Accelerator Physics at Tevatron Collider:

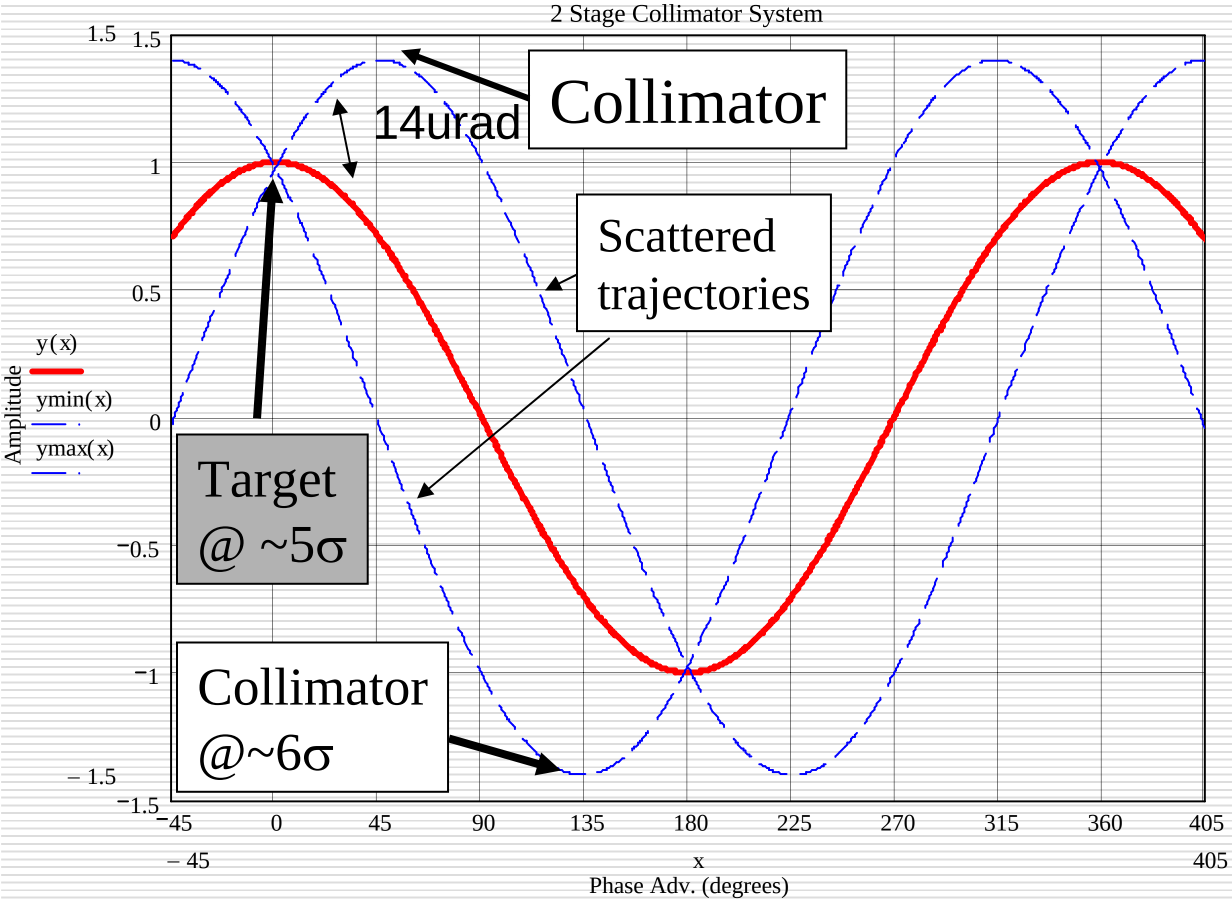
beam physics problems which set ultimate performance

Vladimir Shiltsev

Fermilab

As promised – Horror Story

Two Stage Collimation System



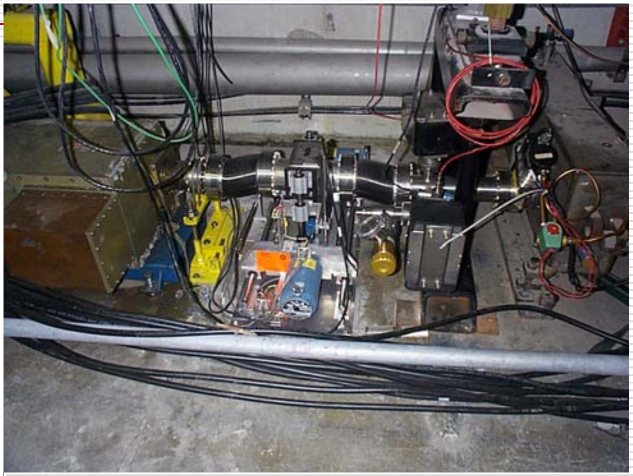
Collimator

14urad

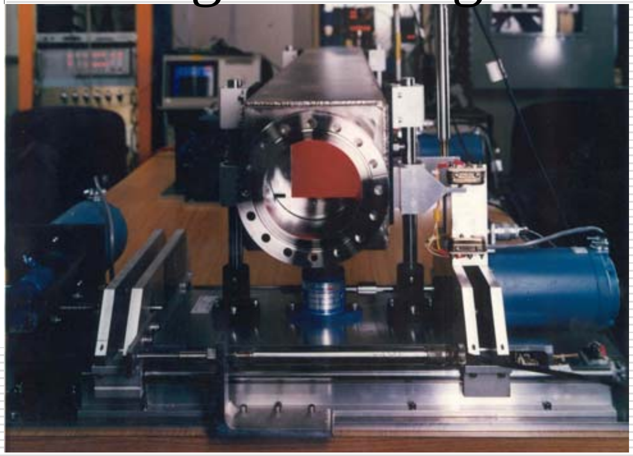
Scattered trajectories

Target @ ~5σ

Collimator @~6σ



6 inch Target w/ 5mm Tungsten Wing



1.5 m collimator

N. Mokhov et.al, “Tevatron Run-II Beam Collimation System” , Proc. PAC 1999, or Fermilab-Conf -99/059.

Tevatron Collimator Layout

12 collimators total:

4 Targets

8 Secondary collimators

Arranged in 4 sets:

2 proton sets

2 pbar sets

Proton Set 1

D49 Tar, E03 & F172 2nd

Proton Set 2

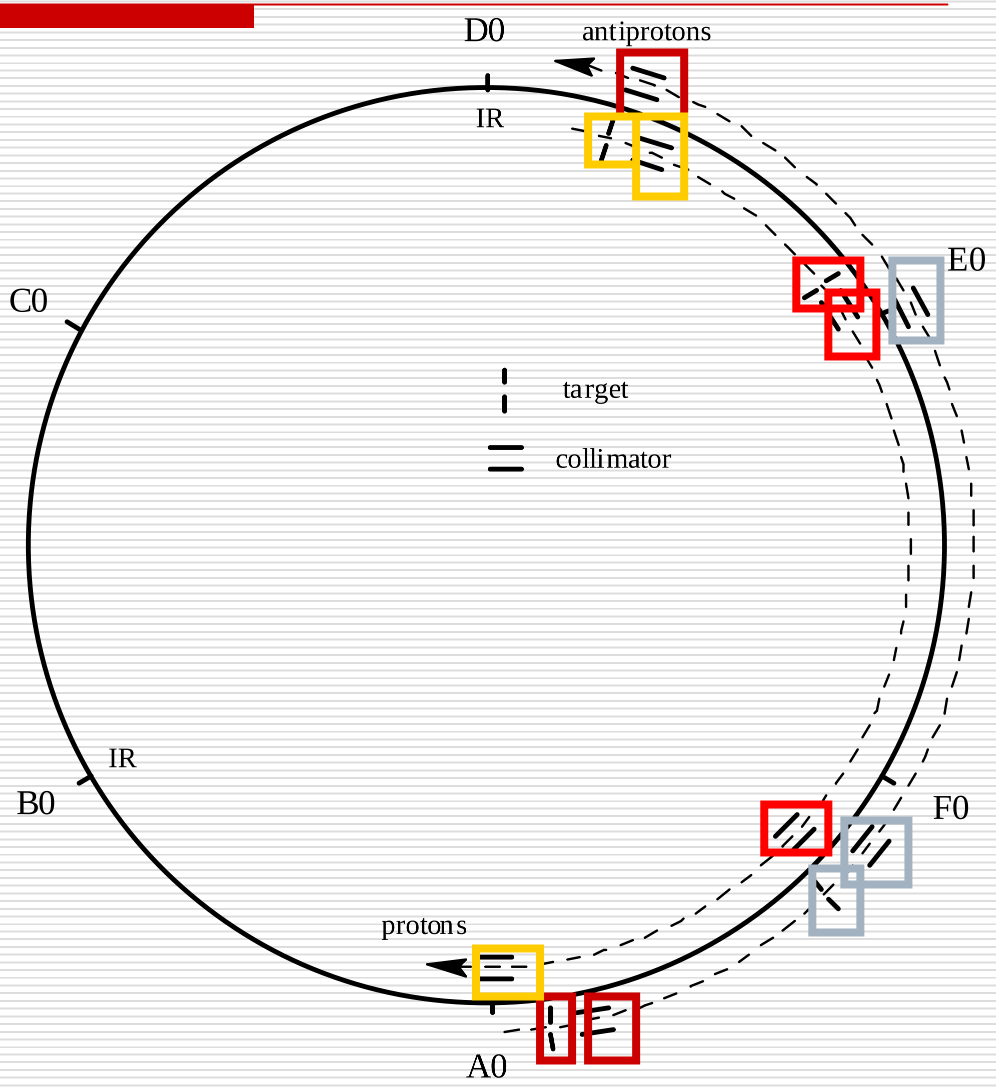
D171Tar, D173 & A0

Pbar Set 1

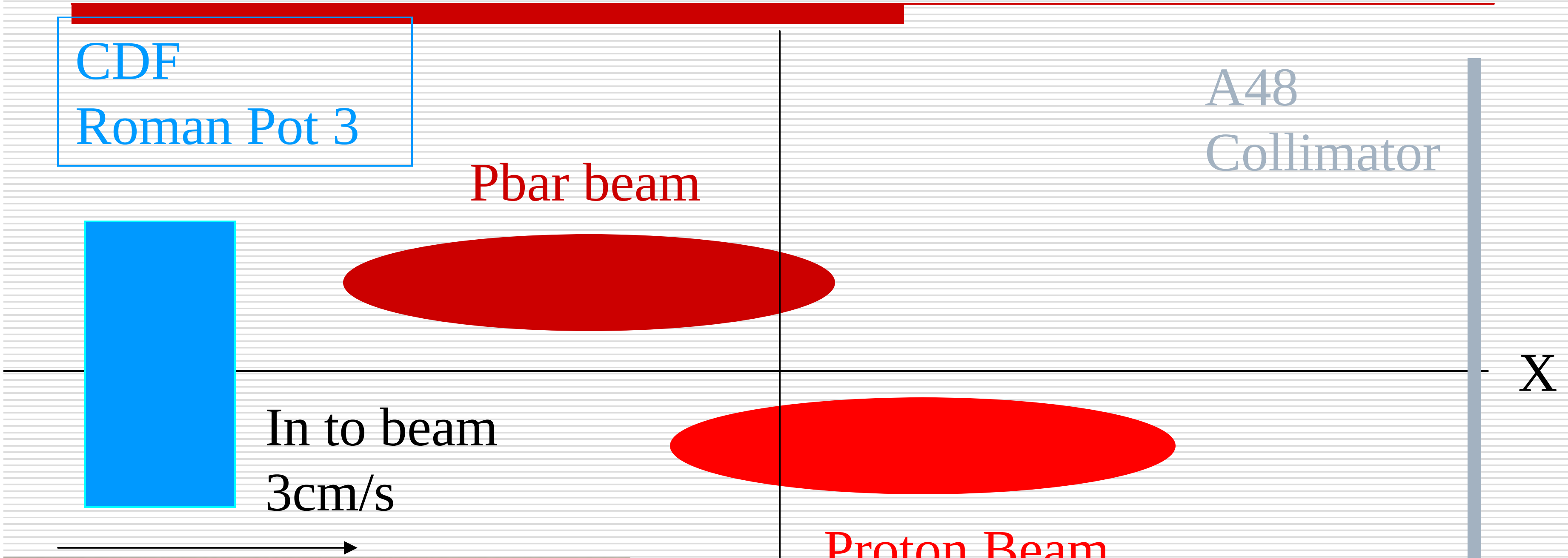
F49 Tar, F48 & D172

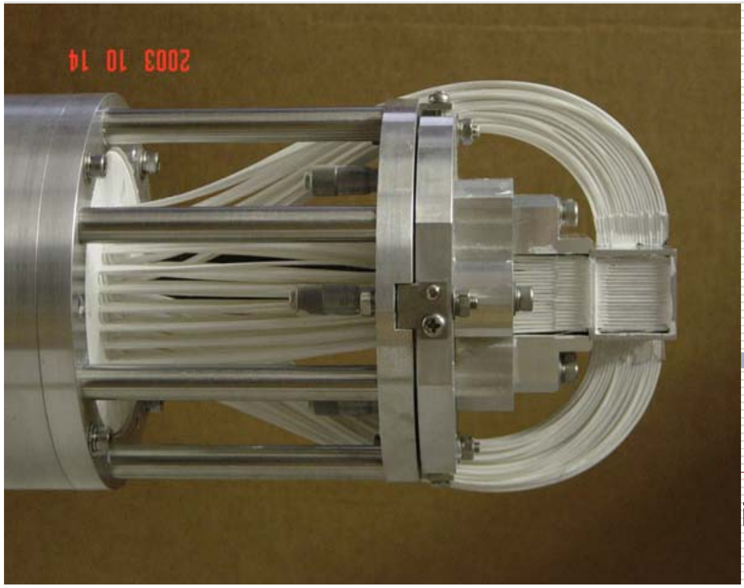
Pbar Set 2

F173 Tar, F171 & E02



Dec.05 2003 Incident

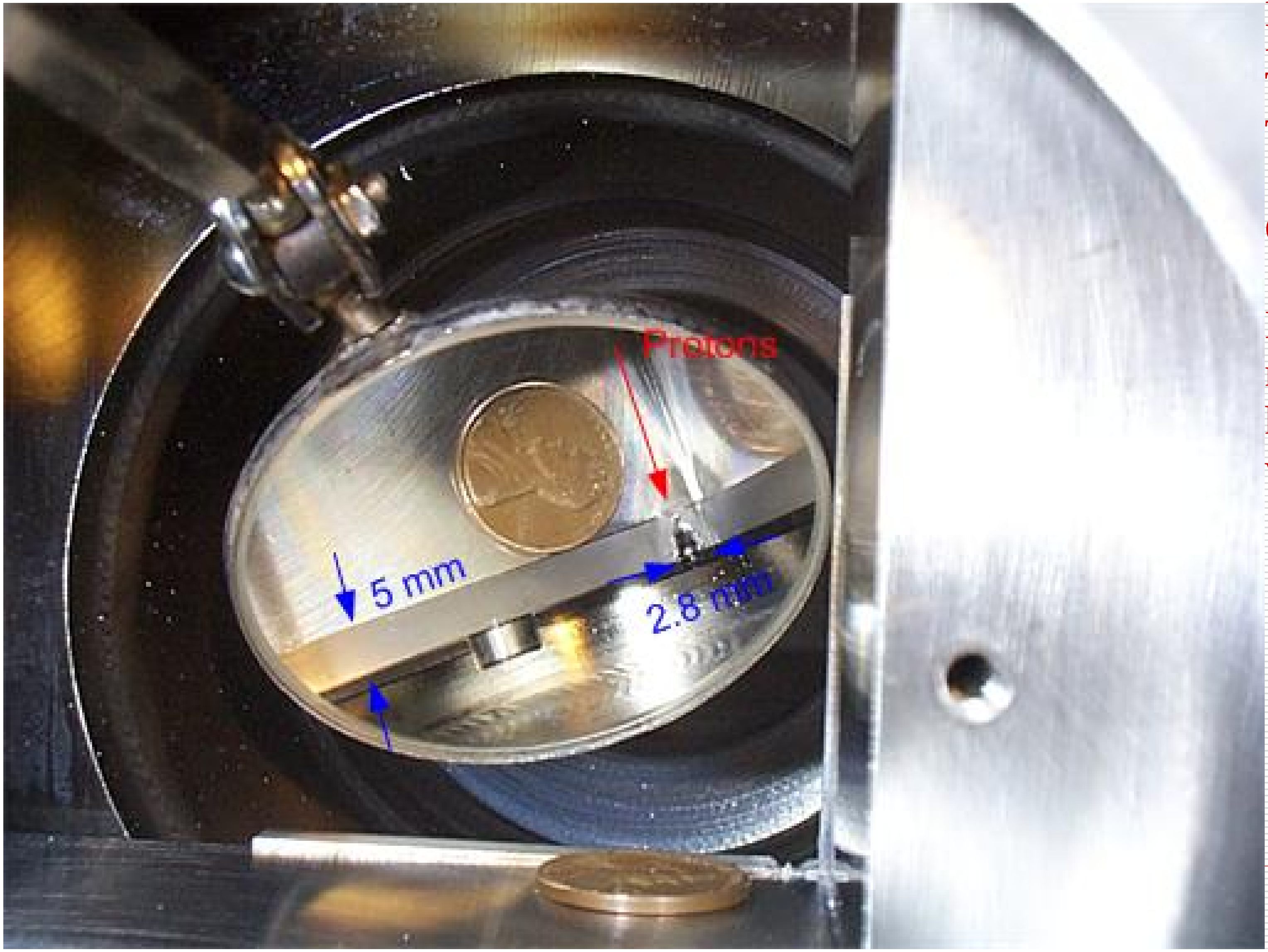




Quenched 5 dipoles at A48;
DI/Dt = .5A/msec -> beam bent

4 Magnets Quench VERY Fast

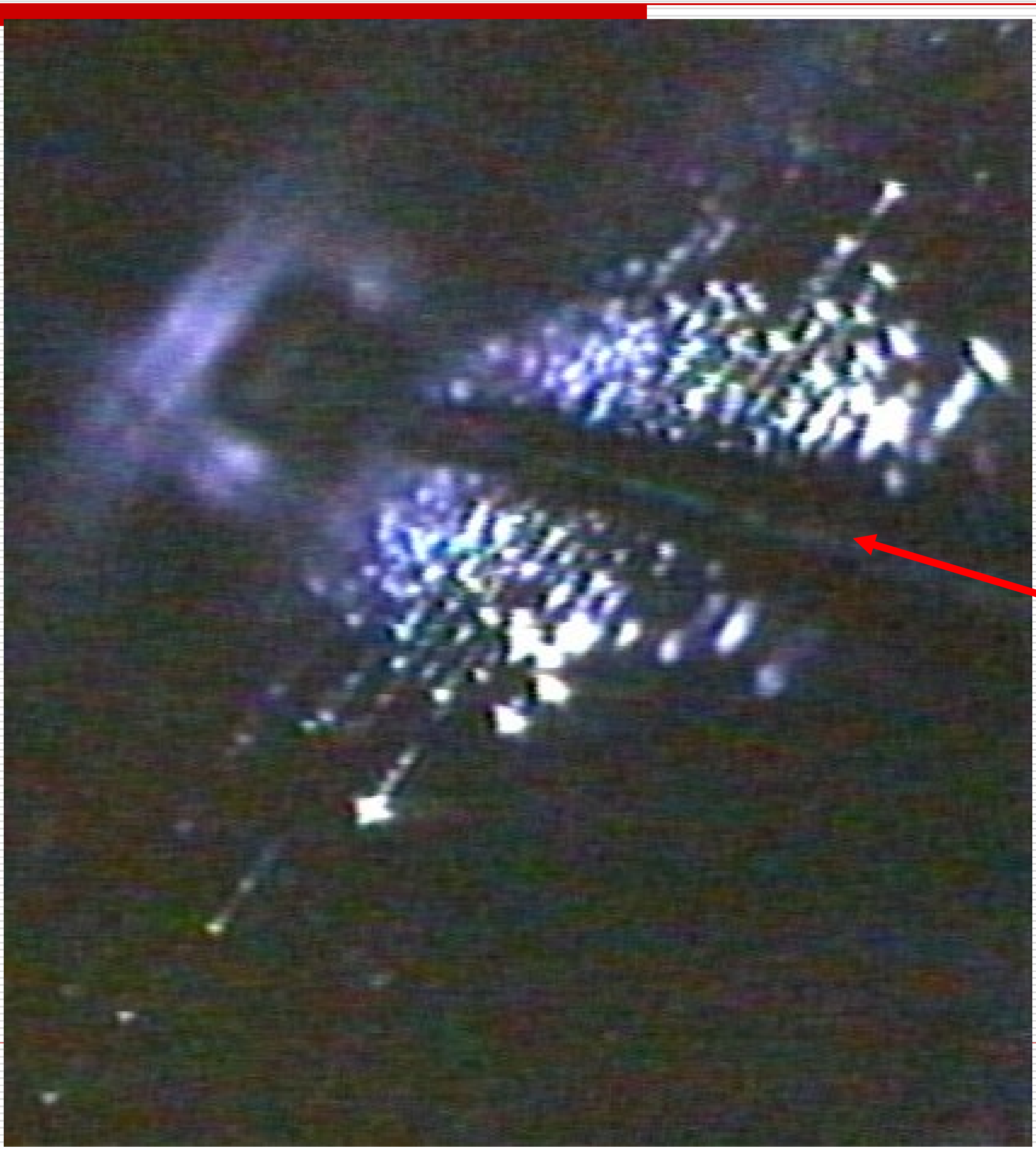
Damage to D49 Primary Collimator Target



Damage to
D49 estimated
Took 20-30 turns
To create hole.

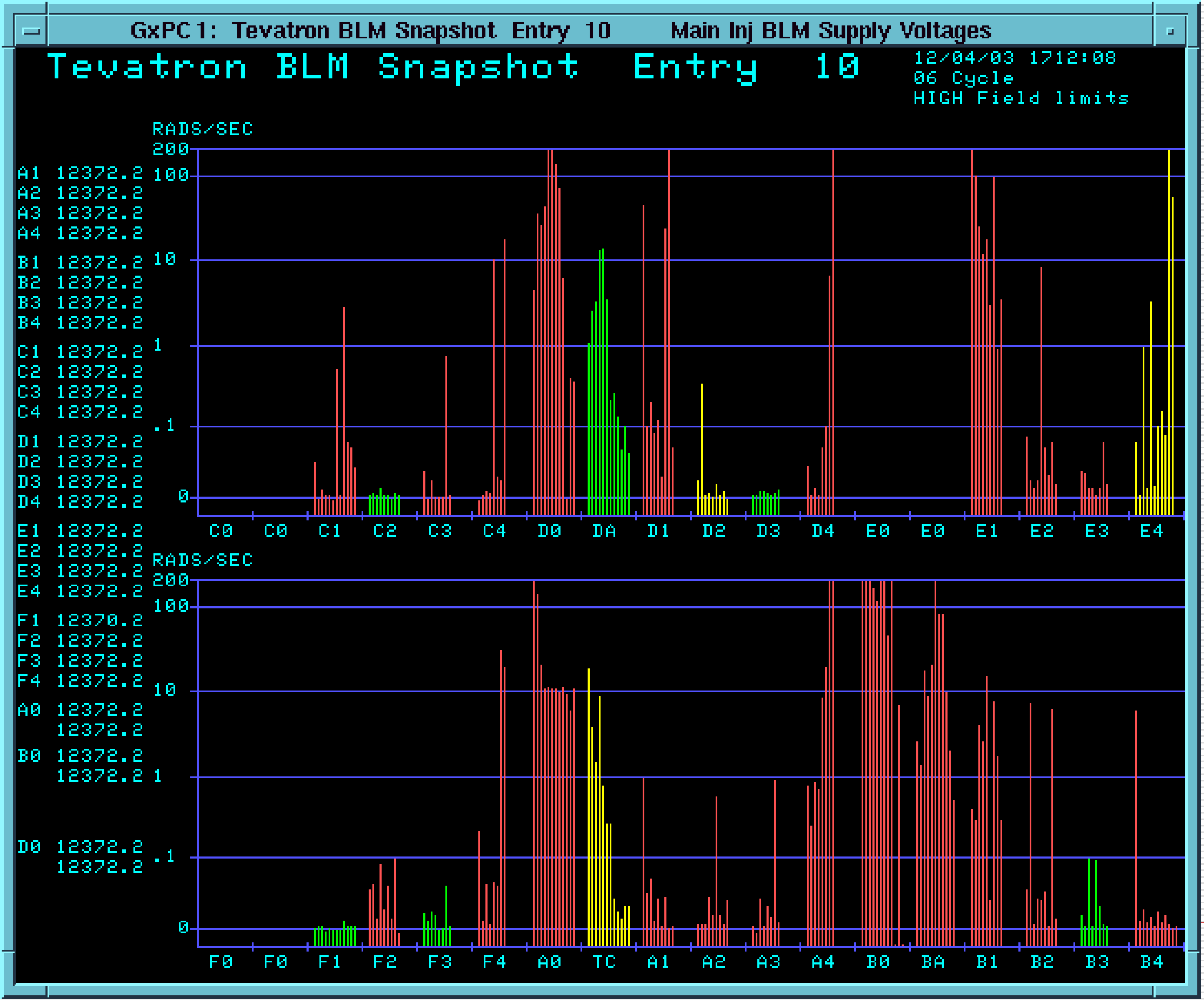
Once the hole
was open allowed
Beam to travel to
next limiting
horizontal aperture
which is E03

Damage to E03 1.5m Collimator



Protons

Tevatron Ring Wide Loss Plot



GxPC 1: Tevatron BLM Snapshot Entry 10   Main Inj BLM Supply Voltages

Tevatron BLM Snapshot Entry 10

12/04/03 1712:08
06 Cycle
HIGH Field limits

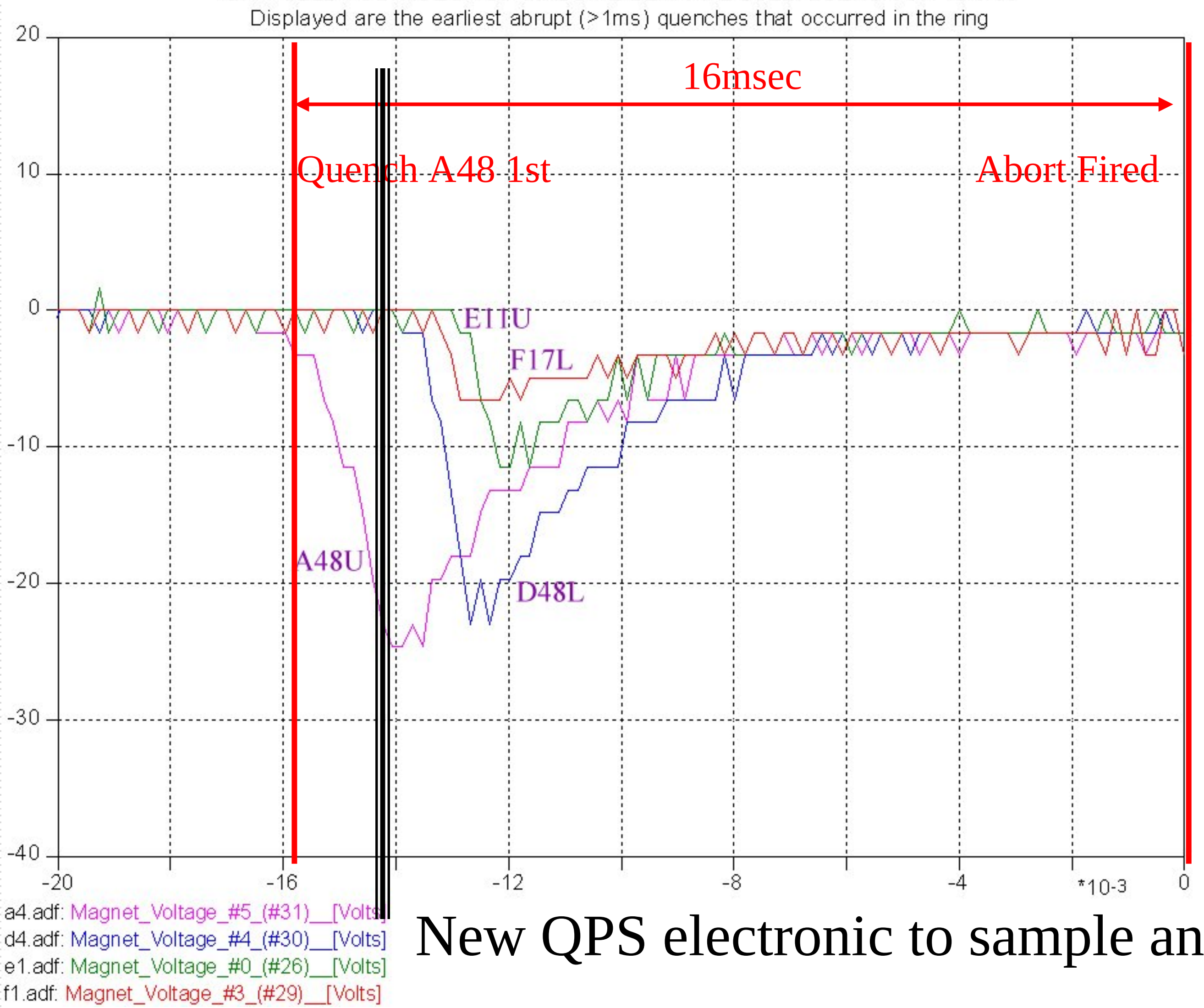
```
A1 12372.2
A2 12372.2
A3 12372.2
A4 12372.2
B1 12372.2
B2 12372.2
B3 12372.2
B4 12372.2
C1 12372.2
C2 12372.2
C3 12372.2
C4 12372.2
D1 12372.2
D2 12372.2
D3 12372.2
D4 12372.2
E1 12372.2
E2 12372.2
E3 12372.2
E4 12372.2
F1 12370.2
F2 12372.2
F3 12372.2
F4 12372.2
A0 12372.2
   12372.2
B0 12372.2
   12372.2


D0 12372.2
   12372.2
```

16 CryoHouses quenched:C19

Conning tower correction element damage requiring C1 to be warmed to room temp for repair (11 days)

Quench Protection System Reaction



16msec

Quench A48 1st

Abort Fired

Development of Quench:

A48U 16msec

D48L 13.5msec

F17L 13msec

E11U 12.5 msec

Before abort

New QPS electronic to sample and react in 2ms

Conclusion:

1) The old Quench Protection System would NOT be able to catch that type of event because it processed data at 60Hz /16.67 msec.

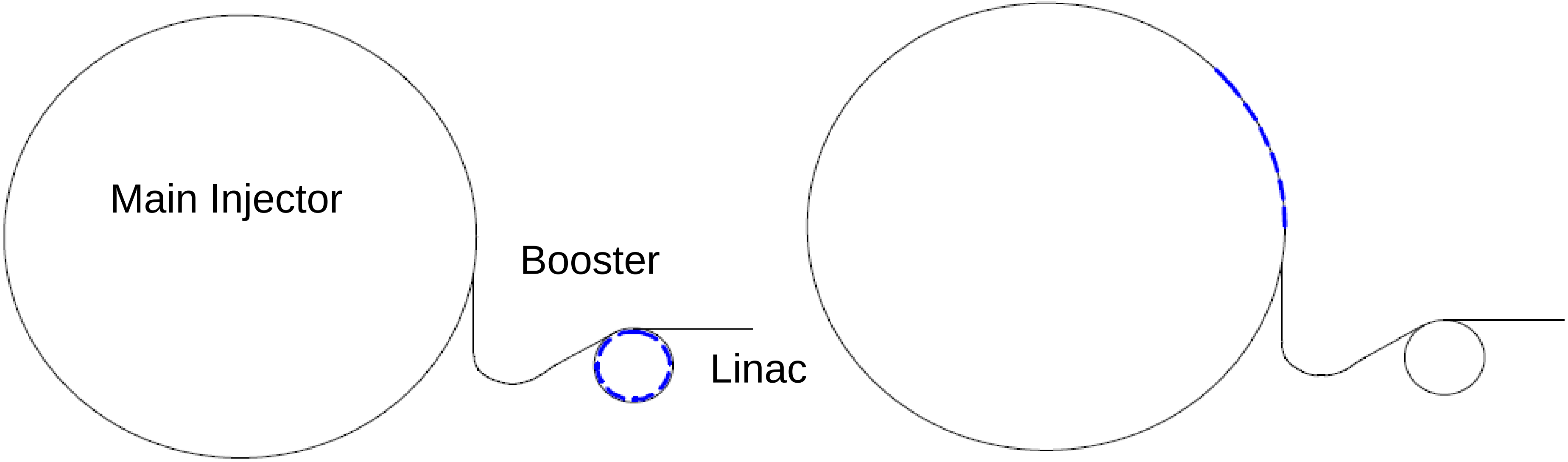
2) New, 2 ms fast quench detection system was developed, installed and, later, worked well itself in similar kind of accidents

3) Roman pots motion control system was fixed… years later the pots were removed whatsoever (both CDF and D0) for another reasons

4) Even though 2 collimator devices were damaged, <u>they provided protection to other components</u>. These devices defined the limiting aperture and are easy to change.

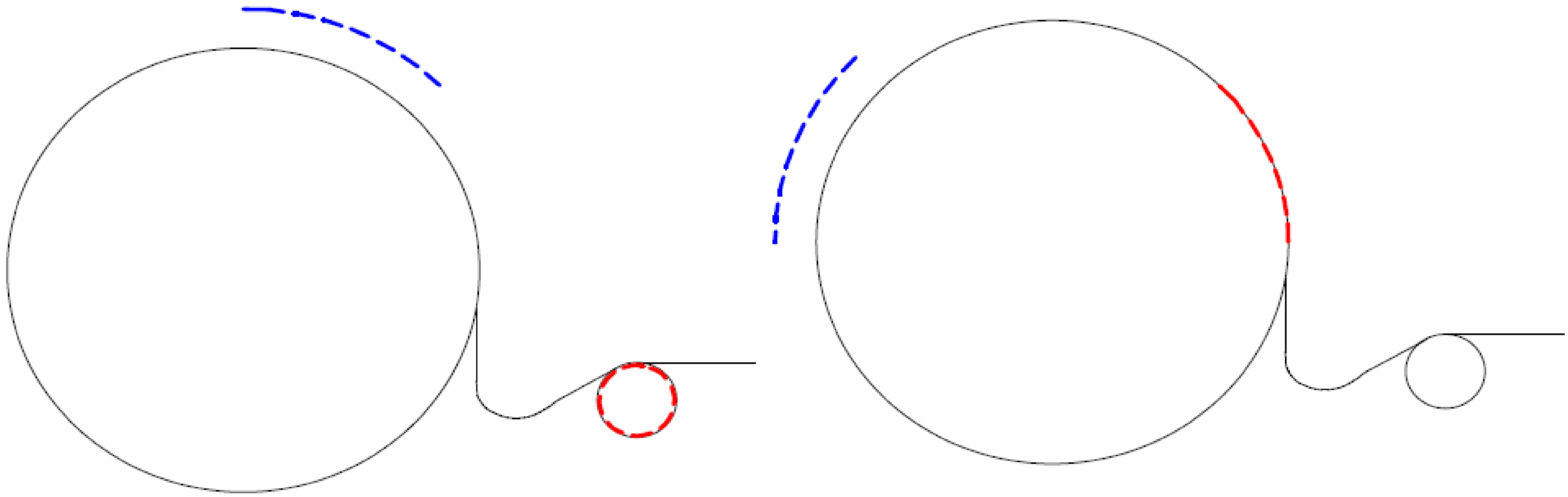
Beam Physics in Main Injector

Slip Stacking - to double #p's on target



- First Booster Batch accelerated in Booster
- First Booster Batch injected onto MI central orbit with RF system A

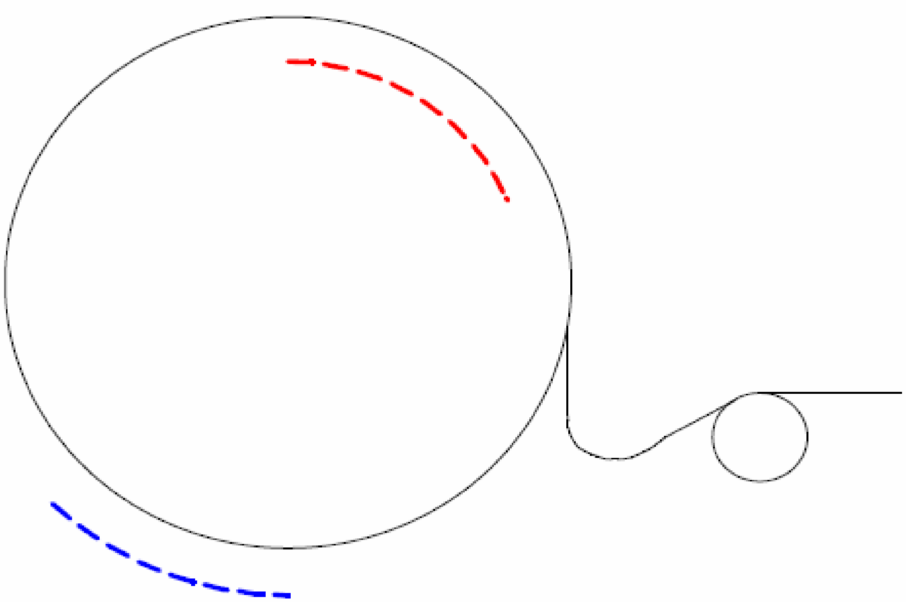
Slip Stacking - 2



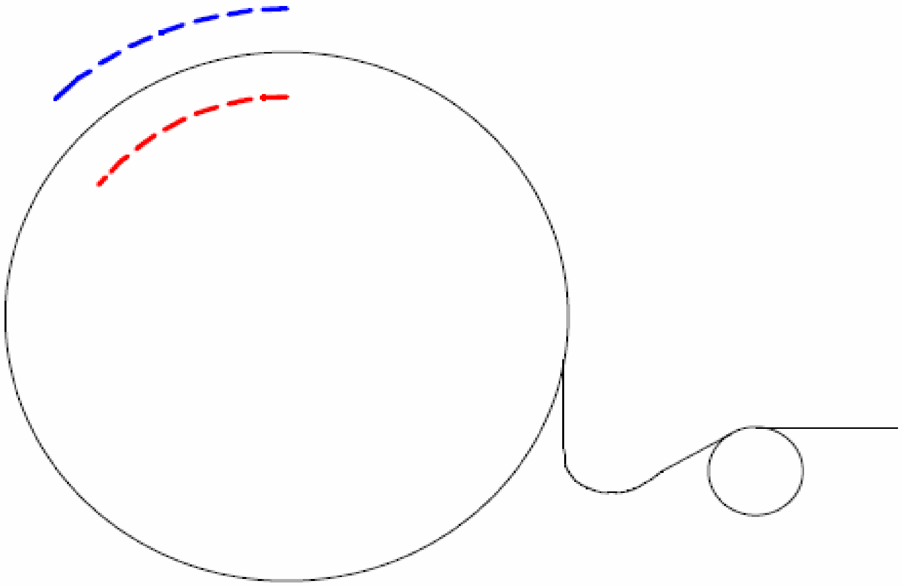
- First Booster Batch slightly accelerated in MI with RF System A
- Second Booster Batch accelerated in Booster

- Second Booster Batch injected onto MI central orbit with RF system B

Slip Stacking - 3

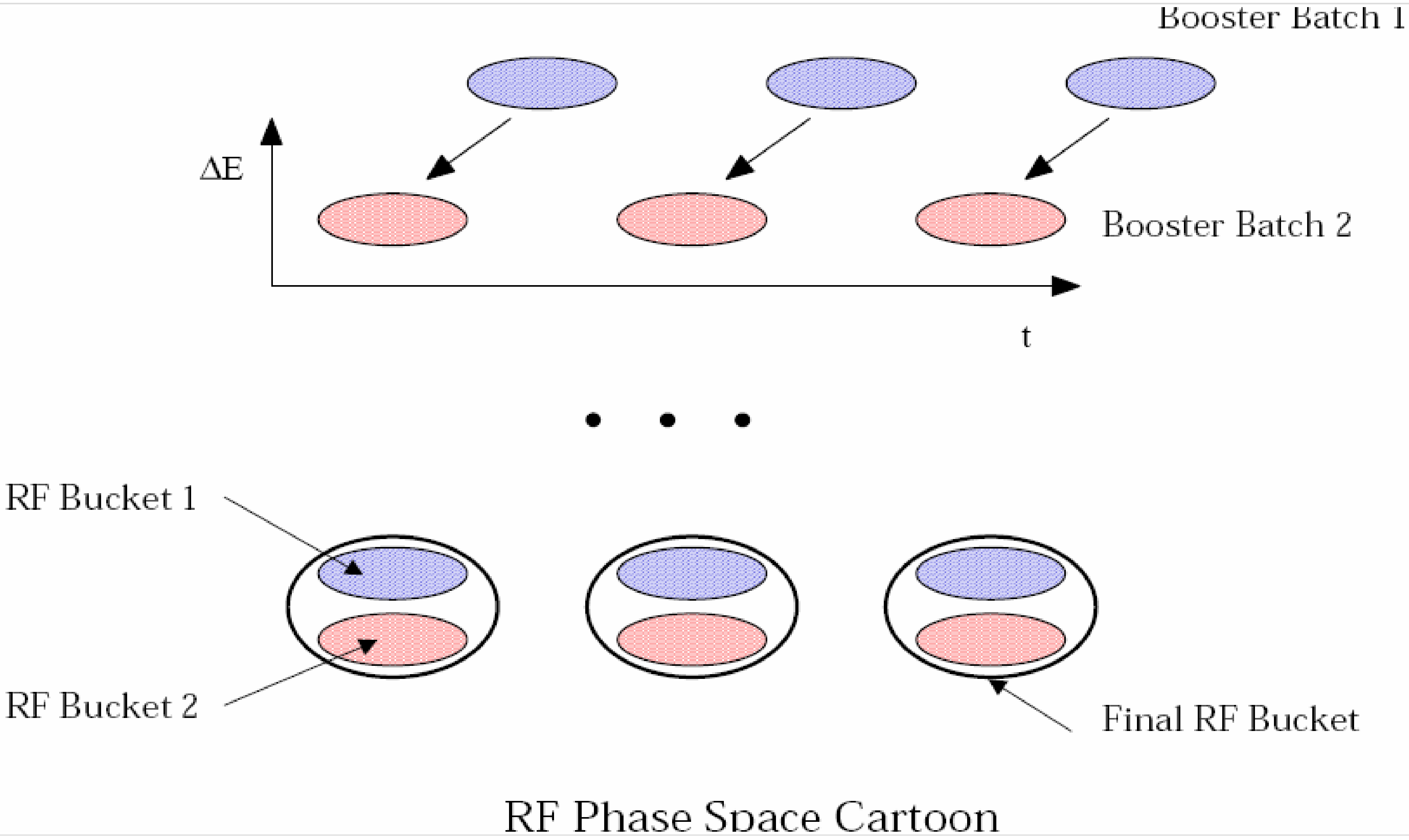


- Second Booster Batch slightly decelerated in MI with RF System B



- Wait till batches line up and snap on RF system C while turning of RF systems A & B

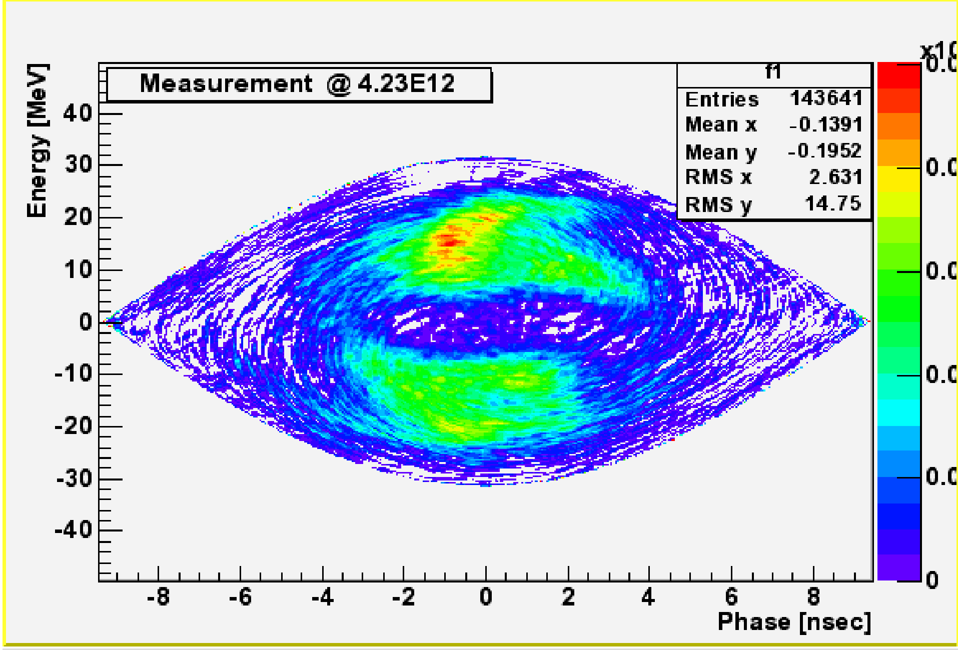
Slip Stacking - 4



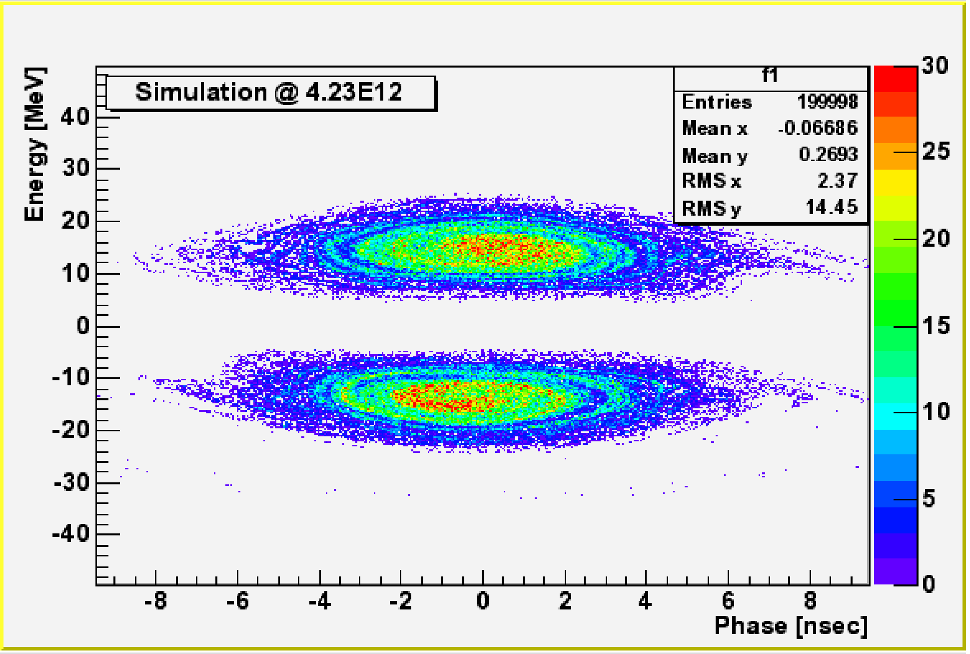
RF Phase Space Cartoon

Slip Stacking – 5

Measurements



Simulation



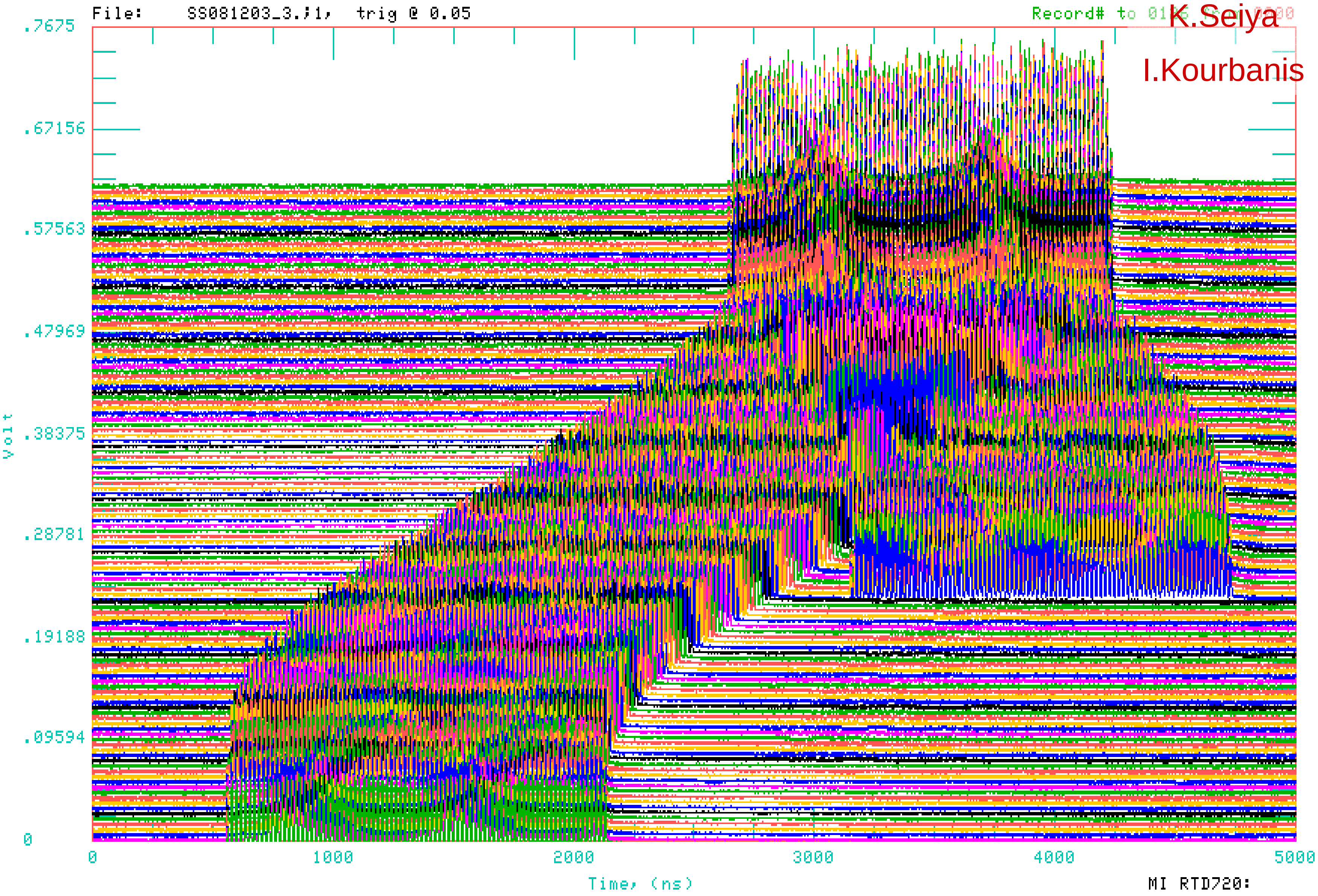
Longitudinal emittance @ recapture ~ 0.35eV-sec

Beam loss ~ <5% !!

Recapture voltage: 1MV

Intensity: 8.5E12 @ Injection

Slip Stacking 6e12 p’s in Main Injector



K.Seiya

I.Kourbanis

Slip Stacking in Main Injector: Summary

Slip stacking is in operation for antiproton production since December 2004 and increased proton intensity on target by 70%.

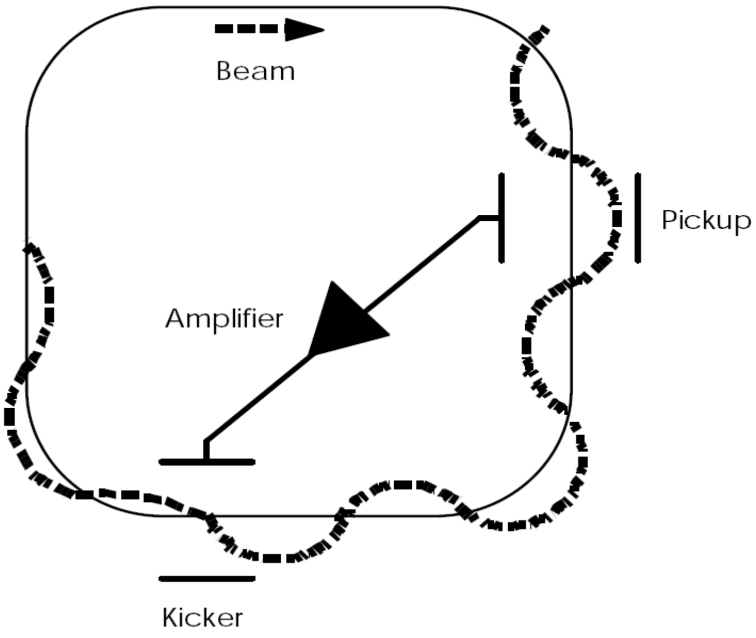
11 batch (instead of 2) slip stacking scheme have already verified.

Beam we send to Pbar and Neutrino targets:

Intensity : 8.2E12 protons per pulse (Pbar),
30E12 protons per pulse (NuMI).
Efficiency: 95.5%.

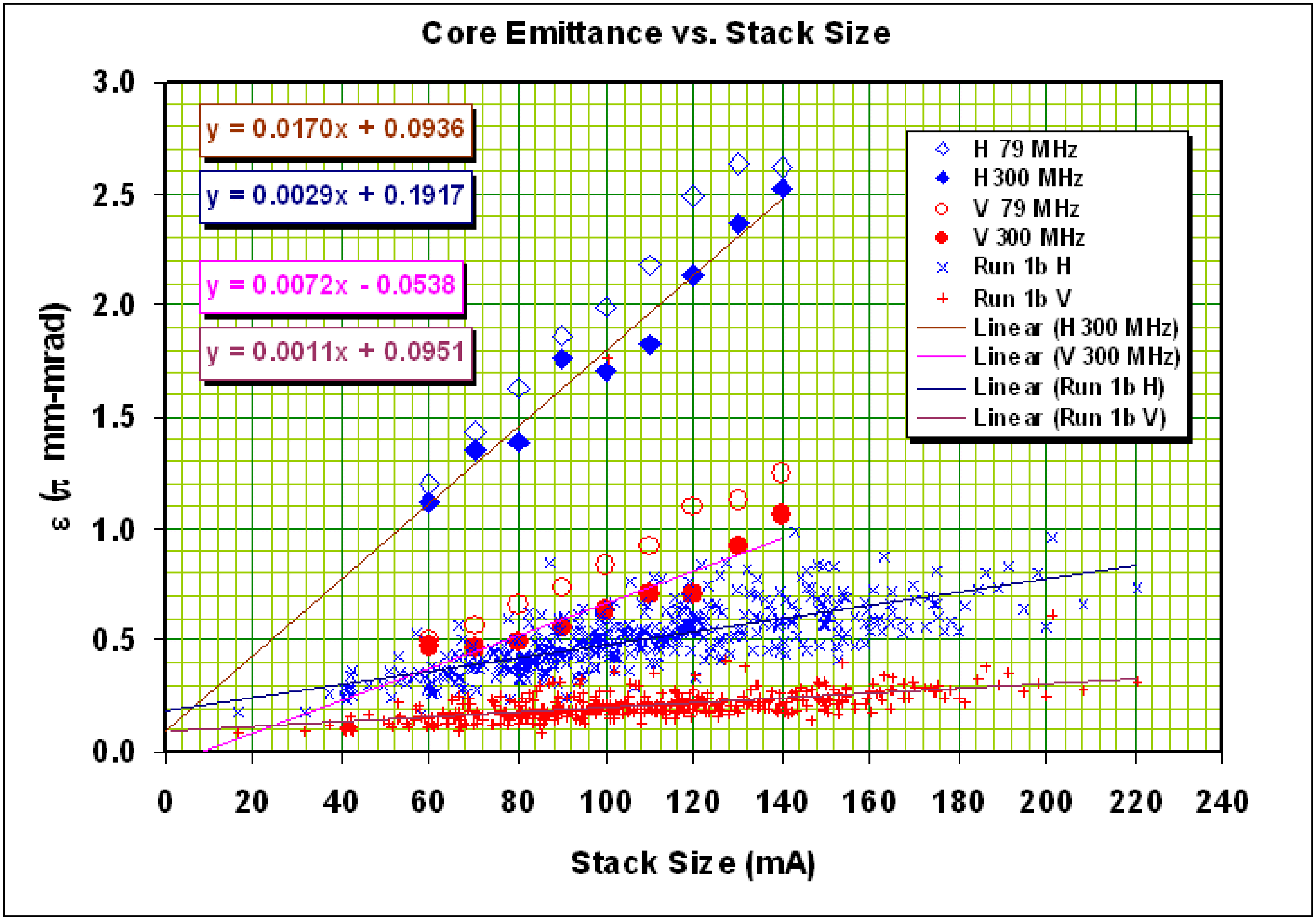
Record intensity: 4.6E13 ppp at 120 GeV.

Stochastic Cooling in AA



Stochastic Cooling signal paths

Antiproton Transverse Emittance Puzzle Early Run II



Overcoming Transverse Emittance Issue

- Before July of 2002, the horizontal emittance of a typical 100 x 10^{10} antiproton stack was about a factor of two larger than the Run II handbook design value
  - At a stack of 100 x 10^{10} pbars the normalized horizontal transverse emittance was about 17 π-mm-mrad
  - The Run II handbook specifies 8 π-mm-mrad at 100 x 10^{10} pbars
- During the period of Nov. 2001 through July 2002, almost 100% of the manpower and machine study time of the Pbar Source department was devoted to trying to reduce the horizontal emittance
- The intra-beam scattering (IBS) heating of the beam is worse now for Run II than it was in Run I because of the changes in beta functions that were the result of the Accumulator Lattice Upgrade

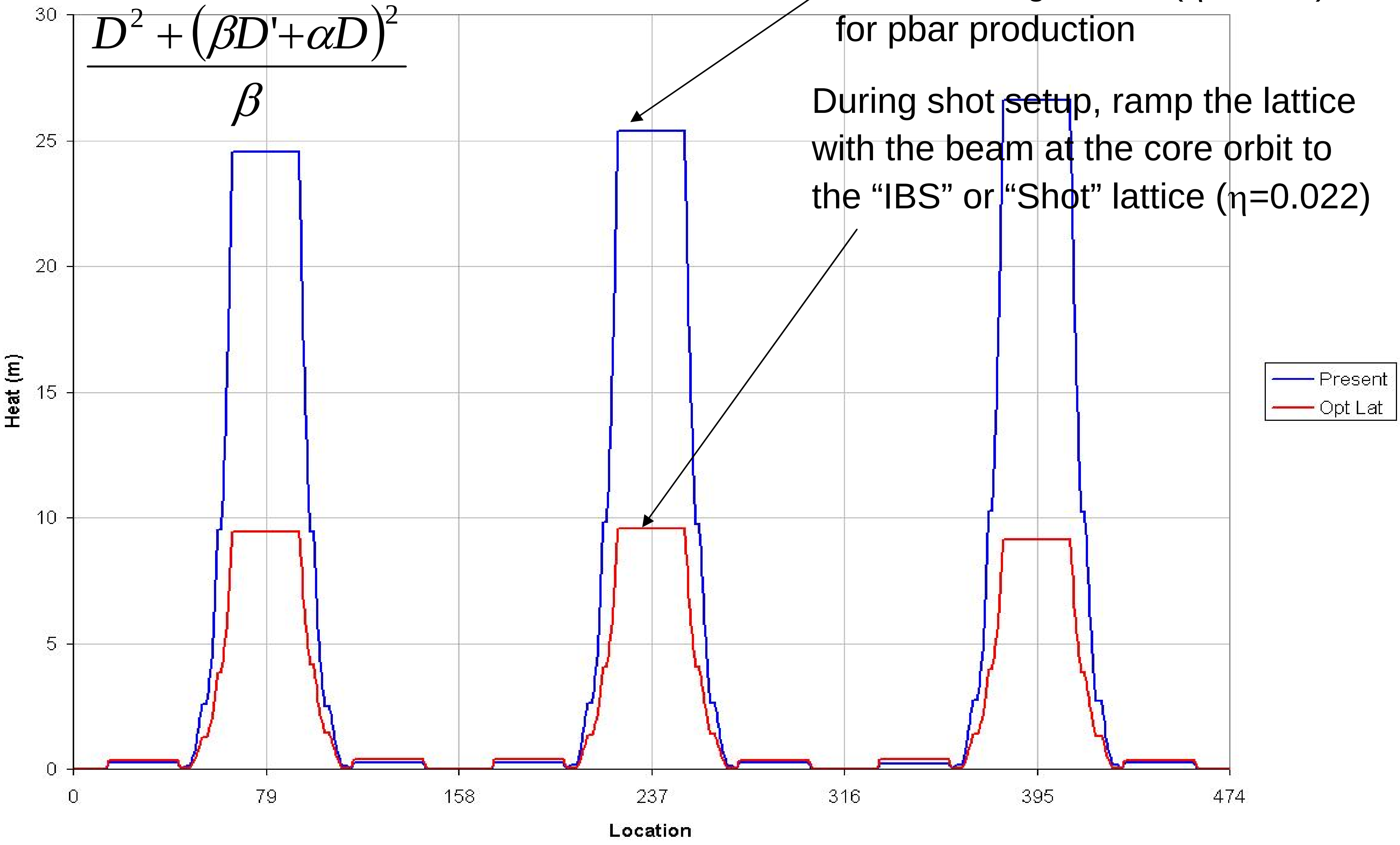
How to Overcome That Transverse Emittance ?

$$\frac{d\varepsilon}{dt} = -\frac{\varepsilon}{\tau_{Stoch.Cooling}} + (IBS\ Heating)$$

$$\varepsilon_{equilibrium} = \tau_{Stoch.Cooling} \times (IBS\ Heating) =$$

$$\propto \tau_{Stoch.Cooling} \times \frac{N_a}{\varepsilon_{Long}^{1/2}\varepsilon_{Transv}^{3/2}} \times \frac{D^2 + (D'\beta - D\beta'/2\beta)^2}{\beta}$$

Accumulator Lattices: “Stacking” and “Shot”

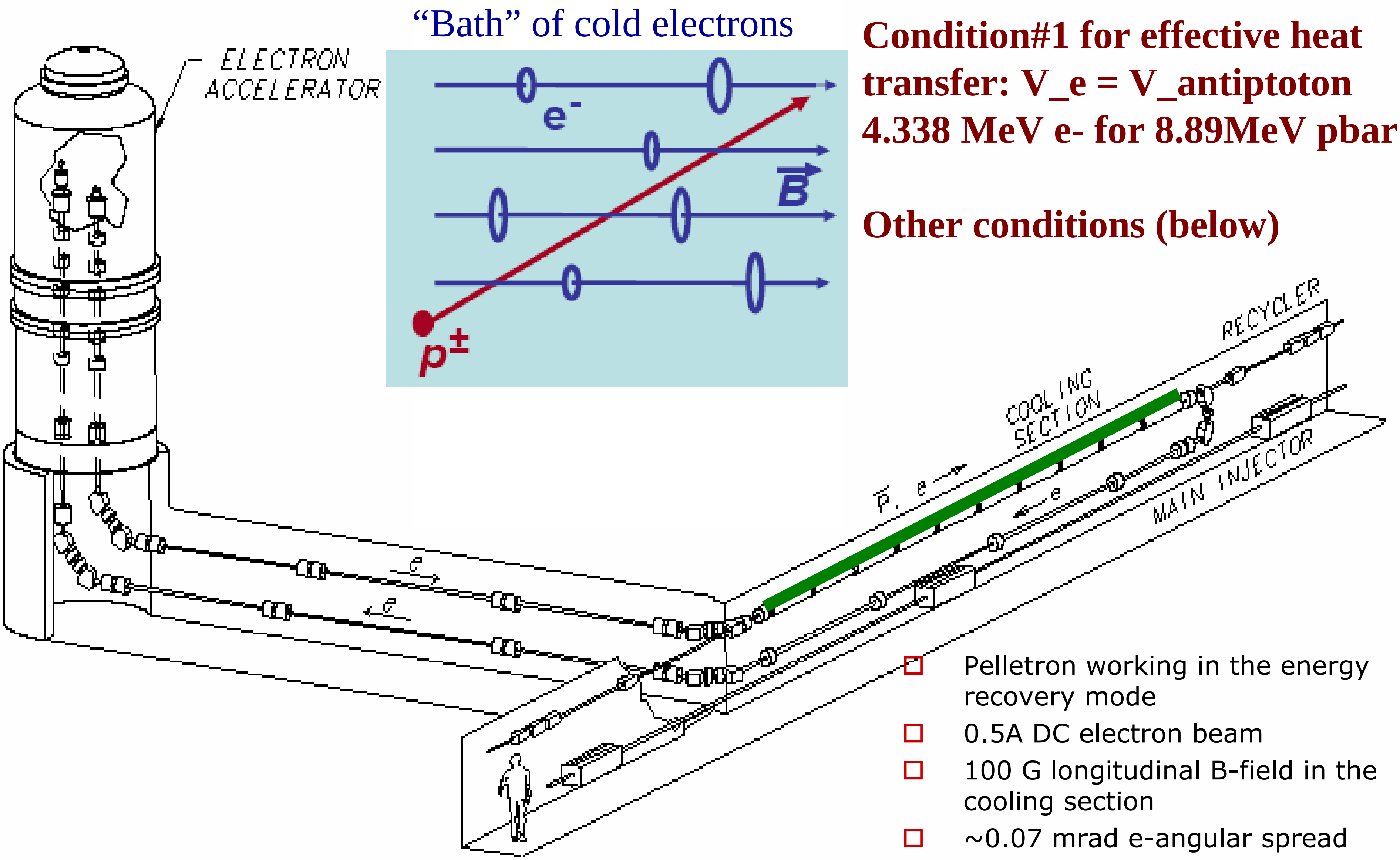


$$\frac{D^2+\left(\beta D'+\alpha D\right)^2}{\beta}$$

“fast stacking” lattice (η=0.012) for pbar production

During shot setup, ramp the lattice with the beam at the core orbit to the “IBS” or “Shot” lattice (η=0.022)

Electron Cooling of 8GeV Pbars in Recycler

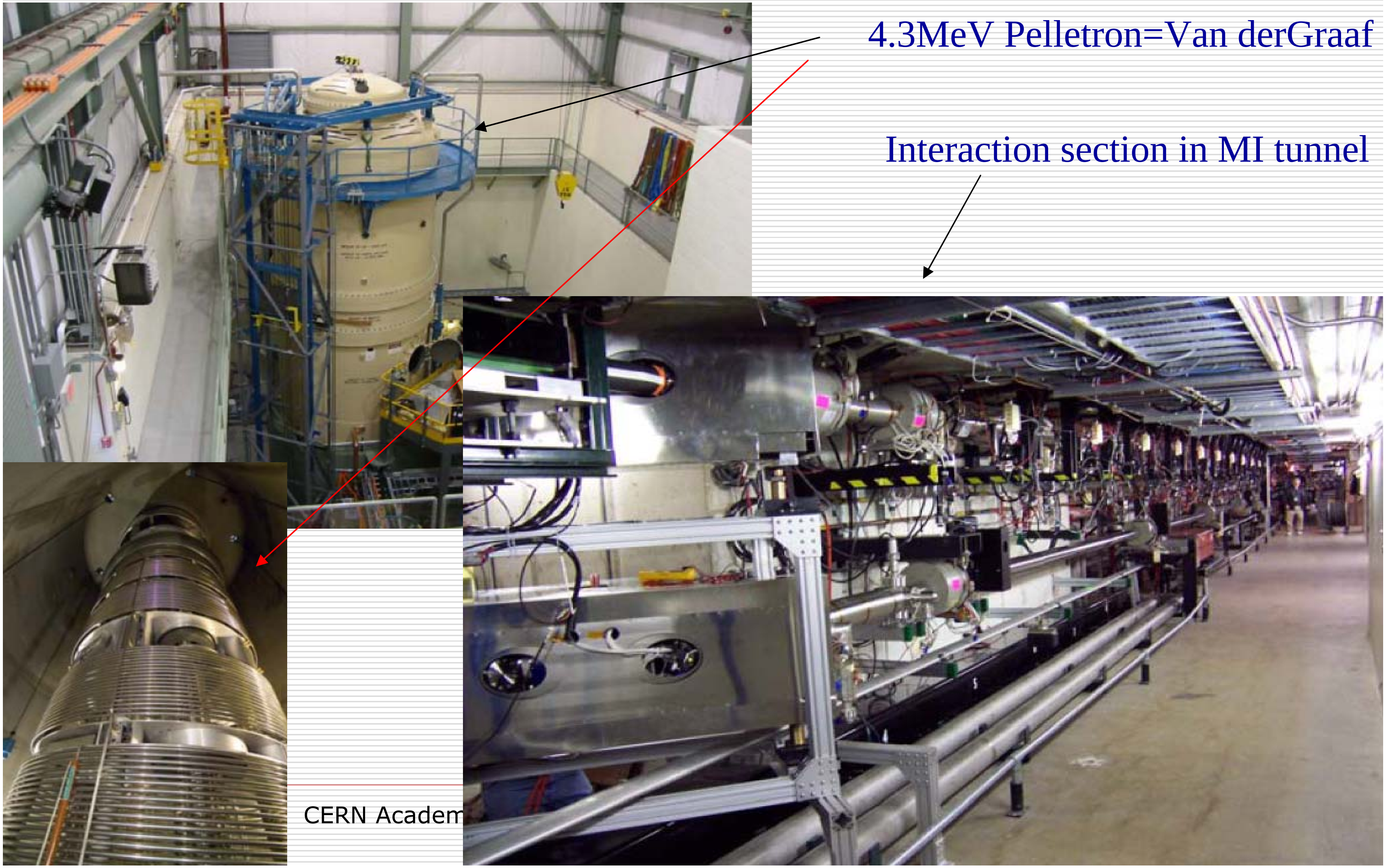

“Bath” of cold electrons

Condition#1 for effective heat transfer: V_e = V_antiptoton 4.338 MeV e- for 8.89MeV pbar

Other conditions (below)

- Pelletron working in the energy recovery mode
- 0.5A DC electron beam
- 100 G longitudinal B-field in the cooling section
- ~0.07 mrad e-angular spread

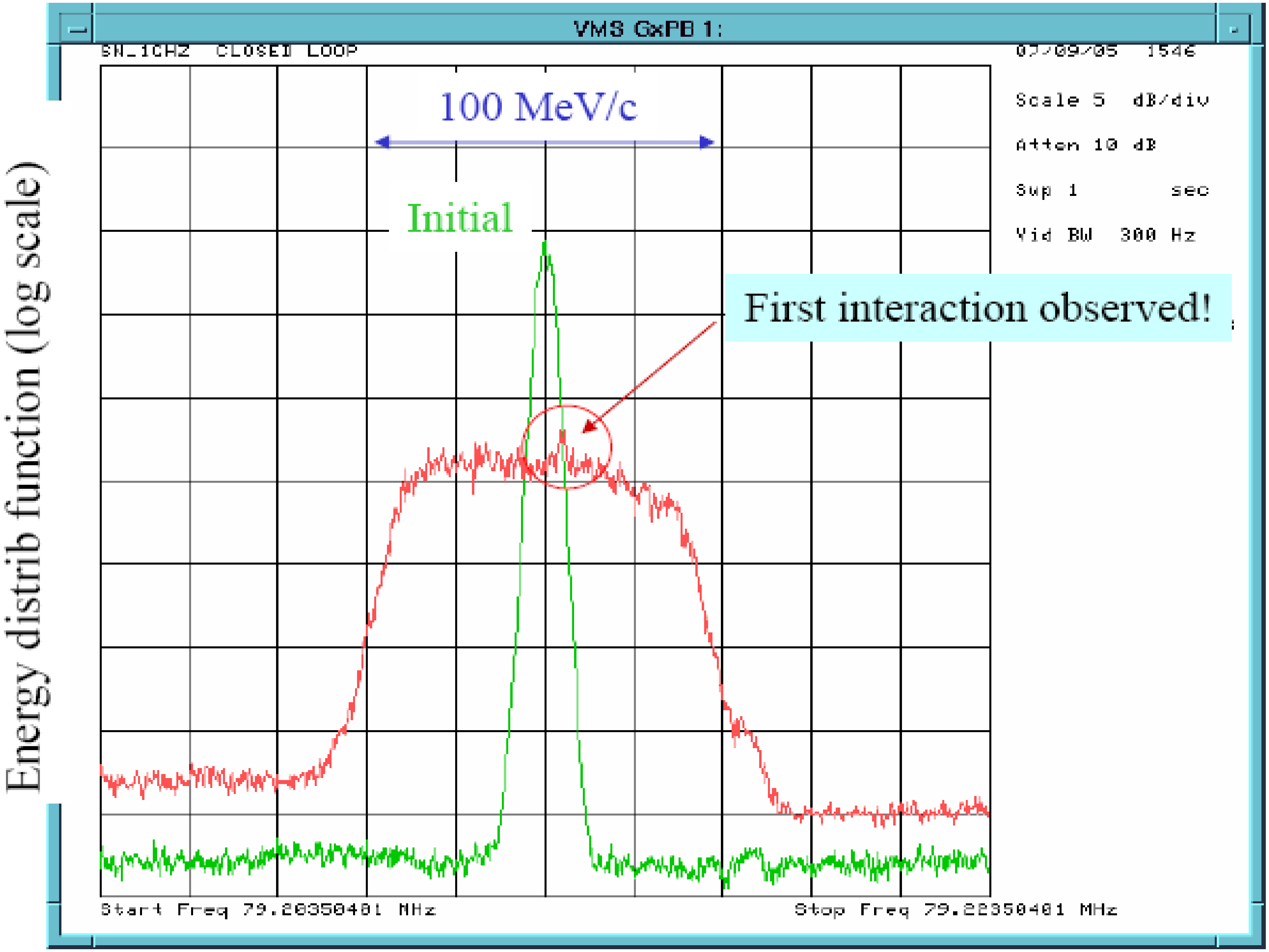
Electron Cooling Device



4.3MeV Pelletron=Van derGraaf

Interaction section in MI tunnel

First e-p Interaction – July 2005



VMS GxPB 1:

SN_1CHZ CLOSED LOOP

07/09/05 1546

Scale 5 dB/div

Atten 10 dB

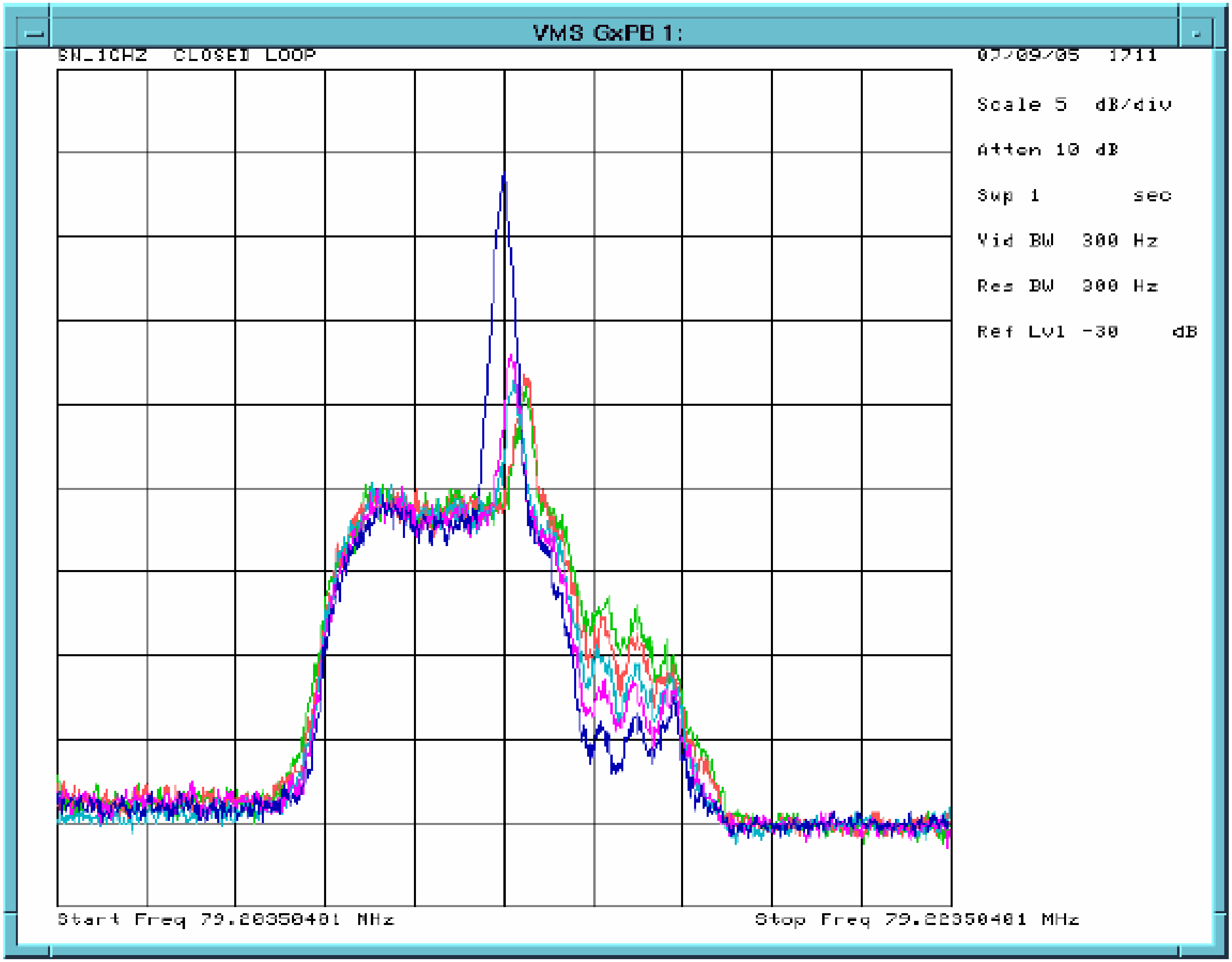
Swp 1 sec

Vid BW 300 Hz

Start Freq 79.20350401 MHz

Stop Freq 79.22350401 MHz

3kV e-energy shift – proton peak follows!



SN_1CHZ CLOSED LOOP

07/09/05 1711

Scale 5 dB/div

Atten 10 dB

Swp 1 sec

Vid BW 300 Hz

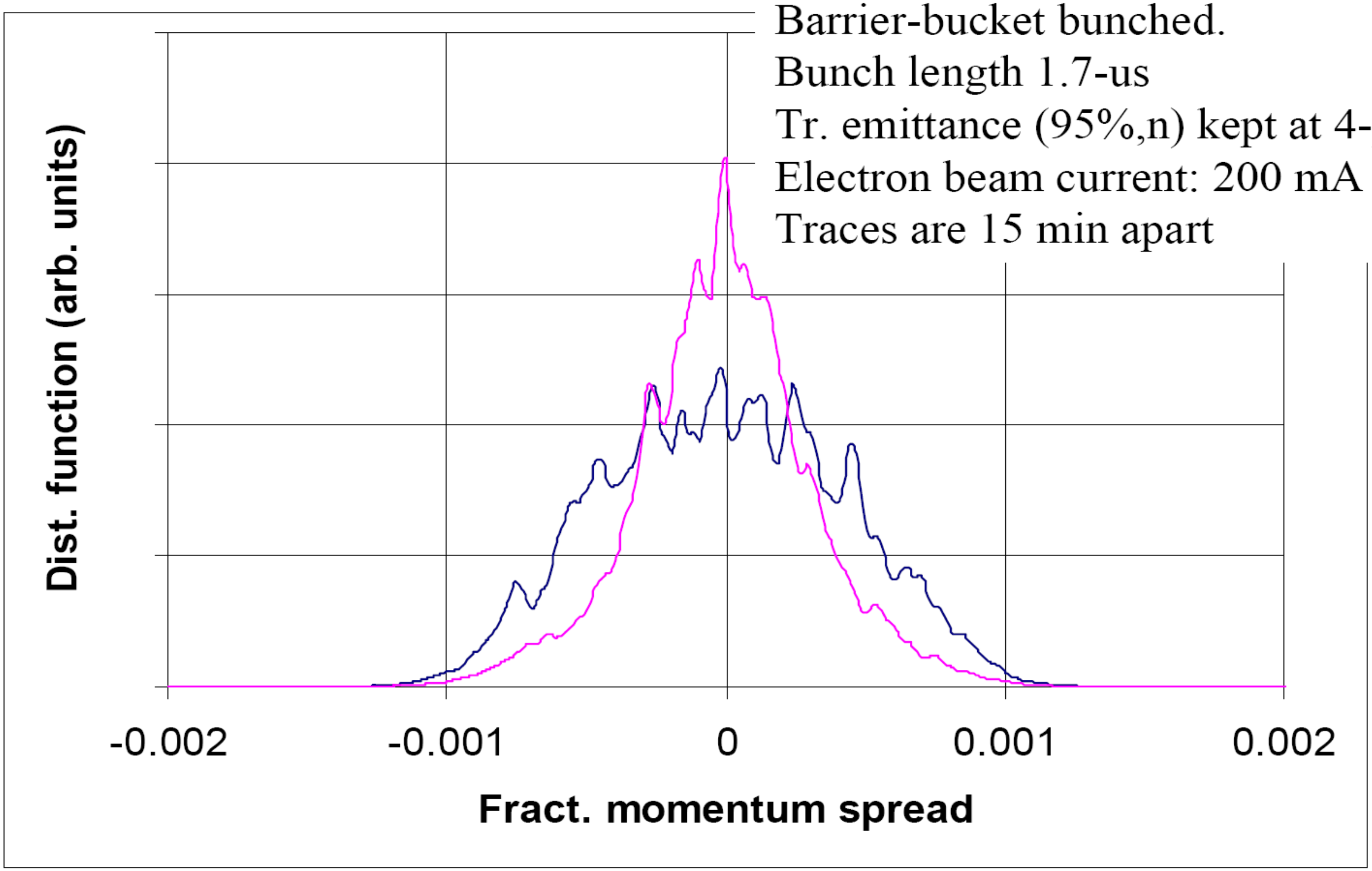
Res BW 300 Hz

Ref Lvl -30 dB

Start Freq 79.20350401 MHz

Stop Freq 79.22350401 MHz

July 15, 2005 – first Cooling demonstration!



Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mra
Electron beam current: 200 mA
Traces are 15 min apart

Electron cooling between transfers/extraction

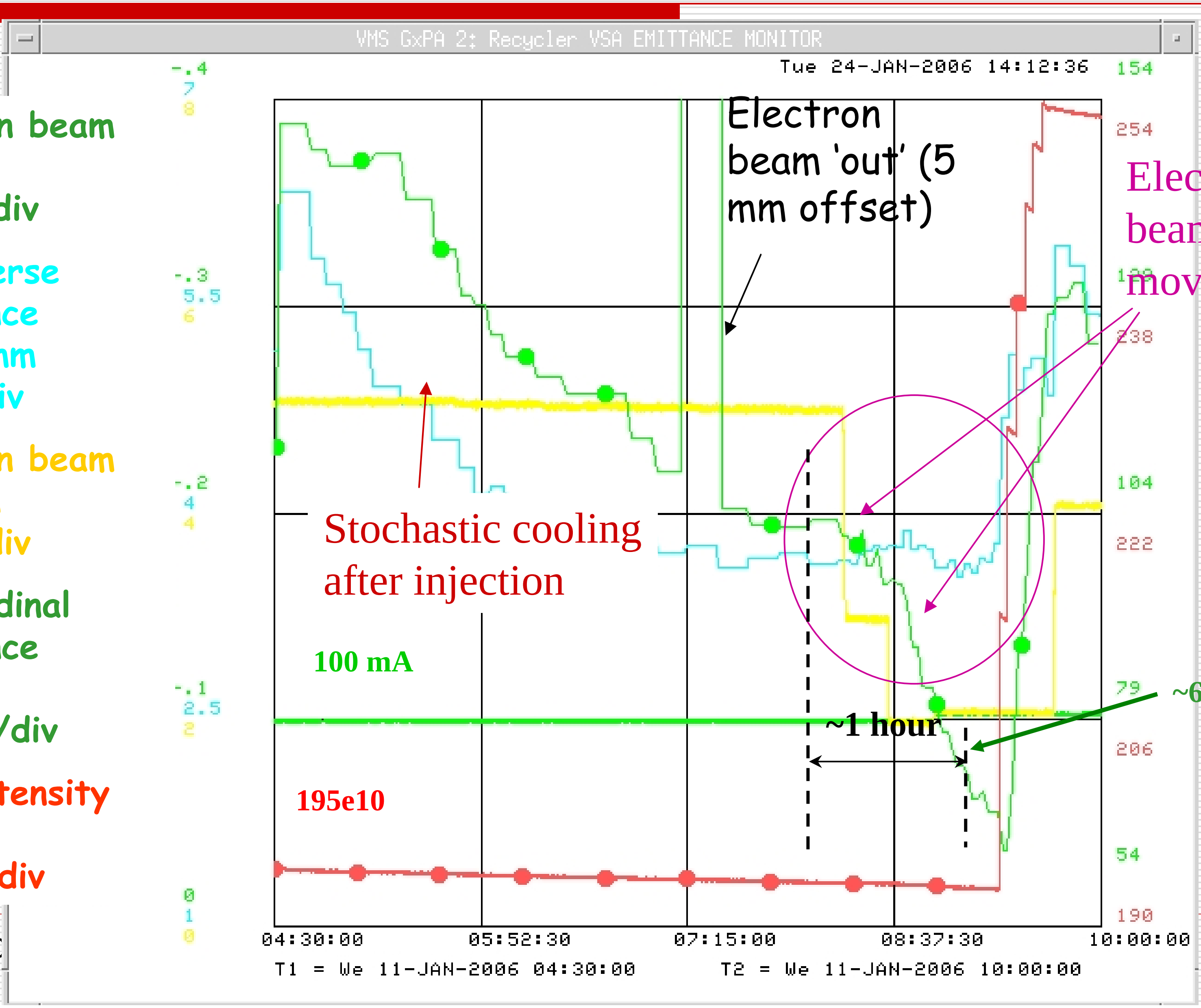
Electron beam current
0.1 A/div

Transverse emittance
1.5 π mm mrad/div

Electron beam position
1 mm/div

Longitudinal emittance (circle)
25 eVs/div

Pbar intensity (circle)
16e10/div



Electron beam 'out' (5 mm offset)

Electron beam is moved 'in'

Stochastic cooling after injection

100 mA

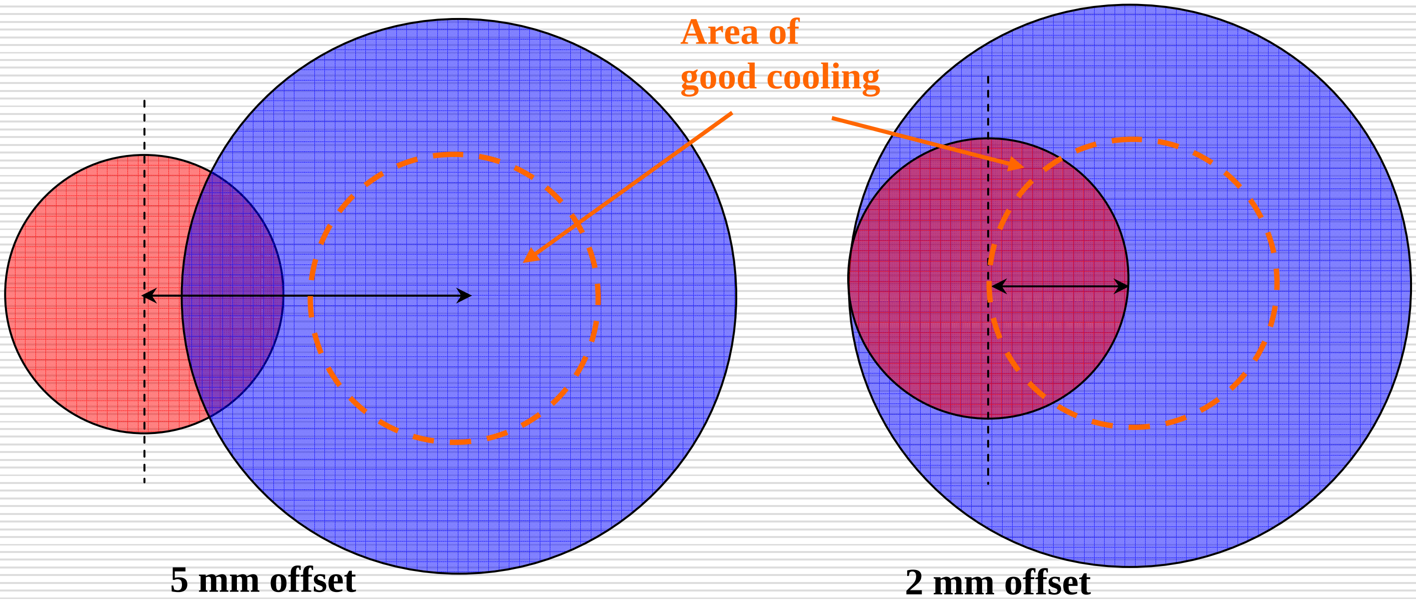
195e10

~1 hour

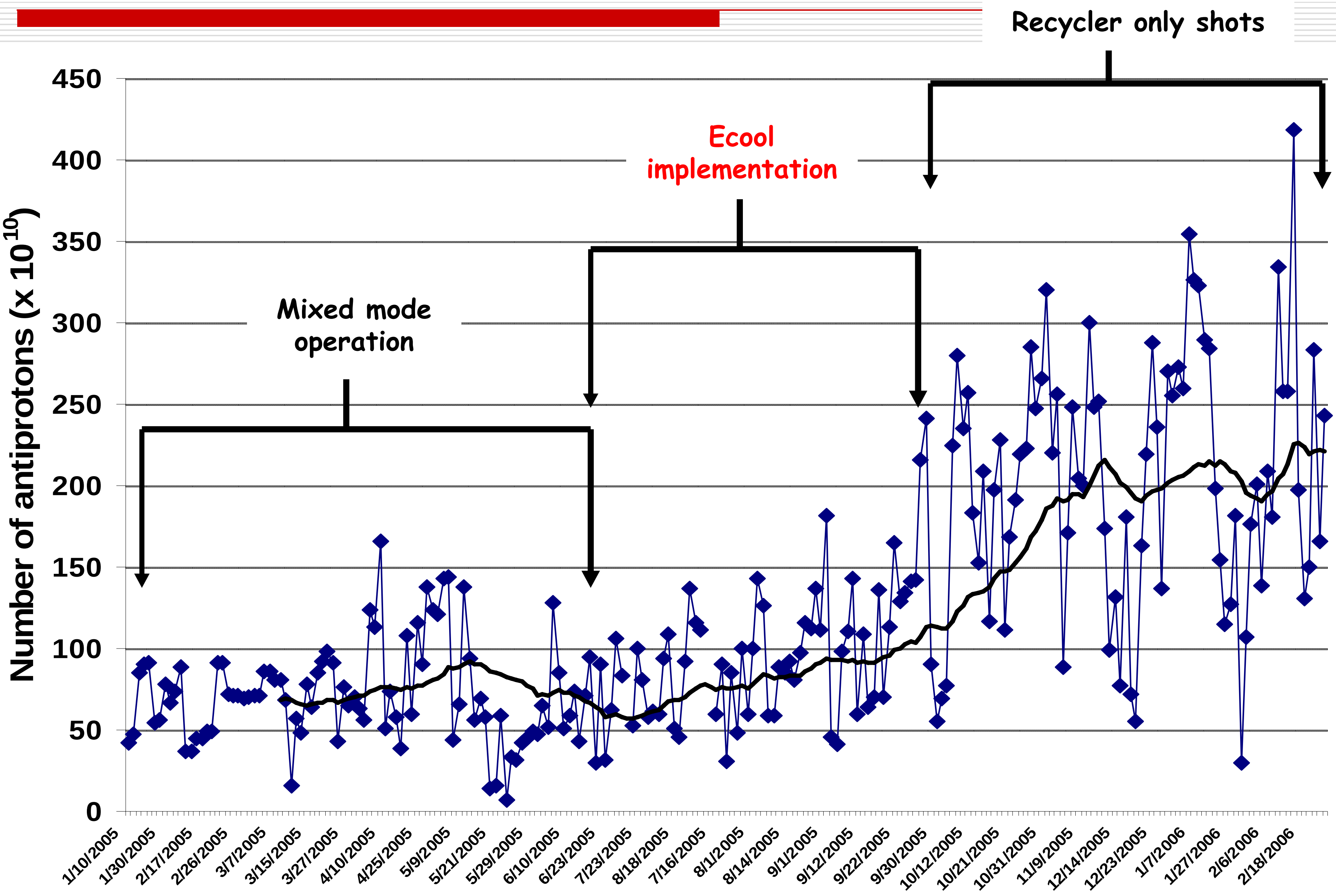
~60 eVs

Adjusting the cooling rate

- Two ‘knobs”
  - Electron beam current
    - Beam stays on axis
    - Dynamics of the gun varies between low and high currents
    - Hence, changing the beam current also changes the beam size and envelope in the cooling section
  - Electron beam position
    - ‘Adjustments’ are obtained by bringing the pbar bunch in an area of the beam where the angles are low



2005-06 progress in # of pbars from RR



Recycler only shots

Ecool implementation

Mixed mode operation

FNAL e-Cooling summary

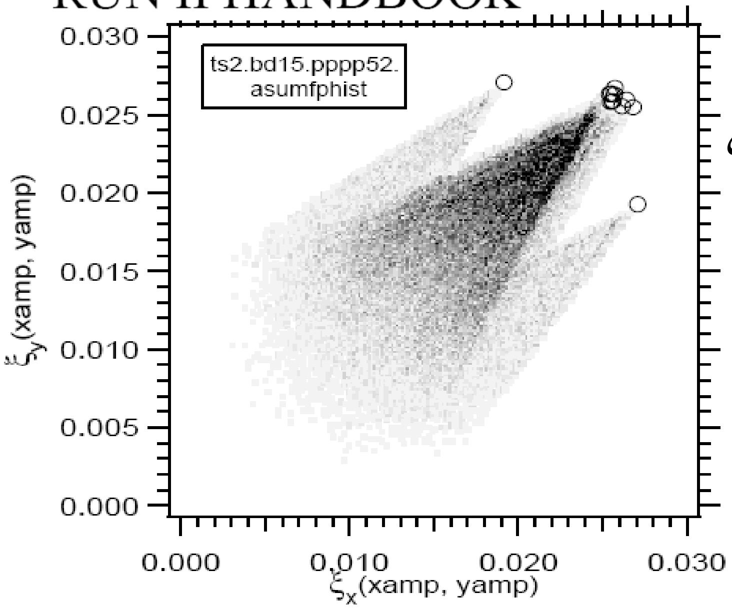
- Fermilab has a unique operational electron cooling system for cooling of 8.9 GeV/c antiprotons
  - Since the end of August 2005, ecooling is being used on every Tevatron shot
  - Allowed ~2xincrease of pbar stash sizes
  - allowed for advances in the TeV peak Lumi
- Recently, changing of the RR operating point Qx/Qy reduced equilibrium emittance of antiprotons used for luminosity production (see some discussion below)

Next will be an interesting interplay of beam-beam effects and instability issues

In the Tevatron

What we knew about Beam-Beam in 2001

RUN II HANDBOOK



TM-1970 (1995)

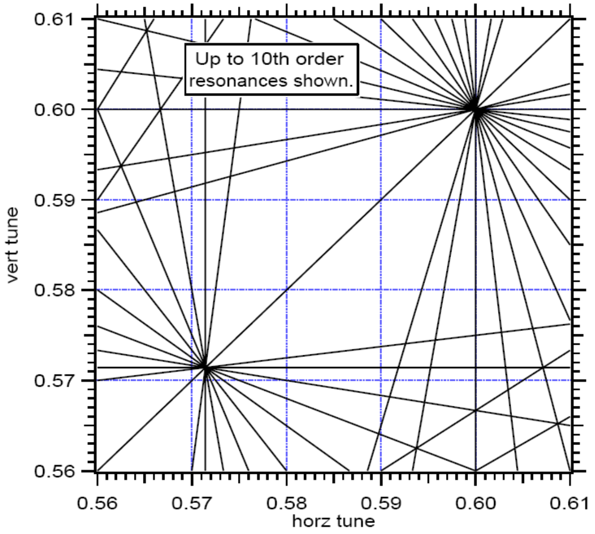
$$\xi = \frac{N_p r_p}{4\pi\varepsilon_p} \approx 0.025$$

Run Ib a) 6x6 → 2 head-on +10 long-range IPs
b) at 150: -7% p's -3% pbars
c) ramp-LB: -3% p's -10% pbar
d) dN_a ~ Emittance (4…14 pi)
e) shrinkage at 150 – small aperture?
f) nothing particularly bad in collisions

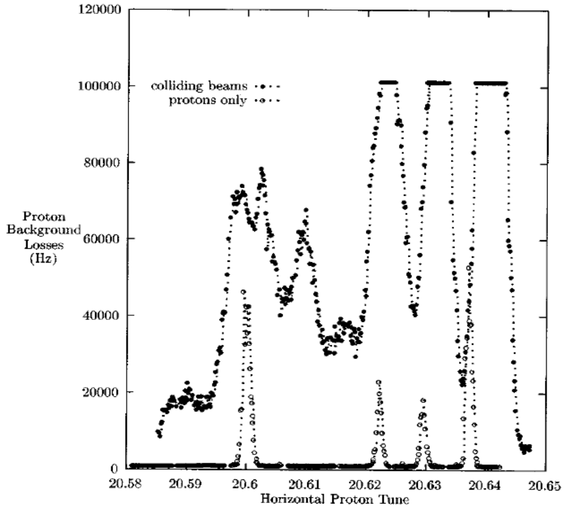
Run II: a) 36x36 → 2 HO +70 LR
b) same head-on tune shifts
c) end-of-train pbar bunches
be different in collisions

Overall = "should be tolerable…as in Run I"

… but 36xn studies in 1995 raised concerns



D. SIERGIEJ, D. FINLEY, AND W. HERR



Peter Bagley

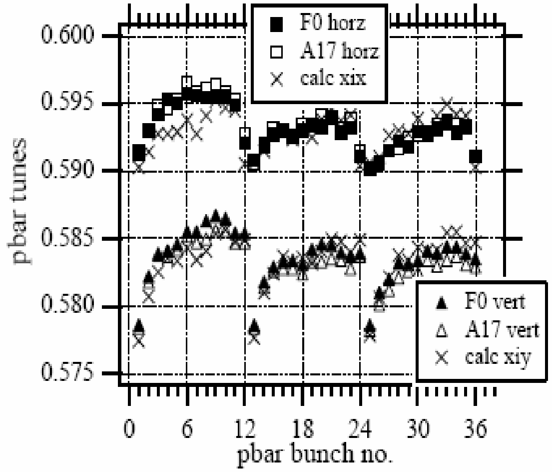
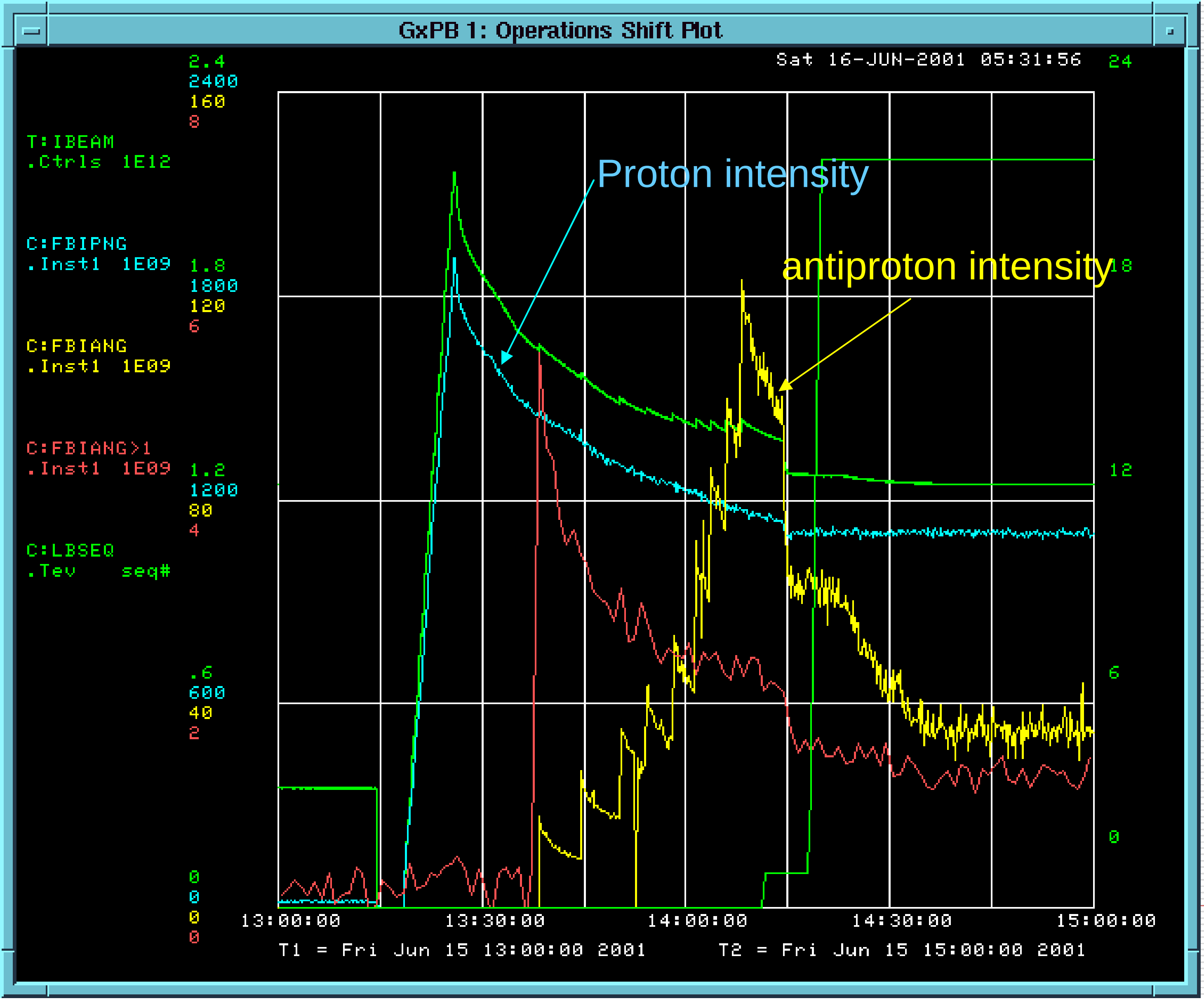


Figure 2 : Measured and Calculated Pbar Tunes for

Tevatron Inefficiencies: 2001



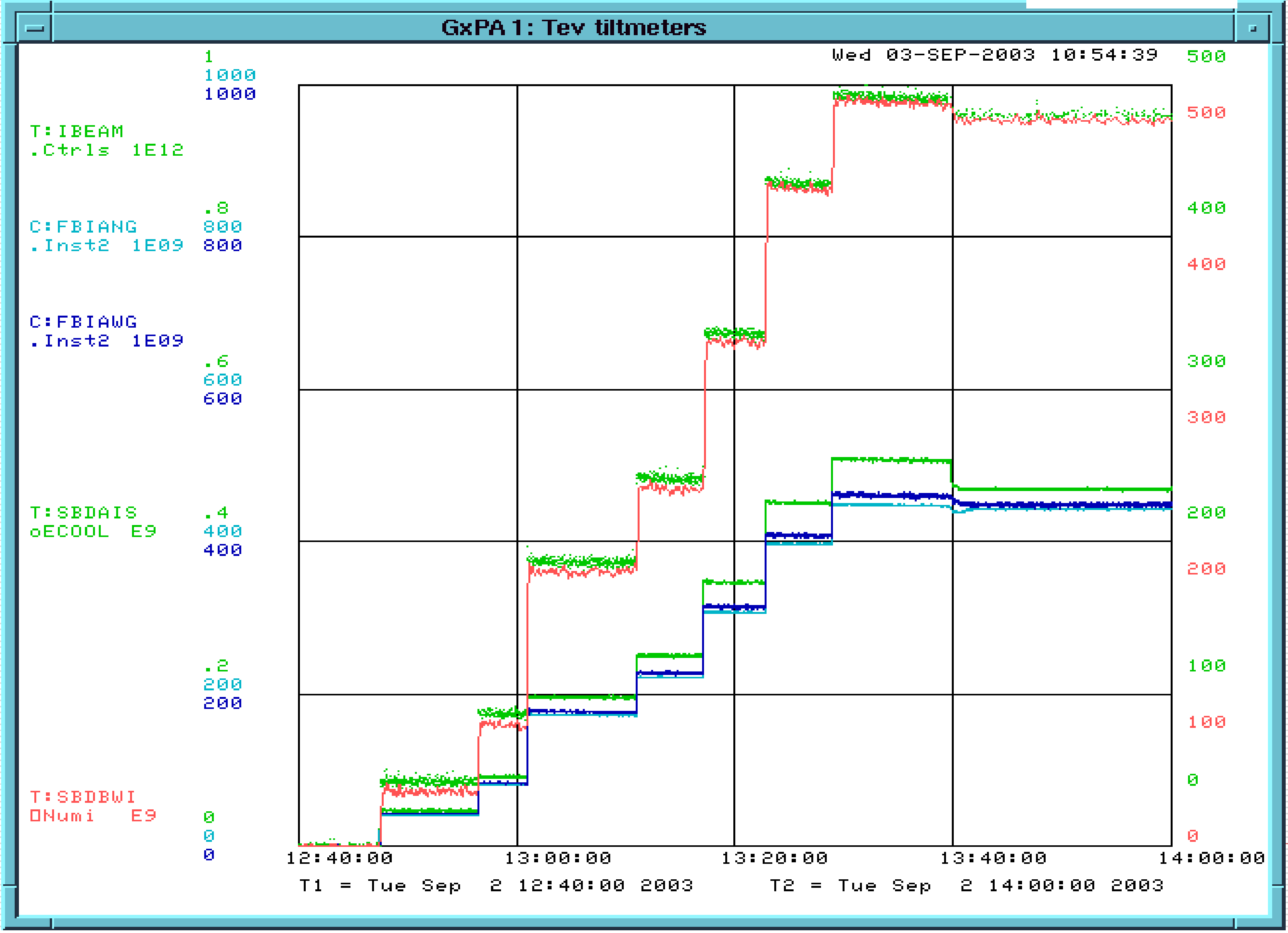
Proton intensity

antiproton intensity

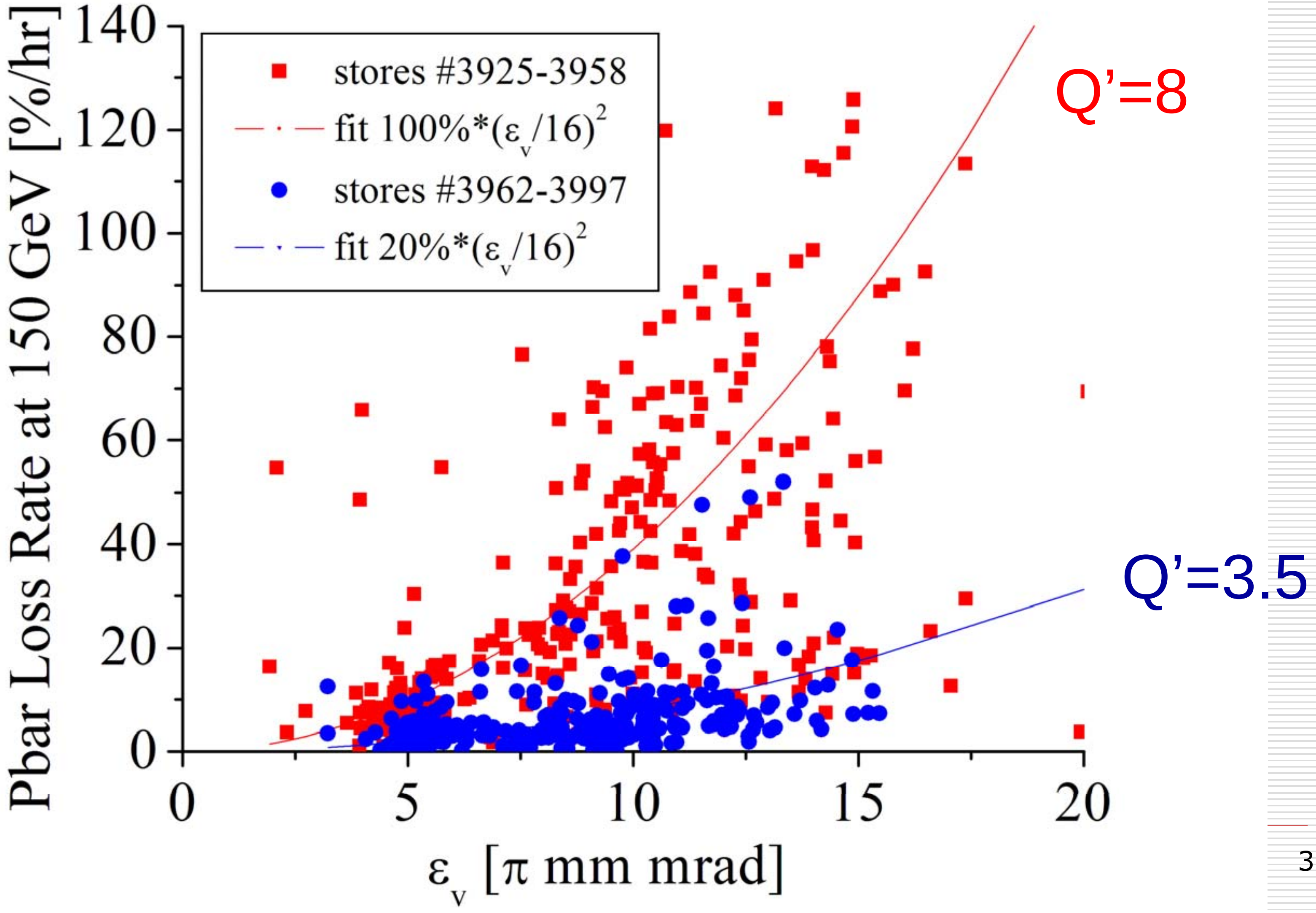
Store #535
Jun 15, 2001

No Other Beam - No Losses! (Pbar Only Store)

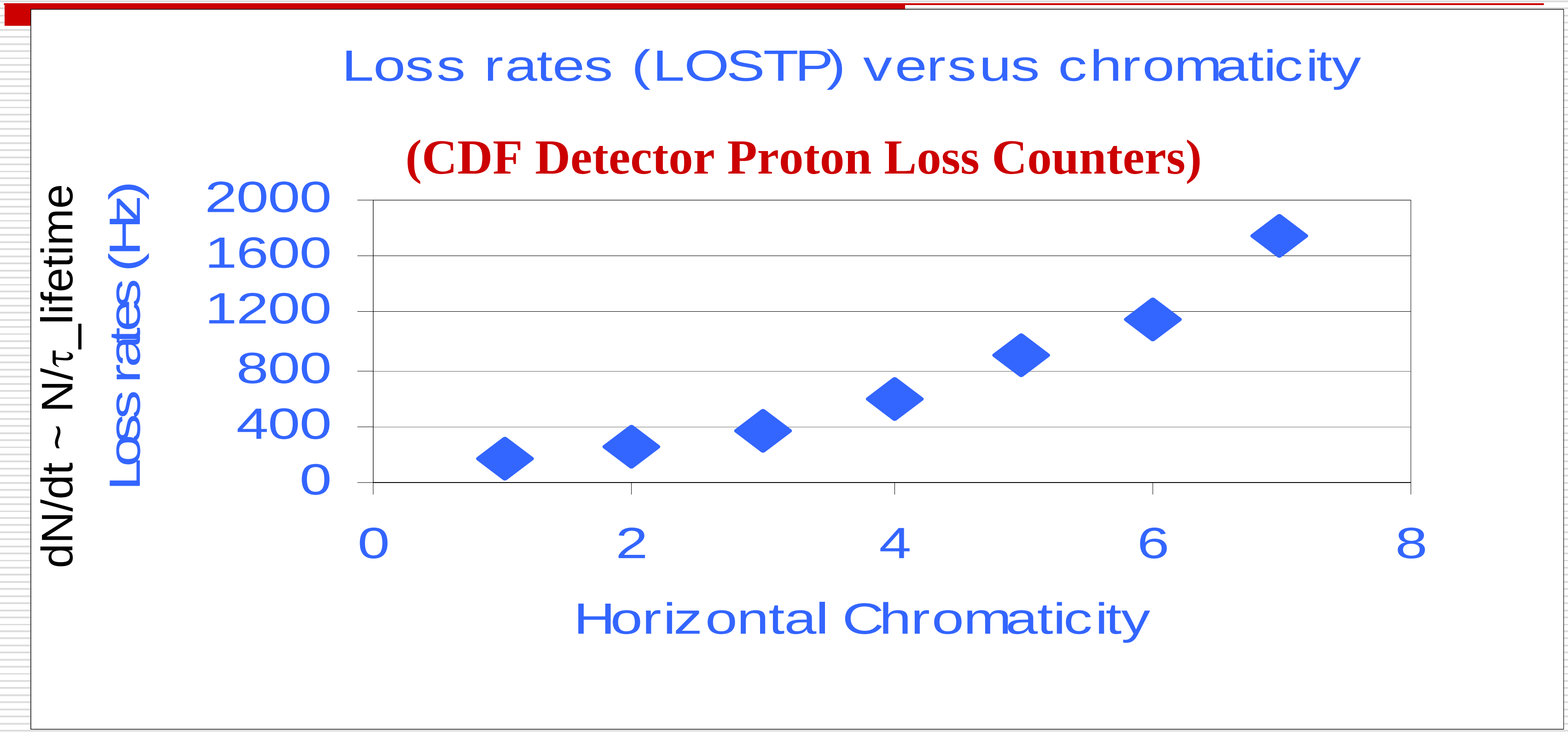
Sep. 02, 2003



Antiproton Lifetime Depends on Chromaticity
Q’=dQ/(dp/p)



Proton Lifetime Depends on Chromaticity – also beam-beam effect



- ☐ But Tevatron could **not** run 250-300e9/protons per bunch at low Q′ (<~6) – instability at 150 GeV

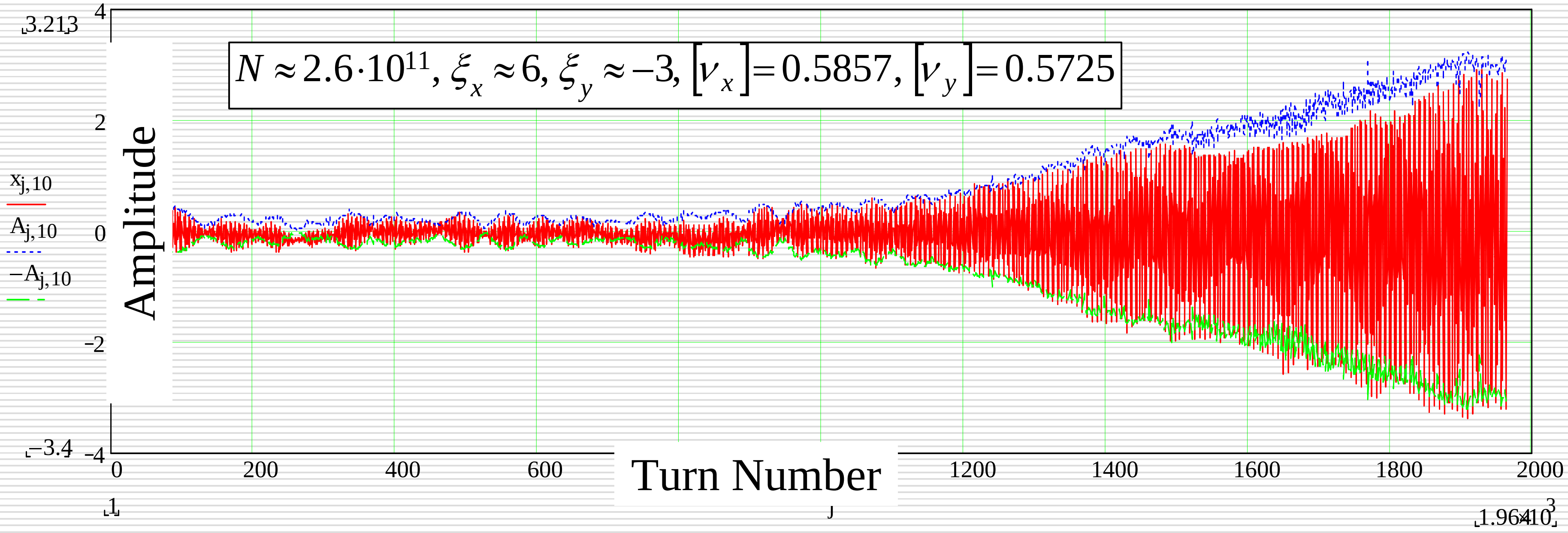
Unstable Head-tail Motion (Weak HT)

Developing head-tail instability with monopole configuration

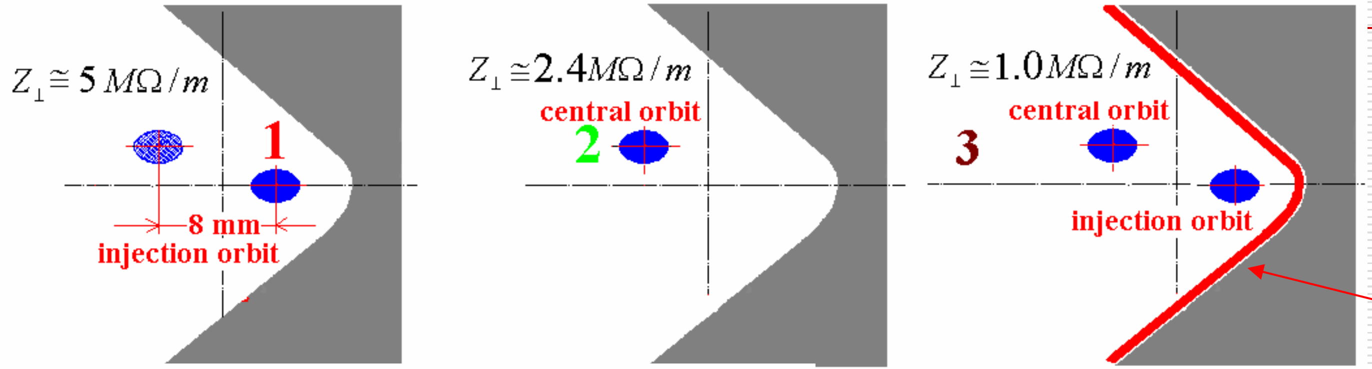
Beam is unstable for $Q'_x = 6$, $Q'_y = -3$

Longitudinal and transverse dampers OFF

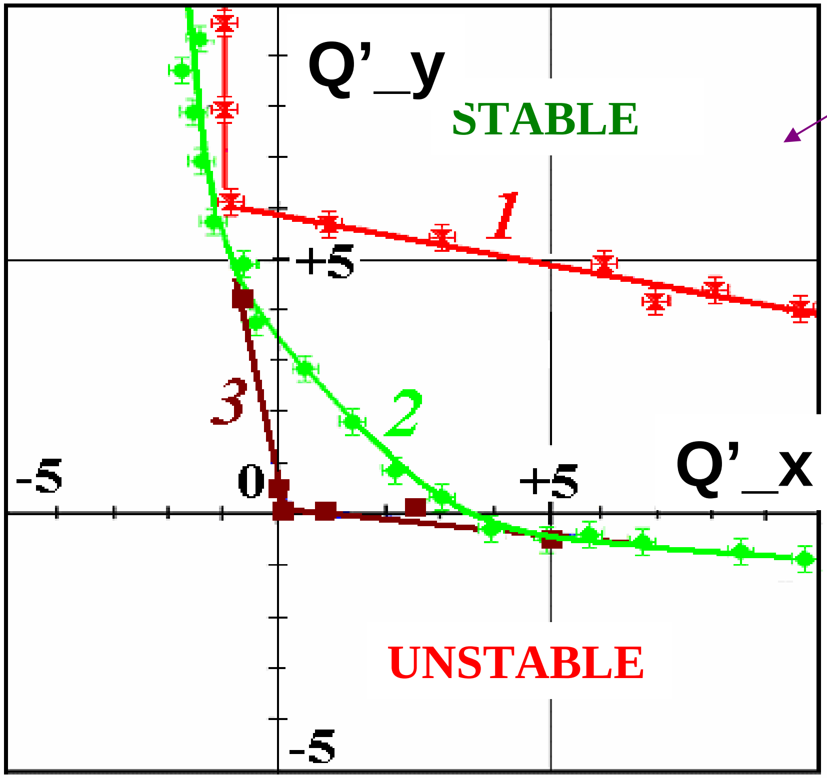
N_p= 260E9/bunch



Transverse Impedance due to Laminated Lambertson magnets (4x3m)



0.4 mm liner CuBe (98+2%)



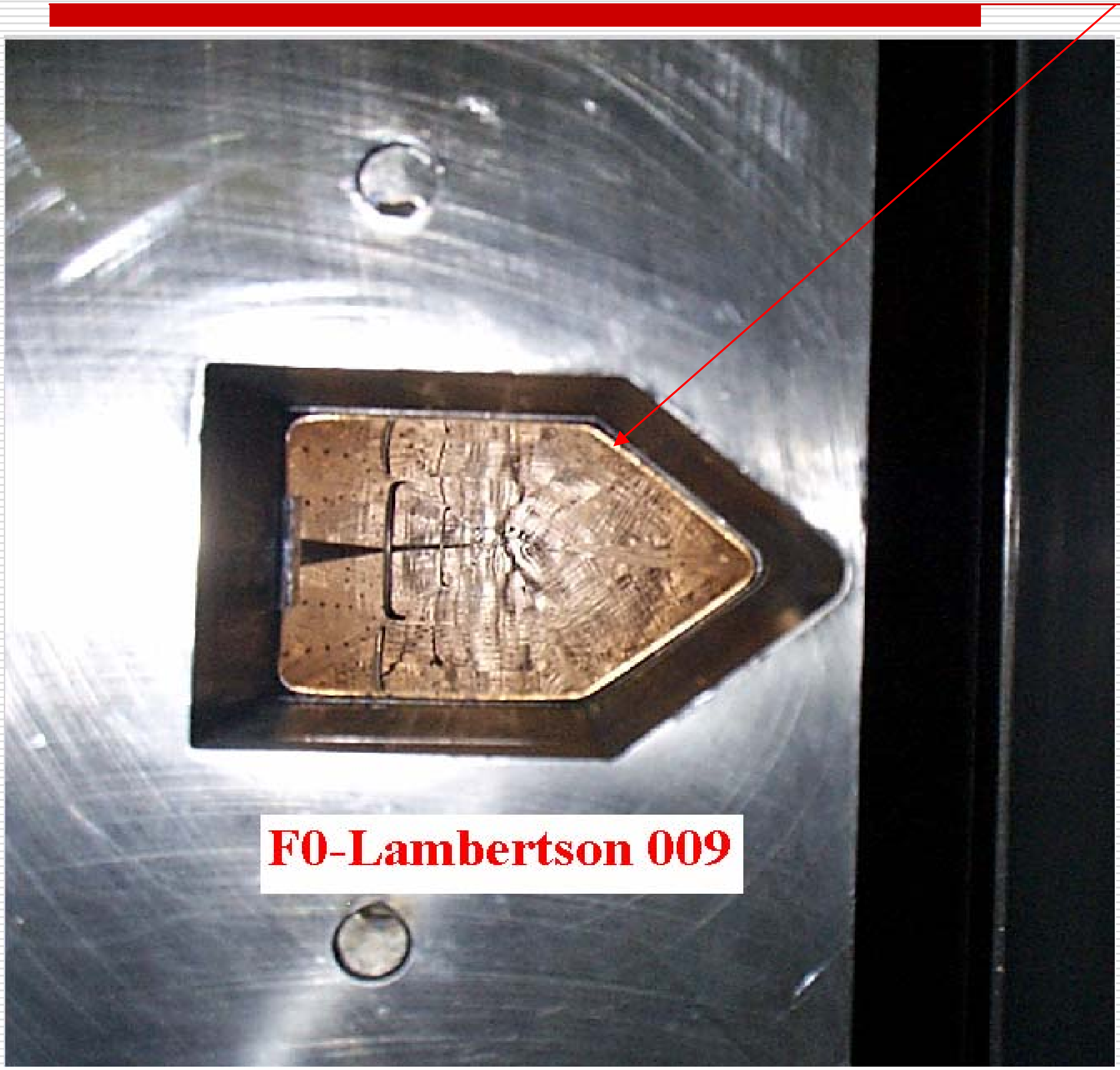
Region of stability of high intensity coalesced bunches (~230e9) on chromaticity plane before (#1 and #2) and after (#3) installation of conducting liner in F0 Lambertson magnets

Total transverse impedance reduced from 5-2.4 MOhm/m to 1 MOhm/m (RW impedance)

Losses at 150 ~ Chromaticity 4→2

Octupoles for safety at C_vh=0

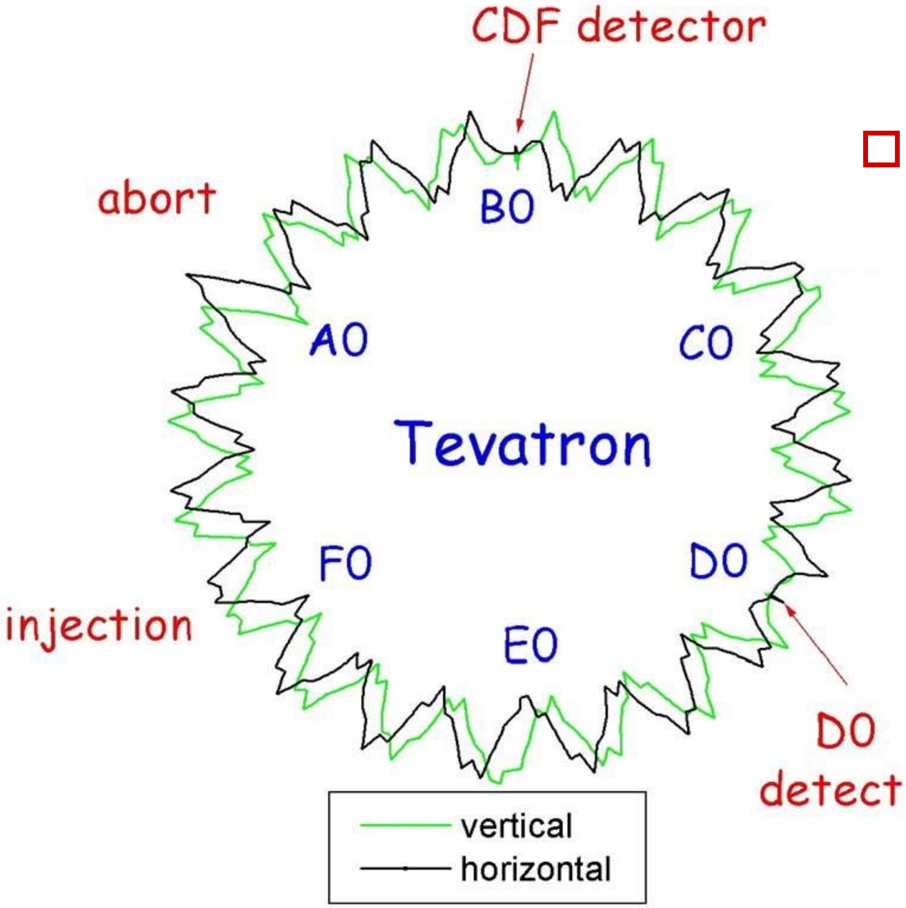
Conducting Liner

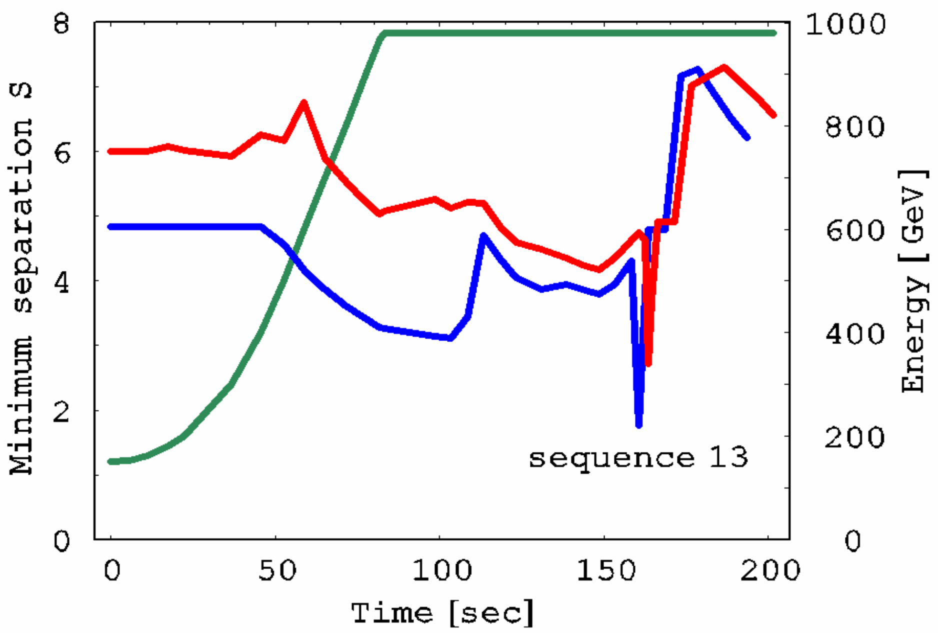


- Allows to operate at chromaticities close to 0

Importance of Helical Orbits

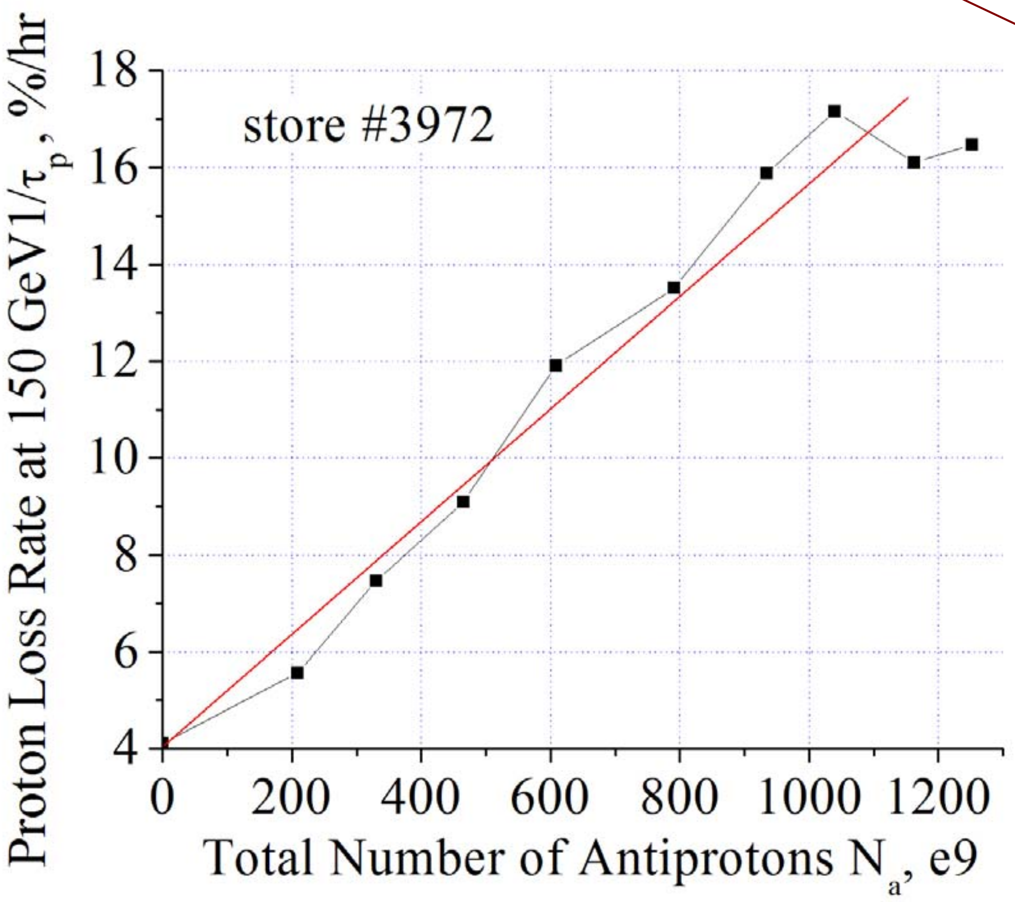
- Beams share beam pipe → be separated
    - Helical separation ~(10-22)mm at 150 GeV
    - ***S*** ~(3-6) mm at 980 GeV
- Lifetime is strong function of ***S***
    - 30 sec at 2σ , 50 hrs at 7σ





Beam Loss at Injection Helix

$$\frac{dN_{a,p}}{N_{a,p}} \propto \sqrt{t} \cdot \varepsilon^{2}_{a,p} N_{p,a} Q'^{2}_{a,p} \times F_1\left(S_{a-p}, Q_{a,p}, \frac{dP}{P}\right)$$

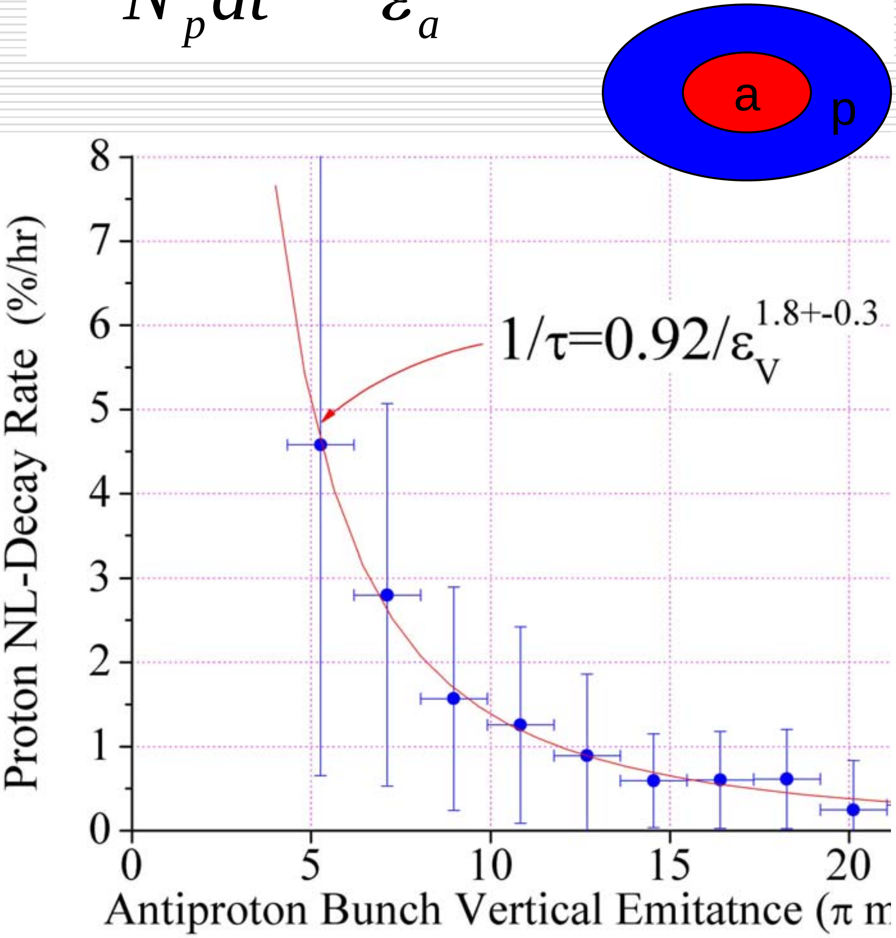


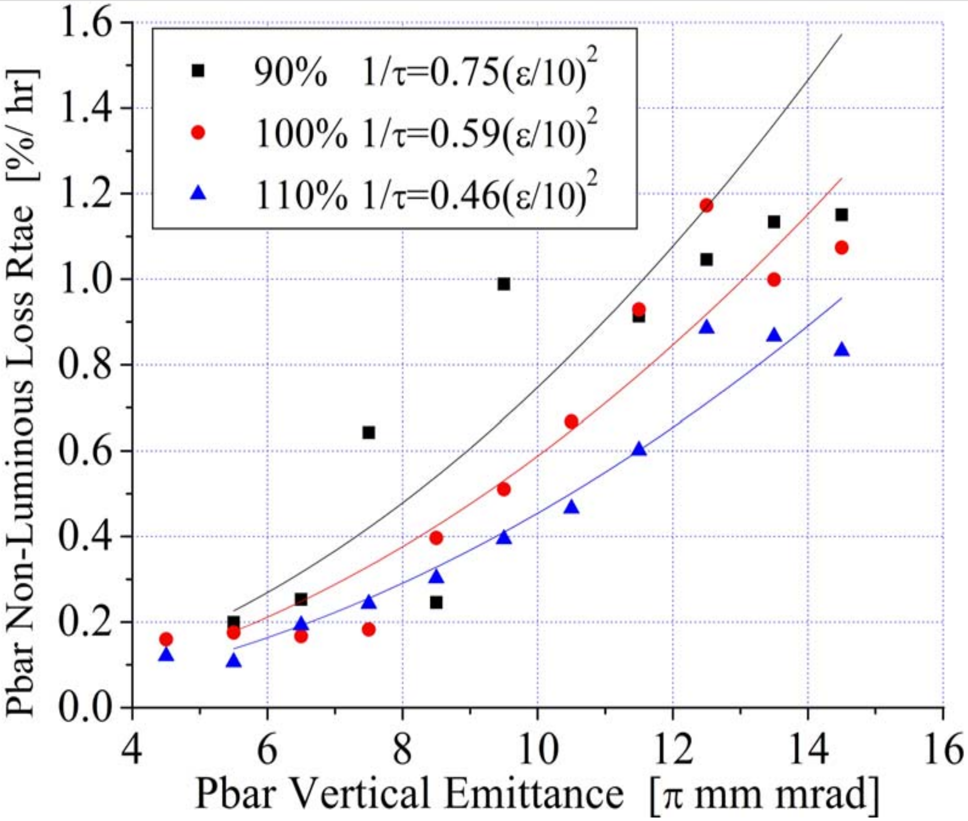
- Small emittances help → AA "shot lattice" and e-Cooling in recycler were very beneficial in that regard
- Smaller p-emittances welcome (inj)

Beam Loss in Collisions

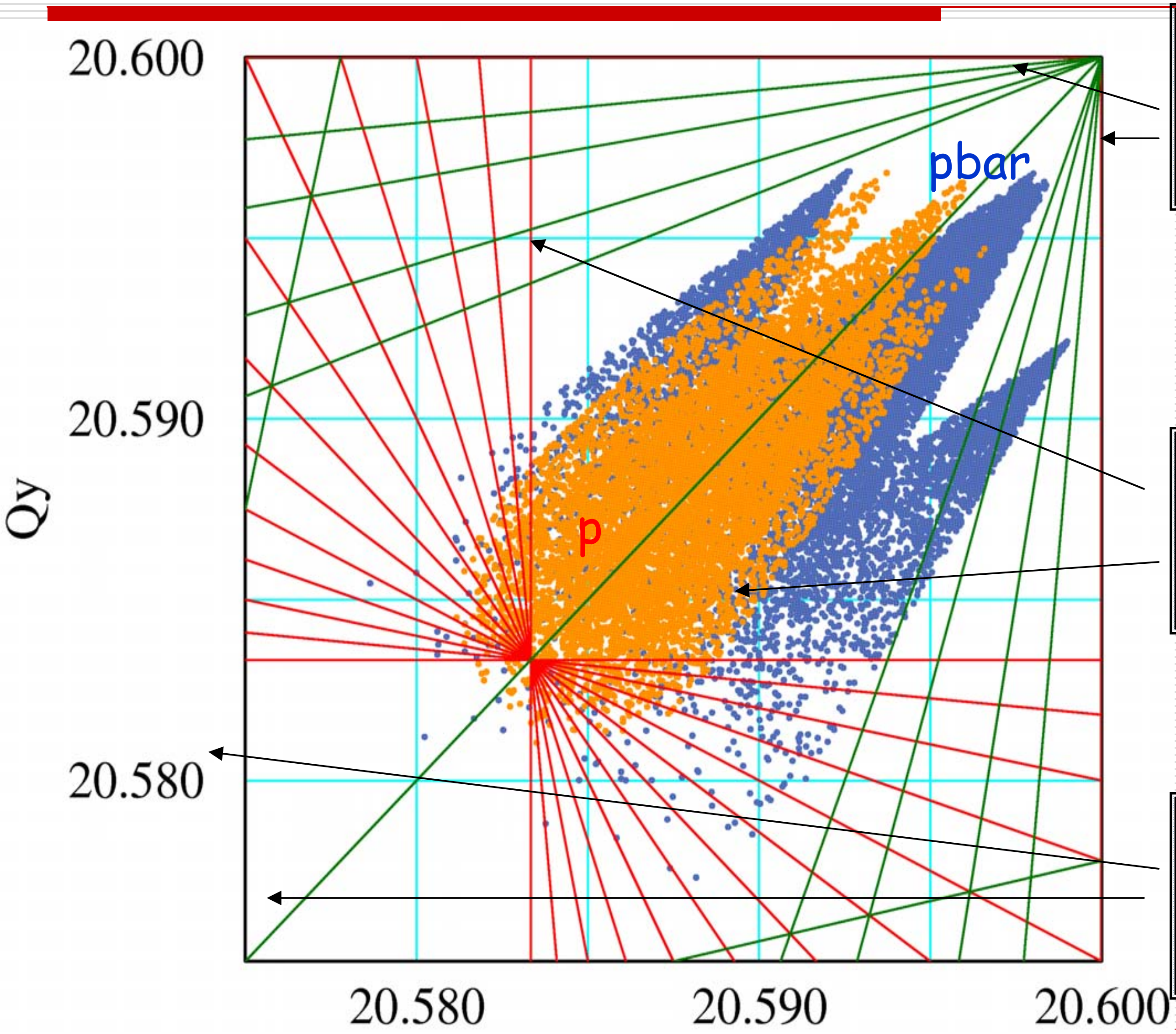
$$\frac{dN_p}{N_p\,dt} \propto \frac{N_a}{\varepsilon_a^2} \times F_3(Q_p, Q'_p)$$

$$\frac{dN_a}{N_a\,dt} \propto N_p \frac{\varepsilon_a^2}{S_{a-p}^3} \times F_4(Q_a, Q'_a)$$





Betatron Tunes of Tev Beams

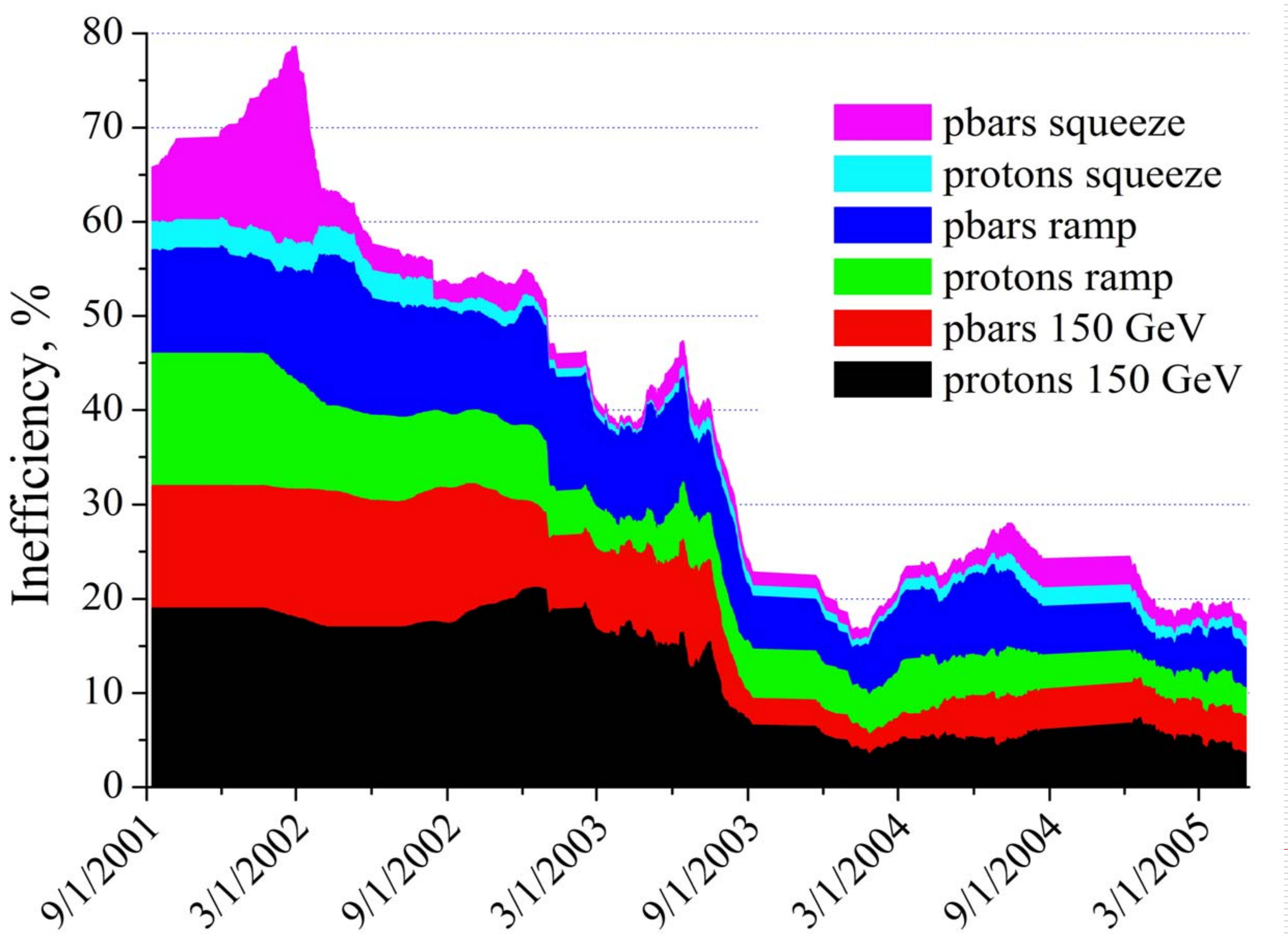


5th order resonances:
Q=3/5=0.600 –
EMITTANCE BLOWUP

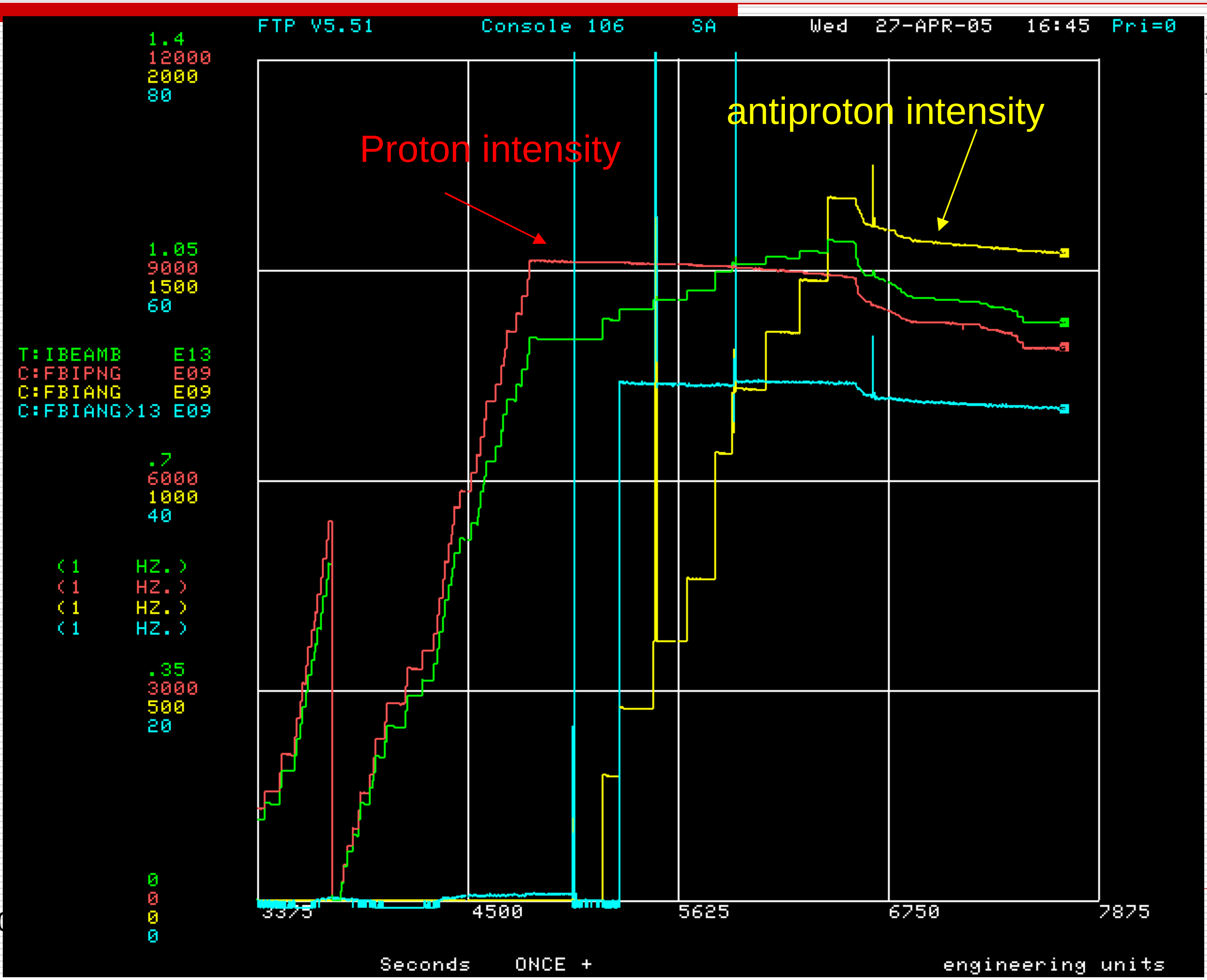
12th order resonances:
Q=7/12=0.583 -
Bad lifetime

7th order resonances:
Q=4/7=0.571 -
HIGH LOSSES

Tevatron Inefficiencies: 2001-2005



Tevatron Inefficiencies: 2005



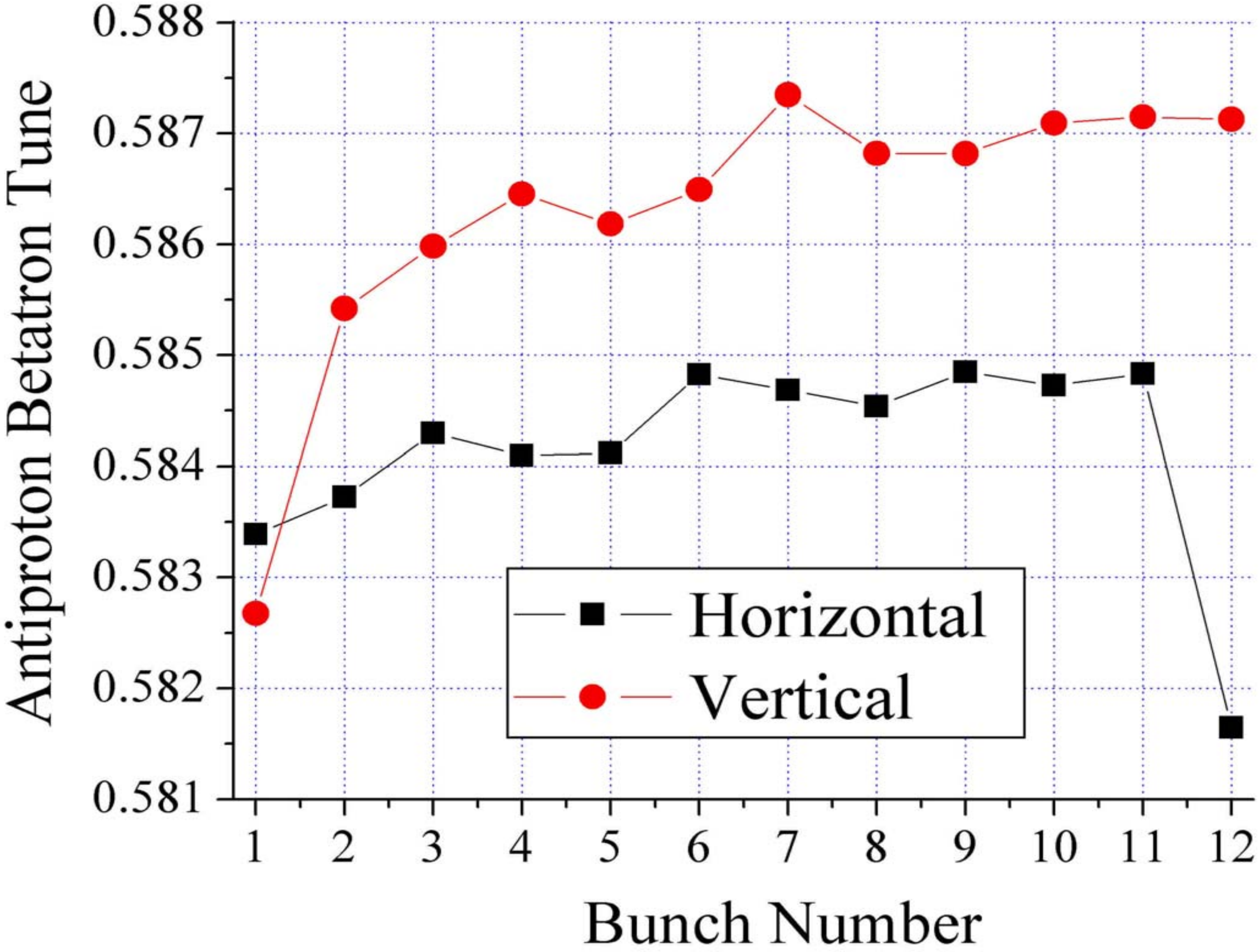
Store #4116
Apr 27, 2005

ONLY ONE

BEAM-BEAM EFFECT WAS LEFT INTACT →

Each bunch is unique – due to LRBB

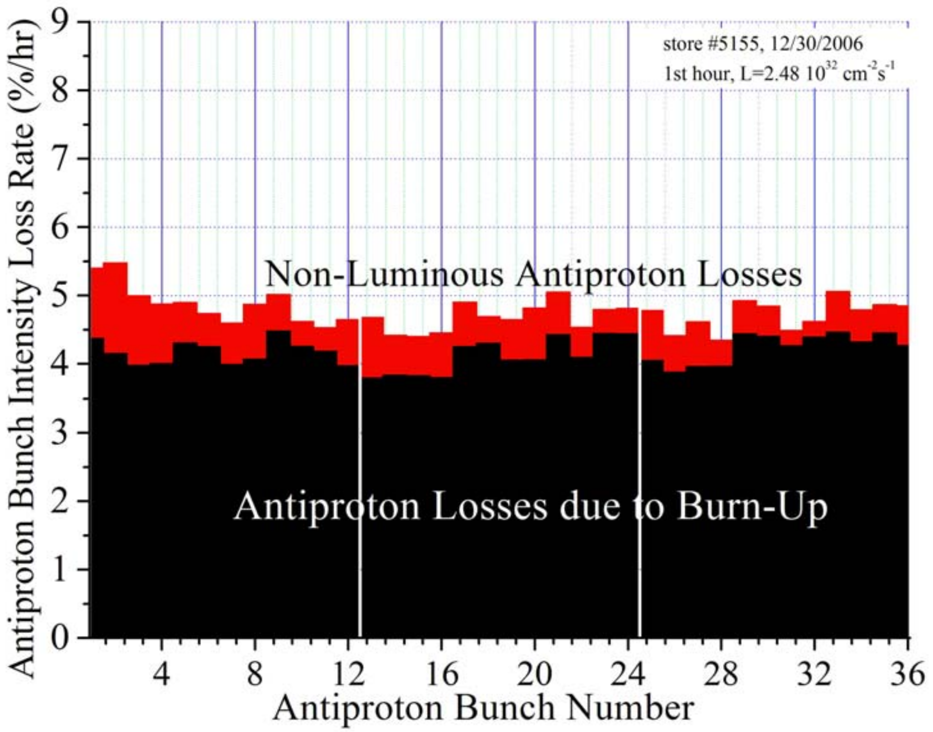
Bunch-by-bunch tune variation ~0.005 – an indication of parasitic beam-beam interactions



Losses of particles due to beam-beam

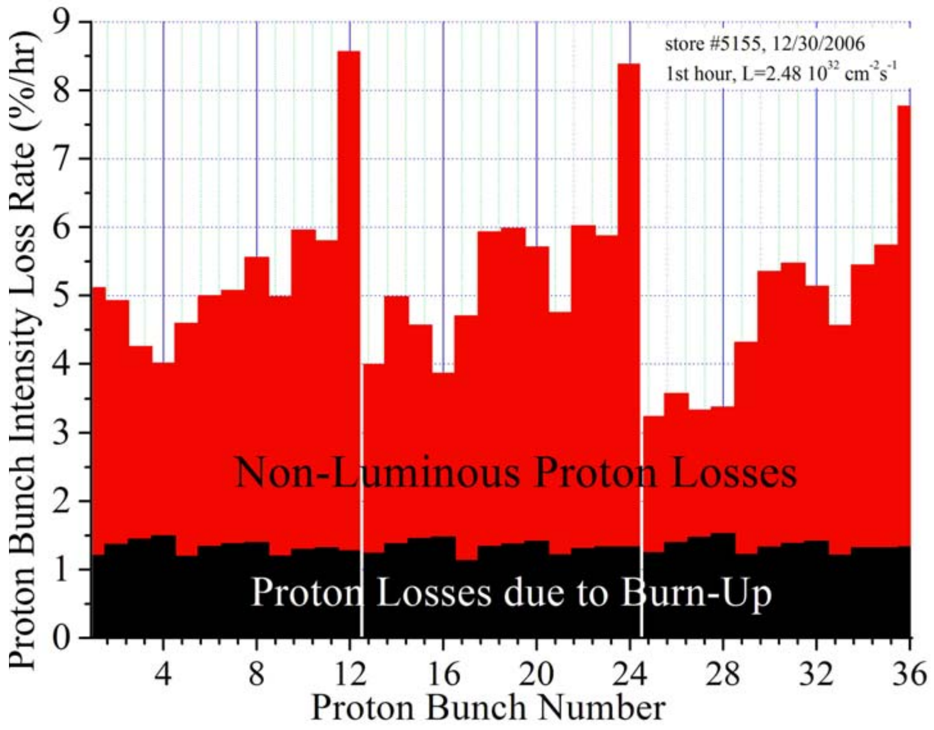
Antiprotons *980 GeV :*

ξ_{max}=+0.024



Protons *980 GeV :*

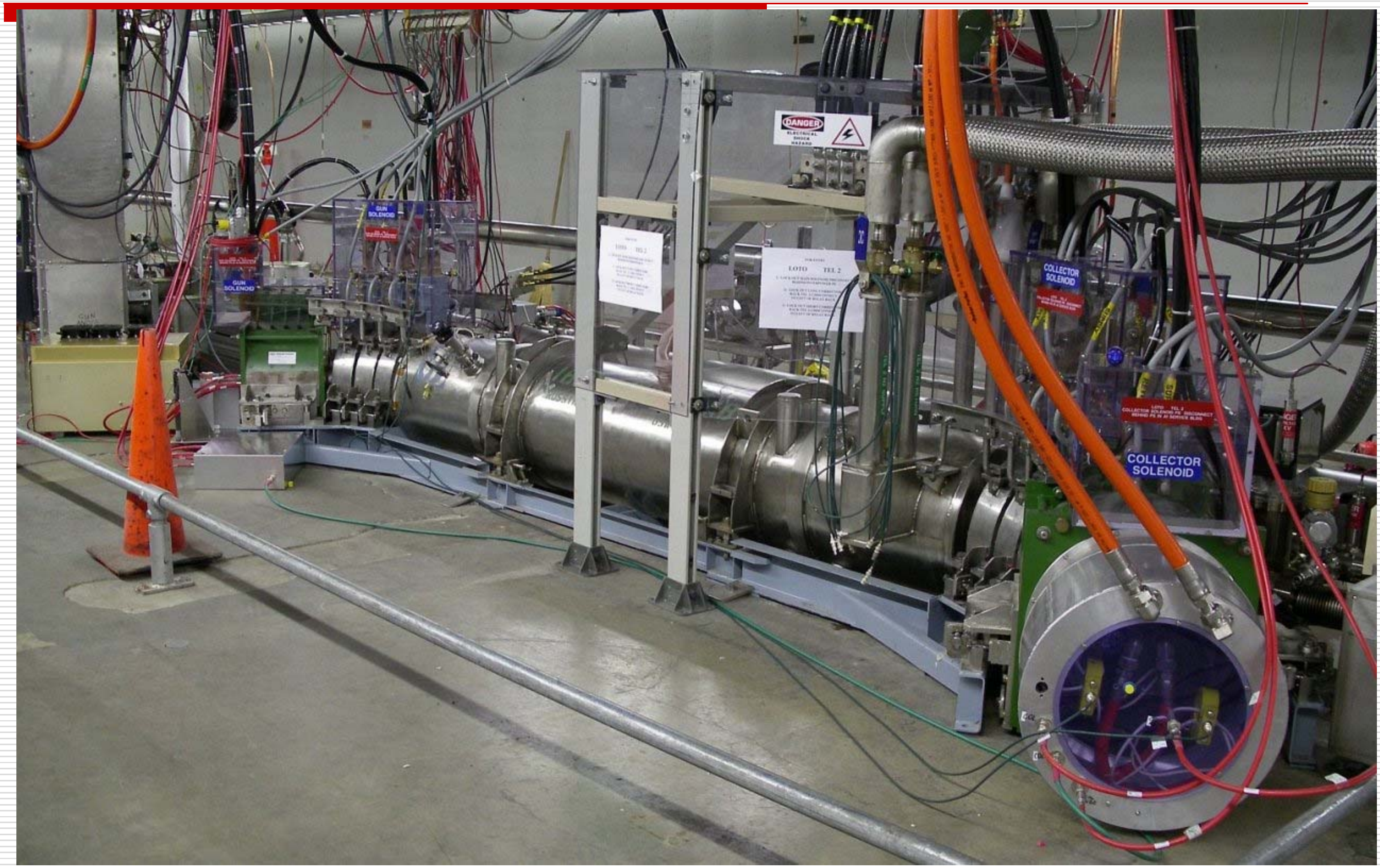
ξ_{max}=+0.016



At present, beam-beam effects are relatively stronger on protons, accounting for some 10-15% loss of the integrated luminosity. Proton loss rates vary greatly from bunch to bunch.

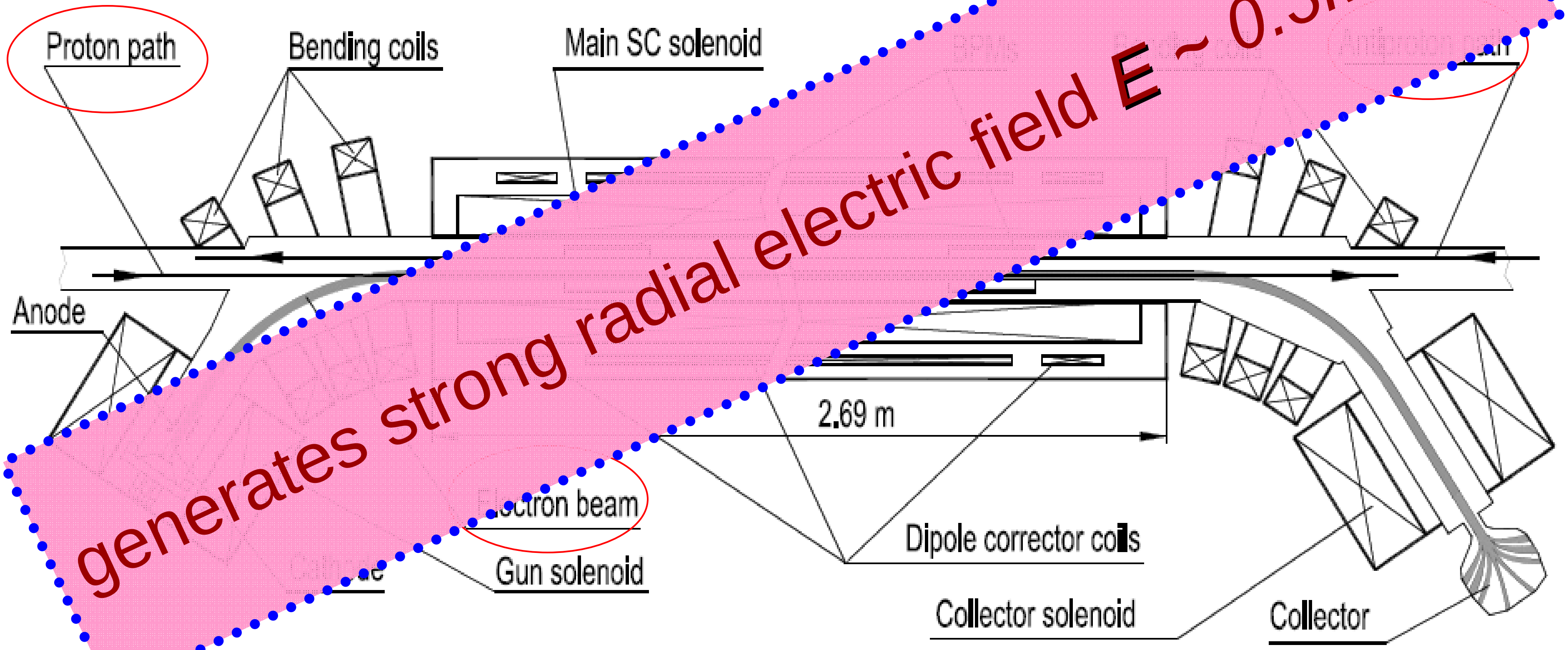
SOLUTION SUGGESTED – TEVATRON ELECTRON LENSES

TEL2 In The Tunnel (A0)



What is Electron Lens?

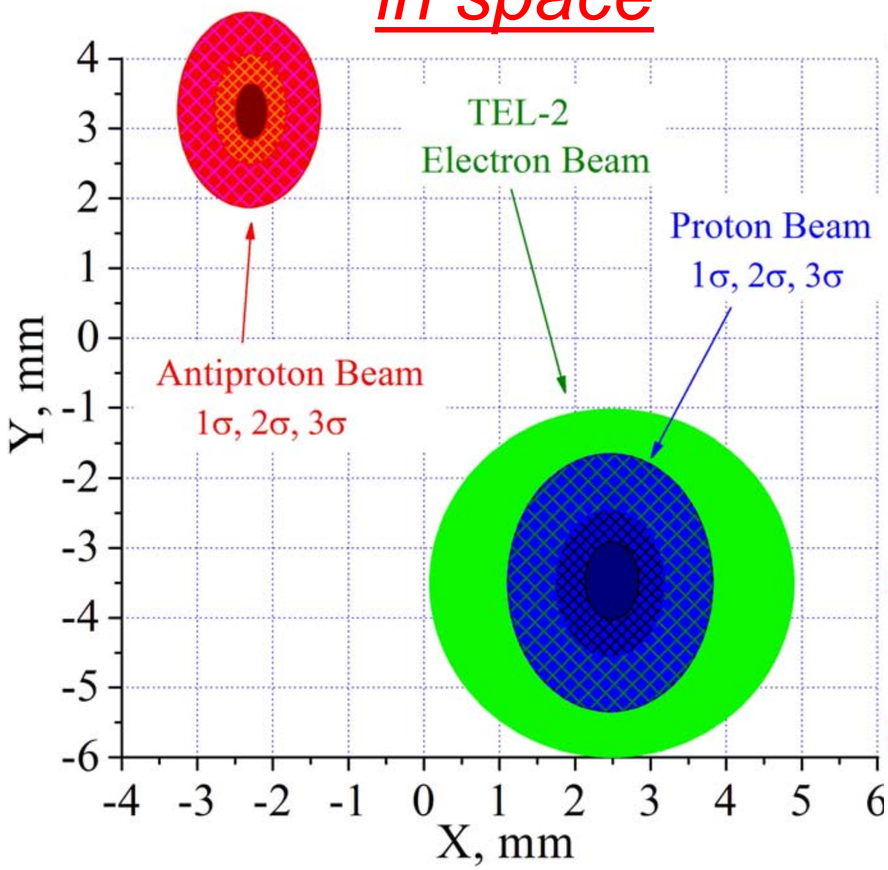
~2 mm dia 2 m long very straight beam of ~10kV, ~1 A electrons (~10^{12}) immersed in 3T solenoid



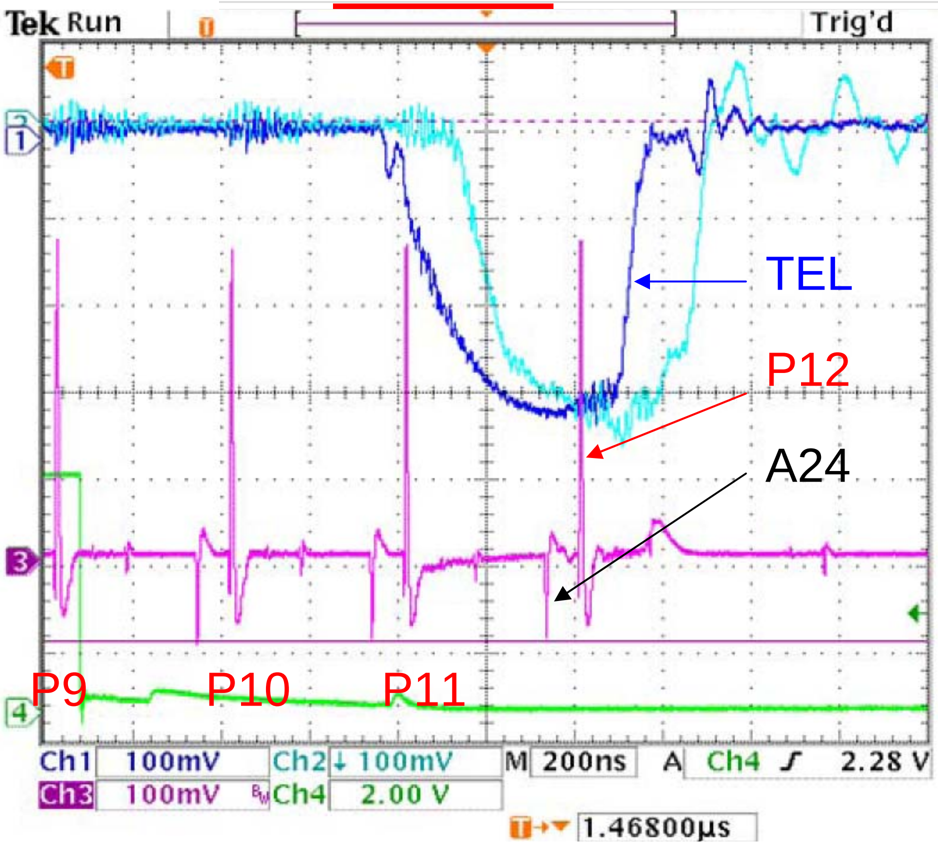
generates strong radial electric field *E* ~ 0.3MV/m

TEL2 e-beam aligned and timed on protons

in space

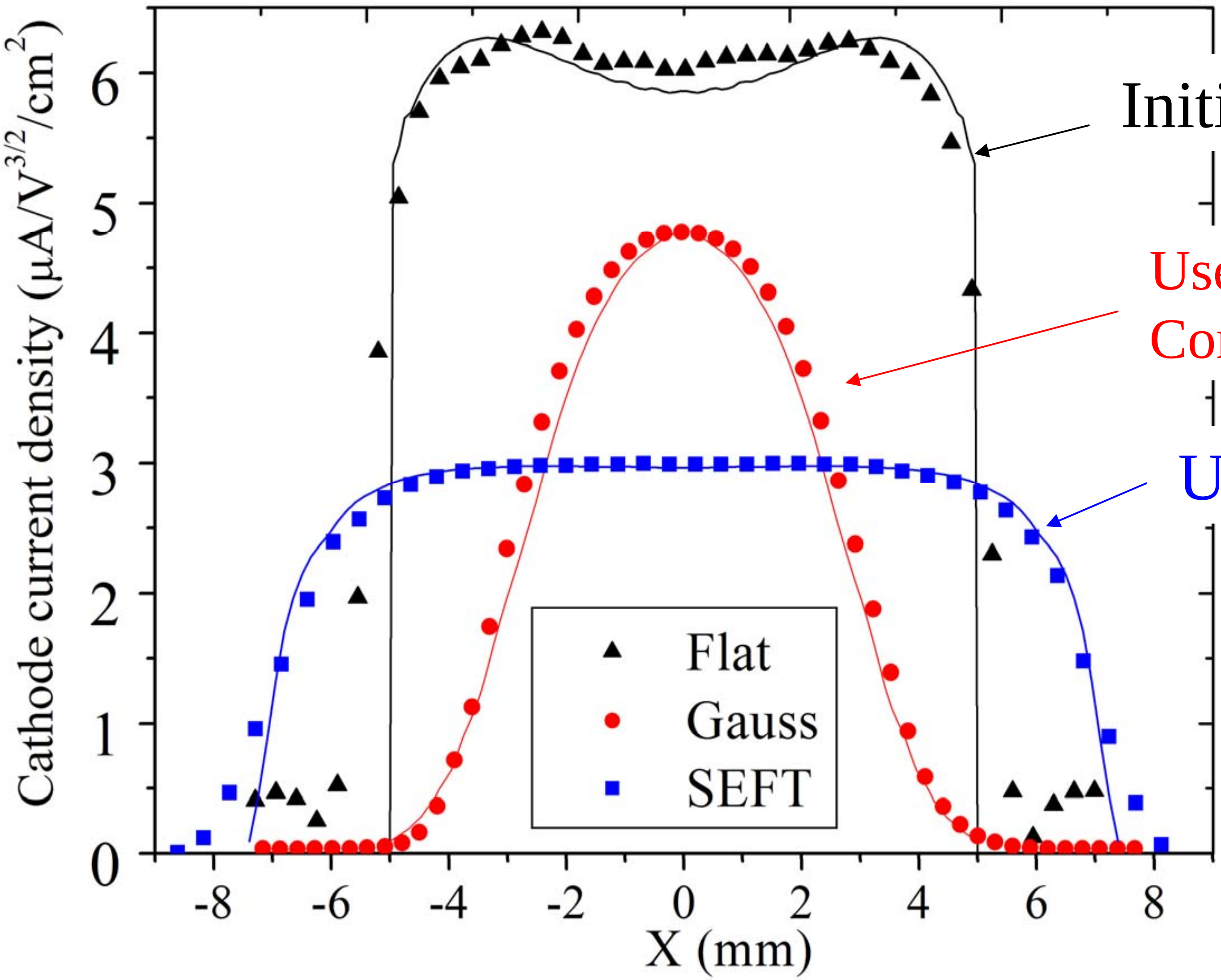


in time



Transverse e-p alignment is very important for minimization of noise effects and optimization of positive effects due to e-beam. *Timing* is important to keep protons on flat top of e-pulse – to minimize noise and maximize tune shift.

Electron Guns Developed for TELs



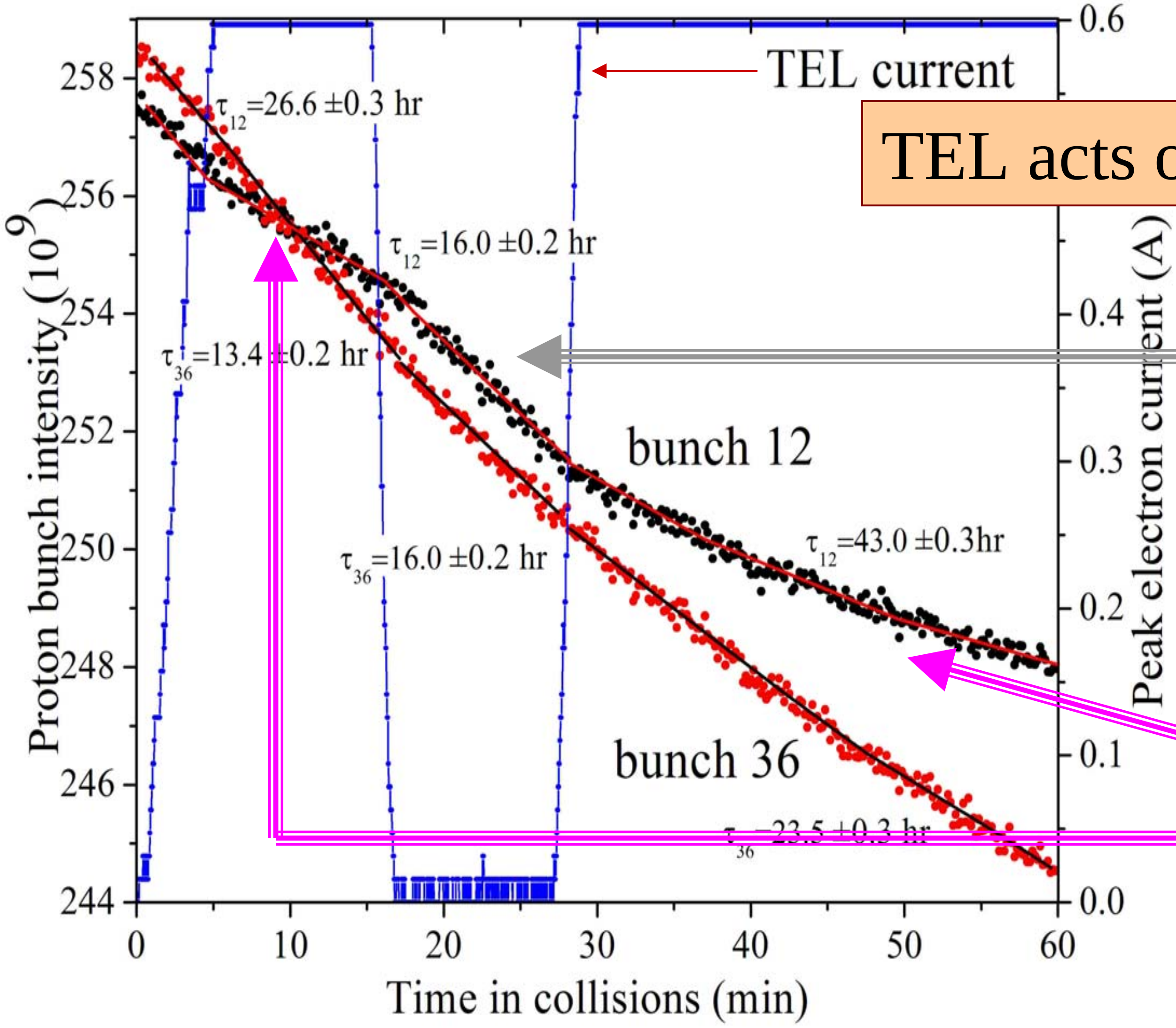
Initial (2001)

Used for Pbar B-B Compensation (2003)

Used now (2005)

E-beam is strongly magnetzed in 4-40 kG magnetic field →
Profile in the interaction region is the same (scaled) as on the cathode

TEL2 on P12: 1st hour of Store #5119



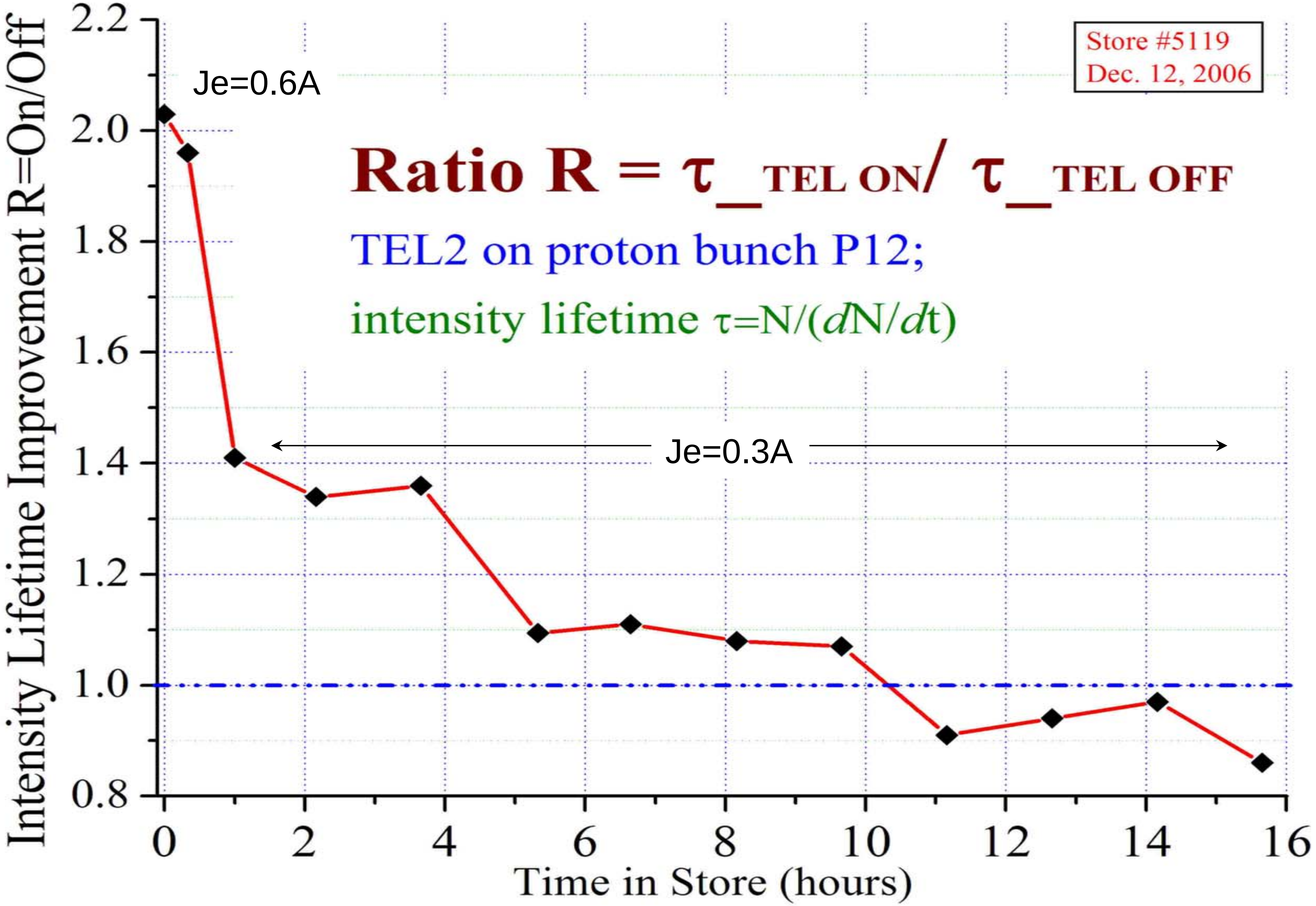
Dec.30, 2006

TEL acts only on bunch #P12

*When TEL **off**:*
bunches #12 and #36
have same lifetime
16 hrs and 16 hrs

*When TEL **on**:*
bunch #12 lifetime
is 2x #36 lifetime:
26.6 hrs vs 13.4 hrs
43.0 hrs vs 23.5 hrs

TEL2 Improves Proton Bunch Lifetime



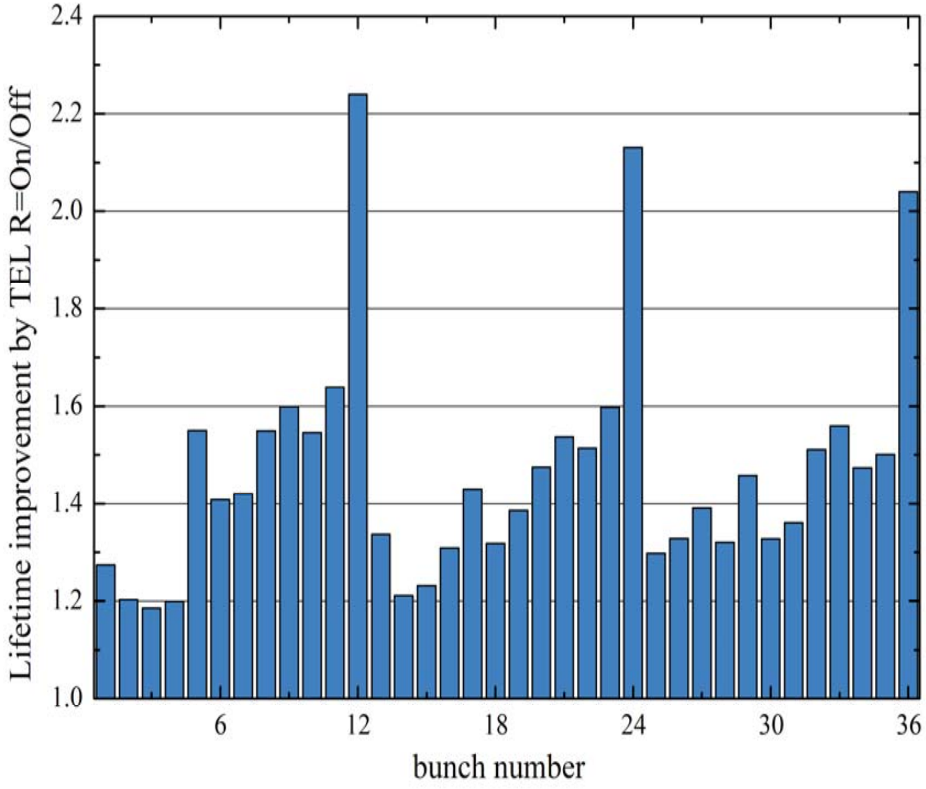
Ratio R = τ_TEL ON/ τ_TEL OFF

TEL2 on proton bunch P12;

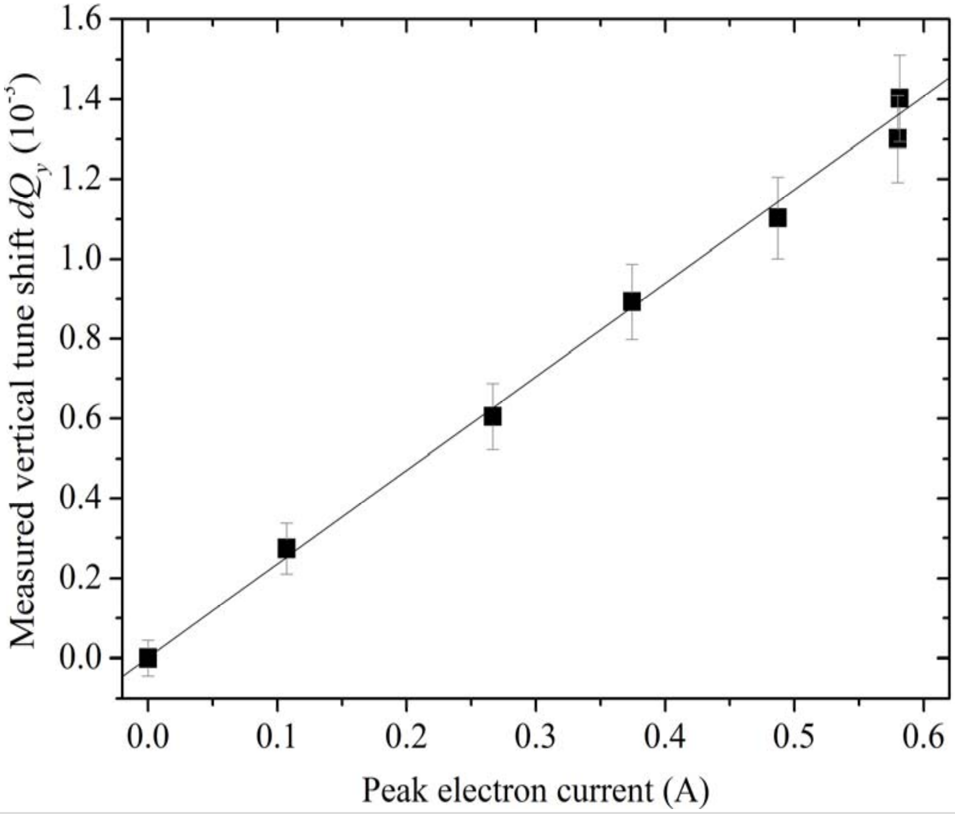
intensity lifetime τ=N/(*d*N/*d*t)

When TEL2 acts on all bunches (DC)

Bunches are not equal !

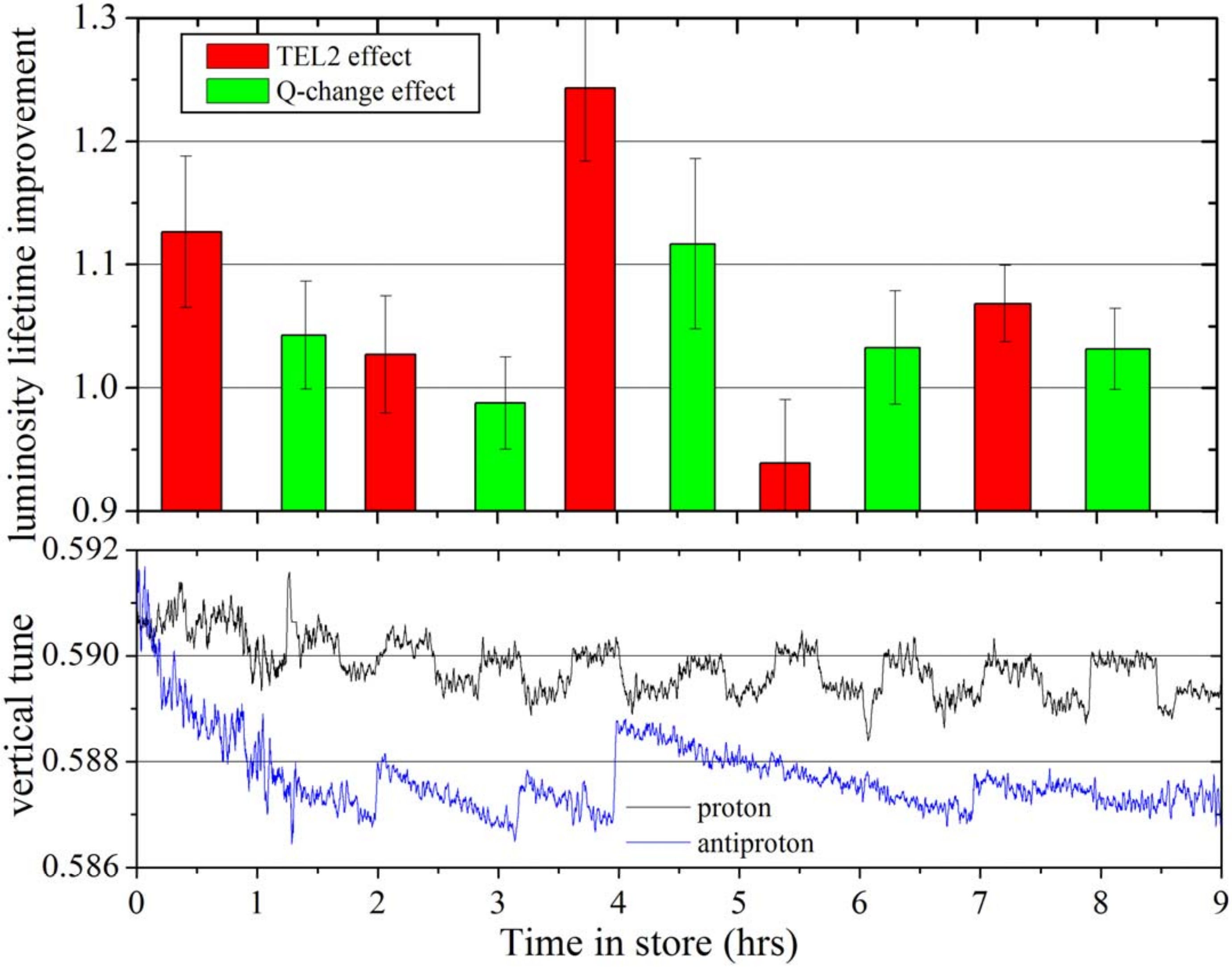


TEL2 moves Q_v up



Bunch P12 has systematically the lowest vertical tune that reduces its lifetime (too close to 7/12 resonance). TEL2 raises the tune up by dQ=+1.5e-3

~12% Increase of Luminosity Lifetime



TEL ***on**:*

dQ=0.001

Effects ~comparable except TEL can affect individual bunches

Summary on Beam-Beam Effects

- We did not expect them to be so strong
- What helped:
  - Optimization of helical separations
  - Reduction of chromaticities (liner,dampers,oct)
  - Reduction of emittances (for LR only)
  - Working point choice and tune control
- Tevatron Electron Lenses are helpful to control proton losses from individual bunches
  - ~*DOUBLE* intensity lifetime
- Near ½-integer WP can further help

On Beam Physics In Tevatron

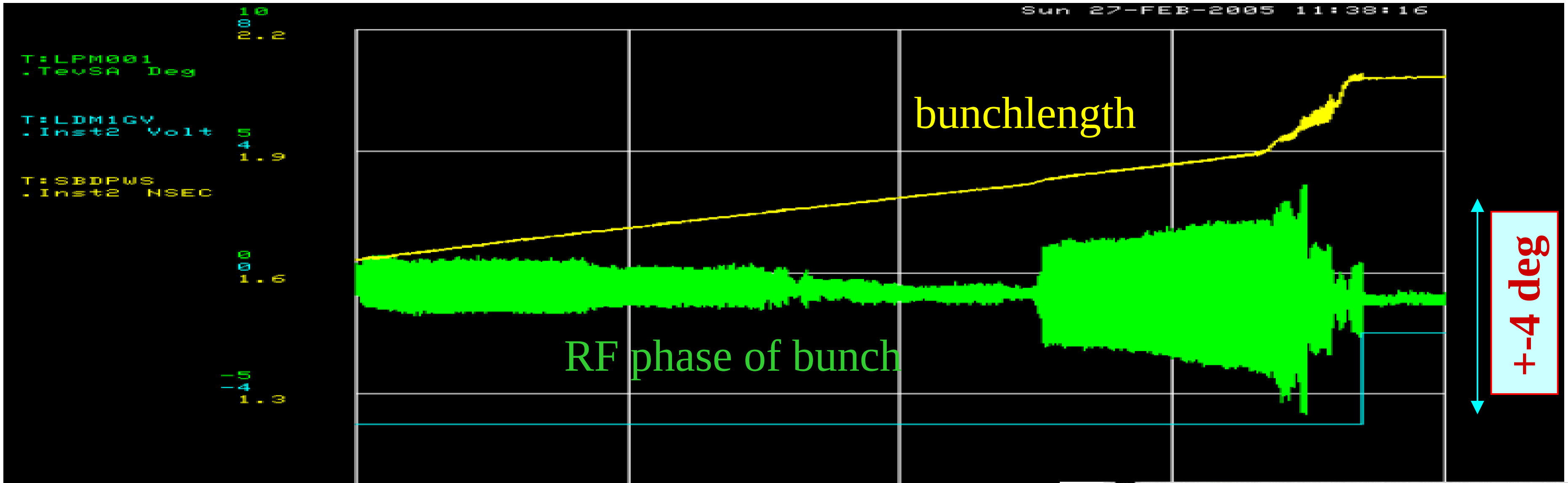
- When all hardware problems resolved and machines run - solving a deep beam physics problem is often the only way to push collider performance further
- Some beam physics issues can be solved with existing tools:
  - “shot lattice”, helices, slip-stacking, new WPs

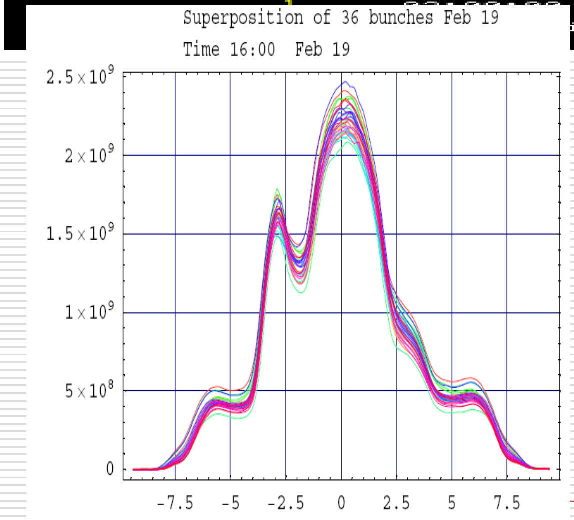
  While others require new developments:
  - electron cooling, electron lenses
- It took a great deal of patience to go thru R&D, beam studies and implementation in Collider operation
- Though collider improvements more obvious, progress in the injector chain propagates thru, too

What can we learn from all that?

Lecture 4 Friday: Lessons for LHC

Sampled Bunch Display and Phase Monitors

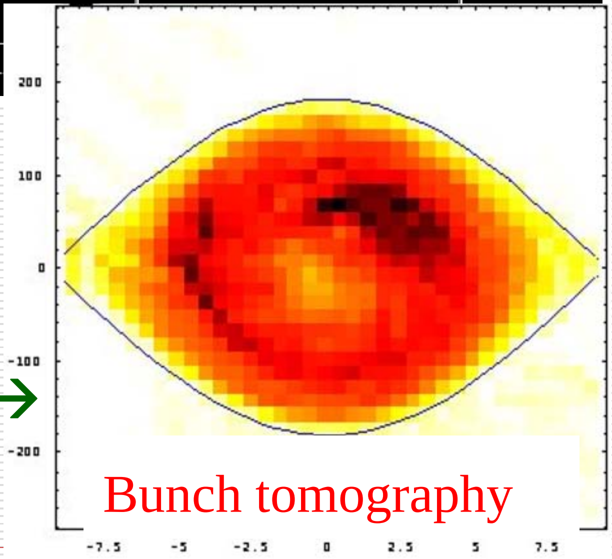




←Weird bunch shapes during instability burst (snapshop taken by SBD)

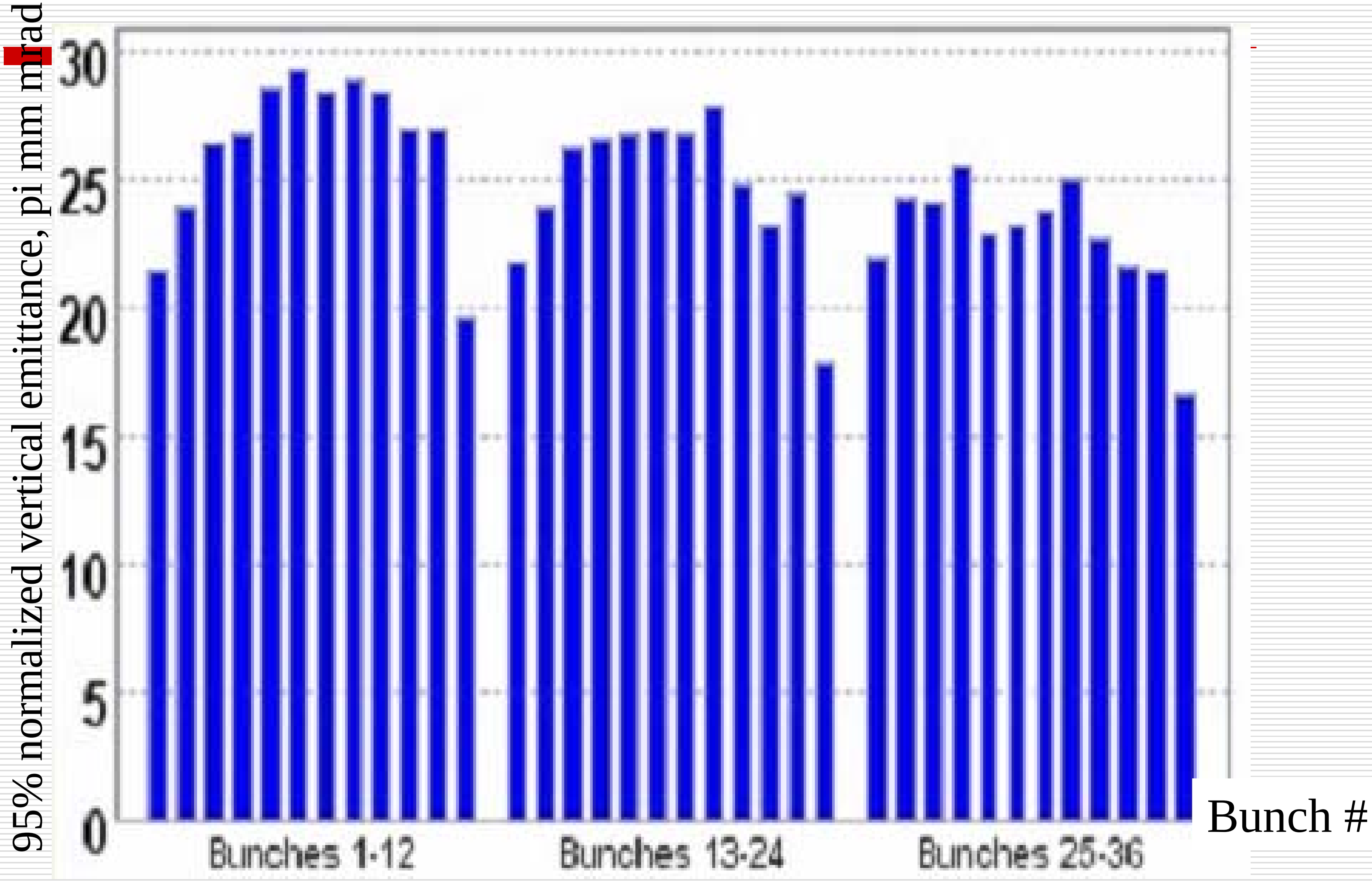
No instability, continuously "dancing" bunches (RWM) →

Fast (200Hz) longitudinal phase monitor is under development

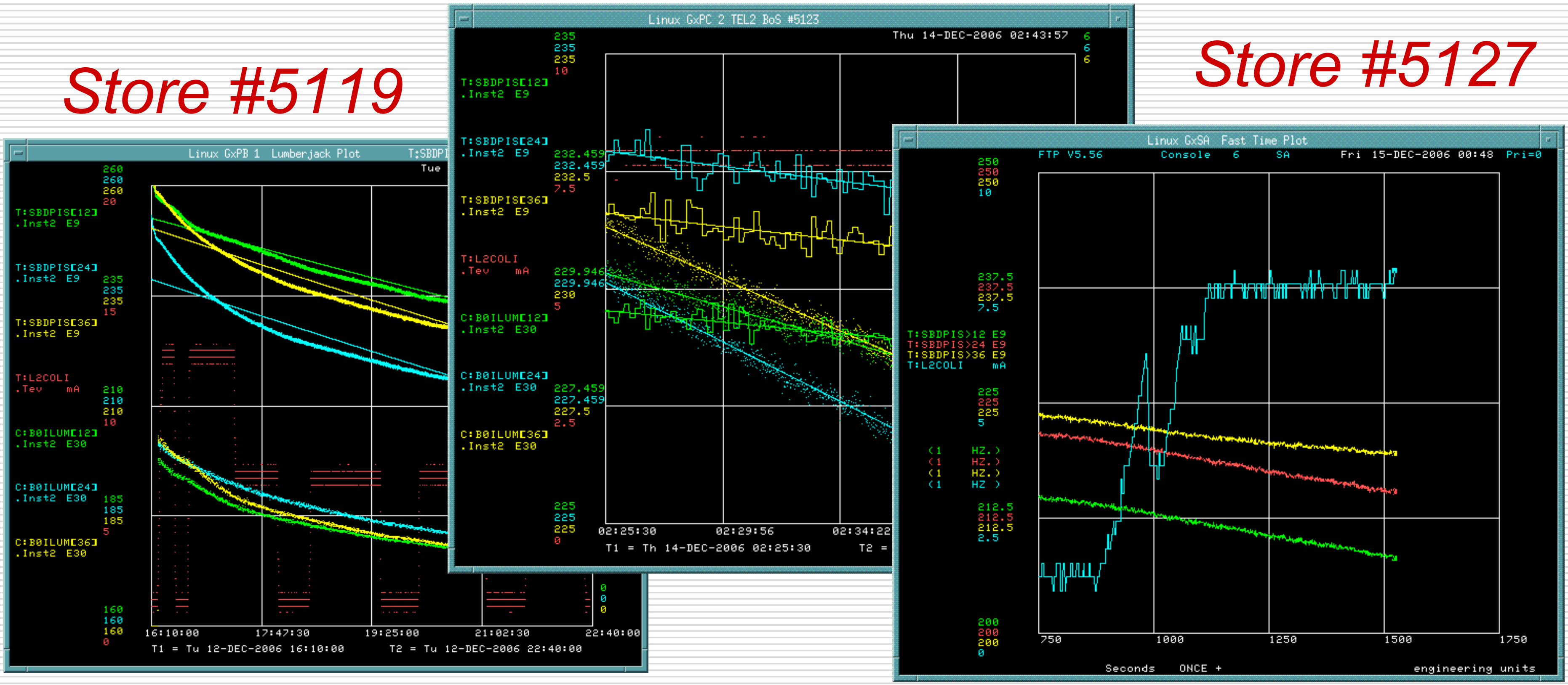


Bunch tomography

“Scallops” in Pbar Bunch Emittances



The Improvement Is Recurrent



Store #5119

Store #5123

Store #5127

>20 HEP stores with active BBC with TELs