Fermilab
Tevatron Operational Status

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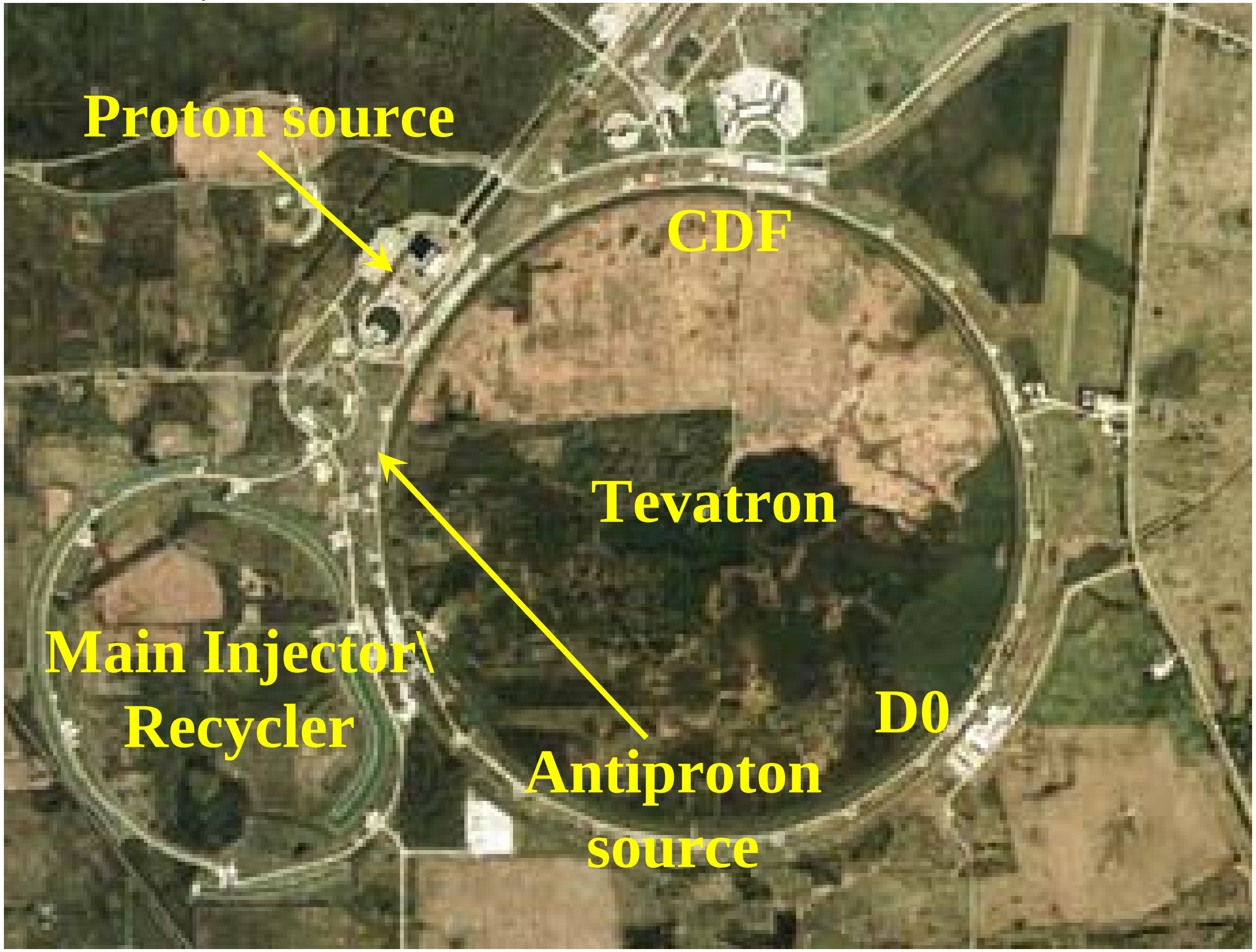
Fermilab Complex

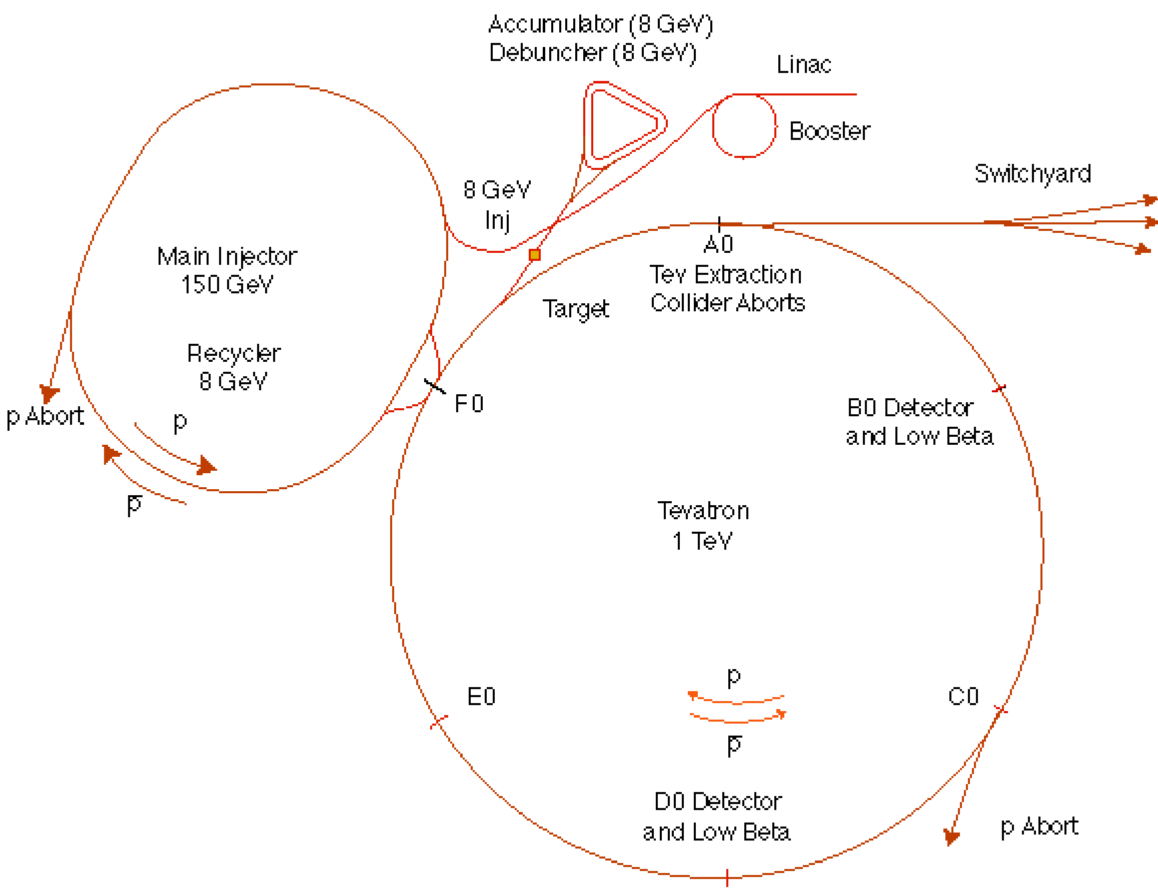
- The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV



Proton Acceleration

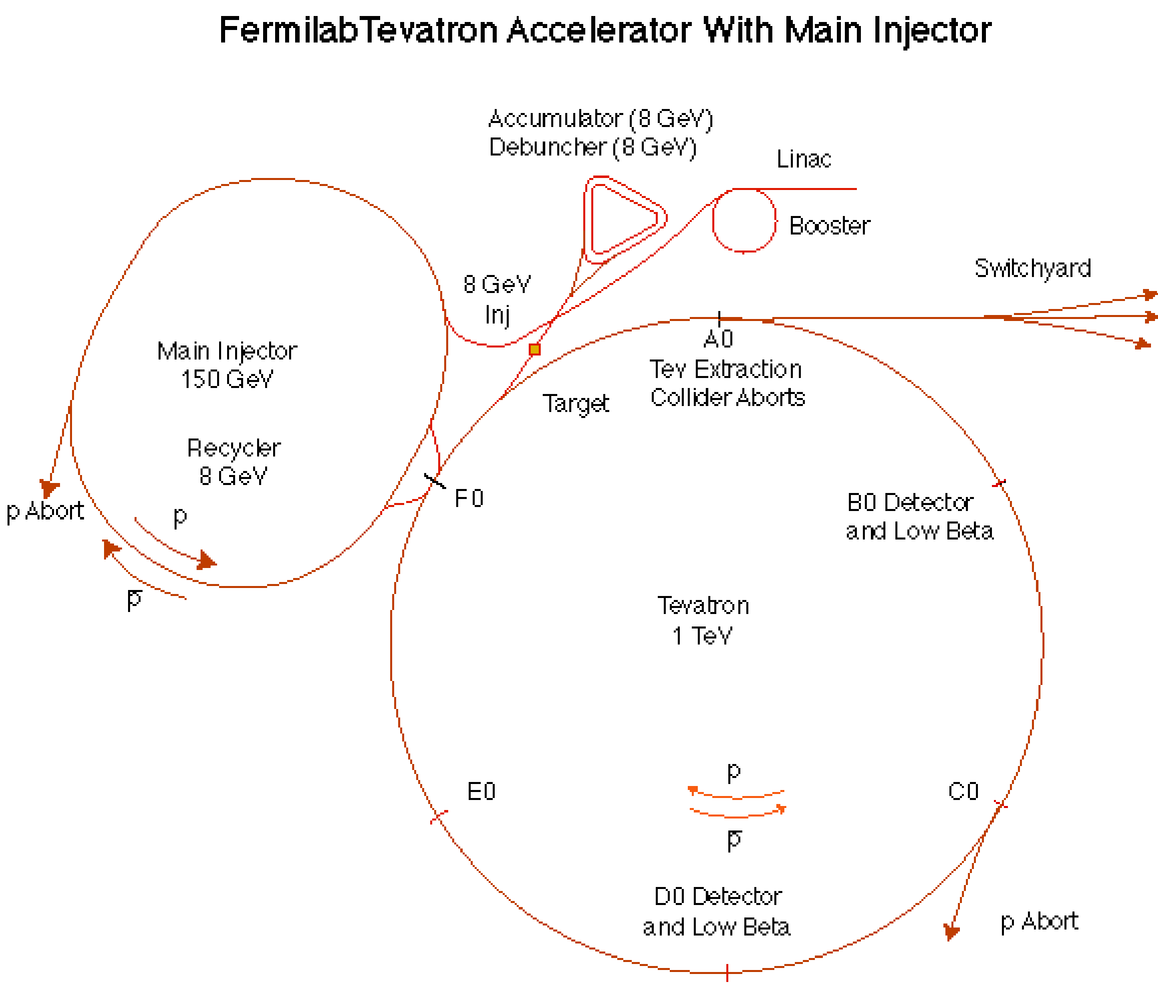
- H- ions are accelerated to 750 keV in the Crockoft-Walton
- H- ions are accelerated to 400 MeV in the Linac
- H- ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 mS in the Booster
- In the Main Injector Protons are accelerated from 8 GeV
  - 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 TEV

Fermilab Tevatron Accelerator With Main Injector



Antiproton Production

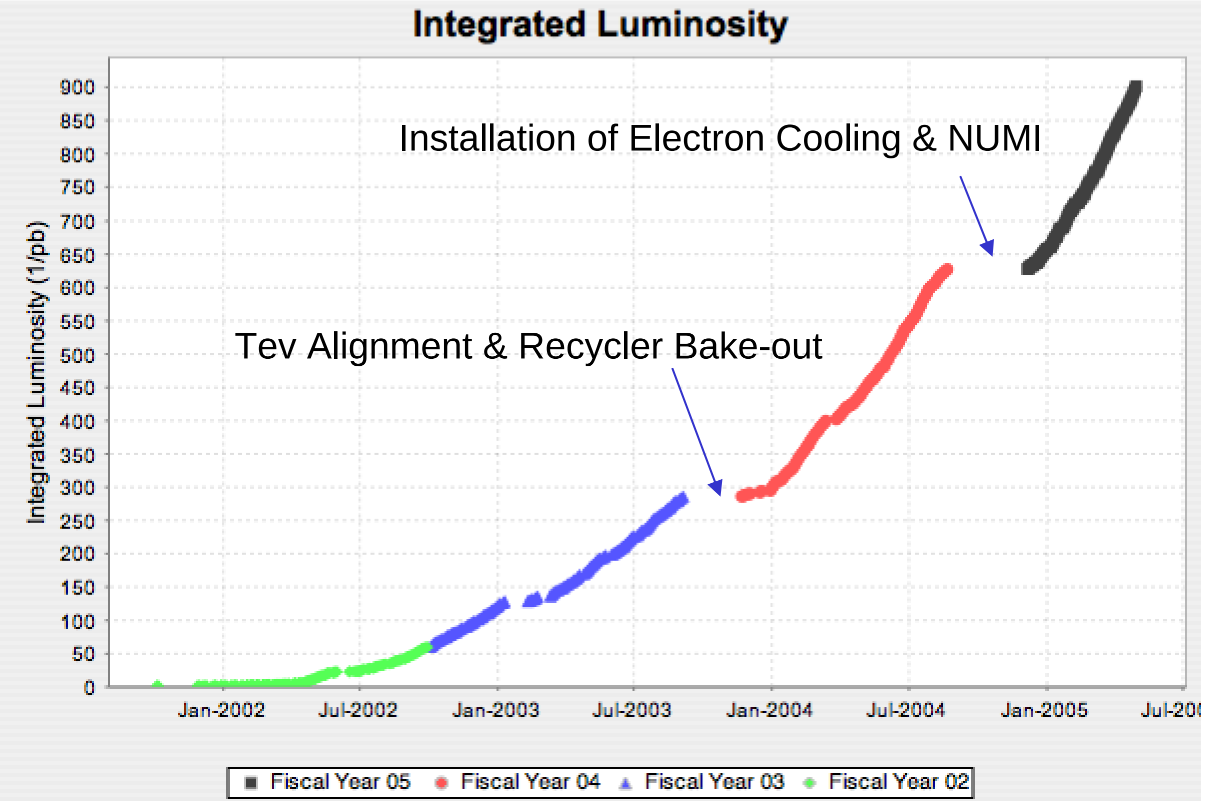
- $1x10^8$ 8 GeV pbars are made every 2-4 seconds by smashing $7x10^{12}$ 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator 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



Collider Parameter Table

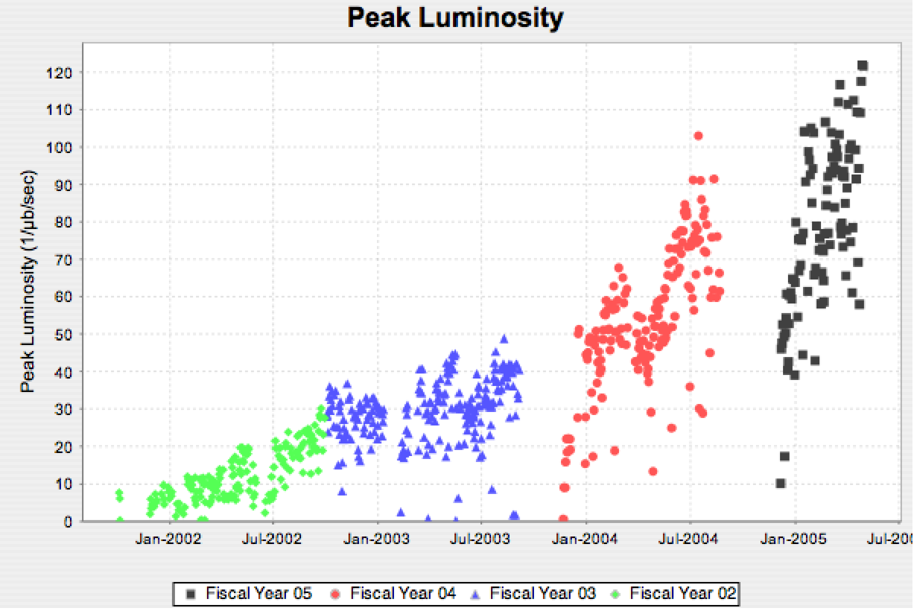
	Luminosity Parameters				
Parameter	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY End Goal (Design)	
Initial Luminosity	121.8	98.1	113.7	96.1	$x10^{30}cm^{-2}sec^{-1}$
Integrated Luminosity per Store	4806	4066.6	3977.5	3369	nb^{-1}
Luminosity per week	-	19	-	16.8	pb^{-1}
Store Length	27.3	29	24.4	20	Hours
Store Hours per week	-	135.5	-	100	Hours
	TEVATRON Parameters				
Parameter	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY End Goal (Design)	
Energy	978	978	978	978	GeV
β*	35	35	35	35	cm
Number of interaction regions	2	2	2	2	
Number of antiproton bunches	36	36	36	36	
Bunch spacing	396	396	396	396	nS
Protons per bunch	243.1	238.5	237.2	260	$x10^{9}$
Antiprotons per bunch	42.8	35.5	41.1	42	$x10^{9}$
Proton Efficiency to Low Beta	62.4	57.9	55.9	-	%
Pbar Transfer efficiency to Low Beta	68.1	62.3	60.9	76	%
HourGlass Factor	0.66	0.67	0.66	0.65	
Effective Emittance	13.9	14.3	14	18.5	π-mm-mrad
	Antiproton Parameters				
Parameter	Best Store	Last 10 Stores (Ave)	Best 10 Stores (Ave)	FY End Goal (Design)	
Zero Stack Stack Rate	13.4	14.8	14.6	24.5	$x10^{10}$/hour
Normalized Zero Stack Stack Rate	2.2	2.3	2.3	3.1	$x10^{-2}$/hour
Average Stacking Rate	6.3	7.2	7.3	10.1	$x10^{10}$/hour
Stacking Time Line Factor	60.6	63.7	67.3	75	%
Stack Size at Zero Stack Rate	382.5	364.1	359.2	300	$x10^{10}$
Protons on Target	6.2	6.3	6.2	8	$x10^{12}$
Start Stack	266.3	219.7	260.8	216	$x10^{10}$
End Stack	40.5	31.2	42.6	15	$x10^{10}$
Unstacked Pbars	225.8	188.5	218.2	201	$x10^{10}$

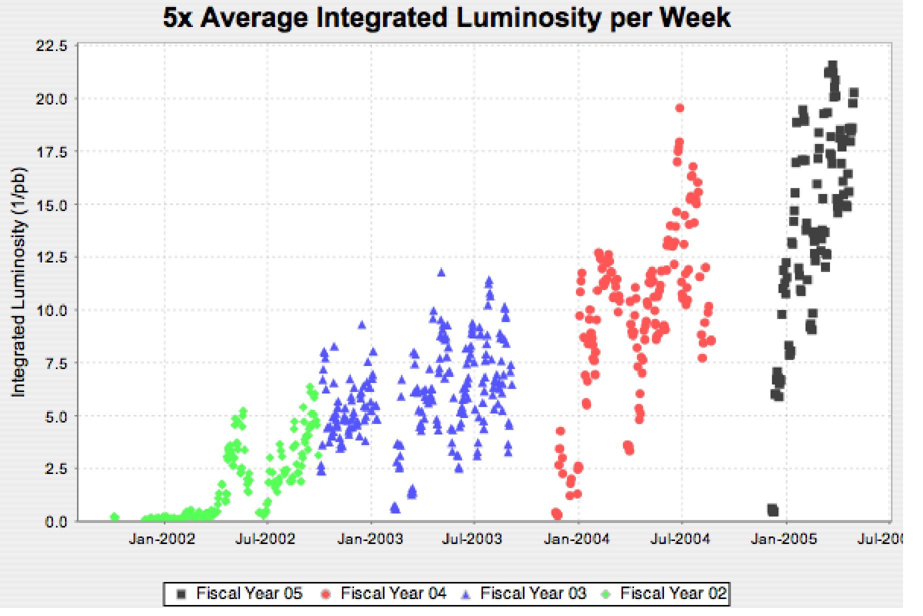
Integrated Luminosity



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

Luminosity History





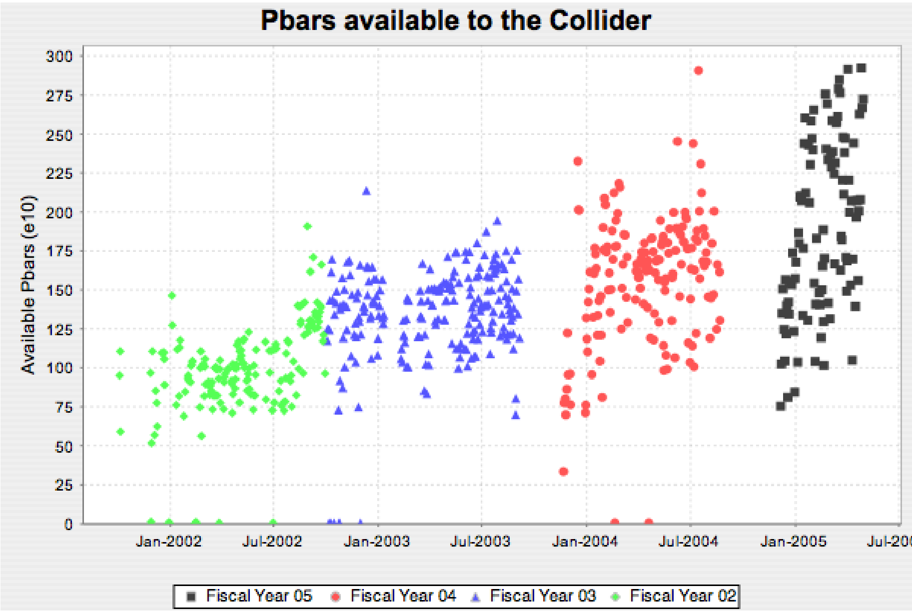
- Luminosity increase is mostly due to:
  - Better performance of the injector chain
  - Introduction of the Recycler into operations
  - Alignment of the Tevatron
  - Decision to "run" the Collider
    - Rigorous approach to attacking operational problems
    - De-emphasis of long periods of dedicated machine studies

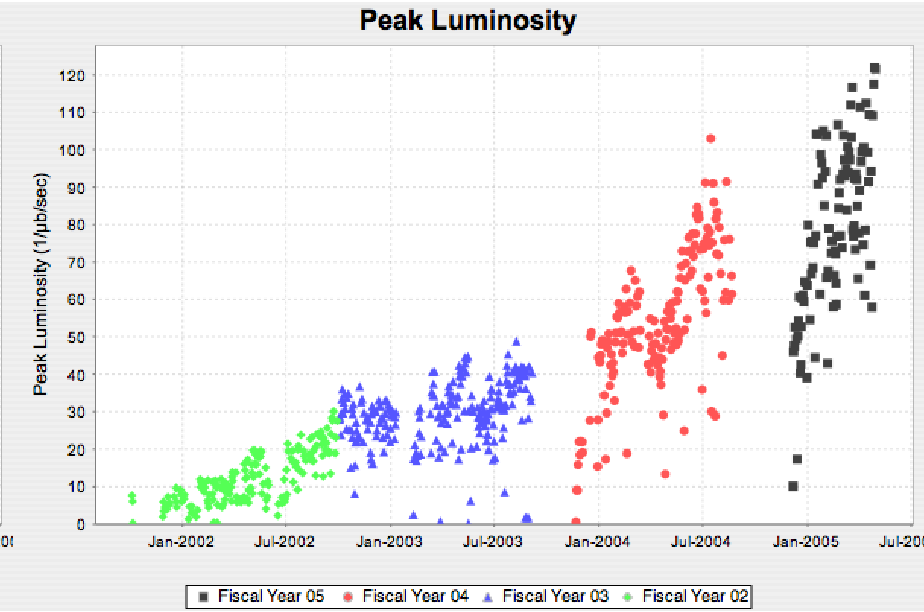
Luminosity

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

- 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 to 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

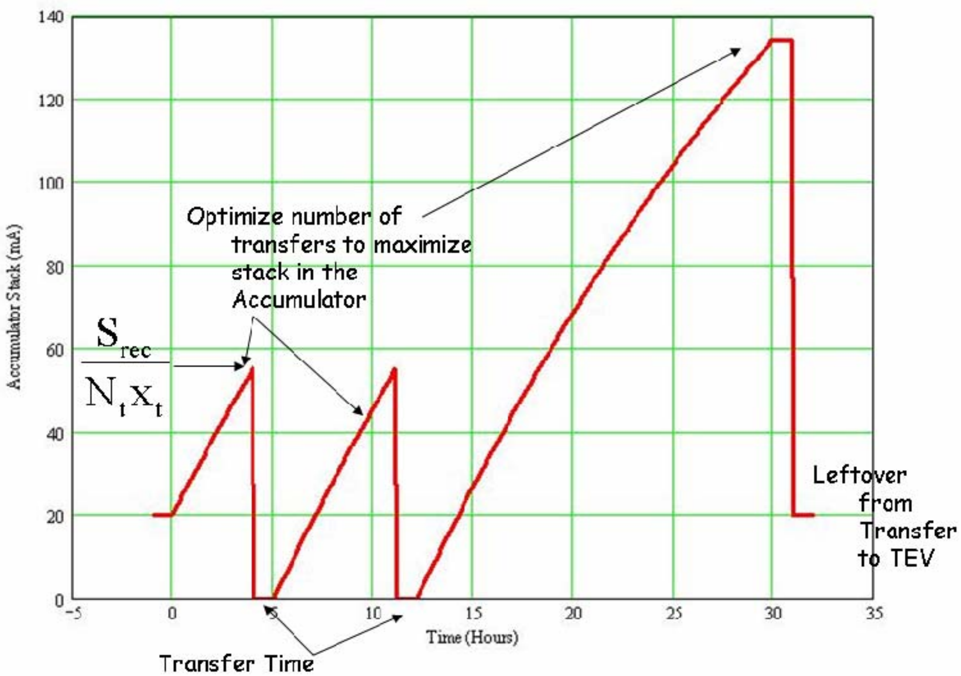
The Recycler

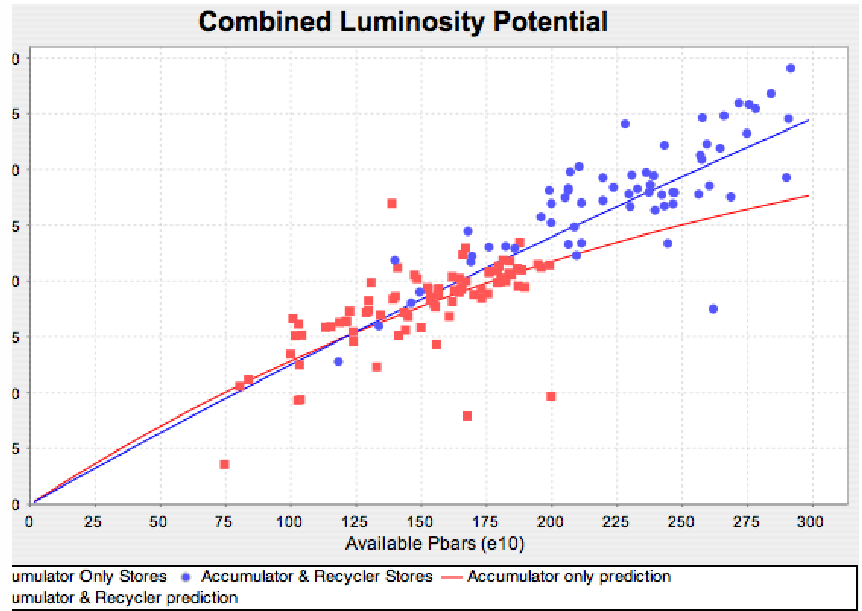
- Features
  - Designed to a be a third stage antiproton accumulator ring
    - Initially uses stochastic cooling
    - Eventually will use electron cooling
  - Shares the same tunnel as the Main Injector
  - Major magnetic elements are made from permanent magnets
- At the end of August 2003
  - The 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
  - Stand alone Recycler shots to the Tevatron (Jan. '04)
  - Stack of >150×10^{10} pbars in the Recycler
- Using the Recycler in "Combined Shots" operations makes it a luminosity enhancement
- Recycler is ready for Electron Cooling

Combined Shots

- Extracting antiprotons from both the Accumulator and the Recycler for the same store i.e.
  - Twelve bunches from the Recycler
  - Twenty four bunches from the Accumulator
- Combined Shot Operation
  - Proposed in February '04 by Brian Chase
  - Initial proposal presented at the April '04 Run II PMG
  - 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
    - $127 \times 10^{30} cm^{-2} sec^{-1}$ recorded May 2005
  - Routine Operations - January 2005
- 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
- Ratio $I_{Recycler}/I_{Accumulator}$ is governed by:
  - Recycler phase space density (cooling)
  - Recycler transfer time (Rapid transfers)
- 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





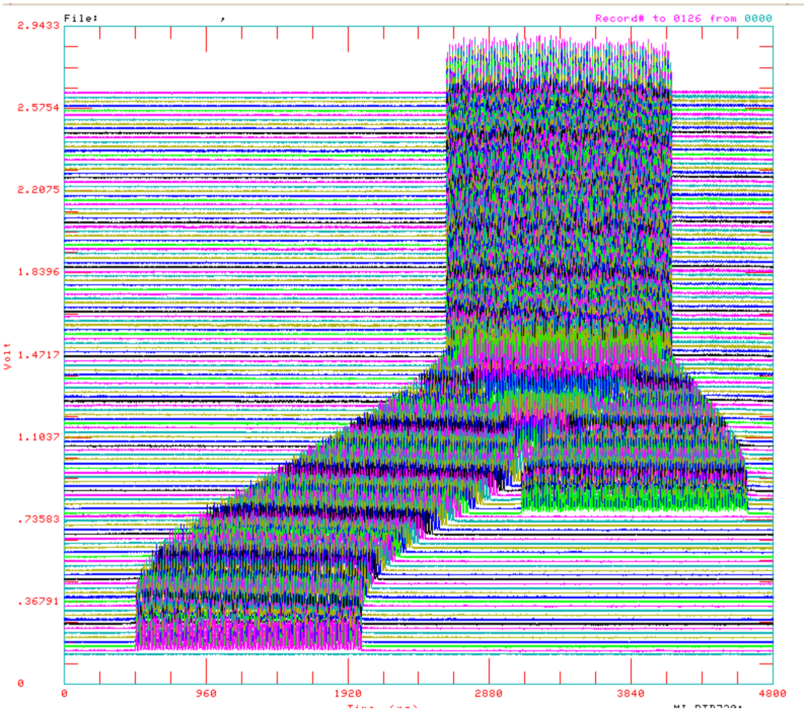
- Luminosity enhancement – larger amount of antiprotons for smaller emittances
  - Accumulator stack size limited to <200 mA
    - Stacking Rate
    - Transverse emittance vs Stack Size

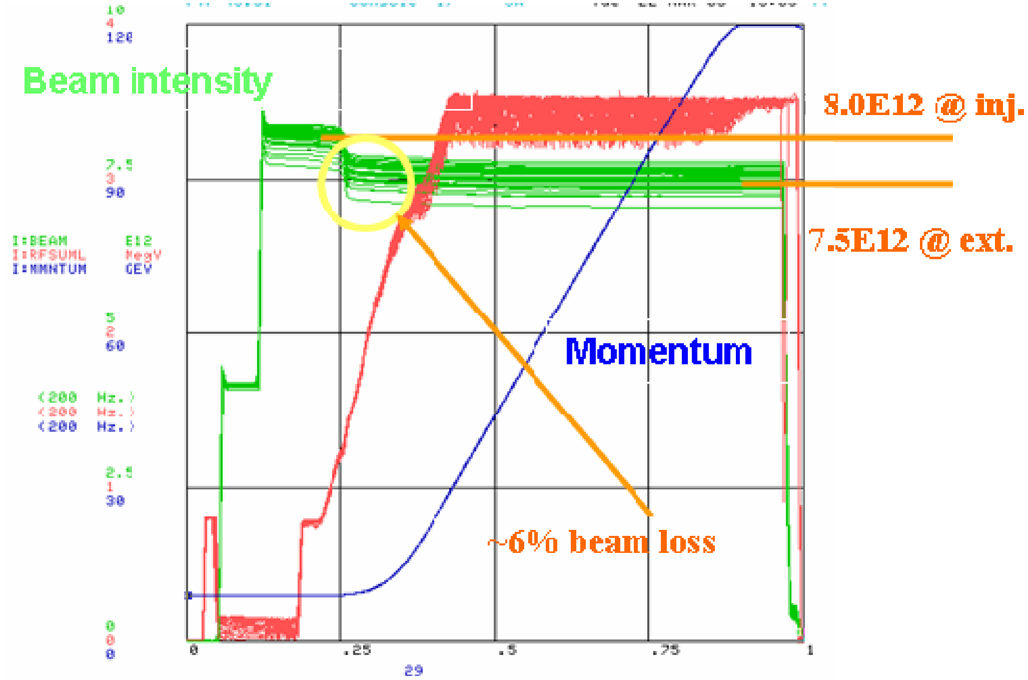
Electron Cooling

- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is to be replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency
- Installation of e-cool equipment in MI-31 and the Recycler tunnel complete
- Commissioning of electron cooling in progress
  - Electron beam circulated in cooling section
  - Commissioning due to be completed by September 2005

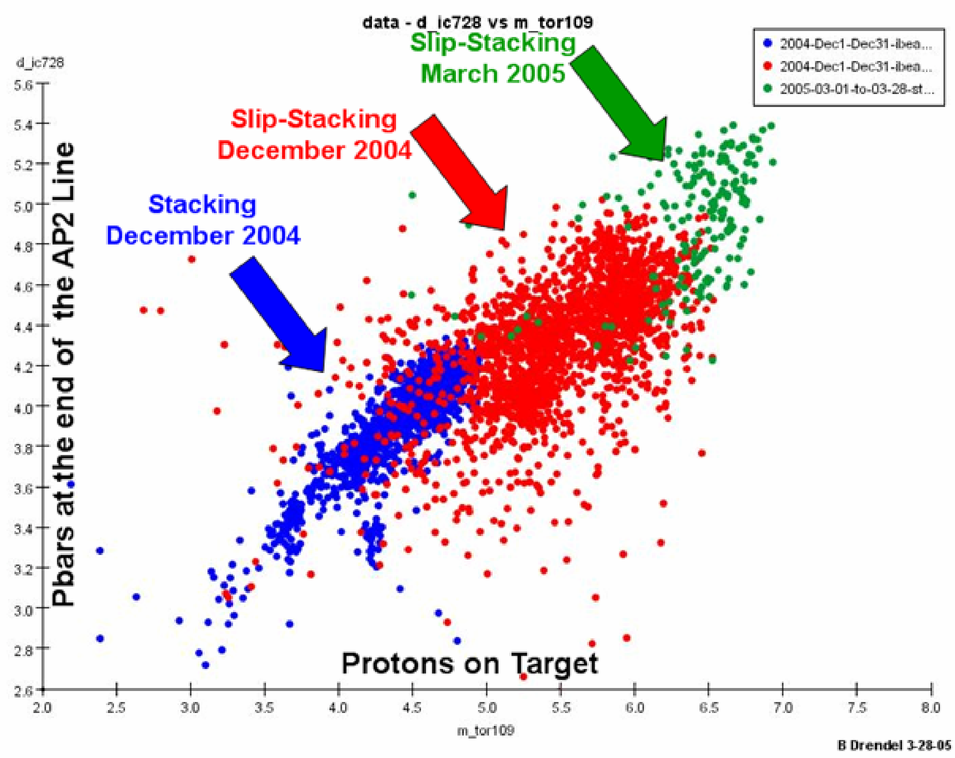
Antiproton Production - Slip Stacking

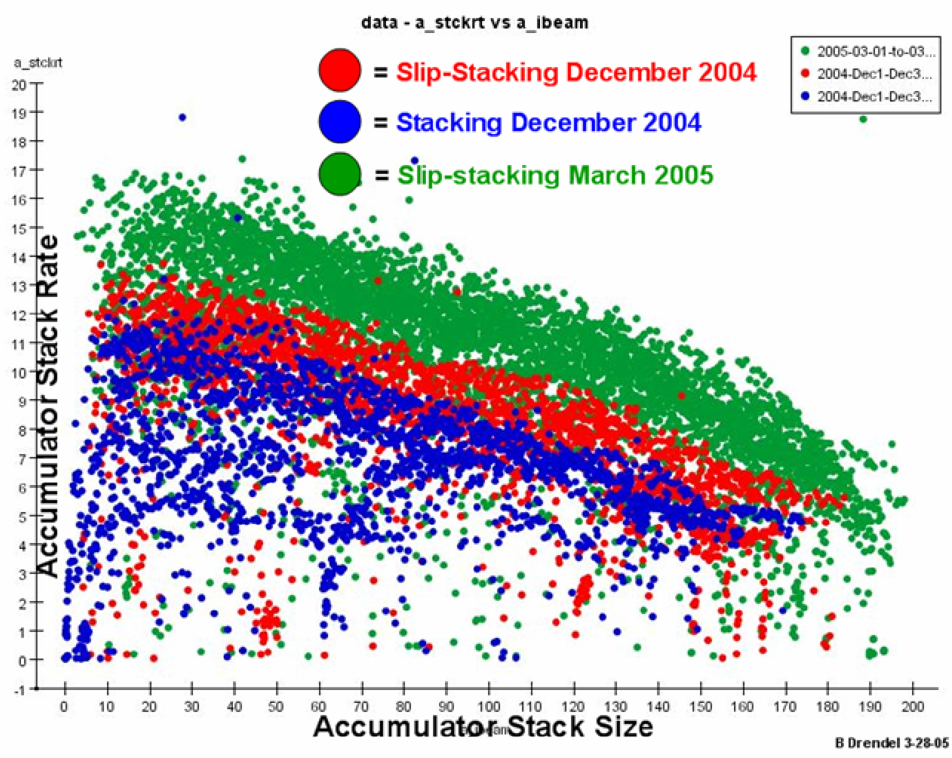
- Slip Stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target





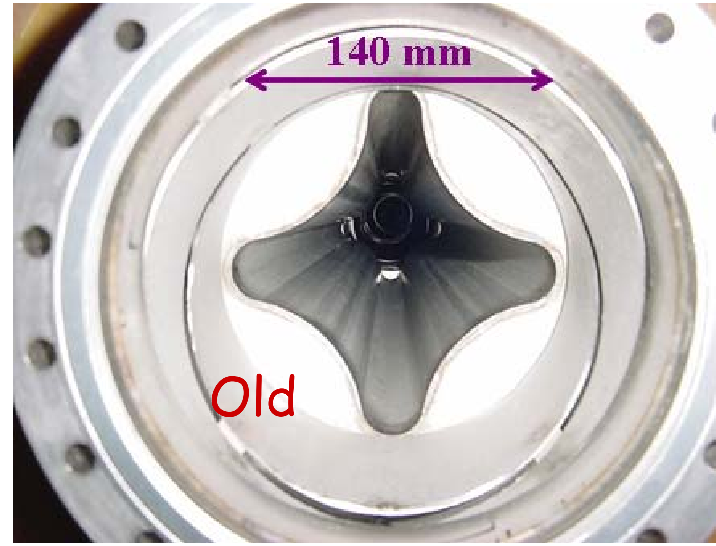
Antiproton Production - Slip Stacking





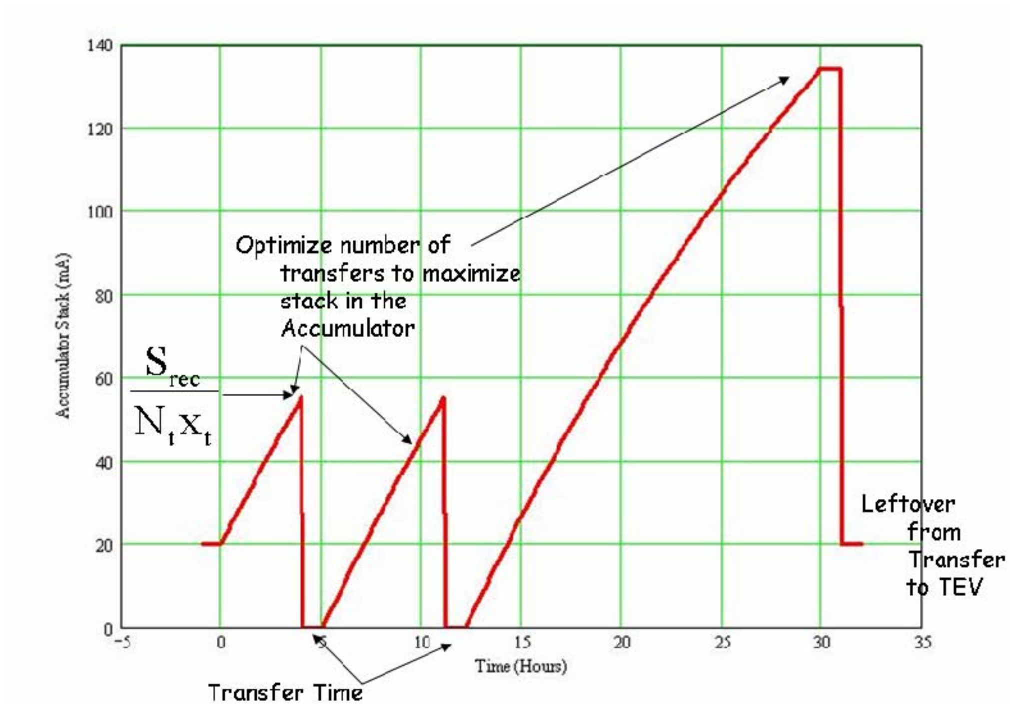
Antiproton Aperture - Pbar Production

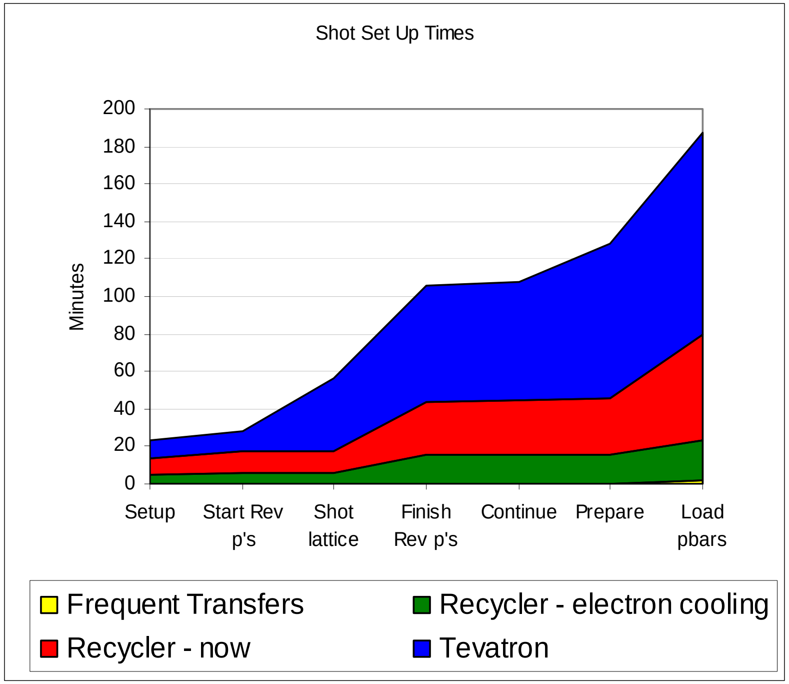
- The measured aperture of the initial stages of the antiproton production chain is about 70% of the available physical aperture.
- An aggressive beam-based alignment program is under development to bring the measured aperture to the physical aperture.
  - Would increase the stacking rate by a factor of 2
- 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 plan to 78% of the available physical aperture which would result in a 25% increase in antiproton production rate



Accumulator to Recycler Antiproton Transfers

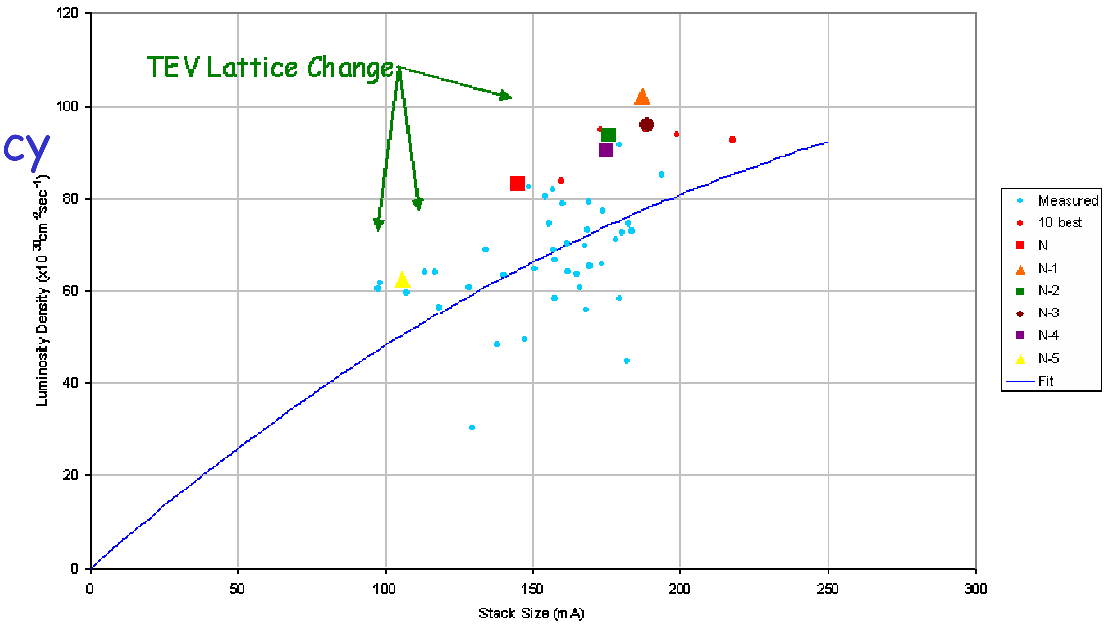
- Transfers between the Accumulator to the Recycler take about 1 hour to accomplish
  - Transfers frequency every 6-8 hours
- To realize the full potential of electron cooling, in the Recycler, this time needs to be reduced to less than 15 minutes
- Adopt a philosophy of being willing to lose a pbar transfer occasionally
  - Transfers frequency faster than every 2 hours





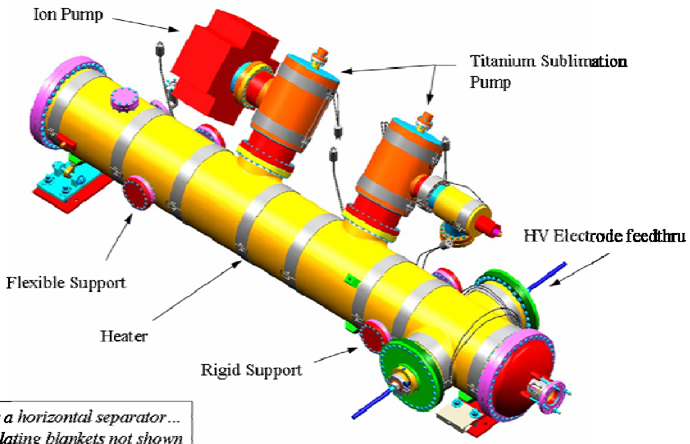
Tevatron Major Accomplishments

- 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

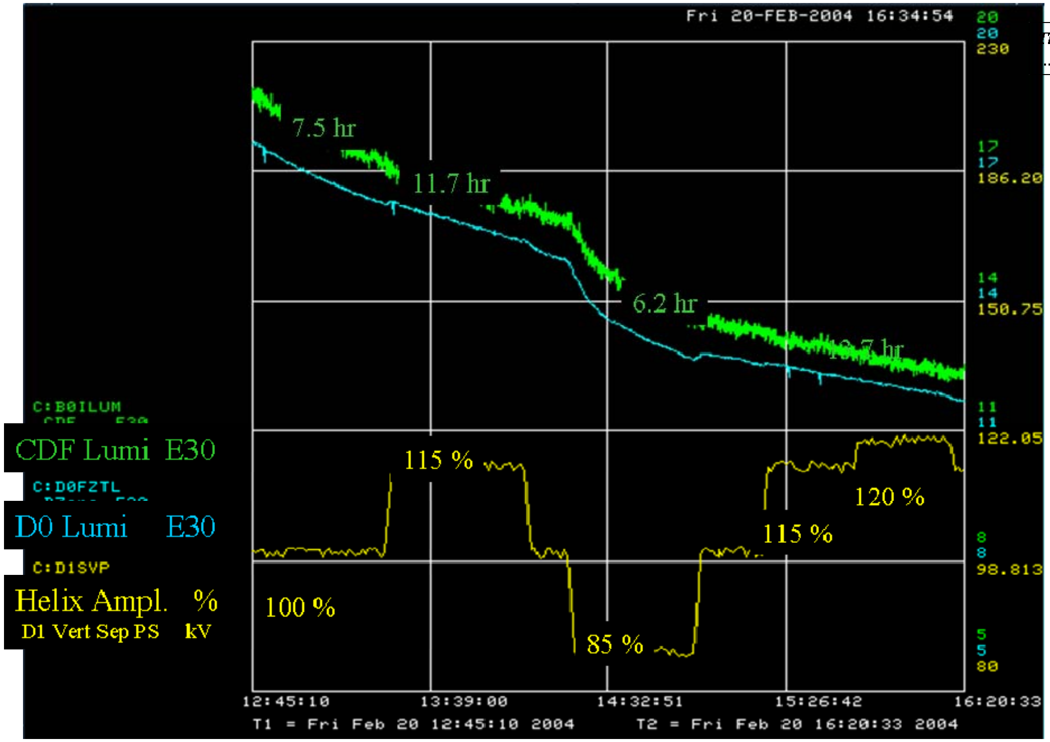


Tevatron Helical Orbit Separation

- More separators
- Higher separator voltage
  - Separator R&D
- Different separator configuration
  - Polarity switches

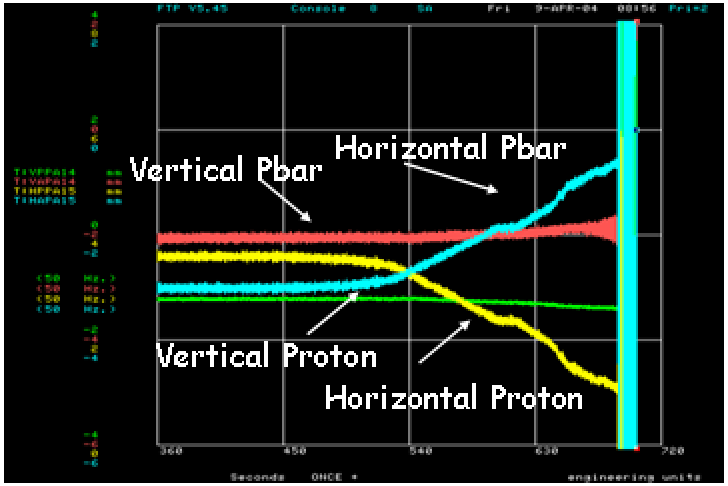


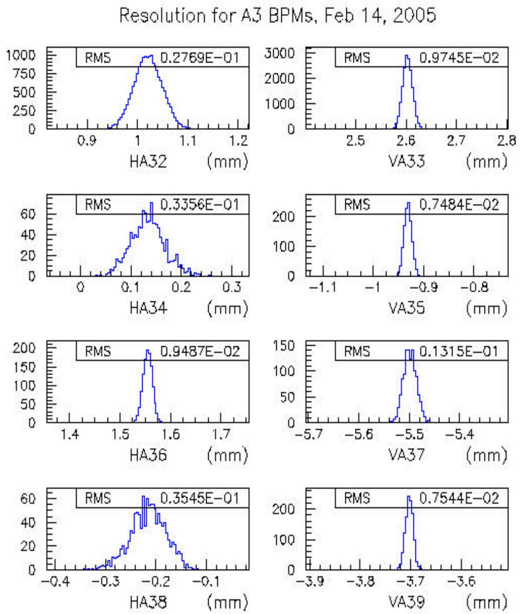
This is a horizontal separator…
…insulating blankets not shown



Tevatron Instrumentation

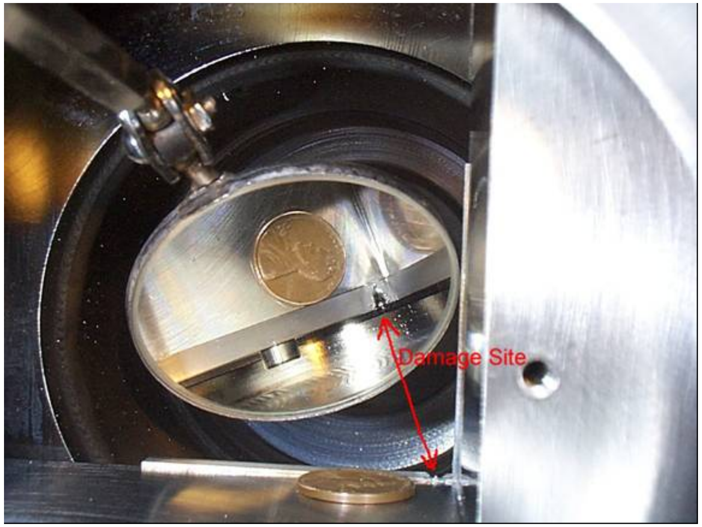
- Tevatron BPM Project
  - Joint CD/AD effort
  - A major success
  - Project making very good progress though completion date has slipped by a few months
  - An order of magnitude improvement in proton position measurements and new for pbars
  - Position resolutions in the range of ~10 - 25 μ
  - Will be extremely useful in understanding beams
    - Can see synchrotron and betatron lines, quadrupole oscillations, H-V coupling, etc.
  - 85% installed
    - ~ 50% connected/ commissioned
- New Beam loss monitor system
- New Ion Profile Monitor

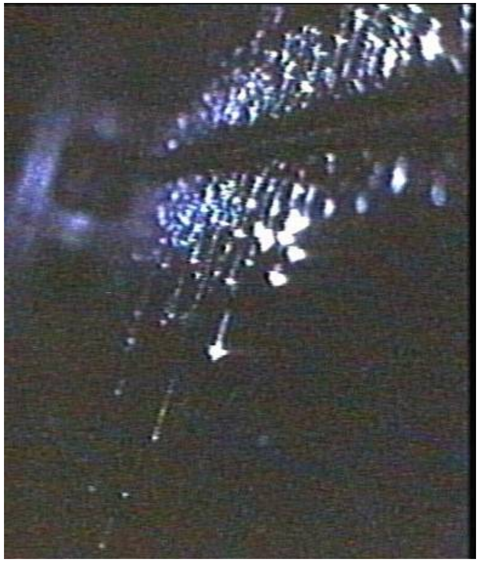




Tevatron Beam Power

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



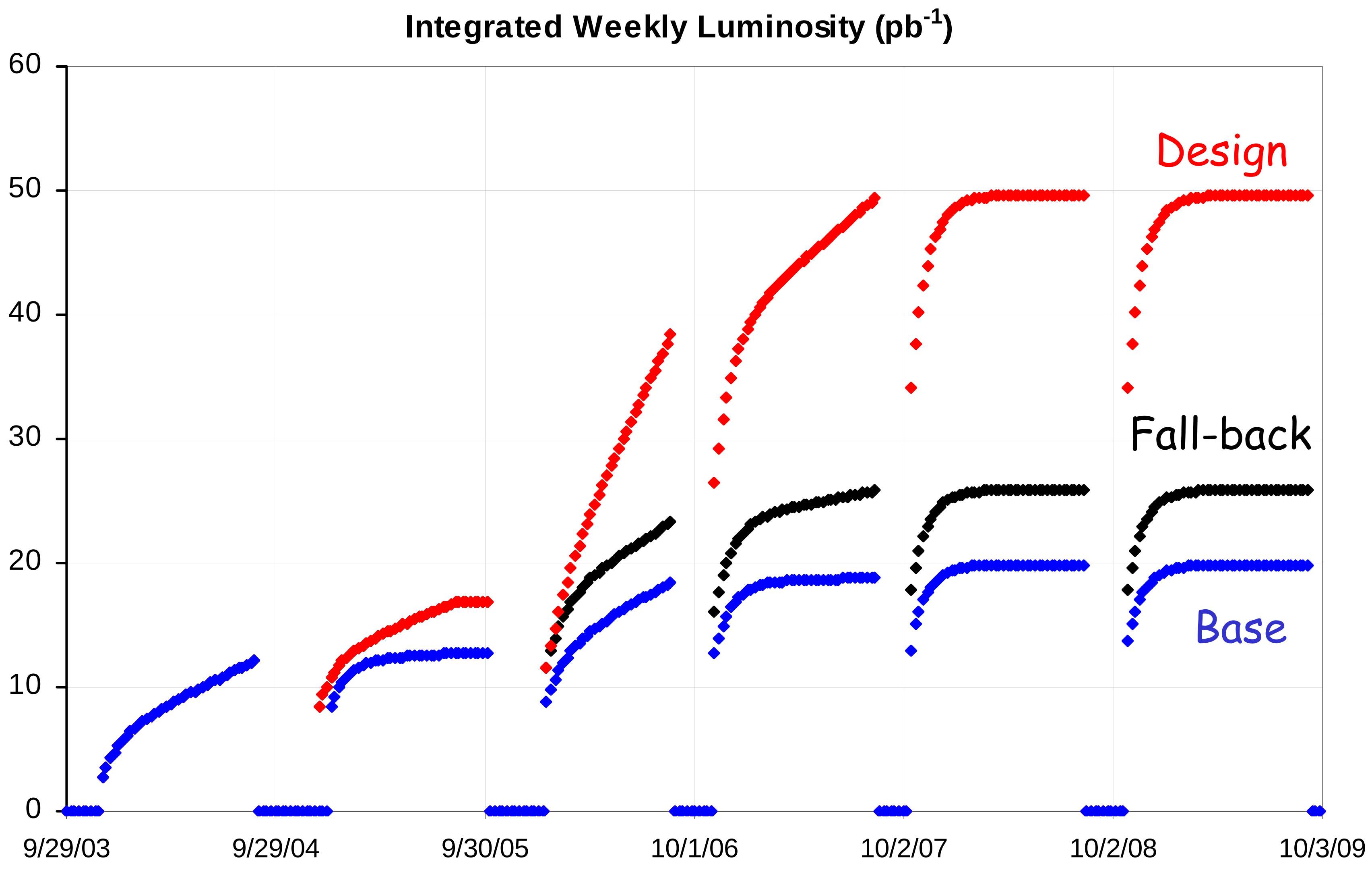


- Proton Beam Current
  - Luminosity is proportional to the number of protons **per bunch** (N_p)
  - The proton beam current is proportional to BN_p
- Fast Beam Loss - can cause serious damage to the detector or the accelerator
  - Run II example: fast beam loss incident initiated by misbehavior of roman pot → losses → fast trip of correctors →beam mis-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

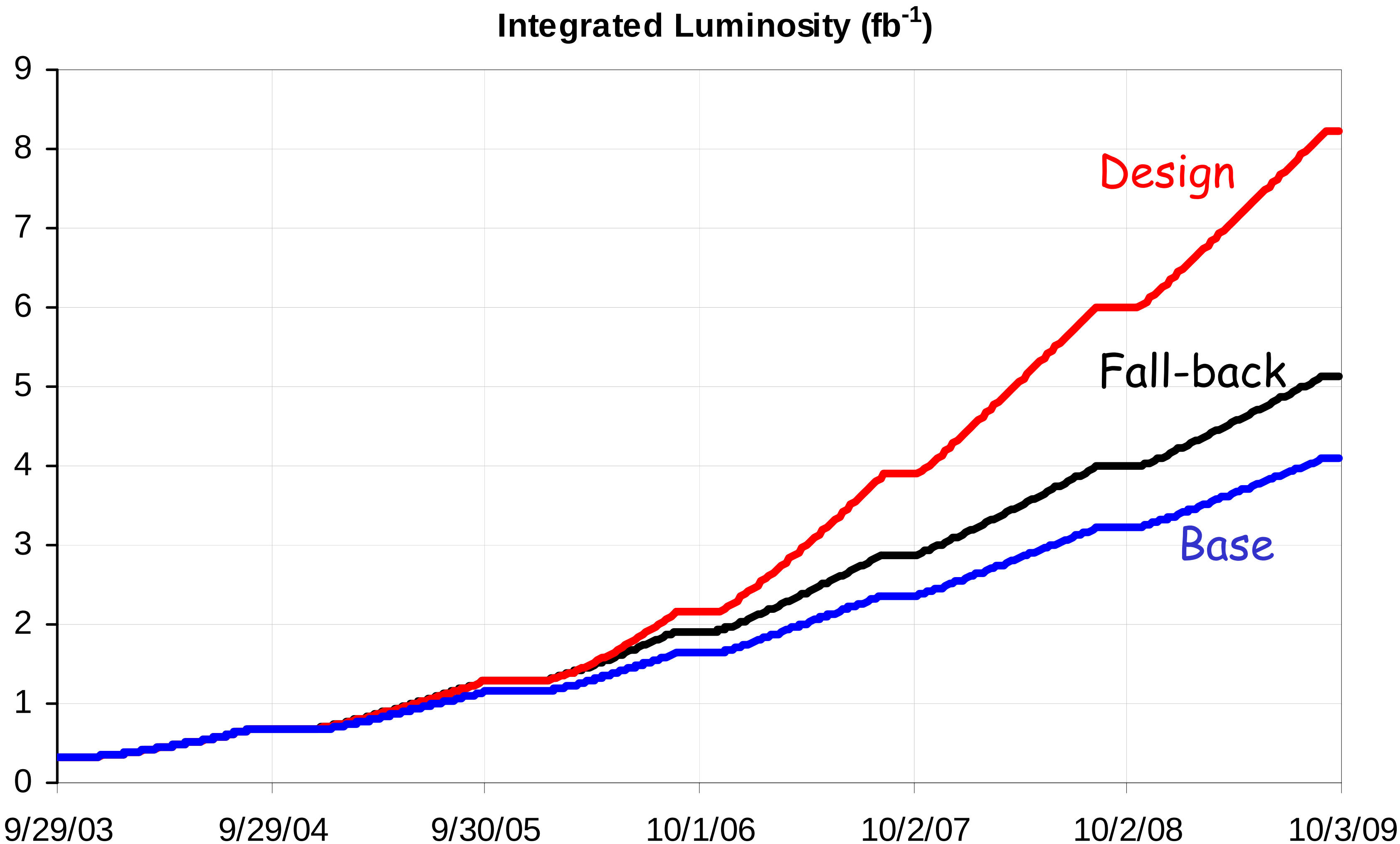
Luminosity Projections

- Our plan is to deliver the design projection,
  - but, develop an understanding of fallback scenarios
  - Combined-source operation and the phased Stacktail upgrade allow more natural introduction of key upgrades (e-cooling and Stacktail upgrades) and provide a more robust fall-back position
- Luminosity Scenarios
  - Design Projection: Electron cooling and Stacktail upgrade
  - Fall-back Projection: no Electron cooling, Combined-source operation beyond 05 (20% gain), Deb→Acc acceptance issues solved
  - Base Projection: no electron cooling, Deb-Acc acceptance only minor improvements and no gain from mixed-source
  - All assume slip stacking and 100 HEP hrs per week average long-term

Weekly Luminosity Projection



Integrated Luminosity



Other Business - Fixed Target FY05 Accomplishments

- Record throughput for MiniBoone
  - 8.0×10^{16} protons/hour
  - Delivered a over 5×10^{20} protons in under 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
  - As NUMI takes the place of SY120 on the antiproton stacking cycles, a new long flattop ramp will keep most of the spill-seconds intact.
- 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

Summary

- Since the last Particle Accelerator Conference in 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
    - De-emphasis of long periods of dedicated machine studies
- The Run II Upgrades are on track to provide over 8fb^{-1} by 2009
  - The Recycler is operational
  - Electron cooling is progressing well
  - 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
  - Stacktail Momentum cooling uprade
  - Rapid transfers between the Accumulator and Recycler