Particle physics experiments

- Particle physics experiments:
  - collide particles to
    - produce new particles
    - reveal their internal structure and laws of their interactions by observing regularities, measuring cross sections,...
  - colliding particles need to have high energy
    - to make objects of large mass
    - to resolve structure at small distances
  - to study structure of small objects:
    - need probe with short wavelength: use particles with high momentum to get short wavelength
    - remember de Broglie wavelength of a particle $\lambda = h/p$
  - in particle physics, mass-energy equivalence plays an important role; in collisions, kinetic energy converted into mass energy;
    - relation between kinetic energy K, total energy E and momentum p :

$$E = K + mc^2 = \sqrt{(pc)^2 + (mc^2)c^2}$$

About Units

- Energy - electron-volt
  - 1 electron-volt = kinetic energy of an electron when moving through potential difference of 1 Volt;
    - 1 eV = 1.6×10^{-19} Joules = 2.1×10^{-6} W•s
    - 1 kW•hr = 3.6×10^{6} Joules = 2.25×10^{25} eV

- mass - eV/c^2
    - 1 $eV/c^2 = 1.78 \times 10^{-36}$ kg
    - electron mass = 0.511 MeV/c^2
    - proton mass = 938 MeV/c^2
    - professor's mass (80 kg) $\approx 4.5 \times 10^{37}$ eV/c^2

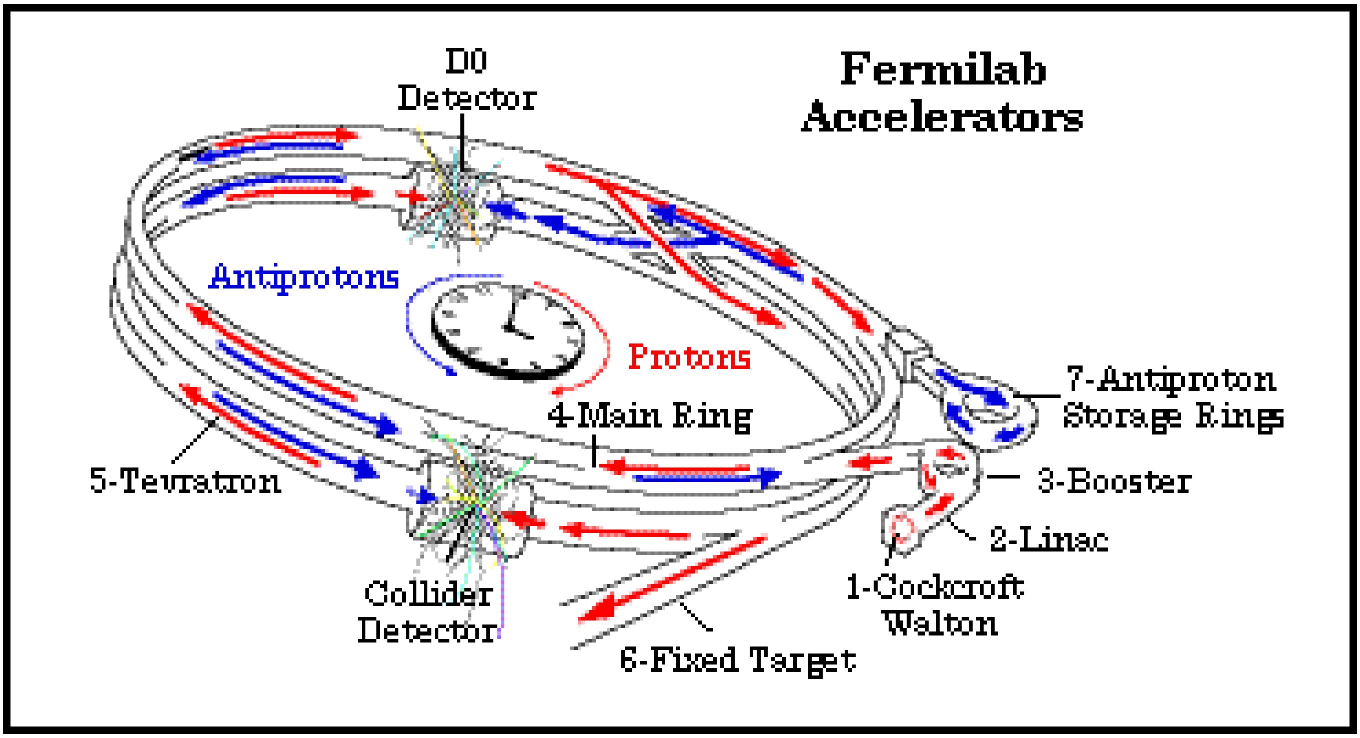
- momentum - eV/c:
    - 1 eV/c = 5.3×10^{-28} kg m/s
    - momentum of baseball at 80 mi/hr $\approx$ 5.29 kgm/s $\approx 9.9 \times 10^{27}$ eV/c

How to do a particle physics experiment

- Outline of experiment:
  - get particles (e.g. protons, antiprotons,….)
  - accelerate them
  - throw them against each other
  - observe and record what happens
  - analyse and interpret the data
- ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger (decide what to record)
  - recording device
  - many people to:
    - design, build, test, operate accelerator
    - design, build, test, calibrate, operate, and understand detector
    - analyse data
  - lots of money to pay for all of this

Accelerator

- accelerators:
  - use electric fields to accelerate particles, magnetic fields to steer and focus the beams
  - synchrotron:
    particle beams kept in circular orbit by magnetic field; at every turn, particles "kicked" by electric field in accelerating station;
  - fixed target operation: particle beam extracted from synchrotron, steered onto a target
  - collider operation:
    accelerate bunches of protons and antiprotons moving in opposite direction in same ring; make them collide at certain places where detectors are installed



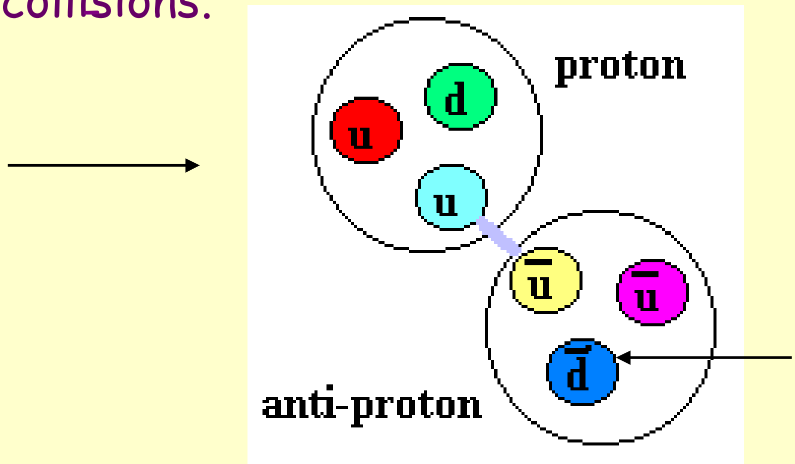
How to get high energy collisions

- Need E_{com} to be large enough to
  - allow high momentum transfer (probe small distances)
  - produce heavy objects (top quarks, Higgs boson)
  - e.g. top quark production: $e^+e^- \to t\bar{t}$, $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$, …
- Shoot particle beam on a target (“fixed target”):
  - $E_{com} = 2\sqrt{Emc^2} \sim 20$ GeV for $E = 100$ GeV, $m = 1$ GeV/c^2

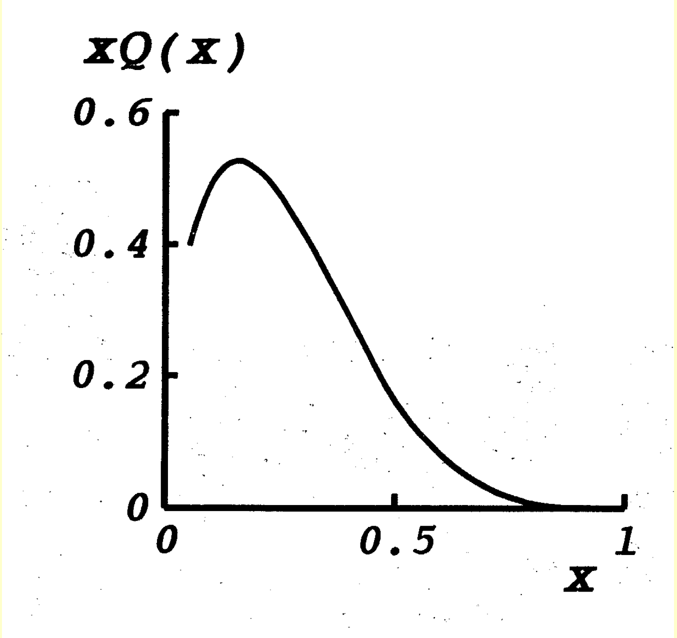
- Collide two particle beams (“collider :
  - $E_{com} = 2E \sim 200$ GeV for $E = 100$ GeV

How to make qq collisions, cont'd

- Quarks are not found free in nature!
- But (anti)quarks are elements of (anti)protons.
- So, if we collide protons and anti-protons we should get some $q\bar{q}$ collisions.



- Proton structure functions give the probability that a single quark (or gluon) carries a fraction x of the proton momentum (which is 900 GeV/c at the Tevatron)

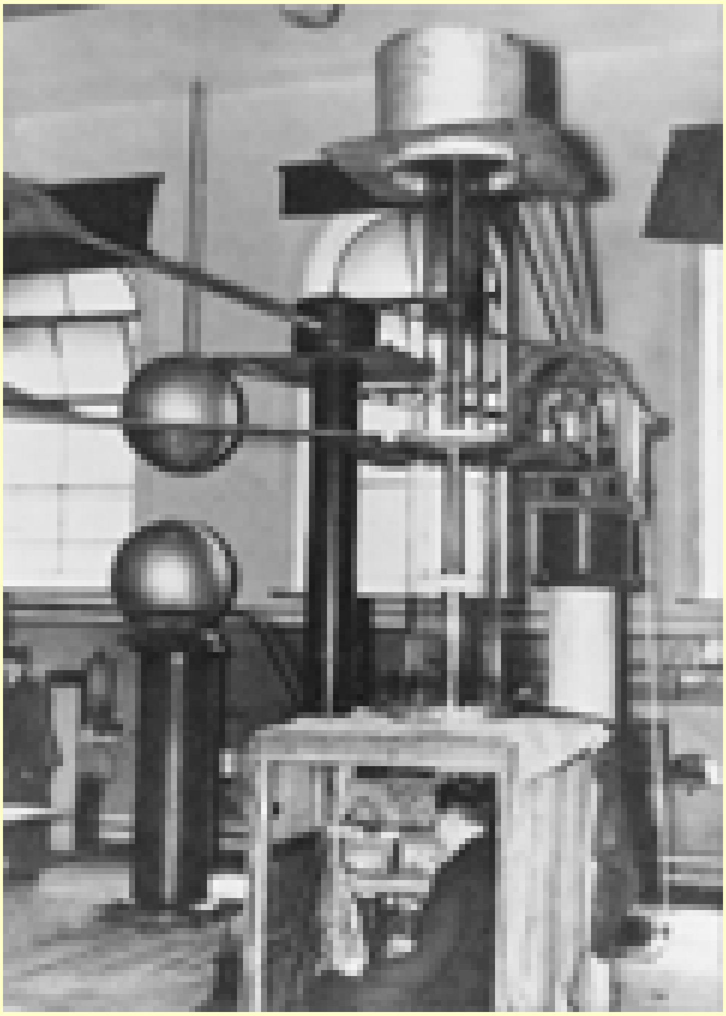


ACCELERATORS

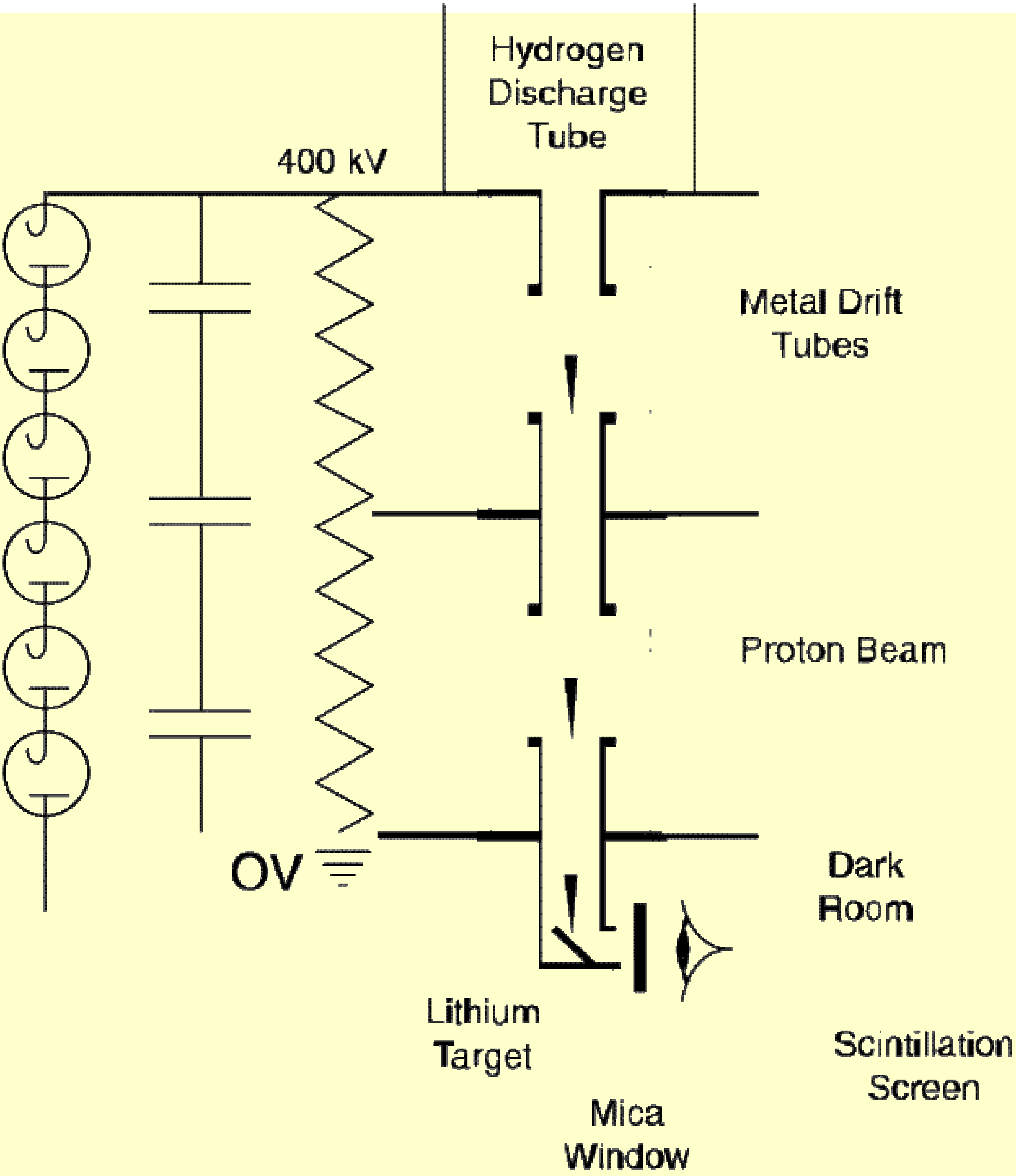
- are devices to increase the energy of charged particles;
  - use magnetic fields to shape (focus and bend) the trajectory of the particles;
  - use electric fields for acceleration.
- types of accelerators:
  - electrostatic (DC) accelerators
    - Cockcroft-Walton accelerator (protons up to 2 MeV)
    - Van de Graaff accelerator (protons up to 10 MeV)
    - Tandem Van de Graaff accelerator (protons up to 20 MeV)
  - resonance accelerators
    - cyclotron (protons up to 25 MeV)
    - linear accelerators
      - electron linac: 100 MeV to 50 GeV
      - proton linac: up to 70 MeV
  - synchronous accelerators
    - synchrocyclotron (protons up to 750 MeV)
    - proton synchrotron (protons up to 900 GeV)
    - electron synchrotron (electrons from 50 MeV to 90 GeV)
  - storage ring accelerators (colliders)

ACCELERATORS, cont'd

- electrostatic accelerators:
  - generate high voltage between two electrodes ⇒ charged particles move in electric field,
    energy gain = charge times voltage drop;
  - Cockcroft-Walton and Van de Graaff accelerators differ in method to achieve high voltage.



Cockcroft-Walton accelerator

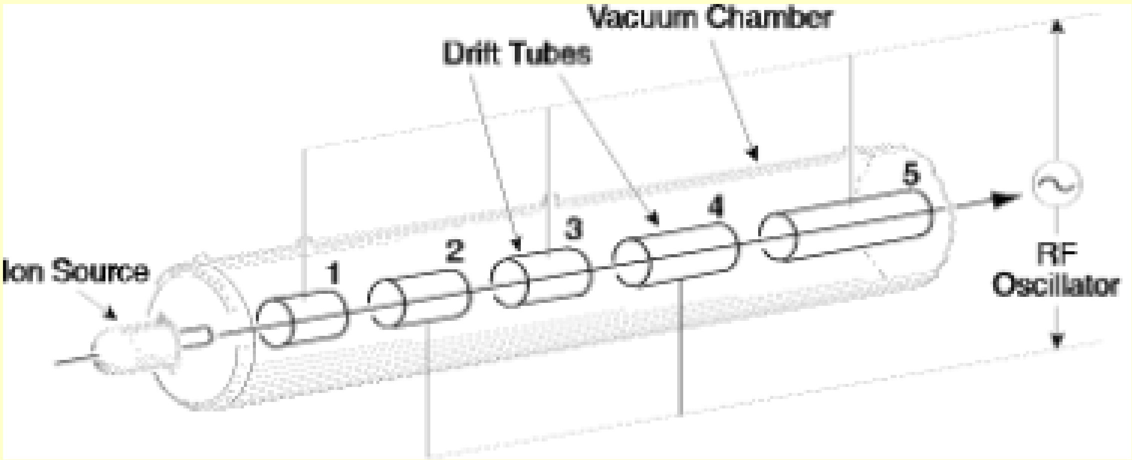


FNAL Cockcroft Walton acc.

- The Cockcroft-Walton pre-accelerator provides the first stage of acceleration;
  hydrogen gas is ionized to create negative ions, each consisting of two electrons and one proton. T
- ions are accelerated by a positive voltage and reach an energy of 750,000 electron volts (750 keV). (about 30 times the energy of
- the electron beam in a television's picture tube.)

Proton Linac

- proton linac (drift tube accelerator):
  - cylindrical metal tubes (drift tubes) along axis of large vacuum tank
  - successive drift tubes connected to opposite terminals of AC voltage source
  - no electric field inside drift tube ⇒ while in drift tube, protons move with constant velocity
  - AC frequency such that protons always find accelerating field when reaching gap between drift tubes
  - length of drift tubes increases to keep drift time constant
  - for very high velocities, drift tubes nearly of same length (nearly no velocity increase when approaching speed of light)



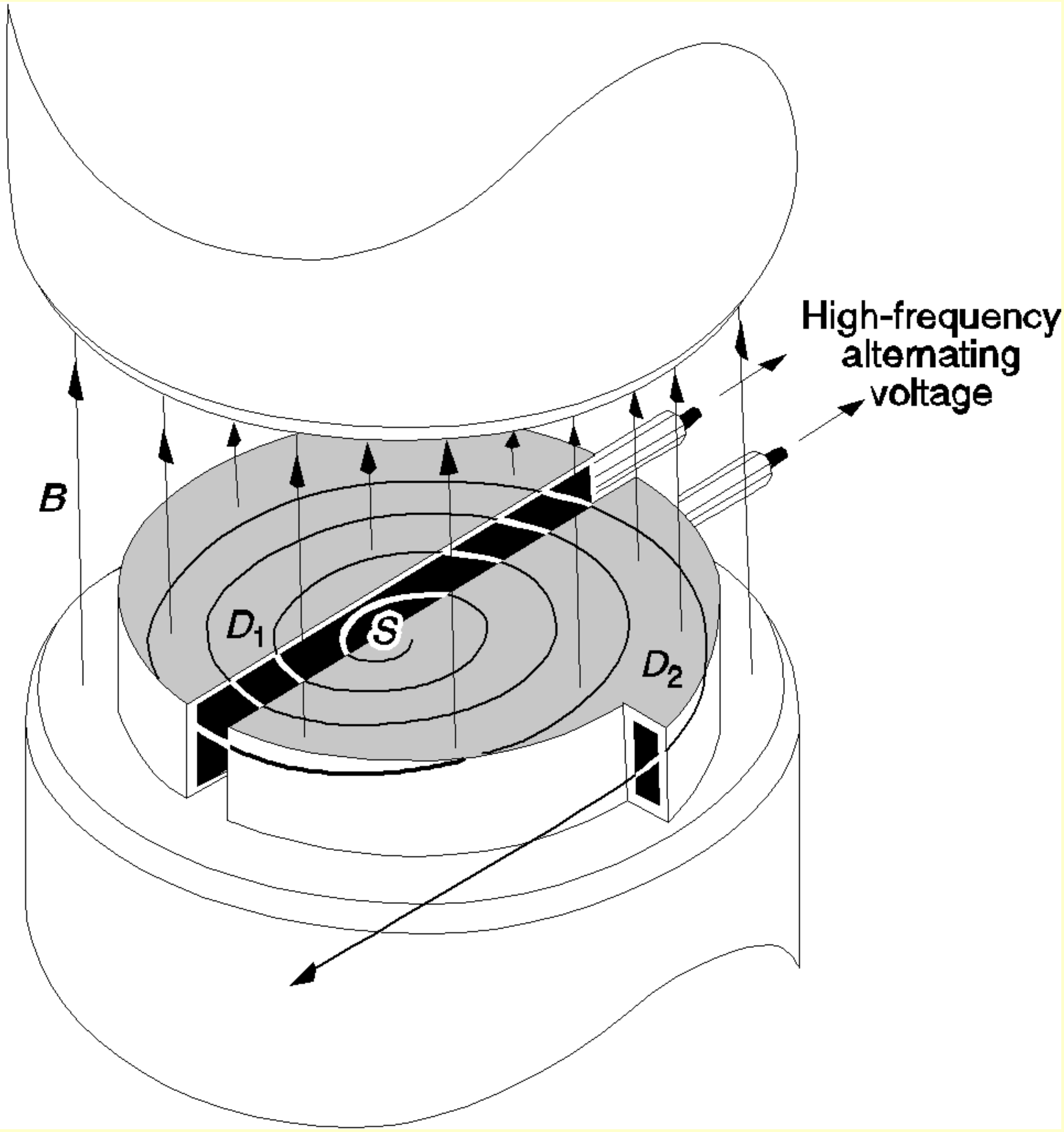
FNAL Linac

- Next, the negative hydrogen ions enter a linear accelerator, approximately 500 feet long.
- Oscillating electric fields accelerate the negative hydrogen ions to 400 million electron volts (400 MeV).
- Before entering the third stage, the ions pass through a carbon foil, which removes the electrons, leaving only the positively charged protons.

CYCLOTRON

- cyclotron
  - consists of two hollow metal chambers called ("dees" for their shape, with open sides which are parallel, slightly apart from each other ("gap")
  - dees connected to AC voltage source - always one dee positive when other negative ⇒ electric field in gap between dees, but no electric field inside the dees;
  - source of protons in center, everything in vacuum chamber;
  - whole apparatus in magnetic field perpendicular to plane of dees;
  - frequency of AC voltage such that particles always accelerated when reaching the gap between the dees;
  - in magnetic field, particles are deflected:
    $p = q \cdot B \cdot R$ p = momentum, q = charge,
    B = magnetic field strength,
    R = radius of curvature
  - radius of path increases as momentum of proton increases time for passage always the same as long as momentum proportional to velocity;
    this is not true when velocity becomes too big (relativistic effects)

Cyclotron



Accelerators: "relativistic effects"

- "relativistic effects"
  - special relativity tells us that certain approximations made in Newtonian mechanics break down at very high speeds;
  - relation between momentum and velocity in "old" (Newtonian) mechanics: $p = m v$ becomes $p = mv\gamma$, with

    $$\gamma = 1/\sqrt{1 - (v/c)^2}$$

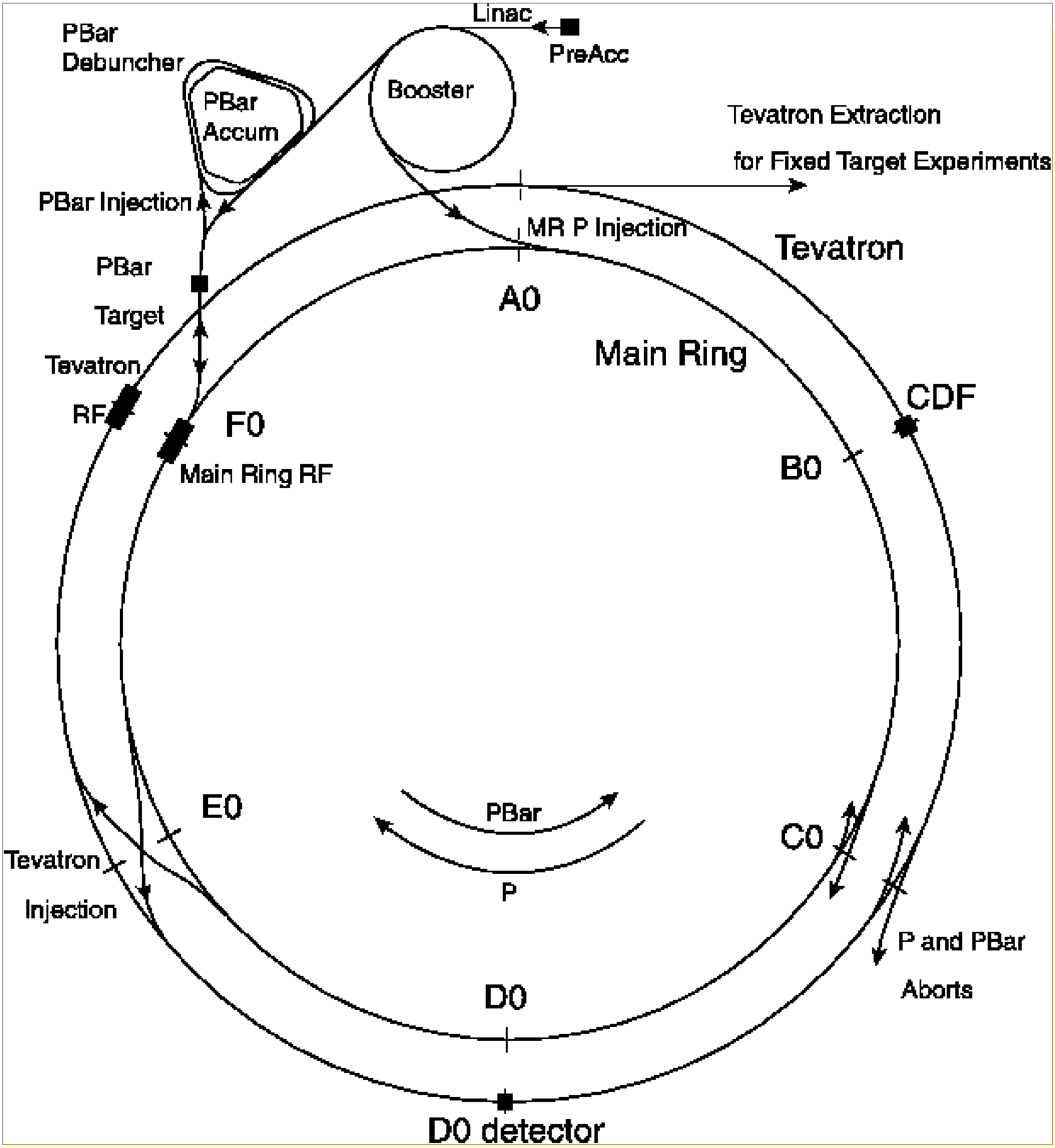
    m = "rest mass", i.e. mass is replaced by rest mass times γ

    - "relativistic growth of mass"
  - factor γ often called "Lorentz factor"; ubiquitous in relations from special relativity; energy: $E = mc^2\gamma$
  - acceleration in a cyclotron is possible as long as relativistic effects are negligibly small, i.e. only for small speeds, where momentum is still proportional to speed; at higher speeds, particles not in resonance with accelerating frequency; for acceleration, need to change magnetic field B or accelerating frequency f or both;

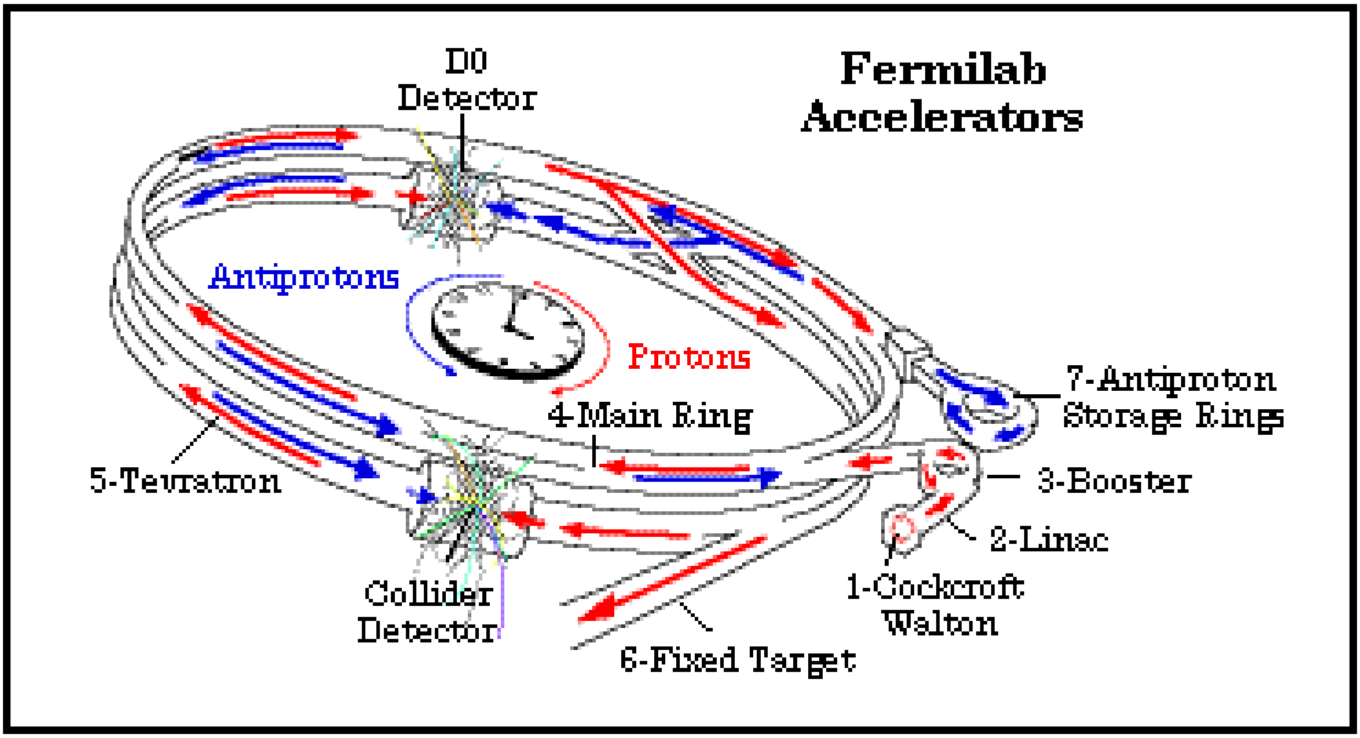
Accelerators, cont'd

- electron linac
  - electrons reach nearly speed of light at small energies (at 2 MeV, electrons have 98% of speed of light);
    no drift tubes; use travelling e.m. wave inside resonant cavities for acceleration.
- synchrocyclotron:
  - B kept constant, f decreases;
- synchrotron :
  - B increases during acceleration,
    f fixed (electron synchrotron)
    or varied (proton synchrotron);
    radius of orbit fixed.

Fermilab accelerator complex

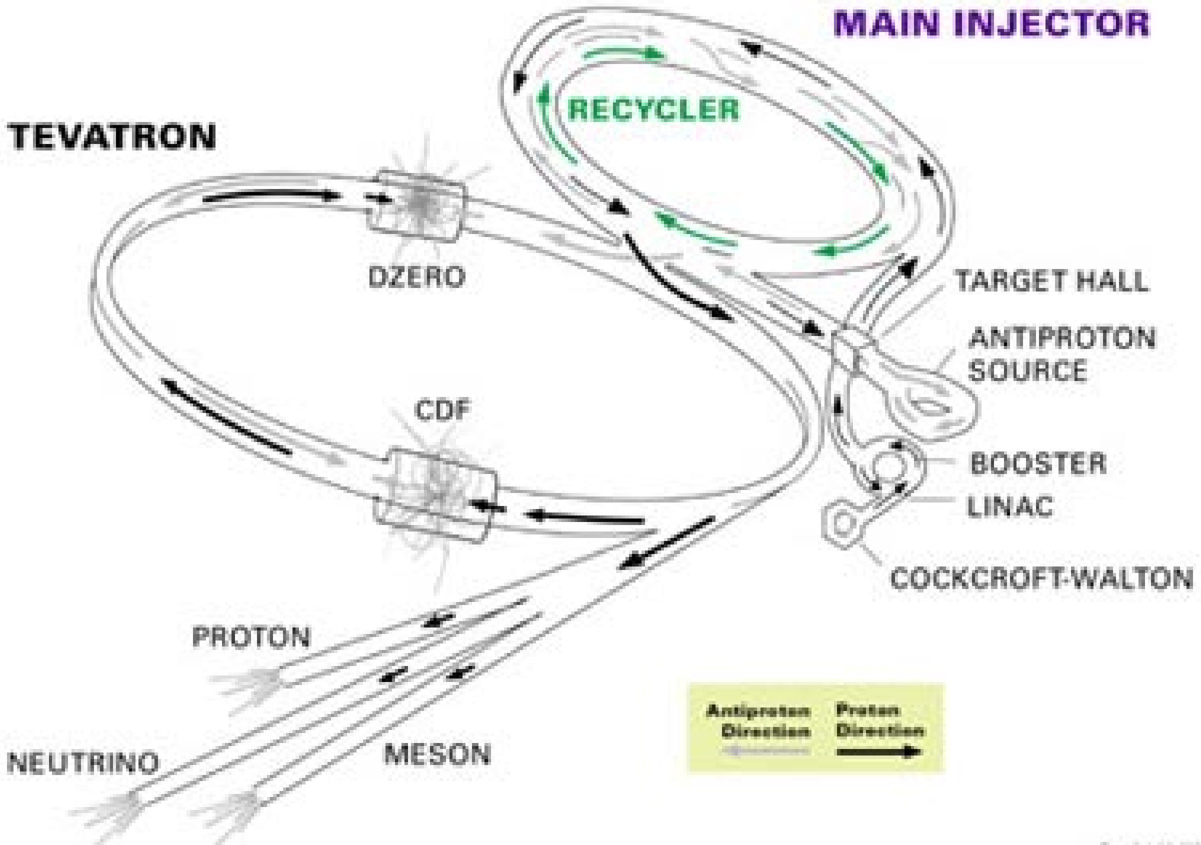


Fermilab Tevatron

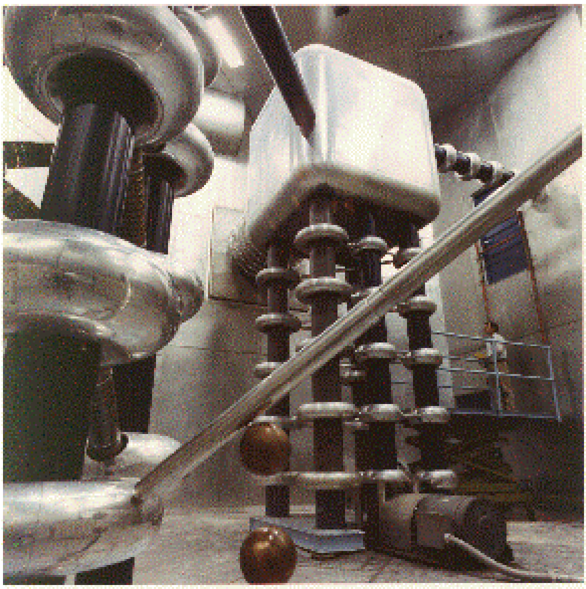


Fermilab aerial view

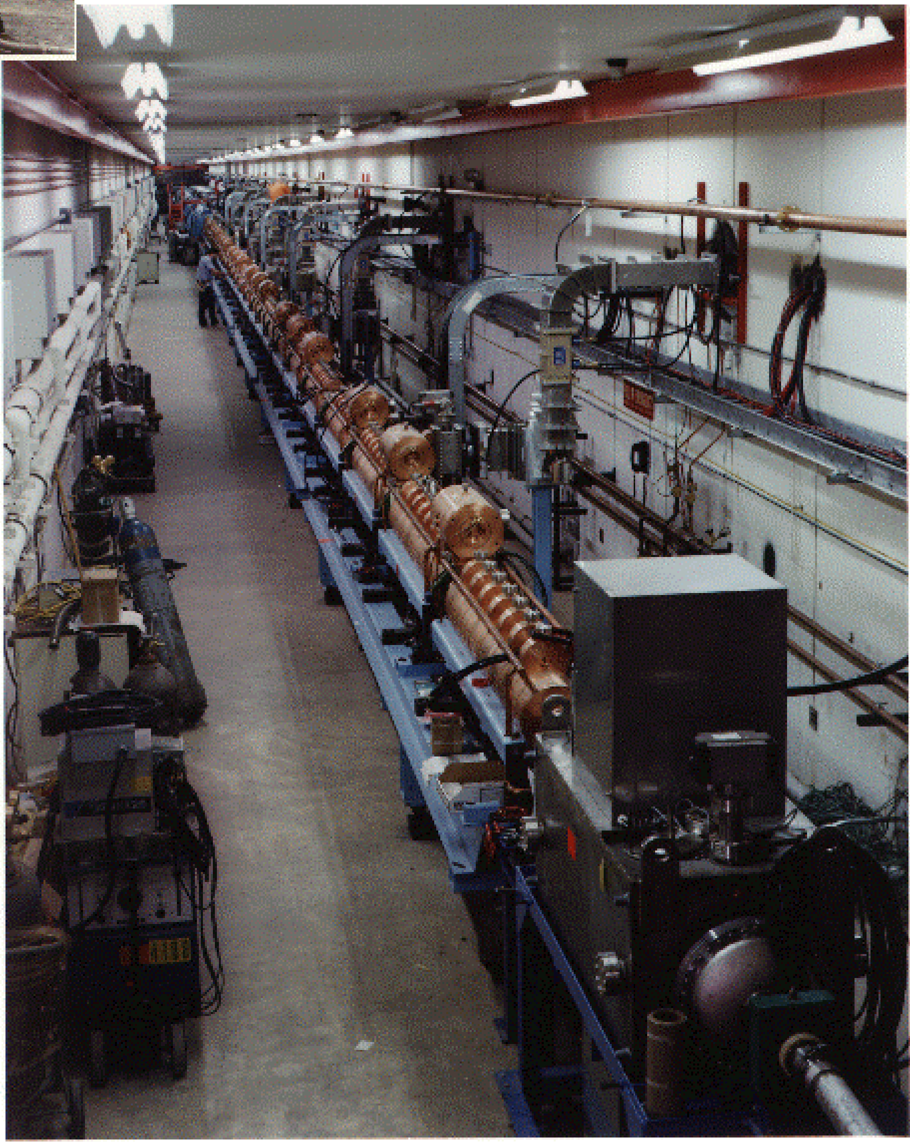
FERMILAB'S ACCELERATOR CHAIN



Birth and death of an antiproton: gestation



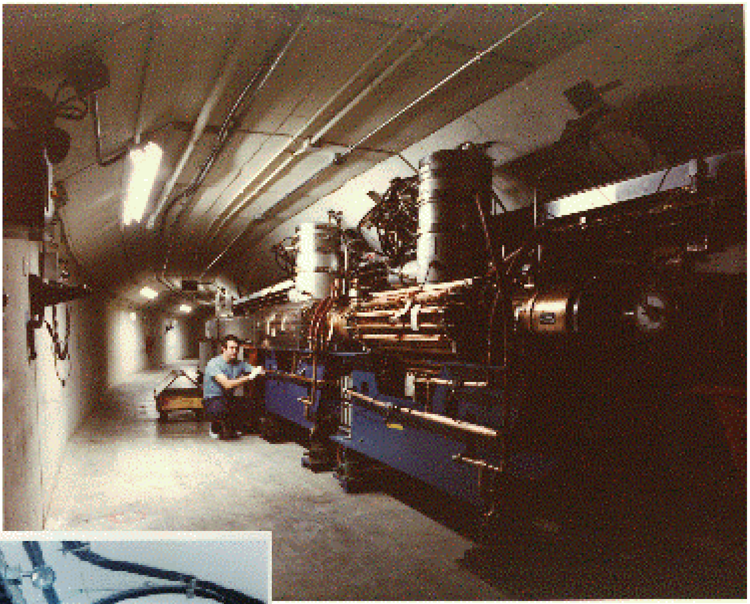
Cockroft-Walton (H^- ions)
1 MeV

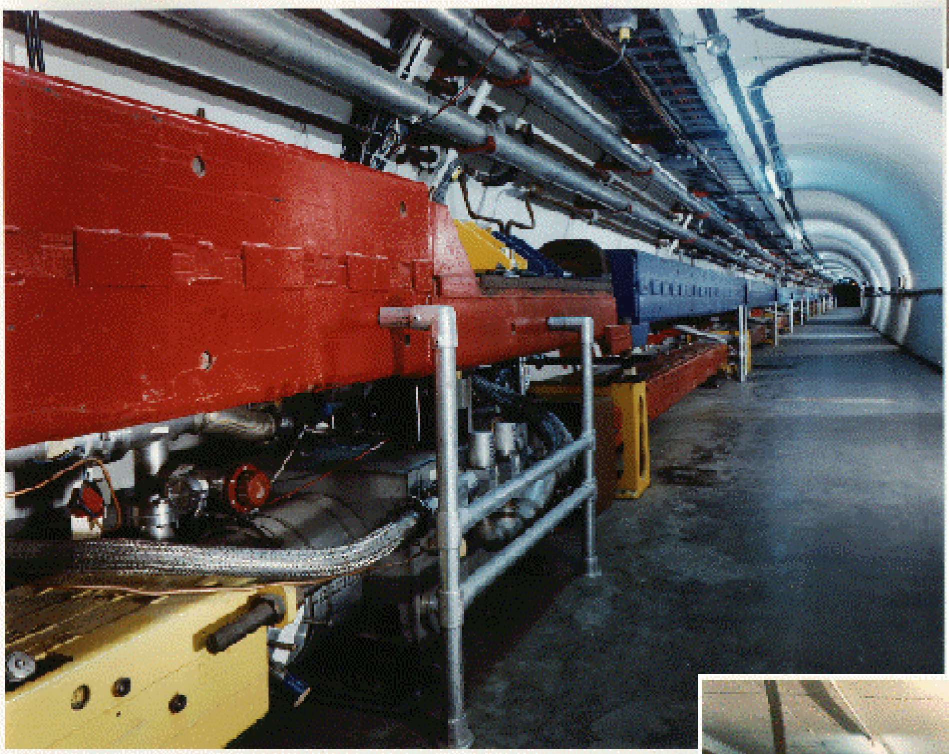


- Linac (H^- ions)
- 400 MeV

Birth... (continued)

- Booster
- 8 GeV

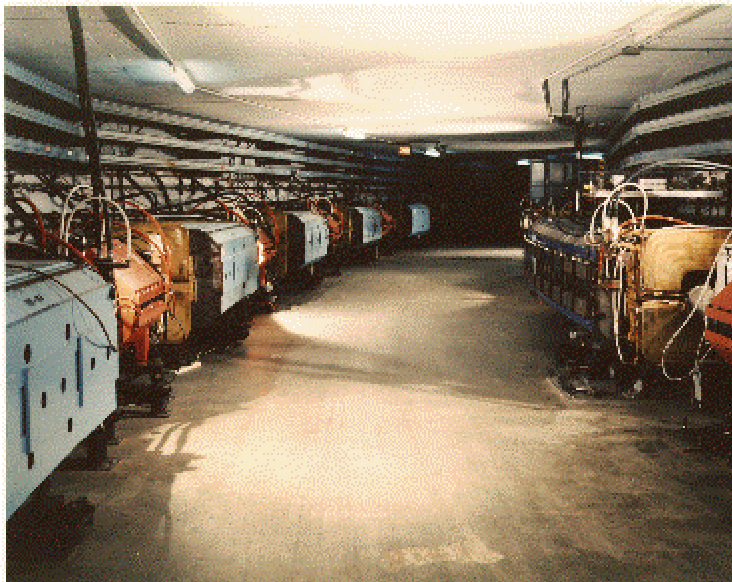




Main
Ring (p's)
120 GeV

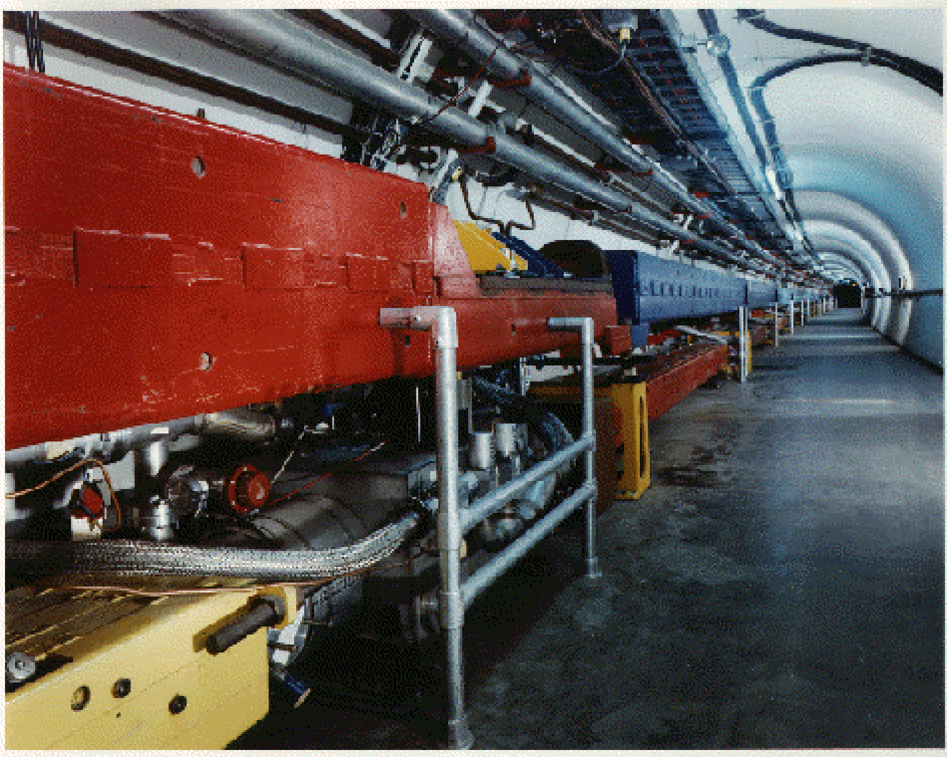
(now replaced
by Main Injector)

- Debuncher and
Accumulator (anti-p's)
8 GeV



Birth and death of an antiproton (cont'd)

- Finally, the accumulated stack of 8 GeV antiprotons, plus a new batch of 8 GeV protons from the Booster, are accelerated to 900 GeV by the Main Ring and the superconducting Tevatron working in tandem.



Main Ring
(p's and
anti-p's)
150 GeV

Tevatron
(p's and
anti-p's)
900 GeV

- The two counter-rotating beams are focused and brought into collision at the CDF and DØ detectors.

Luminosity and cross section

- Luminosity is a measure of the beam intensity
  (particles per area per second)
  ($L \sim 10^{31}/\mathrm{cm}^2/\mathrm{s}$)

- "integrated luminosity"
  is a measure of the amount of data collected (e.g. ~100 pb^{-1})

- cross section σ is measure of effective interaction area, proportional to the probability that a given process will occur.
  - 1 barn = 10^{-24} cm^2
  - 1 pb = 10^{-12} b = 10^{-36} cm^2 = 10^{-40} m^2

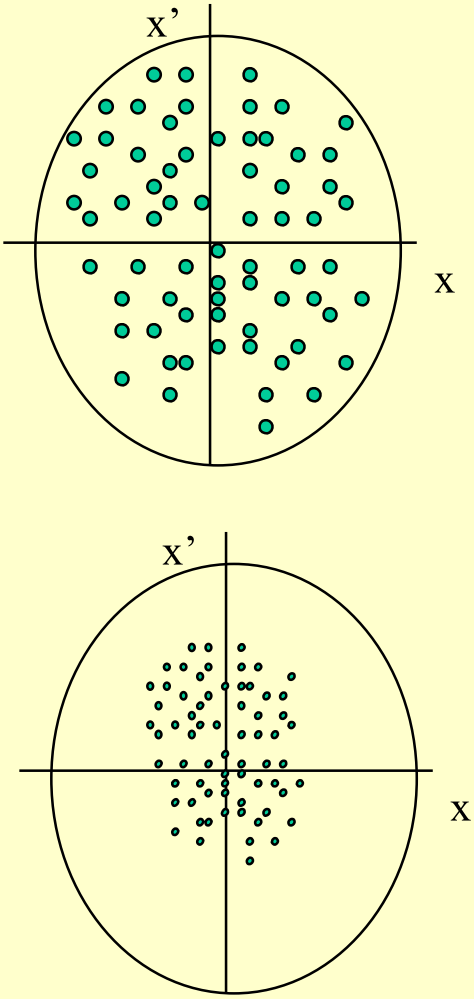
- interaction rate:

$$dn/dt = L \times \sigma \qquad \Rightarrow \qquad n = \sigma \int L dt$$

Stochastic Cooling

(from Paul Derwent's lectures)

- Phase Space compression



Dynamic Aperture (emittance of beam): region of phase space where particles can orbit

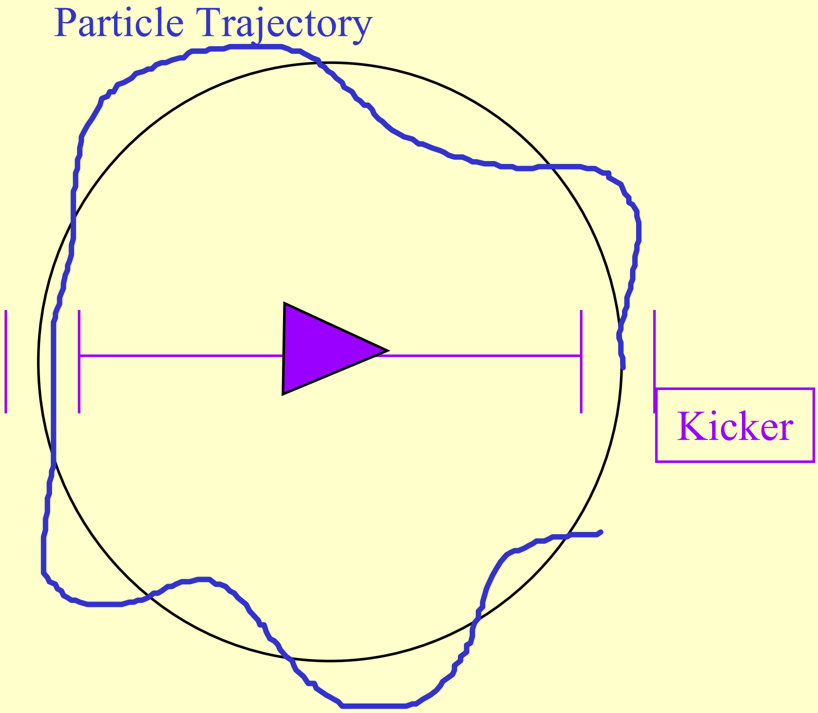
Liouville's Theorem:
local phase space density for conservative system is conserved

Continuous media vs discrete Particles

Swap Particles and Empty Area -- lessen physical area occupied by beam

Stochastic Cooling

- Principle of Stochastic cooling
    - Applied to horizontal betatron oscillation



- A little more difficult in practice.
- Used in Debuncher and Accumulator to cool horizontal, vertical, and momentum distributions
- Why COOLING?
    - Temperature ~ <Kinetic Energy>
      minimize transverse KE
      minimize ΔE longitudinally

Stochastic Cooling in the Pbar Source

- Standard Debuncher operation:
  - 10^8 pbars, uniformly distributed
  - ~600 kHz revolution frequency
- To individually sample particles
  - Resolve 10^{-14} seconds…100 THz bandwidth
- Don't have good pickups, kickers, amplifiers in the 100 THz range
  - Sample N_s particles -> Stochastic process
    - $N_s = {}^{N}/_{2TW}$ where T is revolution time and W bandwidth
    - Measure <x> deviations for N_s particles
  - The higher bandwidth the better the cooling

Betatron Cooling

With correction ~ g<x>, where g is gain of system

  - New position: x - g<x>

- Emittance Reduction: RMS of kth particle

$$\left(x_k - g\langle x\rangle\right)^2 = x_k^2 - 2gx_k + g^2\langle x\rangle^2$$

$$\langle x\rangle = \frac{1}{N_s}\sum_i x_i = \frac{1}{N_s}x_k + \frac{1}{N_s}\sum_{i\neq k} x_i$$

Average over all particles and do lots of algebra

$$\frac{d\langle x\rangle^2}{dn} = \frac{-2g\langle x^2\rangle}{N_s} + \frac{g^2}{N_s}\langle x^2\rangle, \text{where n is 'sample'}$$

$$\Rightarrow \text{Cooling rate } \frac{1}{\tau} = \frac{2W}{N}\left(2g - g^2\right)$$

- Add noise (characterized by U = Noise/Signal)
- Add MIXING
  - Randomization effects M = number of turns to completely randomize sample

$$\Rightarrow \text{Cooling rate } \frac{1}{\tau} = \frac{2W}{N}\left(2g - g^2\left[M + U\right]\right)$$

  - Net cooling effect if g sufficiently small

AntiProton Source

- Shorter Cycle Time in Main Injector
- Target Station Upgrades
- Debuncher Cooling Upgrades
- Accumulator Cooling Upgrades
  - GOAL: >20 mA/hour