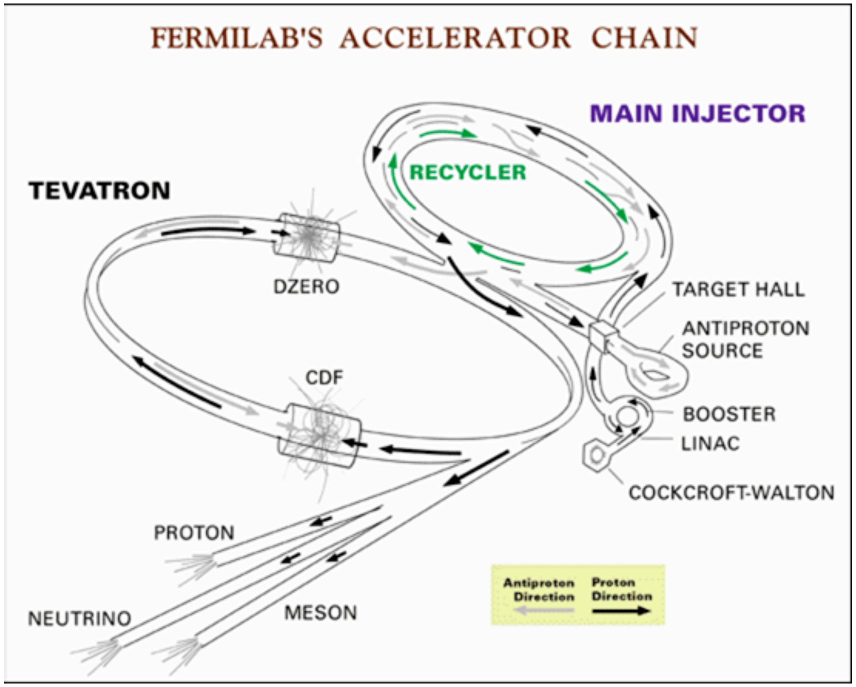
Fermilab



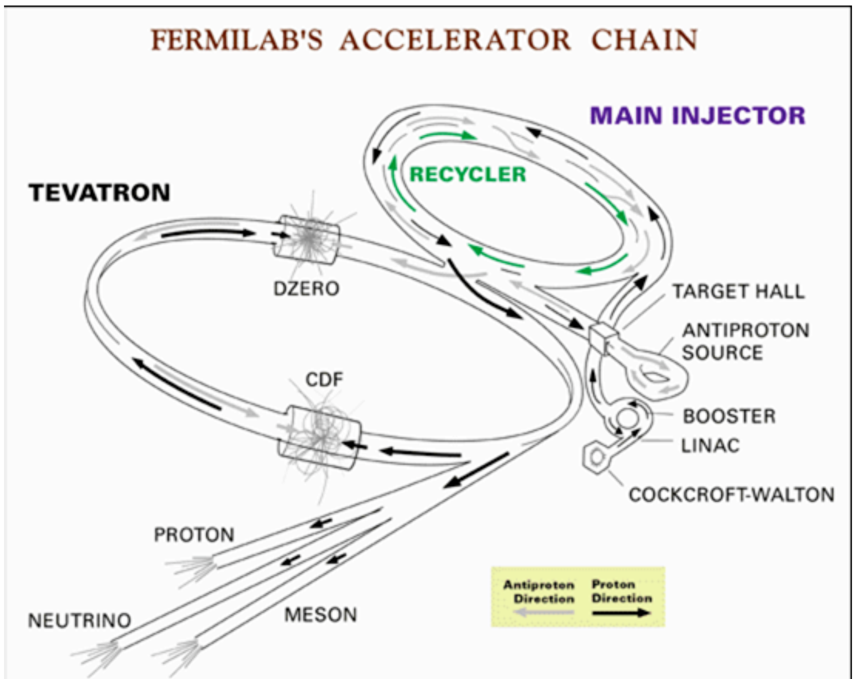
Donna Kubik
Spring, 2005

Fermilab

- Special thanks to many at Fermilab for technical guidance and friendship …among the many are Todd Johnson, Jim Morgan, Dave Capista, Linda Spentzouris, Jean Slaughter

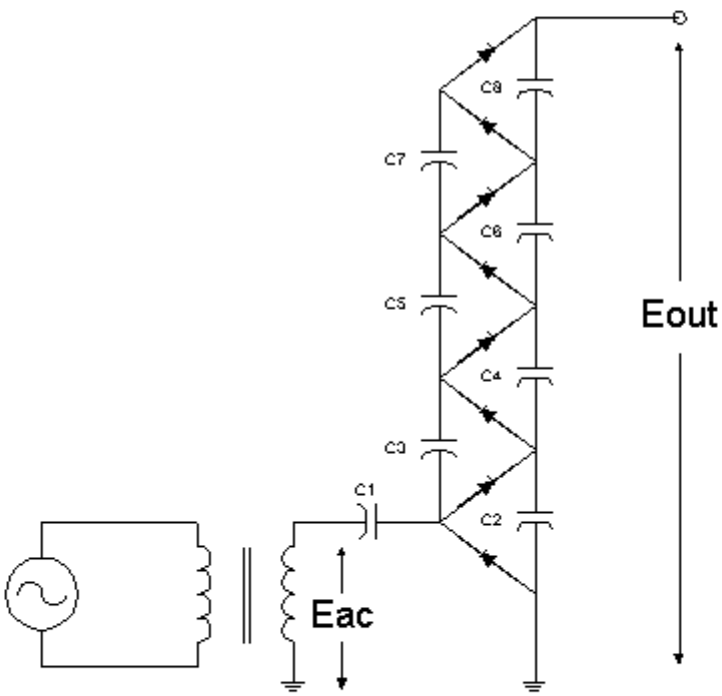
Main Control Room

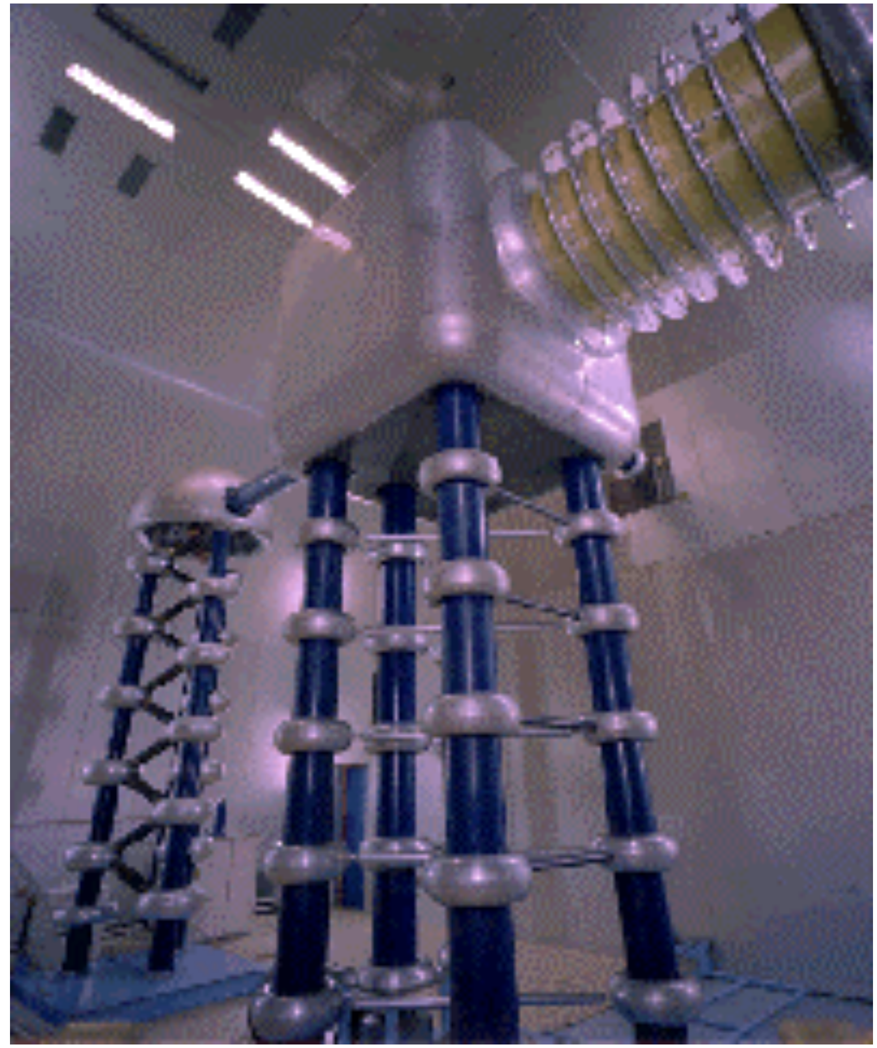
Preaccelerator



Preaccelerator

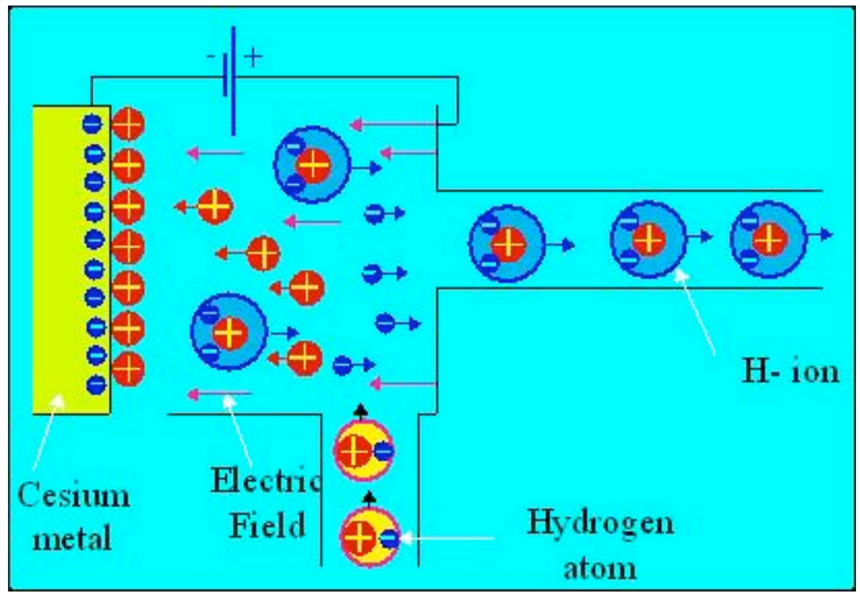
- The Cockcroft-Walton is a classic multistage diode/capacitor voltage multiplier





Production of H^- ions

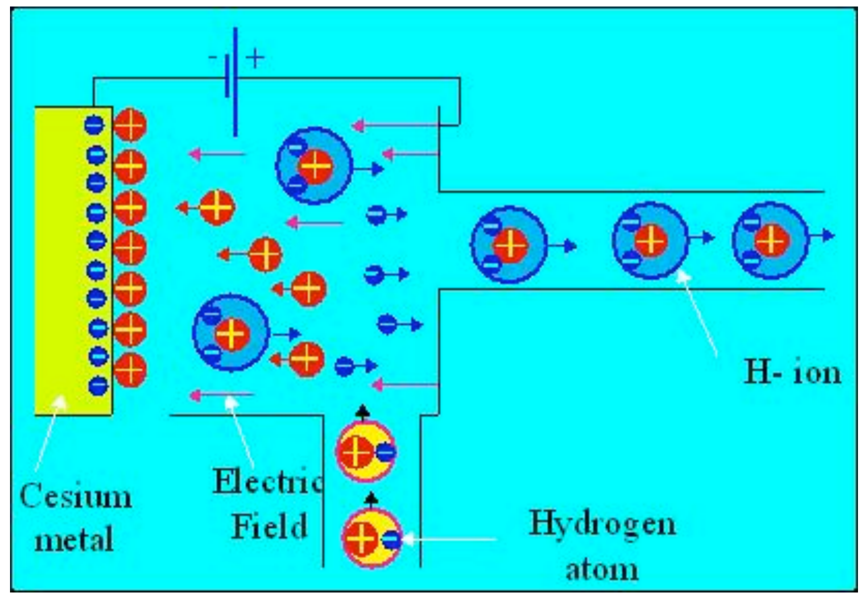
- Place H atom in an electric field and strip away its electron
- Protons will congregate on the Cs metal surface
- The metal has free electrons.
- Cs, with a very low work function, makes it easy to attract electrons from the metal



Production of H^- ions

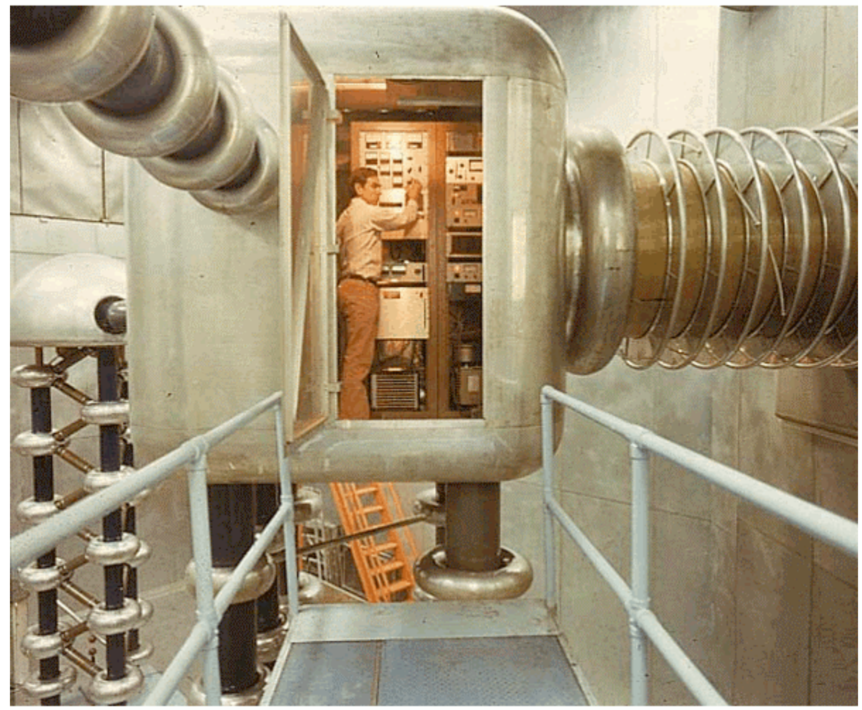
- Every once in awhile, an incoming proton will knock a proton with two electrons off the surface of the Cs

- The negative H^- will move away from the negative surface and get accelerated down the column to 750 keV

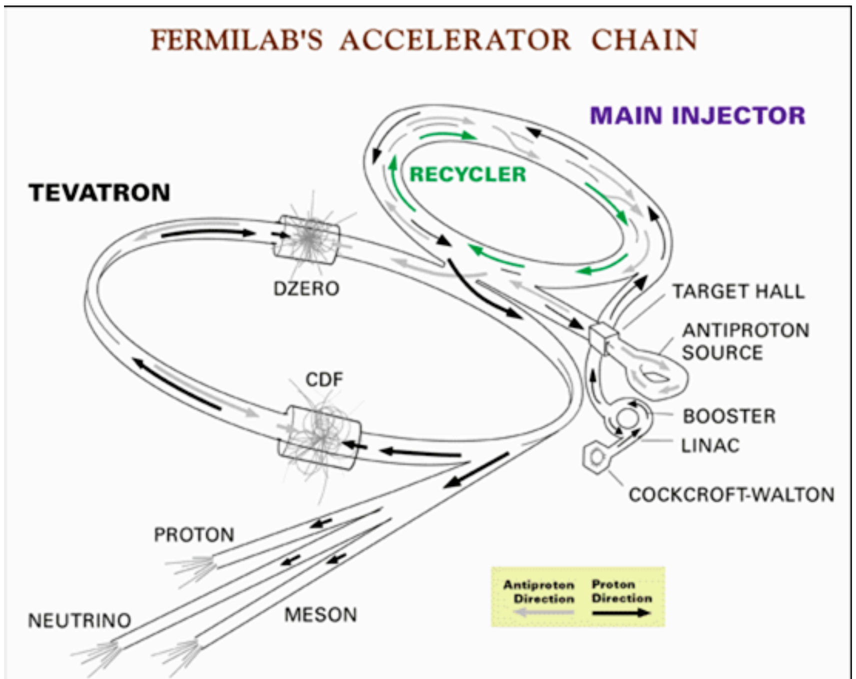


Preaccelerator

- Accelerates H^- ions to 750 keV for injection into the Linac
- Like the Van de Graaff, the accelerator starts out with negative ions, but for a different reason
- H^- facilitates multi-turn injection into the Booster
- This will be described below in the section on the Booster



Linac

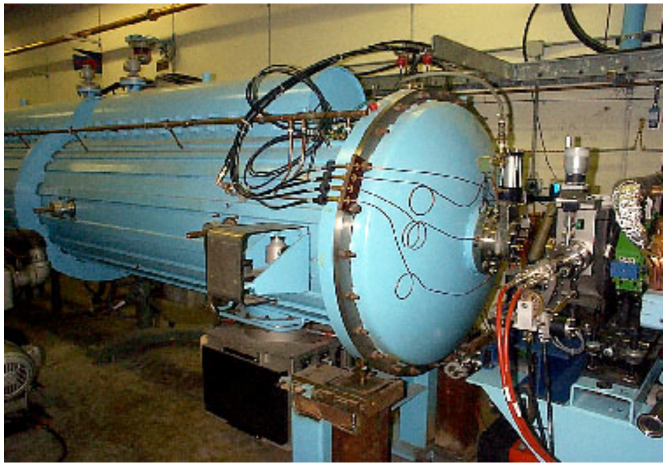

FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
CDF
TARGET HALL
ANTIPROTON SOURCE
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

Linac

- The Linac takes the 750 keV H^- ions from the Preacc, accelerates them to 400 MeV, and then sends them on to the Booster.
- There are five drift tube cavities and seven side coupled cavities
- The drift tube Linac makes up the first stage of the Linac and the side-coupled Linac is the second stage

Drift tube Linac

- Vacuum vessel for drift tube Linac
- Inside the vessels are drift tubes of increasing length to accommodate increasing velocity of the H^-
- There are quadrupoles inside the drift tubes to focus the beam



Side-coupled Linac

- With side-coupled cavities, each individual cell is a separate accelerating cavity coupled to other cells in the module

- The module is not one cavity with drift-tubes but rather several separate cavities powered by the same RF source by coupling.

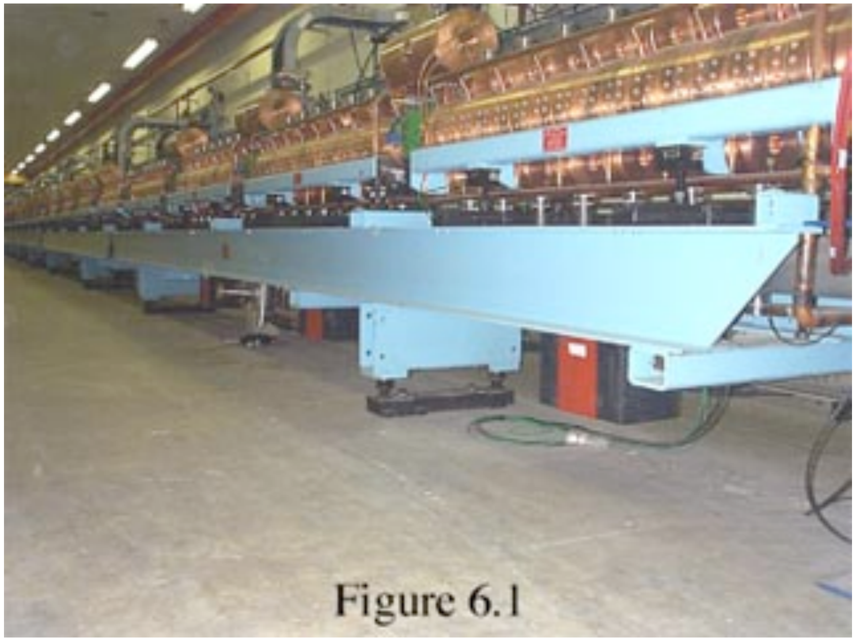


Figure 6.1

Neutron Therapy

- Uses 66 MeV H- ions from the Linac to produce neutrons for cancer therapy at the Neutron Therapy facility (NTF)
- First operational in 1975
- Similar to the Clinical Neutron Therapy System (CNTS) at the University of Washington

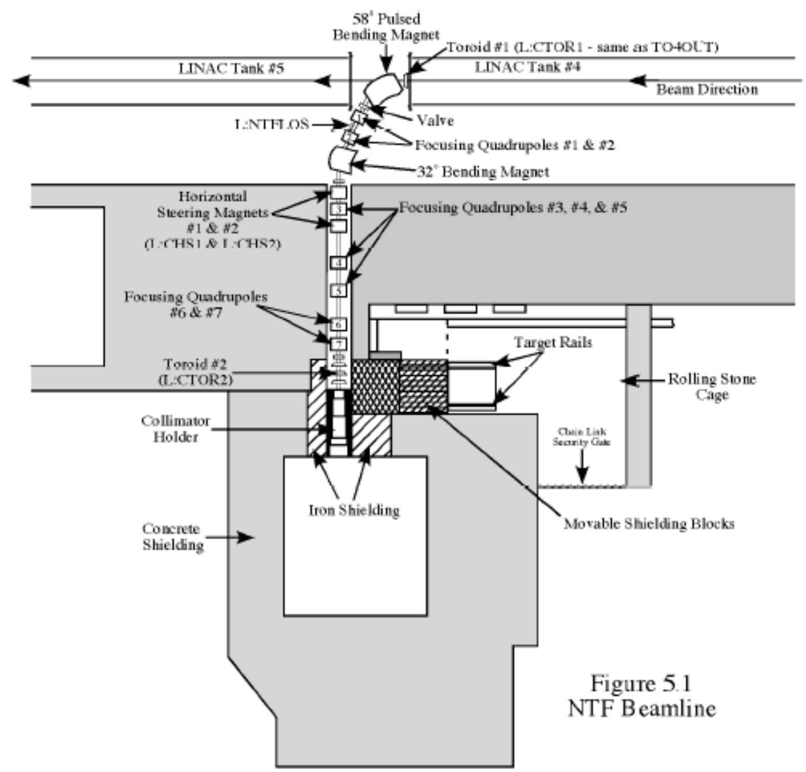
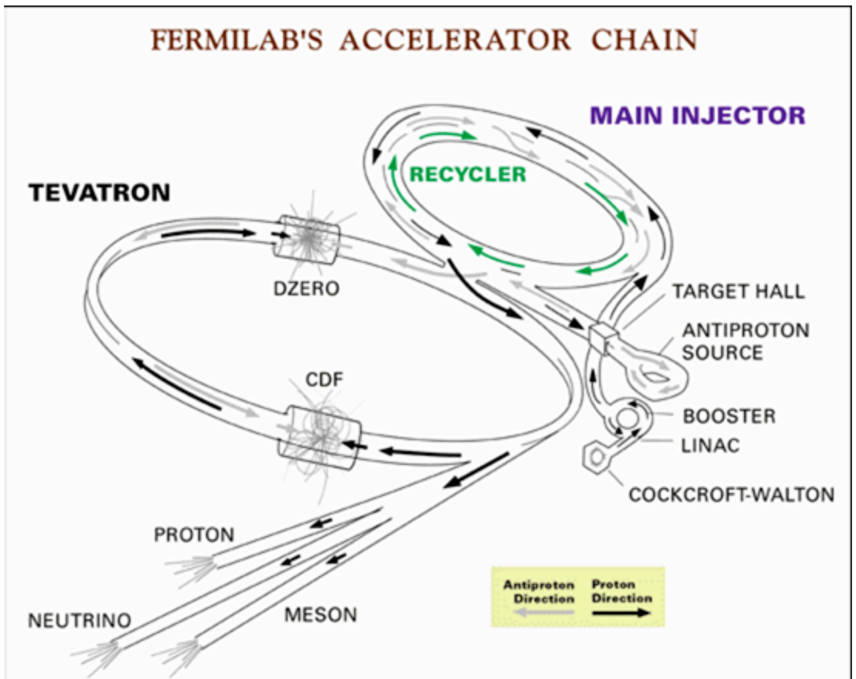


Figure 5.1
NTF Beamline

Booster



FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
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ANTIPROTON SOURCE
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

Booster injection

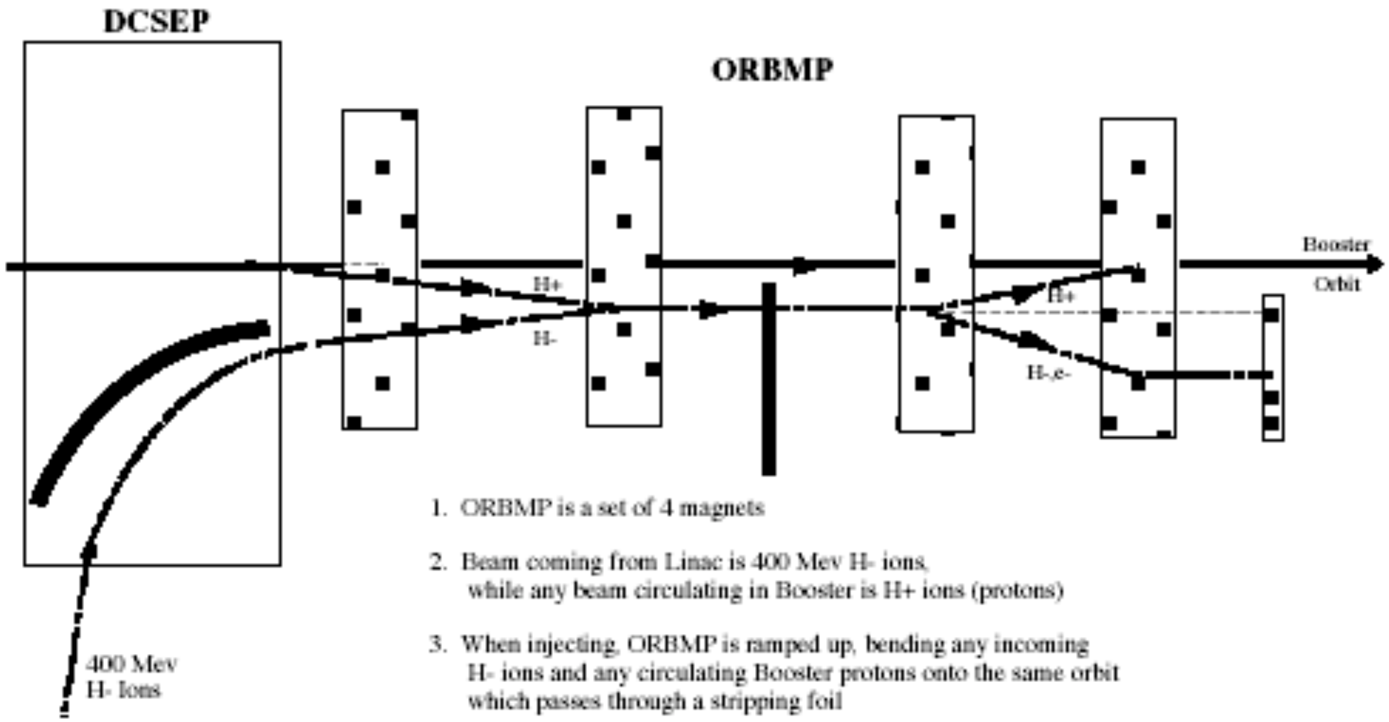
- The revolution period in Booster at injection is 2.22 μsec, while the pulse length in Linac is approximately 40 μs long
- The 400 MeV chopper selects only a portion of the Linac beam; the remainder of the beam is sent to one of the Linac dumps
- Extending the chop width generates multiple Booster turns
- The Linac beam pulse is long enough to run about 18 turns (18 turns would be a 39.96 μs chop length selected from the 40 μsec Linac pulse)
- Operationally, the practical limit for maximum intensity is 5 or 6 turns

The need to inject negative ions

- But how is more than 1 turn added to the Booster without knocking out the protons that are already circulating inside the Booster?

- This is facilitated by injecting negative ions, as described on the next slide.

Orbmp

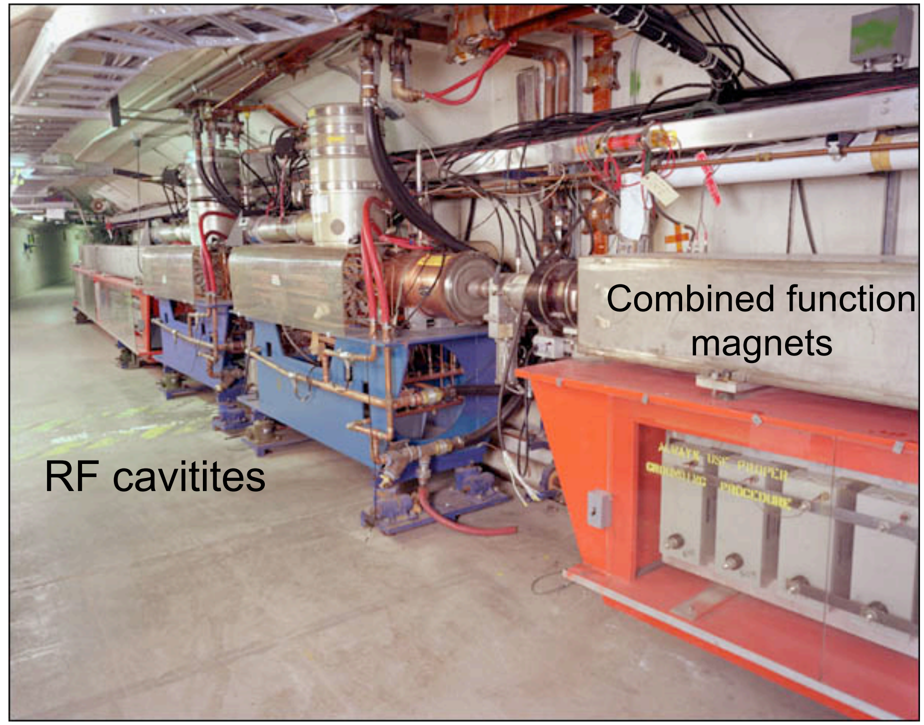


1. ORBMP is a set of 4 magnets
2. Beam coming from Linac is 400 Mev H- ions, while any beam circulating in Booster is H+ ions (protons)
3. When injecting, ORBMP is ramped up, bending any incoming H- ions and any circulating Booster protons onto the same orbit which passes through a stripping foil
4. The foil strips some of the electrons off of the H- ions, making protons
5. Once beam is injected, ORBMP is ramped back down so that the circulating Booster beam does not continue to go through the stripping foil

figure 1.6

Booster

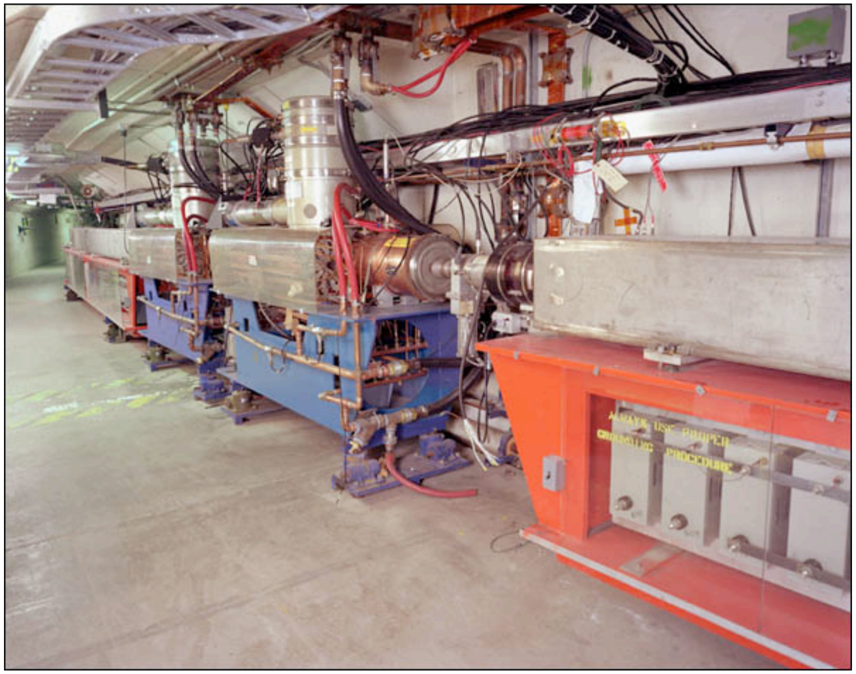
- The booster is a rapid-cycling (15 Hz) synchrotron
- Shown are the combined function magnets and RF cavities
- Total of 17 RF cavities sprinkled around the Booster



FNAL's Booster is very similar to CESR's synchrotron

- Both synchrotrons use combined function magnets and resonant circuits

CESR's synchrotron
Built under the direction of Robert Wilson
First beam in late 1960's?



Fermilab's Booster synchrotron
Built under the direction of Robert Wilson
First beam 1970?

Booster

- The Booster magnets are part of a 15 Hz resonant circuit
- Energy is exchanged between the magnets and the capacitor banks with the power supply making up the losses

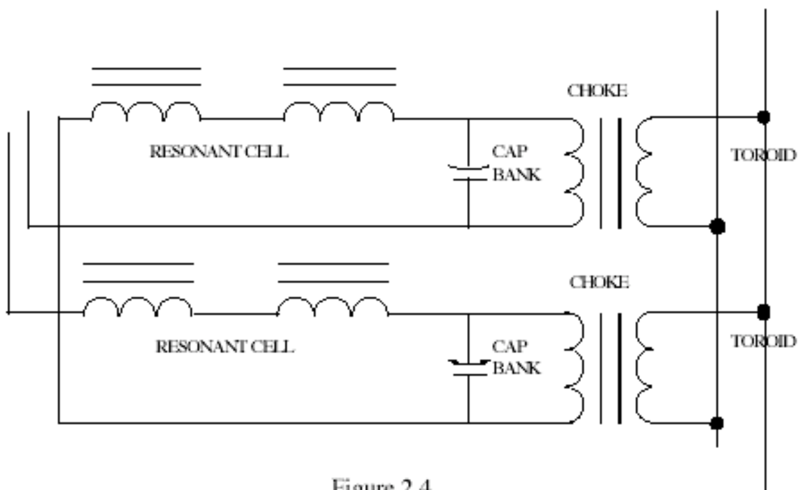
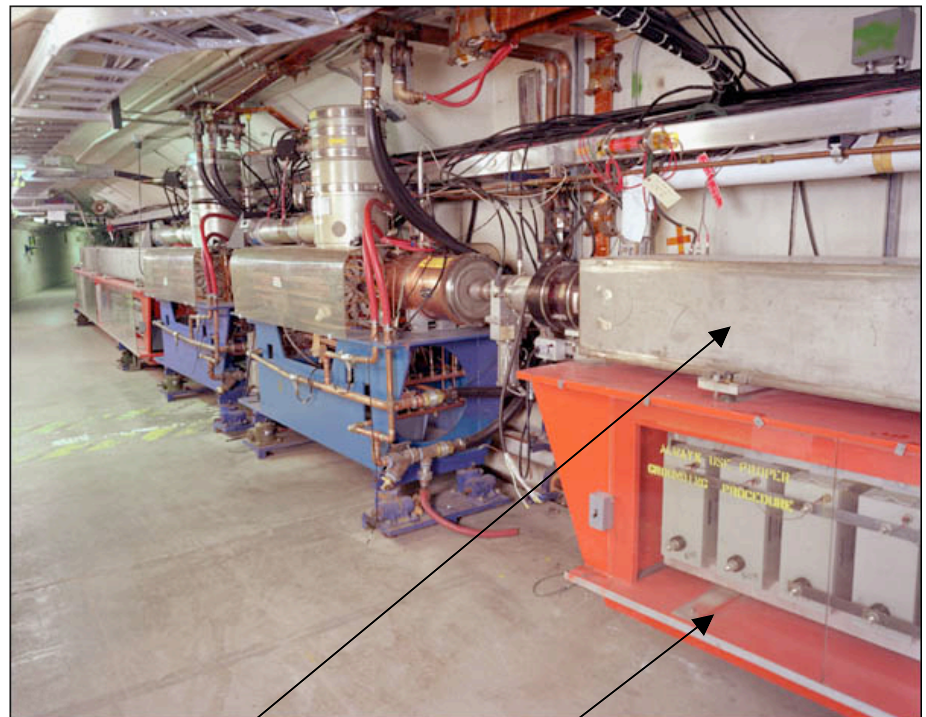


Figure 2.4
Resonant Cell



Combined function Magnets - inductors

Capacitor bank for magnet power-resonant circuit

Booster

- A resonant power supply system uses a sinusoidal current waveform to excite the magnets

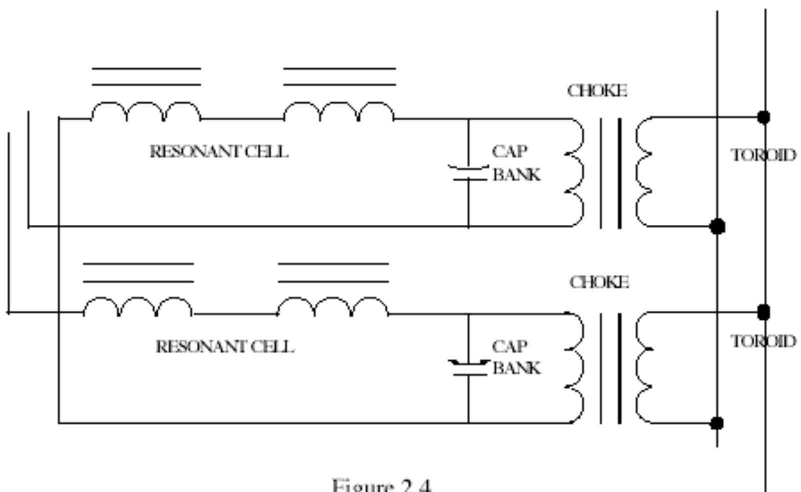
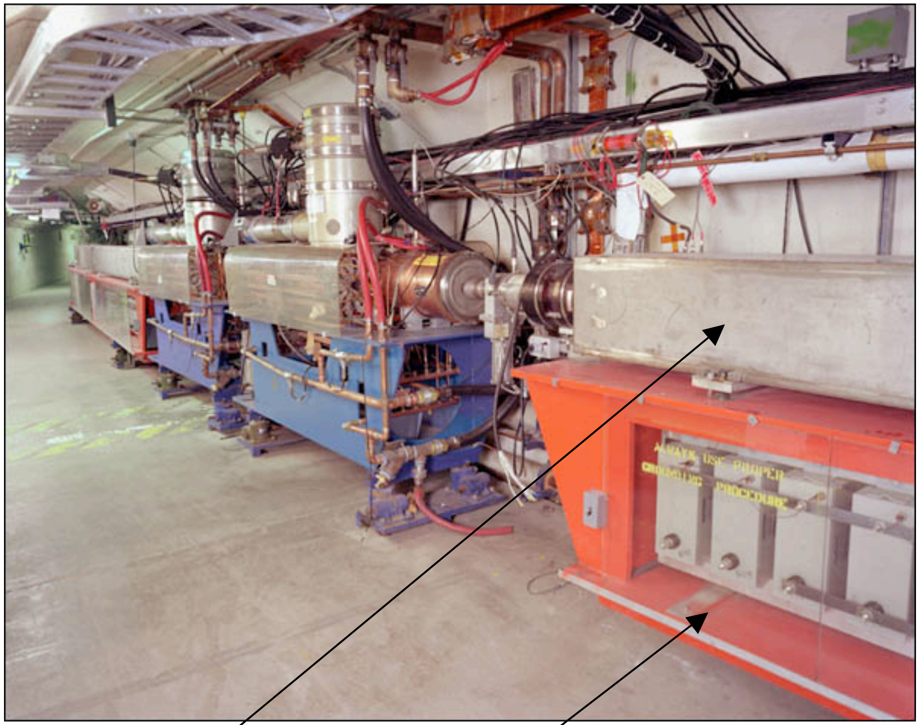


Figure 2.4
Resonant Cell



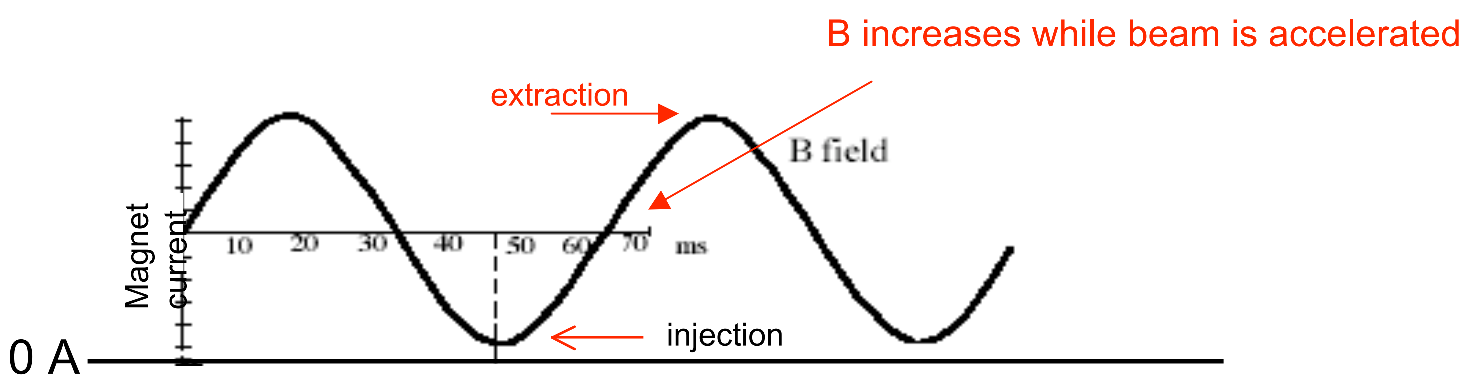
Combined function Magnets - inductors

Capacitor bank for magnet power-resonant circuit

Acceleration

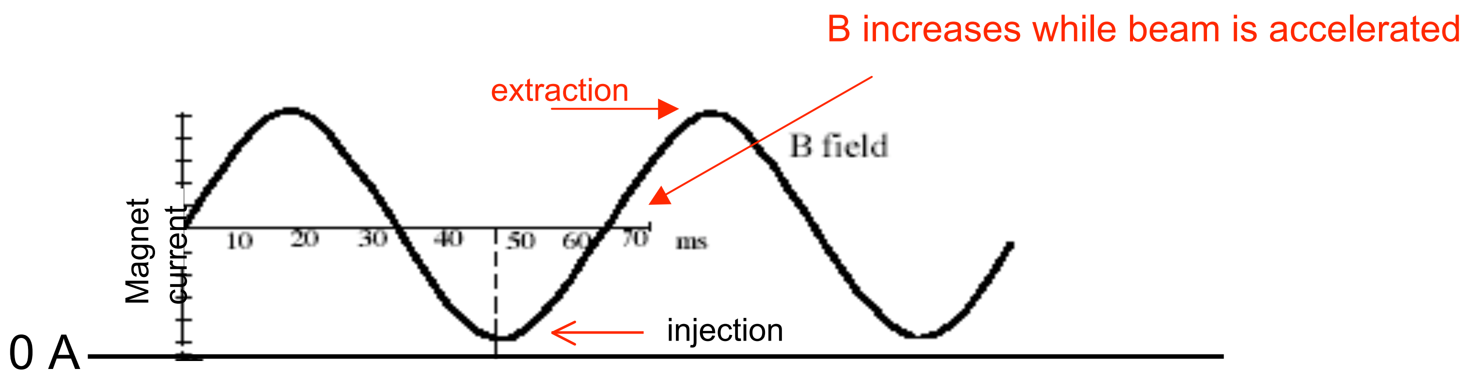
- RF energy, delivered by the 17 RF cavities, accelerates the proton beam over the rising portion of the sinusoidal magnet current waveform.

- Acceleration cycles occur at 15 Hz

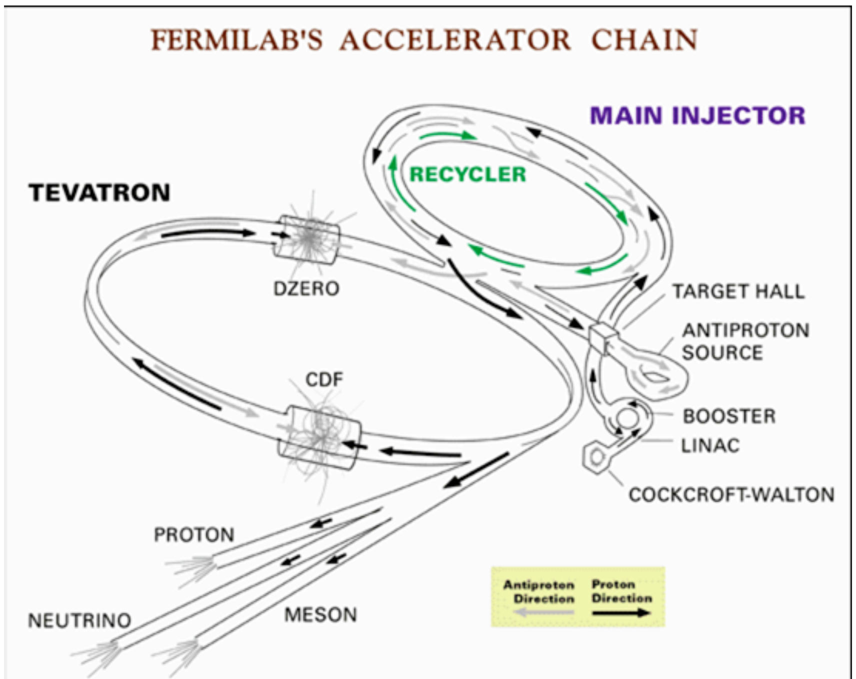


Acceleration

- There is a DC offset to the AC magnet current, so that the curcent is always positive.
- It would be difficult to do multi-turn injection right at the point where the energy is changing the fastest.
- With the offset, injection occurs on the "flatter" part of the sinewave.



Main Injector



Main Injector/Recycler

- The main injector was built to replace the Main Ring in the Tevatron tunnel
- The Main Ring is seen above the Tevatron in the photo.
- The MR was not actually removed, it was abandoned in place.
- The main ring quads (red magnets), however, were removed and reused

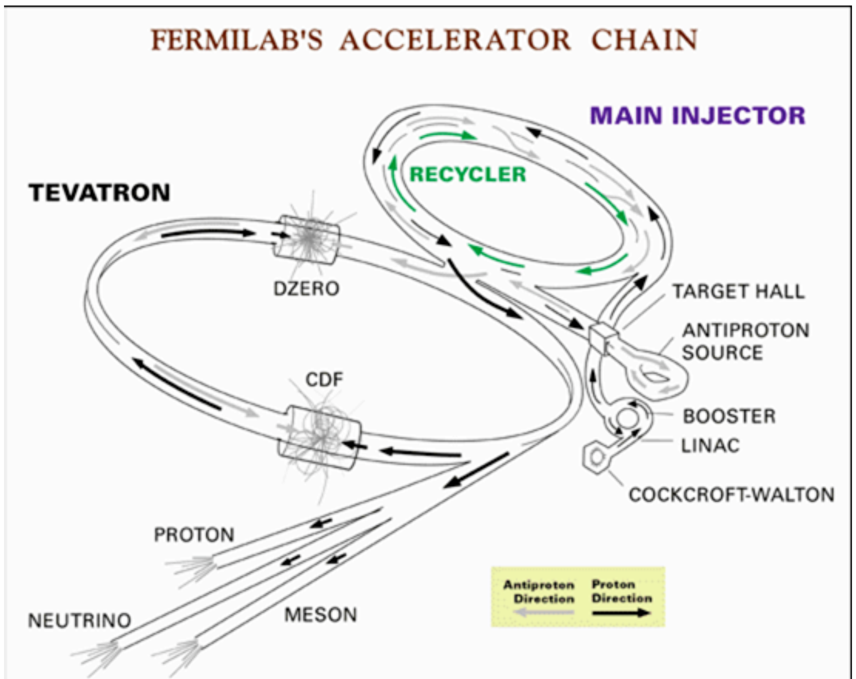
An old view of the Tevatron tunnel with Main Ring magnets still present

Main Injector/Recycler

- Main Injector
  - Accelerates protons
  - Delivers protons for antiproton production
  - Accelerates antiprotons from the Antiproton Source

- Antiproton Recycler (green ring)
  - The Recycler doesn't actually recycle; that plan was given up.
  - Now it stores antiprotons from the Accumulator to limit the peak stack size, which keeps the production rate up.

Antiproton Source



Antiproton Source

- Three main components
  - Target
  - Debuncher
  - Accumulator

Target

- A single batch of protons with an intensity of up to 5 X 10^{12} is accelerated to 120 GeV in the Main Injector

- The beams strikes the nickel production target in the target vault and produces a shower of secondary particles

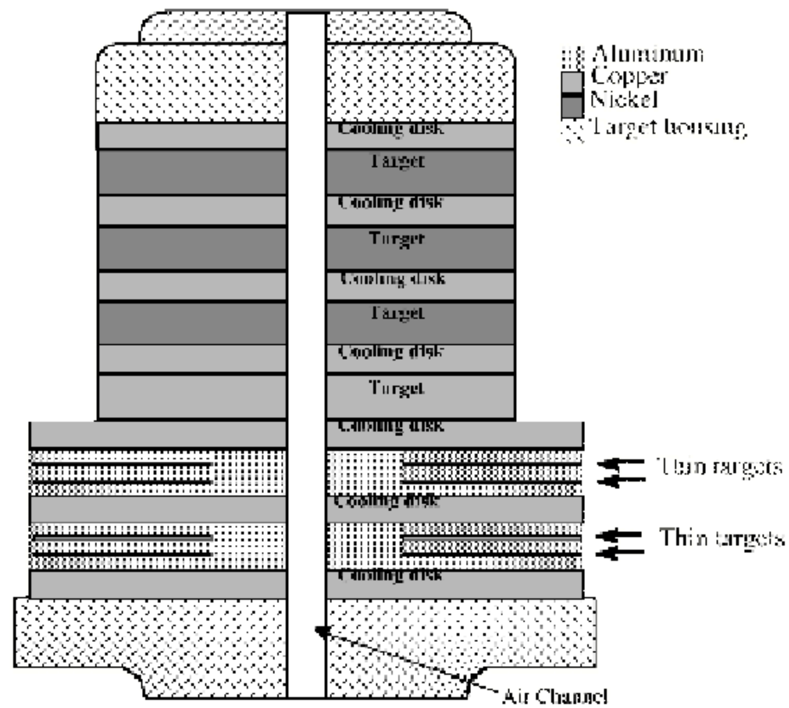


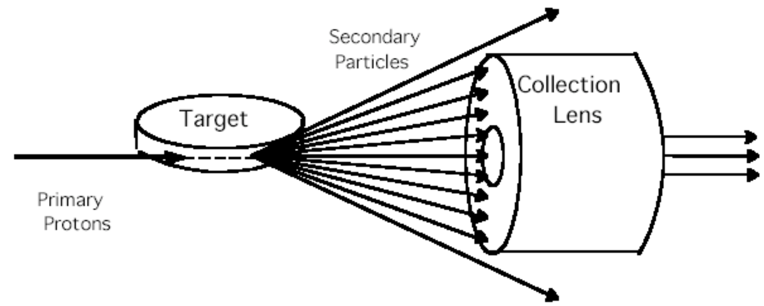
Figure 2.2 Cross section of target assembly

Target

- The resulting cone of secondary particles is focused and made parallel by means of a Lithium lens

- A pulsed dipole magnet bends all negatively-charged particles of approximately 8 GeV into the AP2 line while most of the other particles are absorbed within a beam dump

- From the AP2 line, the anitprotons travel to the debuncher and then to the accumulator



Two types of cooling

- Betatron (or transverse cooling) is applied to a beam to reduce its transverse size, i.e. to reduce its horizontal or vertical emittance

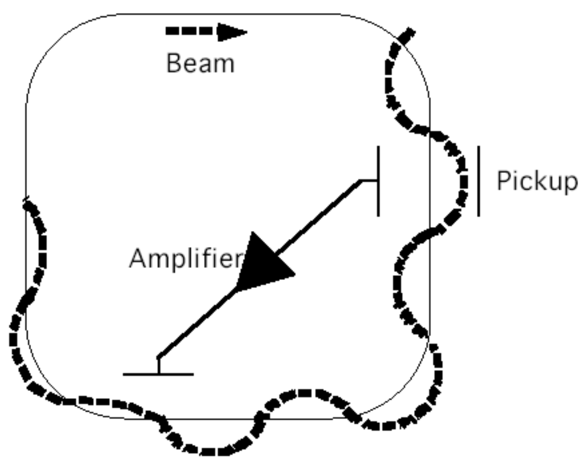


Figure 5.1 One-Particle Model for a Transverse Stochastic Cooling System

- Momentum cooling systems reduce the longitudinal energy spread of a beam by accelerating or decelerating particles in the beam distribution towards a central momentum

Debuncher

- The momentum spread of the 8 GeV beam of secondaries is reduced through bunch rotation and adiabatic debunching.

- Both betatron (transverse) stochastic cooling and momentum (longitudinal) cooling is applied to reduce the beam size and momentum spread

Debuncher
(outer,light blue ring)

D to A

- Just before the next pulse arrives from the target, the antiprotons are extracted from the Debuncher and injected into the Accumulator via the D to A line

D to A line

Accumulator

- Successive pulses of antiprotons are stacked into the Accumulator 'core' by means of RF deceleration and momentum stochastic cooling
- The antiprotons in the core are maintained there by momentum and betatron cooling systems

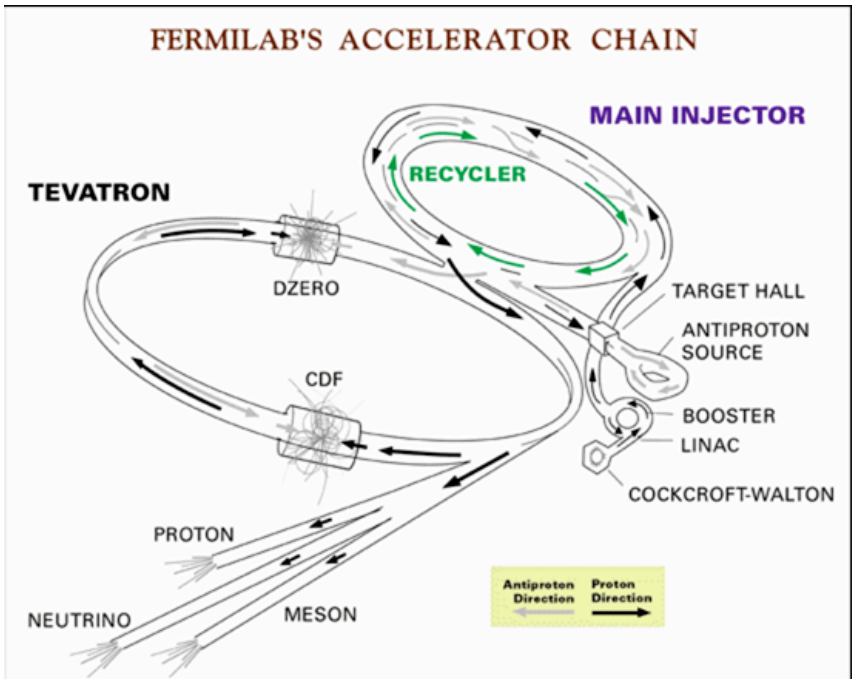
Accumulator
(inner, dark blue ring)

Accumulator

- After several hours, enough antiprotons have been accumulated to initiate a transfer to the Main Injector and Tevatron for a store (or to the Recycler via the Main Injector).

Accumulator
(inner, dark blue ring)

Tevatron


FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
CDF
TARGET HALL
ANTIPROTON
SOURCE
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

Tevatron

- Receives 150 GeV protons and antiprotons
- Cryogenic magnets
- Normal-conducting (warm) RF cavities, all located at FO (do not need to be evenly spaced around the ring)
- Accelerates to 980 GeV
- Stores beam providing p^+p^- collisions for CDF and DO

Tevatron map

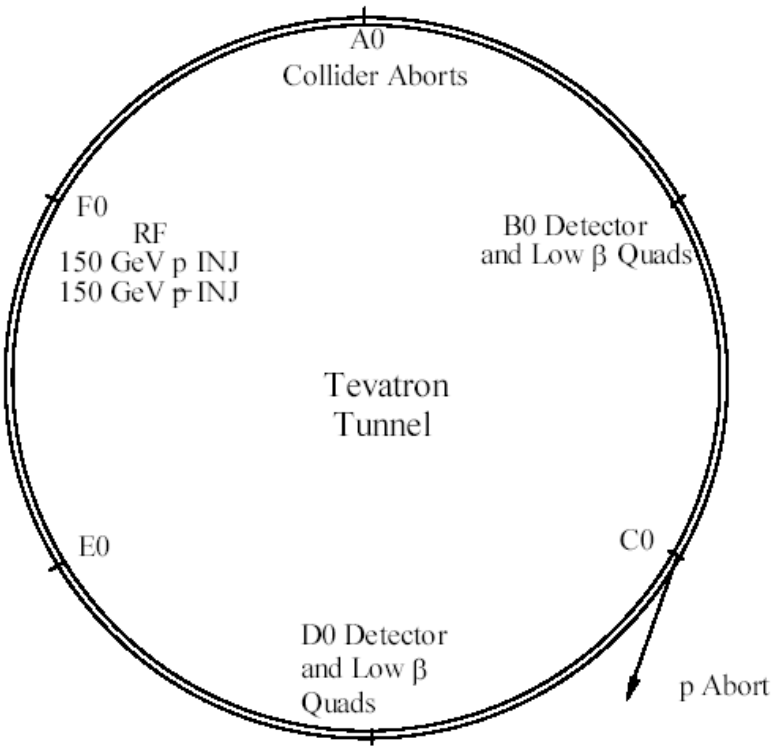
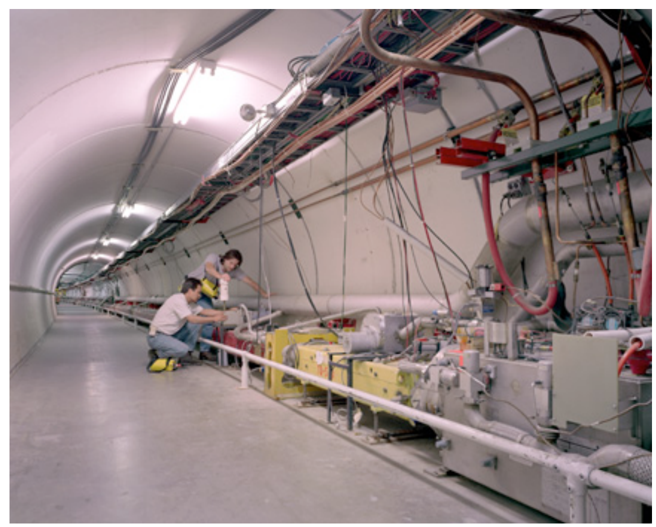


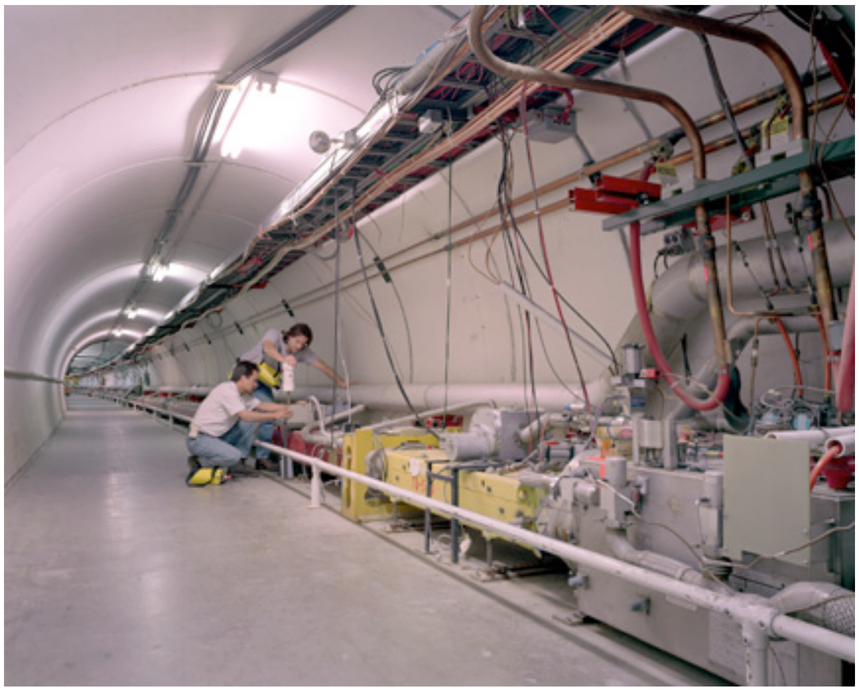
Figure 1.8 Tevatron tunnel.

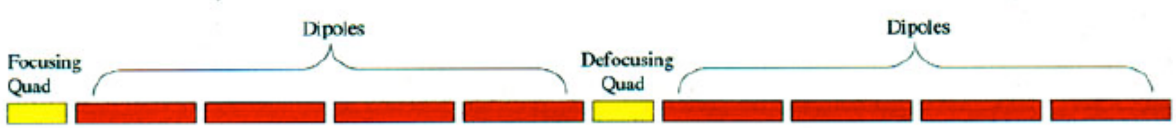
Tevatron magnets

- All Tevatron magnets are superconducting
- 4.2 Tesla bend field (red magnets)
- Quadrupoles (yellow)
- Tevatron correction elements are superconducting coils located within the main Tevatron quadrupole cryostats



Tevatron FODO lattice

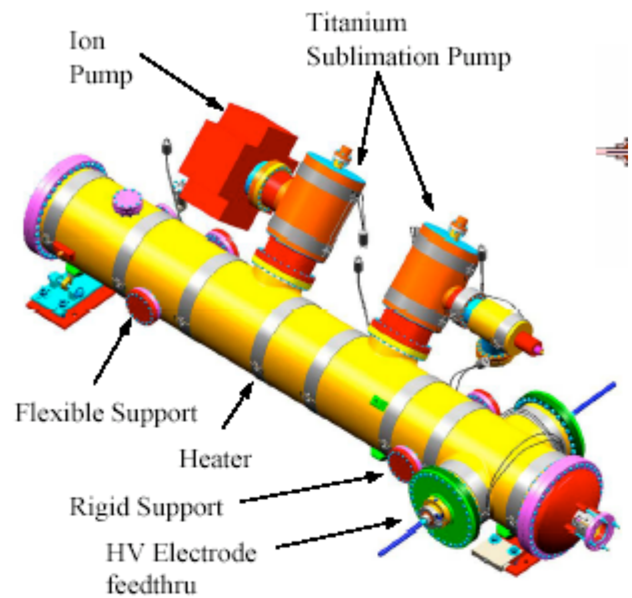




FODO lattice

Parasitic crossings

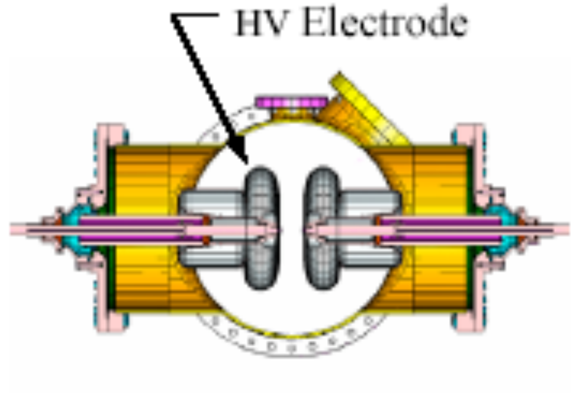
- The Tevatron operates with 3 trains, 12 bunches/train of each species
- This would result in 70 parasitic crossings:
  - (36x2)-2=70
  - Note: the (-2) is because we want the beam to cross at CDF and DO
- So, like CESR, the Tevatron uses separators to minimize the effect of the parasitic crossings



Tevatron separator

Parasitic crossings

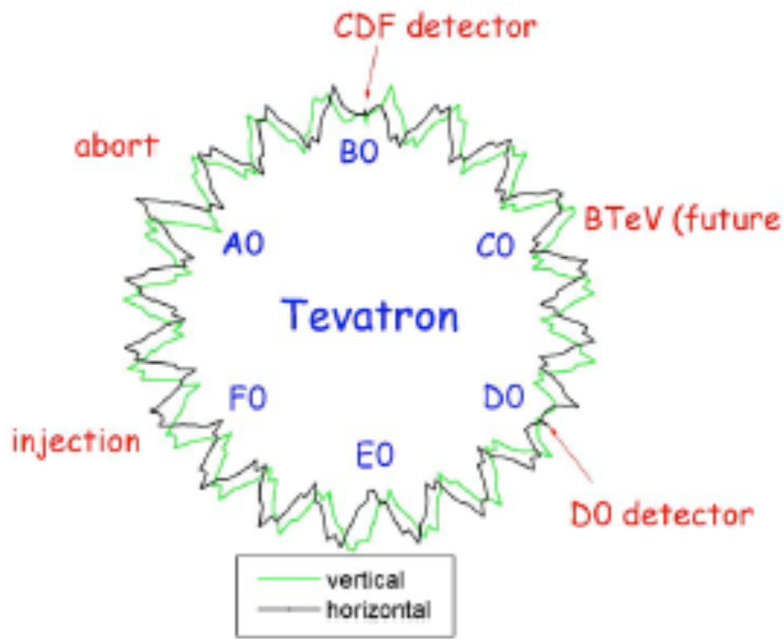
- But unlike CESR, synchrotron radiation is minimal in the Tevatron, so the electrode design did not need to take that into consideration
- The Tevatron separators consist of two “parallel plates”, separated by 5 cm, with a potential difference of 200kV DC between them
- They can be constructed in either “horizontal” and “vertical” configurations. The parts for each type are identical



Tevatron separator

Helix

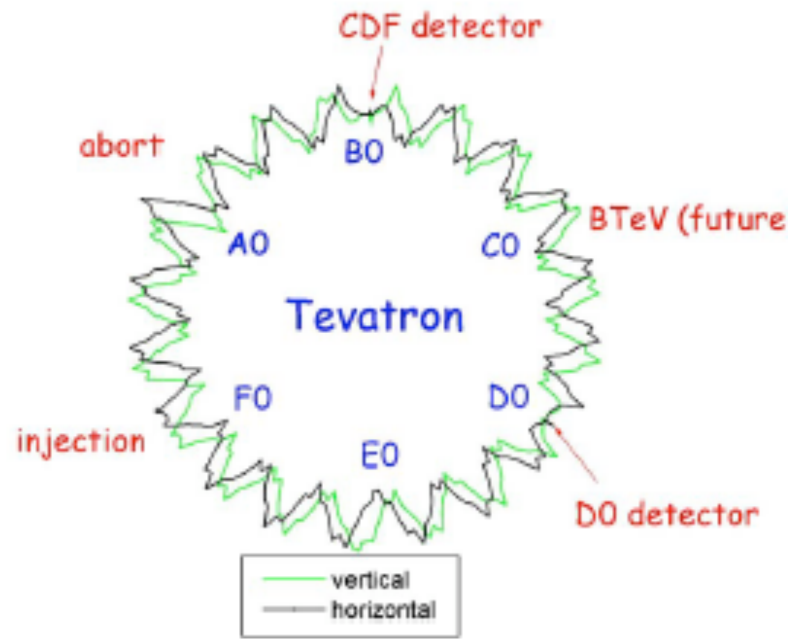
- In CESR, the electrons and positrons were separated with a pretzel orbit in just one plane (horizontal)
- In the Tevatron, the protons and antiprotons are separated via helical orbits
- Horizontal and Vertical separators spaced roughly 90 degrees apart in phase generate the helix (compare circular polarization)



Tevatron separator functions

Helix

- But there is no desire to separate protons and antiprotons at CDF and DO!



Tevatron separator functions

Tevatron energy

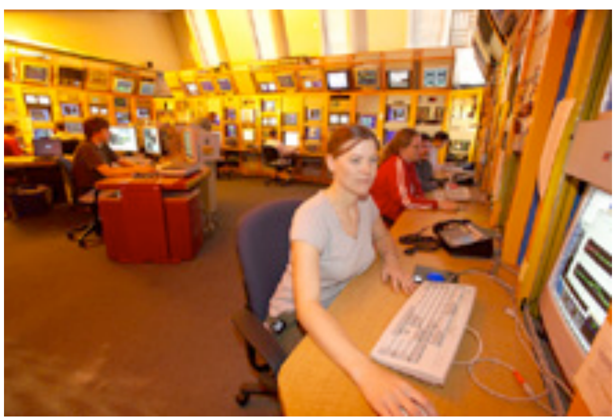
- The energy is calculated from the magnetic field in the dipoles and the revolution frequency.
- The RF frequency is known with great precision, probably better than anything else about the machine.
- The cross section predictions have bigger sources of uncertainty than the energy

Operator’s job

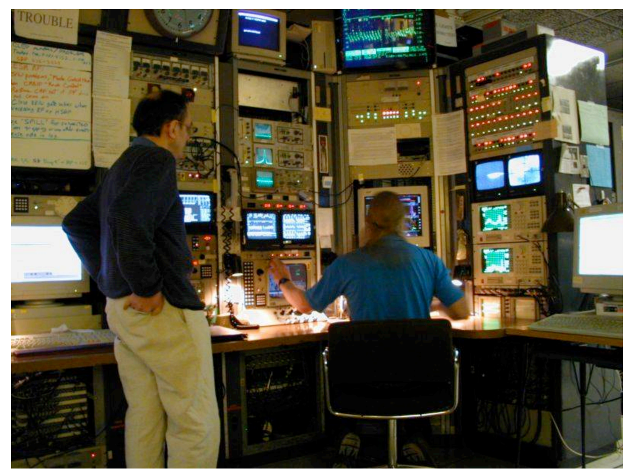
- At first glance, it looks like a Day in the Life of an operator is identical at each accelerator…………

Operator’s job

- Fermilab
  - Maintain luminosity
  - Make sure machine is ready to refill



- CESR
  - Maintain luminosity
  - Make sure machine is ready to refill



Operator’s job

- But the properties of electrons vs. hadrons make a Day in the Life of an operator very different at each machine
- The duration of a “store” (the time before the storage ring must be refilled) differs

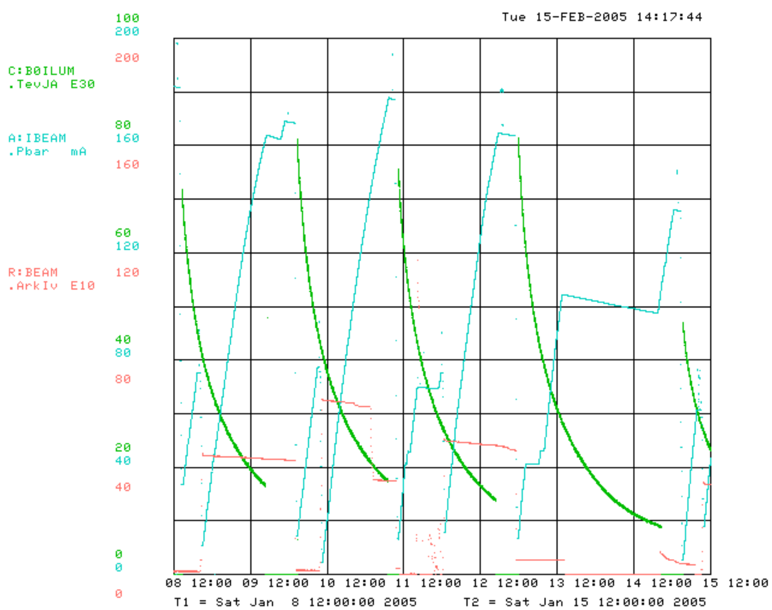
Store duration

- Fermilab
  - Store duration ~ 24 hours
  - Luminosity lifetime
    - 11-13 hours
  - Filling time
    - The Tevatron fill time is ~30 minutes, but the total turnaround time is ~2 hrs with the tune-ups, etc.

- CESR
  - Store duration ~ 1 hour
  - Luminosity lifetime
    - 2-3 hours
  - Filling time
    - 5 minutes

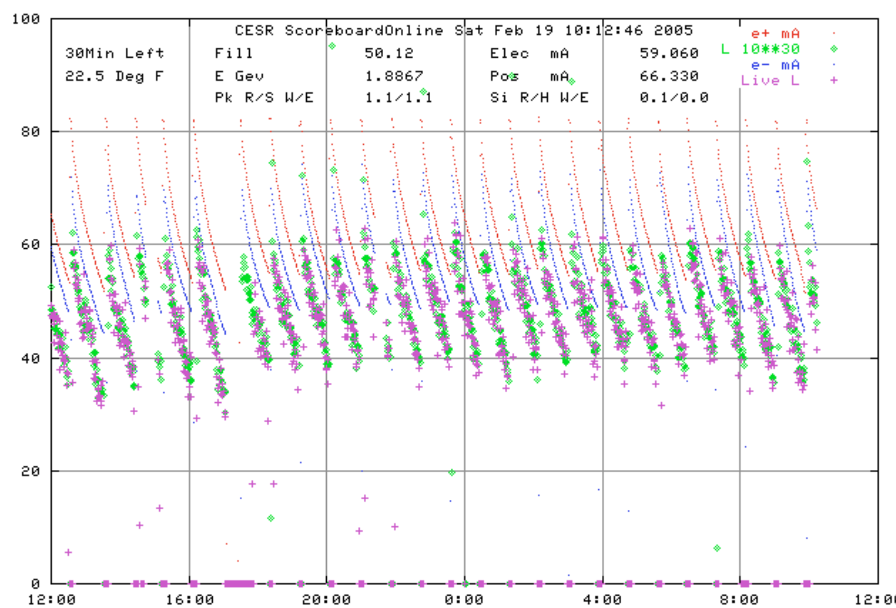
Store duration

- Fermilab



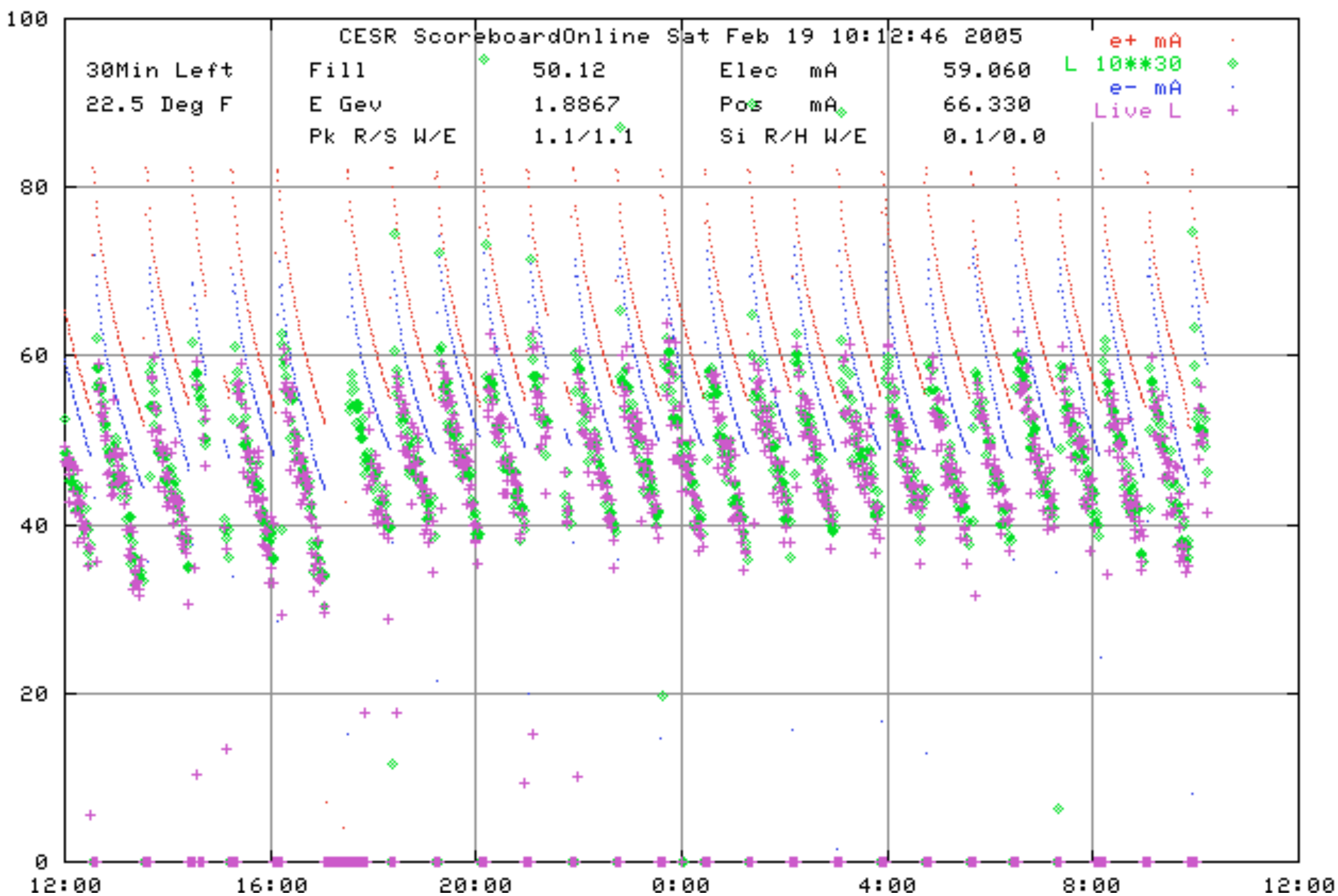
1 day

- CESR



1 day

CESR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22.5 Deg F
Fill
50.12
E Gev
1.8867
Pk R/S W/E
1.1/1.1
Elec mA
59.060
Pos mA
66.330
Si R/H W/E
0.1/0.0
e+ mA
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e- mA
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8:00
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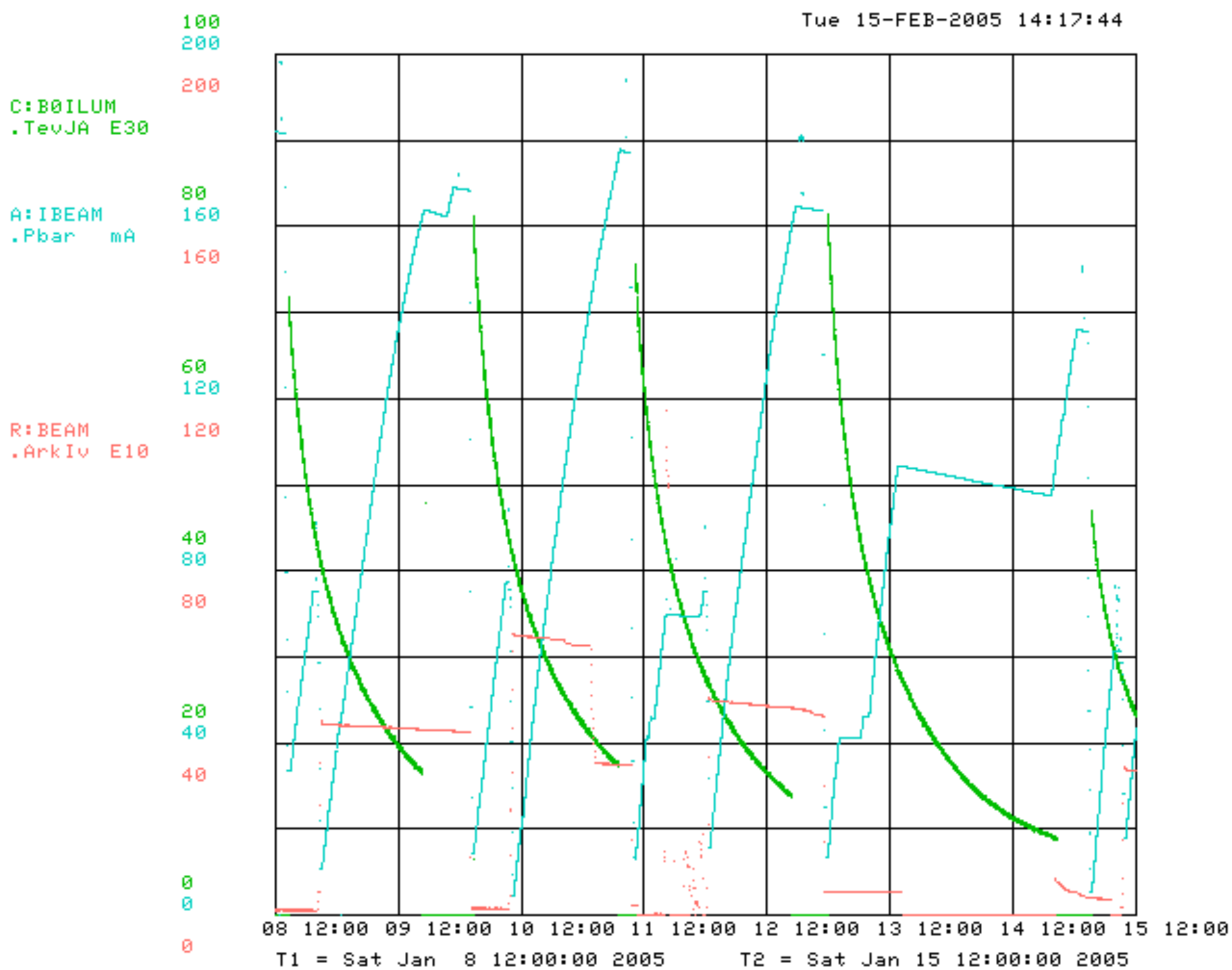
Tevatron



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A:IBEAM
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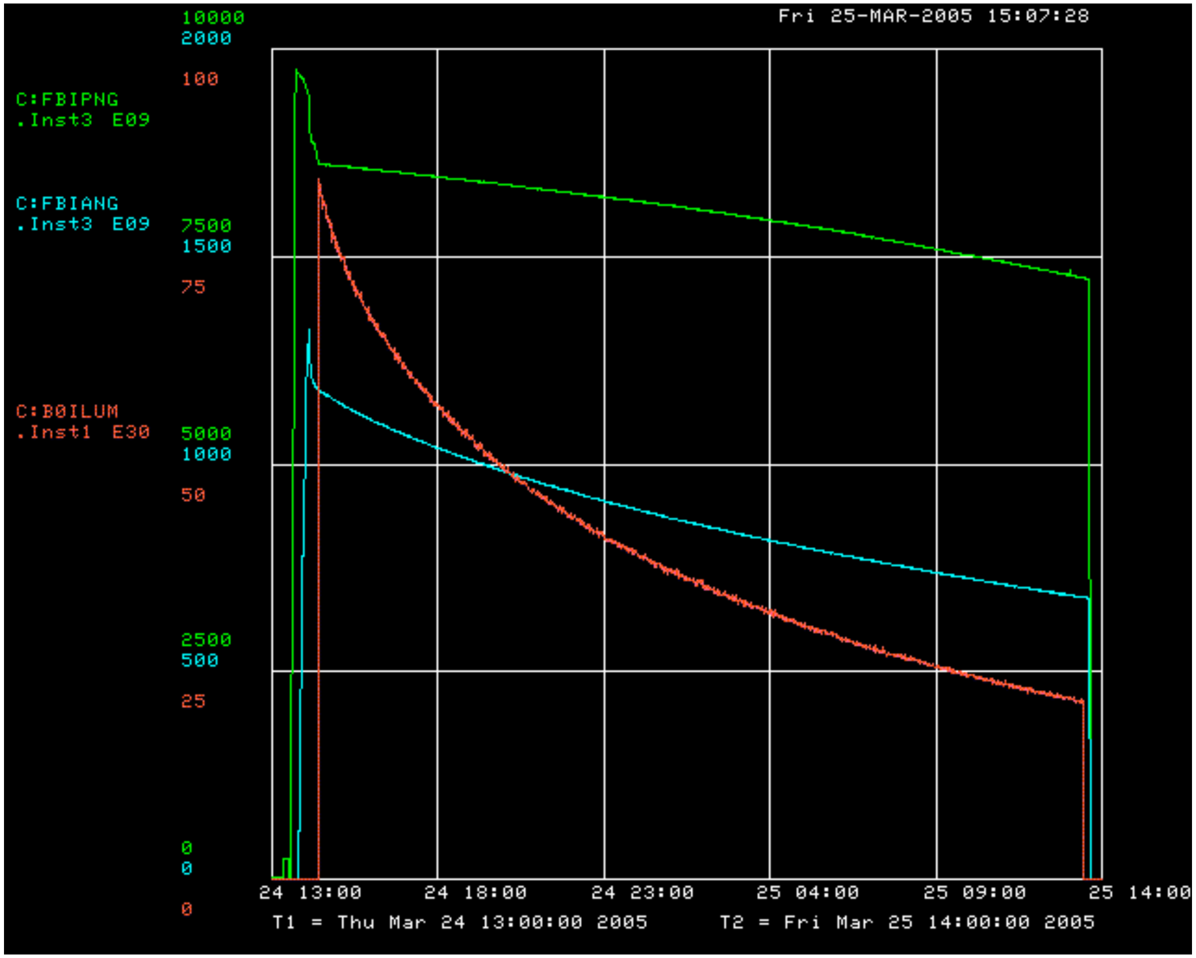
T1 = Sat Jan 8 12:00:00 2005
T2 = Sat Jan 15 12:00:00 2005

Tevatron

Proton intensity

Antiproton intensity
(different scale!)

Luminosity



Why length of stores differ

- Fermilab
  - Lower luminosity
    - 50×10^{30} cm^{-2} s^{-1}
  - Higher energy
    - 980 GeV

- CESR
  - Higher luminosity
    - 1280×10^{30} cm^{-2} s^{-1}
  - Lower energy
    - 5 GeV

Why length of stores differ

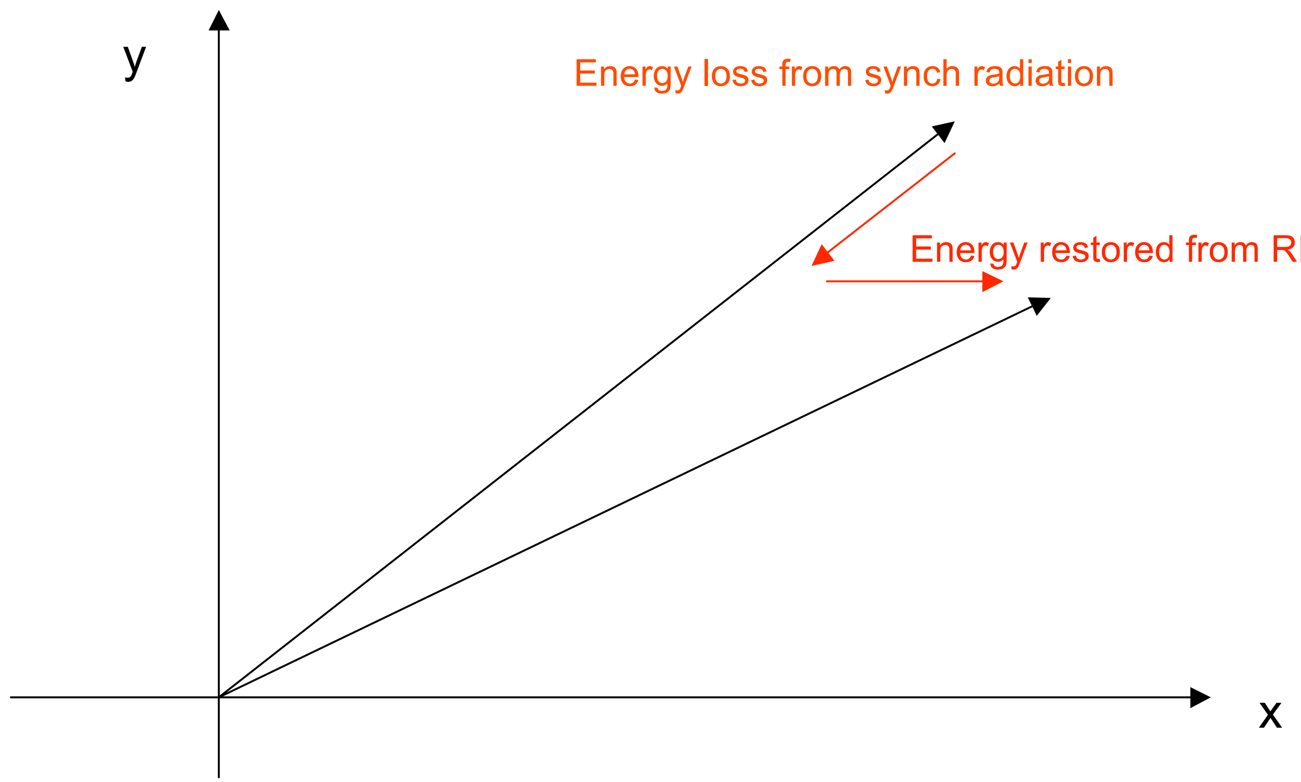
- The combination of lower energy and higher luminosity at CESR results in beams that are more “disrupted” in the collisions, leading to a much shorter lifetime

- In addition, even without any collisions, the lower-energy beams in CESR are more susceptible than the Tevatron beams to other influences, such as beam-gas scattering, which cause beam loss and reduced lifetime

- Even though the electron beams in CESR are radiation-damped, the net effect is a poorer lifetime for the CESR beams

Radiation damping

- Synchrotron radiation reduces the momentum of the particle in the direction of its motion while the acceleration system restored momentum parallel to the central orbit



What happens between stores

- Fermilab
  - Maintain luminosity
  - Attend to any tuning requests from the many experiments (DO, CDF, MiniBooNE, MINOS, Meson Test Beam Facility, etc.
  - Make sure the Preacc, Linac, Booster, and Main Injector, Tevatron are ready for the next fill
  - Accumulate the antiprotons for the next fill
  - Monitor cryogenics
- CESR
  - Maintain luminosity
  - Attend to any tuning requests from CLEO and CHESS
  - Make sure the Linac is ready for the next fill

Operators

- Fermilab
  - Need a crew of 4-5 operators
- CESR
  - One operator

Smooth Operator

~SADE