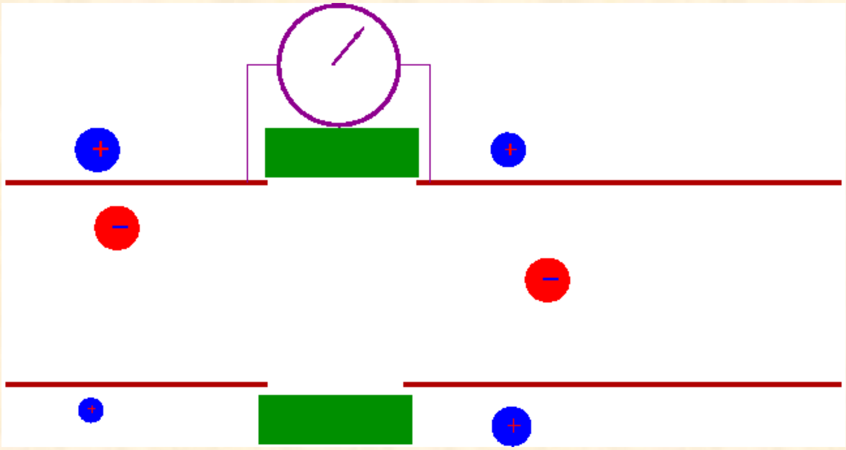




- Any charged particle “radiates”
- These electromagnetic radiations can be detected without disrupting the beam.
- One need to remember that the beam travels at high speed: the radiations will be contained in a 1/gamma cone.

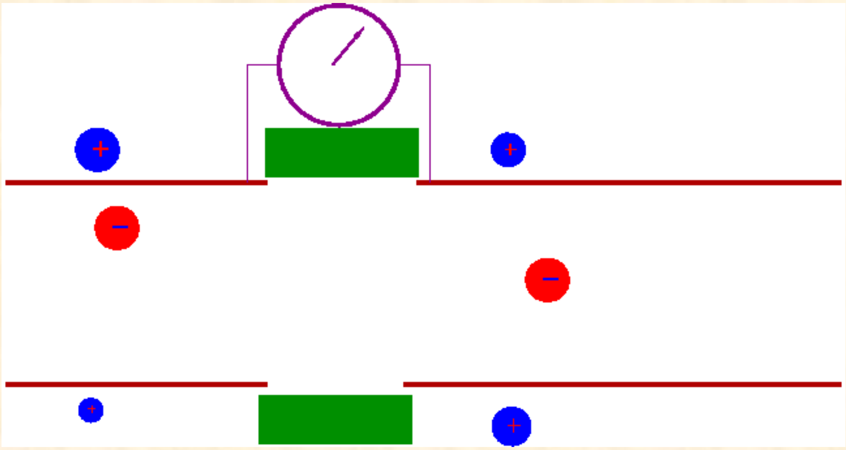
Beam current monitor





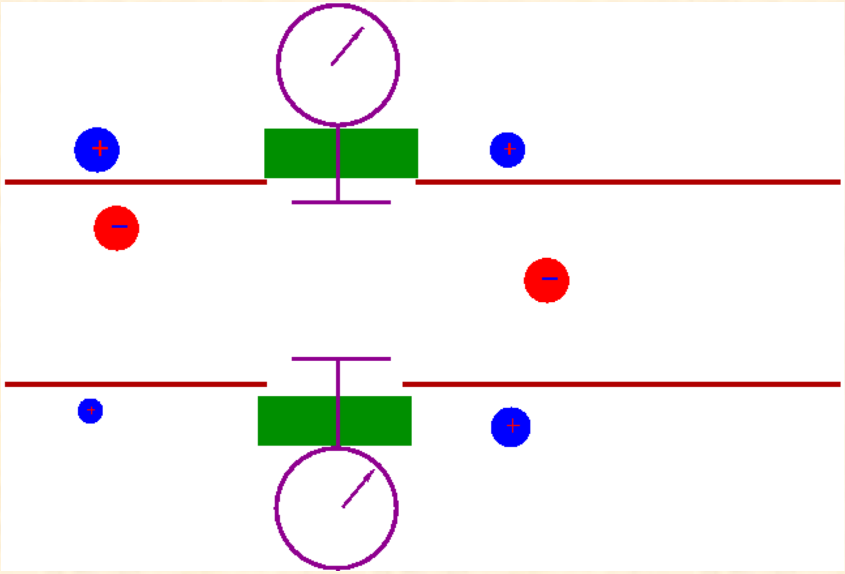
- Remember: as the charge travelling in the beam pipe is constant the current induced on the walls (of the beam pipe) will be independent of the beam position.
- By inserting a ceramic gap and an ammeter the total charge travelling in a beam pipe can be measured.

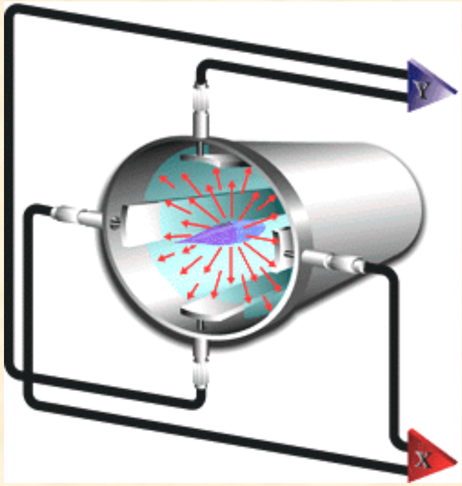
Beam current monitor vs Faraday cup



- Both devices have pros and cons.
- A Faraday cup destroys the beam but it gives a very accurate charge measurements
- A Beam current monitor does not affect the beam but must be calibrated.
- Both tend to be used at different locations.

Beam position monitor

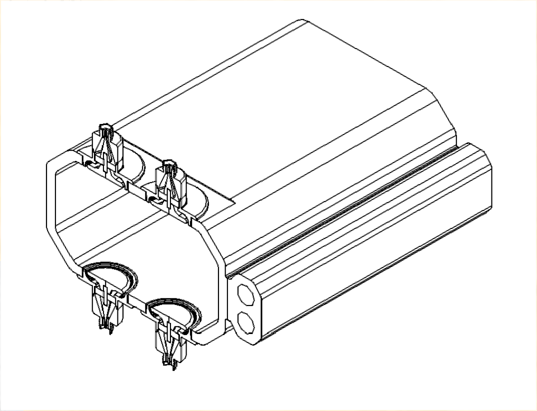


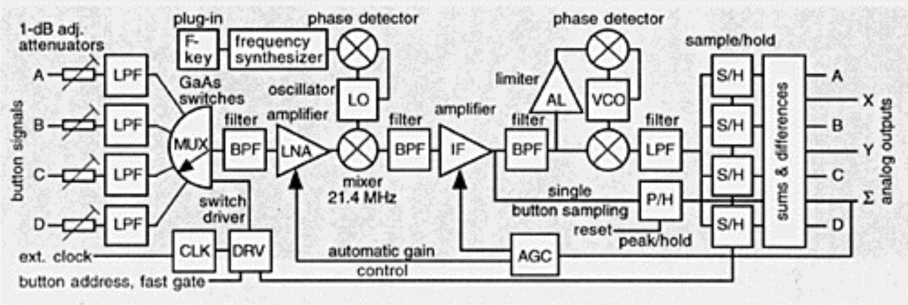


- If instead of measuring the charge all around the beam pipe, two electrodes are positioned at opposite locations, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

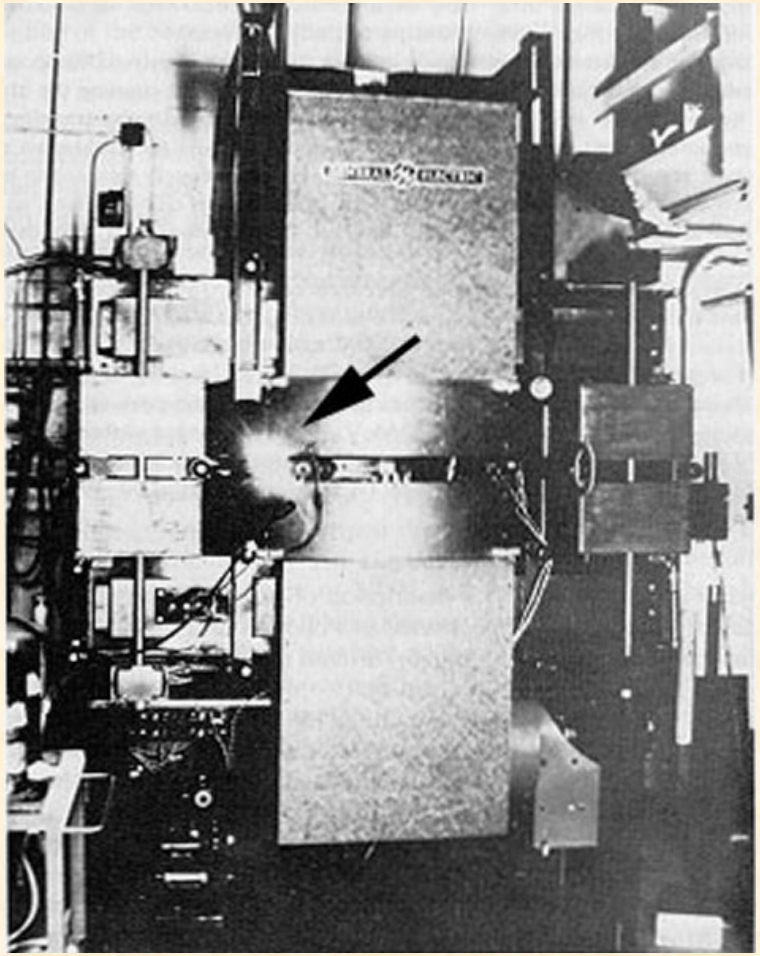
Beam Position Monitor (2)

- BPM are one of the most common diagnostic at an accelerator.
- They exist on many different configurations.
- At synchrotrons it is not possible to have electrodes in the horizontal plane so the electrodes have to be above or below the beam.
- Although the basic principle is simple, very advanced electronics are used to get he best possible precision.
- At Diamond there are 220 BPMs, about 1 every 4 meters in the ring!

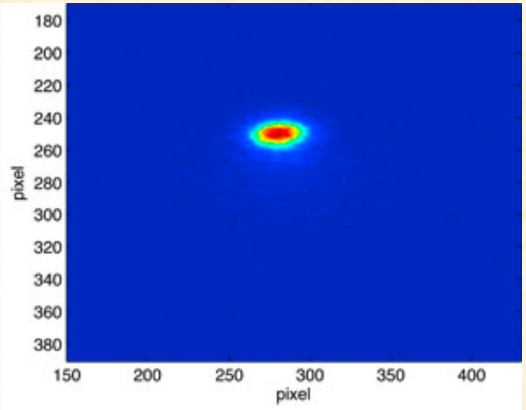




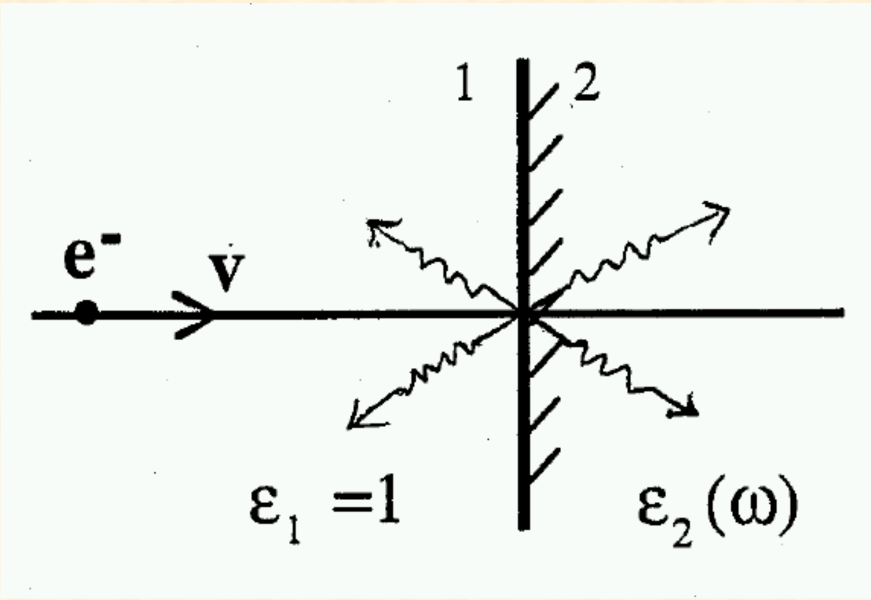
Synchrotron radiation

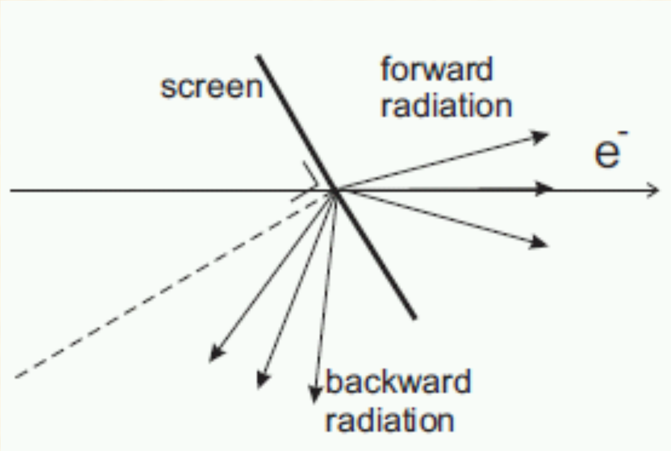


- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



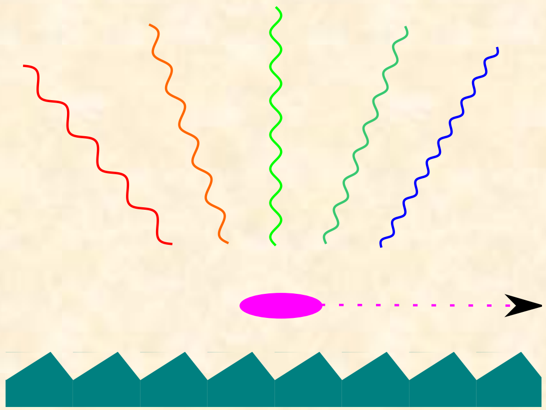
Optical Transition Radiation

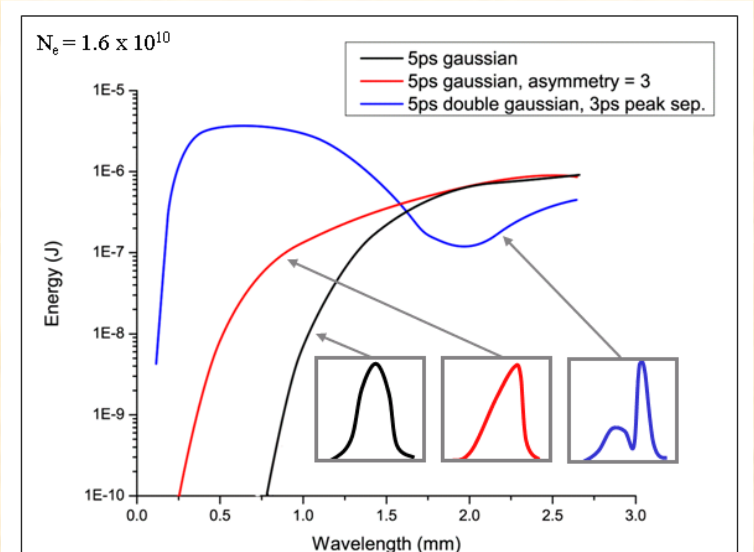




- When a charged particle experiences a transition between two different media continuity equations require some EM signal to be emitted.
- This radiation can be observed by using a 45 degrees screen.
- By imaging the radiation emitted from the screen it is possible to know the beam transverse shape (and possibly other things).

Longitudinal profiles

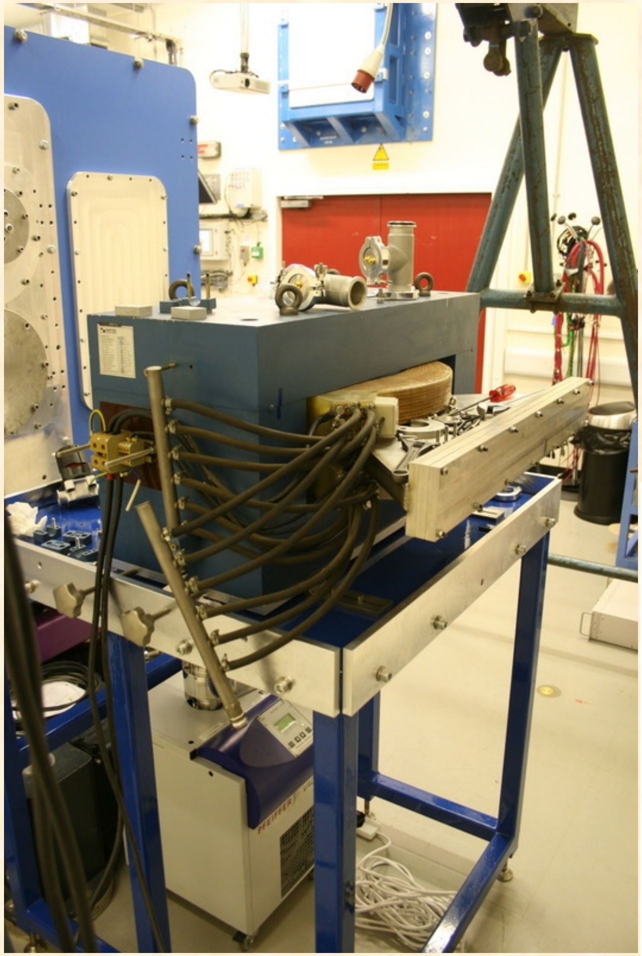




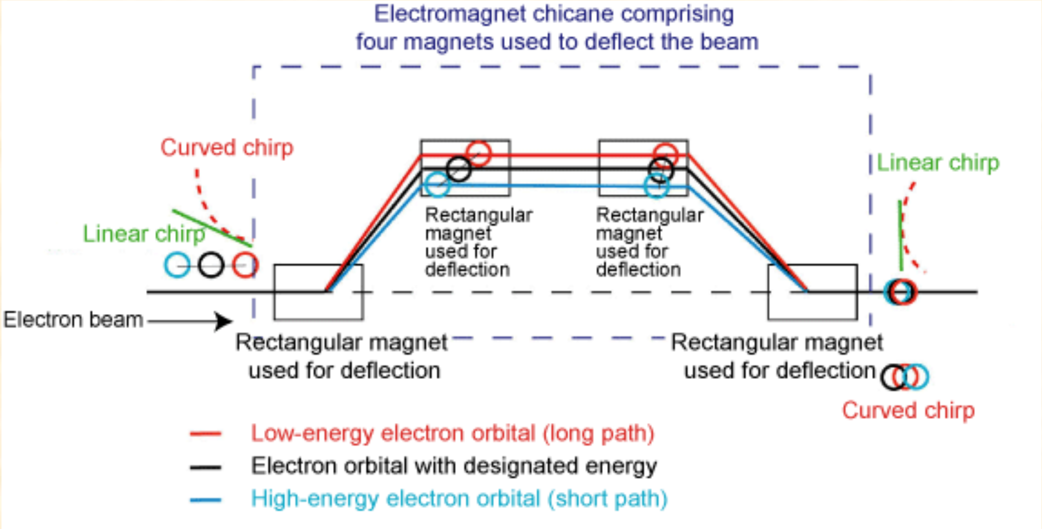
Simulation of different profiles, as would be seen experimentally

- Longitudinal profiles of short beams are one of the most difficult measurement.
- In the Smith-Purcell method a grating is used.
- The beam interacts coherently with the grating and emits radiation.
- The intensity and wavelength of this radiation depends on the longitudinal profile of the beam.
- Several other bunch profile measurement methods rely also on the radiation emitted by the beam.

Energy measurements



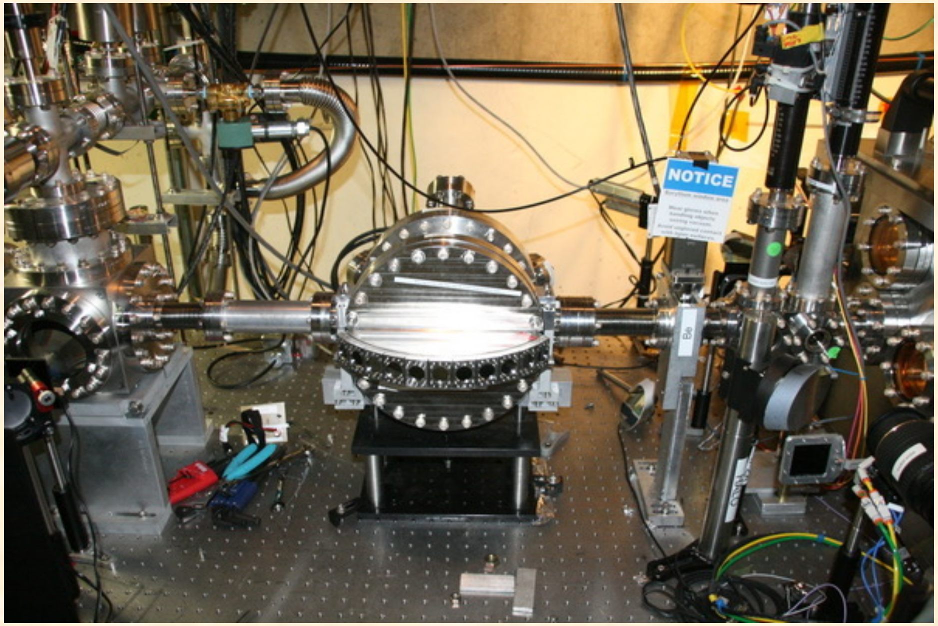
- To measure (or select) the energy of the particles a bending magnet is often the best solution.
- This can be done in an “energy chicane”.



Diagnostics overview

	Interaction with matter	**Charge**
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transv.)	Screen or wire-scanner/LW	Synchrotron rad. OTR/ODR
Size or shape (longit)	RF cavity + screen	Radiation detectors
Energy		Bending magnet
Losses	Scintillator	

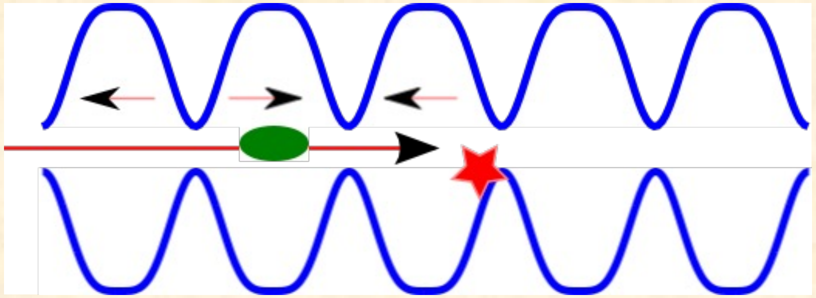
Diagnostics summary



- There are two ways of measuring the properties of a beam:
  - By forcing it to interact with matter
  - By looking at the EM radiation emitted.
- How to build the best diagnostic is then a matter of imagination!

Lecture content

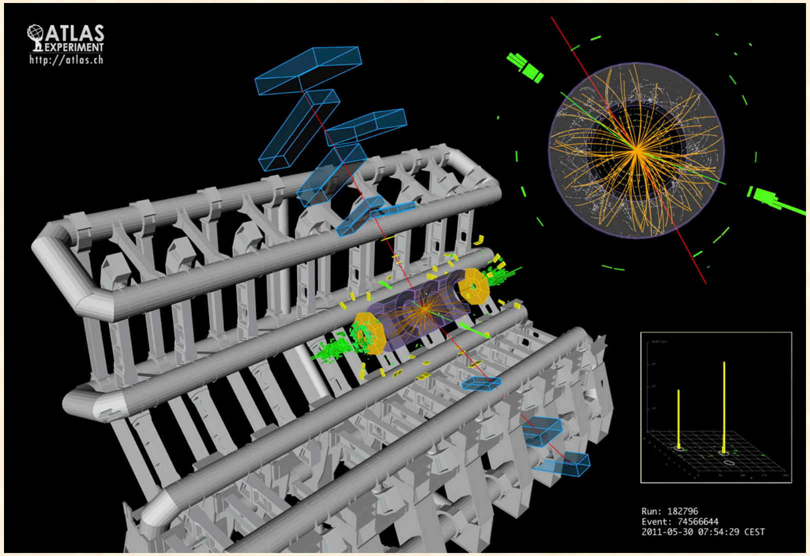
- *History of particle accelerators*
- Basic principles:
  - *Particle sources*
  - *Particle acceleration*
  - *Magnets*
  - *Emittance and beam dynamics*
  - *Beam diagnostics*

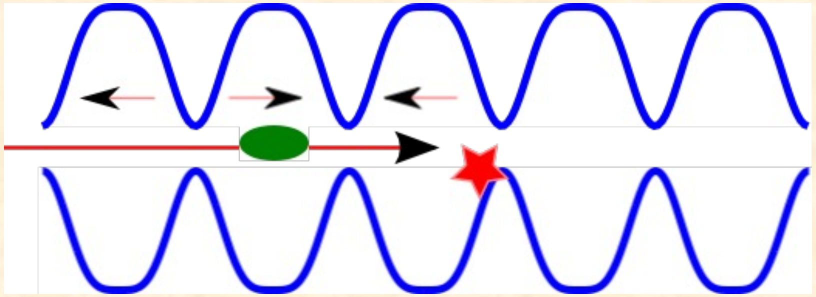


- **Challenges for present and future accelerators**

Challenges: the energy frontier

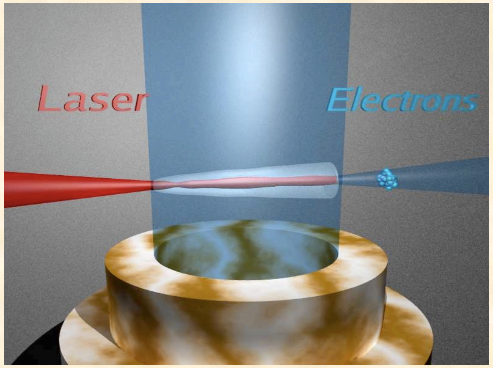
- To discover new particles one often needs higher energy.
- There are 3 main limiting factors:
  - for linear accelerators the energy gradient is limited.
  - for lepton circular, accelerators the energy lost by syncrotron radiation can be equal to the turn by turn acceleration,
  - for hadron rings, one needs magnets strong enough to bend the higher energy particles.
- => The LHC energy upgrade is limited by the magnetic field that can be reached (R&D is in progress).
- => The next lepton collider will either have a very long linac (~20km?) or a very large radius (~100km?)

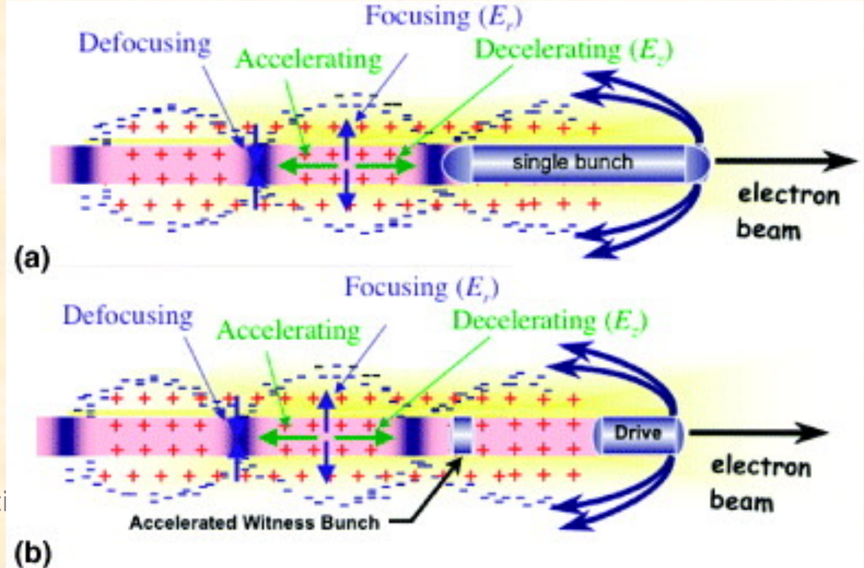




Challenges: the energy frontier New acceleration technique

- To reach higher beam energy for leptons new techniques are studied such as plasma wakefield acceleration driven either by a laser or by a particle beam.



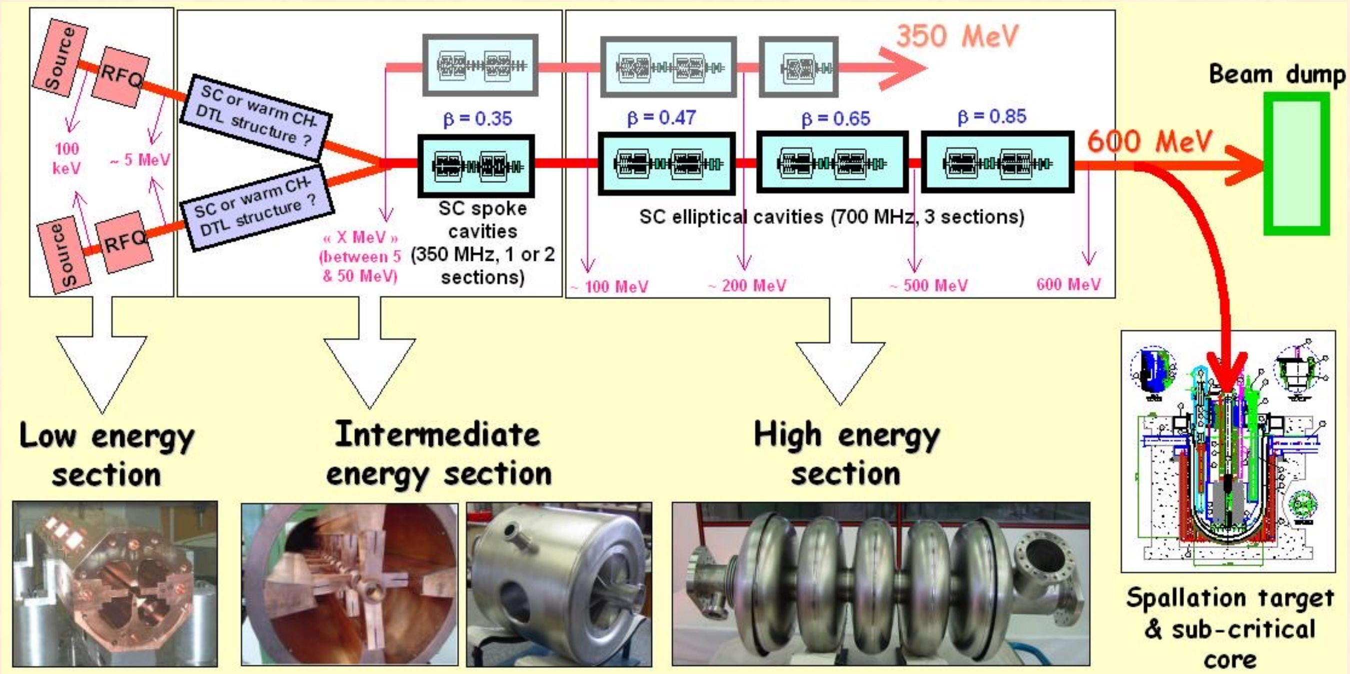


Challenges: the intensity frontier

- Some particles or isotopes have a very low production cross-section.
- To produce them high intensity accelerators are needed.
- Such accelerators have their own challenges: beam dynamics, heating, activation,…

Challenges: the reliablity frontier

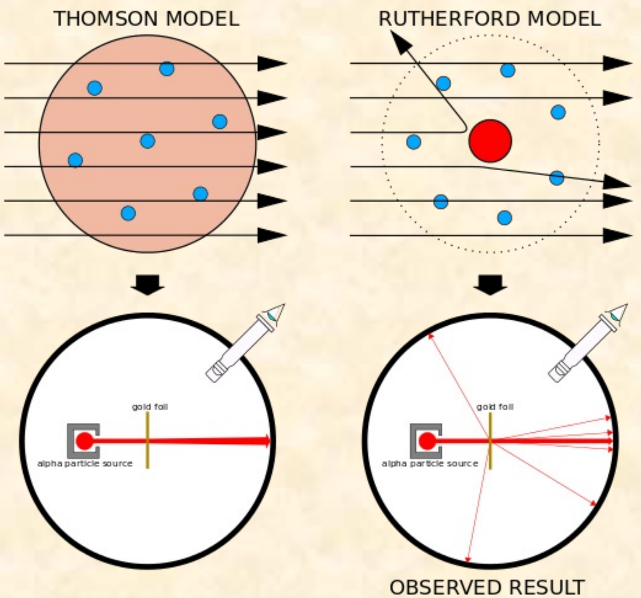
- Particle accelerators could be used to drive sub-critical nuclear reactors (ADS).
- However this requires a very stable particle accelerator with large redundancy.

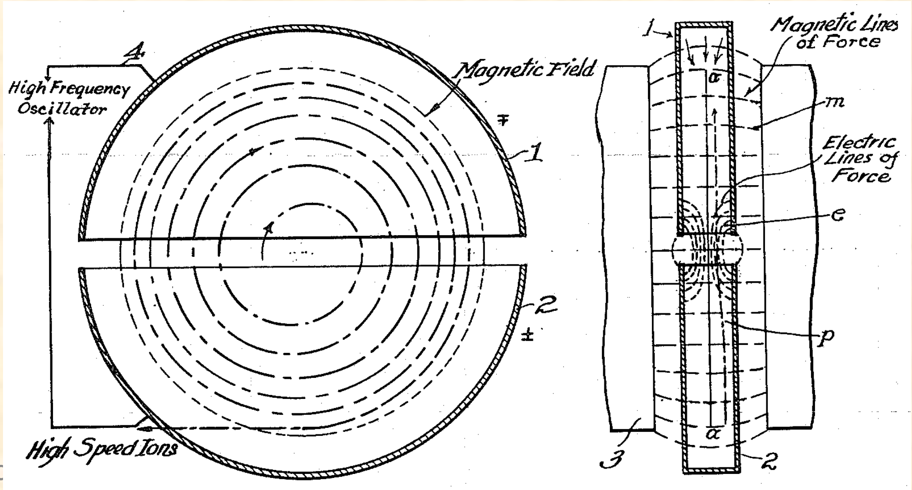


SUMMARY

Summary: History

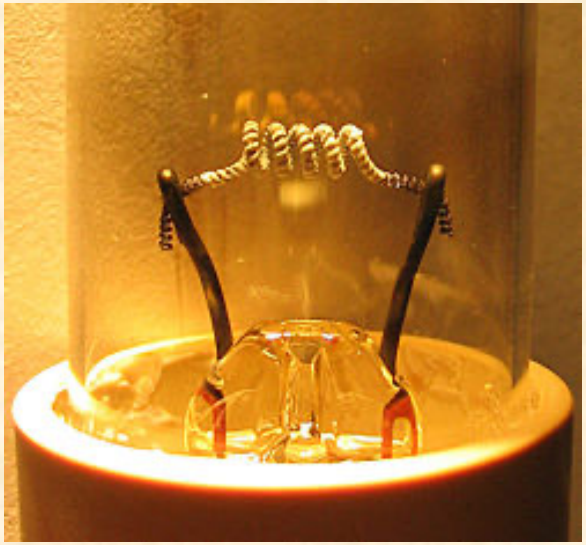
- Particles accelerators were first devised as a way to probe the smallest elements known in matter.
- As the scale of these elements became smaller probes had to be accelerated to higher energy.

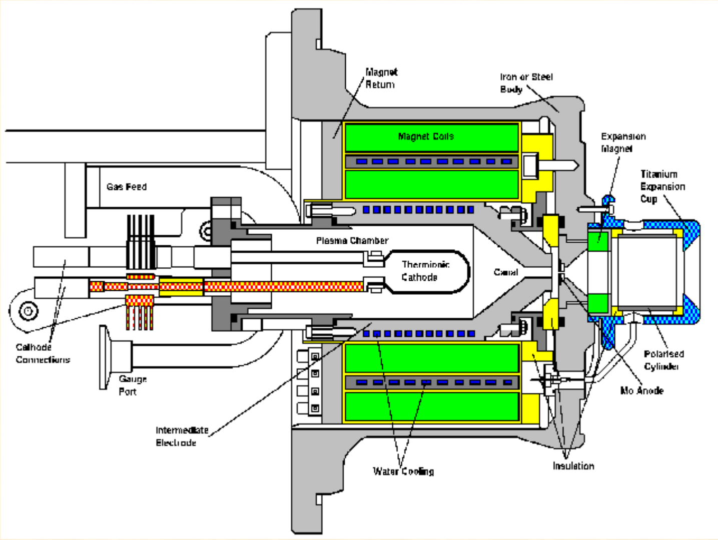




Summary: particle sources

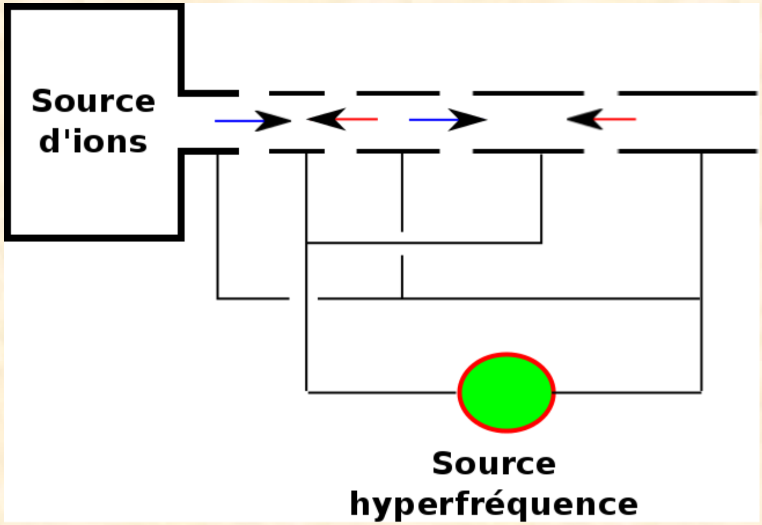
- Particles are extracted from matter either using ionisation or by creating a plasma.
- Guns can be very complex to provide the necessary current and beam quality.

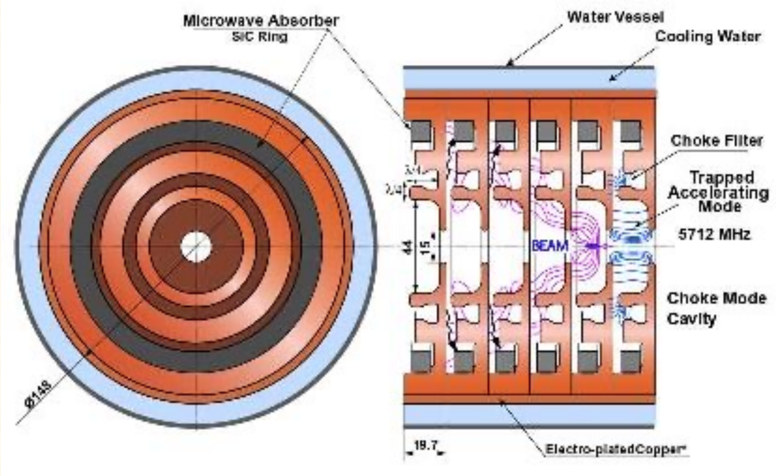




Summary: particle acceleration

- The acceleration of the particles is done by using electric field.
- The most often it is alternating field and this can reach very higher power.

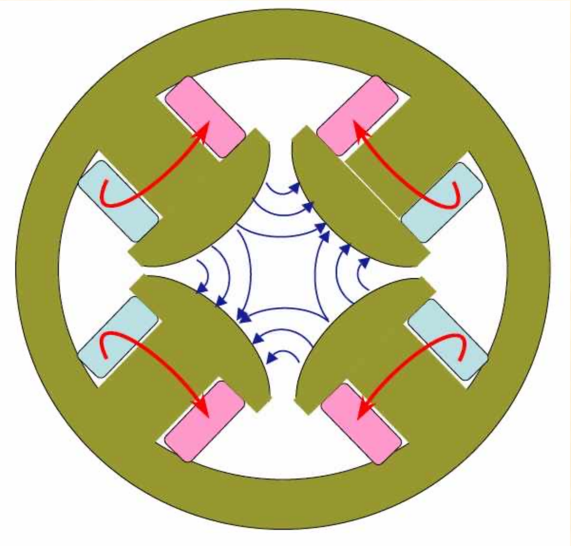


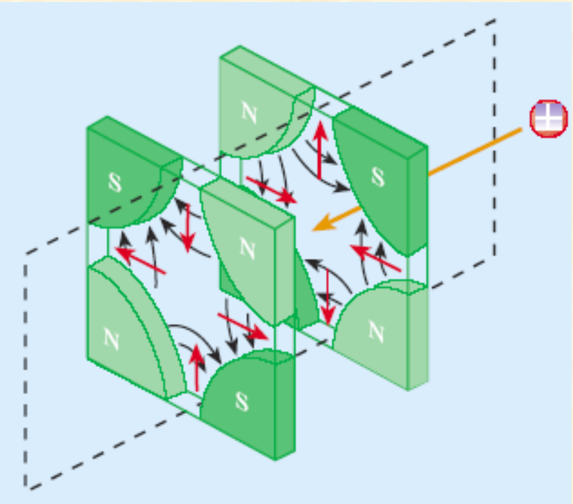


More details in Tuesday's lecture

Summary: Magnets

- The particles are controlled by complicated arrangements of magnets.

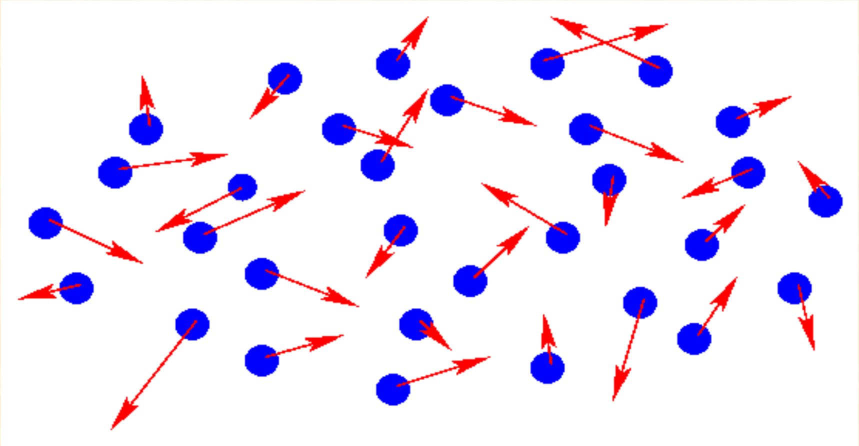




More details in Wednesday's lecture

Summary: dynamics

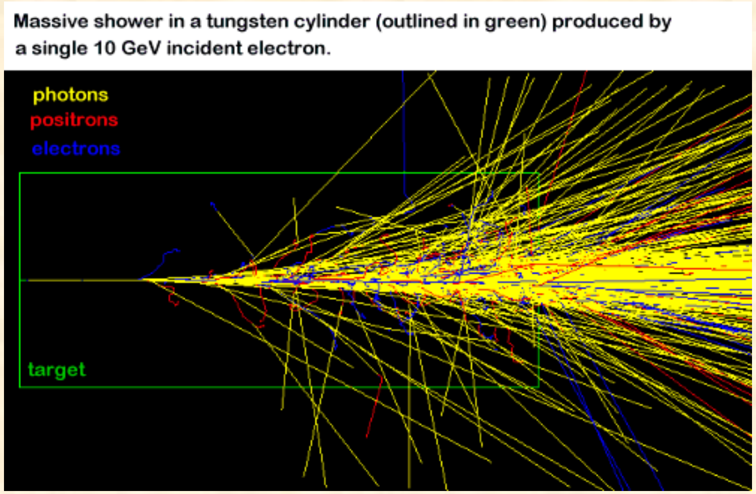
- There are many physical phenomena that act on and in the beam.
- Understanding them is important to control and improve beam quality.

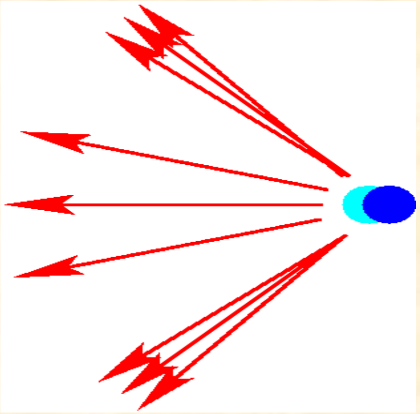


More details in Wednesday's lecture

Summary: diagnostics

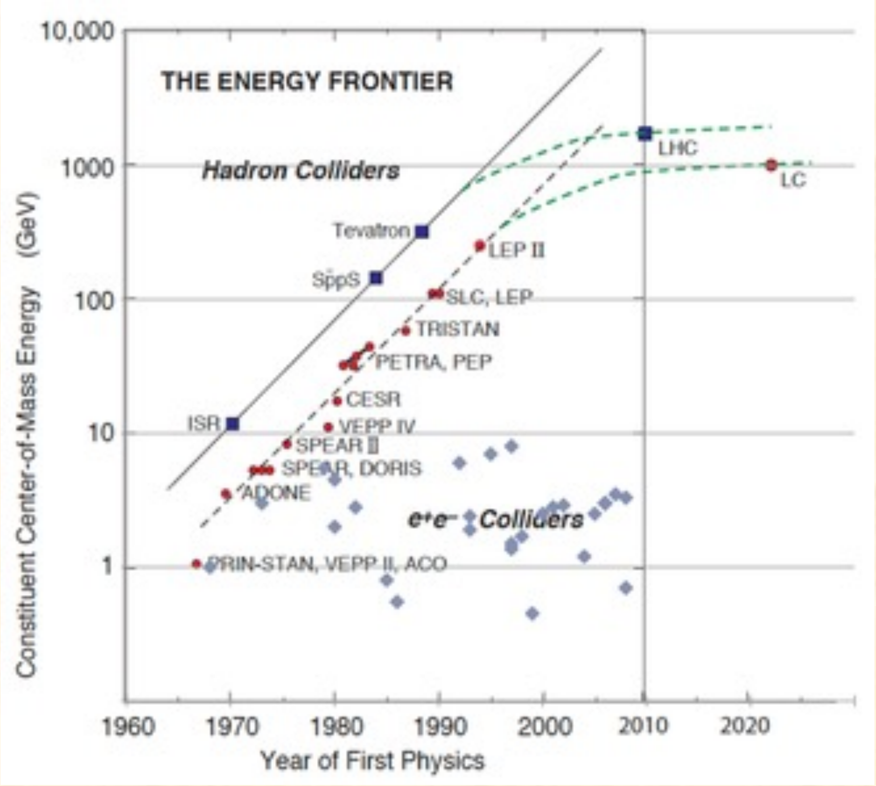
- Particles will deposit energy in matter.
- They will also radiate part of their energy.
- This can be used to learn about their properties in the accelerator.





Summary: challenges

- Accelerators are very complex.
- Recent challenges have limited the growth in performance of the accelerators.
- Both SPIRAL2 and the LHC have their own challenges.



More details in Thursday's lecture

Recommended reading

- Slides of this lecture are available at
  http://lal.delerue.org/teaching/201806_PHENIICS/

- « 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