Making Luminosity in the Tevatron

Paul Derwent

FNAL/BD/Pbar

September 19, 2003

Definitions

- Main Entry: **lu·mi·nos·i·ty**
  Pronunciation: `"lü-m&-'nä-s&-tE`
- Function: *noun*
  Inflected Form(s): *plural* **-ties**
  Date: 1634
  1 a :the quality or state of being luminous **b:**something luminous
  2 a :the relative quantity of light
  b:relative brightness of something
  3:the relative quantity of radiation emitted by a celestial source (as a star)
- Merriam Webster

- **3:** Solar Luminosity:
  $(3.846 \pm 0.008) \times 10^{26}$ W
  PDG

- Lumen: 1 cd sterradian
- 1 candela = luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540 THz and that has a radiant intensity in that direction of 1/683 watts per sterradian
  SI Units NIST

- Accelerator Luminosity
  - Particle Flux Rate per Unit Cross Section
  - #/sec/cm^2

Accelerator Luminosity

- Particles with both transverse and longitudinal distributions traveling in opposite directions

$$L = 2cf_0B \int \rho_+(x,y,z-ct)\rho_-(x,y,z+ct)d^3xdt$$

In the case of 3 dimensional gaussian beams

$$L = \frac{f_0BN_pN_{\bar{p}}}{2\pi\sqrt{\sigma_p\sigma_{\bar{p}}}} \int \frac{e^{-0.5\left(\frac{z-z_0}{\sigma_z}\right)^2}}{\beta^*\left(1+\left(\frac{z-\beta_{\min}}{\beta^*}\right)^2\right)} dz$$

Accelerator Luminosity

$$L = \frac{3\gamma f_0}{\beta^*}(BN_{\bar{p}})\left(\frac{N_p}{\varepsilon_p}\right)\frac{F(\beta^*, \varepsilon_x, \varepsilon_y, \varepsilon_p, \varepsilon_{\bar{p}}, \sigma_p^L, \sigma_{\bar{p}}^L)}{1 + \frac{\varepsilon_{\bar{p}}}{\varepsilon_p}}$$

Number of $\bar{p}$'s	$BN_{\bar{p}}$
Proton beam brightness	N_p/ε_p

Dominant terms for the Tevatron

Run II Parameters

	Typical Run Ib	Typical Run II(1)	FY03 Goal	Run II Target	
Peak Luminosity	1.6	3.7	6.6	33	10^{31} cm^{-2} sec^{-1}
Integrated Luminosity	3.1	6.4	12	70	pb^{-1}/week
Store Hours/week	84	84.7	81	98	hours
Interactions/crossing	2.5	1.0	1.7	8.5	
Pbar bunches	6	36	36	36	
Form Factor	0.59	0.6	0.63	0.63	
Protons/bunch	23	23.5	24	27	$x10^{10}$
Pbars/bunch	5.6	2.1	3.1	13.5	$x10^{10}$
Total Pbars	33.6	75.0	113	486	$x10^{10}$
Peak Pbar Production Rate	7.2	13.5	18	45	$x10^{10}$ /hour
Average Pbar Production Rate	4.2	8.5	11	40	$x10^{10}$ /hour
Pbar Transmission Efficiency	50	61.5	80	85	%
Stack Used	67	128.4	141	572	$x10^{10}$
Beta*	0.35	0.35	0.35	0.35	m
Bunch Length (RMS)	0.6	0.6	0.54	0.54	m
Proton Emittance	23	25.5	20	20	π mm mr
Pbar Emittance	13	13.1	15	14	π mm mr
Store Length	16	14.4	15	9	hours

(1) average for July/August 03

- All Classical (Relativistic) E&M
- Hamiltonian of a charged particle in EM field

$$H = \sqrt{\left(\vec{p} - e\vec{A}\right)^2 c^2 + m^2 c^4} + eV$$

- Small angle approximation around CENTRAL ORBIT
- Set of Conjugate variables:
  - x, x' horizontal displacement and angle
  - y, y' vertical displacement and angle
  - E, s energy and longitudinal position
    - » s = βct sometimes use t instead
- Equation of Motion:

$$\frac{d^2 x}{ds^2} + k(s)x(s) = 0, \text{ where } k(s + C) = k(s)$$

  - C is circumference of accelerator -- Periodicity!
  - Hill's equation: studied in 19th century

Liouville's Theorem

Phase space area of conjugate variables is conserved!

J. Liouville "Sur la Théorie de la Variation des constantes arbitraires" Journal de Math. Pures *et* Appl. P.342, 3, (1838)

Solutions to Equations of Motion

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- Restoring force *k(s)* is dependent on location
  - Dipoles
  - Quadrupoles
  - Drifts
  - Beams!
- General Solution:

$$x(s) = A\sqrt{\beta(s)}\cos(\phi(s) + \phi)$$

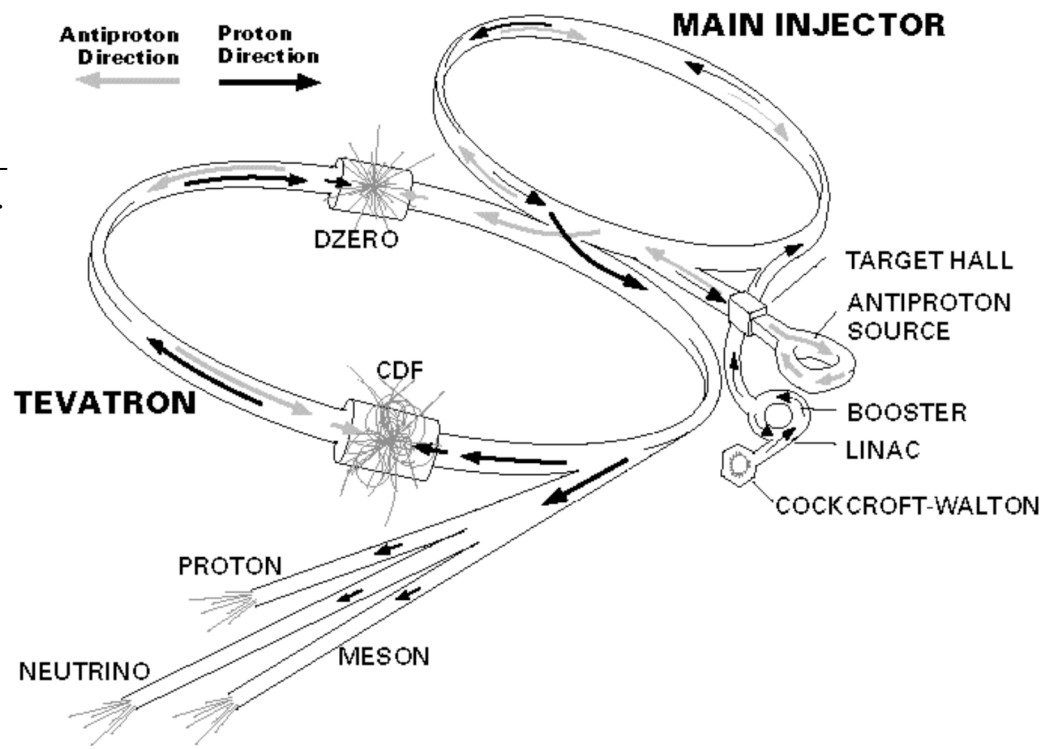
$$\phi(s) = \int \frac{ds}{\beta(s)}$$

$$\text{Tune} = \frac{\phi(C)}{2\pi} = \int_0^C \frac{ds}{\beta(s)}$$

  - β(s) is solution to a messy 2nd order Diff Eqn
- Beam size depends on Amplitude of oscillation and value of β(s)
- Can change Position by changing angle 90° upstream used for extraction/injection/cooling/IP position

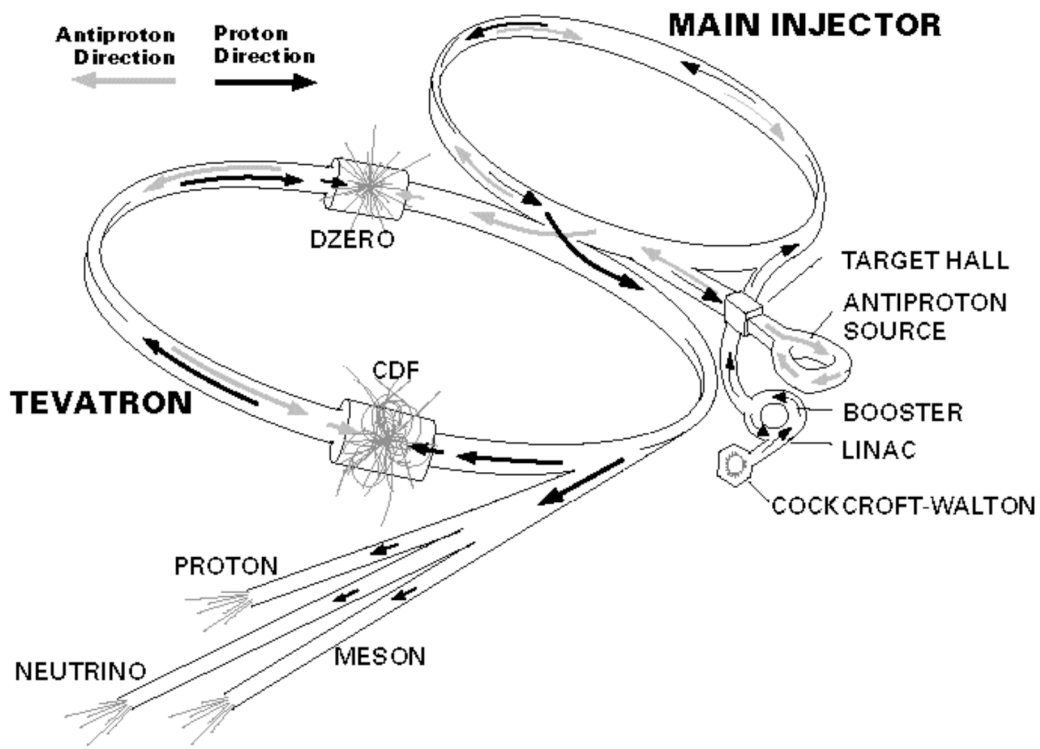
Following the protons

- Proton Production
  - H- ions are accelerated to 750 keV in the Crockoft-Walton
  - H- ions are accelerated to 400 MeV in the Linac
  - H- ions are stripped and multi-turn injected onto the Booster
  - Protons are accelerated from 400 MeV to 8 GeV in 33 mS in the Booster
  - In the Main Injector Protons are accelerated from 8 GeV
    - » to 120 GeV for pbar production in 1.5-2.4 seconds
    - » to 150 GeV for TEVATRON filling in 3.0 seconds
  - Protons are accelerated from 150 GeV to 980 GeV in the TEVATRON



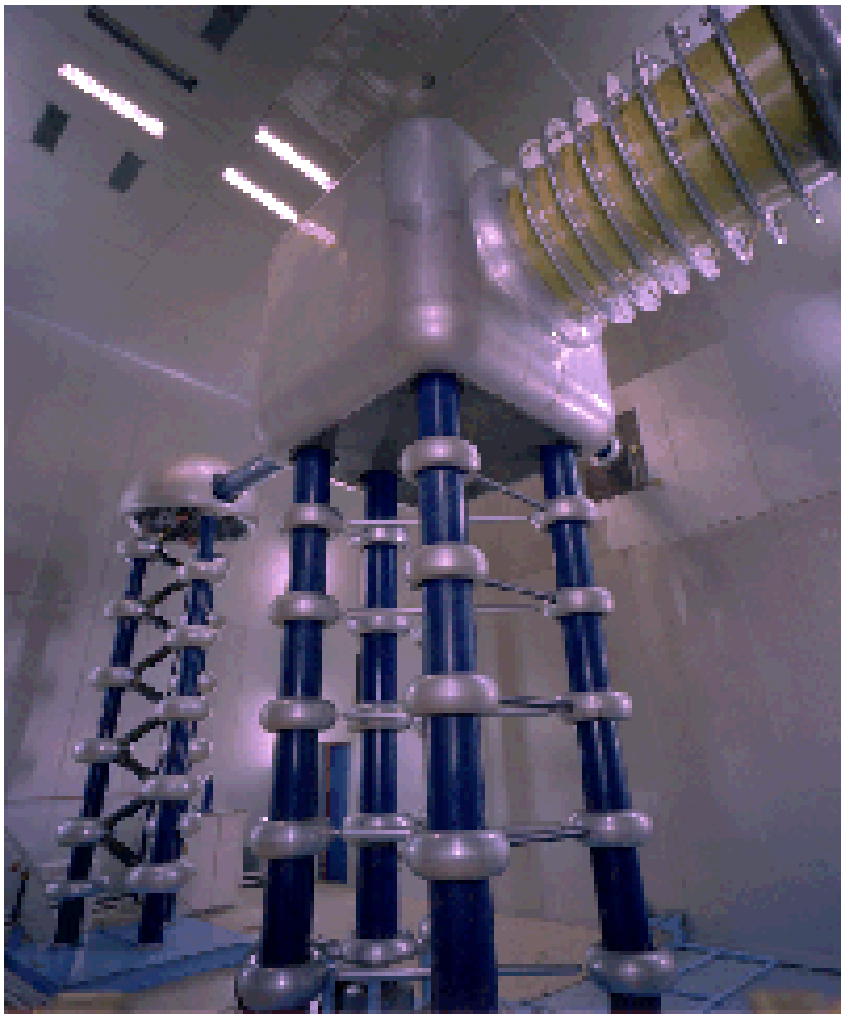
Following the $\bar{p}$'s

- Antiproton Production
  - 85×10^6 8 GeV pbars are made every 2 seconds by smashing 5×10^{12} 120 GeV protons on a Nickel target
  - 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
  - 18,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator Rings
    - » The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
  - 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON



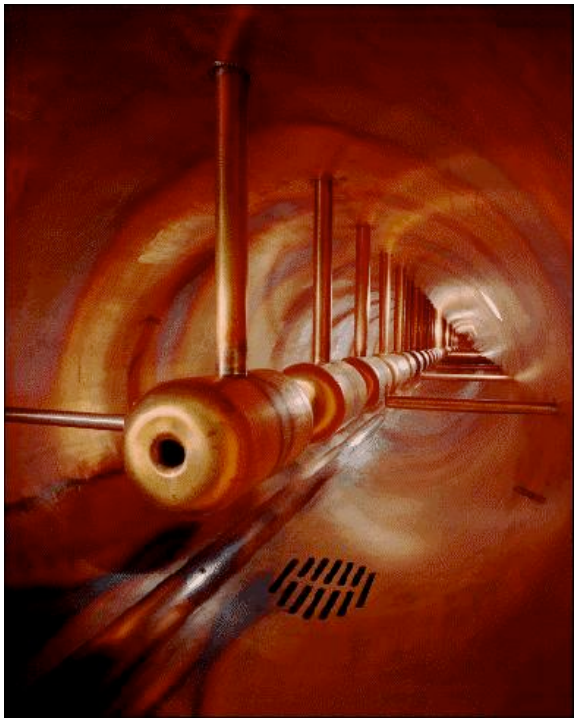
Following the protons

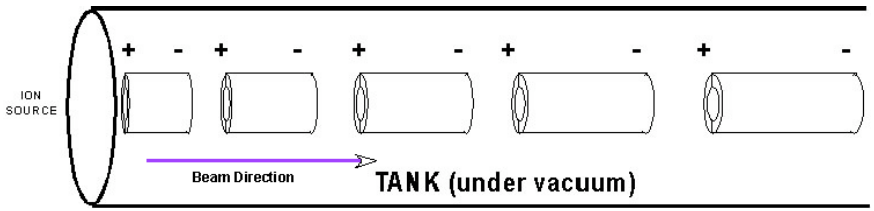
- Pre-Acc:
  - 18 keV 50 mA H^- beam
    - » magnetron surface-plasma source
    - » 15 Hz
    - » 40 μsec pulse
    - » 1.25e13 protons per pulse
  - Cockroft-Walton
    - » 750 keV
    - » Electrostatic accelerator



Linac

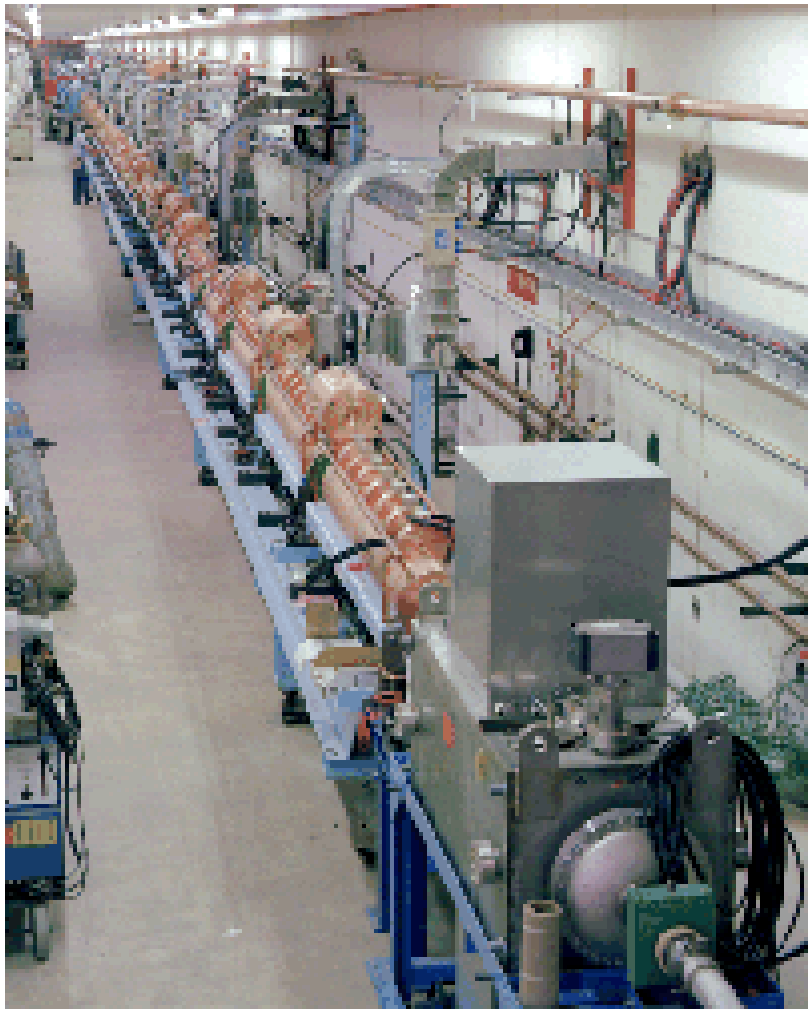
- Two stage linear accelerator H^-
  - First Stage to 100 MeV
    - » Alvarez drift tube
    - » Original design 1970!
    - » 5 201.24 MHz drift tube tanks
    - » 5 MW in 400 μsec pulses
    - » Acceleration in gap
    - » 50% capture efficiency in RF (phasing with respect to synchronous particle)
    - » 6e12 per pulse
    - » 4e9 per ‘Tev RF bucket’





Following the protons

- Second stage to 400 MeV
  - » $30 M upgrade in 1993
  - » Side coupled cavities at 805 MHz (4x drift tube frequency)
  - » 7 10 MW klystrons
  - » FODO lattice between cavities
  - » RF Debunch - recapture in Booster

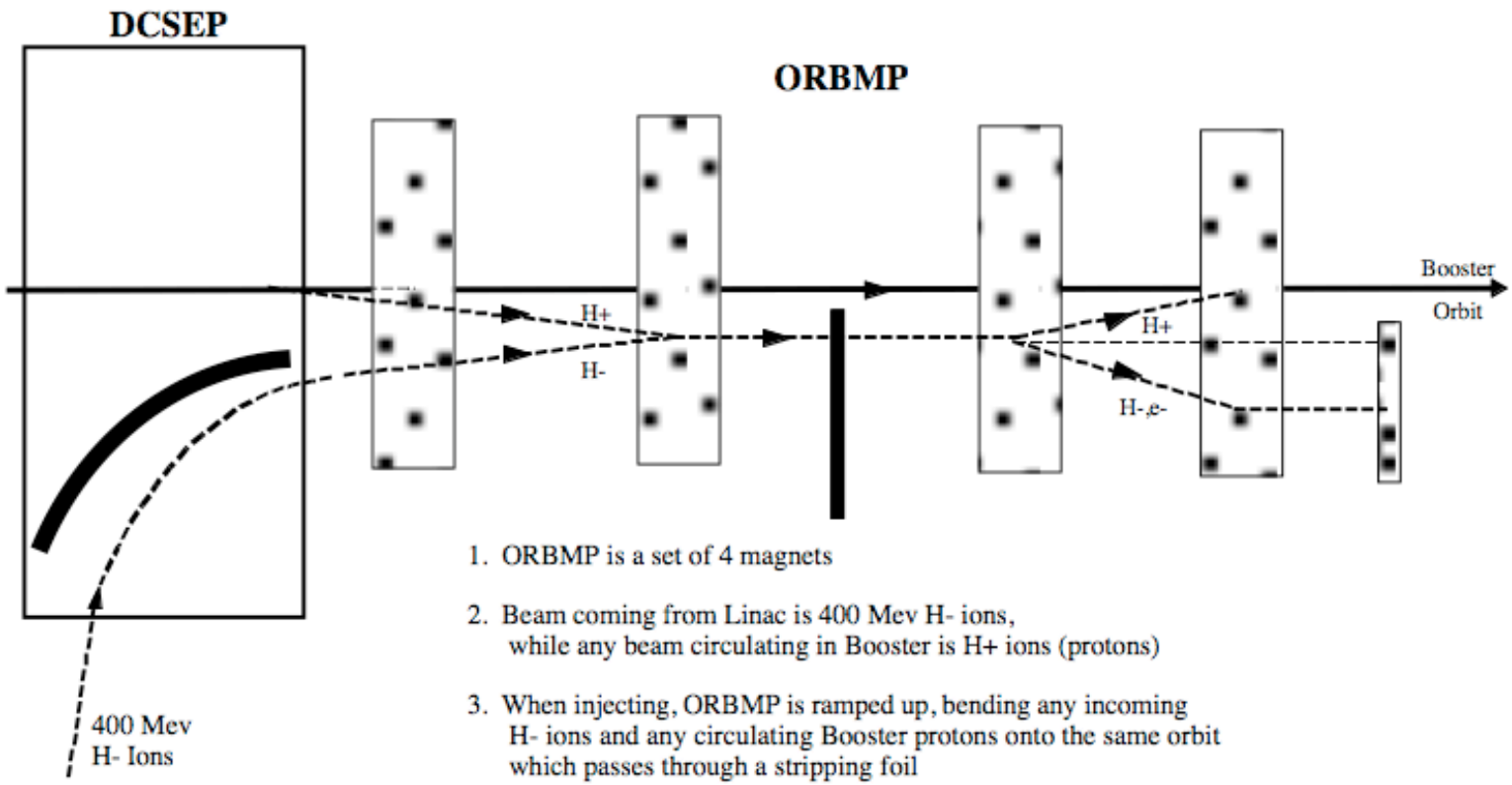


Following the protons

- Booster: Proton Accelerator
  - 400 MeV to 8 GeV
    - » 2.2 μsec of 40 μsec pulse
    - » Single turn 3.3e11
  - 84 RF buckets
    - » 37.9 to 52.8 MHz
  - First trick to beat Liouville:
    - » Multi-turn charge-exchange injection -- sample more of 40 μsec
    - » Overlap injected proton beam to circulating proton beam?
      - Any EM device to kick injected beam on to circulating orbit would kick circulating beam out
      - Inject H^-, strip electrons, circulate protons
    - » 4-5 e12
    - » 60e9 per RF bucket

Following the protons

Long 1 Injection



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

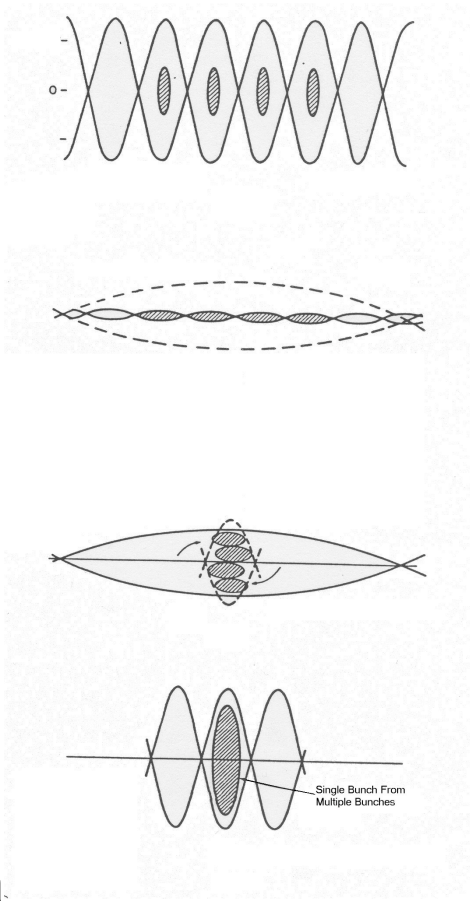
figure 1.6

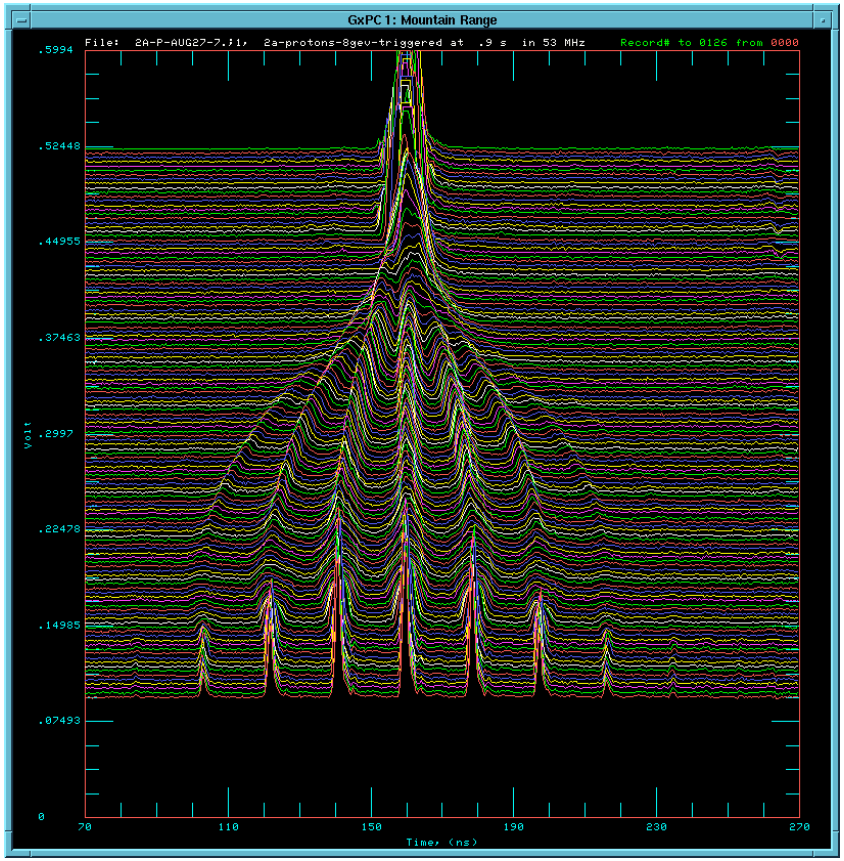
Following the protons

- Main Injector: p and $\bar{p}$ accelerator
  - 8 GeV to 120 GeV for $\bar{p}$ production
    - » Bunch rotation to minimize time spread
    - » Transfer through P1 - P2 - AP1 (120 GeV) to production target
    - » 4-5 e12 to $\bar{p}$ production target
    - » Will rejoin the $\bar{p}$ story a few slides along
  - 8 GeV to 150 GeV for Tevatron operation
    - » 11 turns of 5 (or 7) bunches from Booster
      - Short batch -- time kicker to only transfer 5 of 84 RF buckets
    - » Accelerated to 150 GeV
    - » Next intensity boosting trick!
      - Coalesce batch of 5 into 1 single bunch
    - » Bucket to bucket transfer to TeV
    - » P1 line running in 150 GeV mode
  - 270e9 in RF bucket transferred to Tevatron

Following the protons

- **53 MHz bunch structure h=588**
- **Overlay 2.5 MHz RF h= 28 and 5 MHz h=56**
- **Remove 53 MHz**
- **Allow bunches to rotate**
- **Recapture with 53MHz**

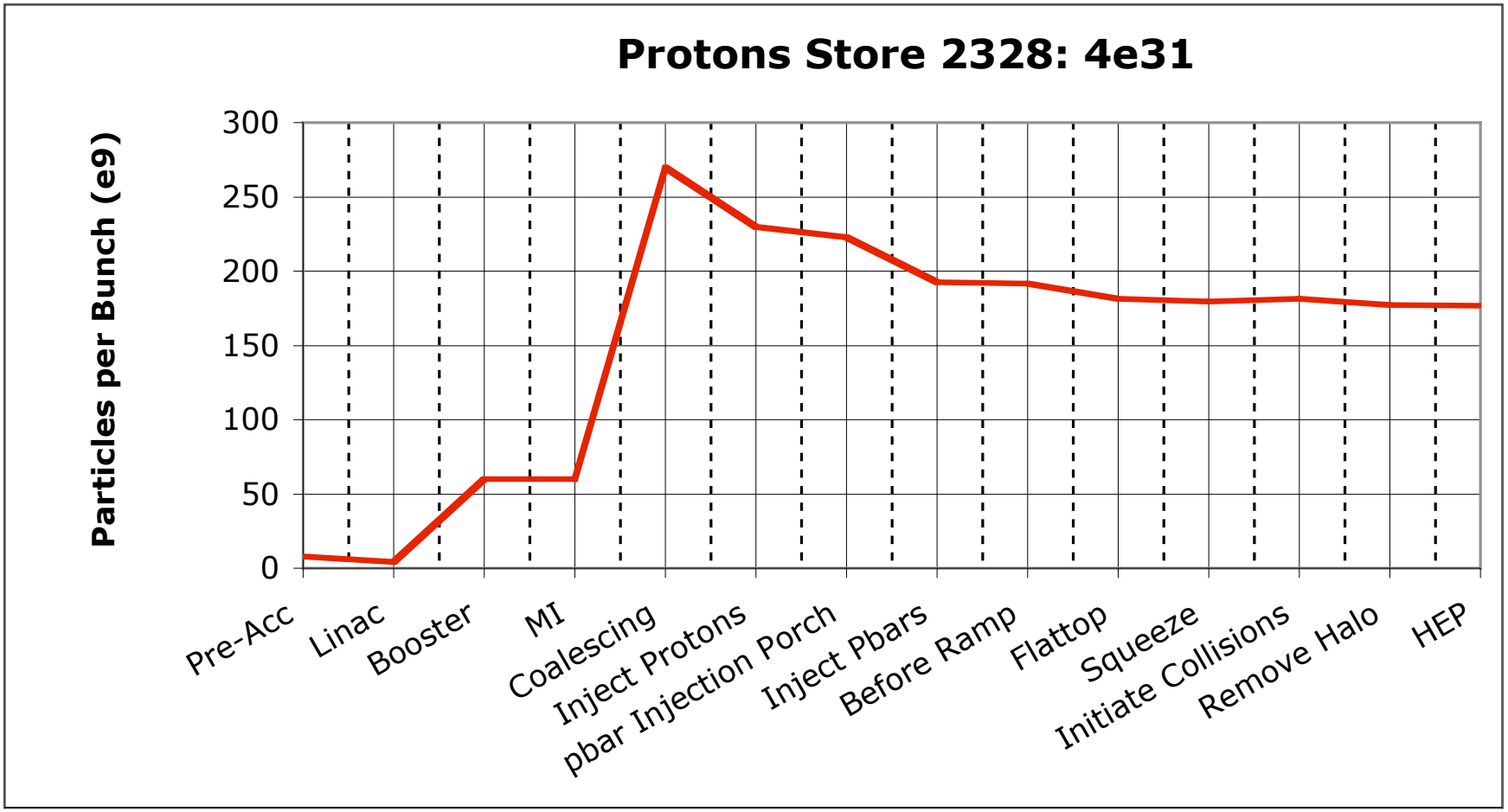




Following the protons

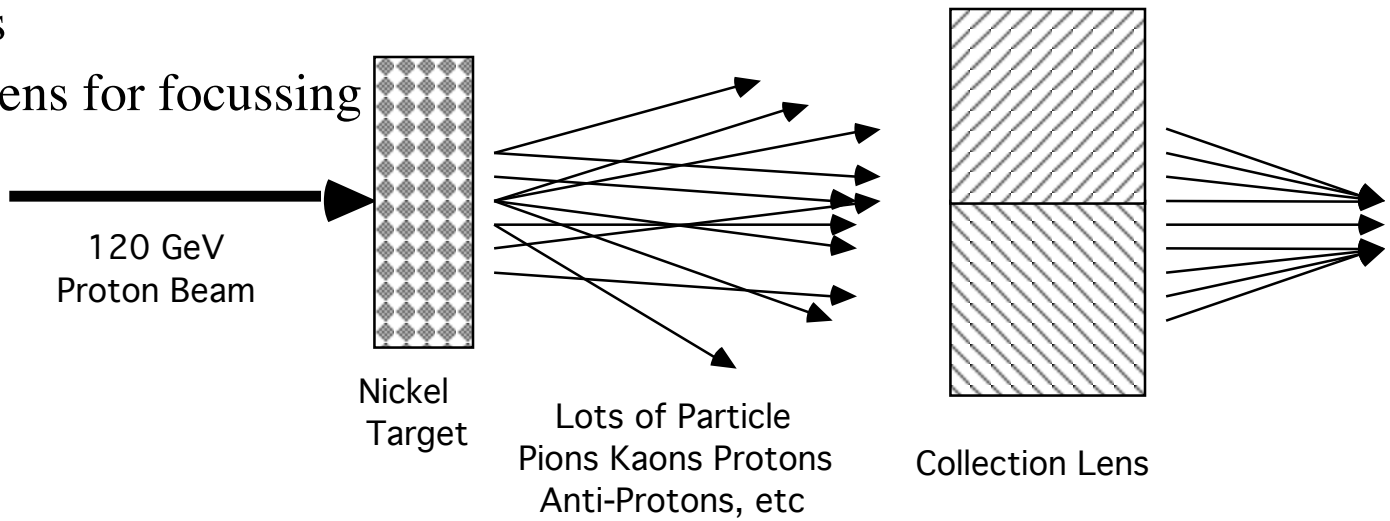
- Beam loading effects
  - Turn off the 53 MHz:
    - » Paraphase the drive…
      - Run $^1/_2$ cavities 180º out of phase
    - » but the cavities still resonate
      - Beam is a current source, cavity is an impedance
      - Beam induced voltage in cavity
      - Feedback and feedforward systems to hold voltage at 0
- Linearize the rotation voltage
  - Alignment of 2.5 MHz and 5 MHz
- Sensitive system which needs constant attention

Beam Intensities through the chain



Following the protons to the $\bar{p}$'s

- 84 bunches, ~1-2 nsec time spread on production target
  - Smaller spot size, larger acceptance
    - » Larger energy depositions
  - Energy Deposition -> melting
    - » ~500 J/g -> T ~ 1700 K
  - Shock Waves -> mechanical deformations
    - » Pressures ~ 5 Gpa (~50000 atmospheres or 725e3 psi)
  - Sweeping system (in small circle) to go to smaller spot size and not destroy targets
- Lithium Lens for focussing



Run II Upgrade:
Slip Stacking Cartoon

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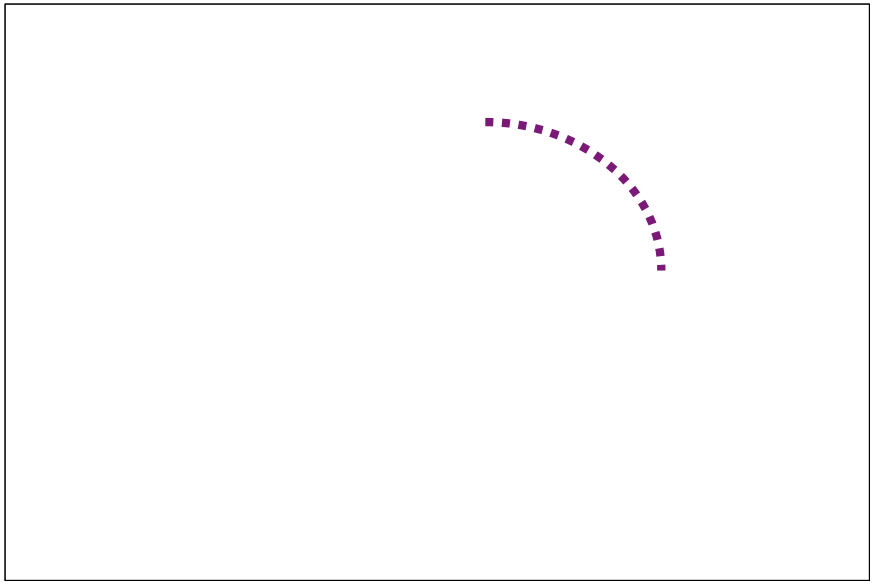
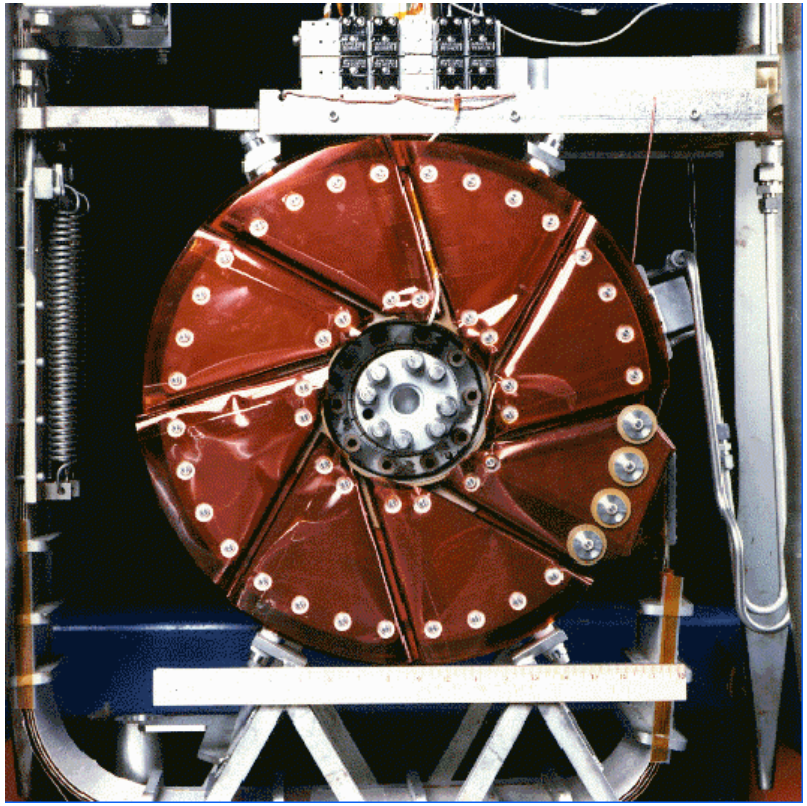
1st Booster Batch injected into Main Injector
Slightly Accelerated and 2nd Booster Batch ready
2nd injected and slightly decelerated
Wait for 2 to line up with 1
Capture into 1 RF frequency



Run II Upgrade: 9e12 on target

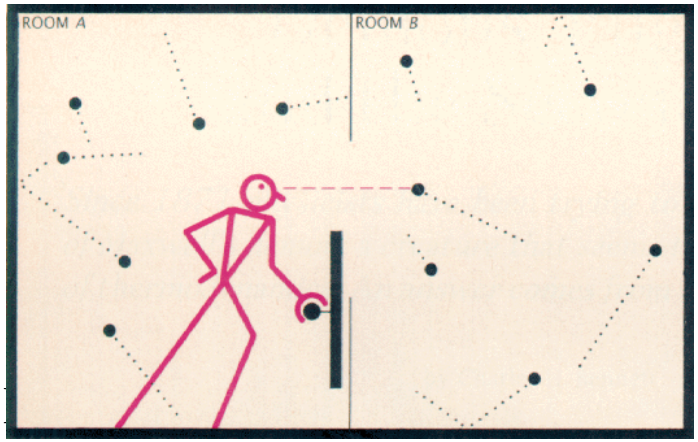
Following the $\bar{p}$'s

- Lithium Lens
  - Longitudinal Current (pulsed 650 kA)
  - Develops Azimuthal Field
  - Radial Focussing Force (H & V in same device!)
  - 750 T/m field strength
    - » Run II Upgrade: 1000 T/m
  - 1 cm aperture (60 mradian acceptance)
- AP2: transfer line to Debuncher
  - 4% momentum spread
  - 250 π mm mr transverse acceptance
    - » Run II Upgrade: 350 π mm mr
- Collect ~20e-6 $\bar{p}$'s/proton on target
- 1.1e6 $\bar{p}$'s per RF bucket
    - » Run II Upgrade: 3.5-4e6 $\bar{p}$'s per RF bucket



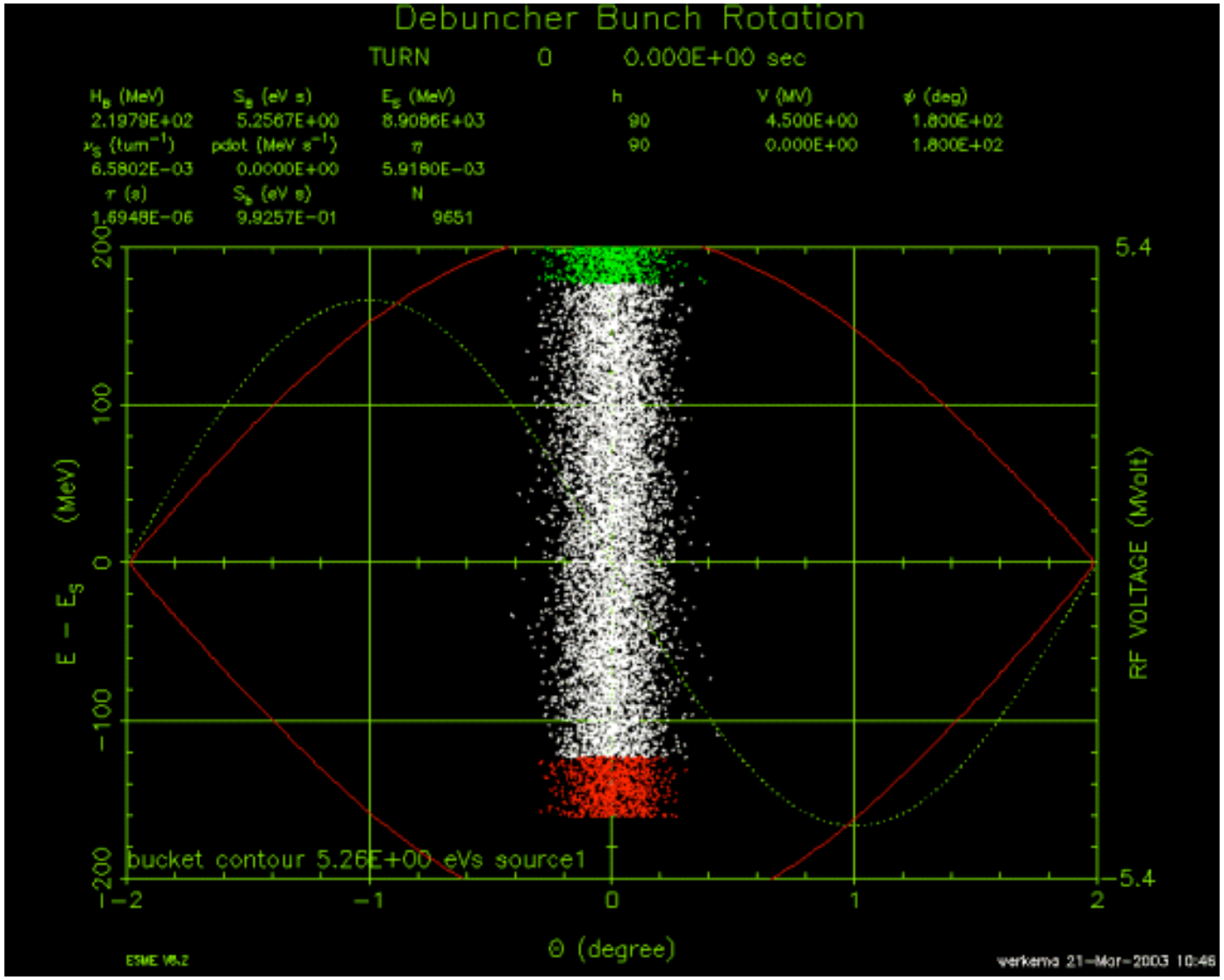
Following the $\bar{p}$'s

- Debuncher: 1.5 - 3 sec cycles
  - Bunch Rotation: 4.5 MV
    - » ~50 μsec rotation
    - » ~50 μsec drive down (4.5 MV -> 60 kV)
    - » Adiabatically turn off remaining RF
    - » Trade energy spread (4% -> 0.1%) into time spread (2 nsec -> 0.8 μsec)
  - Stochastic Cooling
    - » Longitudinal
      - 70 MeV/c -> 7 MeV/c
    - » Transverse (H&V)
      - 250 π mm mr -> 70 π mm mr

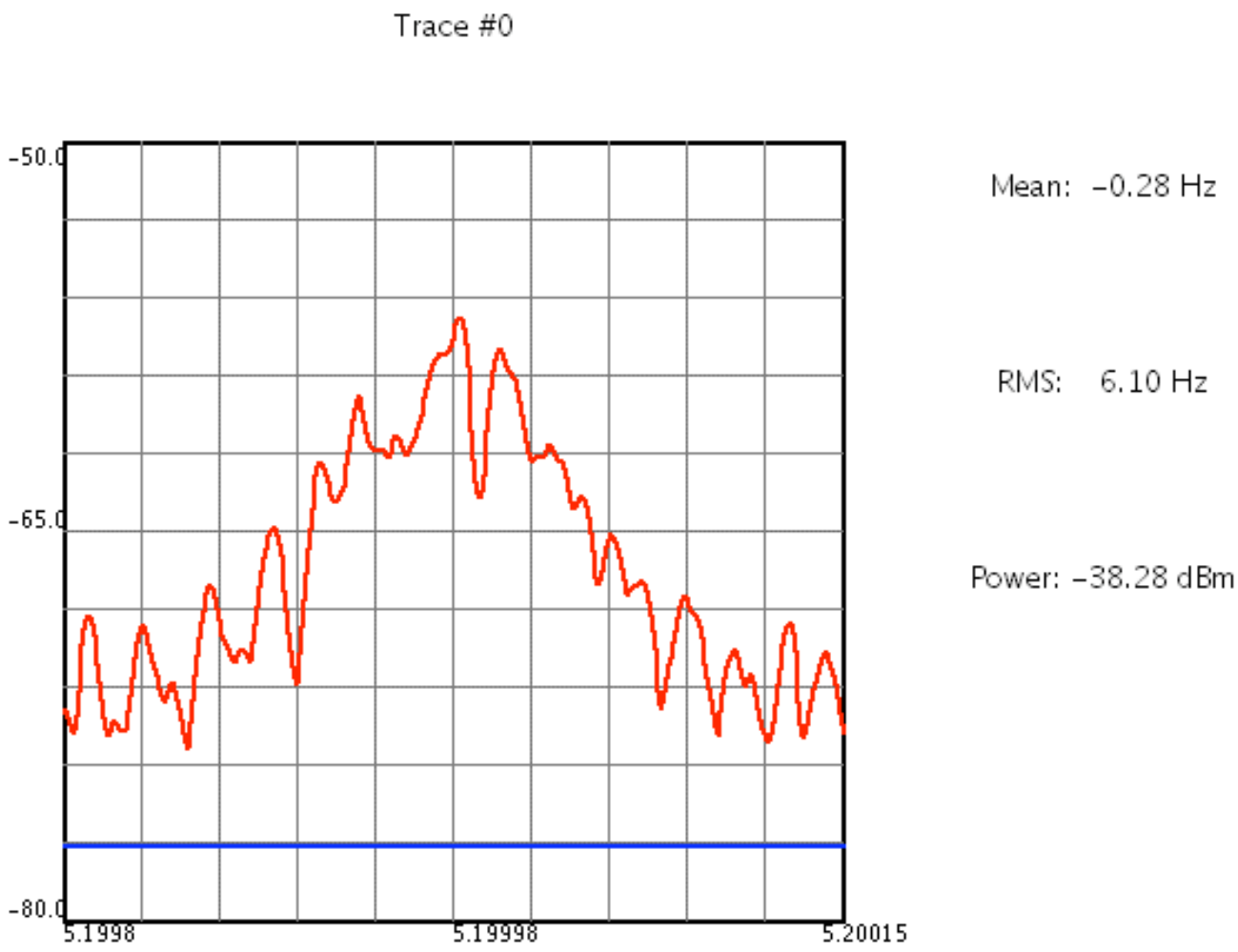


  - 1e6 $\bar{p}$'s per RF bucket (though actually
    - » Run II Upgrade: 3.5e6 $\bar{p}$'s per RF bucket

Following the $\bar{p}$'s

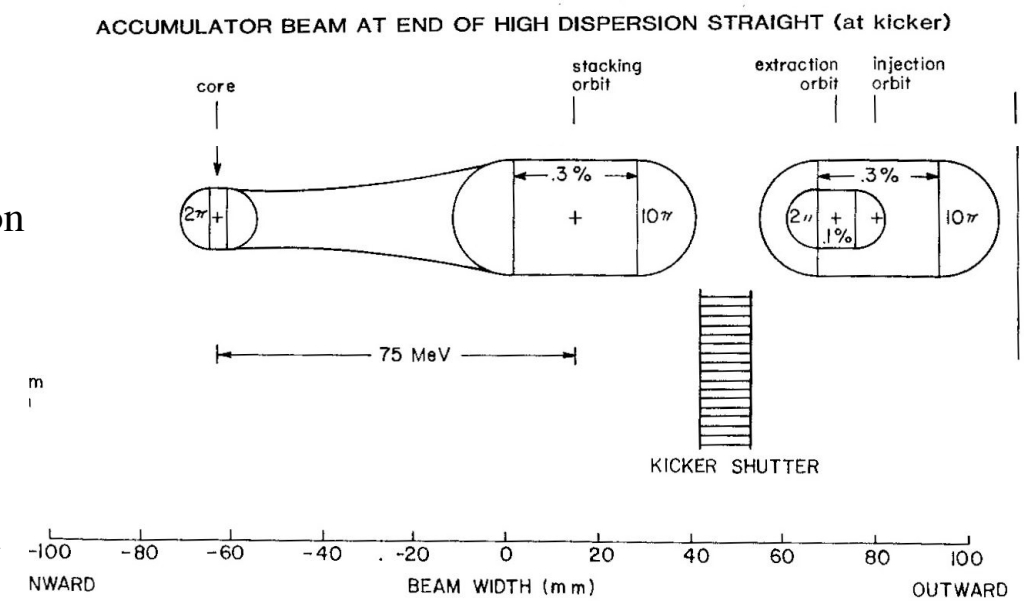


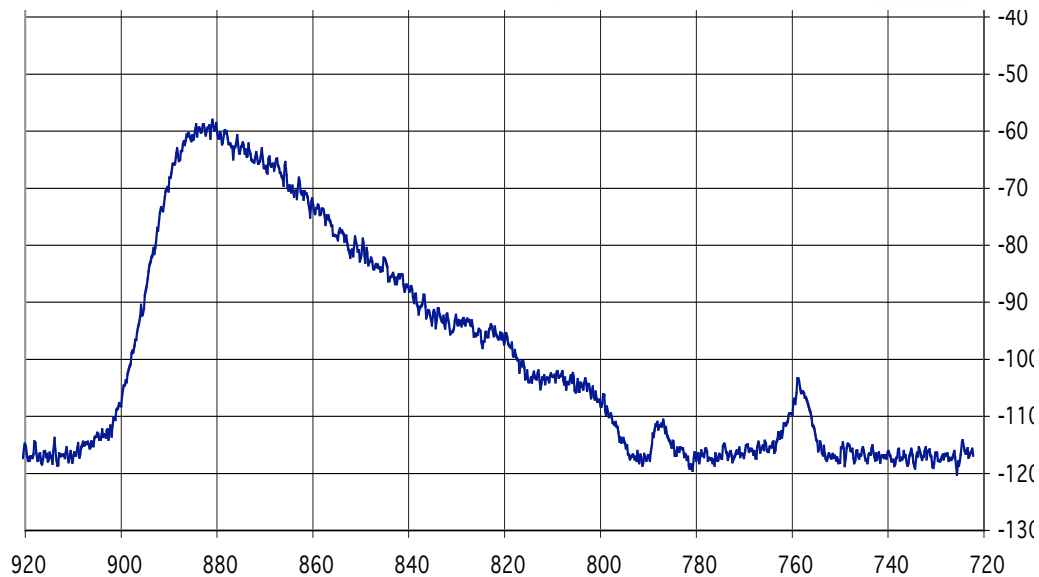
Following the $\bar{p}$'s



Following the $\bar{p}$'s

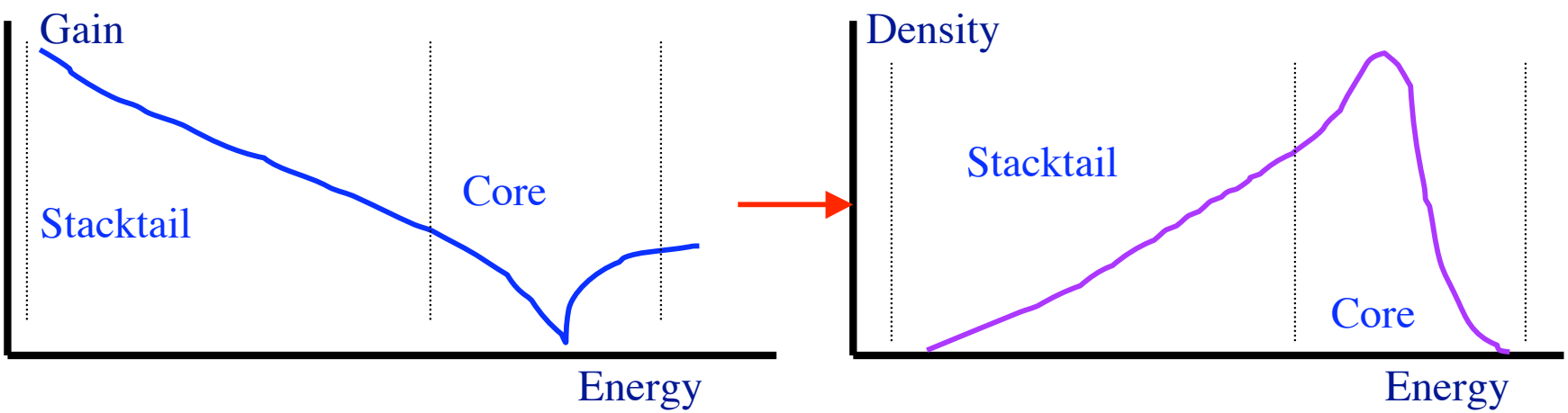
- Accumulator Stacktail Cooling
  - Process
    - » Beam is injected onto the Injection Orbit
    - » Beam is
      - Bunched with RF
      - Moved with RF to the Stacking Orbit
      - Debunched on Stacking orbit
    - » Stacktail pushes and compresses beam to the Core orbit
    - » Core Momentum system gathers beam from the Stacktail
    - » Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core
  - ~2e8 particles per RF Bucket in middle of stacktail (though still DC beam)





Following the $\bar{p}$'s

- Simon van Der Meer solution:
  - Constant Flux: $\frac{\partial \Phi}{\partial t} = \text{constant}$
  - Solution: $\frac{\partial \Phi}{\partial E} = \frac{\Phi}{E_d}$, where E_d characteristic of design $\Phi = \Phi_0 \exp\left[\frac{(E - E_i)}{E_d}\right]$
  - Exponential Density Distribution generated by Exponential Gain Distribution
  - Max Flux = $(W^2 \Phi E_d)/(f_0 p \ln(2))$

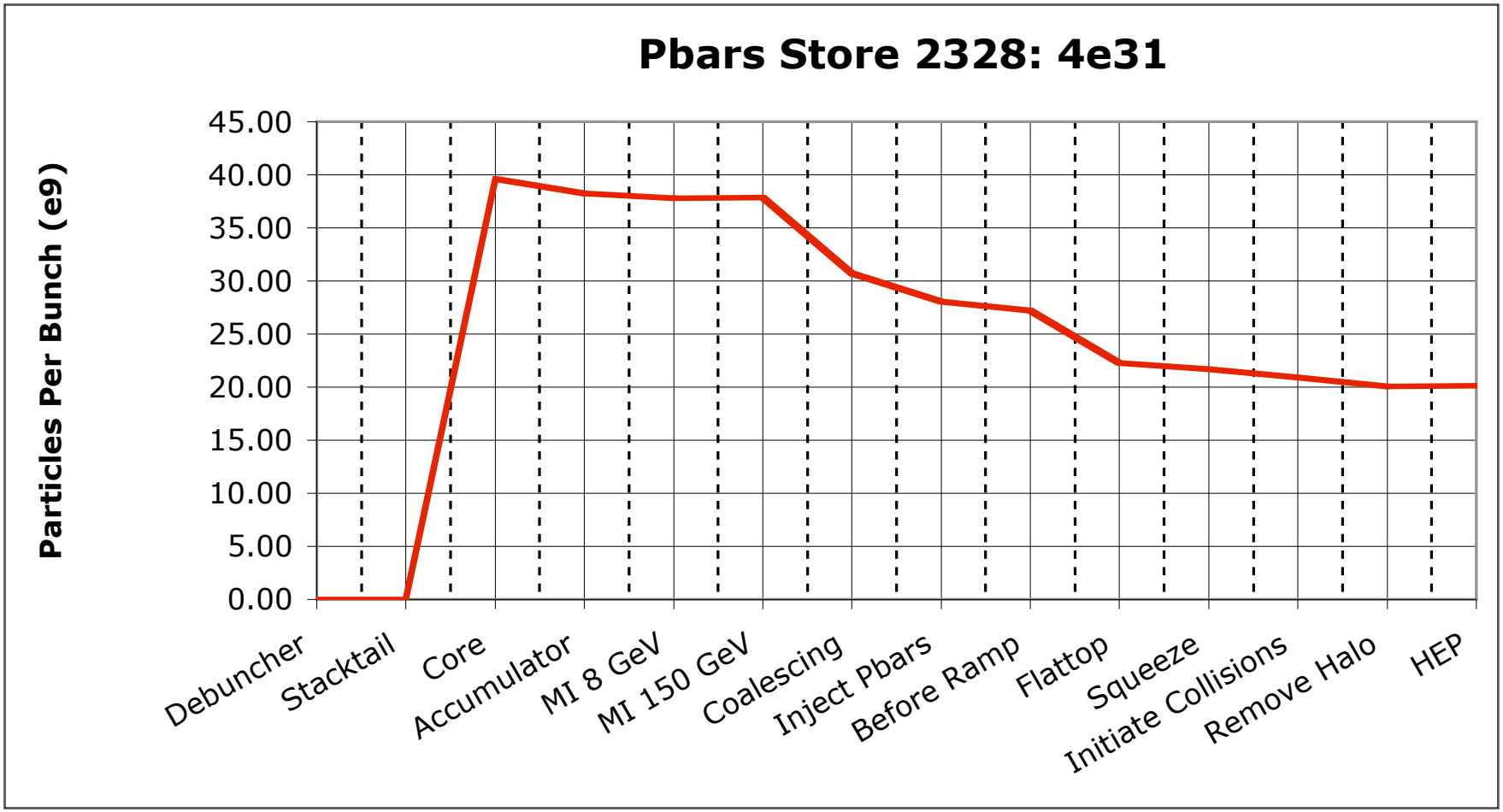


Using log scales on vertical axis

Following the $\bar{p}$'s

- Transfer through AP3 - AP1 - P2 - P1 (8 Gev) into Main Injector
- Main Injector:
  - 8 GeV to 150 GeV for Tevatron operation
    - » Accelerated to 150 GeV
    - » Next intensity boosting trick!
      - Coalesce batch of 5-11 into 1 single bunch
    - » Bucket to bucket transfer to TeV
    - » A1 line running in 150 GeV mode
  - ~30e9 in RF bucket transferred to Tevatron

Beam Intensities in the Tevatron



0.001 in Debuncher 0.1 in Stacktail

From 150 to Collisions

Store 2328: 4e31 Luminosity

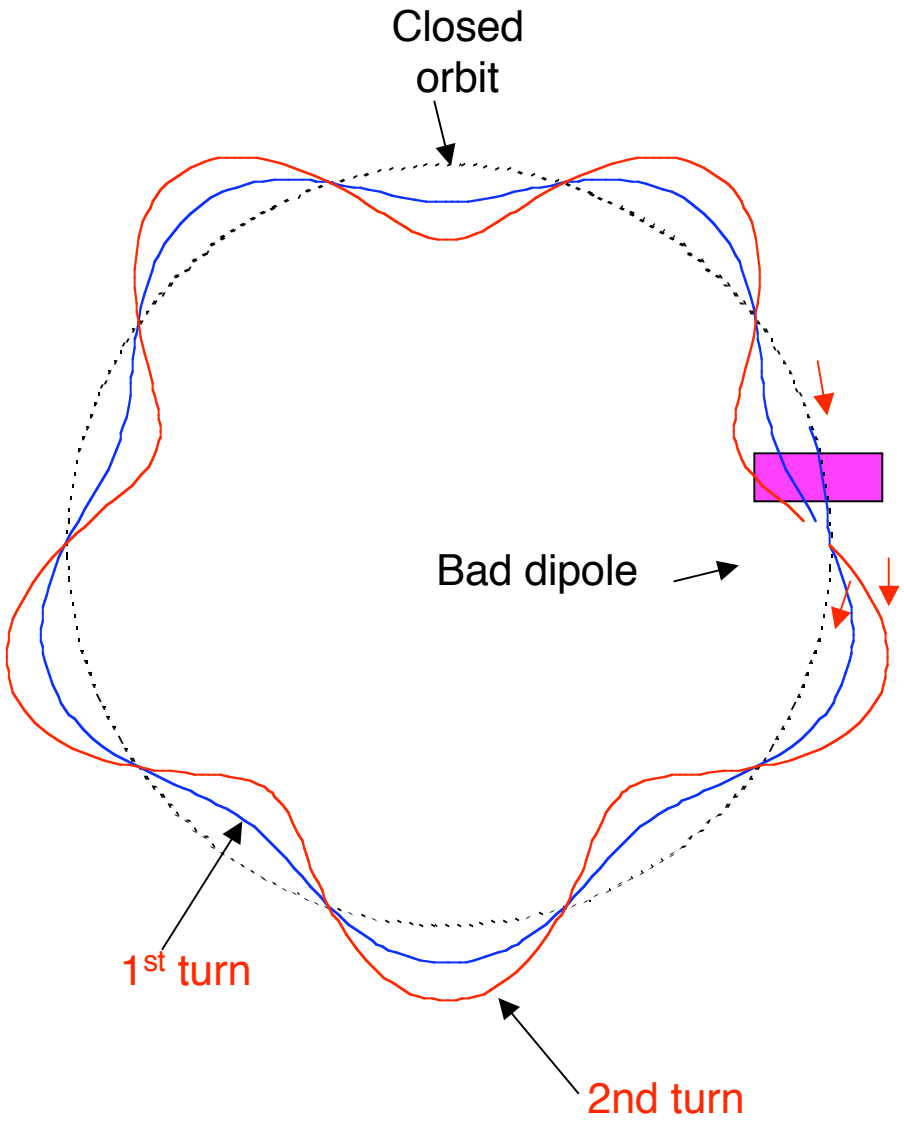
p Intensity		$\bar{p}$ Intensity
230e9	P's are injected on central orbit	-
222e9	Move to injection helix	-
193e9	$\bar{p}$'s are injected on pbar injection helix	28e9
182e9	Ramp from 150 to 980	22e9
180e9	Squeeze	22e9
181e9	Initiate Collisions	21e9
177e9	Remove Halo	20e9
177e9	HEP	20e9

Beam Intensities in the Tevatron

- In one trip around the ring, a single $\bar{p}$ bunch has 2xB collisions with proton bunches
  - The TEVATRON has electrostatic separators so the $\bar{p}$ bunch has a head-on collision with only 2 proton bunches (one at CDF and the other at D0)
  - Head-on collisions are referred to as “short range” interactions
    - » The number of head-on collisions has stayed the same from Run I -> Run II
  - Near-miss collisions are referred to as “long range” interactions
    - » The number of long range interactions has increased 6x from Run I -> Run II for a given luminosity
- The TEVATRON operates in the “strong-weak” regime
  - The number of protons is much greater than the number of $\bar{p}$’s
    - » The non-uniform field of the protons pushes the antiprotons around
      - Single bunch field effects
      - Bunch by bunch field effects
    - » We can ignore the effect of the $\bar{p}$’s on the protons.
- Dominated by effects at 150 GeV with beam on both helices

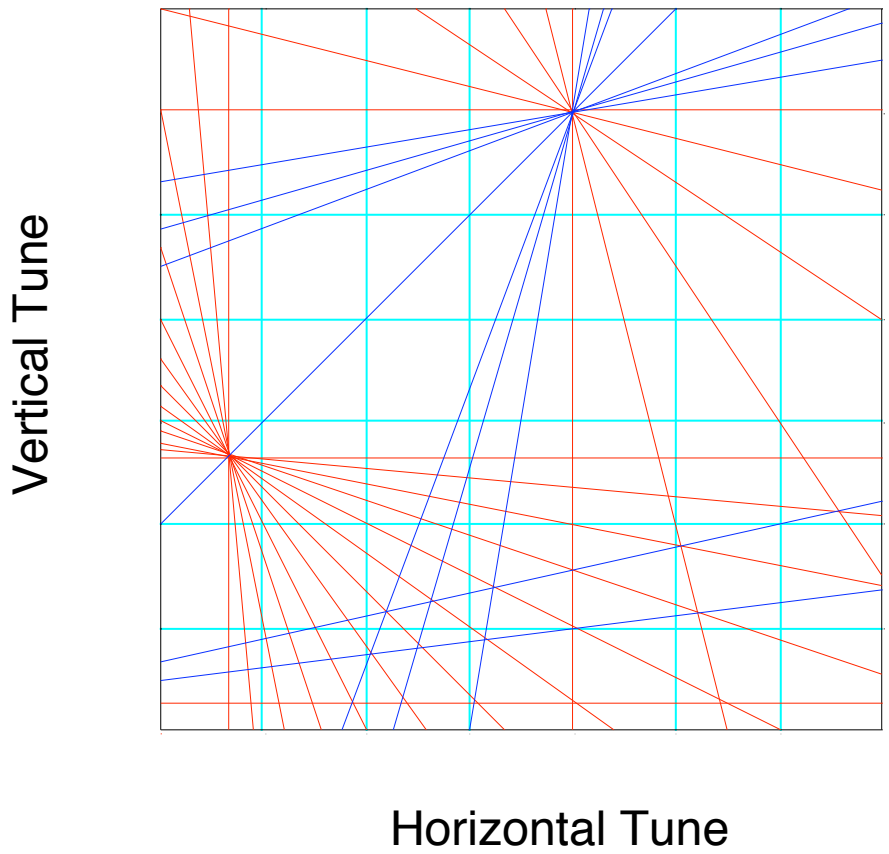
Resonance Lines and Tunes

- The betatron tune is the number of "wiggles" a particle makes as it goes around the machine once
- The tune is proportional to the machine focusing or the quadrupole strength (lattice)
- If the tune is an integer:
  - A dipole error would amplify turn after turn
  - The amplification is proportional to the dipole error
- If the tune is an _ integer a quadrupole error would amplify every other turn, etc…
- For an infinite set of multipoles
  - The tune should **not** be a rational number
  - The growth rate is inversely proportional to the multipole order
  - The growth rate is proportional to the multipole strength



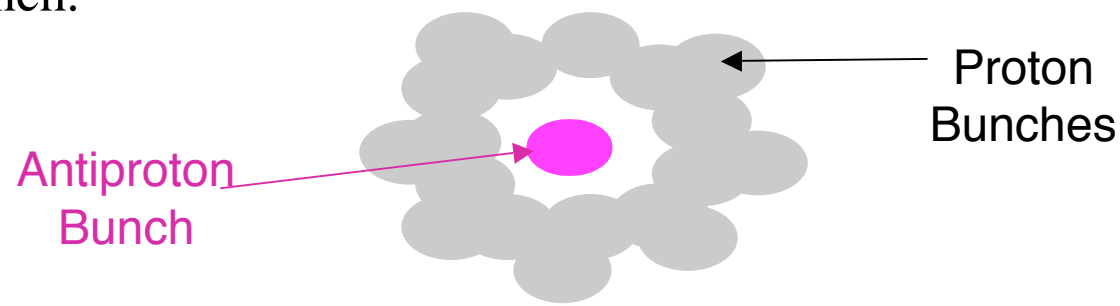
Resonance Lines and Tunes

- The protons will shift the tunes of the $\bar{p}$'s
  - Amplitude dependence
  - Bunch dependence
- The tune-shift and spread of the antiprotons
  - is relatively easy to calculate
  - was well understood going into Run II
- The increased strength of the resonance lines due to the multipole field of the protons
  - Is difficult to calculate with precision
    - » Track many particles for 100 million turns (1 hr lifetime)
    - » Don't know the TEVATRON to that precision
  - Was completely under-appreciated for Run II



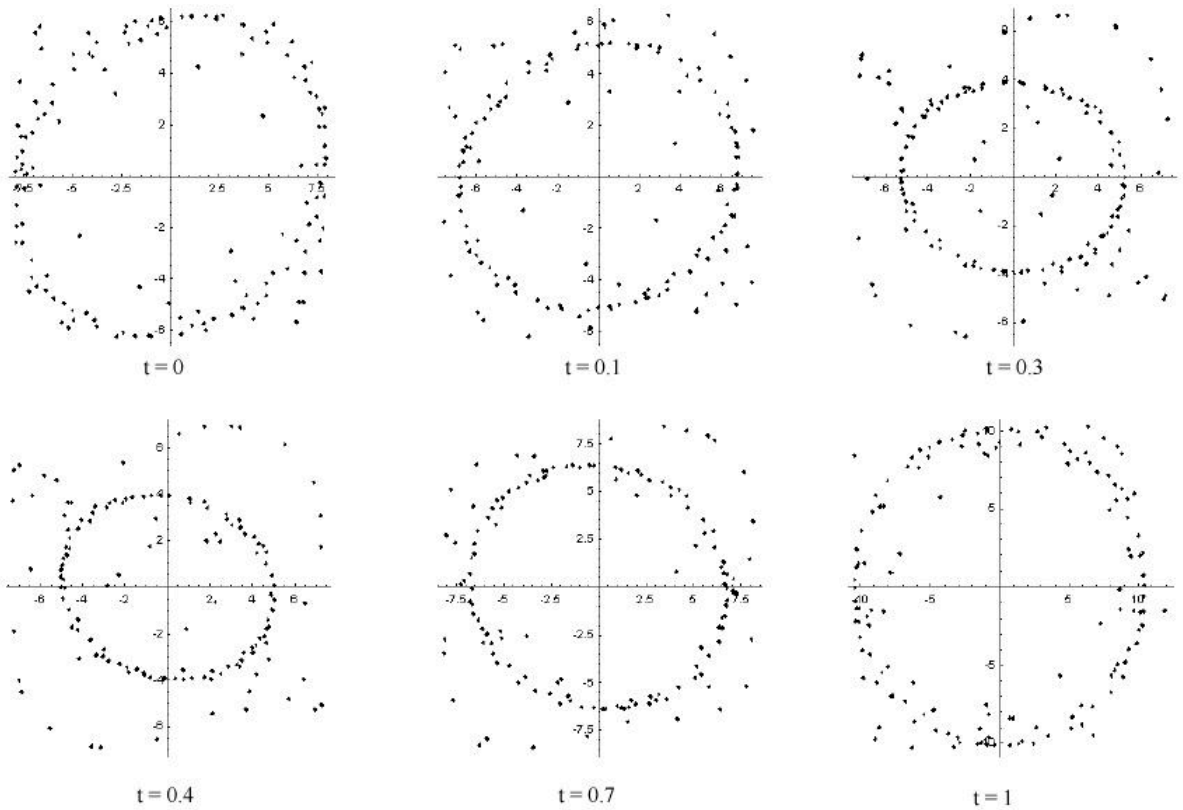
Dynamic Aperture

- Because of the strengthening of the antiproton resonant lines by the proton bunches the proton beam looks like a “soft donut collimator” to an antiproton bunch.



- The effect of the “soft donut collimator” can be reduced by
  - Increase separation between the protons and the antiprotons
    - » Better helices
      - Location constraints
      - Lattice constraints
      - Hardware constraints
    - » Bigger aperture (needed for bigger helices)
  - Active beam-beam compensation
  - Smaller emittance beams
    - » Smaller source emittances
    - » Smaller emittance dilution through the accelerator chain.

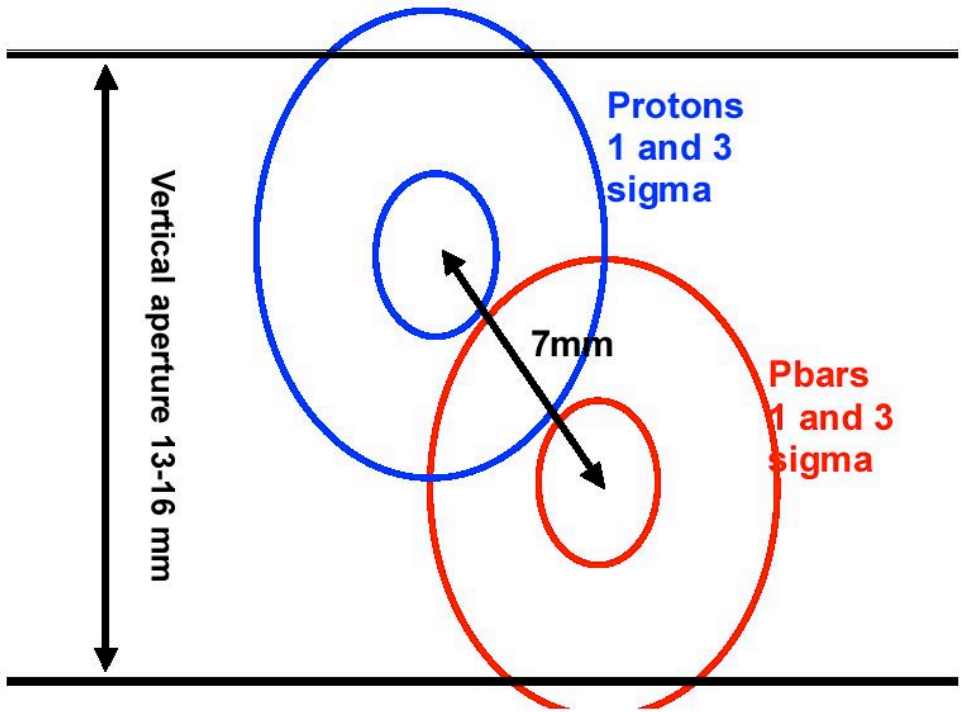
Better Helices in the TEVATRON



- Normalized separations at all possible collision points during the “old” Step 13 -> Step 14 collision cog
  - With beams separated at 1.8, a ~20% beam loss occurred
  - With beams separated at 2.7 with new helices, beam loss is removed

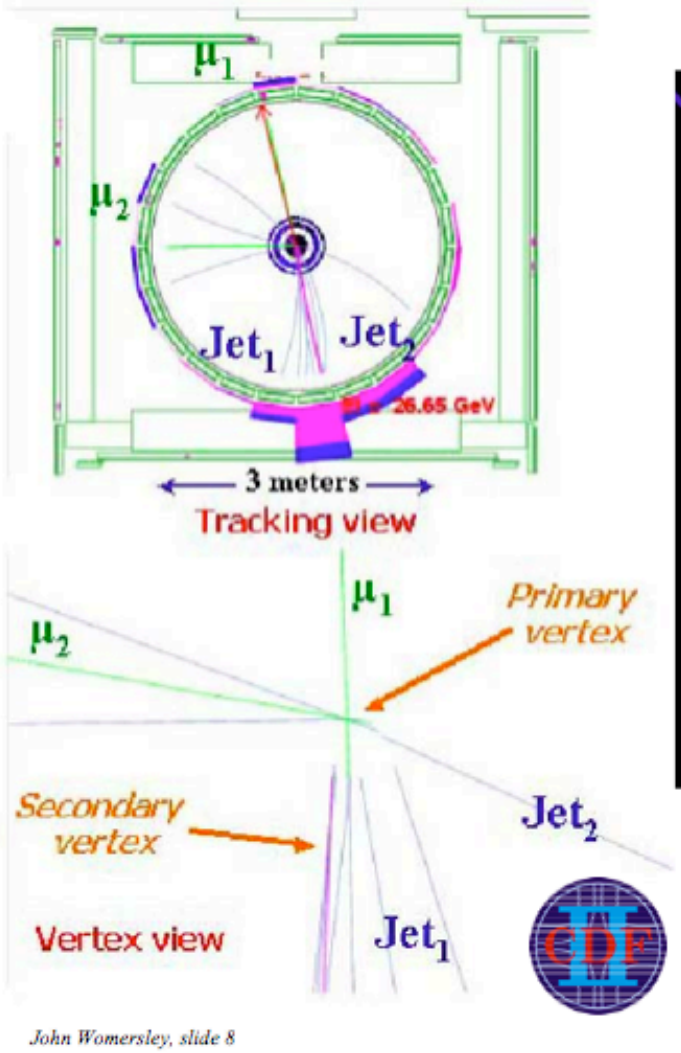
Bigger Aperture in the TEVATRON

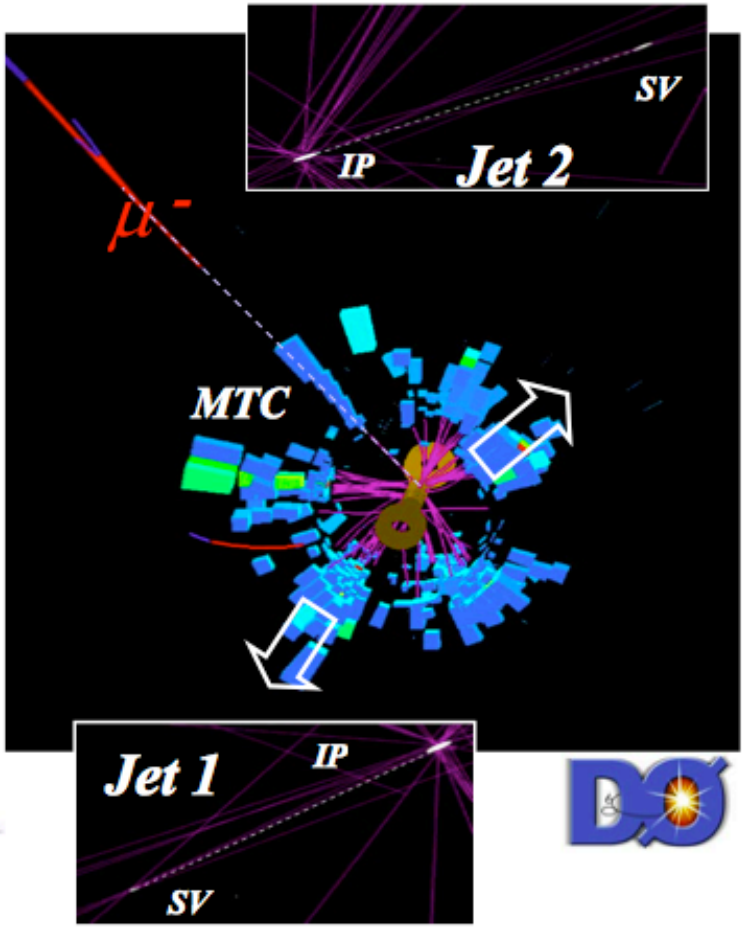
- CO Lambertson Aperture restriction
  - The "tilting" of the helix is limited due to separator constraints
  - The C0 Aperture was increased during the January 2003 shutdown.
    - » New magnets
    - » Beam separation can increase by ~30%
    - » Have yet to exploit larger aperture
  - Better proton performance as have changed impedance of machine and moved further away from onset of instabilities



Improved lifetime at 150 GeV on helix

Collisions





John Womersley, slide 8