

Introduction to Particle Accelerators



Image: The CERN accelerators.

Source: <http://cds.cern.ch/>

What is a particle accelerator?

- A particle accelerator is a scientific apparatus used to accelerate particles (electrons, protons or ions) so that they reach a high energy.
- Particle accelerators are the largest man-made machines.
- They are used for scientific experiments as a giant microscope but have many other applications (more on this topic this afternoon).



Source: <http://cds.cern.ch/>

Does the UK have any particle accelerators?

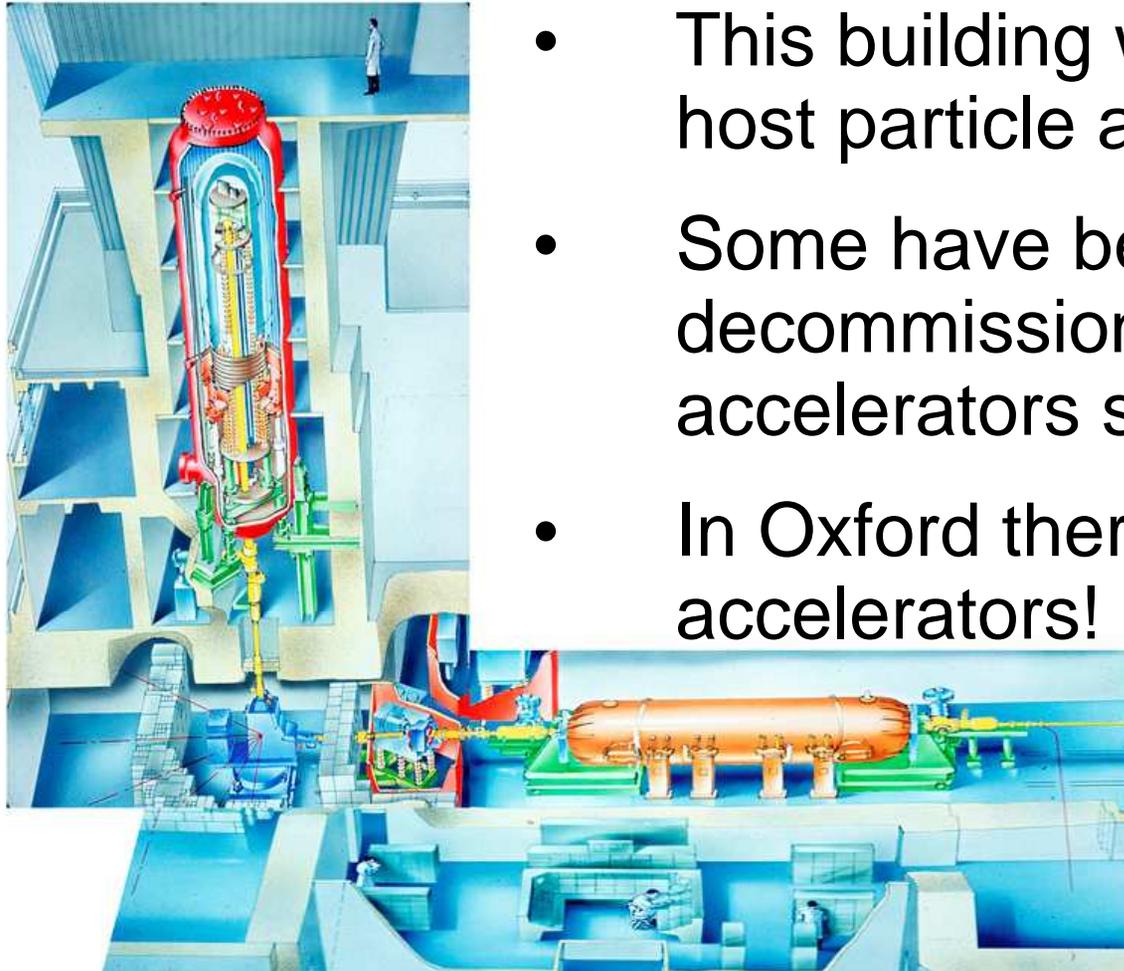
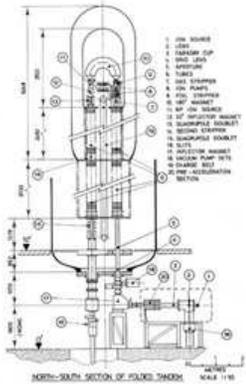
- Although not located in the UK, the LHC is operated by CERN on behalf of the UK (and other member countries).
- Near Oxford, in Hartwell the Diamond Light Source is the largest particle accelerator in the UK.
- Nearby ISIS is another large accelerator used to produce neutrons...



Aerial view of Diamond
<http://www.diamond.ac.uk/>

Even closer...

- This building was built to host particle accelerators.
- Some have been decommissioned but two accelerators still active.
- In Oxford there are 9 particle accelerators!



How many particle accelerators are there in the UK?

- There are more than 150 particle accelerators active in the UK. (excluding cathode ray tube television sets).
- All major cities have a few (usually in hospitals).
- Most of these accelerators are only a few meters long and are used for medicine.



Interactive map available at:

<http://www.adams-institute.ac.uk/accelerators.php>

How large is a particle accelerator?

- The main ring of the LHC has a circumference of 27km.
- Diamond, the largest accelerator in the UK has a circumference of 560m.
- A medical “linac” is typically 1-2m long.
- However the particles that travel in an accelerator are very small...

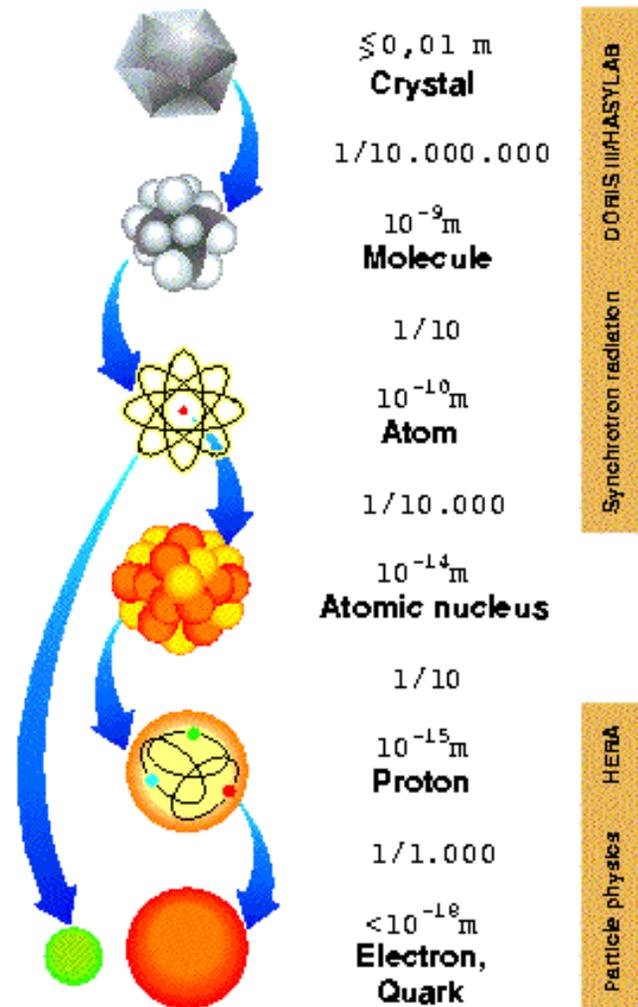


Aerial view of the CERN accelerators.

<http://cds.cern.ch/>

Large machines for small particles

- The particles accelerated are very small:
 - Electrons are too small to be measured.
 - Protons: ~ 1 femtometre ($1\text{fm}=10^{-15}\text{m}$)
 - Ions: ~ 200 picometres ($200\text{pm}=200\times 10^{-12}\text{m}$)
- Particle accelerators are large because they need to bring the particles to very high speed and very high energies.

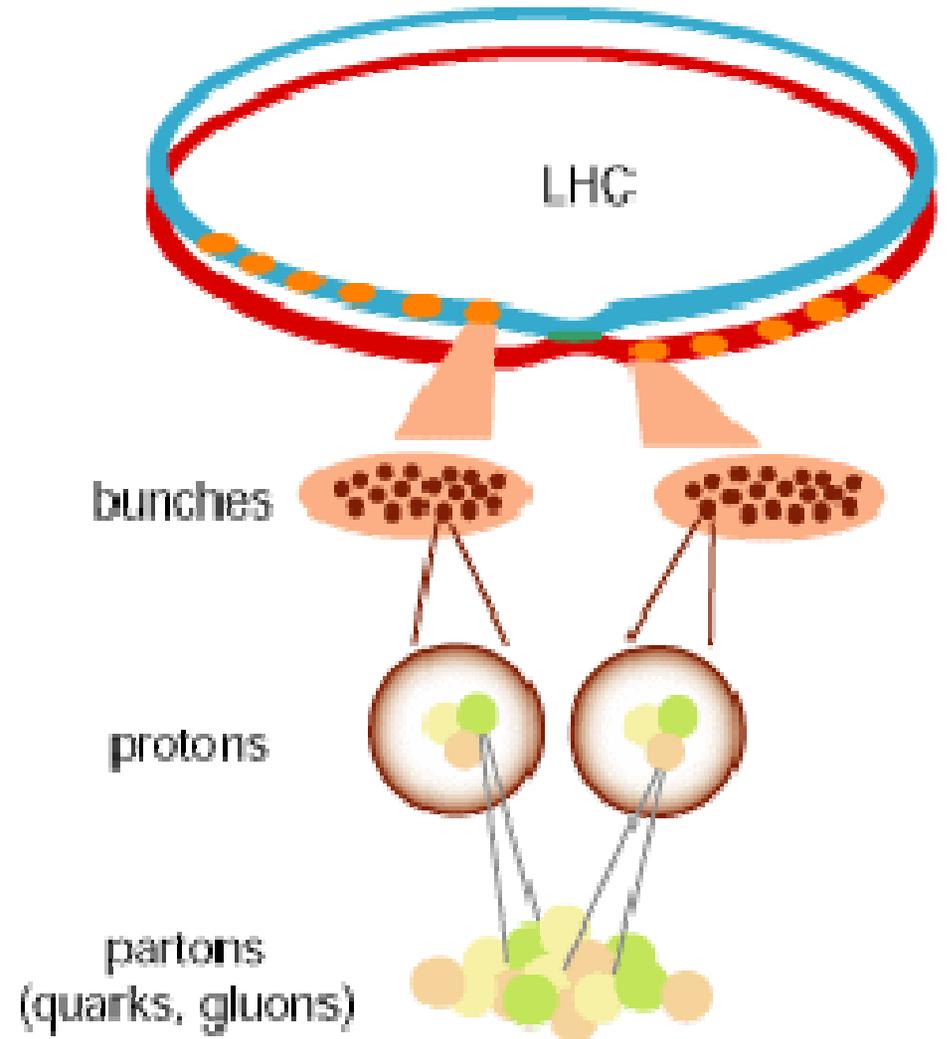


From crystal to quark

<http://www.desy.de/>

How many particles?

- Accelerators do not accelerate particles one by one.
- They accelerate “bunches” containing a large number of particles.
- Several bunches can be present in the accelerator at the same time.
- Example: The LHC can store up to 3000 bunches. Each bunch contains $\sim 10^{11}$ protons.
- The LHC can thus store up to 3×10^{14} protons

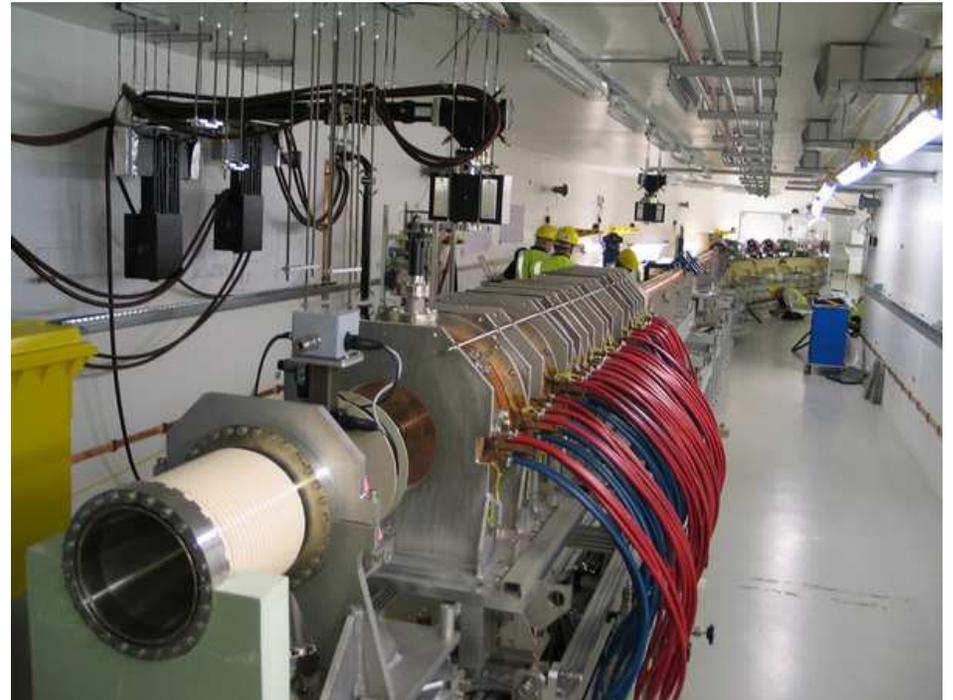


Bunches in the LHC

<http://lhcatome.cern.ch>

How to get the particles?

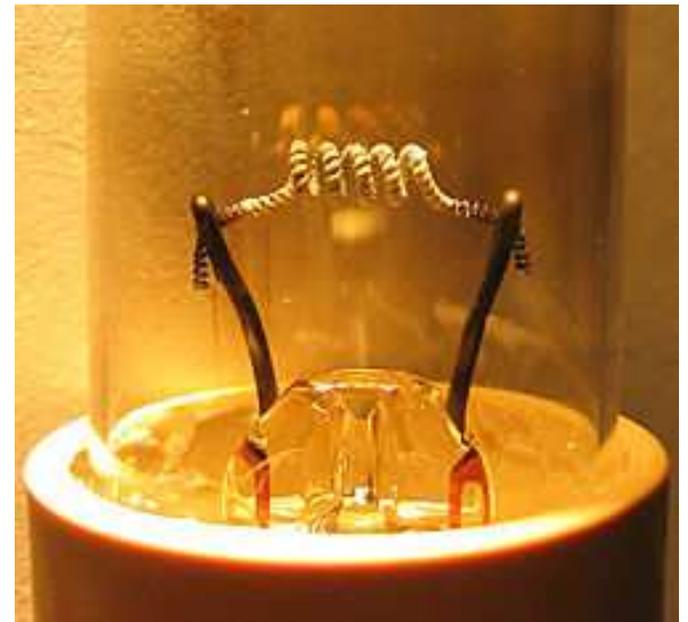
- At the beginning of a particle accelerator there is a “particle gun”.
- It is a device that shoots particle.
- Particle guns for electrons and protons are very different.



The electron gun at Diamond
<http://www.diamond.ac.uk>

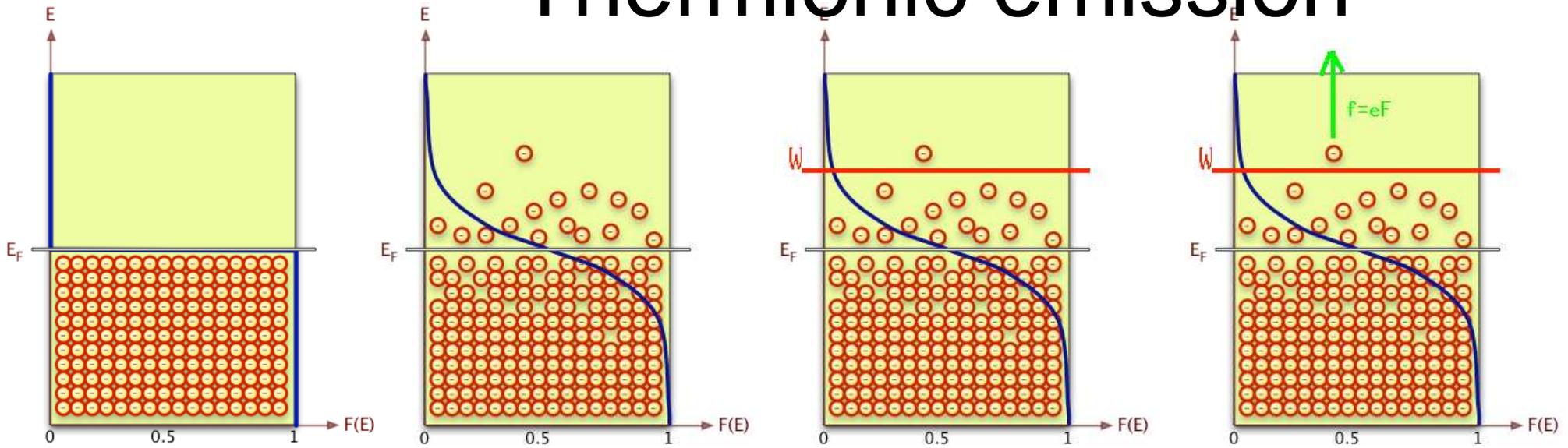
Thermionic electron gun

- The simplest type of electron gun works like the Cathode Ray Tube (CRT) in an old TV set.
- A piece of metal is heated to a high temperature.
- This leads to the emission of electrons (called thermionic emission).
- These electrons are then extracted by an electric field.



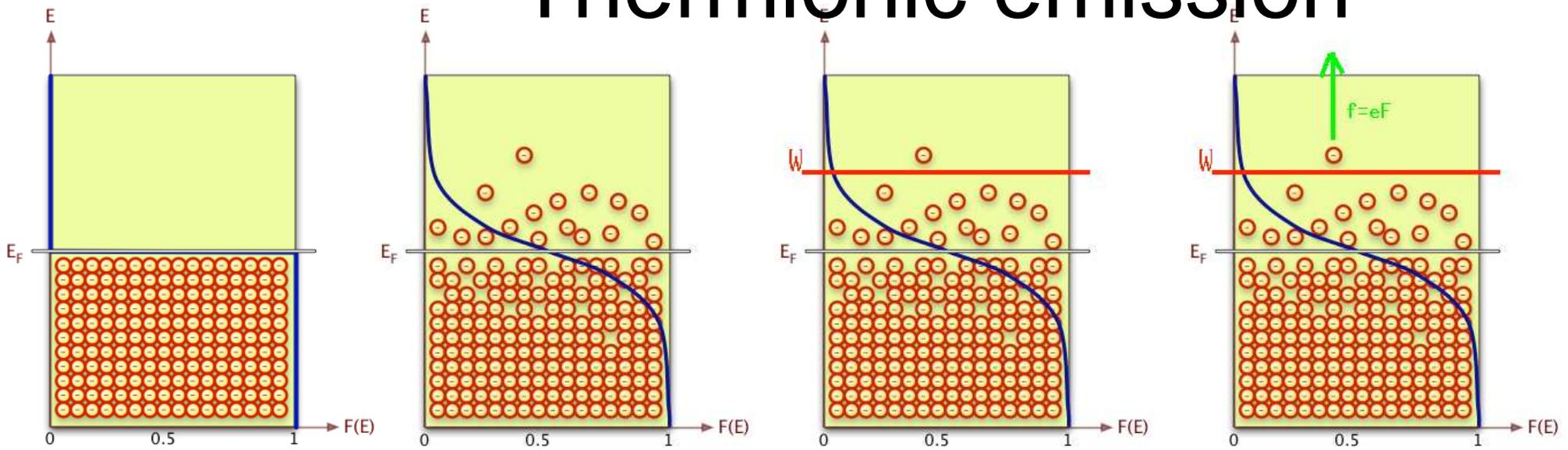
Thermionic emission
wikipedia

Thermionic emission



- Imagine a large tank in which you put some light air balloons.
- If there is no wind all balloons rest at the bottom of the tank.
- If you blow in the tank some balloons will fly around.
- If the air current is strong enough some balloons will fly above the edge of the tank.
- If outside the tank there some wind, some balloons may be carried away from the tank.

Thermionic emission

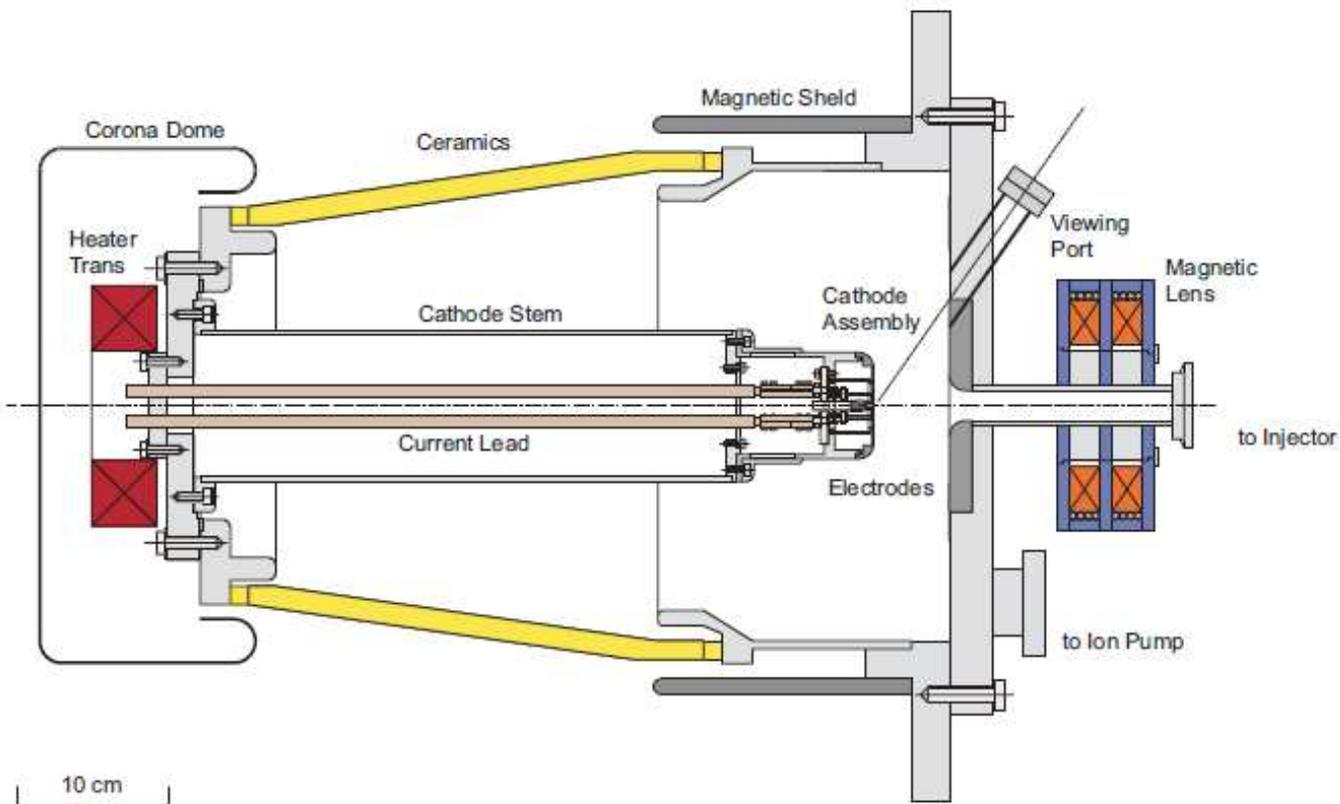


- Thermionic is the same with a metal as “electron tank”.
- In a cold metal all the electrons of the metal are properly ordered.
- If you increase the metal temperature some electrons start to wander around (inside the metal).
- When the temperature is high enough some electron will gain enough energy to escape from the metal.
- If an electric field is applied these electrons can be extracted and the electrons extracted.

Example of thermionic gun

SCSS

500kV Electron Gun

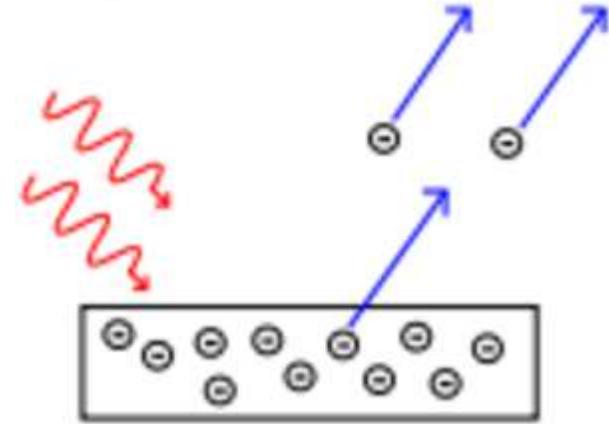


Spring 8 SCSS thermionic gun.

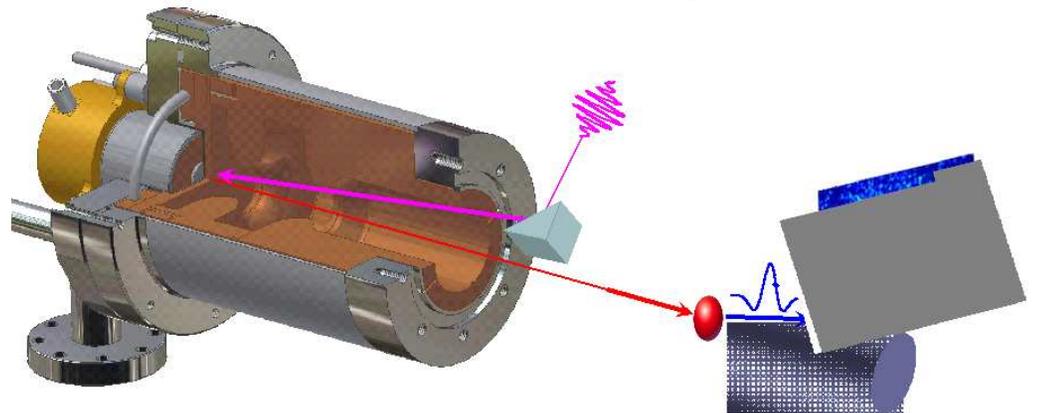
(images source: T. Shintake, Spring-8)

Photogun

- Some recent electron gun use the “photo-electric effect” to extract the electrons.
- Photons (from a laser) are sent on the metal where they kick some electrons out.
- The performance of the beam produced by a photogun are usually better but these guns are more complex to operate.



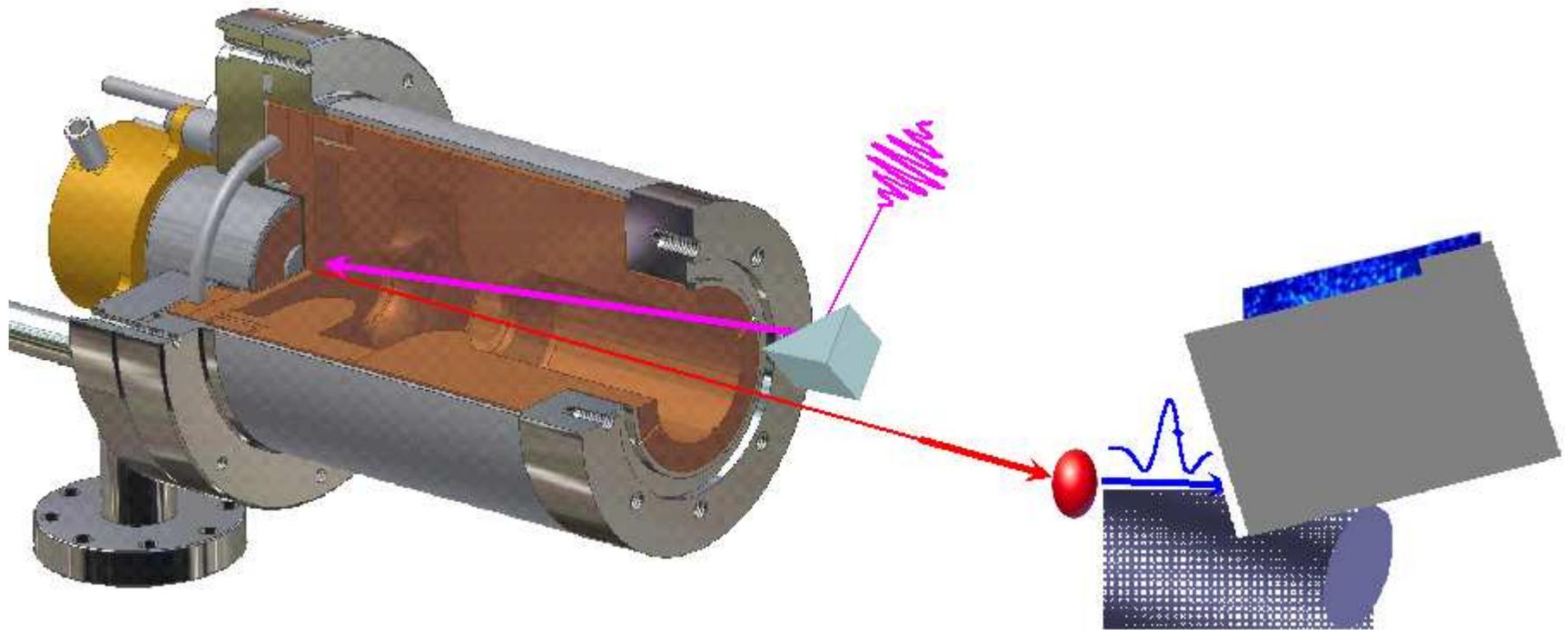
Photoelectric emission
wikipedia



Photogun.

*(images source: J. Luiten,
Eindhoven University of Technology)*

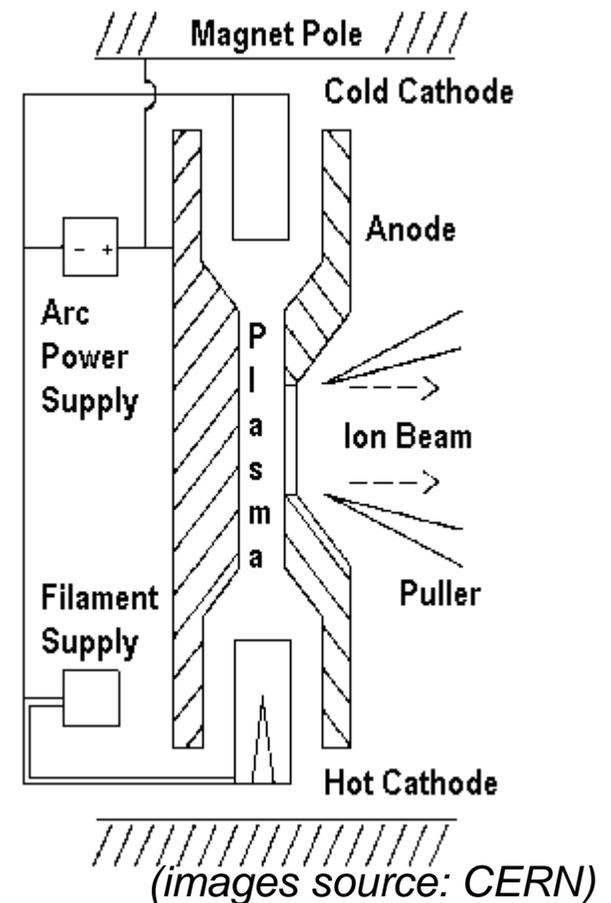
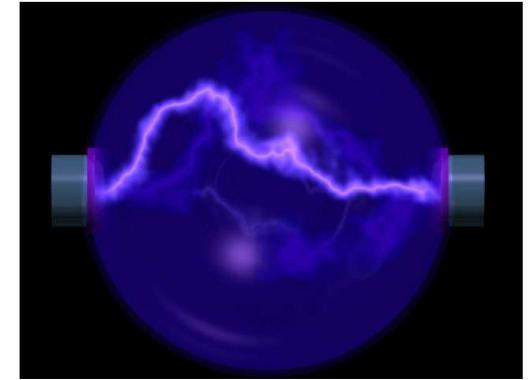
Example of photogun



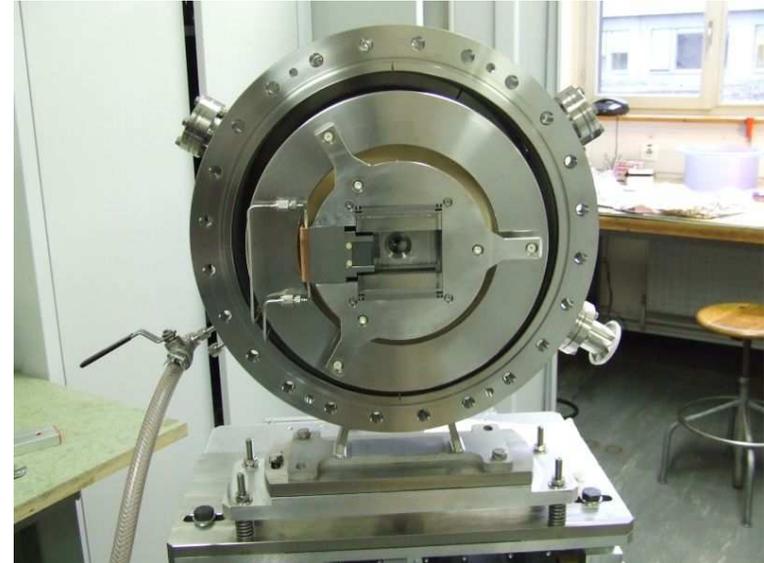
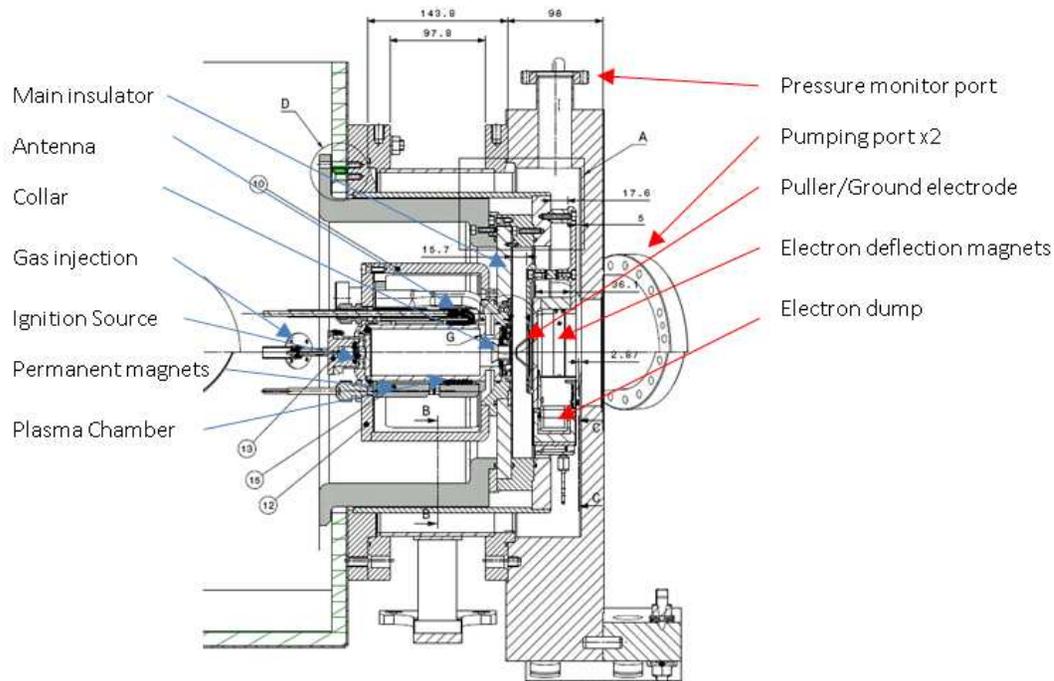
*Photogun.
(images source: J. Luiten,
Eindhoven University of Technology)*

Proton and ion sources

- A proton is an hydrogen atom without its electron (H^+).
- An electric discharge in gas can strip atoms from their electron.
- An electric field can then be used to extract the positively charged particles from the gas.
- This is how protons are produced for the LHC at present.
- This method can be slightly modified to produce any ion (including negatively charged ions).



CERN Linac 4 H- source

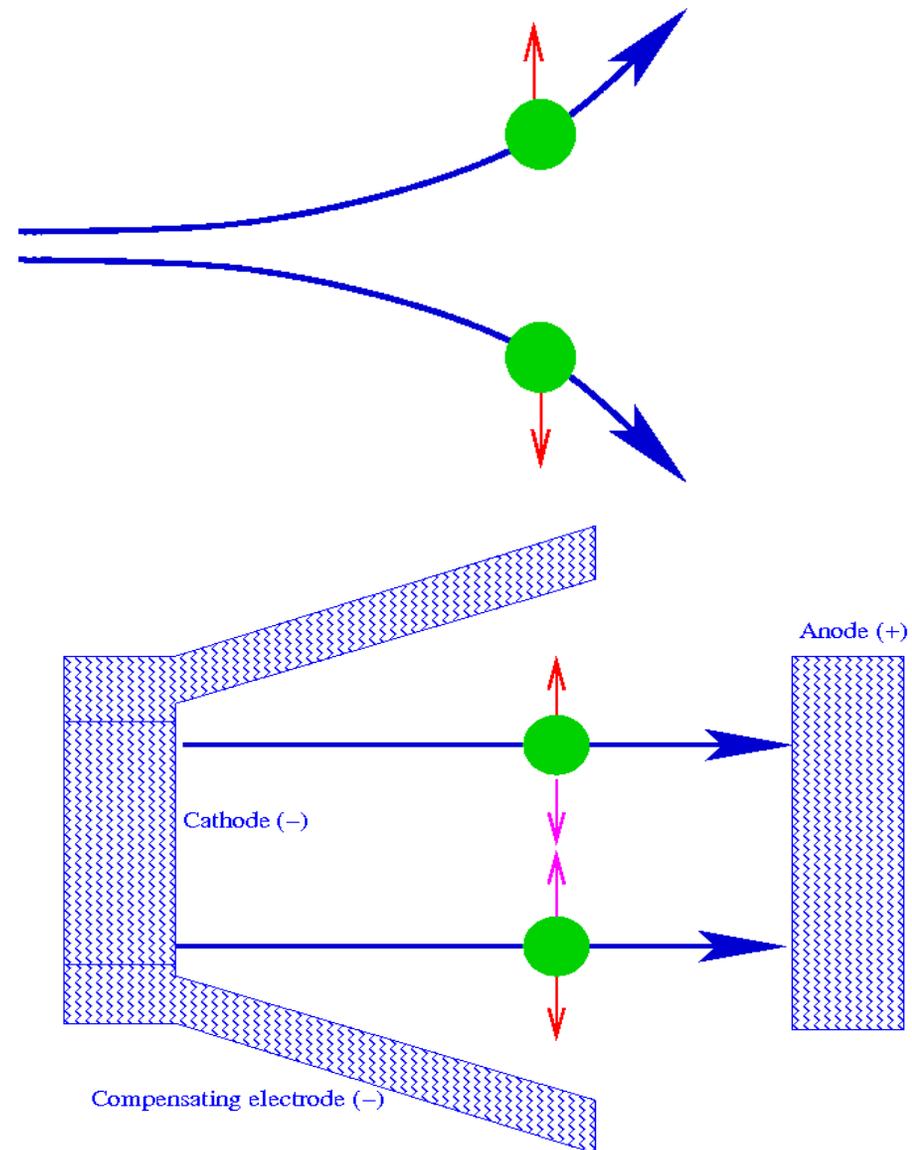


<http://linac4ionsource.web.cern.ch/>

Courtesy Richard Scrivens, CERN

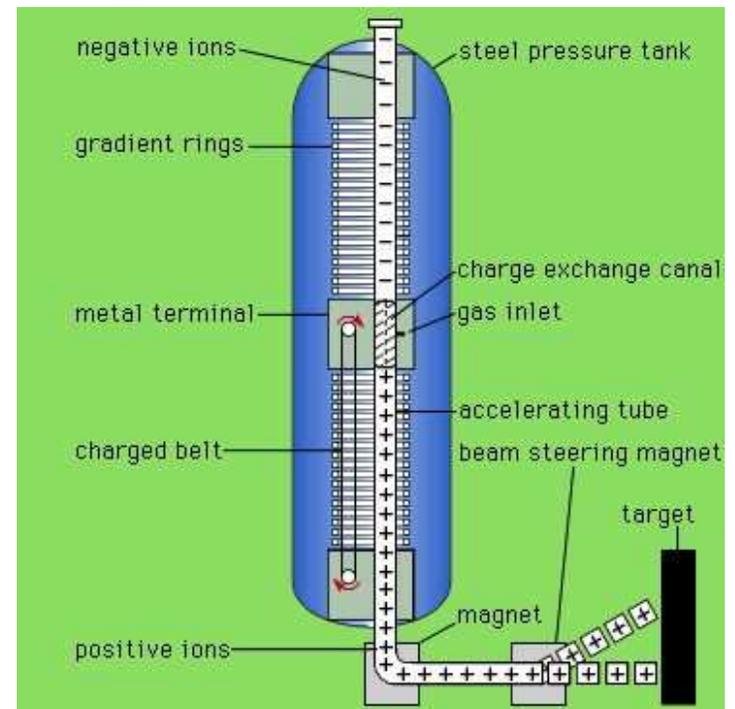
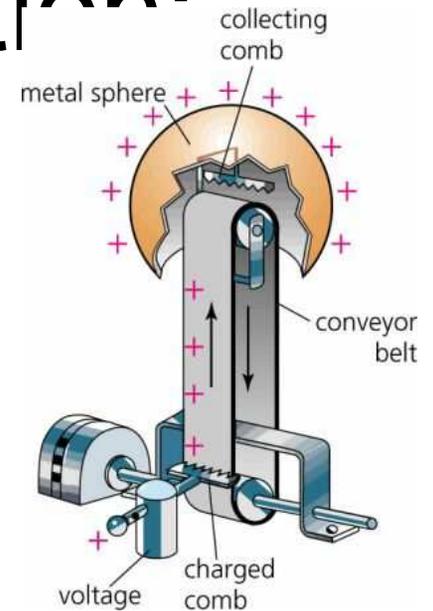
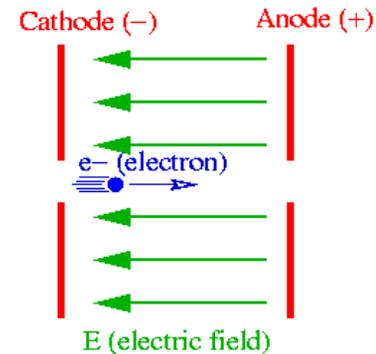
Space-charge

- All the particles in a beam have the same charge.
- The Coulomb forces are very intense. At low energy this is a significant problem known as “space-charge” effect and special electrodes need to be used to compensate for this effect.
- At higher energy this effect becomes negligible as the extra transverse momentum is negligible in comparison with the longitudinal momentum.



Particles acceleration Electric field

- Particles can be accelerated by an electric field:
 $f=qE$
- Electrostatic accelerators use this principle.
- One of the most common type of electrostatic accelerator is called “Van de Graaff” accelerator.
- Tandem accelerators are a modified type of electrostatic accelerators where the charge is changed in the middle.
- Tandem accelerators are commonly used for radiocarbon dating and other applications that need low energy ions.



Equations of motion in a Van de Graaff

$$f = qE$$

$$a = \frac{f}{m} = \frac{qE}{m} = \frac{d^2 x}{dt^2}$$

$$\frac{dx}{dt} = \frac{qE}{m} t + v_0$$

$$x = \frac{qE}{m} t^2 + tv_0 + x_0$$



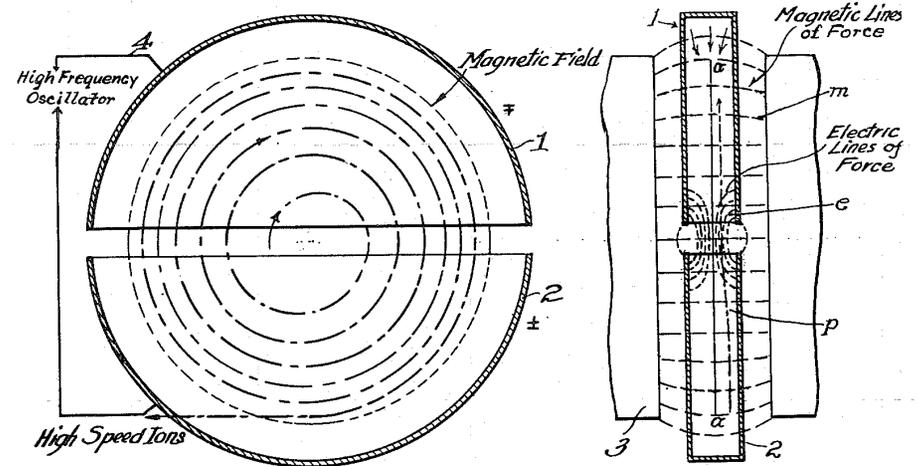
The Oxford teaching accelerator.

Particles acceleration: Cyclotron

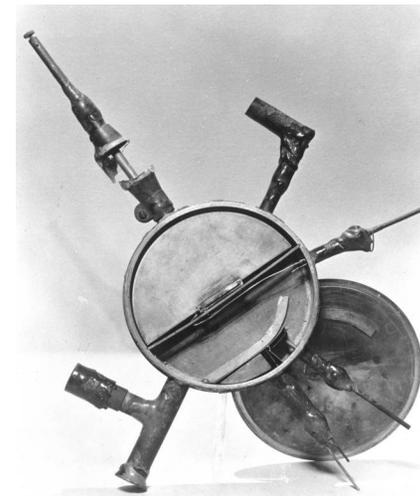
DC electric fields beyond 20MV are very difficult to achieve.

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.

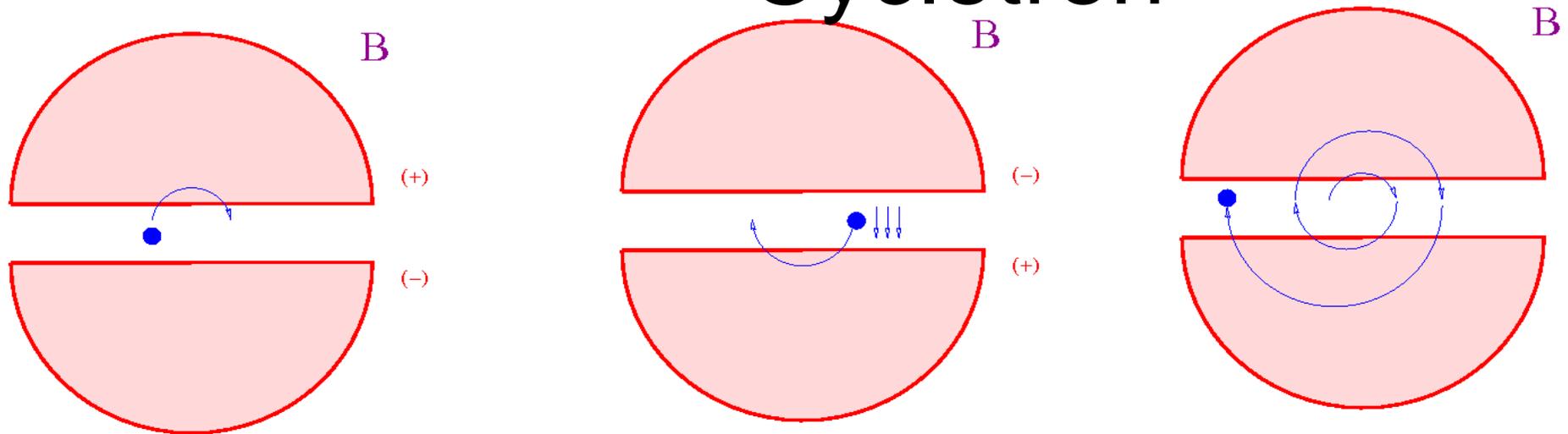


Wikimedia.org



Lawrence's cyclotron
LBNL Image library

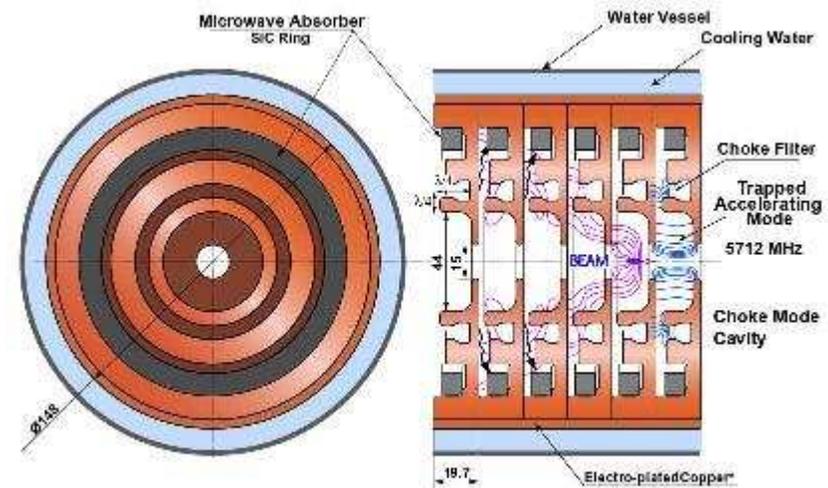
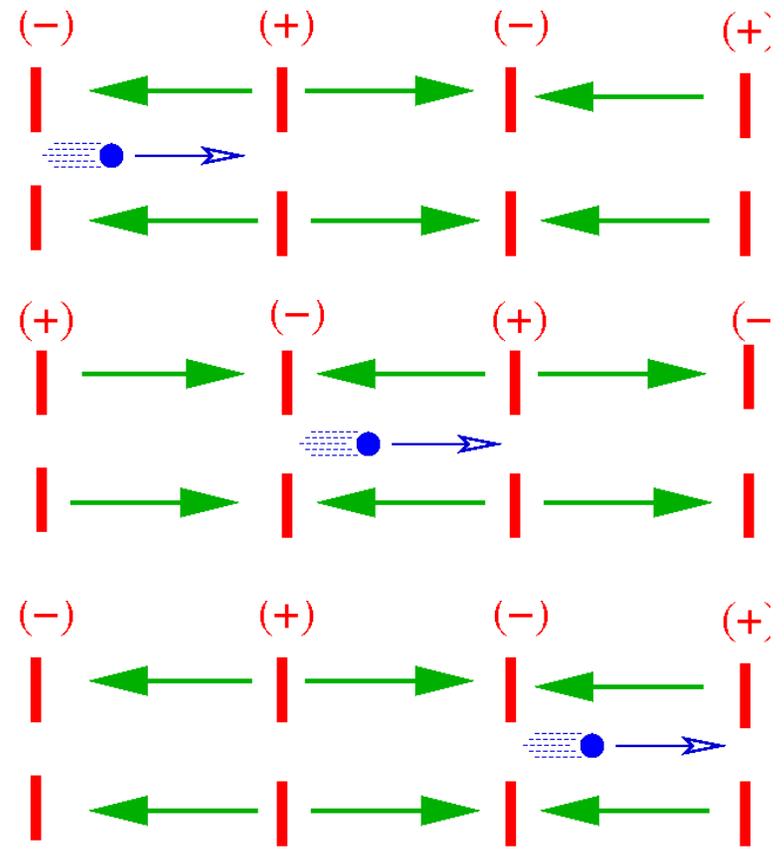
Particles acceleration: Cyclotron



- With an AC potential of only 2000V Lawrence accelerated protons to 80keV!
- In the dees $f=q(v \times B)$
=> as the speed increase the transverse force becomes larger
=> larger radius of curvature.
- Lawrence received the Nobel prize in 1939 for this work.
- Cyclotron can not work at high energy due to relativistic effects.

Particle acceleration: RF wave

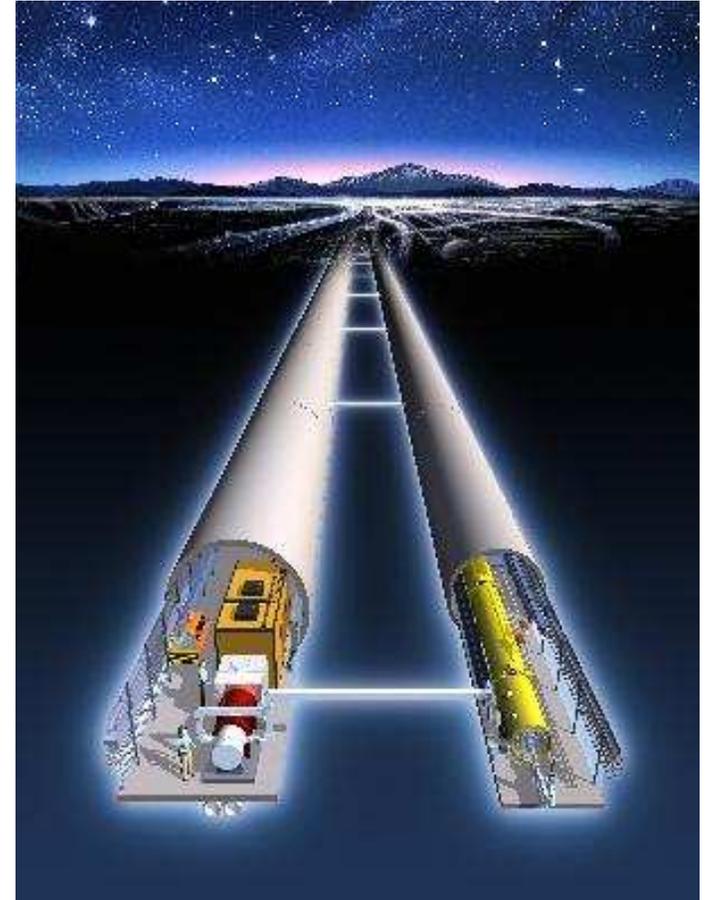
- Another solution to reach higher energies is to have several electrodes with alternating polarity.
- Radio-frequency (RF) cavities use such AC field to accelerate particles to very high energies.
- In a RF cavity the particles “surf” on an electromagnetic wave that travels in the cavity.



(source: Spring-8, Japan)

Linac

- Several RF cavities can be put after each other to create a long accelerating section.
- Typical accelerating gradients are between 10 and 40MV/m.
- To reach 500 GeV a linac needs to be ~25km long!



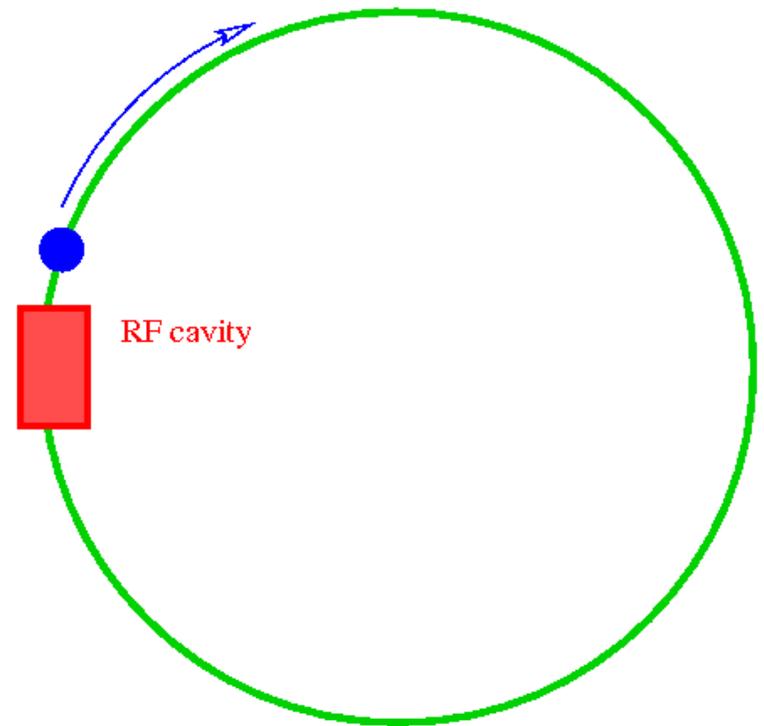
Artist view of the a long linac
Source: <http://www.kek.jp>

Synchrotrons

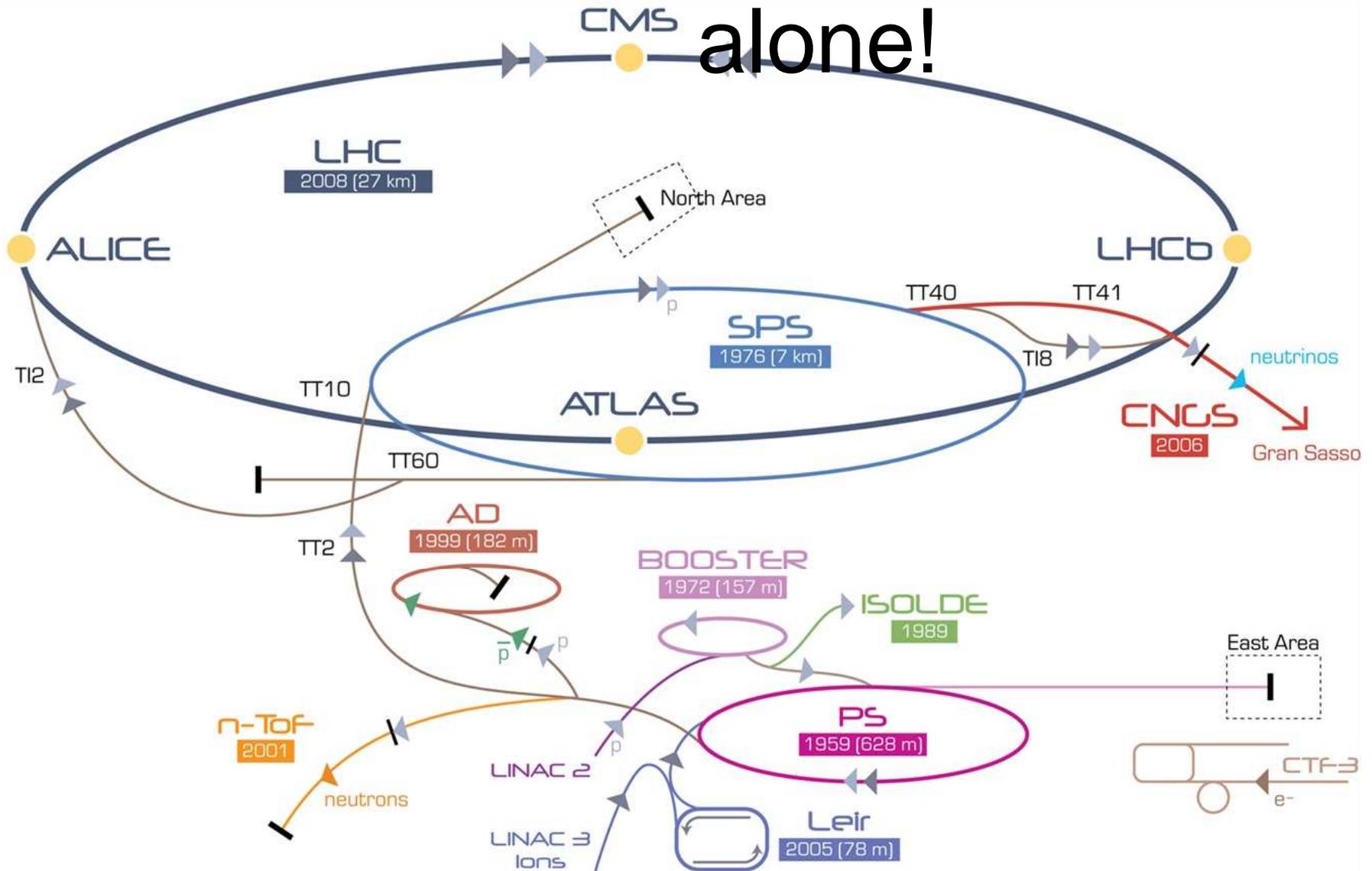
It is possible to modify the principle of a cyclotron by replacing the electrodes by a much smaller RF cavity.

The magnetic field is then usually made by smaller magnets over a large radius. Such machine is called a synchrotron.

Most modern circular accelerators are synchrotrons. (eg: LHC, Diamond, ISIS, ...).



Big accelerators are not alone!



▶ p (proton) ▶ ion ▶ neutrons ▶ \bar{p} (antiproton) \leftrightarrow proton/antiproton conversion ▶ neutrinos ▶ electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF-3 Clic Test Facility CNCS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
 LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

How fast?

- In accelerators particles travel at a very high speed.
- Special relativity has to be used.
- Particles can not travel faster than the speed of light.
- After a few seconds of acceleration the particles are almost at the speed of light.
- Further turns in the accelerator will increase their energy.

Lorentz factor:

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

Energy:

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

Particles energy are usually expressed in Electron Volts (eV) and its multiples: keV, MeV, GeV, TeV,...

Relativistic electrons at Diamond

- The energy at rest (that is the mass times c^2) of an electron is 0.5MeV.
- An electron with an energy of 1 GeV has a Lorentz factor of 2000.
- At Diamond the electrons have an energy of 3 GeV. Hence they have a gamma of 6000.
- Hence these electrons travel at $0.999999997c!$

Energy:

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

$$\gamma = \frac{E}{mc^2}$$



Diamond at night

<http://www.diamond.ac.uk>

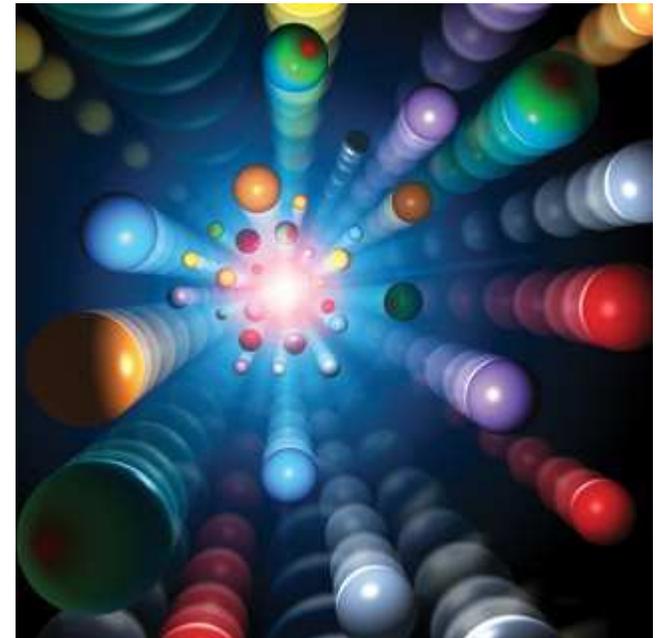
Relativistic protons at the LHC

- The mass of a proton is $\sim 1 \text{ GeV}/c^2$ (The correct value is $0.938 \text{ GeV}/c^2$).
- In the LHC protons can reach an energy of 3.5 TeV.
- Their Lorentz factor is 3500.
- They travel at $0.999999991c$
- Protons in the LHC are “slower” than electrons in Diamond!
- It takes only 90 microseconds to the particles to travel the 27km of the circumference of the ring.

Energy:

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

$$\gamma = \frac{E}{mc^2}$$



<http://quasar9.blogspot.com/>

Charge and current

- The charge of one electron (or one proton) is 1.6×10^{-19} Coulombs.
- The LHC can store up to 3×10^{14} protons.
- This corresponds to a total charge of 4.8×10^{-5} C, that is 48 micro-Coulombs.
- As it takes 90 microseconds for the particles to travel around the ring this corresponds to a current of 0.54 Amps!
Current = Charge/duration



The LHC tunnel
<http://cds.cern.ch>

Beam total energy

- 1 electron-volt is 1.6×10^{-19} Joules.
- $3.5 \text{ TeV} = 560 \text{ nJ}$.
- Hence the full beam of 3×10^{14} protons contains $1.7 \times 10^8 \text{ J}$, that is 170 Megajoule.
- This energy is comparable to that of an Airbus 380 at 100km/h!
- This will double when the beam will reach 7 TeV!
- An energy of 170 MJ over 90 microseconds corresponds to a power of 2 Petawatt!
Power=Energy/time



Airbus A380
wikipedia

More details at <http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/>

Steering the particles

- A magnetic field can be used to deflect the particles.
- Lorentz force:
 $f = q(E + v \times B)$
- The LHC uses very strong magnets to keep its particles in a circular orbit.

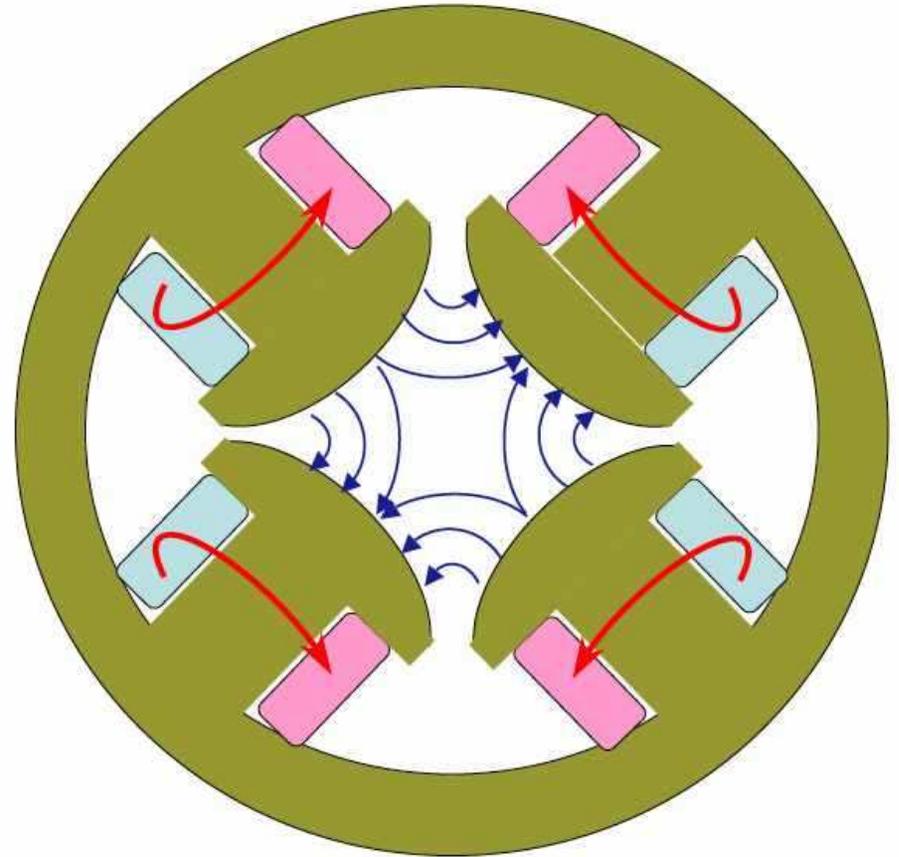


LHC Dipole

<http://lhc-machine-outreach.web.cern.ch>

Focussing the beam

- To focus the beam (ie to change its size) it is necessary to apply a different force on particles on opposite sides of the beam.
- This is done by two pairs of magnets forming a quadrupole.
- However while focusing in one plane the quadrupole will also defocus in the other plane.

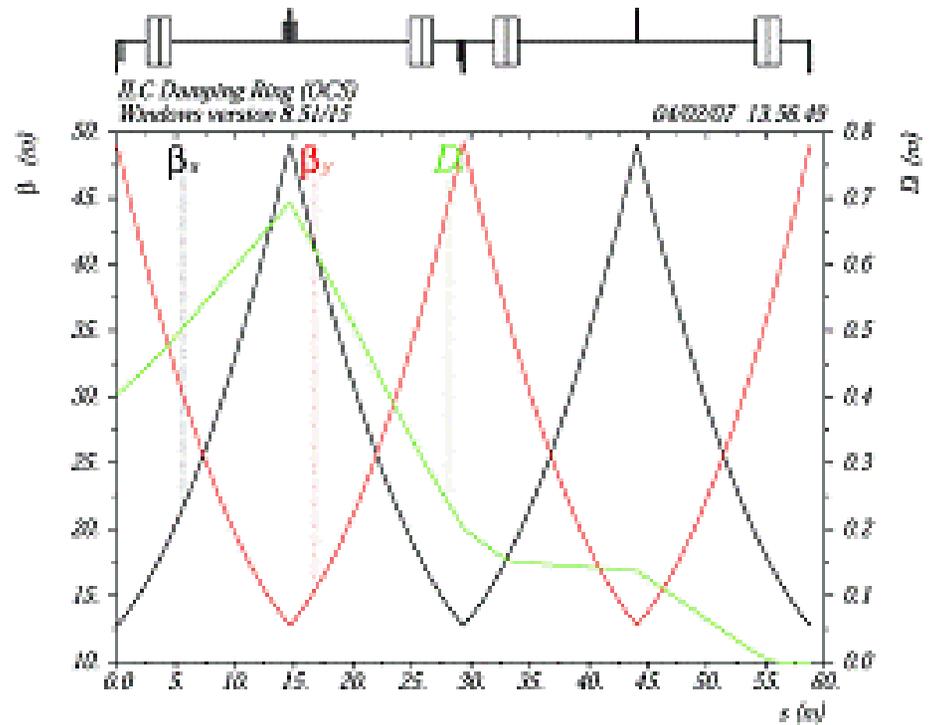


A quadrupole magnet

<http://pbpl.physics.ucla.edu>

FODO lattice

- A quadrupole focuses one plan and defocuses the other plan.
- To keep the beam within a certain envelope quadrupoles can be arranged so that they focus alternatively each plan.
- This is called a “FODO” (Focussing-Defocussing) lattice.
- At a collider the lattice is slightly more complex as space has to be created for the collisions.

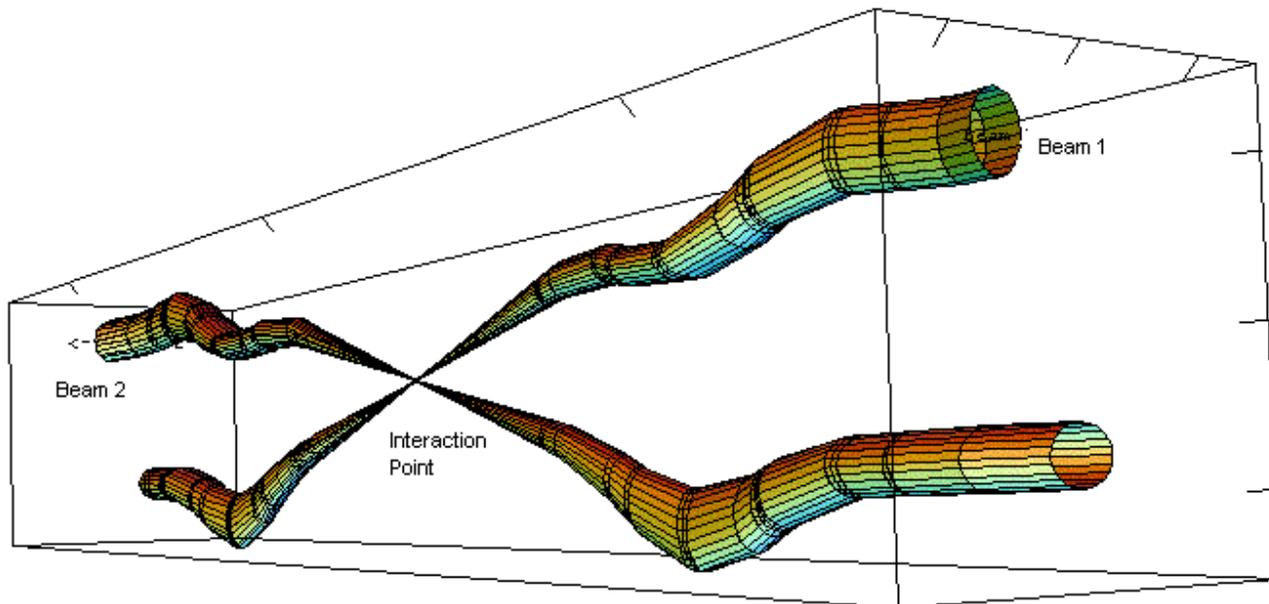


Magnet layout

<http://ilc-china.ihep.ac.cn>

How big is the beam?

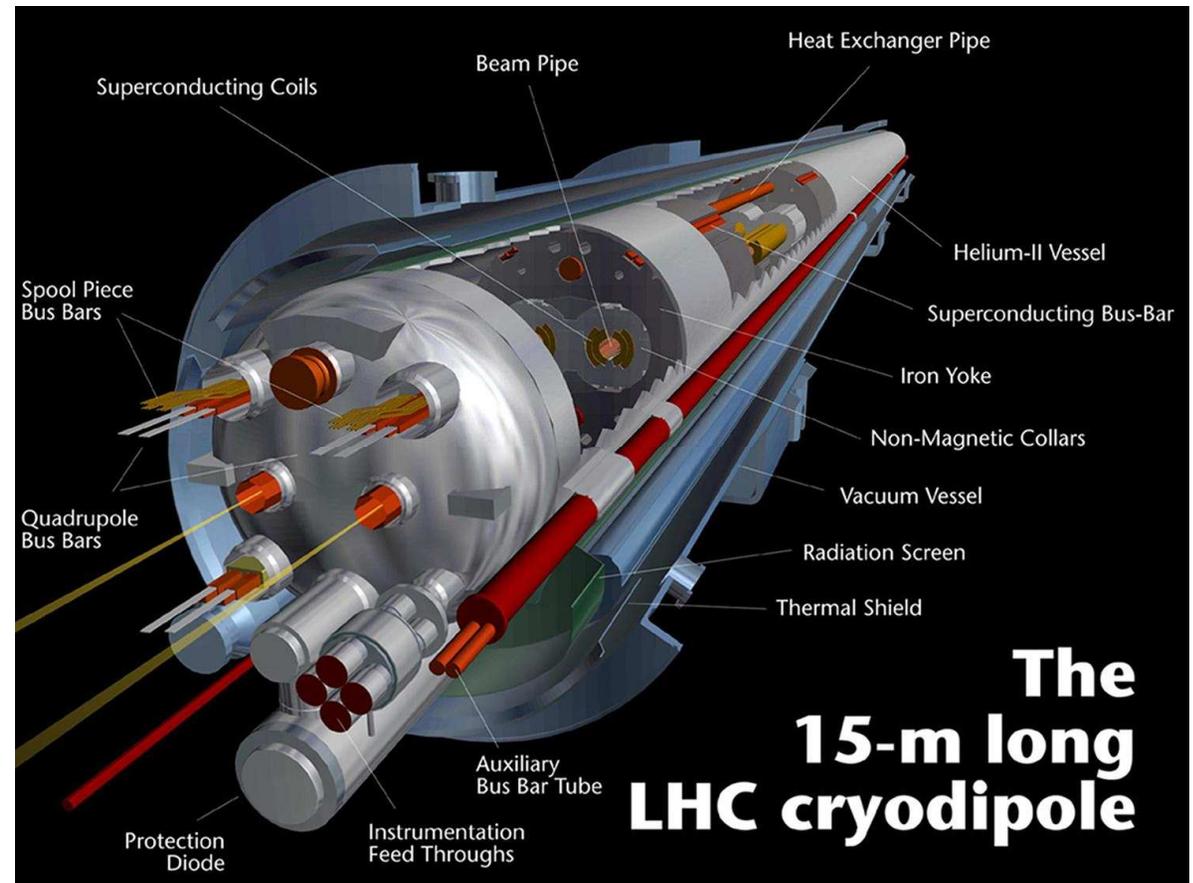
- The beam size varies along the accelerator.
- At ISIS the beam can be as wide as 100mm.
- In Diamond it is only a few hundred micrometers wide.
- In the LHC near the interaction points the beam is only 64 micrometres wide (the size of a human hair).



Beam size in the LHC

Superconducting magnets

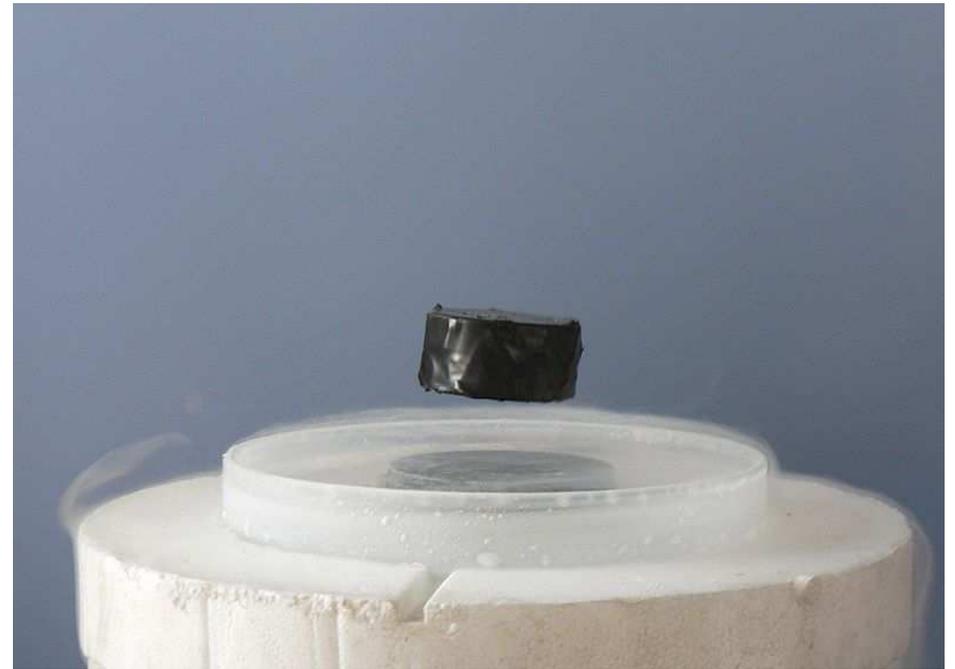
- The intense magnetic field used by the LHC magnets (dipoles, quadrupoles, etc...) requires a high current to flow in these magnets.
- To avoid dissipating large amount of power in these magnets the LHC uses superconducting technology.



<http://cds.cern.ch>

Superconductivity

- A superconducting metal is a metal in which electrons flow without resistance.
- Hence no power is dissipated by the current flow.
- Superconductivity is due to the electrons in the metal reaching a special quantum state.
- Superconductivity occurs at very low temperature (a few K).

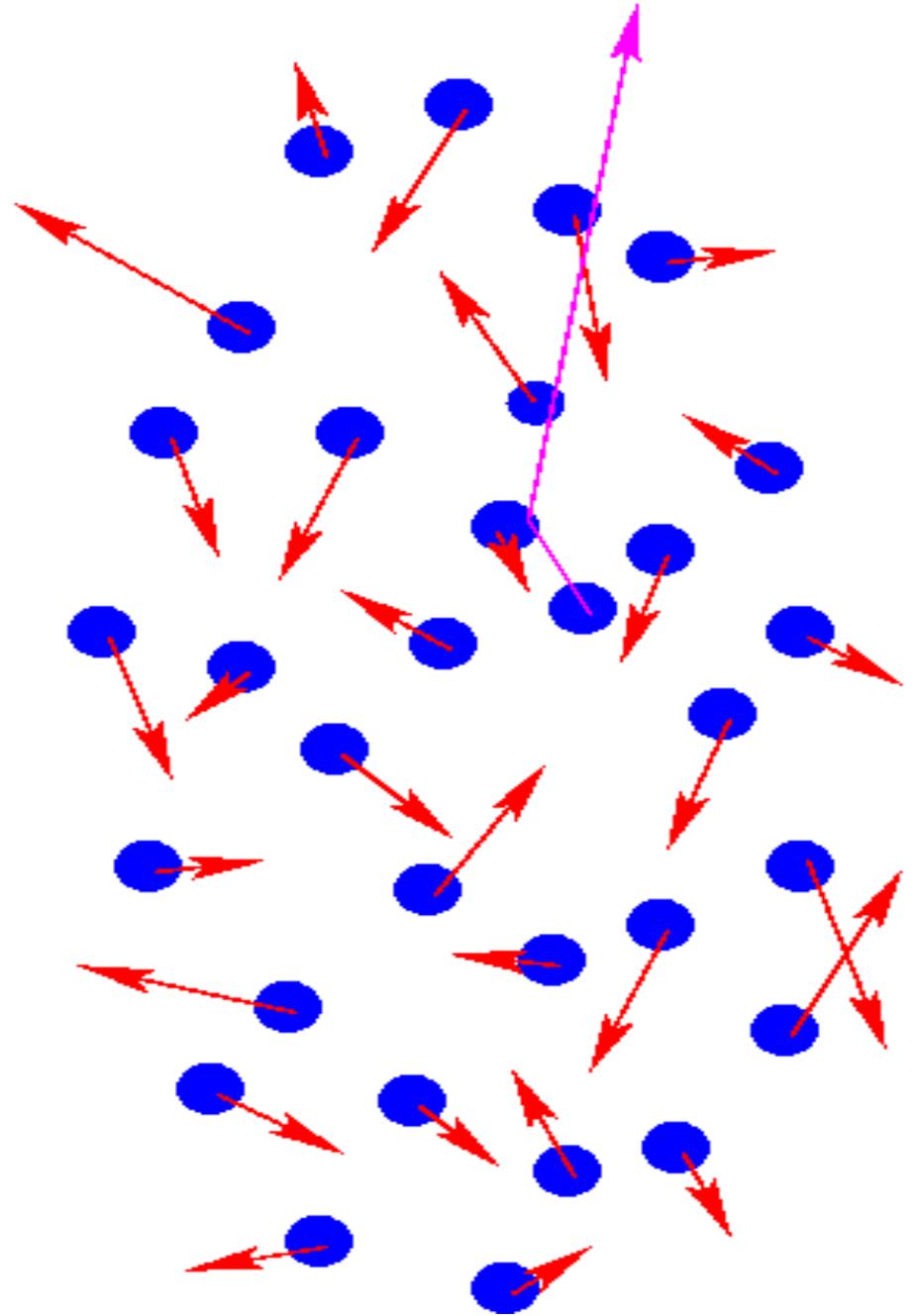


Superconducting magnet levitating

wikipedia

Lifetime

- The beam does not stay for ever in a ring.
- Some particles will scatter on each other and be ejected from the beam.
- Some particles “hit” the walls of the beampipe.
- In some rings the beam lifetime can be only a few minutes.
- In rings where stability is important (such as the LHC or Diamond) the beam lifetime will be several days.



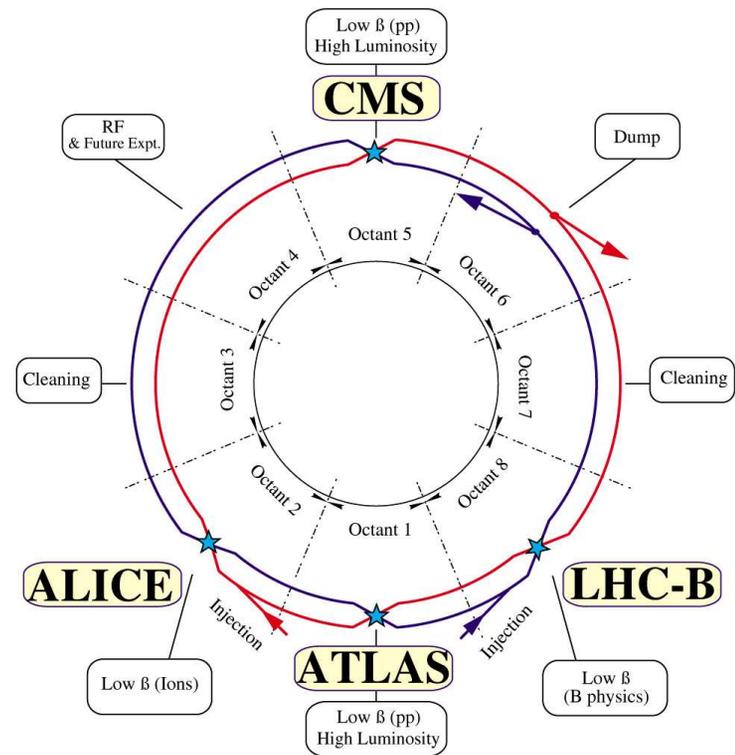
Particle scattering inside a bunch

How do scientists use it?

Particle Physics

- Particle physics experiments are located at several collision points around the ring.
- Special magnets have to be used to strongly focus the beams and collide them in the centre of the experiments.
- Where the two beams collide they exert strong (electromagnetic) forces on each other. This requires special care to keep control of the beam.

LHC LAYOUT

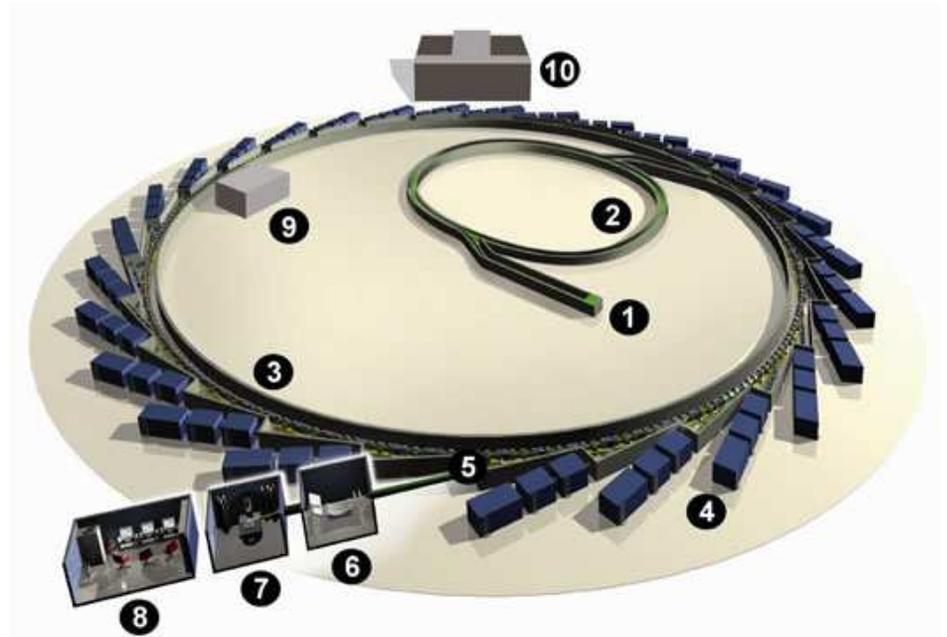


<http://cds.cern.ch>

How do scientists use it?

Light sources

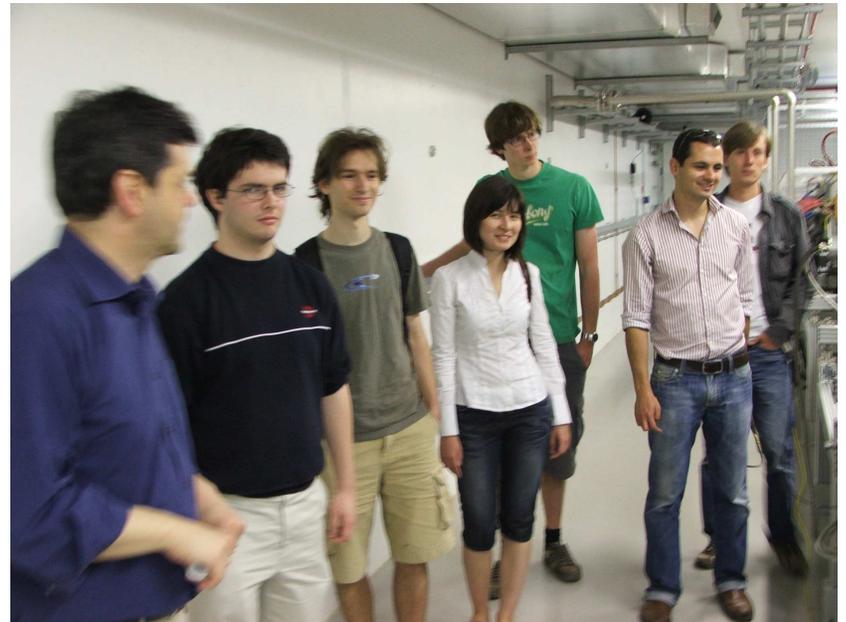
- In a light source like Diamond special magnets are inserted all around the ring to extract more light from the synchrotron.
- Each of these magnets affects the beam and the operators have to take this into account when calculating the trajectory of the particles in the ring.



Diamond and its beam lines
<http://www.diamond.ac.uk>

Can I visit a particle accelerator?

- CERN, Diamond and ISIS have outreach programs and they welcome visitors on special days.
- Most of the time it is not possible to see the accelerators for safety reasons.
- If you want to visit with your class you should contact the PR office beforehand.
- More details on their website:
 - <http://outreach.web.cern.ch/outreach/>
 - <http://www.diamond.ac.uk/> (next open days on 13 November 2010)

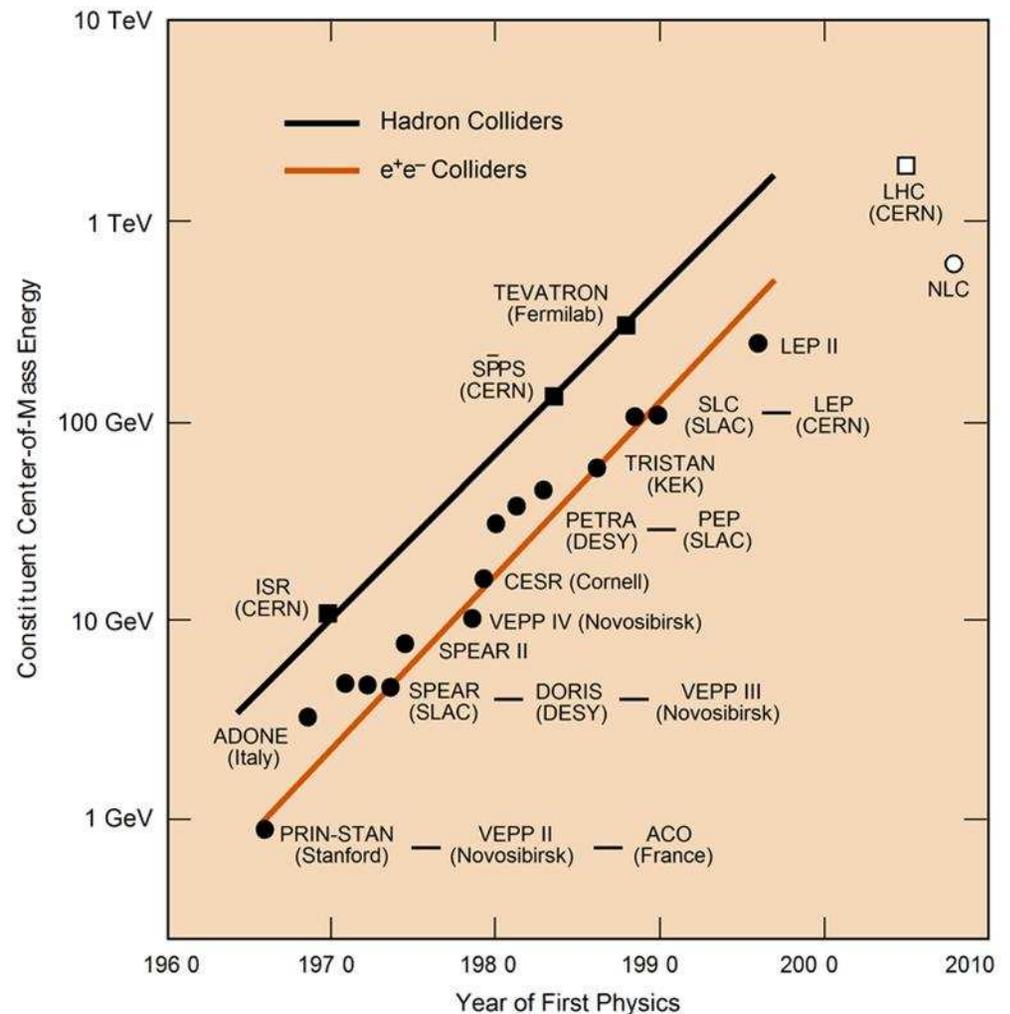


Students visiting Diamond

JAI

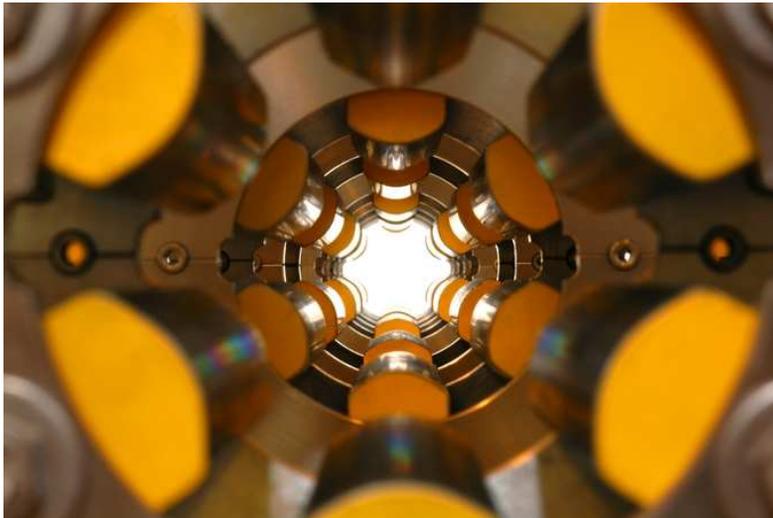
Future accelerators

- The performance of particle accelerators improves regularly.
- It is foreseen that the LHC will operate for several decades. However after a few years of operation it is planned to increase the beam intensity.
- A new generation of light sources called “free electron lasers” (FEL) is currently also being studied.
- Particle accelerators are the biggest scientific machines ever built.
- More and more fields of science rely on them for world leading research.



Useful resources

- Pictures:
<http://cds.cern.ch/>
<http://www.isis.stfc.ac.uk/imagesindex.html>
<http://diamond.ac.uk/Home/Media/images.html>
- Activities:
<https://project-cernland.web.cern.ch/project-CERNland/>
<http://www.particledetectives.net/html/main.html>
<http://www.adams-institute.ac.uk/accelerators.php>
<http://lhc-machine-outreach.web.cern.ch/>



Sextupole magnet

<http://diamond.ac.uk/Home/Media/images.html>