# Tevatron Accelerator Physics and Operation Highlights

Alexander Valishev
for the Tevatron group
**Fermilab**

PAC'11, New York, NY
March 28, 2011

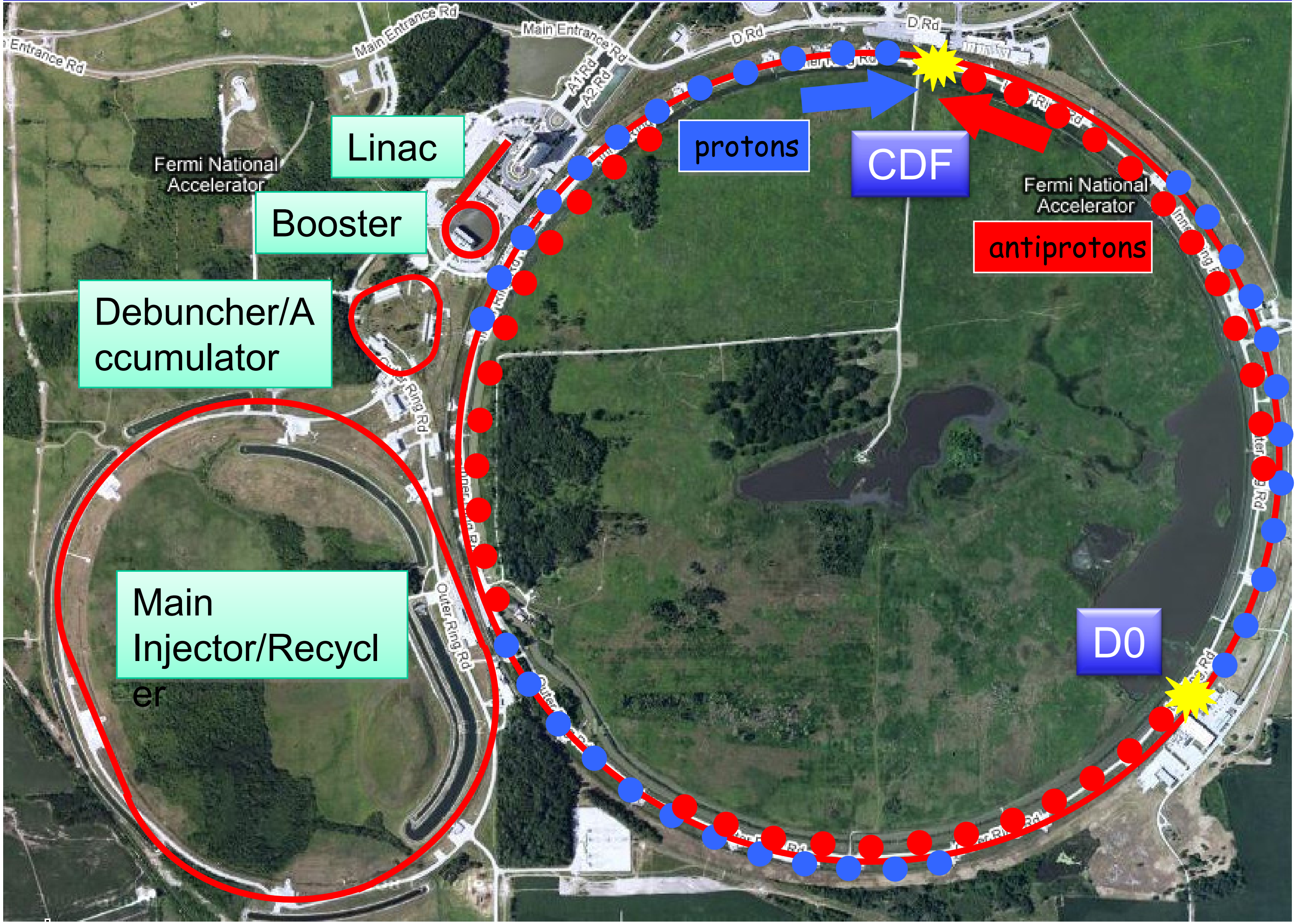
# Acknowledgments


- This report presents the results of work of many people at Fermilab's Accelerator Division and Accelerator Physics Center
- The author would like to thank J.Annala, A.Burov, C.Gattuzo, R.S.Moore, L.Prost, A.Shemyakin, V.Shiltsev, G. Stancari, D.Still, for their help in preparation of this talk.

# Outline

- Run II performance and improvements
- Highlights from the last two years of running
  - Operational improvements
  - Reliability and quench statistics
- Accelerator physics studies
  - Dancing bunches
  - Ghost modes
  - Beam-beam compensation
  - Crystal collimation
  - Hollow electron beam collimator

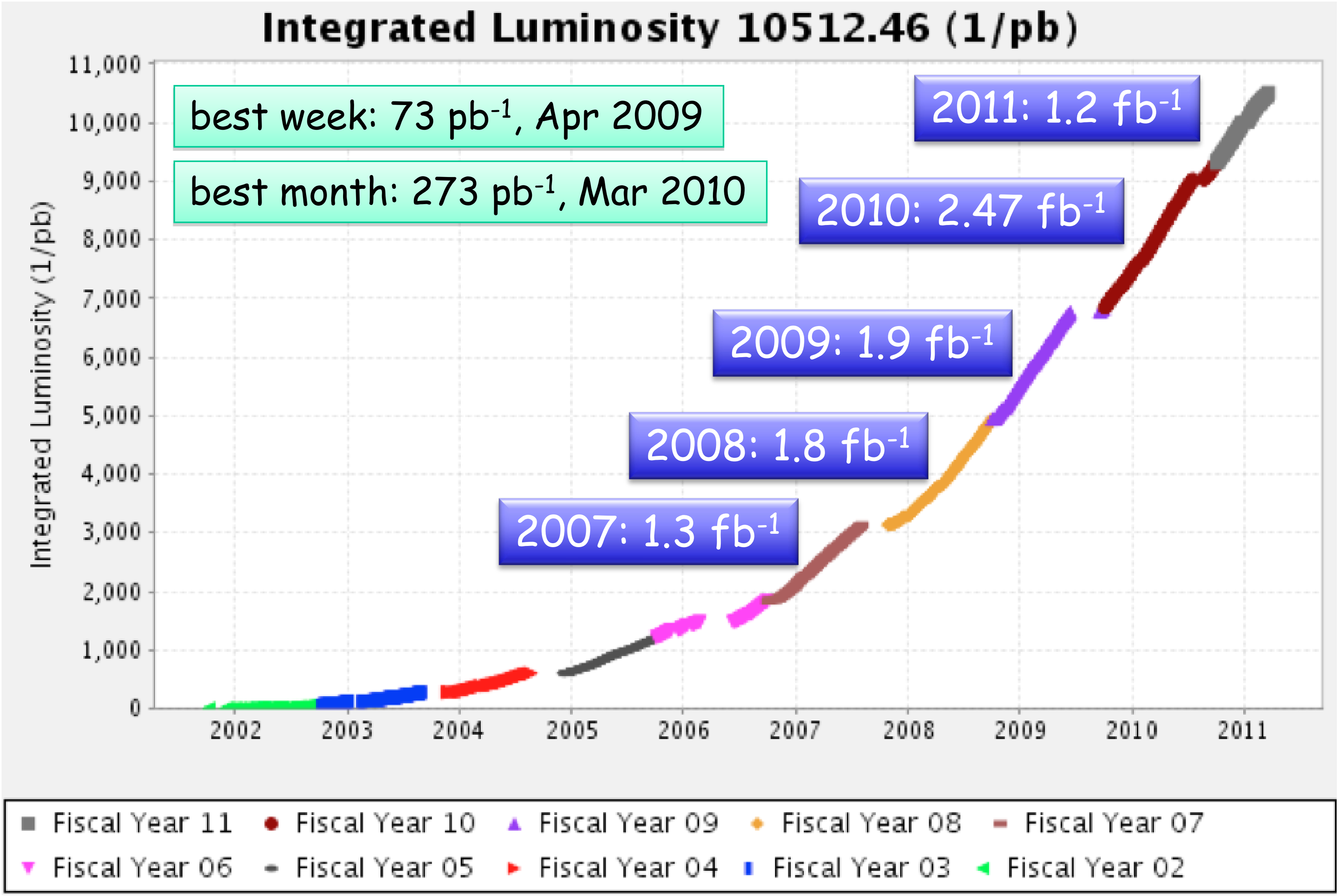
# Aerial View of the Tevatron



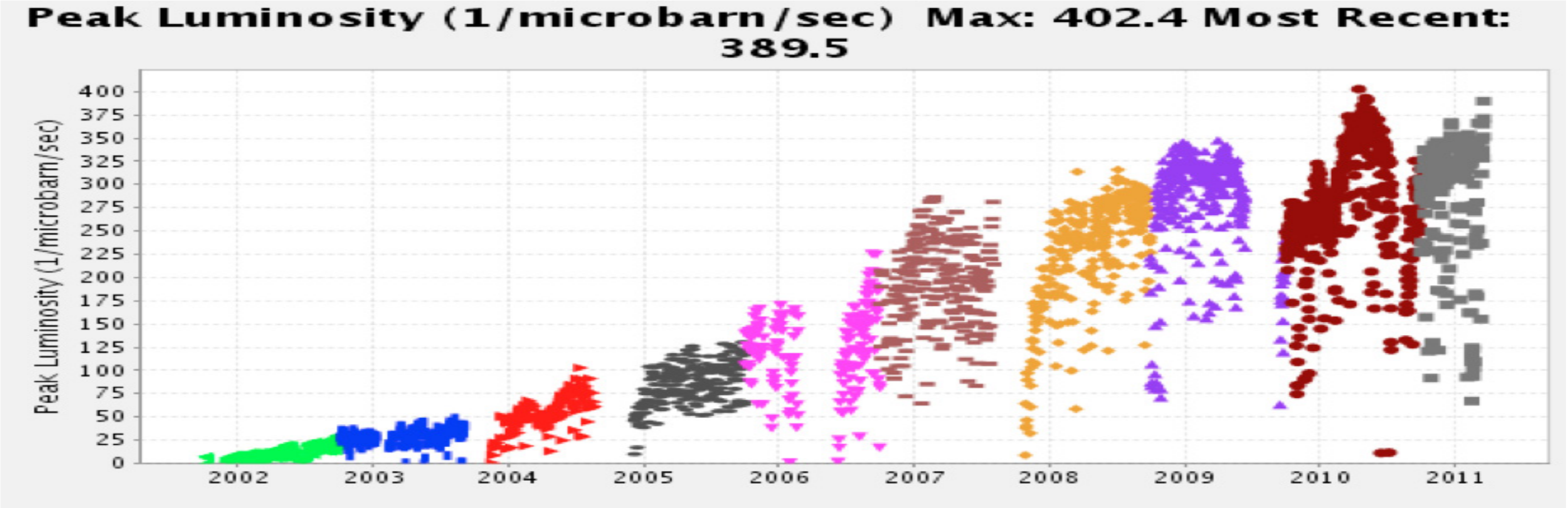
# Tevatron Parameters

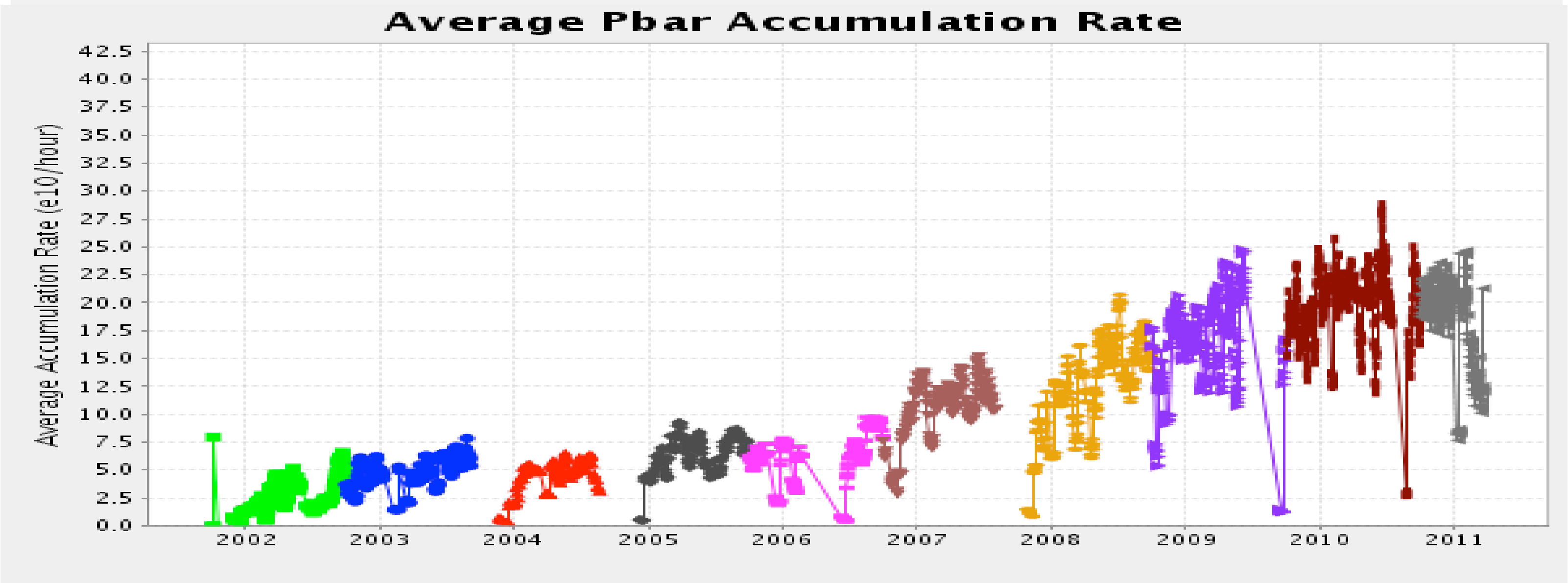
| | |
|---|---|
| Beam energy | 0.98 TeV |
| Number of bunches | 36 |
| Protons per bunch | $2.9 \times 10^{11}$ |
| Antiproton per bunch | $0.9 \times 10^{11}$ |
| Initial proton emittance (95% norm) | 18 $\mu$m |
| Initial antiproton emittance (95% norm) | 8 $\mu$m |
| Initial proton bunch length | 0.55 m |
| Initial antiproton bunch length | 0.45 m |
| $\beta$-function at IP | 0.28 m |
| Betatron tunes ($Q_x$,$Q_y$) | 20.583, 20.585 |
| Initial luminosity | $4.03 \times 10^{32}$ cm$^{-2}$s$^{-1}$ |
| Luminosity lifetime | 5 h |

# Tevatron Run II Integrated Luminosity

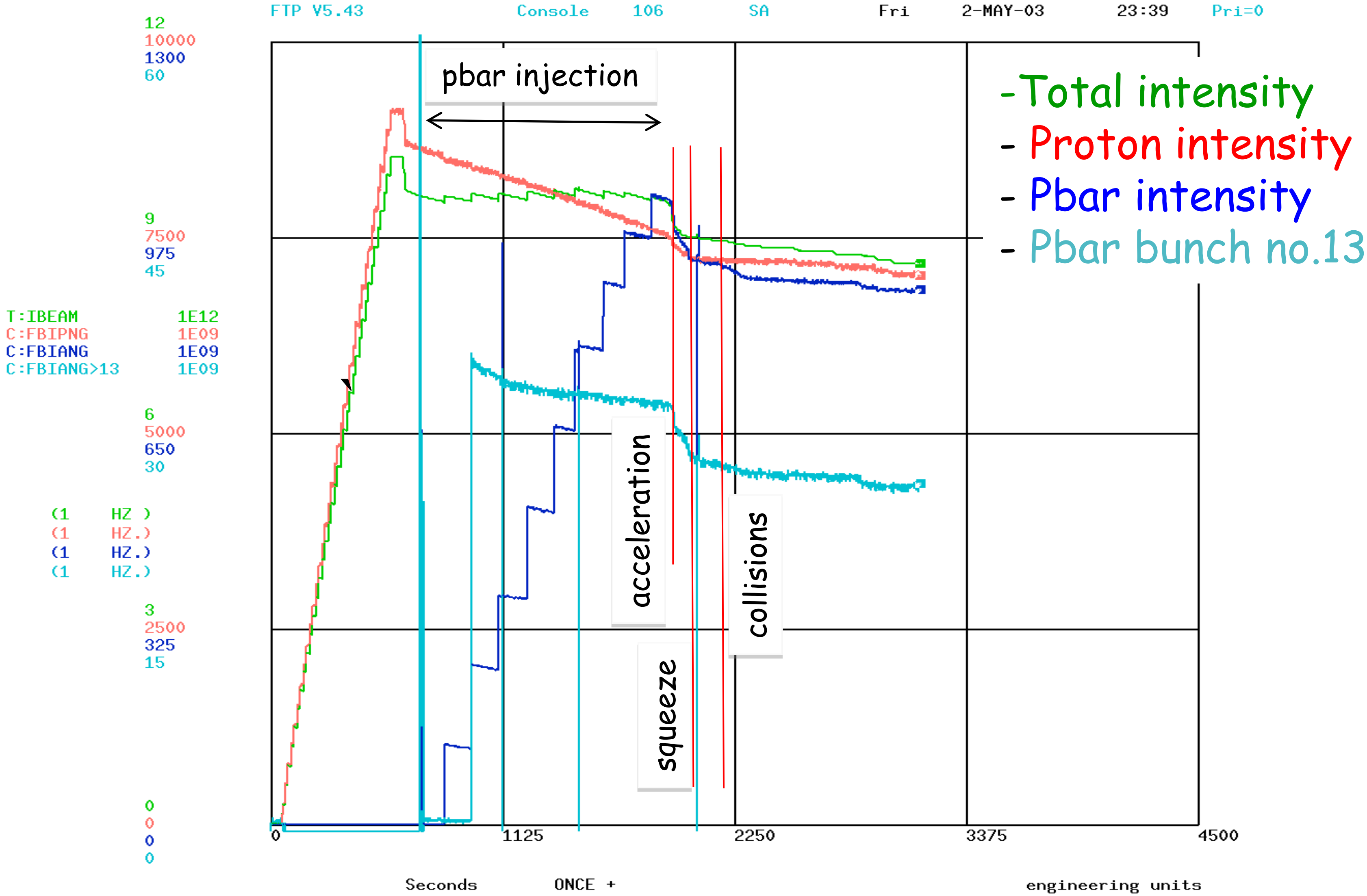


# Initial Luminosity and pbar Accumulation Rate



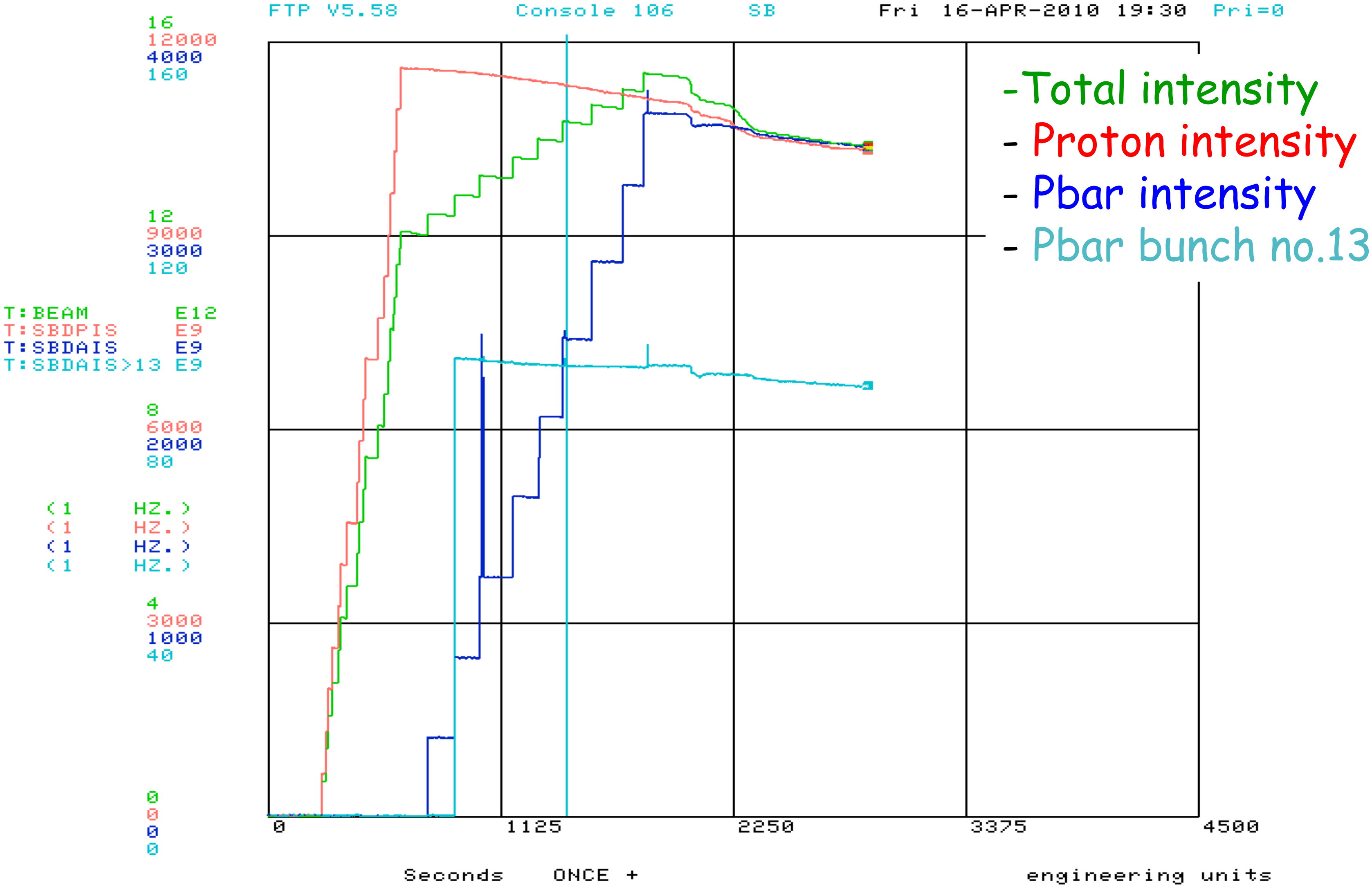



# Collider Fill Cycle for Store 2511 in 2003




Store 2511 $L_0$=0.4x$10^{32}$

# Collider Fill Cycle for the Record Store




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

# Contributions to Luminosity Loss and (Some) Fixes

| | |
|---|---|
| Proton lifetime at 150GeV: currently lose 5% protons and 1% antiprotons | Optimization of sextupoles |
| | Machine impedance (Lambertsons) |
| | Improved injection helix |
| Beam losses on ramp:<br><br>now ~2% | Better helix |
| | Improved coupling (repaired all 800 dipoles) |
| | Improved instrumentation |
| Beam losses in squeeze:<br><br>now 2% protons and <1% pbars | Better helix |
| | Collimation (2010) |
| | Improved aperture |
| $\beta^*$ and beam separation | Better lattice modeling |
| 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, etc. |

# Highlights of the Last Two Years

- Recycler storage efficiency
- Proton scraping in Main Injector
- Quench statistics and Collimation in the squeeze
- Operations strategy

# Recycler Ring (RR)

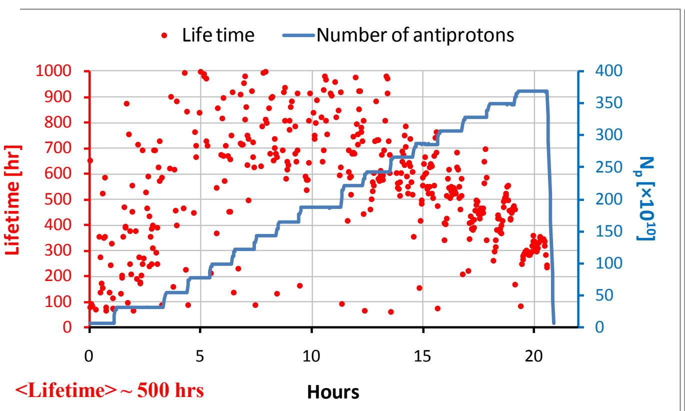
- 8 GeV antiproton storage ring located in the Main Injector (MI) tunnel
  - Accumulates antiprotons coming from the Accumulator and prepares the beam to be sent to the MI/Tevatron
    - Increases 6D phase density of antiprotons by a factor of 50
    - Permanent magnet-based
  - Every 40-50 min, (15 – 25)$\cdot 10^{10}$ antiprotons are transferred from Accumulator through MI in three parcels
    - Became possible with improved electron cooling and streamlined procedures
      - Initially: (40-50) $\cdot 10^{10}$ antiprotons every 75-90 min

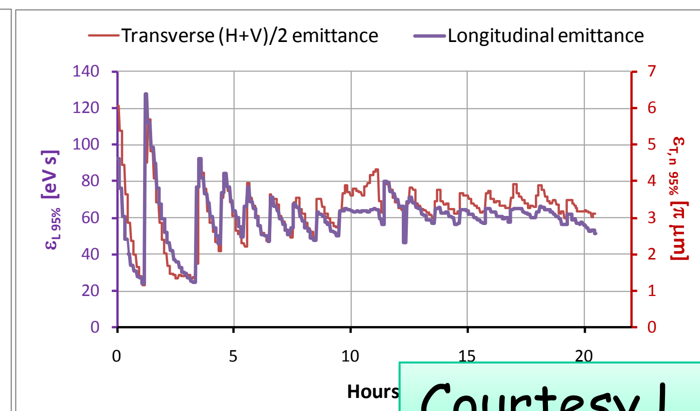

| | |
|---|---|
| Circumference | 3310.4 m |
| Momentum | 8.889 GeV/c |
| Vacuum | $< 5\cdot 10^{-10}$ Torr |
| Life time | up to 1000 hour |
| Max. number of stored antiprotons | $608 \times 10^{10}$ |
| Tunes (H/V) | 25.464/24.468 |

Equipped with stochastic and electron cooling

Typical Recycler accumulation cycle

At $N_p \sim$ (350 – 500)$\cdot 10^{10}$, antiprotons are transferred to MI for acceleration and injection into Tevatron

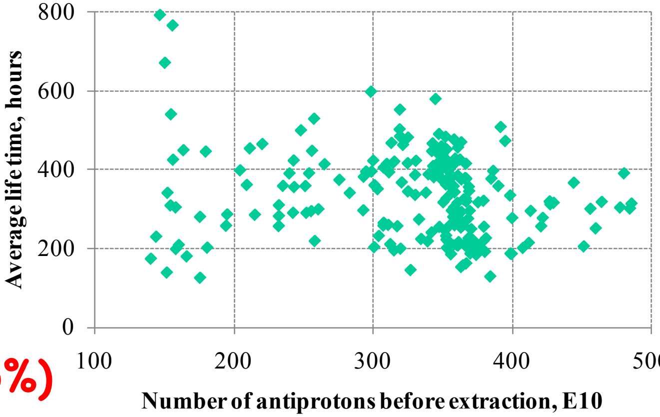



Courtesy L.Prost

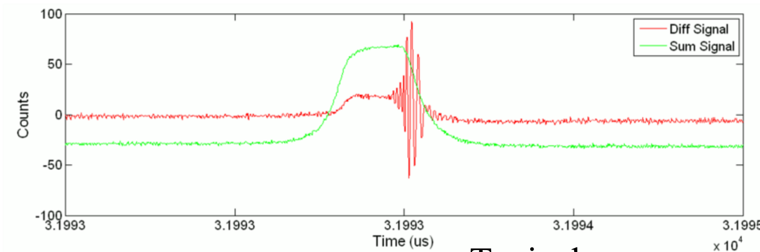
# Recycler Ring operation in 2009-2011

- The average life time improved to 200 - 400 h for Np= (300-525) × $10^{10}$
  - Procedures, improved RF manipulations, improved vacuum
  - The average life time is determined primarily by losses right after injections
    - In steady state, >500 h at 500 × $10^{10}$
  - Typical 'storage efficiency' is ~ 93% **(up 3-5%)**
    - Includes losses due to transfers and the finite RR life time




Average life time in RR vs the number of antiprotons in Aug 2010 – Feb 2011

- Brightness of the antiproton beam is limited by a transverse instability
  - The threshold depends on the longitudinal tails (See WEP114)



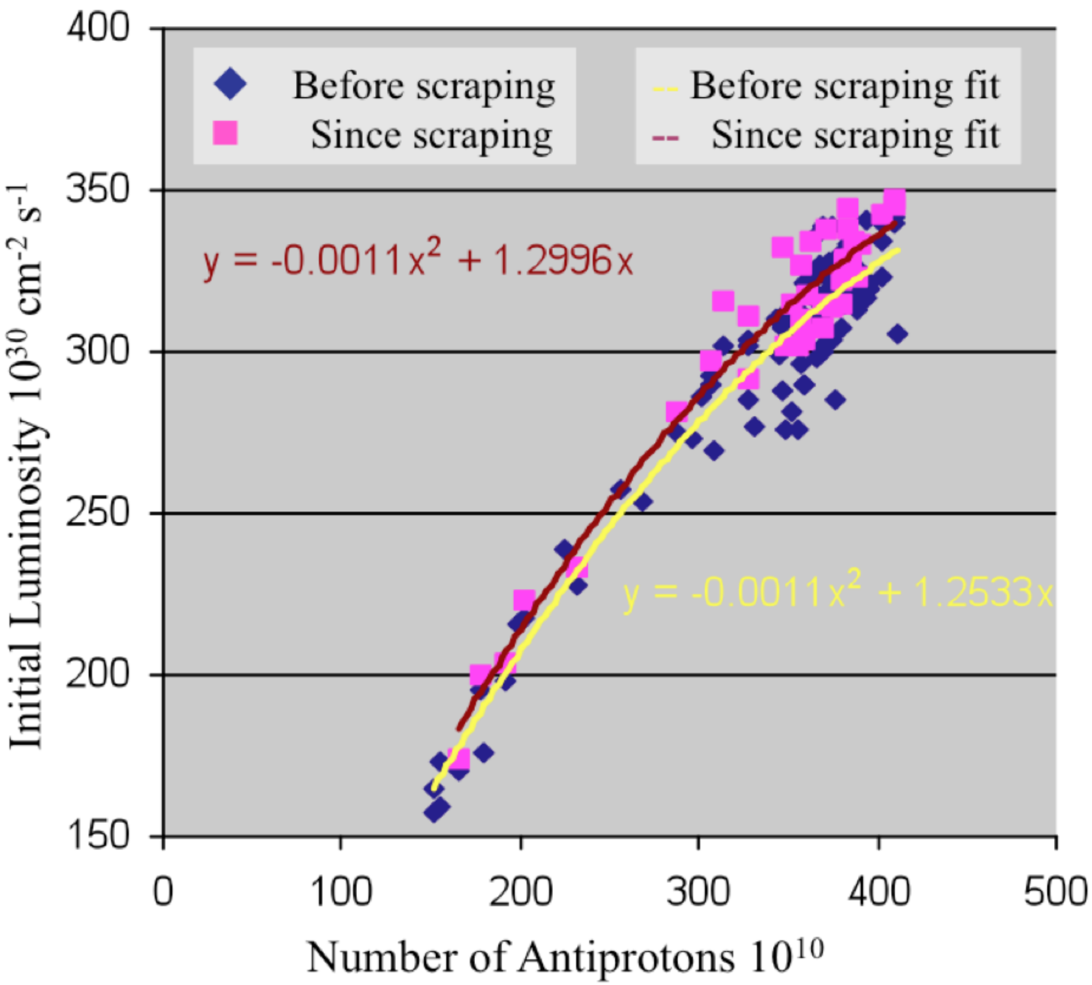

Typical oscillogram of an instability in RR.

- Additional flexibility
  - Capability to extract only a portion of the beam into the same 36 bunches

Also see WEP113, WEP228

Courtesy L.Prost

# Proton Scraping in MI



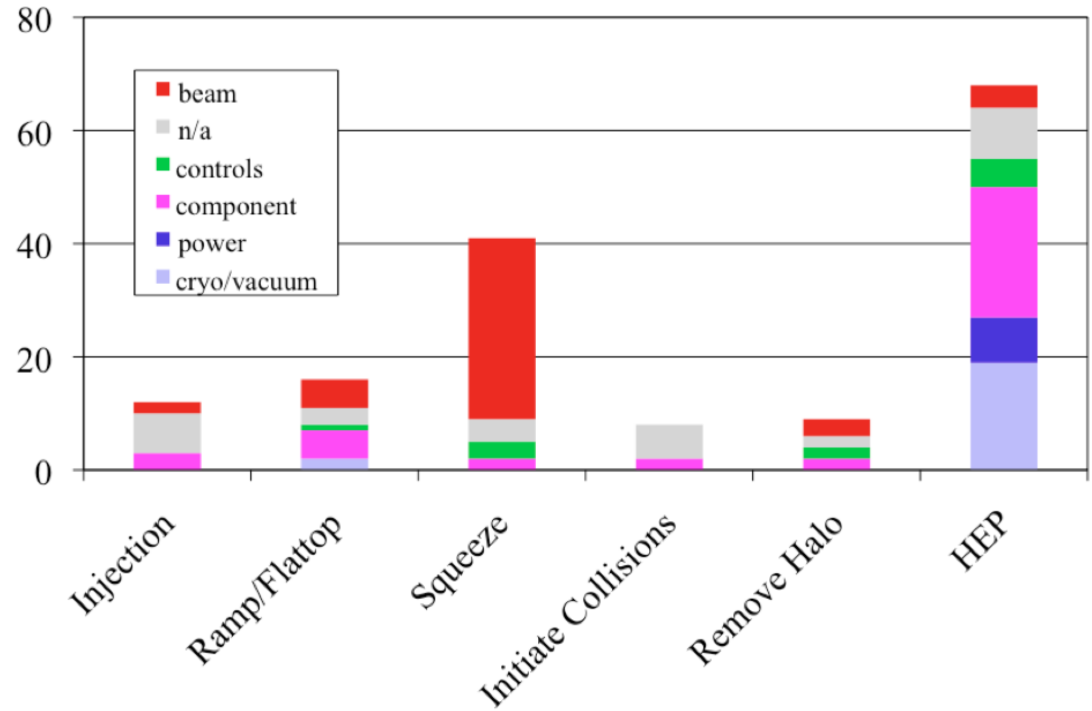

Momentum scraping of proton beam at injection in MI

**3-4%** increase of initial luminosity, better losses

Courtesy C.Gattuso

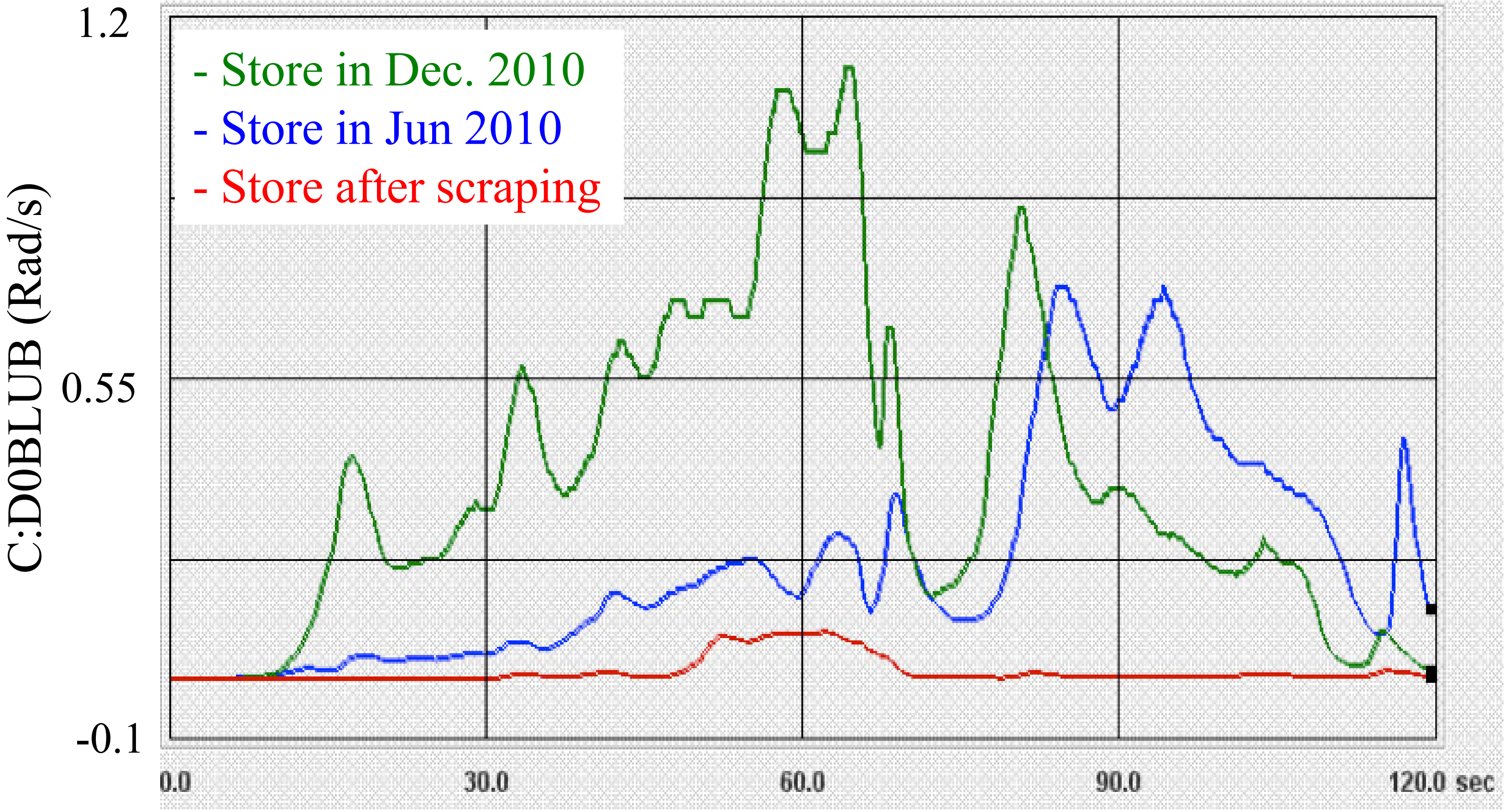
# Quench Statistics

- 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 doses lead to equipment failures at detectors

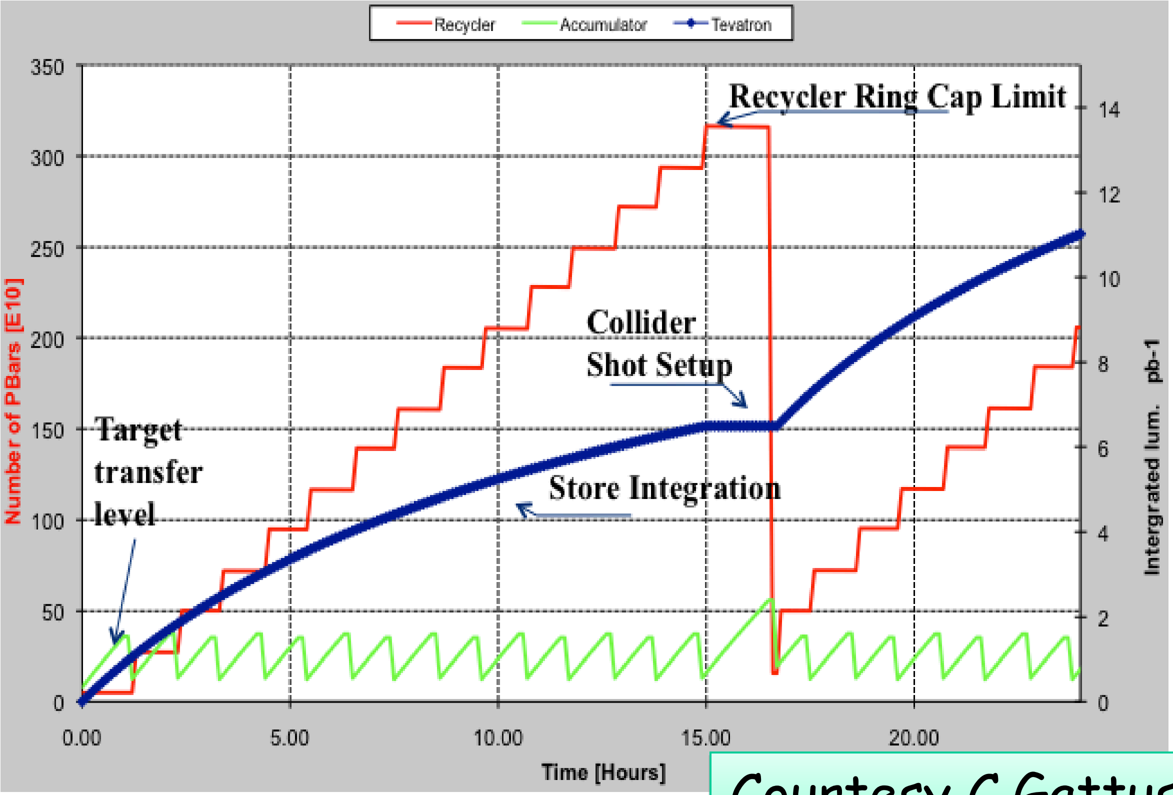
# Collimating Losses in Squeeze




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

# Operations Strategy

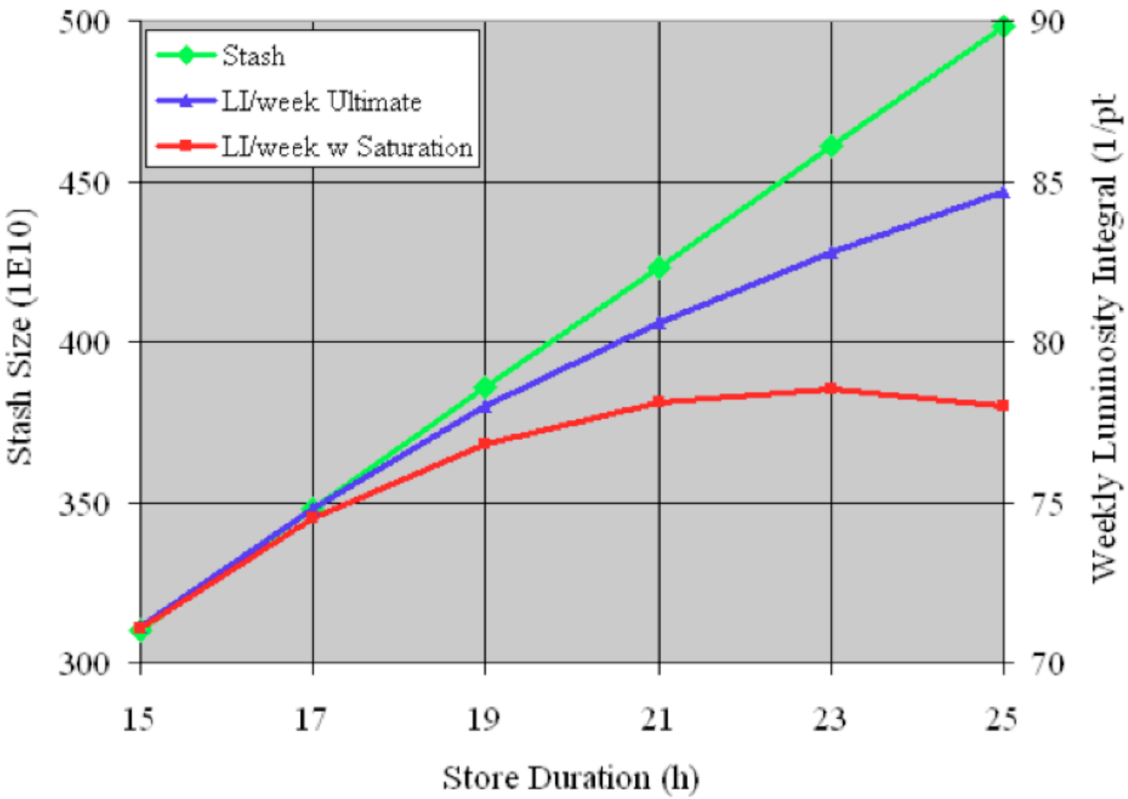
- Model of collider operation
  - Antiproton transmission efficiencies
  - Stacking rate in Accumulator as function of stack size
  - Pbar lifetime in Recycler
  - Tevatron initial luminosity and luminosity decay
  - Shot setup time




Courtesy C.Gattuso

# Optimization of Store Duration

- The model was used to determine the optimal operating parameters to maximize luminosity integral
  - Emphasis on repeatability of stores
  - Model allows to work around exceptions: schedule accesses, studies to minimize impact

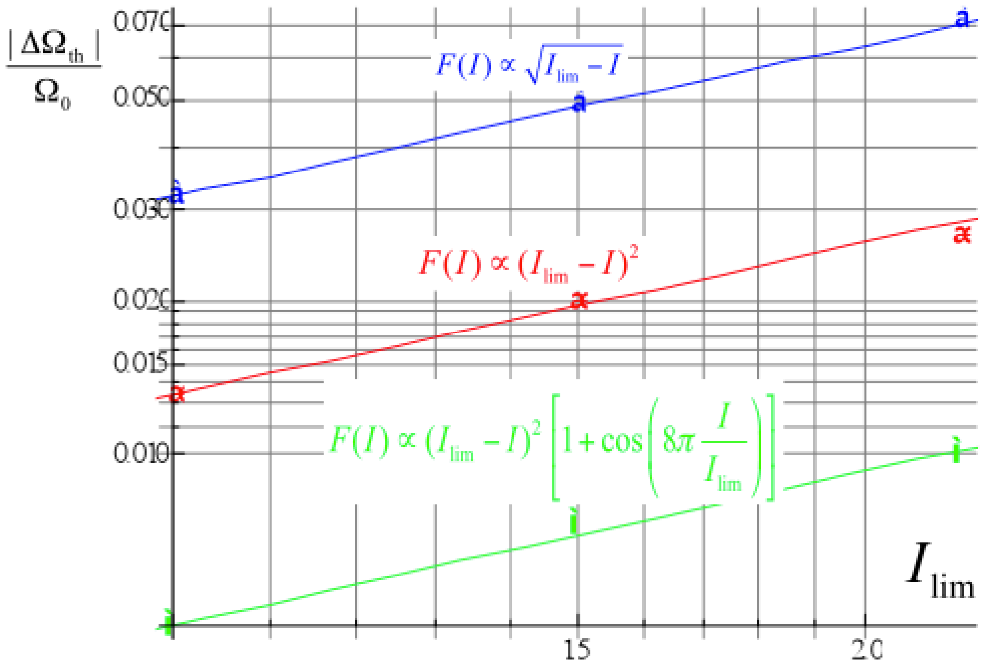


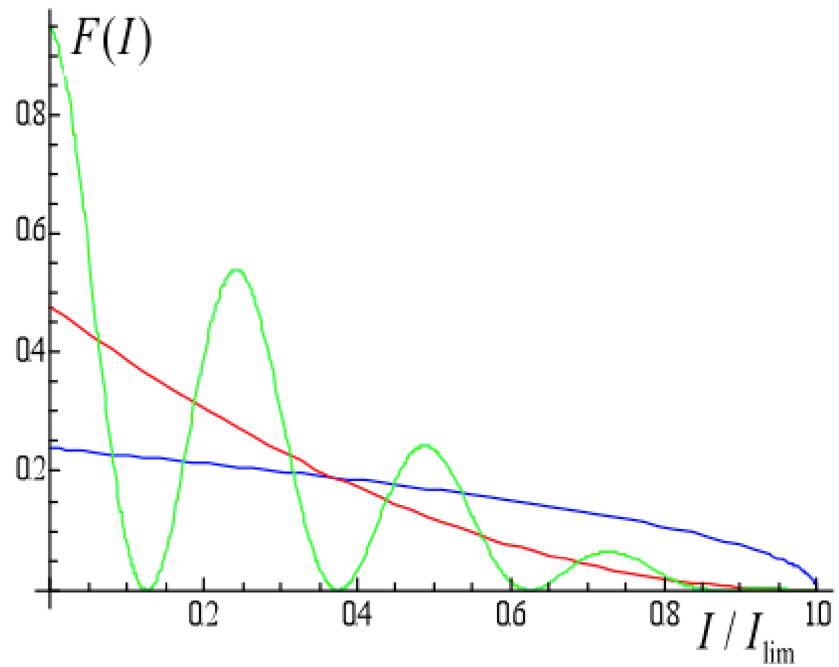
# Accelerator Physics Studies

- Stable machine allows time for studies of accelerator physics
- There is strong interest from Fermilab, CERN, LARP, BNL to use Tevatron for beam physics studies
  - A workshop was held in 2010 to collect the list of topics
  - Currently a program is being generated
- Some experiments are in progress (were done) parasitically or using end-of-store dedicated time:
  - Dancing bunches
  - Ghost modes
  - Beam-beam compensation
  - Crystal collimation
  - Hollow electron beam collimator

# Dancing Bunches

**LLD threshold tune shifts**

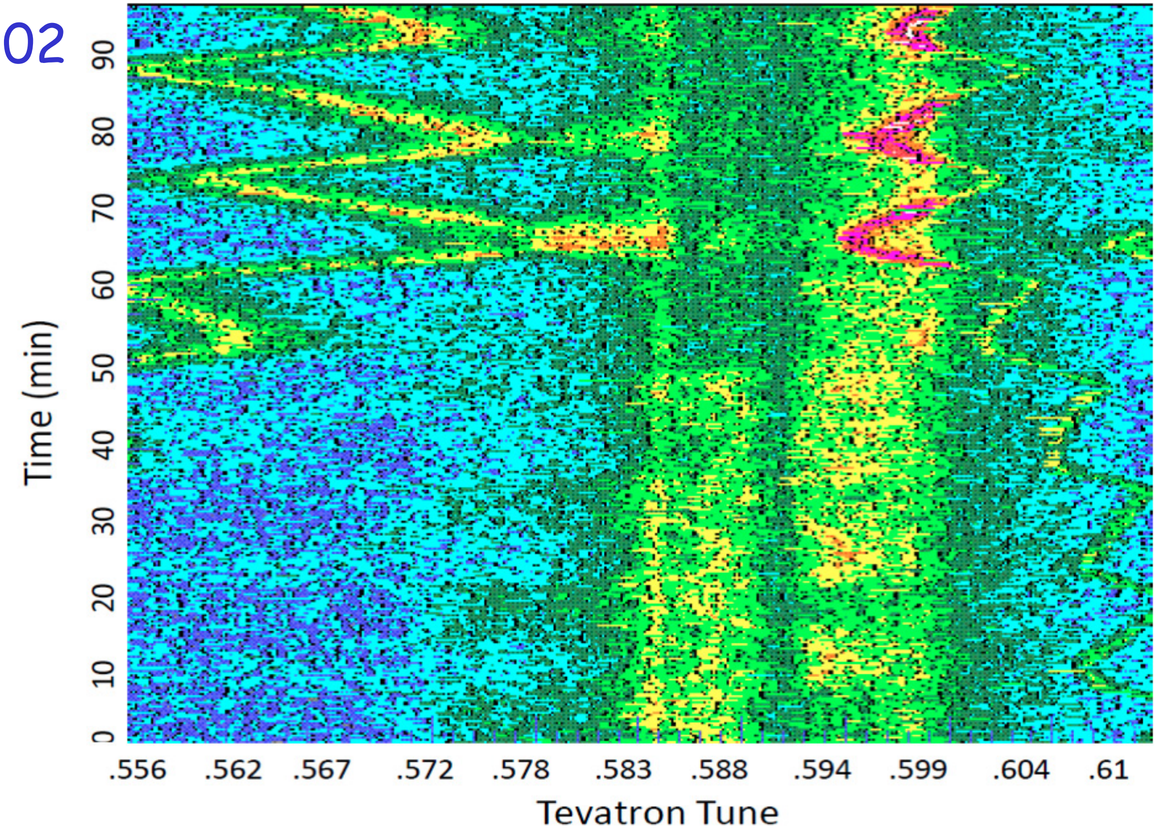


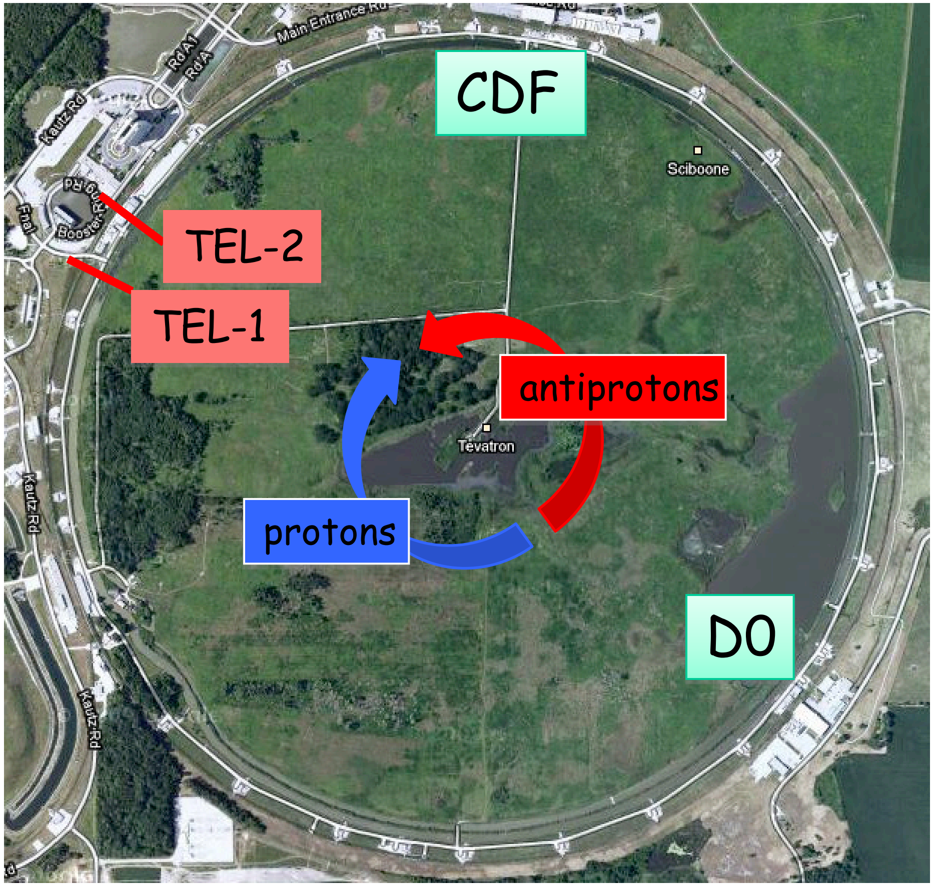

A.Burov talk MOODS4
experimental confirmation WEP116

# "Ghost" Modes

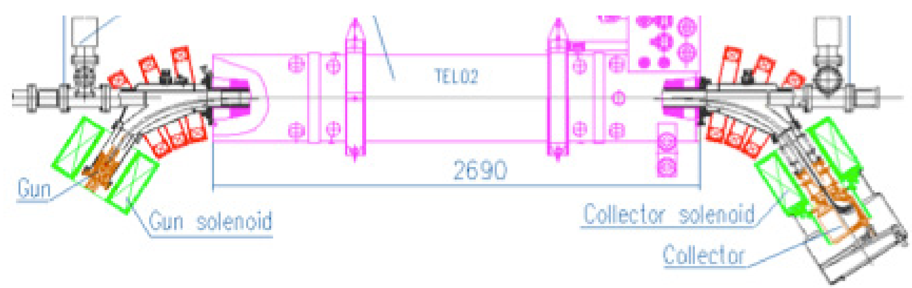
- Ghost lines were present in the Shottky spectra since the early days of Run II
  - They are not stable in time, oscillating with period 15 min to hours
  - Move by as much as 0.02
  - Estimated effect on emittance growth is 0.06 $\pi$ mm mrad/h



# Tevatron Electron Lenses



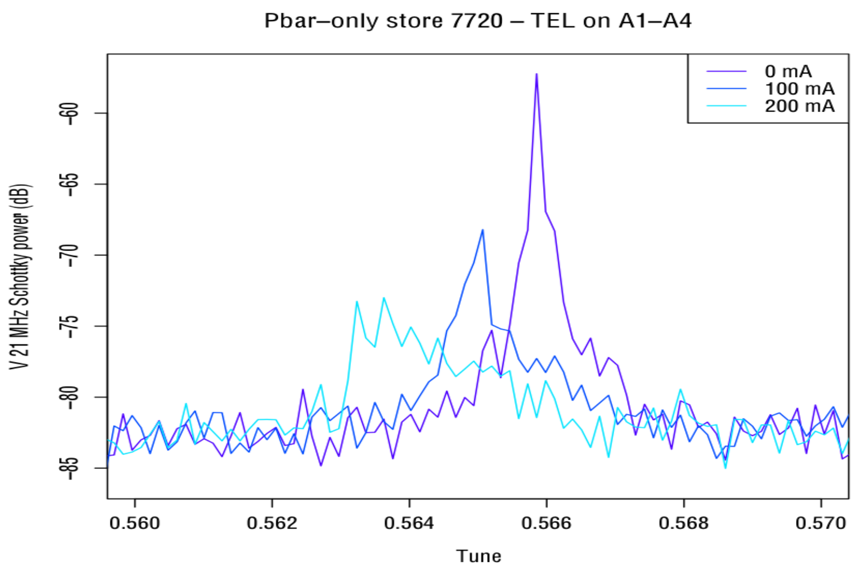

| | |
|---|---|
| e- beam energy | < 10 kV |
| Peak e- current | < 3 A |
| Solenoid B-field | 30 kG |
| Gun B-field | 3 kG |
| e- beam radius (SEFT) | 2.3 mm |
| Interaction length | 2 m |
| TEL-1 $\beta x/\beta y$ | 95/32 m |
| TEL-2 $\beta x/\beta y$ | 66/160 m |



# Electron Lens for Beam-Beam Compensation

LARP

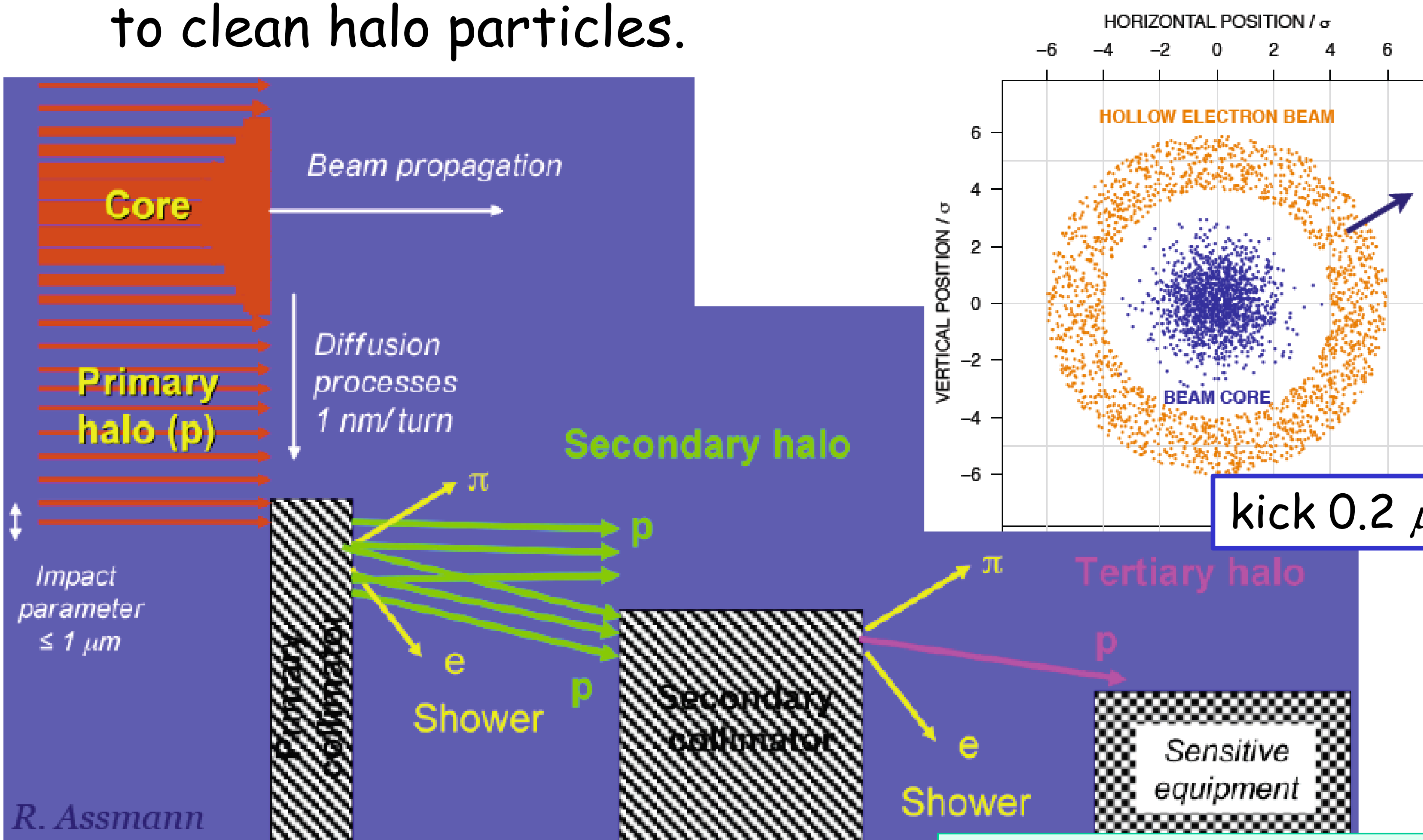
- With Gaussian profile electron beam overlapping with antiprotons, a number of studies were performed
  - Tune shift and tune spread measurements
  - Effect of misalignments
  - Tune scans to determine the effect of TEL on resonances




G.Stancari talk MOODN1

# Collimation with Hollow Electron Lens

- Use hollow profile electron beam as slow diffuser to clean halo particles.

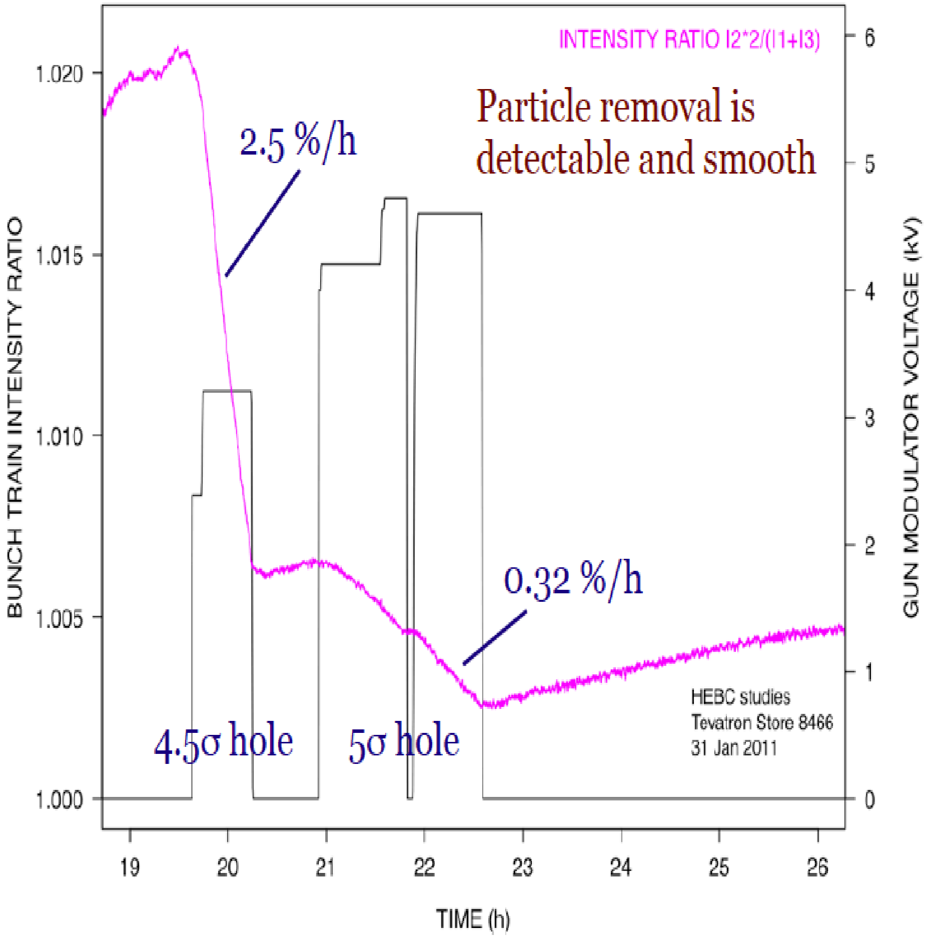


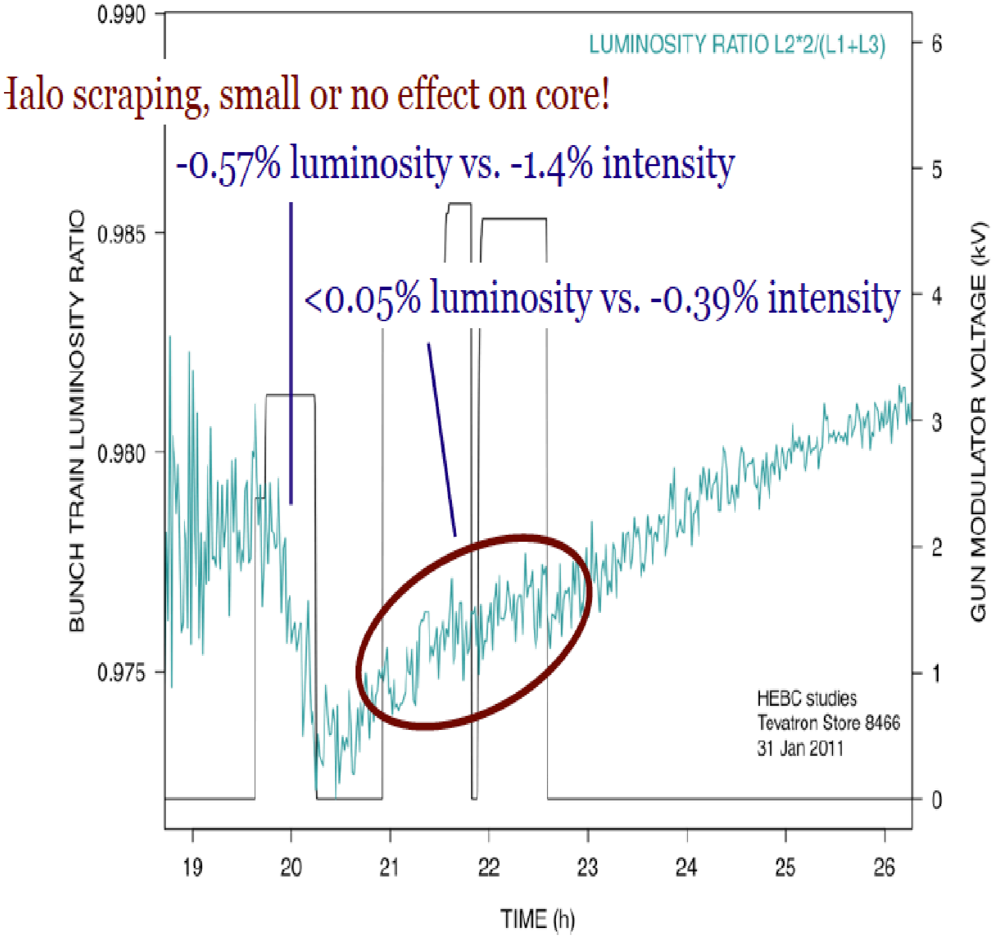

kick 0.2 μrad

G.Stancari et al., MOP147

# Collimation with Hollow Electron Lens

- Hollow e- gun was designed, built and tested
- Installed in TEL-2 in 2010
- First experiments on collimation are successful: demonstrate scraping beam intensity without negative effect on luminosity!



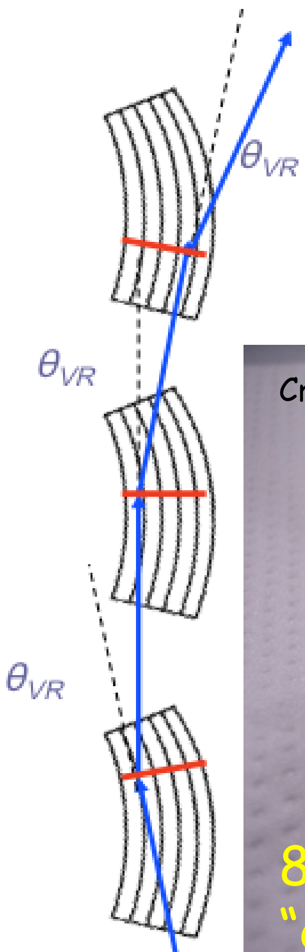



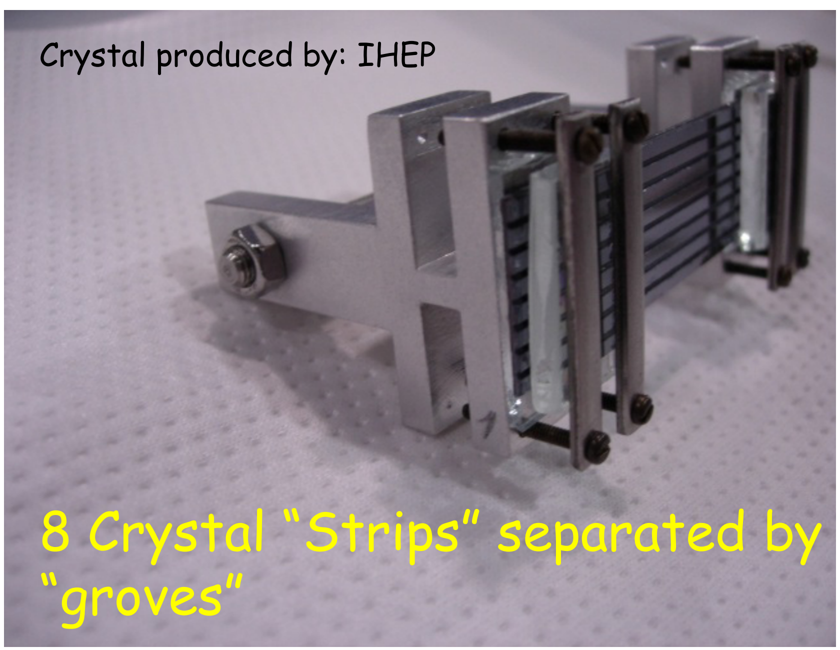
# Collimation with Bent Crystals

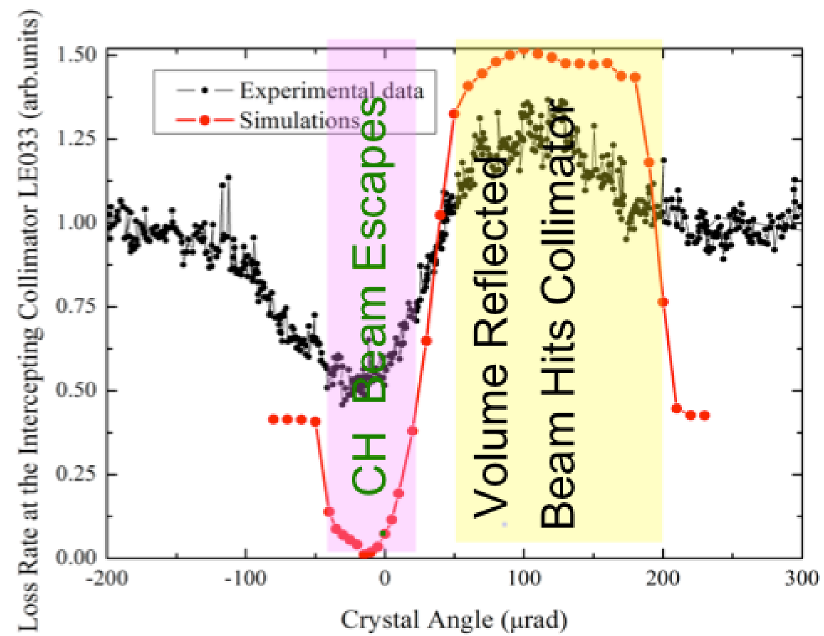
- Deflect halo particles by a large angle using bent crystals
  - Repeated Volume Reflections in an array of parallel crystals results in larger deflection, *e.g.* at $E$=1 TeV:

$$One\ crystal \quad \theta_{VR} = 8\,\mu rad;\ \theta_{bend} = 200\,\mu rad$$

$$8\ crystals \quad \theta_{VR} = 8\times 8 = 64\,\mu rad$$




V.Zvoda talk MOODN1

# Summary

- Numerous improvements in the Tevatron collider complex allowed stable operation at initial luminosities of 3.5-4 $\times 10^{32}$ $cm^{-2}s^{-1}$
- The weekly integrated luminosity exceeded 70 $pb^{-1}$, average ~50 $pb^{-1}$
- For a 25 year-old machine, the Tevatron is exceptionally reliable averaging 110-120 hours of HEP time per week
- Recent operational improvements targeted mostly reliability and efficiency of operations and account for approx. 10-13% of luminosity
- Tevatron is a test bed for many accelerator physics experiments
  - Beam collimation
  - Beam-beam effects and their compensation
  - Beam dynamics
  - Instrumentation and optics