CHAPTER 8

Accelerators

Lecture Notes For

PHYS 415

Introduction to Nuclear and Particle Physics

To Accompany the Text

Introduction to Nuclear and Particle Physics, 2^{nd} Ed.

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World Scientific

Introduction

- Probing ever shorter distance scales requires higher and higher energy accelerators.
  - de Broglie: $$\lambda = \frac{h}{p}$$
  - Wavelength of probe is connected to spatial resolution.
- No accelerator can come close to energies seen in cosmic rays, but cosmic rays:
  - Have a broad spectrum of energies.
  - Have small luminosities.
  - Cannot be controlled.

Introduction, cont'd.

- Accelerators are used in a variety of ways:
  - Medicine and biology
  - Geophysics
  - Condensed matter physics
  - Food and sewage treatment
  - Nuclear and particle physics, …
- Accelerator advances have resulted in:
  - Enormous gains in energy
  - Very low *emittance* beams: higher intensities and better definition of kinematics
  - High beam currents
  - Colliding beams (higher center-of-mass energies)
  - Polarized beams
  - Variety of particles accelerated for applications/research

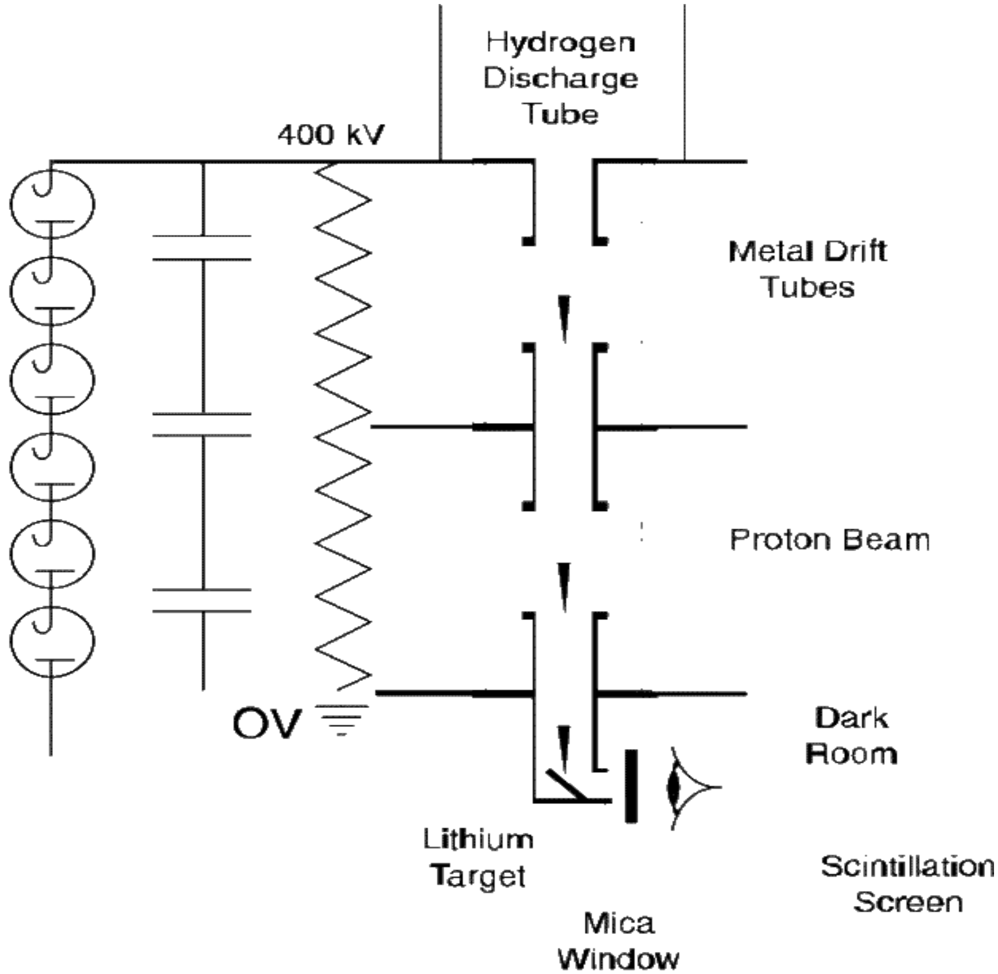
Cockcroft-Walton Accelerators

- Electrons are added to or removed from atoms to produce ions.
- Ions are injected between sets of electrodes maintained at successively higher voltages:

$$T = qV$$

- Limited to ~1 MeV. Beyond ~1MV potential, electrical breakdown occurs.
- Often used as first stage acceleration in higher energy machines.

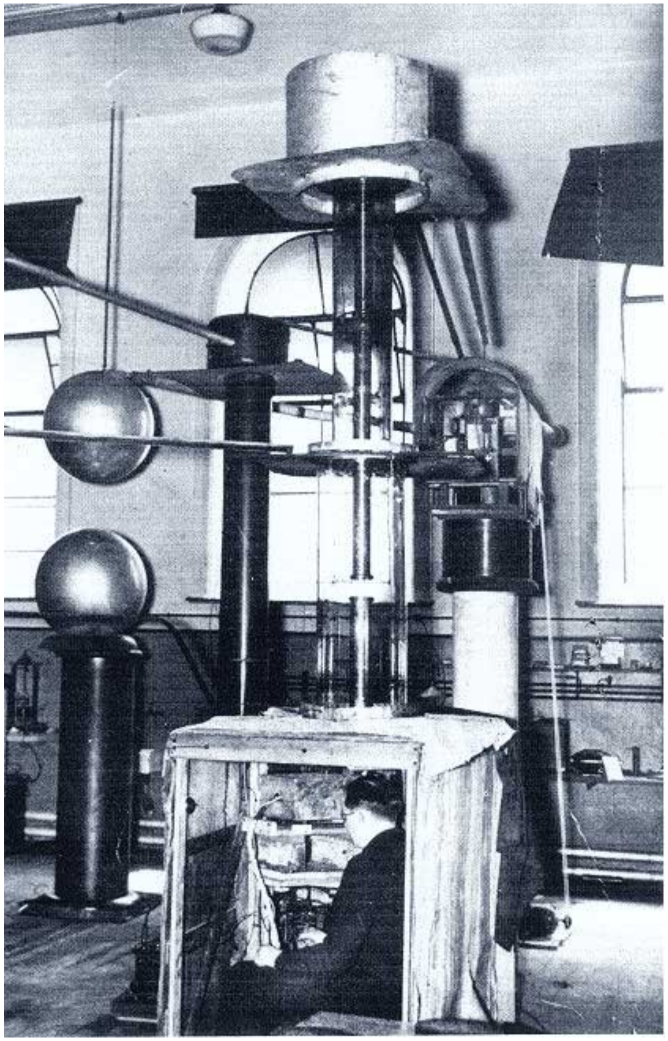
Schematic of Cockcroft-Walton Accelerator



From http://www.hep.fsu.edu/~wahl/Quarknet/summer2002/talks/accelerators.ppt

Cockcroft-Walton Accelerator

From http://www.aip.org/history/lawrence/images/epa-13.jpg



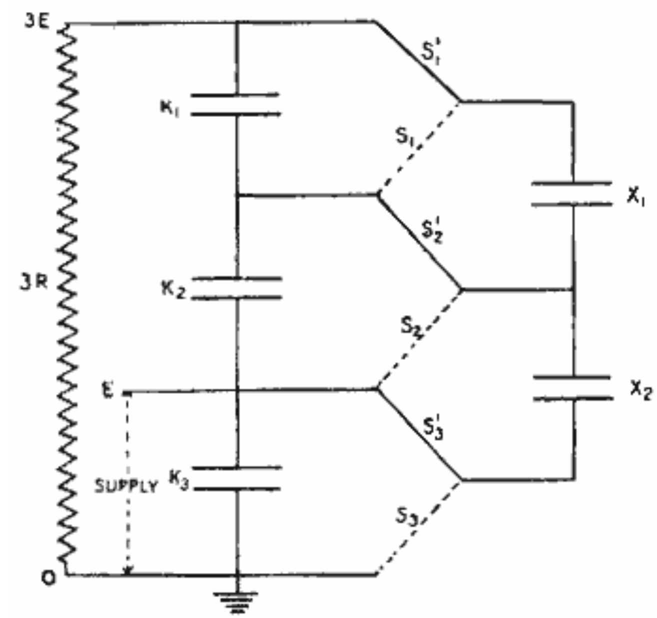
Cockcroft-Walton accelerator installation
at the Cavendish Laboratory

Used hydrogen ions (i.e. protons) to break up Lithium nuclei:

$$^{7}\mathrm{Li} + p \rightarrow \alpha + \alpha$$

Cockcroft-Walton Voltage Multiplier

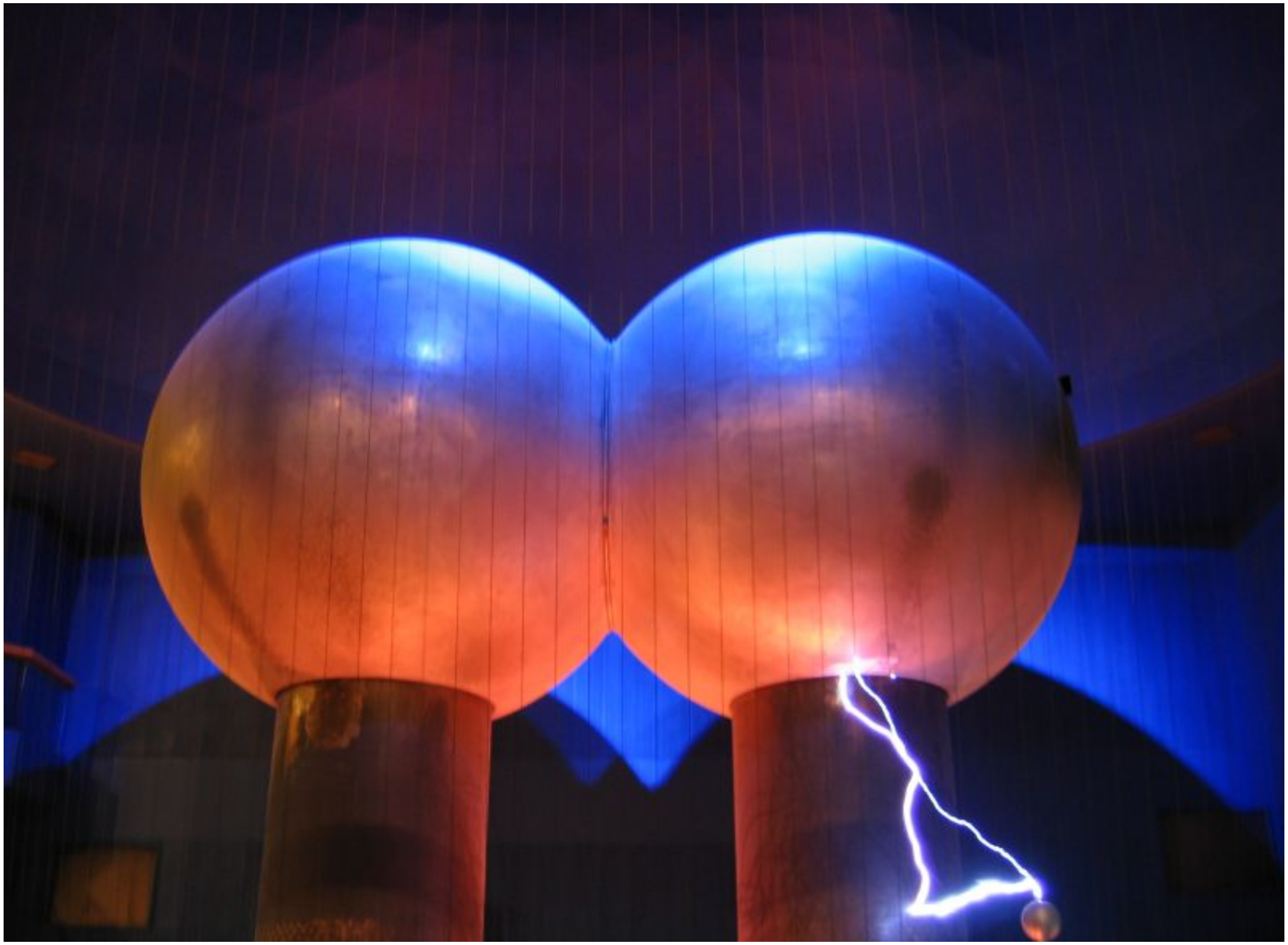
From http://img.tfd.com/wiki/1/12/Particle_accelerators_1937.jpg
National Science Museum, London



Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.

From http://www.aip.org/history/lawrence/images/epa-14a.gif

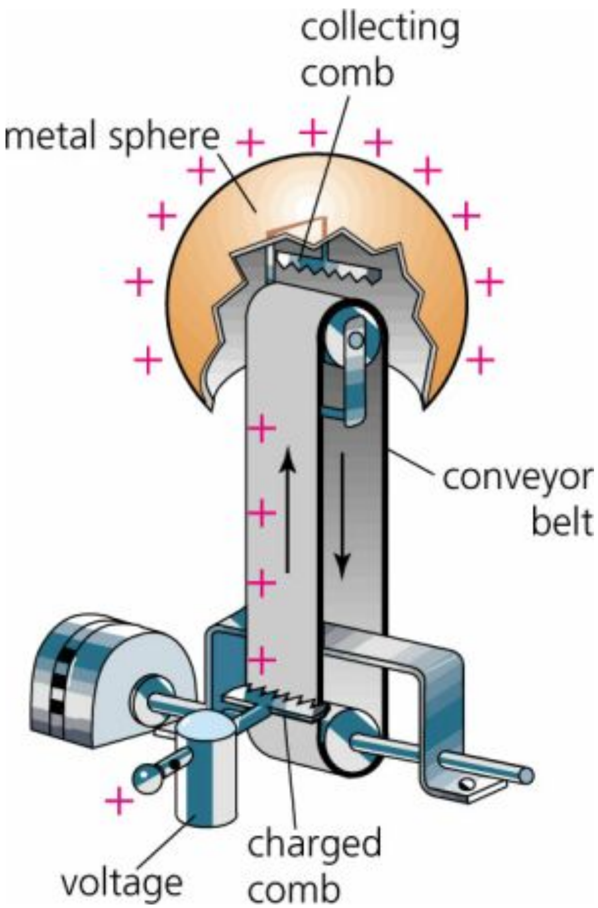
Van de Graaff Accelerator

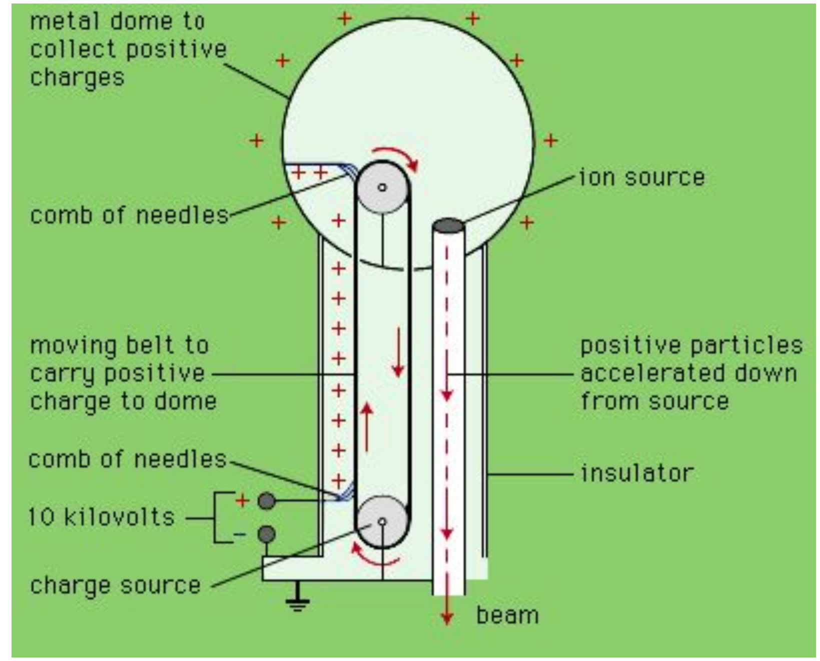


From http://upload.wikimedia.org/wikipedia/en/5/53/BosMusOSci_VanDGLightening.jpg

Operating Principle

From http://chem.ch.huji.ac.il/~eugeniik/history/graaff_generator_scheme1.jpg





http://chem.ch.huji.ac.il/~eugeniik/history/graaff_scheme12.jpg

HV ionizes gas and ions are transported by conveyor belt to dome.

Charge resides on conductor’s surface.

Motor provides work needed to transfer more charge to surface of dome.

Highest potentials (~12 MV) are limited by breakdown of pressurized gas which fills chamber.

Tandem Van de Graaff

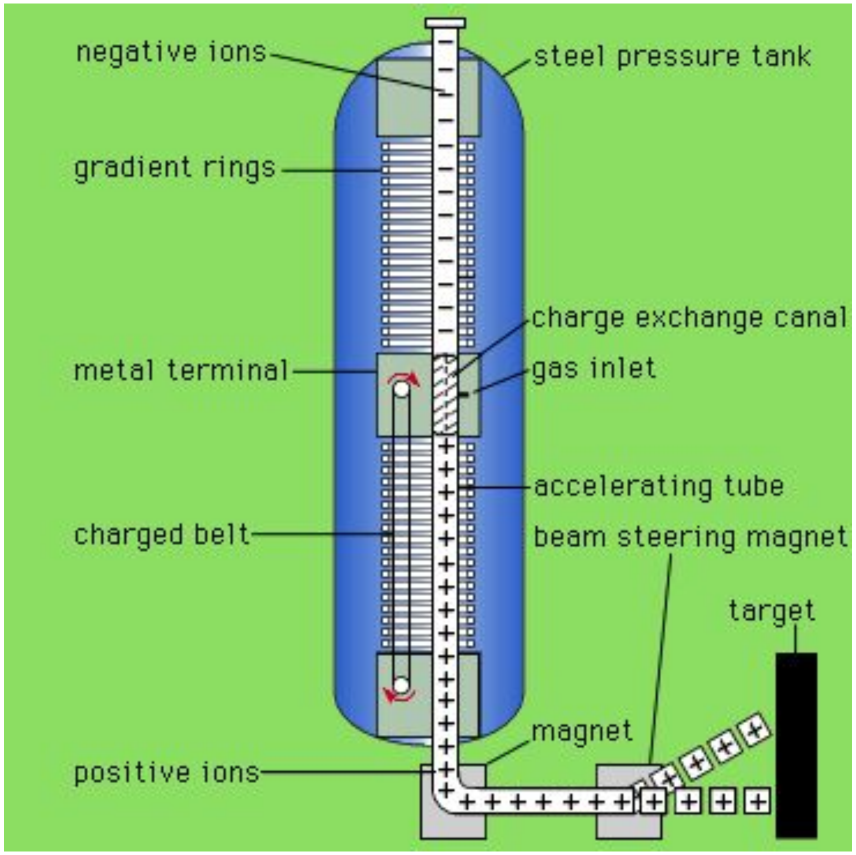
Protons are pre-accelerated.

Protons acquire two electrons within gas becoming negative hydrogen ions.

The negative ions are accelerated to the positive terminal.

They are then stripped of electrons, producing protons.

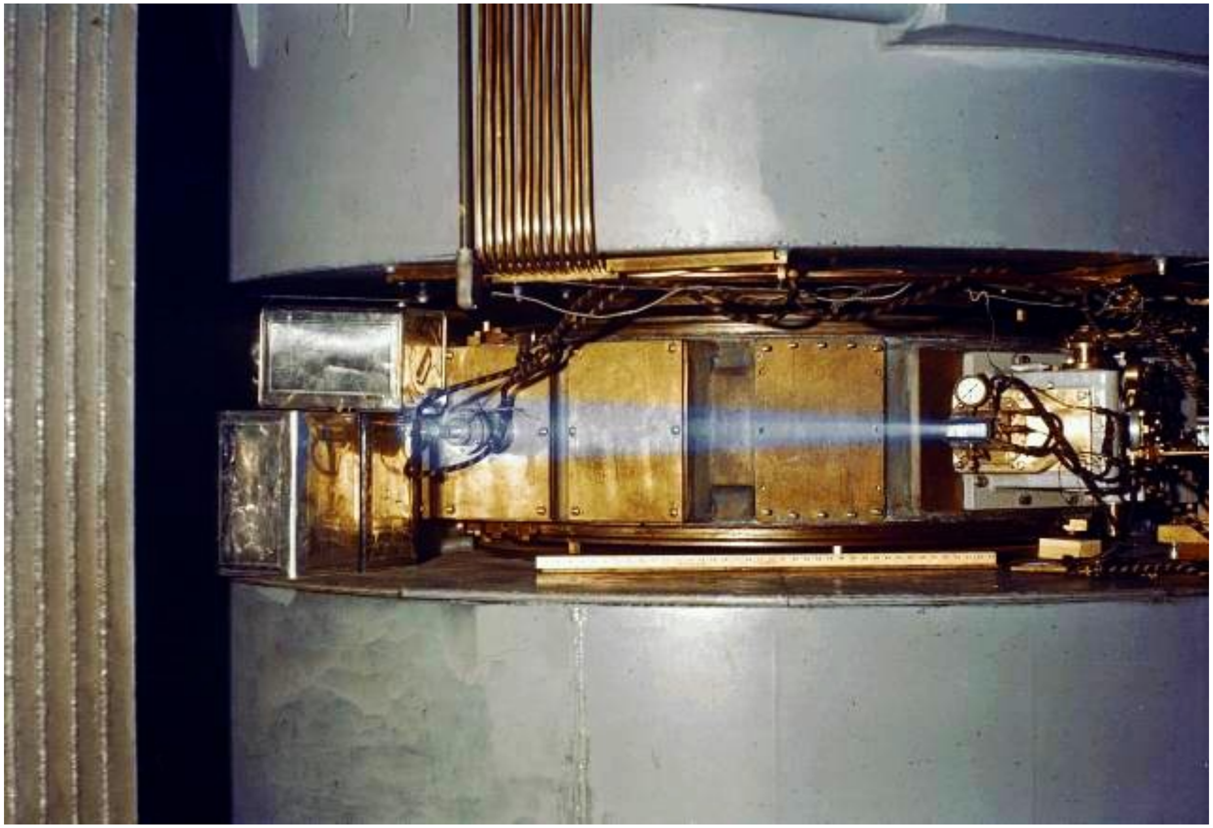
Protons are repelled by the same terminal, effectively doubling the energy (~25 MeV)



http://chem.ch.huji.ac.il/~eugeniik/history/graaff_scheme11.jpg

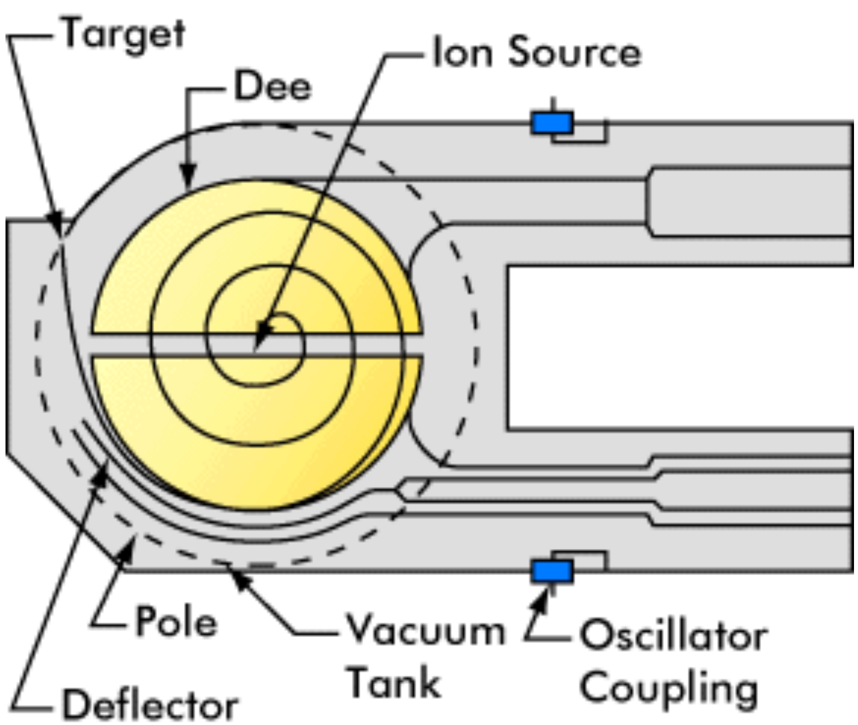
Cyclotrons

60-inch cyclotron, circa 1939, showing beam of accelerated ions (perhaps protons or deuterons) escaping the accelerator and ionizing the surrounding air causing a blue glow.



From http://upload.wikimedia.org/wikipedia/en/b/ba/Cyclotron_with_glowing_beam.jpg

Cyclotrons



From http://www2.slac.stanford.edu/vvc/art/images/cyclotron.gif

Alternating voltage is applied to “Ds”.

Electric field in gap between Ds accelerates particles.

Magnetic field (perpendicular to plane of figure) causes spiral orbit.

Particle is extracted and strikes a target.

Cyclotron Frequency

- Magnetic force provides centripetal acceleration. Non-relativistically:

$$ma = m\frac{v^2}{r} = \frac{qvB}{c} \quad \text{(cgs units!)} \;\Rightarrow \frac{v}{r} = \omega = \frac{qB}{mc}$$

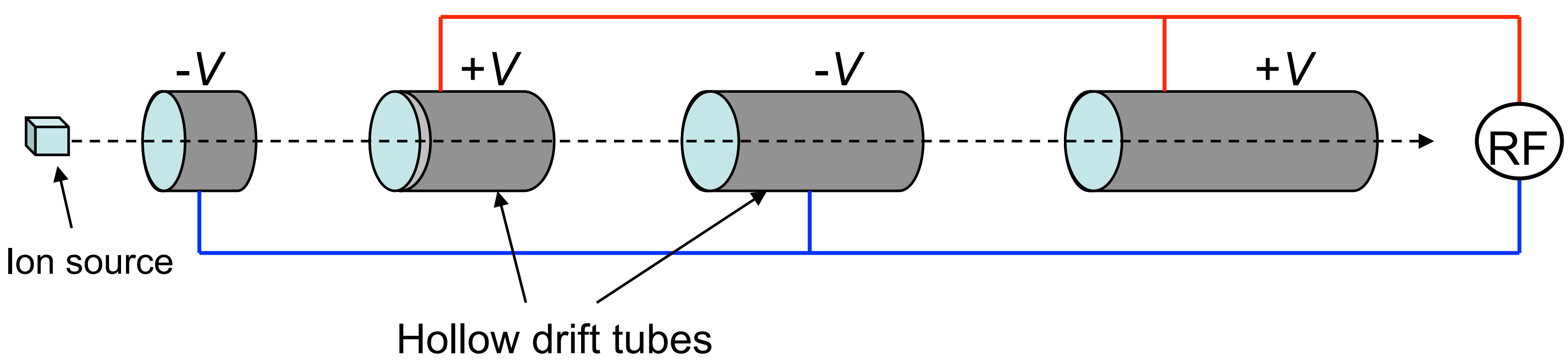
- Cyclotron frequency: $\nu = \frac{\omega}{2\pi} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{B}{c}$
- Energy at extraction radius, *R*:

$$T_{\text{max}} = \frac{1}{2}mv_{\text{max}}^2 = \frac{1}{2}m\omega^2R^2 = \frac{1}{2}\frac{(qBR)^2}{mc^2}$$

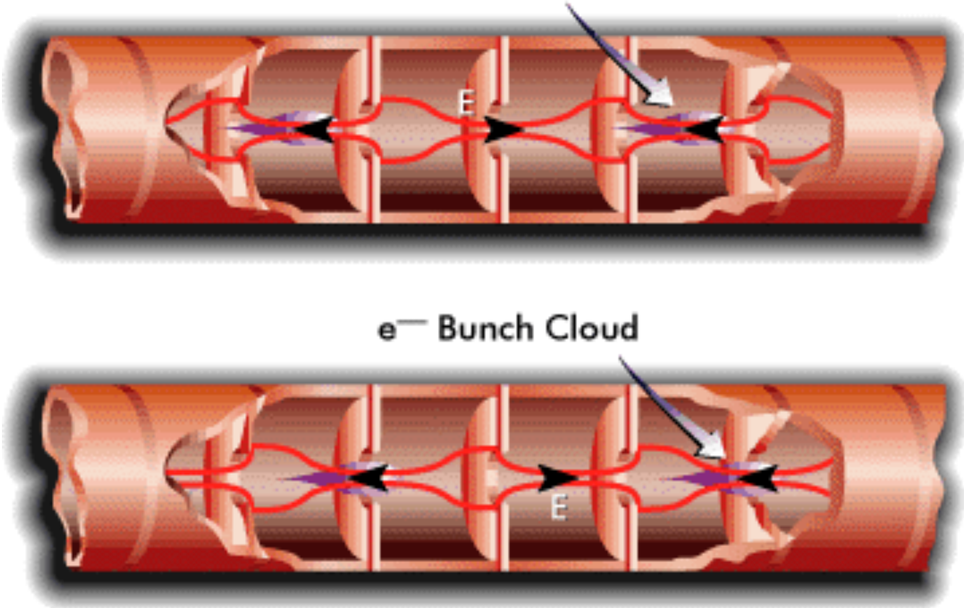
- For protons, T_{max}~20 MeV. For relativistic energies, above relations are not valid and design must be modified: *synchrotron*.

Linear Accelerators (Linacs)

- Electric fields accelerate charged particles.
- The fields must be in phase with the particle's motion, so that the particle continually accelerates. The polarity of fields must periodically reverse. For non-relativistic particles, drift tubes increase in length as particle speed increases.
- Electrons use microwave fields for acceleration which supply energy lost by *synchrotron radiation*.
- Largest Linac: Stanford Linear Accelerator (SLAC) - 50 GeV



Accelerating Cavities



1/20,000,000,000 second later
(notice how far the bunches have moved)

The bunches of electrons are shown in purple.

The red lines indicate the resulting electric fields in the cavities.

The arrows on the red lines show the direction of the electric fields.

From http://www2.slac.stanford.edu/vvc/art/images/ecloud.gif

Synchrotrons

- For relativistic particles in a magnetic field:

$$\frac{d\vec{p}}{dt} = \frac{d}{dt}\left(\gamma m\vec{v}\right) = \frac{q}{c}\vec{v} \times \vec{B}$$

- Since the particle's speed remains fixed:

$$\rightarrow \gamma m\frac{d\vec{v}}{dt} = \gamma m\frac{d}{dt}\left(\vec{\omega} \times \vec{r}\right) = \gamma m\vec{\omega} \times \frac{d\vec{r}}{dt} = \gamma m\vec{\omega} \times \vec{v} \Rightarrow \omega = \frac{qB}{\gamma mc}$$

$$\Rightarrow \nu = \frac{\omega}{2\pi} = \frac{1}{2\pi}\left(\frac{qB}{mc}\right)\sqrt{1 - \frac{v^2}{c^2}}$$

Synchrocyclotrons and Synchrotrons

$$\nu = \frac{1}{2\pi}\left(\frac{qB}{mc}\right)\sqrt{1-\frac{v^2}{c^2}}$$

- As $v \to c$, either ν decreases or B increases, or both.
  - B constant, ν decreases: **synchrocyclotron**
  - B varied, regardless of ν: **synchrotron**
    - Electron synchrotron: B varied such that ν is constant.
    - Proton synchrotron: B and ν are both varied.

Synchrotron Orbit vs. Momentum

- For a final orbit radius of *R*:

$$p = \gamma m v = \gamma m(\omega R) = \gamma m\left(\frac{qB}{\gamma mc}\right)R = \frac{qBR}{c} \Rightarrow R = \frac{pc}{qB}$$

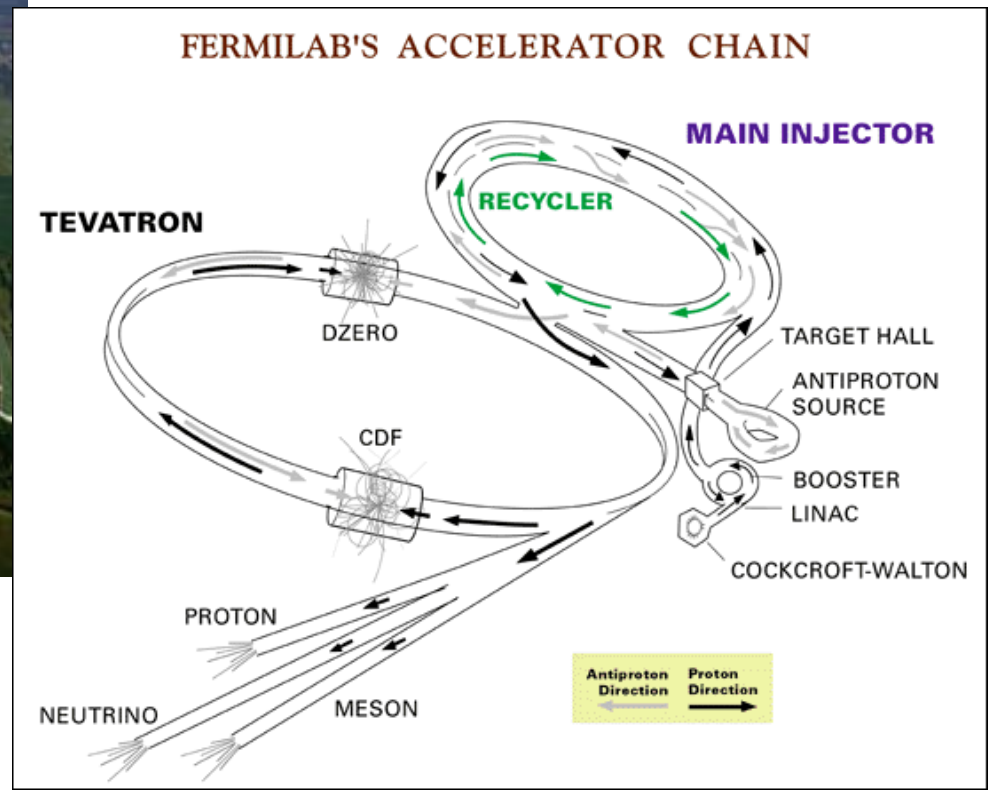
- For a particle of charge *e*:

$$R\ [\mathrm{m}] \approx \frac{p\ [\mathrm{GeV/c}]}{0.3B\ [\mathrm{T}]}$$

- For 30 GeV energy and 2 T magnetic field: $R \approx 50$ m
  - For a cyclotron style synchrocyclotron, this implies a very large magnet and a prohibitive cost.
  - For high energies, synchrotrons are the preferred method.
  - Also, for light particles such as electrons, **synchrotron radiation** causes substantial energy loss: electron synchrotrons are generally of larger radius.

Fermilab

http://www.fnal.gov/pub/inquiring/physics/accelerators/99-912-12.jpg

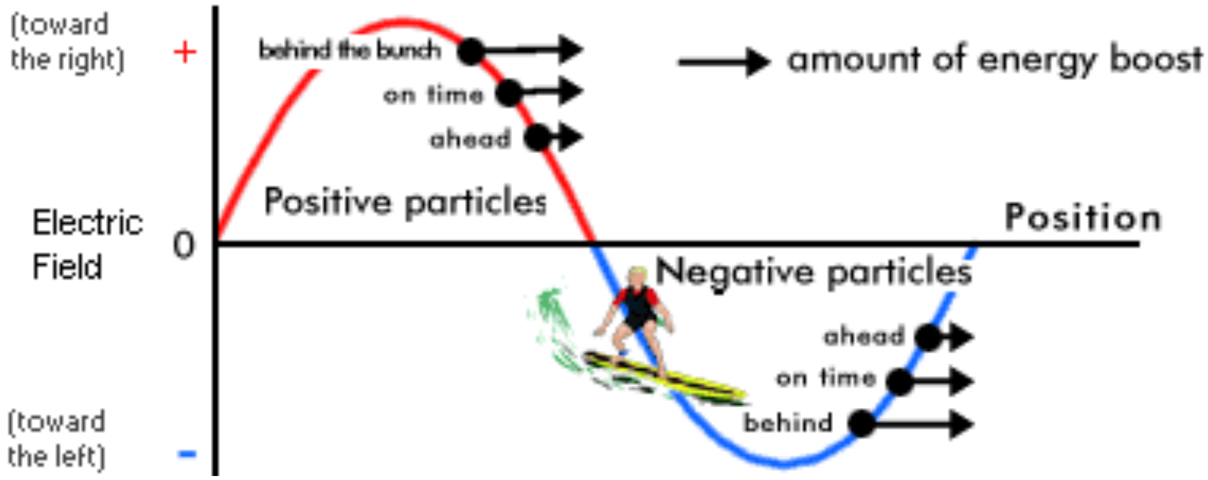


http://www.fnal.gov/pub/about/whatis/picturebook/images/00_635.gif

B field increases as particles accelerate
$\Rightarrow$ orbit radius remains fixed

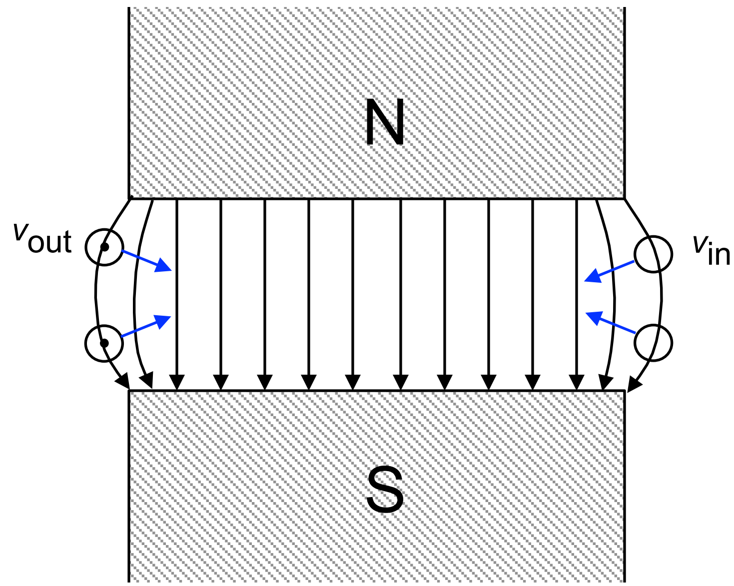
Phase Stability

- Particles tend to **bunch** in time and those with extreme deviations are essentially lost.
  - Particles earlier than nominal receive less force.
  - Particles later than nominal receive more force.



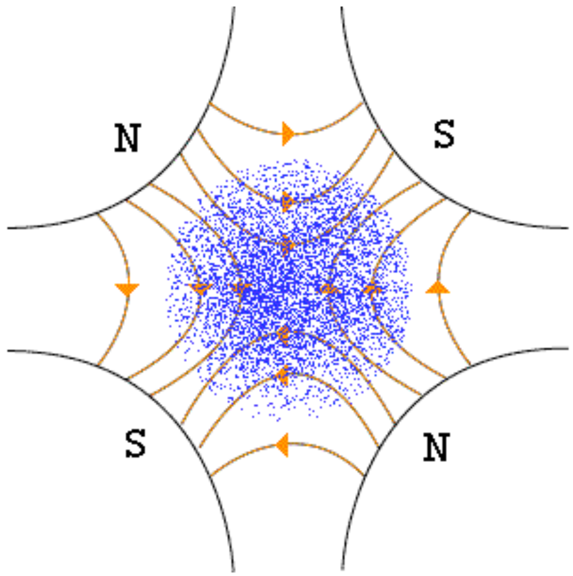
From http://www2.slac.stanford.edu/vvc/art/lg-surfer.gif

Vertical Stability and Betatron Oscillations

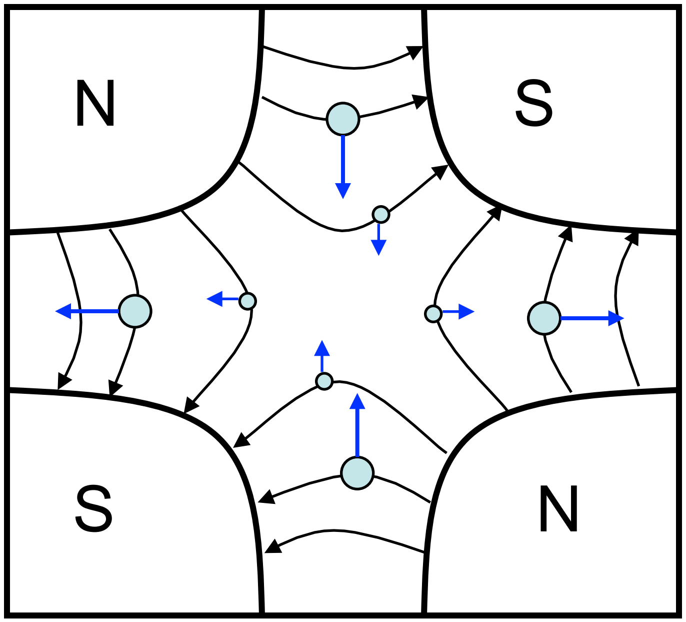


- Slow or fast particles will tend to have orbits near magnet edges.
- Fringing fields of bending magnets produce forces which tend to restore particles to the nominal (horizontal) orbit plane.
- Particles execute motion about this nominal plane: **betatron oscillations.**

Strong Focusing (Quadrupole Magnets)



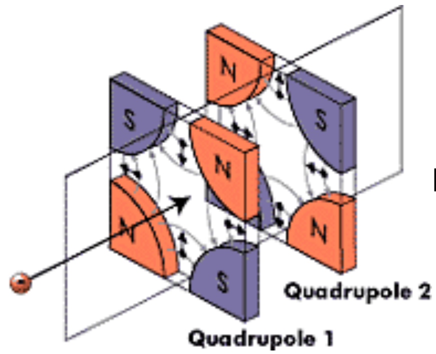
http://www-bd.fnal.gov/public/images/agfocus.gif



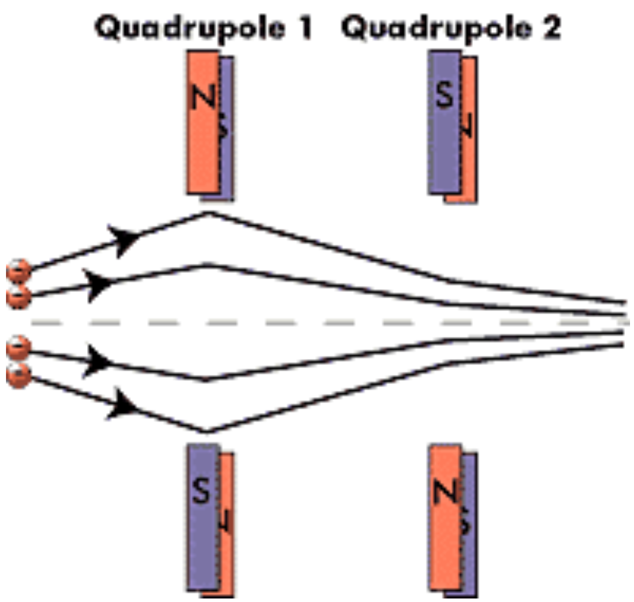
Forces shown on positively charged particle

Alternating Gradient Focusing

A pair of quadrupole magnets can producing focusing in both transverse dimensions.



http://www2.slac.stanford.edu/vvc/art/magnet1b.gif



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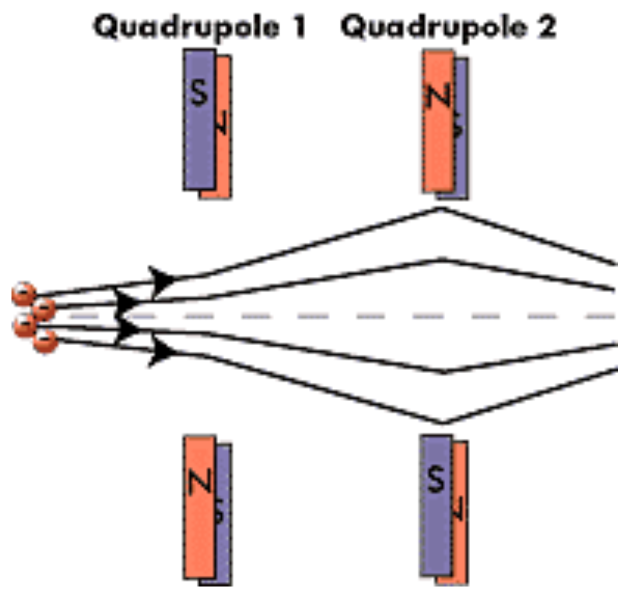


http://www2.slac.stanford.edu/vvc/art/magnet3.gif

Accelerator Optics

- In addition to the main bending (dipole) magnets, many accelerators employ a large number of other “correcting” magnets: quadrupoles, sextupoles, octupoles, etc.
- These magnetic elements are designed to keep the beam profile within design specifications, so that the beam does not impact the vacuum enclosure.
- Also, the beam is usually desired to have a small profile (emittance), in order to maximize the luminosity for colliding beams.

Colliding Beams

- Consider a particle of total energy *E*, striking an equal mass particle at rest. The energy available for creating new particles is:

$$E_{CM}^{TOT} = \sqrt{s} = \sqrt{\left(E + mc^2\right)^2 - \left(E^2 - \left(mc^2\right)^2\right)} = \sqrt{2\left(mc^2\right)^2 + 2mc^2 E}$$

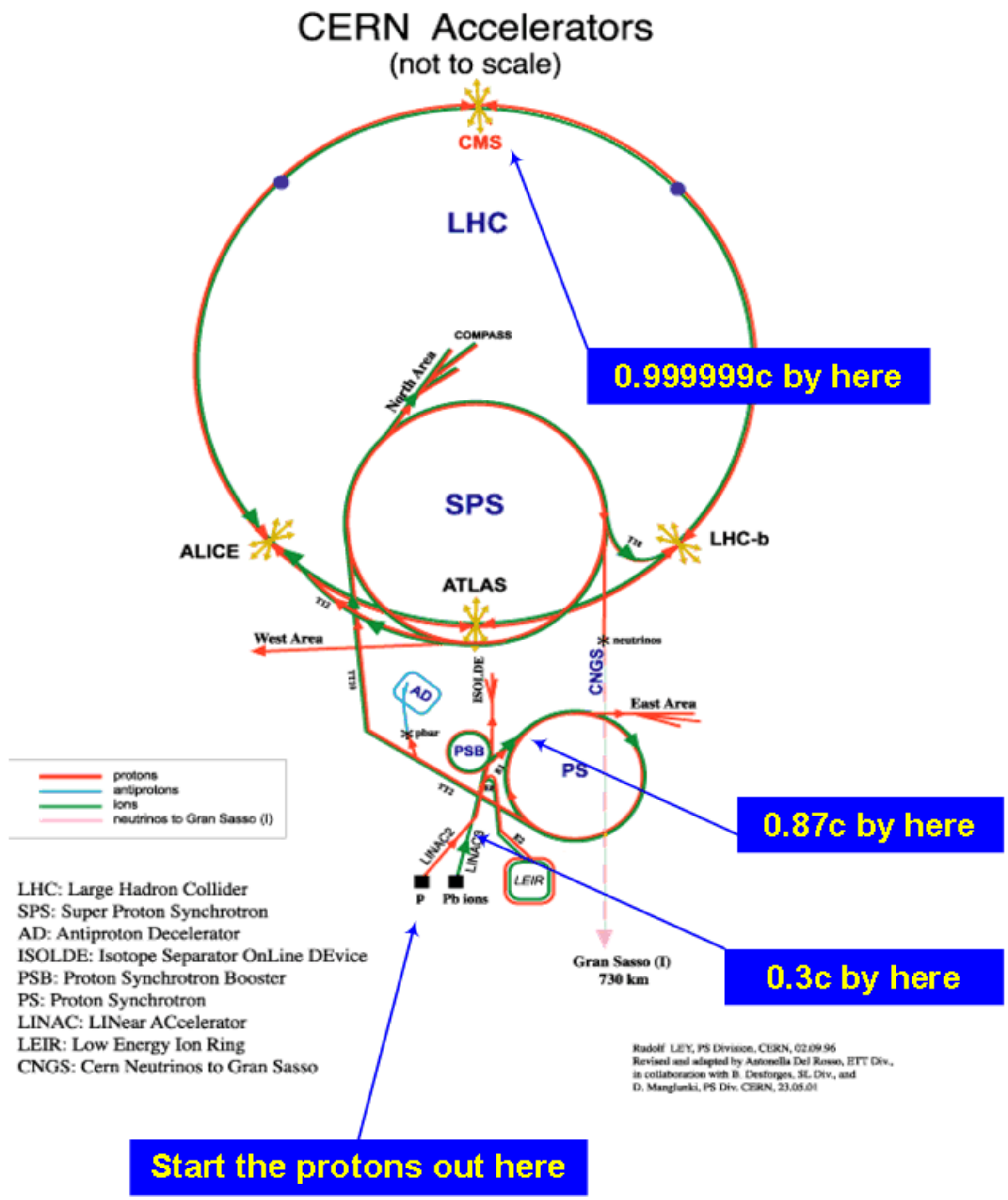
$$\xrightarrow{\text{high energy}} \sqrt{2mc^2 E}$$

- Contrast this with the case of a head-on collision of two equal mass particles, each with energy *E*:

$$E_{CM}^{TOT} = \sqrt{s} = 2E$$

- The available energy for the fixed target case goes as $\sqrt{E}$, whereas the colliding beam case goes as *E*.

CERN LHC



http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/images/complex/Cern-complex.gif