Fermilab

Tevatron Operations: Issues and Plans

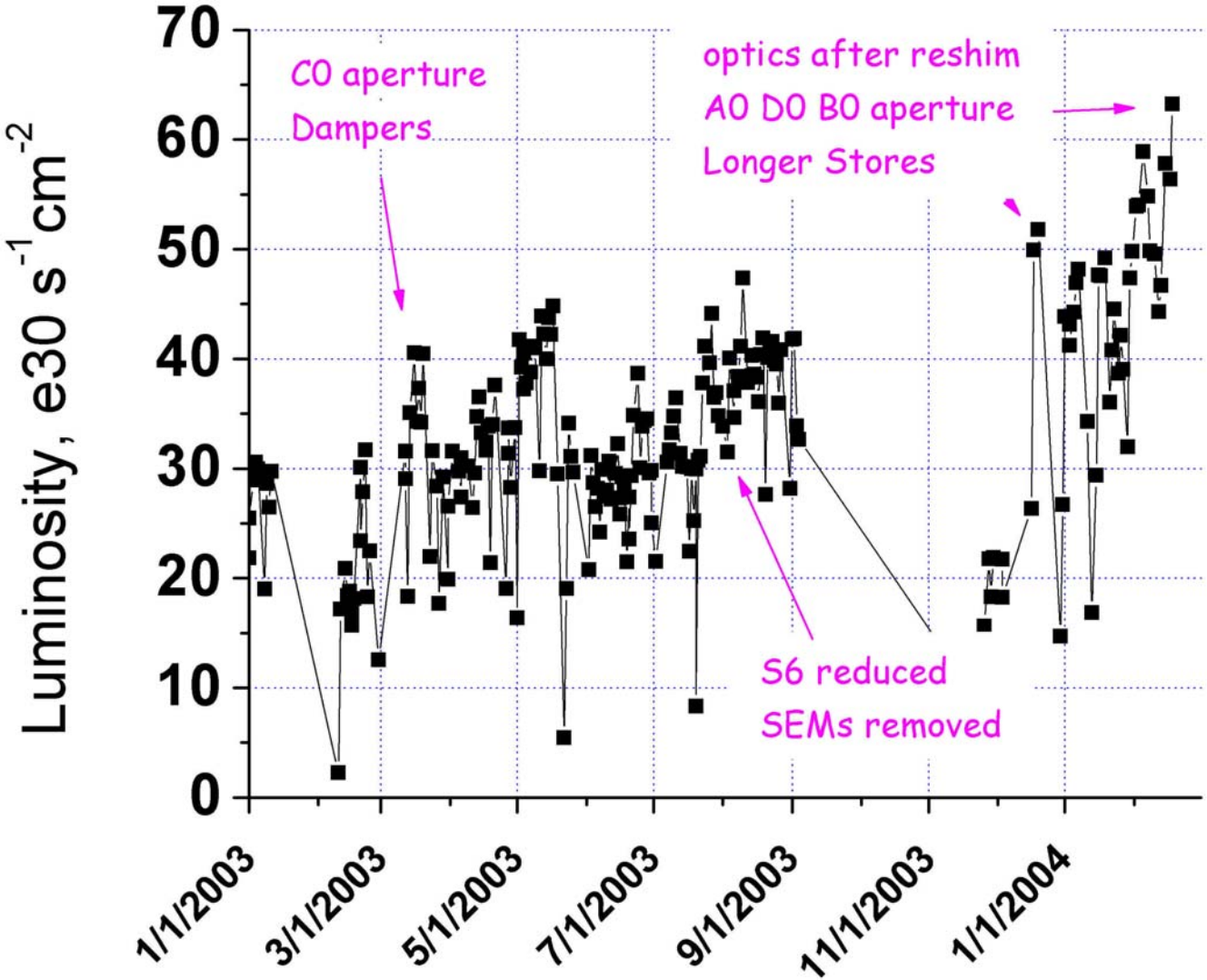
Beam-Beam Phenomena

Vladimir Shiltsev

Content:

- Tevatron Operations:
  - Luminosity and transfer efficiency progress
  - Chromaticity drift after shutdown
  - Orbit drifts – ATL law
  - Reliability
- Beam-Beam Phenomena:
  - Reality vs Luminosity Model
  - Scallops
  - Bunch tunes vs theory
  - Proton losses
  - Beam-beam compensation

Tevatron Luminosity Progress



Luminosity Progress: Facts and Reasons

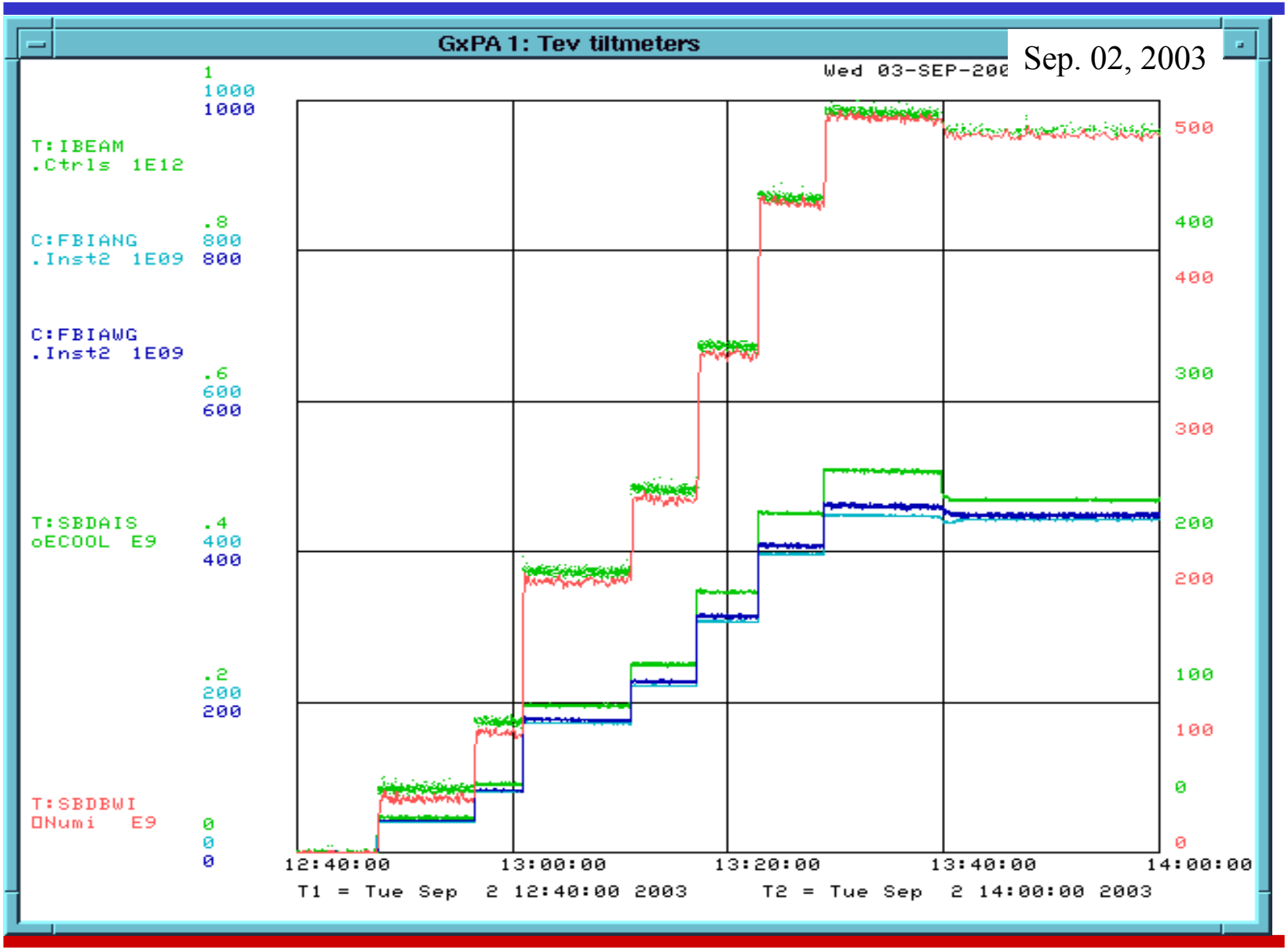
- 197 stores, 12 records peak *L* since Feb'03:
  - 4.0e31 broken in Mar'03 #2502
  - 4.4e31 before shutdown #2887
  - 6.3e31 in Feb'04 #3245

		gain
C0 Lambertsons Removed /Dampers (Z_T reduced, N_p increased)	TeV	x 1.25
S6 cuircuit tuned/SEMs removed (differential C_v,h, emittance blowup fixed)	TeV/Lines	x 1.10
Reshimming/Alignment/Longer stores (smaller emm's, open aperture, big stacks)	TeV	x 1.35
	total	x 1.85

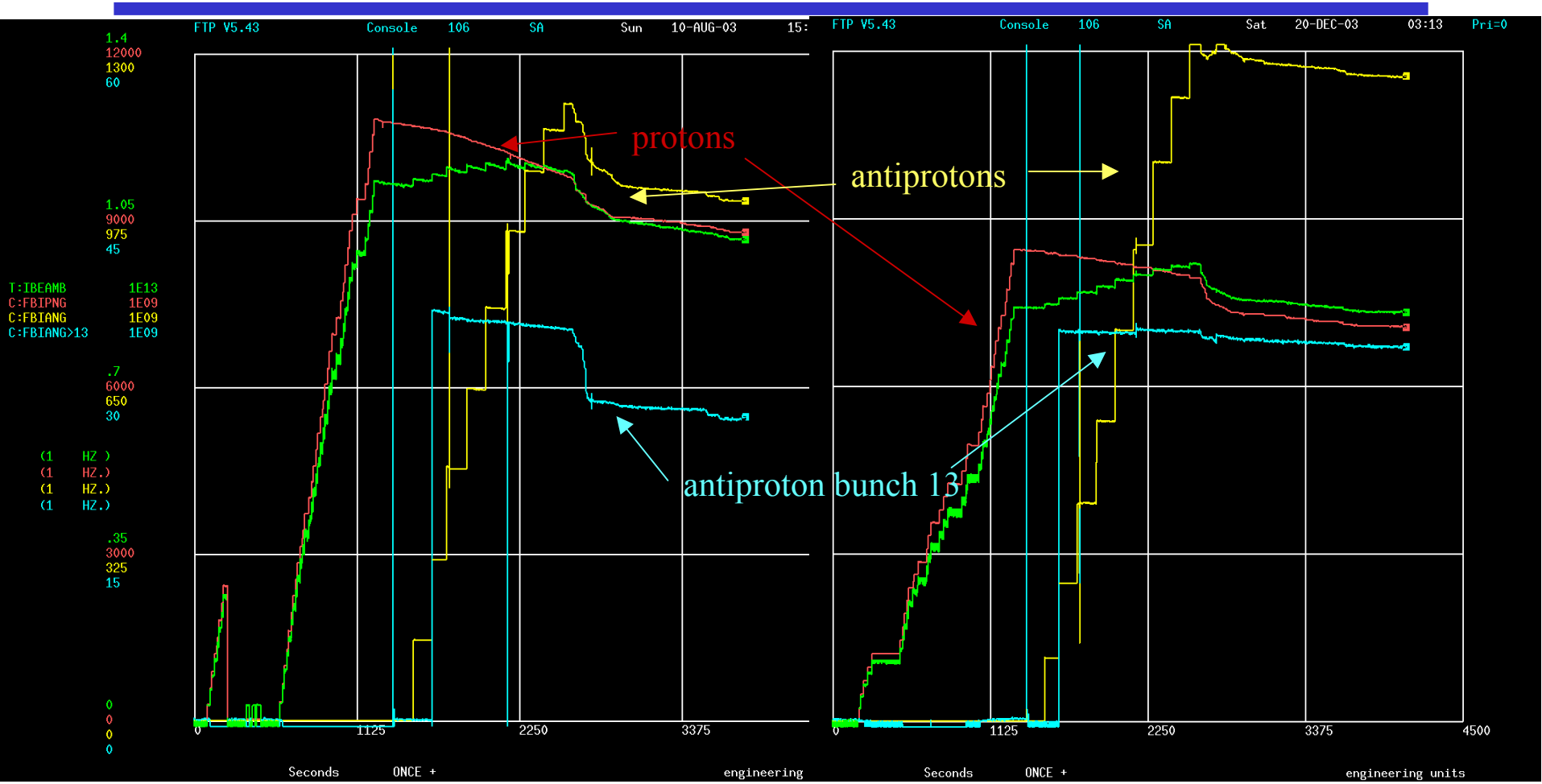
Fight for better Tevatron

	10/02	03/03	09/03	02/04	$p\bar{p}$ only
Record Luminosity, e30	36	41	50	63	n/a
Protons/bunch	170e9	205e9	245e9	245e9	same
Pbars/bunch	22e9	23e9	25e9	30e9	same
P-loss at 150 GeV	14%	10%	8%	5%	5%
Pbar-loss at 150	9%	4%	2%	2%	2%
P-loss on ramp	6%	5%	5%	4%	3% *
Pbar-loss on ramp	8%	11%	8%	6%	2%
Pbar-loss in squeeze	5%	2%	3%	1%	0%
… at the beginning of store:					
Pbar lifetime at HEP, hr	~40	~35	~35	~30	~900
Proton lifetime at HEP, hr	~90	~60	~20	~100	~300 *
Eff.emittance lifetime, hr	~14	~26	~31	~16	n/a
Luminosity lifetime, hr	~10	~13	~10	~9	n/a

Pbar Only Store: <4% loss from Inj to LB



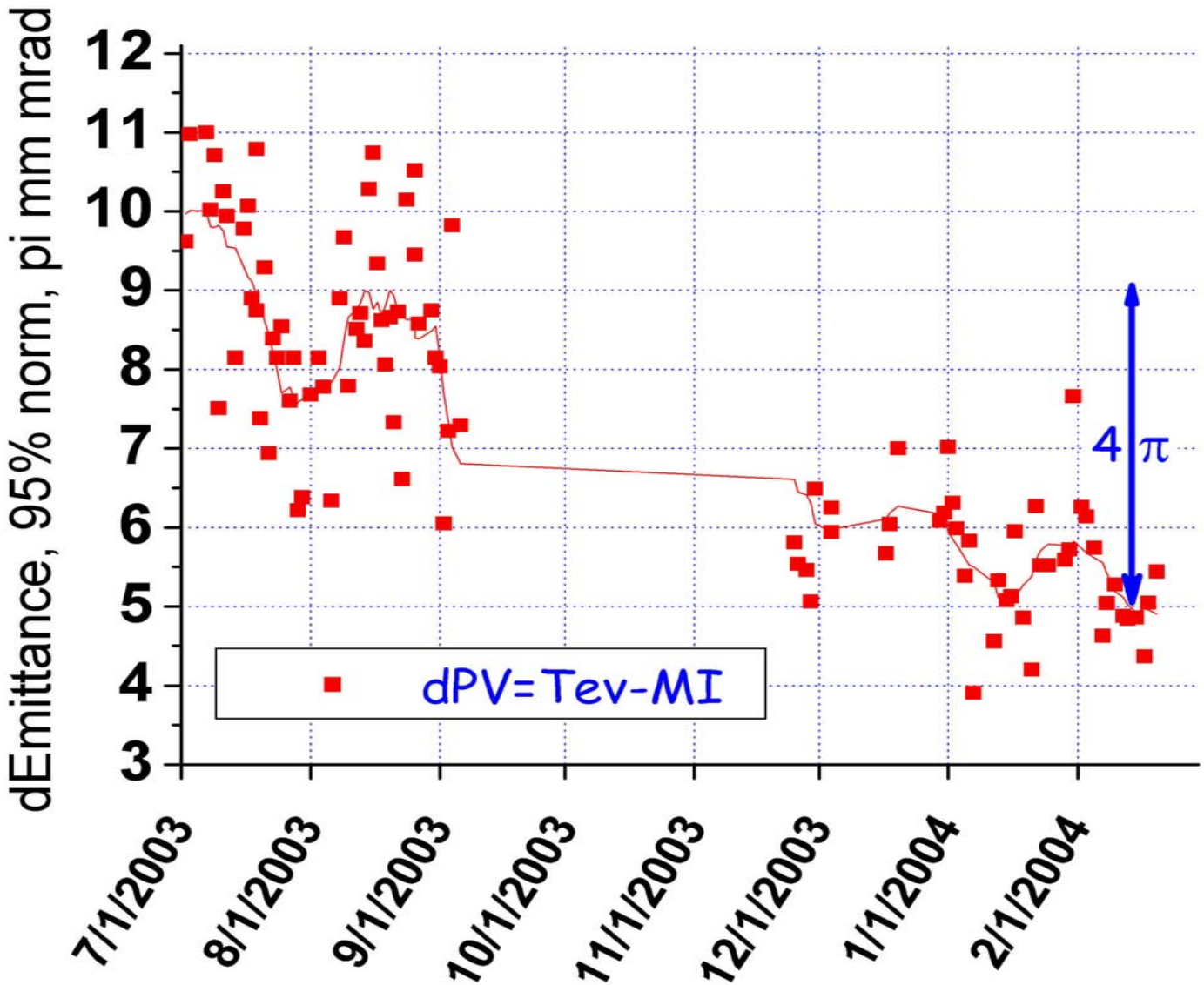
Impact of the Fall Shutdown



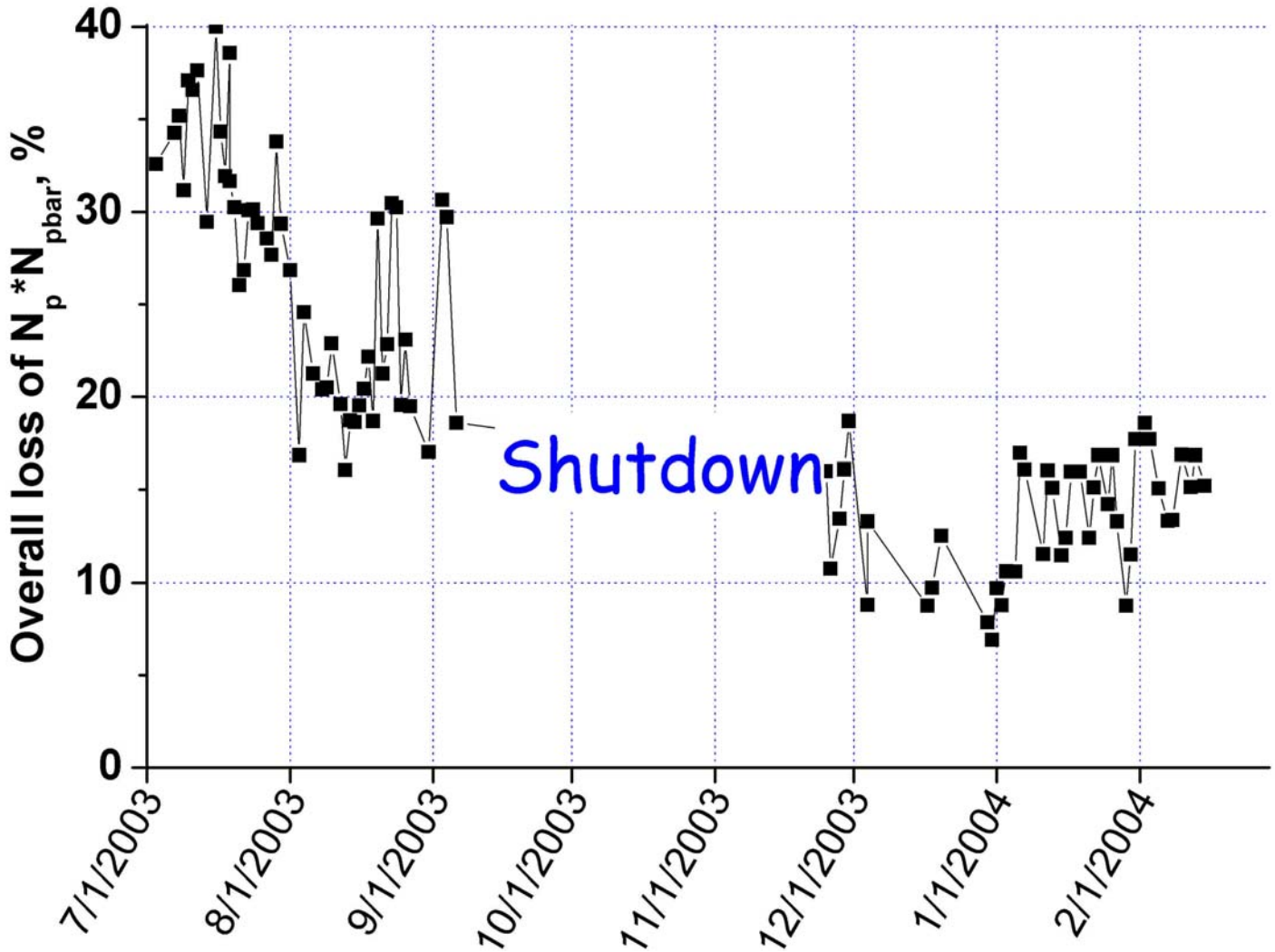
Store 2887: Pre-shutdown record (4.9E31)

Store 3108: Right after-shutdown record (5.2E31)

Emittance Dilution in MI→Tev Transfer



Efficiency of (Protons x Pbars) in Tevatron

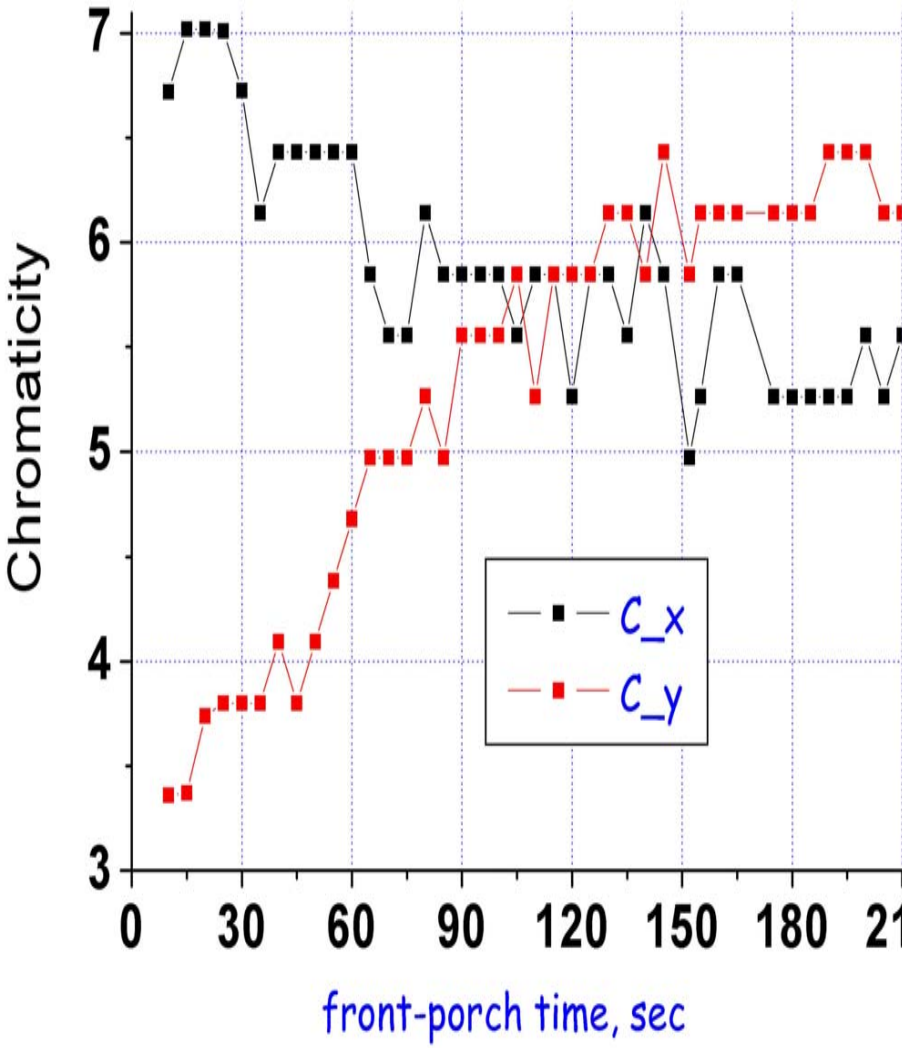


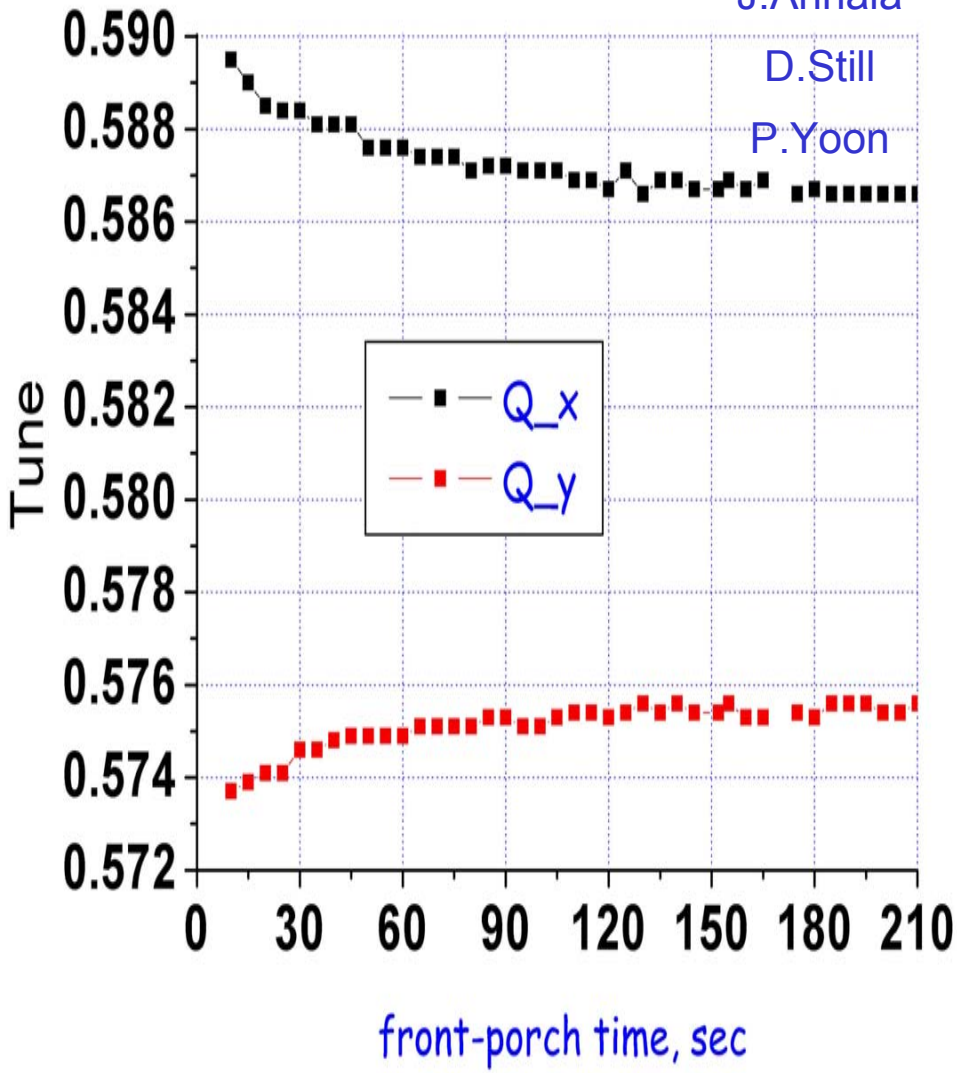
Chromaticity and Tune Drifts Changed

J.Annala

D.Still

P.Yoon



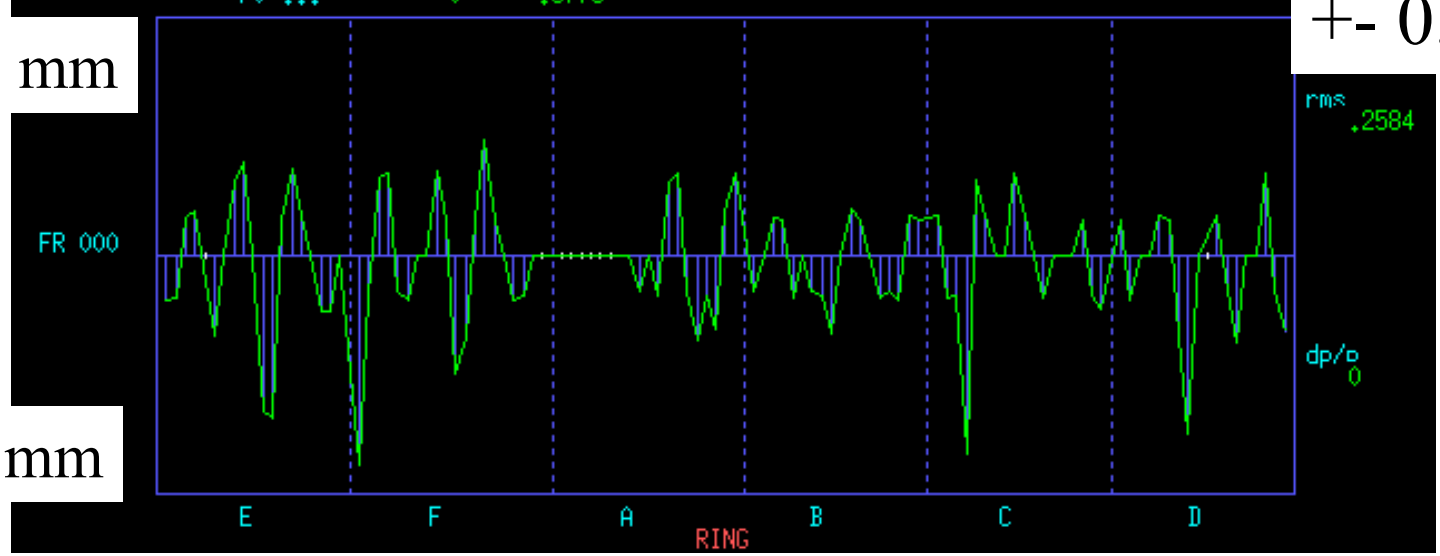


Orbit Drifts

profile (| 1 mm) HORZ prot-bunch F 89.9 17-FEB-2004 15:07:51

	E	F	A	B	C	D
11 ...	-.18	-.16	NoBeam	-.15	.17	.15
13 ...	-.17	.33	NoBeam	0	-.17	-.18
15 ...	.16	.35	NoBeam	.16	-.16	0
17 ...	.19	-.15	NoBeam	.15	-.83	0
19 ...	NoBeam	-.18	NoBeam	-.17	.32	.17
22 ...	-.33	0	0	0	.17	.15
24 ...	0	0	0	-.15	0	-.33
26 ...	.31	.36	-.15	-.16	0	-.74
28 ...	.4	.15	0	-.32	.35	0
32 ...	0	-.49	-.16	0	.17	NoBeam
34 ...	-.65	-.34	.31	.2	0	.17
36 ...	-.68	.15	.35	.15	-.17	-.15
38 ...	.15	.49	-.15	0	0	-.36
42 ...	.37	.15	-.35	-.17	0	0
44 ...	.17	0	-.16	-.15	0	0
46 ...	0	-.18	-.3	-.18	.15	.35
48 ...	-.23	-.16	.19	.17	-.16	-.15
49 ...	-.23	0	.35	.15	-.22	-.31
A0 ...		NoBeam	NoBeam			
F0 ...	0	-.8773				

+1 mm

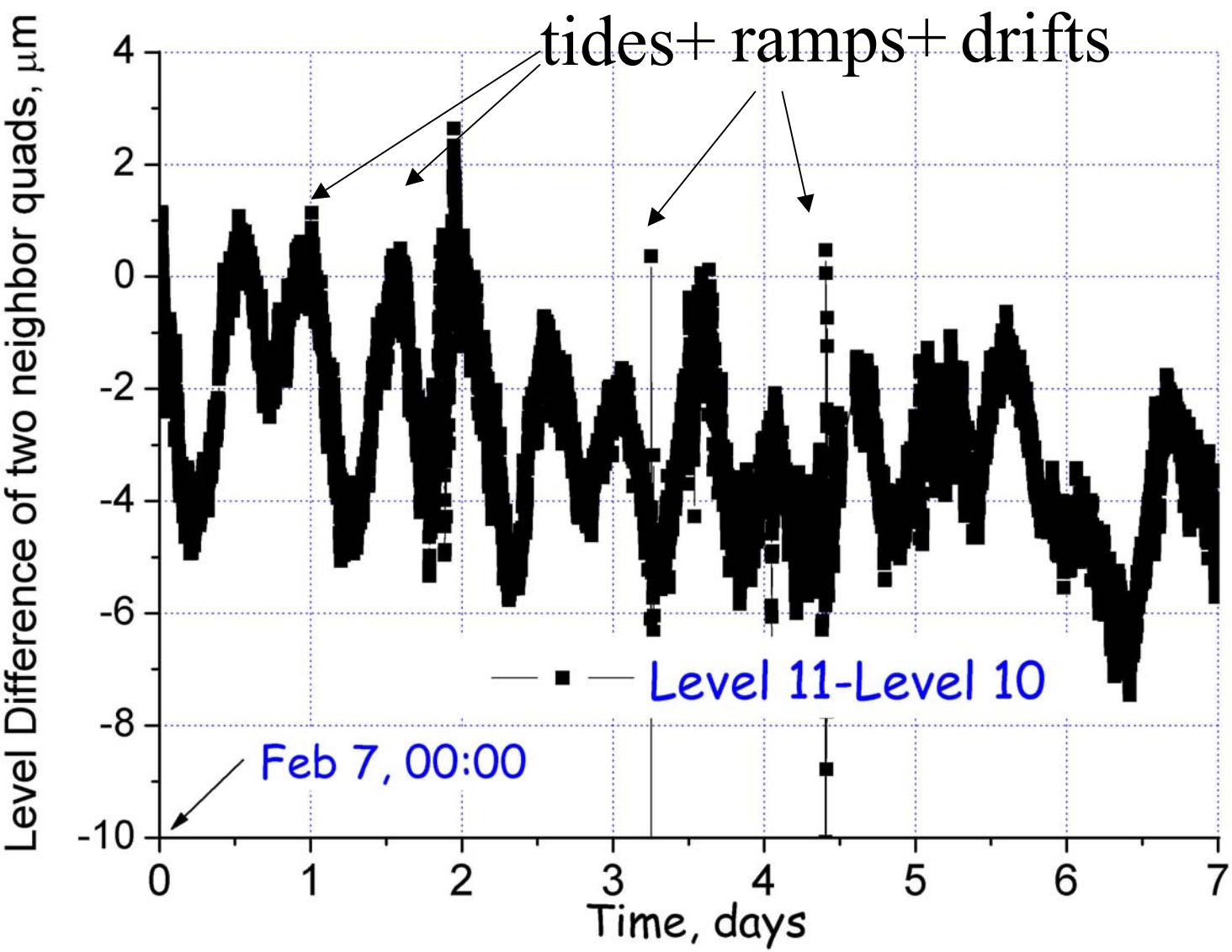


-1 mm

store 3240
minus
store 3206

19 days→
0.26 mm rms
+- 0.7 mm p-p

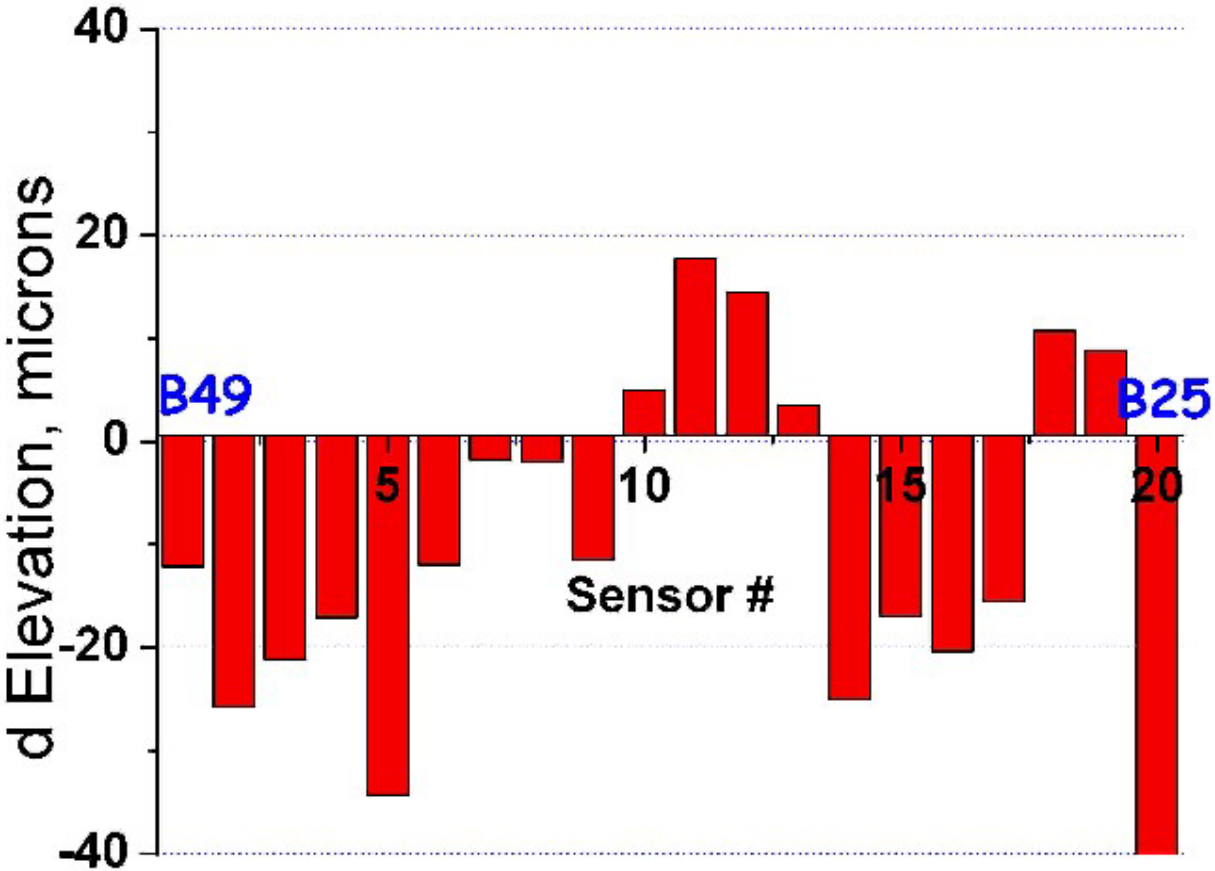
Drift of Quad Positions : HLS in B-sector



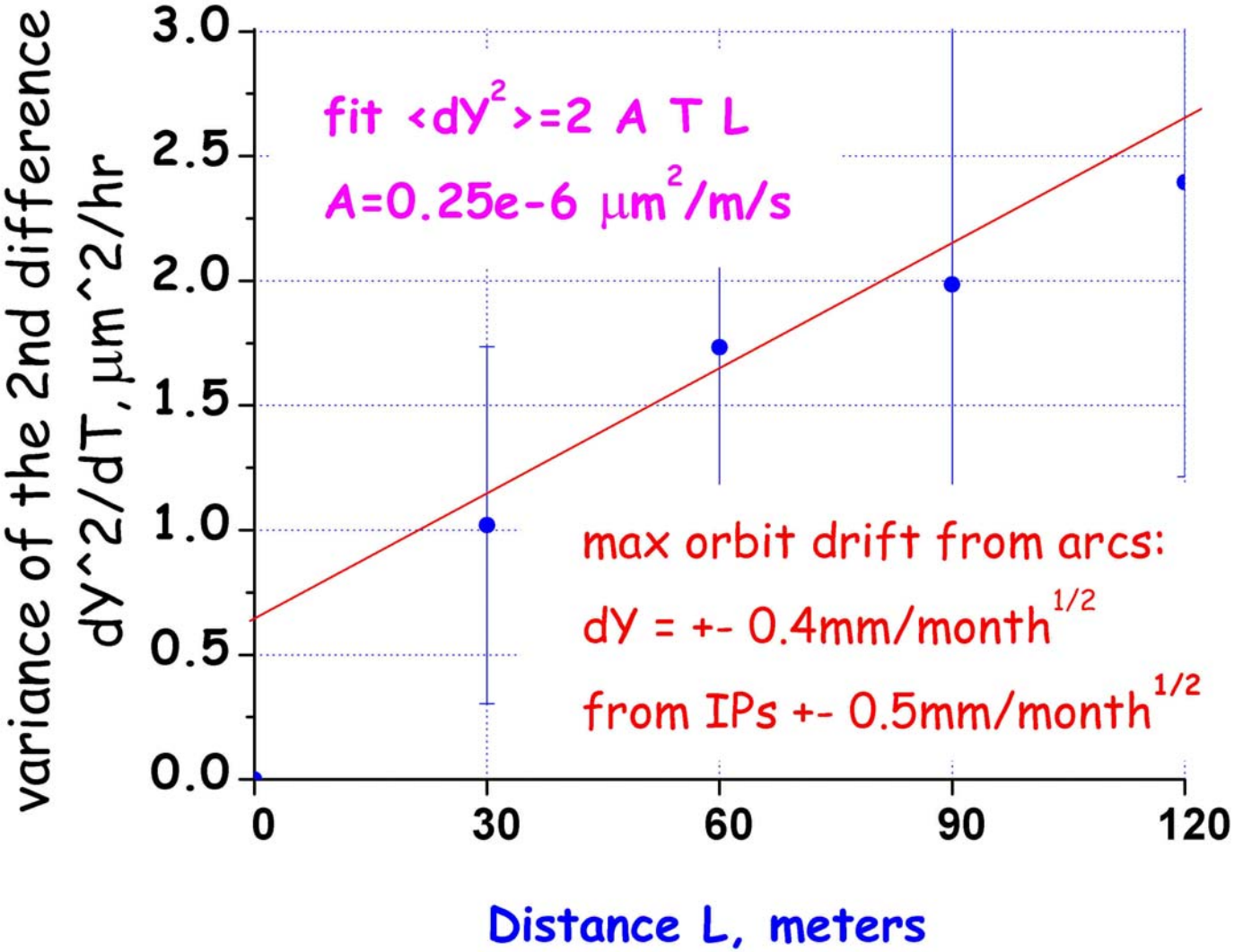
A.Chupyra
and BINP,
T.Johnson
T.Bolshakov

Drift of Quad Positions : HLS in B-sector

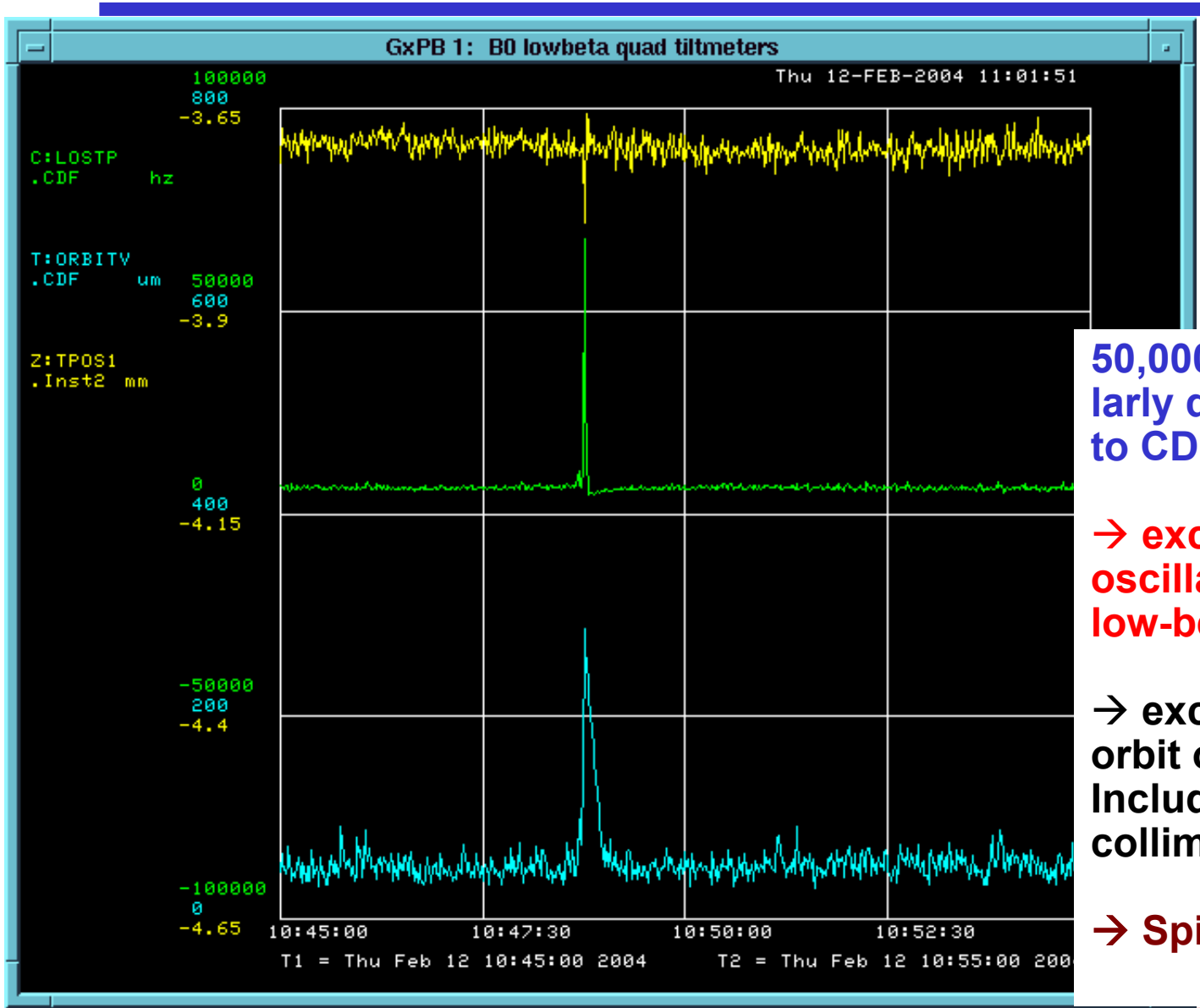
Change of vertical quad position btw Jan 7 and Feb 1, 2004



Natural Ground Diffusion:ATL Law in B-sector



Another News: Trucks…



T.Johnson

D.Plant

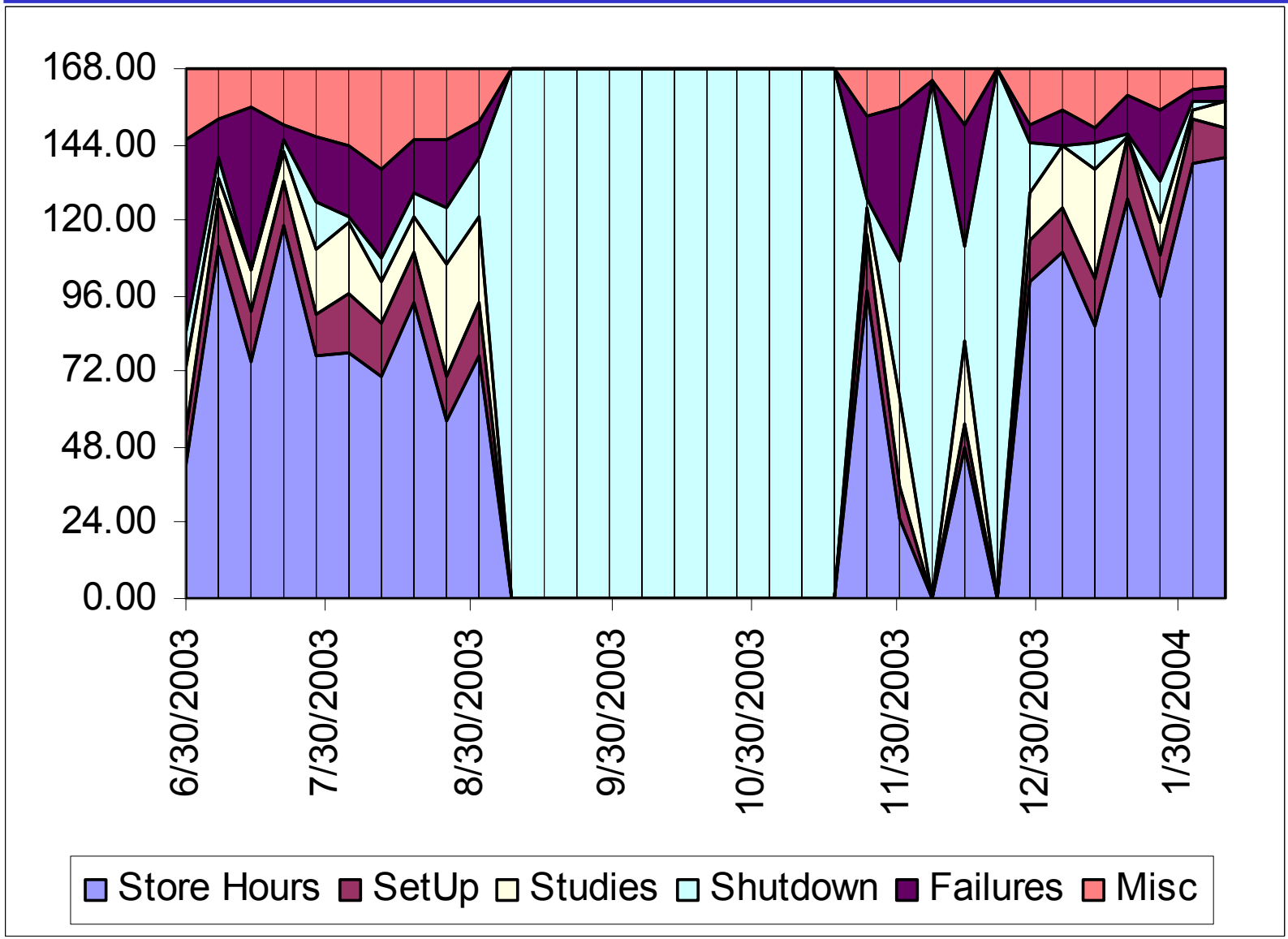
50,000 lb trucks regularly deliver cryogens to CDF and D0

→ excite 12 Hz vert oscillations of B0 low-betaquads

→ excite 50-100 micron orbit oscillations, Including at the collimators

→ Spikes in CDF losses

Tevatron Time Breakdown



Reasons for Store Termination : Since 07/01/03

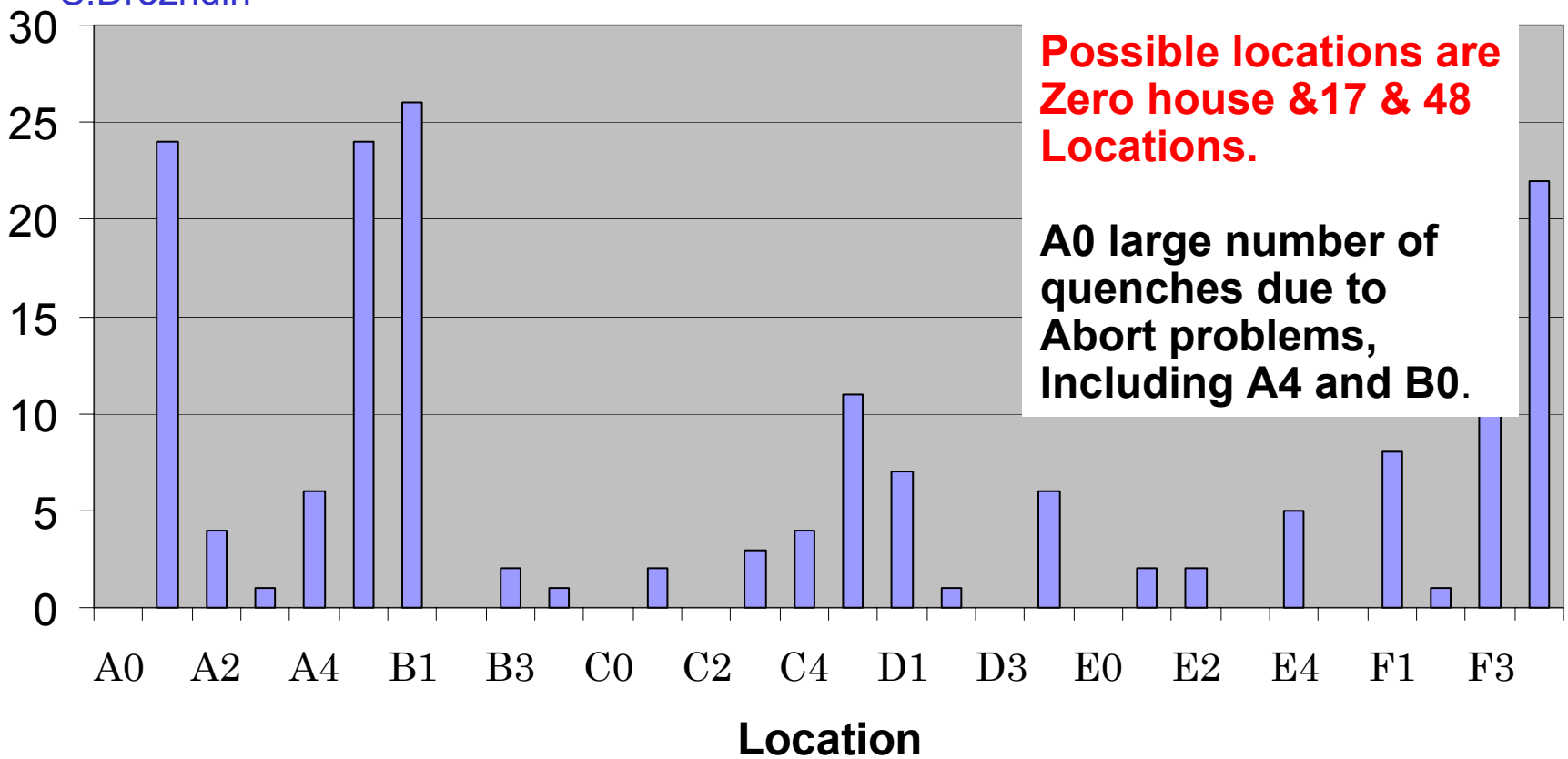
Controls	2	
Correction Magnet Systems	3	
Cryogenics	4	
Experimental Areas	1	
Glitches/Lightning	5	
Human Error	2	
Instrumentation	0	
Kickers	0	
Low Beta Quadrupoles	1	
Magnet Failure	0	
Miscellaneous	2	
Quench	1	
Quench Protection System	2	
Separators	1	
Tevatron Power Supplies	0	
Tevatron RF	8	- all before shutdown, fixed long damper, desensitised to RF glitches → none since 11 '03
Utilities	2	
Vacuum	2	
Total (97 stores):	36	

Locations of Tev Quenches → Passive Shielding?

D.Still

N.Mokhov

S.Drozhdin



Passive Shielding
<u>Not</u> possible in 2 & 3 Houses. (no room)

Possible locations are Zero house &17 & 48 Locations.

A0 large number of quenches due to Abort problems, Including A4 and B0.

Next Steps:

- Run octupoles and reduce chromaticities → 5-15% in L
- Fix optics and reduce β^* → 5-10% in L
- Roll 4 quads in P1 line to further. → 3-7% in L
- Reduce beam-beam effects (see below) → 2-10% in L
- Commission inj dampers to reduce $d\varepsilon$ at inj → 2-5% in L
- Implement b2 recommendations → 1-? % in L
- Continue alignment and aperture improvements → ??
- Diagnostics upgrades (BPMs, IPMs, low-β quads..) → ??
- Reduce downtime (crystal collim., shielding, etc) → ??

Beam-Beam Phenomena in the Tevatron

Shaving at 150 GeV, "square root" losses

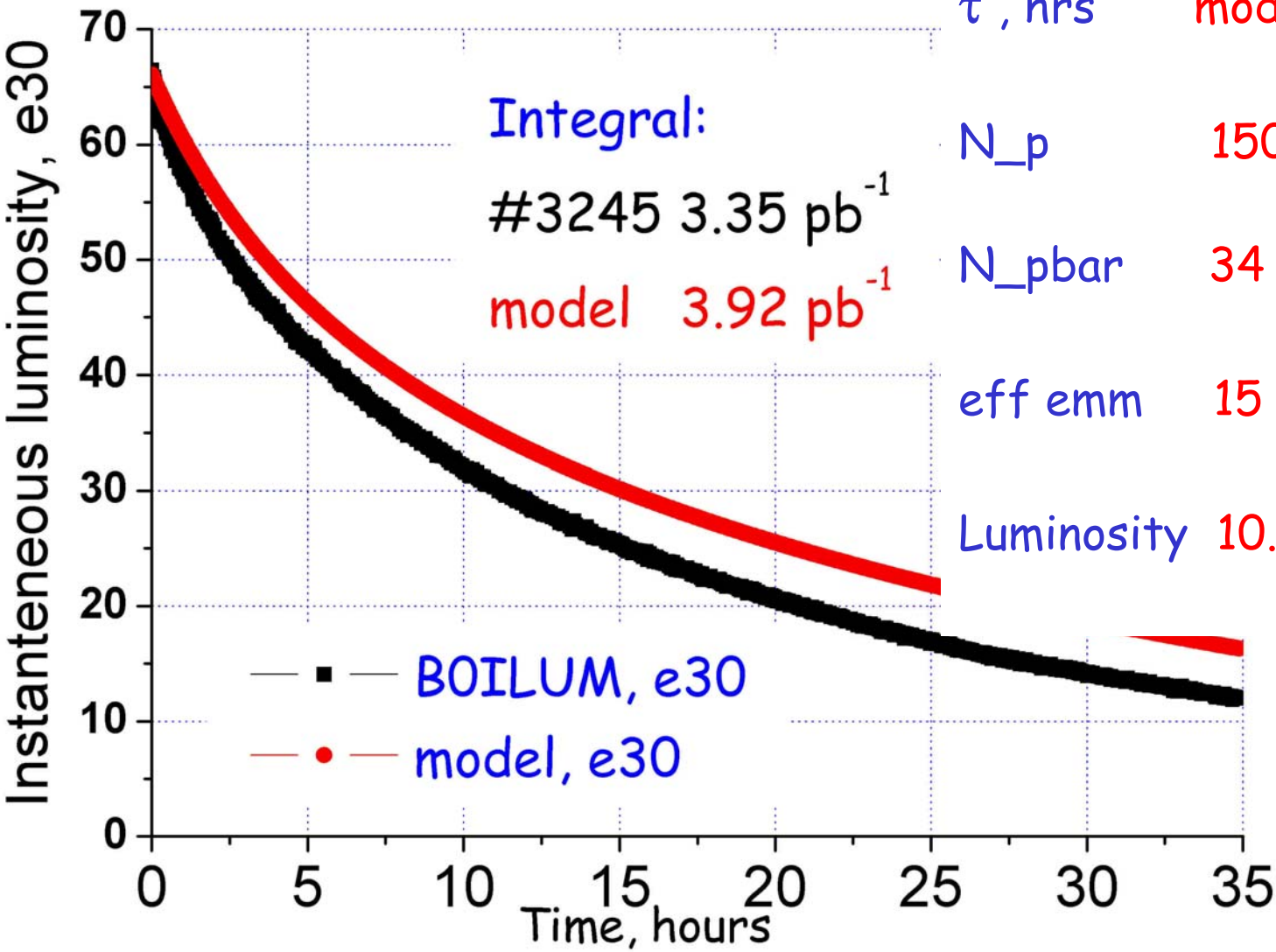
Less of a problem now

Losses on ramp

Some progress, too

Lifetime at Low-Beta →

Model w/o Beam-Beam and Store 3245



τ , hrs	model	#3245
N_p	150	150
N_pbar	34	32
eff emm	15	12
Luminosity	10.6±1	8.2

Beam-Beam Tune Shifts

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

head-on tune shift per IP, now with N_p=245e9 and 95% emittance 20p

total max head-on tuneshift is 0.018 for pbars, 0.004 for protons

tune shift for separated beams is smaller:

$$\Delta\nu = \sum_i \frac{\beta_i N_p r_p}{2\gamma\pi d_i^2} = \sum_i \frac{2\xi}{(d_i/\sigma_i)^2}$$

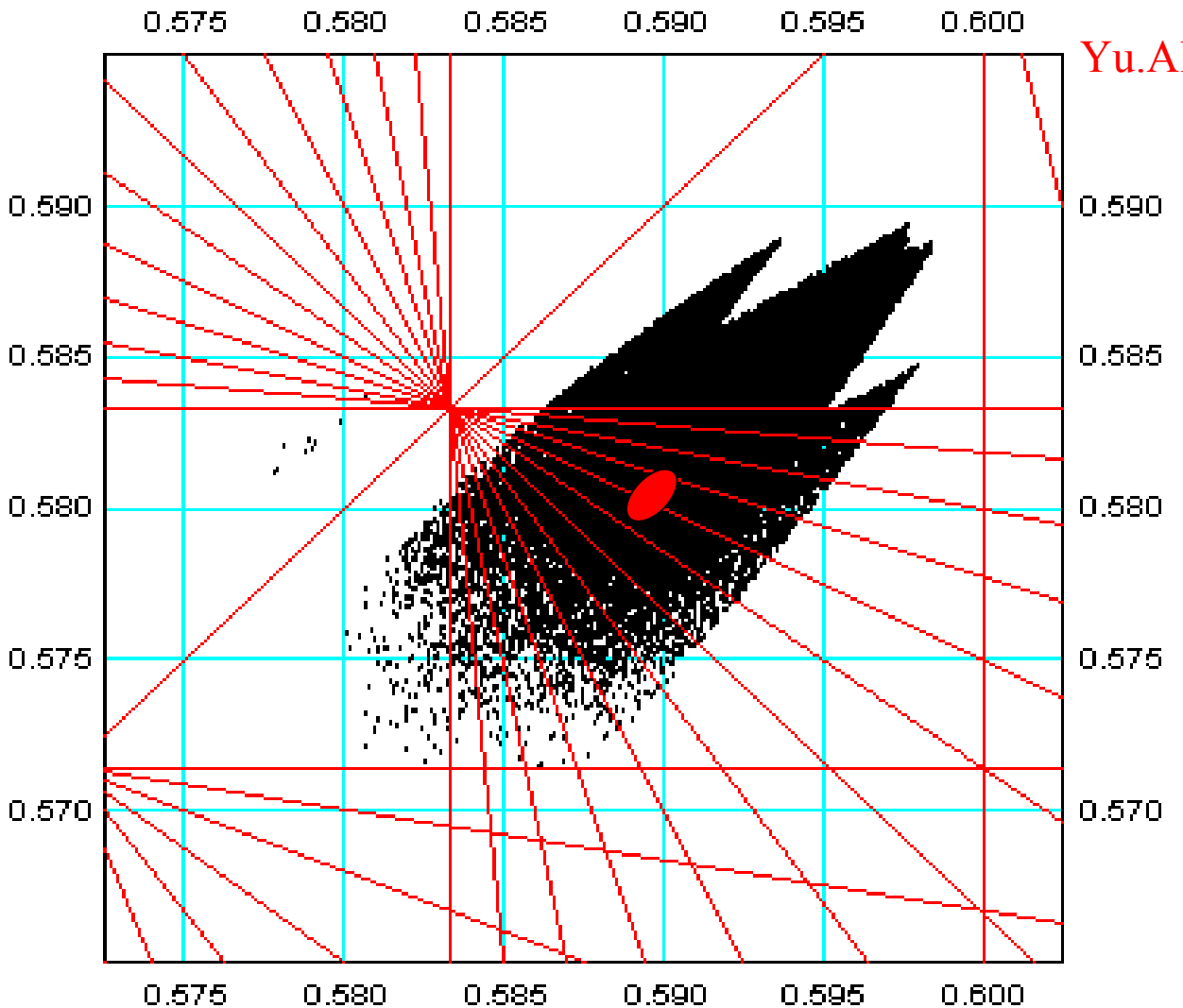
but: a) always present

b) MANY near-misses i = 70

c) different bunch-by-bunch

d) HV separator limited: gd^2 scales as V^2 / g

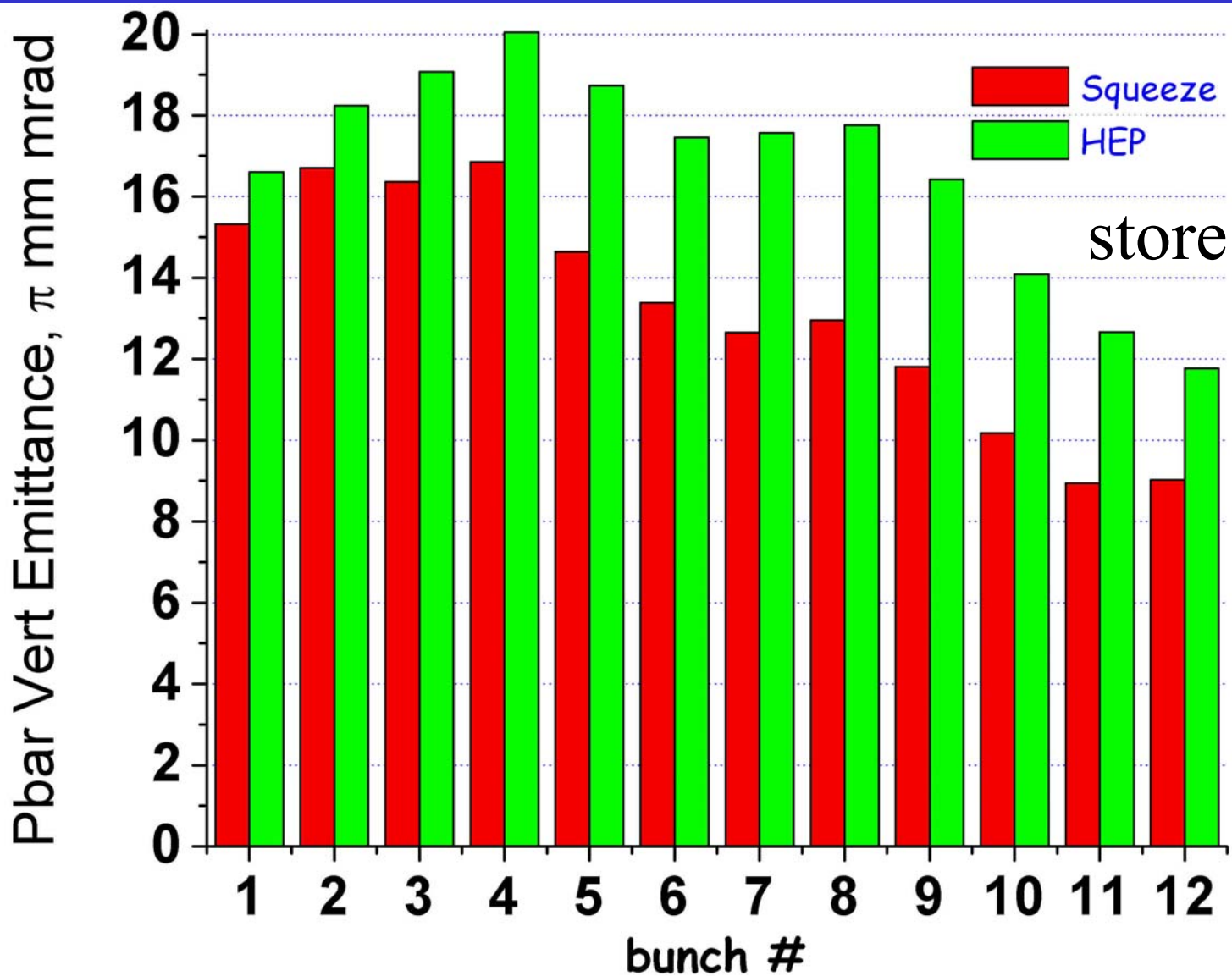
Tevatron Working Points



Yu.Alexahin

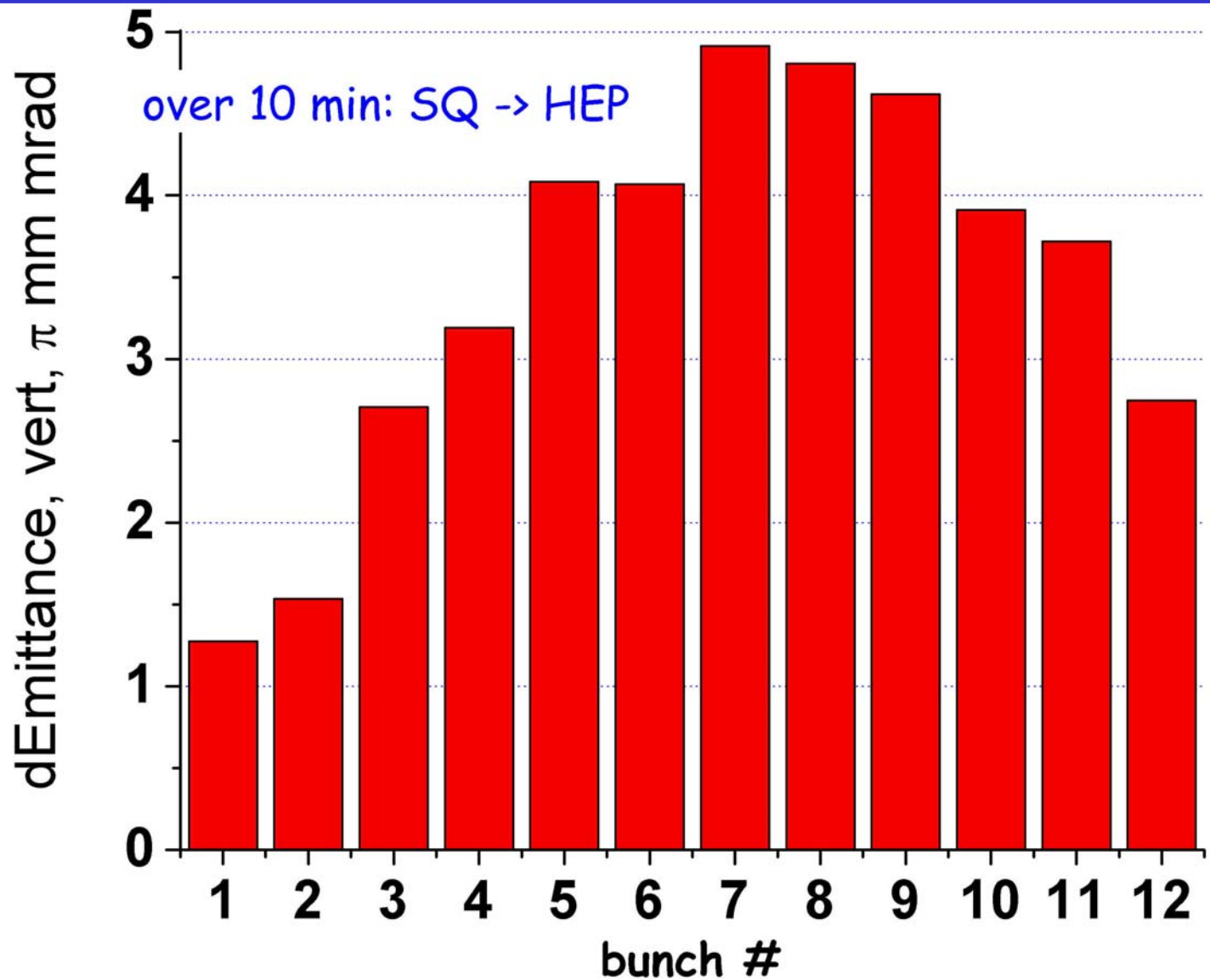
Protons: 20 π
250e9/bunch

Evolution of Pbar Emittance

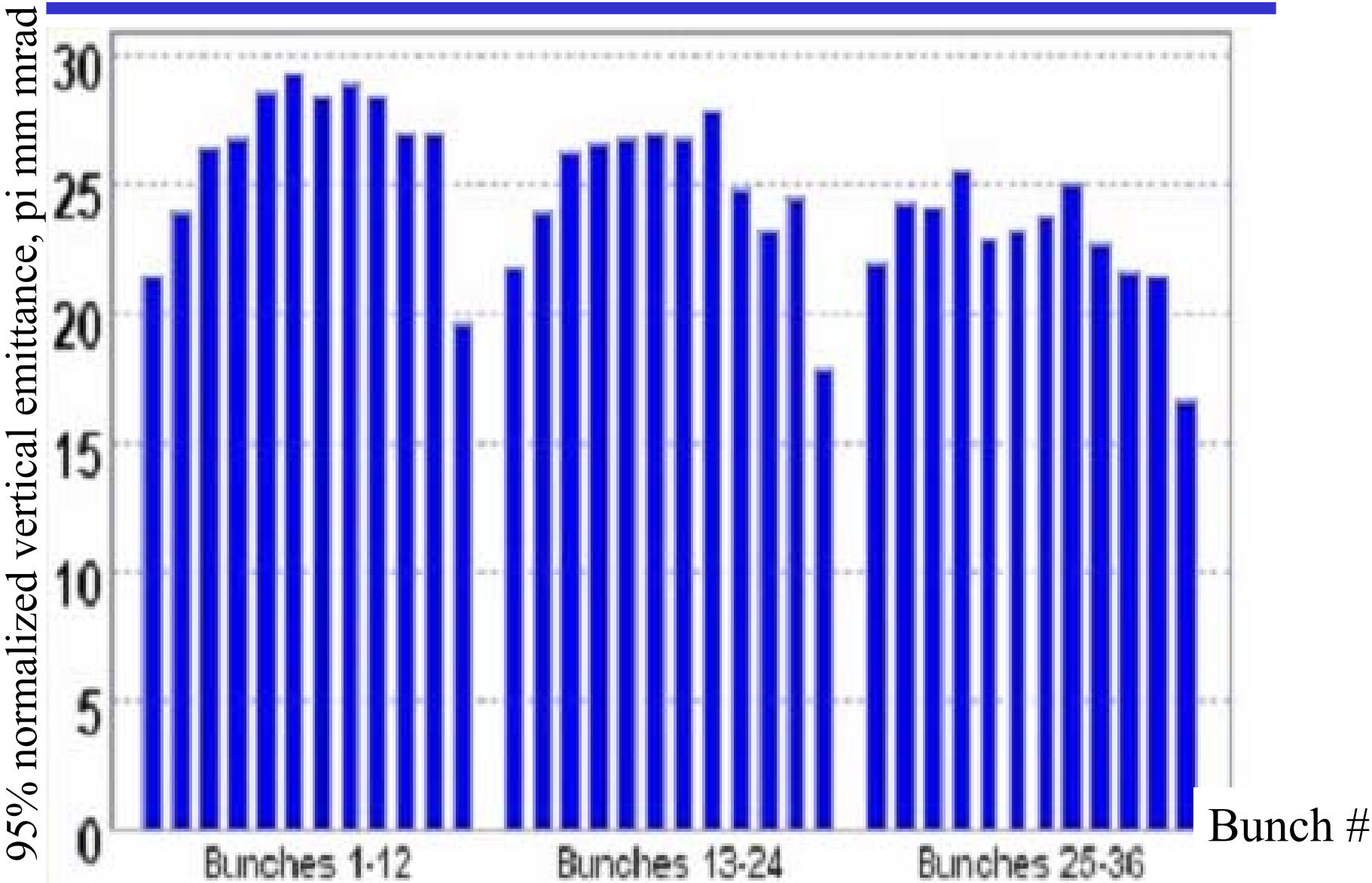


store #3231

Pbar Bunch Emittance Growth



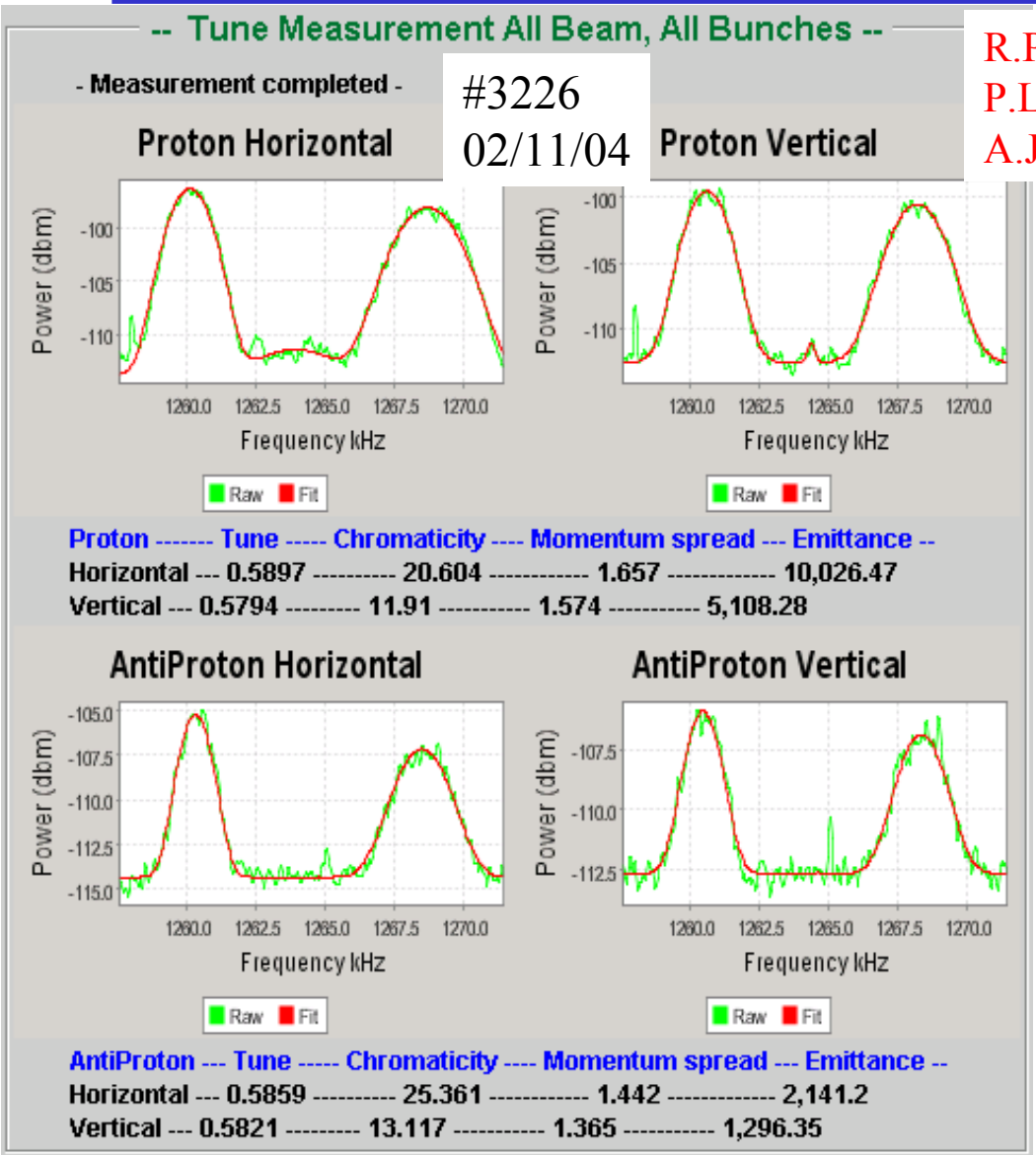
"Scallops" in Pbar Bunch Emittances



Facts about "Scallops"

- "Scallops" is beam-beam phenomenon, started to occur after N_protons exceeded 180e9/bunch in ~Jan 2003, do not take place in every store even with N_p >180e9/bunch
- "Scallops" occur in both planes, but often more prominent in vertical
- Duration of faster emittance growth is 15-60 min
- Pbar emittance does not exceed the proton one
- "Scallops" are dependent on tunes, strong near Q=0.6; vertical tune change –0.002 can significantly reduce scallops, that has also been confirmed by TEL studies.
- Small "scallops" were seen in protons
- Scallops are the same in all three trains of bunches (vary <20%)

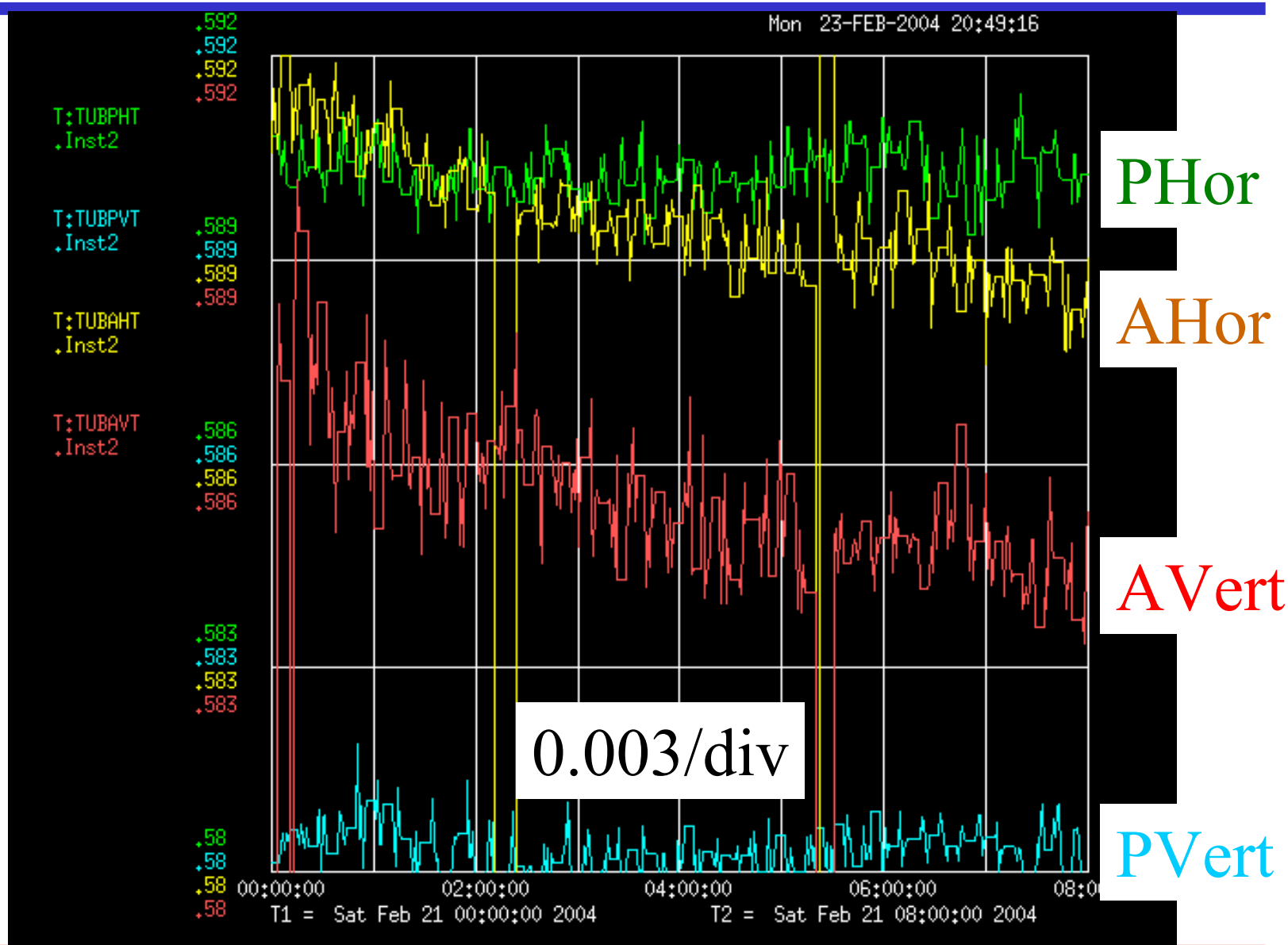
1.7GHz Schottky Spectra



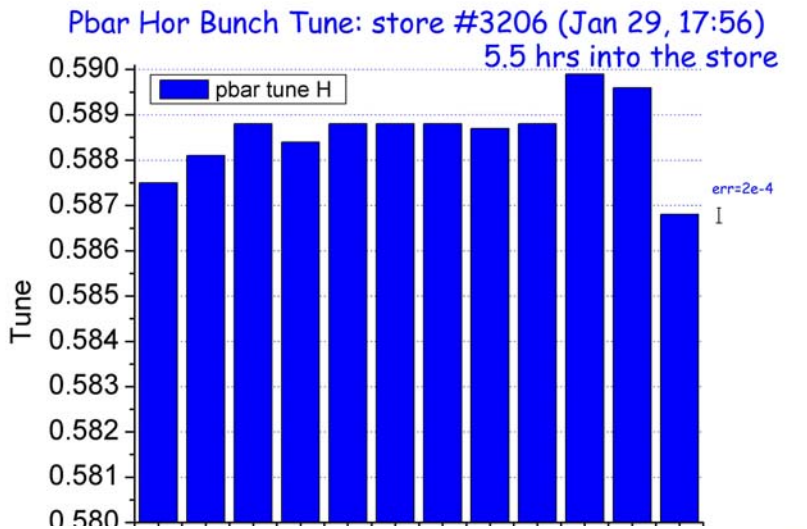
R.Pasquinelli
P.Lebrun
A.Jansson

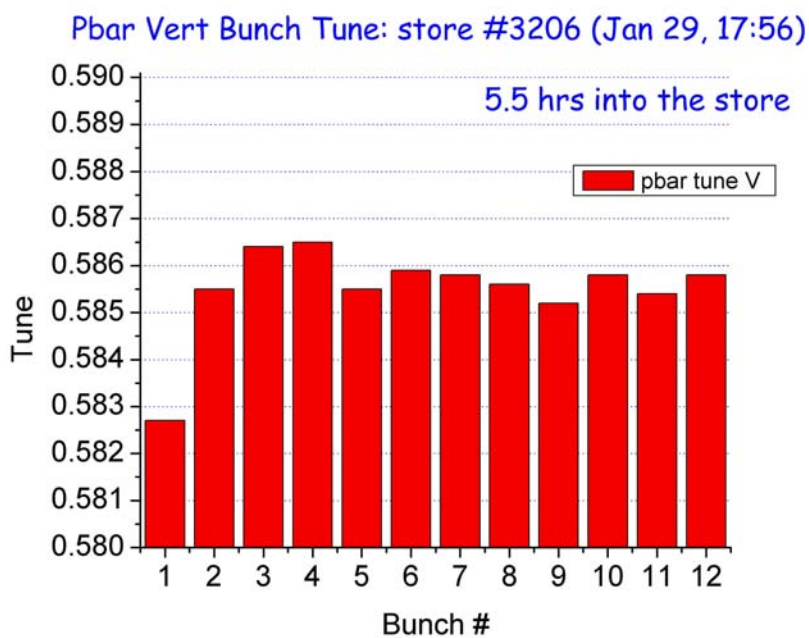
- Q and 1-Q lines are seen
- Fit gives:
  - Betatron frequency
  - dP/P ∝ sum of two widths
  - C_vh ∝ difference of two widths
  - Emittance ∝ area under the peaks
- Can do that for each bunch

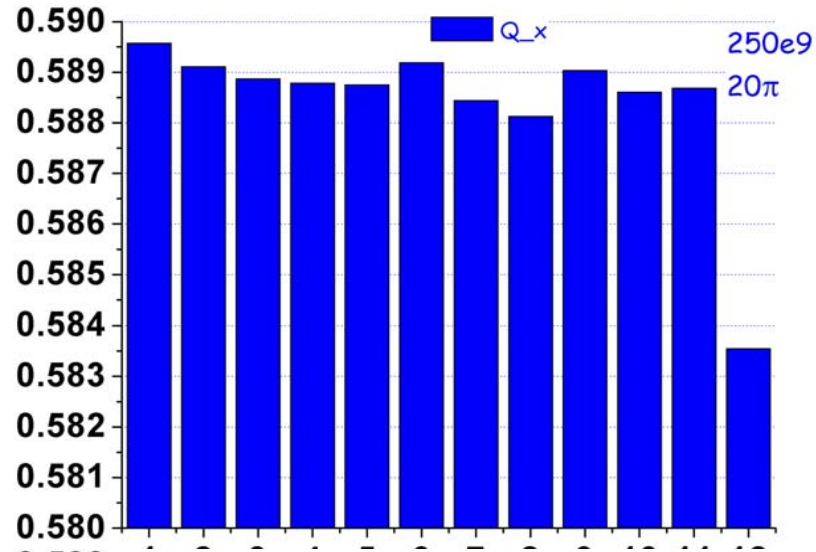
Pbar Tunes Drift Down due to Beam-Beam

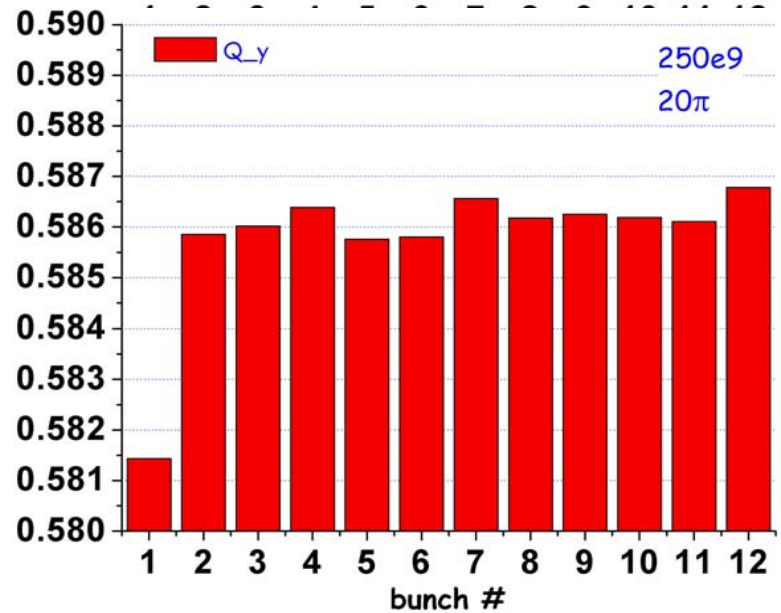


Measured vs Calc'd Pbar Bunch Tunes

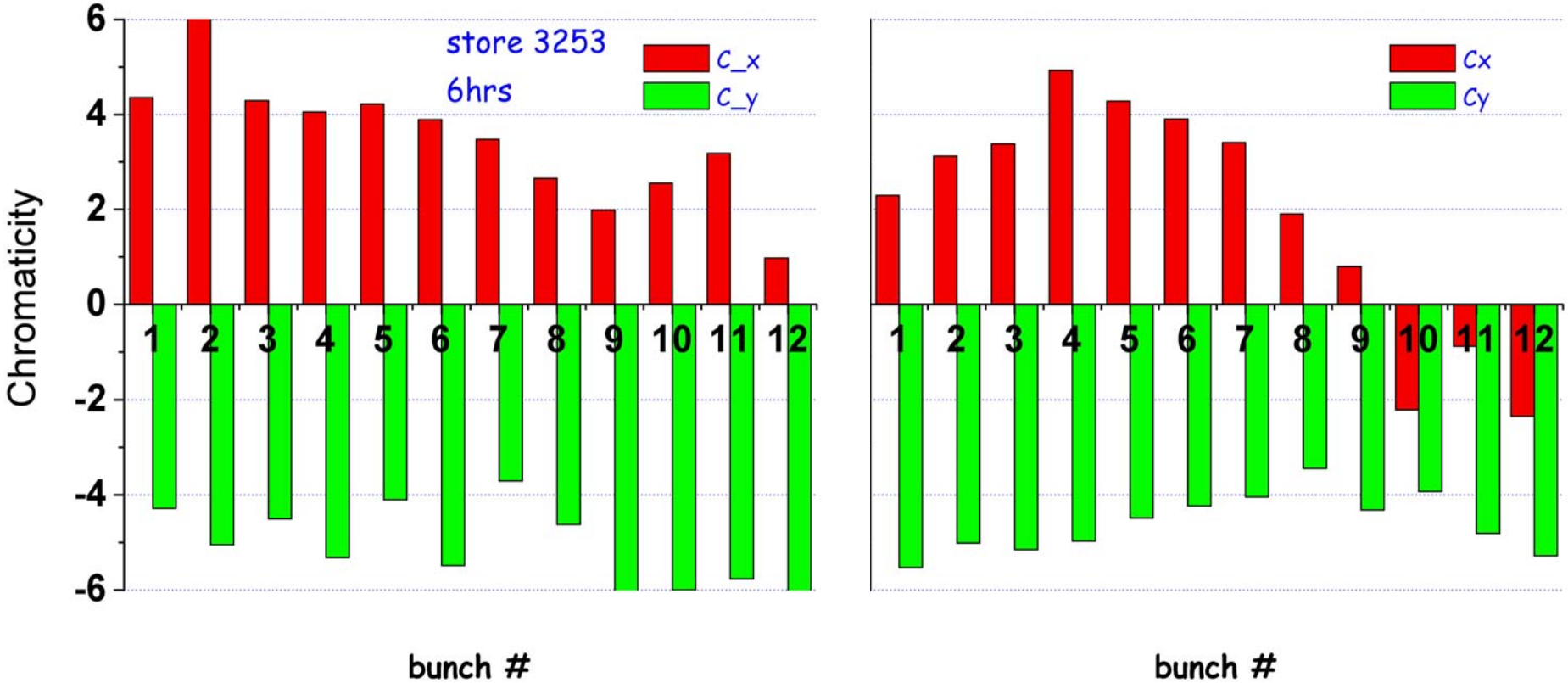




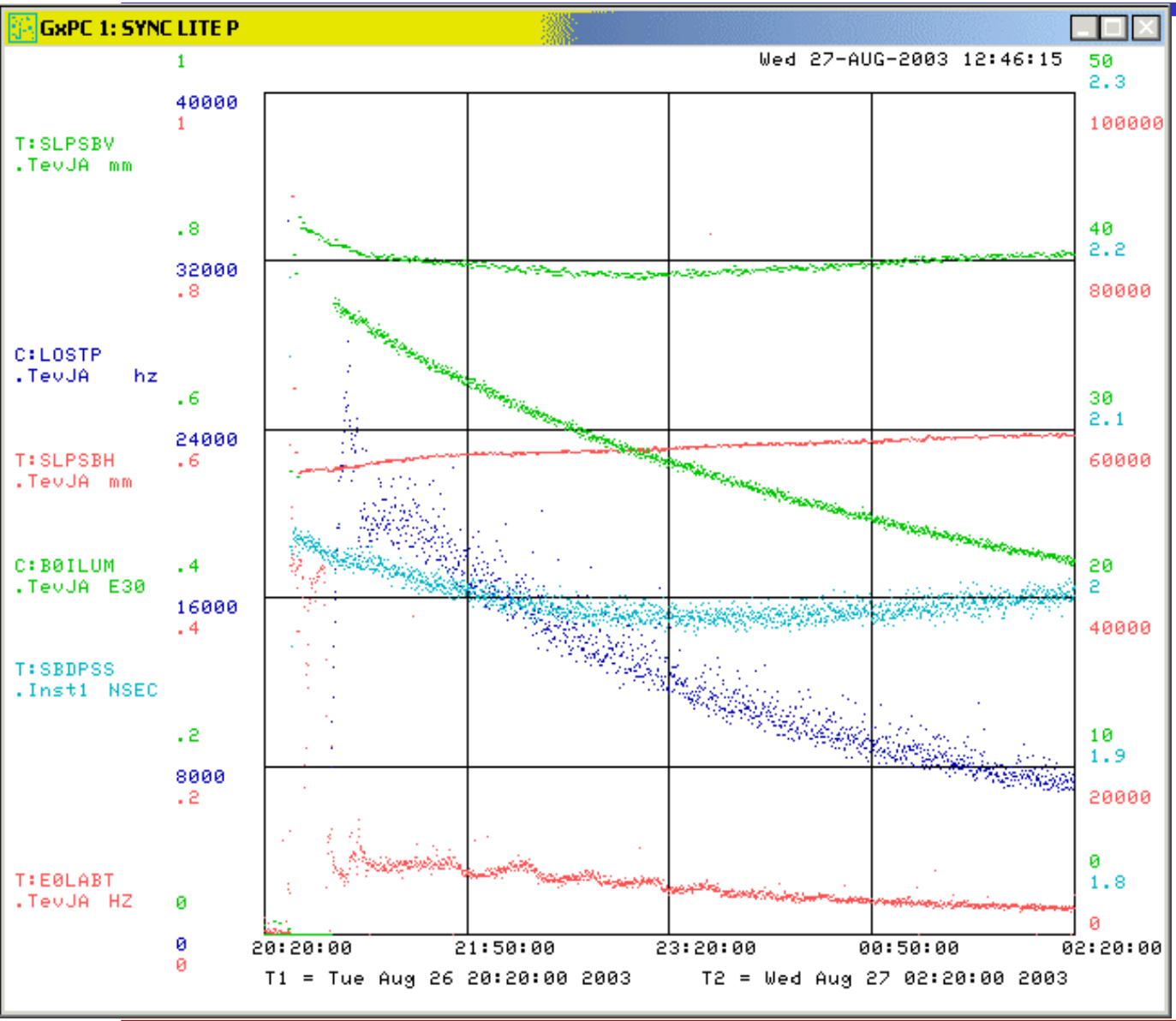




Measured vs Calc'd Chromaticites

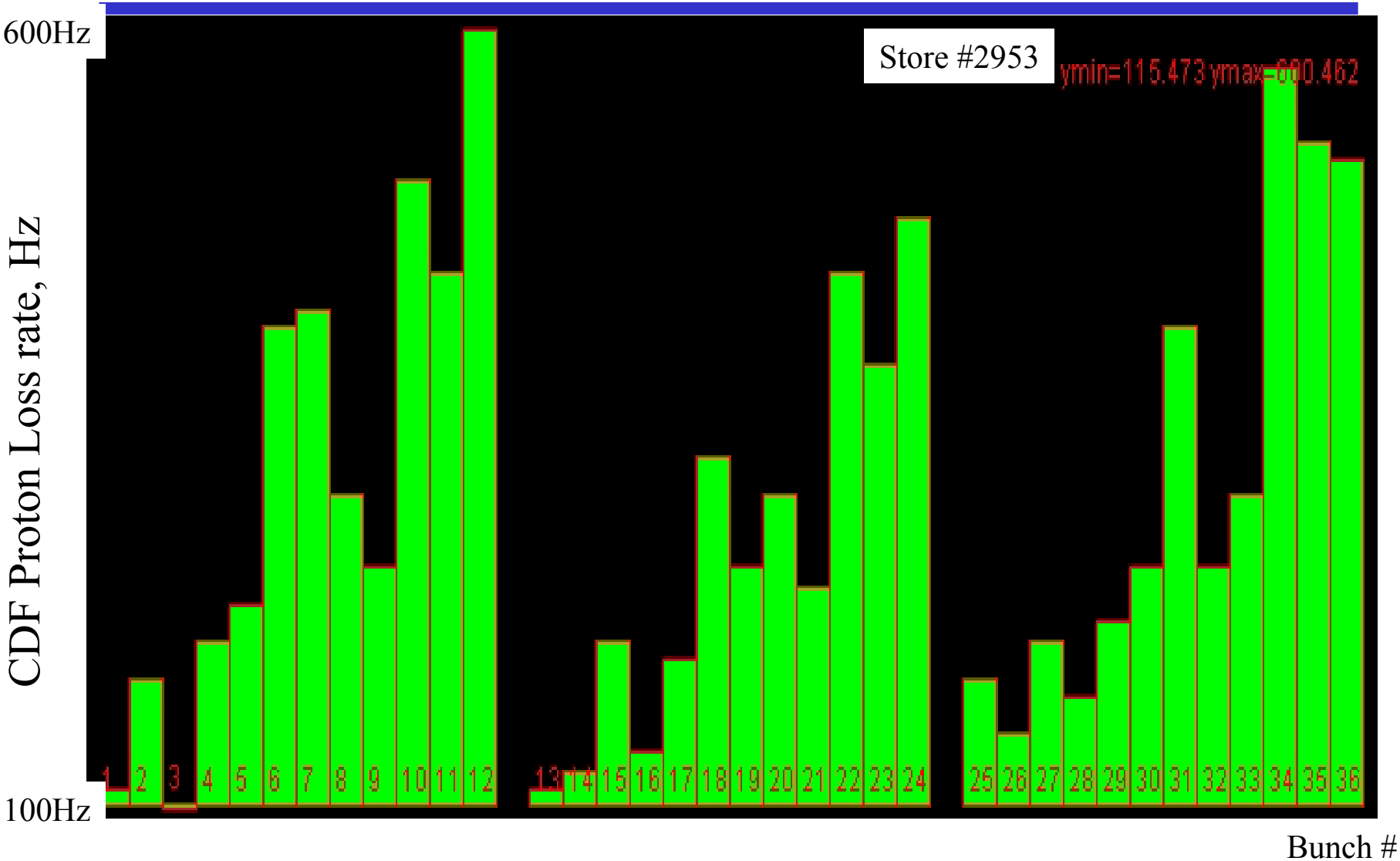


High Proton Losses and Shaving at HEP



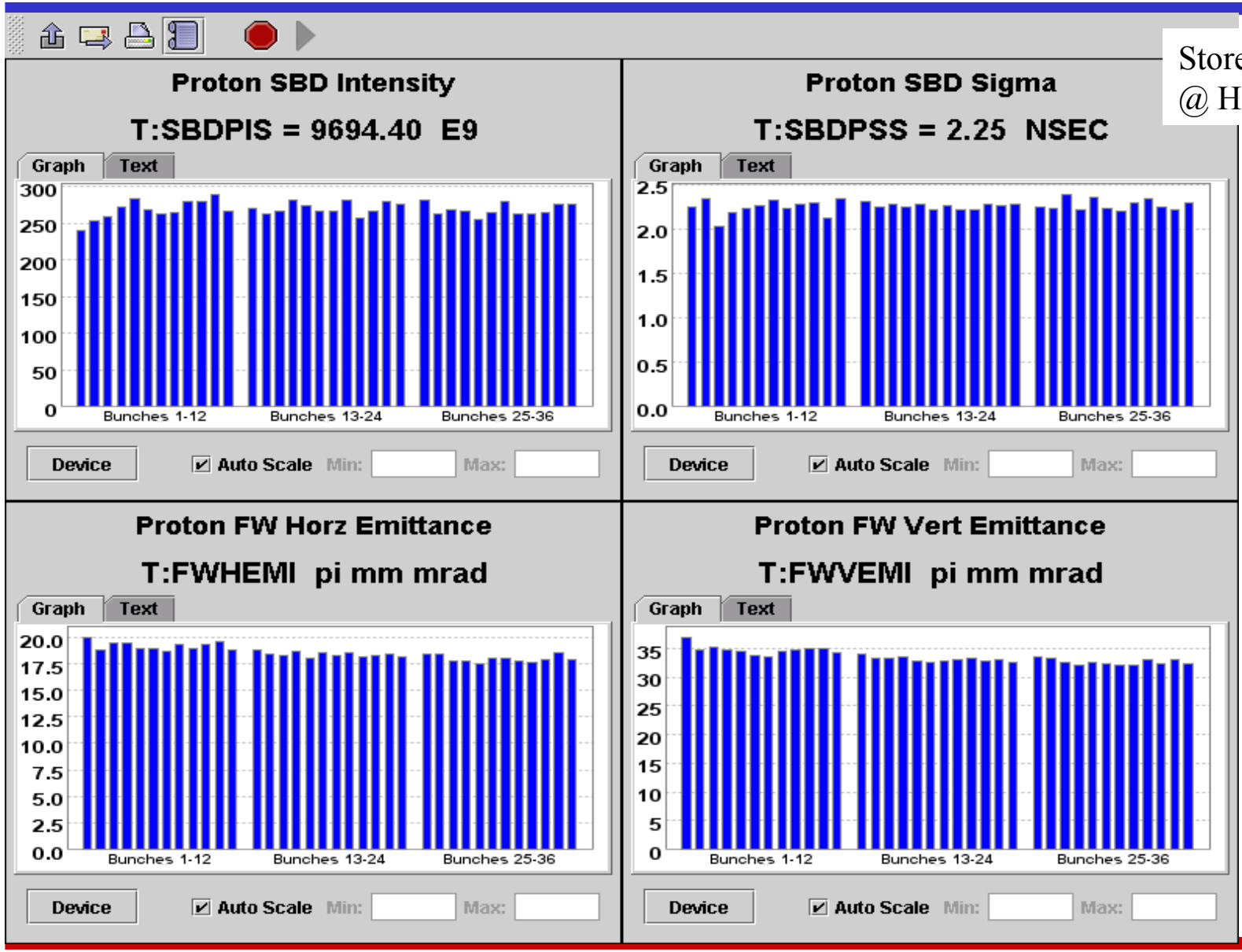
- (re)Started at the end of July'03
- Empirically found that reduced C_v and variation of tunes can help but not drastically
- Cogging scan was not helpful
- Losses >5 times smaller without pbars
- Losses vary bunch-by-bunch ("staircase")

Proton losses induced by Pbars

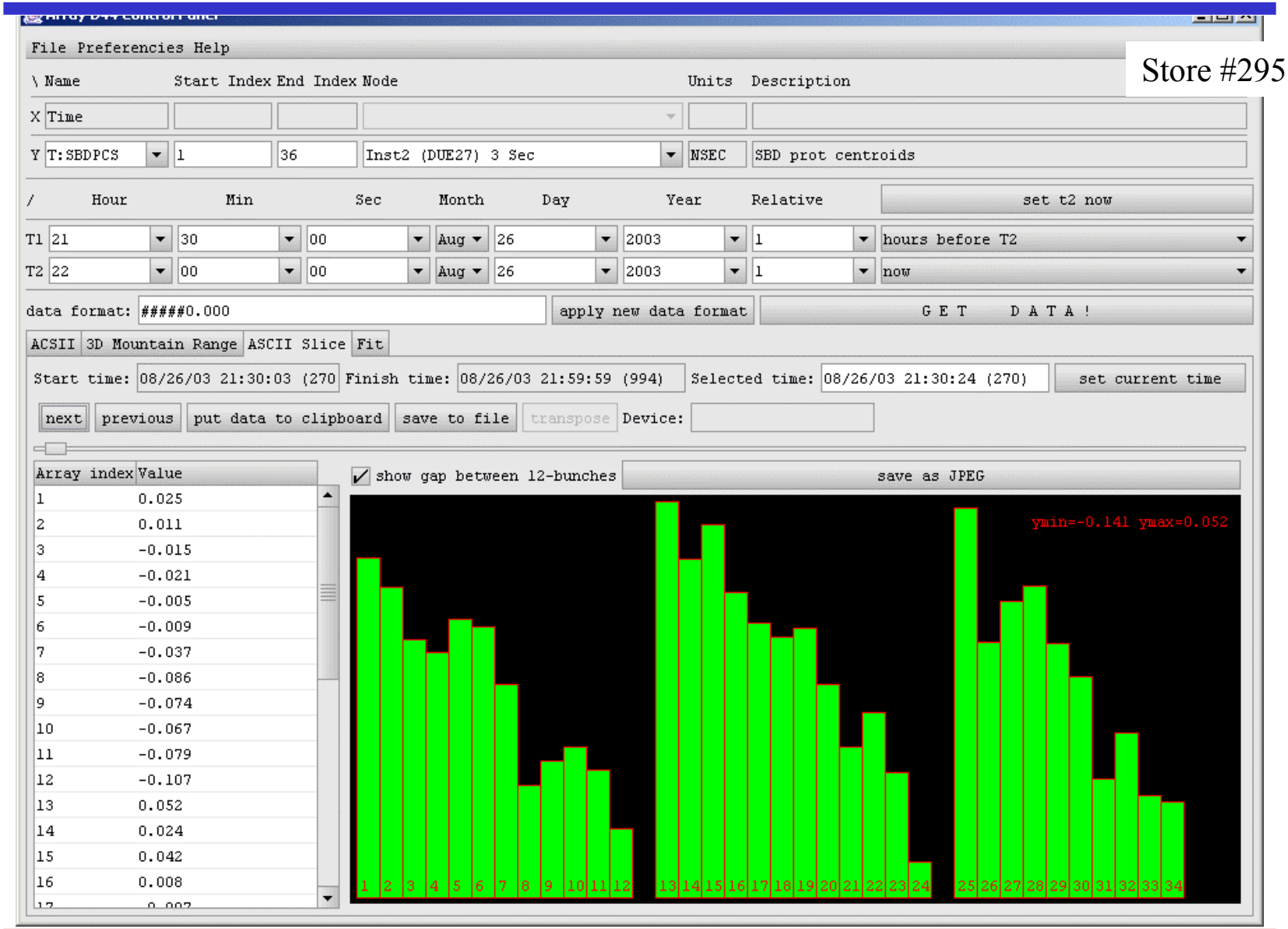


Proton Intensity and Emittances ~Uniform

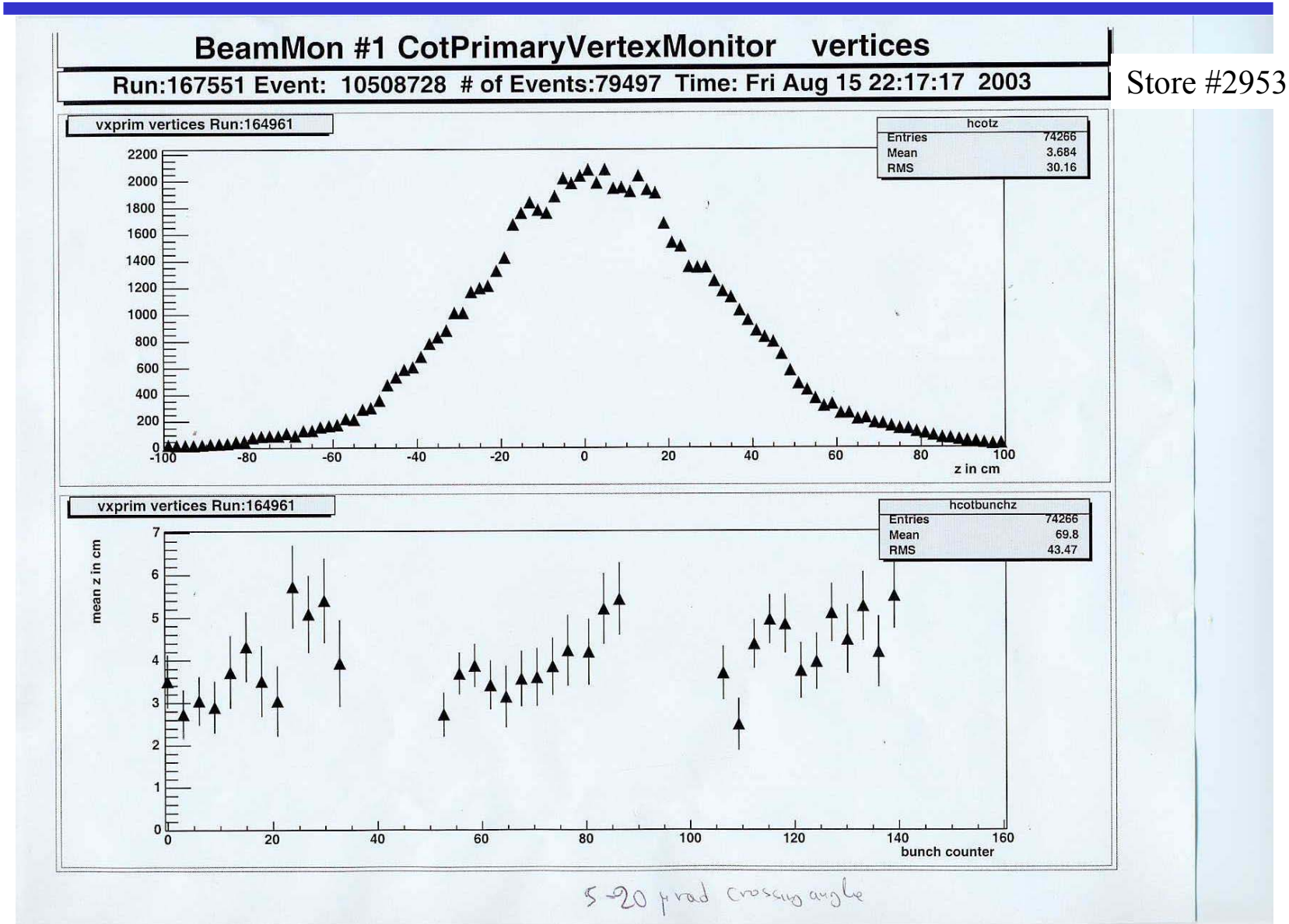
Store #2932
@ HEP



Proton RF Phase - Beam Loading



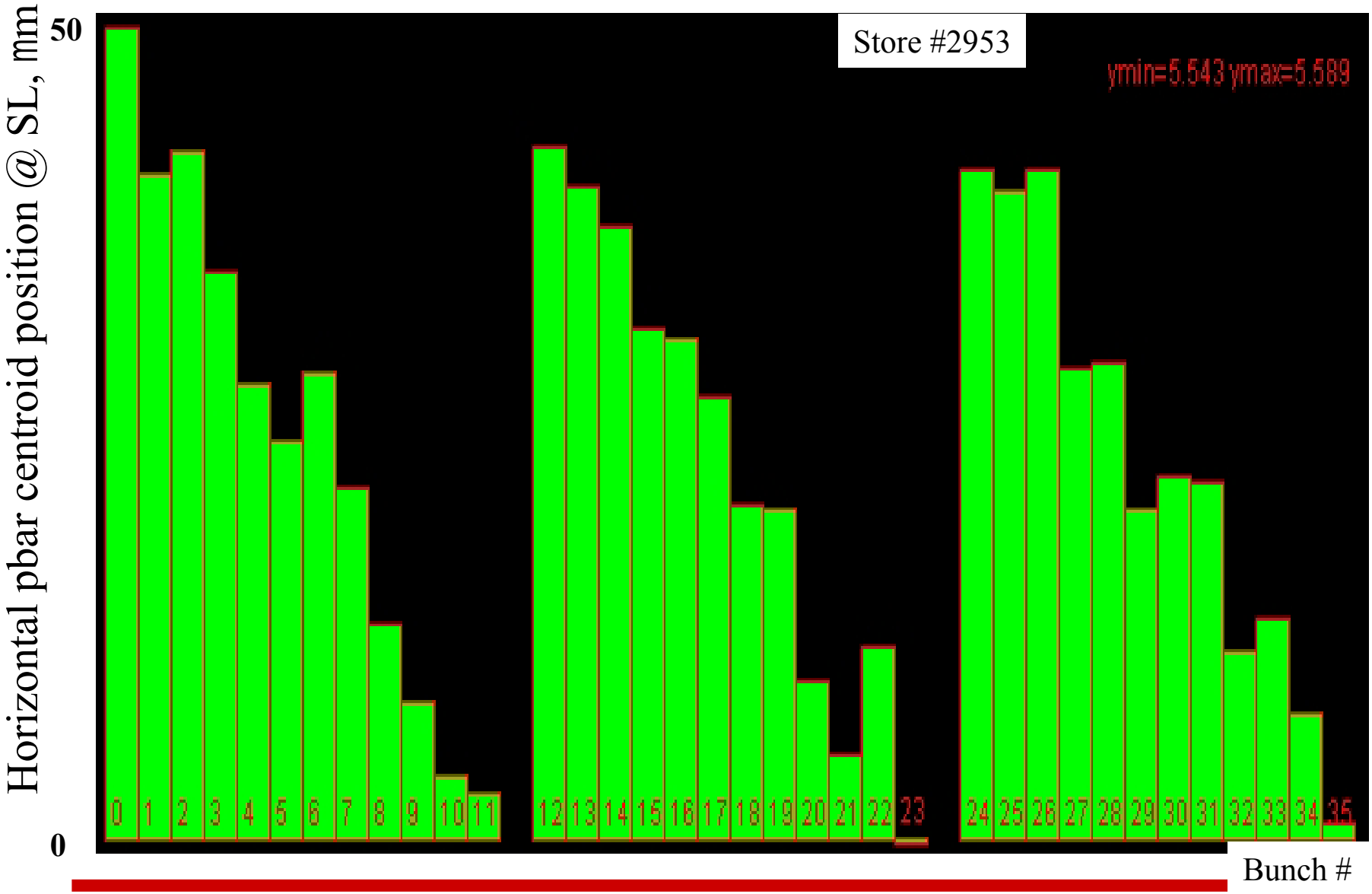
→ results in 3cm variation of IP z-position



Store #2953

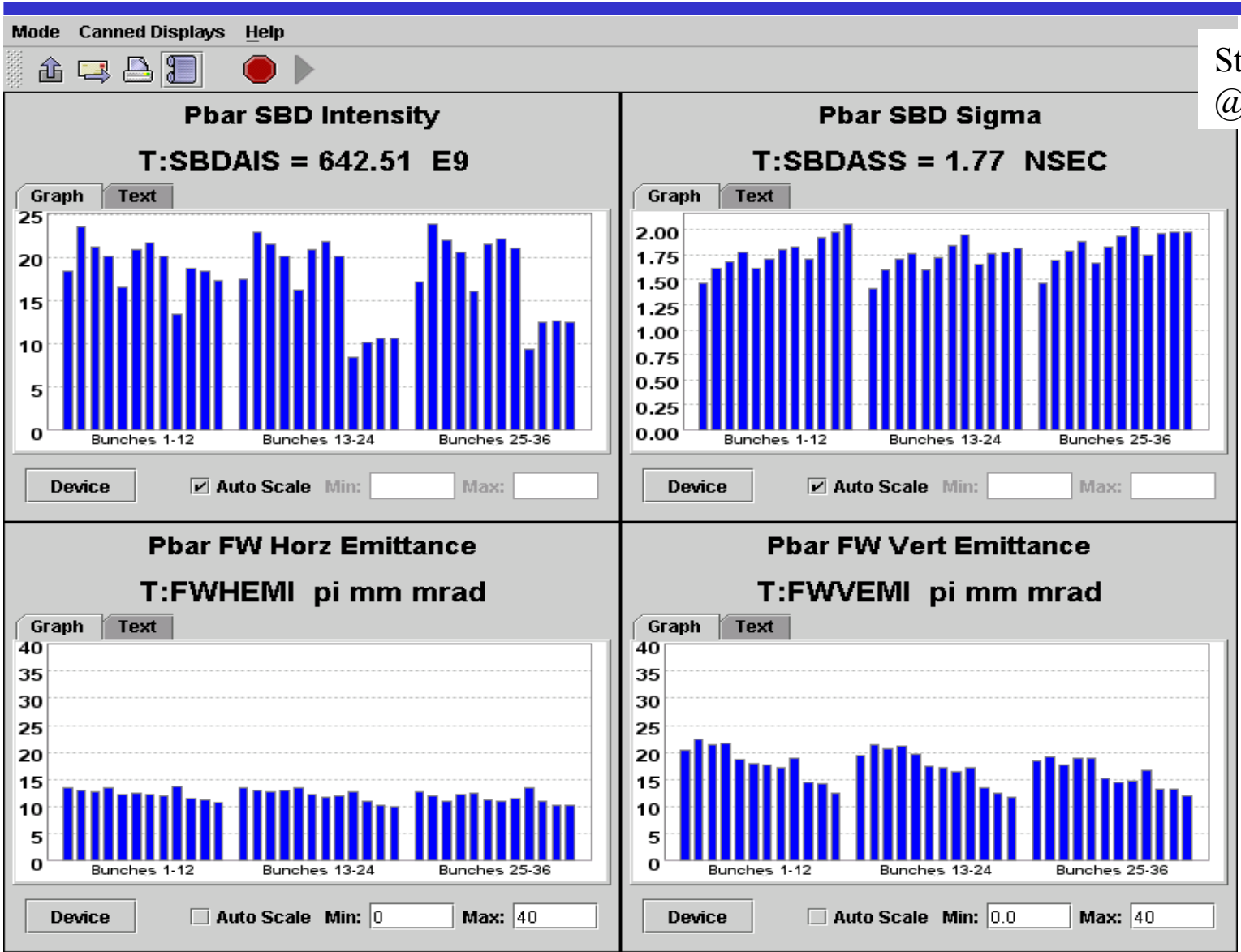
5-20 μrad crossing angle

Pbar bunch positions vary due to beam-beam

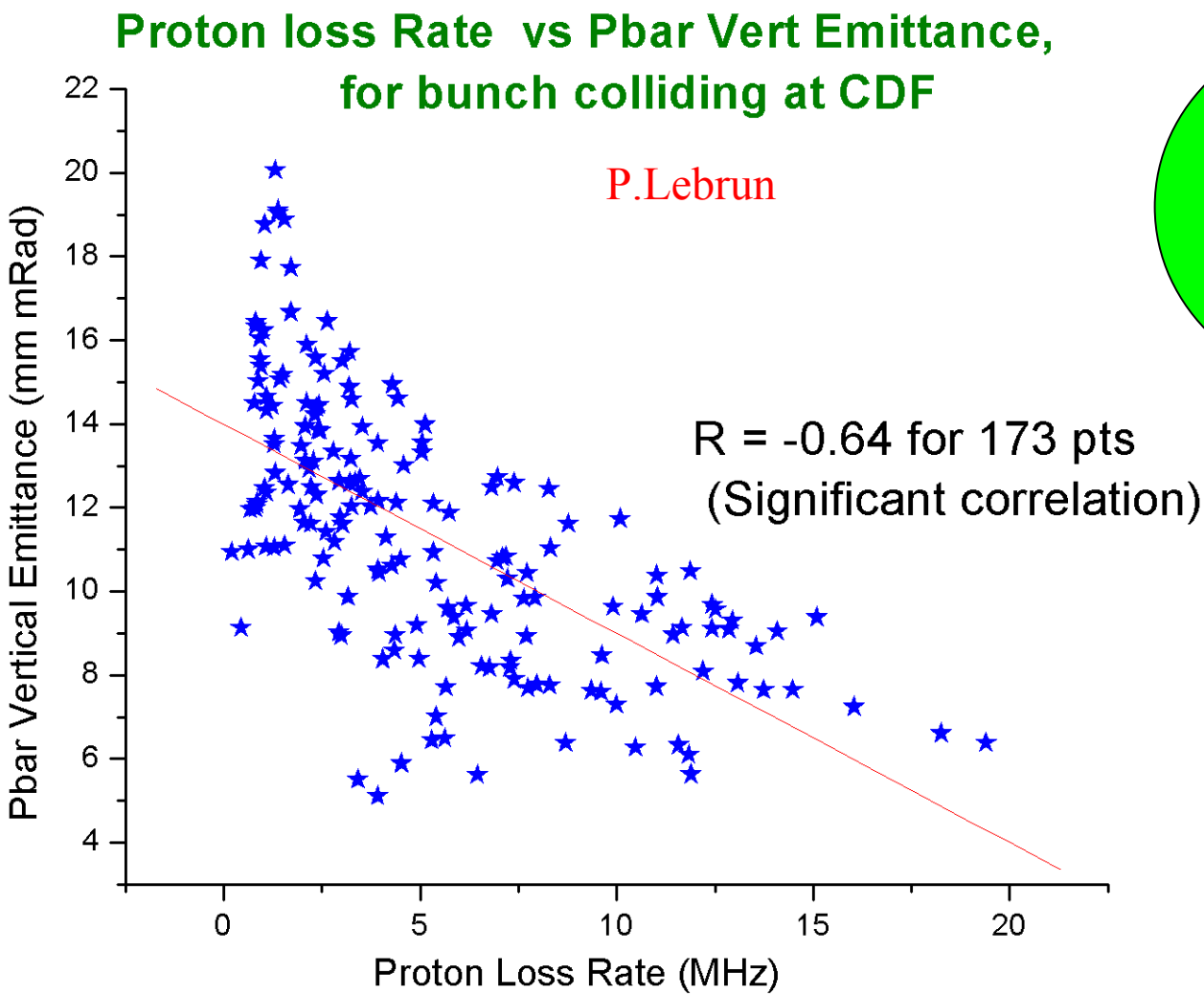


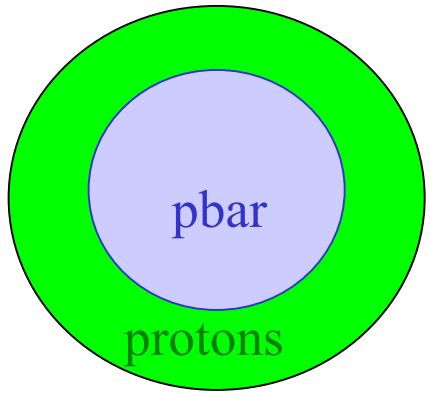
Pbar bunch intensities and sizes VARY (from AA)

Store #2932
@ HEP

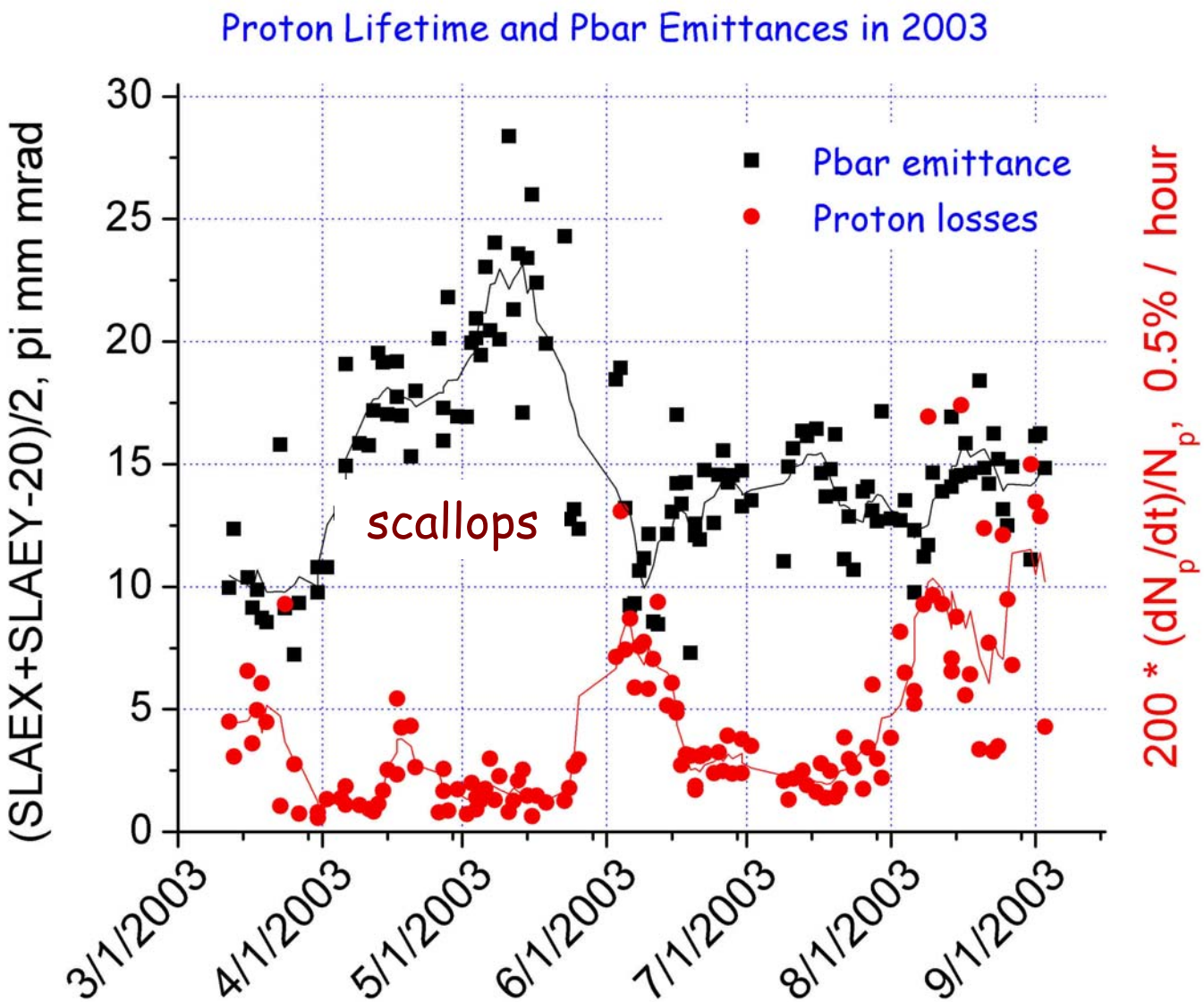


Loss of protons due to pbar non-linearities





Pbar Emittance Matters for Proton Losses @ HEP



These Losses Less of a Problem Now

Reasons:

a) Proton emittance reduced : MI→Tev inj dilution reduced after shutdown, smaller p-emittances from Booster since Jan'04

b) Pbar emittance increased : due to larger stacks we shoot from nowdays

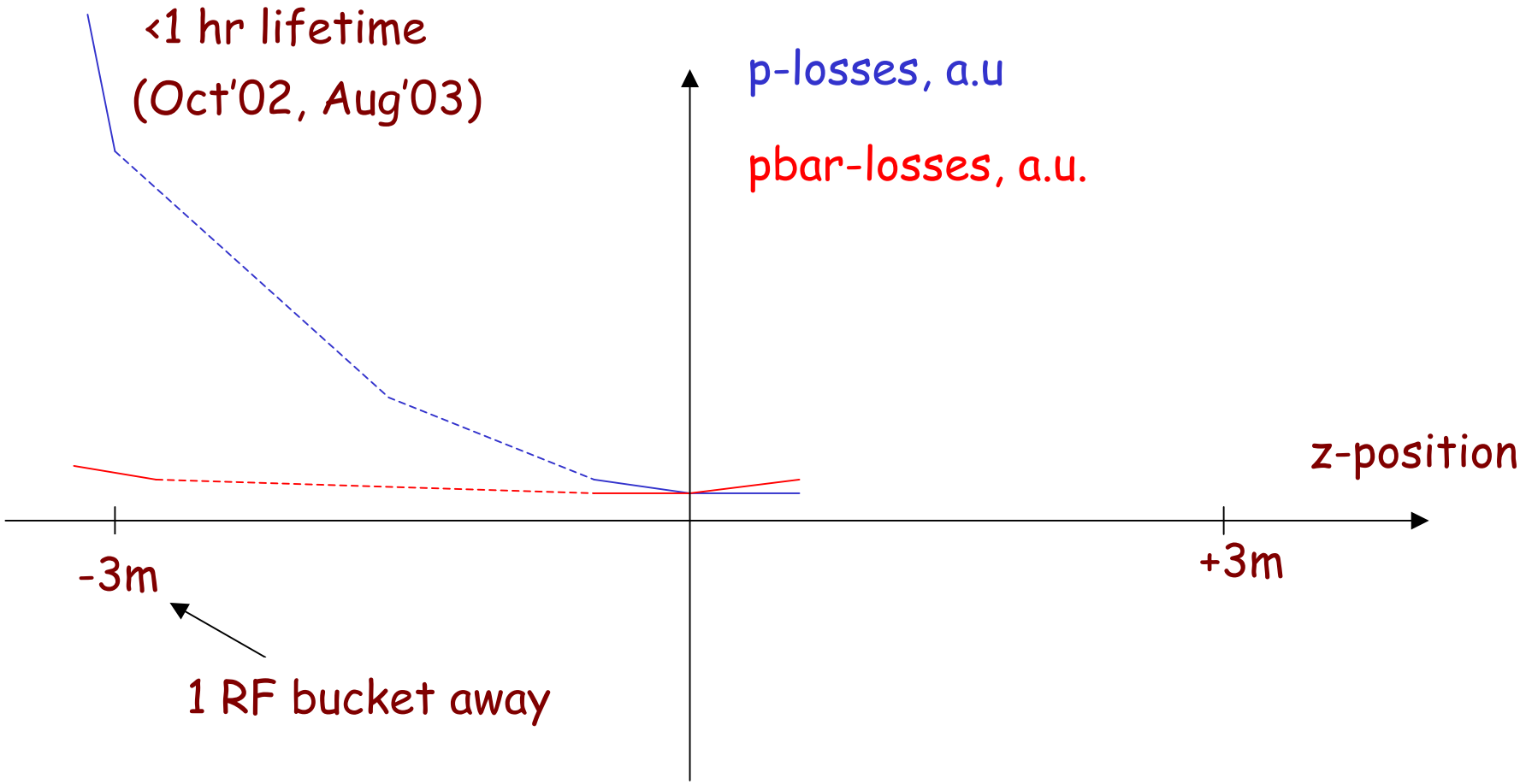
Possibilities for future:

a) Explore wider tune region

b) Shave protons in MI

c) BBcompensation

Just Another Puzzle: Collisions OFF-Waist



… need more systematic studies

How to Counteract the Beam-Beam

Pbar,p loss at 150, ramp	larger aperture & helix
	lower chromaticity
	smaller beam sizes
	Wire-BBC - ?
Emm, Lumi lifetime at HEP	larger helix
	lower chromaticity
	TEL-BBC ("scallops")
	Wire-BBC - ?

TEL and Wire BBC Complimentary

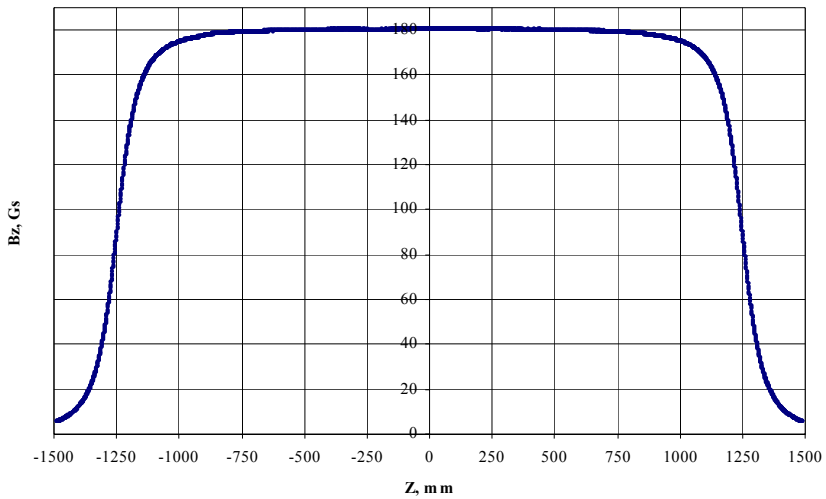
$$beam - beam\ diffusion = f\left(\frac{strength\ of\ resonance}{distance\ to\ resonance}\right)$$

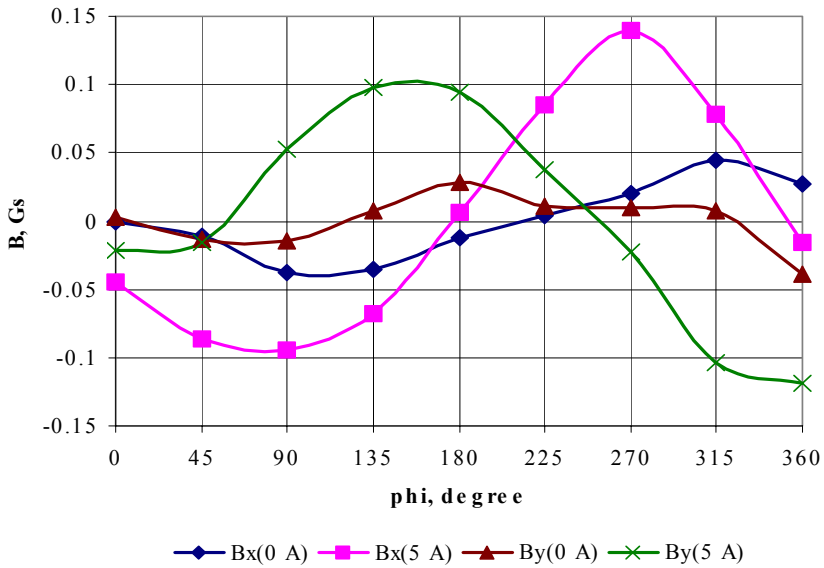
- TEL is good for tune control, DC (e.g. head-on BBC) or on bunch-by-bunch basis (parasitic BB)
- It's not easy for the TEL to control strength of resonances – e.g., lifetime with Tel was significantly improved only after major hardware change (e-gun design to generate smooth edge e-beam)
- Wires are good for DC resonance strength control
- Wires might be helpful for both head-on and parasitic beam-beam

BBC: Status and Plans

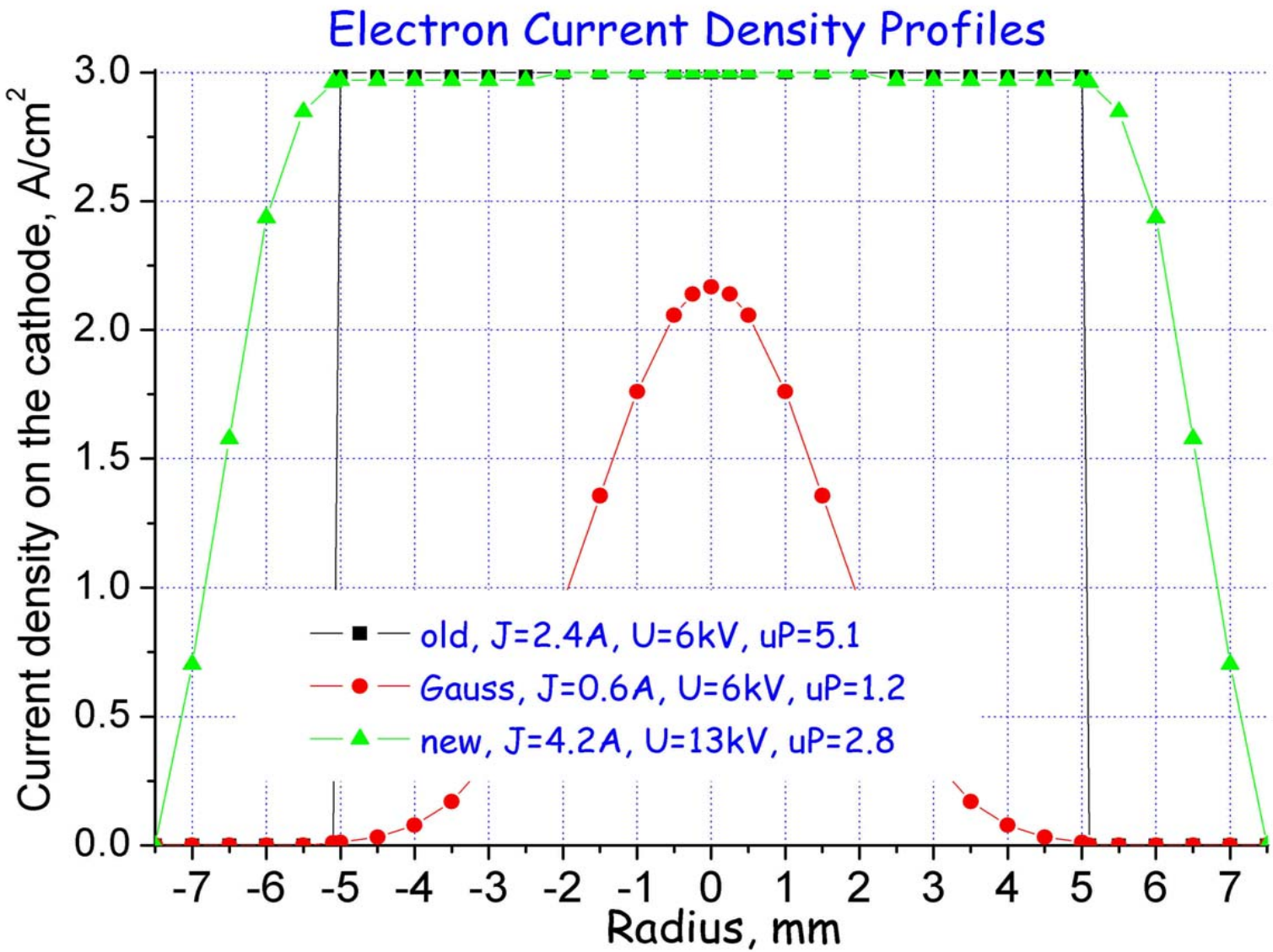
- Past:
  - TEL-1 installed at F48 — Feb 2001
  - max tuneshift dQ~0.009 achieved — 2001-2002
  - TEL-1 operational for abort gap cleaning — since Jan'2002
  - Gaussian gun fixed p-lifetime — Feb 2003
  - 1st indication of BBC with TEL — May 2003
- Present:
  - Improve diagnostics (tunes, BPMs) — July'03-now
  - Re-build a team for future work — July'03-now
  - Theory of Wire Compensation — Oct'03 -now
- Future:
  - Wire BBC review — May 2004
  - Build, test and install TEL-2 as spare — Oct 2004
  - Build 13kV HV modulato — Feb 2005
  - Commission TELs for BBComp — 2005-2006

Spare magnets are being built at IHEP → 05/04

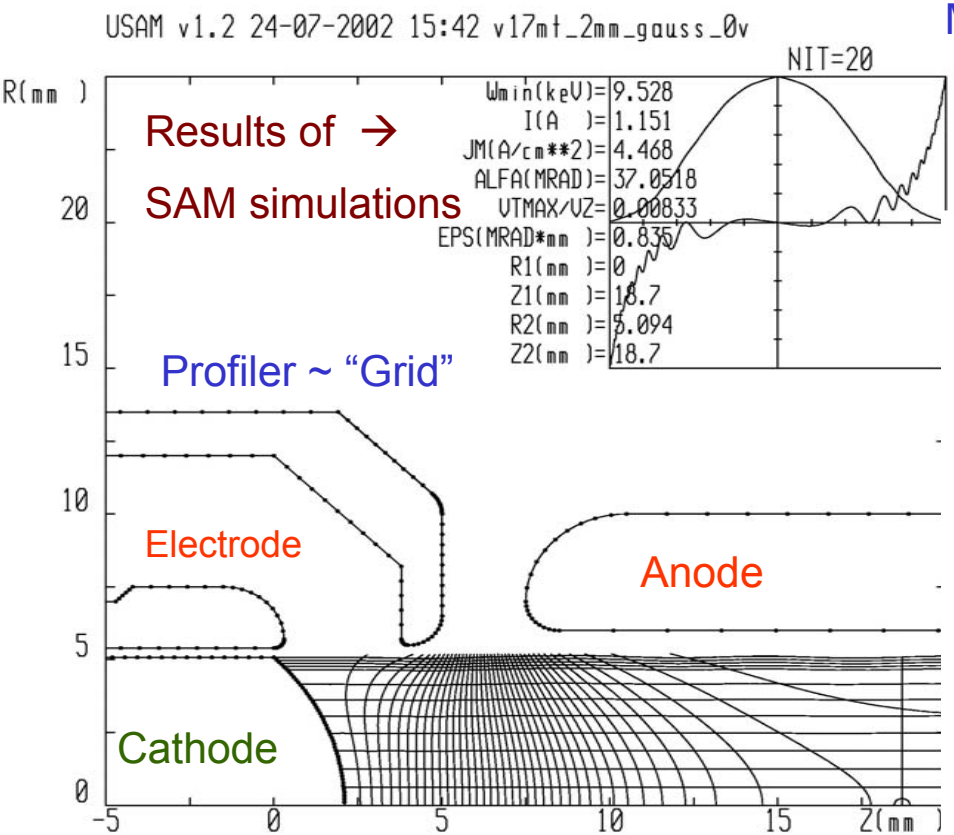




Need wider beam => new HV modulator



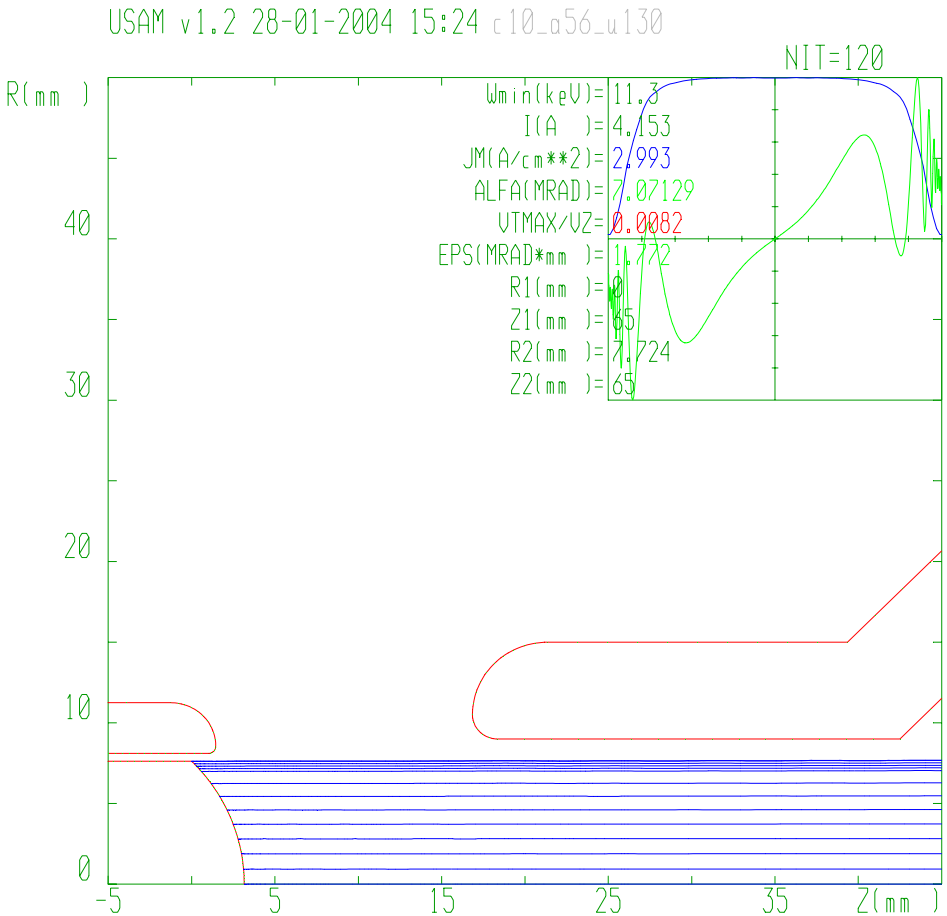
Need of Smooth Edges → Gaussian Gun, "Hat" Gun



M.Tiunov

BINP

New gun design ("hat") to be installed in FY'04 shutdown



Installed in Jan'2003

Conclusions on Beam-Beam Phenomena

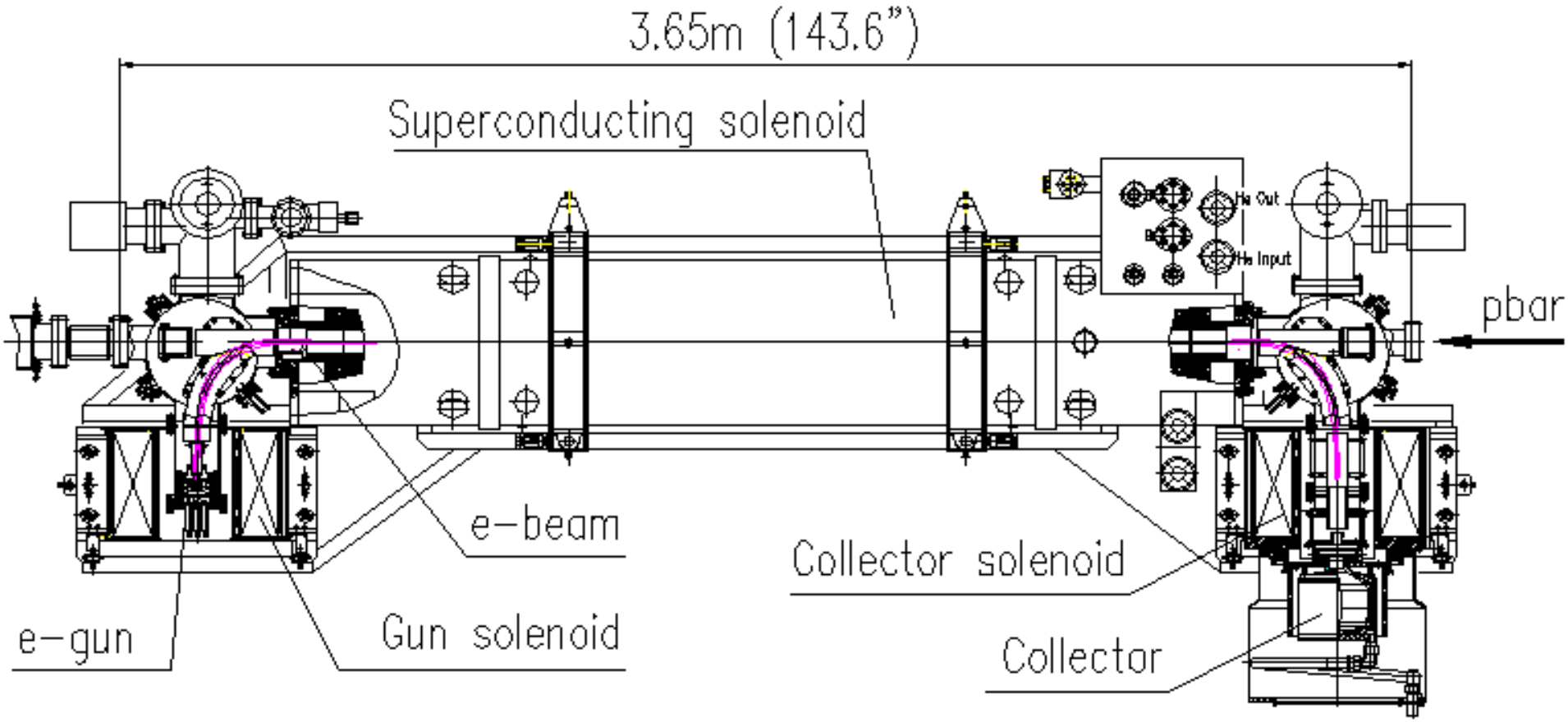
- Beam-beam effects significantly affect performance of the Tevatron
- There are some operational successes (proton lifetime at HEP, 5* helix) , but, in general, the beam-beam effects require more studies and modeling
- Prospects for study time are brighter than at the start of FY'04 (see some results in R.Moore's talk)
- Beam-beam modeling is underway, coordinated by T.Sen (incl. two groups at FNAL, SLAC, LBL, BINP) – micro-review Mar 5, 2004
- Beam-Beam Compensation projects (TEL and Wires) have a potential of lifetime improvement, will undergo reviews in FY'04

Backup Slides

Rebuilding the BBC team

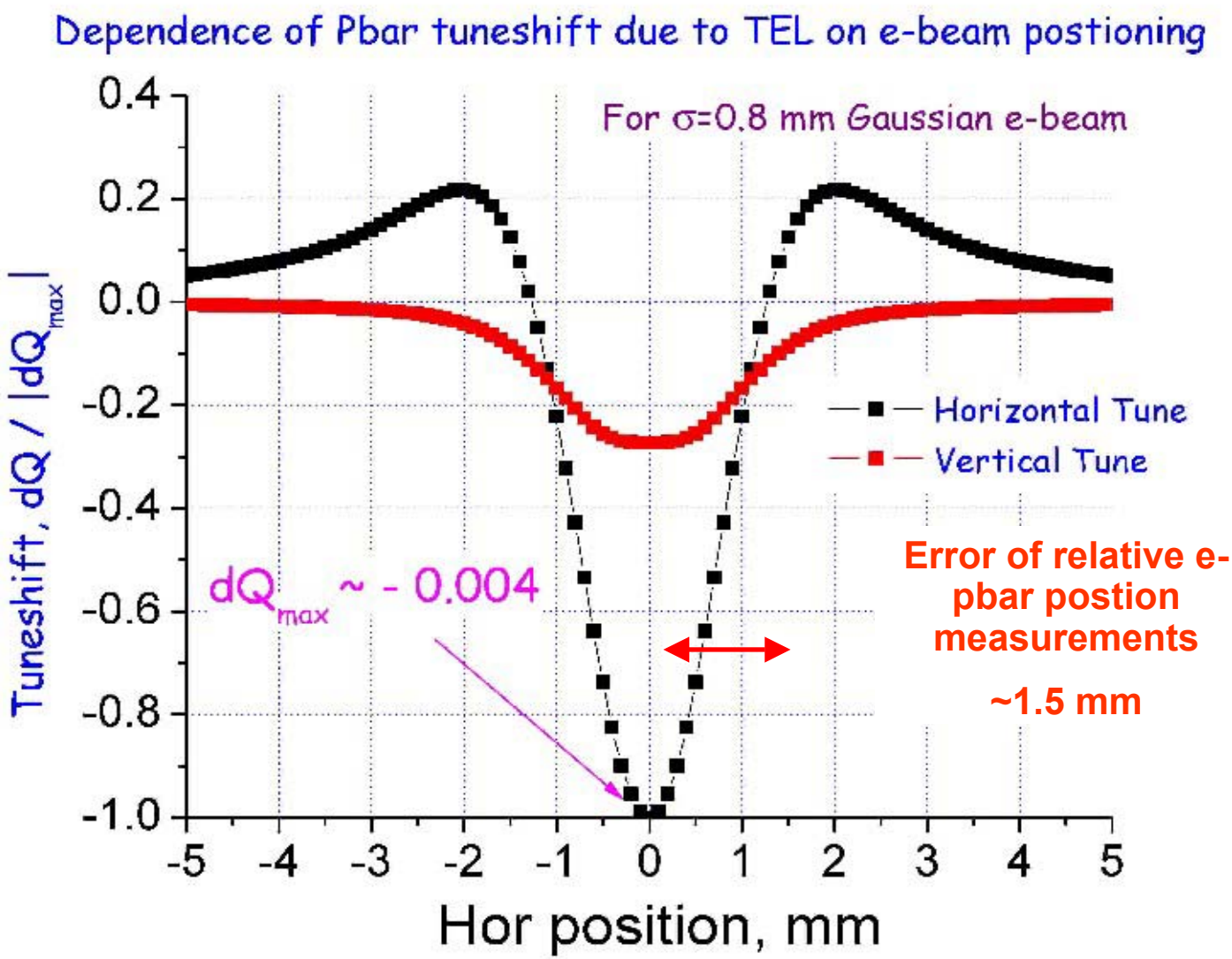
- Over the last 6 mos: 0.25FTE
  - 10% V. Shiltsev – management (planning, scheduling), studies
  - 25% XL.Zhang – TEL-1 maintenance, tuneup, spares, studies
  - 5% K.Bishofberger, H.Pfeffer, G.Saewert
- Need for the next year (s): 6.5 FTE
  - e-system engineer (offer to G.Kuznetsov)
  - postdoc (offer to L.Prost)
  - overall support (20% of Jim Volk)
  - QPS and PSs (2FTE from EE)
  - 16kV modulator R&D (1FTE from EE or TD)
  - tests, magnetic measurements (0.6 FTE - visitors)
  - cryo (0.25 FTE – Alex Martinez?)
  - studies and theory (1.5 FTE – Valishev(GS), VS+YA)

Spare TEL: main components

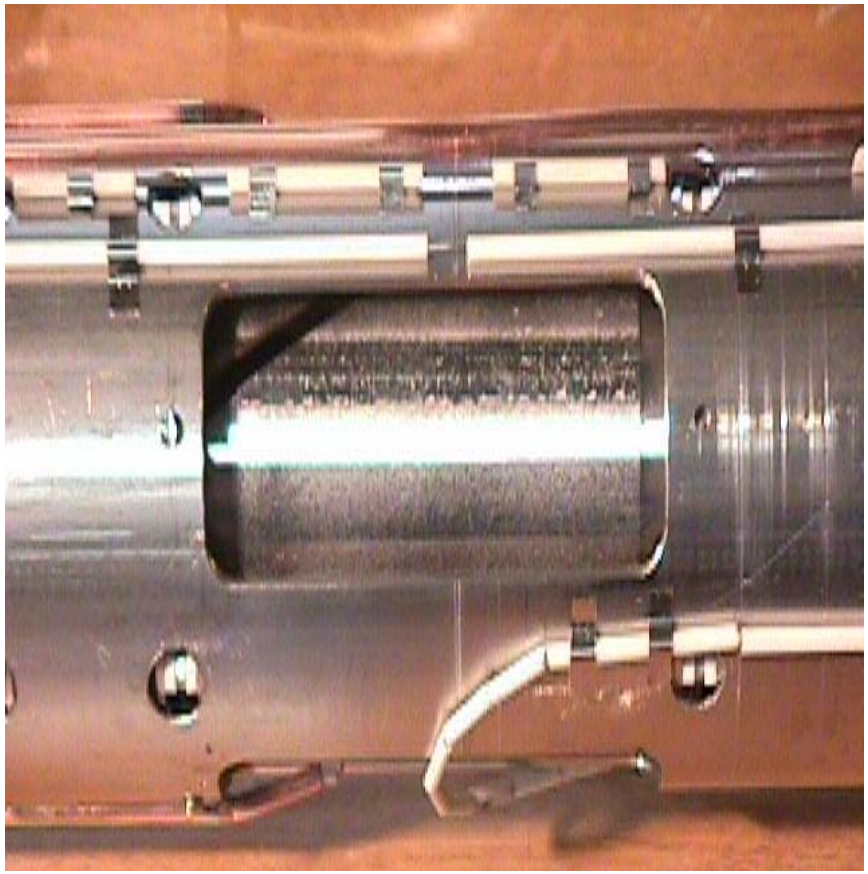


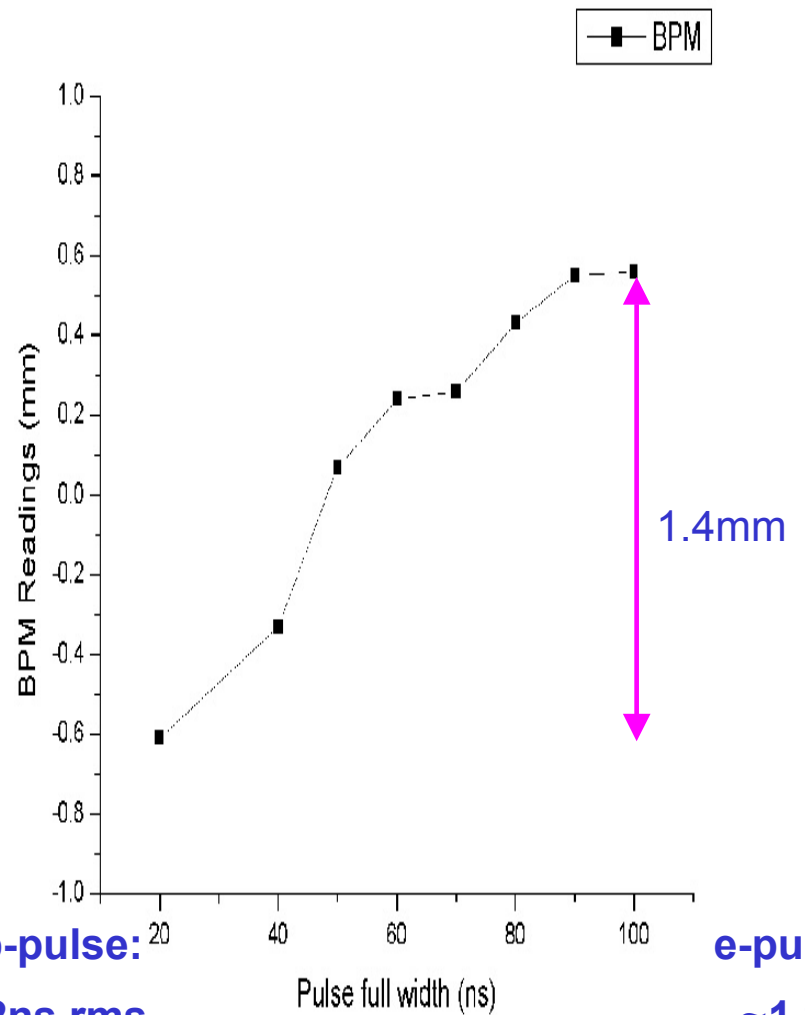
+ HV Modulator, HV+HC PSs, Cryo, QPs, Vacuum, Controls, Diagnostics, Cables

e-pbar alignment is crucial



TEL BPMs – Need to Be Improved





p-pulse:

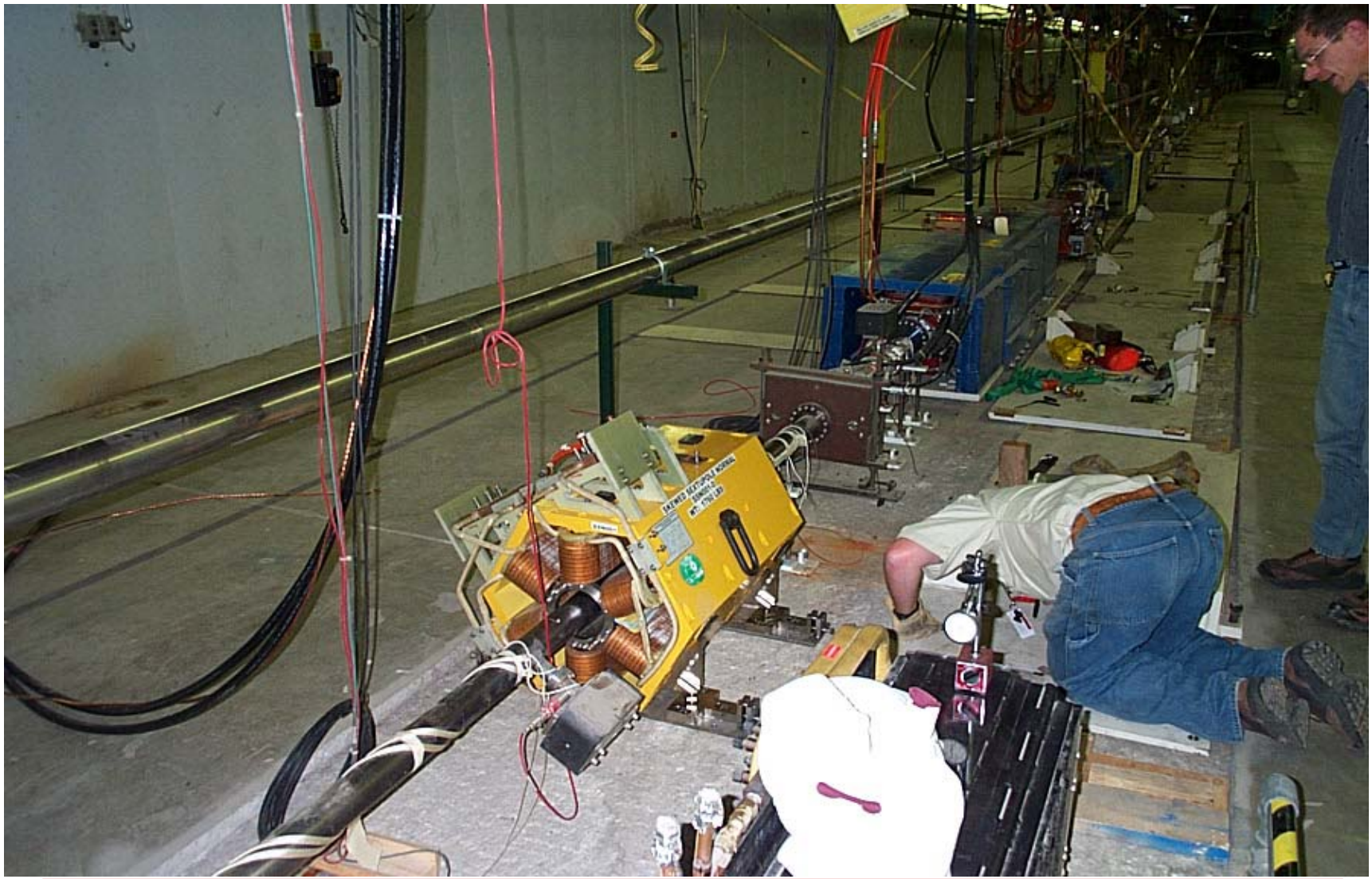
2ns rms

e-pulse:

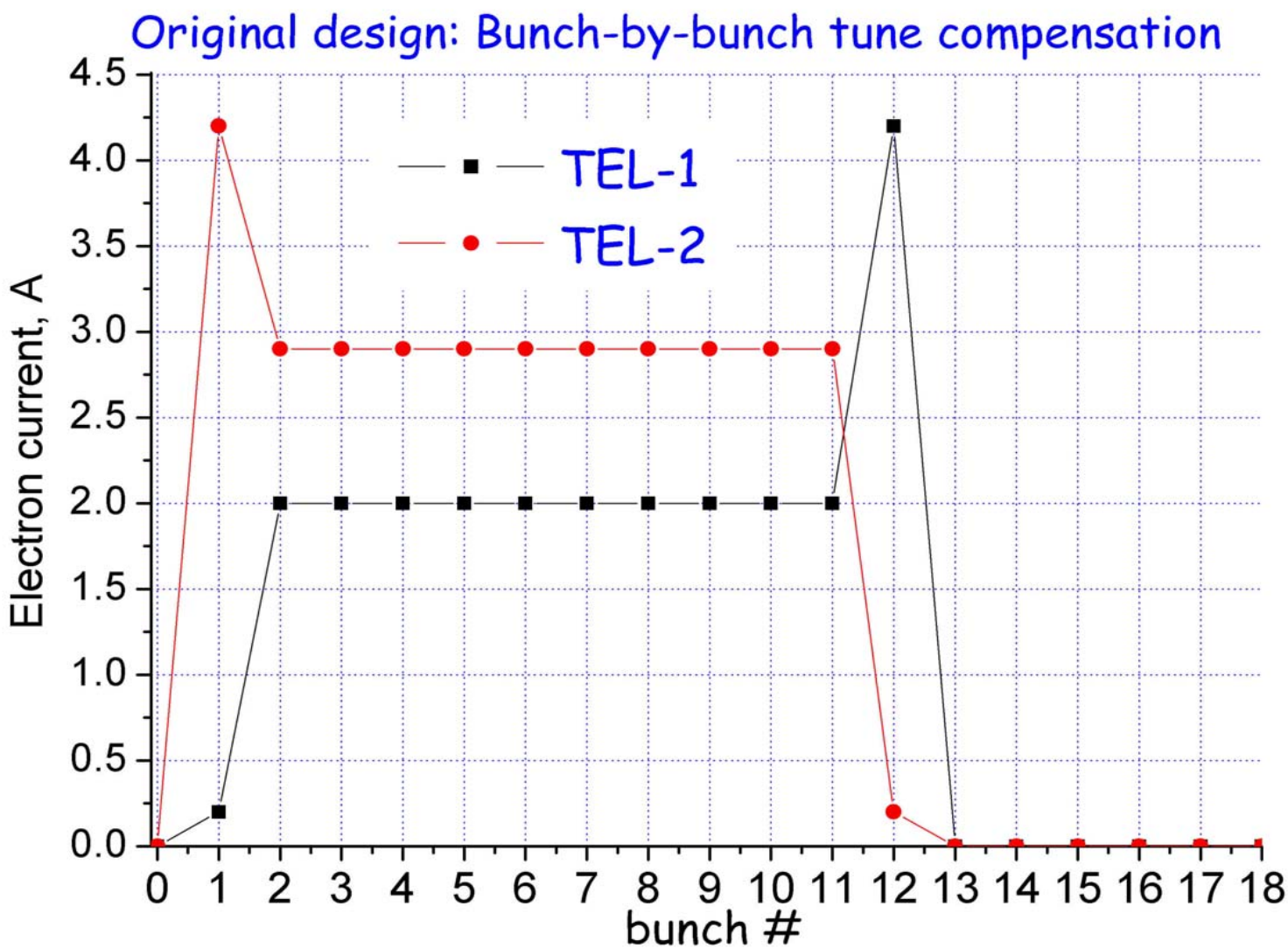
~1 ms

- *Calibrate BPMs X(f) in the tunnel with variable pulse generator -need access (missed that in Oct)*
- *Calibrate BPMs using longitudinal waves in e-beam excited by protons - need study time, to do*
- *Install new BPMs – already designed, need to be tested and installed next shutdown*

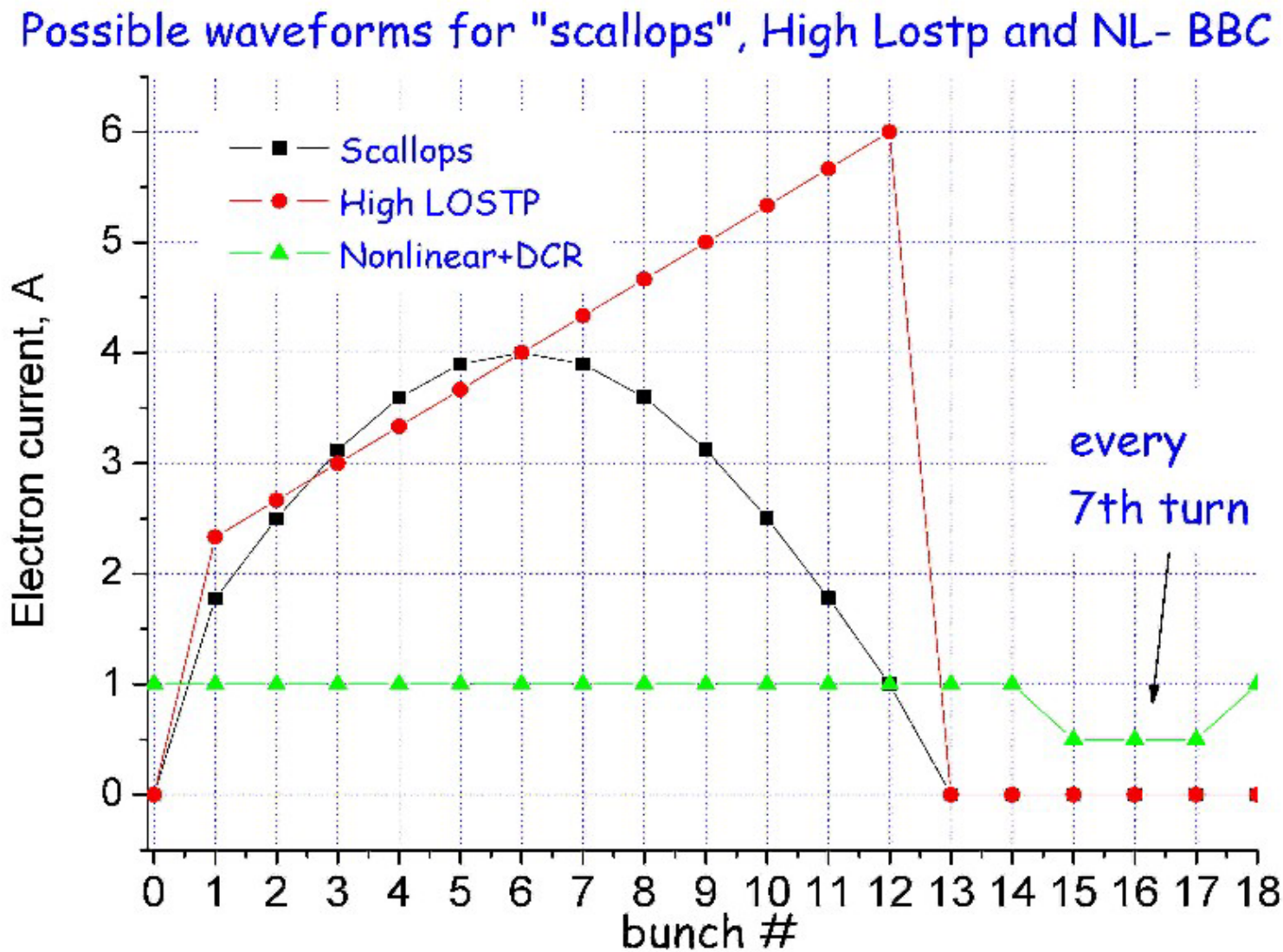
TEL2 @ A11 - radlevels under investigation



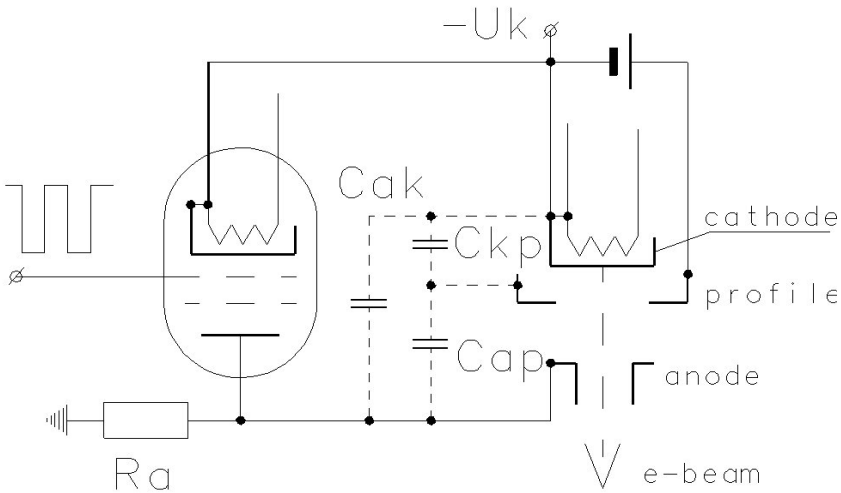
HV Output Waveform depends on what to BBC

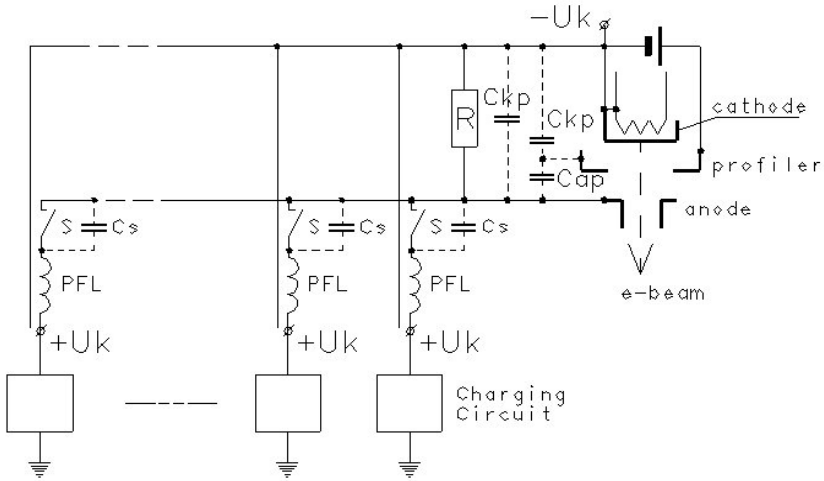


or like that… ?

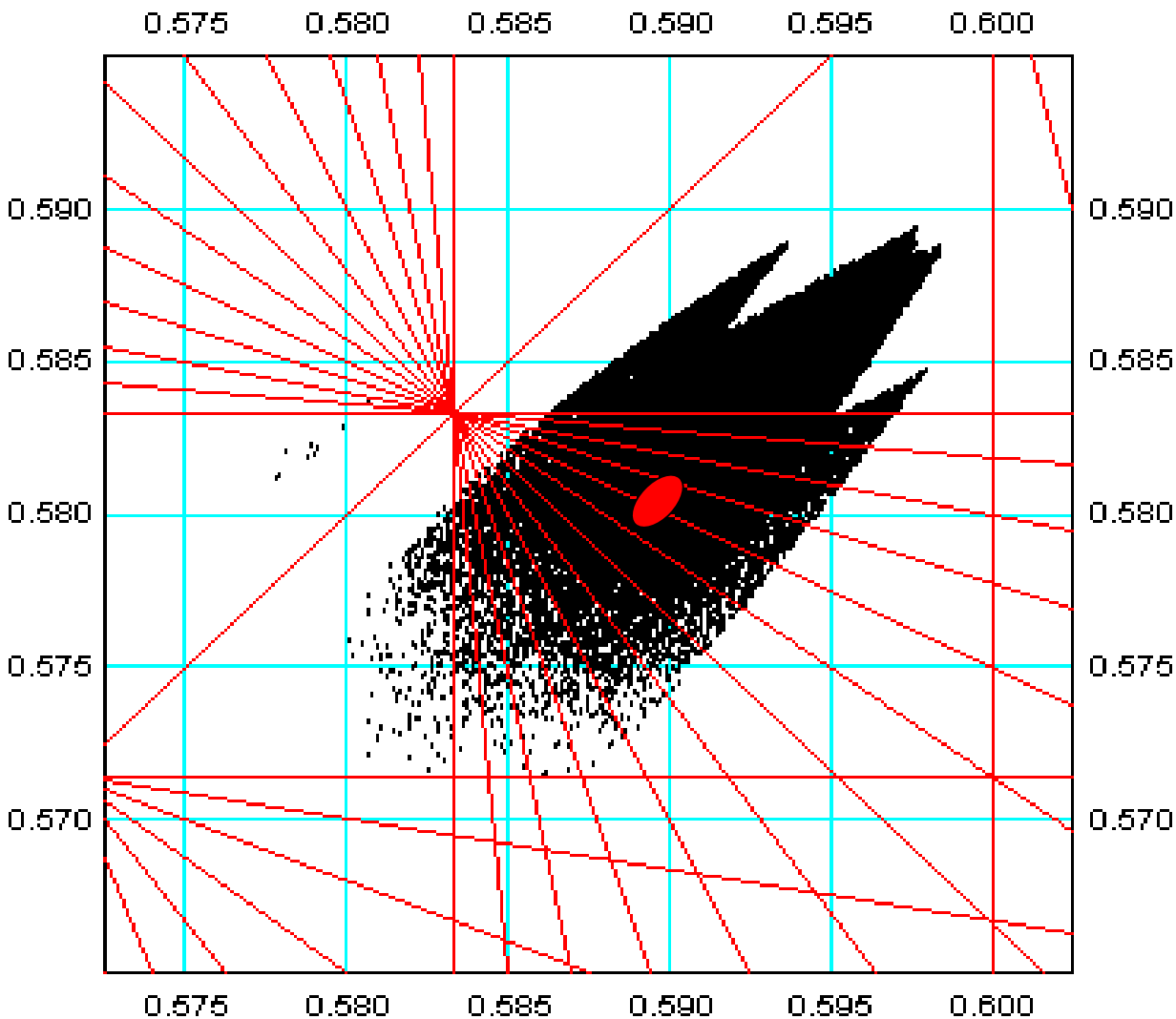

Possible waveforms for "scallops", High Lostp and NL- BBC
Scallops
High LOSTP
Nonlinear+DCR
every
7th turn
Electron current, A
bunch #
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Two approaches to 12-15 kV HV modulator





Pbar bunch tunes in collisions – Calc'd



P.Bagley

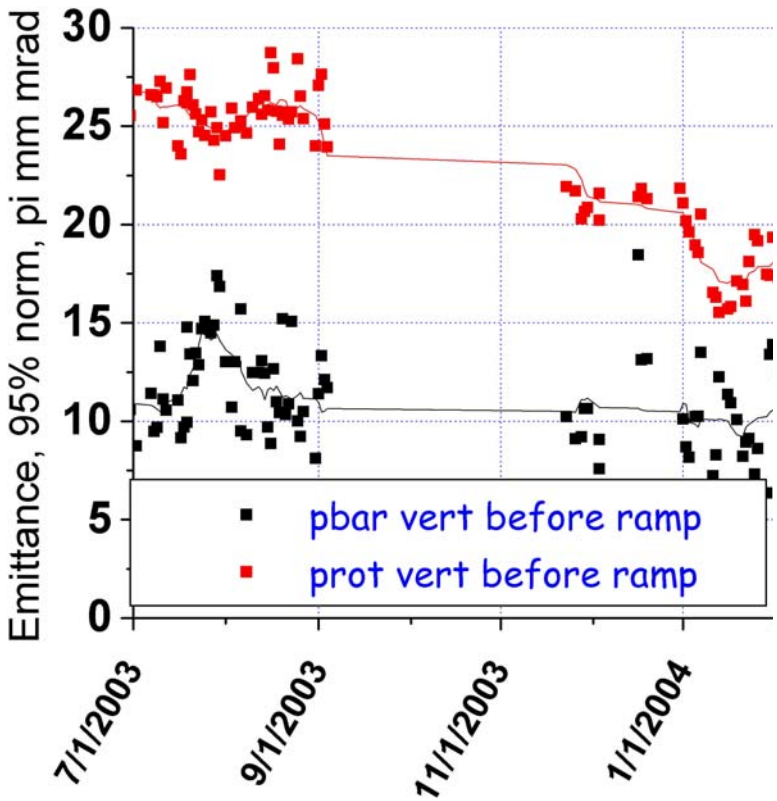
Yu.Alexahin

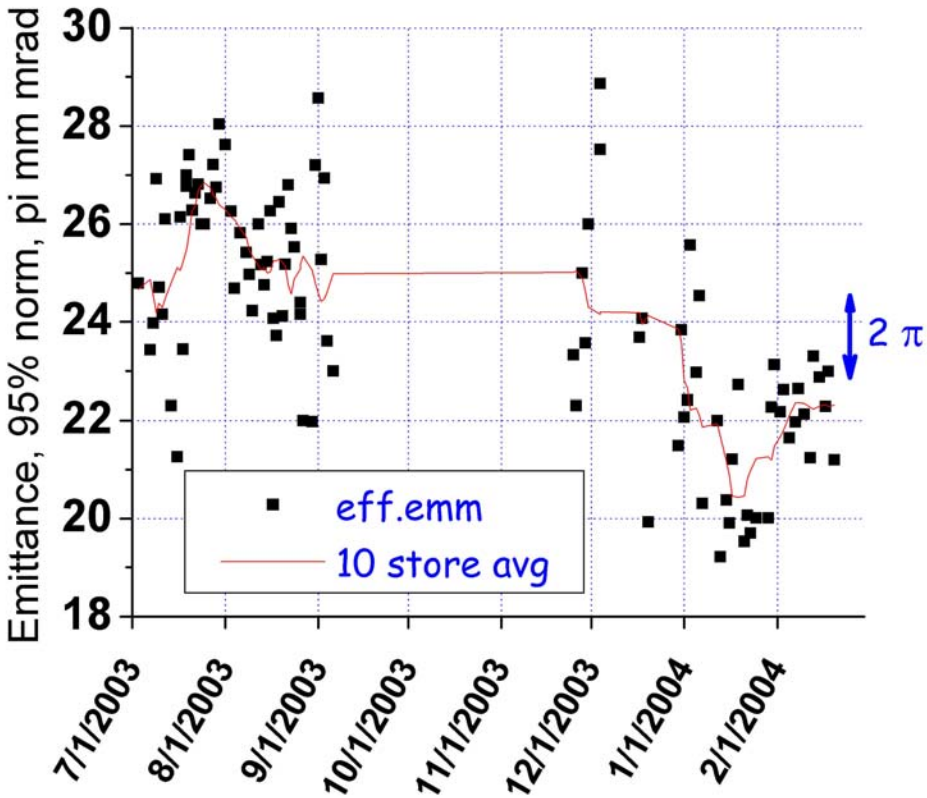
T.Sen

D.Shatilov

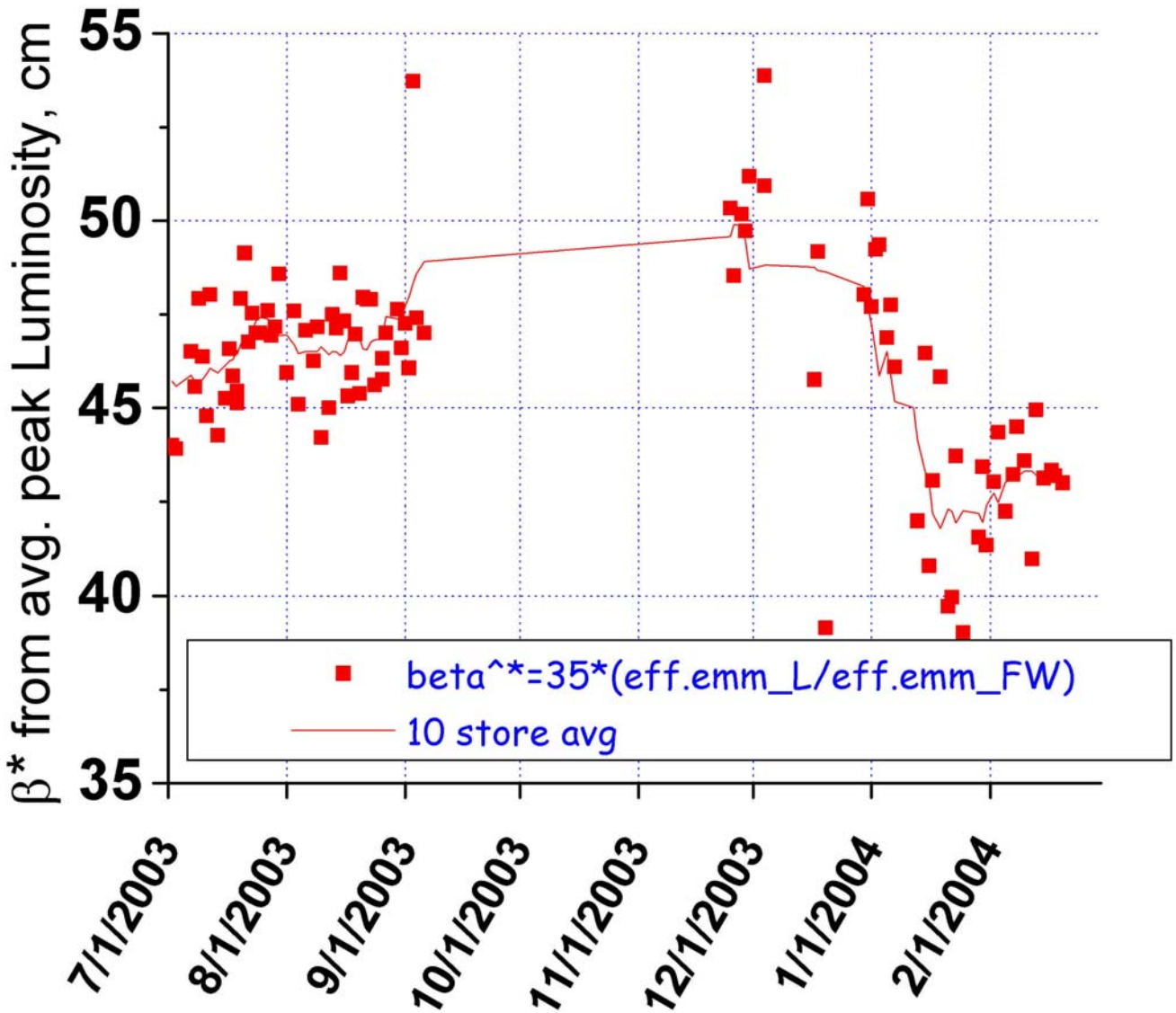
In 1996, P.Bagley found a good agreement between his calculations and measurements (though the lattice was somewhat different)

Backup slides 1

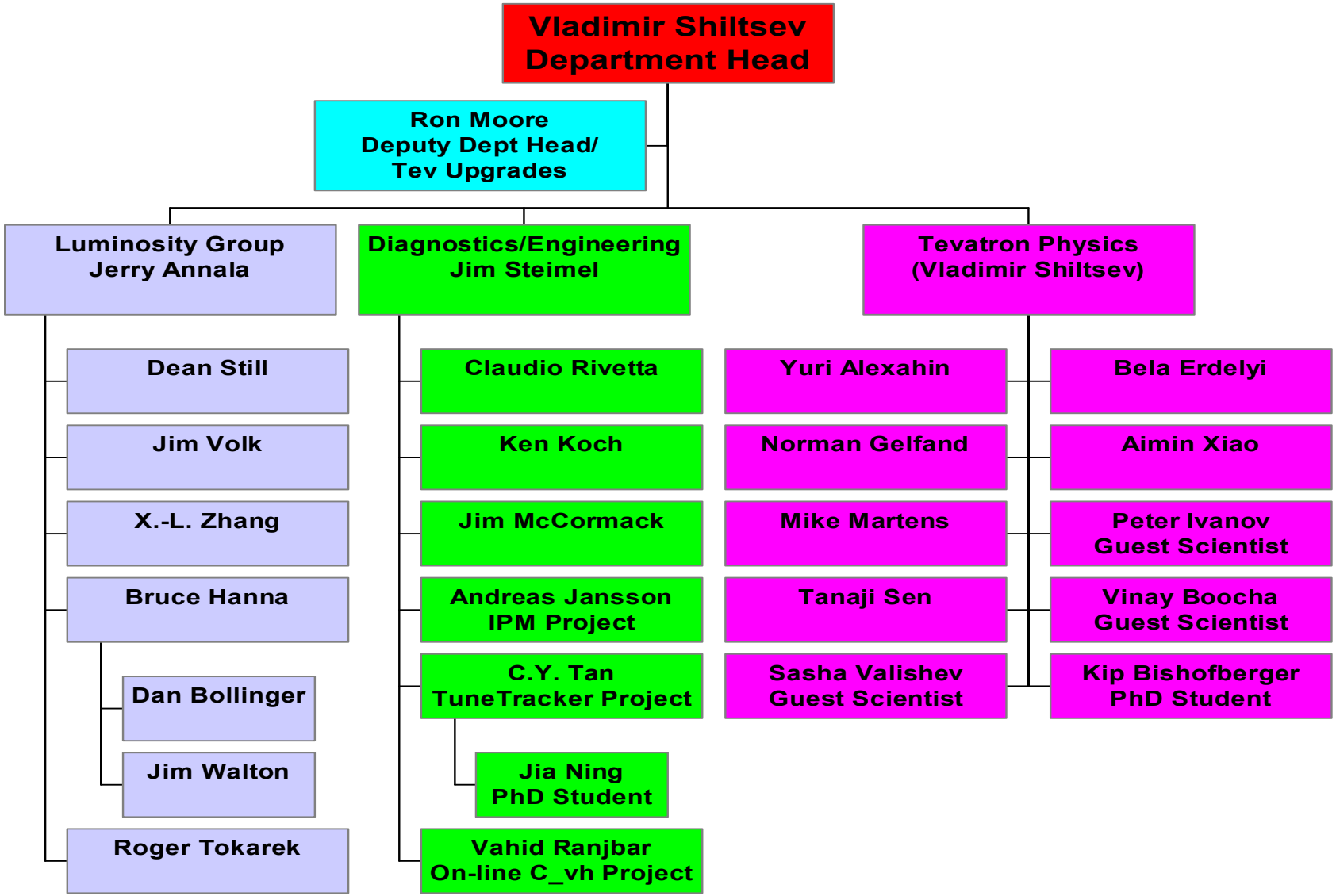




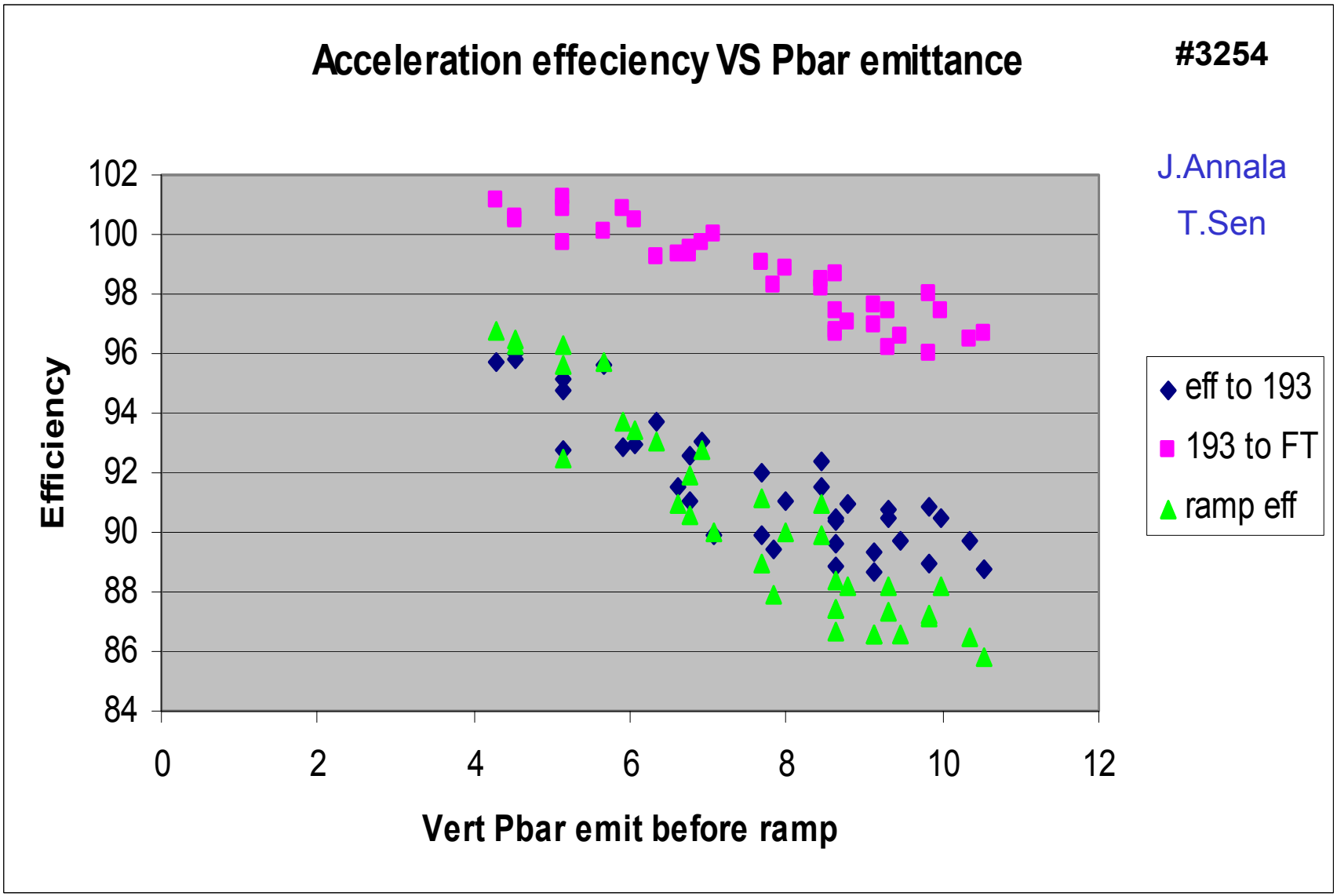
Backup slides 2



Tevatron Department Organization Chart



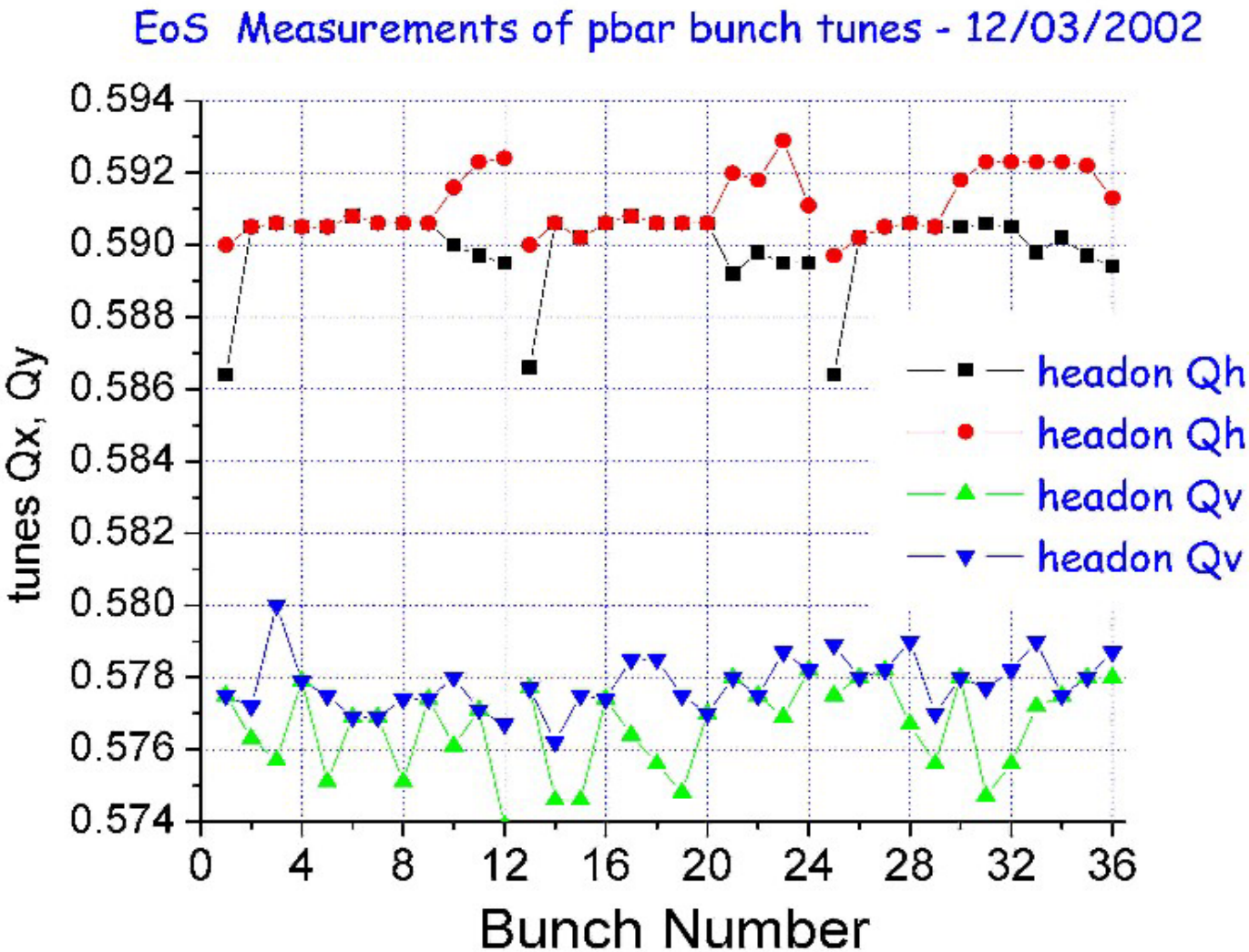
Pbar Loss on Ramp: Aperture+Emittance+Beam-Beam



History of TEV Tune Measurement Systems

- 21MHz Schottky
  - since last century, main tool nowdays
  - automatic tunefitter by Lebrun (2003) – operational, 15 sec
  - unsuccessful attempt to separate pbars – Huening, 2003
  - TevChrom application by Lebrun (2004) – to be tested
- 21MHz Schottky and bunch tickler:
  - 1996 Bagley successful measurements
  - 2002 Tan, Shiltsev, Zimmermann, Zhang used TEL and Damper
  - Significant emittance growth, losses
- Tan's Pbar Tunemeter
  - Built in 2001, in 2002 found "not good" by Sen and Tan
  - Fast emittance growth, beam loss… disassembled (parts for dampers)
- New 1.7GHz Schottky:
  - 2003 Pasquinelly&Co, soft (fit) by Jansson
  - pbar/p bunch tunes and chromaticity – still questions
  - New tunefitter under development by Lebrun (2004)
- Tan's "tunetracker" – great expectations, early 2004
- Vahid's "Head-tail" monitors – same, tunes+chroma+coupling

Tickler Experiment



CYTan

XLZhang

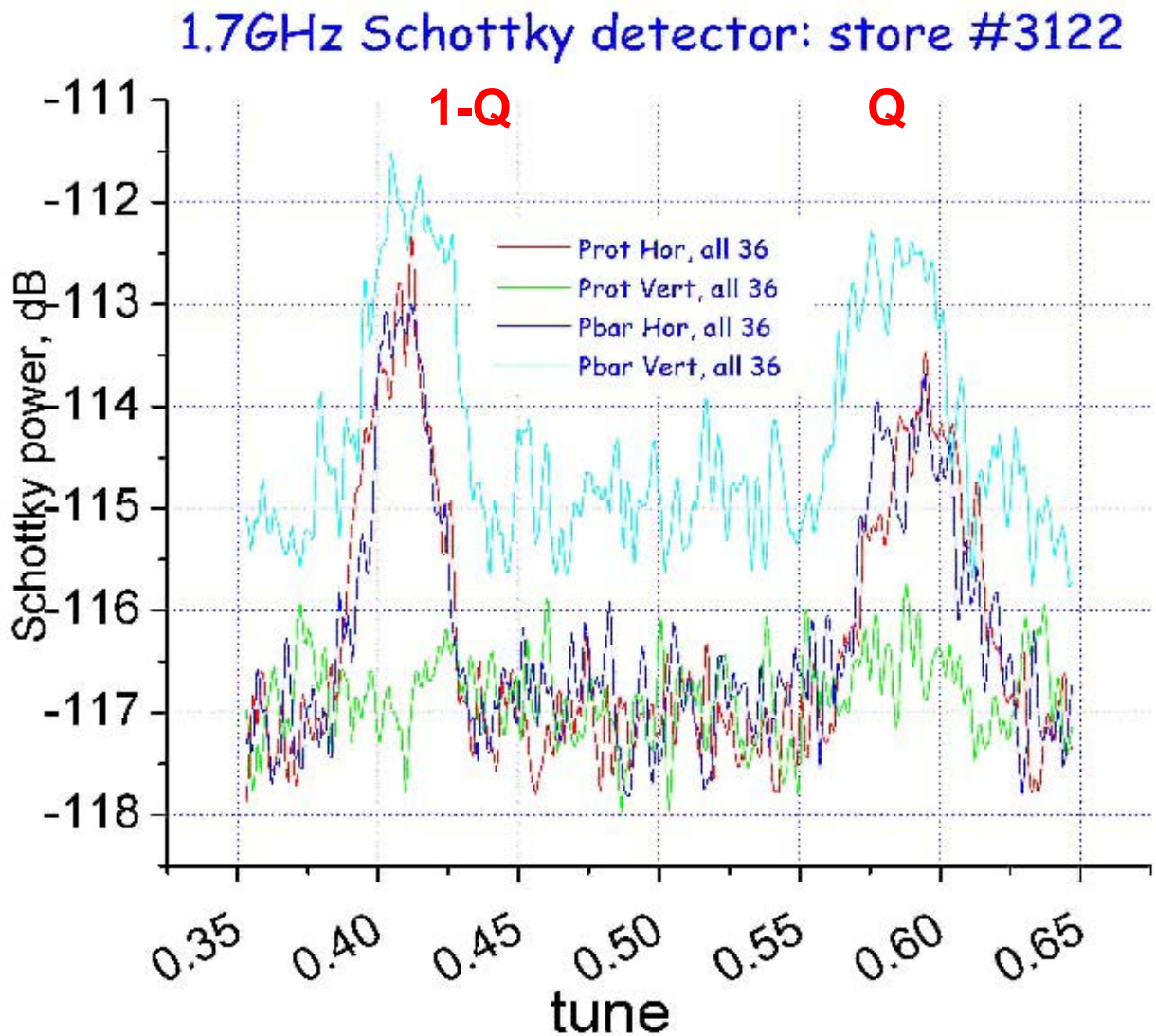
F.Zimmermann

V.Shiltsev

Either TEL or damper kicker were used as noise source

Tune Diagnostics for BBC

- *is needed to see tune changes of individual pbar and p bunches*
- *significant progress in software development for 1.7GHz Schottky monitors : W101 page (RP, AJ), "new tunefitter" (PL)*
- *works well when gated on all 36 bunches, repeatability is 0.0005-0.001 – enought for tuning*
- *not enough signal (S/N 1-2dB) when gated on individual pbar bunches or triples (e.g. 2,14,26)*
- *still can not make full sense of the spectra: tune and chromaticity distribution along bunch train is not what expected and previously seen*
- *alternative to 1.7GHz Schottky – "tunetracker" (CYTan), be available in spring (summer?) 2004*



Specs on Tune Measurement System (draft)

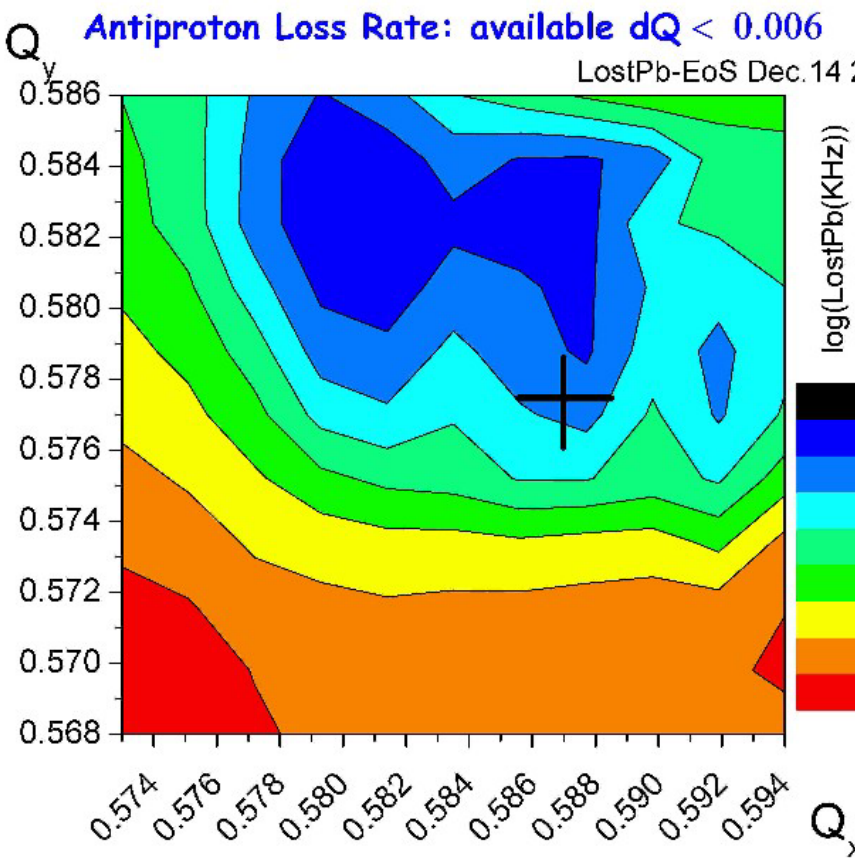
- accuracy of dQ §0.001 with typical intensities
- reports every 2 seconds or faster
- both protons and pbars
- for every bunch
- non-destructive, tolerable de/dt<0.2 p mm mrad/hr
- measures chromaticity - desirable
- measures coupling - desirable
- works for uncoalesced beam
- potential to be used for tune feedback df¥0.5Hz

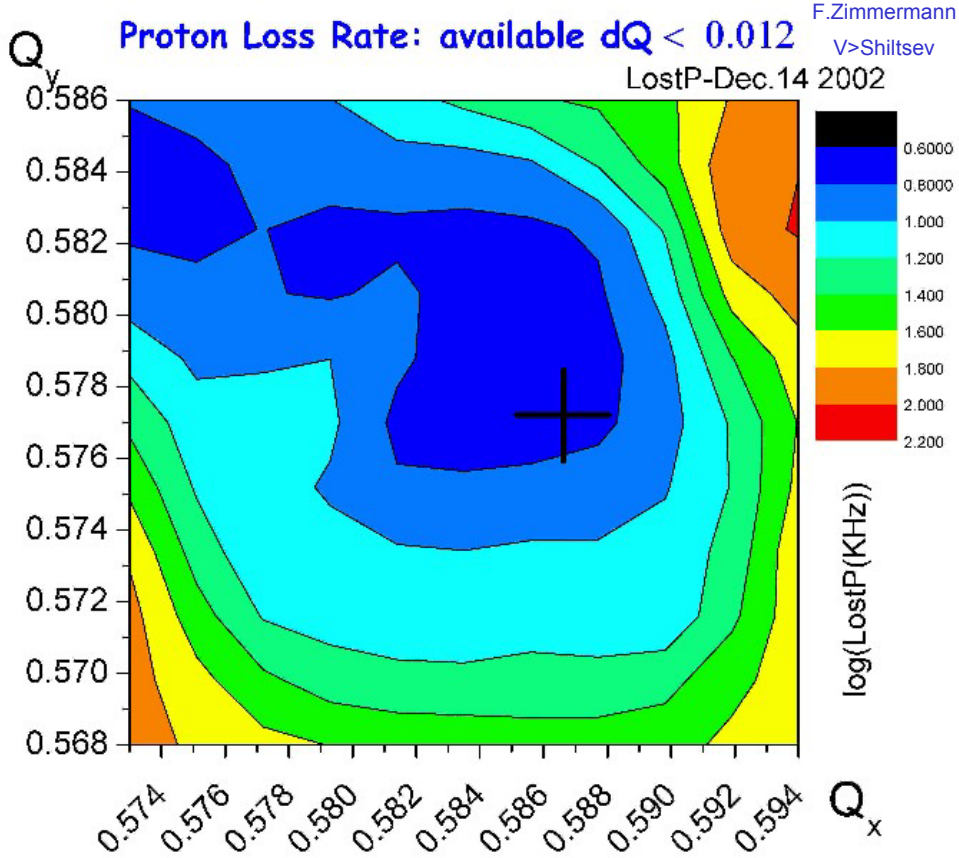
Longitudinal Beam Diagnostics Requirements

parameter	avg	indiv	accuracy	rate	comments	avail
Bunch length	yes	yes	1% (0.02ns)	1 sec	RMS, Gaussian	Yes
Bunch emittance	yes	yes	2% (0.08eVs)	1 sec	95% Alvin; rms	Yes
Inj.oscill dE,dj_{RF}	yes	yes	1MeV/1 deg	event	BLT	Yes
Centroid wrt RF	yes	yes	0.1ns	1 sec		Yes
Relative timing	yes	no	0.2ns	1 sec	Pbar wrt p, alarm	~ Yes
Oscillation ampl	yes	yes	0.1ns (2 deg)	1 sec	From dampers ?	No?
Oscill frequency	yes	no	2% (1e-5)	15sec	Tunefitter ?	No?
Bunch intensity	yes	yes	1% , 0.3e9	1 sec		Yes
Satellites intens	yes	yes	10%	15sec	WideGate/NG	~ Yes
Abort gap intens	yes	3 gaps	30% of 1e-9	3 sec		No?
Shape type	yes	no	???	1 sec	figure of merit ?	~ Yes
Tomography	no	select	5%	event		No
RF Phase noise	yes	cavity	10mrad	1 sec	J.Reid, 5-100 Hz	~ Yes

Beam-Beam Effects: Losses @ HEP

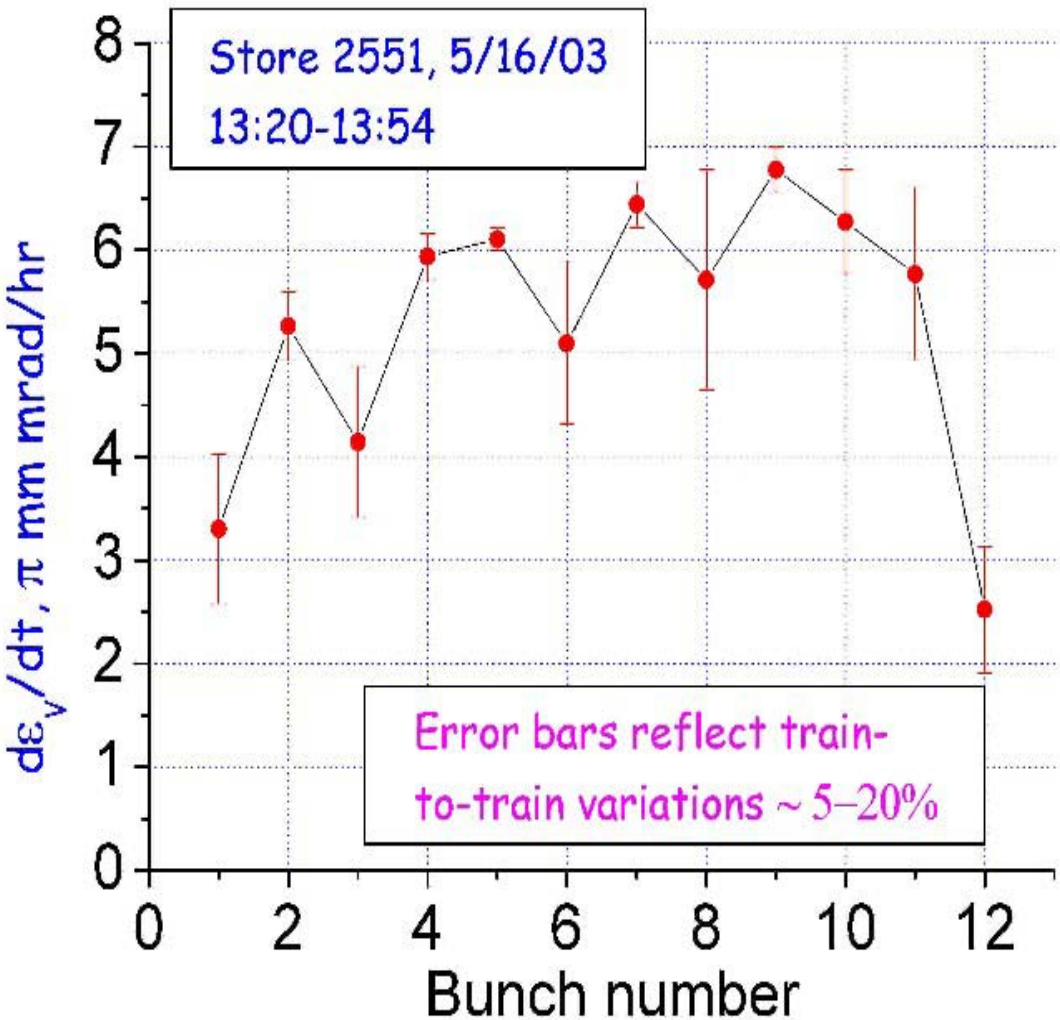
V.Zhang, M.Xiao
K.Bishoberger,
F.Zimmermann
V>Shiltsev





- At the beginning of the store available WP area is even smaller dQ < 0.004 … and this is at N_p=180e9
- No available tune space expected above 240e9 → that's where we are now

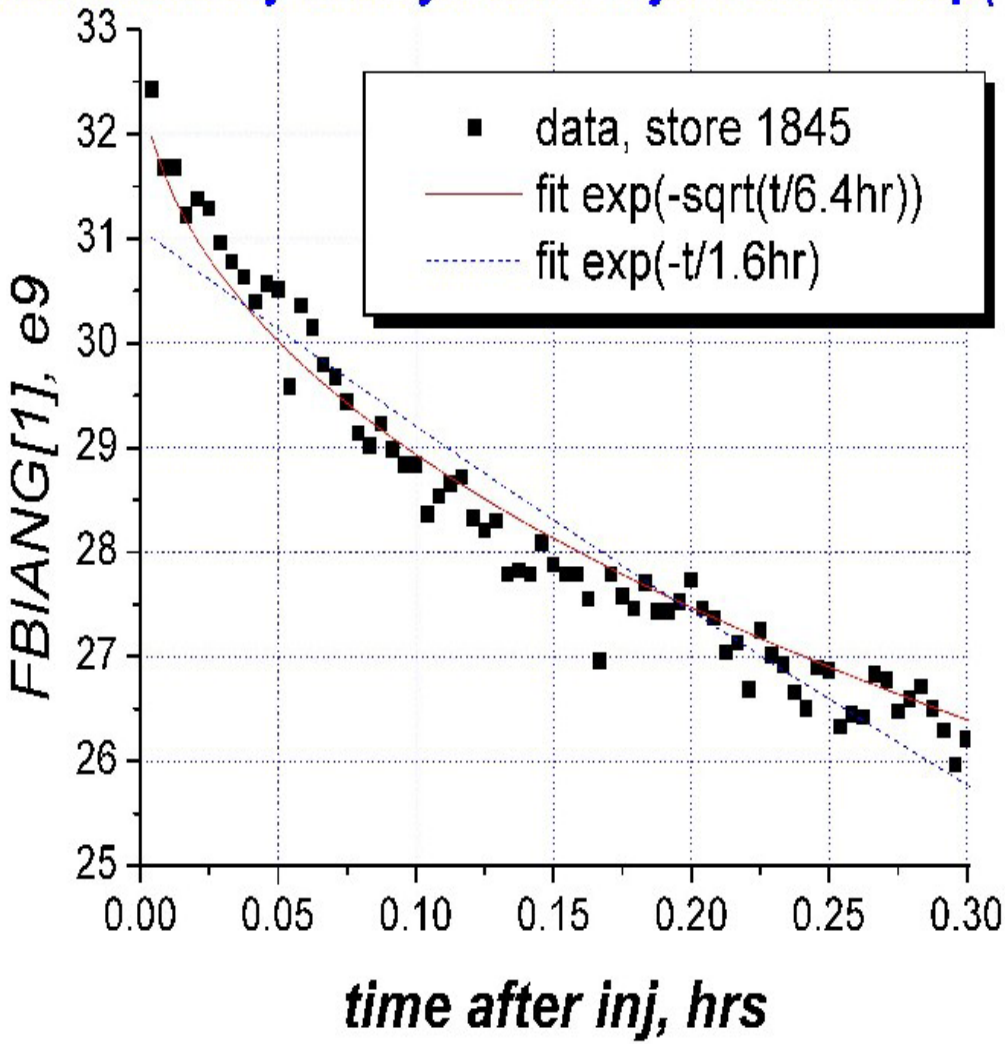
Pbar Vert Emittance Growth Rate



- "Scallops" is beam-beam phenomena, they started to occur after Nprotons exceeded 180e9/bunch
- "Scallops" do not take place in every store even with N_p >180e9/bunch "Scallops" occur in both planes, but often more prominent in vertical
- "Scallops" seem to be dependent on tunes , e.g. vertical tune change – 0.002 can significantly reduce scallops
- Small "scallops" are seen in protons
- Scallops are the same in all three trains of bunches (variations <20%)

Beam-Beam @ Injection: Shaving

Pbar intensity decays after injection as $\exp(-t^{0.5})$

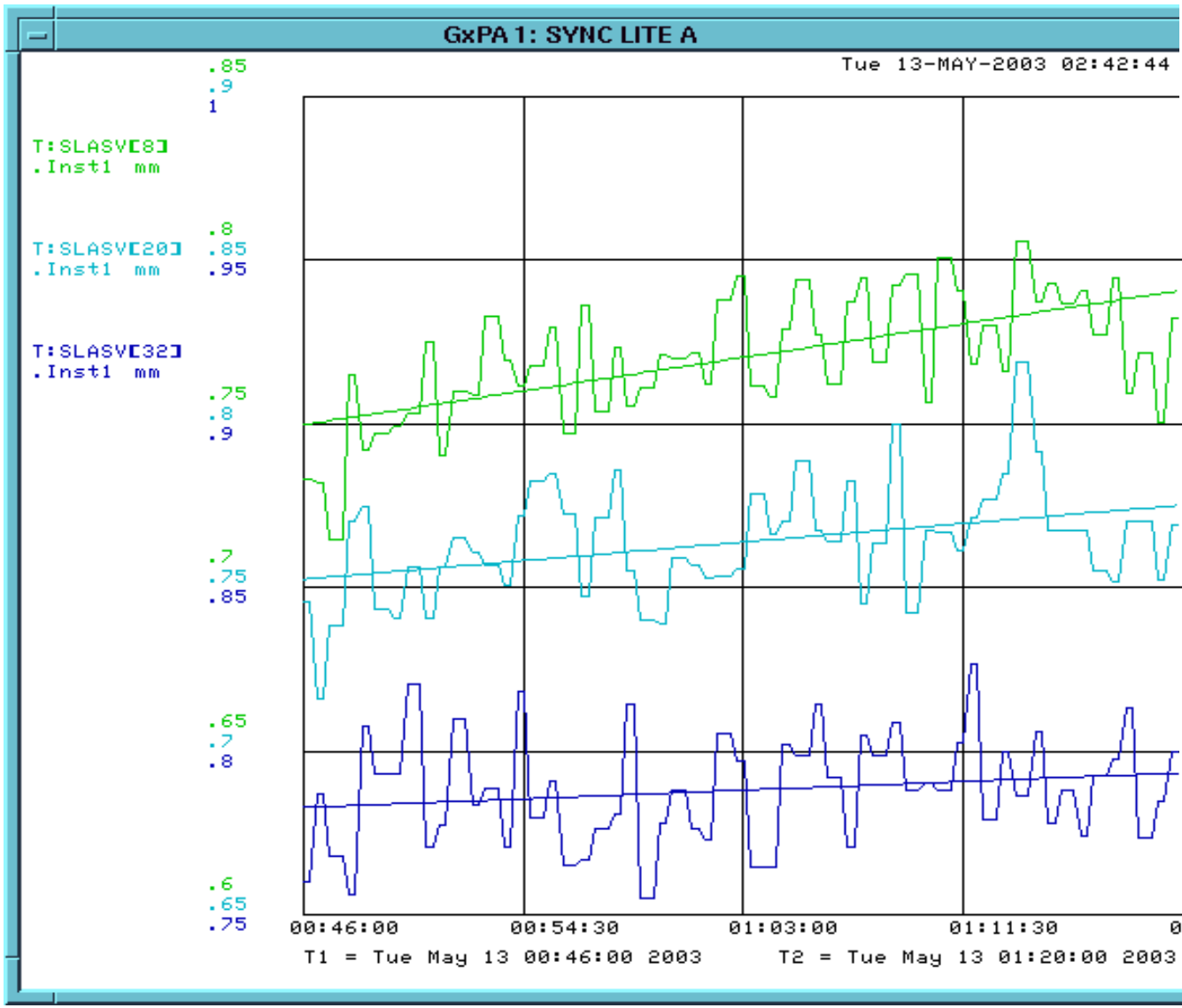


- dN_pbar scales approx. as
  - **Sqrt(time)**
  - **Chromaticity^*a*, *a*=1..2**
  - **N_protons^*b*, *b*=0.5…1 (?)**

Also

- **Larger for larger emittance**
- **Larger for larger dp/p**

TEL Suppresses Pbar V-Size Growth: ½ hr in store



Store #2540

May 12, '03

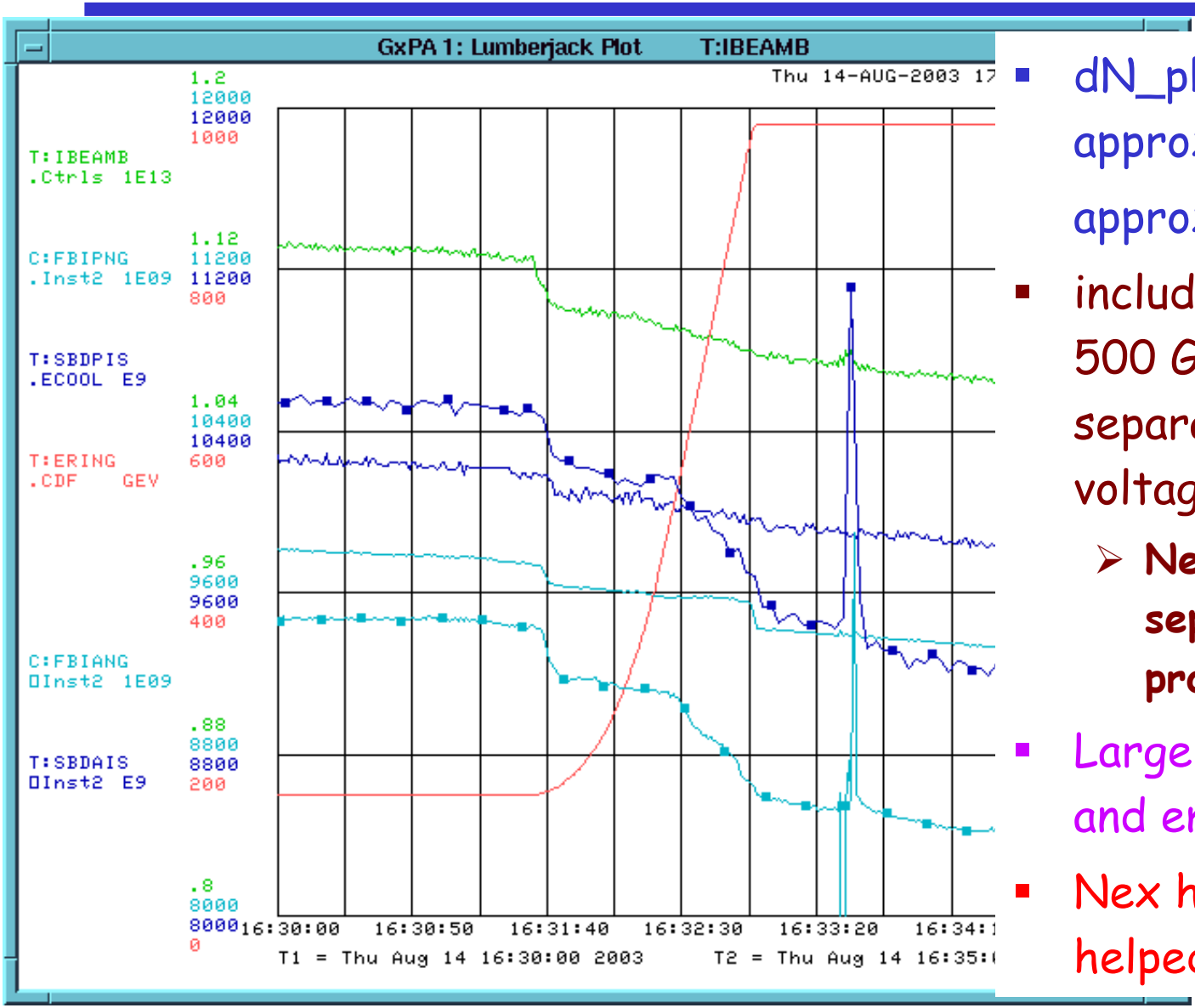
A9 : 4.1 p mm mrad/hr

A21 : 2.2 p mm mrad/hr

A33 : 1 p mm mrad/hr

-TEL on it

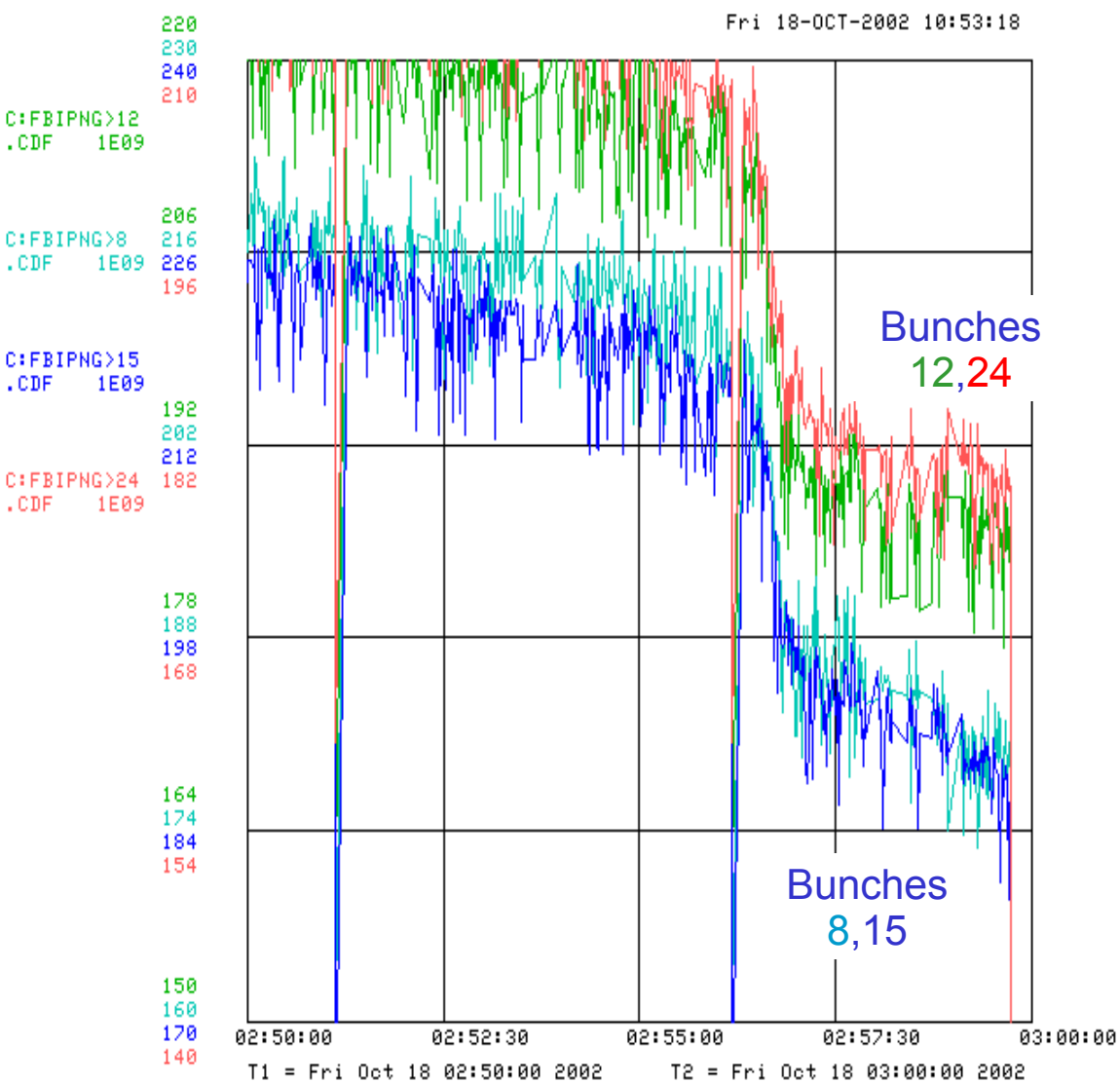
Pbar loss on ramp on Ramp



- dN_pbar on ramp approx 8%

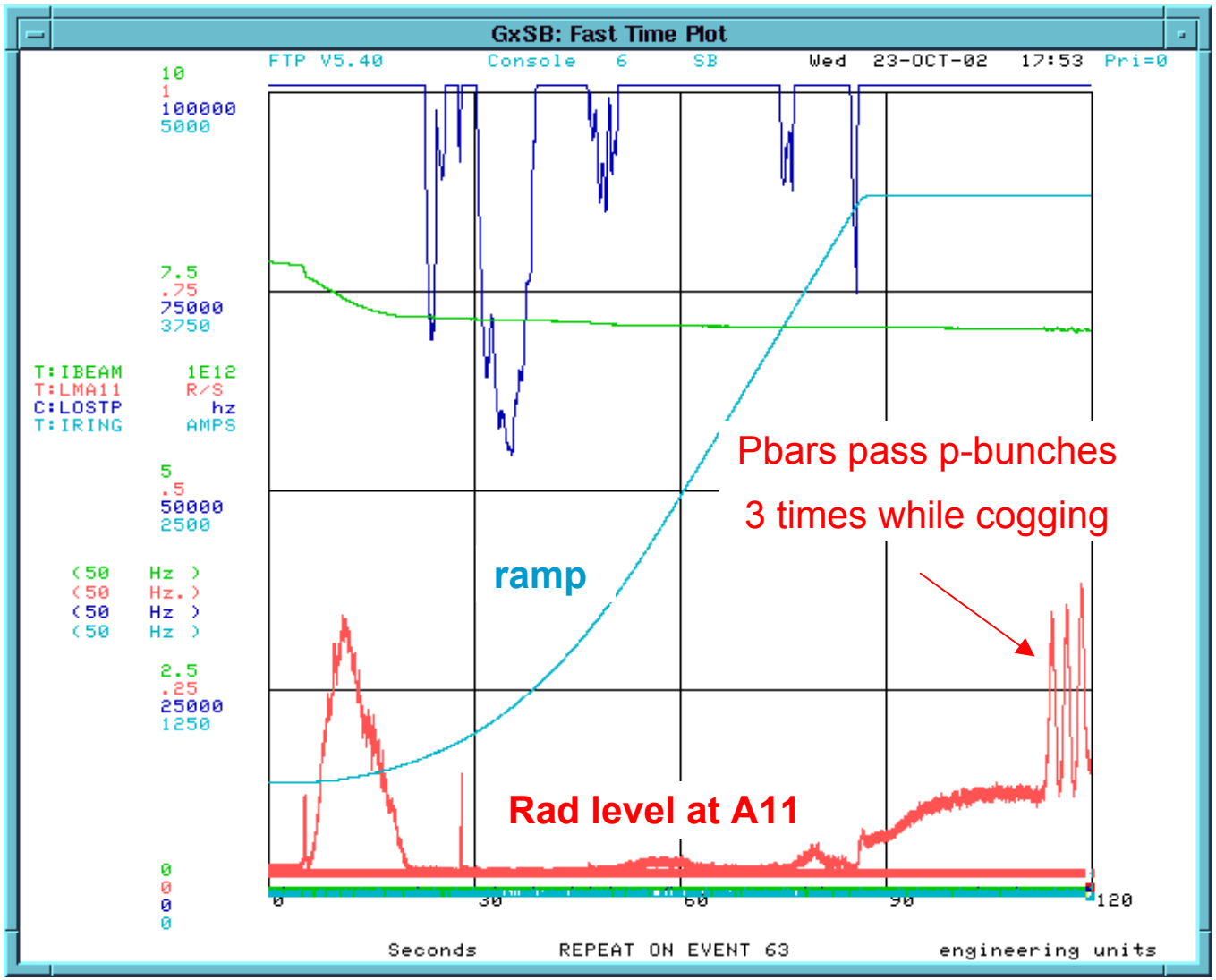
  approx 2% no p's
- including 5-6% above 500 GeV where separators reach max voltage
  - **Need $2^{1/2}$ stronger separators (Run II project)**
- Larger for larger dp/p and emittances
- Nex helix (Sep'03) helped a bit (1-2%)

Beam-Beam Effects in Protons - 2002



- See losses in squeeze in store #1868
  - Losses of bunches #12,24,36 were small (1e9/min)
  - All other bunches lost intensity very fast (4e9/min)
  - That resulted in quench at A11

Proton Losses While Cogging Pbars



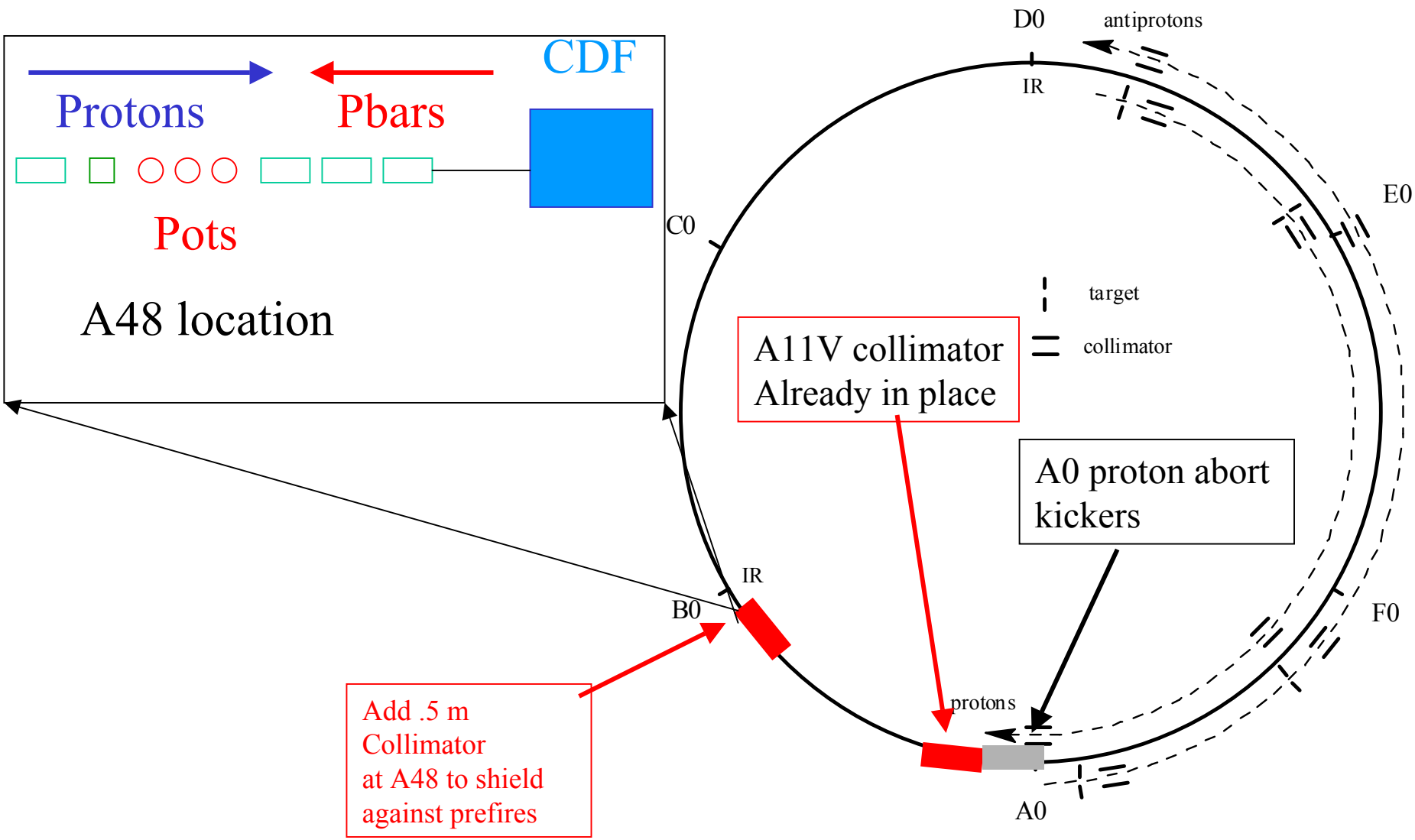
16 house Quench Dec, 5, 2003

Dean Still
Fermilab Tevatron Department
12/12/2003

Acknowledgments

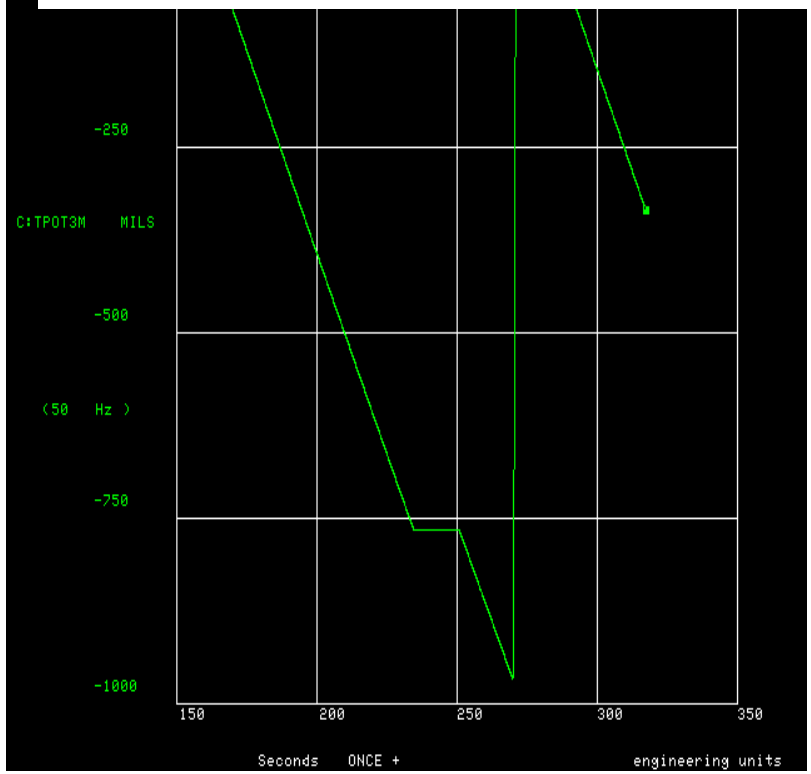
The data, analysis and conclusions presented come from many people and departments in order to carefully and accurately describe the events of the 16 house quench on December 5, 2003. I would like to thank and acknowledge all those who contributed. The list is of personnel is long but these are the main contributors: J. Annala, B. Hanna, T. Johnson, D. Wolff, B. Flora, N. Mohkov, S. Drozhdin, B. Hendricks and Mechanical support, CDF pot personnel.

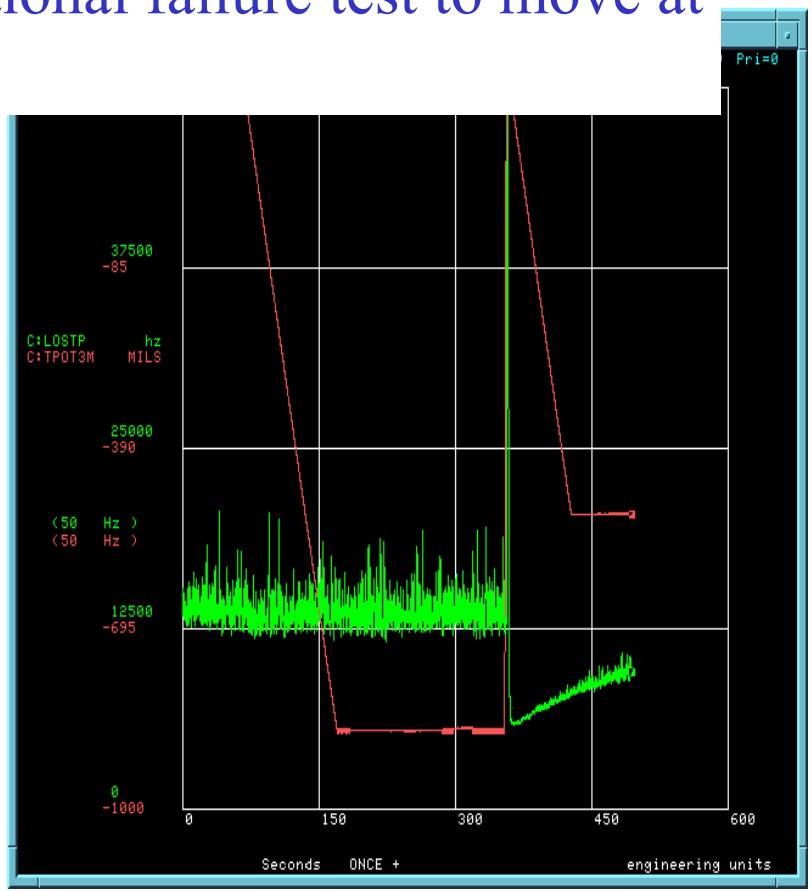
Addition of A48 Collimator to Protect against A0 abort kicker prefires



CDF Pot 3 Position

Pots have been found in additional failure test to move at 1200mils/sec.



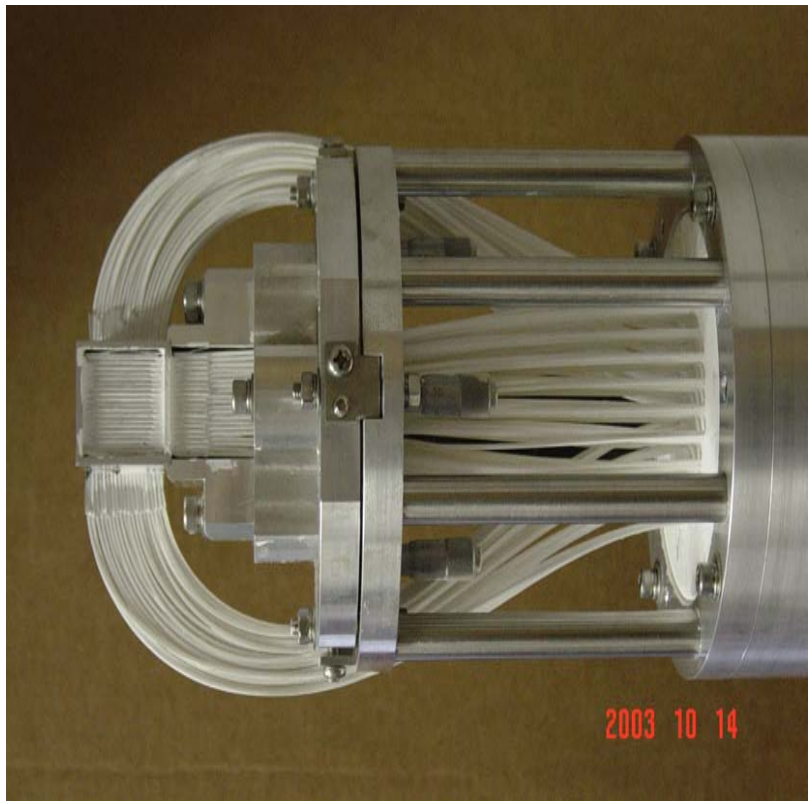


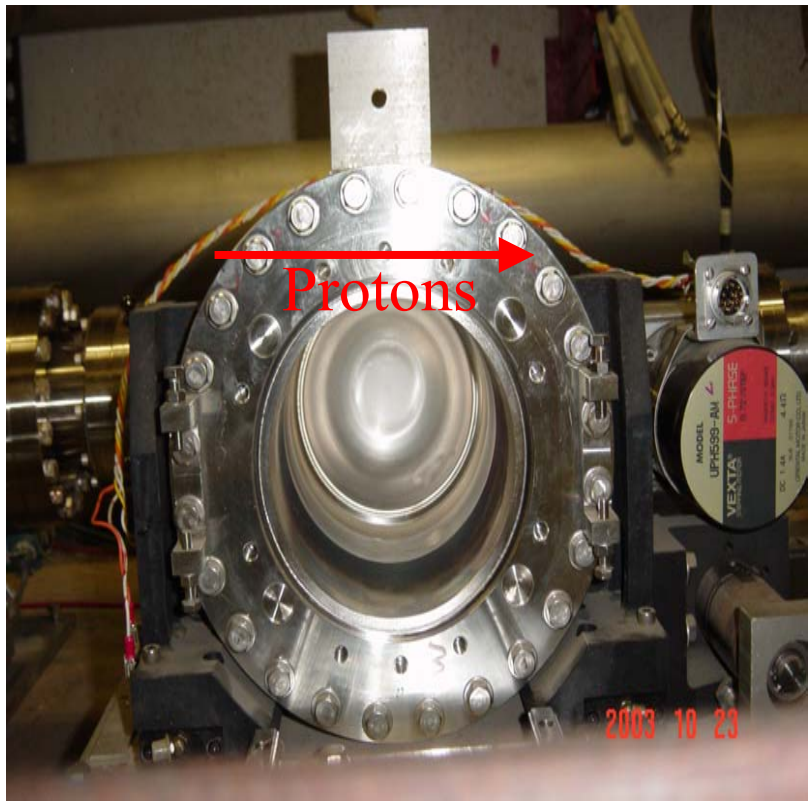
Reproduced after quench
On Dec 5, 2003

Similar incident on
~ 3/17/03

Pot 3 Pictures

Pots did NOT sustain any damage: Can conclude that they did not hit primary beam.

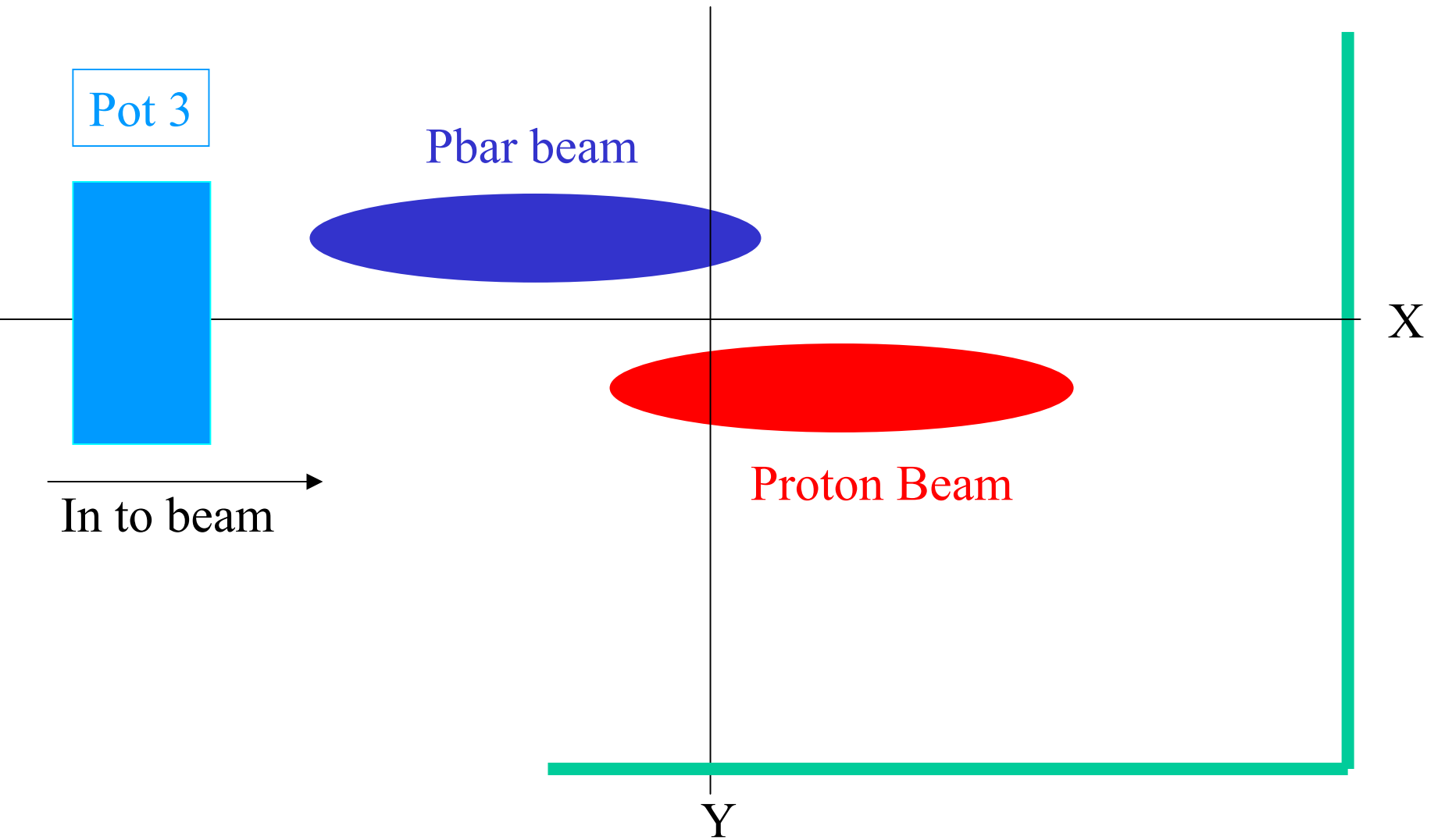




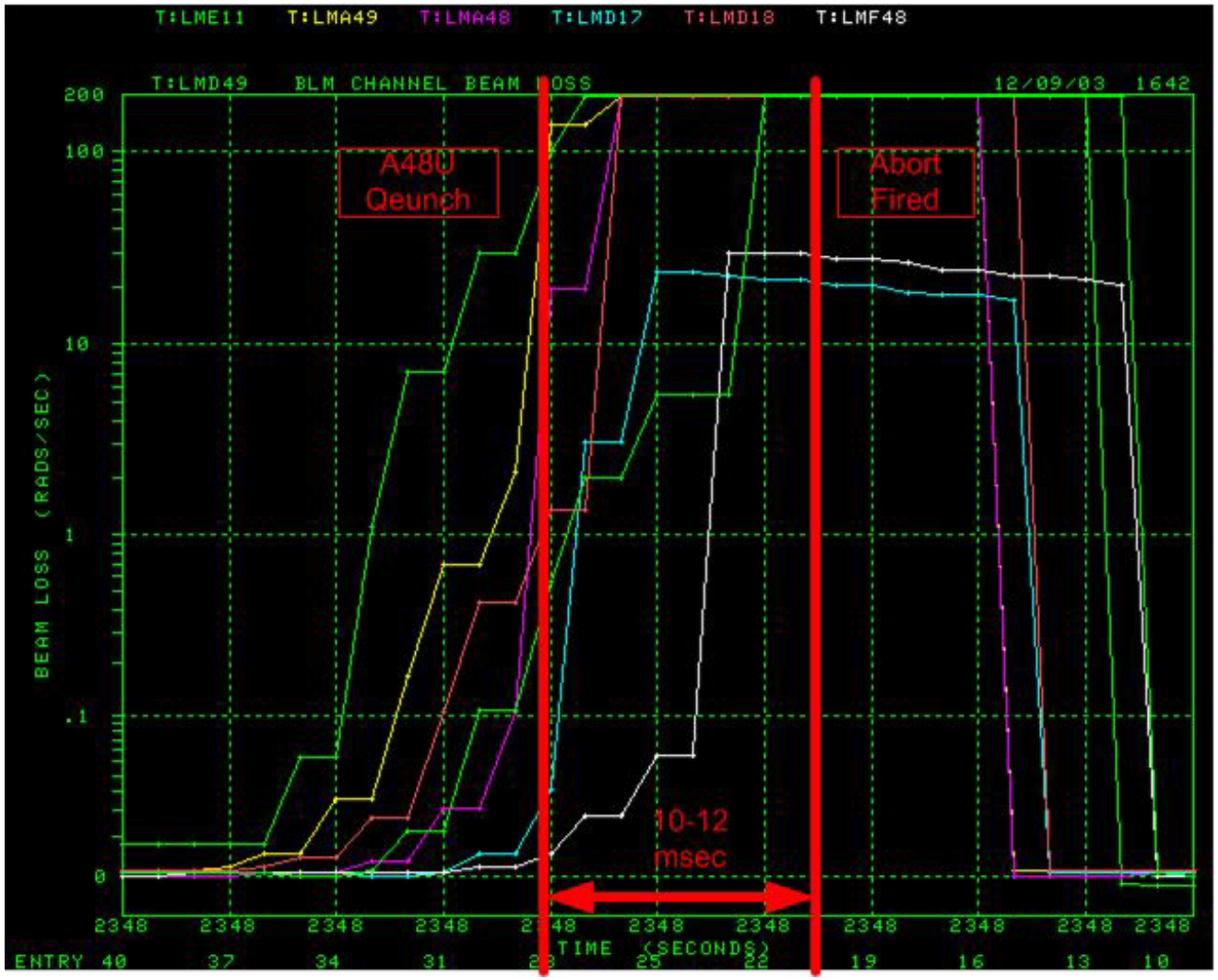
These are pictures before Dec 5,2003

(Courtesy CDF Pot Personnel)

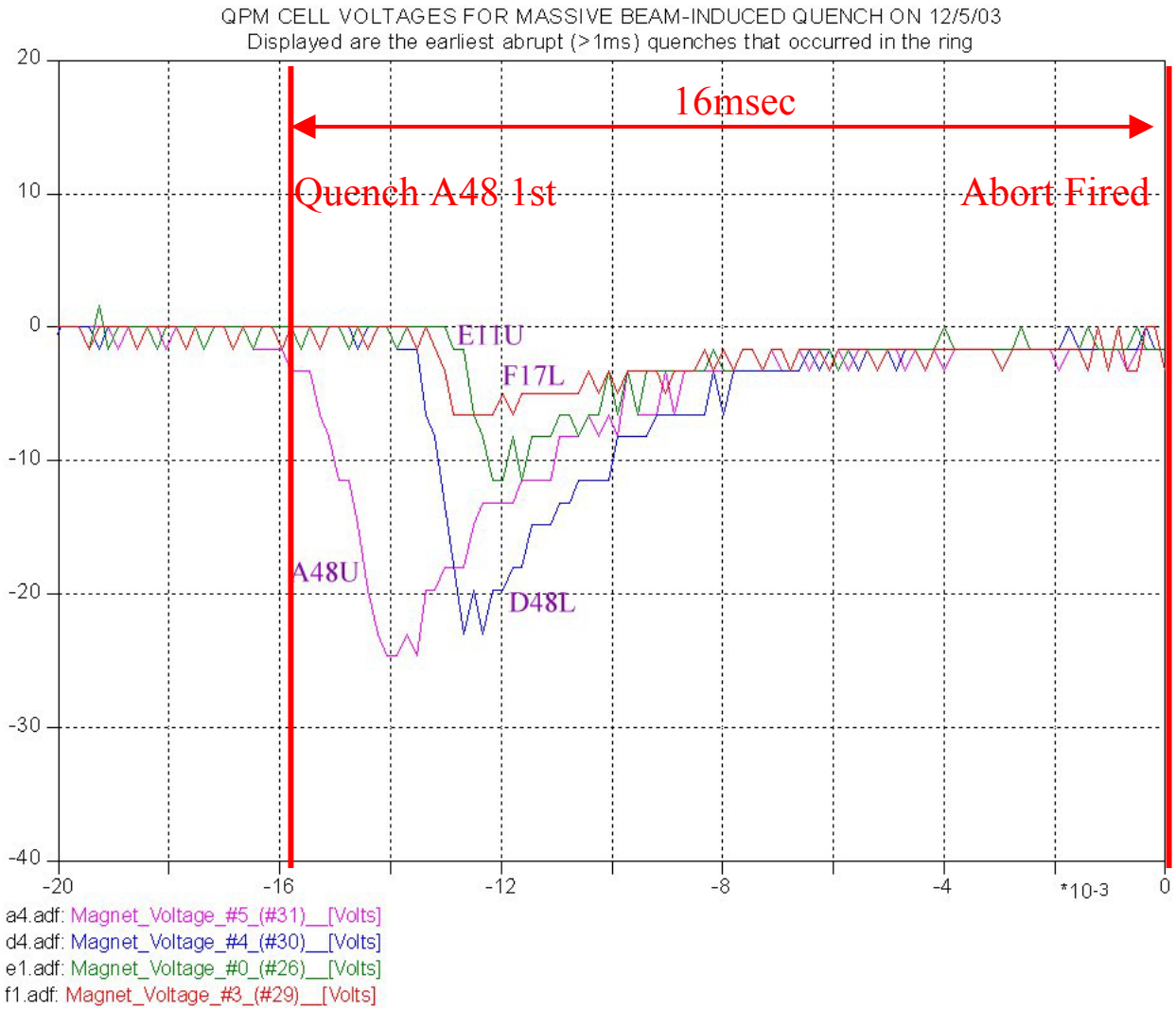
A48 Location



T44 loss of Quench



QPM Over Sample Buffer



Quenched 5 dipoles at A48; DI/Dt = .5A/msec

Development of Quench:

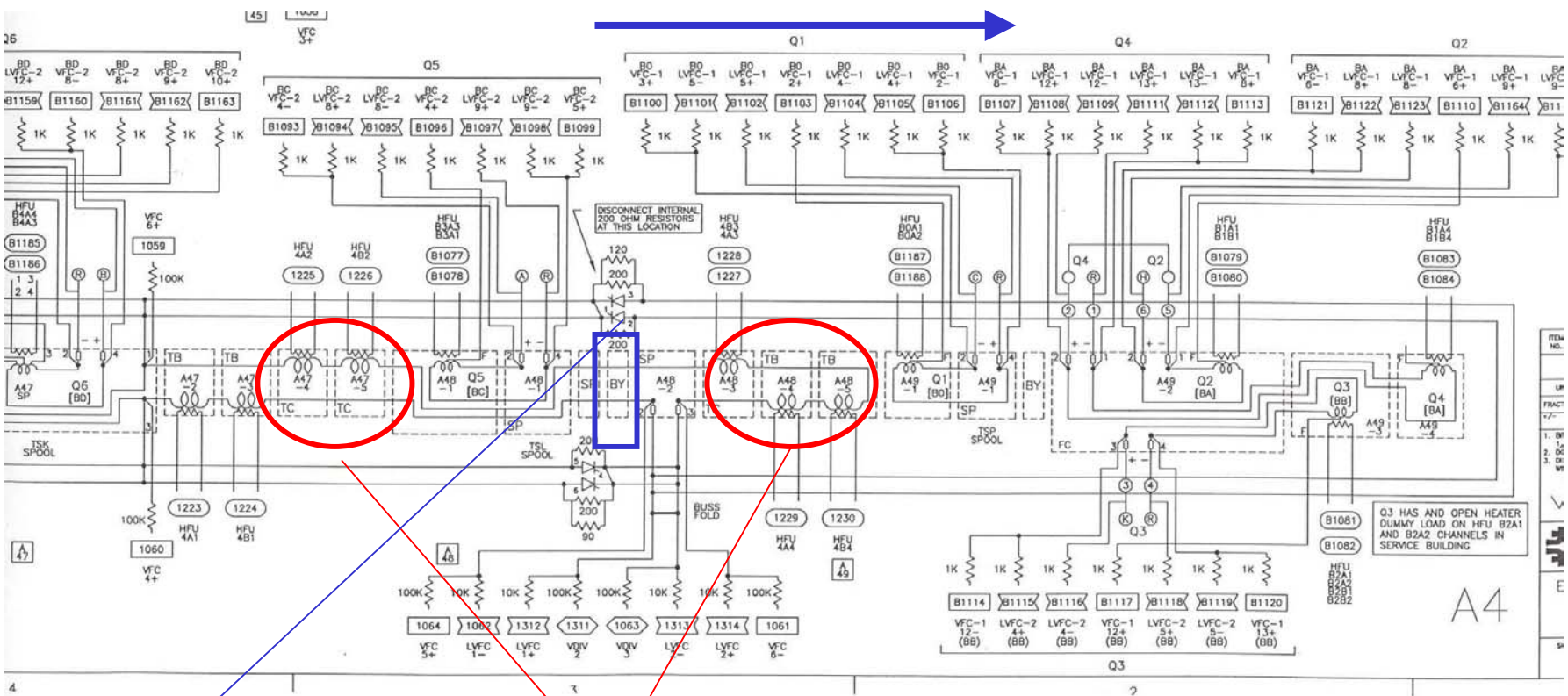
A48U 16msec
D48L 13.5msec
F17L 13msec
E11U 12.5 msec

Before abort

(Courtesy D. Wolff & EE Support)

A48 Bus Drawing

Protons



Pot 3 location

A48U quenching dipoles: Looses current At .5A/msec

Displacement at D49 Target due to A48 Dipole Quench

location	betaX	phase advance	phase from col	radians	Displacement at collimator in mm
A47-4	61	20.3	10.933	68.69406	-0.026792767
A47-5	95	20.313	10.92	68.61238	-0.039417491
A48-3	215	20.324	10.909	68.54327	-0.066606399
A48-4	335	20.327	10.906	68.52442	-0.085562357
A48-5	480	20.33	10.903	68.50557	-0.105280213
D49 col	87	10.651	20.582	129.3205	-0.038580551
					-0.362239778

Using Dan Wolff's estimate that the current was coming out of A48U at a rate of 1/2 amp/msec.

A Dipole give 8 mrad of bend at 4350 amps, so we get 1.8 mrad of bend per amp.

The dipoles in the half cell are losing .9 mrad of kick per msec.

The displacement at the collimator is given by the sum of

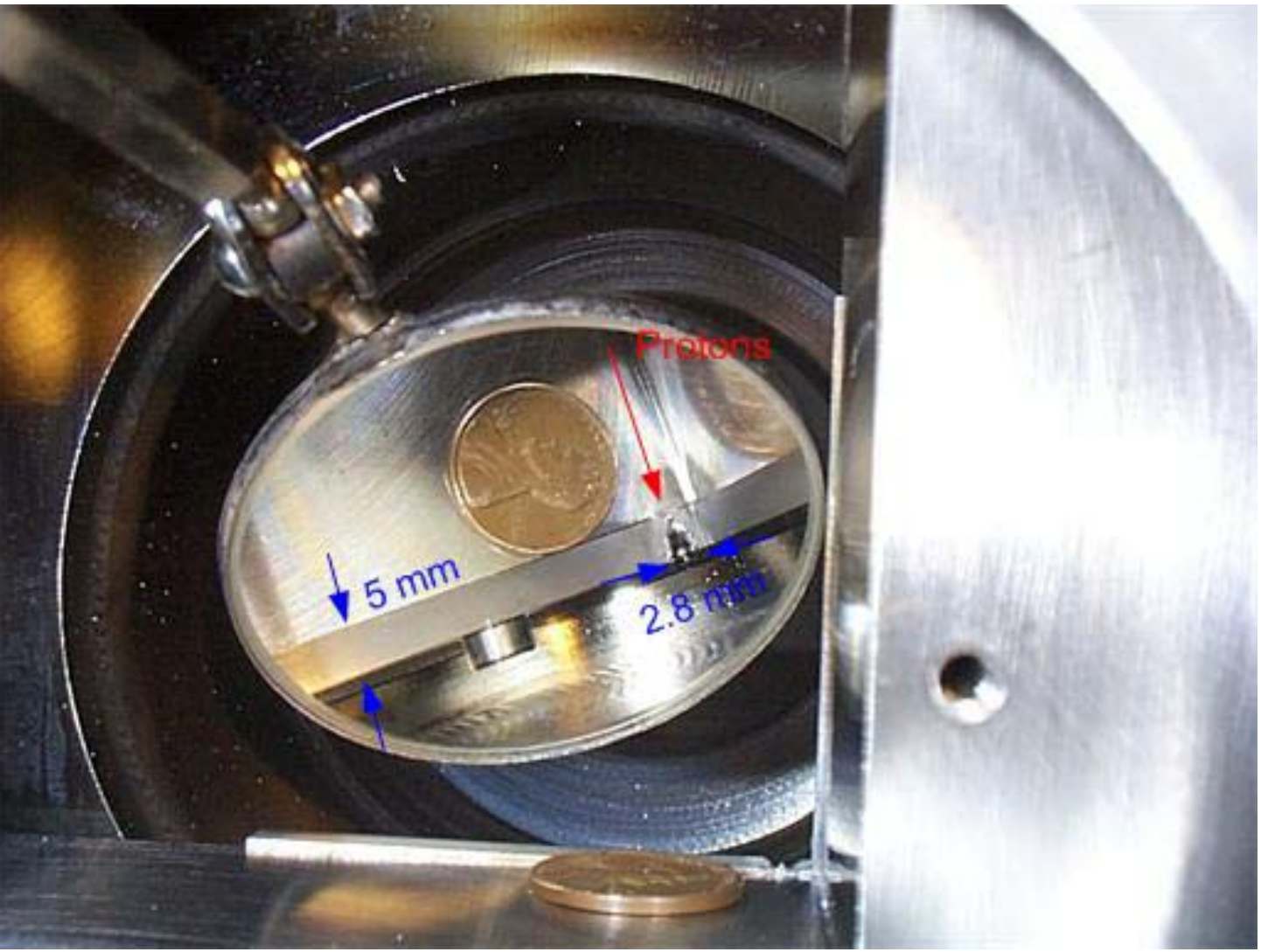
Dx = q sqrt(β1b2)sin(Y2-Y1)

Where location 2 is the collimator, and location 1 is each of the dipoles in cell A48U

Dx @ D49(mm)	time
-0.36	1 msec
-0.72	2 msec
-1.09	3 msec
-1.45	4 msec
-1.81	5 msec
-2.17	6 msec
-2.54	7 msec
-2.90	8 msec
-3.26	9 msec

(Courtesy J. Annala Tevatron Dept.)

Damage to D49 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

Simulation of losses on collimators

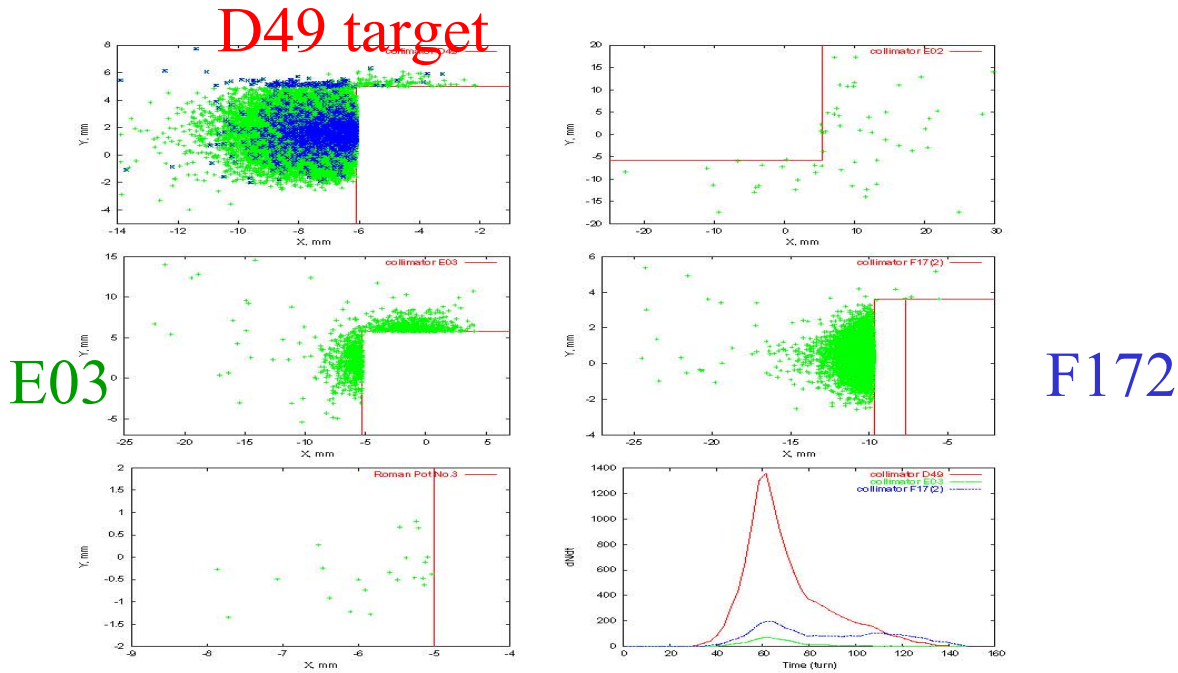
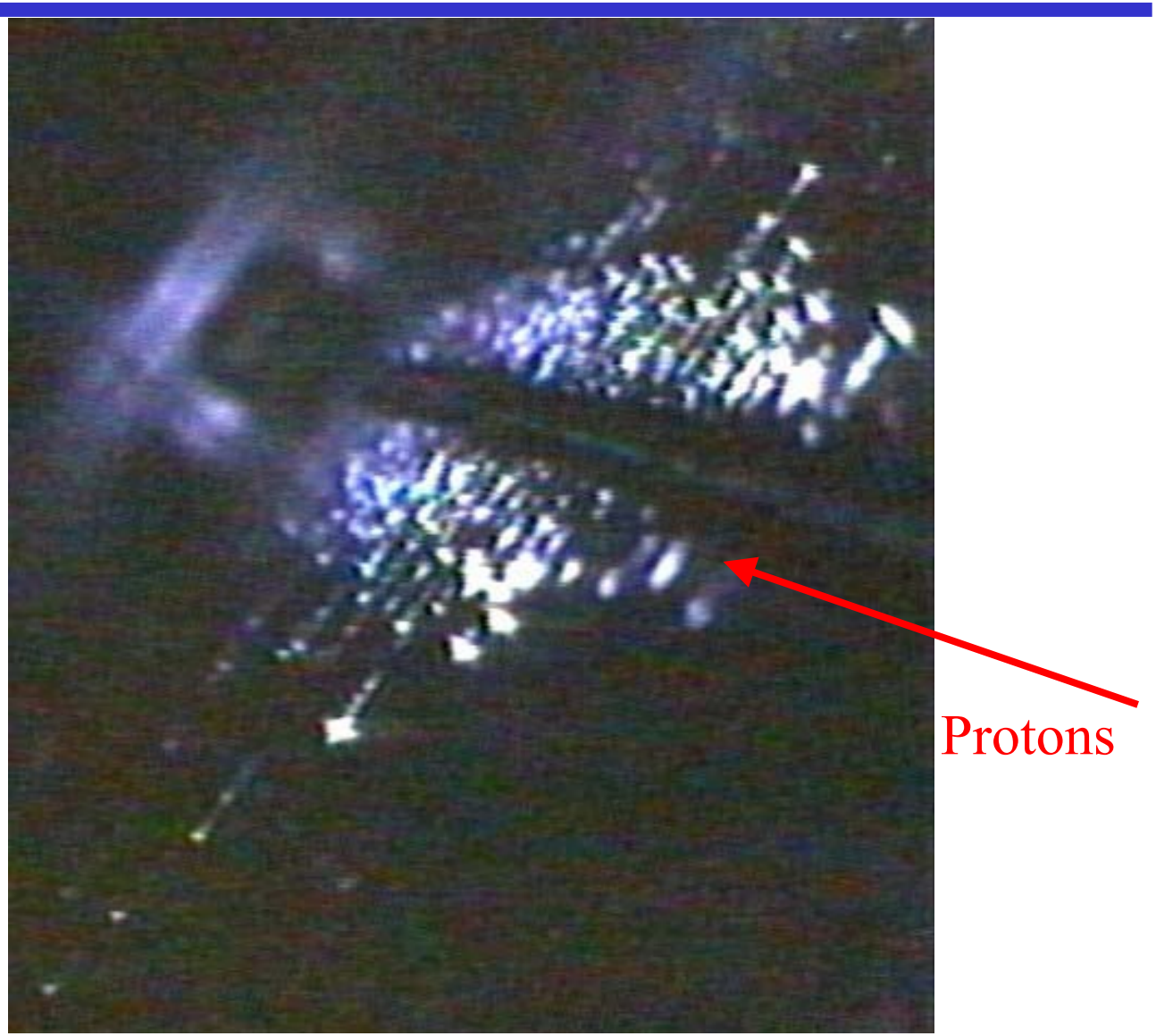


Figure 14: Particle hits at the collimators D49, E02, E03, F172 and at Roman Pot No.3 at dynamic simulations of quench of 5 main dipoles at A48 region. Time histogram of hits is shown on bottom-right of figure. Field degradation rate is $dB/B = 2.386 \times 10^{-5}$. Horizontal collimator F17(2) is retracted from working positions by 3 mm back, all others are retracted by 1 mm. The collimator D49 is assumed is melting with a rate of 0.04 mm per turn.

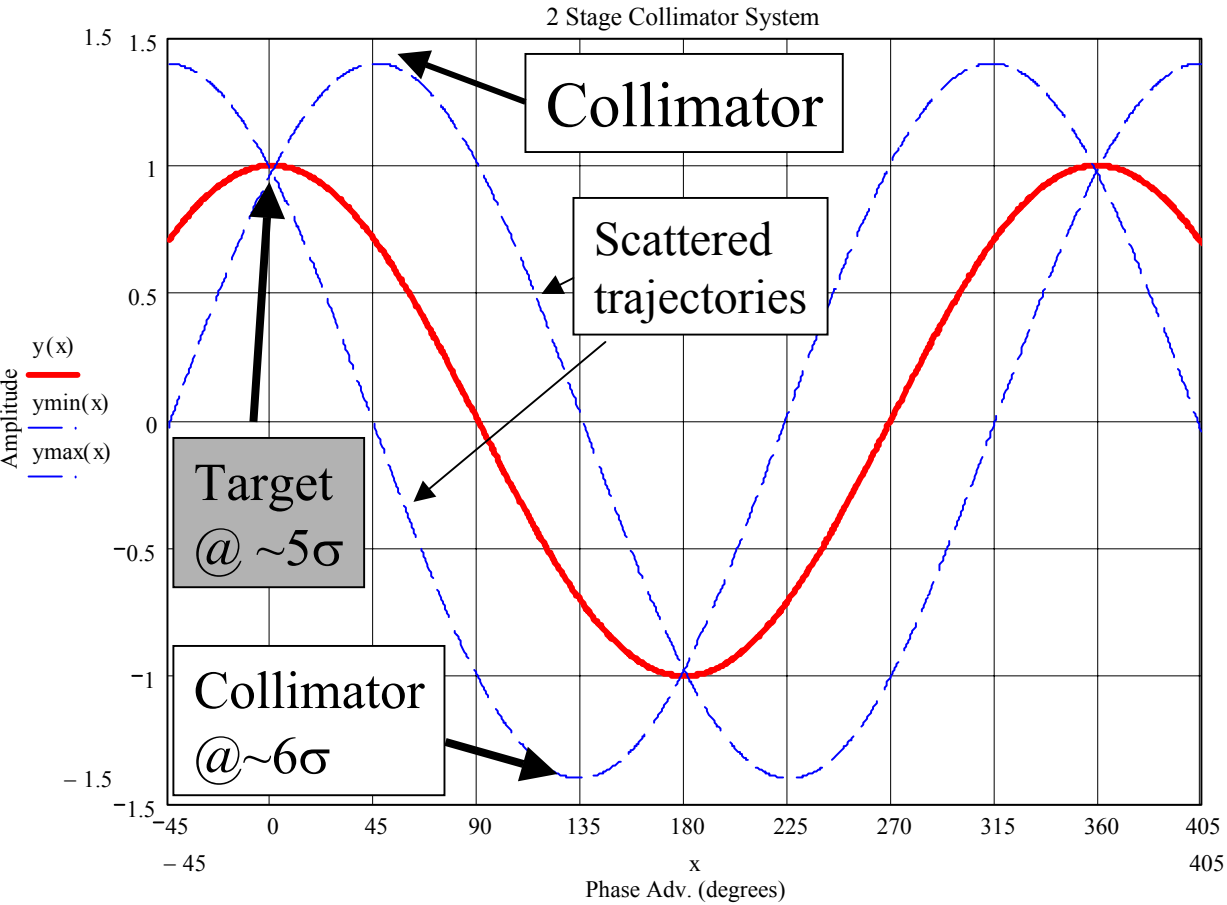
15

(Courtesy S. Drohzdin)

Damage to E03 1.5m Collimator

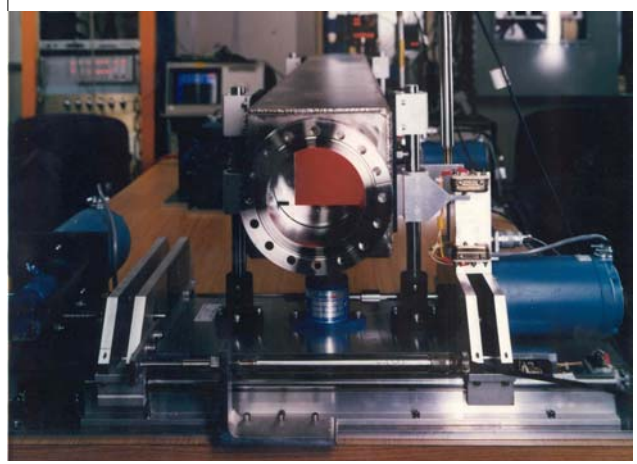


2 Stage Collimator System



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

6 inch Target w/ 5mm Tungsten Wing



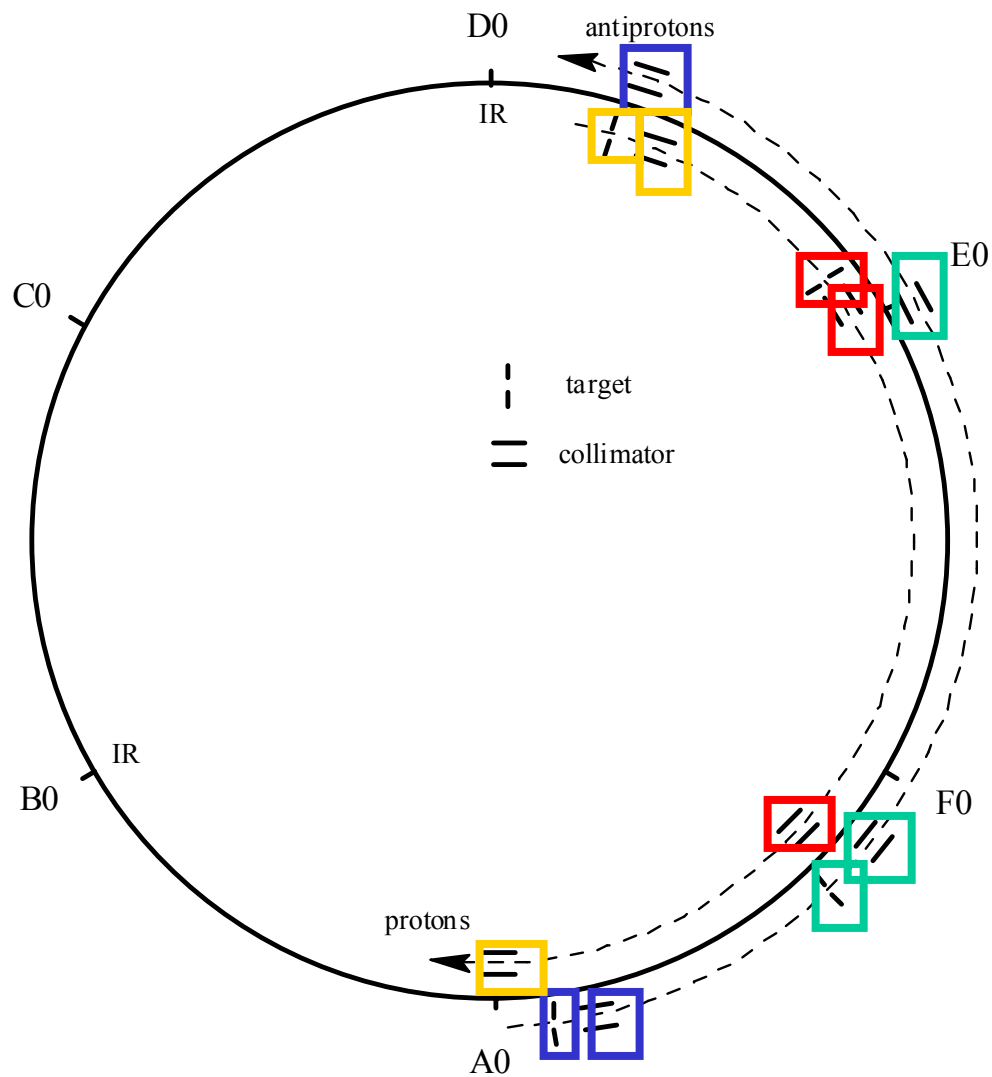
1.5 m collimator

Tevatron Collimator Layout

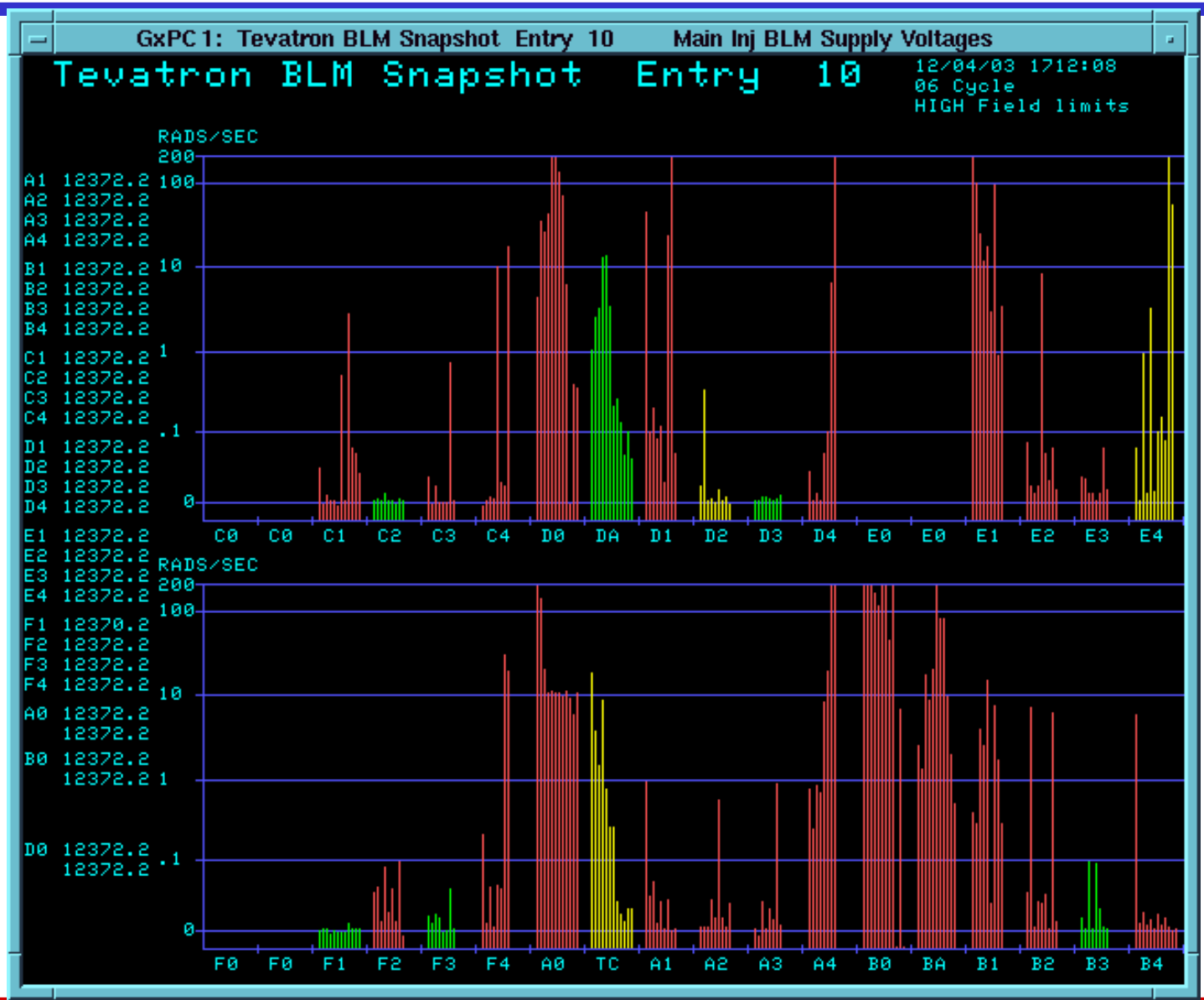
12 collimators total:
4 Targets
8 Secondary collimators

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



Tevatron Ring Wide Loss Plot



Result of quench at C19.

Conning tower correction element damage requiring C1 to be warmed to room temp for repair.

Conclusion:

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

2) It might have been possible to stop damage to collimators with different loss monitor protection system other than SVX. This needs discussion and possible loss monitor hardware system upgrade.

3) Even though 2 collimator devices were damaged, these devices defined the limiting aperture and are easy to change and provided protection to other components.