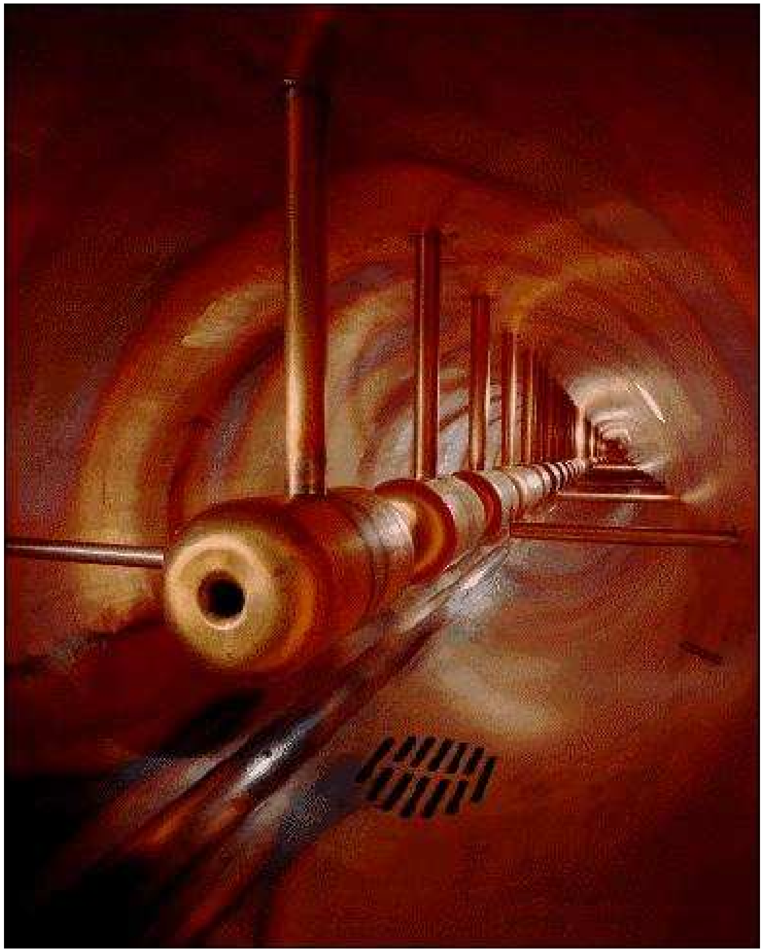
1. Overview and history of Particle accelerators



- Course introduction
- Early accelerators
- The CERN accelerators
- Light sources

Course introduction

- There will be 12 lectures given by Dr David Urner, Dr Riccardo Bartolini and myself.
- Some problems will be given at the end of each lecture. We will discuss the answers on the first lecture by the same lecturer the following week.
- You can find the material relevant to this option at http://www-pnp.physics.ox.ac.uk/~delerue/accelerator_option/
- For those who have never seen a particle accelerator, there will be a visit of the Teaching accelerator on Wednesday 2nd week and a visit of the Diamond Light Source on Friday week 6. Please email me (nicolas.delerue@physics...) if you would like to join these visits.

Recommended reading

- An introduction to particle accelerators,
  Edmund Wilson, QC787.P3 WIL
- The physics of Particle accelerators, Klaus Wille, QC787.P3 WIL
- 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
- Some material is linked from the option website.

Why study particle accelerators?

- There are more than 150 accelerators currently in use in the UK.
- They have wide ranging applications well beyond physics: health, life science, materials and even archaeology!

Interactive map available at:
http://www.adams-institute.ac.uk/accelerators.php

Why study...

- The construction, design and operation of particle accelerators uses knowledge from different branches of physics: electromagnetism, high frequency electronics, solid states physics, optics, vacuum technology, cryogenics, ...
- Learning about particle accelerator is a good opportunity to learn about many different physical phenomenon.

Lectures synopsis

Image: PETRA at DESY

Week 1

- History and over view of particle accelerators
- Particle Sources (Guns)
- Particle acceleration (Linacs and RF)

Week 2

- Beam Optics (Overview, Lattices, …) (2 lectures)
- Liouville's theorem / Emittance

Week 3

- Beam Dynamics, Imperfections, Resonances
- Space charge and Instabilities
- Diagnostics

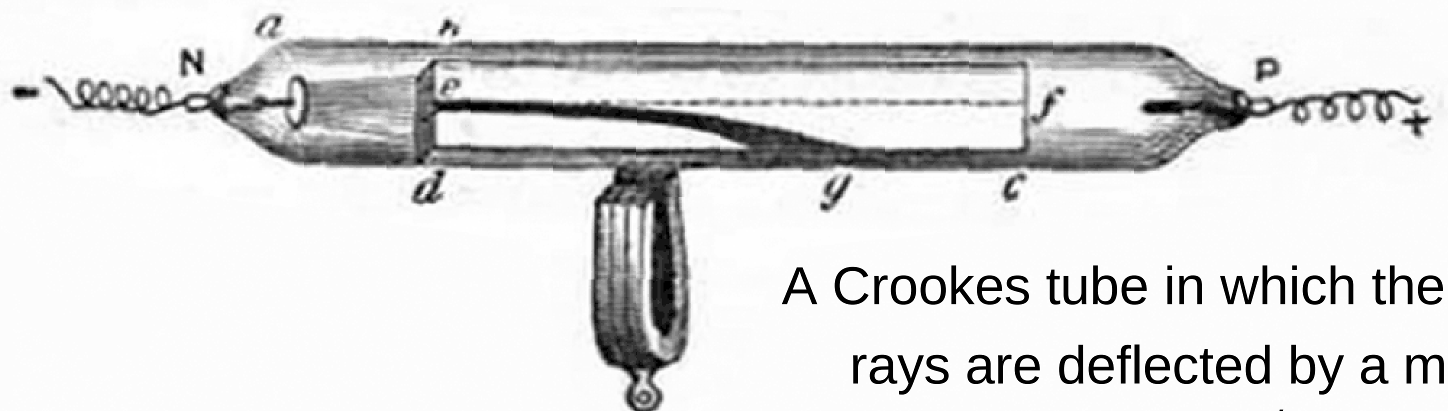
Week 4

- Life at a Particle Accelerator (Diamond)
- Accelerators in High Energy Physics
- Accelerators outside High Energy Physics

Early accelerators

1870: Discovery of the cathode rays by William Crookes

- Charged rays
- Propagation from the Cathode to the anode



A Crookes tube in which the Cathode rays are deflected by a magnetic field.

Images source: Wikipedia

1896: J.J. Thomson shows that the cathode rays are made of “particles” and measure the charge/mass ratio.

These particles are called “electrons”

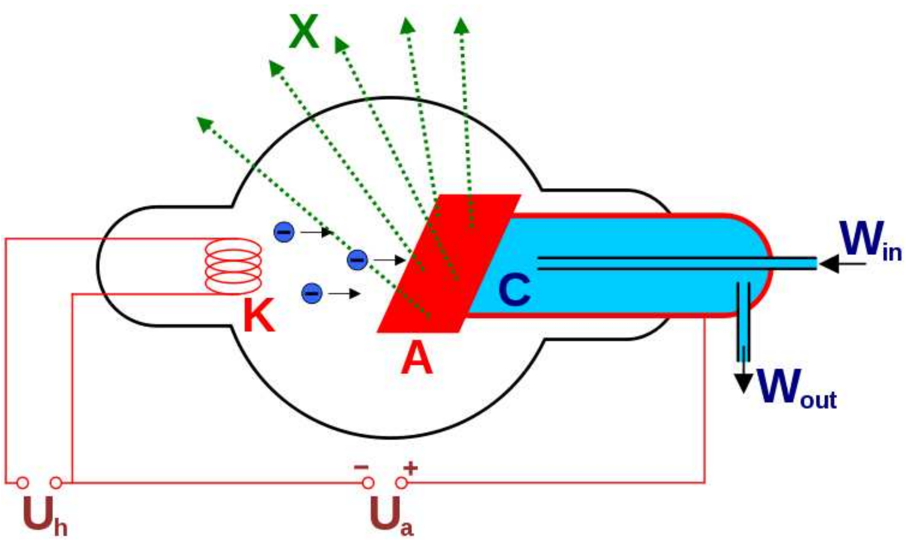
More about particles production in lecture 2 (tomorrow).

X-rays

1895:

Röngten discovers that some radiations produced by cathode rays can travel through paper and photographic plates: X-rays!

X-ray image of the hand of Röngten's wife.(image source: wikipedia)



An X-ray tube: the electrons are accelerated by an electric field and generate X-rays when they hit a target. (image source: wikipedia)

When accelerated electrons (>5keV) hit a metallic anode, their kinetic energy is transferred to the target. X-rays are produced by ionization of inner shell electrons and by Bremsstrahlung.

Bremsstrahlung

- A charged particle emits radiation when it is accelerated.
- An electron that Coulomb scatters on a heavy nucleus will change direction => acceleration
- Bremsstrahlung, braking radiation, is the name of the radiation emitted when a charged particle scatters on a heavy nucleus.
- When a charged beam hits an object, X-rays are emitted. This is used to produce X-rays in hospitals but it is also a source of hazardous radiations in accelerators.
- Bremsstrahlung is similar to synchrotron radiation that will be discussed later today.

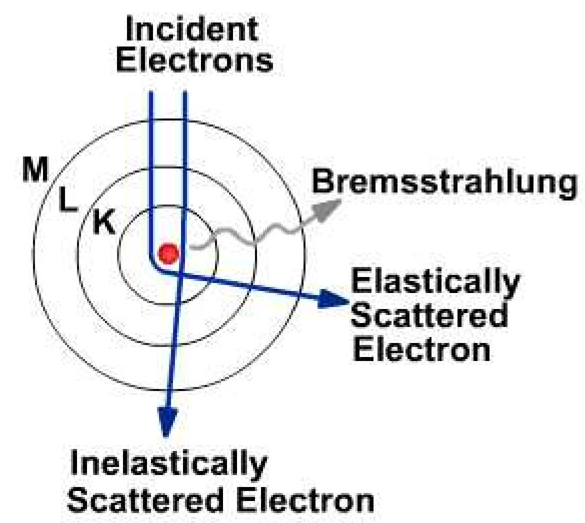
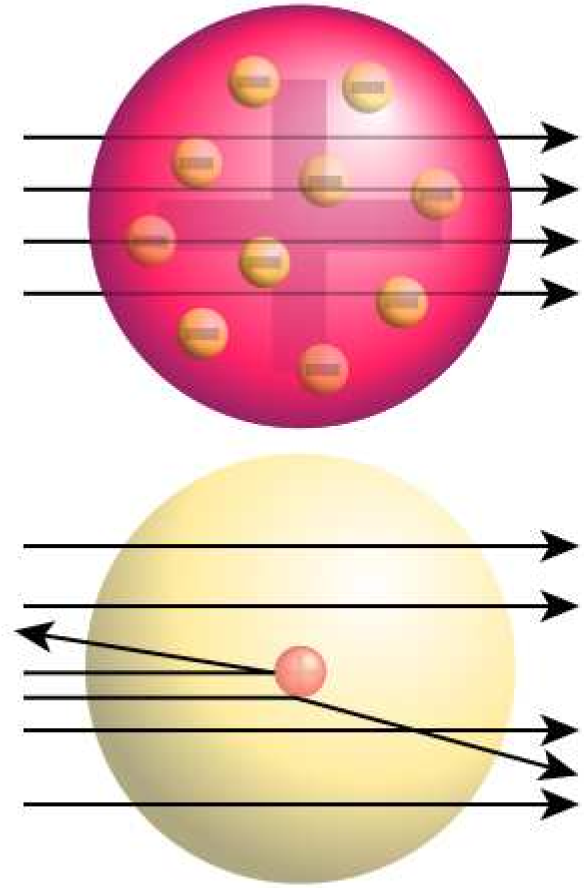


Image source: http://www.ndt-ed.org/EducationResources/

Rutherford scattering experiment

- In 1909 Rutherford studied the scattering of alpha particle on a gold foil.
- The best explanation of the scattering pattern observed was that gold atoms were made of a hard core (now known as the nucleus) surrounded by a cloud of electrons.



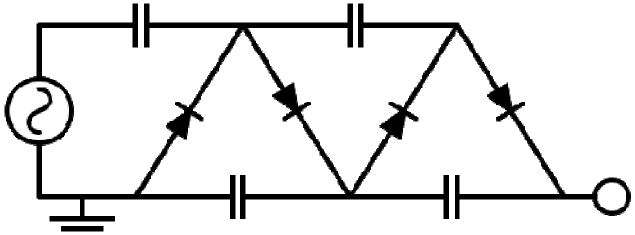
Trajectory of alpha particles in a uniformly charged sphere (top) and in a real gold nucleus (bottom) (image source: wikipedia)

Improved resolution

- In quantum mechanics the wavelength of an object is related to its energy by $\lambda = \frac{h}{p}$
- The reach better resolutions, the energy of the probe must be increased.
- The energy of the electrons in Cathodic ray tubes is limited by the electrostatic generators available.
- In the 1930s several generators where invented to produce high electric fields.

Cockroft-Walton generator

- To generate high potential (and high electric fields) Cockroft and Walton used a voltage multiplier made of diodes and capacitors.



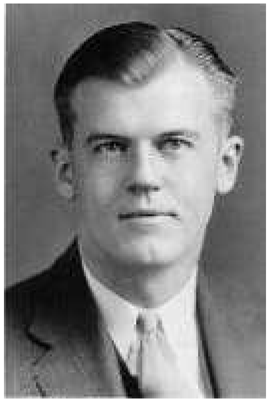
- The first half-cycle will load the first capacitor to its peak voltage. The second half-cycle loads the second capacitor and so on...

A Cockroft-Walton generator (image source: wikipedia)

Splitting the atom

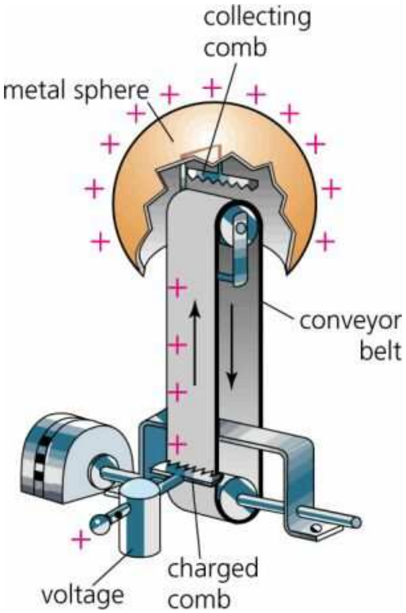
- By using their generator Cockroft and Walton were able to accelerate protons to hundreds of keV.
- In 1932 they bombarded Lithium with 700 keV protons and transmuted it into Helium and other elements.
- This was the first time that a particle accelerator had been use to trigger a nuclear reaction.
- Cockroft and Walton were awarded the Nobel prize for this work in 1951.

Van de Graaff generator



Robert Van de Graaff
1901-1967
B.Sc. Oxford 1926
D.Phil. Oxford 1928

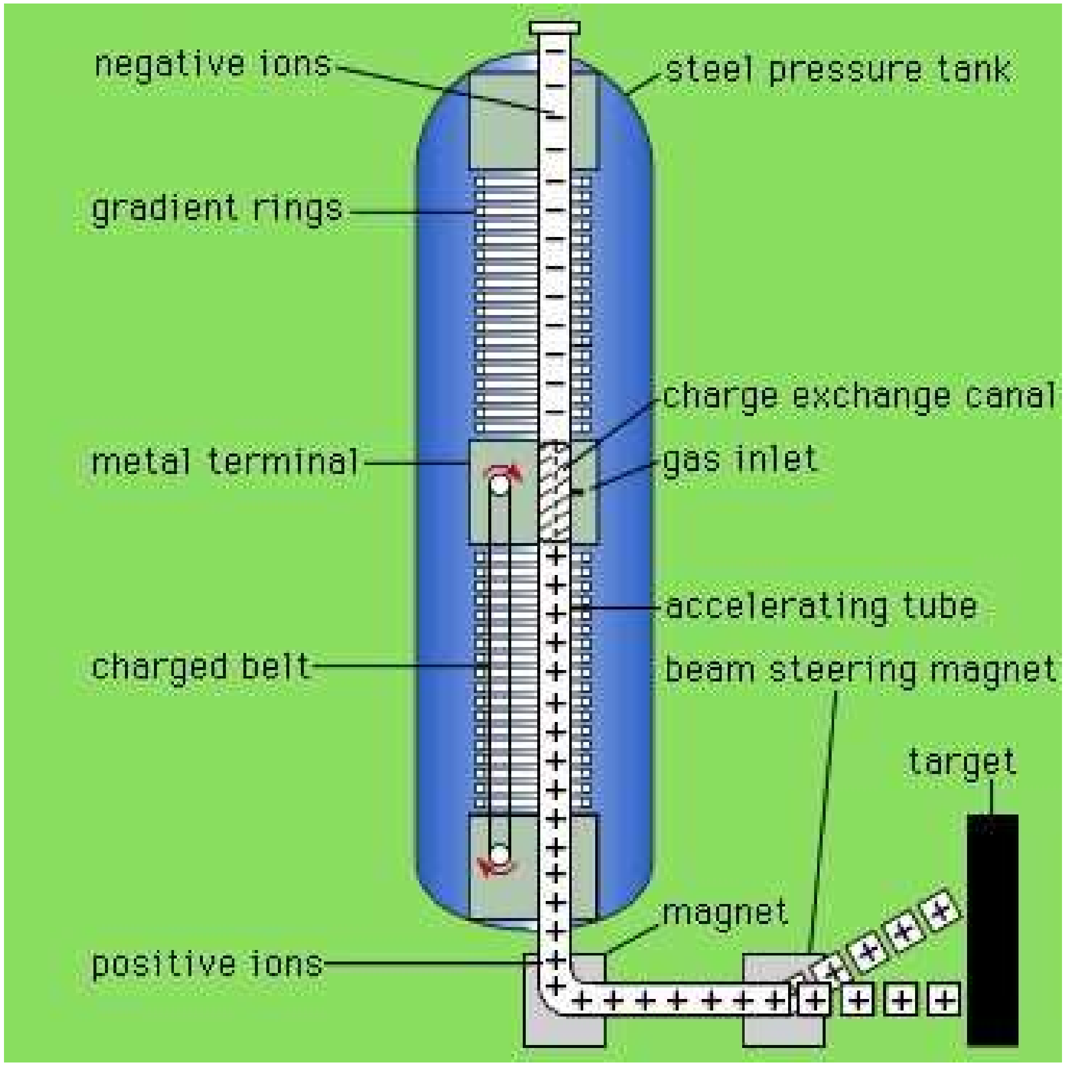
- In 1929 Van de Graaff proposed another design to reach high voltages.
- In a Van de Graaff generator charges are mechanically carried by a conveyor belt from a low potential source to a high potential collector.
- Van de Graaff generator can reach several MV and are still used in DC accelerators (like the accelerator used for Nuclear practicals in the DWB).



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

Tandem accelerators

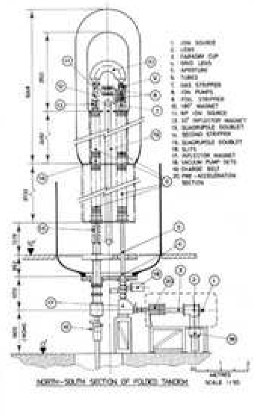
- It is possible to increase the energy reach of a Van de Graaff accelerators by using a “tandem” accelerator.
- Such accelerator has two stage:
  - In the first stage negative ions (with extra e-) are accelerated from ground to a positive high voltage.
  - These ions are then stripped of 2-3 electrons in a stripper and become negative.
  - They are then accelerated further by going from the positive high voltage to DC.

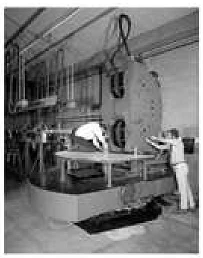


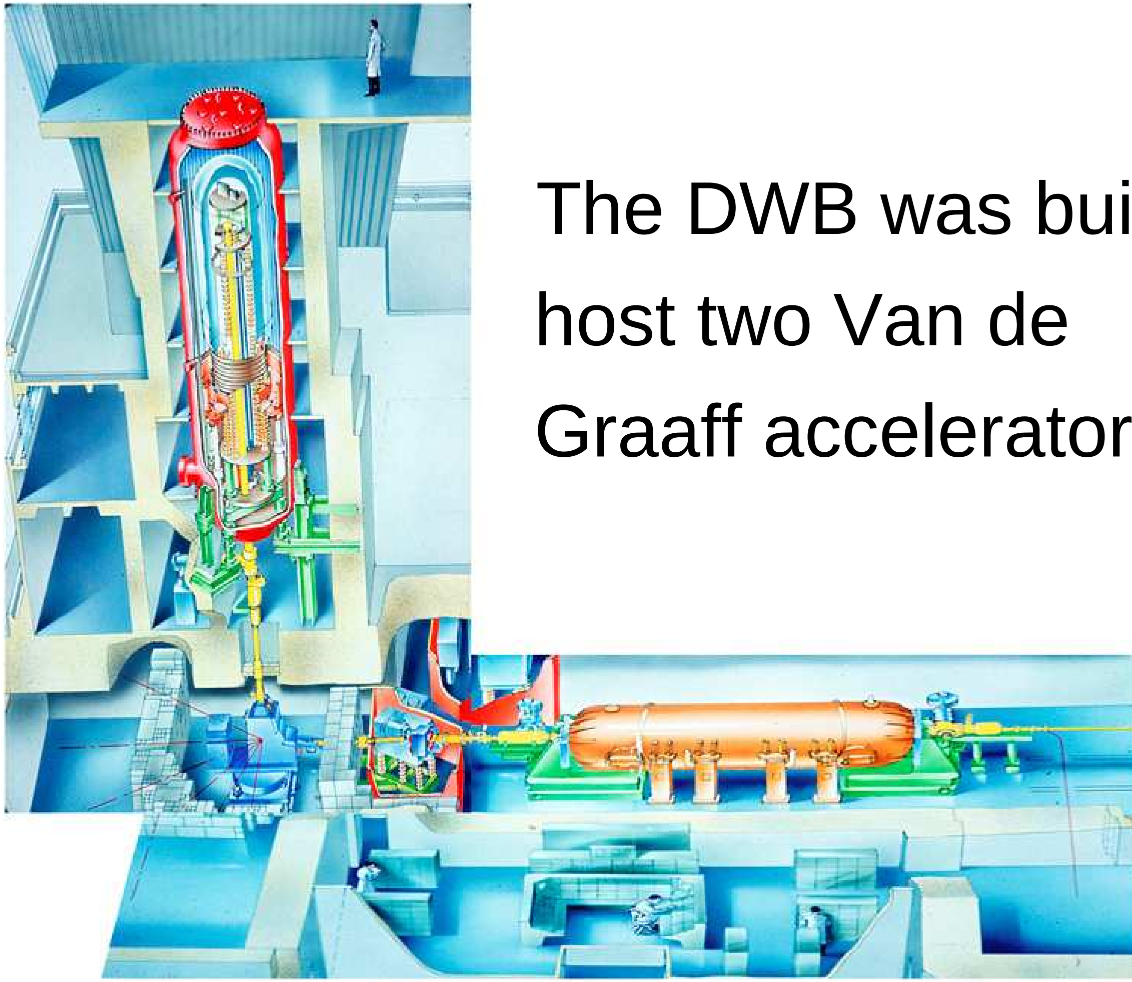
Example: 10MV Van de Graaff can accelerate C^- to 10 MeV and then C^{2+} to 30 MeV.

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

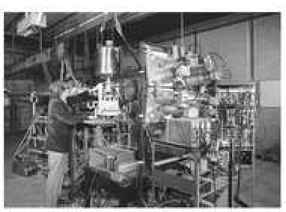
Oxford's first particle accelerators

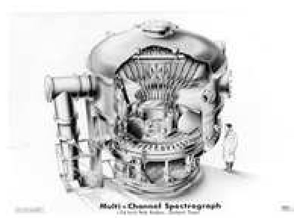


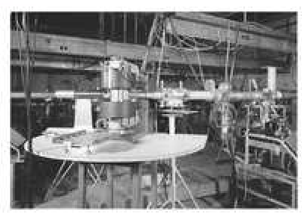




The DWB was built to host two Van de Graaff accelerators.

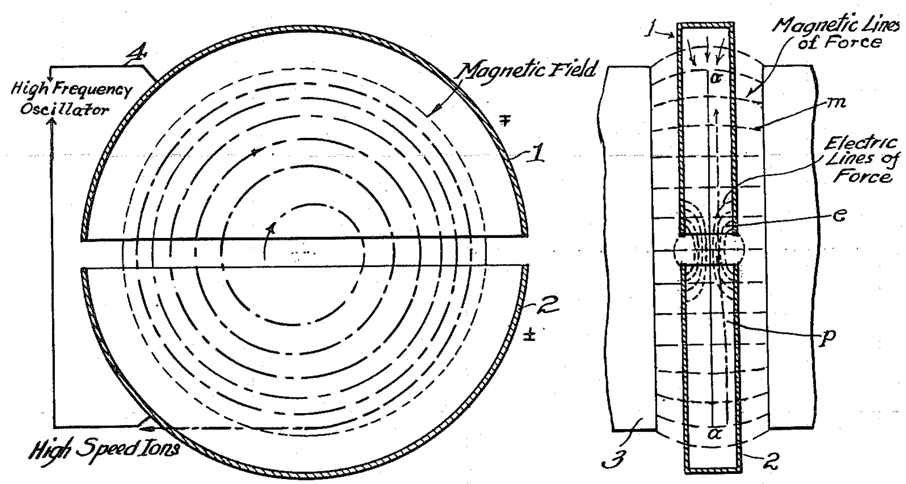






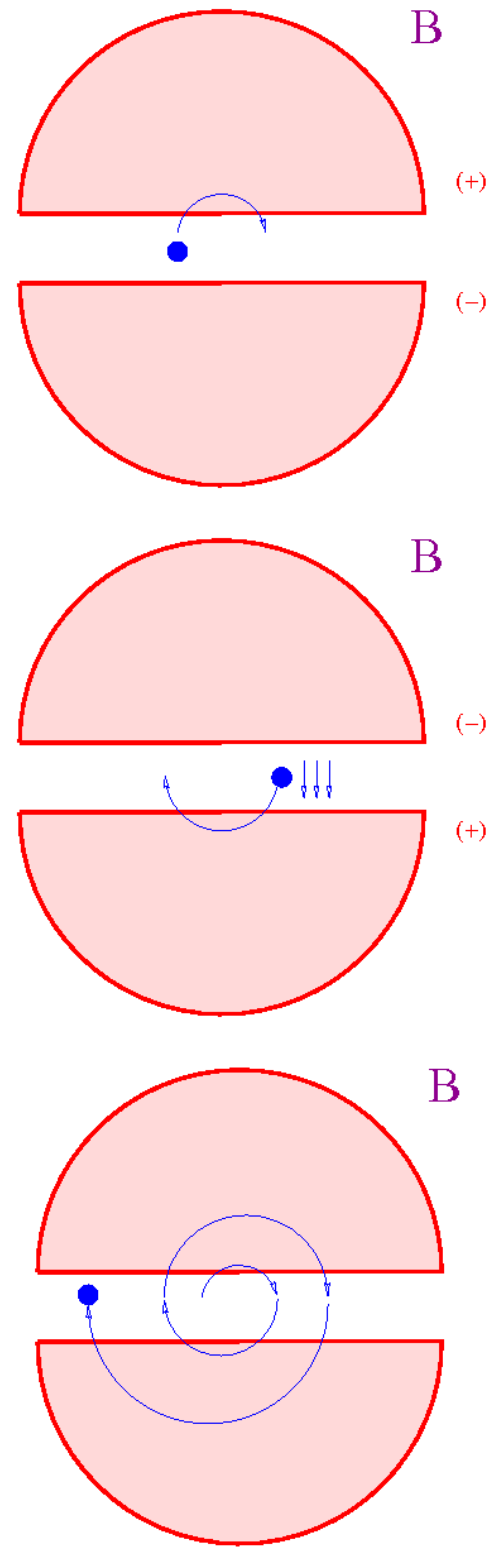
Cyclotron

- 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 1931Lawrence designed a “cyclotron”, a circular device made of two electrodes placed in a magnetic field.



Cyclotron (2)

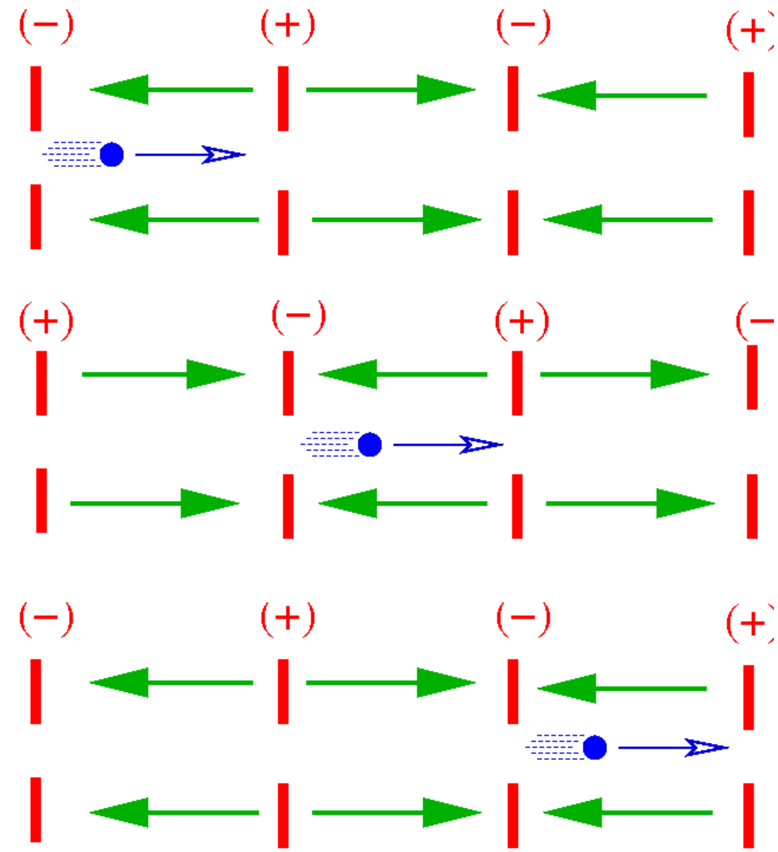
- Due to the magnetic field the particles follow a circular trajectory
- By reversing the electric field of the electrode between two gap crossing it is possible to accelerate the particles.
- With an AC potential of only 2000V Lawrence accelerated protons to 80kV!
- Lawrence received the Nobel prize in 1939 for this work.



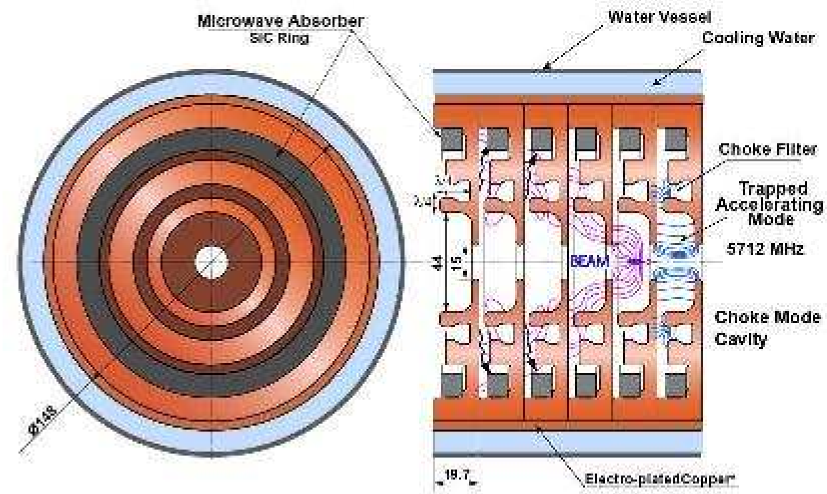
Limitations of cyclotrons

- Cyclotrons increase the energy of the particles by the same amount of energy at each turn.
- At low energy, the particles cross the gap at fixed frequency.
- At higher energy when relativistic corrections start to matter, the frequency at which they cross the gaps starts to decrease (the particles travel at the same speed ~c but follow a longer path).
- This can be addressed by varying the drive frequency but only all particles in the cyclotron are nearly at the same energy.
- There are also issue due to the non-uniformity of the magnetic field toward the edge of the cyclotron.

RF acceleration



- 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.

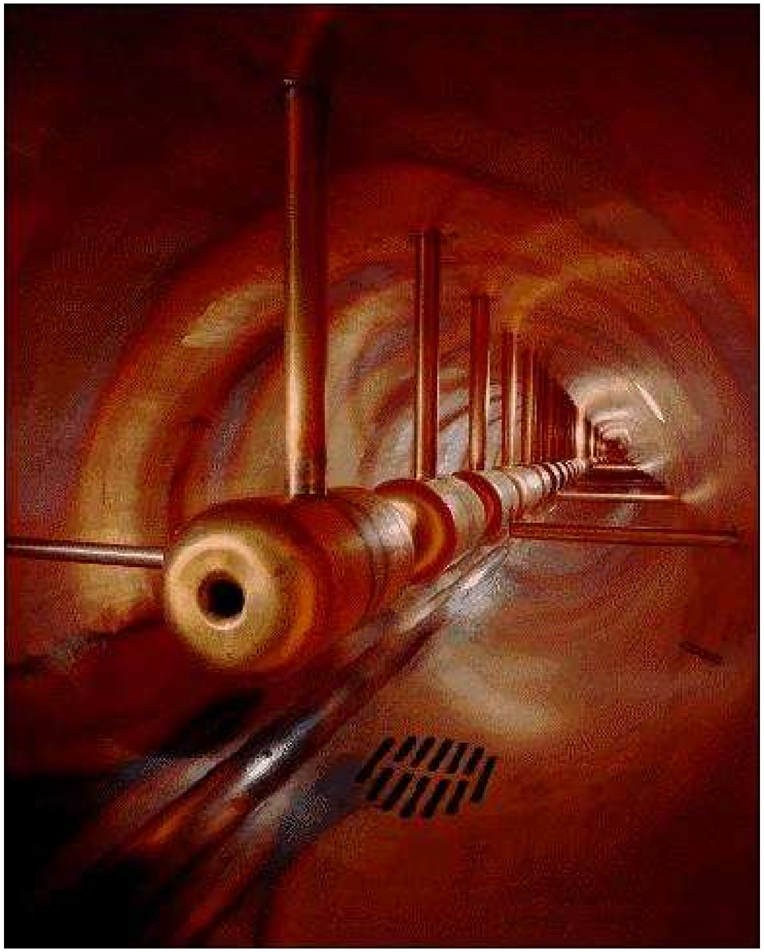


(source: Spring-8, Japan)

RF accelerators (2)

Now we face the opposite problem:

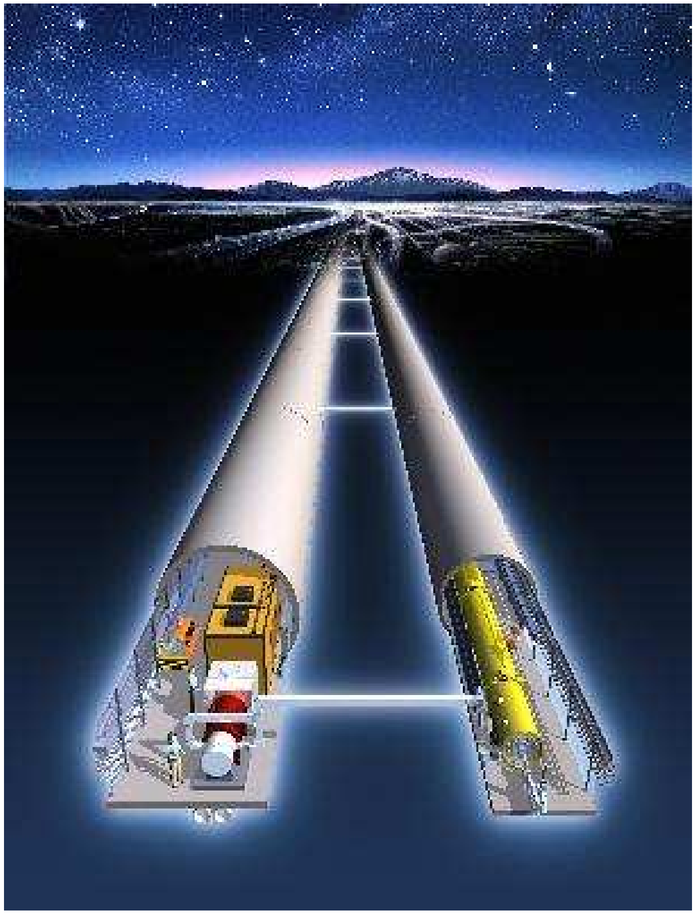
- The first stages of an AC accelerator are quite complicated because the speed of the particles keeps changing and thus the spacing between cavities is changing.
- Once the particles reach the speed of light, the cavities can be evenly spaced.



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!



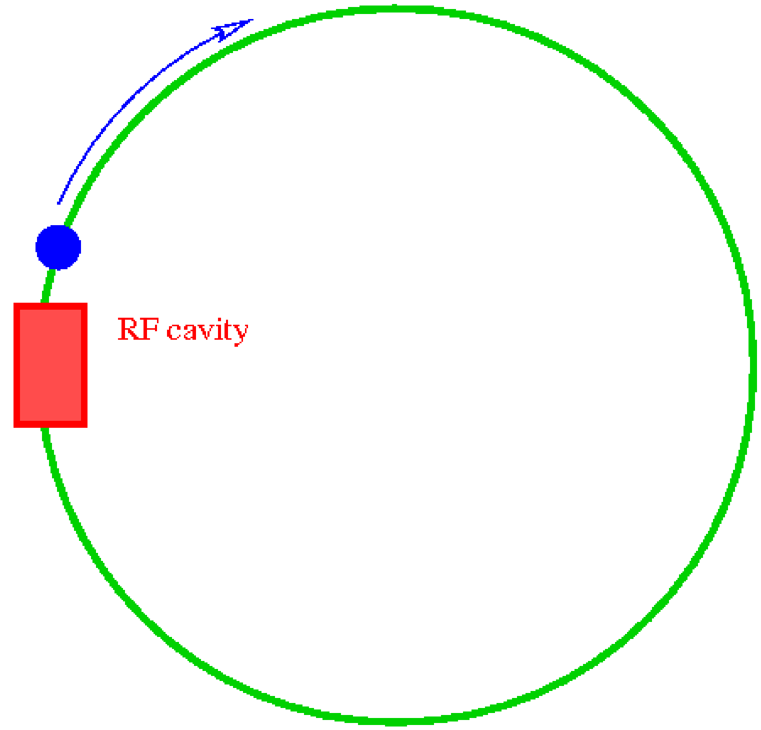
Artist view of the ILC
(source: KEK)

The lecture on Friday will explain how linacs work

Synchrotrons

It is possible to modify the principle of a cyclotron by replace 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.



Next week's lecture will deal with synchrotrons

Quizz

The LHC will accelerate protons up to 7 TeV. Which technology is best suited for such acceleration?

(a) An accelerator using alternating voltage

(b) A tandem Van de Graaff accelerator

?

Answer: (a)

- Protons can be accelerated directly. In an electrostatic accelerator this would require a 7 TV potential. **Too Much!**
- It is also possible to accelerate H^- ions in a tandem accelerator and strip them into protons.
  To reach 7 TeV, this would require 3.5 TV. **Still too Much!**
- By using an AC accelerator, an alternating field of a few MV (repeated many times) is enough to accelerate protons to several TeV...
- The LHC is a synchrotron, as are Diamond, the Tevatron, PETRA,…

Kinematics

- The first accelerator based nuclear physics experiments were done by shooting particles on a target.
- In such case the centre of mass energy is given by:

$$\sqrt{s} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}$$
$$\sqrt{s} = \sqrt{(E_1)^2 - (P_1)^2} = \sqrt{2E_1 mc^2}$$

- But if the particles have the same energy and opposite momentum:

$$\sqrt{s} = \sqrt{(2E)^2} = 2E$$

- Higher centre of mass energies can be reached when the two beams have opposite momentum.

Cyclotron radiation

- Energy radiated by an accelerated charge:

$$\frac{dP}{d\Omega} = \frac{e^2 a^2}{4\pi c^3} \sin(\theta^2)$$

- Acceleration experienced by a charge in a field B travelling at a velocity v:

$$a = \frac{e\,v\,B}{m}$$

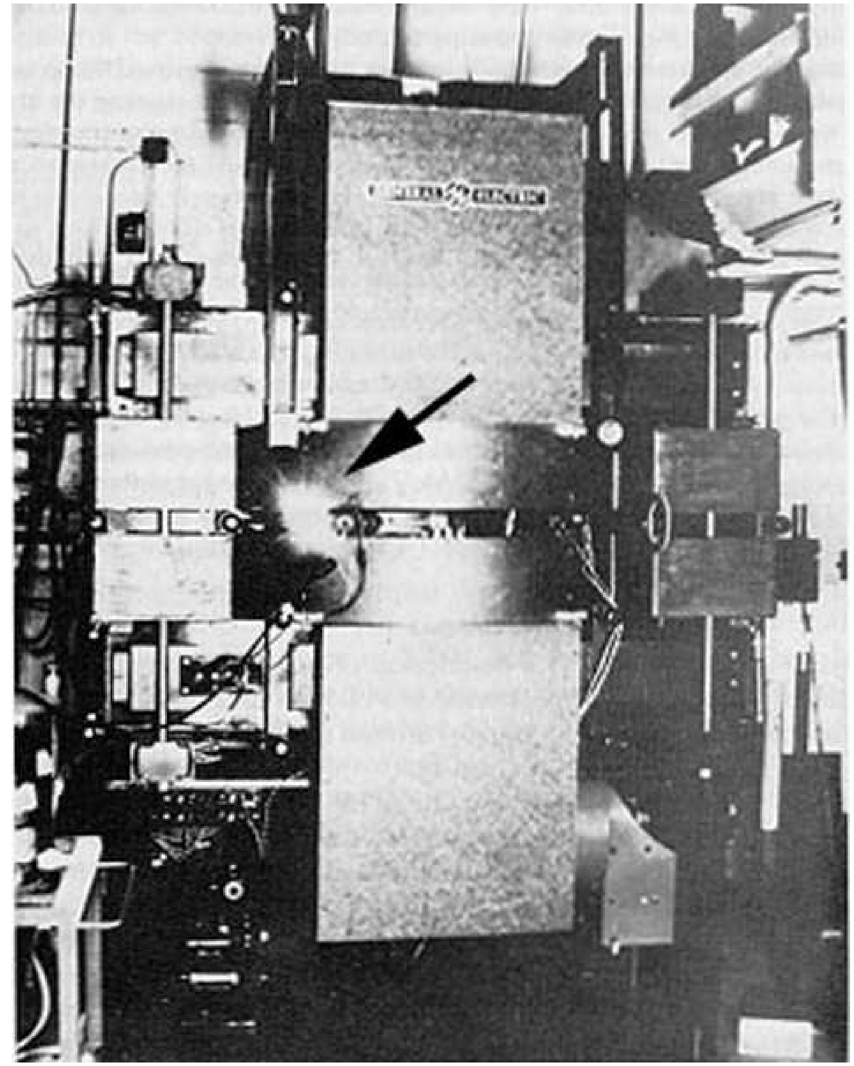
- hence

$$\frac{dP}{d\Omega} = \frac{e^4 v^2 B^2}{4\pi m c^3} \sin(\theta^2)$$

- Charged particles in a magnetic field radiate energy. This is known as cyclotron radiation.

Synchrotron radiation

- Synchrotron radiation is similar to cyclotron radiation (with a more complicated derivation) but for relativistic particles. (beamstrahlung is also similar)
- This means that particles in a circular accelerator will radiate some of their energy.
- This can be used as a powerful source of X-rays but it also limits the energy that can be reached by synchrotrons.



Discovery of Synchrotron radiation in 1946
Source: wikipedia

Colliders

- Colliding beams is much more difficult than just accelerating them!
- The first collider was ADA (Anello di Accumulazione) built in 1961.
- In a collider it is possible to reach much higher energies but the number of collisions is significantly reduced.

In week 4 we will review the applications of colliders

AdA in a glass case at Frascati National Laboratory

Luminosity and brilliance

- Luminosity and brilliance are quantities used to benchmark the performance of an accelerator.
- The “luminosity” is used in nuclear and particle physics (colliders) to estimate the number of particles per unit time that interact with a target or that collide.
- The “brilliance” is used in light sources (synchrotrons) to estimate the amount of light produced, it is the number of photons in a given spectral range per unit time, per unit surface.

Getting a high luminosity

$$\frac{dN}{dt} = L\sigma \qquad L = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

To reach a higher luminosity you can:

- Increase f, the bunch crossing frequency
- Increase the particle intensity n1 and n2
- Reduce the size of the beams
- Change the shape of the beams: round beams have a larger area than elliptical beam!
- BUT each of these “improvements” come with drawbacks that we will study in future lectures.

In week 3 we will discuss what these drawbacks are.

Brilliance

$$B = \frac{\Phi}{4\pi^2 \Sigma_x \Sigma_\theta \Sigma_y \Sigma_\phi}$$

$$\Sigma_x = \sqrt{\sigma_{x,el} + \sigma_{x,\gamma}}$$

- The brilliance gives a measure of the intensity of the light produced by a light source.
- It is the flux of photons (in a given spectral range) divided by the size and the divergence of the photon beam.
- Units: photons/sec/(mm.mrad)^2/0.1% BW
- Brilliance can be improved by making the beams smaller and more collimated. We will study in future lectures why this is not always easy to do.

An example of accelerator complex: The CERN accelerators

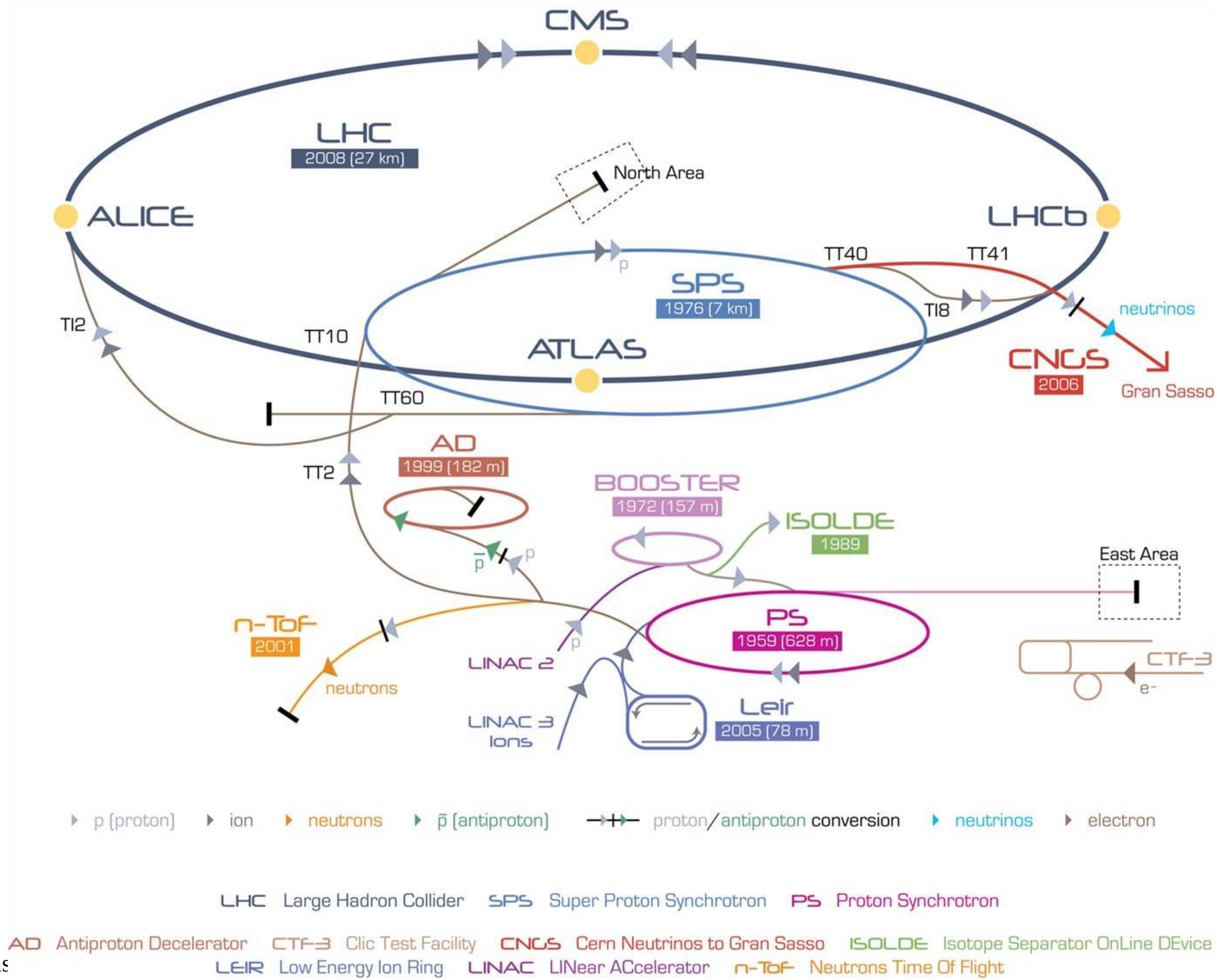
The LHC at CERN

- The LHC at CERN is the largest accelerator in the world.
- Particles are not directly produced and accelerated in the LHC, there is several pre-injectors.
- Often pre-injectors were themselves leading accelerators in the past.

Inside the LHC
Source: CERN

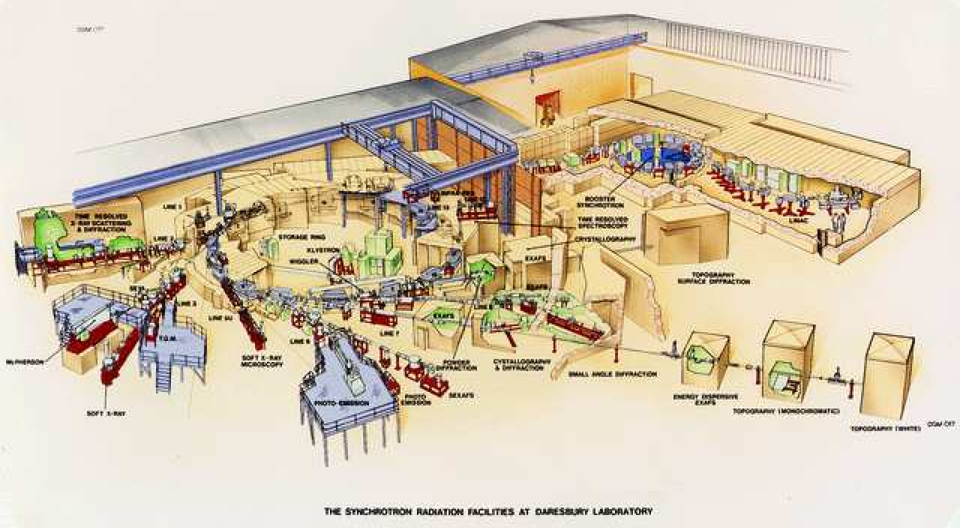
Limitations of accelerators

- Accelerators built to operate at low energy can have difficulty accelerating particles to high energies.
- High energy accelerators can not efficiently accelerate low energy particles.
- Particles are transferred from one accelerator to the next by “transfer lines”.


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

Light sources

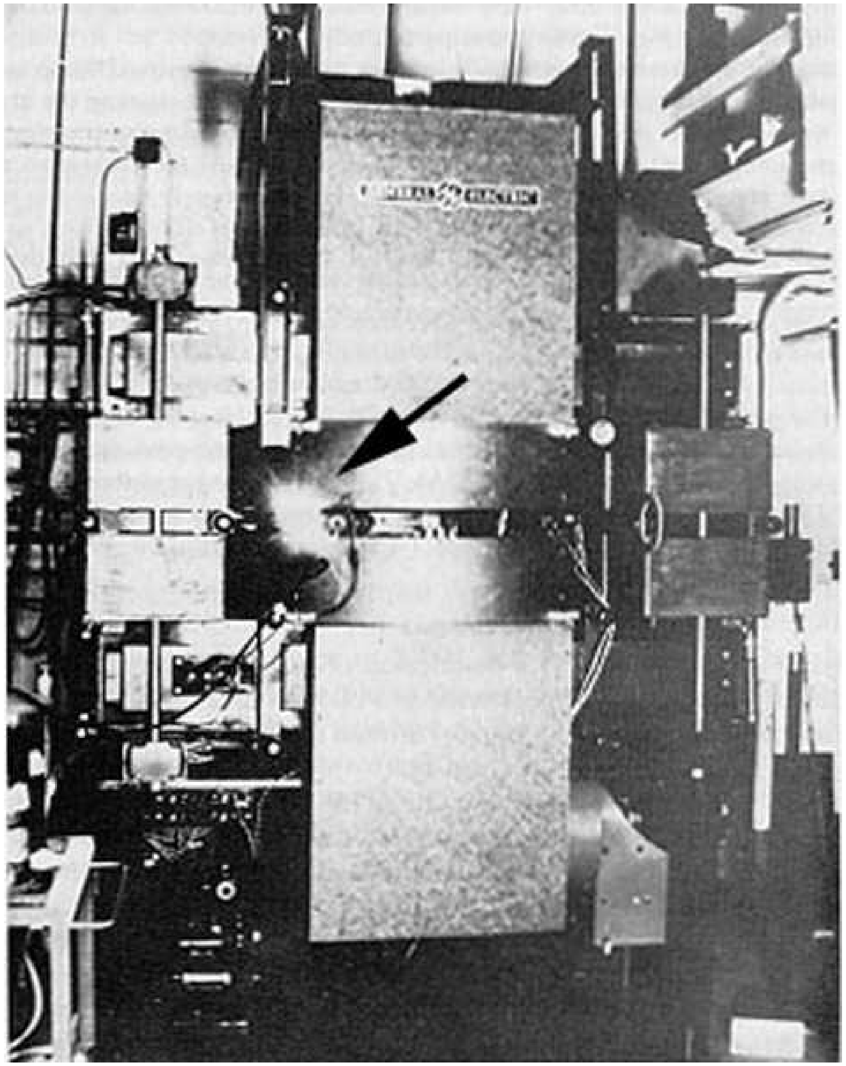
- Circular accelerators emit radiation
- With some tuning it is possible to make them emit an intense flux of radiation at a useful wavelength
- Some machines have been built entirely for this purpose, including two in this country:
  - SRS at Daresbury (now decommissioned)
  - Diamond at Harwell in Oxfordshire



Source: Diamond

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.

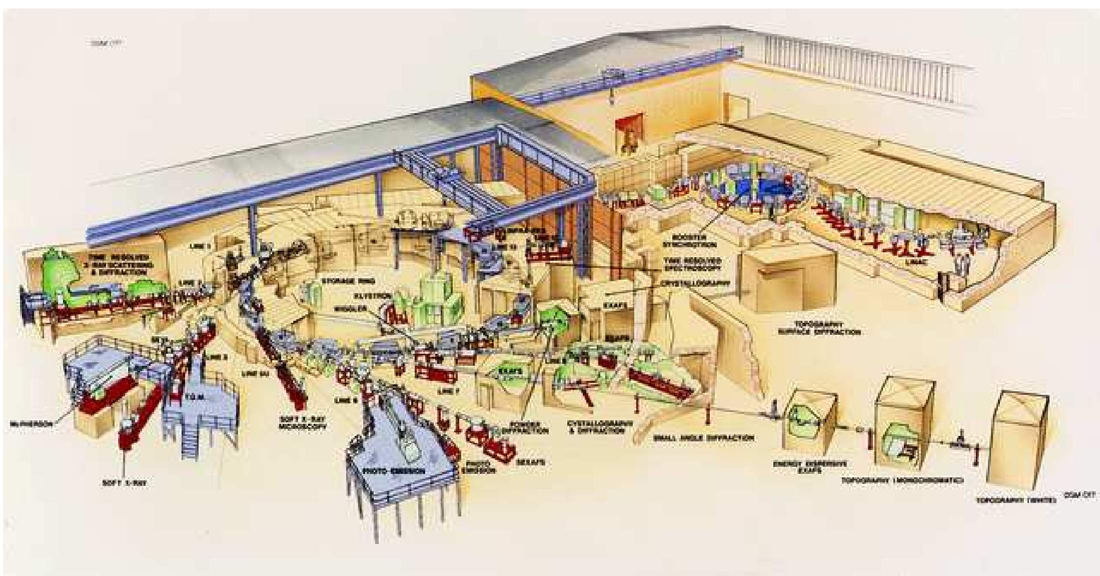


Discovery of Synchrotron radiation in 1946

Source: wikipedia

2nd generation light sources

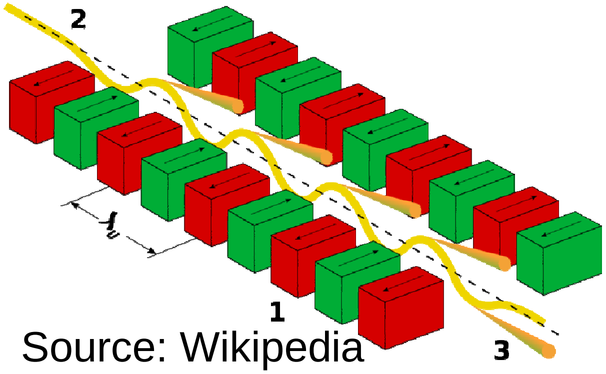
- In the 1980s machine dedicated to the production of light were built.
- The first one was the SRS (Synchrotron Radiation Source) at Daresbury.
- In these machines the light is extracted from the bending magnets and delivered to users.



THE SYNCHROTRON RADIATION FACILITIES AT DARESBURY LABORATORY

3^{rd} 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...).
- Diamond in Harwell (Oxfordshire) is a 3^{rd} generation light source.
- We will visit Diamond on Friday week 6.



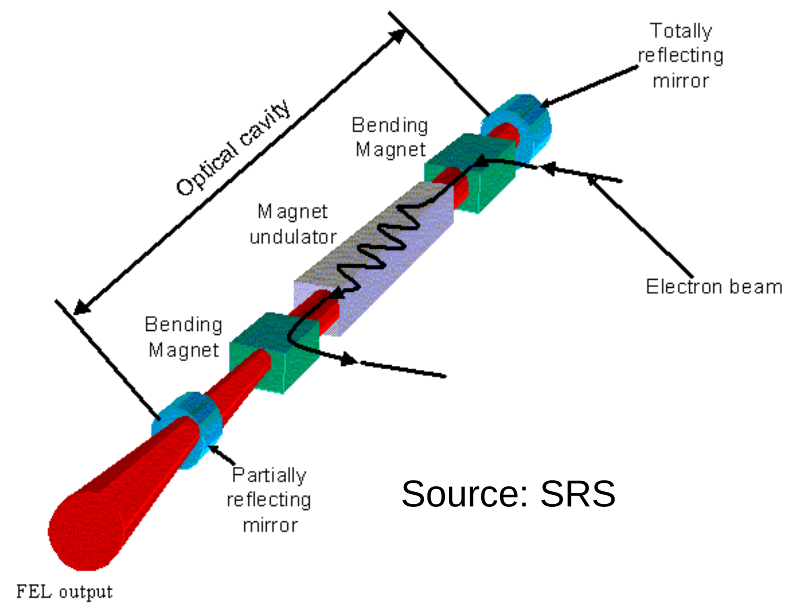
Source: Wikipedia


Undulator, *Source: Diamond*


Source: Diamond

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

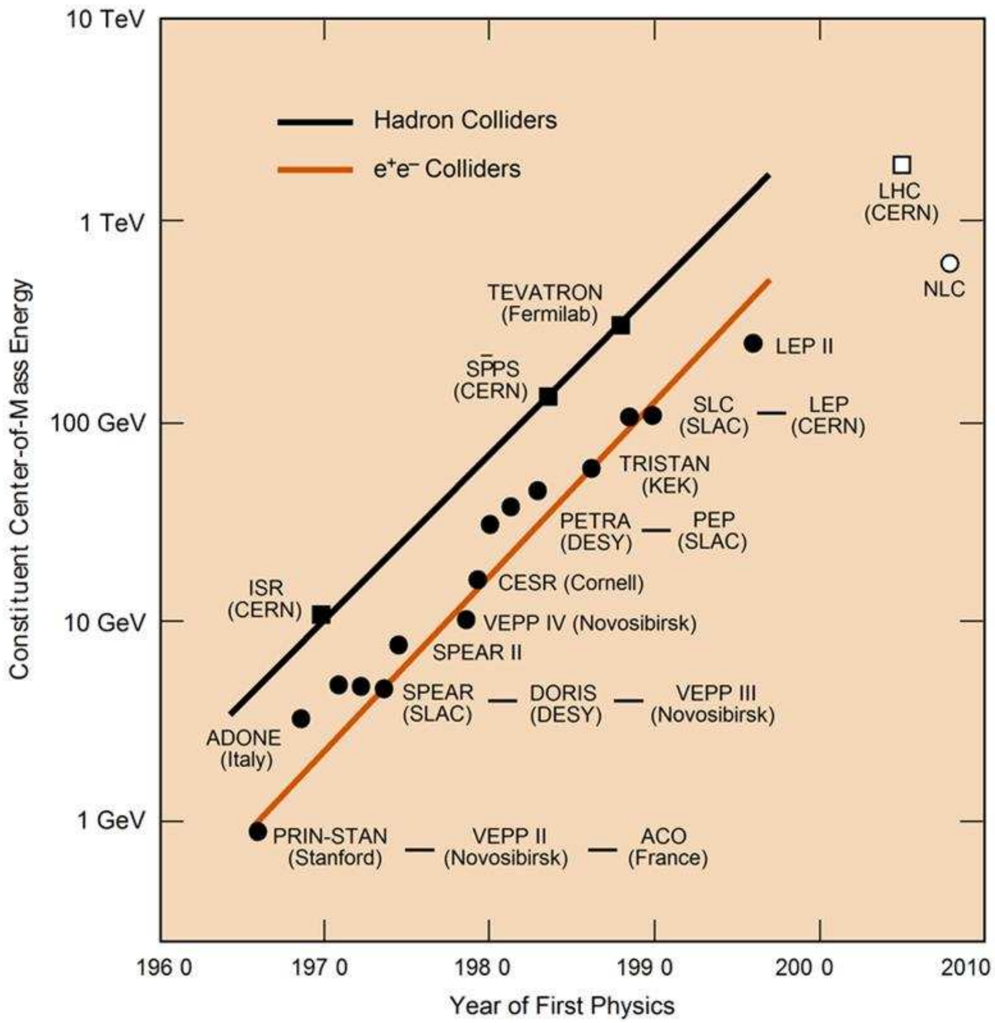
- The photons emitted in an undulator can stimulate the emission of more photons from the bunch.
- Free electron lasers (FEL) use this phenomena to generate photon beams with an even higher brilliance.
- FEL form the 4^{th} generation of light source. Some have started to operate in the past few years.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



Source: SRS

Progress

- Accelerators are progressing at a fast pace.
- A better understanding of the underlying physics allows higher luminosity and better brilliance.
- As the beams get better, new applications are considered...
- During the coming lectures we will study how accelerators work and what the current challenges are.



Source: Symmetry magazine

Problem set 1

is available online at

http://www-pnp.physics.ox.ac.uk/~delerue/accelerator_option/