Physics with Accelerators
Part II

R. Dixon

Equation of Motion

- Beam travel along s
- Transverse beam direction is x
- Then focusing system satisfies:

$$x'' + K(s)x = 0$$

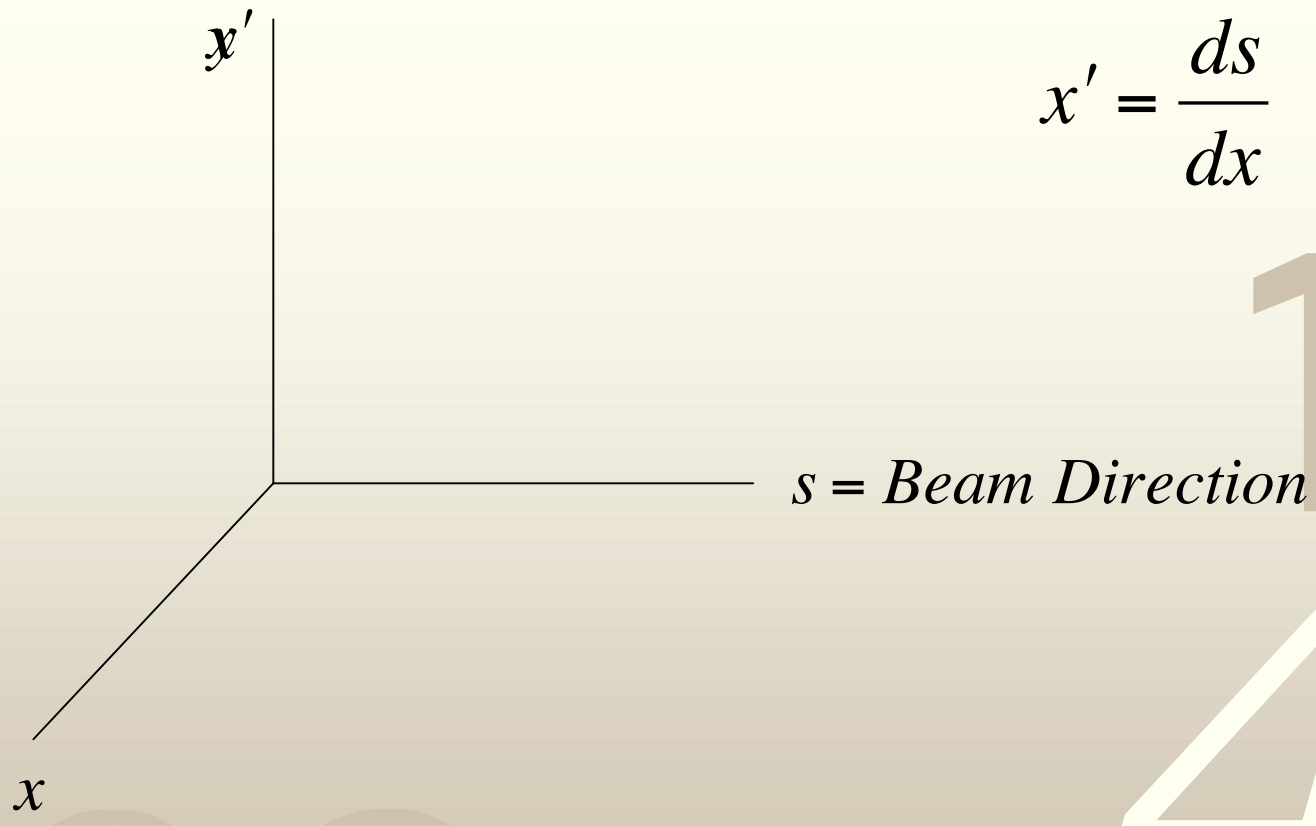
- This is an harmonic oscillator where the spring contant depends on s
- Solution:

$$x(s) = A\sqrt{\beta(s)}\cos[\Psi(s) + \delta]$$

- Assumes motion is periodic with period K(s)= K(s+C) and A is related to the Courant-Snyder parameters by:

$$A^2 = \gamma(s)x(s)^2 + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2$$

Coordinate System



$$x' = \frac{ds}{dx}$$

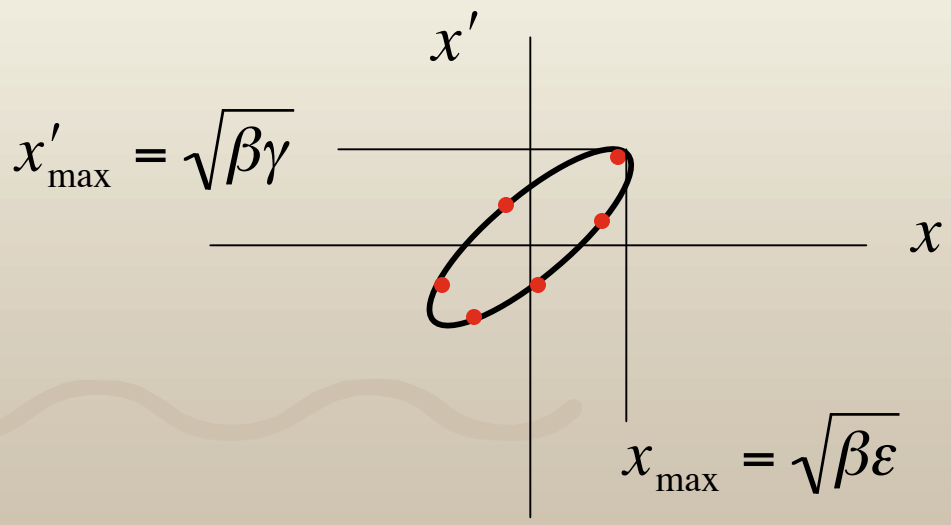
Lattice Functions

$$x'' + K(s)x = 0$$

$$x(s) = A\sqrt{\beta(s)}\cos[\Psi(s) + \delta]$$

$$A^2 = \gamma(s)x(s)^2 + 2\alpha(s)x(s)x'(s) + \beta(s)x'(s)^2 = constant$$

This is an ellipse with $area = \pi A^2 \equiv \varepsilon$



Superconducting Synchrotrons

- Advantages
  - Higher magnetic fields
  - Smaller power requirment
- Issues
  - Magnets sensitive to energy loss of the beam
    - Quenches
      - Potential damage to magnets
      - Recovery time to get magnets cold again
  - Tevatron
    - Fixed Target
    - Collider

The Tevatron

- World's Highest Energy particle accelerator
  - Still! Commissioned in 1983
  - 1st superconducting accelerator
  - Circumference = 2π km (+/- 5 cm!) = 4 miles
  - At 1 TeV, protons, antiprotons are traveling at speed of 0.9999996 *c* !
  - One round trip for a proton takes 21 μsec (48,000 revolutions/second)
- Acceleration takes place with 8 RF cavities, total ~20 m. Rest of circumference is magnets, bringing particles back to the cavities!
- Two beams circulate about the ring in opposite directions, only few mm apart, and brought into collision at two detector regions
- While collisions only generate 1-2 watts of power, as shown earlier, the stored energy of the beam is
  - $36 \times (3\times10^{11}) \times (1000 \times 10^{9} \times 1.6 \times 10^{-19}\ J)$ = **1.7 MJ** !
    - 1.7 MJ = kinetic energy of a 6 ton truck moving at 60 mph
    - 1.7 MJ ~ 2 jelly doughnuts
  - If lost in one revolution, instantaneous power: 1.7 MJ / 21 μsec = **80 GW**!

Tevatron Overview

- Synchrotron providing proton-pbar collisions @ 980 GeV beam energy
- Tevatron radius = 1 km $\Rightarrow$ revolution time ~ 21 μs
- Virtually all of the Tevatron magnets are superconducting
  - Cooled by liquid helium, operate at 4 K *fun fact: ≈350 MJ stored energy!*
- 36 bunches of protons and pbars circulate in same beampipe
  - Electrostatic separators keep beams apart except where/when desired
- Injection energy is 150 GeV
  - Protons injected from P1 line at F17
  - Pbars injected from A1 line at E48
- 3 trains of 12 bunches with 396 ns separation
- 2 low β (small beam size) intersection points (CDF and D0)
- 8 RF cavities (near F0) to keep beam in bucket, acceleration
  - 1113 RF buckets (53.1 MHz $\Rightarrow$ 18.8 ns bucket length)

Quench Protection

- Monitor Voltage across each coil. Normal V=0
- When V≠0
  - Abort the beam
  - Fire heaters in magnets
  - Bypass current around magnets
  - Dump energy in resistor banks

Magnet Damage

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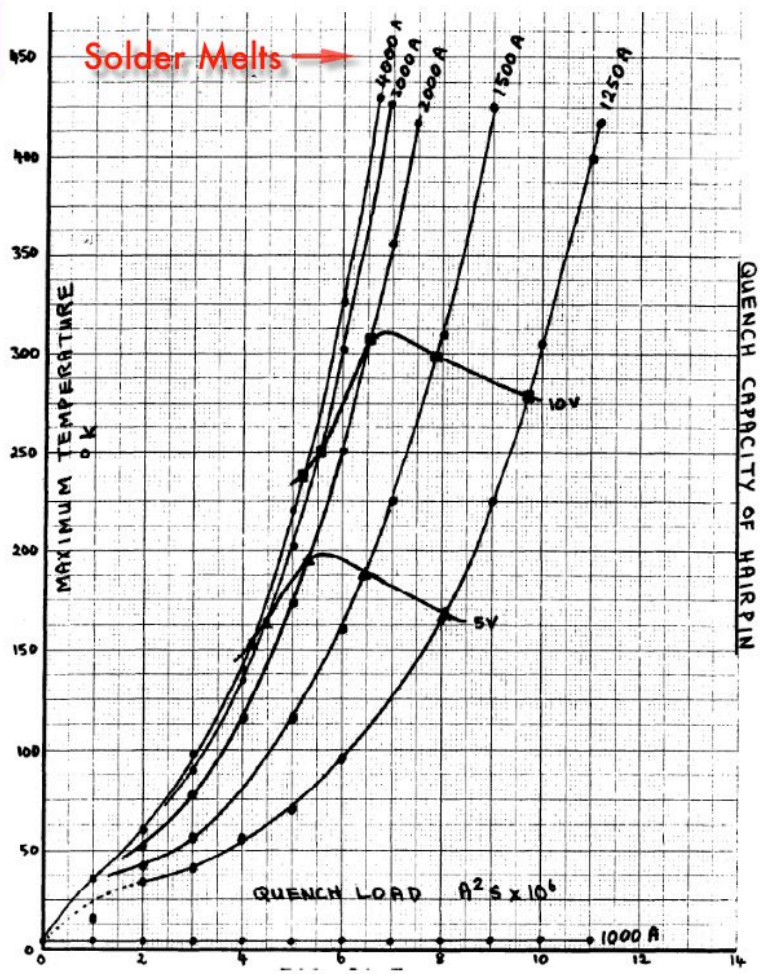
Quench Temperature Rise

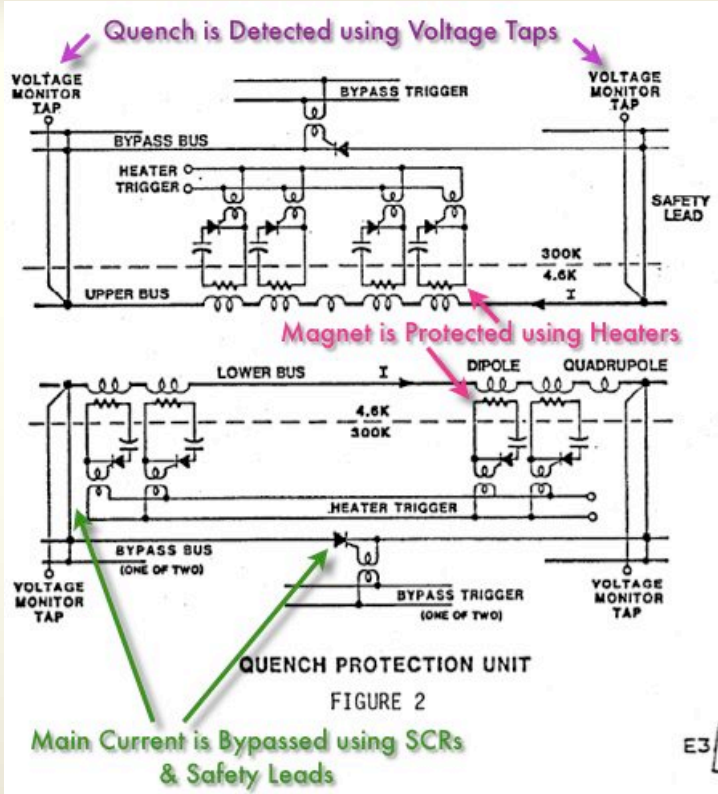
At 4.4 KA, it takes only 350 mS to destroy a 7 meter Tevatron magnet.

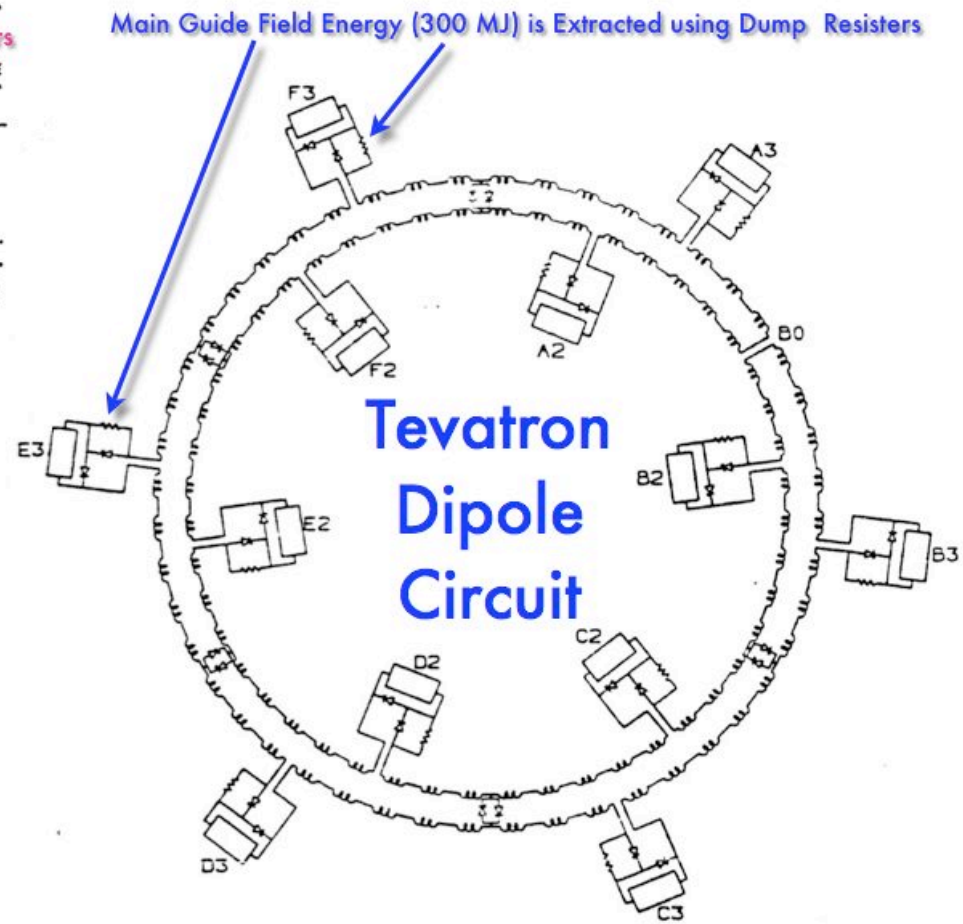
Adiabatic Limit

$$\int_{t_0}^{t_1} I(t')^2 dt' = A \cdot A_{cu} \cdot \int_{T_0}^{T} \frac{c(T')}{\rho(T')} dT' \equiv F(T)$$



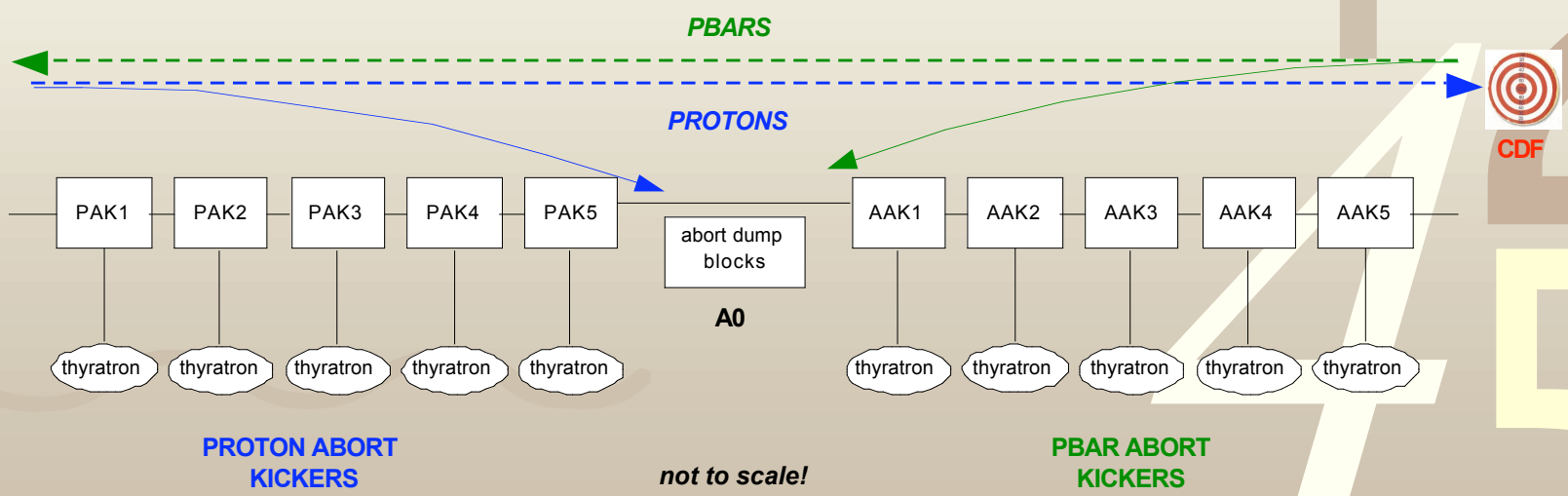
Tevatron Quench protection





Aborting the Beam in the Tevatron

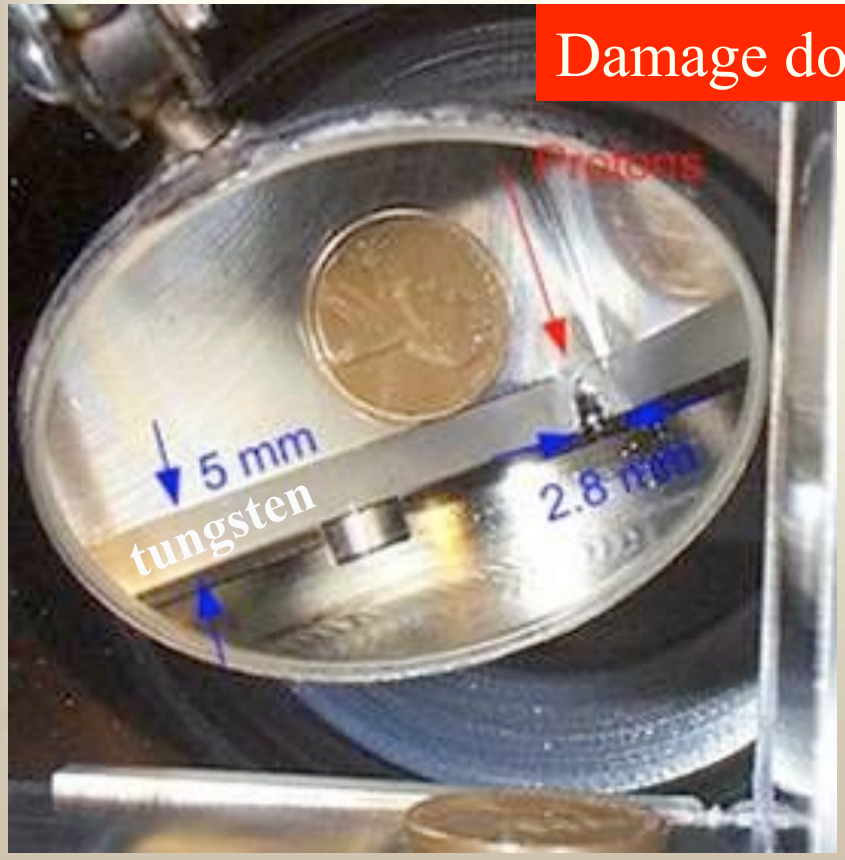
- Abort kickers ramp up synchronously in gap between P24/P25 (A36/A1)
  - 70% full voltage when next bunch passes by; enough to kick into dump
- Beam in abort gap while kickers rising gets kicked, but not into dump
  - Can circulate with large distortion, strike apertures downstream, cause quenches, …
  - Collimators at A11, A48 help protect CDF
- Abort kicker pre-fires happen when 1 thyratron breaks down spontaneously
  - Other abort kickers automatically fire < 1 turn later to kick rest of beam into dump
  - Tubes holding off 36 kV @ 980 GeV over entire store – many hours
  - Thyratrons are conditioned at higher voltages, but pre-fires can (will) still occur



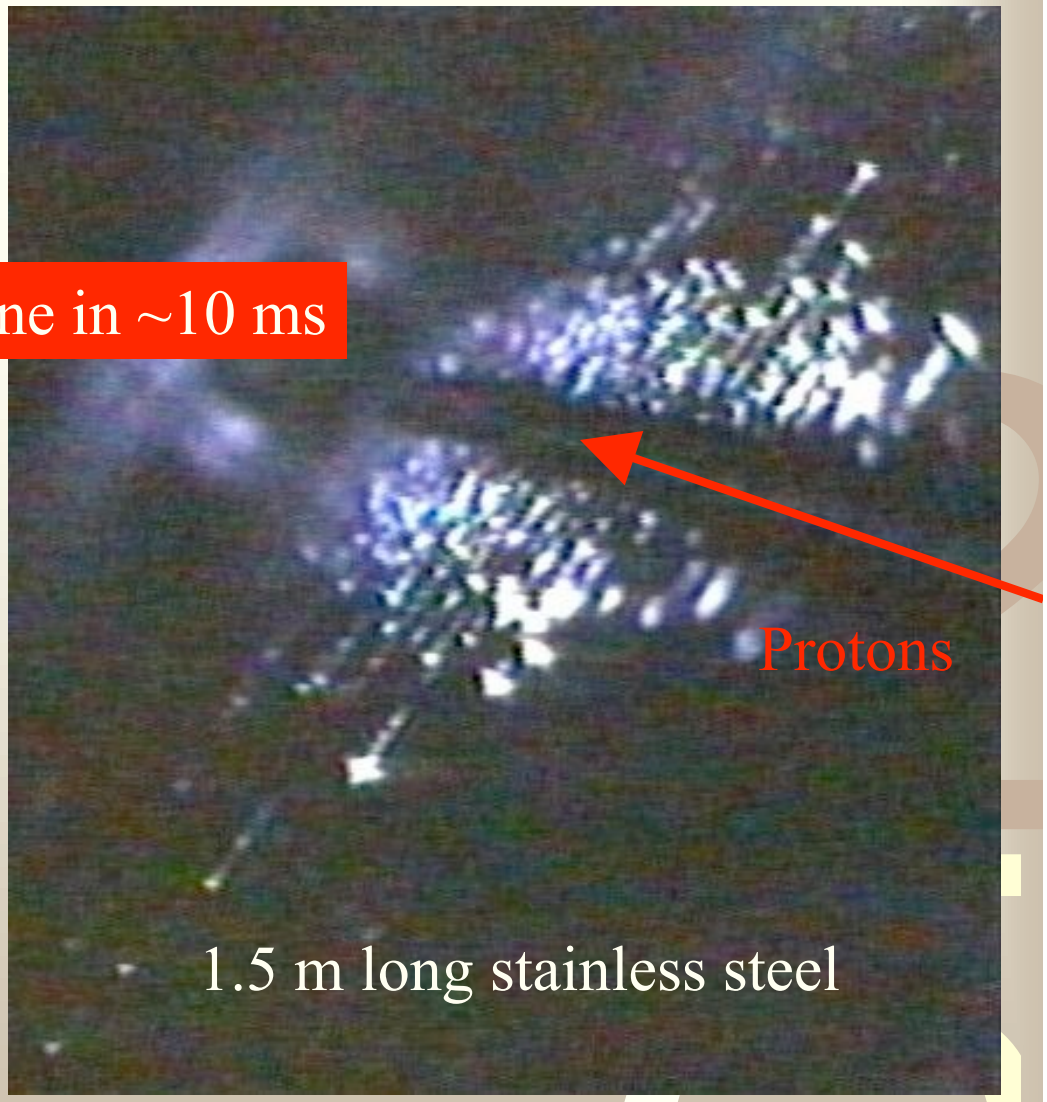
Destroyed Collimators in Tevatron

stored beam energy

10^{13} protons @ 1 TeV ≈ 1.6 MJ



Damage done in ~10 ms



Making Antiprotons

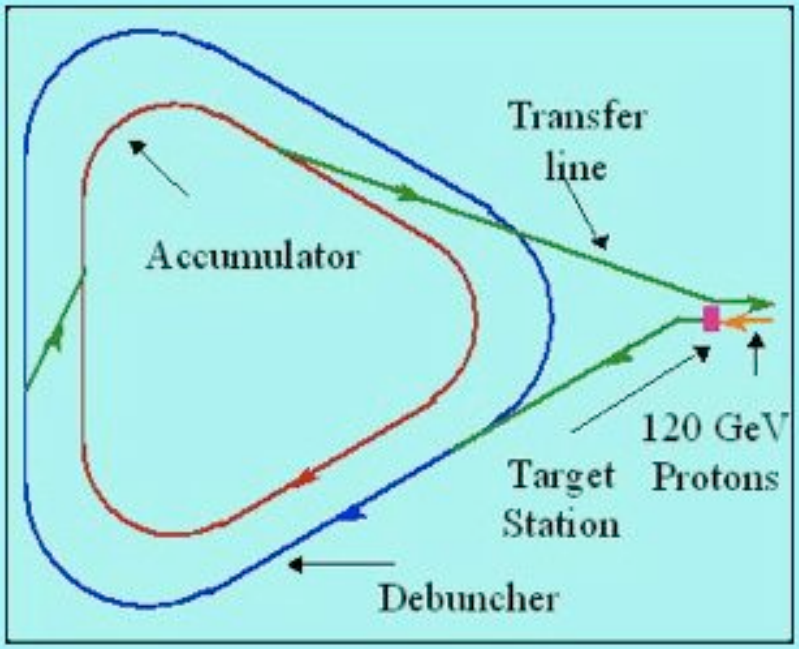
The Anti-Proton Source consists of three major components:

The **Target Station**

The **Debuncher**, an 8 GeV synchrotron

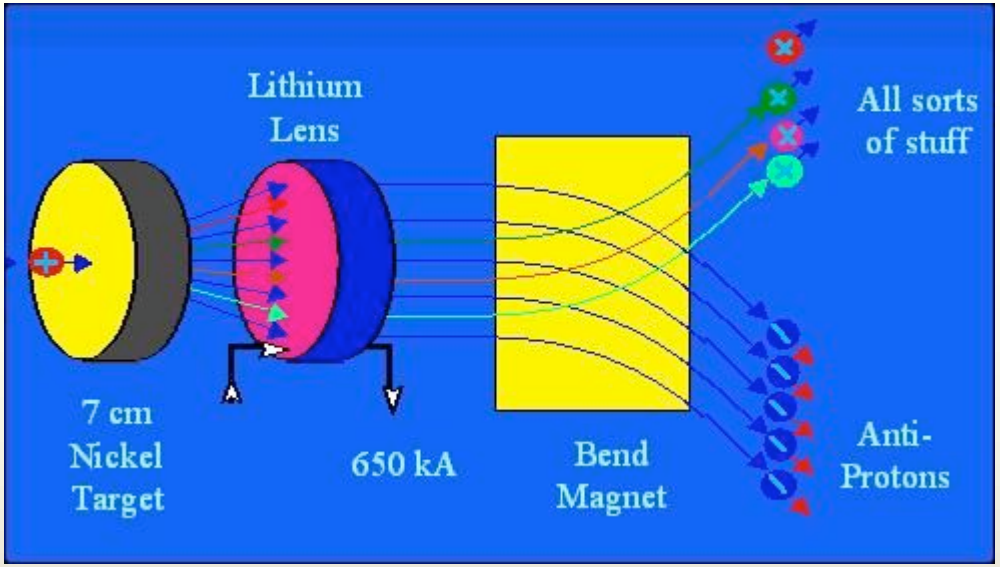
The **Accumulator**, an 8 GeV synchrotron

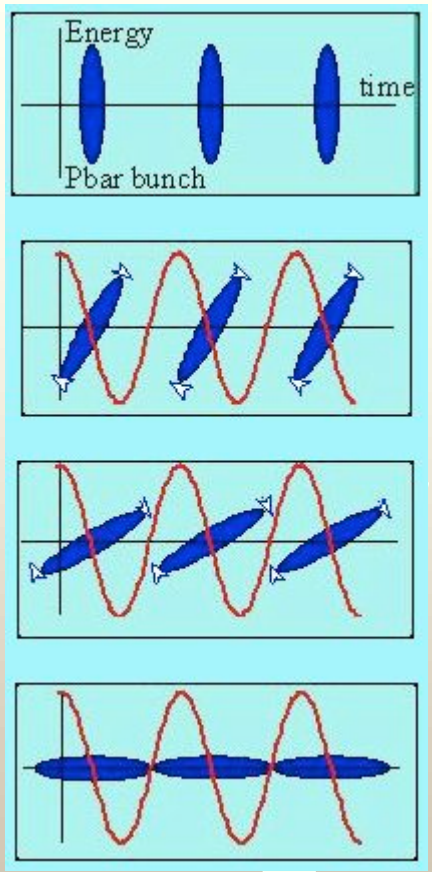
The key to accumulating a large number of antiprotons is **Stochastic Cooling**

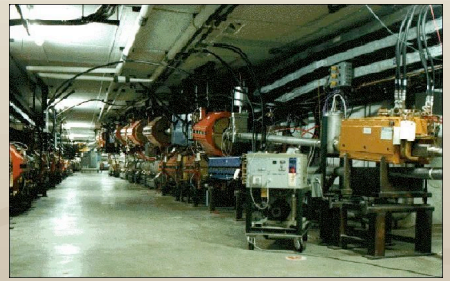


Stacking Rate ~ 20 X 10^{10} per hour

Some Antiproton Details

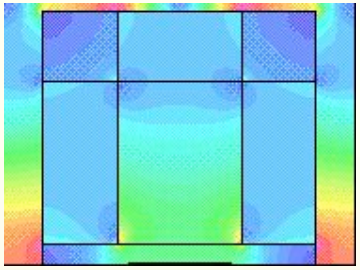




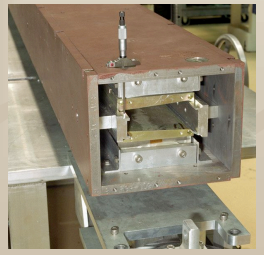


Recycler Synchrotron

- Originally built to recover left-over antiprotons at the end of a Tevatron colliding beams store
- Resides in Main Injector tunnel, near ceiling
- Later, realized more efficient to store antiprotons previously conditioned in the Antiproton Source, and *then* send to the Tevatron -- actually provides higher luminosity overall when used this way
  - Will store up to ~6 Trillion antiprotons
  - Permanent magnets are used -- not electromagnets (since beam is stored at one energy -- 8 GeV)
  - Has been used successfully to set luminosity records in the Tevatron
  - Continuing to improve



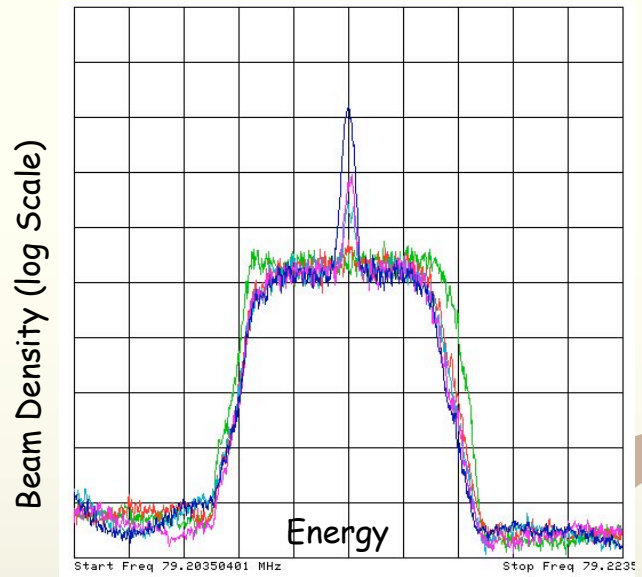
Permanent Magnet field map



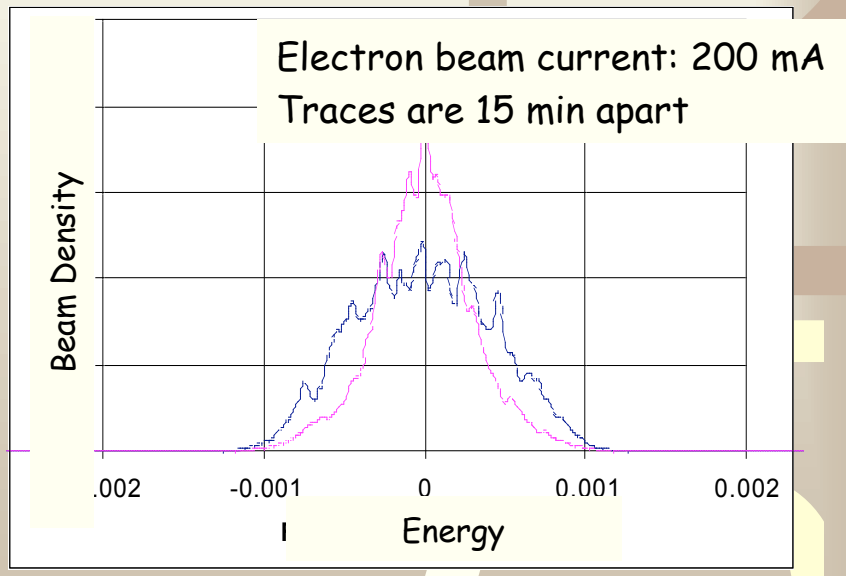
magnet

Pelletron

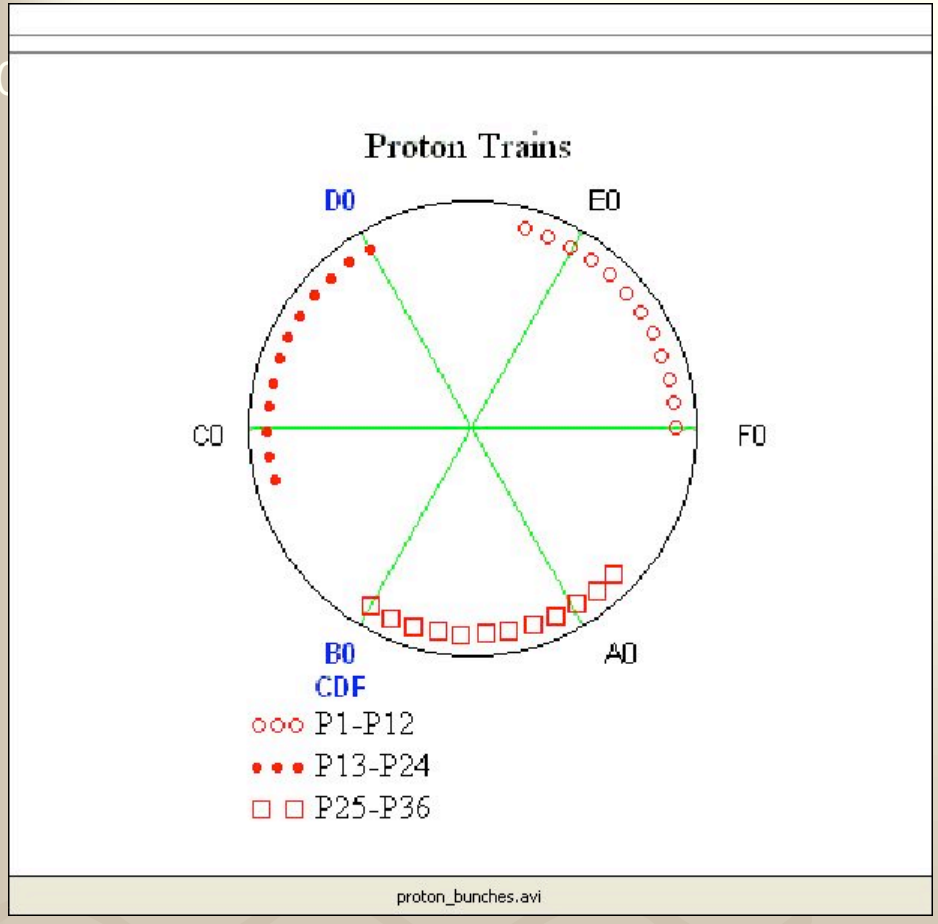
Recycler Electron Cooling

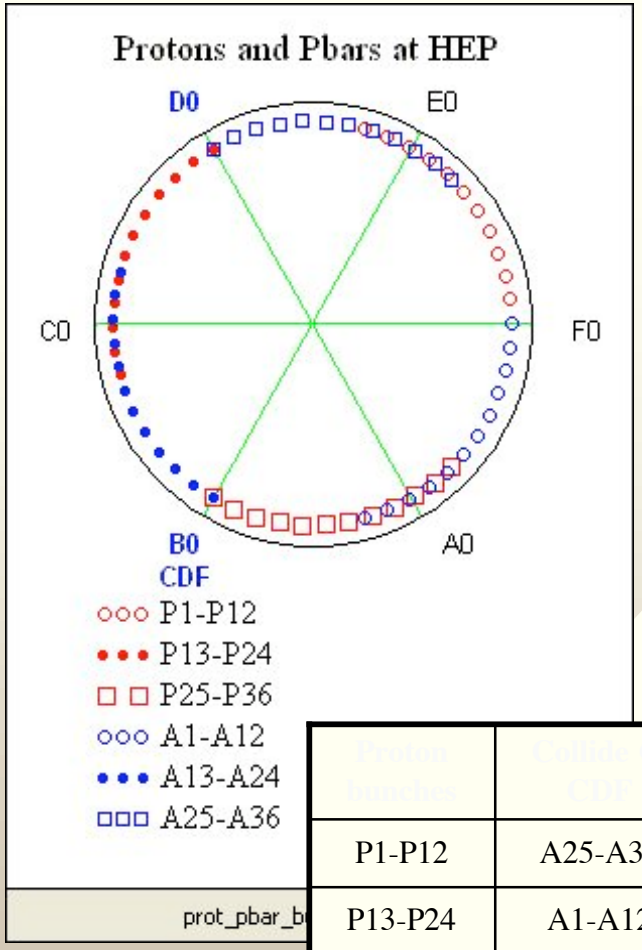


- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005
  - By the end of August 2005, electron cooling was being used on every Tevatron shot



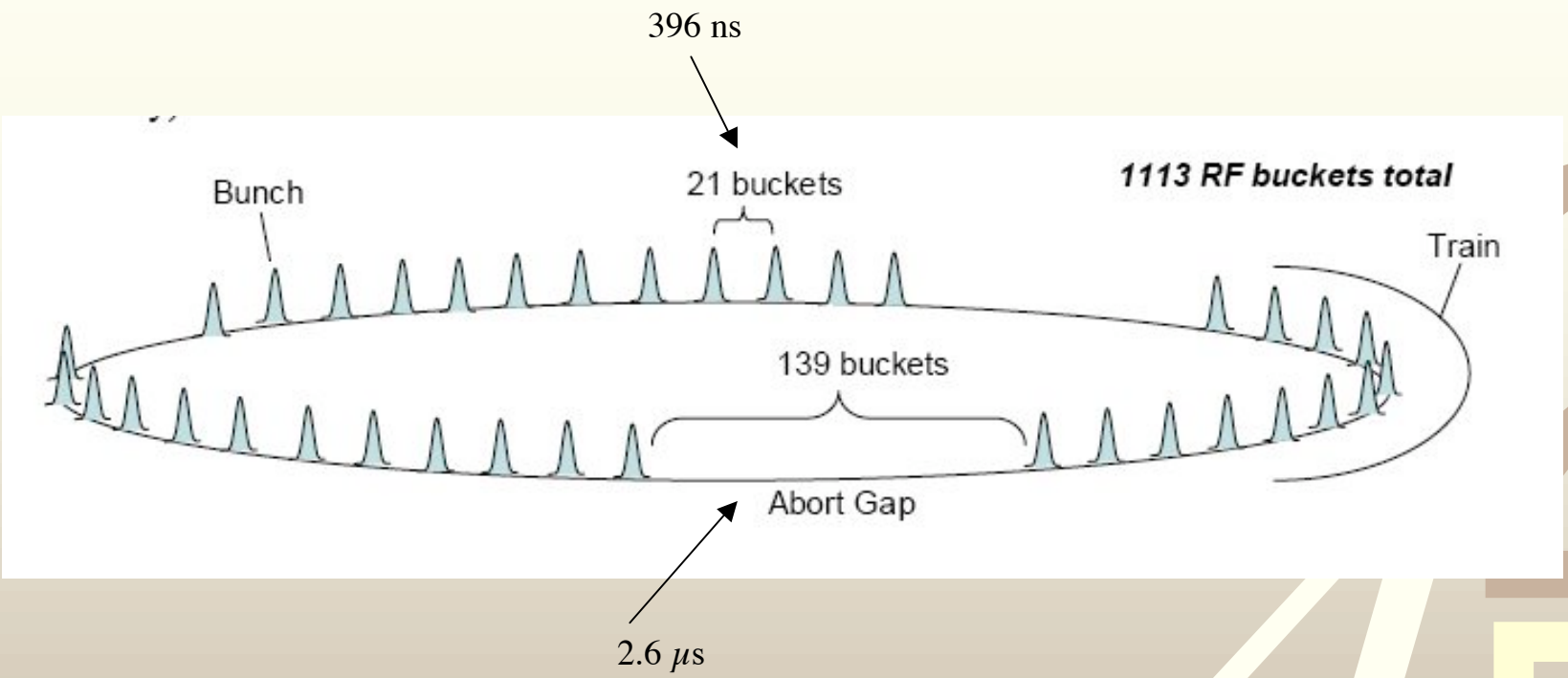
Bunch Positions





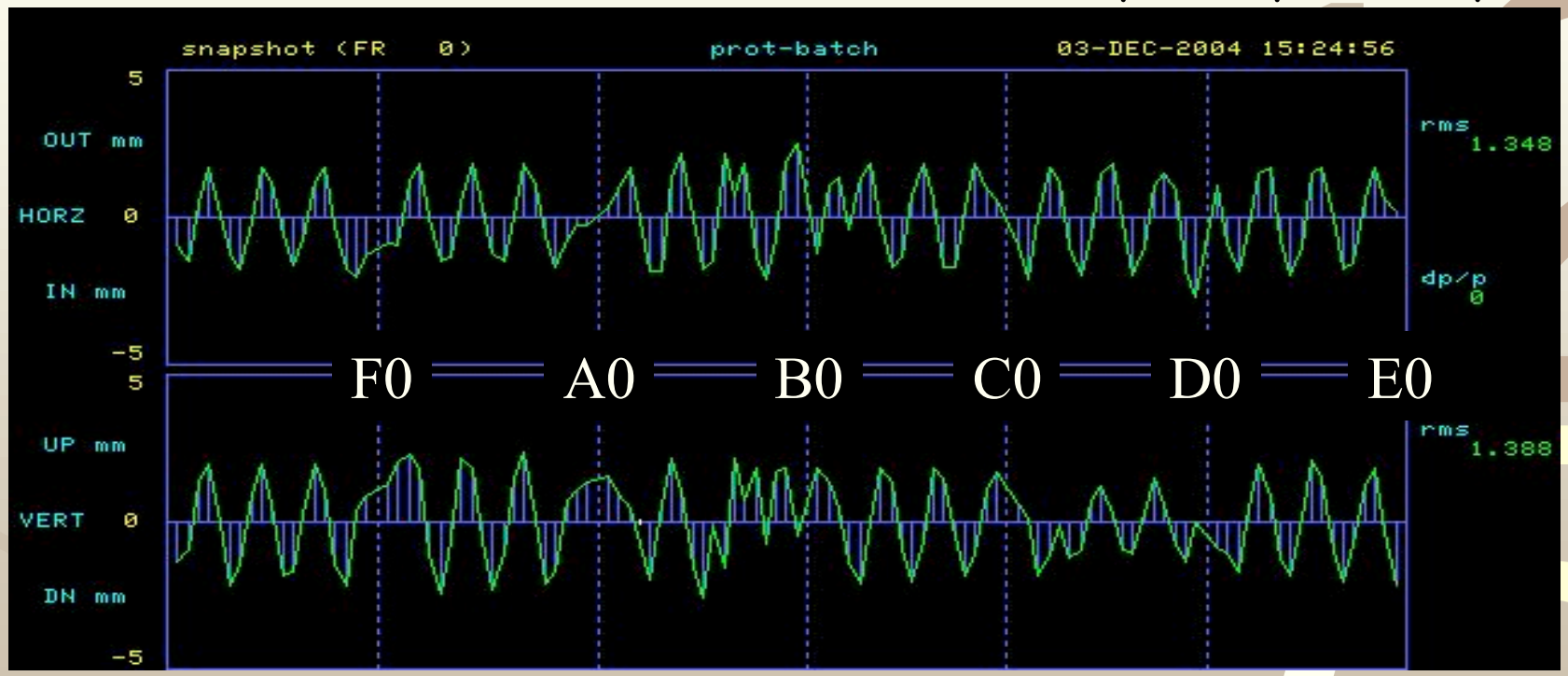
Proton bunches	Collide @ CDF	Collide @ D0
P1-P12	A25-A36	A13-A24
P13-P24	A1-A12	A25-A36
P25-P36	A13-A24	A1-A12

Tevatron Bunch Structure

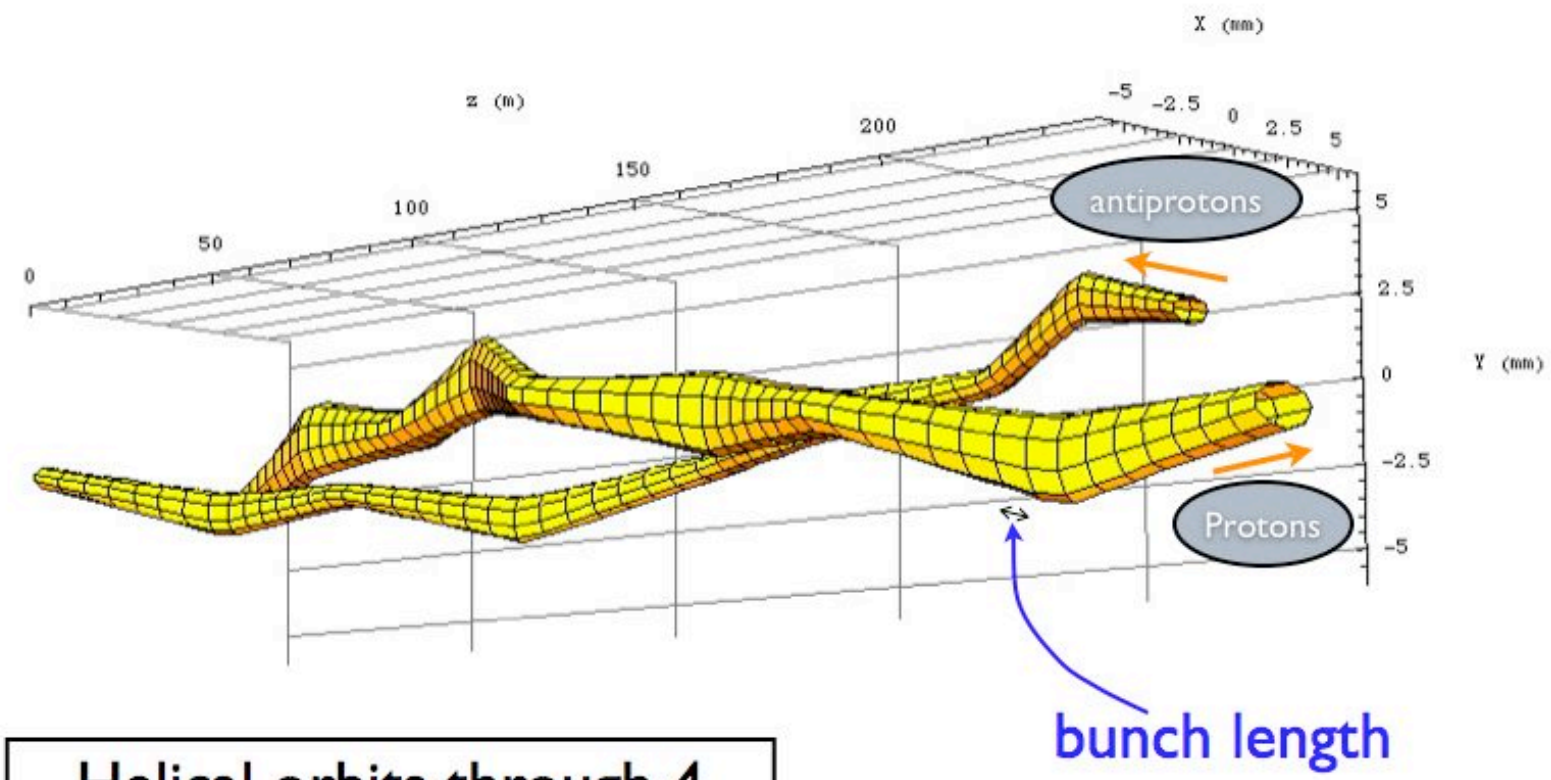


Helix

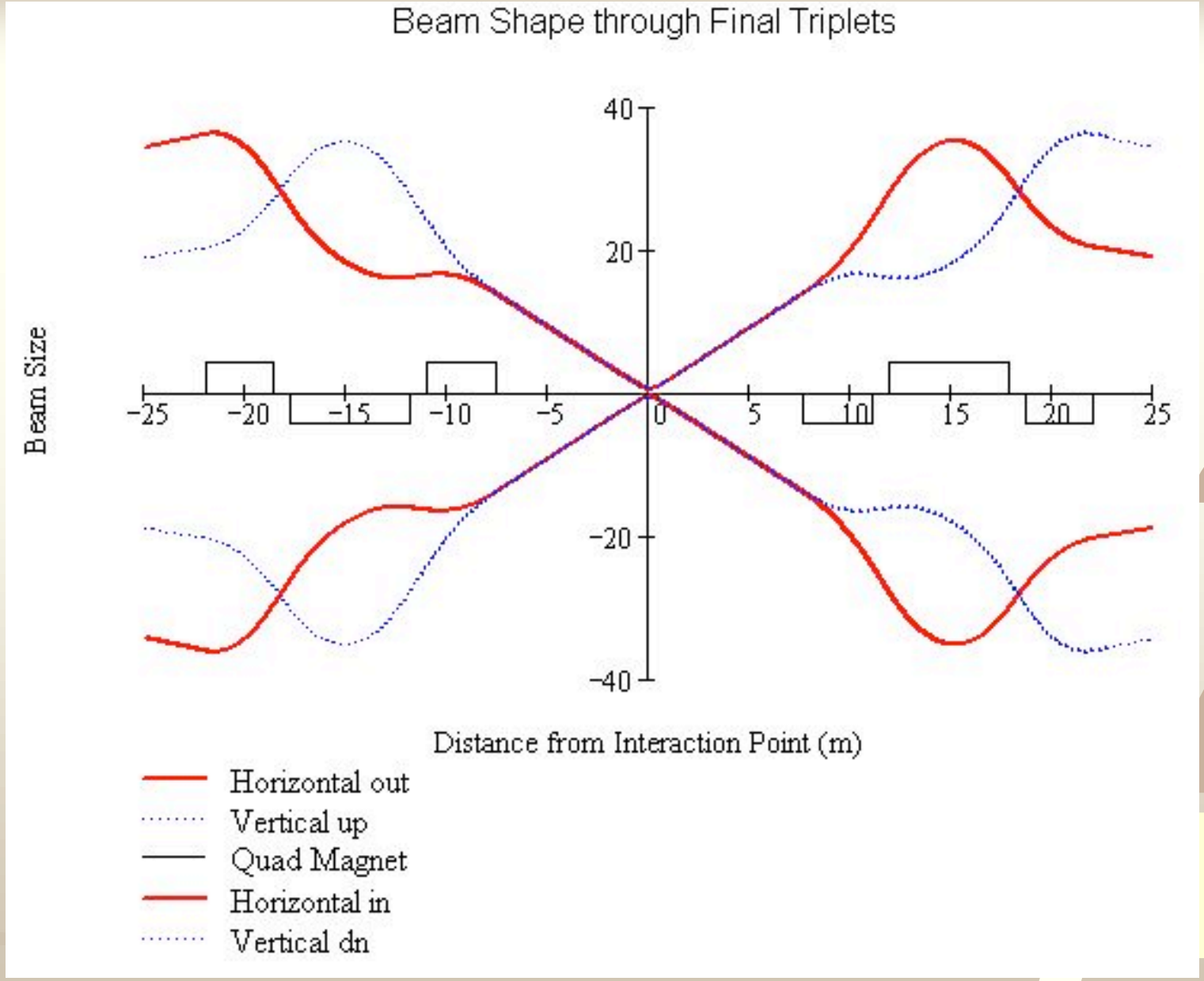
- Protons & pbars spiral around each other as they revolve in opposite directions
  - Deliberately running beams off-center by several mm
- Can control tunes, etc., of each beam (nearly) independently



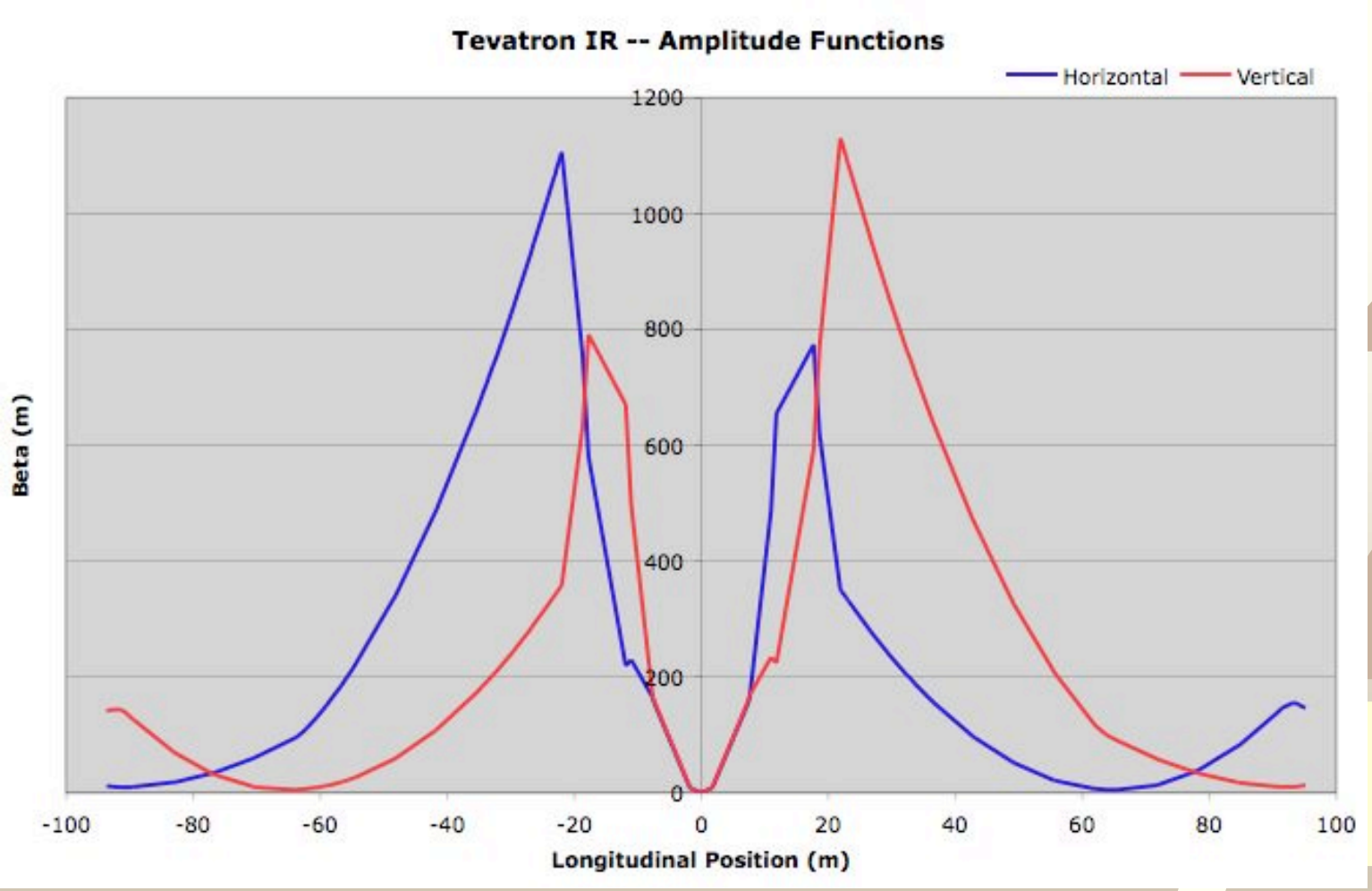
Tevatron Beam Envelopes



Helical orbits through 4 standard arc cells


Beam Shape through Final Triplets
Beam Size
40
20
-20
-40
-25
-20
-15
-10
-5
0
5
10
15
20
25
Distance from Interaction Point (m)
Horizontal out
Vertical up
Quad Magnet
Horizontal in
Vertical dn

Tevatron Low Beta Section



Accelerator Instrumentation

- Beam Position Monitors
- Loss Monitors
- Flying wires
- Schottky Detectors
- Synchrotron Light Detectors
- Ion Profile Monitors
- Optical Transition Radiation Detectors
- Motion sensors

Beam Position Monitor

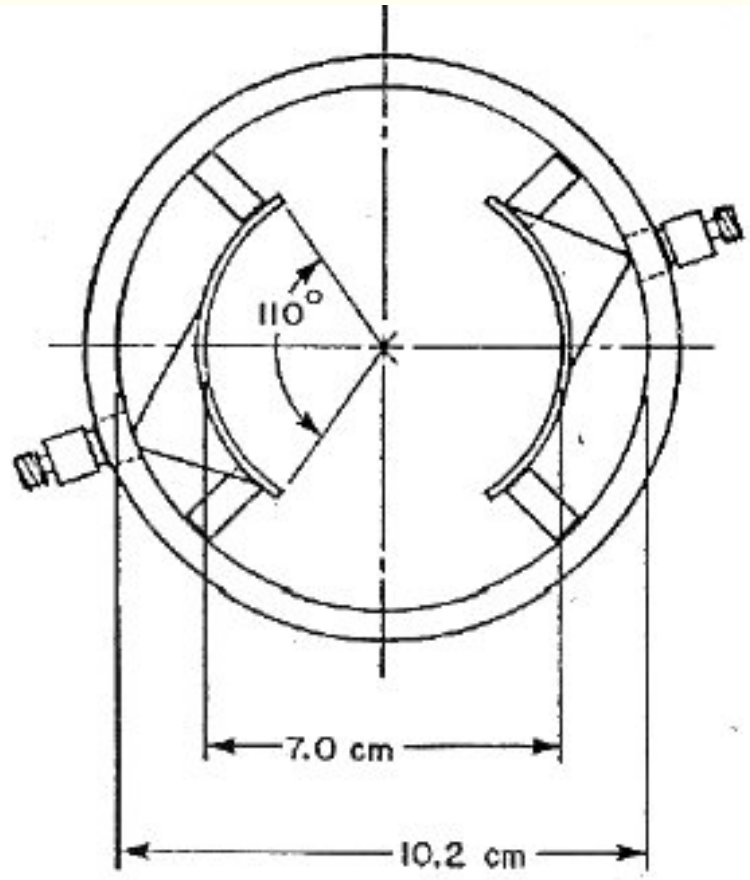
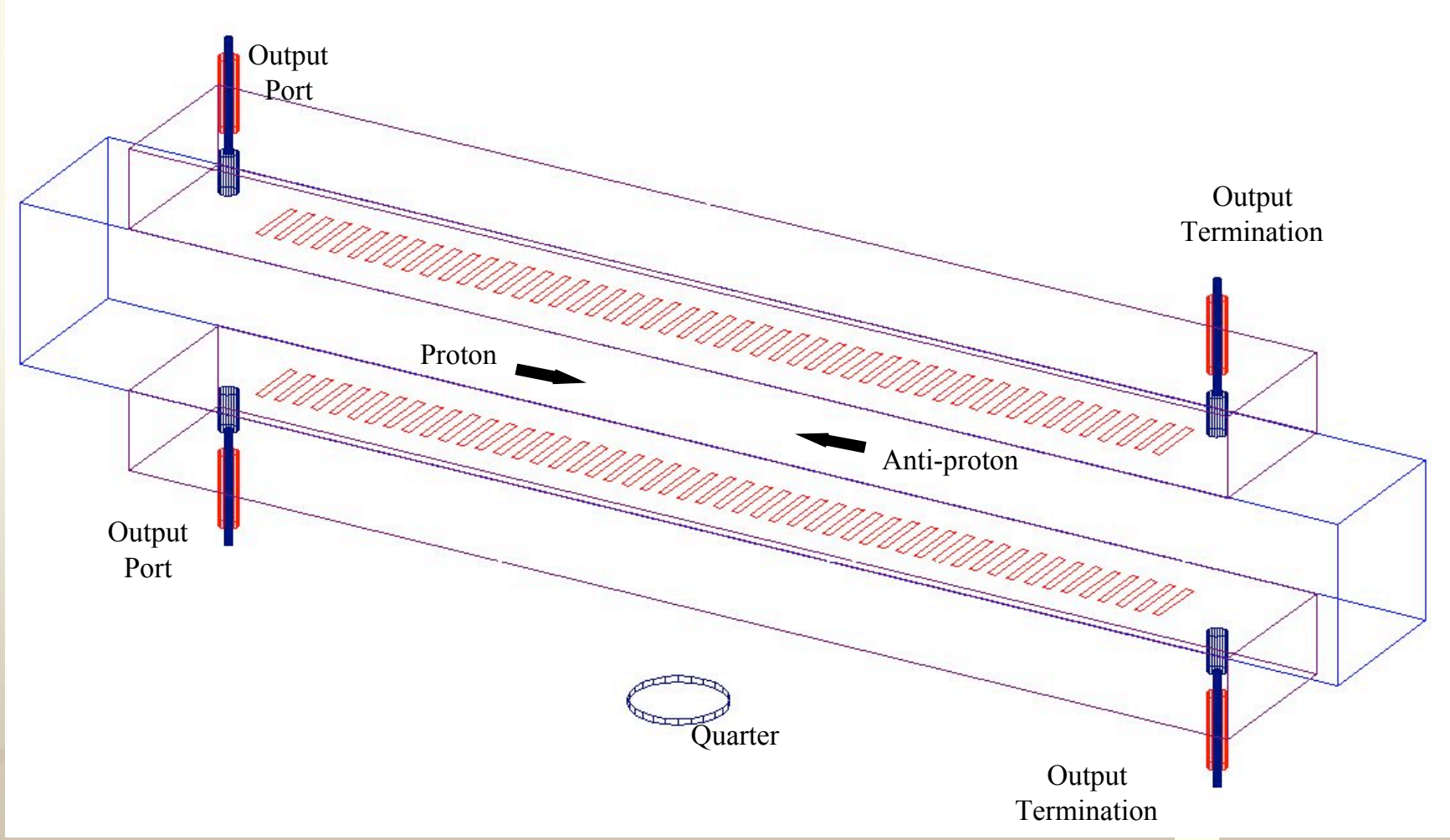


Figure 9.1 : Tevatron BPM and Specifications

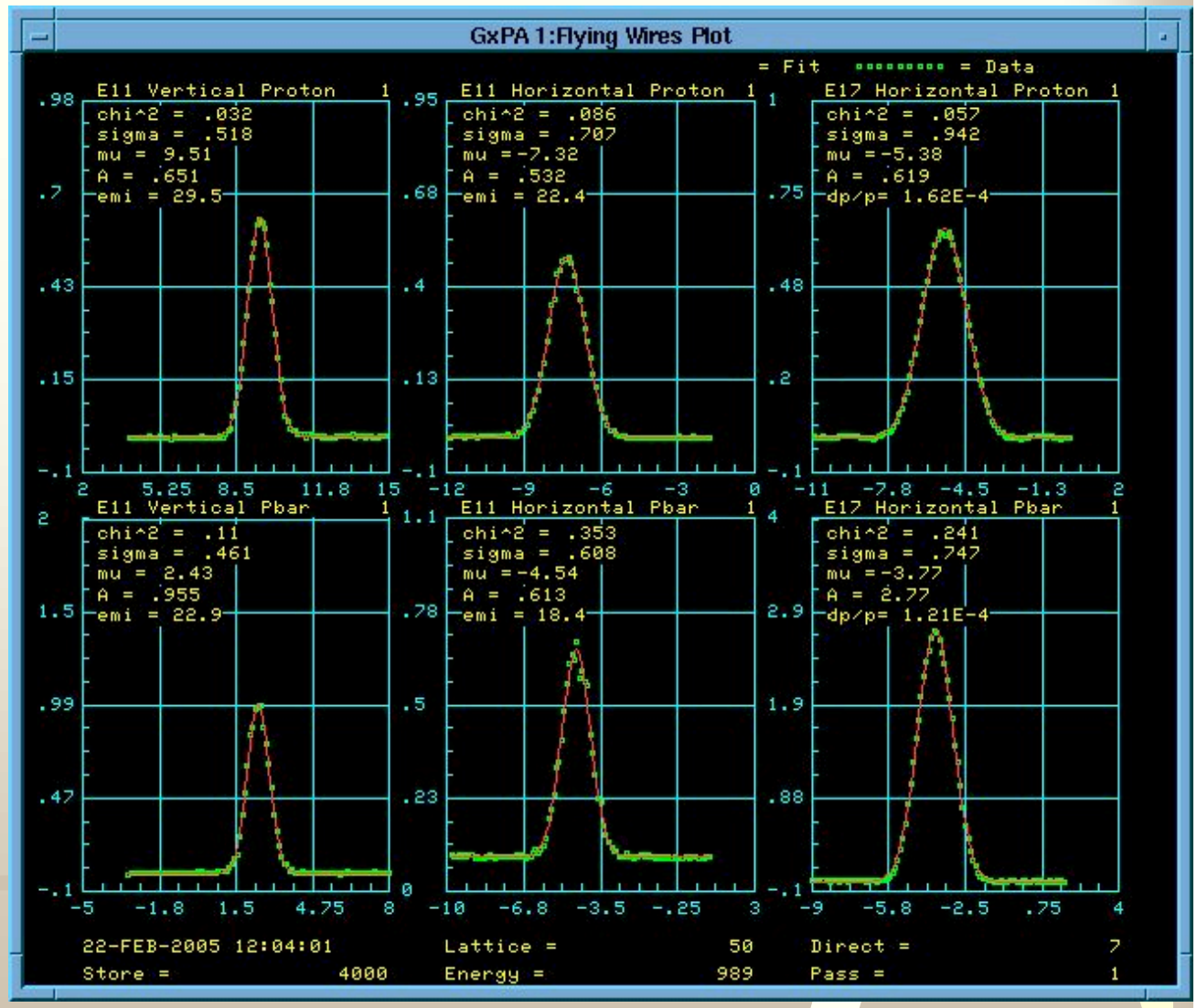
Slow Wave Structures



Flying Wires

- Fly wires through beams
- Scatted particles detected in scintillator paddles
- Can cause loss spikes in CDF/D0
- Measure transverse beam profiles

- New wires are thinner (7 _m), cause less loss
- Fly every hour during HEP to see emittance evolution



Magnet Motion

- How do see magnet motion?
  - Tiltmeters, LVDTs, water levels, surveys
- Observed magnet motion on different time scales
  - Slow drift over weeks, months
    - Ground motion, etc.
  - Wiggles, jumps over seconds, minutes, hours
    - Quenches, earthquakes, HVAC, weather, tides
  - Vibrations at few _ tens of Hz
    - Traffic, pumps
- ~_m magnet motion near IPs give ~mm orbit changes in arcs
  - Readily observable during stores using Beam Position Monitors (BPMs)
  - Can cause spikes in background

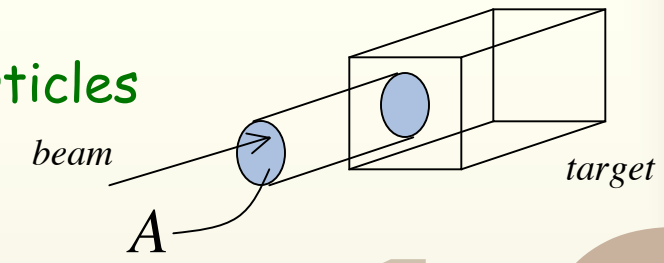
Sumatra Earthquake 3/28/05

Experiments with Accelerators

- Fixed Target
  - Center of Mass Energy
  - Counting Rates
  - Beam types
  - Spill structure
- Collider
  - Center of Mass Energy
  - Luminosity
  - e+e-,PP,PP
  - Bunch Structure

Counting Rate

- Fixed Target Experiments:
  - *Illuminate* a target with beam particles
  - Rate of "interactions" --



$$R = \frac{N_{Tar} N_{Beam}}{T} \sigma$$

$$R = \frac{\rho_{Tar} A_{Tar} l_{Tar}}{grams/Particle_{Tar}} N_{Beam} \sigma_{Tot}$$

Center of Mass Energy

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$$s = (\underset{\sim}{P}_1 + \underset{\sim}{P}_2) \bullet (\underset{\sim}{P}_1 + \underset{\sim}{P}_2)$$

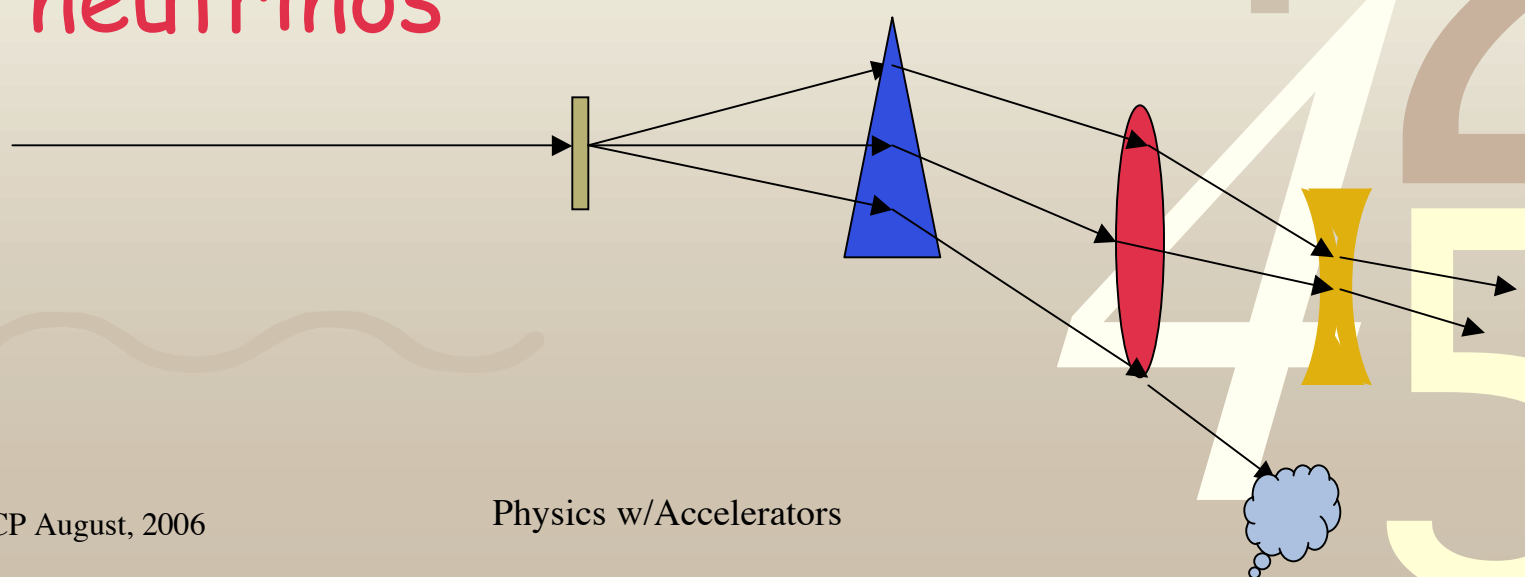
$$= m_1^2 + m_2^2 + 2E_1E_2 \approx 2(800)m_1 \approx 1600$$

or

$$\sqrt{s} = 40\ GeV$$

Beam

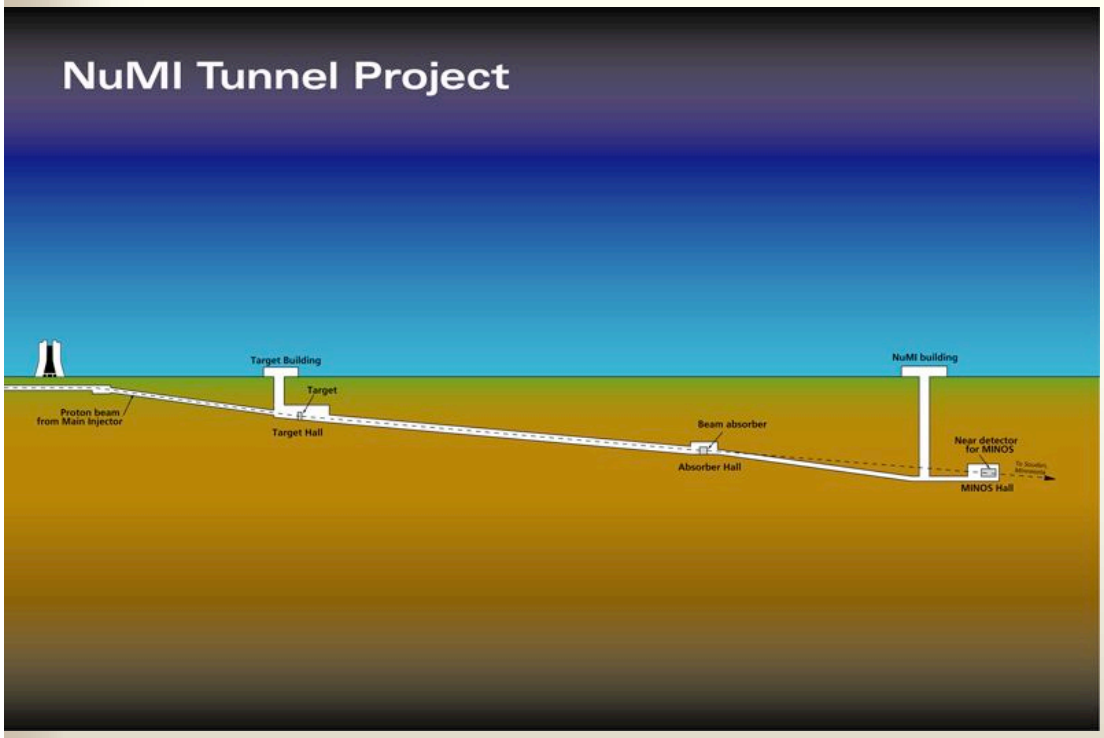
- Primary Protons (or electrons)
- Secondaries
  - pions, kaons, antiprotons, hyperons,muons, electrons,photons,and neutrinos

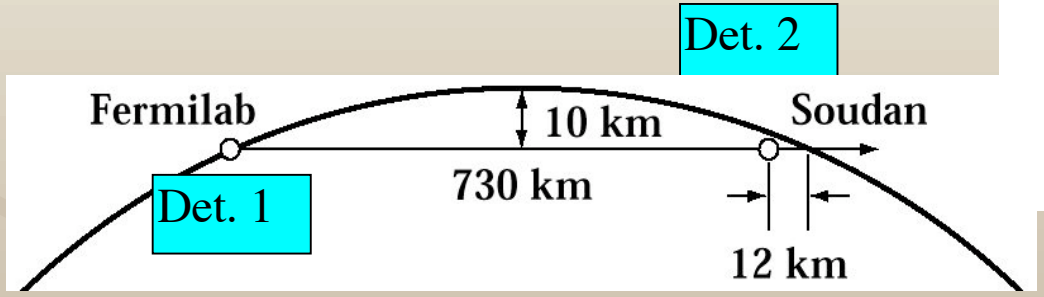


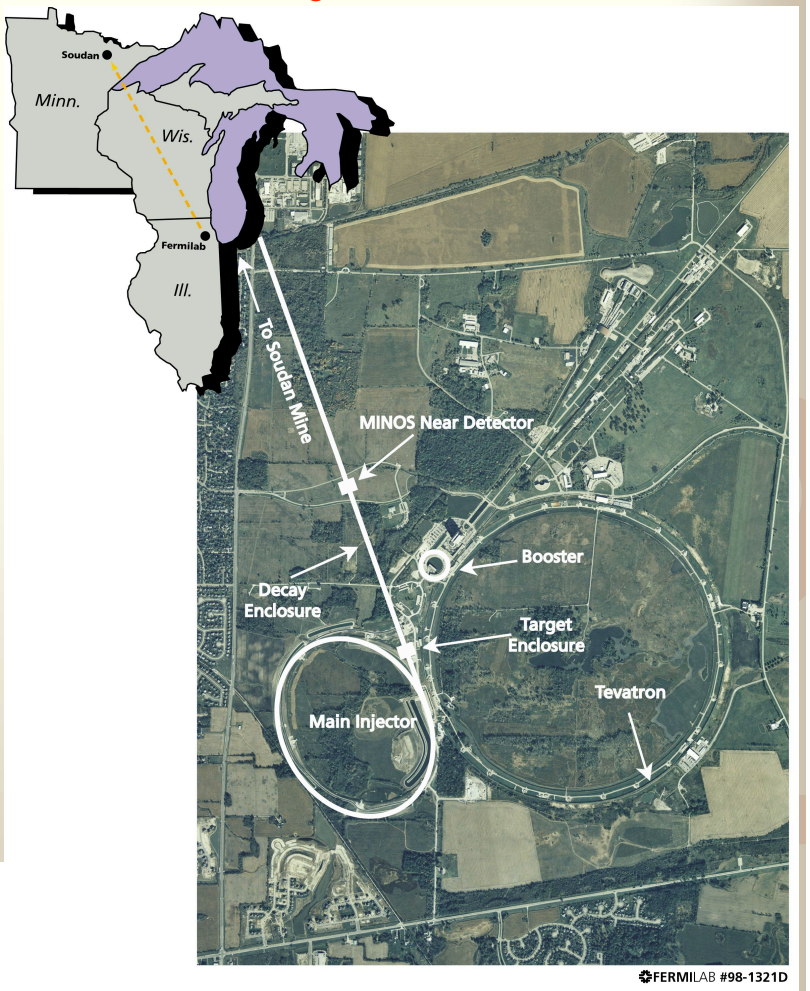
Spill

- RF = 53 MHz
  - Slow spill (over seconds)
    - I bunch every 19ns
      - For low intensity beams not every bucket is populated
    - Spill quality
      - Superbuckets-- difficult to extract beam uniformly
  - Single Turn Extraction (Neutrinos)
    - 8 GeV primary beam neutrinos-- <1.5 μsec
    - 120 GeV primary neutrinos-- <10 μsec

Neutrinos at the Main Injector

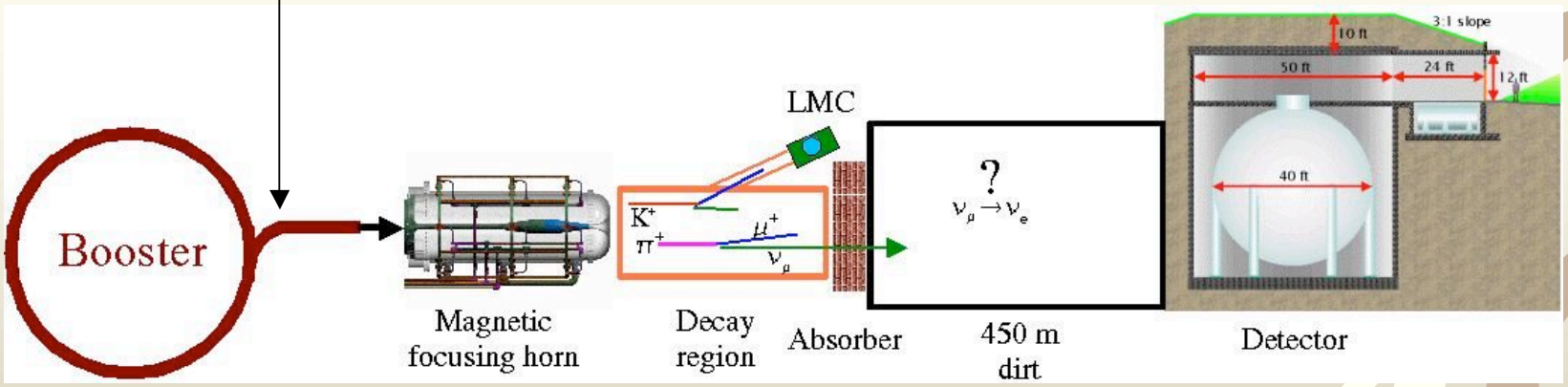






MiniBooNE

8 GeV neutrinos



ν_e Appearance

Colliders

- $P\bar{P}$
  - One beam pipe
  - Requires antiproton production==>time and reliability issue
  - No linear collider version
  - Energy shared between constituents
- PP
  - 2 machines
  - Crossing angles
  - Energy shared between constituents
- e^+e^-

  One beam pipe

  Full energy of the beam available for the collision
- ep
  - 2 machines

Center of Mass Energy

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$$s = (\underset{\sim}{P}_1 + \underset{\sim}{P}_2) \bullet (\underset{\sim}{P}_1 + \underset{\sim}{P}_2)$$

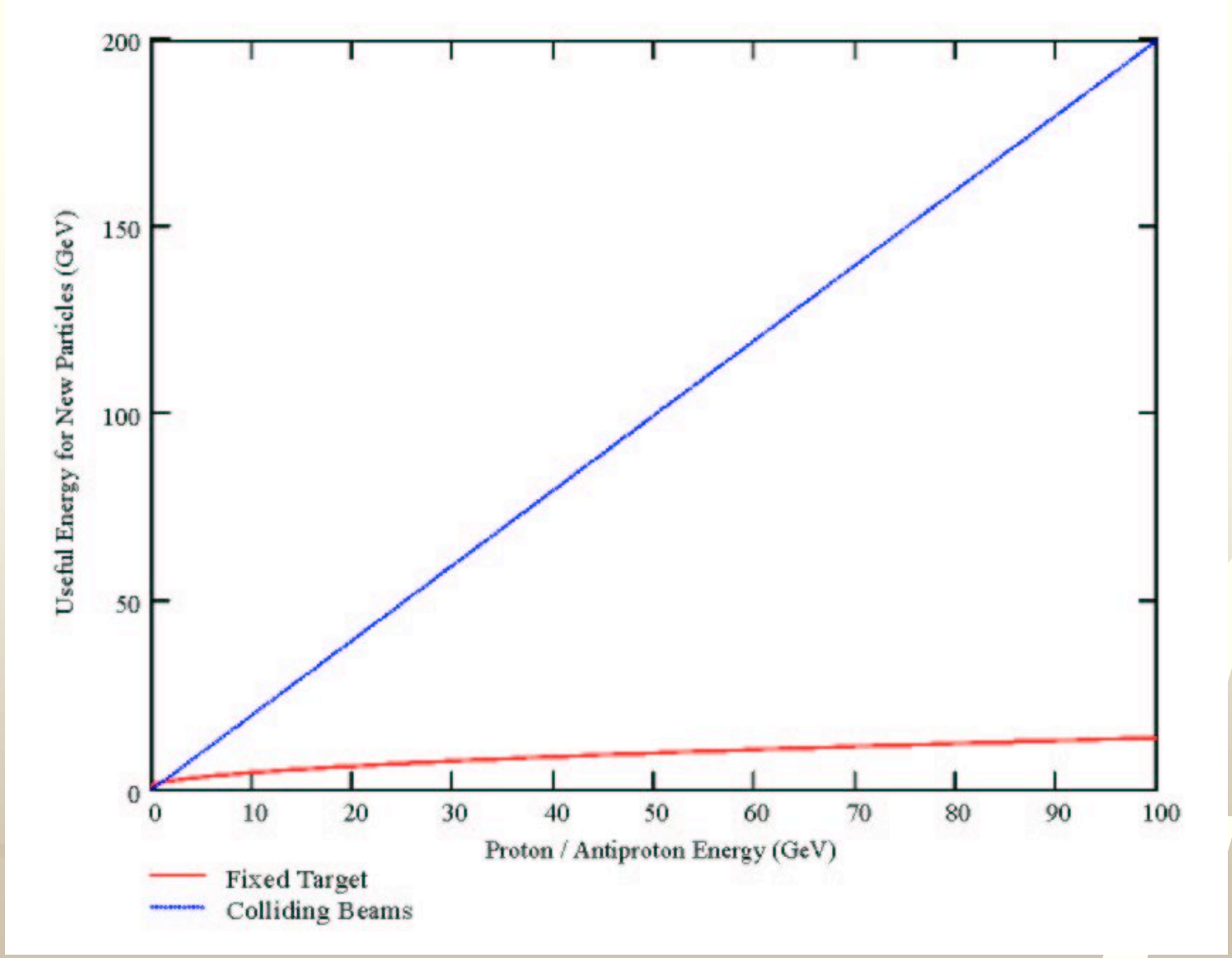
$$S = m_1^2 + m_2^2 + 2E_1E_2 + 2p_1p_2 \approx 2(E^2 + p^2)$$

$$\sqrt{s} \approx 2(980^2 + 980^2) = 1960 GeV \quad \text{Tev}$$

or

14000 GeV LHC

Available Energies



Luminosity

$$L = \frac{nfN_p N_A}{A}$$

n is the number of bunches

f is the revolution frequency

N_p and N_A are the number of protons and antiprotons in the beam

A is the area of the beam

$$L = \frac{nfN_p N_A}{A} F(\theta)$$

Where $F(\theta)$ depends on bunch length, crossing angle, and beam size as a function of z in the interaction region

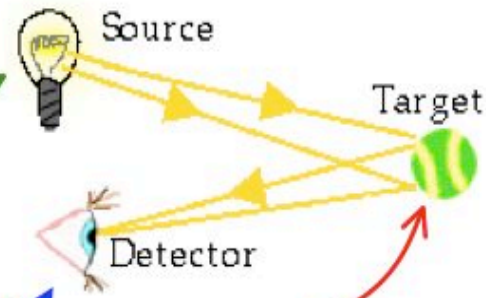
Some Numbers…

- For Tevatron operation,
  - $N_{protons} = 2\text{x}10^{11}$, $N_{antiprotons} = 4\text{x}10^{10}$,
  - $f = 36 \text{ x } (3\text{x}10^5 \text{ km/sec})/6 \text{ km}$,
  - $A = \pi\ (60\ \mu\text{m})^2 = \pi\ (0.0060\ \text{cm})^2$
  - ---> $L = 1 \text{ x } 10^{32}\ \text{cm}^{-2}\ \text{sec}^{-1}$
- Cross section of a proton/antiproton collision

  $\sim 6 \text{ x } 10^{-26}\ \text{cm}^2$
- So, we get, and wish to detect, about $6 \text{ x } 10^6$ collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store data at this rate (and they do!)
- Each proton/antiroton has energy of

  $980\ \text{GeV} = 980 \text{ x } 10^9 \text{ x } (1.6 \text{ x } 10^{-19}\ \text{J}) = 1.6 \text{ x } 10^{-7}\ \text{J}$
- So, *power* delivered in the collision region is only about

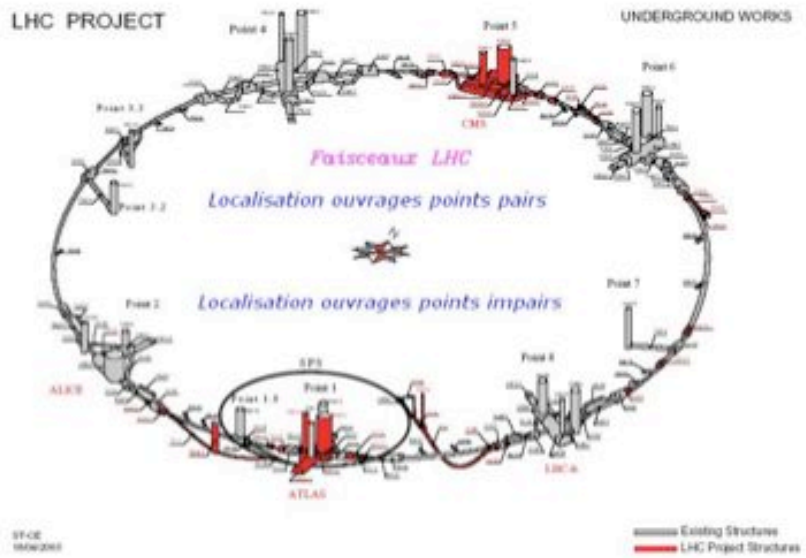
  $2 \text{ x } 1.6 \text{ x } 10^{-7}\ \text{J} \text{ x } 6 \text{ x } 10^6\ /\text{sec} \sim 2\ \text{watt!}$



Bunch Intensities

- Trade off between intensity per bunch and number of interactions per bunch
- In general, detectors must deal with more than one interaction per bunch

General Map

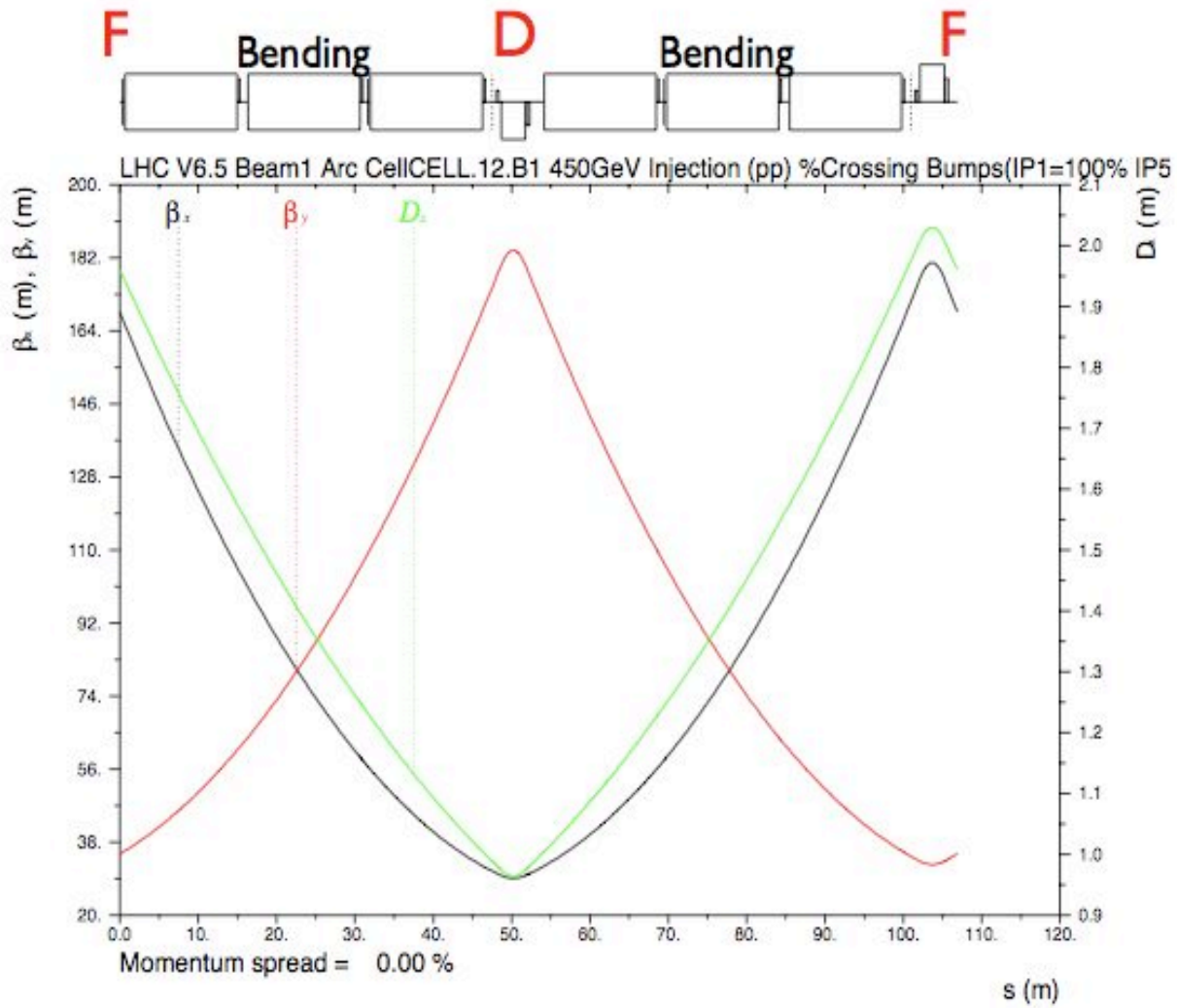


Underground Facilities

red = LHC project

rest = from LEP

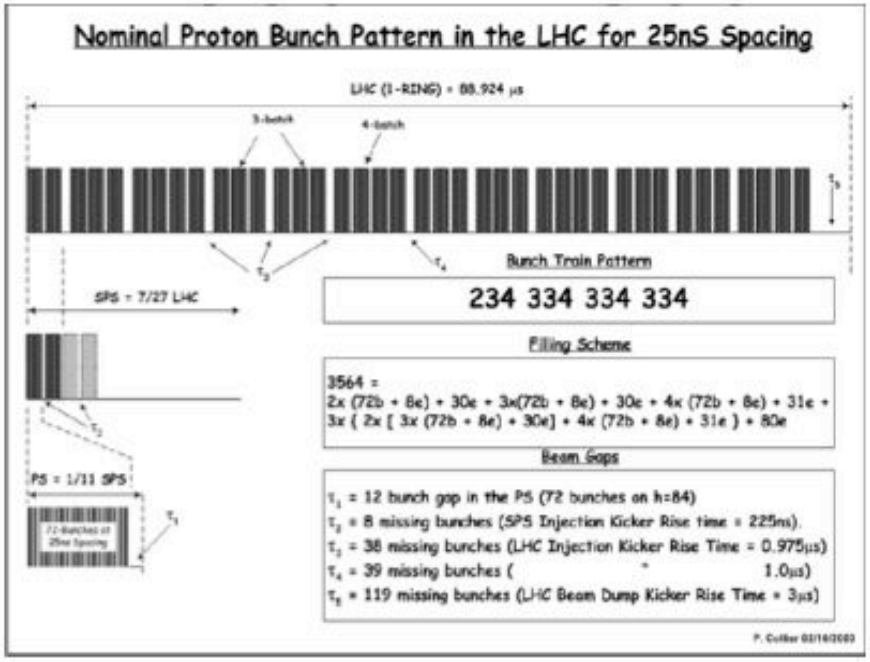
Standard Cell



Bunch Spacing

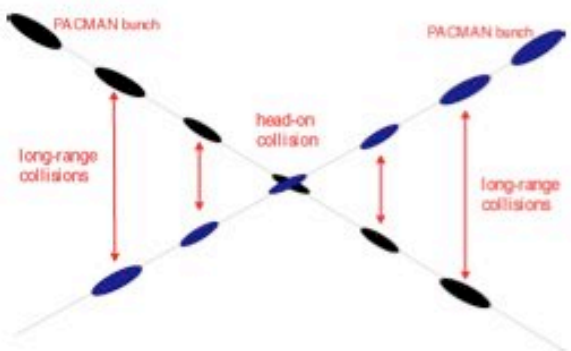
- Quoted as 25 nsec, but structure is more complicated due to filling scheme from the SPS.
- So, there will be various gaps created, with minimum spacing 25 nsec...

Hence, fewer bunches than simply 27km/7.5m ...



Why a Crossing Angle?

- Across each interaction region, for about 120 m, the two beams are contained in the same beam pipe
- Thus, there would be ~(120/(7.5/2)) ~ 30 bunch interactions through the region
- Want a single Head-on collision ***at*** the IP, but will still have long-range interactions on either side
- Beam size grows from IP, and so does separation; can tolerate beams separated by ~10 sigma
- $d/\sigma = \theta \cdot (\beta^*/\sigma^*) \approx 10$
  $\longrightarrow \quad \theta = 10 \cdot (0.017)/(550) \approx 300\ \mu\text{rad}$



Luminosity

- When adiabatically accelerated, the beam size will vary inversely to square root of momentum

$$\sigma^2 = \beta^* \, \epsilon_N \, / \, \gamma$$

β^*	= optical function of the accelerator
$\pi \cdot \epsilon_N$	= rms phase space area of particle oscillatons

$$\text{Tev: } \sqrt{(0.35 \text{ m})(4 \text{ mm-mr})/1000} = 66 \ \mu\text{m}$$
$$\text{LHC: } \sqrt{(0.55 \text{ m})(4 \text{ mm-mr})/7000} = 17 \ \mu\text{m}$$

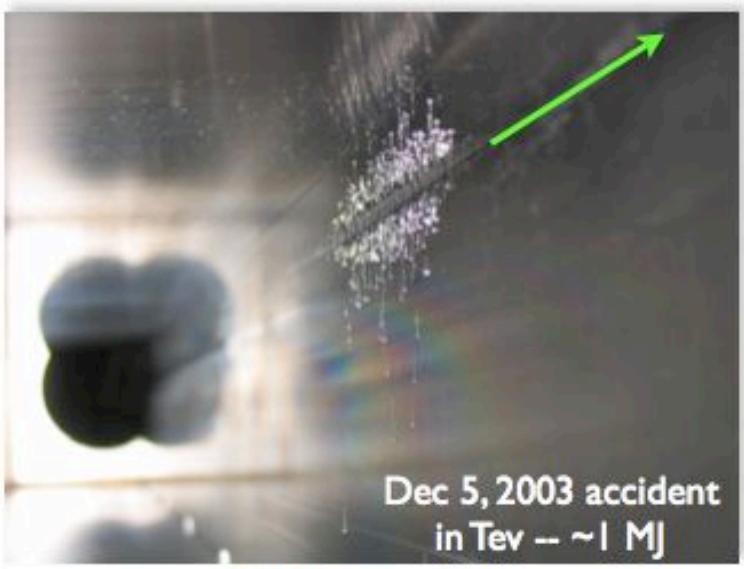
- Put it together, requires 10^{11}/bunch...

for $N \approx 10^{11}$,

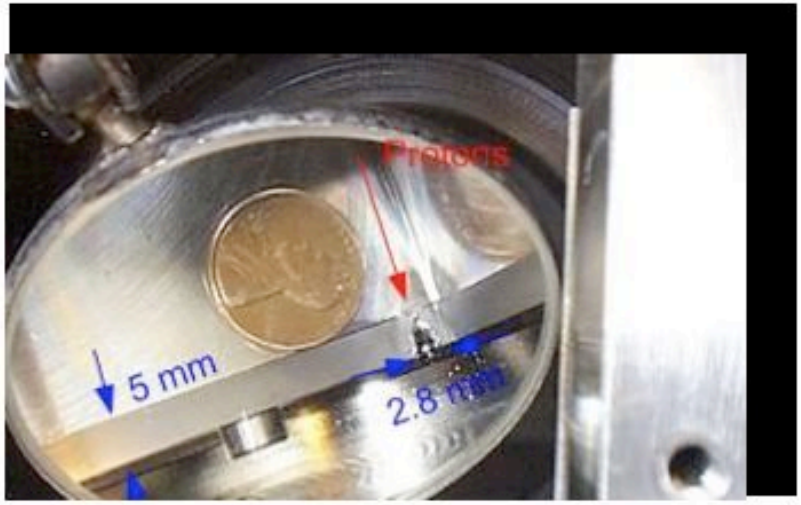
$$\mathcal{L} = \frac{(10^9/25)(10^{11})^2}{4\pi(17 \cdot 10^{-4})^2 \text{cm}^2 \text{sec}} \cdot 0.85 \approx 10^{34} \ \text{cm}^{-2}\text{sec}^{-1}$$

Major Accelerator Issues

- Stored Energy
  - Tevatron = 1-2 MJ per beam; LHC = **360** MJ !
  - extensive collimation and protection system



E03 1.5m collimator



D49 target

Major Accelerator Issues

- IR Protection
  - not only stored energy of beam, but also the product power at the IP:

$$(60\ \mathrm{mb})(10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1})(2\times 7\cdot 10^{12}\ \mathrm{eV}) = 1.3\ \mathrm{kW}$$

significant fraction of this power will be deposited into SC magnets at each IR!

Certainly an issue for future increases in luminosity

The Future…

Compare hadrons and leptons

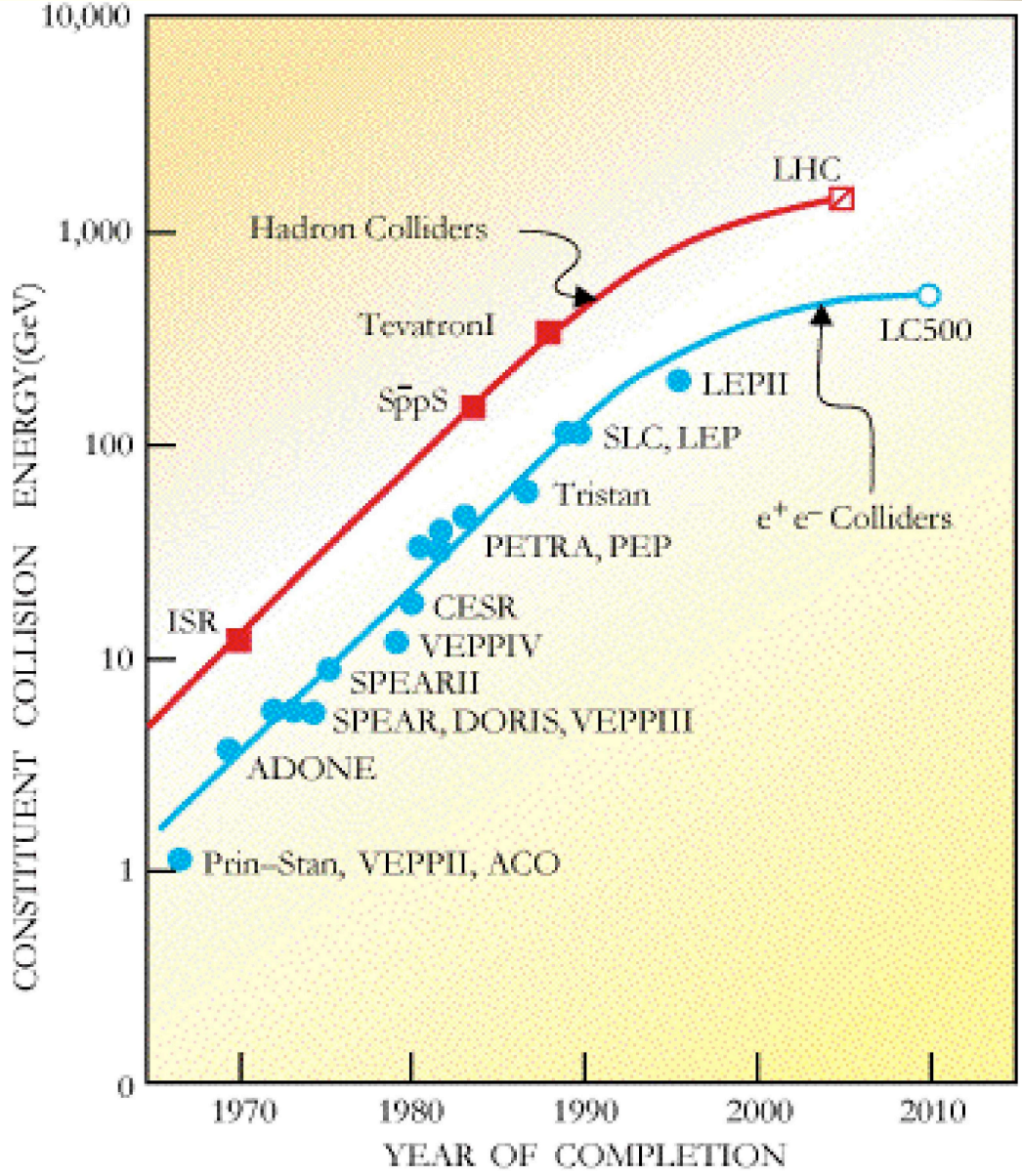
- constituent hadron collision energy is about 1/10 of total hadron beam energies (protons made up of quarks!)
- constituent lepton collision energy is all of total lepton beam energies

Great growth in accelerator- based science during past half-century.

Slower in recent years…

- projects have become large
- necessarily international
- using same old technology

However, present projects require many people and offer many opportunities



Wrap Up

- Accelerator physics is an intricate application of classical physics
- I hope I have familiarized future experimenters with accelerator issues and parameters
  - I hope I have attracted a few people to accelerator physics
- Clever ideas are needed to go to higher energies in the future