Fermilab

Tevatron Operational status and Possible Lessons for the LHC

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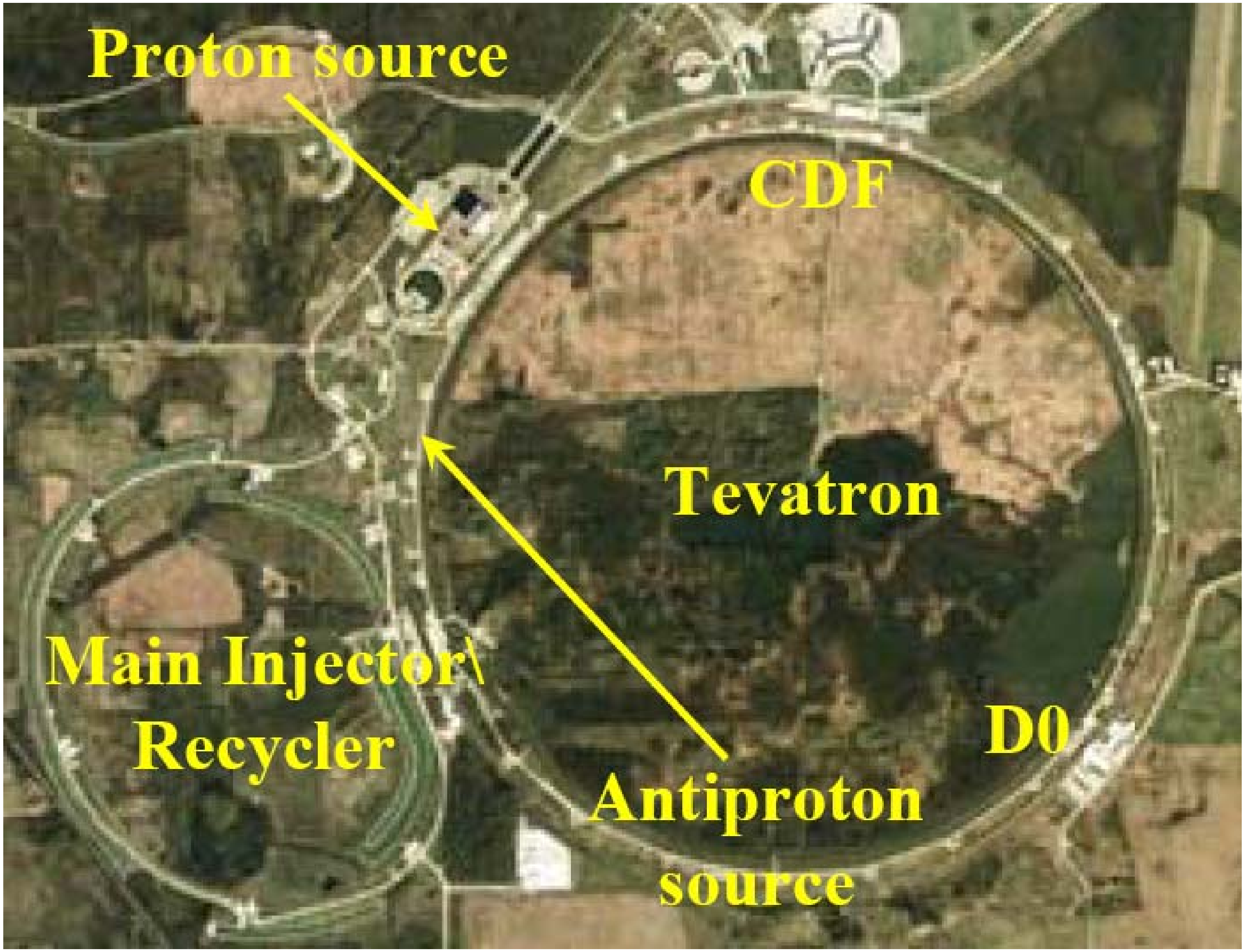
June 26-30, 2006, Edinburgh, Great Britain

Contents

Tevatron is a $P-\bar{P}$ Collider Operating at 980 GeV



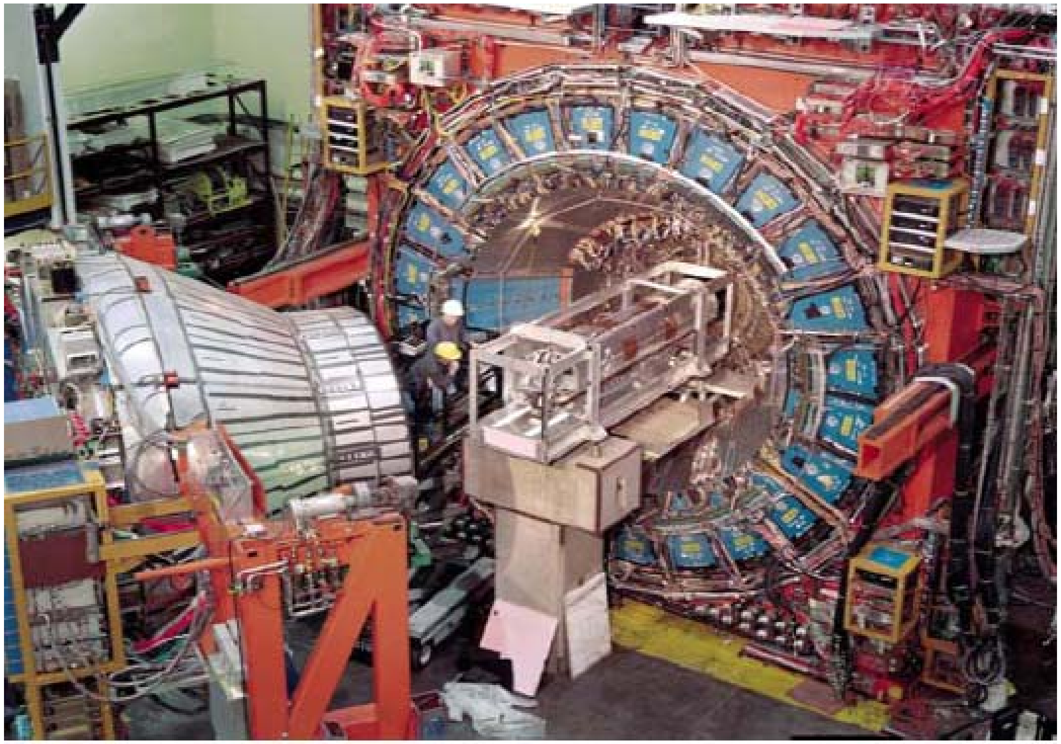
- H^- source, 35mA
- Electrostatic accel. 750 keV
- Linac, 0.4 GeV
- Booster, 0.4–8 GeV
- Main injector, 8-150 GeV
- Debuncher, 8 GeV
- Accumulator, 8 GeV
- Recycler,8 GeV
- Tevatron, 980 GeV

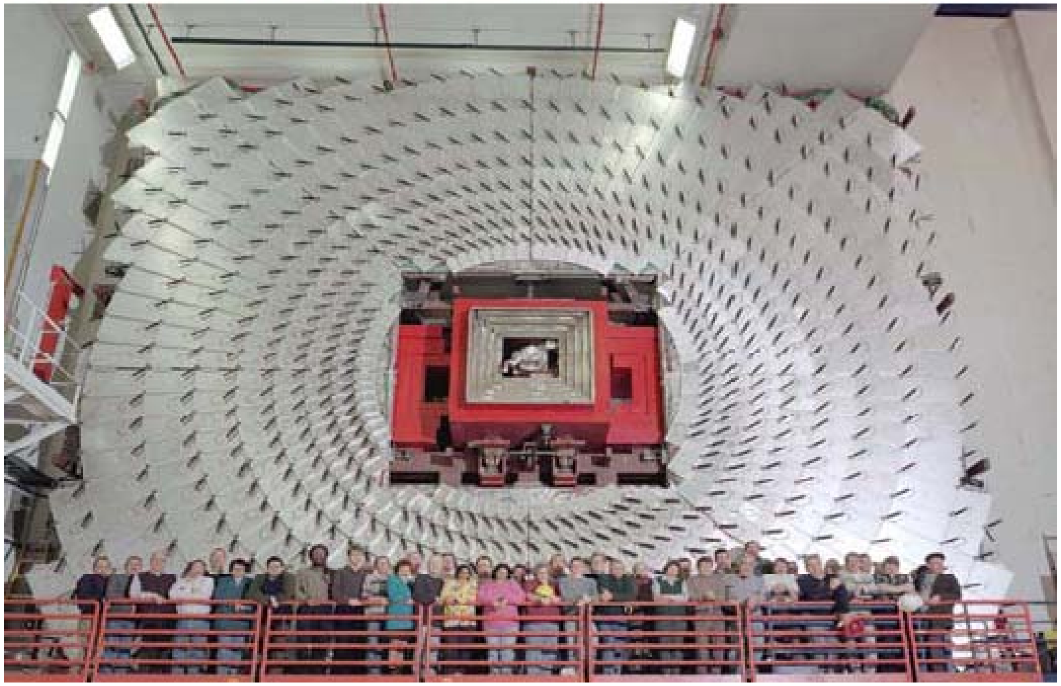
Present status

Complex just came out of 3 month shutdown: Feb. 22 – May 25, 2006

Physics Program

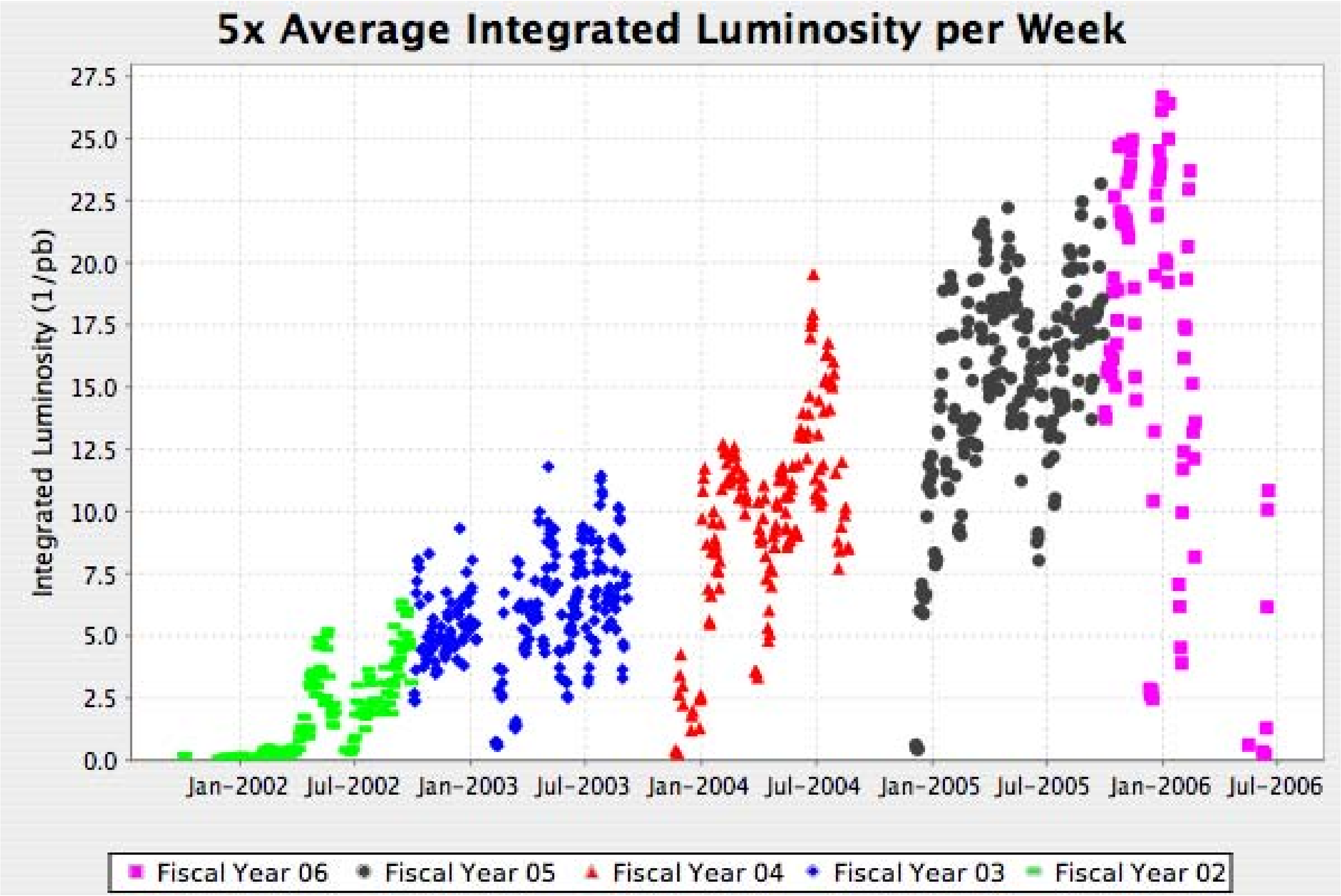
- Highest energy collider
- Two detectors
  - 1500 collaborators + students and postdocs
- The greatest high energy physics before LHC is operational
  - Higgs boson search
  - B-physics
  - Extra-dimensions
  - ...
- Success critically depends on the luminosity growth





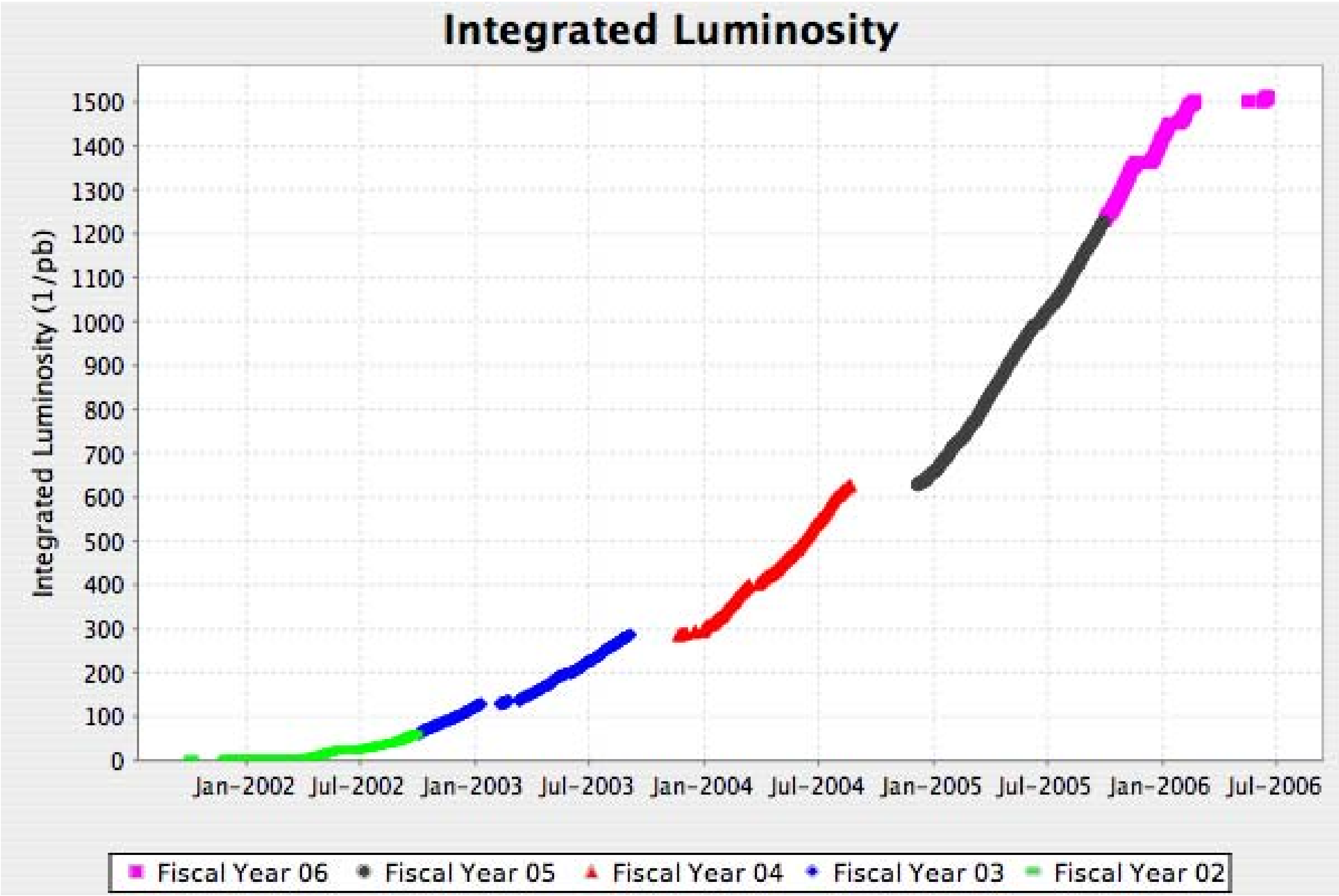
Major Accomplishments FY05-FY06

- Commissioning of Electron Cooling (July 2005)
- Recycler-Only Operations (October 2005)
- Peak Luminosity of $172 \times 10^{30} cm^{-2} sec^{-1}$ (January 2006)
- Average of 2 detectors (CDF - $185 \times 10^{30} cm^{-2} sec^{-1}$)



Major Accomplishments FY05-FY06 (continue)

- Weekly integrated luminosity of 24.4pb^{-1} (December 2005)
- Antiproton Stack of 4.36×10^{12} in the Recycler (January 2006)
- Amount of antiprotons stacked in 1 hour 20.1×10^{10} (February 2006)
- Total Run I I Luminosity Integral is about 1.5 fb^{-1}

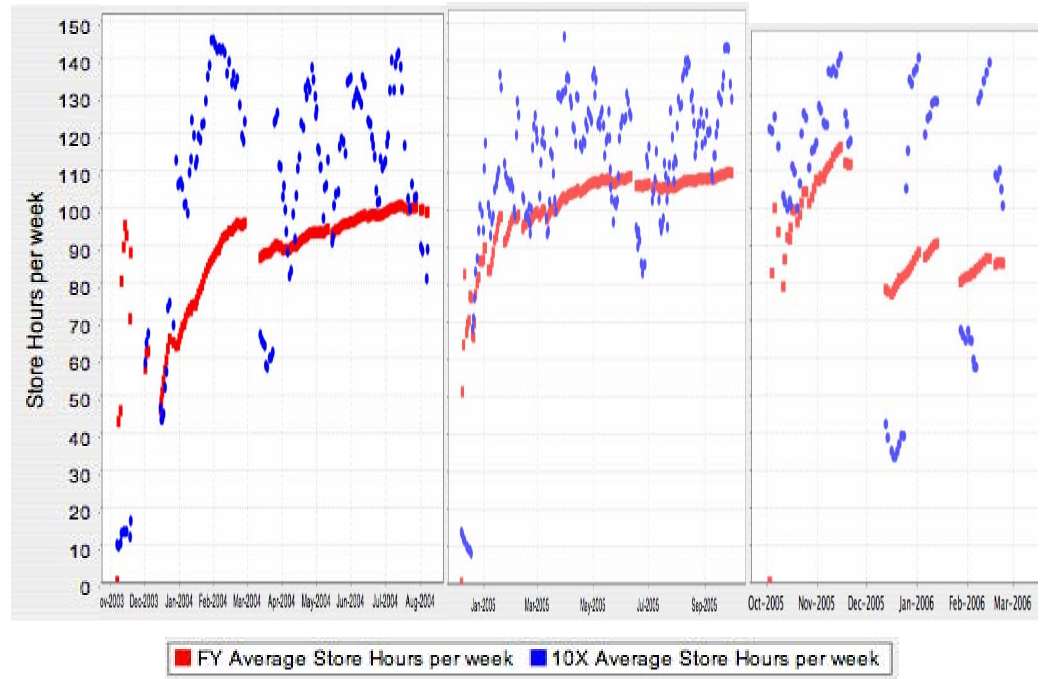


Tevatron Failures

- Major failures of Tevatron magnets
  - 0 in FY05
  - 3 in FY06
    - shortfall of integrated luminosity

Tevatron Component Failures in Run II

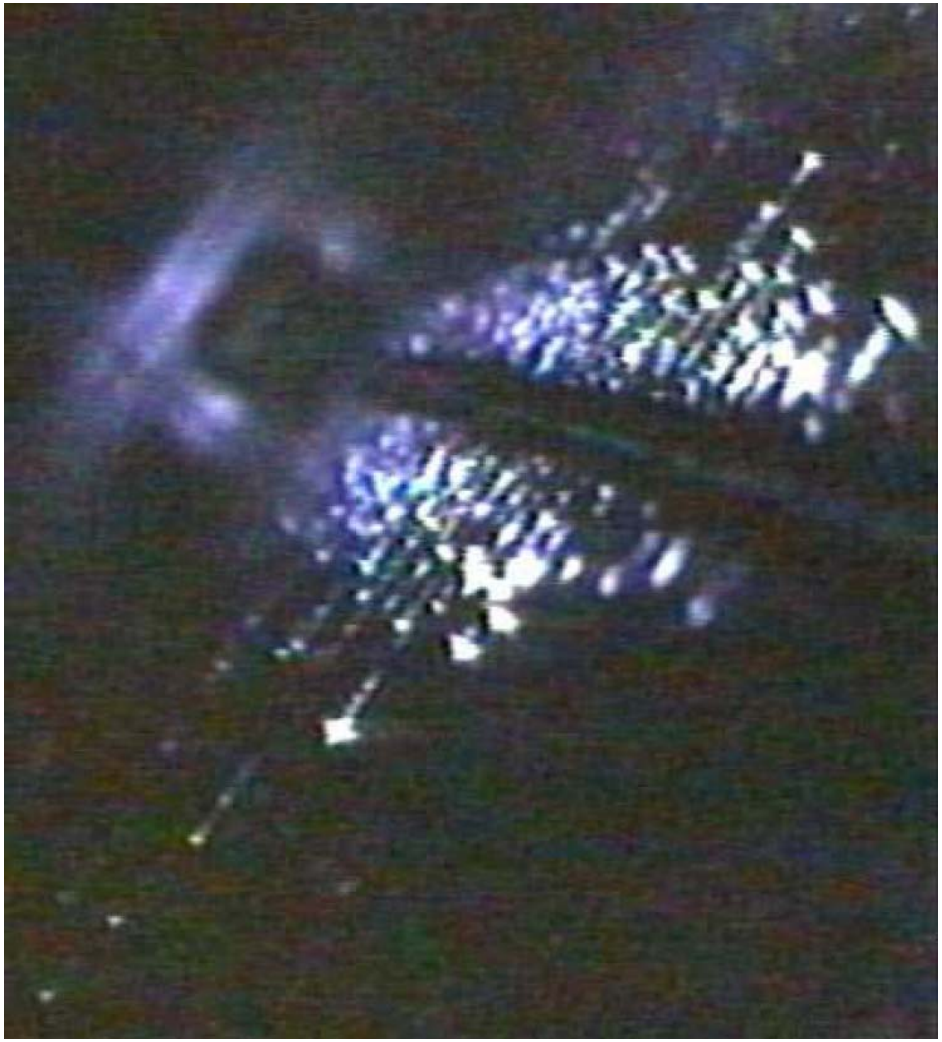
Average store hours per week



FY-2004 *FY 2005* *FY 2006*

Date	Time lost	Description	Sector
29-Apr-01		Cryostat vacuum leak	D13
21-May-01		Helium leak at corrector feed-through	F13
8-Jul-01		Helium leak on spool	F47
18-Aug-01		Helium leak	F44
1-Mar-03	12 days	Safety lead ground fault	A13
5-Dec-03	12 days	Helium leak at corrector feed-through caused by catastrophic beam loss	C19
20-Dec-03	10 days	Cryostat vacuum leak	B14
15-Mar-04	12 days	Helium leak caused	A44
21-Nov-05	3 weeks	Helium leak caused by stuck Kautzky valve	B17
14-Jan-06	2 weeks	Cryostat vacuum leak (air)	A44
22-Feb-06	1 week+s-d.	Helium leak caused by stuck Kautzky valve	F47

Tevatron Failures – (2) Direct Beam Damage



- Beam Accident at Tevatron on December 5, 2003
- 16 of 24 house quench
- Major fraction of 1.5 MJ beam lost in the ring
- Two weeks to repair
- The reason of the massive quench was found to be caused by a CDF Roman Pot reinserting itself back into the beam after it was issued a retract command.
- Analysis of the quench data and collimator damage allowed us to restore a detailed sequence of events and quantitative characteristics of the accident
- See details in Nikolai Mokhov report at HB-2006 (Tsukuba)

Tevatron Failures – (3) Tevatron Quenches

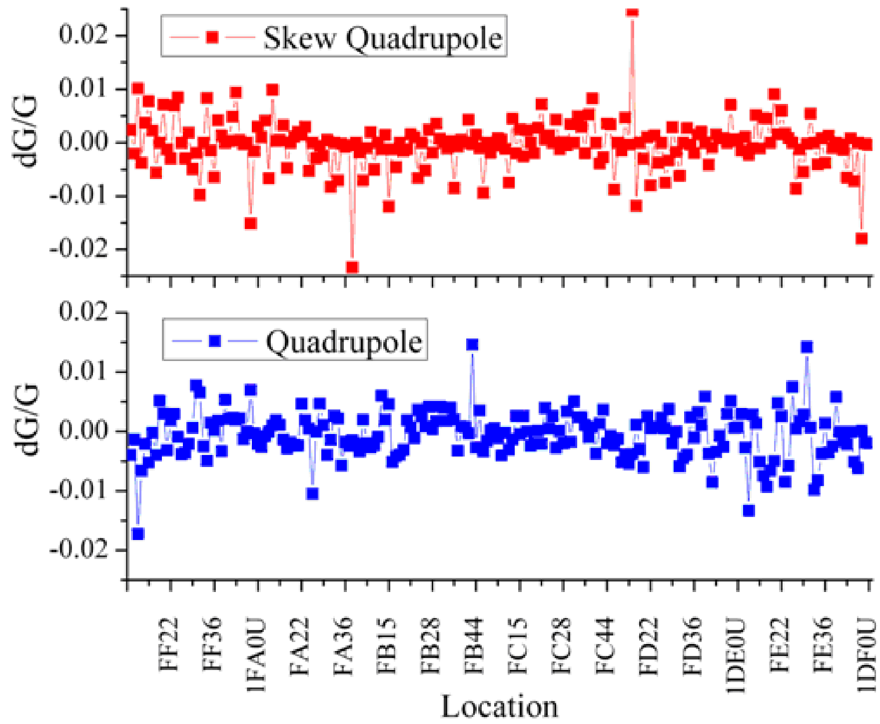
- All three Tevatron magnet failures in FY 2006 were induced by components that failed to operate properly during “mild” quenches
  - Mild quench –10-15K magnet temperature, < 1 hour recovery
  - Major quench –100k magnet temperature, multi-hour recovery
- Two of the magnet failures were the result of failed “Kautzky”(pressure relief) valves.
  - We view this as a systematic failure
  - We replaced the failed part in all of the Tevatron Kautzky valves (~1200) during this shutdown
- We also repaired all known cold leaks (F4, E2, A3, B4)

Tevatron Improvements

- Completed Tevatron BPM system installation and commissioning
  - An order of magnitude improvement in proton position measurements
  - Pos. measurements for antiprotons
  - Position resolutions in the range of ~10-25 μm
- Improved accuracy of optics meas.

Relative errors of focusing strength of IR quad, units of 10^{-3}

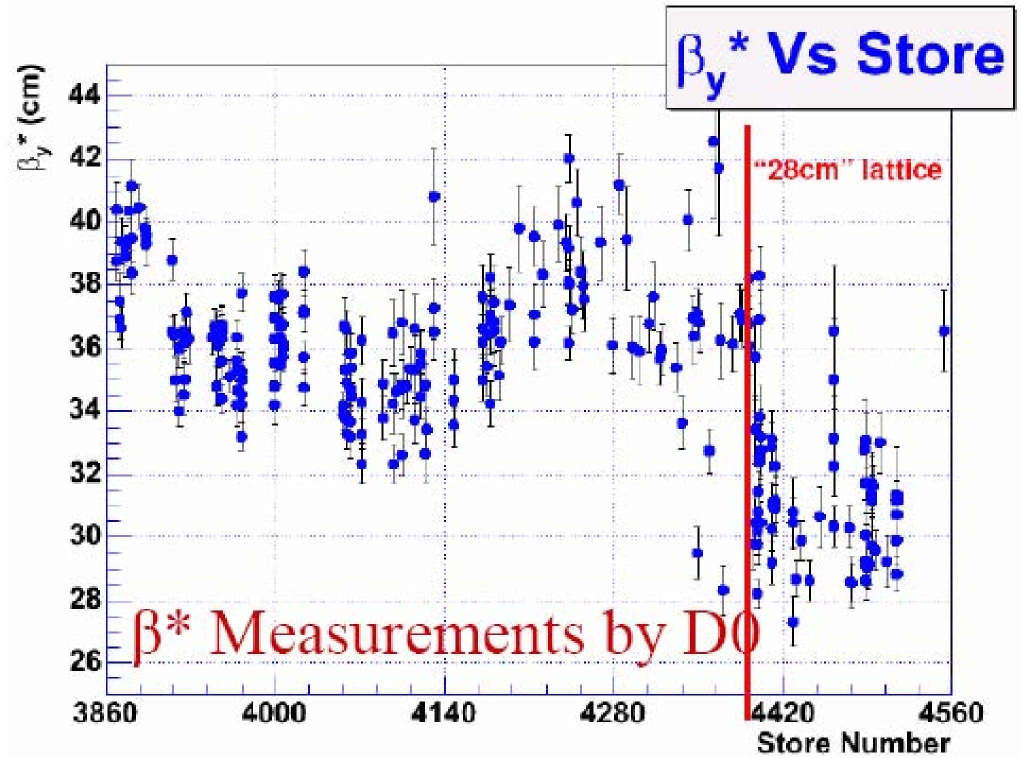
NAME	Inj.	Low Beta	NAME	Inj.	Low Beta
B0Q3	4.34	-11.18	D0Q3	-1.01	-9.49
B0Q2	4.62	-1.87	D0Q2	21.58	-0.83
B0Q3D	-1.32	-0.09	D0Q3F	0.77	0.24
B0Q3F	-1.37	-0.47	D0Q3D	0.20	-1.84



Relative errors of focusing strength for IR quads units of 10^{-3}

Tevatron Improvements (2)

- 28 cm ß* + optics correction
  - Lattice measurements exploited new BPM electronics
  - Tested at end of stores; implemented in September
- Pbar tune stabilization during HEP
  - Keep pbar tunes > 7/12 as beam-beam tune shift decreases over a store
  - Helps maintain pbar lifetime
- Orbit stabilization during HEP
  - Compensate for "fast" low-beta quad motion
  - Eliminate halo spikes @ CDF & D0, maintain lifetime



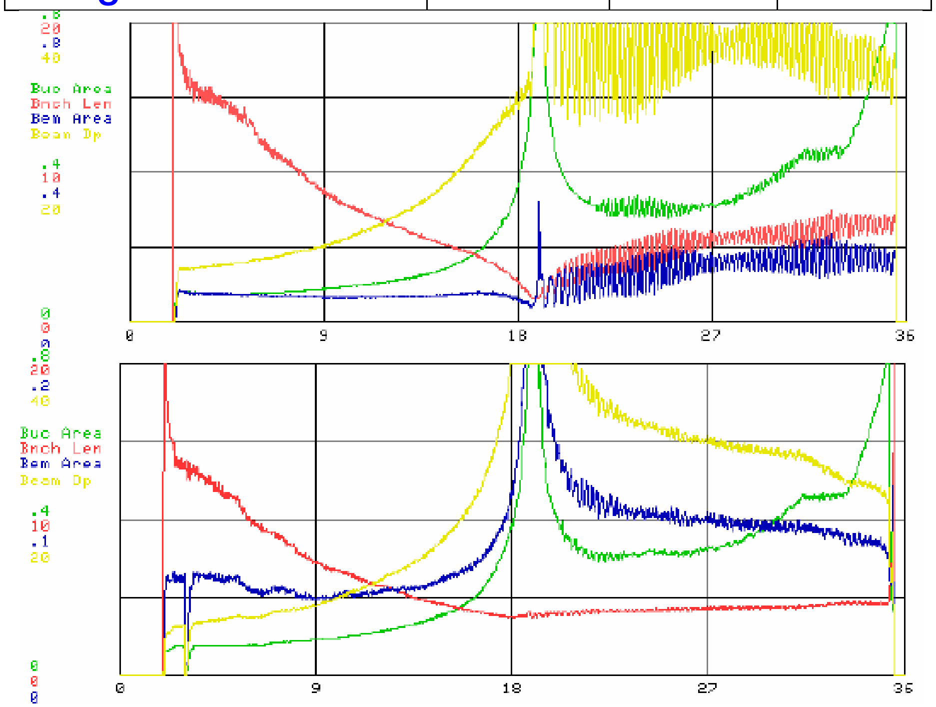
ß Measurements by D0*

Protons on Target

Strong effort to improve operation of proton accelerators (Jun.05– Feb.06)

- **Booster**
  - Longitudinal Dampers
    - Dipole Mode 0, 1, 2, 52
    - Quadrupole Mode 1
  - RF Cavity balancing

	Initial	Final	
Intensity	3.9	4.5	$x10^{12}$
Long. emittance	0.2	0.12	eV-s



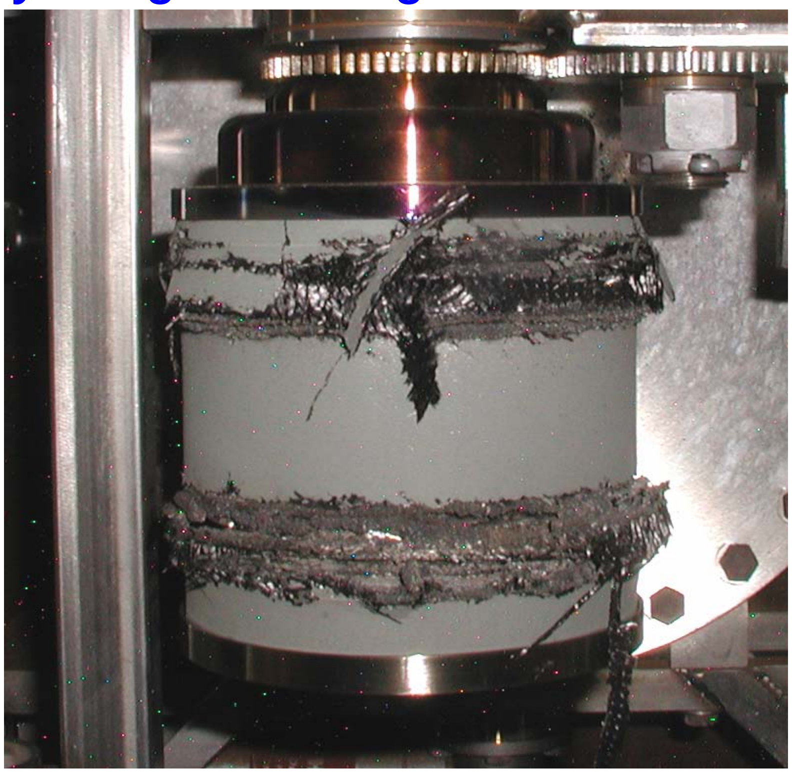
Bunch parameters before and after (L_{bunch})

- **Main Injector**
  - Slip-staking improvements
    - Beam Loading
    - Longitudinal Matching
    - Bunch length on target during Mixed mode cycles

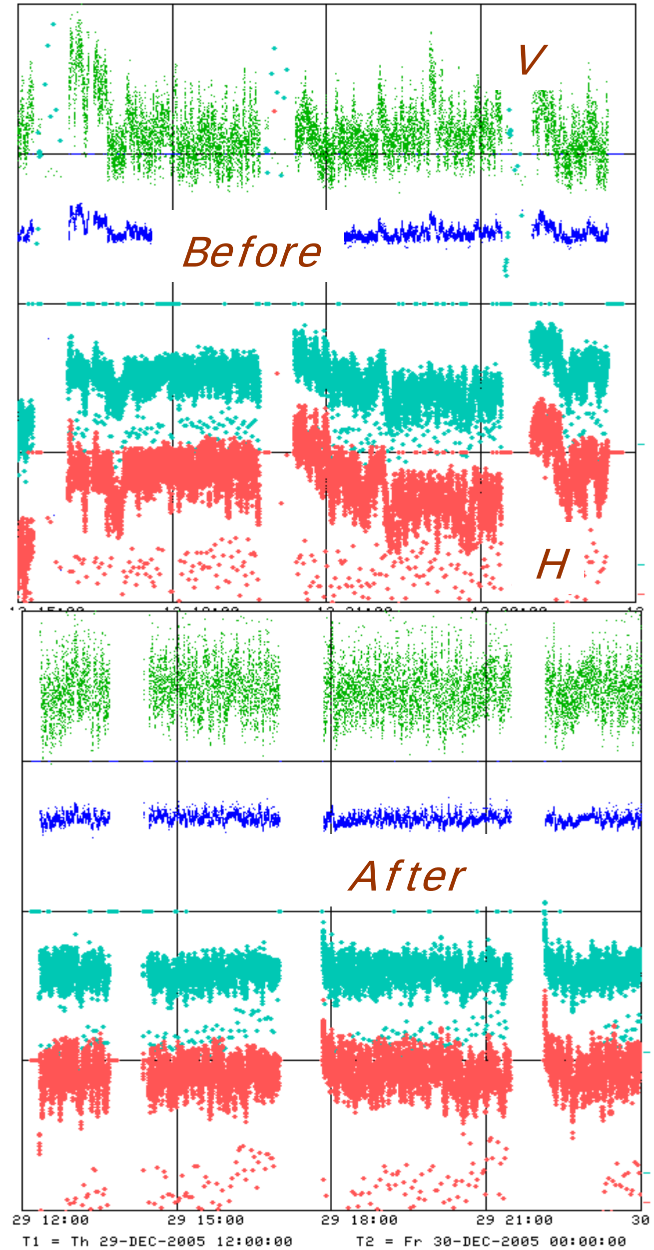
	Initial	Final	
Intensity	6.2	8	$x10^{12}$
Long. emittance	2	1.5	ns
Efficiency	75	95	%

Protons on Target (2)

- Beam position stabilization on target
- Optics correction for better focusing of proton on the target
  - Smaller betas
  - D_{xy}=0
  - Rms beam size of ~220 μm is limited by target damage



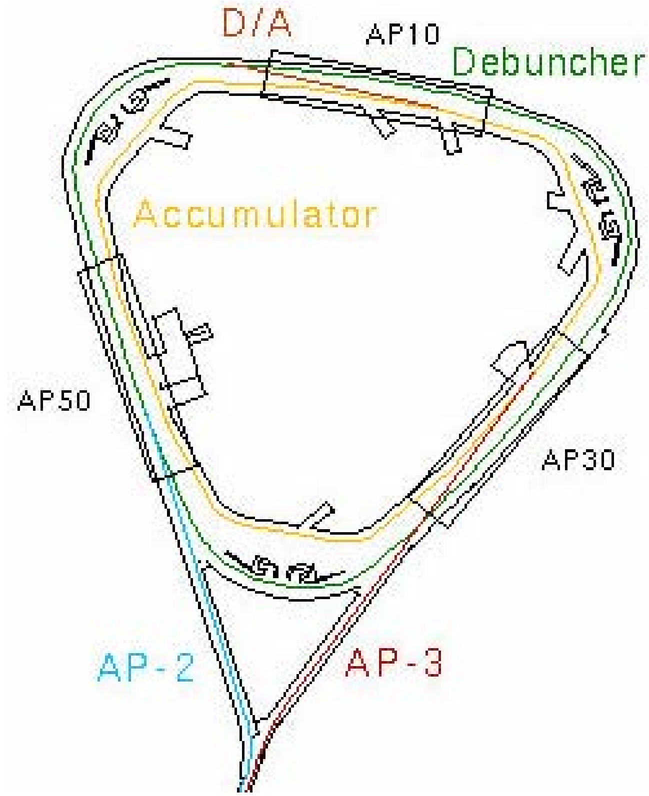
Result of beam overfocusing on the target



BPMs in AP1 line

Antiproton Production

Simplified review of operations



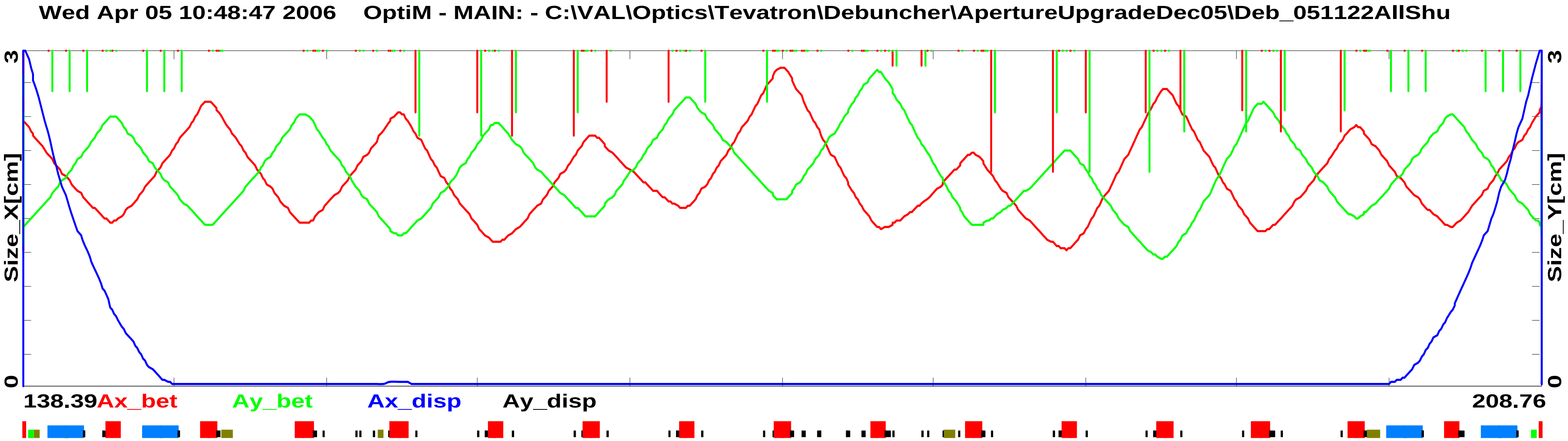
- Every 2-3 seconds $8\cdot10^{12}$ protons at 120 GeV from MI injector sent to the target of about 10 cm length
- Li lens located at ~30 cm from target (center-to-center) reduces initially large angular spread
- 8 GeV (±2.5%) antiprotons and other secondaries (μ, π, …) are transported to Debuncher, N~10^8
- After stochastic L&⊥ cooling in Debuncher antiprotons are sent to Accumulator
- 4 stochastic cooling systems (stacking, long. core, H and V) are used to stack and cool antiprotons in Accumulator
- After storing ~$5\cdot10^{11}$ antiprotons in Accumulator (~3 hour) they are sent to Recycler
- ~$3\cdot10^{12}$ antiprotons are stored in Recycler (~24 hour) and then sent to Tevatron

Antiproton Production (2)

Orbit correction in AP-2 line and Debuncher

- Stacking rate is proportional to $\varepsilon \Delta p/p$, where $\varepsilon = \varepsilon_x = \varepsilon_x$
- New Optics in Debuncher takes into account aperture limitations
  - Stochastic cooling pickups, extraction kicker and injection septum
  - It would not be possible without accurate optics measurements (see WEPCH057, Vladimir Nagaslaev)

	Initial design	Initial measured	New design	Present measured
ε_x [mm mrad]	34	30	40.5	35.3
ε_y [mm mrad]	31	25	37.5	34.6



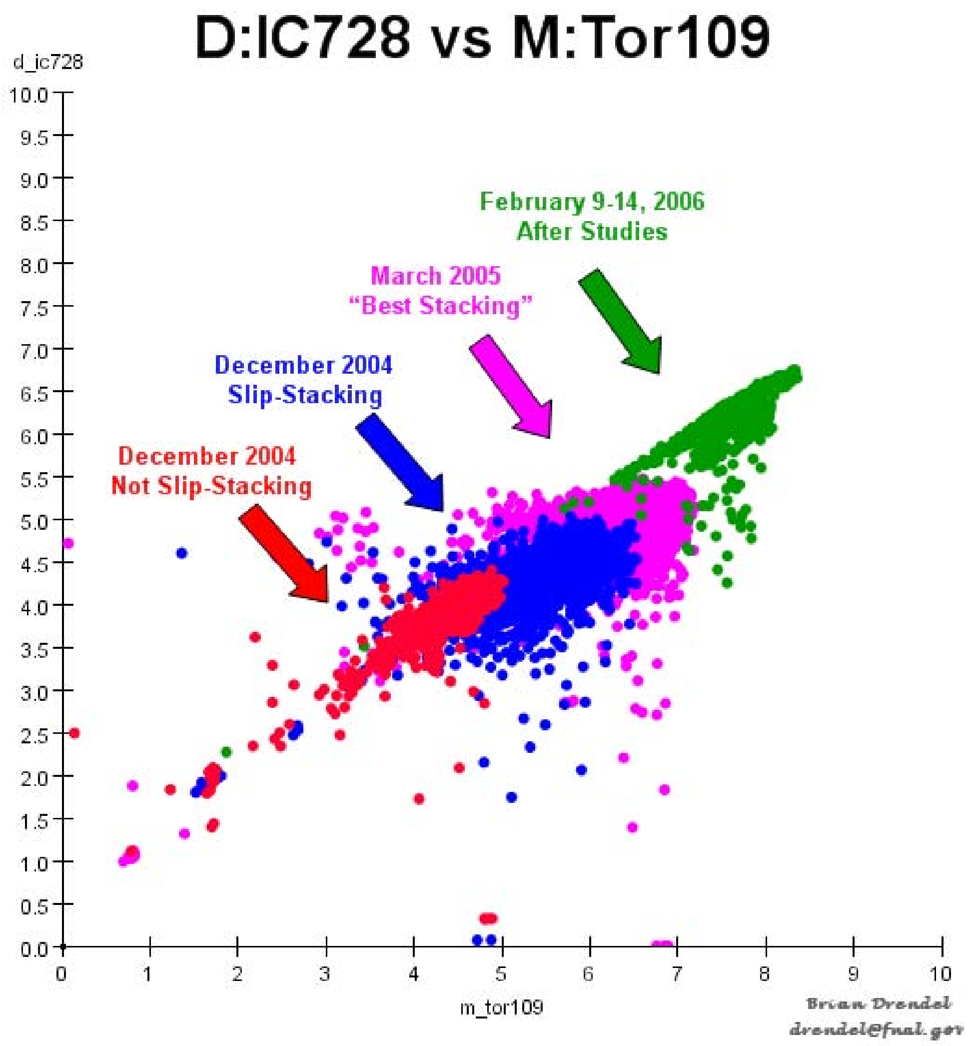
Beam envelopes in the Debuncher AP-10 straight line for H&V acceptances of 40.5 and 37.5 mm

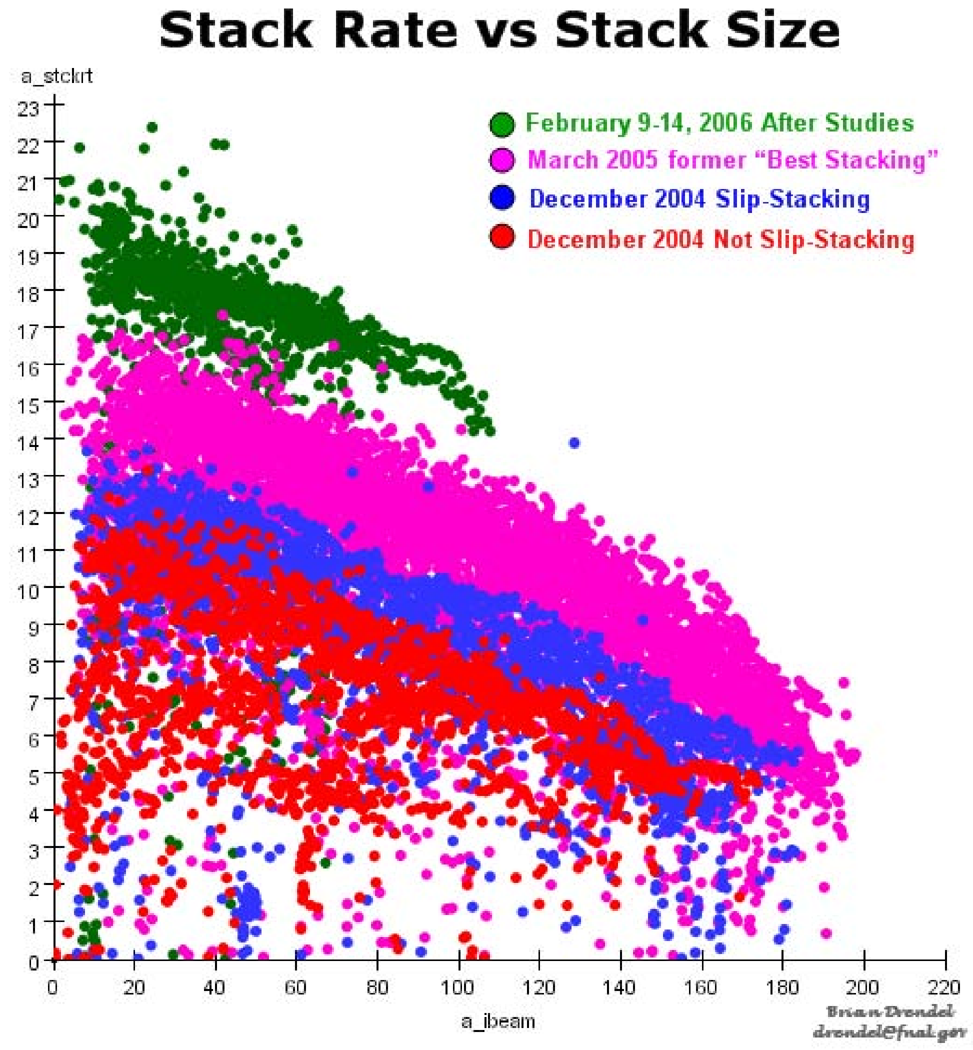
Antiproton Production (3)

Recent Stochastic cooling improvements

- Gain ramping in Debuncher - to cool faster
  - Transverse systems - ramp the gain up
  - Longitudinal systems - ramp the gain down
- Longitudinal core cooling system
  - Had been using 4-8 GHz system as a helper for the 2-4 GHz core system. Decided it was time to move to 4-8 GHz.
  - That suppressed inverse particle flux (from core to stack) and resulted in faster stacking
  - That was the last step allowed to achieve 20.1 mA/hr

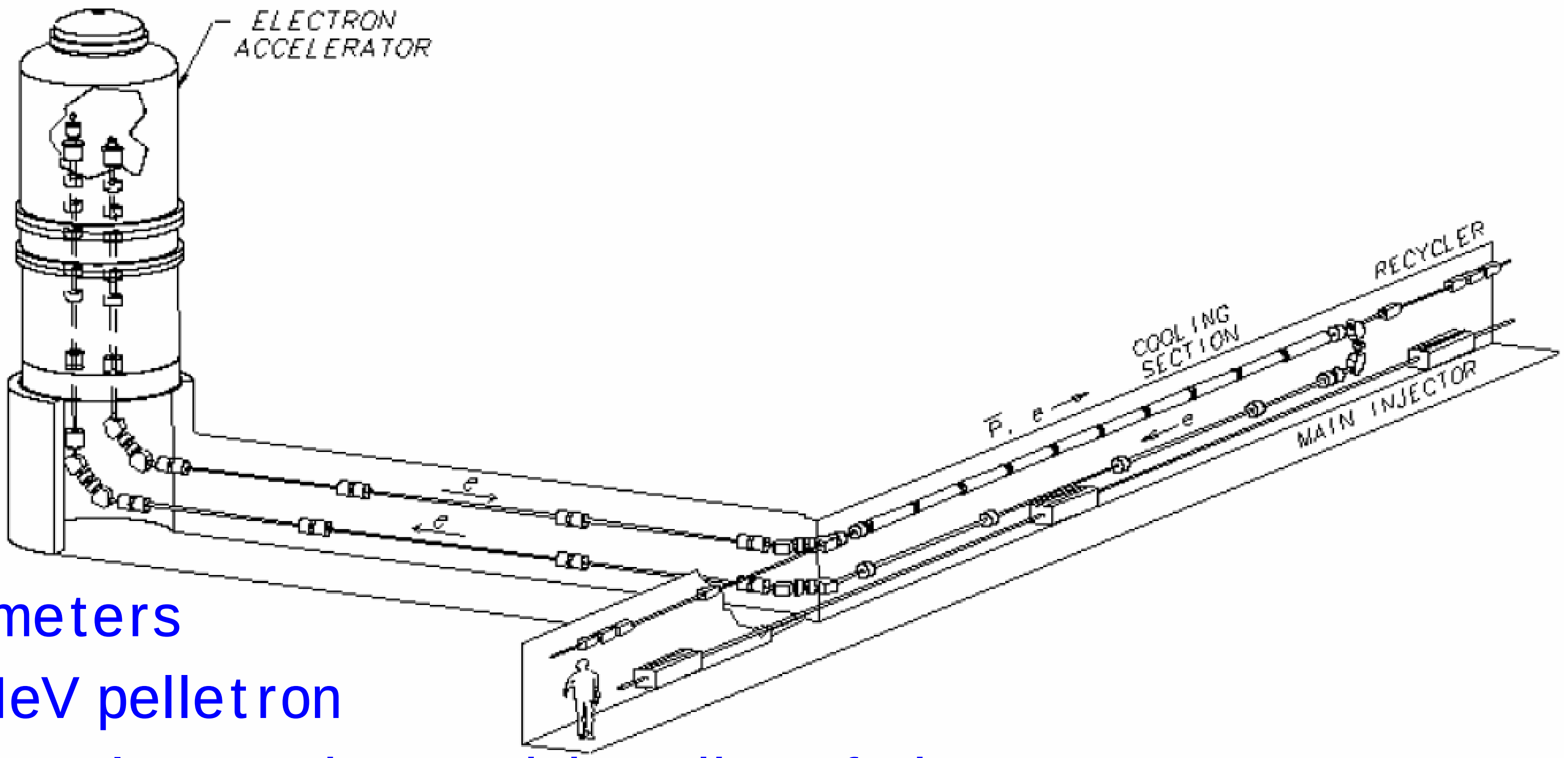
Antiproton Production (4)





Electron Cooling

- In comparison with stochastic cooling the electron cooling performance is not affected by number of antiprotons
  - The only way to form sufficiently dense beam
- Simultaneous operation of electron and stochastic coolings



- Main Parameters
  - 4.34 MeV pelletron
  - 0.5 A DC electron beam with radius of about 4 mm
  - Magnetic field in the cooling section: 100 G
  - Interaction length – 20 m (out of 3319 m of Recycler circumference)

Electron Cooling (2)

What makes Fermilab electron cooler unique?*

- No strong longitudinal magnetic field accompanying electron beam all the way from gun to collector
  - Angular-momentum-dominated beam transport line
  - Phase advance Q~6
  - Fully coupled motion
  - Length of beam transport~70 m
- Cooling with low-magnetic field – something that had never been tested, B=100 G
- 15 times higher energy than any cooler before (GSI ~0.3 MV)

Pelletron

Cooling section

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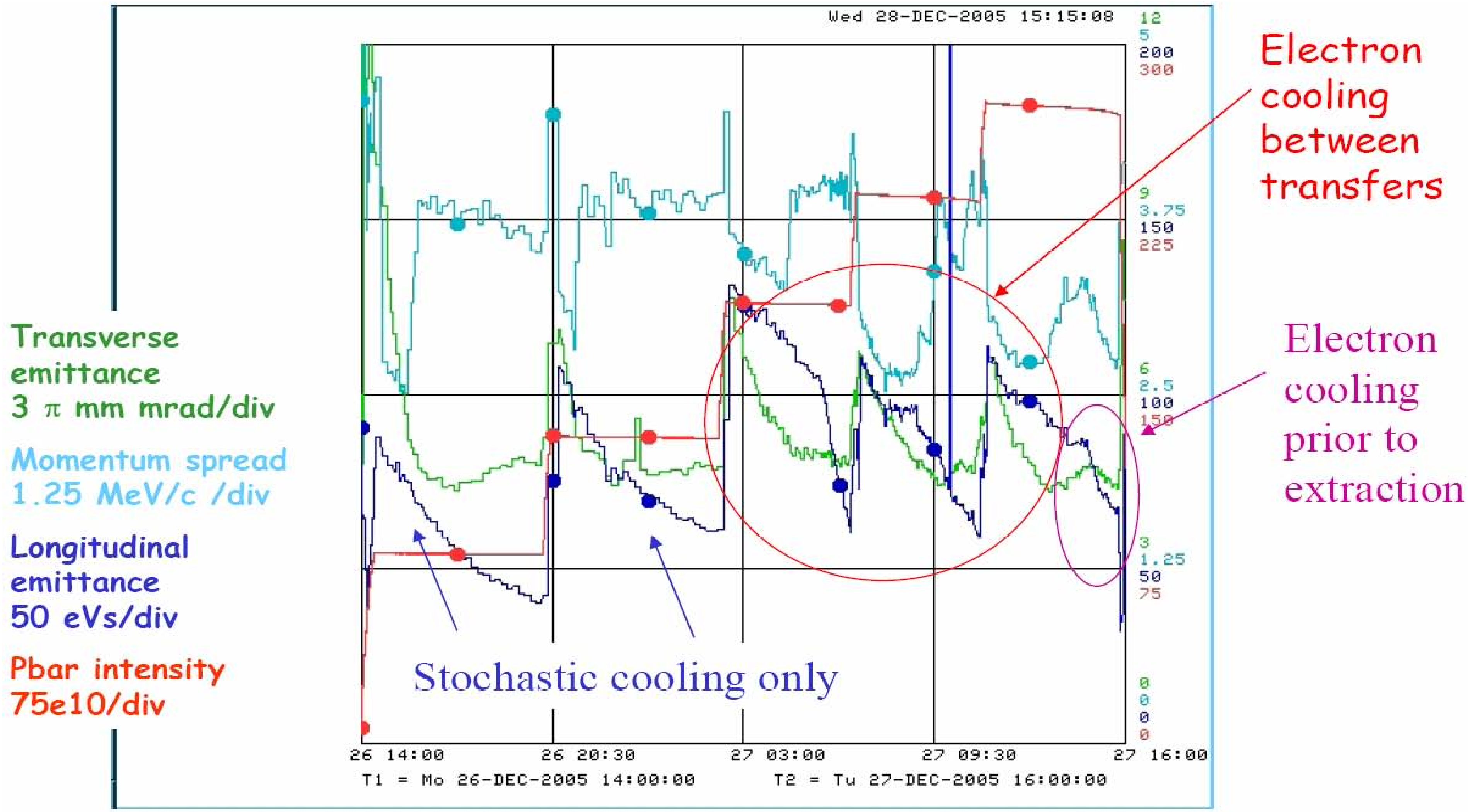
* *See: TUPLS007 - Sergei Nagaitsev , TUPLS069 - Alexander Shemyakin, , TUPCH098 – Daniel Broemmelsiek*

Storing Antiprotons in Recycler

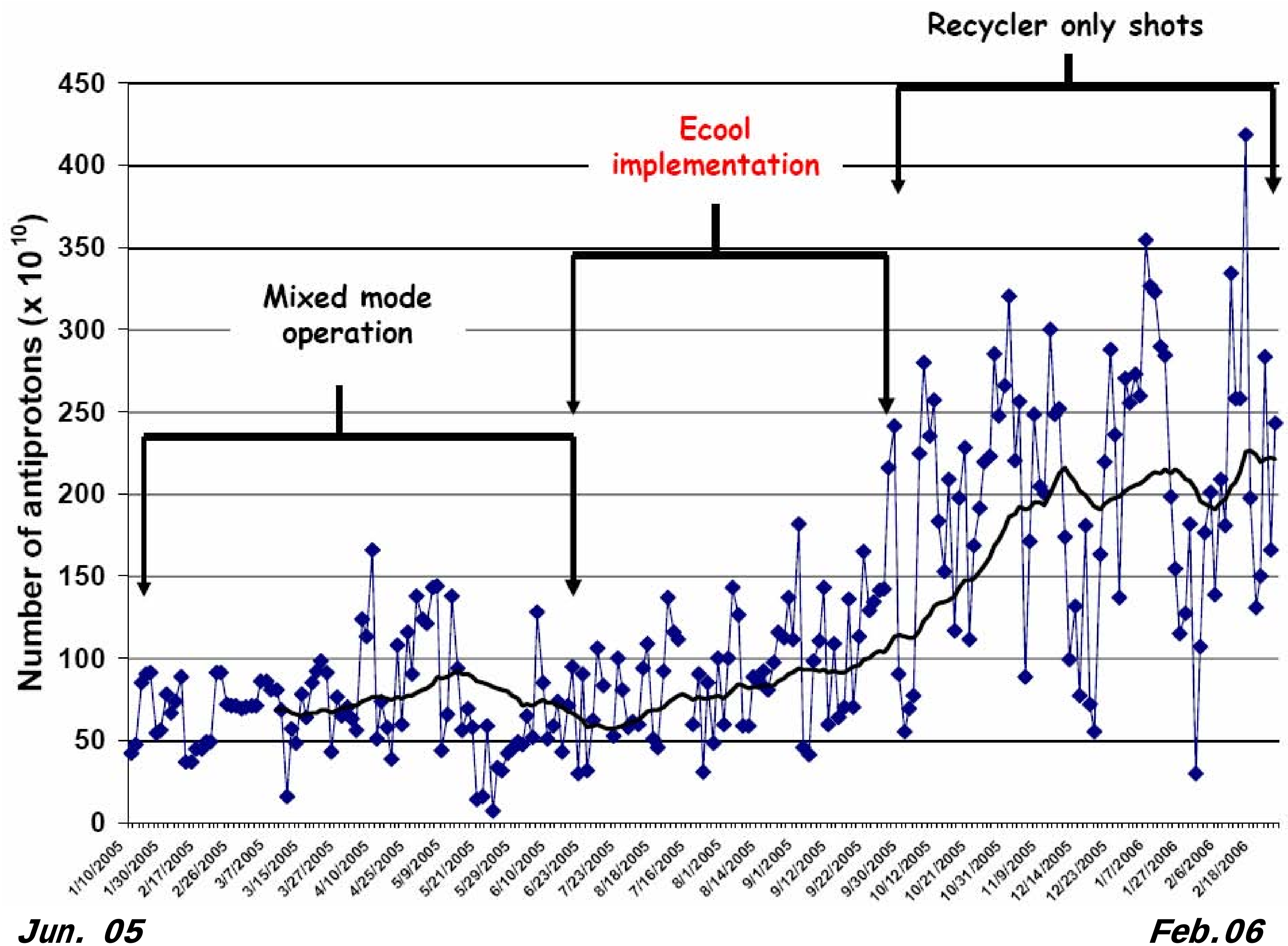
Recycler cooling sequence

- Stacking rate in Accumulator drops with stack size
  - Transfers to Recycler after ~$50{\cdot}10^{10}$ allows to stay close to maximum stacking rate



Storing Antiprotons in Recycler (2)

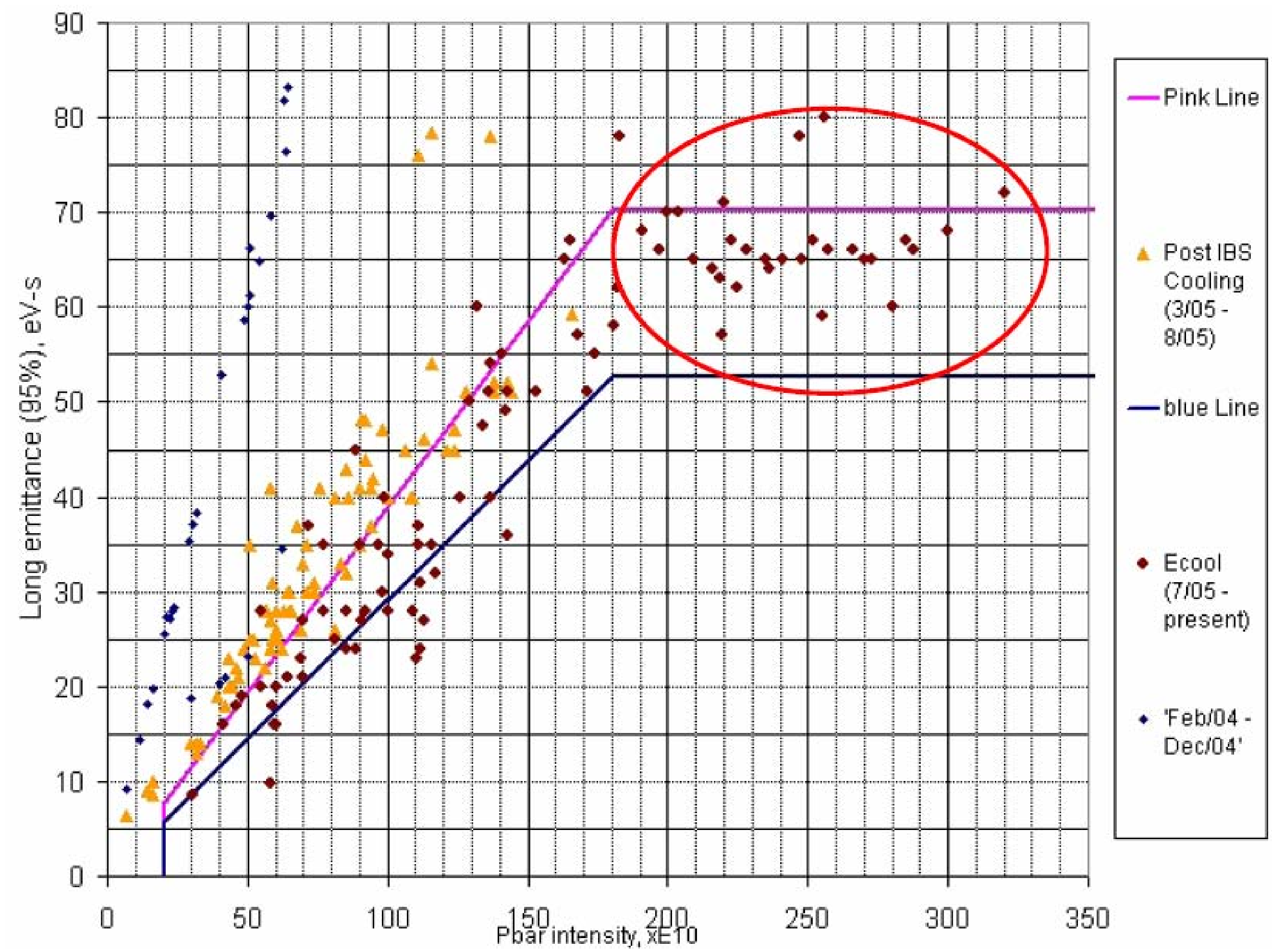
Changes in Recycler operational status



Evolution of the number of antiprotons available from the Recycler

Storing Antiprotons in Recycler (3)

- Both stochastic and electron coolings operate
- Electron cooling is more effective for longitudinal degree of freedom
- One long bunch (~1 km of 3 km) to prevent storing of the ions
- Extraction: 9 transfers of 4 bunches each

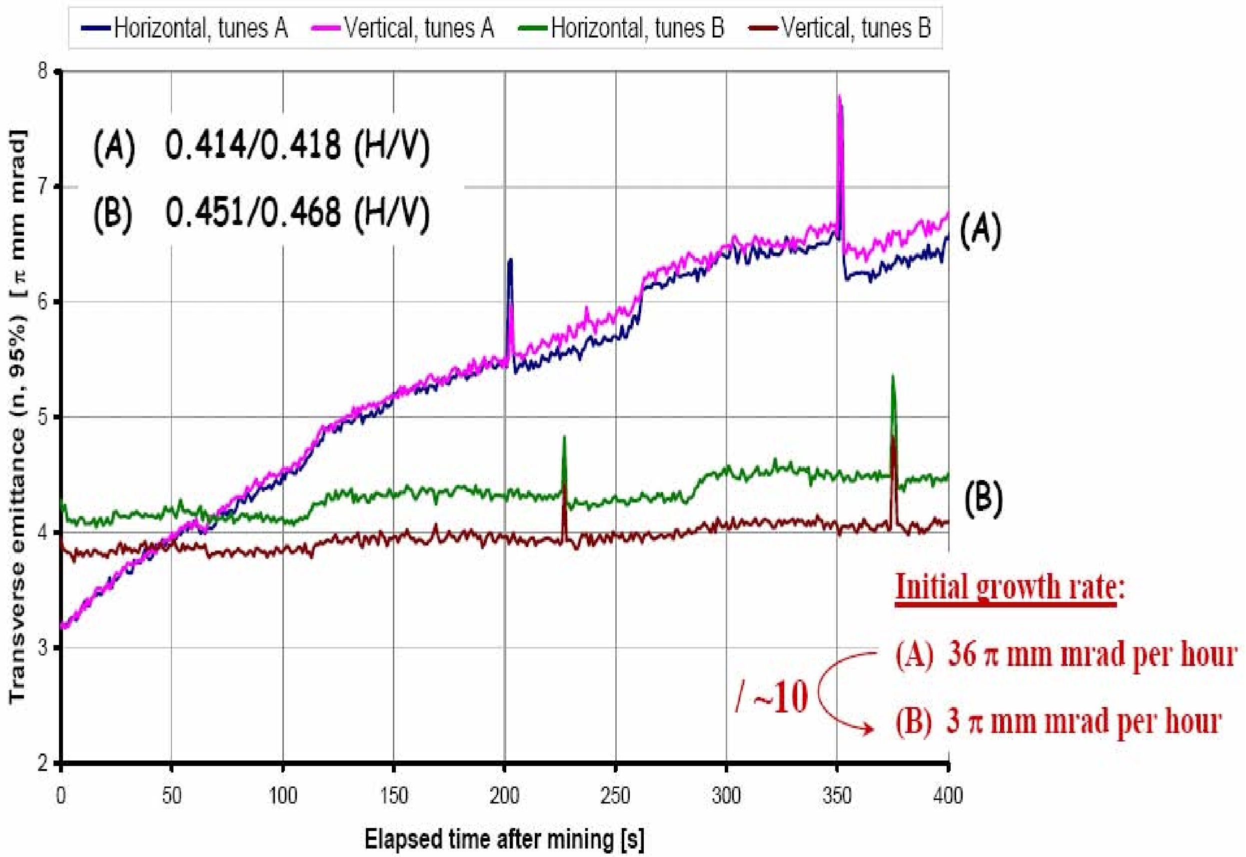


Recycler longitudinal emittance with electron cooling

Storing Antiprotons in Recycler (4)

Recycler instabilities

- Instabilities limit 6D phase density of the beam
- Resistive wall is stabilized by transverse dampers (~20 MHz) (see THPCH065 Alexei Burov)
  - ♦ Dampers Upgrade during shutdown (~90 MHz)
- Emittance growth due to mining
  - ♦ Likely due to quadrupole instability (see Alexei Burov at HB-2006)
  - ♦ Coupling decrease suppressed emittance growth and the lifetime degradation

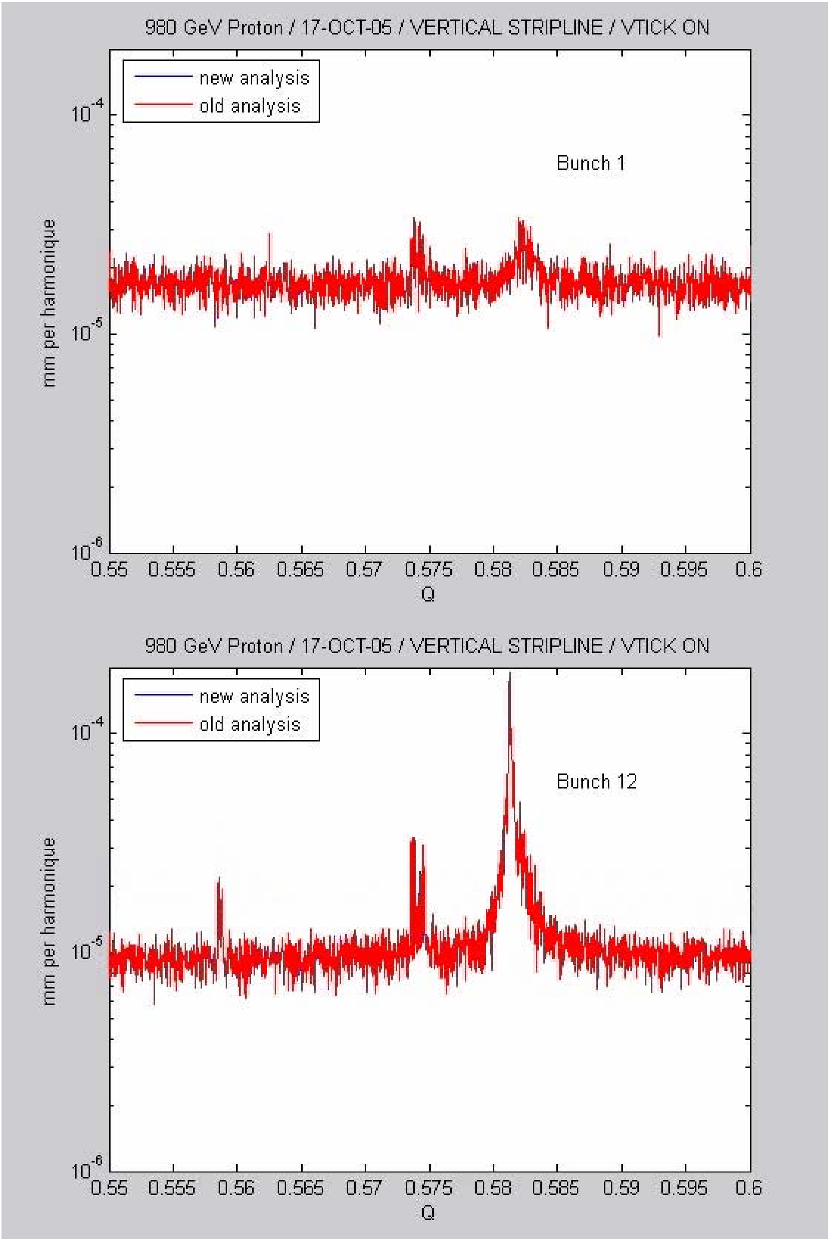


Plans for further luminosity growth

- Ultimate goal is to double luminosity $1.67 \cdot 10^{32}$ => $3 \cdot 10^{32}$ $cm^{-2}s^{-1}$
  - ♦ Presently: ∫Ldt~1.5 fb => by end of 2009 ∫Ldt~4-7 fb
- Antiproton production is a cornerstone of further luminosity growth
  - • $20 \cdot 10^{10}$ pbars/hour => $30 \cdot 10^{10}$ pbars/hour (by next summer)
  - ♦ Aperture improvement in AP2 line and Debuncher (15-30%)
  - ♦ Lithium lens (0 - 15%)
  - ♦ RF voltage in Debuncher (5%) (currently running on old tubes)
  - ♦ Stochastic cooling systems
    - • Debuncher cooling with minor modifications should support such increase
    - • Calculations for Stack tail system yield: it can support ~$30 \cdot 10^{10}$ pbars/hour
      - ⇒ Planned gain correction moves it to ~$44 \cdot 10^{10}$ pbars/hour
        - o sufficiently large margin
  - ♦ Beam transfers and Accumulator aperture (5-10%)
- Tevatron improvements
  - ♦ Should support increased number of antiprotons
    - • Beam stability, Beam-beam
  - ♦ Working point change to get larger tune area
    - • New sextupole circuits for correction of second order chromaticity
    - • Increased number of protons

What is useful for the LHC

- Good understanding of IBS and luminosity evolution
- Beam-beam effects
- Optics measurements and correction
- Measurements of machine non-linearity
- Transverse damper on Tevatron
  - Operating at injection ~ 0.5 hour without beam degradation
  - We know how to do it better
- High precision BPM as a Schottky monitor



Difference in response for bunches 1 and 12 for submicron excitation od vertical beam motion

Conclusion remarks

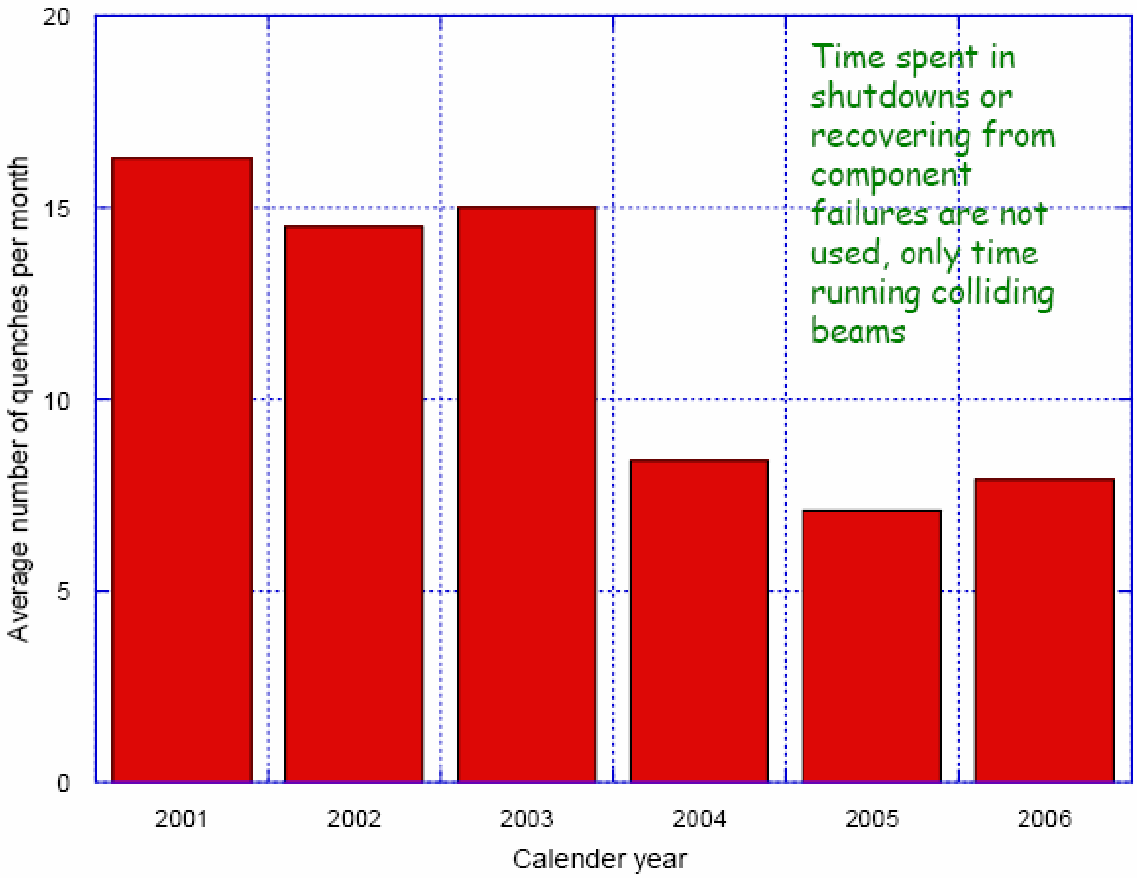
- Success of the Tevatron run II is based on large number of improvements
  - Often results of an improvement are visible much later, when other bottle necks are open
- A few believes which guide us through
  - When difficult time comes: Believe it is doable!!!
  - Reality is different from design – base your judgments on reality
  - Look around – you always loose somewhere but you will gain on something else
  - There is no magic – all complications have reasons
- Reality
  - Solutions which require minimum time in the control room usually win
- Dialectic contradiction between management and scientists
    - Management – plans, budgets, team work
    - Scientist – interest, joy of science, why it happens
  - Mutual understanding is extremely important

- Discipline in operations - Large project consequence – Otherwise the machine does not work
  - Well prepared studies, procedures
- No doubts the good top management is important for the success but it would not be possible without enthusiasm, knowledge and devotion of many physicists and engineers. In the final score that is their hard work, often at nights, made collider operating so well.
- Our best wishes for the LHC success. It will shape the future of High Energy physics

Backup transparencies

Operational Status of the Collider

- We consider that the first two years of Run II were devoted to collider commissioning
- In July 2003, we declared that the collider is operational
  - Studies better focused and organized
  - Since then, the number of Tevatron quenches is down dramatically



Average number of quenches per month