Operational experience from Tevatron and relevance for HL-LHC

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CERN, Review of Hollow E-Lens Needs for HL-LHC
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Acknowledgments

- The entire Tevatron Team!
- Dean Still, Vladimir Shiltsev, Giulio Stancari, Miriam Fitterer.

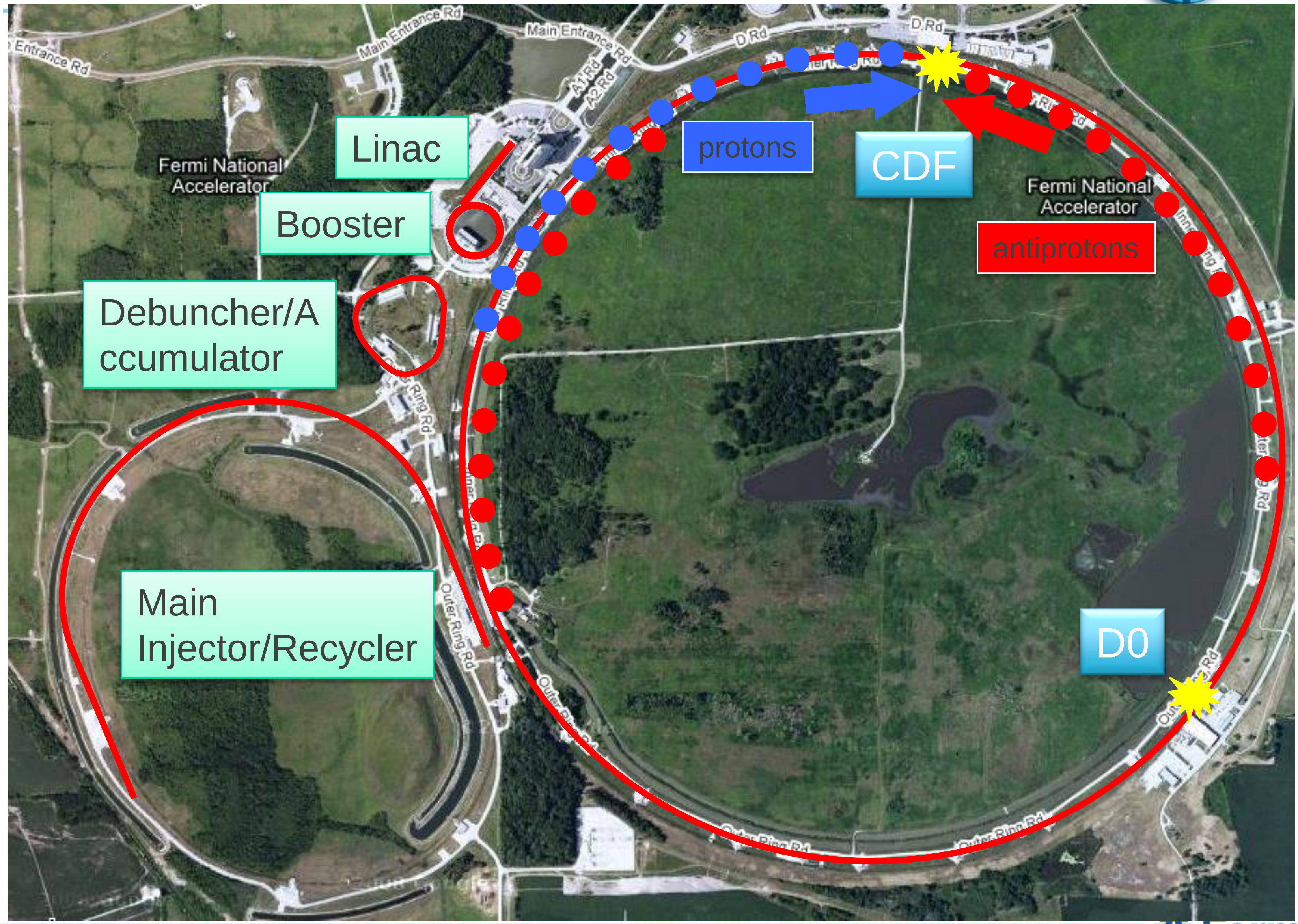
LARP

Questions

High Luminosity LHC

- What did we learn about losses and halo removal from the Tevatron experience that can be relevant for HL-LHC?
- General description of machine and operations. Lost stores and losses vs. machine cycle. Major causes of losses. Collimation system performance.
- E-lens uses, reliability, and compatibility with collider operations.
- What performance can we expect in HL-LHC? Tracking simulations on expected halo survival vs. amplitude, removal rates, and effects on the core – talk by M.Fitterer.
- Measured effects of depleted halo population with hollow e-lens and relevance for HL-LHC – talk by G.Stancari.

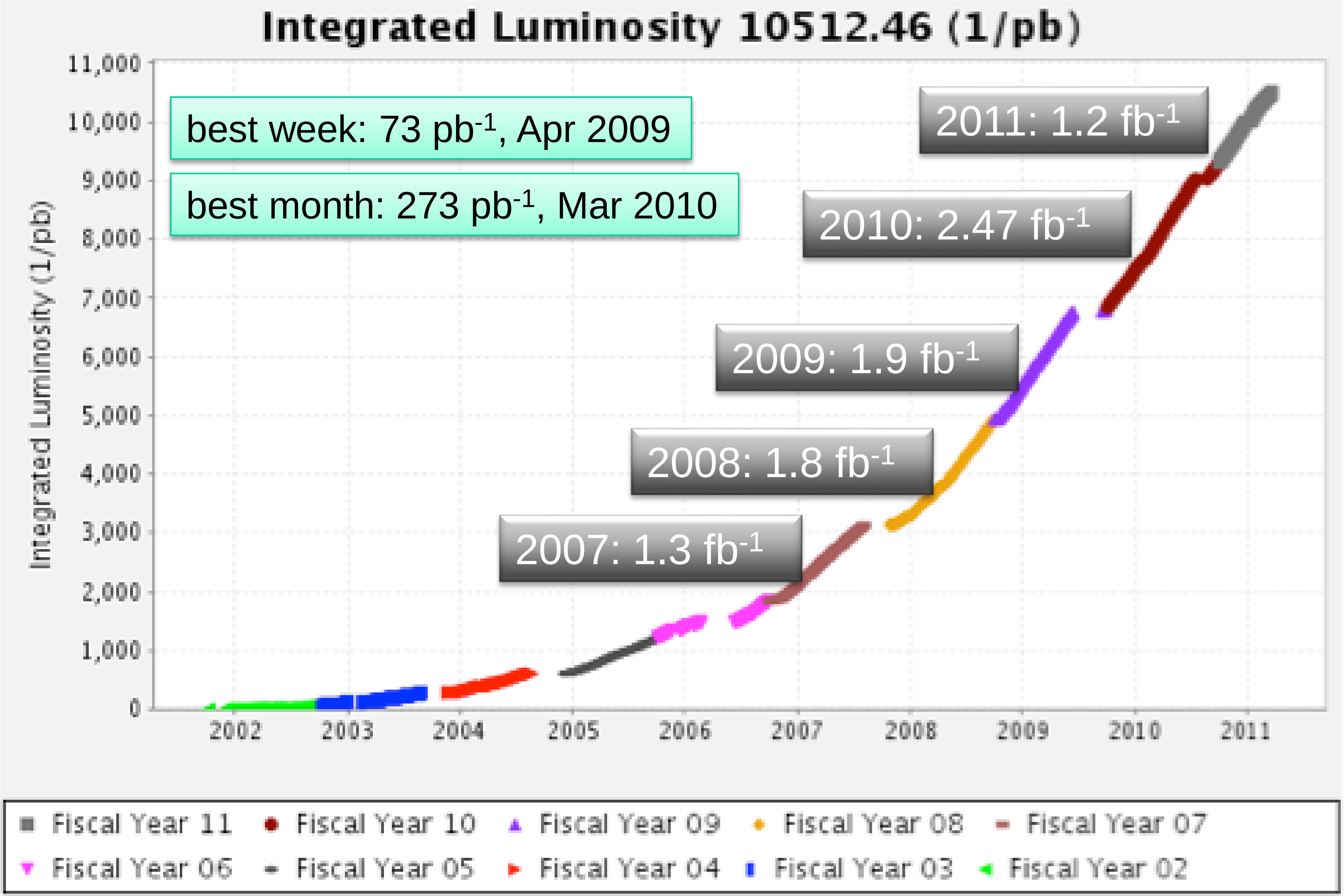
Aerial View of Tevatron



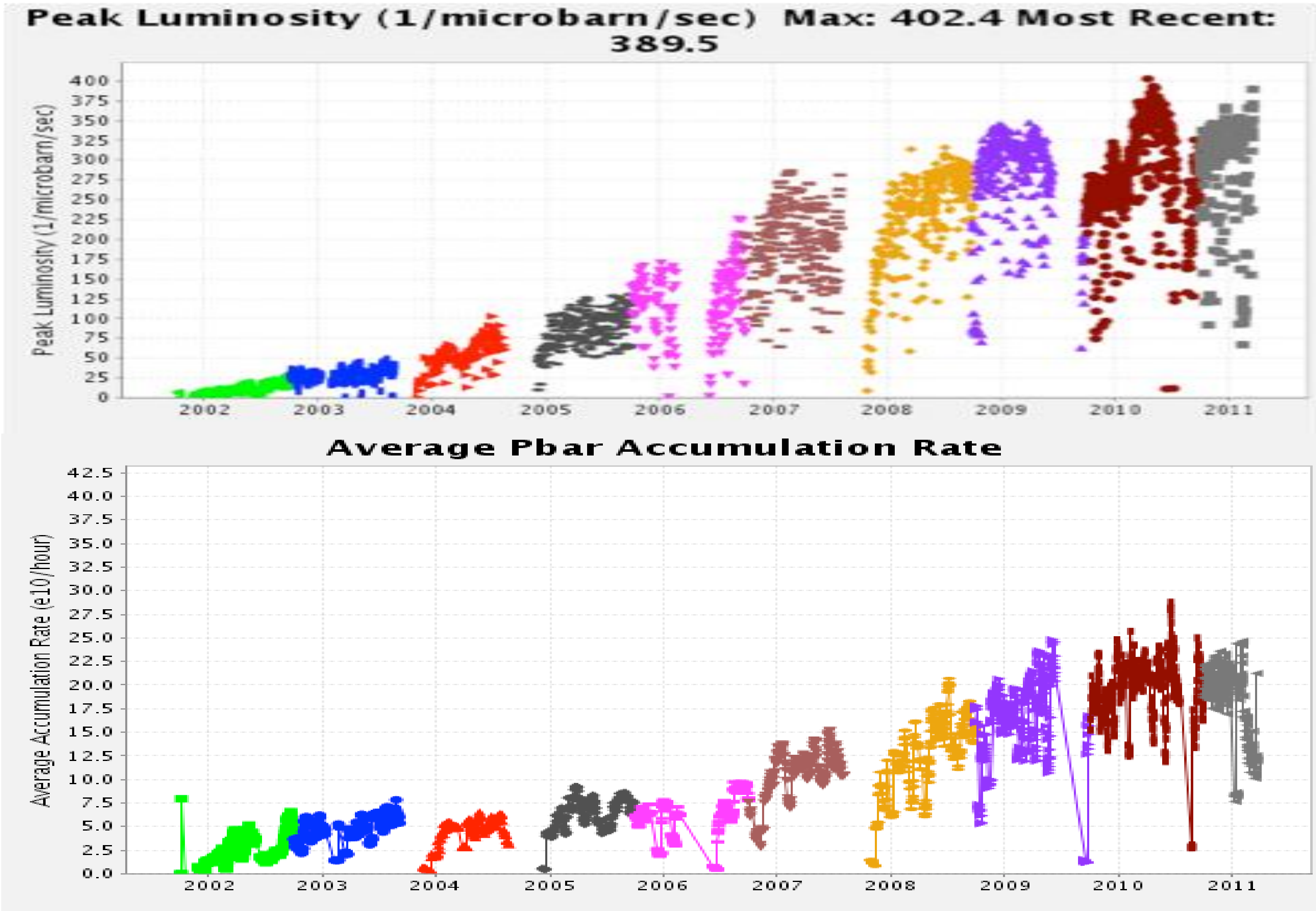
Tevatron Parameters

Beam energy	0.98 TeV
N bunches – 2 beams in one vacuum pipe!	36 (3×12)
Beam stored energy	2 MJ
Protons per bunch	2.9×10^{11}
Antiproton per bunch	0.9×10^{11}
Initial proton emittance (95% norm)	18 μm
Initial antiproton emittance (95% norm)	8 μm
Initial proton bunch length	0.55 m
Initial antiproton bunch length	0.45 m
Initial momentum spread	0.0012
β-function at IP	0.28 m
Betatron tunes (Q_x,Q_y)	20.583, 20.585
Record initial luminosity	4.3×10^{32} $cm^{-2}s^{-1}$
Initial luminosity lifetime	5 h

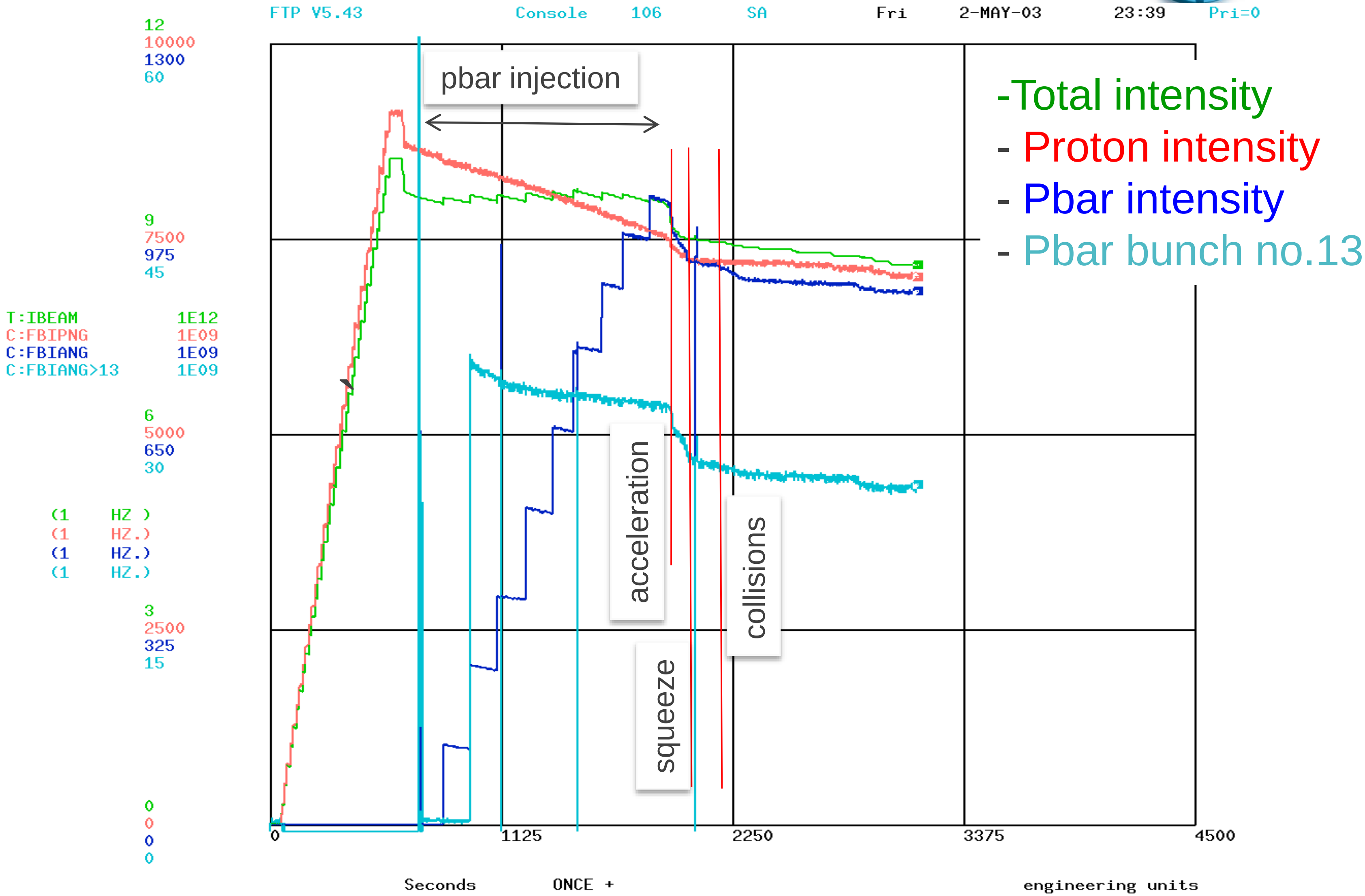
Tevatron Run II Integrated Luminosity



Initial luminosity and $\bar{p}$ Accumulation Rate

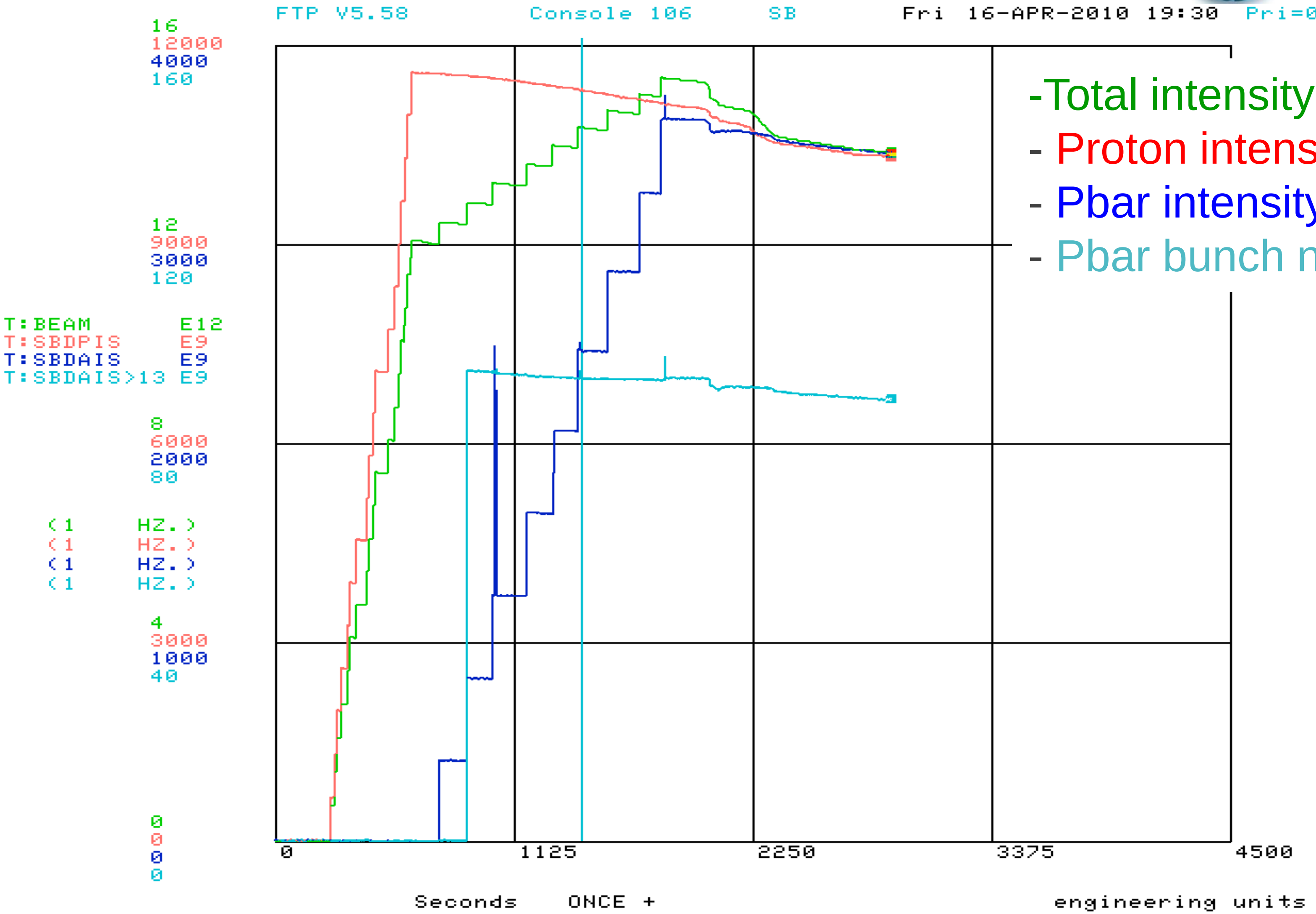


Collider Fill Cycle for Store 2511 in 2003



Store 2511 L_0=0.4x10^{32}

Collider Fill Cycle for the Record Store



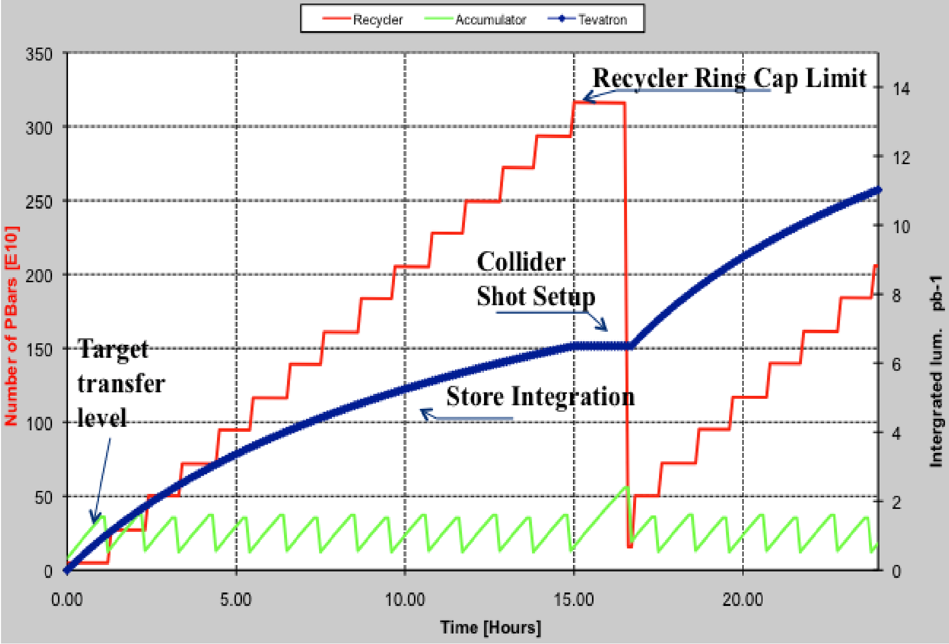
Record Store 7747 $L_0=4x10^{32}$

Contributions to Luminosity Loss and (Some) Fixes

Beam lifetime at 150GeV: Ultimately were losing 5% protons and 1% antiprotons	Optimization of sextupoles
	Machine impedance (Lambertsons)
	Improved injection helical orbits
Beam losses on ramp: ultimately ~2%	Better helical orbits (beam-beam separation)
	Improved coupling (repaired all 800 dipoles)
	Improved instrumentation (machine reproducibility)
Beam losses in squeeze: 2% protons and <1% pbars	Better helical orbits
	Collimation (2010)
	Improved aperture
β^* and beam separation	Better lattice control
Luminosity lifetime: dominated by luminous losses, IBS. Beam-beam ~5%	Better helix
	New proton working point
	Second order chromaticity
Reliability: in FY2010 averaged 120 store hours/week (71%)	cryo, controls, TEL, orbit stabilization, collimation

Operations Strategy

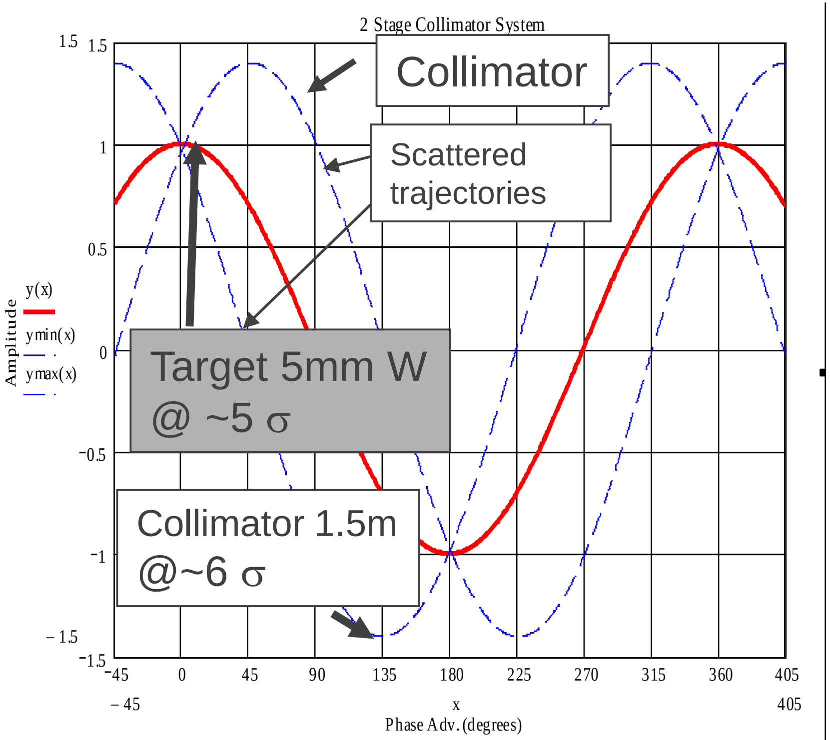
- Model of collider operation
  - Antiproton transmission efficiencies
  - Stacking rate in Accumulator as function of stack size
  - Pbar lifetime in Recycler
  - Tevatron initial
    - Luminosity
    - Luminosity decay
  - Shot setup time
- The model was used to determine the optimal operating parameters to maximize luminosity integral

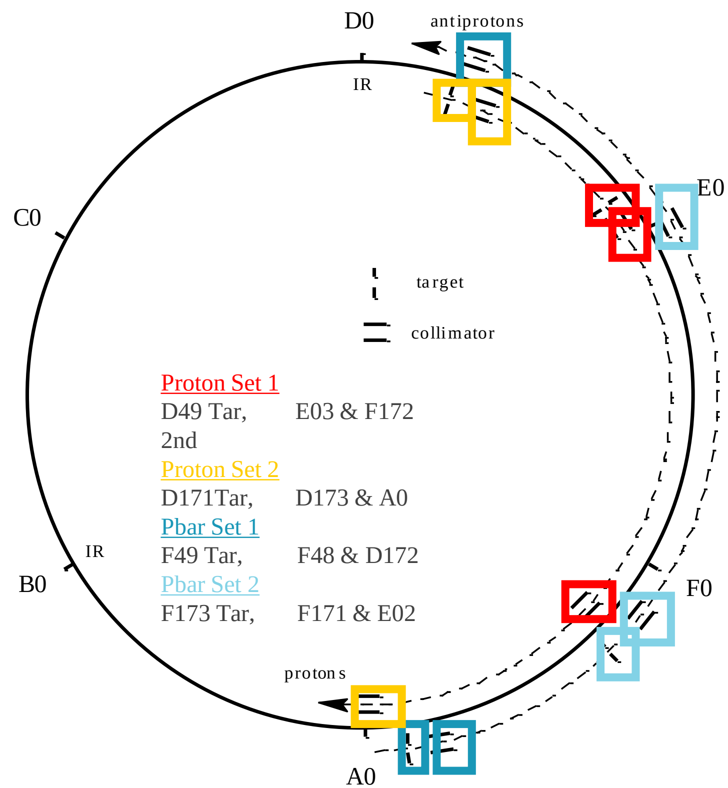


Tevatron Collimation System

Two-Stage Halo Removal System

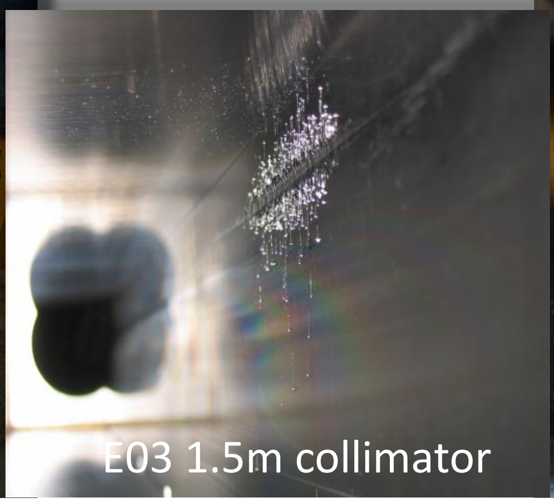
- 4 primary W targets
- 8 secondary L-shaped collimators

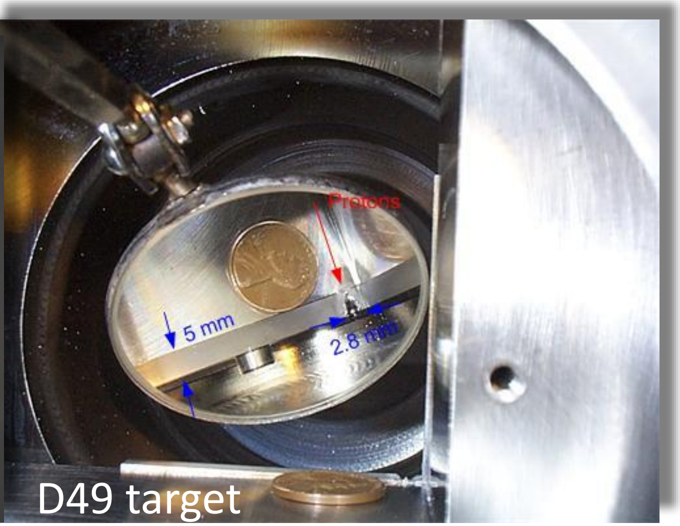




Protection Against Catastrophic Failures

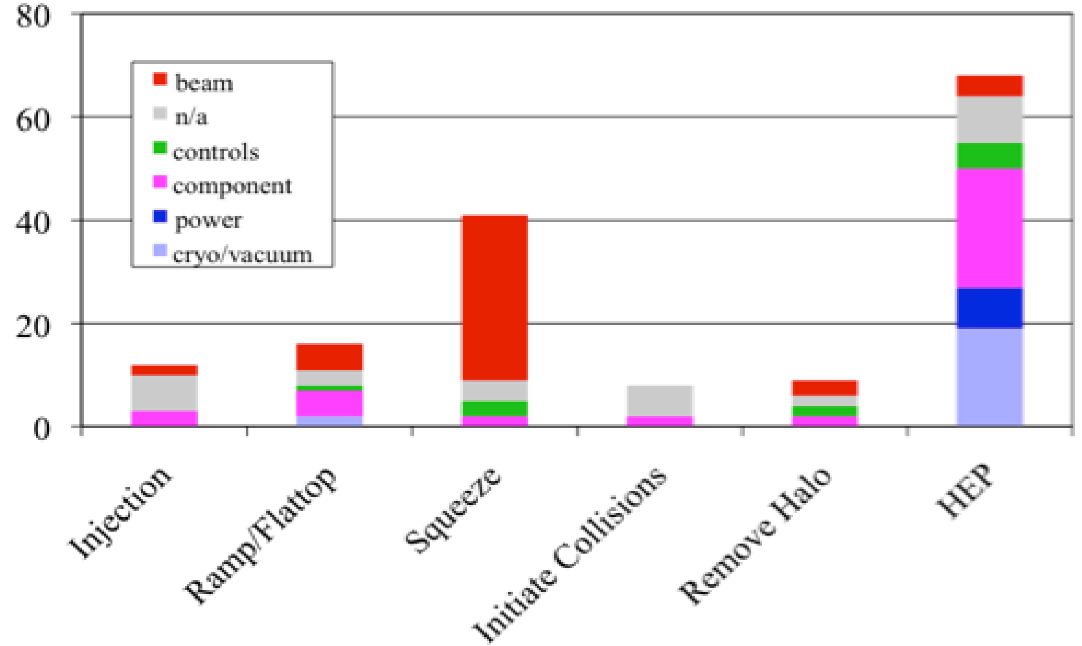
- December 5, 2003
  - First learned of a new category of quench called a "Fast Quench"
  - A Roman Pot moved into beam due to a controls error causing beam loss damaging 2 collimators and 2 spool pieces (3 correction elements)





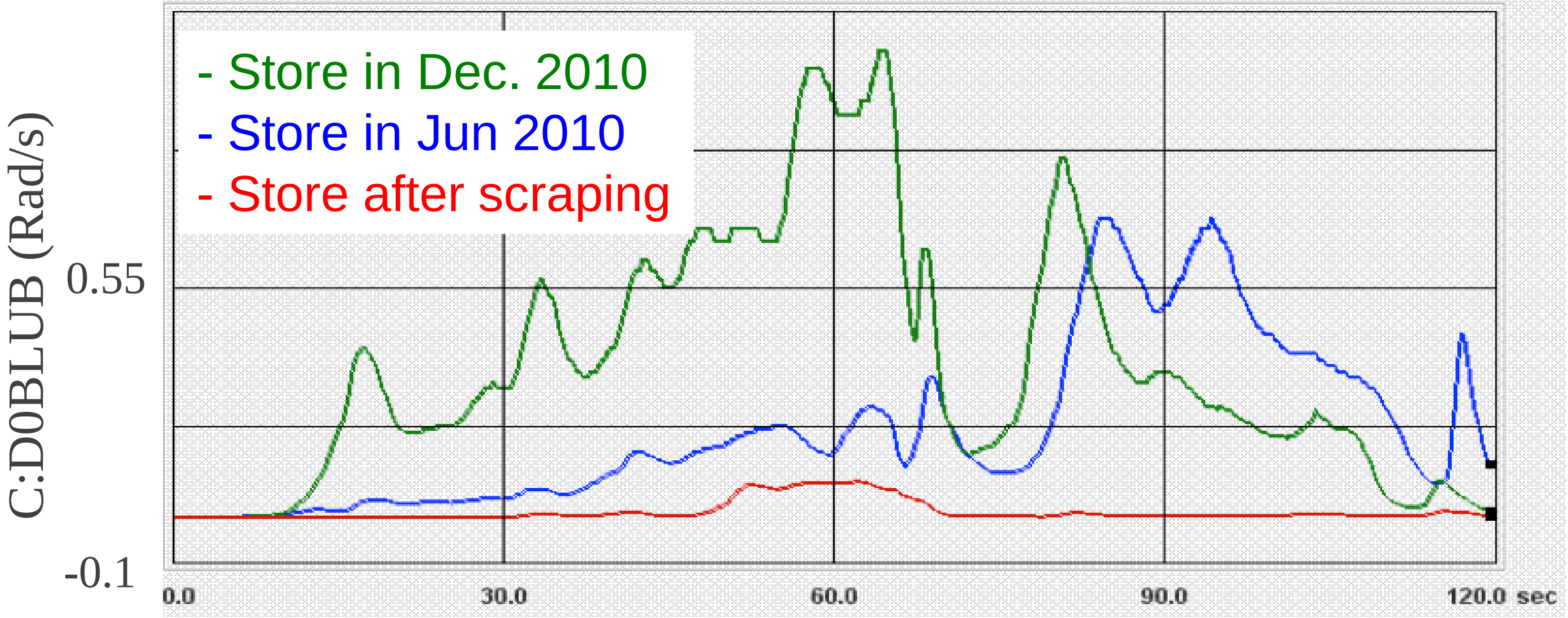
Quench Statistics

- Total quenches in HEP mode Oct.2007-Mar.2011: 154
- Percentage
  - Ramp: 16
  - Squeeze: 41
  - Collisions: 68
- 32 quenches in squeeze were caused by beam dynamics related losses



- Total number of stores 1200 – one in 40 lost in squeeze, between Apr. 09-Mar.11 14 of 372 lost in squeeze – one in 30
- A quench during squeeze accounts for ~8pb^{-1} – lost ~3% integral
  - Integrated dose leads to equipment failures in detectors

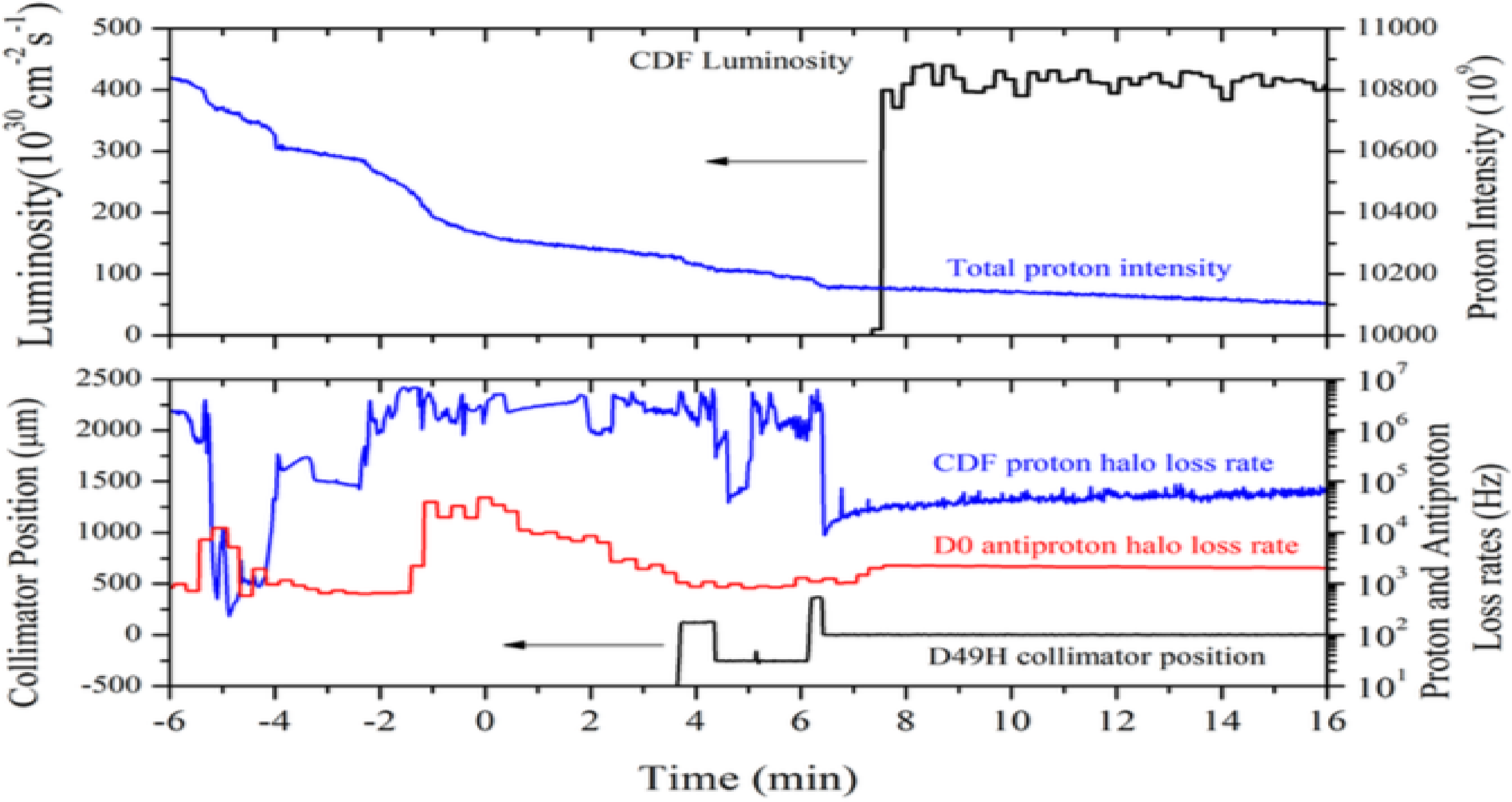
Collimating Losses in Squeeze



A single proton collimator + orbit control reduced losses.
Since implementation in Dec. 2010 114 stores – no quenches in squeeze

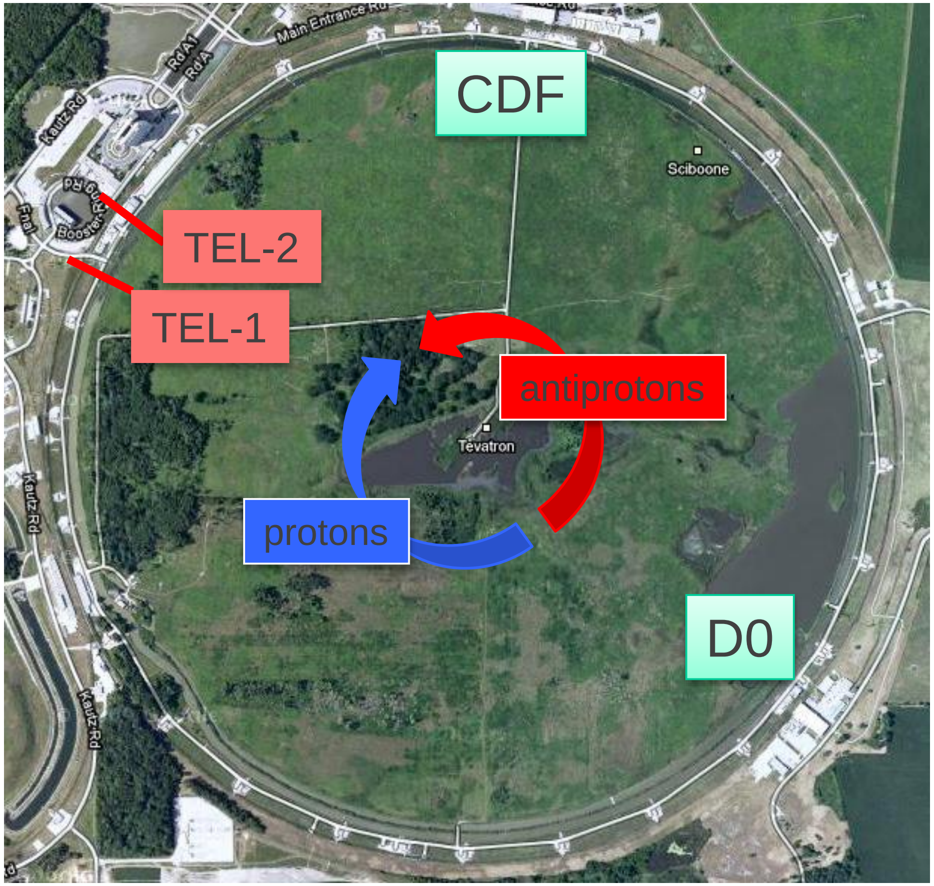
- Halo was generated through fast (seconds) beam-beam mechanism
- Cleaning with collimators was sustainable at Tevatron intensity/energy

Losses in HEP



- Often detectors "blinded" by losses (not by pile-up) in the first minutes of a store – soft collimator would be beneficial, and would result in integrated luminosity improvement.

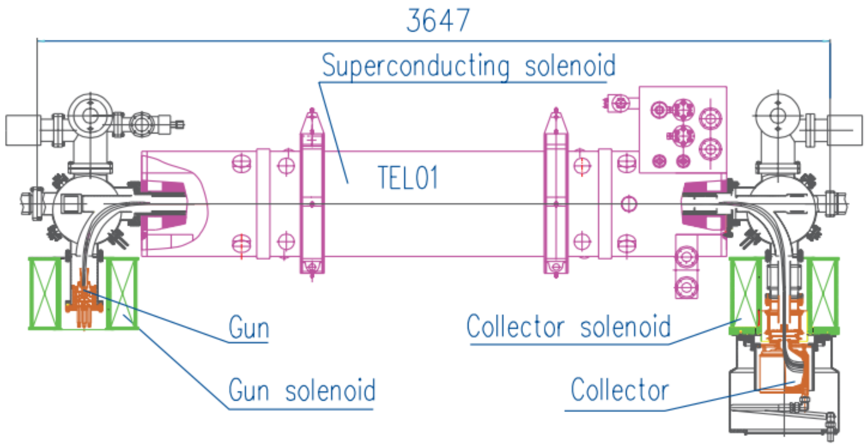
Tevatron Electron Lenses

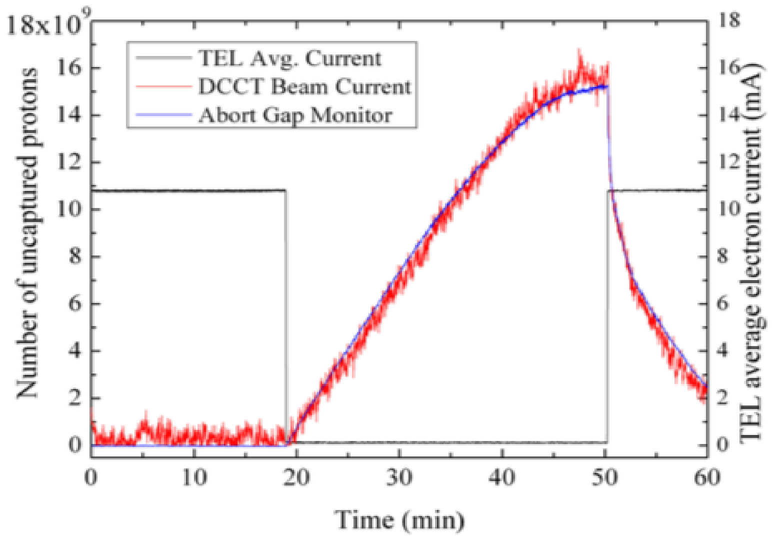


e- beam energy	< 10 kV
Peak e- current	< 3 A
Solenoid B-field	3 T
Gun B-field	0.3 T
e- beam radius (SEFT)	2.3 mm
Interaction length	2 m
TEL-1 $\beta x / \beta y$	95/32 m
TEL-2 $\beta x / \beta y$	66/160 m

- V.Shiltsev, *Electron Lenses for Super-Colliders*, Springer 2015
- V. Shiltsev et al., Phys. Rev. ST AB 11 (2008) 103501
- V.Shiltsev et al., NJP 10 (2008) 043042
- G. Stancari et al., Phys. Rev. Lett. 107 (2011) 084802

TEL-1

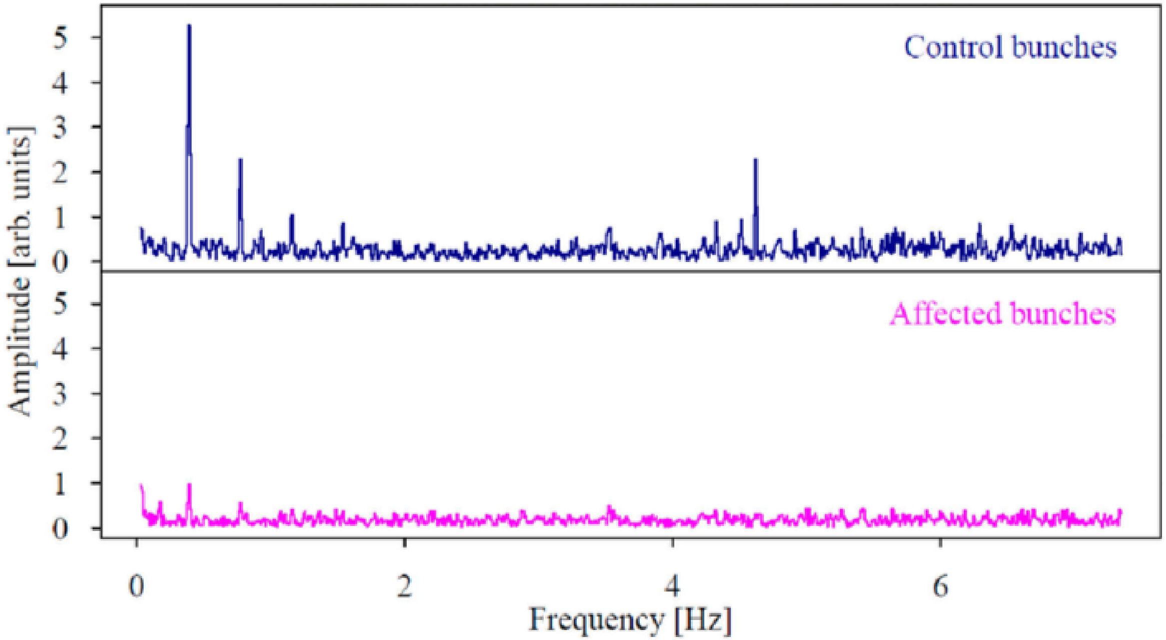




- In continuous operation 24/7 2001-2011
  - Excellent reliability record
    - 5 failures (2 of them in-tunnel electronics)
    - 1 trip resulted in store abort
  - Lessons: beam stability, noise, shape, control, etc.
- Mostly used for smooth abort gap cleaning
  - Also a versatile tool for beam removal – once scraped *all* beam after abort kickers failure
- Long-range beam-beam compensation demonstration

TEL-2

- Commissioned in 2006-2007
- Nonlinear transverse beam profile, head-on beam-beam compensation studies
- Studies of coherent stability of e-p system
- *Hollow-beam collimation studies* – talk by G.Stancari



Conclusion

- Beam loss, especially uncontrolled, was a major factor in Tevatron Run II collider operations
- The two-stage collimation system was mostly adequate in stable beam operation and protected against catastrophic failures
- Transition modes (ramp, squeeze) posed the biggest threats owing to complex long-range beam-beam configuration
- Tevatron Electron Lenses demonstrated remarkable reliability and versatility in collider operations
  - Uncaptured beam removal
  - Beam-beam compensation
  - Collimation
- Much experience gained in modeling/simulations

2011 - 2016

Fermilab's second director and 1988 Nobel Prize Laureate Leon Lederman (left) and Bob Mau watch as Dr. Helen Edwards terminates the final beam in the Tevatron collider in the Fermilab Main Control Room on September 30, 2011