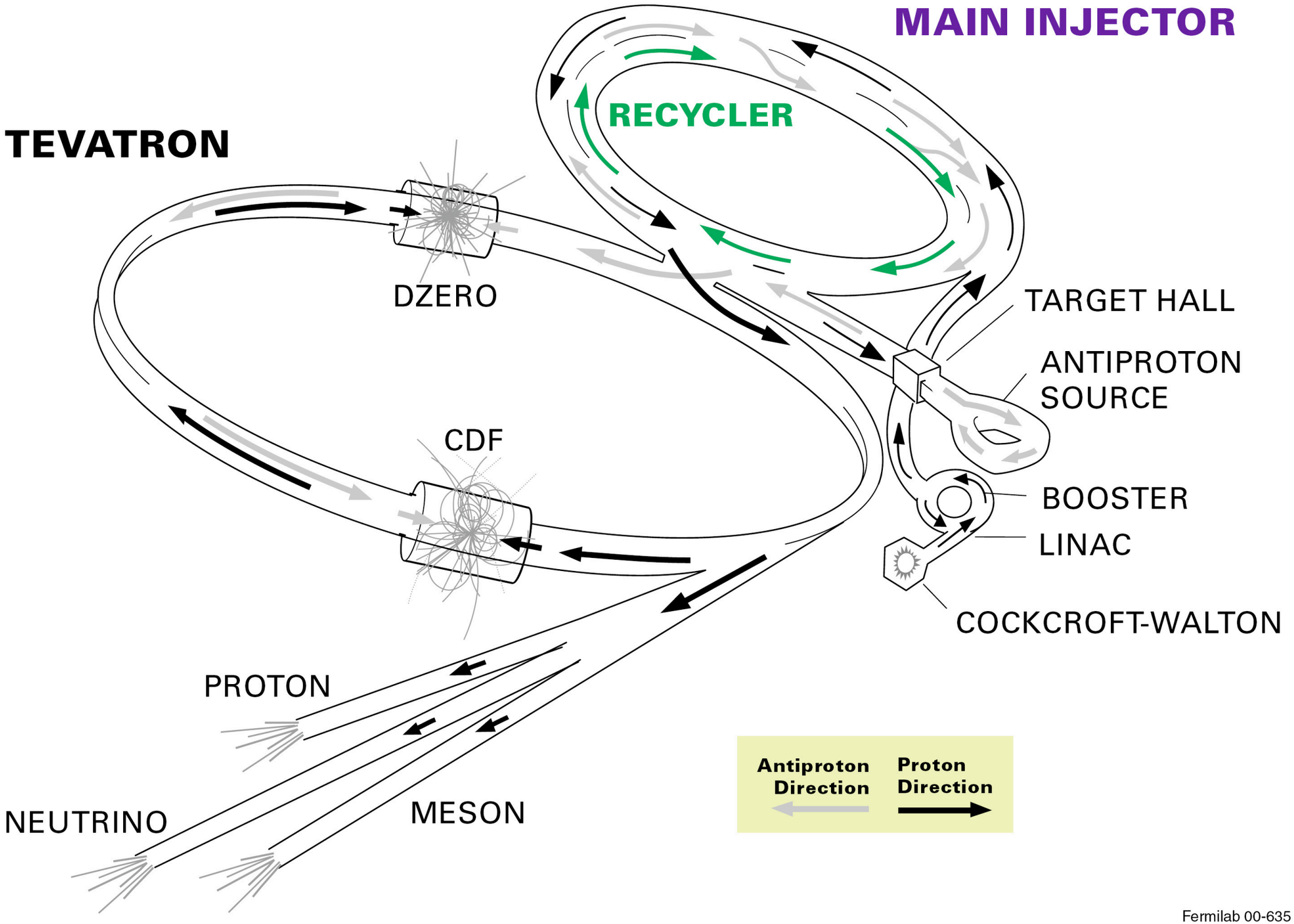
The Fermilab Accelerator Complex

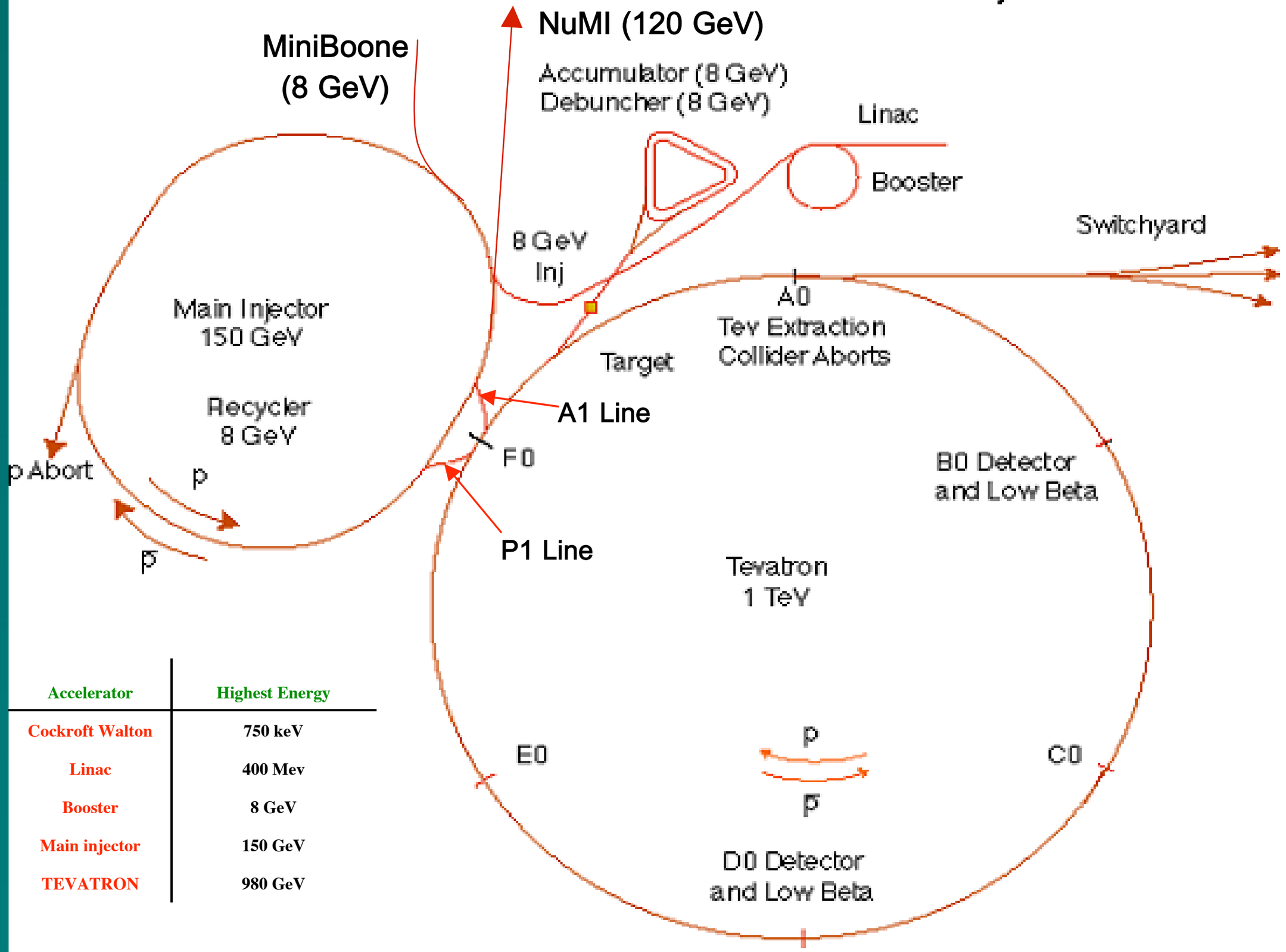
R. Dixon

FERMILAB'S ACCELERATOR CHAIN



Fermilab 00-635

FermilabTevatron Accelerator With Main Injector



Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

Physics Program

- SY120 Test Beam Program
  - Meson Test area
  - Beams 1 GeV to 120 GeV
- Neutrino Program
  - Booster Neutrino Beam using 8 GeV protons
  - NuMI/MINOS program using 120 GeV protons from the Main Injector
- Tevatron Collider Program
  - Proton-antiproton Collisions at 980 GeV
  - Two interaction regions occupied by the CDF and D0 detectors

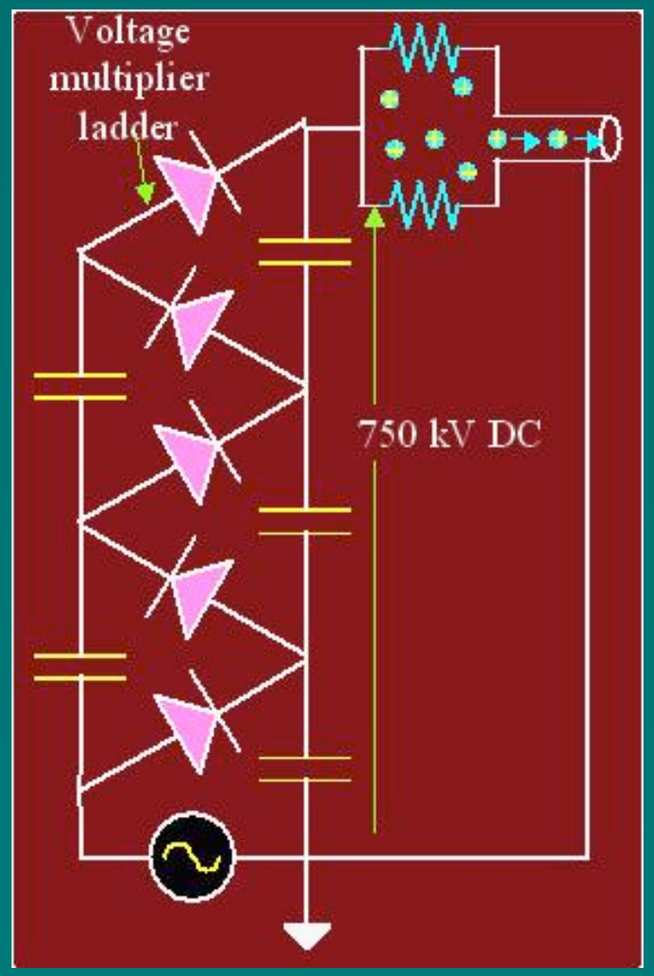
Fermilab's Accelerators

The Fermilab Accelerator Complex is made up of a complex 'chain' of accelerators, some in series, some in parallel to accelerator protons, produce antiprotons and store both

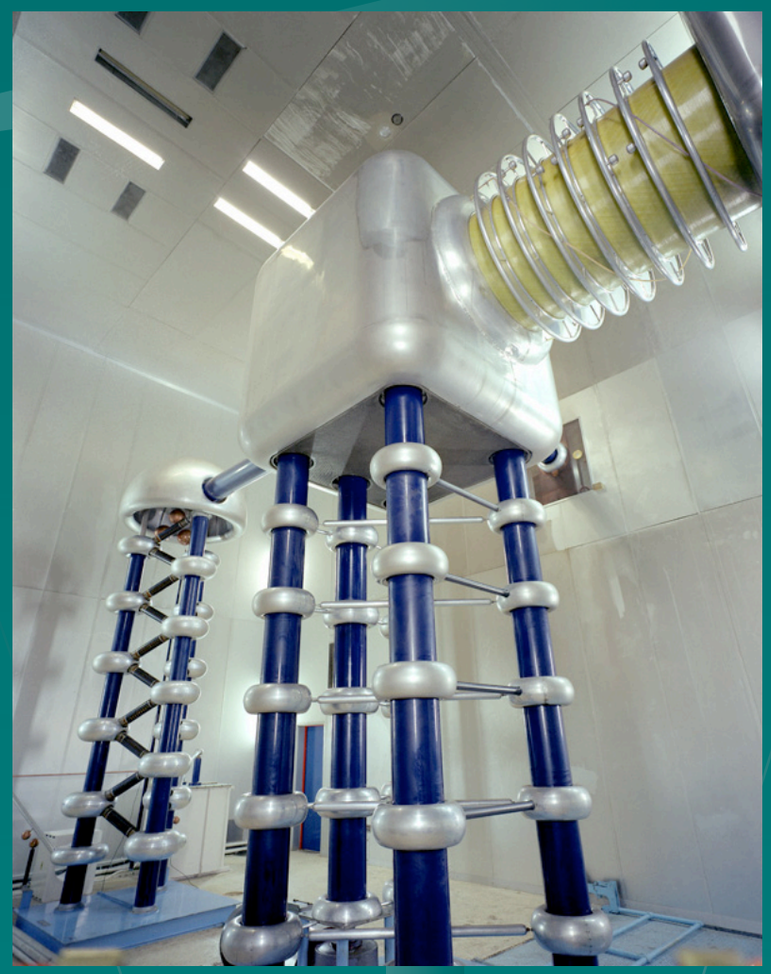
1) Cockcroft-Walton source and "pre-accelerator" (Preac) 0 to 750 keV
2) Linear Accelerator (Linac) 0.75 MeV - 400 MeV
3) Booster Synchrotron 400 MeV - 8000 MeV (= 8 GeV)
4) Main Injector Synchrotron 8 GeV - 150 GeV
5) Tevatron Synchrotron 150 GeV - 1000 GeV (= 1 TeV) (*actually*, operates at 0.98 TeV)
6) Antiproton Debuncher-- 8 GeV
7) Antiproton Accumulator-- 8 GeV
8) Anitiproton Recycler-- 8 GeV
9) Pelletron (electrons at 4.8 MeV)

Cockroft Walton

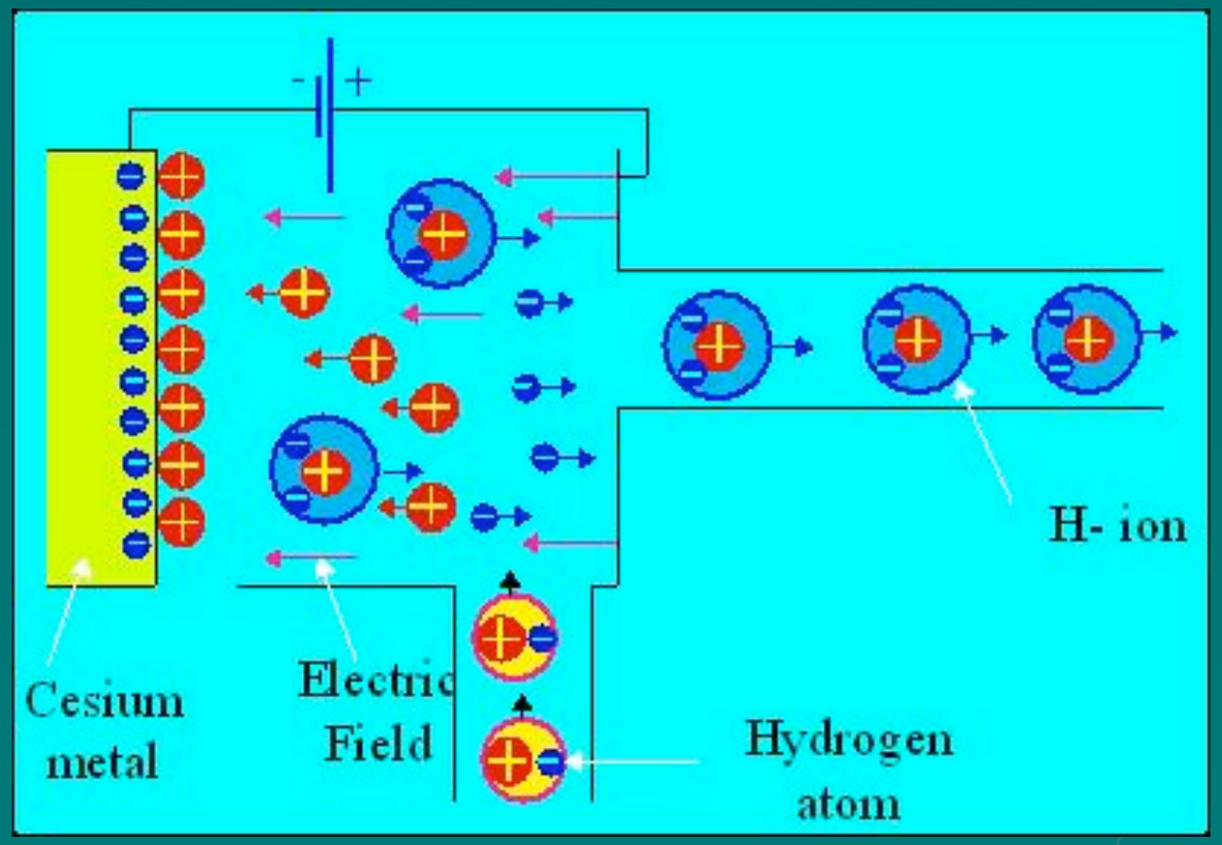
- Two 750 KeV H^- ma sources
- Beam is injected into the Linac from either source



Converts AC voltage V to DC voltage n x V

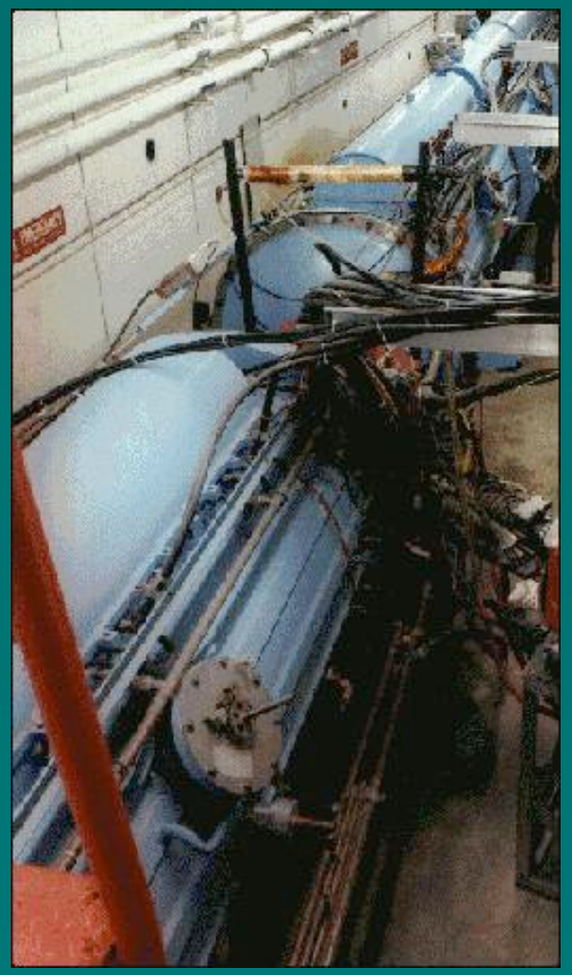


H^- Source



- Hydrogen is drawn to the cesium surface
- Cesium gives up an electron easily
- Some hydrogen atoms with 2 electrons are knocked off the cesium by incoming Hydrogen ions

Linac

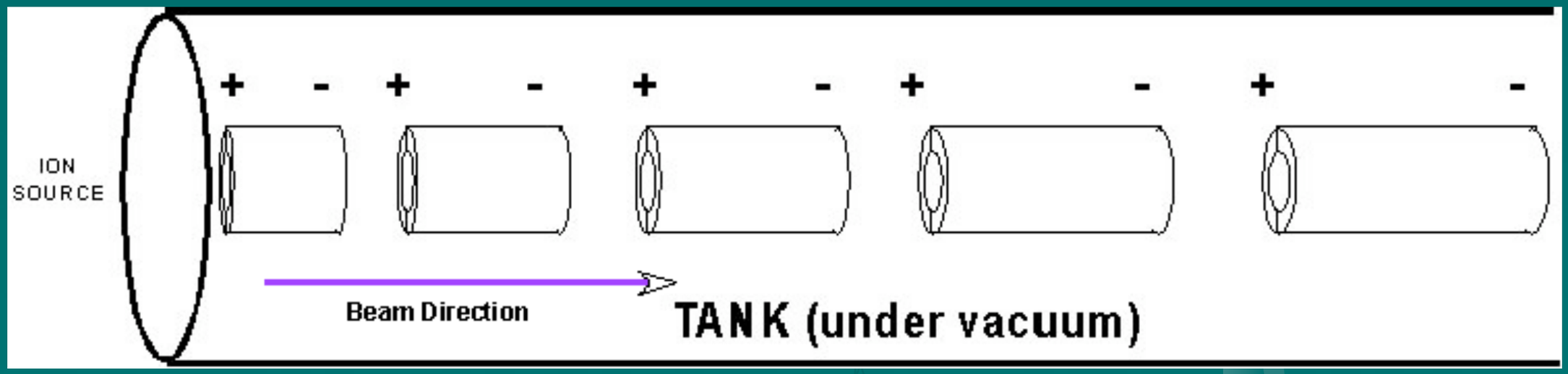


Linac Tank

Inside Linac Tank
Upstream Drift Tubes

Downstream Side-Coupled Cavities

Drift Tube Linac



- Drift Tube Kinetic Energy -- 200 MeV
- Total Linac Kinetic Energy-- 400 MeV
- RF Frequency Drift Tube Portion-- 200 MHz
  - Five 5- Megawatt triode power amplifiers
- RF Frequency of Side-Coupled Portion-- 805 MHz
  - Seven 12 Megawatt Klystrons
- Bunch spacing-- 5 ns
- Pulse length (Max) 50 ms (typical-- 20 ms or 4000 bunches)
- Current ~ 36 ma

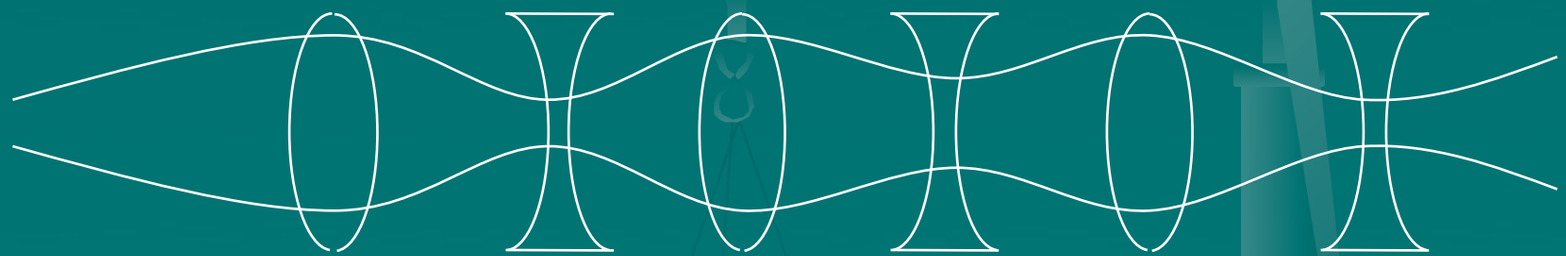
8 GeV Booster Synchrotron

- Ramps at 15 Hz with ~ 10 cycles filled with beam
  - LC resonant circuit
- Multi- turn injection of H^- from the Linac
  - H^- stripped on first turn for multi turn injection
- Radius = 75 meters
- Number of bunches = 84
- Protons accelerated to 8 GeV (Kinetic energy) ~ .99c
- Final RF Frequency = 53 MHz
  - Slurs at ~ 1 GHz per second
- Provides protons to Main Injector
- Provides protons to 8 GeV neutrino target (BNB)

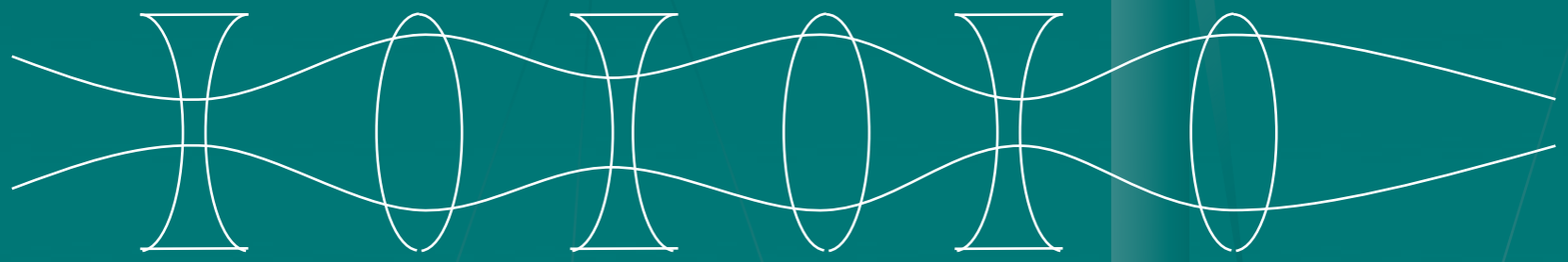
Alternating Gradient Focusing

- By alternating the polarity of the Quadrupole magnets, they serve to alternately focus and defocus the beam, keeping it stable in all directions simultaneously

Left/Right

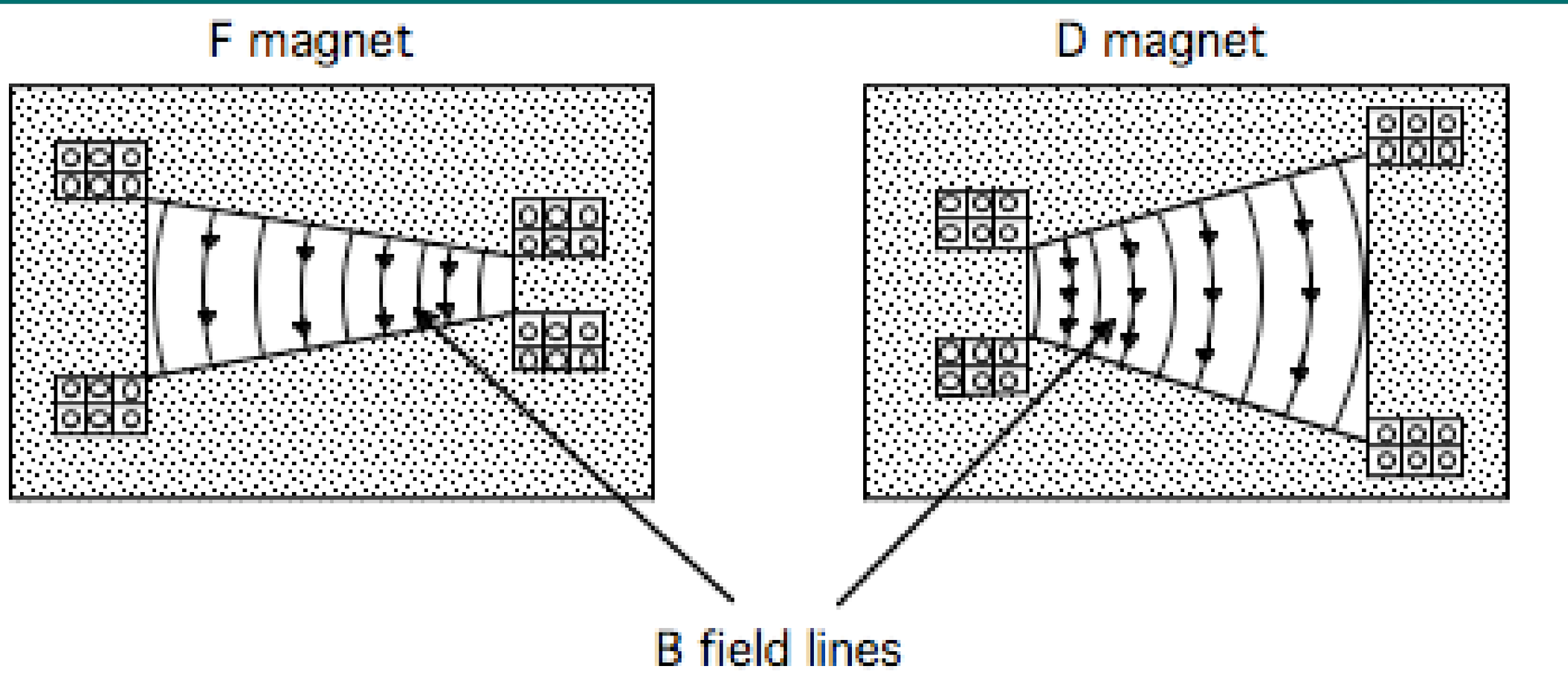


Up/Down

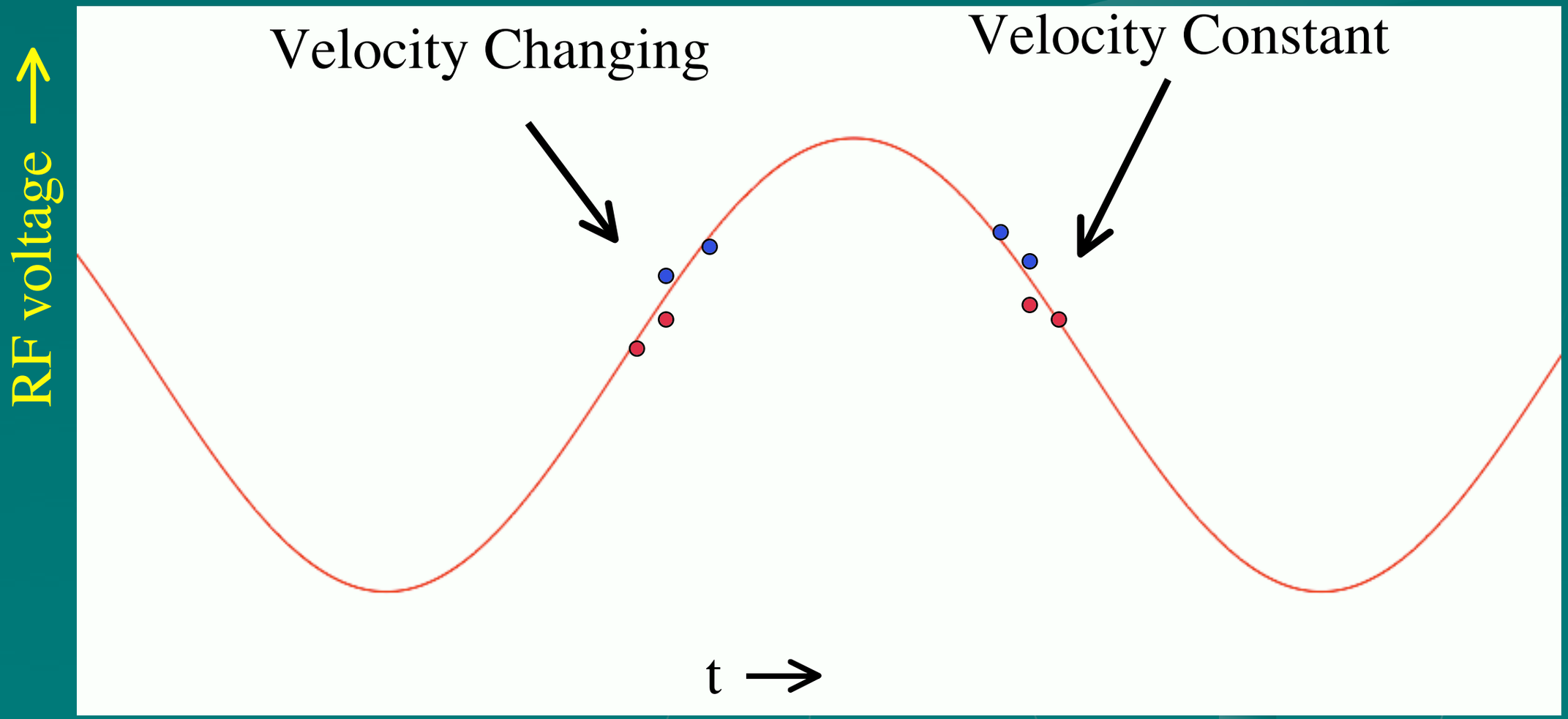


- Smaller magnets are used to fine-tune the beam trajectory, and to perform special orbit manipulations
  - Note: The beam in the Tevatron, for example, is only ~1 mm wide! Its orbit is controlled to a fraction of a mm! Yet, the orbit itself is 6.28 km (4 mi) around!

Combined Function Dipoles



Phase Stability



Stable area = RF Bucket

8 GeV Booster Synchrotron

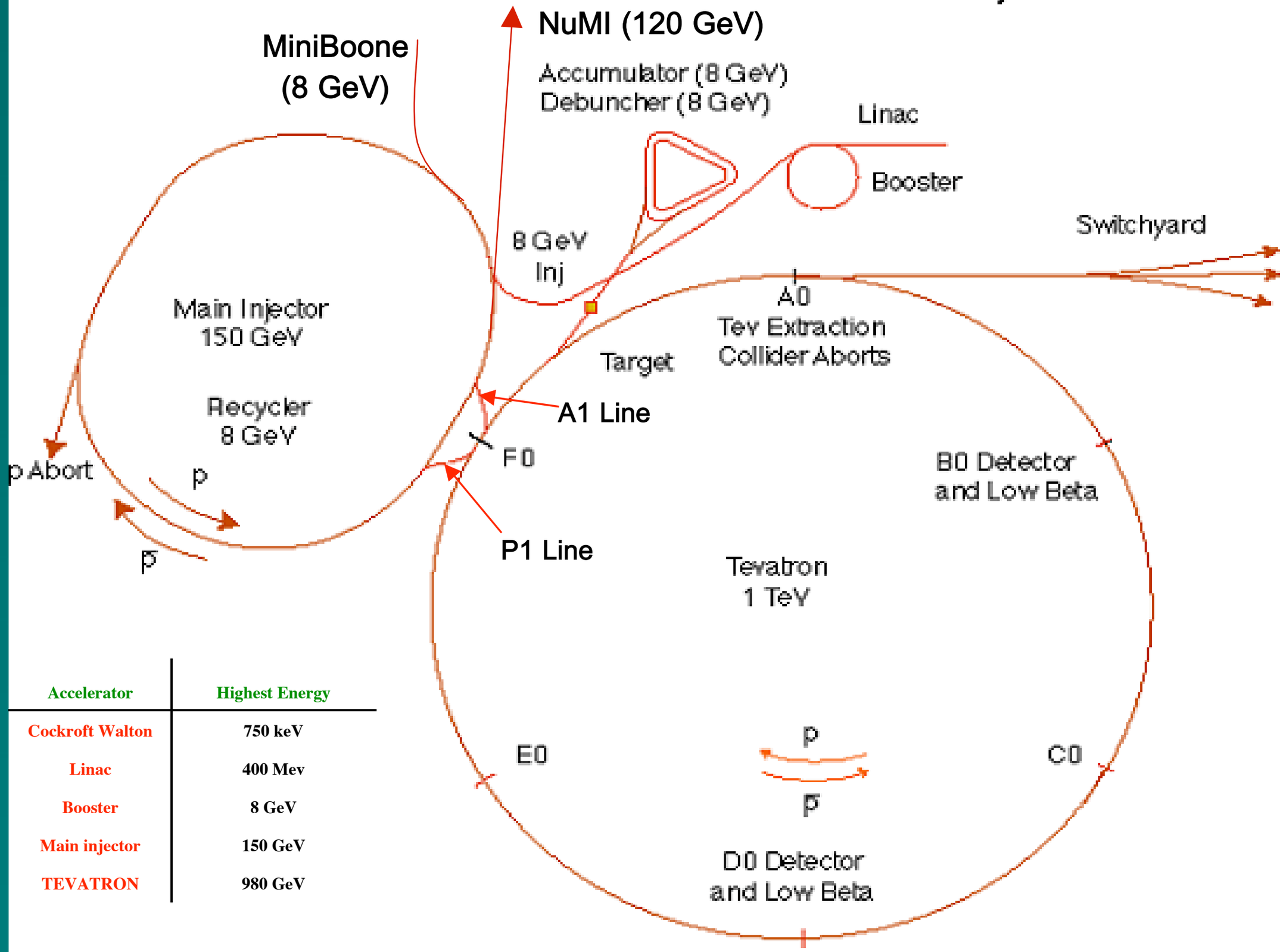
Combined function magnets

RF Cavities

Main Injector

- 8 GeV to 150 GeV
- 53 MHz Coalescing to 2.5 MHz
- Supplies beam to
  - Antiproton target--120 GeV protons
  - Neutrino beam (NuMI)-- 120 GeV protons
  - Tevatron Collider-- 150 GeV coalesced protons from Booster+ 150 GeV coalesced antiprotons from Recycler
  - Recycler-- 8 GeV antiprotons from the Accumulator
  - SY120 test beam area-- 120 GeV protons

FermilabTevatron Accelerator With Main Injector



Accelerator	Highest Energy
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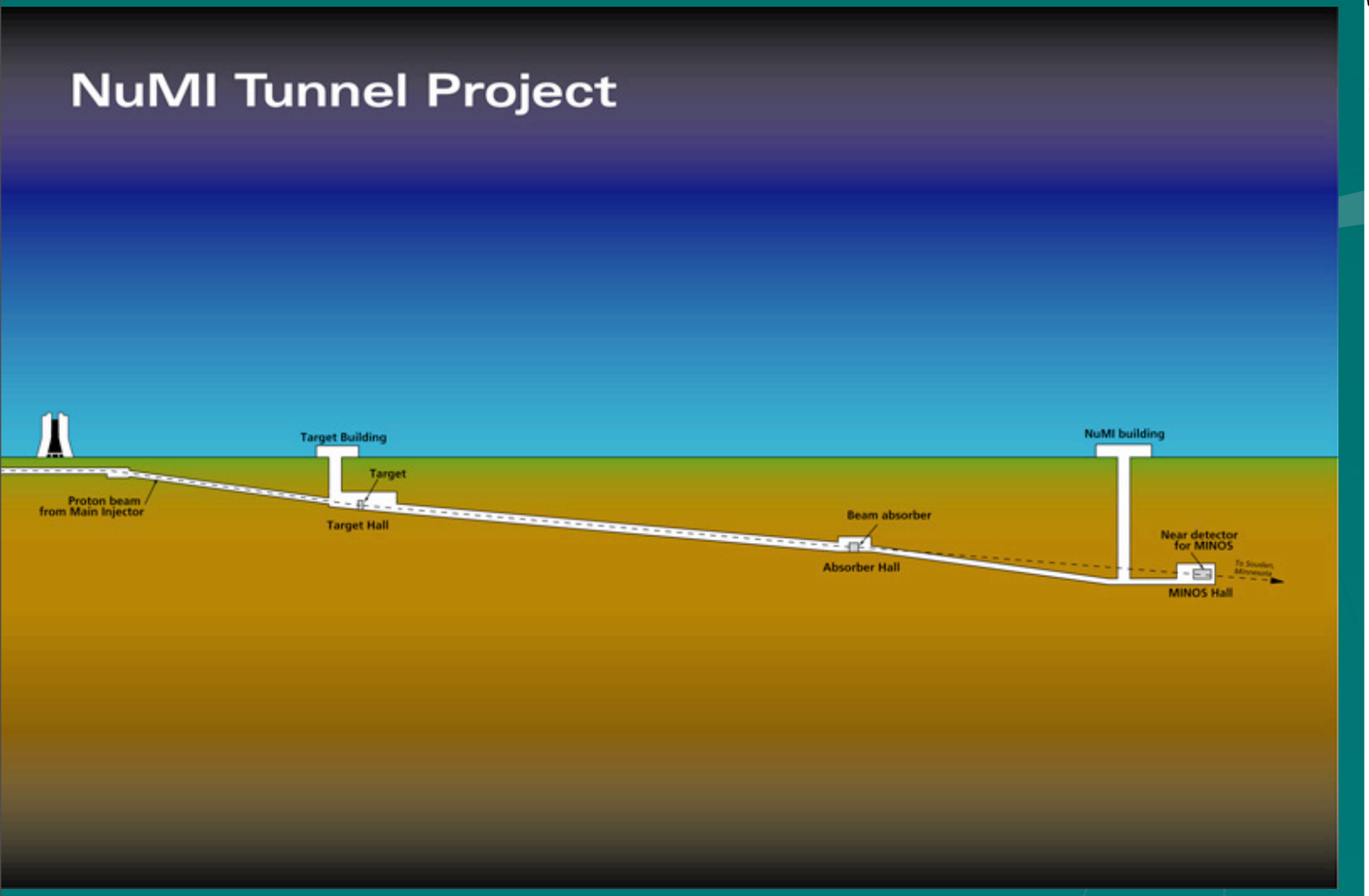
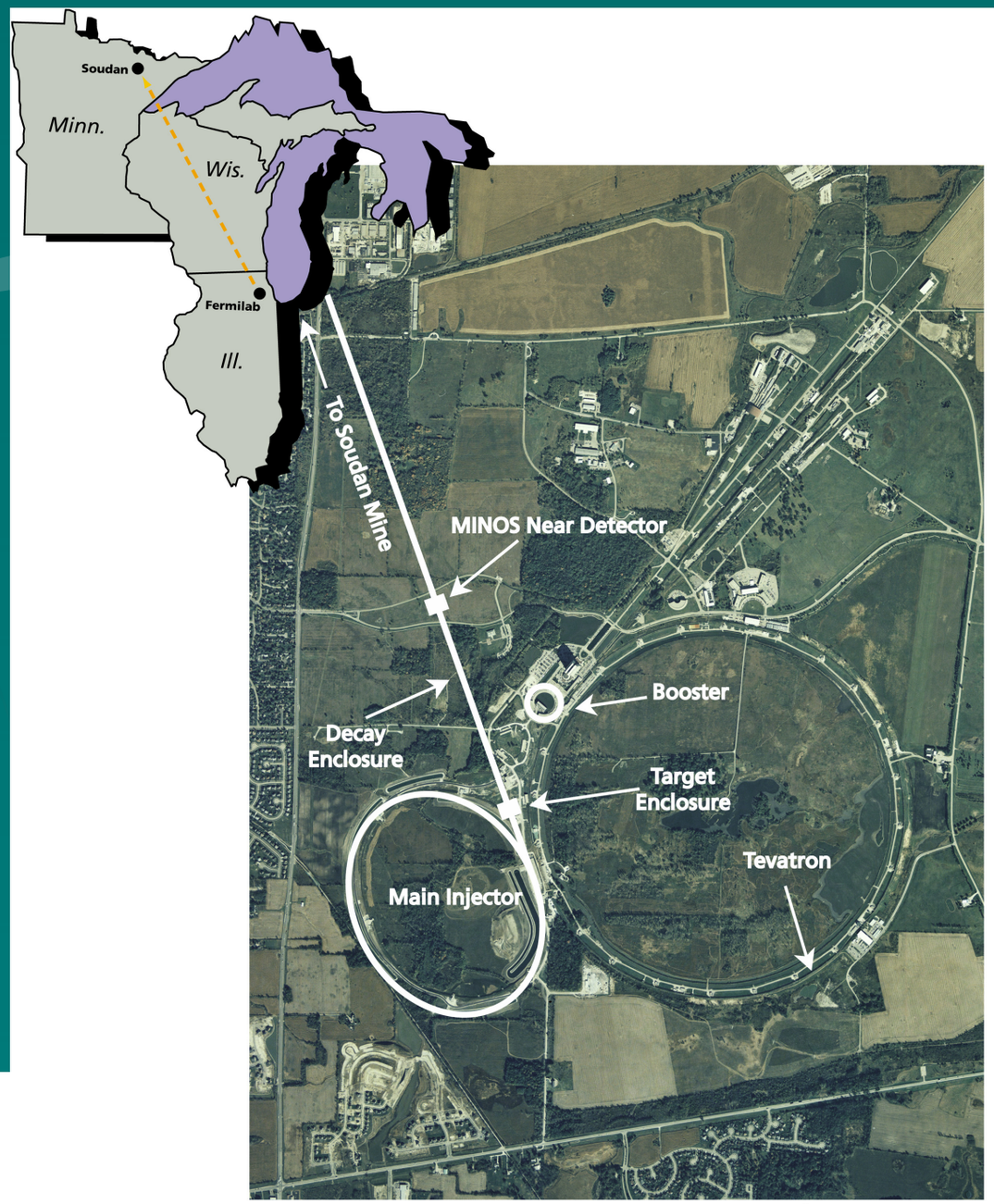
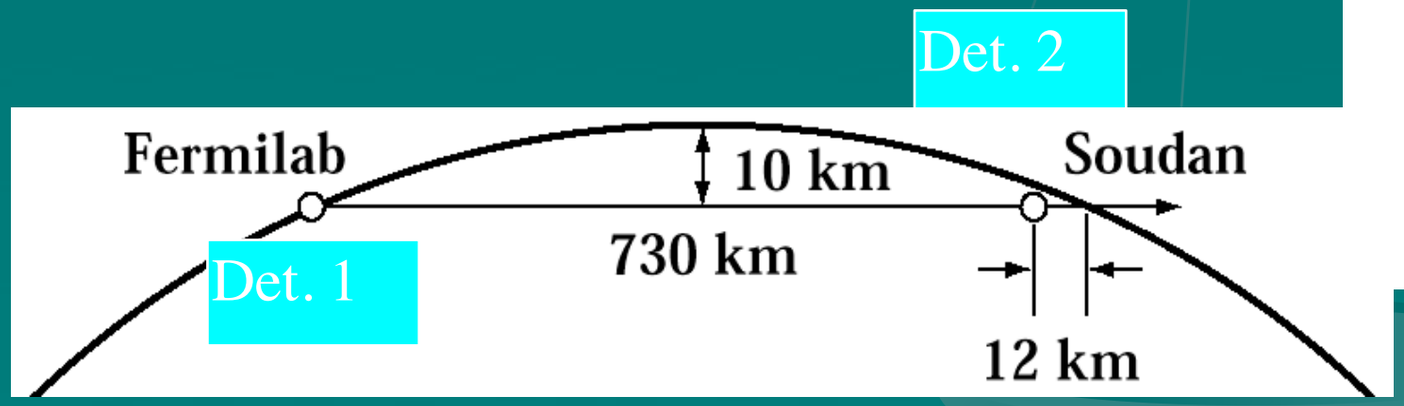
TEVATRON	980 GeV

Main Injector/Recycler

Neutrinos at the Main Injector



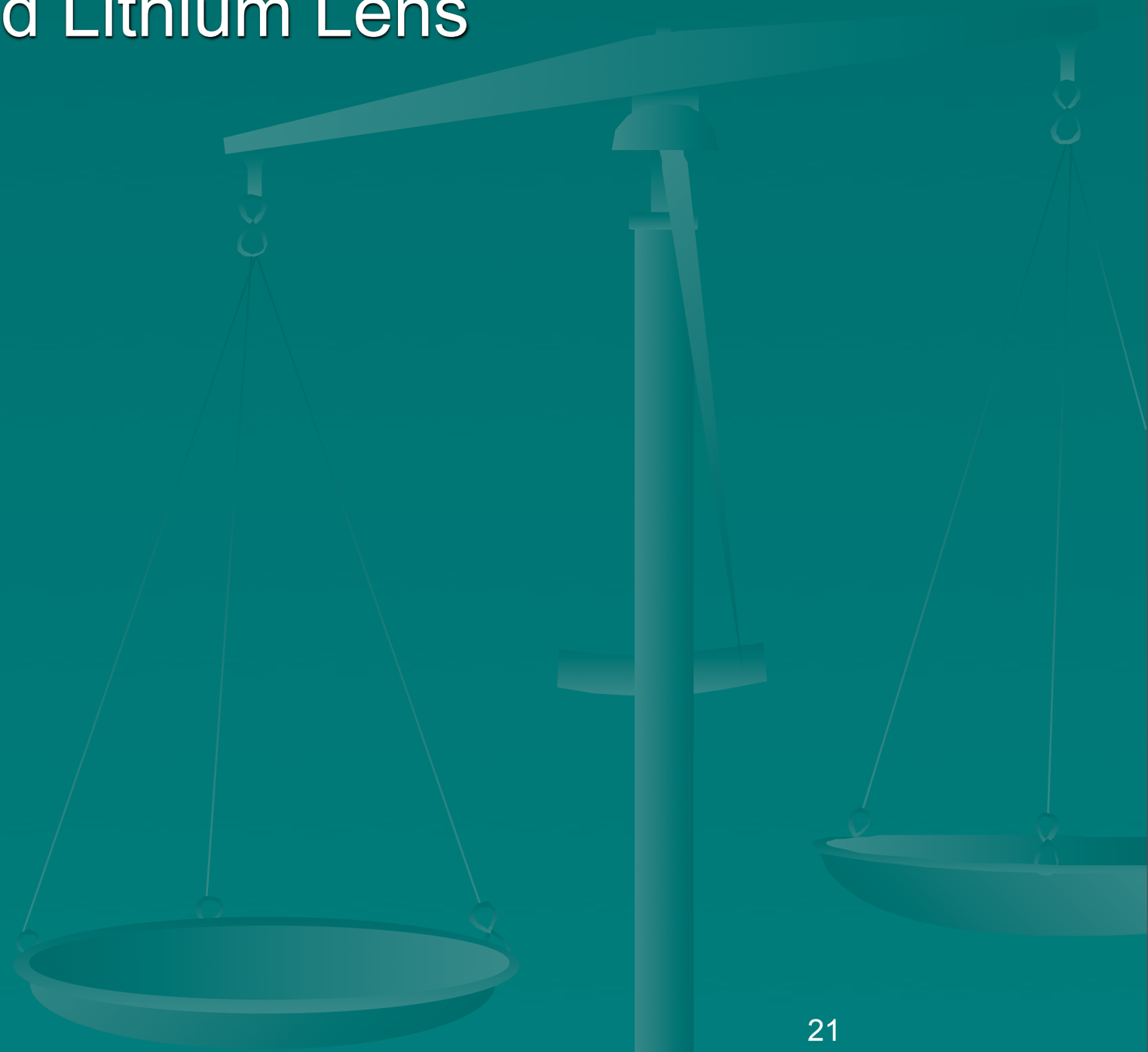




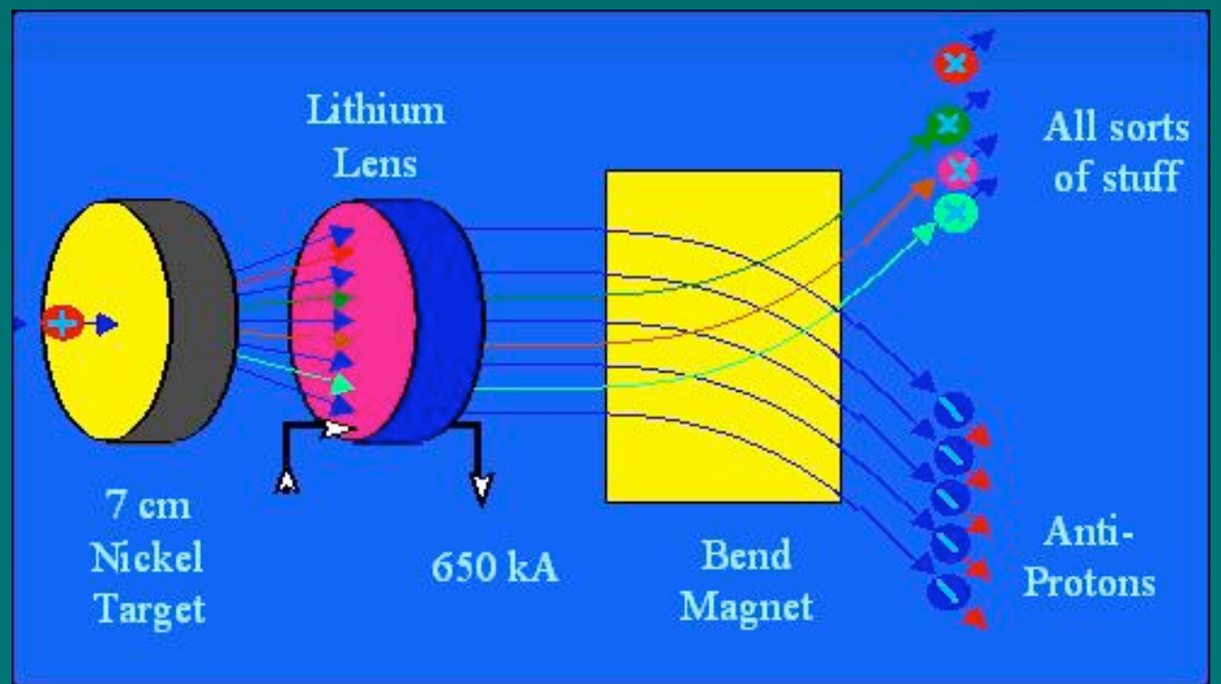
Antiproton Source

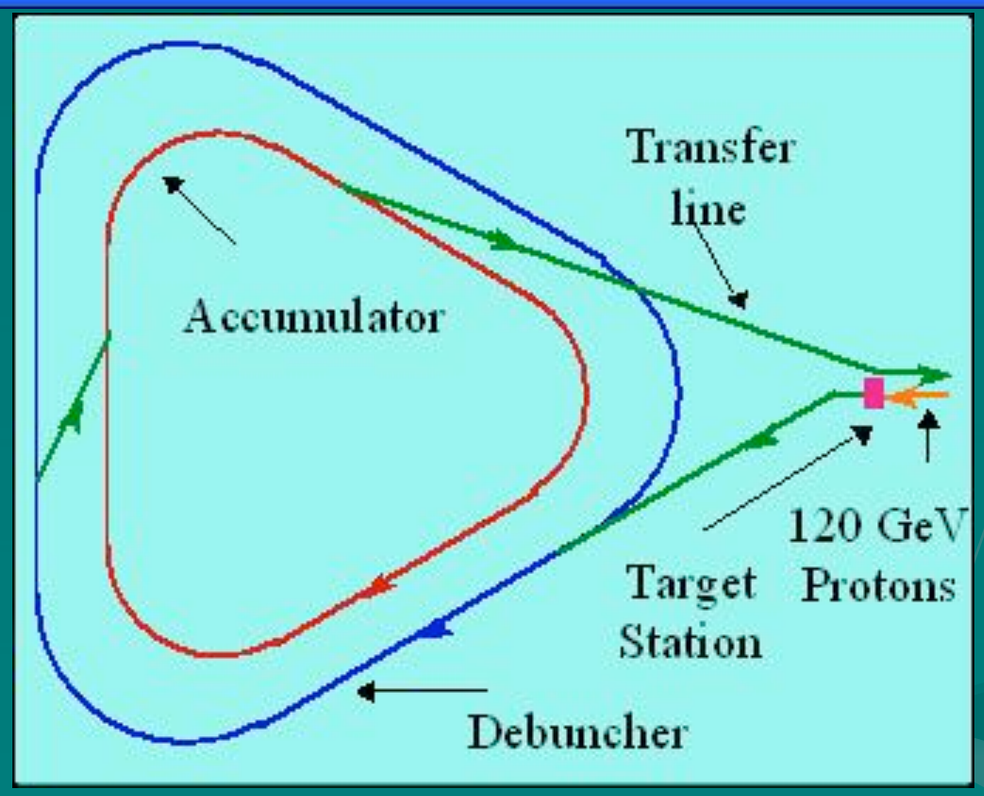
Antiproton Source

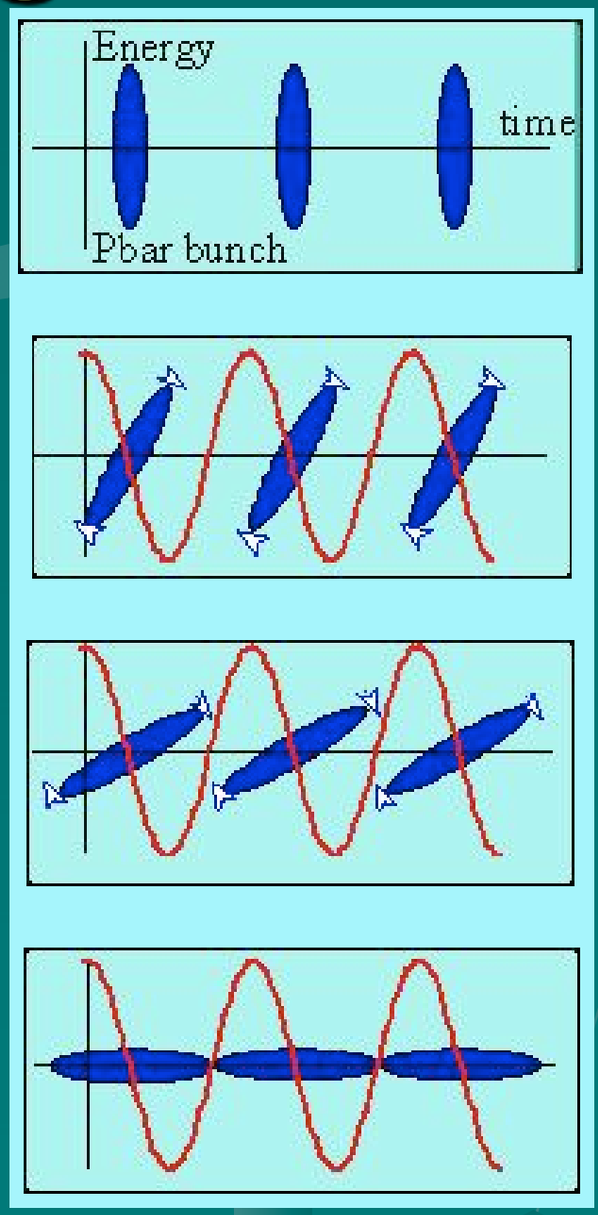
- Antiproton target and Lithium Lens
- Debuncher
  - 53 MHz
  - 8 GeV
  - Bunch rotation
  - Stochastic cooling
- Accumulator
  - 53 MHz
  - 8 GeV
  - Stochastic cooling
  - Stacktail



Producing and Collecting Antiprotons

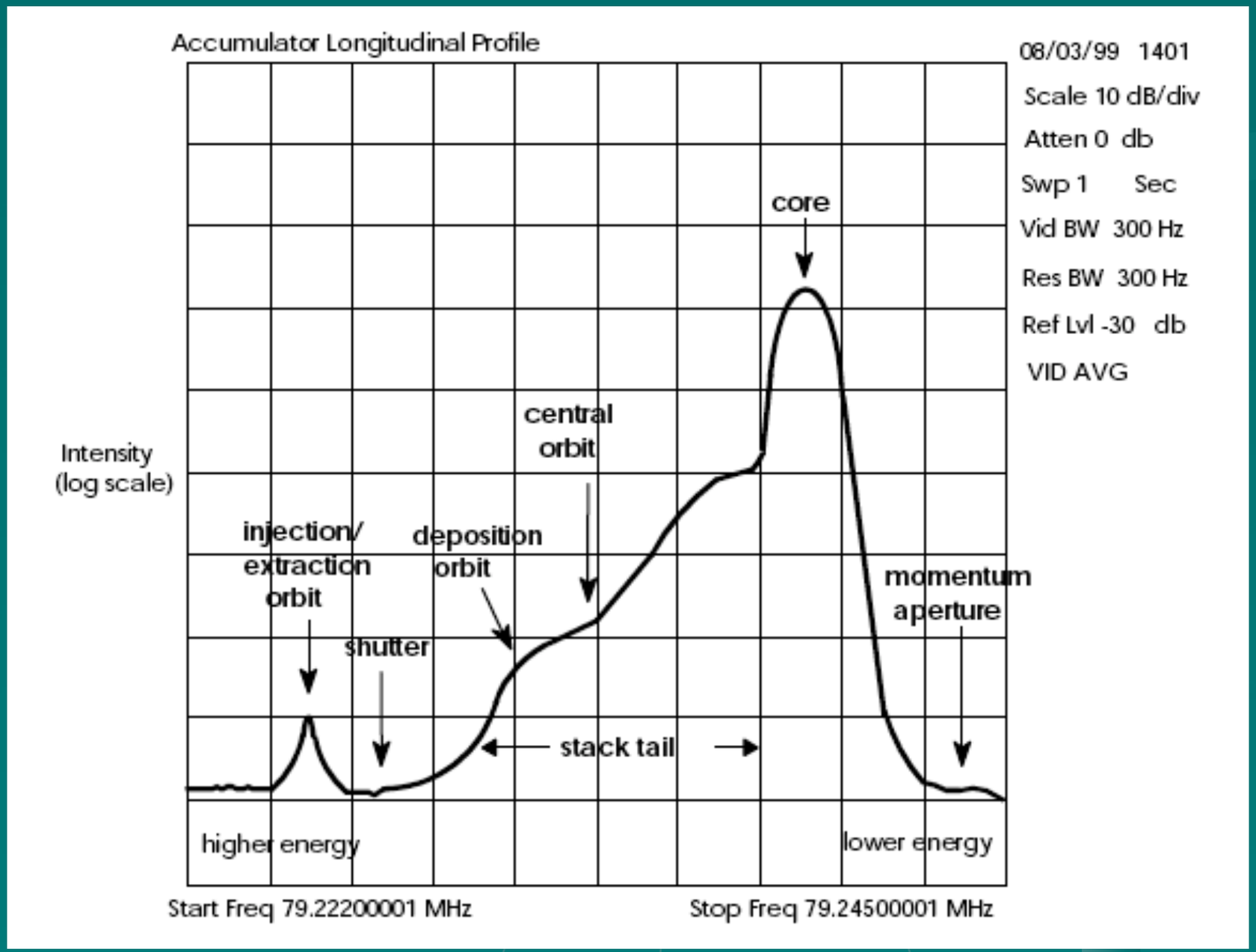






Debuncher Bunch Rotation

Cooling Antiprotons



Debuncher and Accumulator

Recycler and Pelletron

- Purpose: To stash and cool antiprotons from the Accumulator using stochastic cooling and electron cooling
- Located in the Main Injector Tunnel
- Recycler
  - 8 GeV
  - Permanent magnet dipoles
  - Pelletron for Electron Cooling
  - Beam held in RF barrier buckets for cooling
- Recycler receives antiprotons from the accumulater via the Main Injector
- Antiprotons are accumulated, stored, and cooled for injection into the Tevatron via the Main Injector

Pelletron

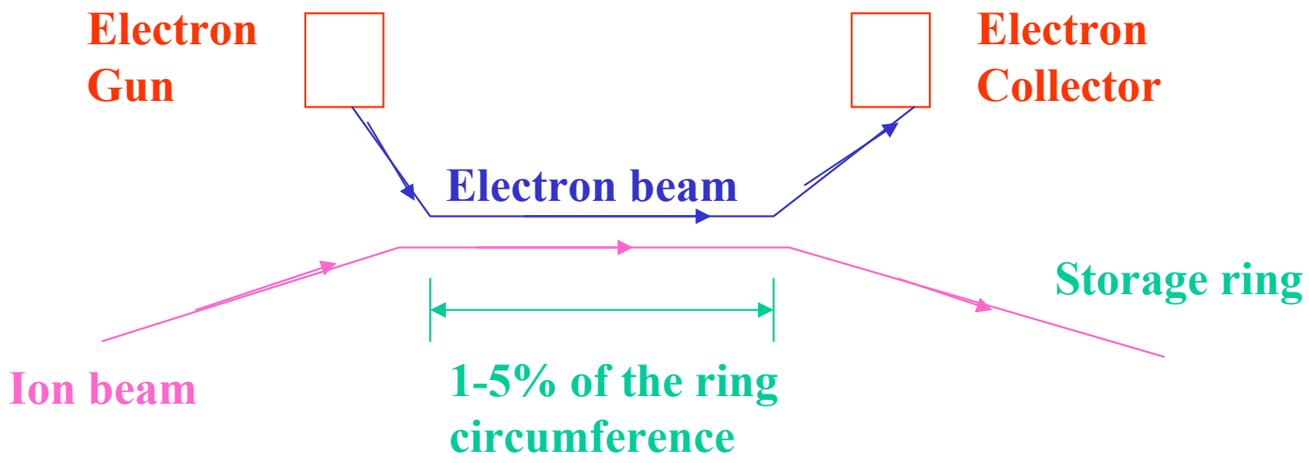
- 4.8 MeV electrons injected into 8 GeV antiproton beam in the Recycler and extracted after 20 meters
- Electron beam provides longitudinal cooling for the Antiprotons

Electron Cooling

How does electron cooling work?

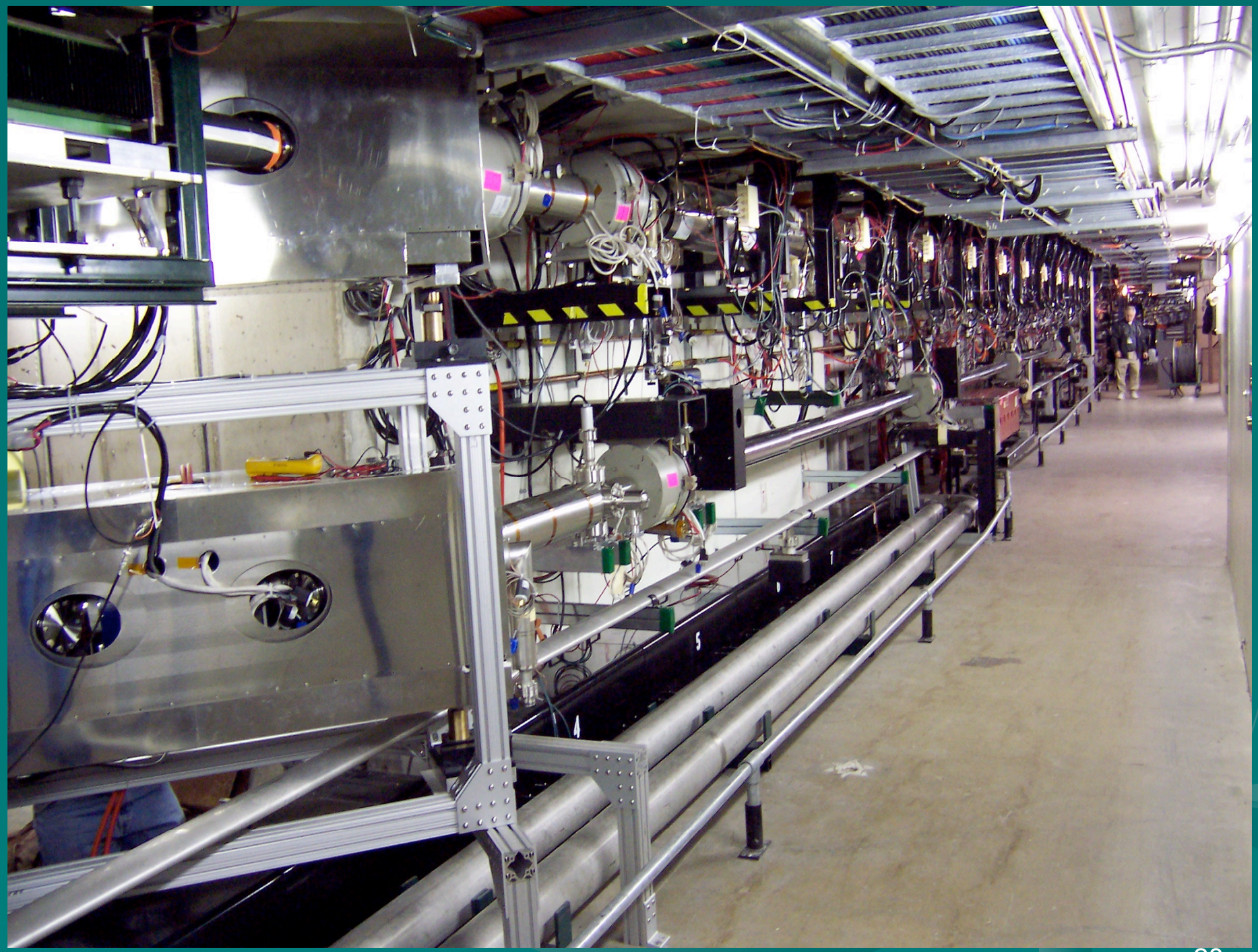
The velocity of the electrons is made equal to the average velocity of the ions.

The ions undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.



Sergei Nagaitsev (Fermilab/AD)

Electron Cooling Beamline



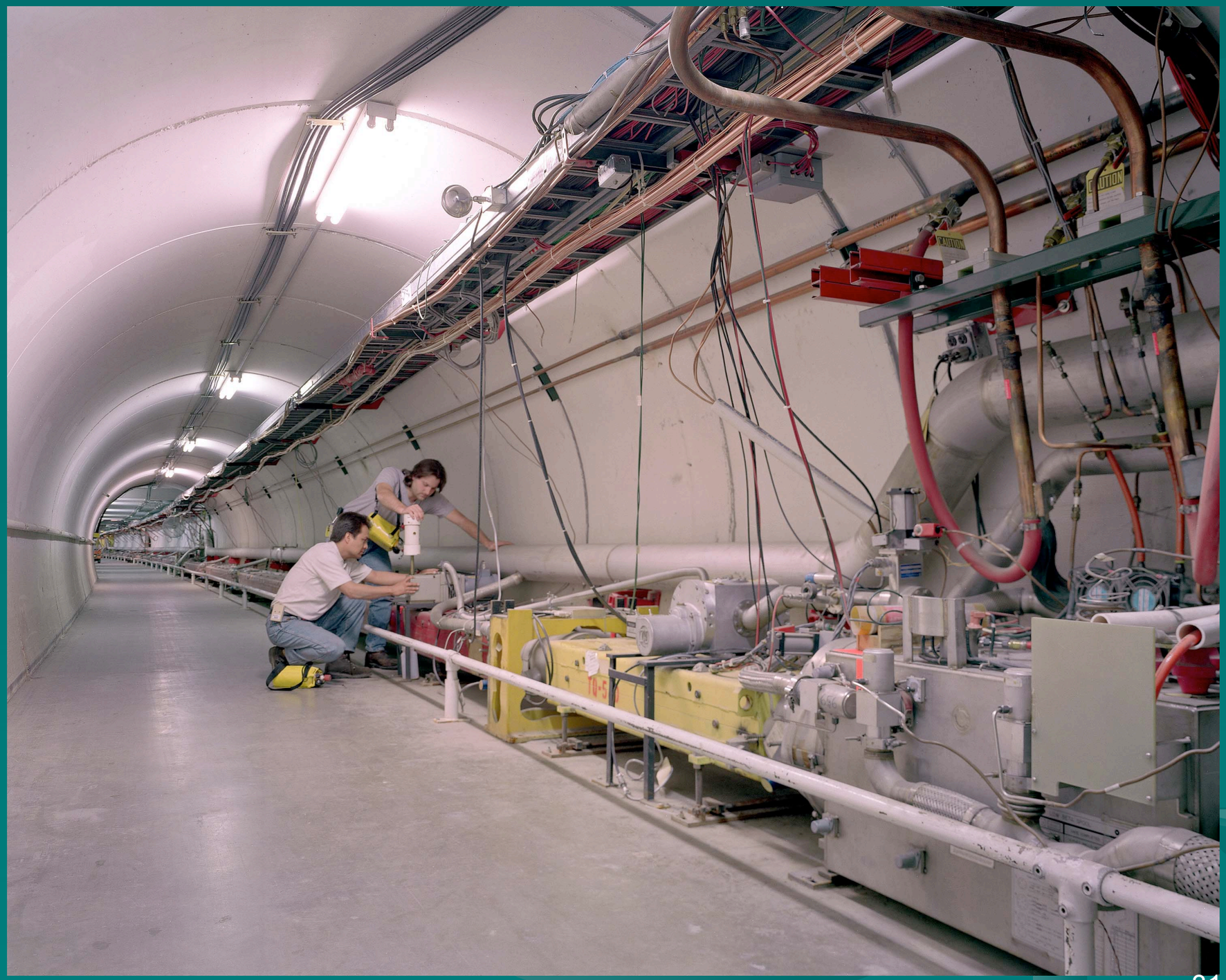
Fermilab Tevatron

Fermilab 03-390-02D

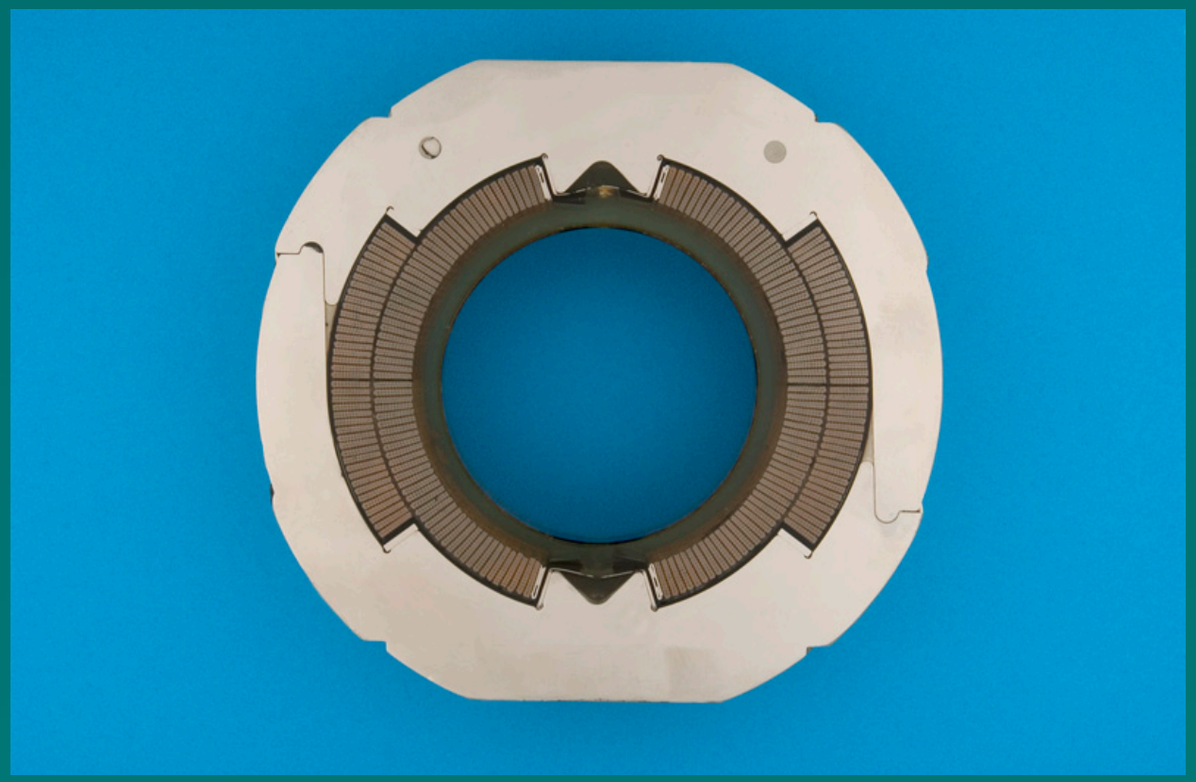
Tevatron Collider Parameters

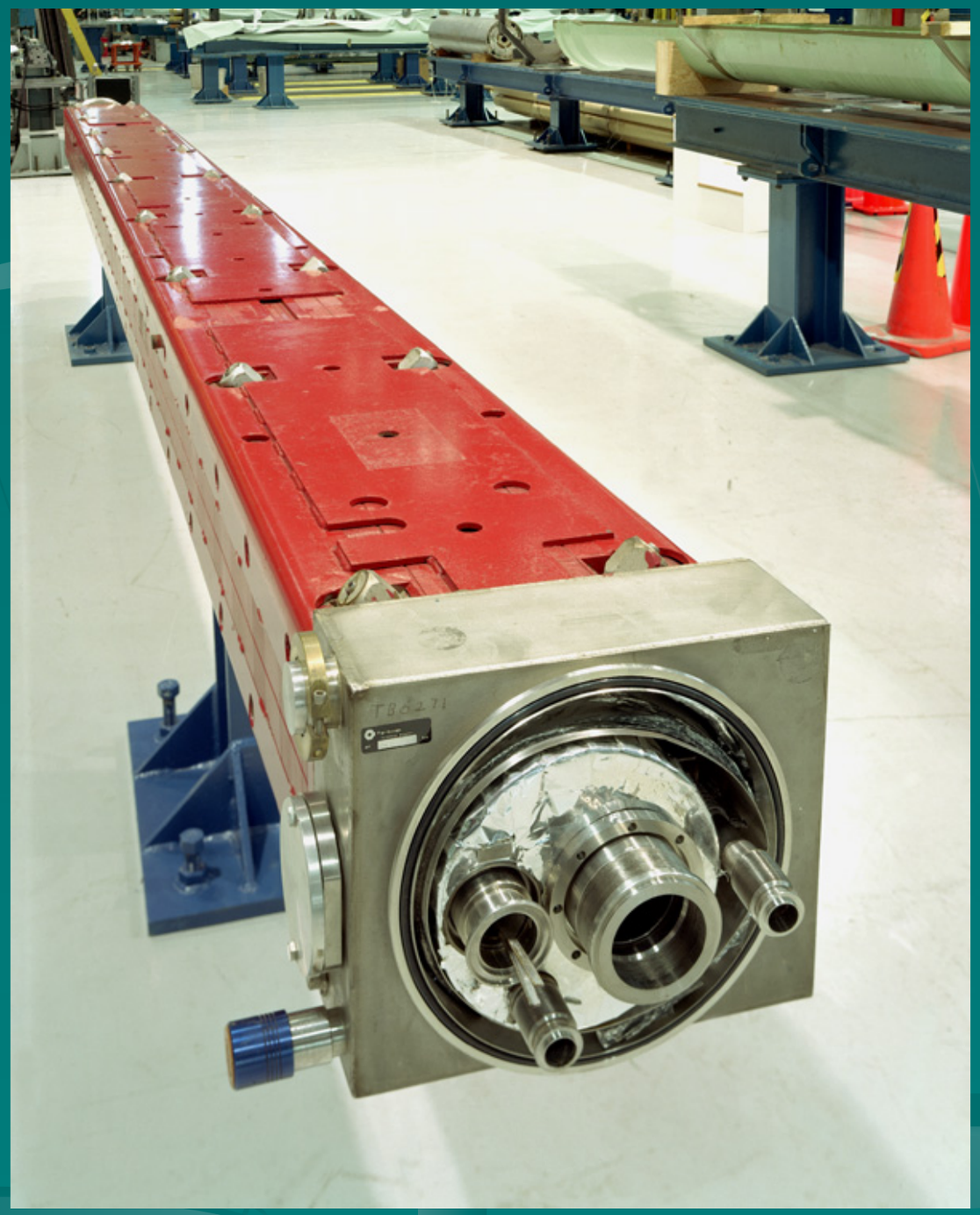
- First superconducting synchrotron and storage ring (1983)
  - Coils operate at 4.5 degrees Kelvin
- One TeV (980 GeV in practice)
  - Injection energy = 150
  - Two low beta sections with Beta* ~ 30 cm
  - Initial Luminosity ~ 3 X 10^{32} $cm^{-2}s^{-1}$
- R = 1 kilometer
- RF Frequency = 53 MHz
- 36 bunches of protons and 36 bunches of antiprotons
  - Bunch spacing ~ 400 ns
    - 3 bunch trains of 12 bunches each
  - Proton and antiproton beams separated by electrostatic separators except at the two collision regions
  - Stored Energy in Magnets~ 350 MJ
  - Stored Energy in beam ~ 2 MJ

Tevatron Tunnel



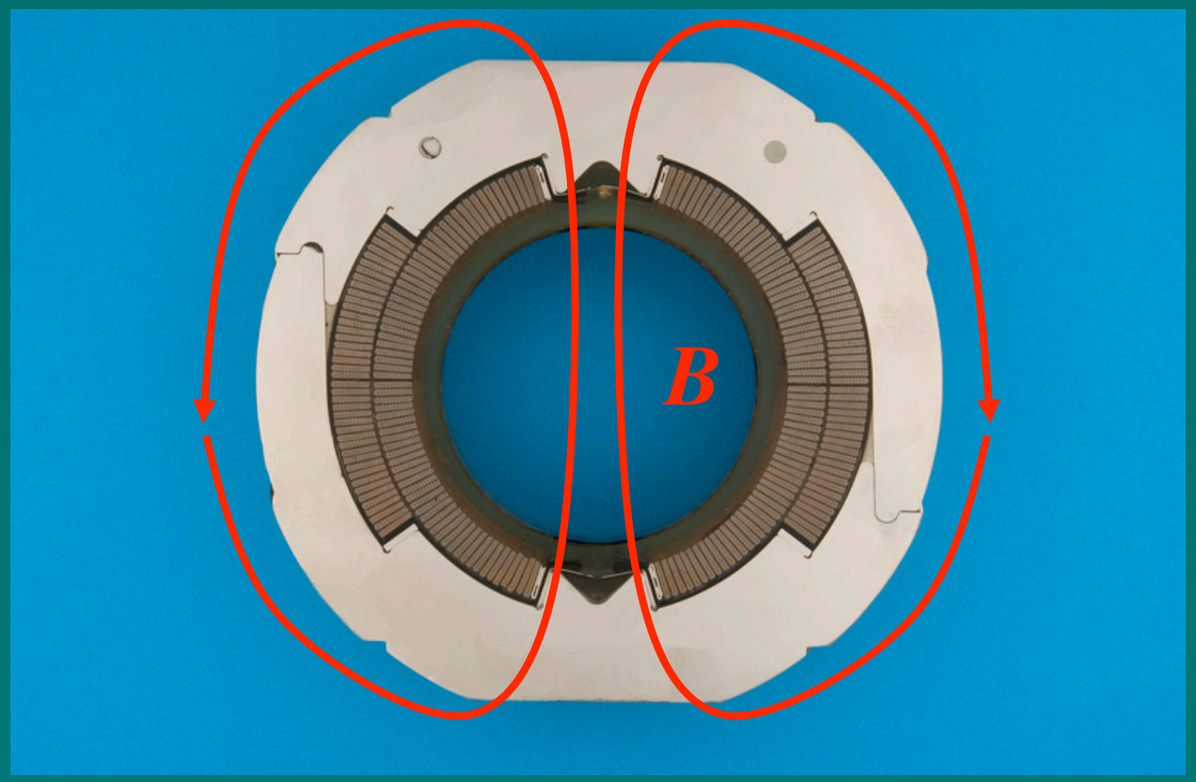
Superconducting Tevatron Magnet

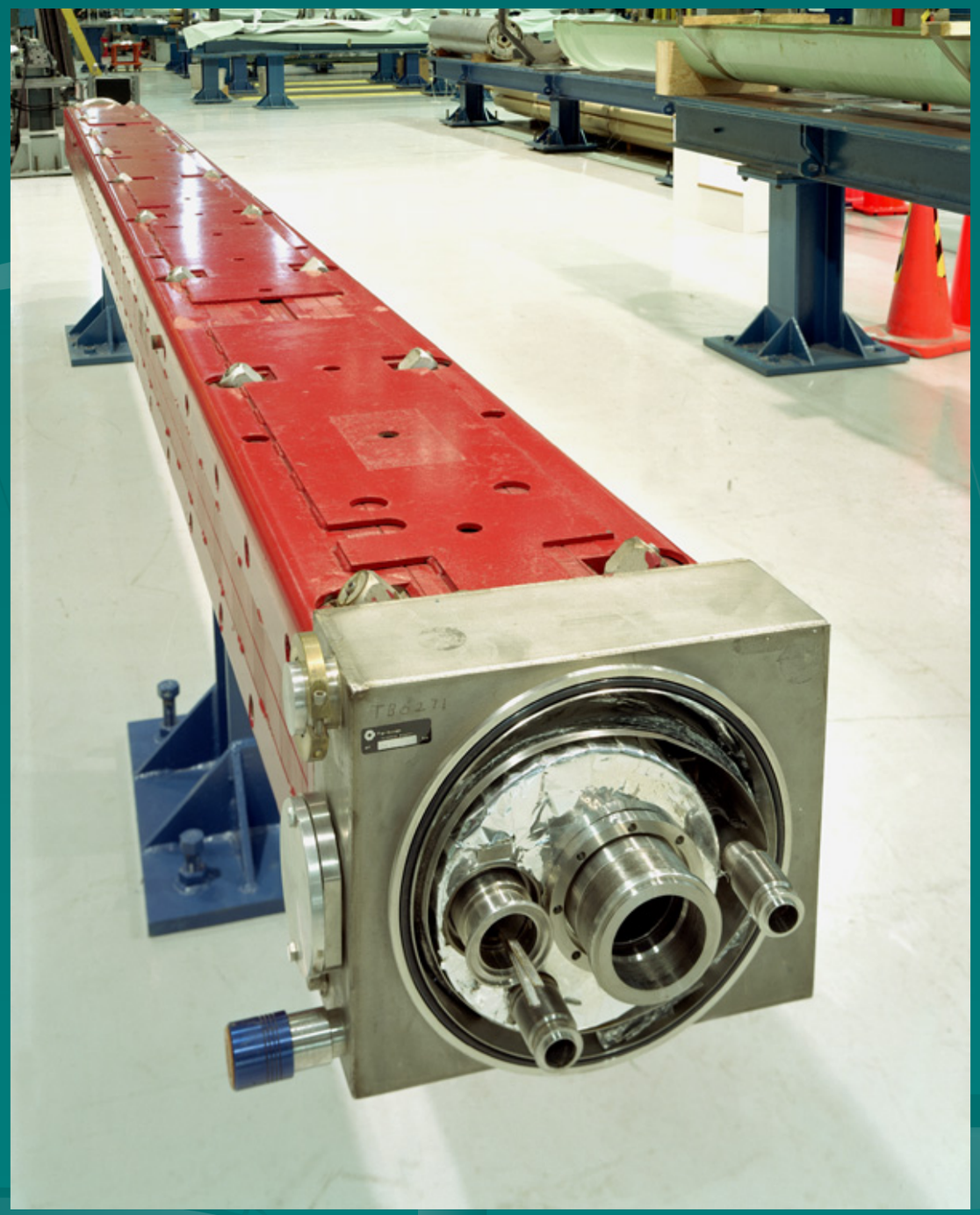




- Outside is at room temperature; inside is at 4°K!
- Field is 4.4 Tesla @ ~4,000 A
- Each magnet is ~20 ft long, and weighs about 4 tons
- ~1000 magnets in the Tevatron (~800 dipoles, ~200 quadrupoles)

Superconducting Tevatron Magnet





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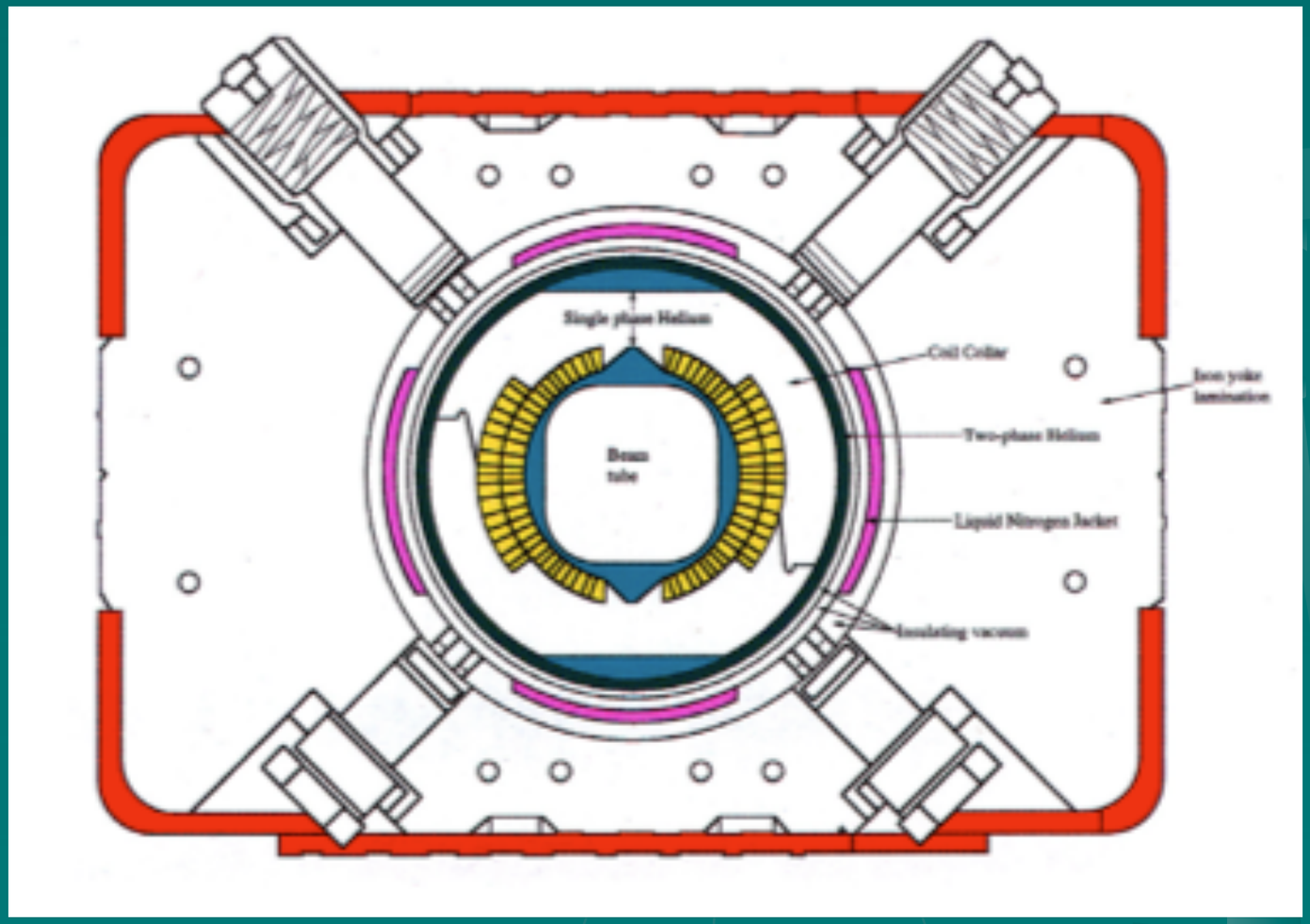
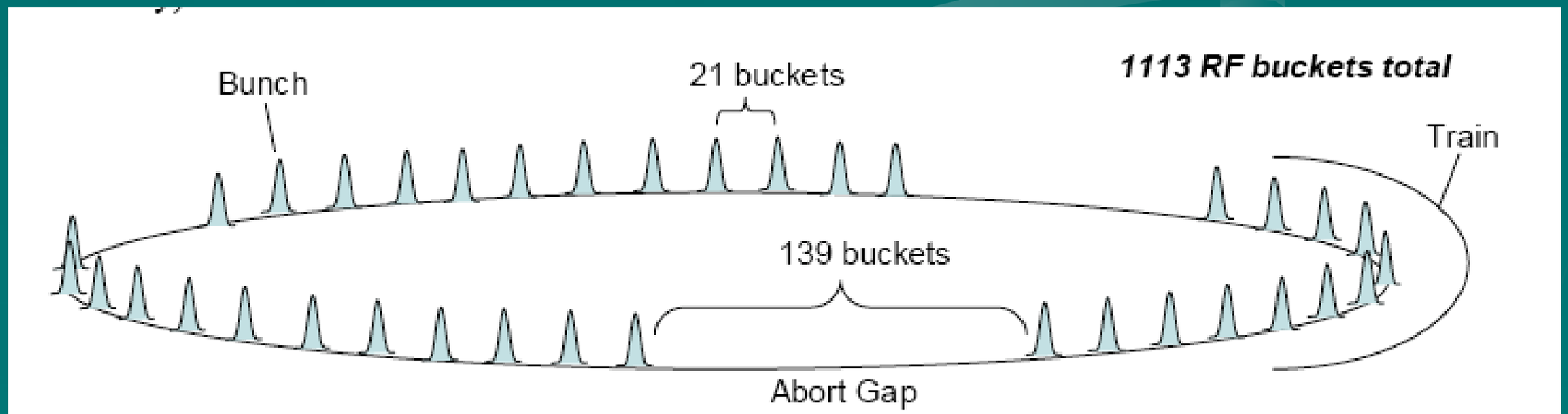
Tevatron Magnet



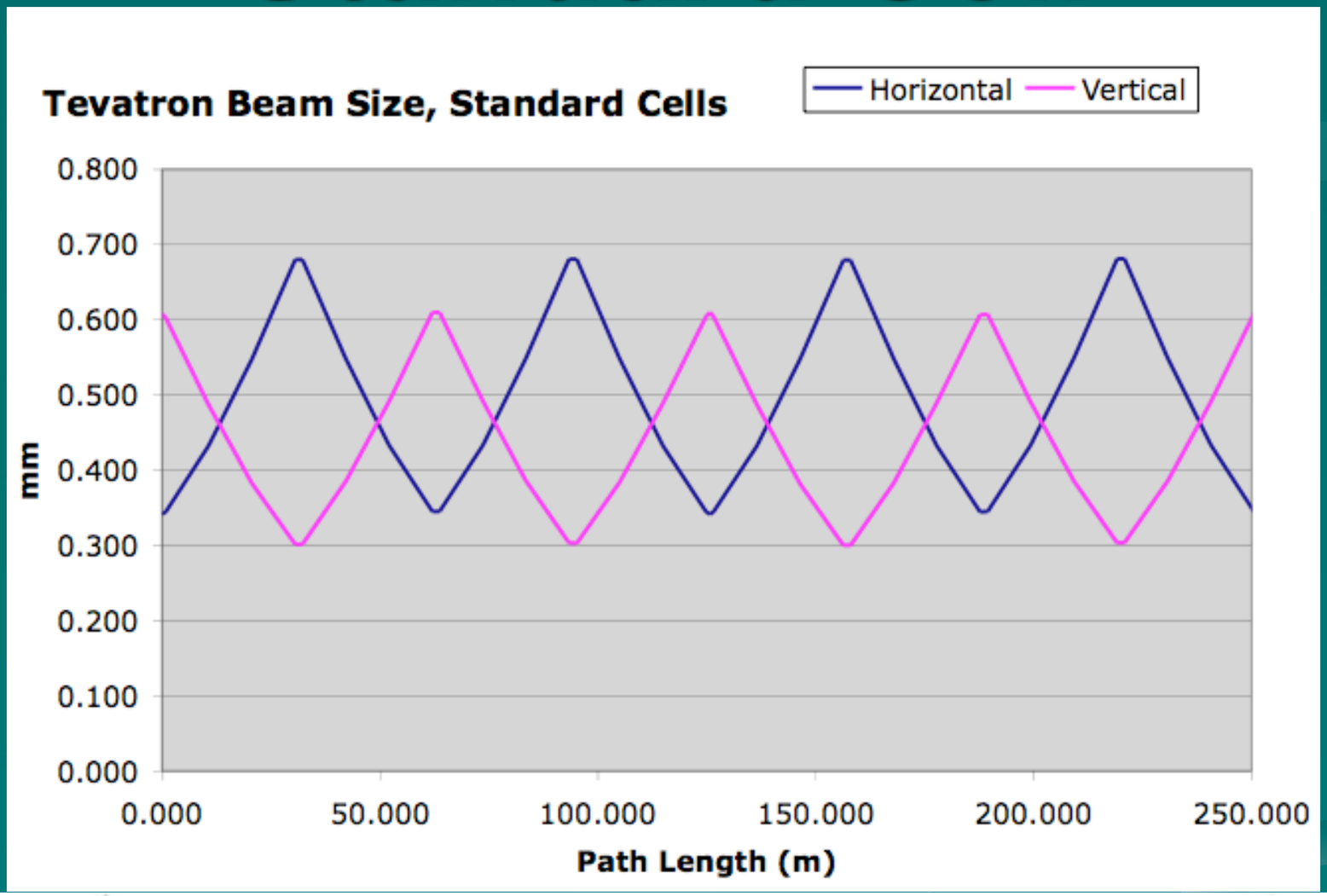
Cross section of a Tevatron Magnet

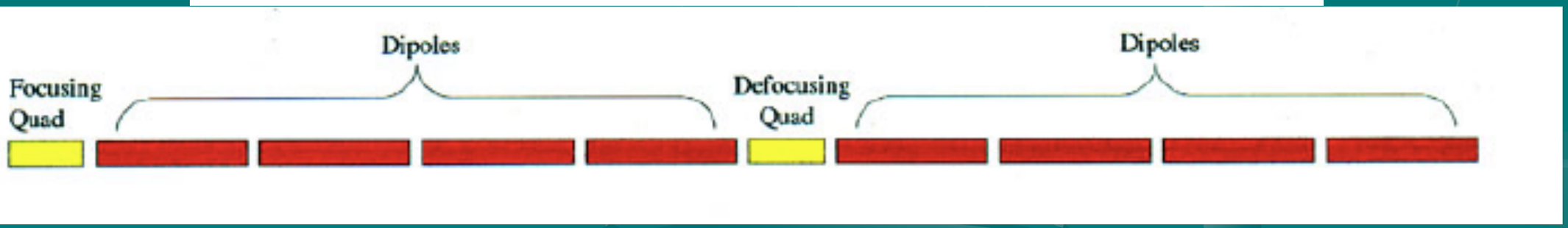
Cold bore/warm iron

Tevatron Bunch Structure

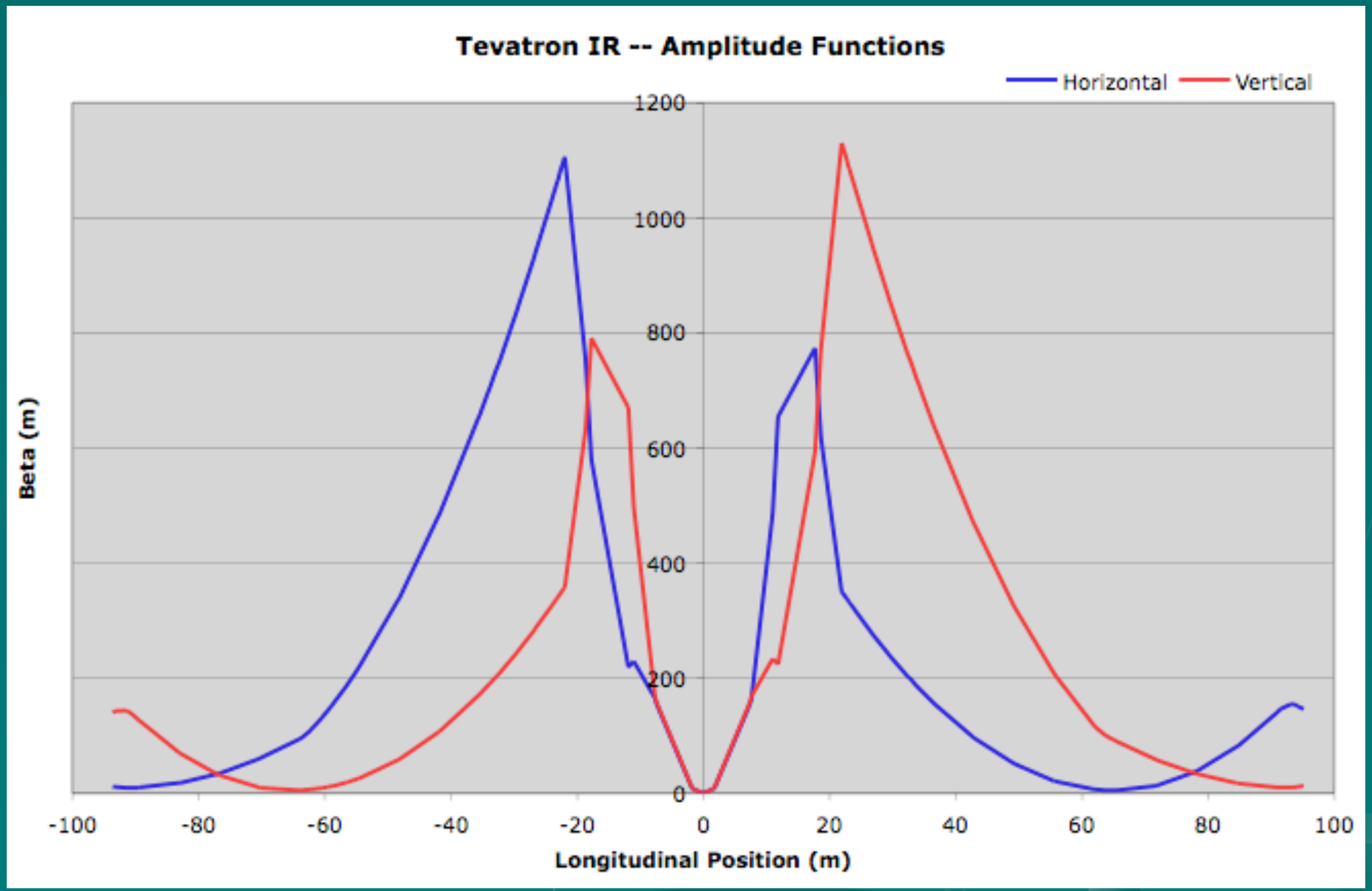


Tevatron Lattice Standard Cell

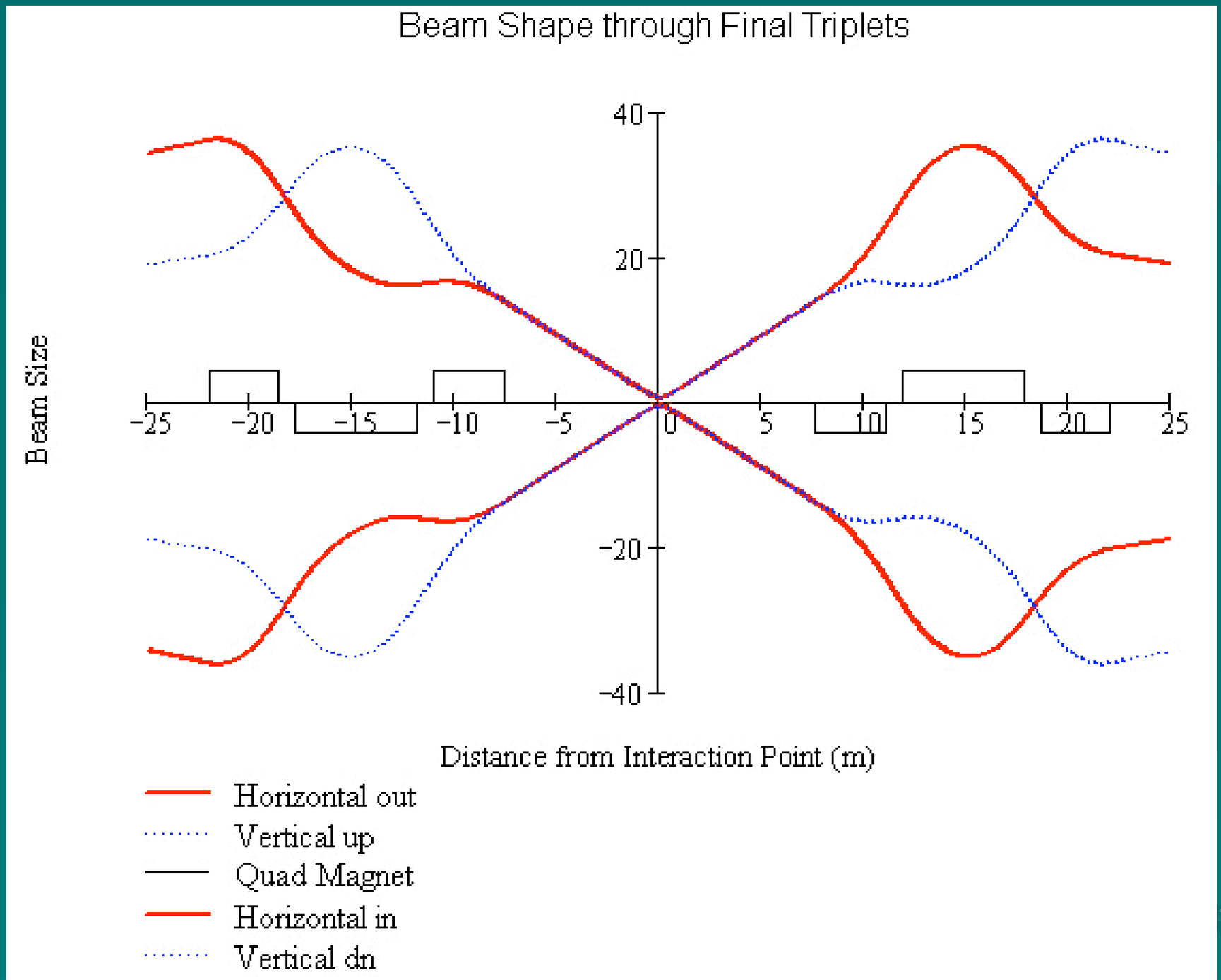




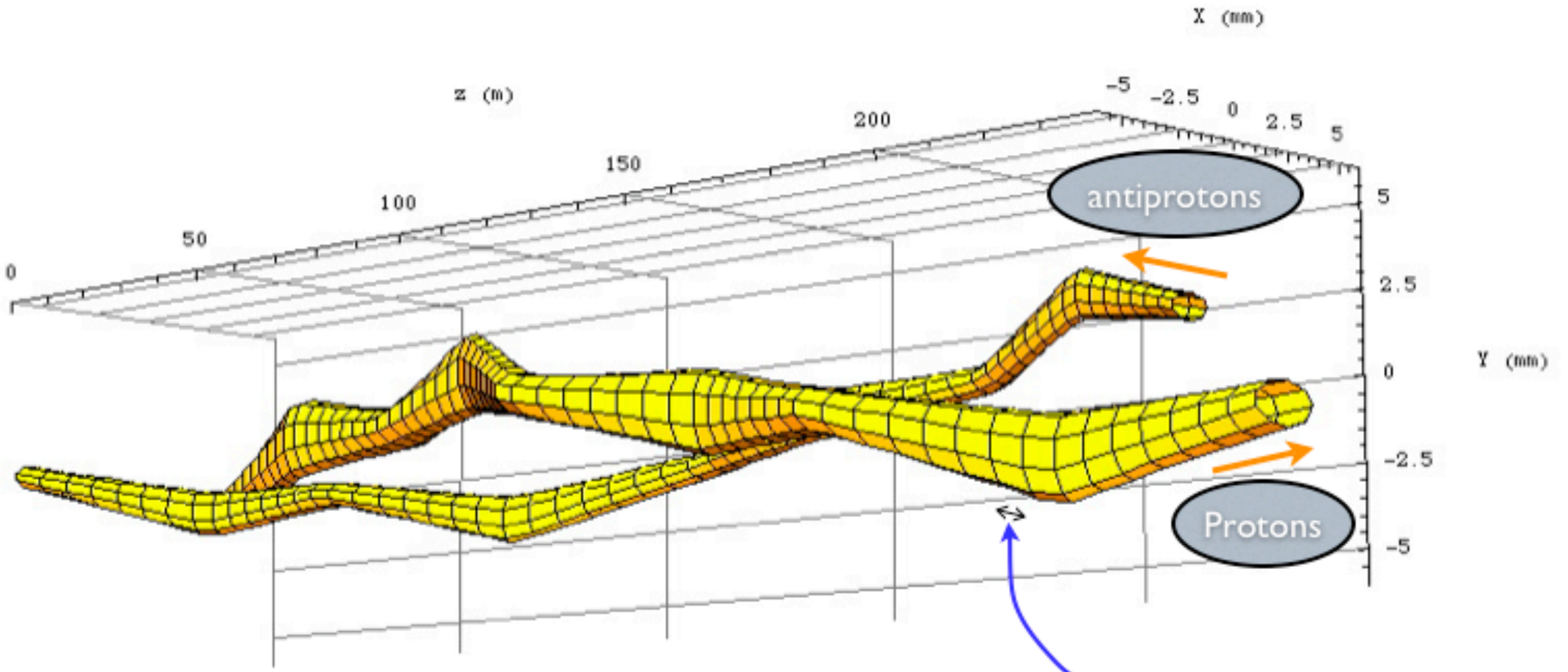
Tevatron Low Beta Section



Low Beta Sections



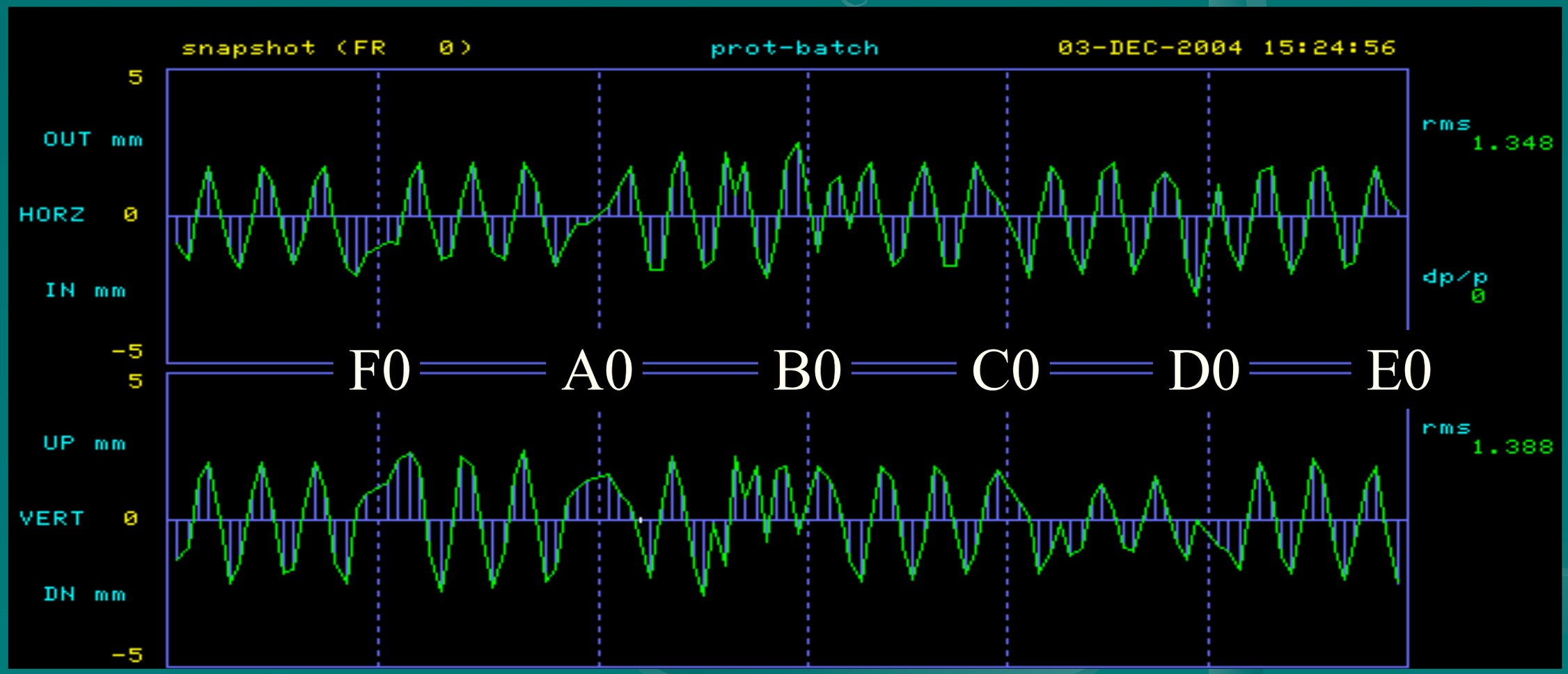
Tevatron Beam Envelopes



Helical orbits through 4 standard arc cells

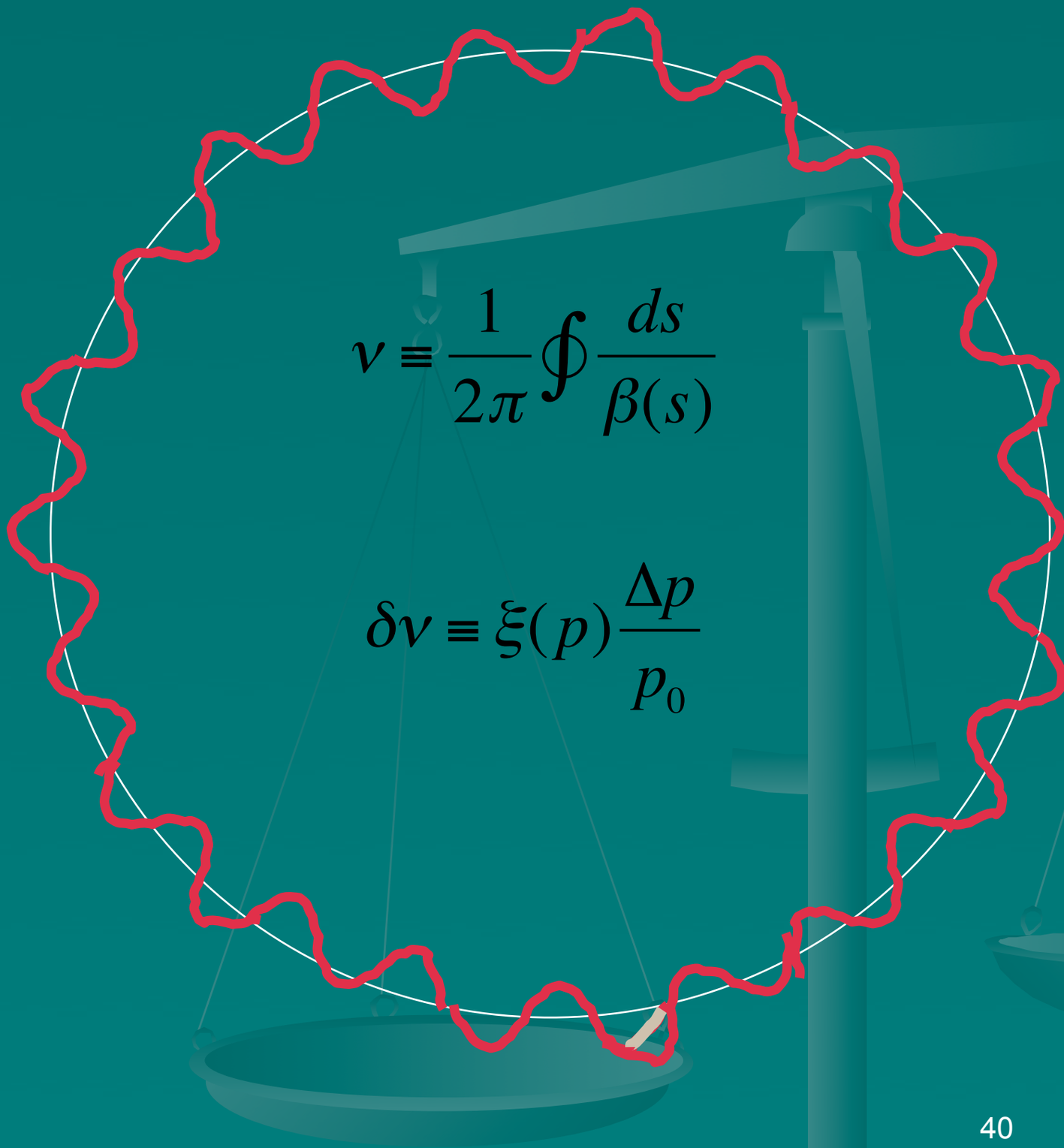
Helix

- 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
- Helix size limited by physical aperture @ 150 GeV, separator voltage @ 980 GeV



Tune and Chromaticity

- Number of oscillations in one turn is the tune
- Chromaticity, ξ, describes the way the tune varies with momentum



$$\nu \equiv \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

$$\delta\nu \equiv \xi(p)\frac{\Delta p}{p_0}$$

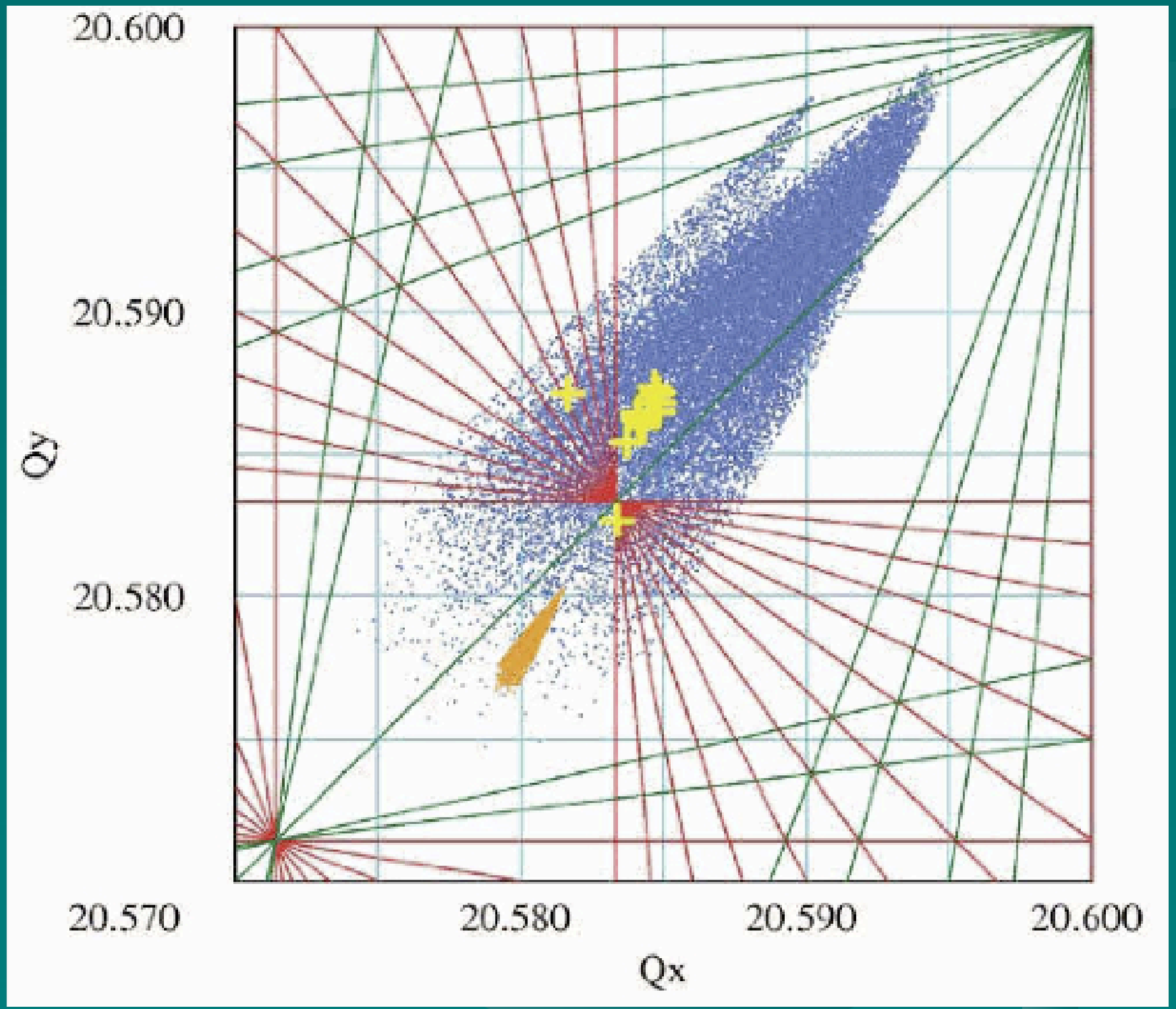
Beam Stability

- Remember tune

$$\nu \equiv \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$$

- If tune is an integer particle takes the same path around the accelerator every time
- If tune is a half integer, the path is the same every other time, and so on . . .

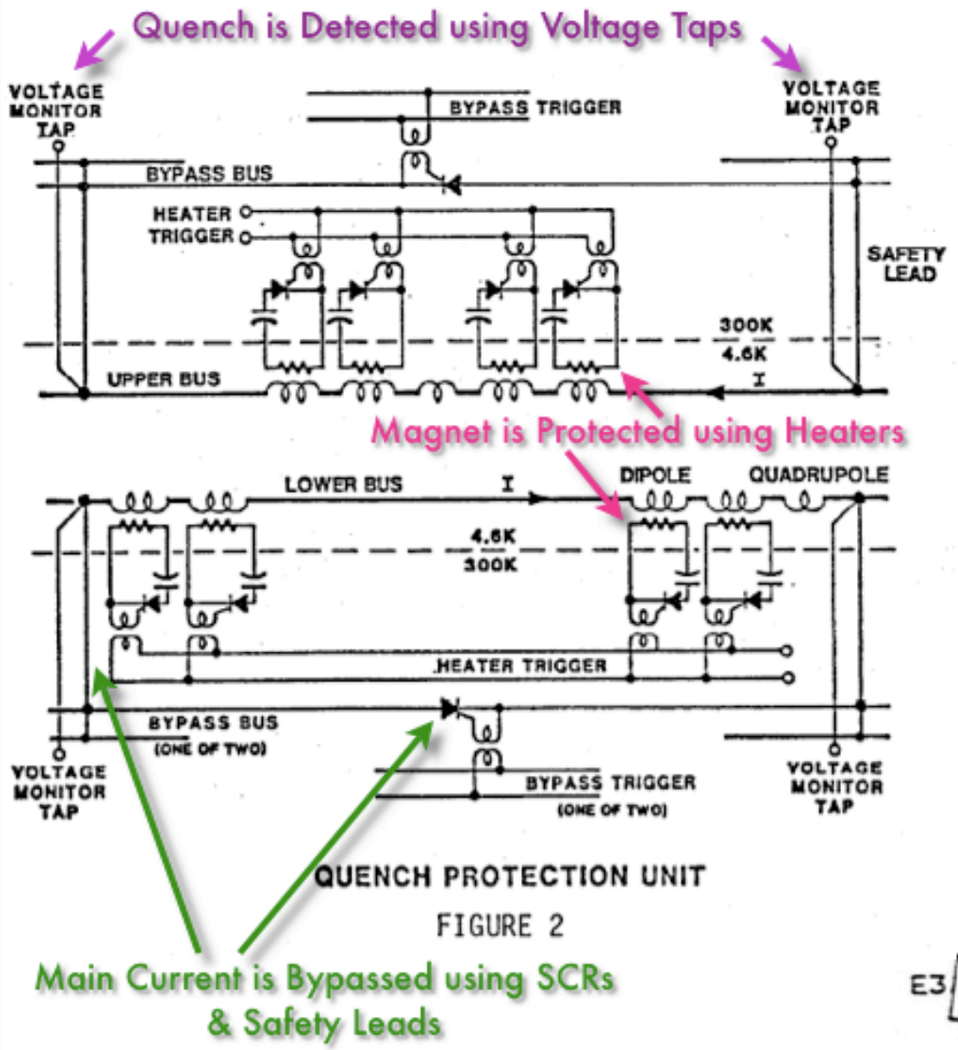
Tune Plane of the Tevatron

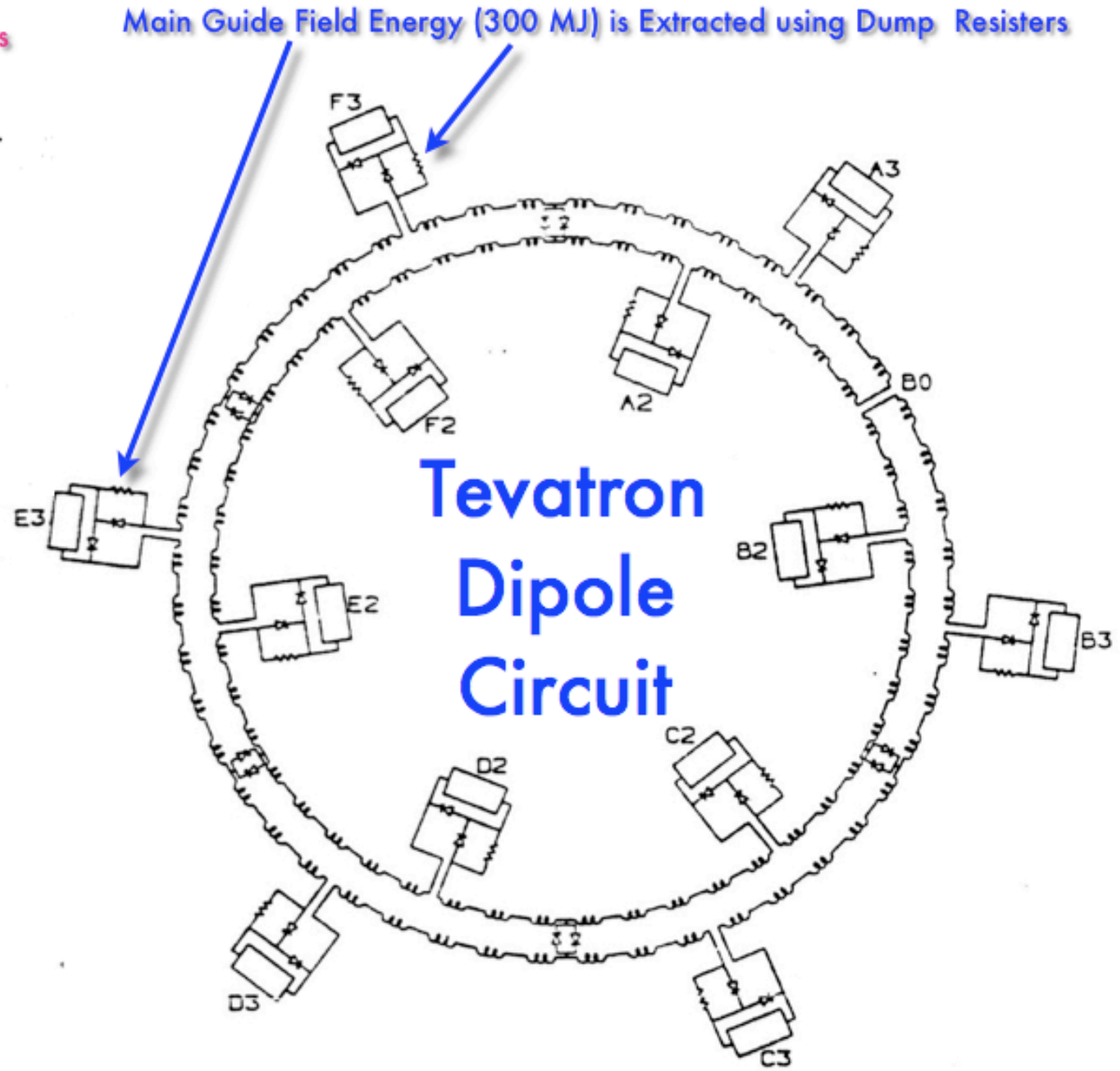


Quenches and Magnets

- Stored energy in B=350 MJ==> Magnets must be protected from quenches
  - 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

Tevatron Quench protection





Accelerator Instrumentation

- Beam Position Monitors
- Loss monitors
- Flying wires
- Schottky Detectors
- Synchrotron Light Detectors
- Ion Profile Monitors

Beam Position Monitor

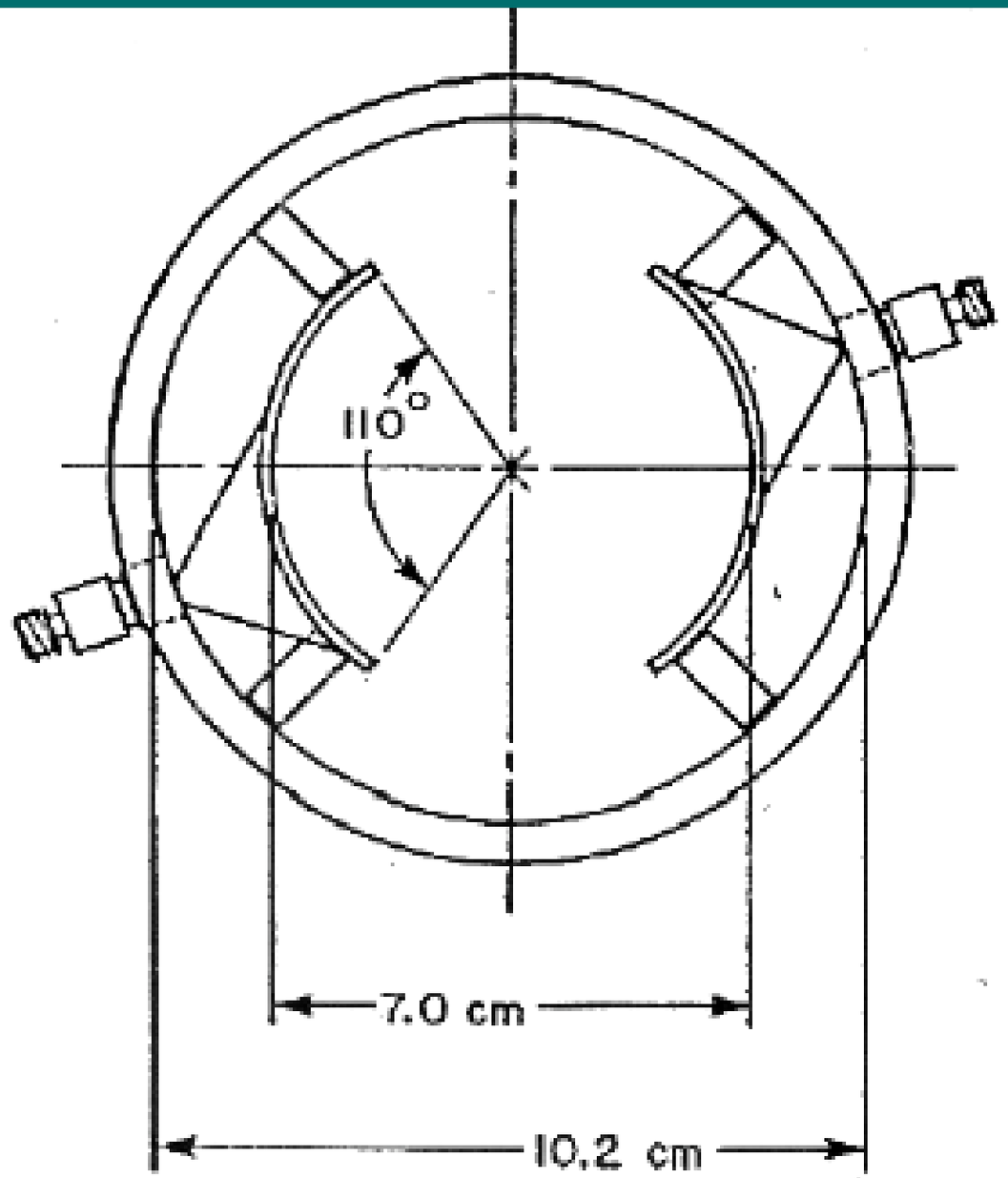
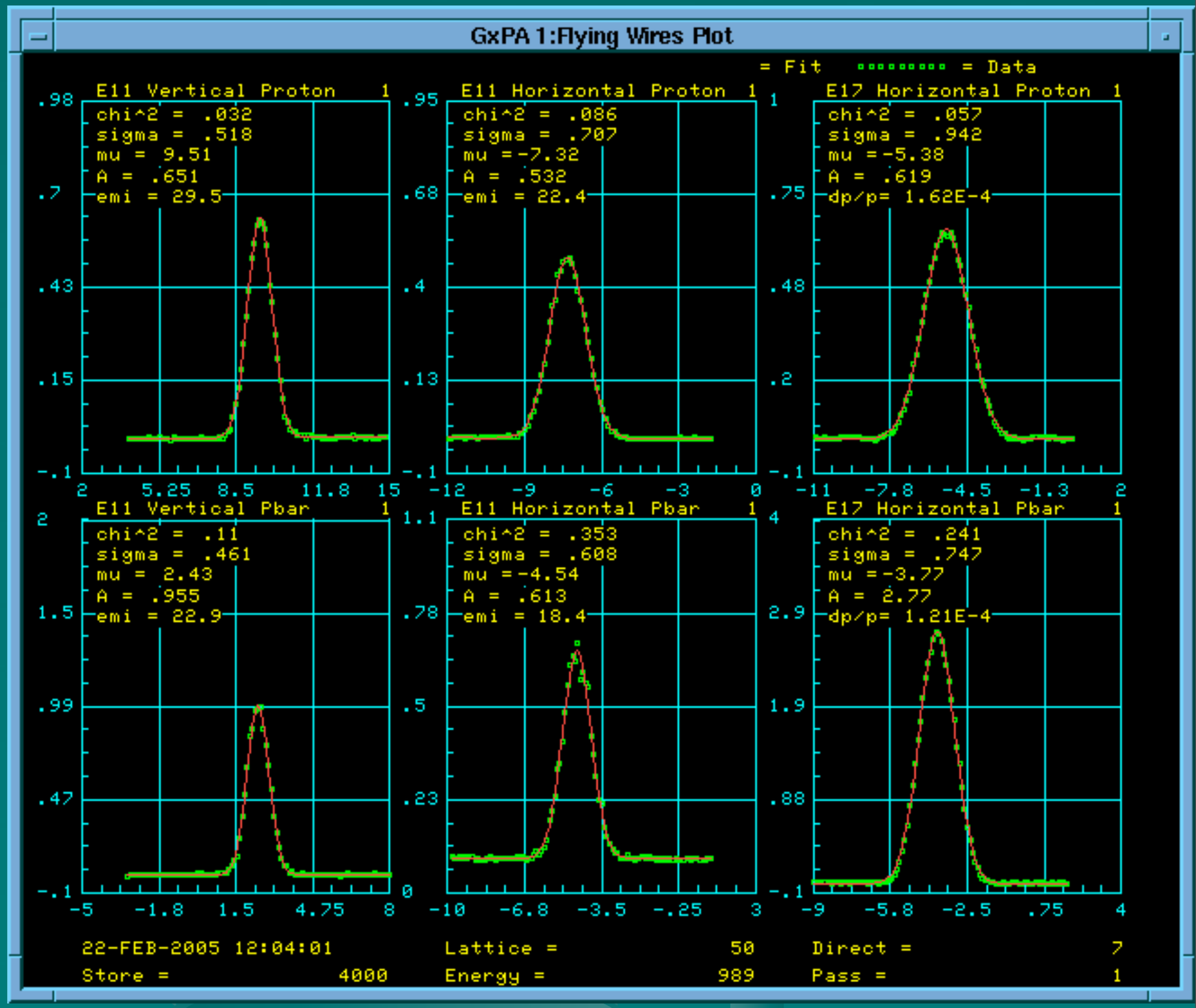


Figure 9.1 : Tevatron BPM and Specifications

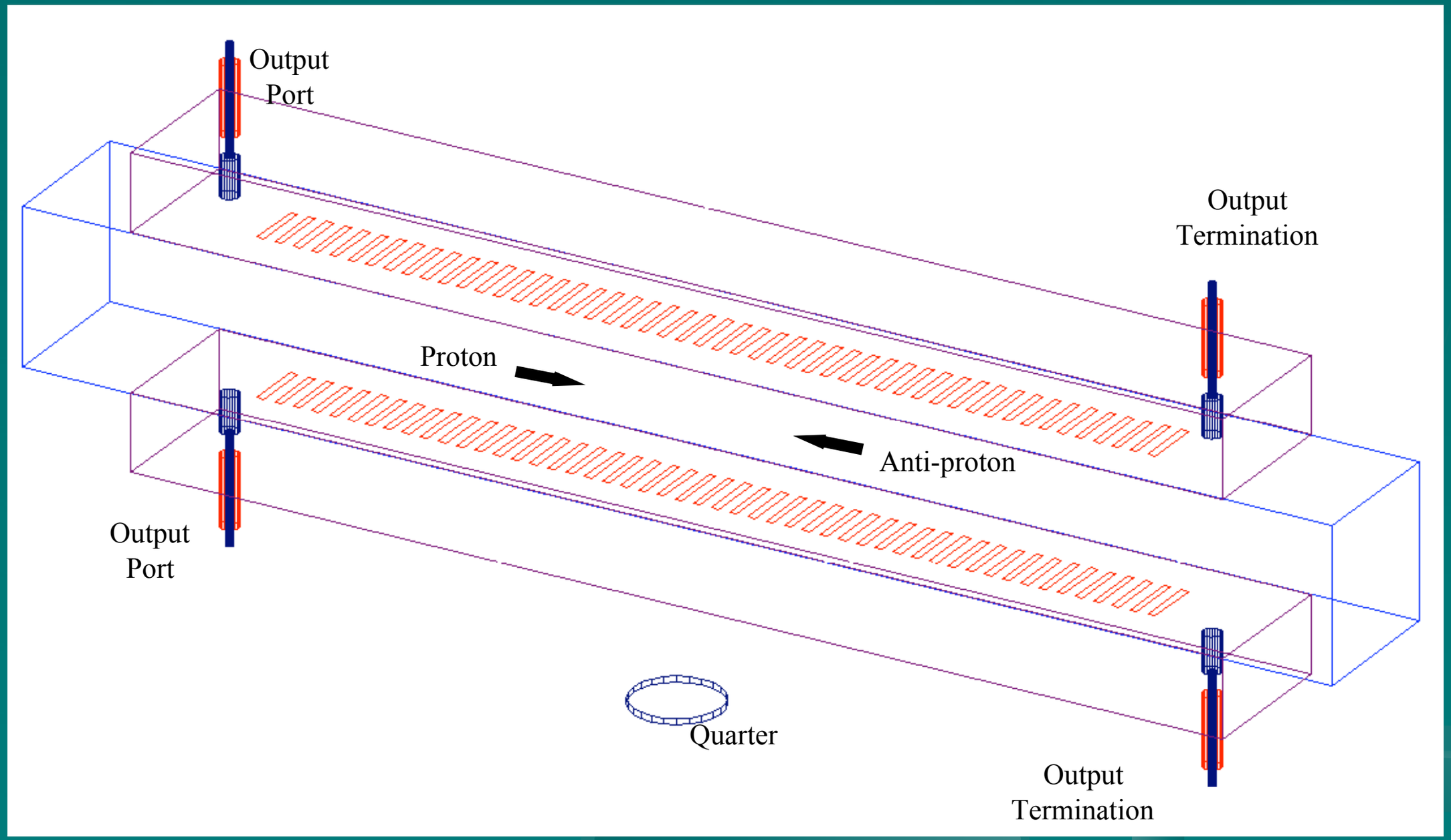
$$S = \frac{a-b}{b+a}$$

Flying Wires

- Fly wires through beams
- Scatted particles detected in scintillator paddles
- Can cause loss spikes in CDF/D0
- Measure transverse beam profiles
- Fly every hour during HEP to see emittance evolution



Schottky Detector



Summary

- The Fermilab Accelerator Complex uses 9 accelerators to produce beam for
  - Tevatron Collider Operations
  - A neutrino beam produced with 8 GeV protons
  - A neutrino beam using 120 GeV primary protons
- Anitiprotons for the collider are produced by 120 GeV protons from the Main Injector
  - Four accelerators are used to accumulate, cool, and store them for use by the Collider
    - Debuncher
    - Accumulator
    - Recycler
    - Pelletron