Tevatron Collider Run II Status

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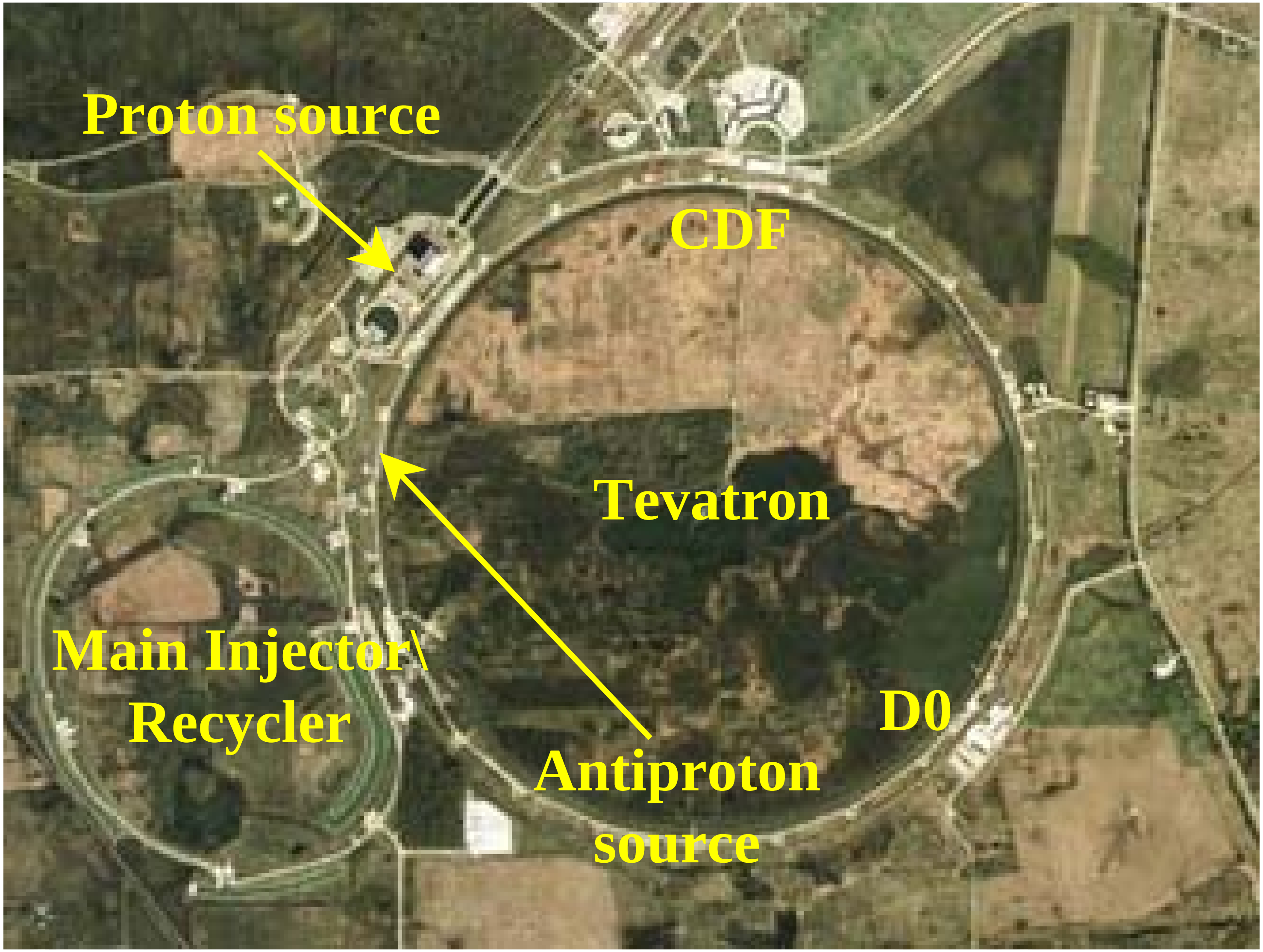
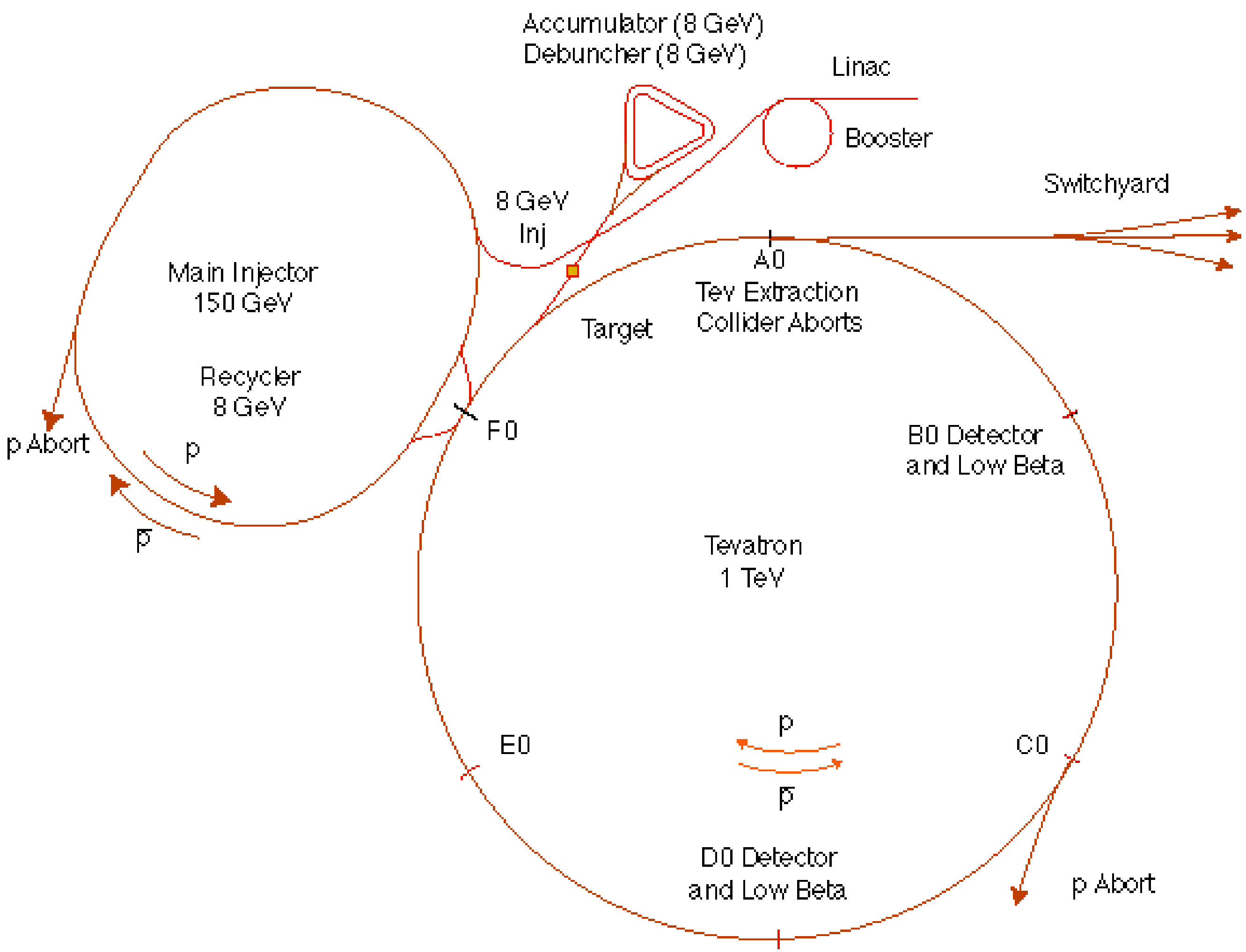
Tevatron Collider Overview



Tevatron Collider Overview

FermilabTevatron Accelerator With Main Injector



Run II Milestones

- September 1998 - Main Injector commissioning begins
- May 2000 – first attempts to unstack Pbars from the Accumulator
- June 2000 – pbars extracted from Accumulator, accelerated to 150 GeV in the Main Injector
- August 2000 - 980 GeV protons in the Tevatron reestablished
- August 2000 – Pbars in the Tevatron
- October 2000 – 36 x 36 collisions achieved at 980 GeV
- March 2001 - Run II officially begins
- August 2002 - Initial luminosity 2.6 x 10^{31} $cm^{-2}s^{-1}$
  - exceeds best of Run I
- September 2002
  - 3.015 x 10^{31} $cm^{-2}s^{-1}$ initial luminosity achieved
  - 80 pb^{-1} integrated since Run II began

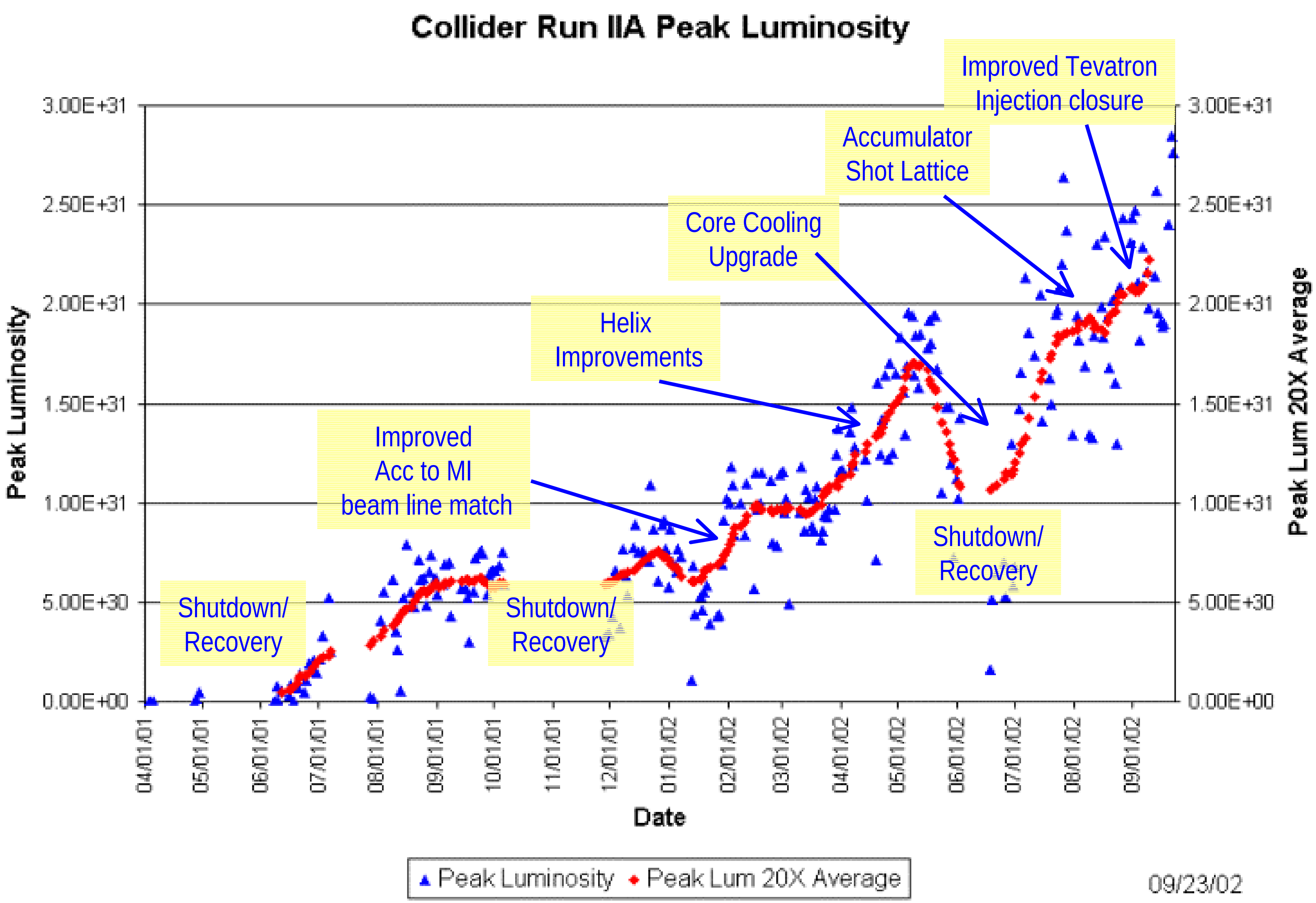
Parameter List

RUN	Ib (1993-95) 6 x 6	Run IIa (36 x 36)	Current best
Protons/bunch	2.3×10^{11}	2.7	2.1
Antiprotons/bunch	0.55×10^{11}	0.3	0.17
Total Antiprotons	3.3×10^{11}	11	6.1
Pbar Production Rate	6.0×10^{10}/hour	20	12.4
Proton Emittance	23π mm-mrad	20π	20π
Antiproton Emittance	13π mm-mrad	15π	20π
β^*	35 cm	35	35
Energy	900 GeV	1000	980
Bunch Length (rms)	0.60 meter	0.37	~0.60
Crossing Angle	0 μrad	0	0
Typical Luminosity	$1.6 \times 10^{31} cm^{-2} s^{-1}$	8.6	3.0 best-to-date
Integrated Luminosity	3.2 pb^{-1}/week	17.3	4.3
Bunch spacing	~3500 nsec	396	396
Interactions/Crossing	2.5	2.3	2.3

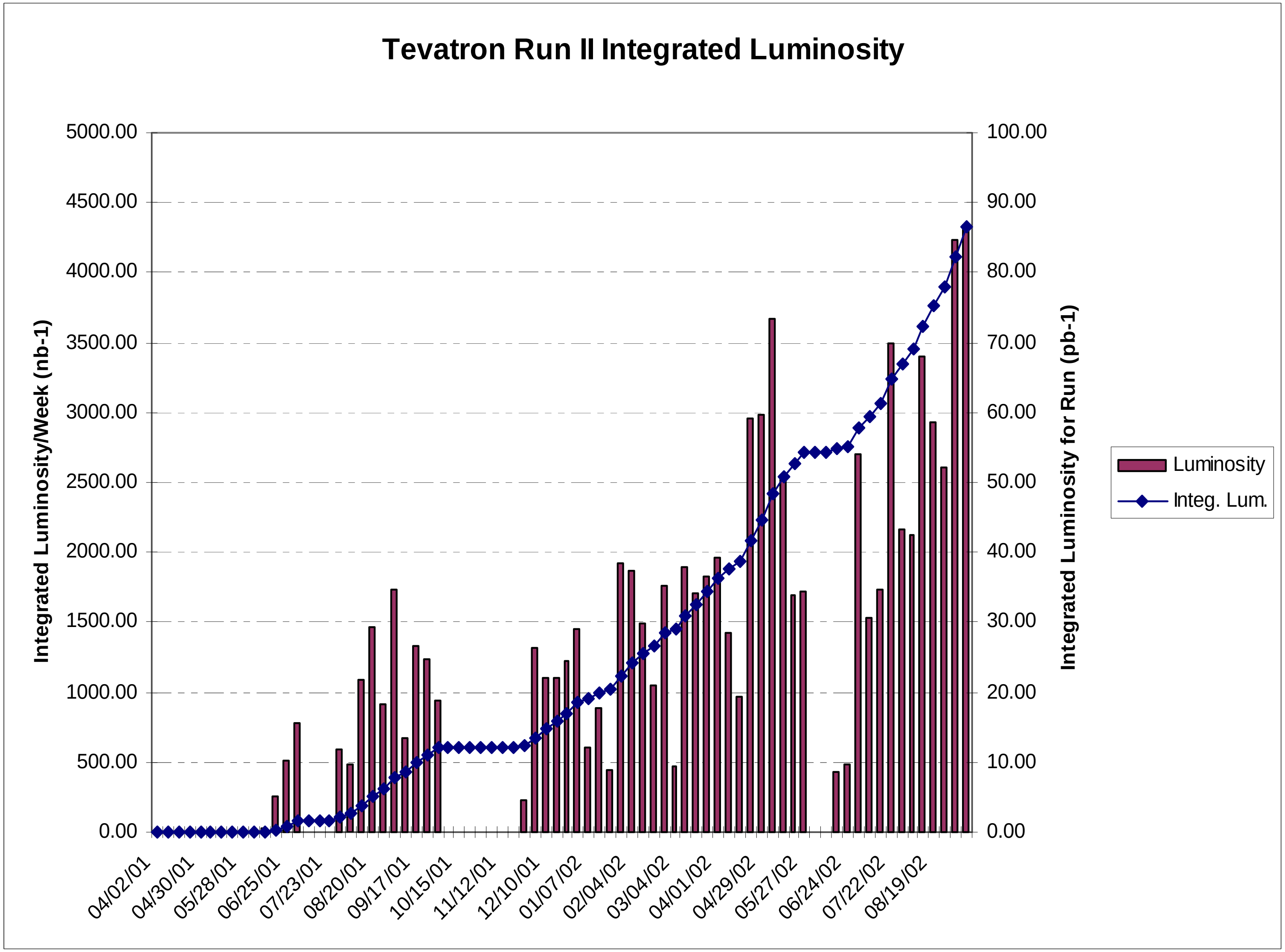
Performance to Date

	Run IIa design	Current best	Missing factor
Antiproton Stacking Rate	18 x 10^{10}/hour	12.4	1.45
Maximum Antiproton Stack	16.5 x 10^{11}	19.0	-
Total Antiprotons	11 x 10^{11}	6.1	1.8
Accumulator to Tevatron transmission	80%	55 40 typical	2
Antiprotons/bunch at low β	0.33 x 10^{11}	0.17	1.9
Protons/bunch at low β	2.70 x 10^{11}	2.11	1.28
Emittance at low β	17.5 π-mm-mrad	25π	1.43
Peak Luminosity	8.6 x 10^{31} cm^{-2} s^{-1}	3.01	2.85
Integrated Luminosity	17.3 pb^{-1}/week	4.8	3.6

Performance – Peak Luminosity



Performance – Integrated Luminosity



Accomplishments

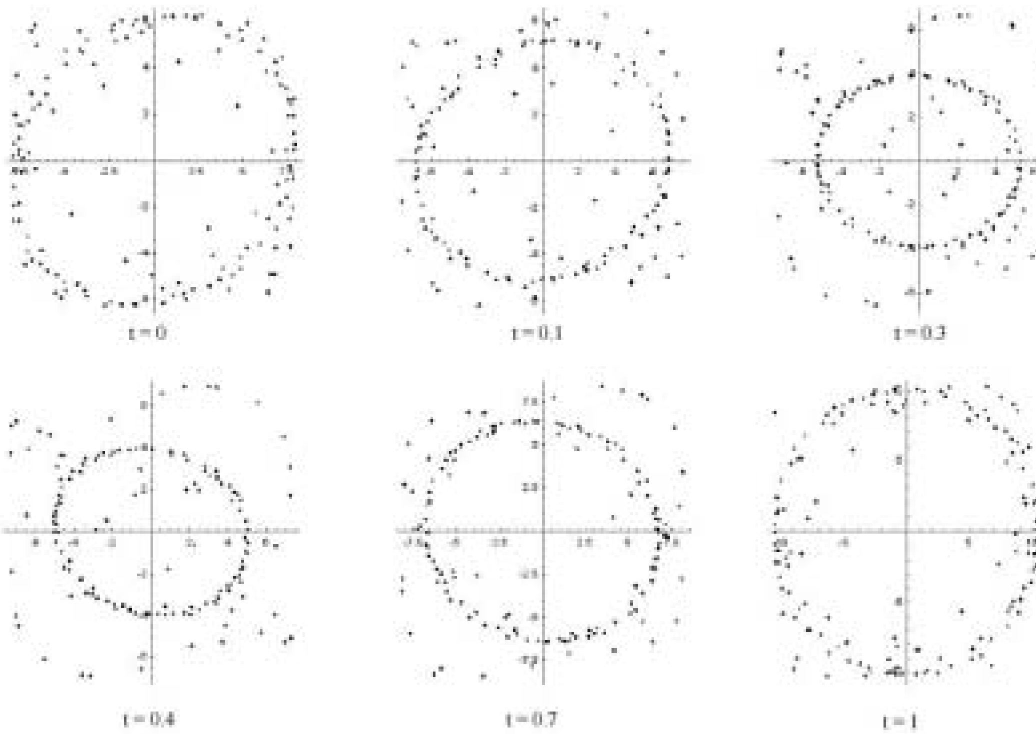
- Luminosity improvements have come from
  - Tevatron Helix adjustments
  - Antiproton emittance reduction
    - Upgraded Accumulator Core Cooling
    - Accumulator Lattice
  - Tevatron Injection closure
  - Countless work on all parts of the Tevatron complex
    - Proton and antiproton coalescing in the Main Injector
    - Radiofrequency feed-forward compensation
    - Kicker timing
    - Instrumentation improvements
    - to name but a few…

Tevatron Helix

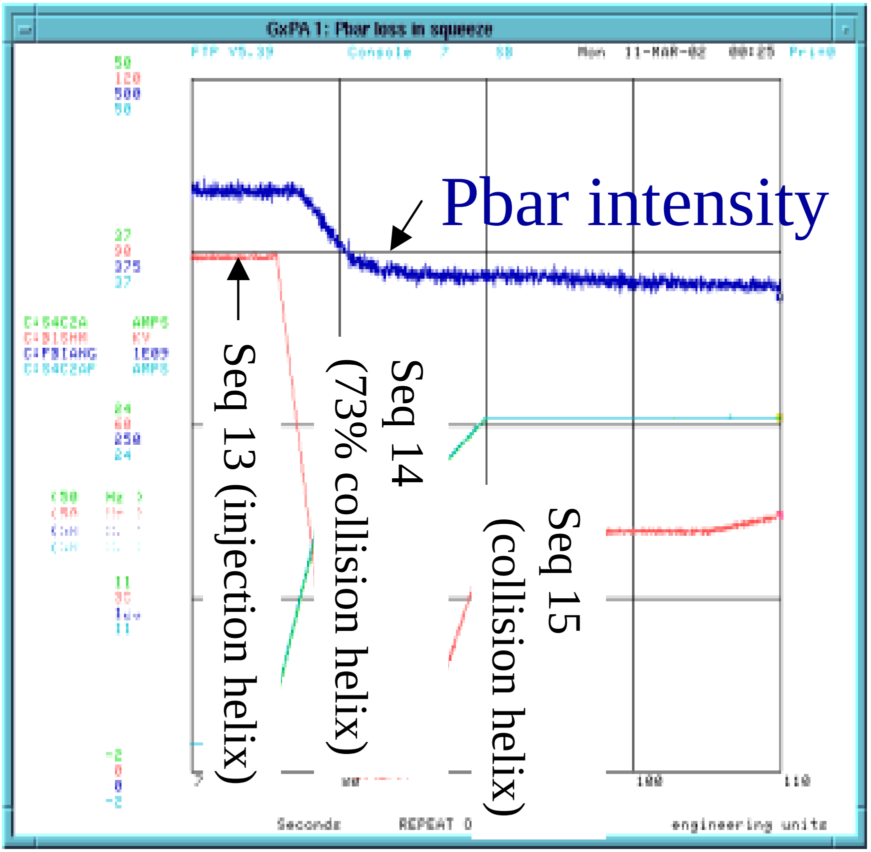
- Significant improvements were made by modifying the original helix
  - low β squeeze efficiency went from 75% to 97%
  - able to increase proton intensity by 80%
  - helix size currently limited by physical aperture

Tevatron Helix

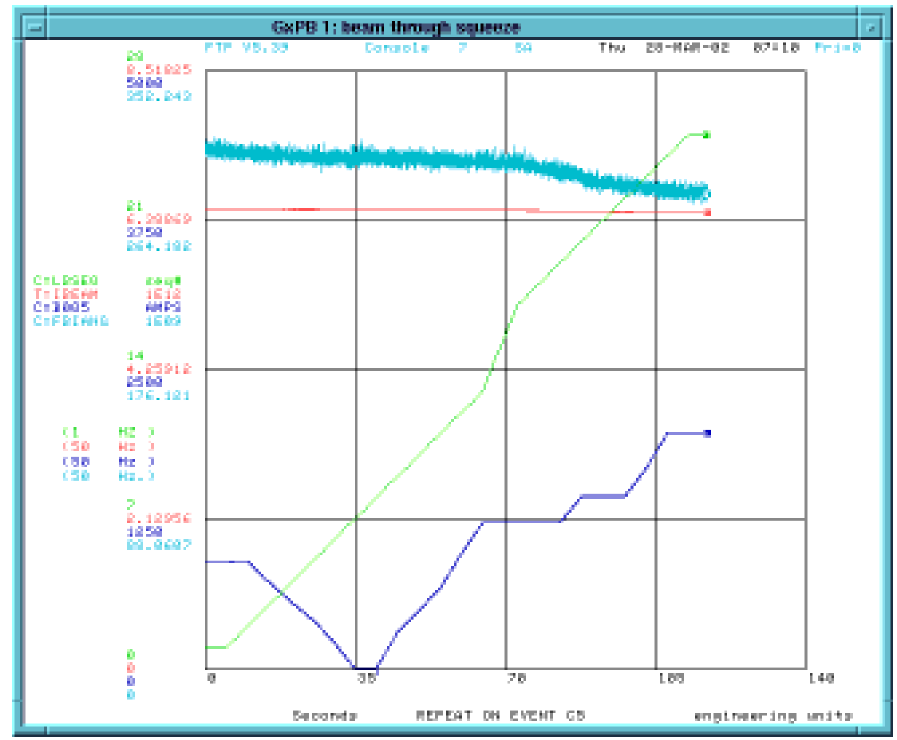
- Normalized separations at all possible collision points during the “old” Step 13 → Step 14 collision cog
  - With beams separated at 1.8σ, a ~20% beam loss occurred
  - With beams separated at 2.7σ with new helices, beam loss is removed



Tevatron Helix



before improvement



after improvement

Antiproton Emittance Reduction

- At onset of Run II, the horizontal emittance of a typical 100 x10^{10} antiproton stack was about a factor of 2 larger than the Run II design value
- Horizontal emittance growth caused by
  - Intra-beam scattering (60%)
  - Trapped ions (40%)
- The intra-beam scattering (IBS) heating of the beam worse for Run II than it was in Run I due to changes in β functions that were the result of the Accumulator Lattice Upgrade
- The Accumulator lattice was changed to handle the anticipated factor of 3 increase in pbar flux due to the Main Injector Project.

Cooling Bandwidth increased 2x

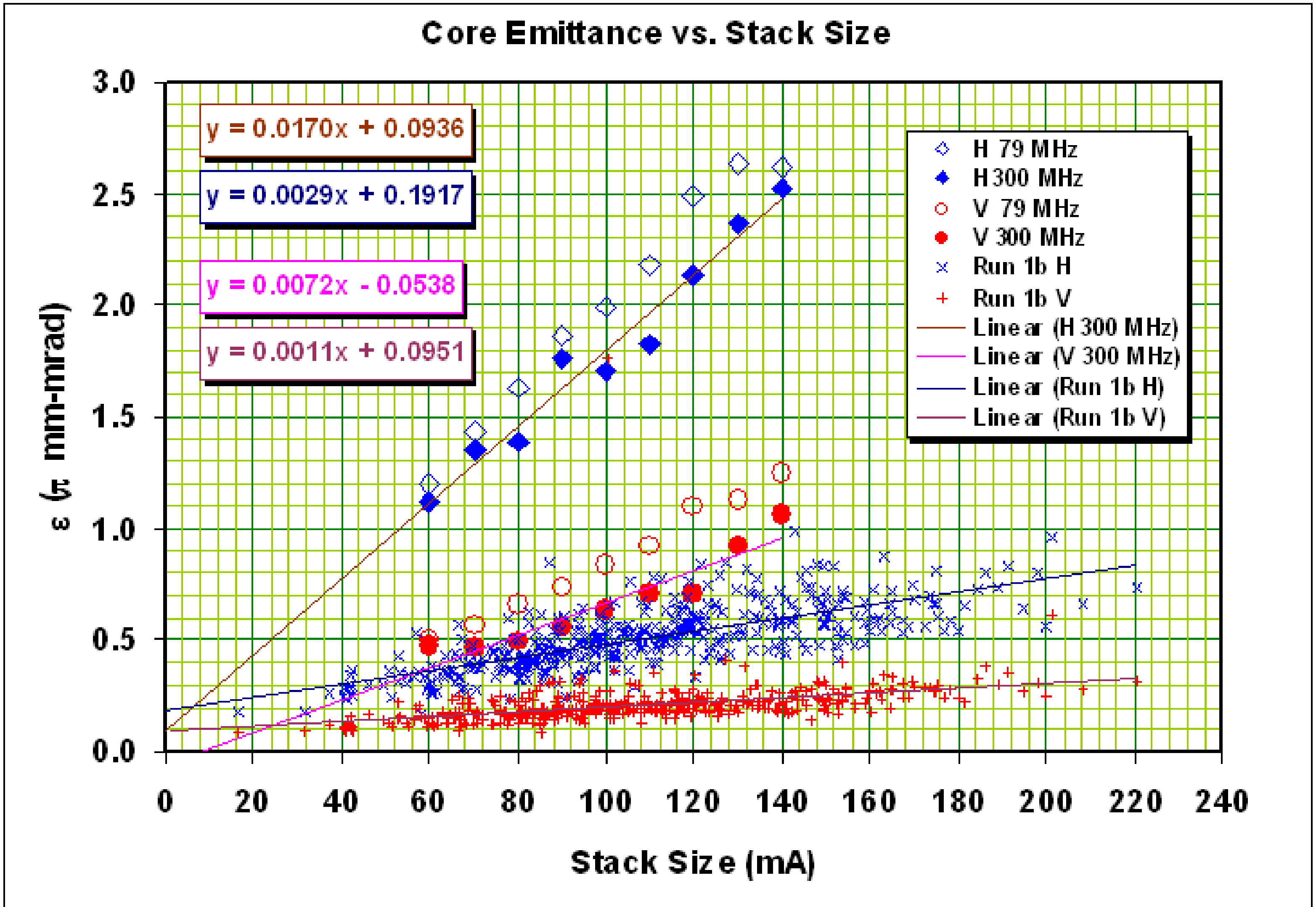
Slip factor changed by lattice to keep cooling system stable

Stack Rate

$$\Phi = \frac{W^2 \eta E_d}{f_0 \, p \ln\left(F_{min} / F_{max} \right)}$$

- η change caused 2.5x larger IBS heating term than for Run I

Antiproton Emittance Reduction



Antiproton Emittance Reduction

Novel two-fold plan developed to reduce the transverse emittance:

- Better transverse stochastic cooling of the Accumulator core.
  - Bandwidth increased by a factor of 2
  - Center frequency of the band increased by a factor of 1.5
- Dual lattice operation mode of the Accumulator
  - Keep the “stacking” lattice (η=0.012) for pbar production
  - During shot setup, ramp the lattice with the beam at the core orbit to the “shot” lattice (η=0.022)
    - Intra-beam scattering heating reduced by a factor of 2.5
    - Cooling rate increased by a factor of two due to increase in mixing due to the change in η

$$\frac{d\varepsilon}{dt} \approx -\frac{\varepsilon}{\tau_{cool}} + \frac{Heat}{\varepsilon^{3/2}}$$

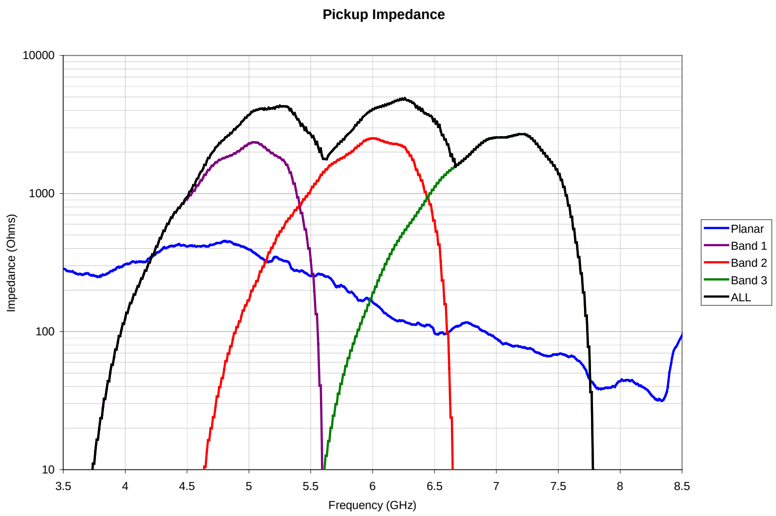
$$\frac{\varepsilon_{old}}{\varepsilon_{new}} = \left(\frac{\tau_{cool_{old}}}{\tau_{cool_{new}}} \frac{Heat_{old}}{Heat_{new}} \right)^{2/5} = (2 \times 1.5 \times 2)^{2/5} \times \left(\frac{0.4 + 0.6}{0.4 + \frac{0.6}{2.5}} \right)^{2/5} = 2.4$$

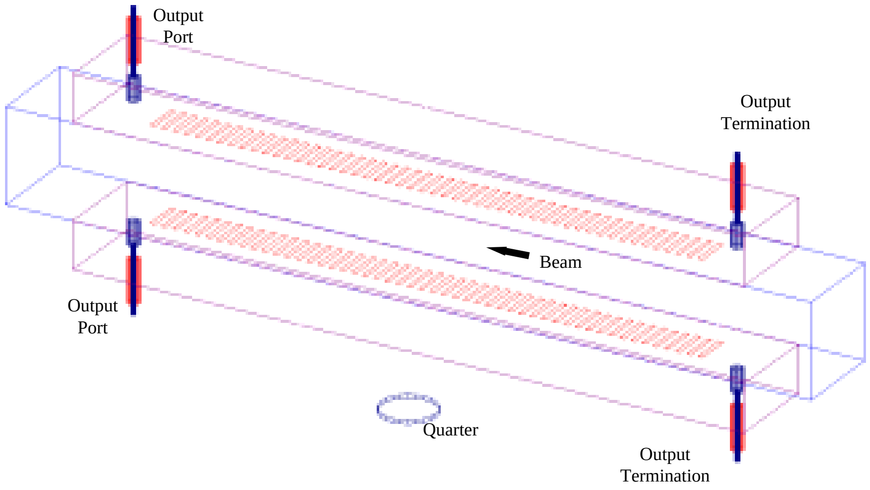
- Center freq.
- Ions
- IBS
- Bandwidth
- Better Mixing
- Reduced IBS

Antiproton Emittance Reduction

- Improved Core Cooling installed during June 2002 shutdown
- Planar loops replaced with slotted waveguide arrays in 3 bands per plane
  - From 2-4, 4-6 GHz
  - To 4.4 – 7.6 GHz
- Higher Bandwidth
- Better signal to noise
- Emittance reduction realized

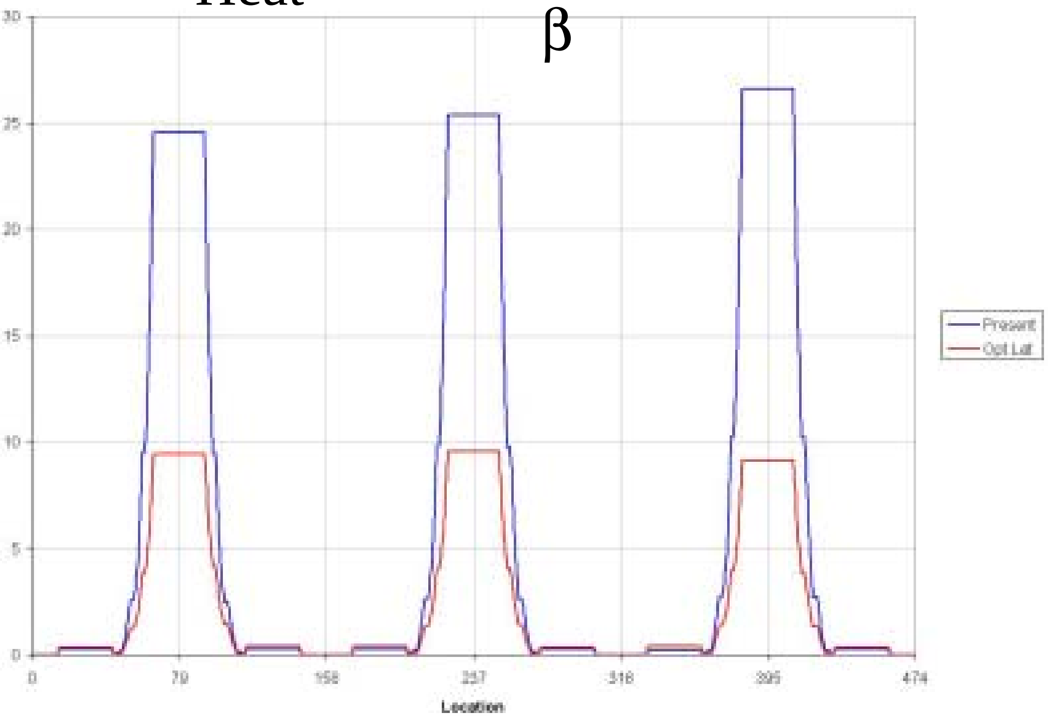
Accumulator Core Cooling Upgrade





Accumulator Shot Lattice

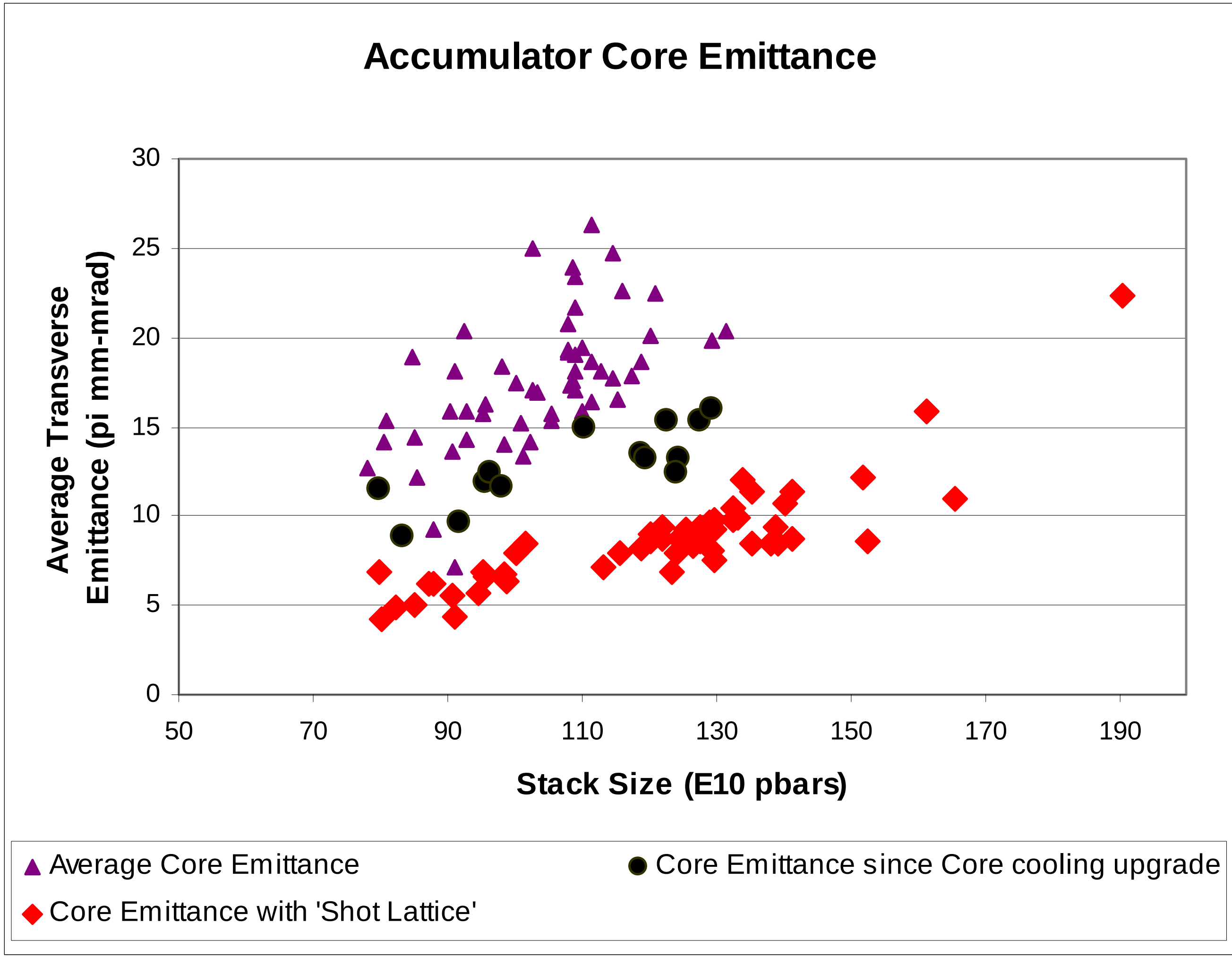
$$\text{Heat} = \frac{D^2 + (\beta D' + \alpha D)^2}{\beta}$$



- 'Shot Lattice' designed and commissioned
- Ramps between the stacking lattice and the shot lattice commissioned
  - 100% efficient in beam intensity and beam size.
- Further reduction in transverse emittance has been realized
- Currently requires dumping remaining stack after Tevatron store is loaded
- Future work to build ramps to preserve remaining stack

Antiproton Emittance Reduction

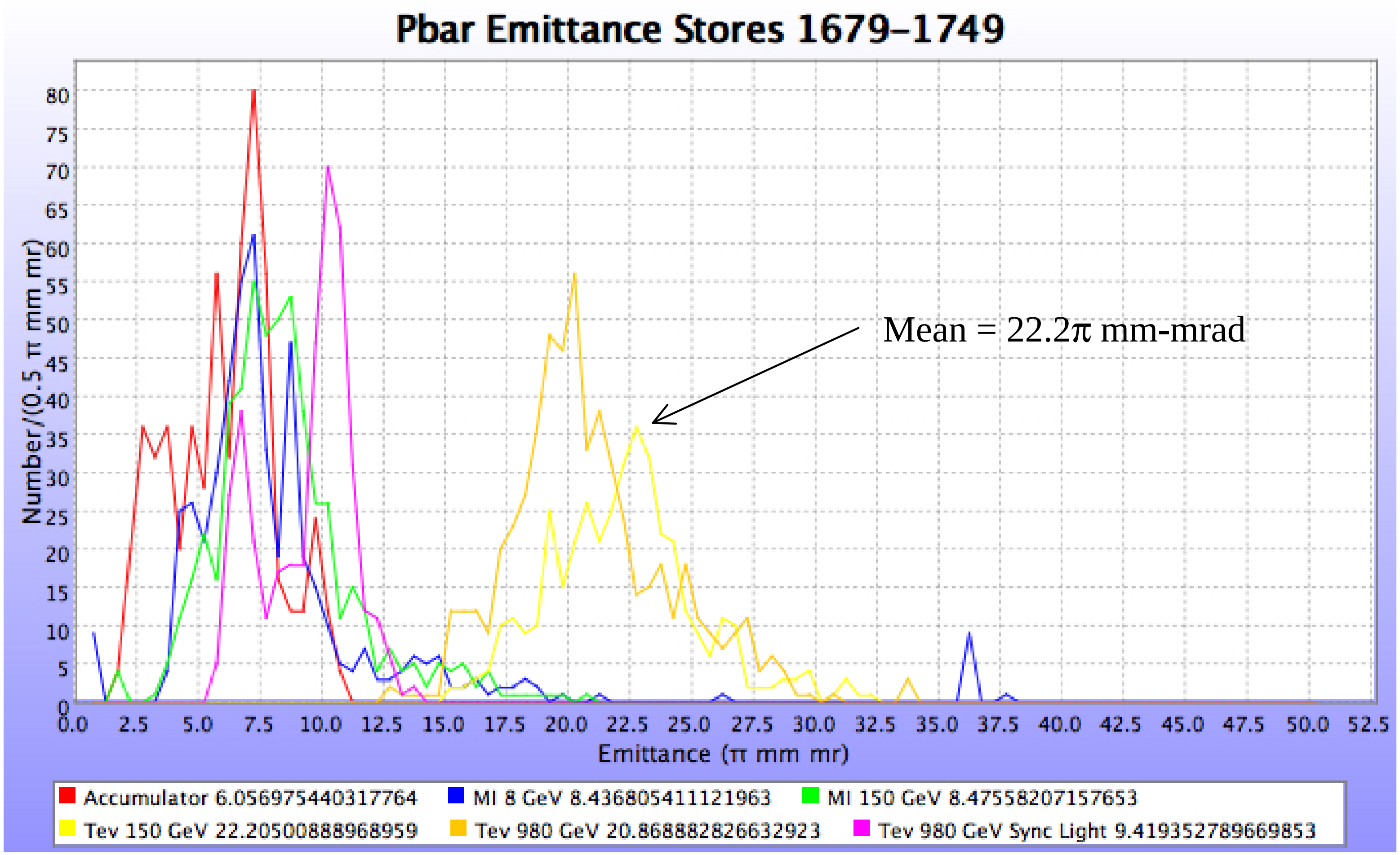
- Factor of 2-3 reduction in antiproton transverse emittance
- Reduction propagated into Main Injector
- Translated into an increase in Pbars in the Tevatron at collision
- Marginal decrease in Tevatron emittance
- Possible to make use of larger stacks



Tevatron Injection closure

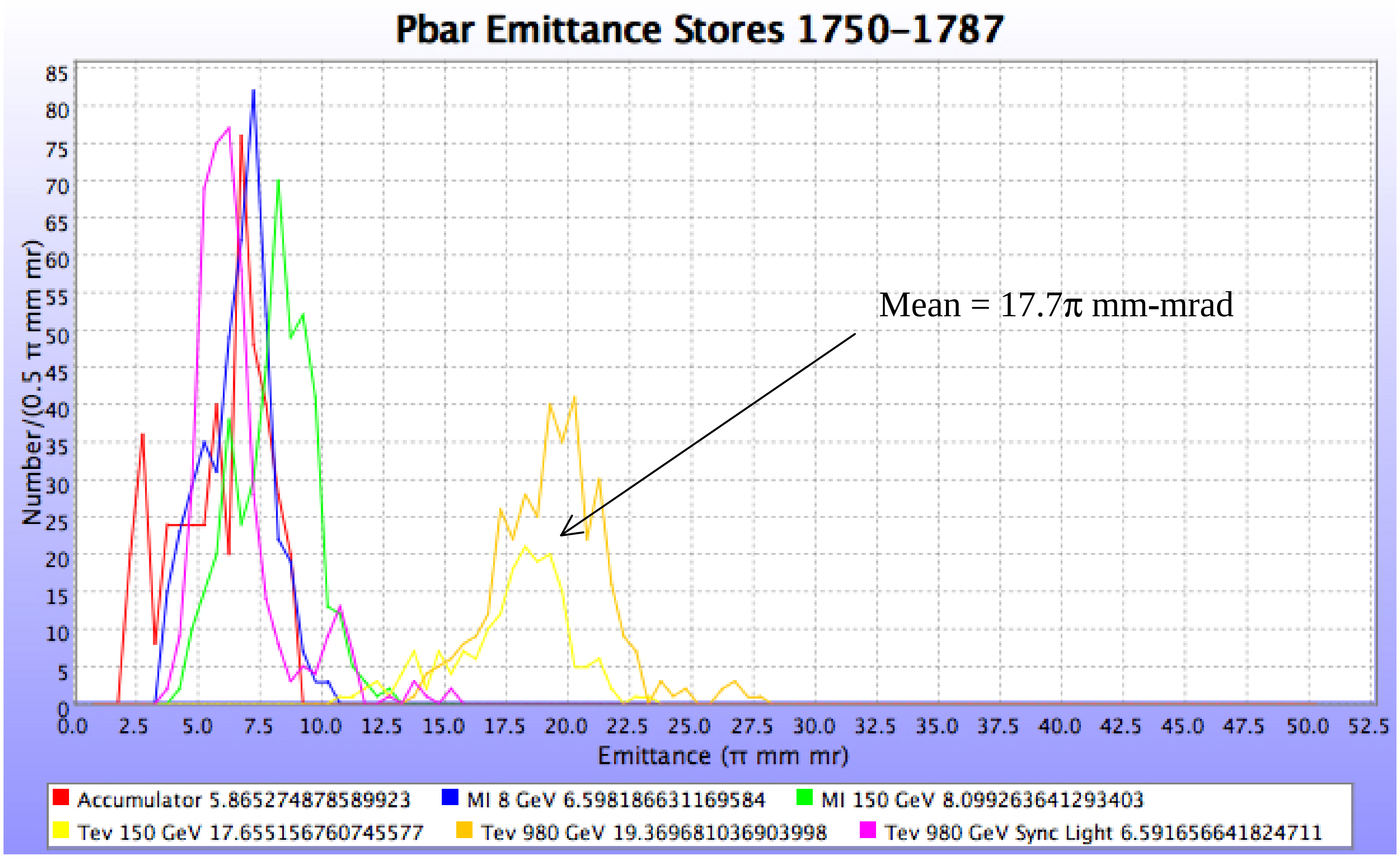
- Reduction of antiproton injection oscillations into the Tevatron has met with success
  - Turn-by-turn position detectors in both planes
  - All four bunches sampled for 64 turns
  - Algorithm/application to correct
  - 150 GeV emittance reduced by 4π mm-mrad (18%)

Tevatron Injection closure



Prior to Injection oscillation correction

Tevatron Injection closure



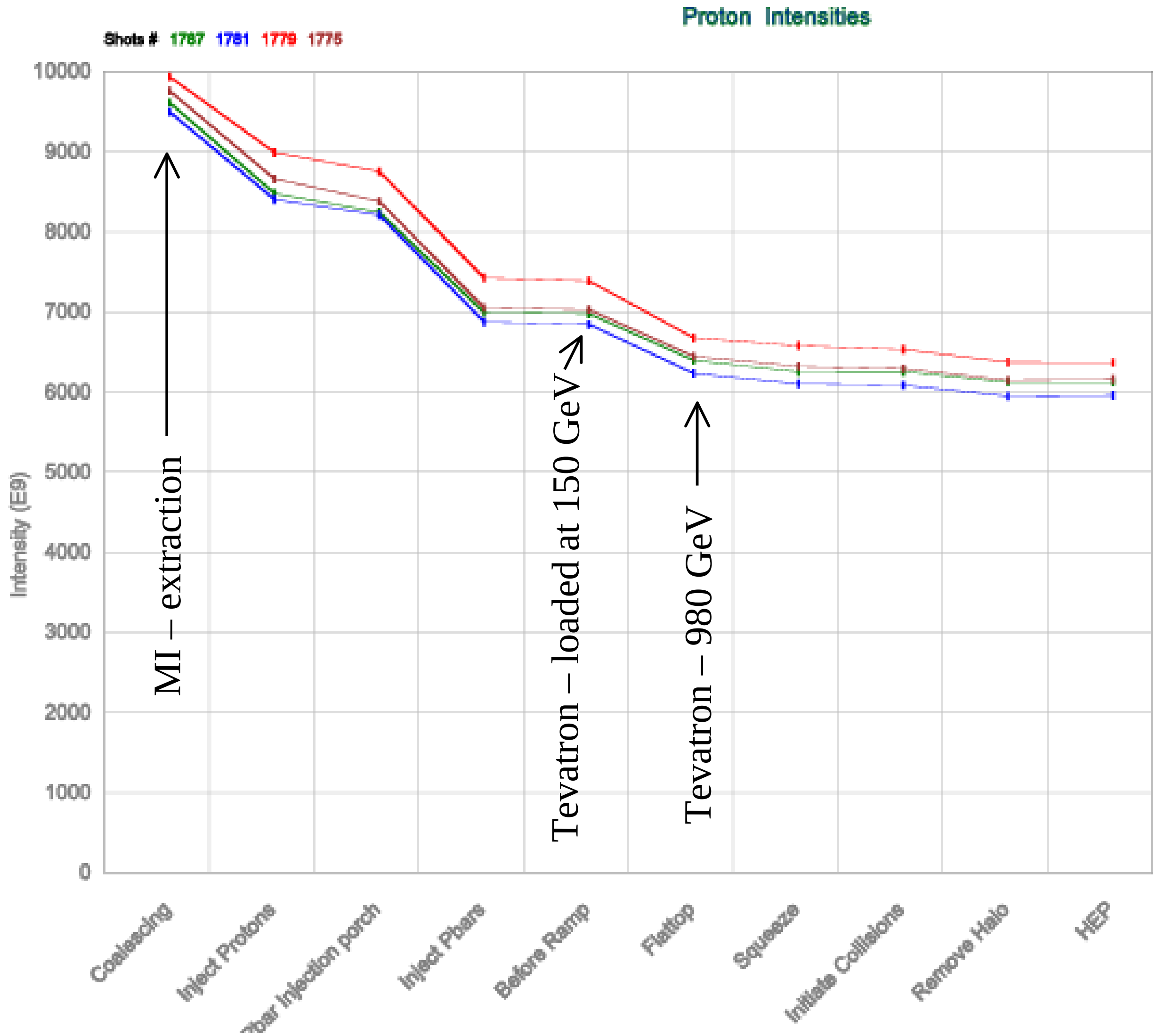
With Injection oscillation correction

Outstanding Issues/Challenges

- Antiproton source and Main Injector are close to meeting Run II goals:
  - Protons
    - Intensity/bunch >250 E9/bunch injected into the Tevatron
    - Emittances routinely 20π mm-mrad at 150 GeV leaving the MI
    - Longitudinal emittance remains questionable
  - Antiprotons:
    - Intensity/bunch as high as 30 E9/bunch after MI coalescing
    - Emittances routinely less than 10π mm-mrad leaving the MI
    - 80% or more of stack used

Outstanding Issues/Challenges

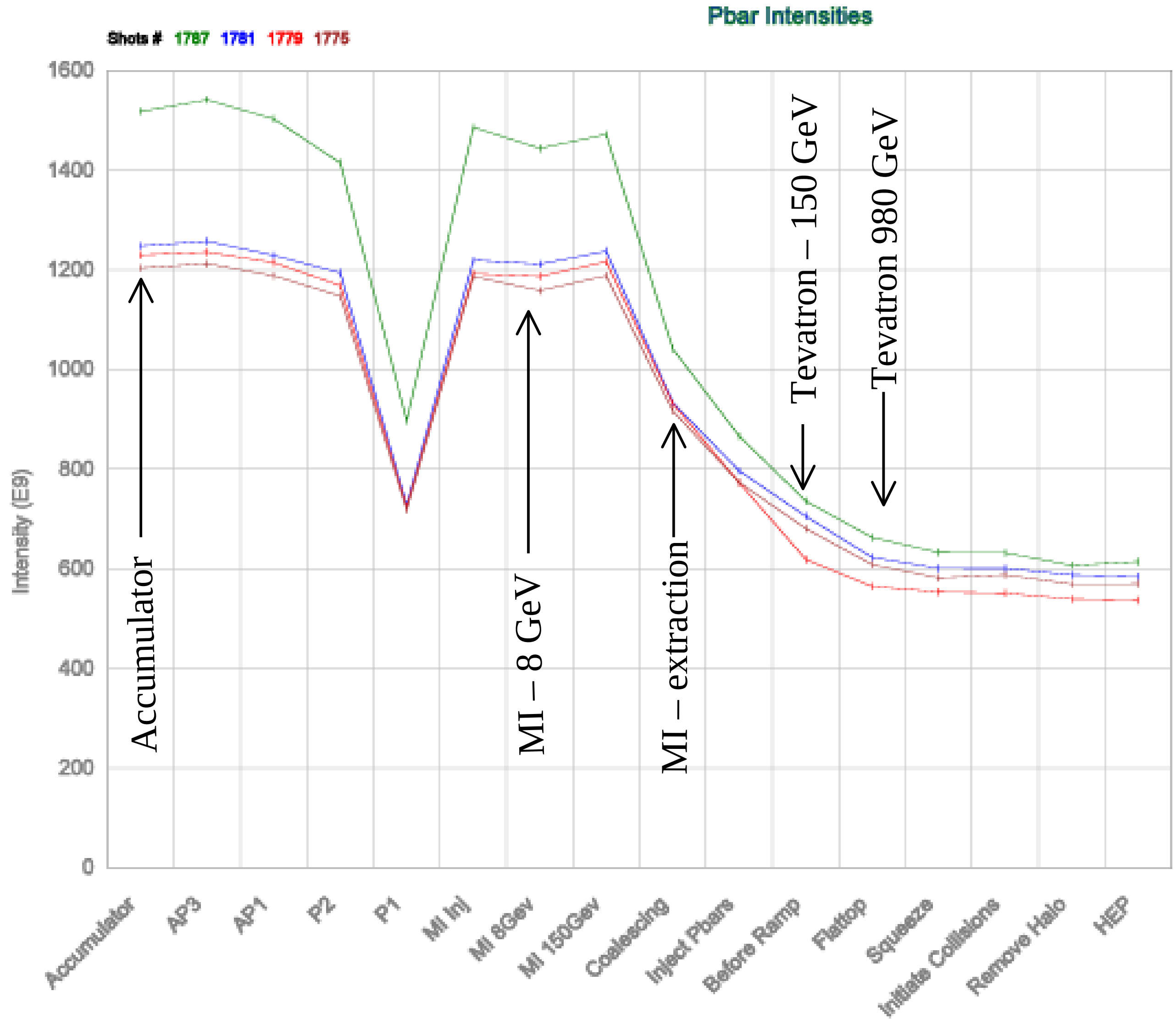
- Recent Proton Performance
  - Transmission from MI at 150 GeV to Tevatron at 980 GeV collisions
  - Initial intensity 10000 E9
  - 70% efficiency



Outstanding Issues/Challenges

Recent Antiproton Performance

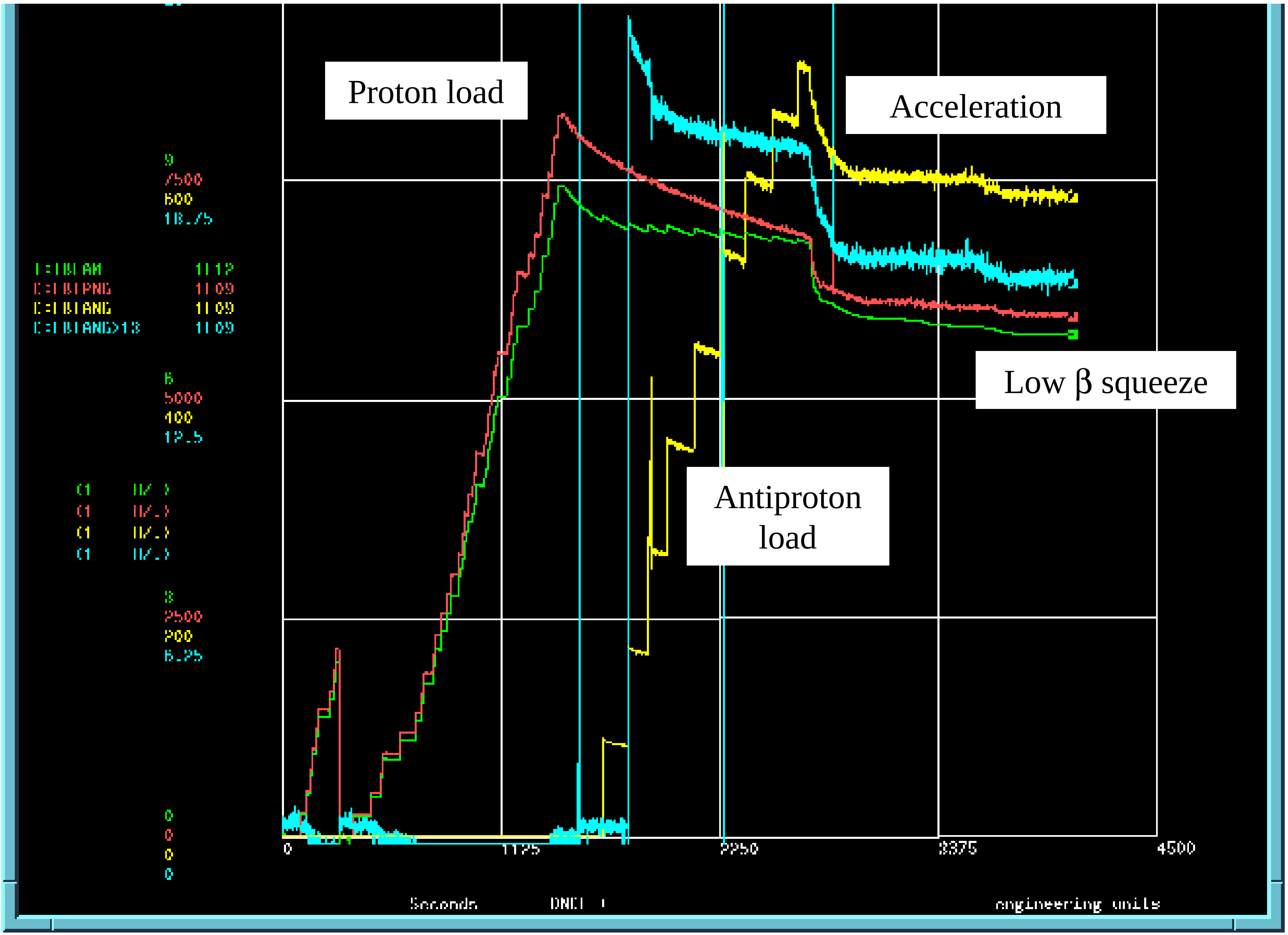
- Transmission from Accumulator at 8 GeV to Tevatron at 980 GeV collisions
- Initial intensity 1200 - 1500 E9
- 40% efficiency



Tevatron Issues

- Beam-beam effects
  - Proton intensity effect
  - Emittance and aperture effects
  - Tune, κ, CV,H, orbit effects
  - Lifetime in collisions
- Instabilities
  - Coherent transverse and longitudinal
  - Incoherent transverse and longitudinal
- Detector background
  - Losses due to vacuum and DC beam

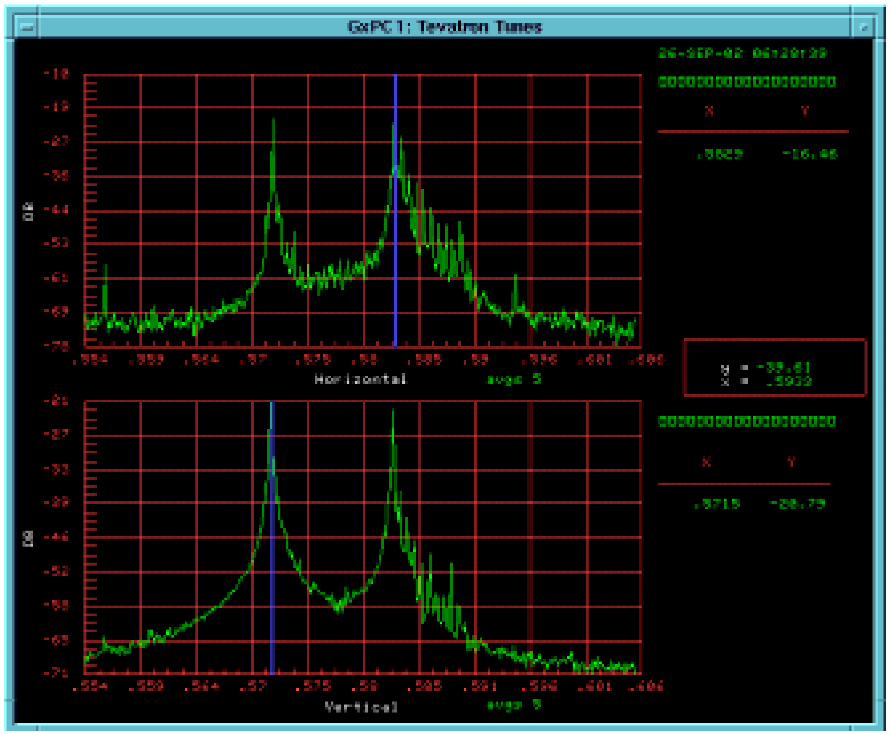
Tevatron Issues



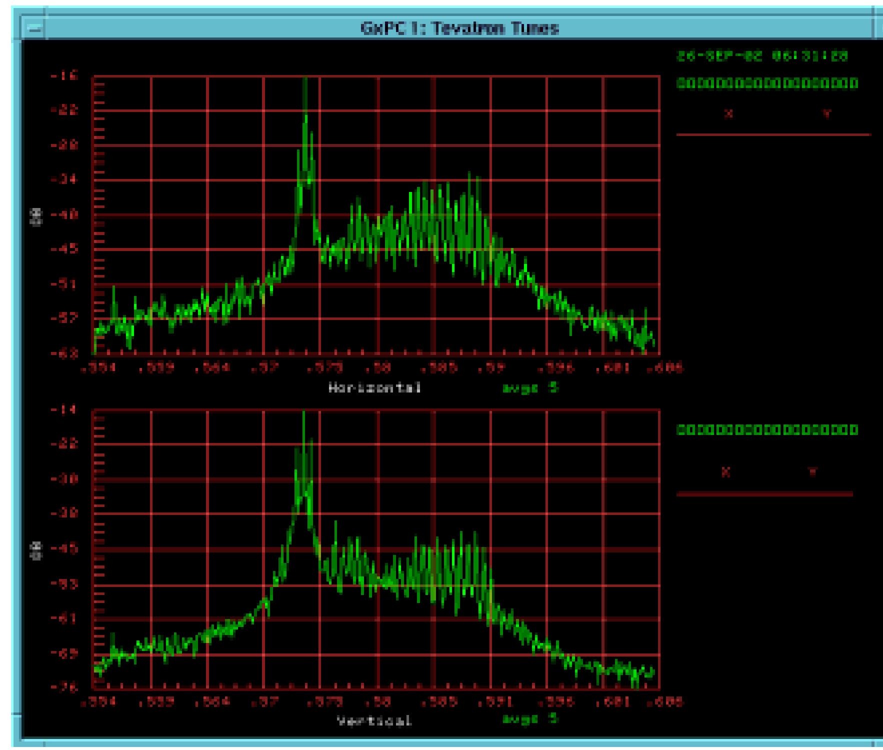
Beam-Beam Effects – 150 GeV

Issue	Solution	Impact on Luminosity	Schedule
Increased Proton Intensity	Transverse Dampers	30% to L_0	Horizontal commissioning in progress, vertical to follow (this month)
Improve injection aperture and emittance growth	Improved MI to Tevatron transfer line match	6% to L_0	Matching in progress
Improve injection aperture and emittance growth	Turn-by-turn position diagnostics and orbit closure algorithm	6% to L_0	Pbar system in operation
Improve injection aperture and emittance growth	Fast injection dampers	5-10% to L_0	Early 2003
Limited aperture and separation at 150 GeV	Replace C0 Lambertson magnets with larger aperture dipoles (double the vertical aperture)	10% to L_0	Next extended shutdown
Limited aperture and separation at 150 GeV	Improved optics across A0 straight section	5-10% to L_0	Early 2003
Time-dependent tune and coupling drift at 150 GeV	Tune drift compensation	2-5% on integrated L	Put into operation last week

Beam-Beam Effects – 150 GeV



Horizontal damper off
Coherence in tunes



Horizontal damper on
Horizontal tune flattened

Beam-Beam Effects – 980 GeV

Issue	Solution	Impact on Luminosity	Schedule
Drifting tunes during store	On-line tune stabilization	4-10% in integrated Luminosity	Long-term
Low lifetime – restore to Run I values (>15 hours)	Explore larger helix separation	10-30% in integrated Luminosity	Long-term
Low lifetime – restore to Run I values (>15 hours)	Optimize tunes for most bunches	up to 30% in integrated Luminosity	Long-term
Pbar tune shift by protons	Beam-beam compensation with electron lens	10% in integrated Luminosity	Long-term

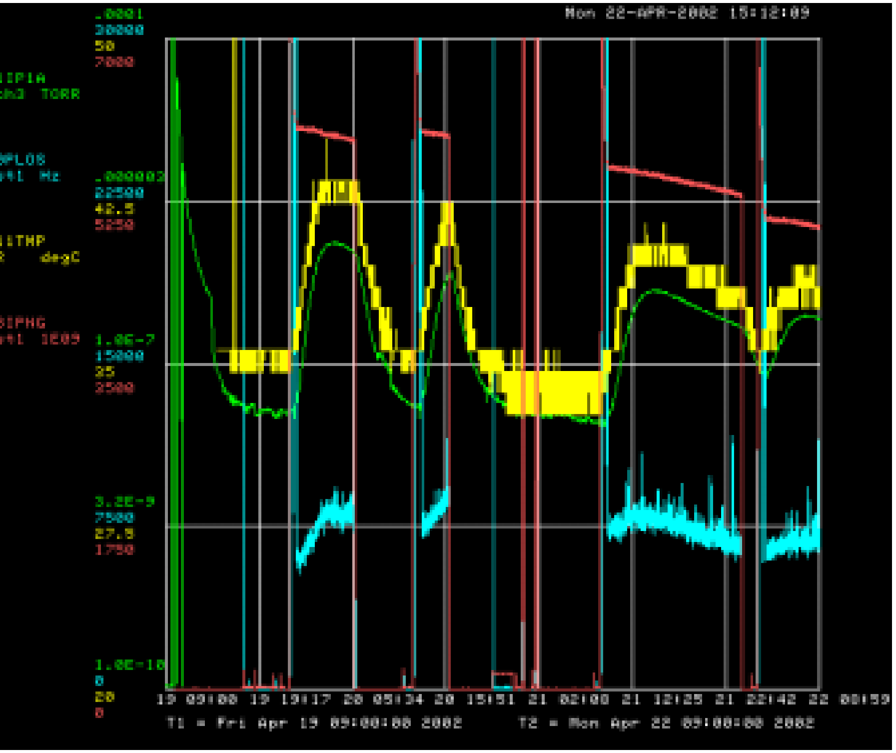
Instabilities

Issue	Solution	Impact on Luminosity	Schedule
Coherent transverse beam blow-up at all beam energies	Transverse dampers, additional investigation	see above	Damper commissioning in progress
Coherent longitudinal bunch by bunch beam blow-up	Longitudinal bunch-bunch dampers, additional investigation	better understanding	Longitudinal damper in operation at 150 and 980 GeV
Coherent ‘dancing bunches’	Observed, under study	better understanding	December 2002
Incoherent bunch length growth	Observed, under study	better understanding	early 2003

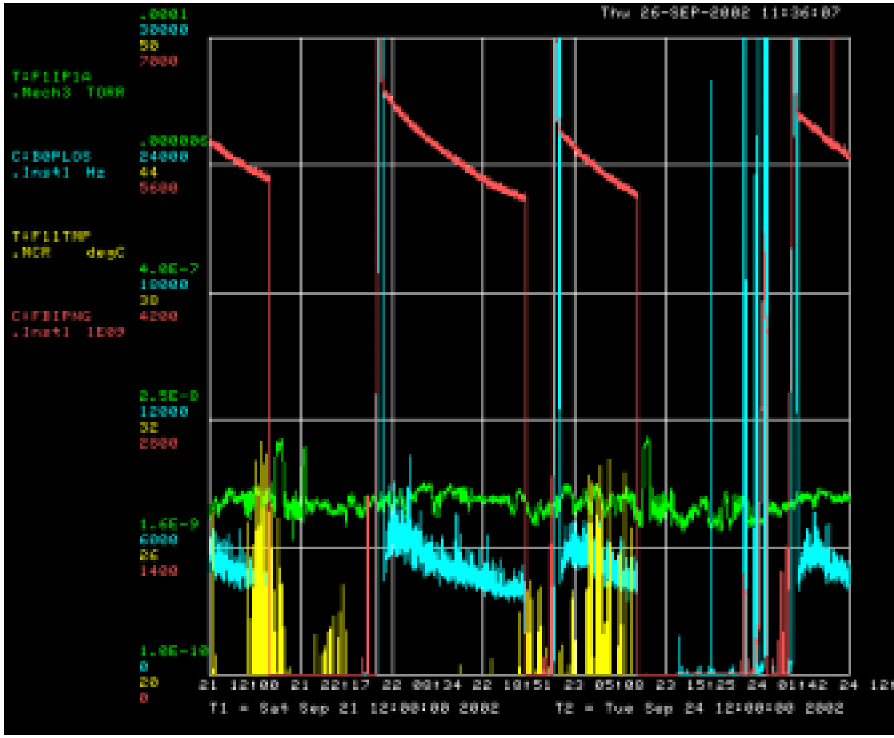
Detector Background

Issue	Solution	Impact on Luminosity	Schedule
DC beam in abort gap	Clearing with Tevatron Electron lens	-	In operation
Intensity-dependent losses at CDF	Replace outgassing ferrite material in wall current monitor	-	completed during previous extended shutdown
Luminosity lifetime	Improve Tevatron vacuum by a factor of 2	10% in integrated Luminosity	2003 as shutdowns permit

Detector Background



Before vacuum repair



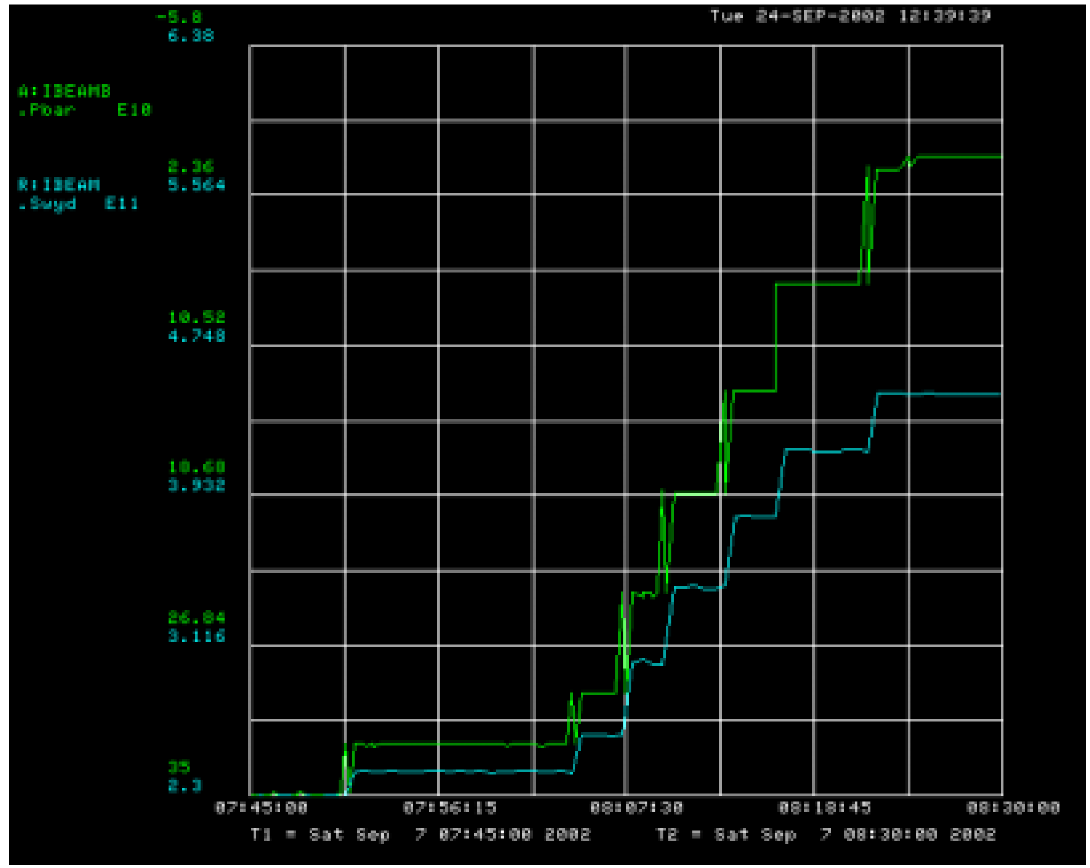
Recent behavior

Future Prospects

- In current configuration, the maximum achievable luminosity is ~10 x 10^{31} $cm^{-2}s^{-1}$
- Recycler is necessary for further luminosity upgrades
  - Commissioning continues in parallel with Collider operation
  - Pbars stacked and cooled
  - Integration into Collider operation in 2003

Recycler Status

- Pbars to Recycler via Main Injector
  - 63% transmission
  - Lifetime ~100 hours



Reliability

- ~70% of stores ended intentionally
- Average store length is 14.87 hours
- Of stores ended intentionally, average length is 17.3 hours
- Of stores lost, average length is 9.5 hours
- Most stores ended unintentionally are due to a failure associated to operating a superconducting accelerator (44%)
  - Quench Protection
  - Refrigeration

Schedule

- Collider Operation
  - 40 hours of Collider improvement studies every other week
- Parasitic
  - Machine development in all accelerators
  - Recycler commissioning
  - MiniBooNe
  - Switchyard 120
- Interruptions for repairs as necessary
- No scheduled extended shutdowns until at least January 2003

Summary

- Current peak Luminosity is 3.01 x 10^{31} $cm^{-2}s^{-1}$
- Integrated Luminosity has reached 4.8 pb^{-1}/week
- The Tevatron Collider is operating at least as well as Run I peak performance
- Luminosity improvement has been slower than hoped for, but the slope is positive
- Injectors are providing the necessary beams for L_0 = 6 x 10^{31} $cm^{-2}s^{-1}$
- Much effort has already spent to achieve current level of performance
- Tevatron major issues are
  - Injection aperture and lifetime
  - Beam-beam effects
  - Instabilities
- Identification and mitigation of luminosity impediments continues

Acknowledgements

- Summary of work by Fermilab Beams Division
- Assistance from every part of the lab, including CDF & D0 collaborators
- Grateful for outside help