An Overview of Tevatron Collider Run II at Fermilab

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- Overview of the Accelerator Complex
  - Main Injector
  - Pbar Source
  - Recycler
- Tevatron Performance and Issues
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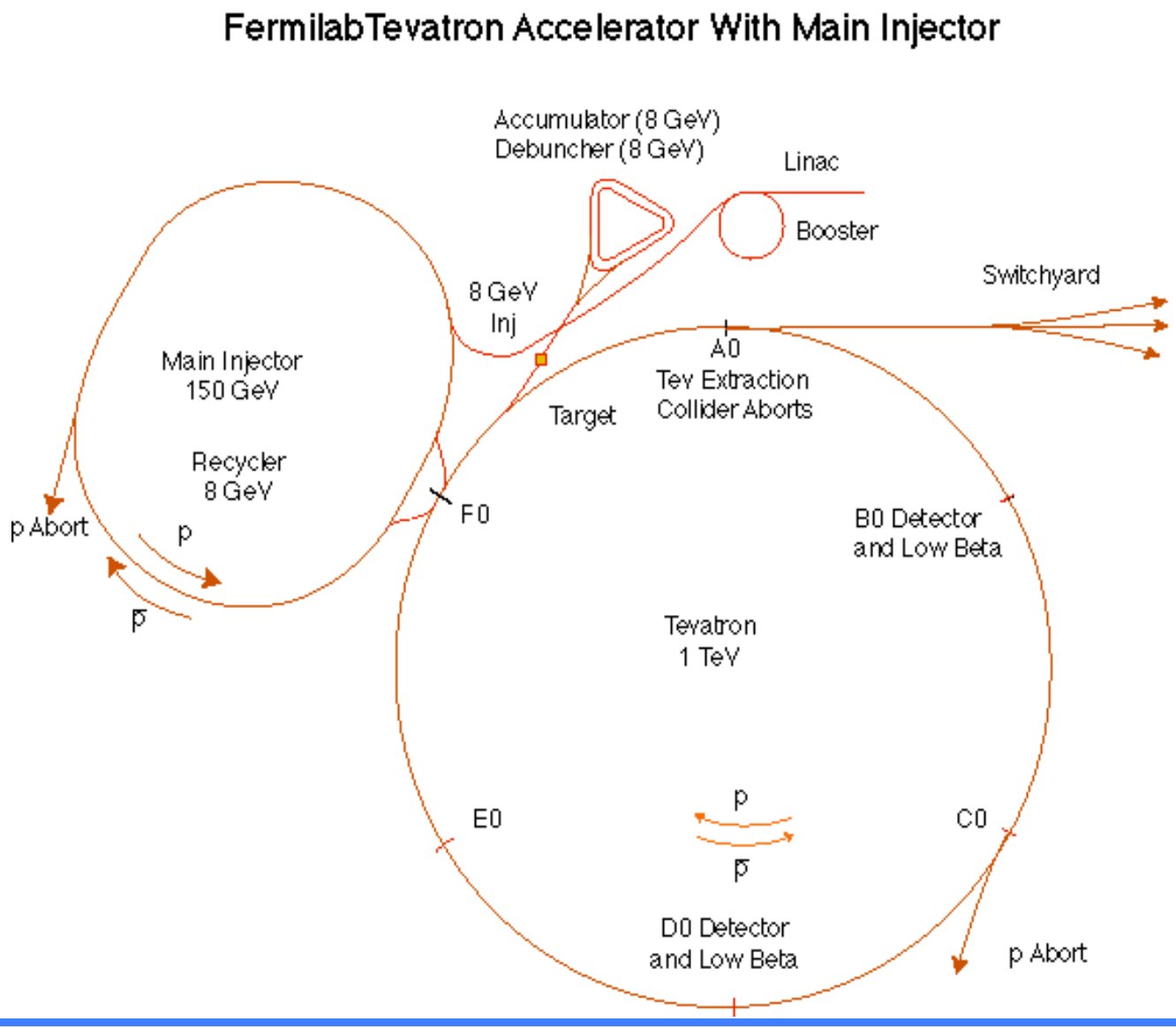
Fermilab Accelerator Complex



What's new/different for Run II?

- Main Injector
  - Replaces the Main Ring (was inside Tev tunnel)
- Recycler Ring
  - 8 GeV storage ring for pbars in MI tunnel
- Tevatron
  - # bunches: was 6x6, now 36x36
  - Beam energy: was 900 GeV, now 980 GeV
  - New two-stage collimation system

- Run IIa – deliver 2 fb^{-1}, peak $\mathcal{L}$ = 8.6 E 31 cm^{-2} s^{-1}
- Run IIb – deliver > 5 fb^{-1}, peak $\mathcal{L}$ = 2-5 E 32 cm^{-2} s^{-1}

Proton Source

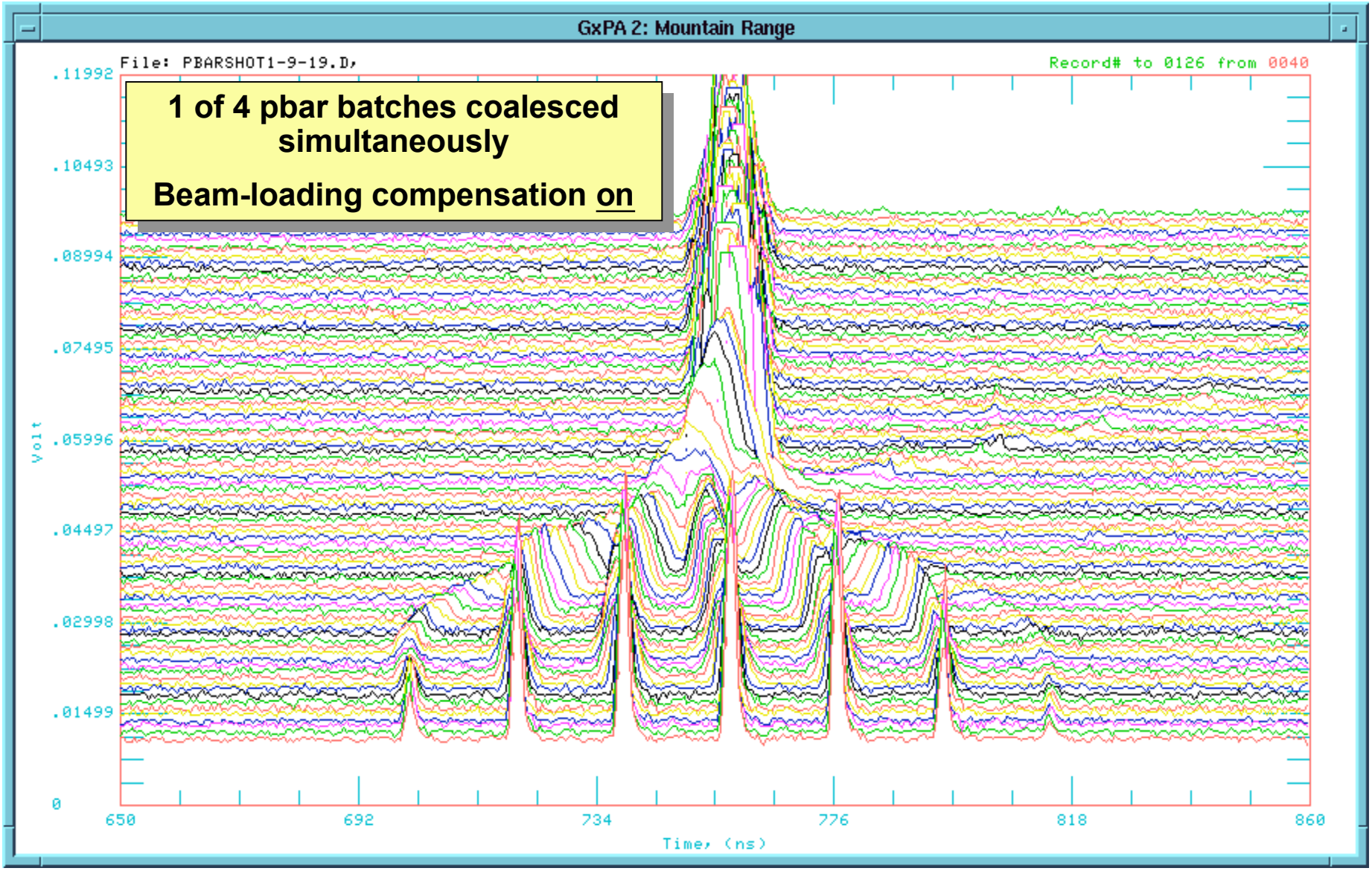
- 25 keV H^- ion source
- 750 keV Cockcroft-Walton accelerator
- Linac: accelerate H^- to 400 MeV
  - 116 MeV Alvarez linac (201.25MHz)
  - 400 MeV side-coupled cavity linac (805 MHz)

- Booster: 8 GeV synchrotron
  - Stripper foil at injection removes e^-
  - Output = 4.5-5.0 E12 in 84 bunches
  - Longitudinal emittance ~0.15 eV-sec

Main Injector (MI)

- Replaced Main Ring (formerly in Tev tunnel)
  - Higher rep rate for stacking
  - Simultaneous stacking and fixed target running
- Many operating modes
  - Pbar production: up to $5*10^{12}$ 120 GeV protons
  - Tevatron protons/pbars:
    - Accelerate 8 GeV to 150 GeV
    - Coalesce 7-9 proton bunches 90% eff into 270-300 E9 bunch
    - Coalesce 7-11 pbar bunches 75-85% eff into 20-30 E9 bunch
  - Transfer 8 GeV pbars Accumulator Recycler
  - Provide protons for neutrino production

f Pbar Coalescing in Main Injector



Pbar Source

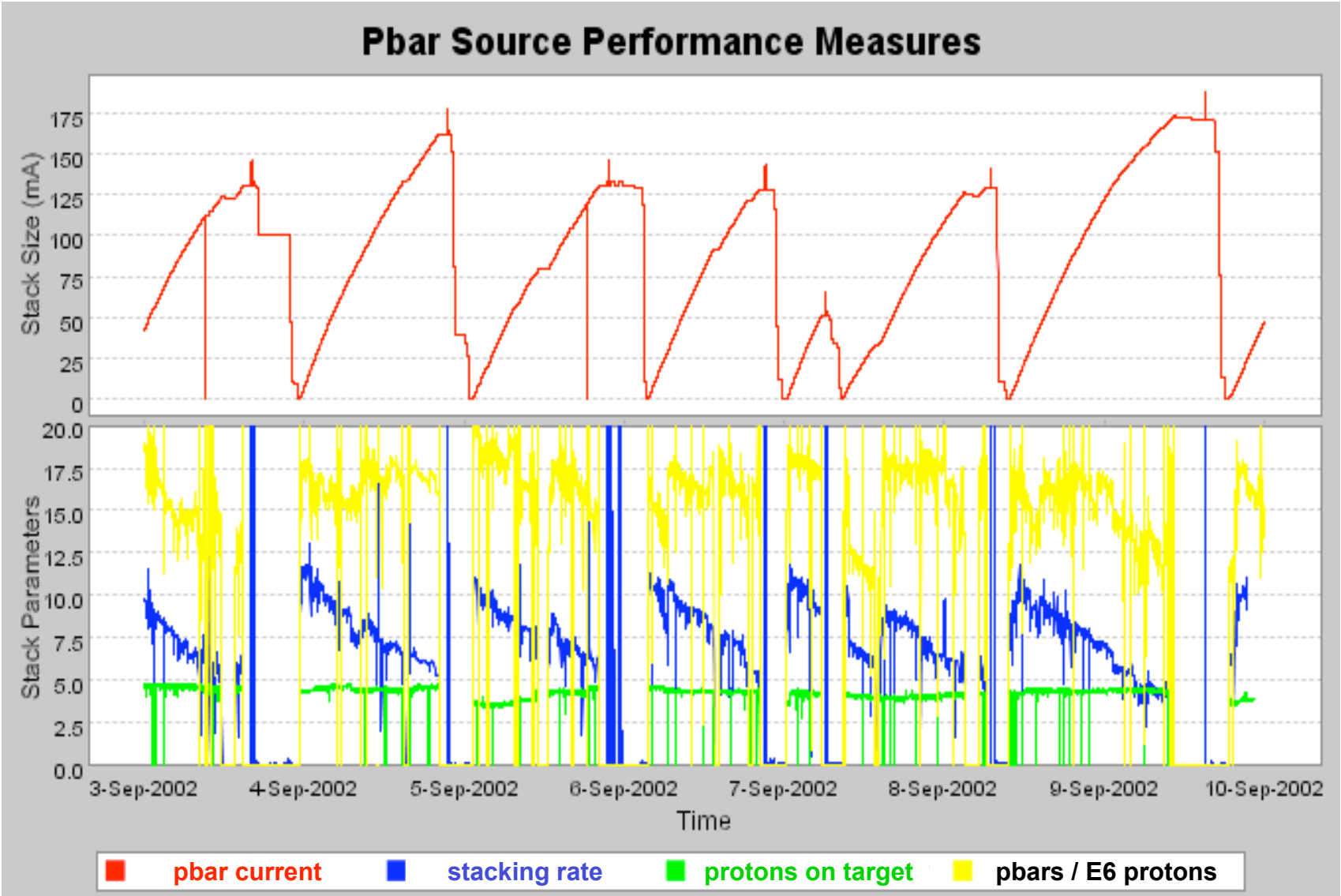
- Up to $5*10^{12}$ p (120 GeV) strike Ni target
- Li lens (740 Tesla/m) collects neg secondaries
- Pulsed dipole bends pbars down transfer line toward Debuncher, Accumulator
- Stack rate = 6-11 mA/hr depending on stack size
- Efficiency ~ $(13\text{-}18)*10^{-6}$ pbars/proton on target
- Transverse emittances vary linearly with stack size
  - New core cooling system and lattice optimized for shots allow 5-12 π mm*mrad (95%) for typical stacks

Pbar Production Goals

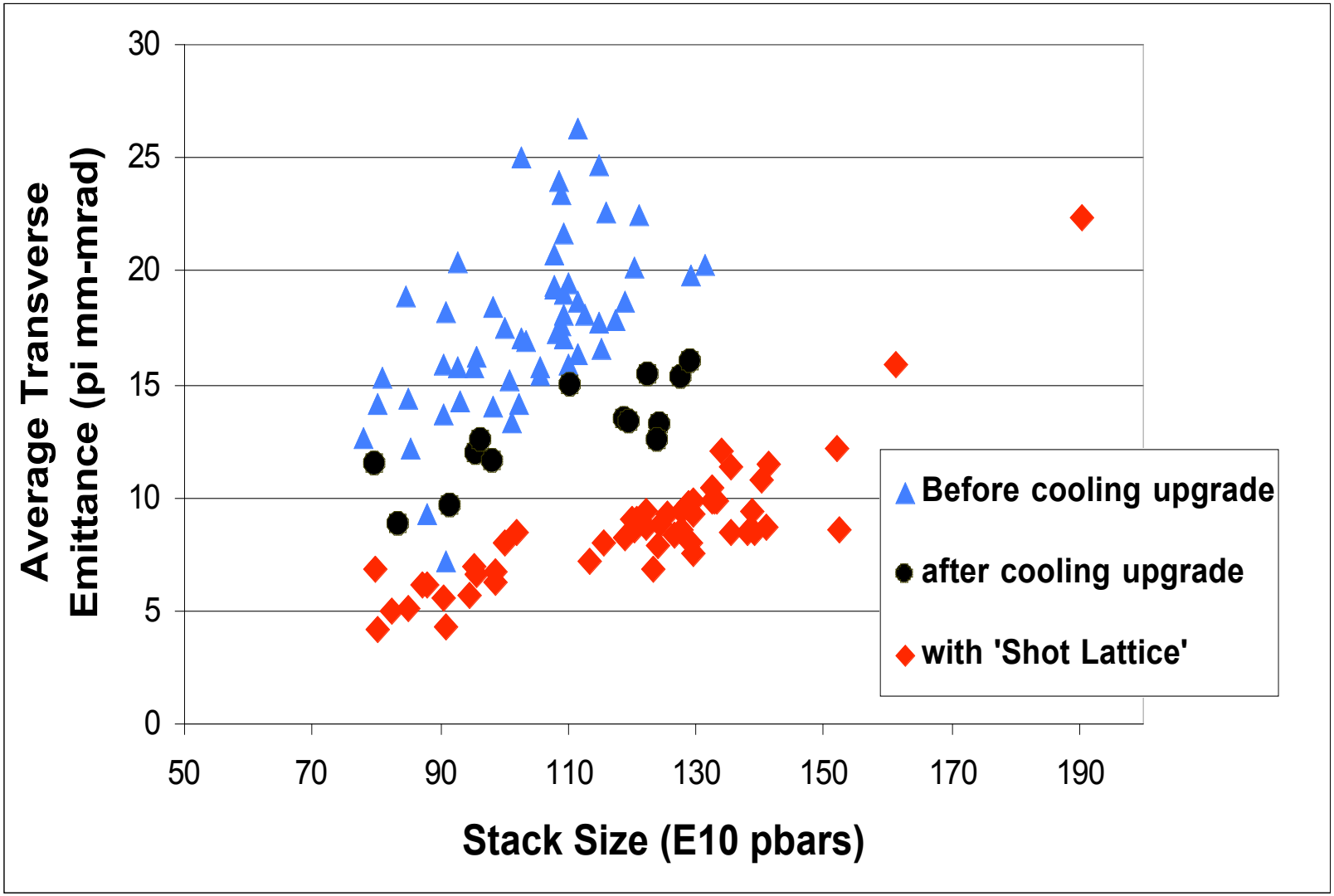
	Current	Run IIa goal
Protons/pulse on target (E12)	4.2-4.5	5
Stacking cycle rep rate (s)	2.5	< 2
Max pbar stack rate (E10/hr)	12.4	18
Max pbar stack (E10)	190	165

- Plans to increase stacking rate
  - Raise proton intensity on target
  - Decrease cycle time - want < 2.0 sec
  - Improve collection efficiency
    - Increase Li lens gradient
    - Increase aperture of transfer line target station Debuncher

Pbar Stacking for 1 Week



Pbar Transverse Emittance vs Stack Size



Recycler Ring (RR)

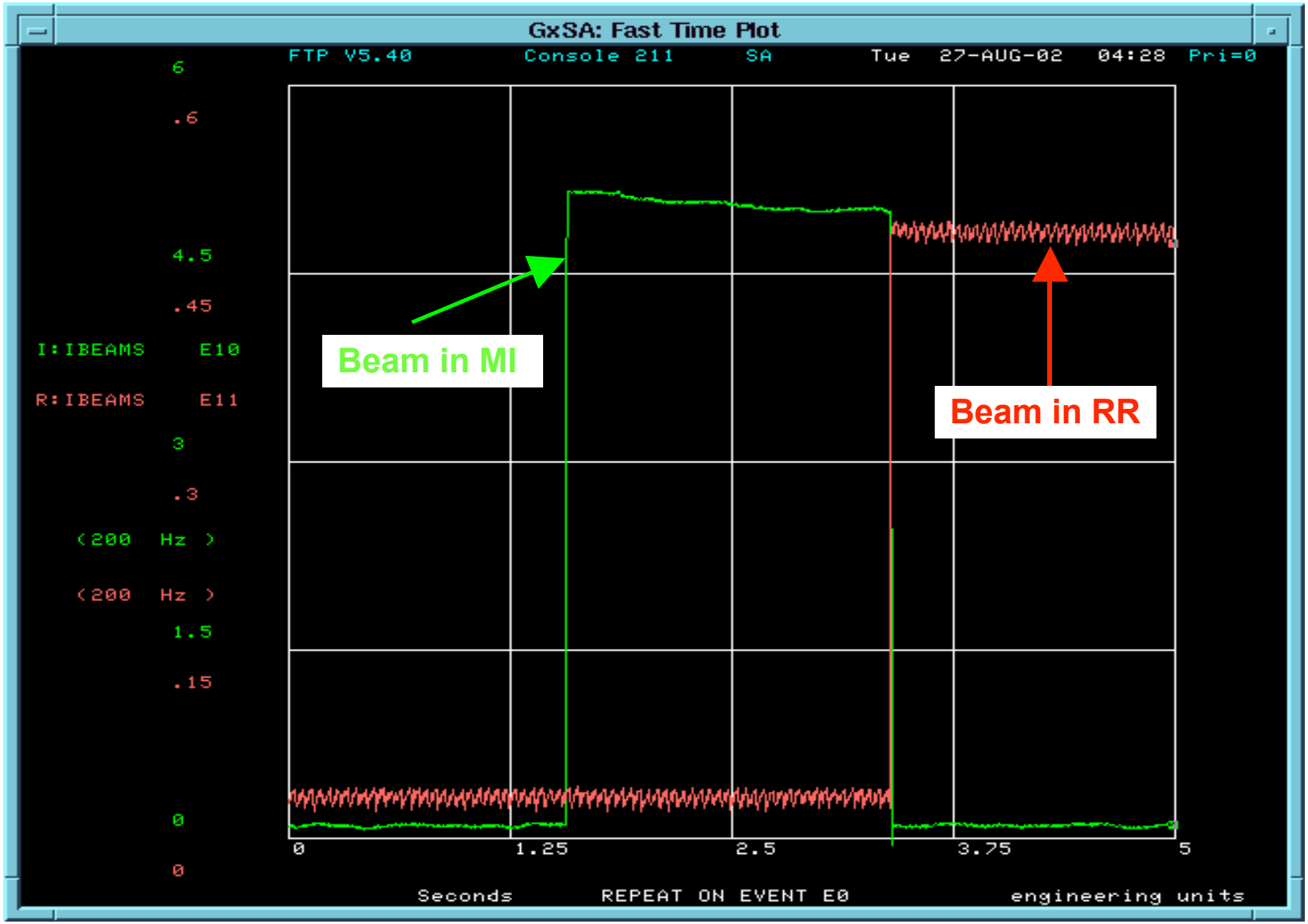
- 8 GeV storage ring for pbars in MI tunnel
  - Shoot small pbar stacks from Accumulator → Recycler to maintain higher stacking rate in Accumulator
  - Recycle pbars left (50-70%) after Tevatron store
- MI → RR pbar injection efficiency > 90%
- Stacking efficiency → 70%
  - Problem with RF manipulations understood
- Stochastic cooling commissioned
  - 10 → mm mrad/hr cooling rate (not yet optimized)
  - 3-4 → mm mrad/hr heating rate (beam-gas interactions)
- Achieved 110 hr lifetime for 40E10 pbars
  - With MI ramping, cooling

Recycler Plans and Goals

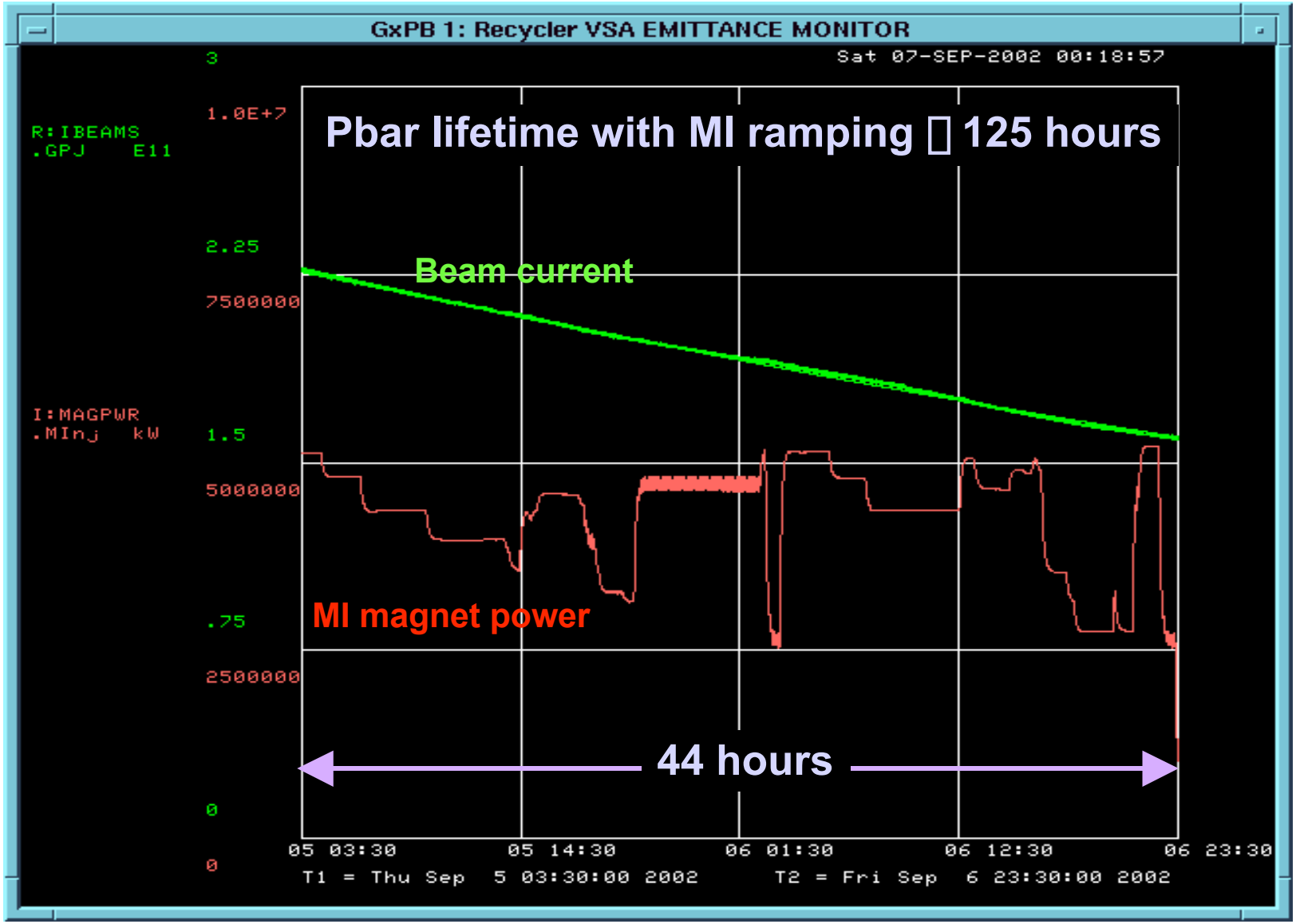
	Goal
Stored pbar intensity (E12)	2
MI → RR efficiency	95%
Stacking efficiency	90%
Lifetime with 2 E12 pbars (hr)	> 200
Emittance (π mm mrad)	< 10

- Improve vacuum to reduce heating rate factor 3-4
  - Double # ion pumps, improve bake out system
- Upgrade BPMs, IPMs, Schottky detectors
- Integrate RR into operations in 2003

Recycler Injection Efficiency



Recycler Stored Pbar Lifetime



Tevatron Overview

- Collides 36□36 protons and pbars @ 980 GeV
- Radius = 1 km
- 2 low □ intersection points
- 1113 RF buckets (53.1 MHz)
- 3 trains of 12 bunches with 396 ns separation
- Emittances at start of stores: 18-22 □ mm mrad (95%)
- Bunch lengths at store start: proton/pbar 2.1/1.8 ns
- Overall efficiencies
  - protons MI □ HEP: 55-65%
  - pbars Accumulator □ HEP: 40-50%

f Tevatron Luminosity Formula

$$L = \frac{10^{-6} f\, B\, N_p N_{\bar{p}} (6\beta_r \gamma_r)}{2\pi\beta^* (\varepsilon_p + \varepsilon_{\bar{p}})} H(\sigma_l / \beta^*)$$ **(10^{31} cm^{-2} sec^{-1})**

f = revolution frequency = 47.7 KHz

B = # bunches = 36

$\beta_r \gamma_r$ = relativistic beta x gamma = 1045

β^* = beta function at IR = 35 cm (can reduce to 30cm?)

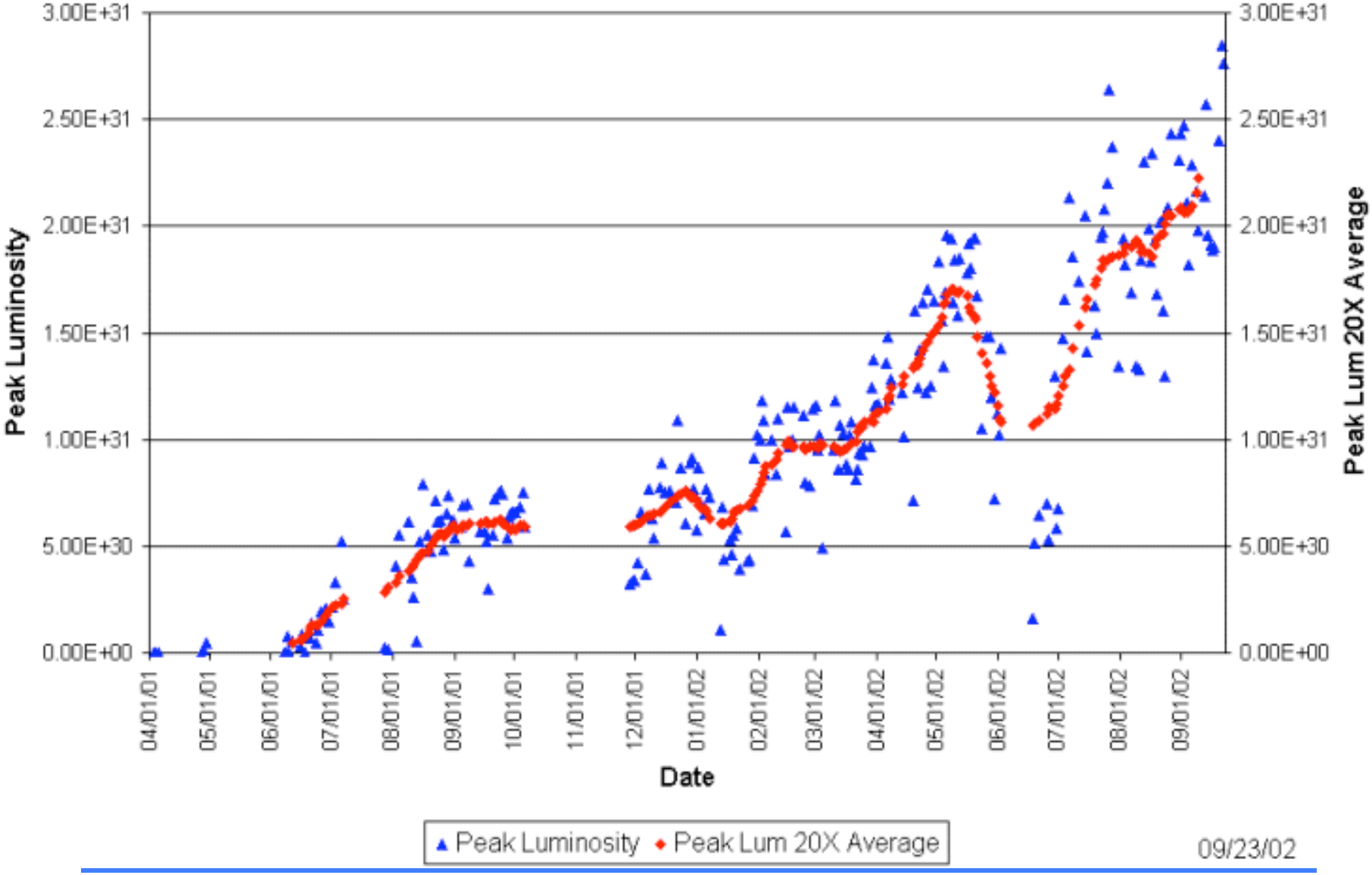
H = hourglass factor = .60 - .75

N_p , N_{pbar} = bunch intensities (E9)

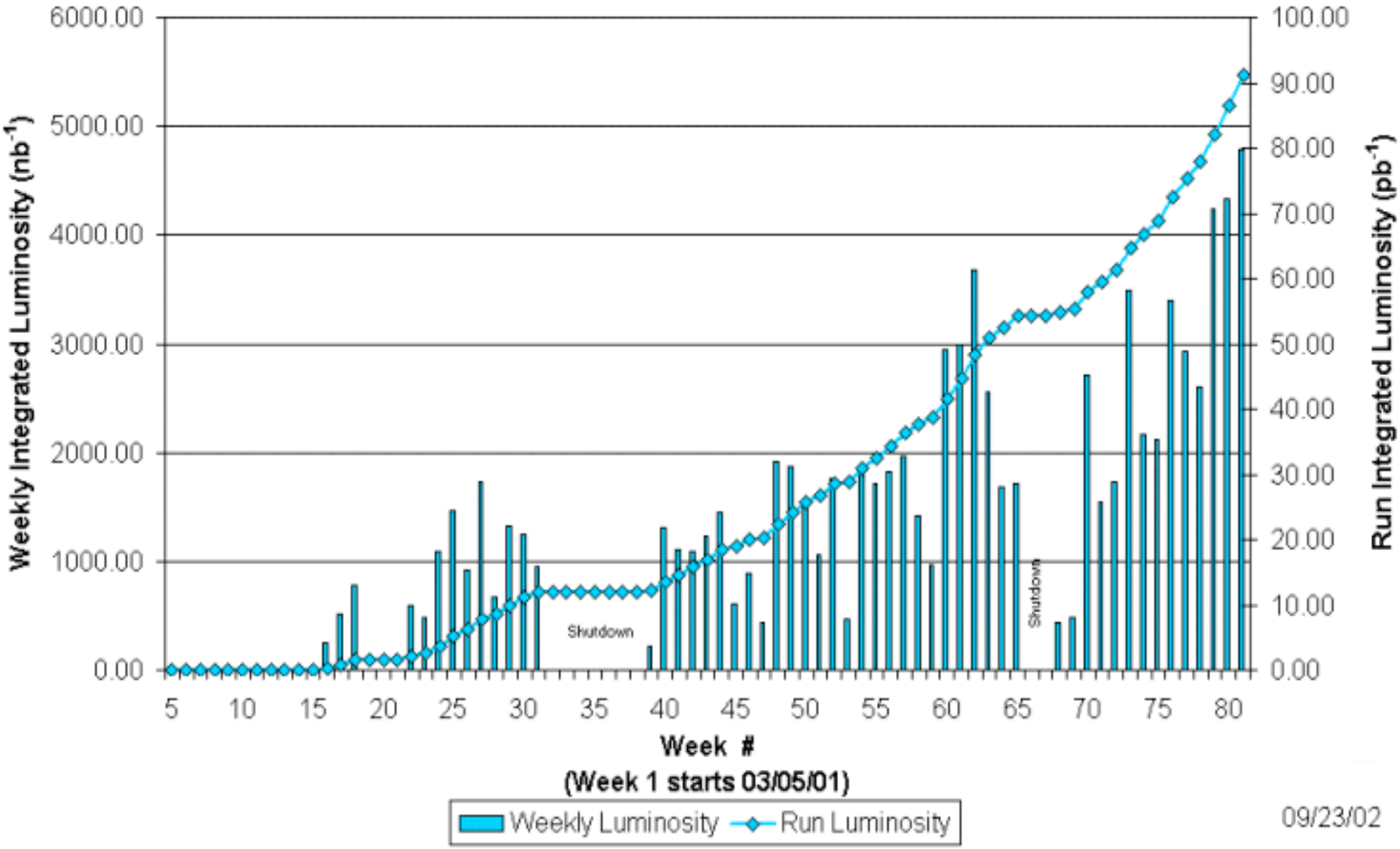
ε_p , ε_{pbar} = transverse emittances (π-mm-mrad)

σ_l = bunch length (cm)

Run IIa - Peak Luminosity



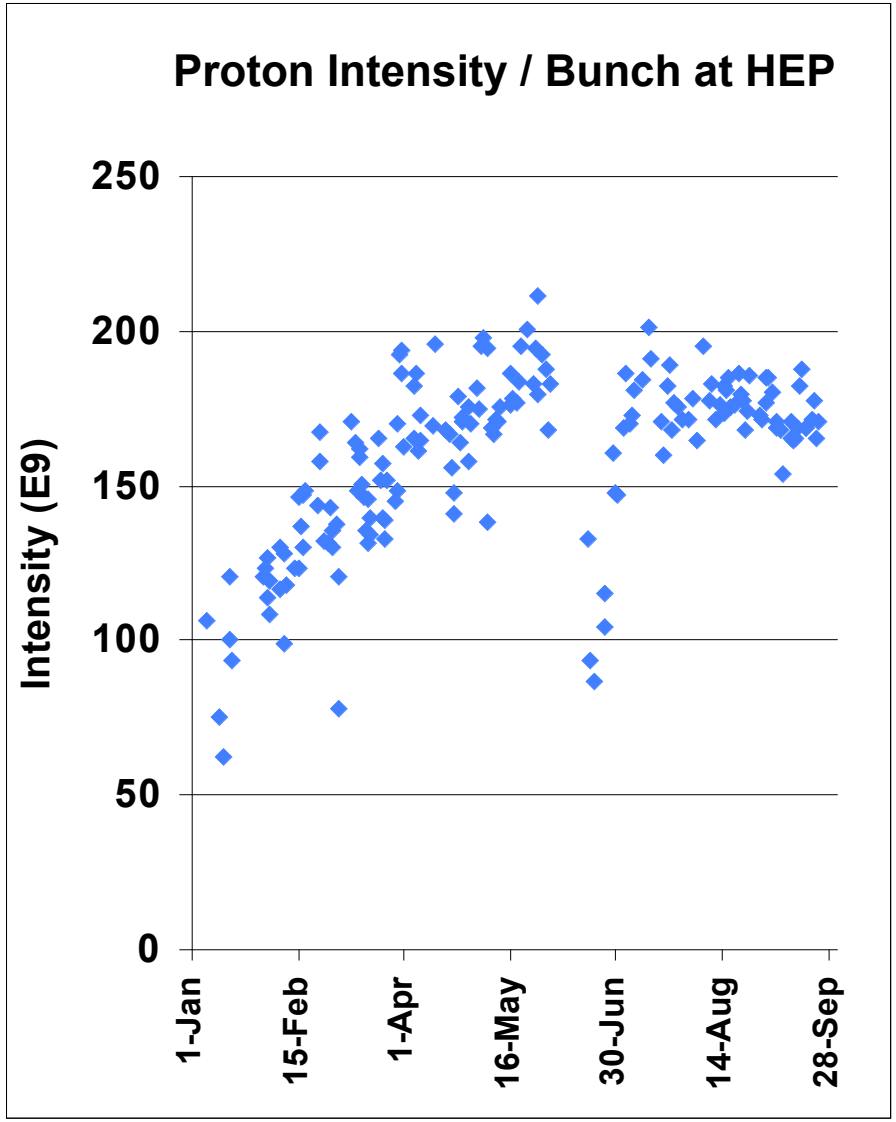
Run IIa - Delivered Luminosity

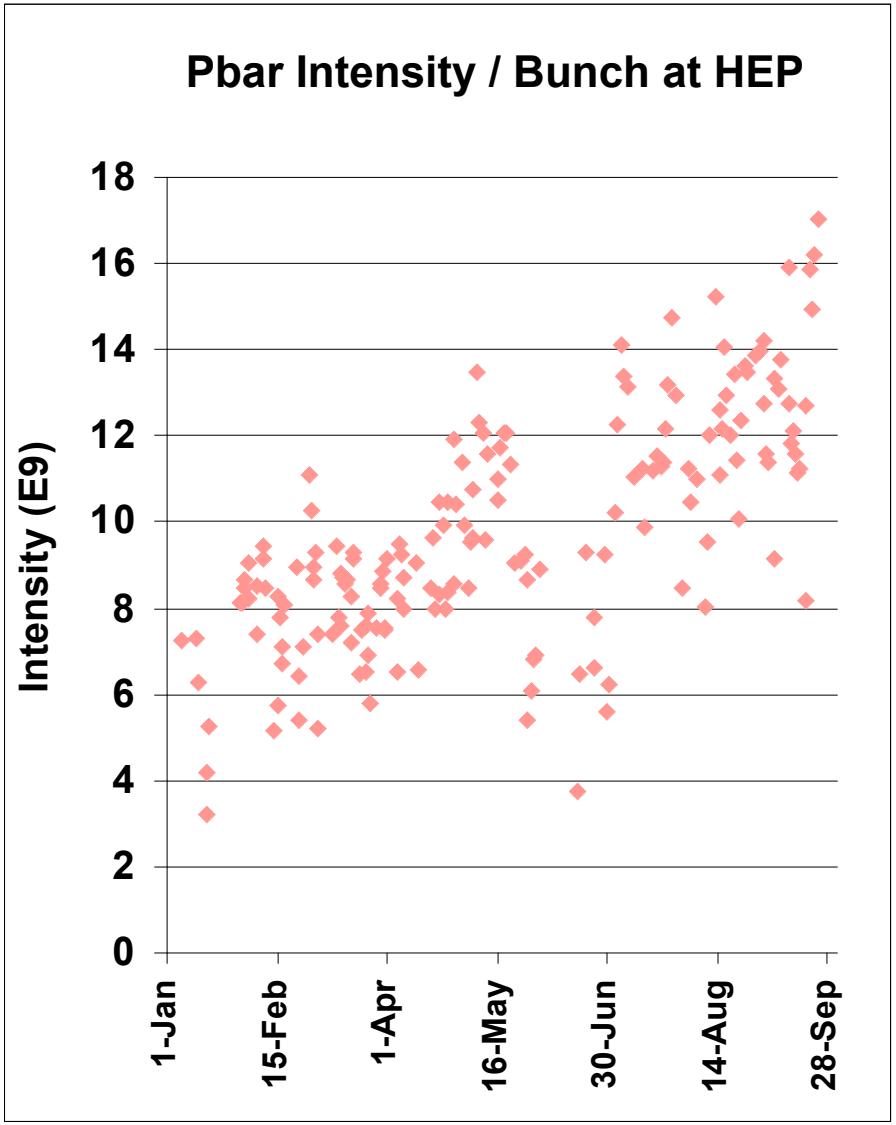


Luminosity Parameters

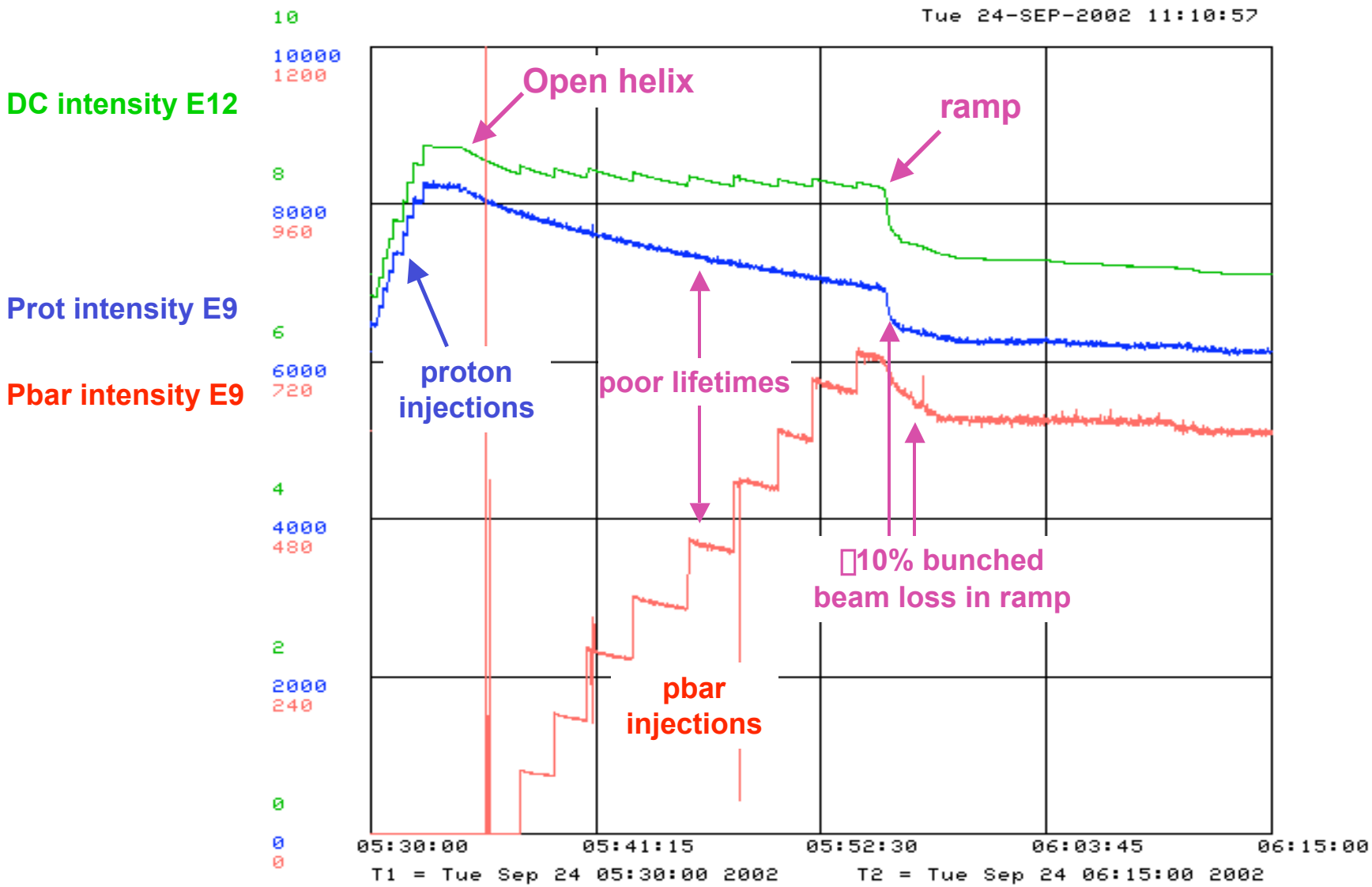
	Highest store to date	Overall Best to date	Run IIa goal
Max pbar stack rate (E10/hr)	-	12.4	18
Max pbar stack (E10)	165	190	165
Pbar efficiency Accumulator HEP (%)	40	58	80
# pbars/bunch @ HEP (E9)	17.1	17.1	33
# protons/bunch @ HEP (E9)	170	211	270
Peak luminosity (E30 cm^{-2} s^{-1})	30.2	30.2	86

Bunch Intensities in 2002





Tevatron Efficiencies



Lifetime Issues at 150 GeV

- Poor proton lifetime on helix ~ 2 hr
  - Lifetime on central orbit OK > 20 hr
  - Instability prevents lower chromaticity (currently = 8)
  - Limited success using octupoles, will try again soon

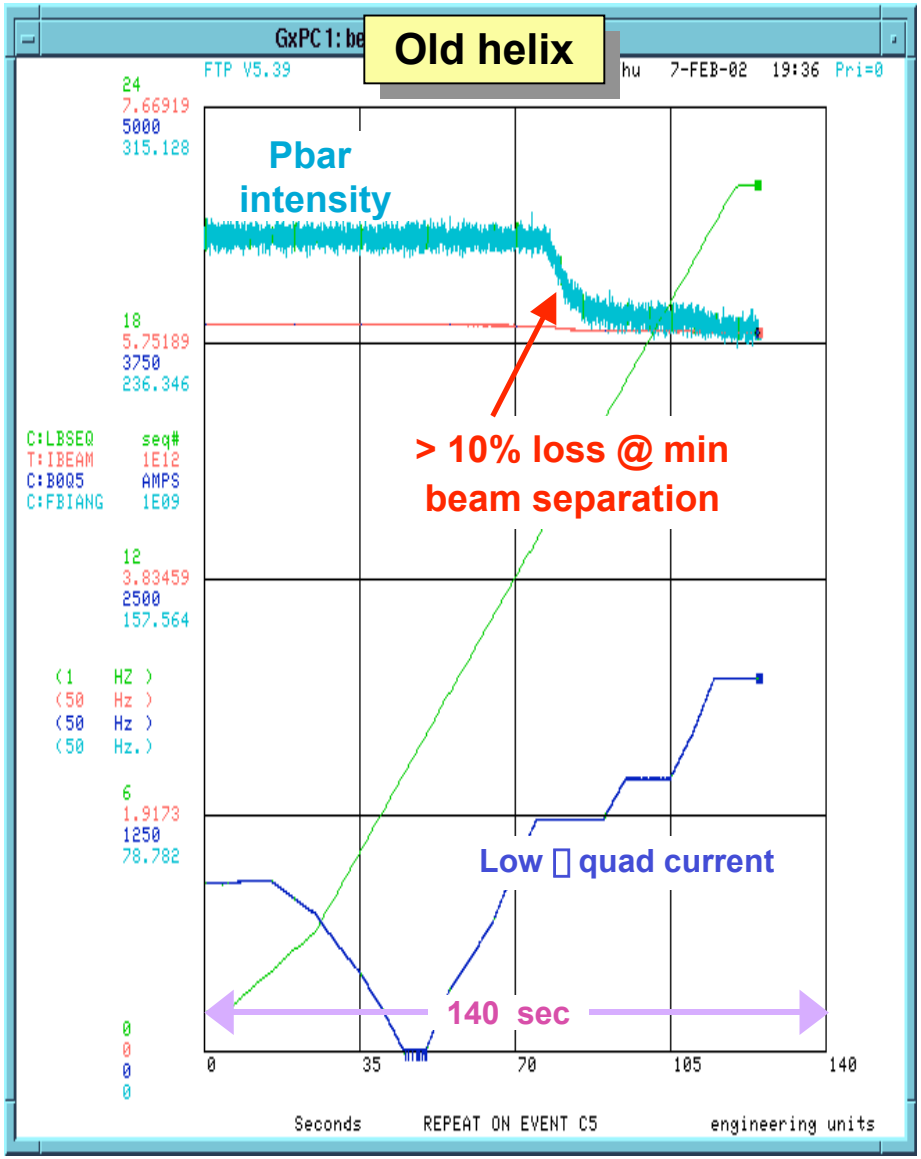
- <u>Beam-beam effects</u> □ poor pbar lifetime 1-3 hr
  - Pbar lifetime without protons ~ 20 hr
  - Try to expand helix, but limited by apertures
    - Replace lambertsons @ C0 – gain 25 mm vertically
    - Modify high □ section formerly used for fixed-target extraction
    - Both modifications to be done in Jan 2003

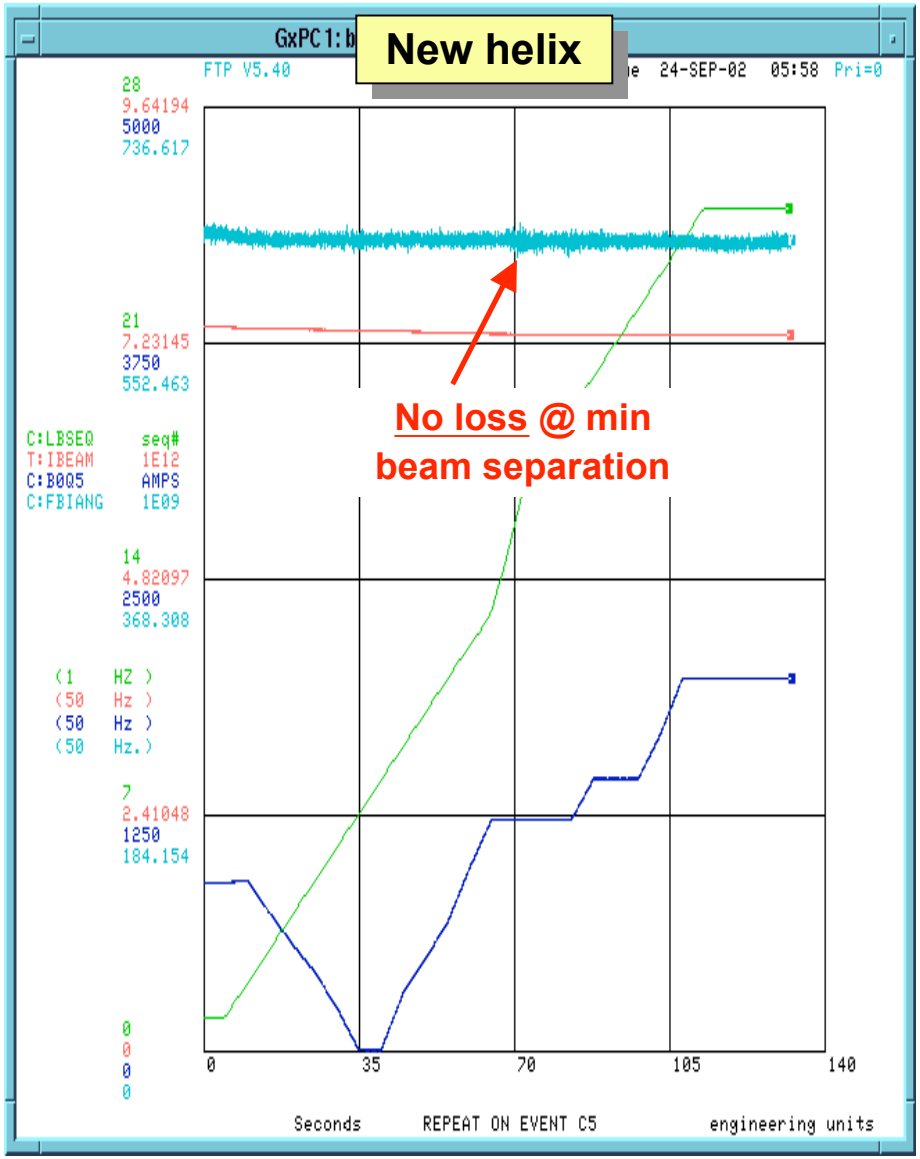
f Beam-Beam Effects at 980 GeV

- Suffered 10-20% pbar loss during squeeze
  - During transition from injection to collision helix
  - Minimum beam separation was only ~1.8
  - New helix increased min beam separation to ~3
  - Pbar loss during essentially eliminated

- lifetime 9-10 hrs in first two hours of store
  - Increase helix separation to reduce long-range beam-beam effects? (72 "parasitic" crossings)
  - Pbar tune shift depends position in train
    optimize tunes for most bunches
  - Use electron lens to compensate pbar tune shifts

Pbar Loss During Squeeze

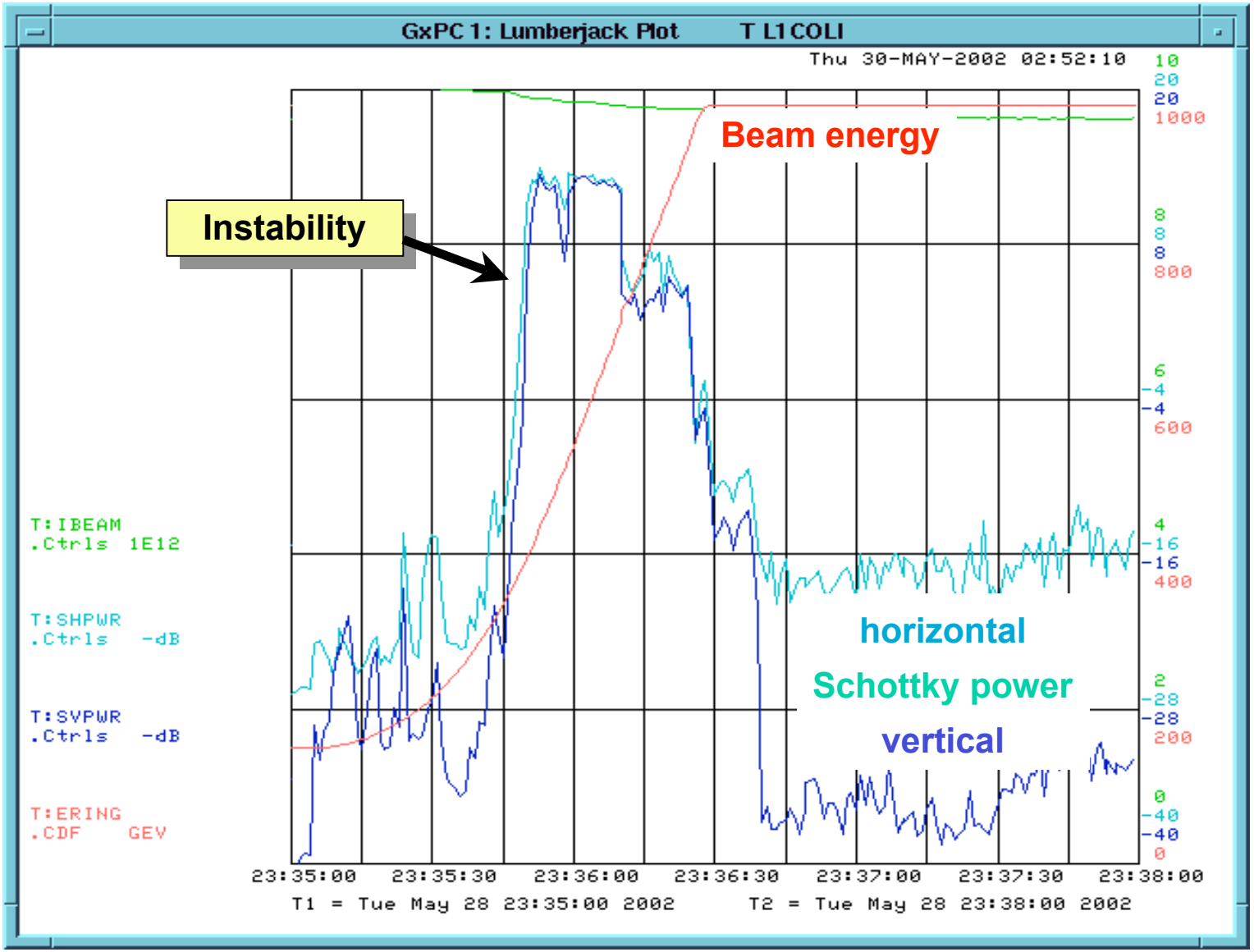




Proton Transverse Instability

- Intensity-dependent: appears ~170 E9/bunch
  - Single bunch weak head-tail phenomenon?
- Can occur at 150 GeV, up ramp, at 980 GeV
  - Schottky powers rise quickly ~ 200 ms
  - Proton and pbar emittances blow up ⇒ lower ⇒
- Try to prevent/control instability via:
  - Raising chromaticities
  - Adjusting coupling and tunes
  - Limiting p intensity to ~240 E9/bunch at injection
- Constructing bunch-by-bunch transverse dampers
  - Want lower chromaticity at injection, collisions

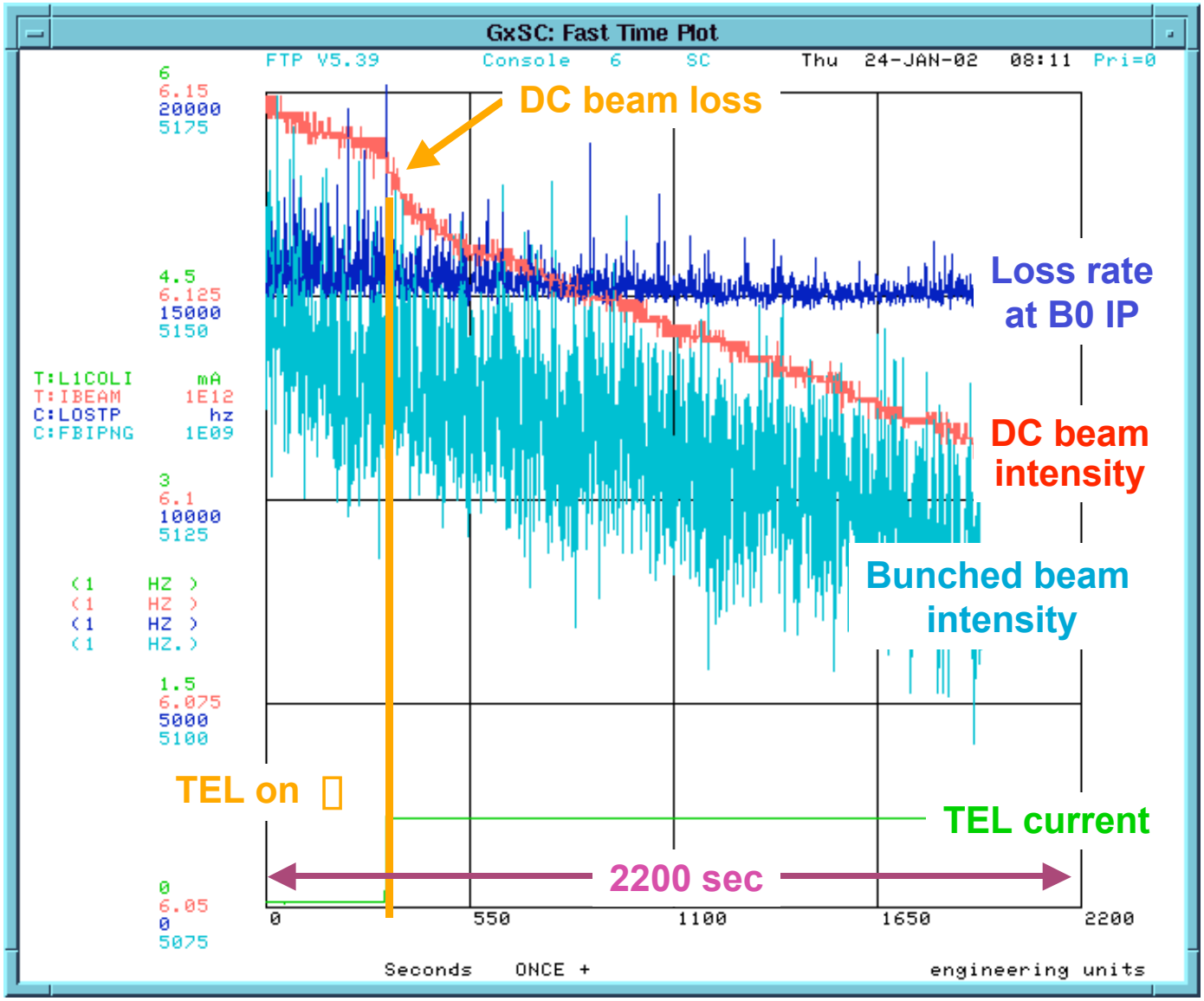
f Transverse Instability On Ramp



Tevatron Electron Lens (TEL)

- Designed to compensate beam-beam tune shift of pbars
  - Fire 10 keV e^- beam in time with pbar bunches
  - Achieved tune shifts up to 0.009 while maintaining beam lifetime of ~100 hr (proton-only studies)
  - Not yet used operationally for compensation
- Used to remove DC beam from abort gaps
  - Phenomenon not yet understood causing beam to leak out of RF buckets (RF phase error?)
  - Kickers hit DC beam in gaps, caused repeated quenches
  - Fire TEL in gaps every 7 turns to excite resonance
  - Reduces background at B0 collision hall

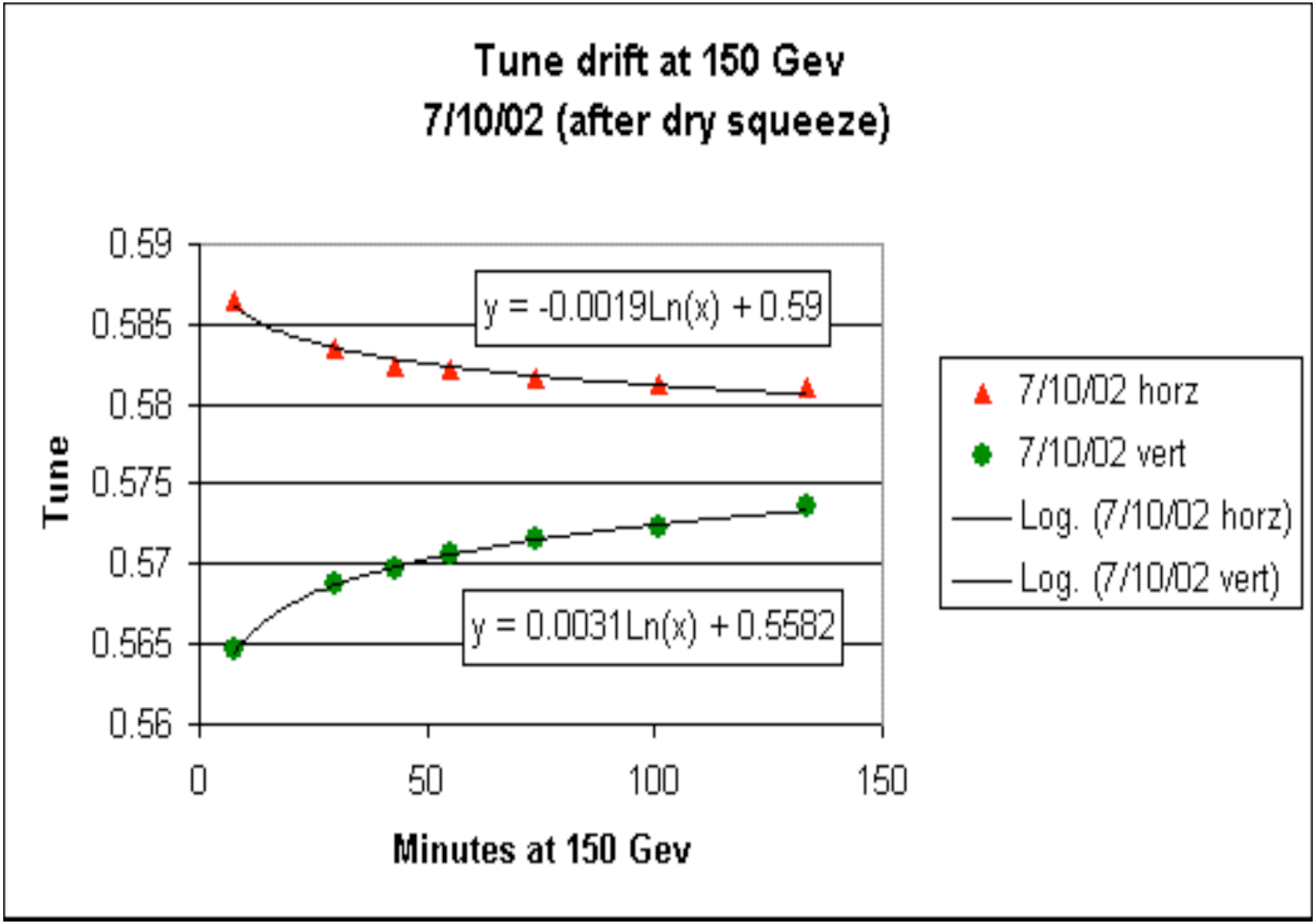
Removing DC beam with TEL



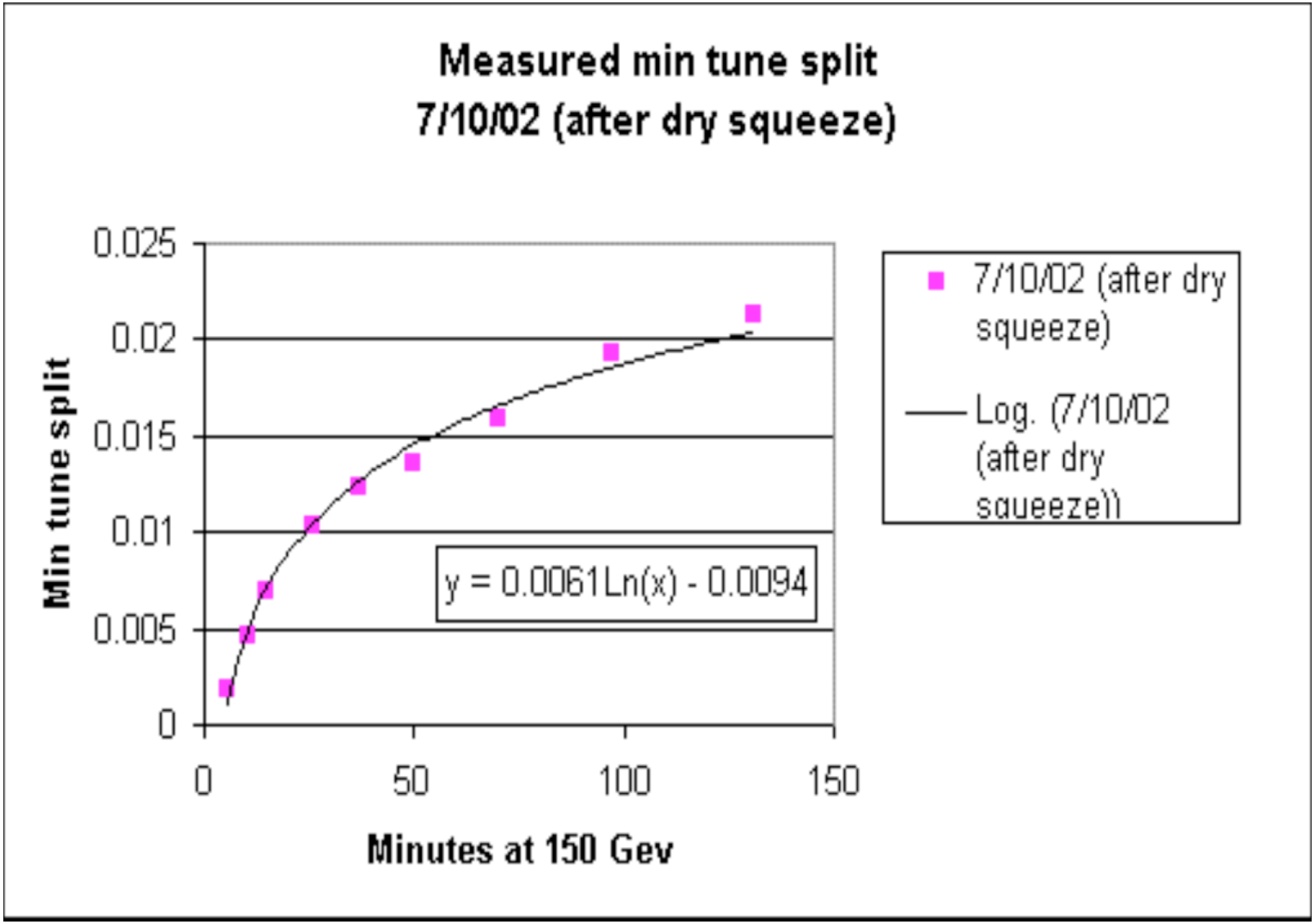
Tune and Coupling Drifts at 150 GeV

- Chromaticity drift from b_2 component in dipoles well-known from Run I
  - Compensated automatically by varying sextupole currents
- New for Run II, tune and coupling also vary logarithmically after returning to injection energy
  - Makes injection tune-up more difficult
- Likely caused by persistent currents in the superconducting dipoles and quadrupoles
- Recently implemented compensation with normal, skew quads similar to chromaticity scheme
  - Tune drift now < 0.001 after 3 hours
  - Coupling drift not measurable

Tune Drift @ 150 GeV



Coupling Drift @ 150 GeV

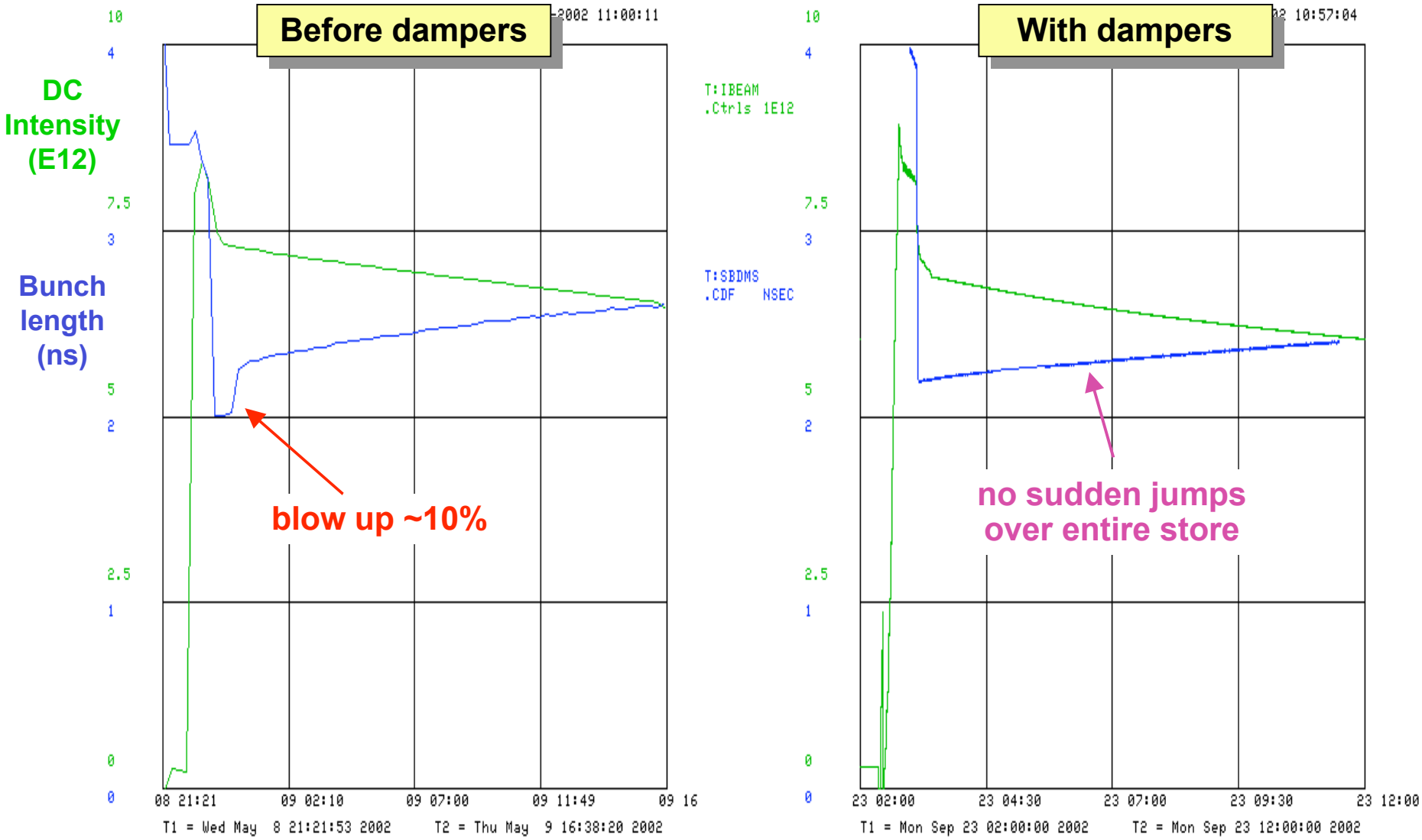


Longitudinal Instability

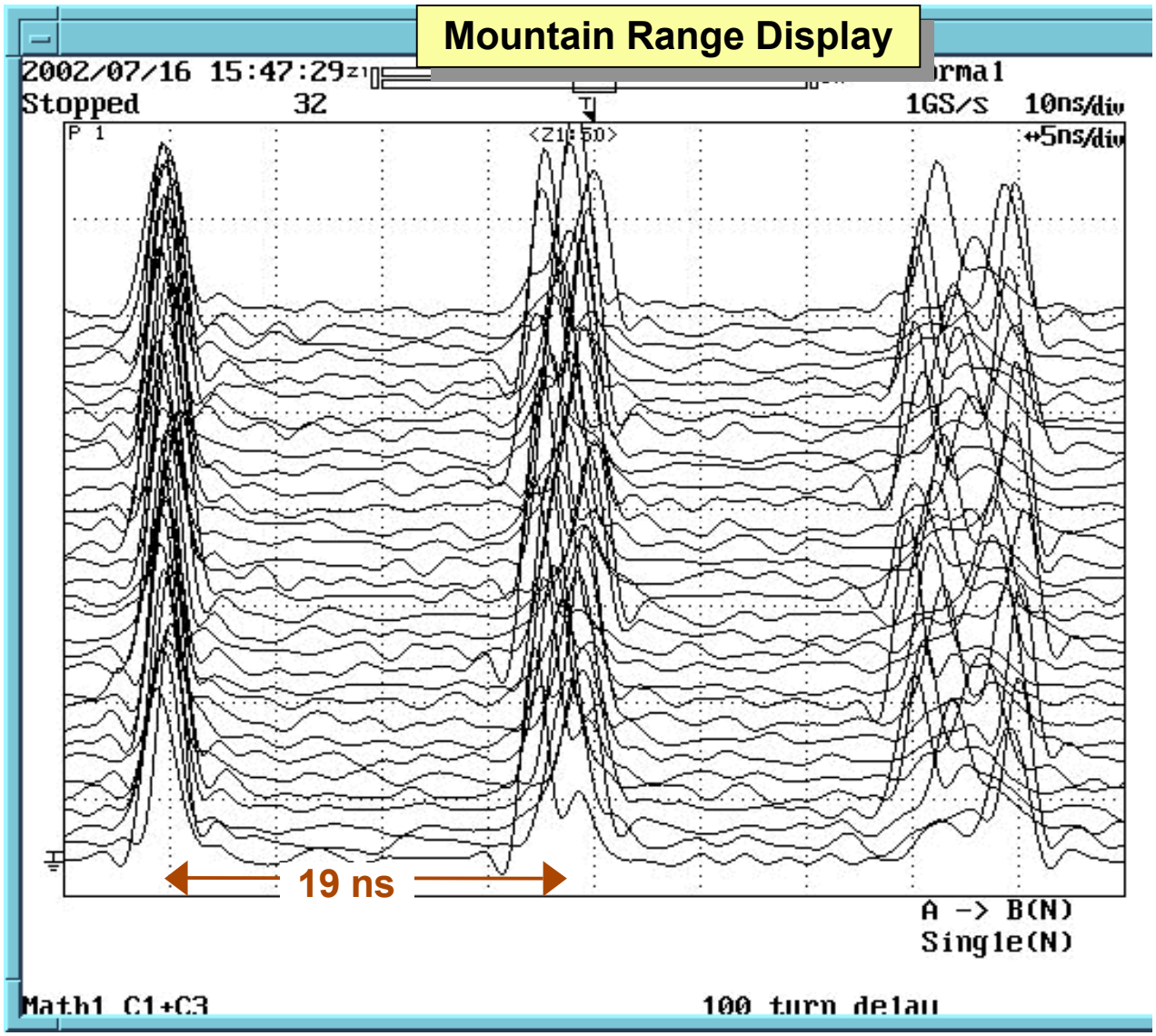
- Proton bunch length blow-ups during stores
  - Intensity-dependent
  - Usually only one or a few bunches would suffer
  - Problem solved by bunch-by-bunch longitudinal dampers to damp mode 0 and mode 1 oscillations

- "Dancing bunches" in uncoalesced beam
  - Large amplitude oscillations that slowly decay (minutes), depend on bunch position
  - Bunches seem coupled weakly
  - Developing model of this curious phenomenon

Bunch Length Evolution During Stores

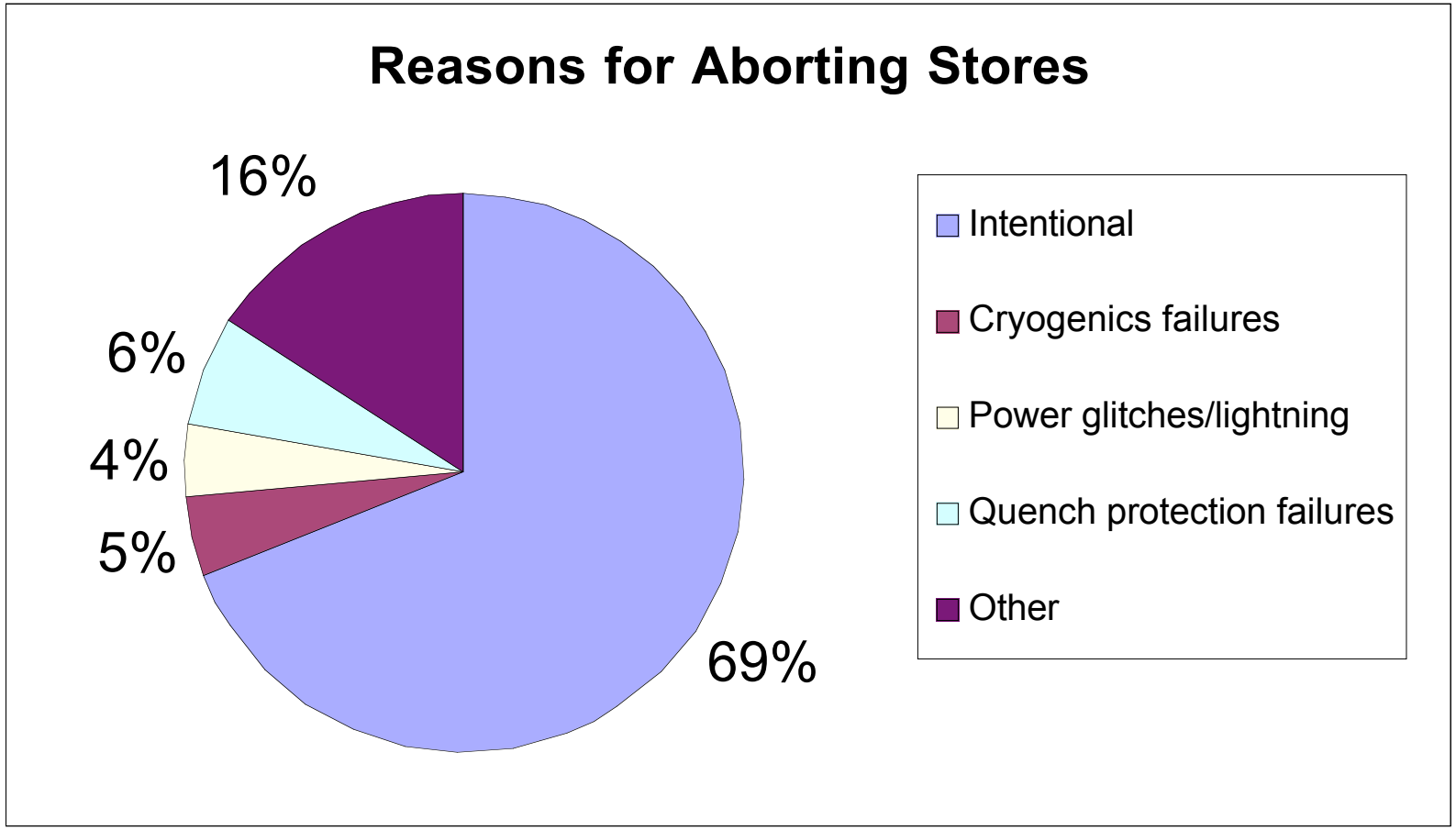


Dancing Bunches



- Beam in 30 buckets
- 100 Tevatron turns (~2 ms) between traces
- Synch freq ~ 30 Hz
- Oscillation amplitude depends on bunch, changes slowly with time

Tevatron Reliability



- 195/283 stores ended intentionally average duration = 17.4 hrs
- 88/283 stores ended unintentionally average duration = 9.7 hrs

Run IIa Plans

- 6 week shutdown in Jan 2003
  - Recycler vacuum work
  - Tevatron: replace C0 lambertsons, modify A0 lattice
- Total 200 pb^{-1} by Jun 1 2003 for conferences
- Integrate Recycler into Operations late in 2003
  - Pbar shots to Tevatron
  - Recycle pbars left after HEP stores
- Run IIa goal = deliver 2 fb^{-1}
- Long shutdown for Run IIb preparations
  - Accelerator and experiments

Run IIb Plans

- Reach 1-5 E32 cm^{-2} s^{-1} peak luminosity

- Need more pbars!
  - Slip-stacking in MI more p on pbar production target
  - Electron cooling in RR for 5 E12 pbars

- Shorter bunch spacing in Tevatron?
  - Concerned about beam-beam effects @ 132 ns spacing
    - Studying 264 ns and luminosity-leveling with 396 ns
  - Need more separators, faster injection kickers
  - Crossing angle at IPs

f

Summary

- Many changes in complex for Run II
- Initial Run II progress slow, getting better
  - Issues: beam-beam effects, instability, Recycler
- Complex running well lately
  - Now consistently above Run I peak luminosities
  - Recycler making progress
- Delivered over 90 pb^{-1} to the experiments
- Getting to higher luminosities
  - control proton instability in Tevatron
  - get more pbars to collisions (stack faster, improve efficiencies)
- Looking forward to delivering 2 fb^{-1} and beyond!