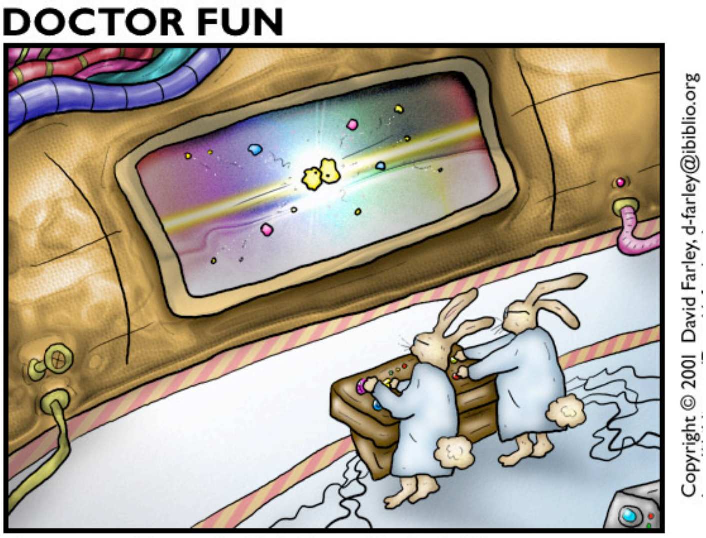
Subatomic Physics:

Particle Physics Handout 5

The Large Hadron Collider (LHC)



Bunny researchers at the High Energy Candy Collider generate exotic short-lived isotopes of Peeponium.

Use the LHC as an example to learn about accelerators and colliders in general.

- Accelerating techniques: linacs, cyclotrons and synchrotrons
- Synchrotron Radiation
- The LHC
- Colliders energy and luminosity

Learn the **concepts**, not the details (energy, numbers of proton, temperature, size etc) of the LHC.

Particle Acceleration

Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.

- e^+, e^-, p, $\bar{p}$, $\mu^\pm$(?) and **Au, Pb & Cu nuclei** have been accelerated so far...

Why accelerate particles?

- High beam energies ⇒ high E_{CM} ⇒ more energy to create new particles
- Higher energies probe shorter physics at shorter distances
- De-Broglie wavelength: $$\frac{\lambda}{2\pi} = \frac{\hbar c}{pc} \approx \frac{197\ \text{MeV fm}}{p\ [\text{MeV}/c]}$$
- *e.g.* **20 GeV/*c*** probes a distance of **0.01 fm**.

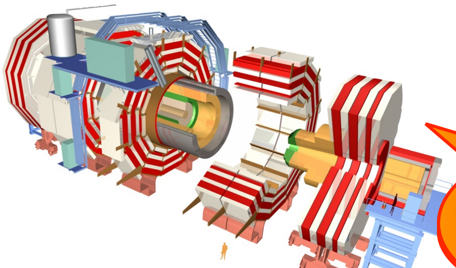
An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.

The LHC and its Experiments

The LHC is designed to accelerate protons to energies up to 7 TeV and Pb ions to 2.76 TeV/ nucleon.

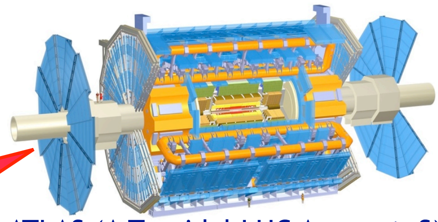
This year the LHC accelerated protons to 3.5 TeV and Pb ions to 1.38 TeV/nucleon.

There are four points in the LHC where beams collide. Each collision points hosts an experiment:

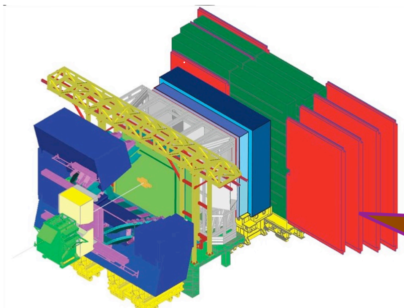


CMS (Compact Muon Solenoid)

General purpose experiments: look at high energy proton-proton collisions



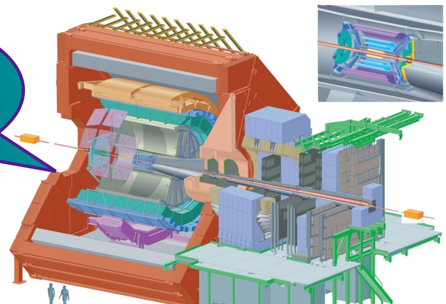
ATLAS (A Toroidal LHC ApparatuS)



LHCb (LHC beauty experiment)

Specialised Experiment: to study bottom hadrons

Specialised Experiment: to lead ion collisions and the "quark-gluon-plasma"

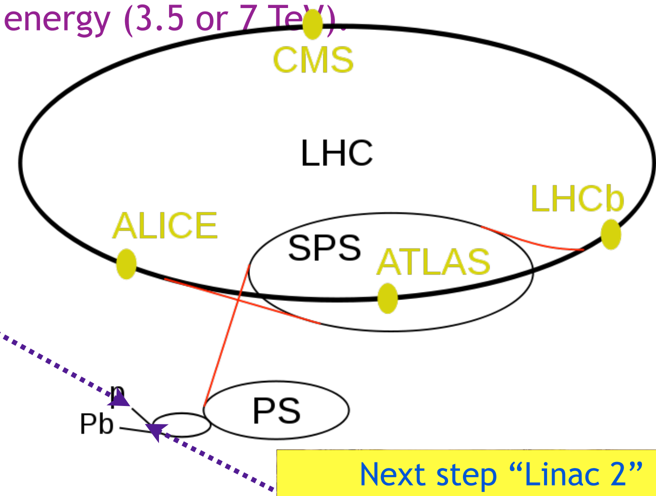


ALICE (A Large Ion Collider Experiment)

The CERN Chain of Accelerators

- Various accelerators and acceleration techniques are used to accelerate protons (or Pb) to their final energy (3.5 or 7 TeV).

Proton source: bottle of hydrogen. (0.2ng /day)

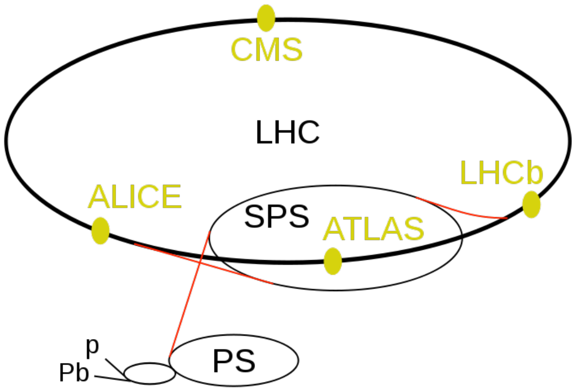


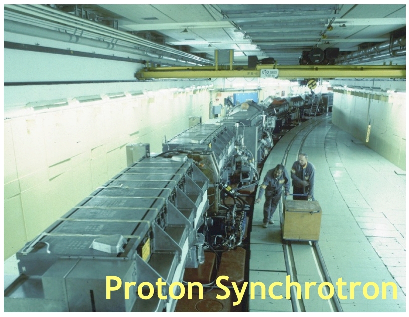
Hydrogen gas is fed into **duoplasmatron** source: which ionises the gas.

Output proton KE ~ 100keV

Next step "Linac 2" accelerates protons to 50 MeV

Synchrotrons in LHC Chain

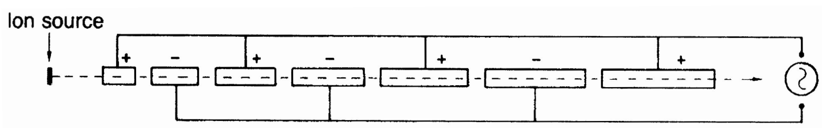


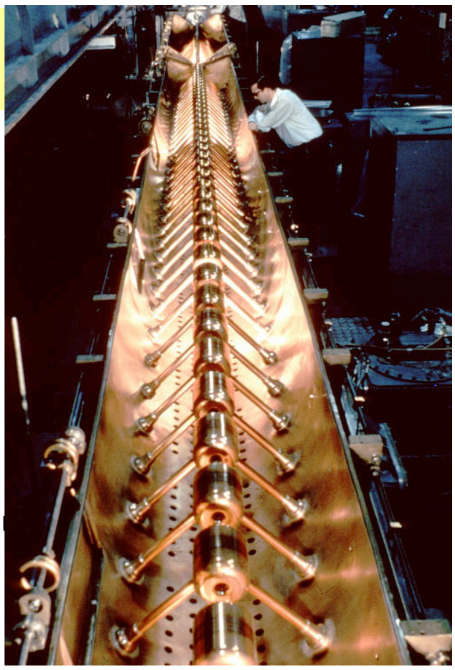


- Three synchrotrons pre-LHC:
  - **PS Booster:** accelerates proton from 50 MeV to 1.4 GeV
  - **Proton Synchrotron (PS)**: accelerates protons from 1.4 GeV to 25 GeV
  - **Super Proton Synchroton (SPS)**: accelerates protons from 25 GeV to 450 GeV
- **Protons are then transferred from SPS are transferred to LHC - also a synchrotron.**

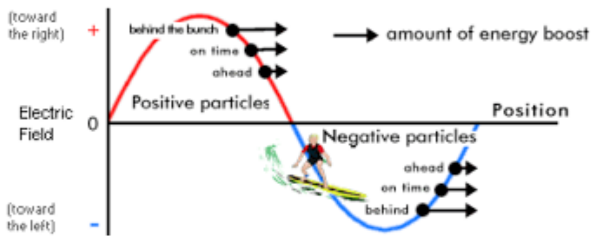
Linacs

- Charged particles in vacuum tubes accelerated by very high frequency alternating current "Radio Frequency" (RF)
- RF frequencies typically a few 100 MHz
- Field strengths – few MV/m requires specialised power sources: "klystrons"

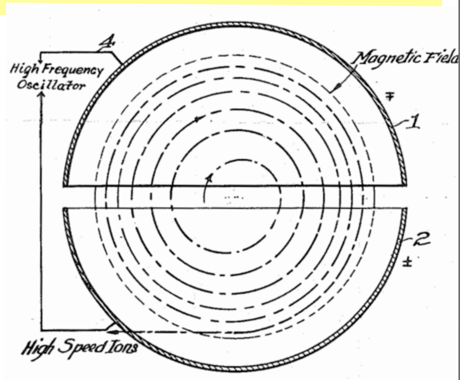




- The tubes act as Faraday cages: when the particles are in the tubes they feel no force
- Outside of the tubes they feel the potential difference between successive tubes, they accelerate forward
- Alternating current ensures that the difference always has the correct sign for acceleration.

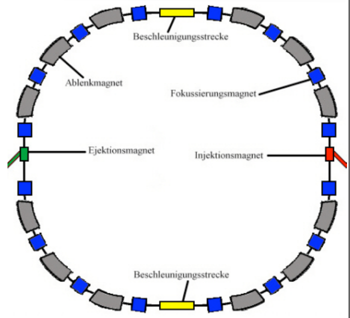


Cyclotrons and Synchrotrons



- **The Cyclotron: Two D-shaped electrodes - perpendicular magnetic field**
  - Constant frequency AC current applied to each electrode
  - Can to accelerate particles to ~**10 MeV**
  - At higher energies relativistic effects take over, circular path cannot be maintained need...

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



- **Synchrotron accelerators** use variable $\boldsymbol{B}$-field strength and radio frequency $\boldsymbol{E}$-field, synchronised with particle speed to accelerate charged particles to relativistic energies.
- Series of dipole (bending) and quadrapole (focussing) magnets
- Beams have a constant radius in a synchrotron.
- In a circular accelerator $|\vec{p}| = q|\vec{B}|R$ $\quad p[\mathrm{GeV}/c] \approx 0.3\, B[\mathrm{T}]\, R[\mathrm{m}]$

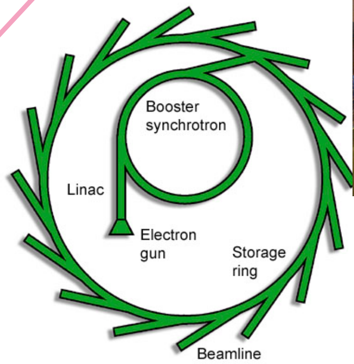
  ⇒ For high momentum beams need high field and/or large radius
- Synchrotrons can be used as **storage rings** and **colliders**.

Synchrotron Radiation

- In a synchrotron the accelerated charged particles emit photons: **synchrotron radiation.**

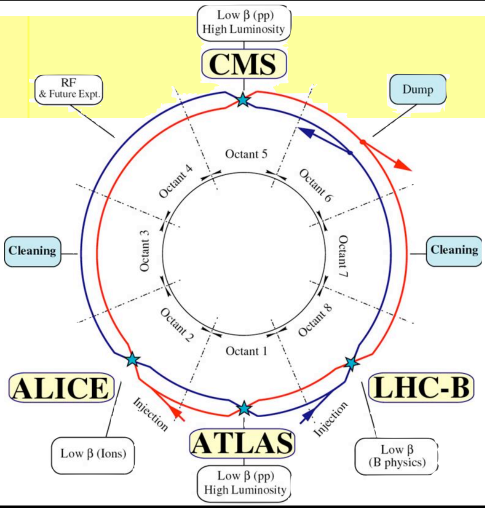
- The energy lost every turn depends of the energy and mass of the particle ($\gamma = E/m$) and the radius of the orbit, ρ:

$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\epsilon_0 \rho}$$

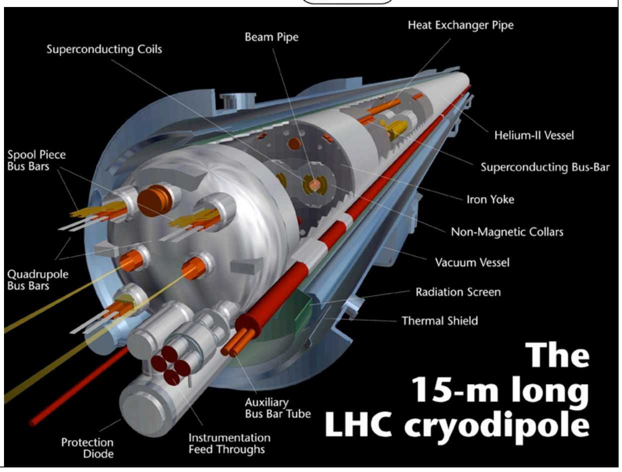


- Synchrotrons are used as high-energy photon sources
- In a storage ring, the energy lost due to synchrotron radiation must be returned to the beam to keep the collision energy constant.

The LHC Synchrotron



- LHC circumference is 27 km.
- LHC accelerates proton from **450 GeV** to **7 TeV** over ~20 minutes.
- ***B***-field varies from **1.18 T** to **8.33 T**.
- Once at 7 TeV the beams are steered to collide at the four collision points.
- The accelerator chain is used once every 10 - 15 hours to create and accelerate enough protons to fill LHC. The two protons orbits are filled successively.
  - Main accelerating structure are 1232 15 m dipole magnets.
  - Magnets operate at 1.9K
  - Peak field in magnet coil 8.76T



LHC Energy

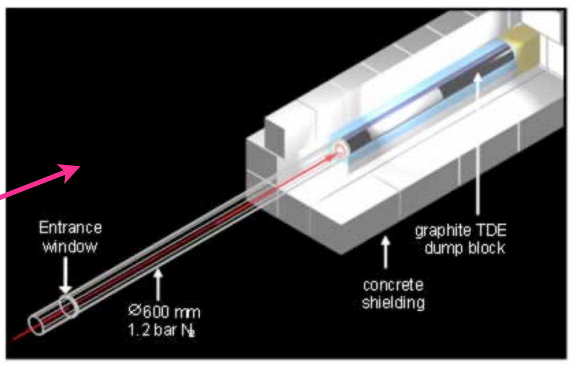
- The beam is not continuous stream of protons: at maximum luminosity protons will be grouped into 2808 bunches, 25 ns apart, in each direction.
- Each bunch consists of up to ~1.15×10^{11} protons, ~1 cm long and ~1 mm across.

$$E_{\text{beam}} = N_p \, n_b \, \gamma \, m_p \, c^2$$

γ = Relativistic factor
N_p = Number of protons per bunch
n_b = Number of bunches

- With 1.15×10^{11} protons per bunch and 2808 bunches: $E_{\text{beam}} = 362$ **MJ.**
- This is equivalent to 120 elephants charging 120 elephants at full attack speed.

- Each individual proton-proton collision has an energy of 14 TeV: equivalent to two mosquitos flying into each other, **but in a very small area!**
- At the end of the 10-15 hour collision period, the beams are dumped into a dedicated beam dump: water-cooled graphite and steel surrounded by lots of concrete.



LHC Luminosity

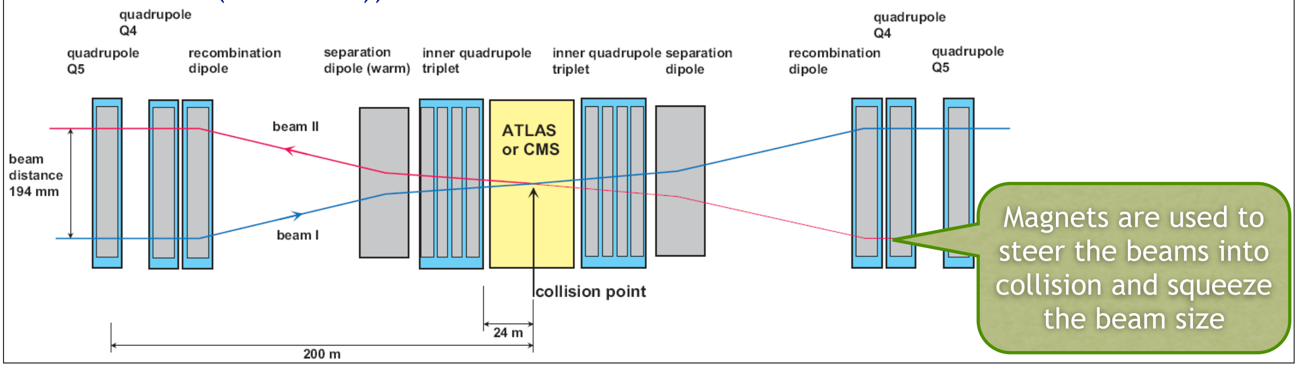
$$N(\text{interactions}) = \sigma \int \mathcal{L}\, \mathrm{dt}$$

- For a given process (eg creating a Higgs boson), $\boldsymbol{\sigma}$ is fixed for a given $\boldsymbol{E_{CM}}$.
- To maximise number of events: maximise instantaneous luminosity, $\mathcal{L}$, and run for as long as possible.

$$\mathcal{L} = \frac{N_p^2\, n_\mathrm{b}\, f_\mathrm{rev}}{A}$$

f = Revolution frequency
A = Effective area of collision
n_b = Number of bunches
N_p = Number of protons per bunch

- At the collision point bunches are squeezed to 16 μm across to maximise luminosity.
- Design $\mathcal{L}$ for LHC is $\mathbf{10^{34}\ cm^{-2}\ s^{-1}}$: $O(\mathbf{100\ fb^{-1}})$ per year (100 times more intense than Tevatron (next best))



Summary

- We accelerate particles to obtain more $\boldsymbol{E_{CM}}$ in order to produce new, as yet, undiscovered particles.

- Long-lived charged particles may be accelerated in a magnetic field.
- An accelerator complex uses a system of **Linacs** and **Synchrotrons** to accelerate particles to the desired energy.
- Synchrotrons can also be used to store energetic particles.
- Synchrotron radiation: energy loss due to photon emission
  - ➡ energy need to be added back to beam at a collider
  - ➡ can be exploited produce high frequency gamma rays

- The LHC is a proton - proton synchrotron accelerator.
- Can also be used for accelerating Pb ions.
- Superconducting magnets operating at cryogenic temperatures are used to accelerate the protons to 7 TeV.
- LHC is used to store the protons beams, and bring them into collision at four points - where the four experiments are located.
- LHC is world’s highest energy accelerator and is designed to be the highest luminosity collider.