Tevatron
Machine Status and Performance Projections

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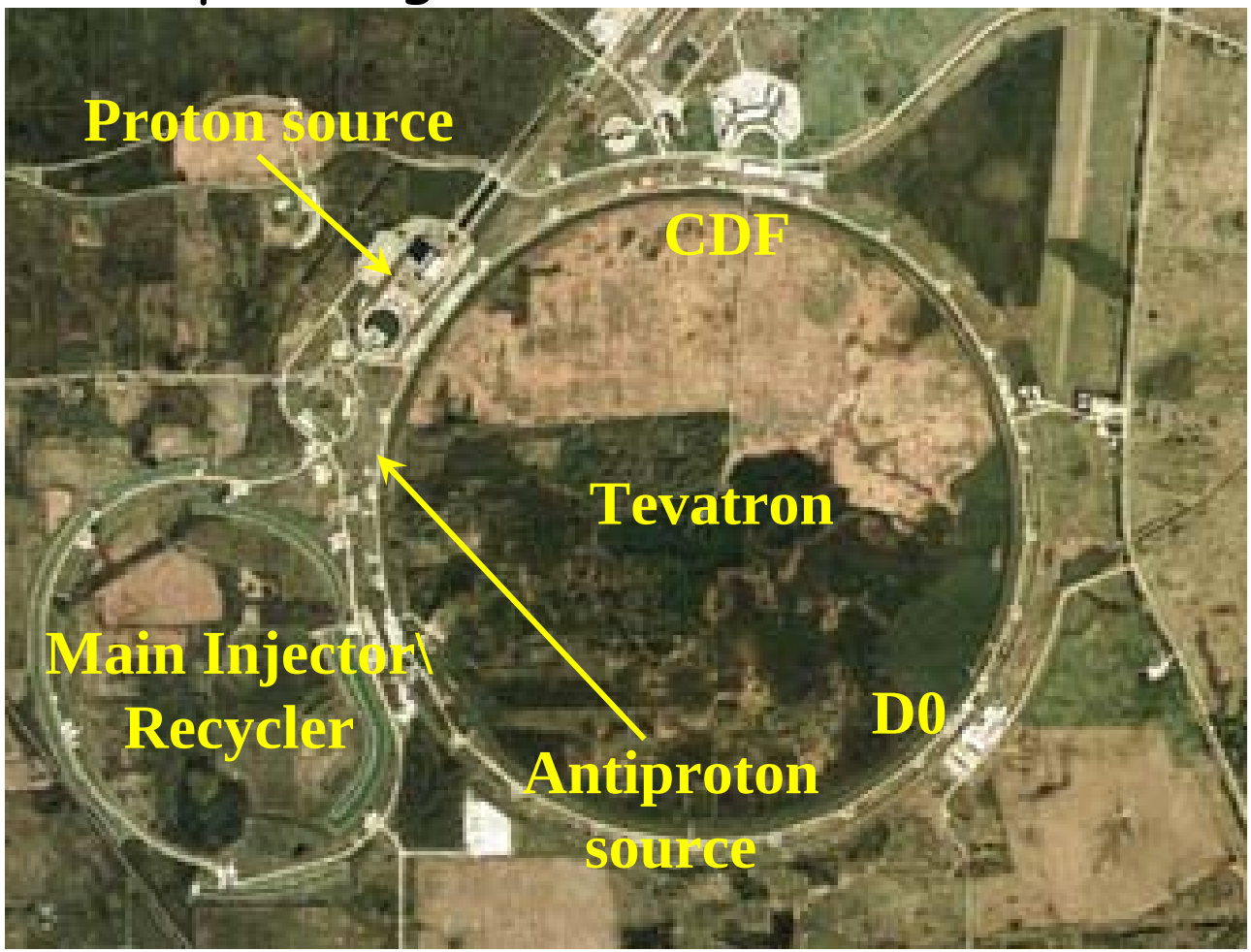
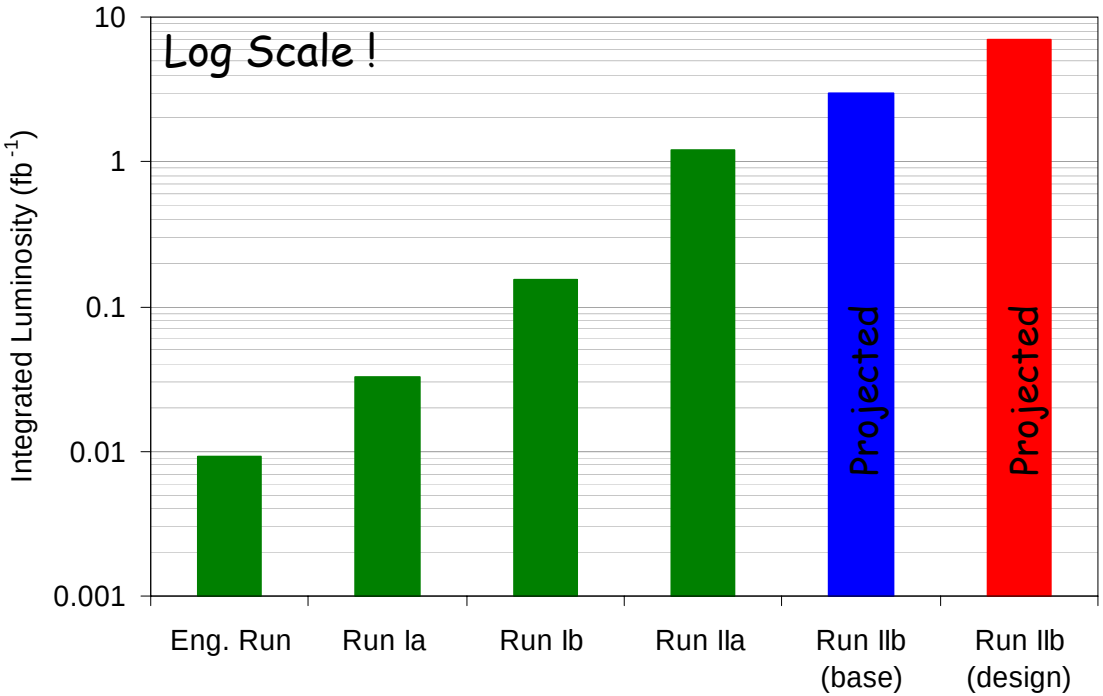
Fermilab Complex

- The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV

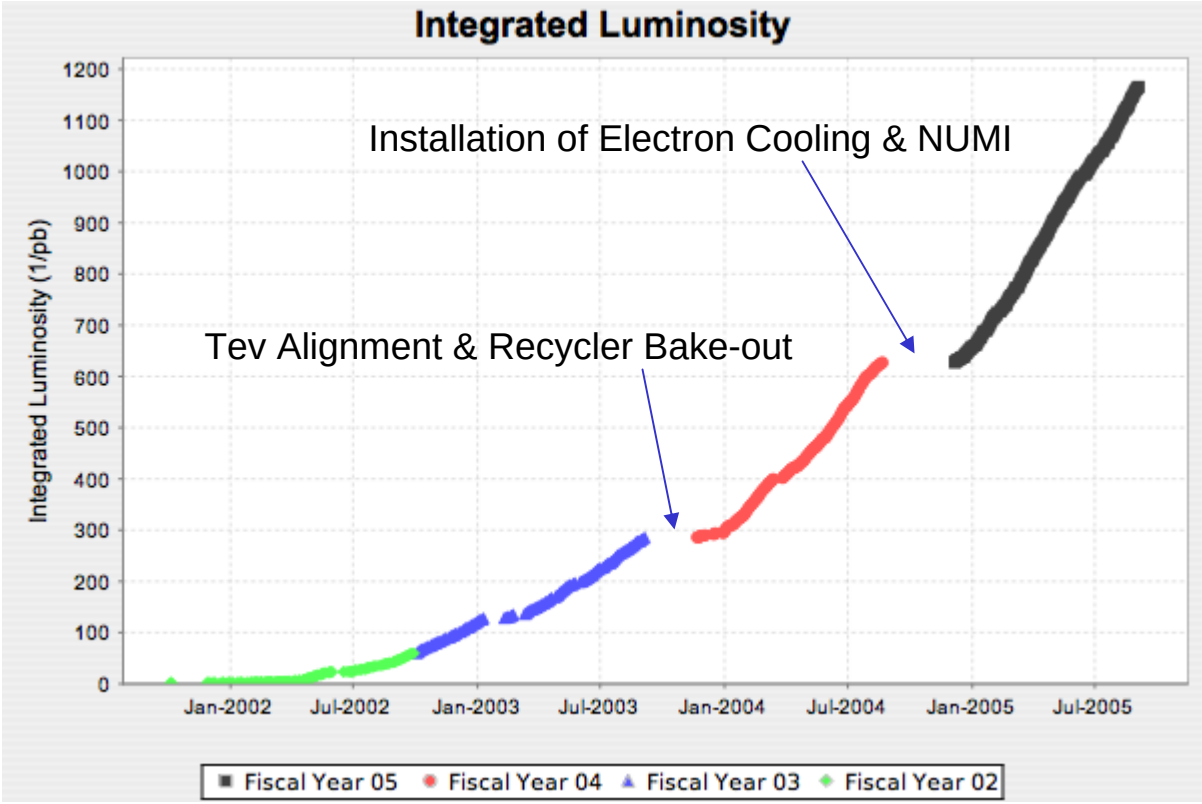


Collider Luminosity History (per detector)

- 1986-1987 Eng. Run I
  - .05 pb^{-1}
- 1988-1989 Eng. Run II
  - 9.2 pb^{-1}
- Run Ia (1992-1993)
  - 32.2 pb^{-1}
- Run Ib (1994-1996)
  - 154.7 pb^{-1}
- Run IIa (2002-2005)
  - 1200 pb^{-1}
- Run IIb (2006-2009)
  - 3,000 – 7,000 pb^{-1}
- Run IIa + IIb (2002-2009)
  - 4,300 – 8,100 pb^{-1}

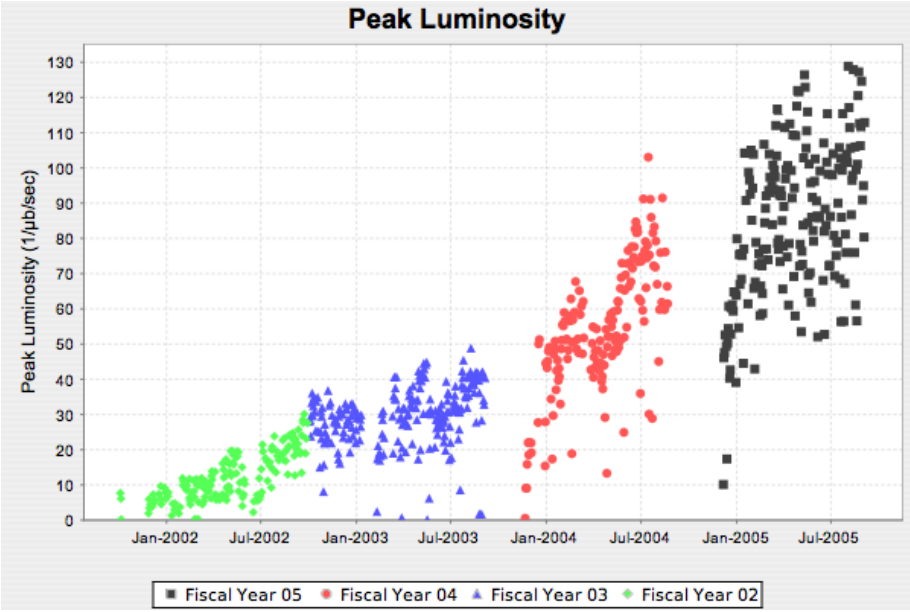


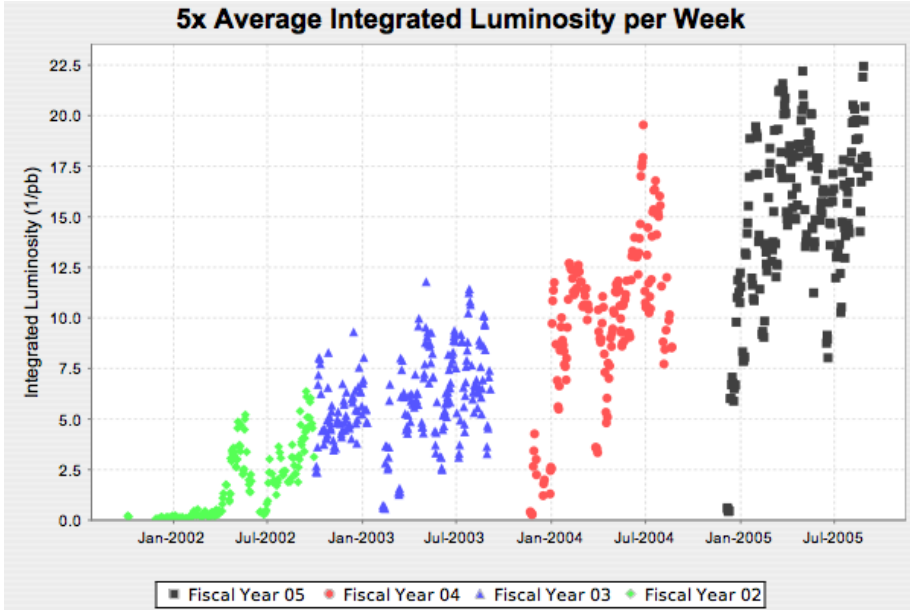
Integrated Luminosity



- Since June 2003, the Tevatron has seen a 3-fold increase in
  - Peak luminosity
  - Integrated luminosity per week
  - Total integrated luminosity

Luminosity History





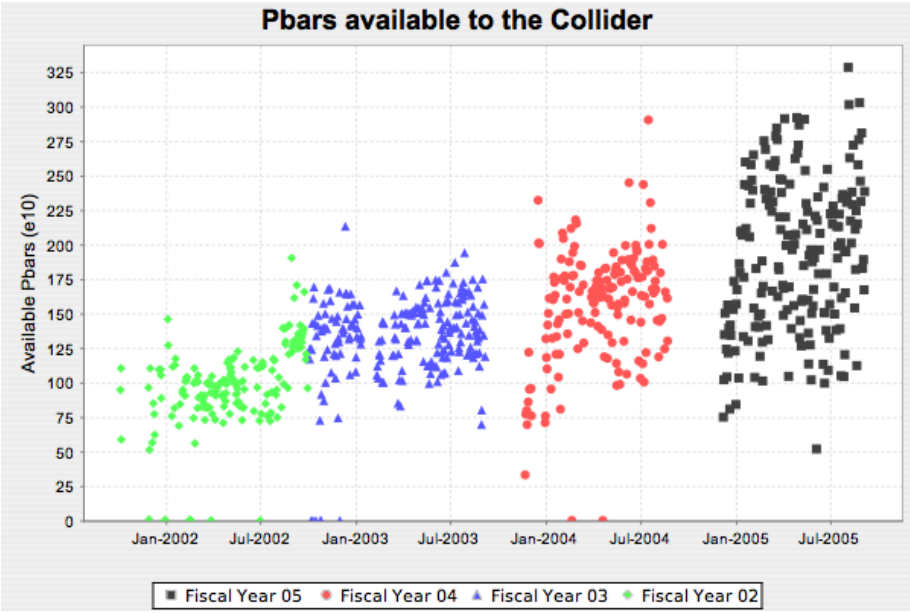
- Luminosity increase is mostly due to:
  - Better performance of the injector chain
  - Introduction of the Recycler into operations
  - Alignment of the Tevatron
  - Decision to "run" the Collider
    - Rigorous approach to attacking operational problems
    - Focused study philosophy

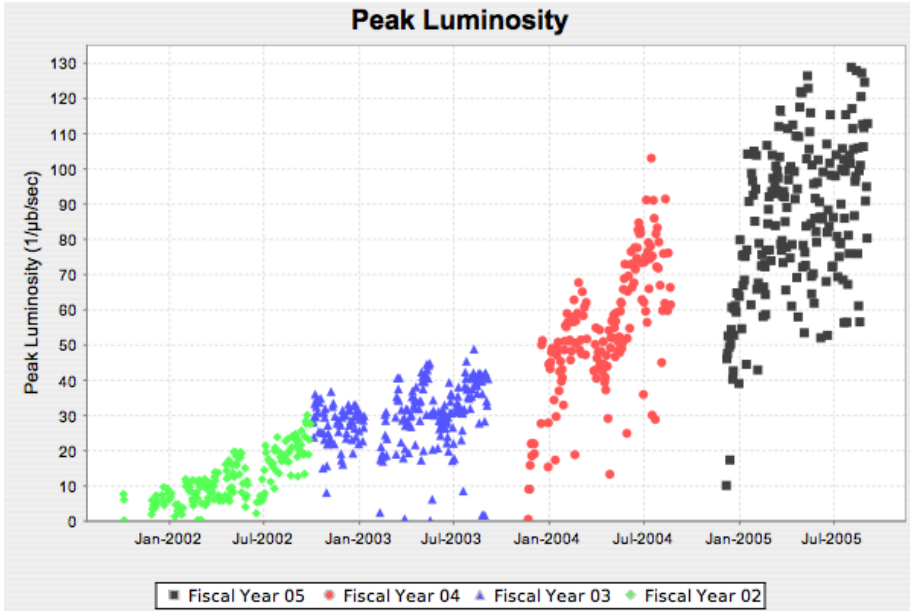
Luminosity

$$L = \frac{3\gamma f_o}{\beta^*} B N_{\bar{p}} \frac{N_p}{\varepsilon_p} \frac{F\left(\beta^*, \theta_{x,y}, \sigma^L_{p,\bar{p}}, \varepsilon_{p,\bar{p}}\right)}{\left(1 + \varepsilon_{\bar{p}} / \varepsilon_p\right)}$$

- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
    - Beam-Beam effects
  - Antiproton emittance
  - F<1

Antiprotons and Luminosity

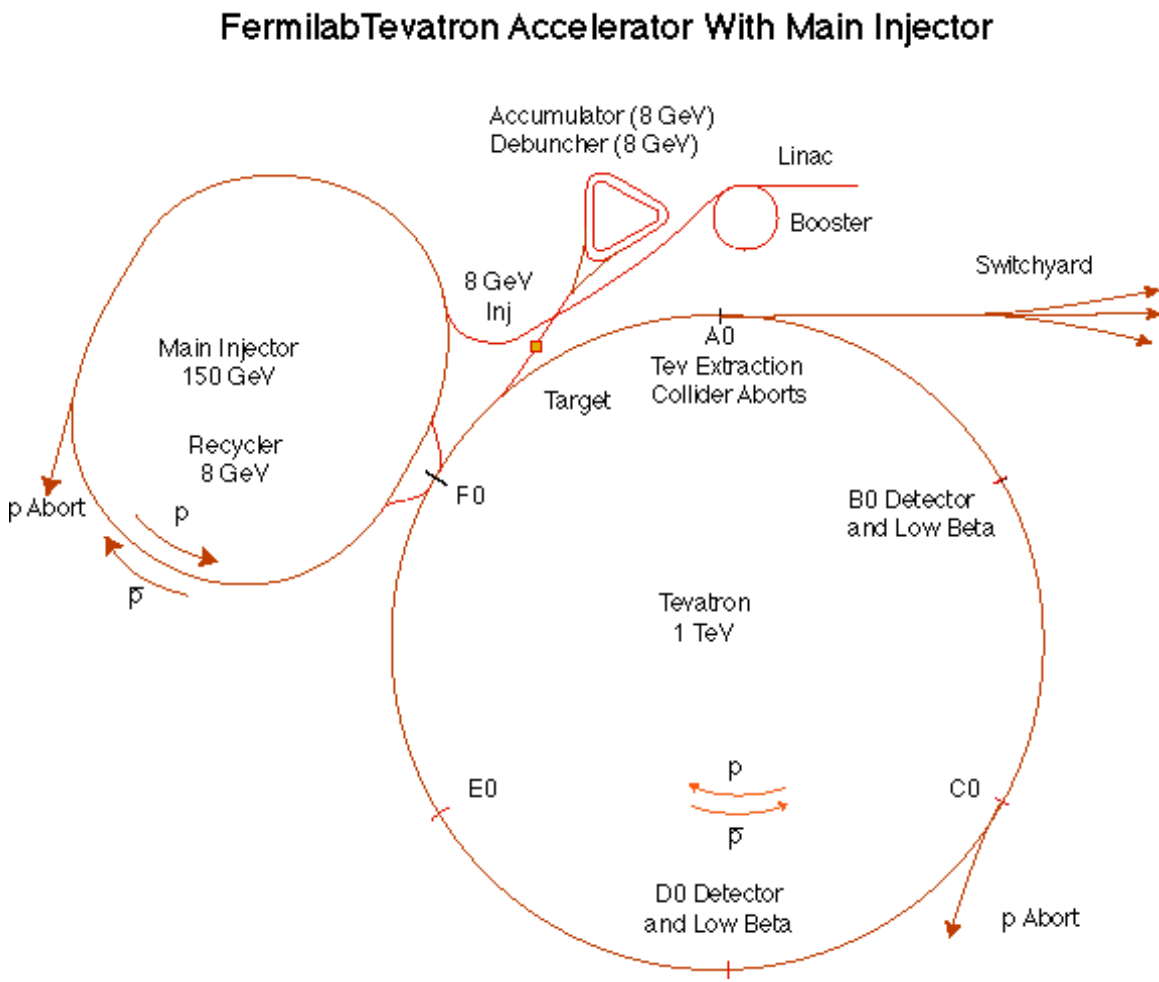




- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Antiproton Production

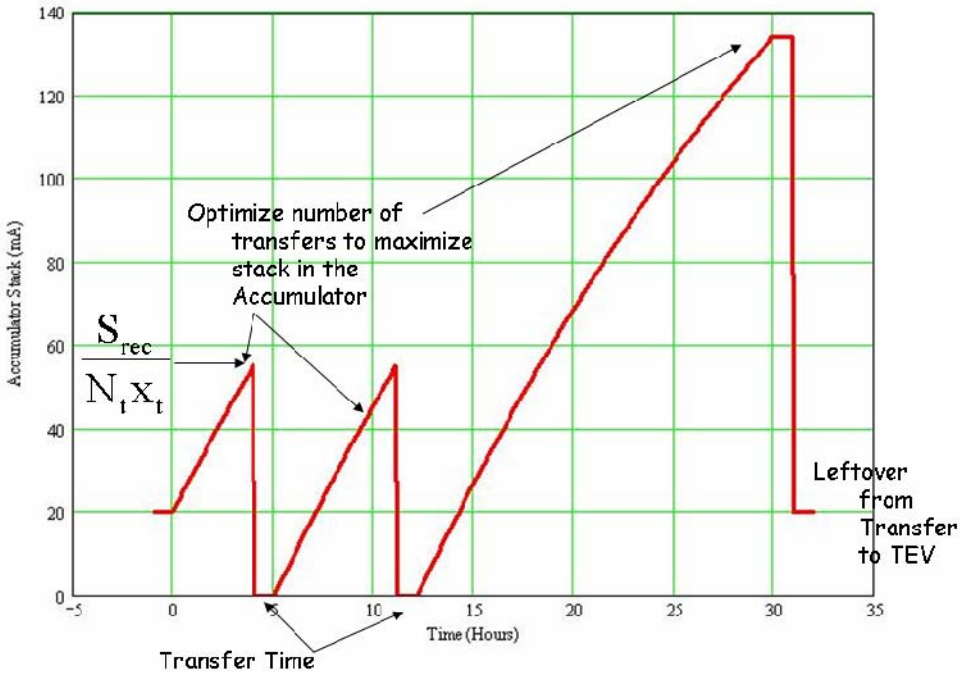
- $1x10^8$ 8 GeV pbars are collected every 2-4 seconds by striking $7x10^{12}$ 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of $600x10^6$
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON

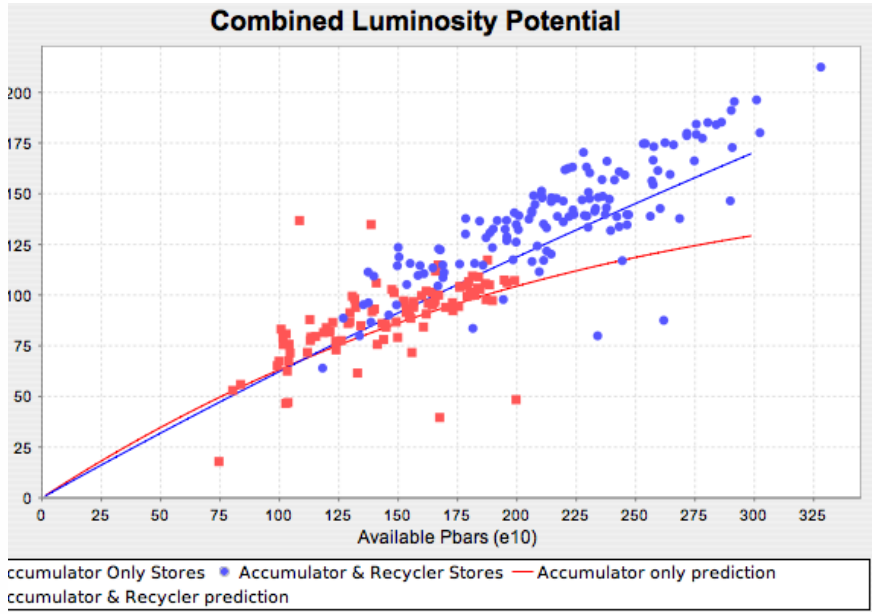


Combined Shots

- Extracting antiprotons from both the Accumulator and the Recycler for the same store eg.
  - Twelve bunches from the Recycler
  - Twenty four bunches from the Accumulator
- Reasons
  - Flexibility in the Run II Upgrade schedule
    - Natural merging of commissioning of electron cooling
  - Push Recycler commissioning progress by plunging it into operations
  - Luminosity enhancement – larger amount of antiprotons for smaller emittances
    - Accumulator stack size limited to <200 mA
      - Stacking Rate
      - Transverse emittance vs Stack Size
- Combined Shot Operation
  - Concept proposed in February '04
  - Dual energy ramps in the MI completed and tested by May '04
  - First Attempt 6/13/04
  - Record Luminosity
    - $103 \times 10^{30} cm^{-2} sec^{-1}$ recorded 7/16/04
    - $129 \times 10^{30} cm^{-2} sec^{-1}$ recorded August 2005
  - Routine Operations - January 2005
- Obstacles
  - Stacking Rate
  - Injector Complex 8 GeV energy alignment
  - Longitudinal emittance in both the Accumulator and Recycler
  - Transfer time between Accumulator to Recycler

Combined Shots





- Luminosity enhancement – larger amount of antiprotons for smaller emittances
  - Accumulator stack size limited to <200 mA
    - Stacking Rate
    - Transverse emittance vs Stack Size

Collider Parameter Table

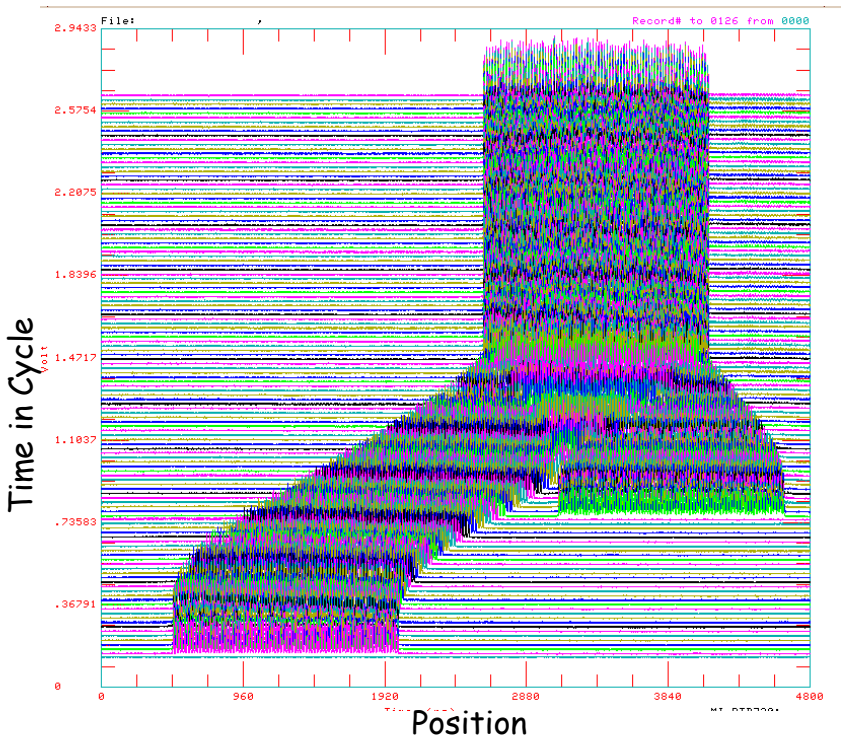
Luminosity Parameters									
Parameter	Last Store	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY Average	Previous FY	FY End Goal (Design)	FY End Goal (Base)	
Initial Luminosity (Average)	112.7	128.6	106.8	124.2	84.5	71.1	96.1	80.7	$x10^{30}cm^{-2}sec^{-1}$
Integrated Luminosity per Store (Avera	966.7	4802	3334.4	4339.5	2829.2	2660	3369	3190	nb^{-1}
Luminosity per week (Averaged)	-	-	18.2	-	13.9	11.8	16.8	12.7	pb^{-1}
Store Length	3	33.9	21.4	25.7	22.1	24.5	20	25	Hours
Store Hours per week	-	-	116.8	-	108.4	108.3	100	100	Hours
Shot Setup Time	3	1.9	2.7	2.4	2.9	2.6	2.6	2.6	Hours
TEVATRON Parameters									
Parameter	Last Store	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY Average	Previous FY	FY End Goal (Design)	FY End Goal (Base)	
Protons per bunch	225	225.9	239.5	238.6	231.9	247.3	260	260	$x10^{9}$
Antiprotons per bunch	42.8	50.3	39.4	45.1	32.8	29.9	42	34	$x10^{9}$
Proton Efficiency to Low Beta	62.6	67	64.7	63.8	62.2	72.7	-	-	%
Pbar Transfer efficiency to Low Beta	72.3	70.1	70.8	69.8	70.8	74	76	74	%
HourGlass Factor	0.67	0.67	0.66	0.67	0.67	0.68	0.65	0.65	
Effective Emittance	14.1	14.7	14.5	14.2	15.1	18.1	18.5	17	π-mm-mrad

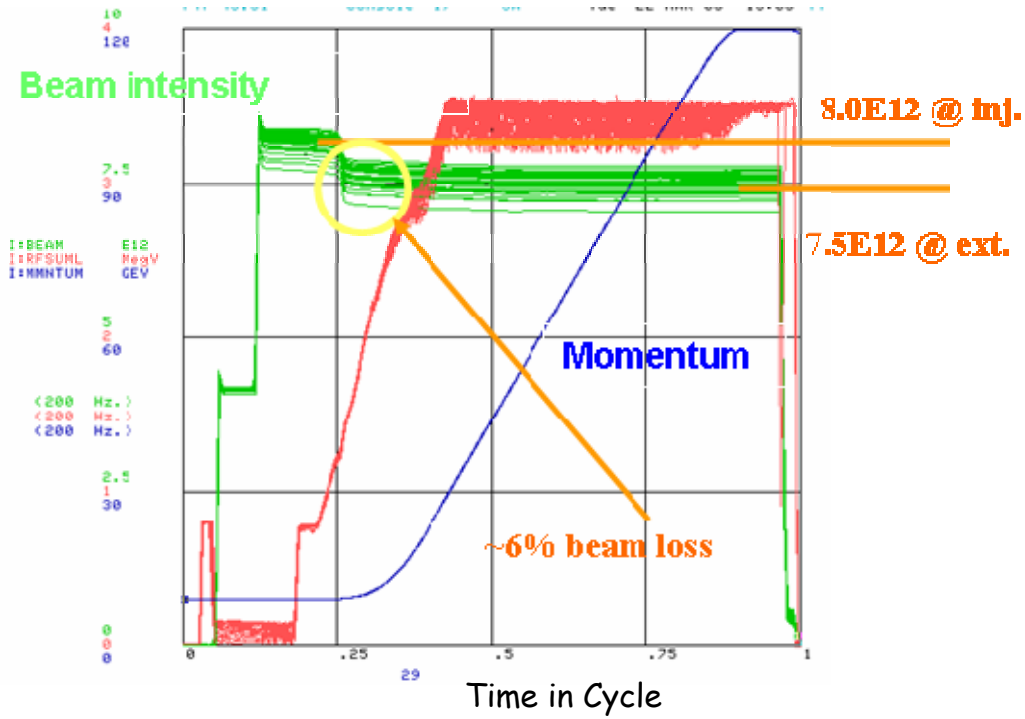
Run II Upgrades

- More protons on the antiproton target
  - Slip stacking
    - MI Beam loading compensation
    - Booster Cogging
  - Intensity Goals:
    - Base: 6.5×10^{12}
    - Design: 8.0×10^{12}
- Better antiproton collection efficiency
  - Lithium lens gradient upgrade
  - AP2-Debuncher aperture increases
    - Physical aperture increases
    - Beam based alignment
  - Production Goals at a 2 second cycle time:
    - Base: 15×10^{-6}
    - Design: 21×10^{-6}
- Better cooling
  - Accumulator Stacktail
  - Electron cooling in the Recycler
  - Average Stacking Rate Goals:
    - Base: 9.7×10^{10}/hour
    - Design: 21.7×10^{10}/hour
- Rapid Antiproton Transfers
  - Transfer Time Goals
    - Base: 45 minutes
    - Design: 15 minutes

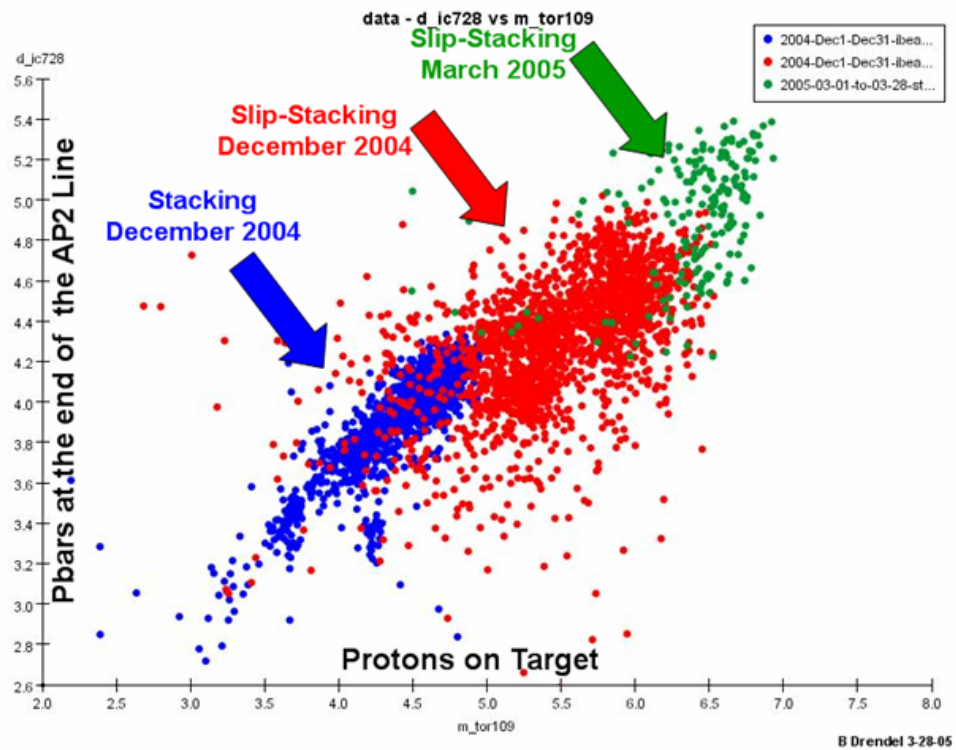
Antiproton Production – Slip Stacking

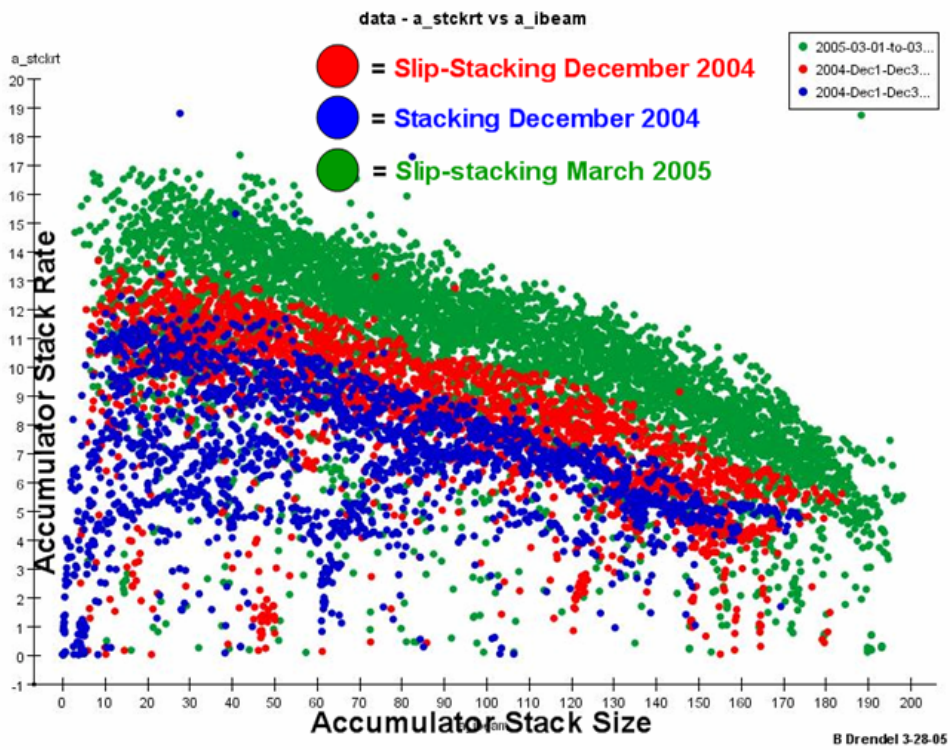
- Slip Stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target





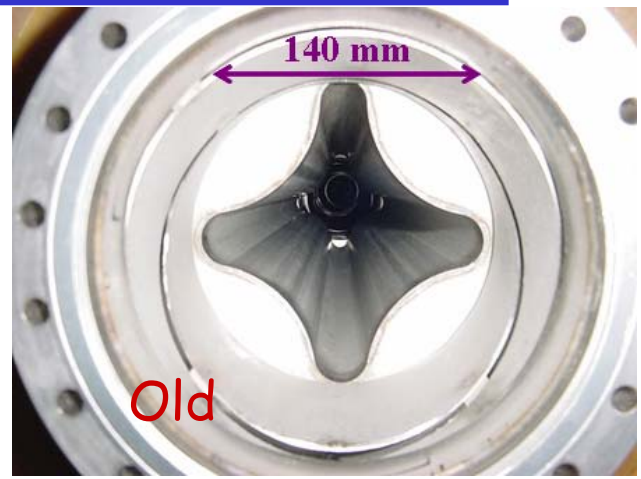
Antiproton Production – Slip Stacking





Antiproton Aperture - Pbar Production

- The measured aperture of the initial stages of the antiproton production chain is about 65% of the available physical aperture.
- An aggressive beam-based alignment program is under development to bring the measured aperture to the physical aperture.
  - Would increase the stacking rate by over a factor of 2
  - The final design goal is to achieve 77% of the physical aperture which will increase in stacking rate by 40%
- The beam based alignment scheme consists of 5 major components
  - Independent control of the quad gradients (done)
  - Beam position measurement system to measure orbit distortion due to varying quad gradients (in- progress)
  - Orbit control devices to center the beam through the quads (done)
  - Moveable control of tight apertures (stochastic cooling arrays) (in progress)
  - Loss monitor system to measure losses at tight apertures (done)
- Most of the recent focus has been to complete the instrumentation upgrade
  - Extremely small beam currents ~10μAmps
- The goal for this year is to increase the aperture for each plane from 65% to 72% of the available physical aperture which would result in a 20% increase in antiproton production rate

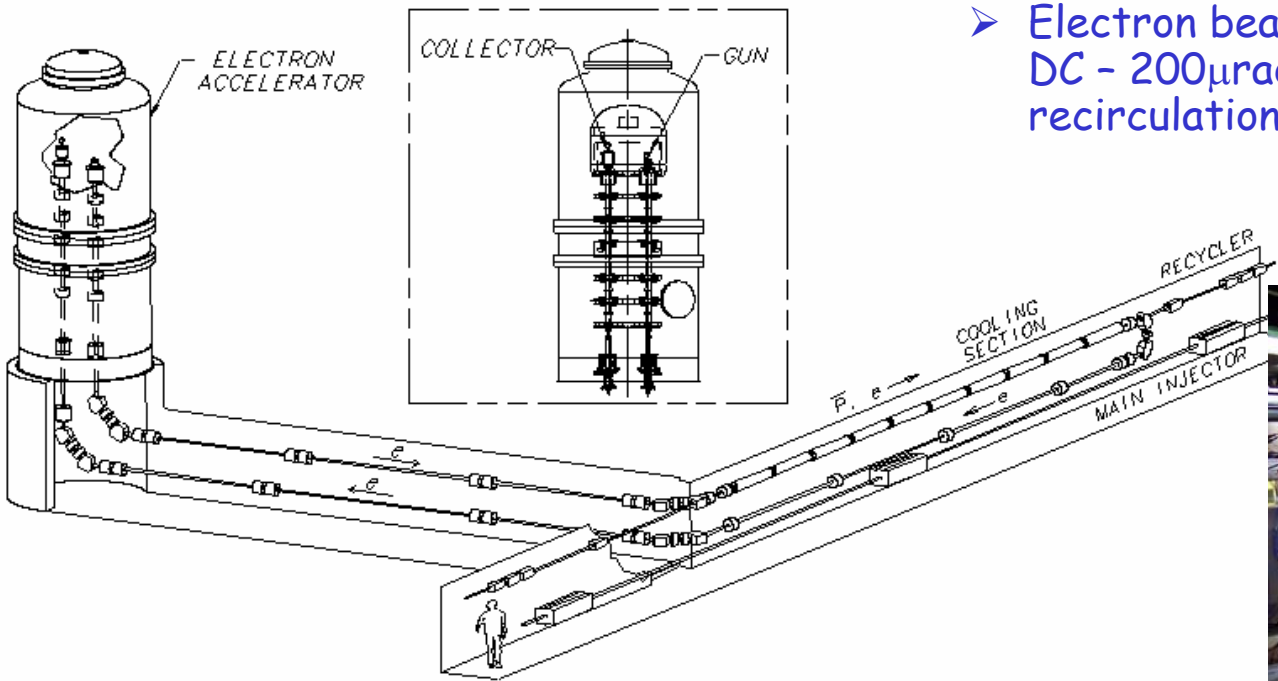


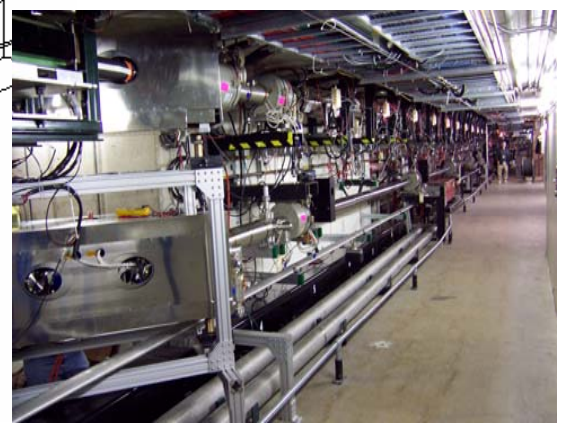
Recycler

- Features
  - Designed to a be a third stage antiproton accumulator ring
    - Initially uses stochastic cooling
    - Now starting to use electron cooling
  - Shares the same tunnel as the Main Injector
  - Major magnetic elements are made from permanent magnets
- At the end of August 2003
  - The Recycler was "on the ropes"
    - Lifetime was < 60hrs
    - Transverse emittance growth was 12π-mm-mrad/hr
  - Took drastic measures
    - Lengthened the Fall 03 shutdown to bake the entire Recycler
    - Instituted the Pbar Tax (Investment) to guarantee the Recycler adequate study time and access to the tunnel
    - Re-organized the Accelerator Physics Dept. to give the Recycler and Tevatron more accelerator physicists
- Recycler bake-out was extremely successful
  - Transverse emittance growth reduced by a factor of 10-20
  - Lifetime > 600 hours
- Recycler commissioning has progressed rapidly
  - Using the Recycler in "Combined Shots" operations makes it a luminosity enhancement
    - Operational January 2005
  - Transverse Damper commissioned August 2005
    - Stacks larger than $150x^{10}$ pbars now possible
  - Stand alone Recycler shots to the Tevatron (Sept 2005)
    - Stack of $190x10^{10}$ pbars in the Recycler
    - $92x10^{30}cm^{-2}sec^{-1}$ Luminosity
- Electron Cooling commissioned July 2005
  - By the end of August 2005, electron cooling is used on every Tevatron shot

Recycler Electron Cooling

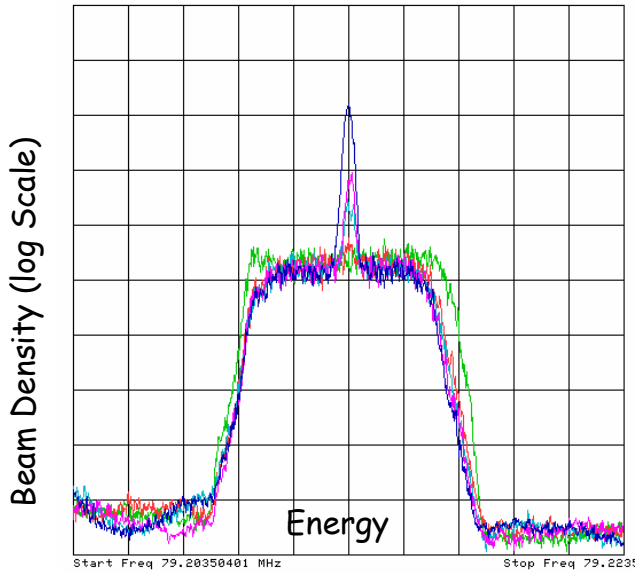
- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency

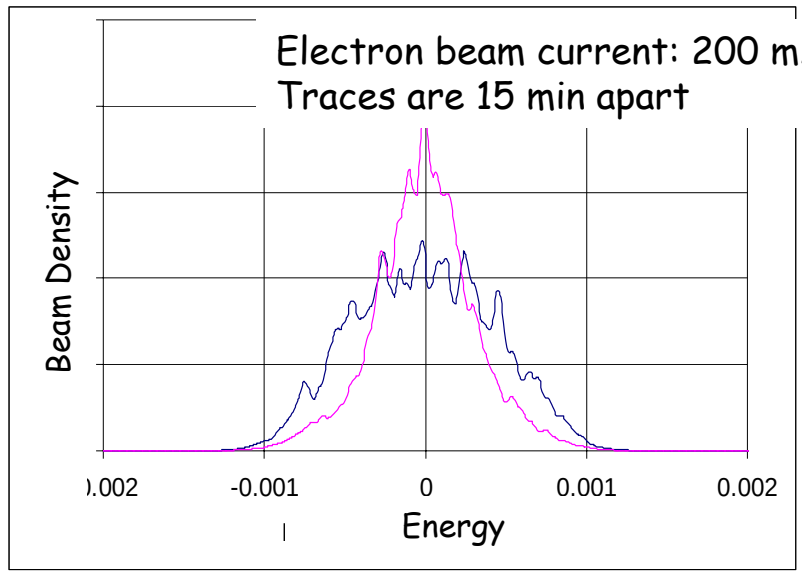




Recycler Electron Cooling

- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling goals
  - Can presently support final design goal of rapid transfers (30eV-Sec/2hrs)
  - Can presently reliably support stacks of 250×10^{10} (FY06 design goal)
  - Have achieved 500 mA of electron beam which is the final design goal.





Recycler-Only Operations

- Recycler has been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120x10^{10} pbars
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size can now be increased to over 200x10^{10} pbars
- The Collider complex is now transitioning from Combined Shot mode to Recycler-Only mode
  - Faster average stacking.
  - Smaller pbar emittances in the TEV
  - In Recycler-Only mode we will no longer need
    - The Accumulator shot lattice
    - Pbar-Tev shot setup
    - Dual energy ramps in the Main Injector
    - Complicated RF states
  - In addition, the Neutrino program will benefit because the Accumulator will spend most of the time with small stacks, hence fast cycle times.
- Transition should be complete by November 1, 2005

Stacking Progress

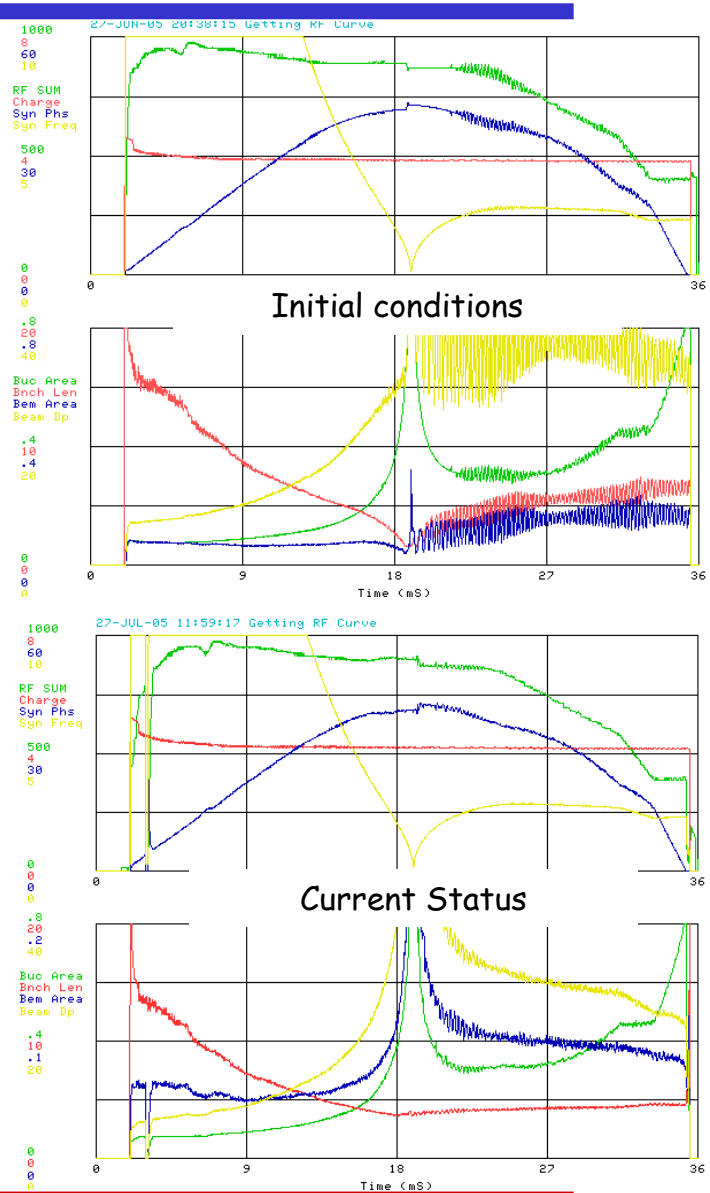
- The cornerstone of the Run II upgrades is antiproton production.
- The Phase 3 goal for the zero-stack stack rate is 20×10^{10} pbars/hour.
- Our best value to date is 17×10^{10} pbars/hour
- We have formed a special team of 20 people, dedicated 100%, to focus on antiproton production
  - Booster Extraction
  - Main Injector Slip Stacking
  - Antiproton Source
  - Instrumentation
- The goal of the stacking team is to:
  - Document the current state of the complex for antiproton stacking.
  - Formulate a study plan and needed instrumentation to reach 20×10^{10} pbars/hour
  - Successfully execute the plan by March 2006.
- The team meets twice a week at Tuesdays and Thursdays at 9 am in the Huddle to discuss overall progress and integration with collider operations.

Stacking Team - Booster Extraction

Goals

	Initial	3/1/2006	Final	Status	
Intensity	3.9	4.2	4.5	4.2	$x10^{12}$
Emittance	0.2	0.12	0.12	0.08	eV-Sec
Momentum Spread	18	18	18	12	MeV

- Remaining Tasks
  - Stronger Mode 1 damping
  - Transverse Damper
  - 8 GeV Bunch Rotation Reliability
  - RF Step at Transition
  - Operational Streamlining
    - Instrumentation
    - App. Programs



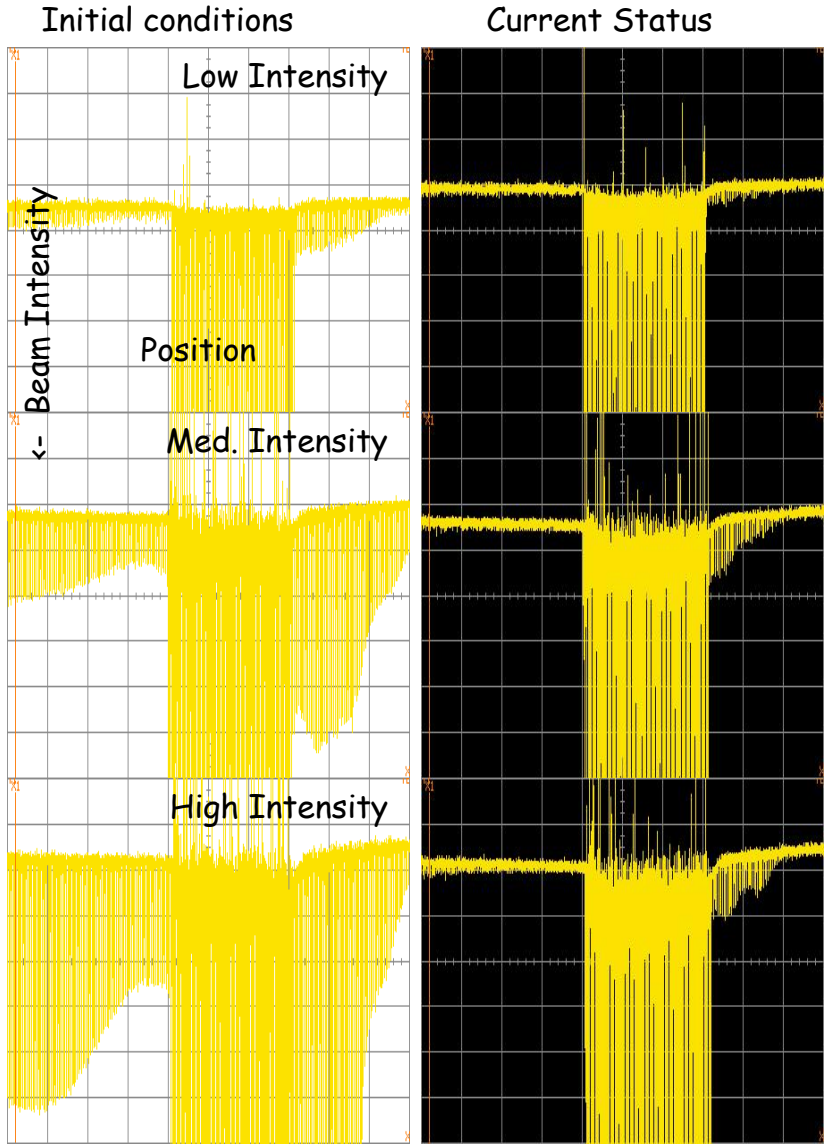
Stacking Team - Main Injector Slip Stacking

Goals

	Initial	3/1/2006	Final	Status	
Intensity	6.2	7.2	8	7.4	$x10^{12}$
Bunch Length	2	1.5	1.5	1.8*	nS
Efficiency	75	95	95	90	%

*Effective Bunch length on Mixed Mode Cycles

- Remaining Tasks
  - Reduce effective bunch length on target
    - Beam loading during Mixed-Mode 120 GeV Bunch Rotation
    - Elimination of difference between Pbar-Production-Only cycle and Mixed-Mode cycle
  - Operational Streamlining



Antiproton Source

	Initial	3/1/2006	Final	Status	
Beam on Target	6.2	7.2	8	7.4	$x10^{12}$
Production	15	17	21	13*	$x10^{-6}$
Cycle Time	2.2	2.2	2	2.2	Sec.

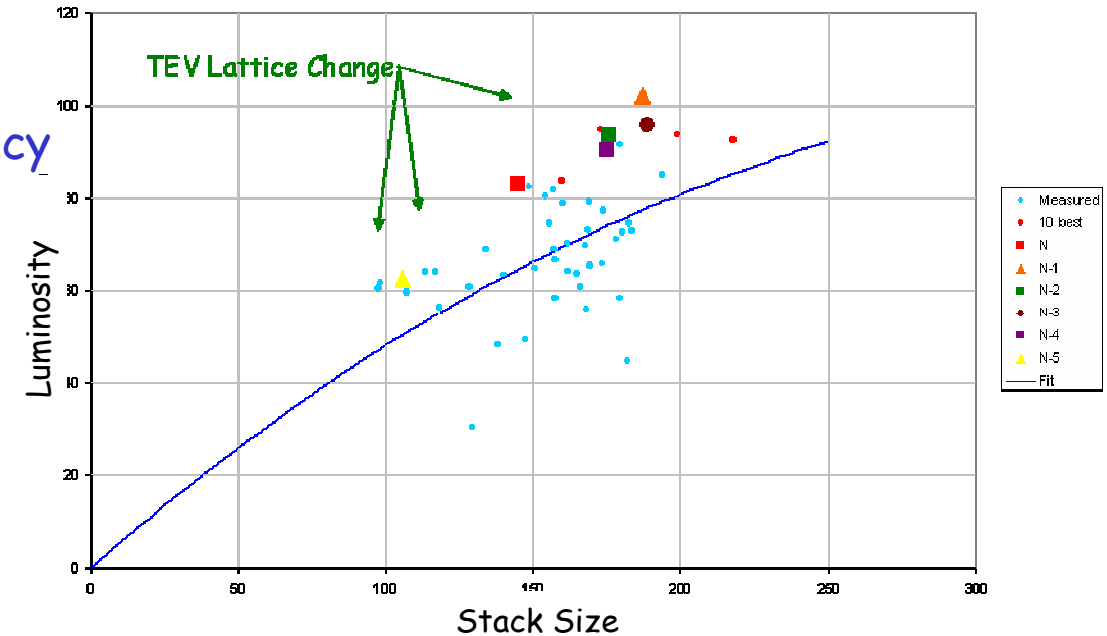
*During Mixed Mode Cycles

- Remaining Tasks
  - Beam base alignment effort of the AP2 and Debuncher
    - AP2 BPMs complete
    - Ready to upgrade Debuncher BPMs to see 53 MHz pbars
    - Differential Orbits for the AP2
    - Magnetic measurement of the upstream aperture of AP2
  - Correct the intensity dependence of Debuncher transverse cooling
    - Optimize transverse gain ramping
    - Optimize A10 straight section aperture
    - Correct of matching of D/A line
  - Optimize the flux through the Stacktail for Recycler-Only operations
    - Reduce StackTail Heating
      - Eliminate Vertical Dispersion in the Accumulator
      - Center Stacktail tanks
    - Implement 4-8 GHz momentum cooling during stacking
    - Speed up ARF1 curves
    - Lower the energy of the Stacktail deposition orbit
  - Rapid Transfers
    - Optimize P1-AP3 line and Main Injector to Recycler line for large $\Delta p/p$
    - Commission Pbar Injection Damper
    - Attempt transfers without reverse proton tune-up

Tevatron Major Accomplishments

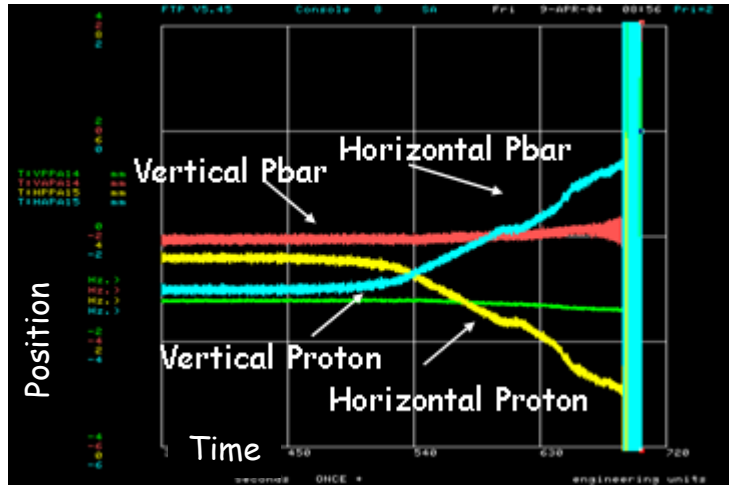
- Alignment Projects
  - Tev-Net
  - Smart bolt retro-fit
  - Dipole Un-Rolls
  - P1 Line roll
  - IP low-beta regions
  - Tight aperture areas
- Alignment Results
  - Better injection efficiency
  - Smaller emittance at collisions
  - Better ramp efficiency
  - Better store-store reproducibility

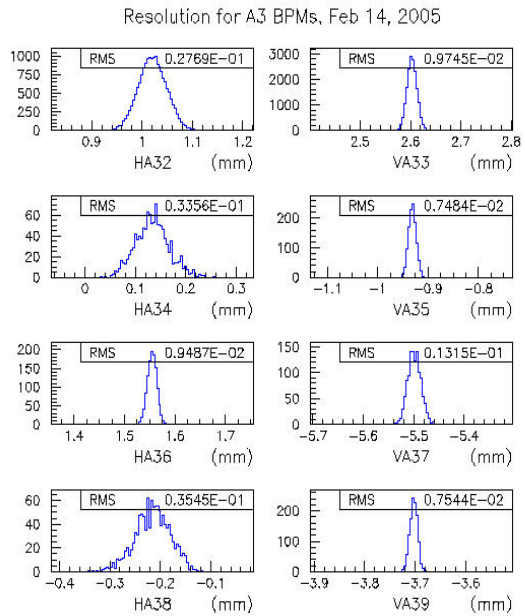
- New Low Beta optics (April 04 – June 04)
  - 20-30% increase in luminosity
  - Smaller beta*
  - Smaller emittance



Tevatron Instrumentation

- Tevatron BPM Project
  - Joint CD/AD effort
  - A major success
  - Project complete
  - An order of magnitude improvement in proton position measurements and new for pbars
  - Position resolutions in the range of ~10 -25 μ
  - Is extremely useful in understanding beams
    - Can see synchrotron and betatron lines, quadrupole oscillations, H-V coupling, etc.
- New Beam loss monitor system
- New Ion Profile Monitor

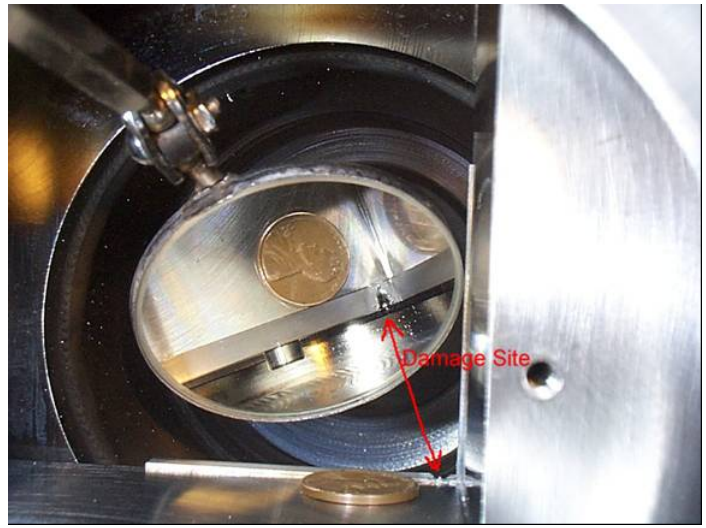


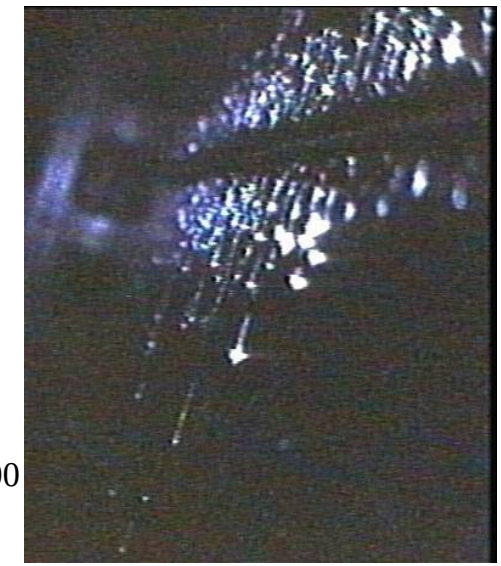


Tevatron Beam Power

$$L = \frac{3\gamma f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*, \theta_{x,y}, \varepsilon_{p,\bar{p}}, \sigma^L_{p,\bar{p}}\right)}{\left(1 + \varepsilon_{\bar{p}}/\varepsilon_p\right)}$$

- Proton Beam Current
  - Luminosity is proportional to the number of protons **per bunch** (N_p)
  - The proton beam current is proportional to BN_p
- Fast Beam Loss - can cause serious damage to the detector or the accelerator
  - Run II example: fast beam loss incident initiated by misbehavior of roman pot → losses → fast trip of correctors →beam miss-steer
  - Each proton/pbar bunch is a bullet – in Russian roulette
  - Add collimator protection where possible
  - Assertions:
    - Every serious beam incident should be fully diagnosed
    - Implication digested by the experiments.
    - Any corrective action will likely involve work on the accelerator
  - Unmasking of inputs for protection
  - New BLM system as abort input
  - Kicker Pre-fires
    - Collimator design
    - Abort block reconfiguration





Note:

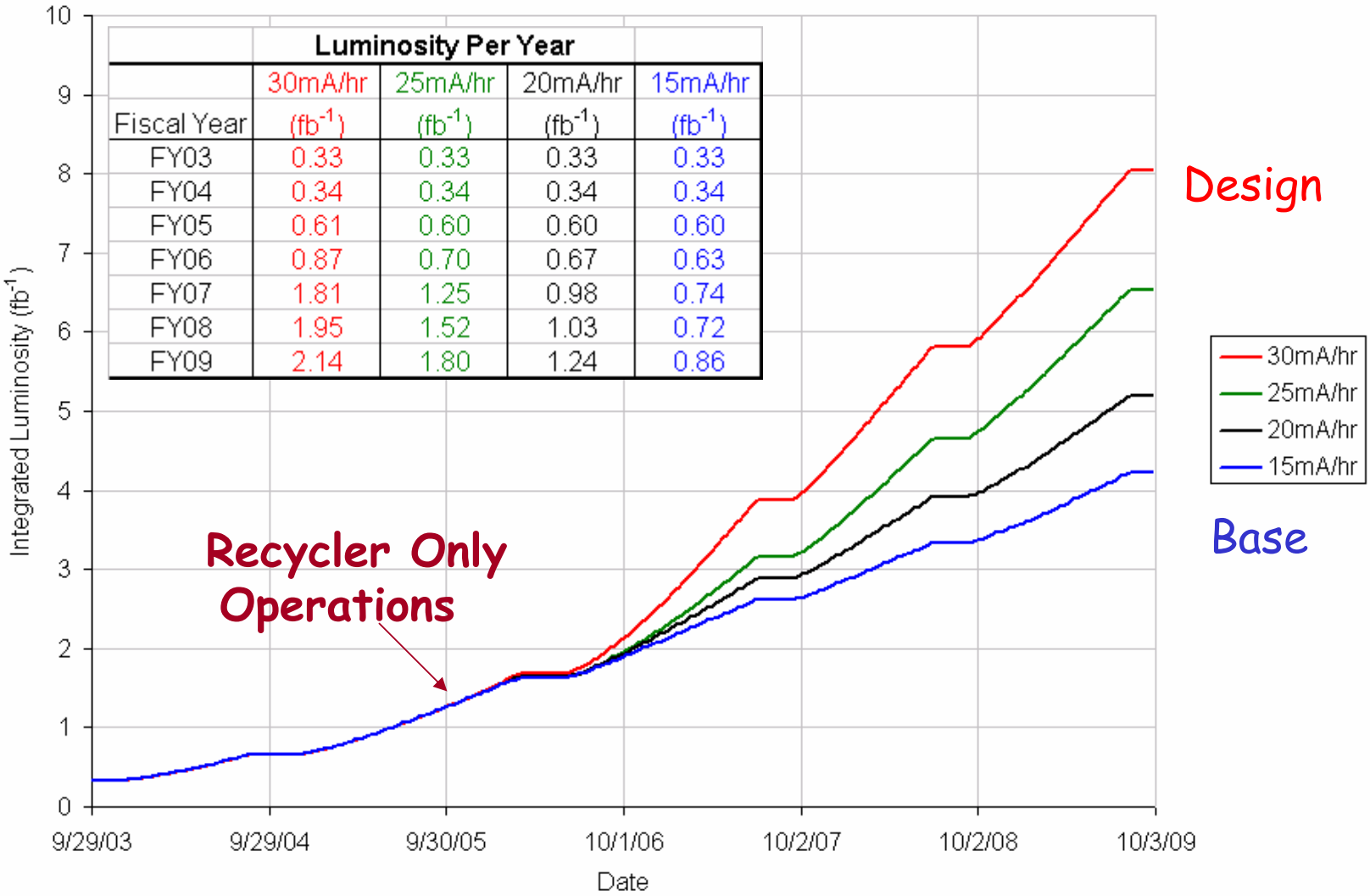
$$\frac{E_{\text{stored}_{\text{LHC}}}}{E_{\text{stored}_{\text{Tev}}}} > 1000$$

Luminosity Projections

- Our plan is to deliver the design projection,
  - but, develop an understanding of fallback scenarios
  - With electron cooling commissioning going well, the major uncertainty is the stacking rate
- Luminosity Scenarios
  - Design Projection:
    - Electron cooling
    - 15 minute Accumulator to Recycler transfers
    - Peak Stack rates of 30 mA/hr
  - Fall-back Projection:
    - Electron cooling
    - ½ hour Accumulator to Recycler transfers
    - Peak Stack rates of 20-25 mA/hr
  - Base Projection:
    - Electron cooling
    - 3/4 hour Accumulator to Recycler transfers
    - Peak Stack rates of 15 mA/hr

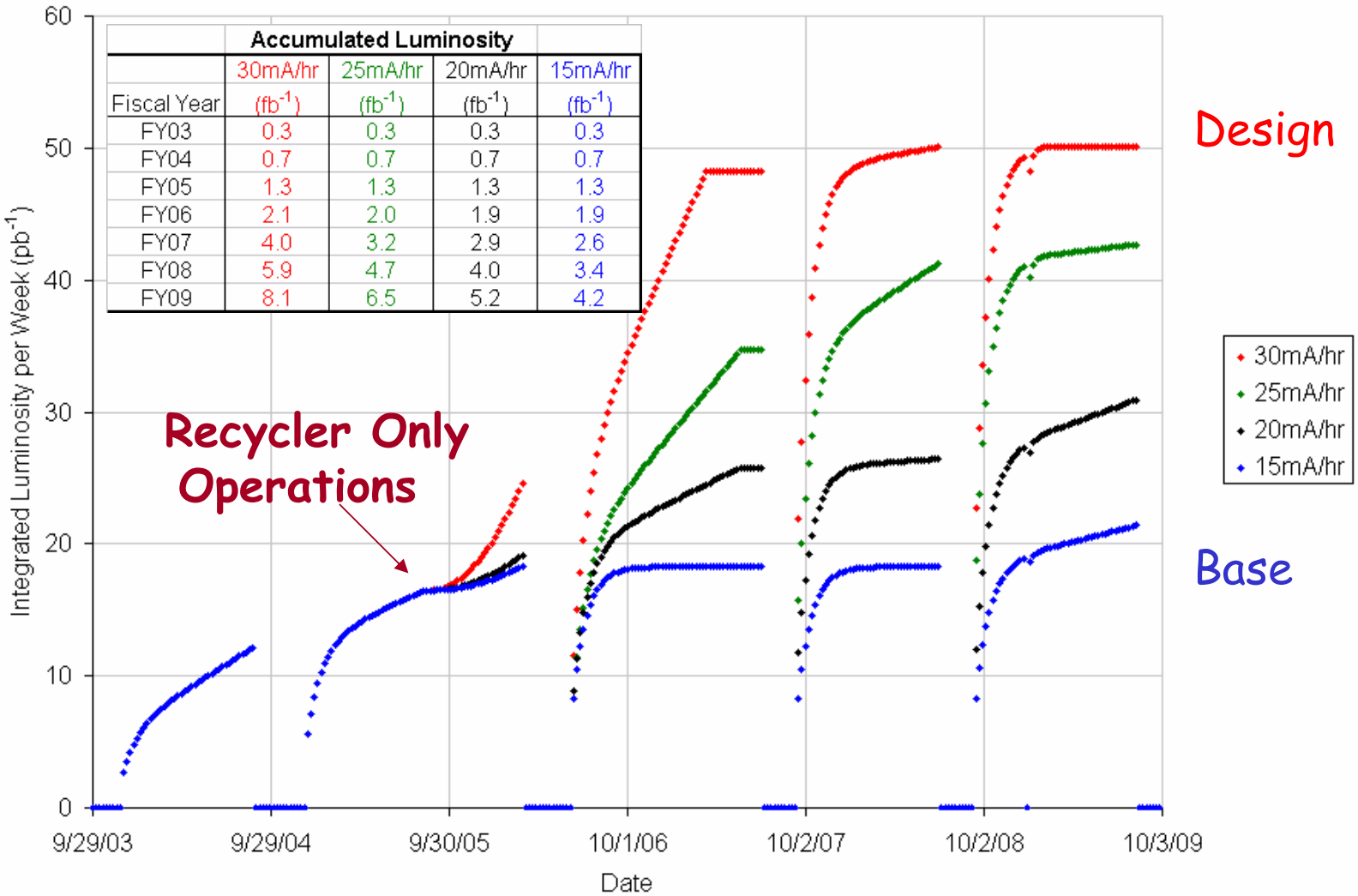
Integrated Luminosity

	Luminosity Per Year			
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.33	0.33	0.33	0.33
FY04	0.34	0.34	0.34	0.34
FY05	0.61	0.60	0.60	0.60
FY06	0.87	0.70	0.67	0.63
FY07	1.81	1.25	0.98	0.74
FY08	1.95	1.52	1.03	0.72
FY09	2.14	1.80	1.24	0.86

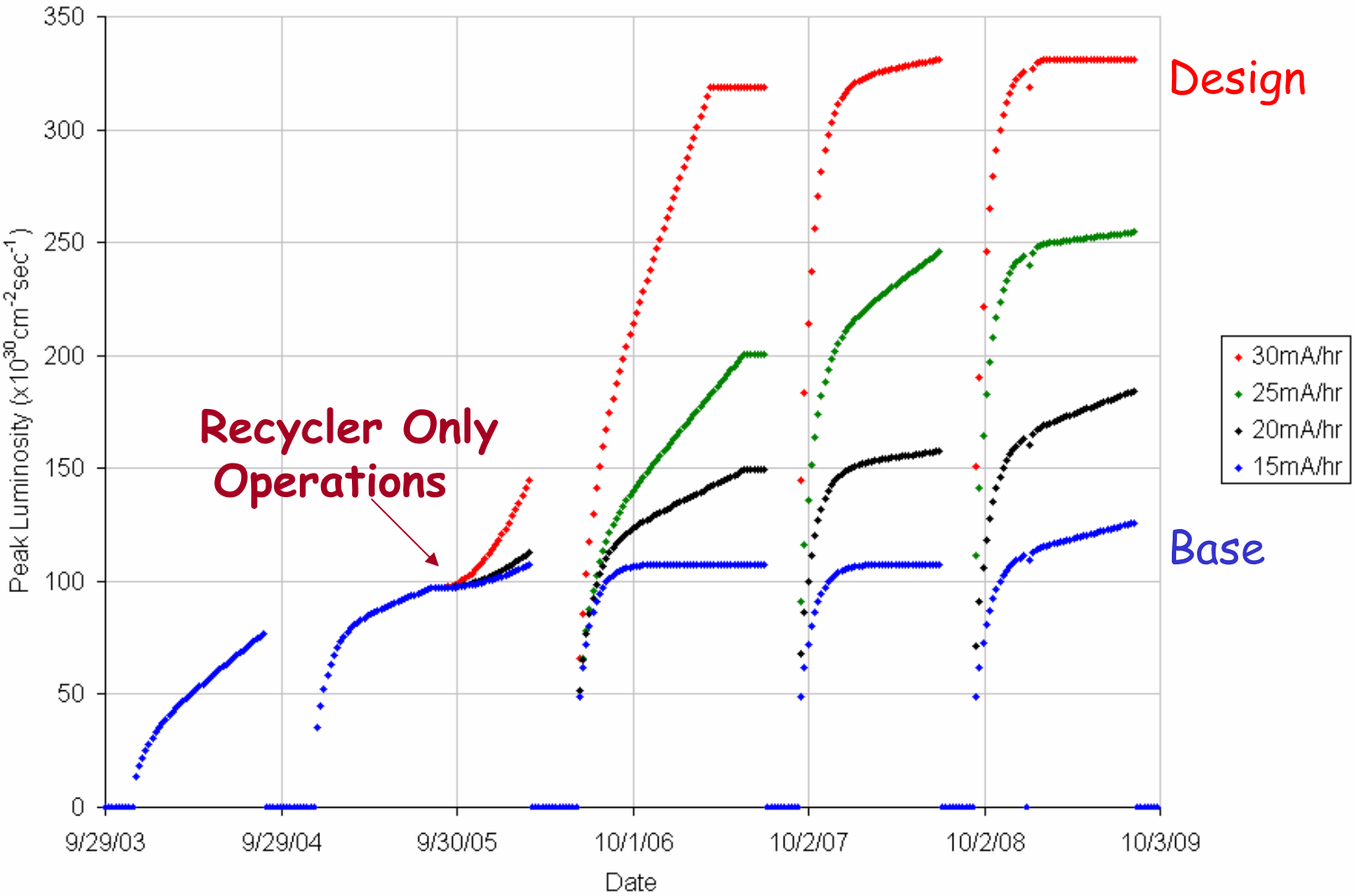


Weekly Luminosity Projection

	Accumulated Luminosity			
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.3	0.3	0.3	0.3
FY04	0.7	0.7	0.7	0.7
FY05	1.3	1.3	1.3	1.3
FY06	2.1	2.0	1.9	1.9
FY07	4.0	3.2	2.9	2.6
FY08	5.9	4.7	4.0	3.4
FY09	8.1	6.5	5.2	4.2

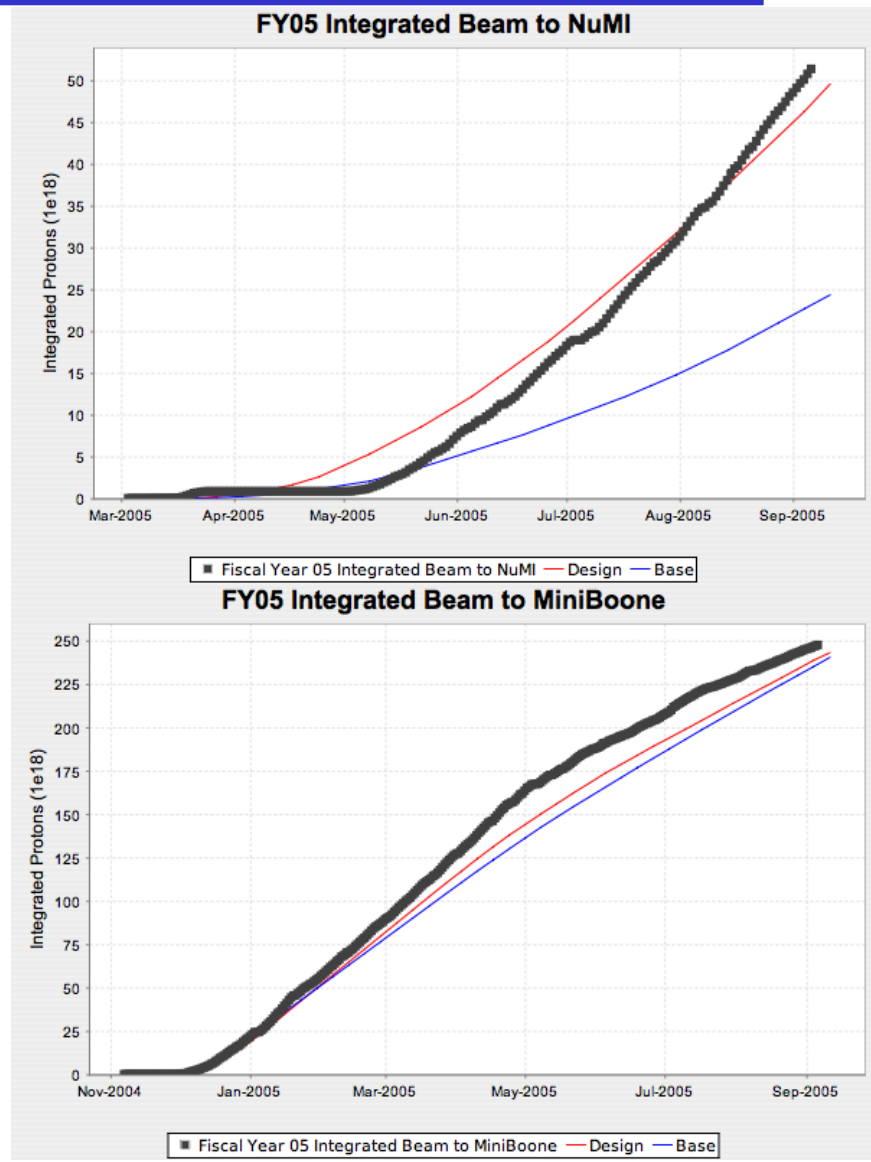


Peak Luminosity Projection



Major Expansion of the Neutrino Program

- NUMI commissioned
  - First beam on Dec. 4, 2004
  - Around the clock operations on March 14, 2005
  - Target problems April 2005
  - Have resumed operations in Mixed-Mode antiproton stacking cycles
- Record throughput for MiniBoone
  - 8.0×10^{16} protons/hour
  - Delivered a over 6×10^{20} protons in three years of running
- Routine running of Mixed Mode for SY120 with slip-stacking for pbar production
  - A factor of 7 more spill seconds then originally allocated
  - Now, a long flattop ramp keeps most of the spill-seconds intact.



Summary

- Since June 2003, the Tevatron has seen a 3-fold increase in:
  - Peak luminosity
  - Integrated luminosity per week
  - Total integrated luminosity
- Luminosity increase is mostly due to:
  - Better performance of the injector chain
  - Introduction of the Recycler into operations
  - Alignment of the Tevatron
  - Decision to "run" the Collider
    - Rigorous approach to attacking operational problems
    - Focused study philosophy
- The Run II Upgrades are on track to provide over 8fb^{-1} by the end of 2009
  - The Recycler is operational
  - Electron cooling is commissioned and operational!
  - Slip Stacking is operational
- The major challenge left in Run II is the increasing the antiproton production rate
  - AP2- Debuncher aperture upgrade
  - Debuncher to accumulator transfers
  - Rapid transfers between the Accumulator and Recycler