Tevatron Collider Commissioning

Lecture II: Plumbing

Hardware Issues and Their Treatment

Paying Attention to Details

Beam Diagnostics and Maintenance

Boosting Collider Performance

Vladimir Shiltsev

Fermilab

Collider Run Is Like a Military Campaign

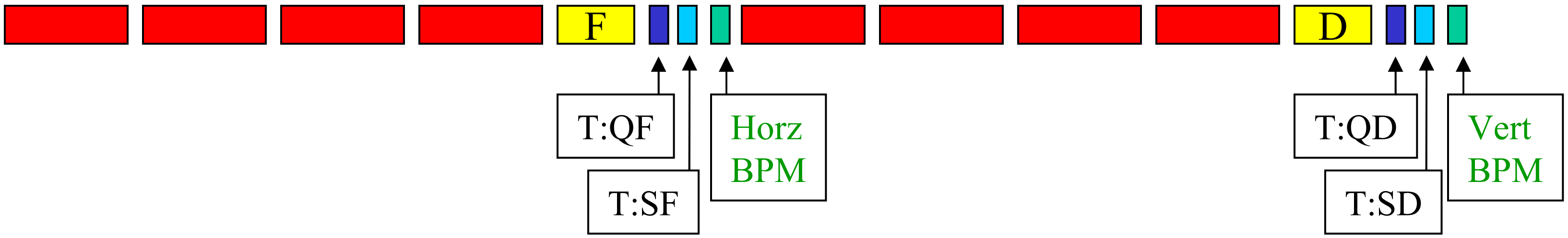
"In principle, war is simple business… but fighting is tricky"

Carl von Clausewitz
"On a War"

First, we need good magnets

Tevatron Optics

	Dipoles	Quads	Spools
Number	772+2	90+90	88+88



Tevatron Dipole

(There are 772 Tevatron dipoles)

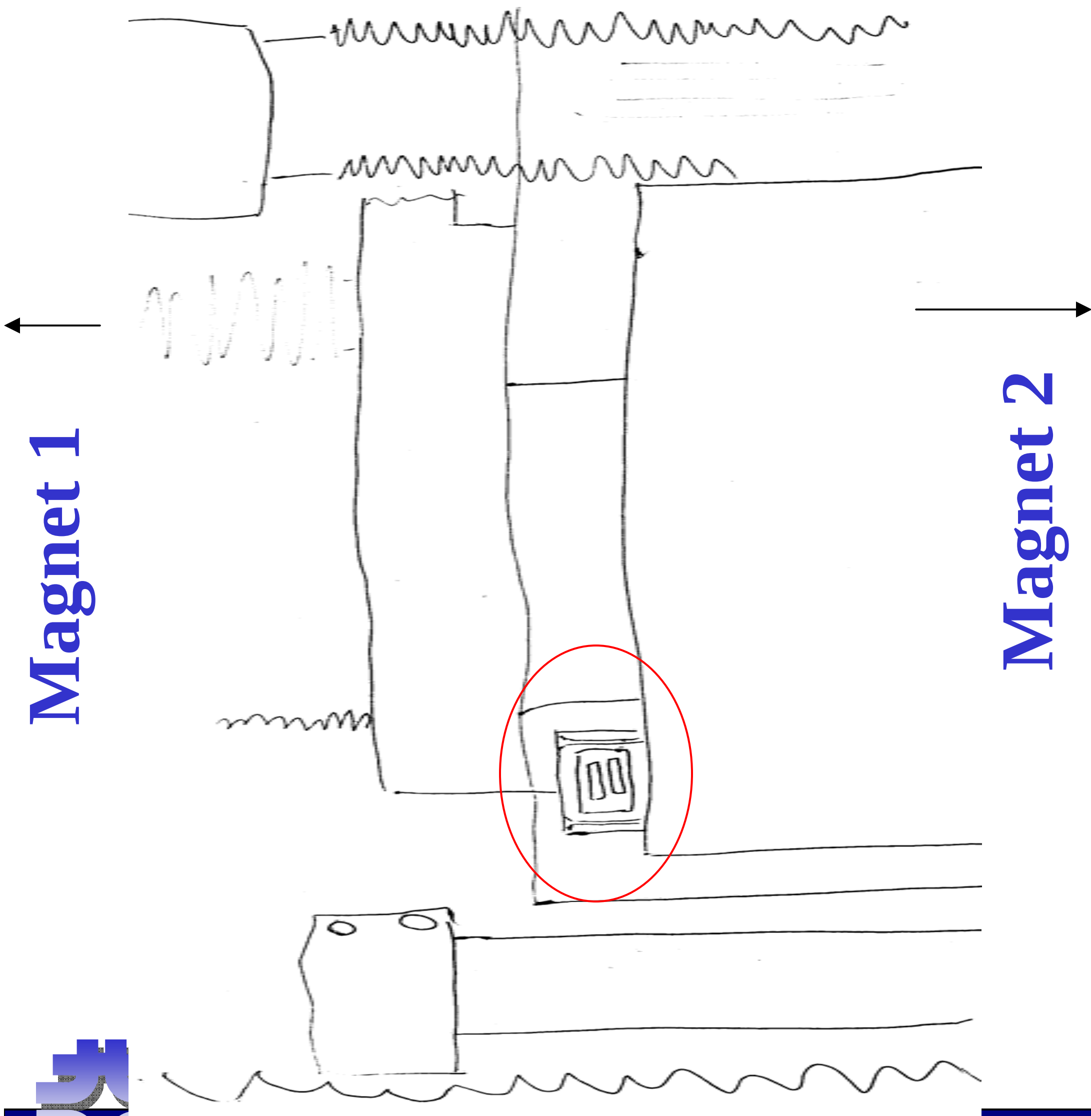
Tevatron Quadrupole

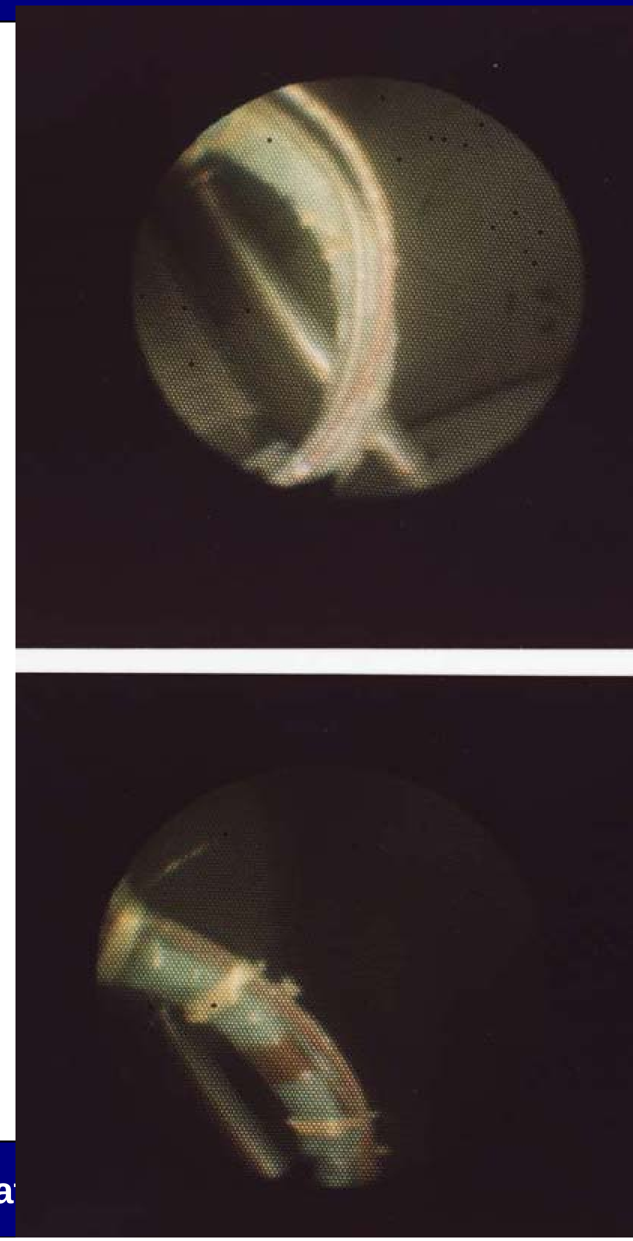
Tevatron Quad corrector

Tevatron Sextupole corrector

Tevatron Beam Position Monitor

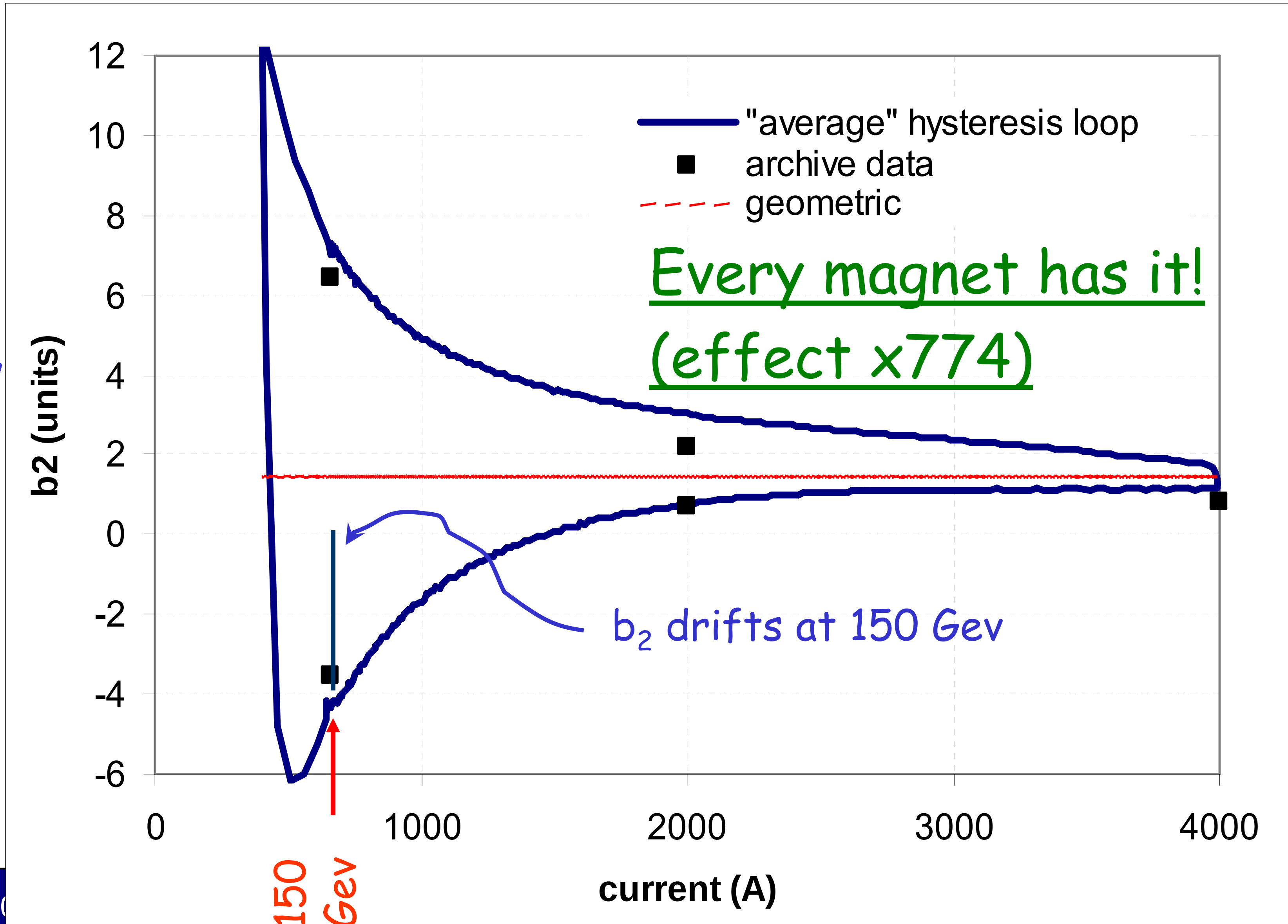
Inside Tev Magnet: X-ray and boroscope



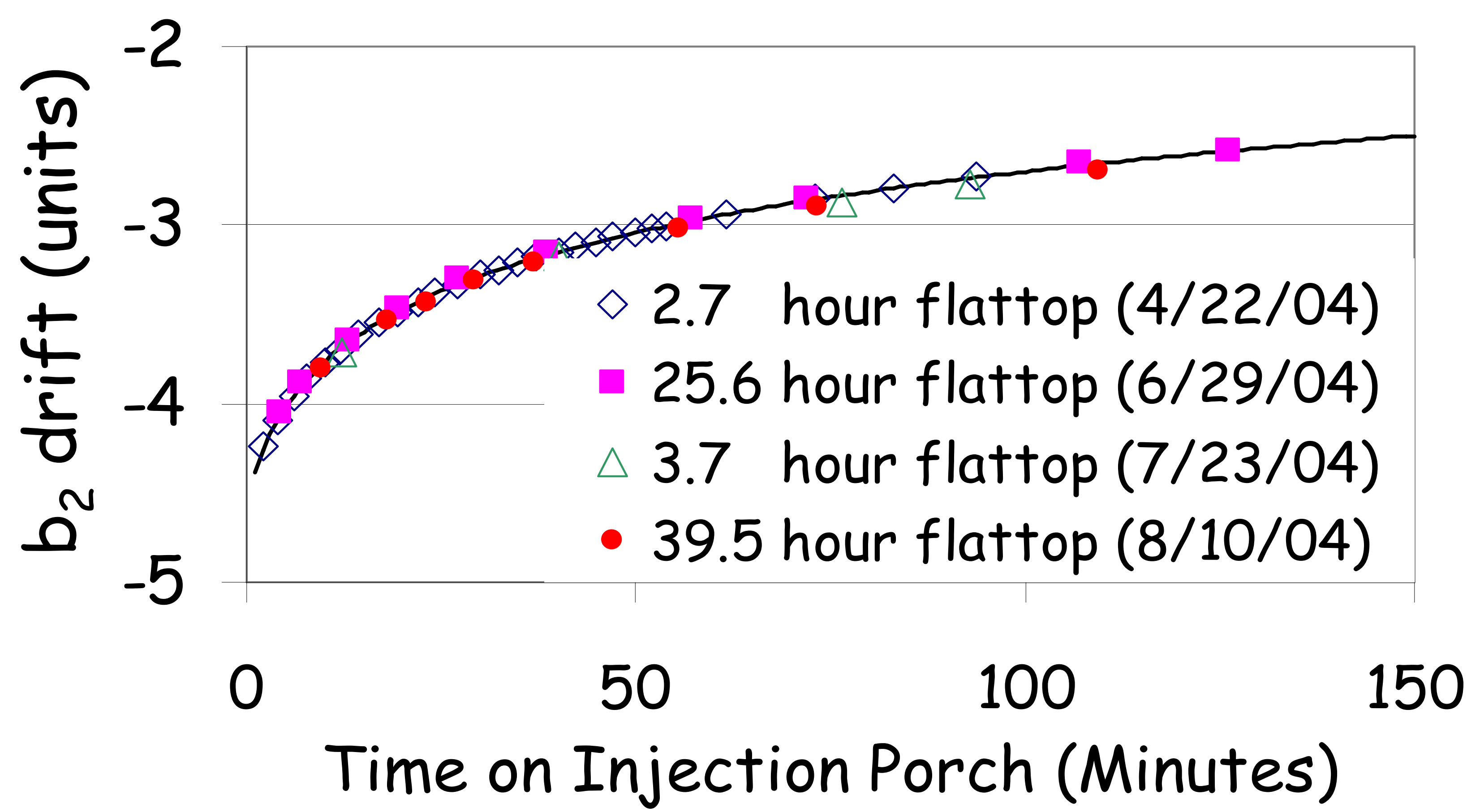


Sextupole Component - Not Zero! Not Constant!

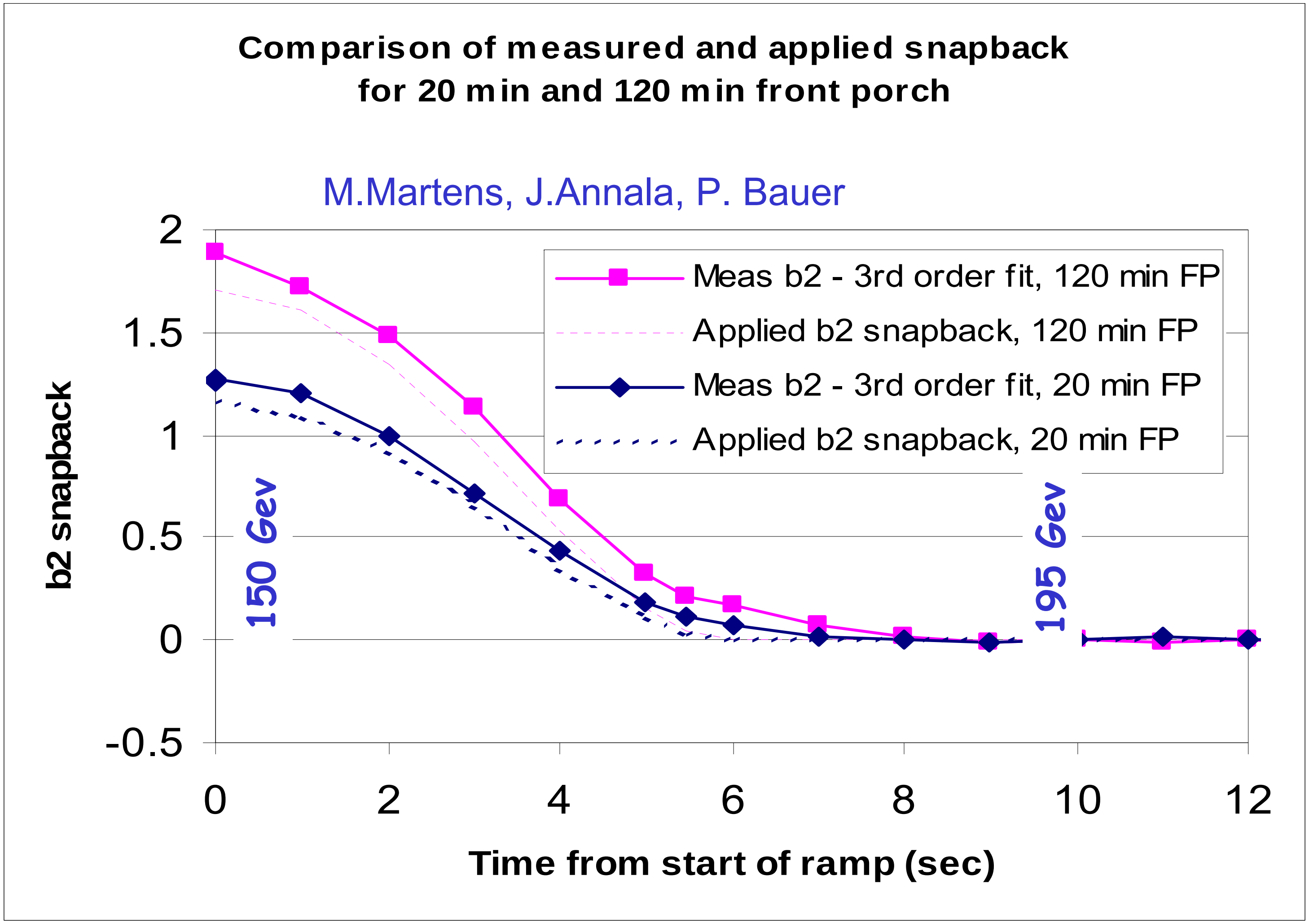
1 unit
=1e-4
dB/B
at r=1"



Measured b_2 Drift in Tevatron @150 GeV



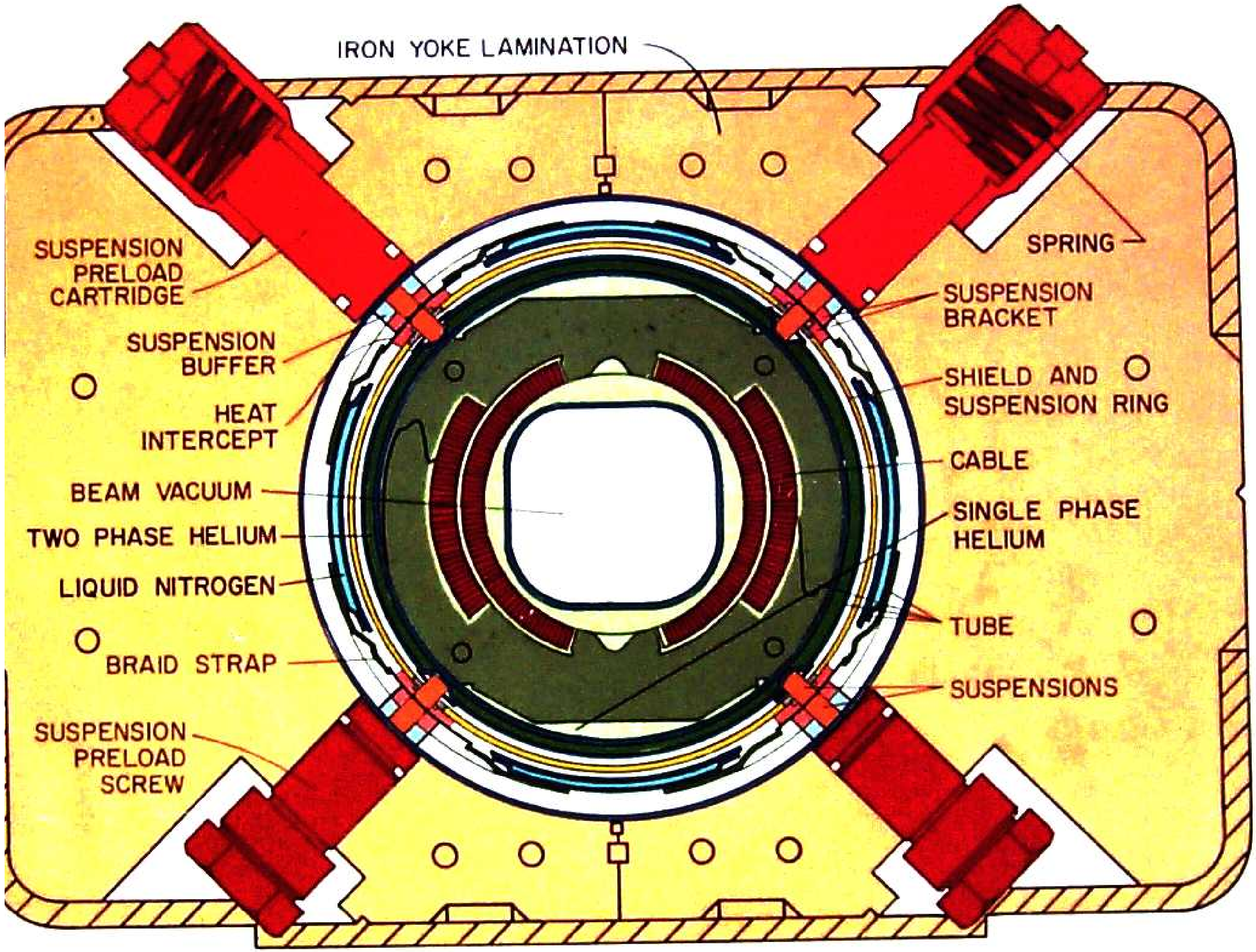
Ramp: b2 Snapback Compensation



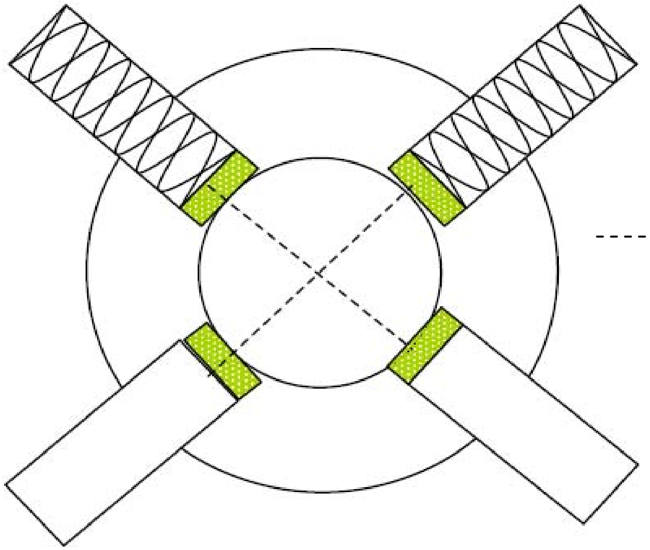
b_2 snapback is correctly compensated (for shot setup conditions.)

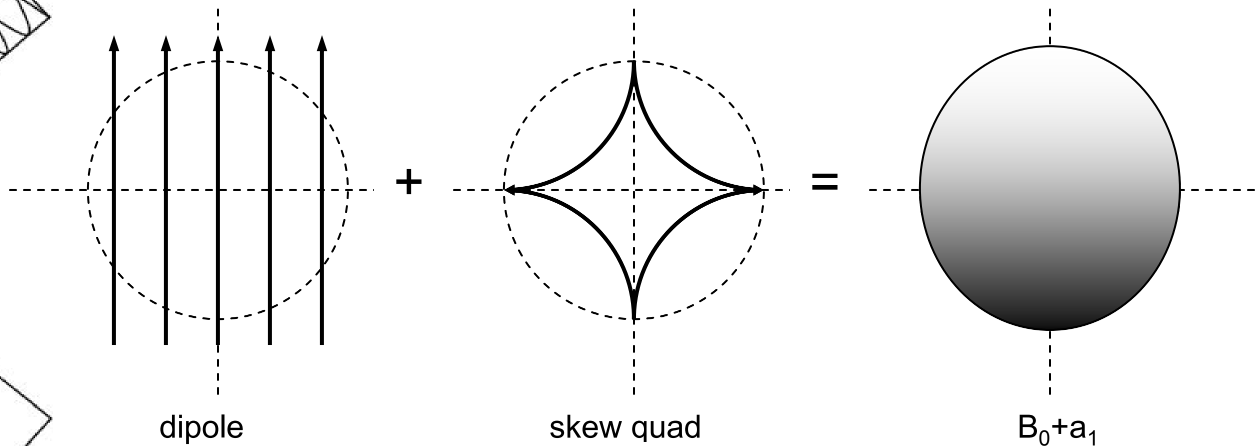
Age Effect: SC Coils Sank wrt Iron Yoke

After ~20 years of operation, the coil block sank wrt iron yoke under strong forces of springs in "**smart bolts**" (smashed G10 spacers)



Reshimming=Lifting Up SC Coils





dB_skew/B_dipole=1.4e-4
at 25.4 mm

Solution: add 140 micron shims to the bottom suspensions to raise the coil block. In 3 years we did it for all 774 dipoles (18 "smart" bolts and 18 lower bolts per magnet) → coupling reduced as expected and correspondingly beam size mismatch at injection

GOOD MAGNETS

NEED TO BE

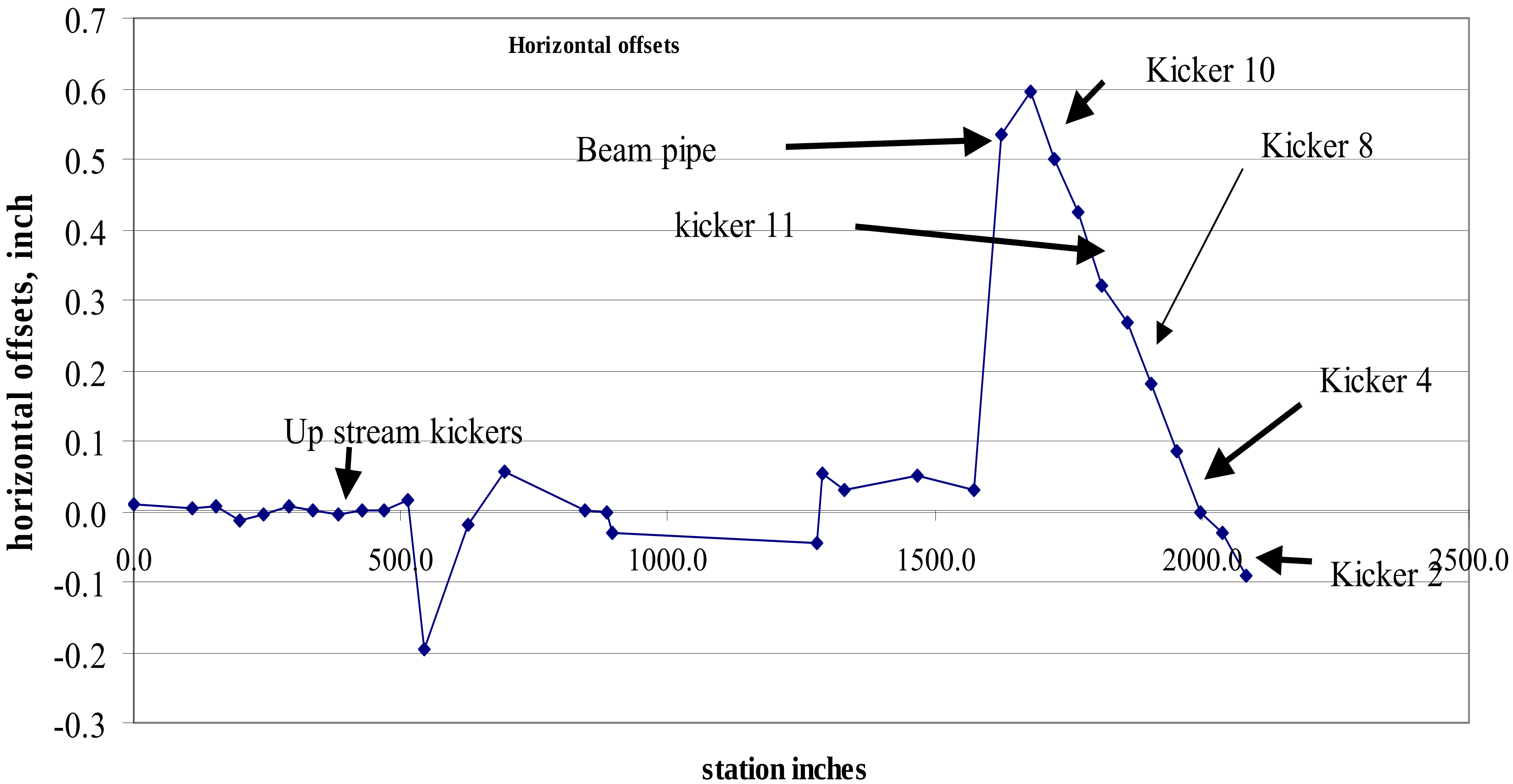
WELL ALIGNED

Tev Alignment: What it really means…

Rusty Stands

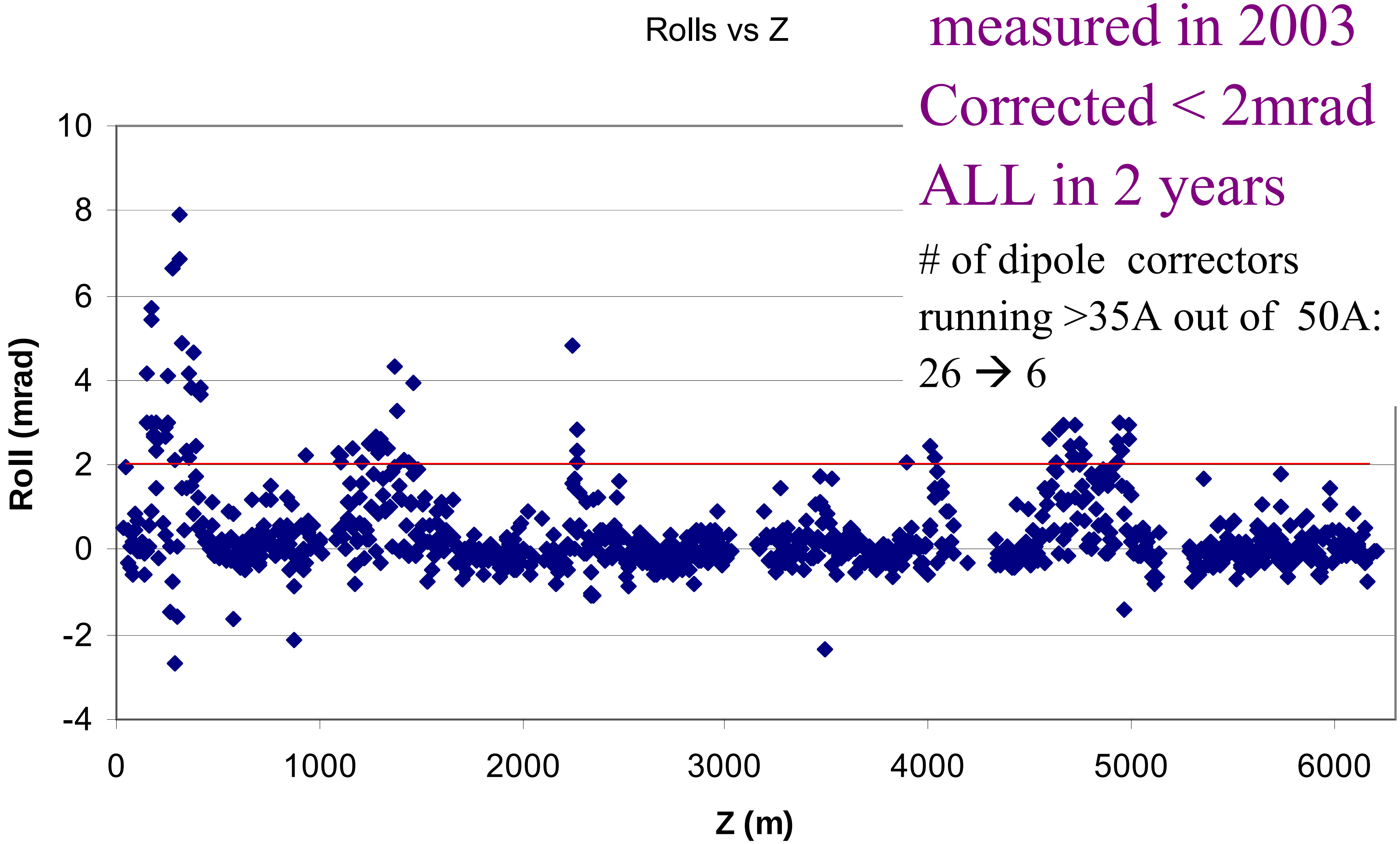
ALL rusty stands
replaced since 2003

Mis-Alignment → Fix → Open Apertures



- *Another ¼" misalignment fixed at D0*

Tevatron Magnet Rolls



measured in 2003

Corrected < 2mrad

ALL in 2 years

# of dipole correctors running >35A out of 50A: 26 → 6

Orbit Drifts due to Magnet Moves

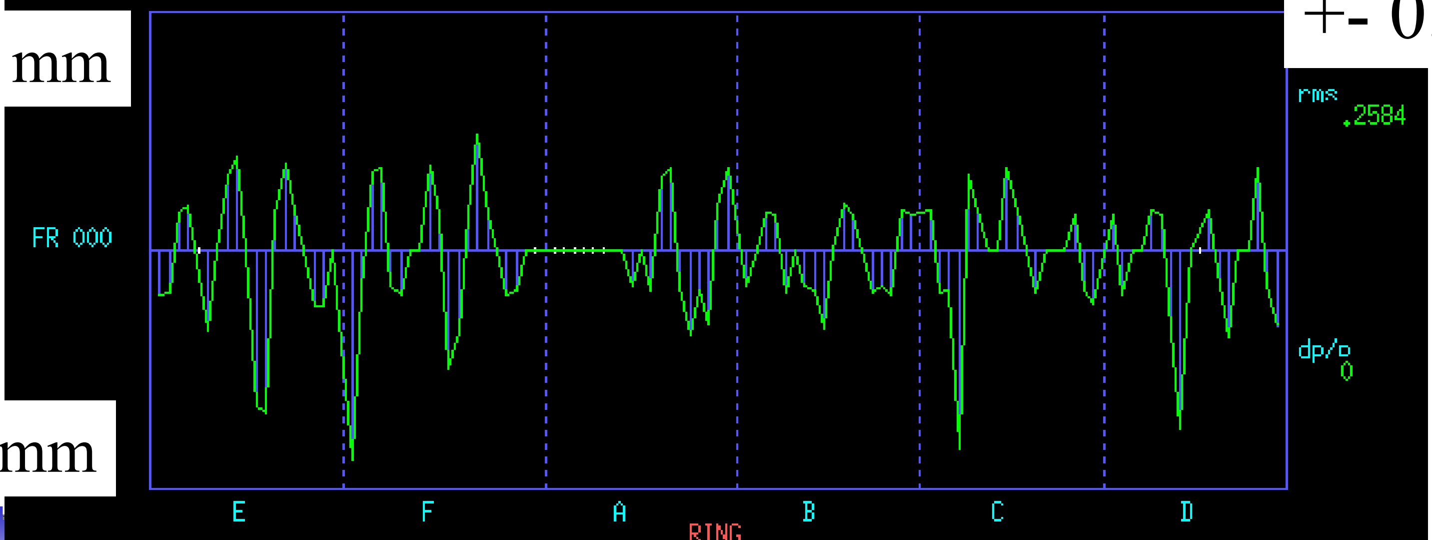
profile (| 1 mm) HORZ prot-bunch 89.9 17-FEB-2004 15:07:51

	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				

store 3240
minus
store 3206

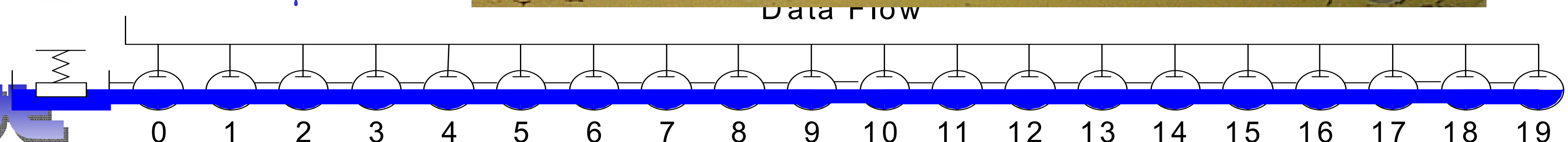
19 days→
0.26 mm rms
+- 0.7 mm p-p

+1 mm

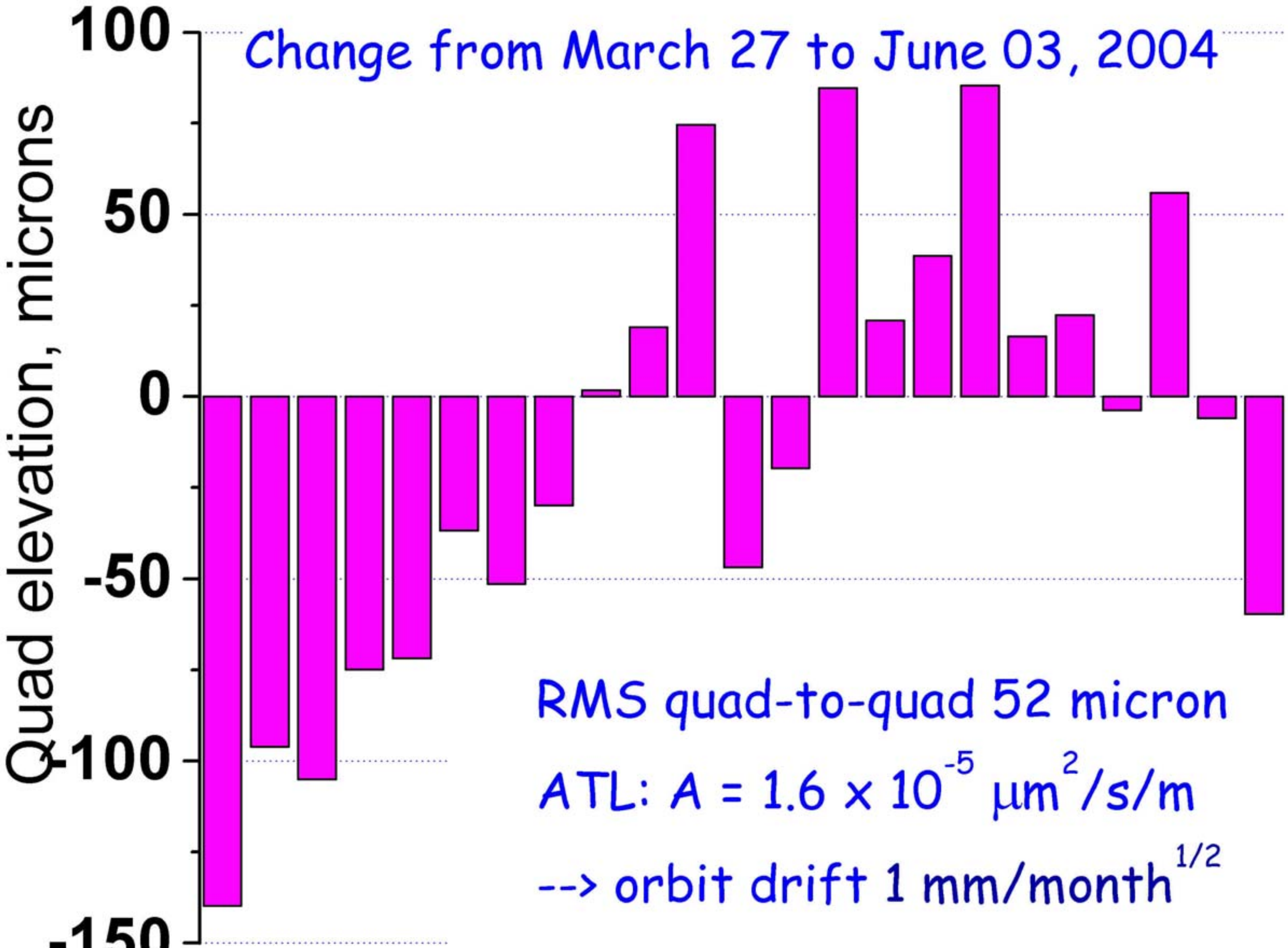


-1 mm

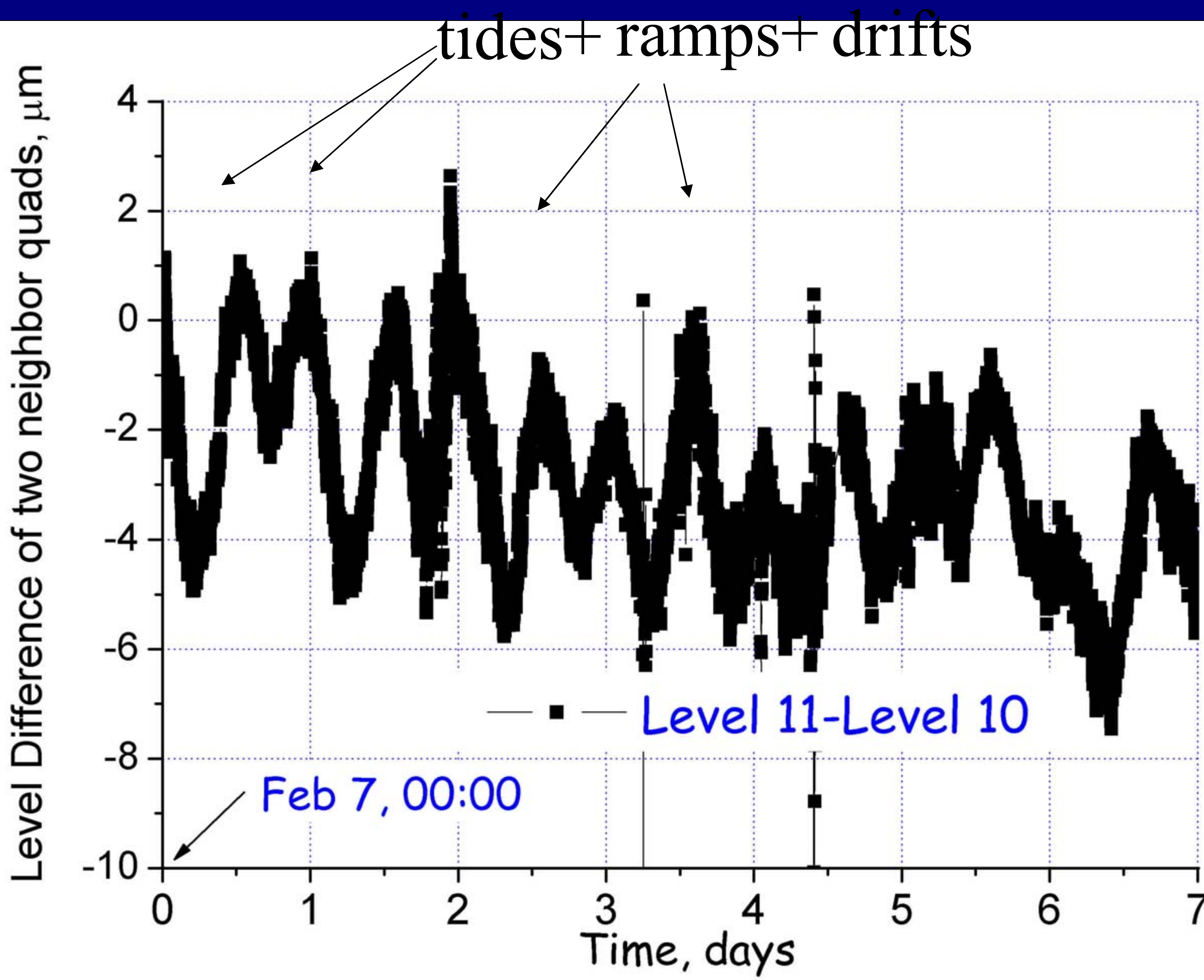
Tev On-Line Survey System (Plumbing)



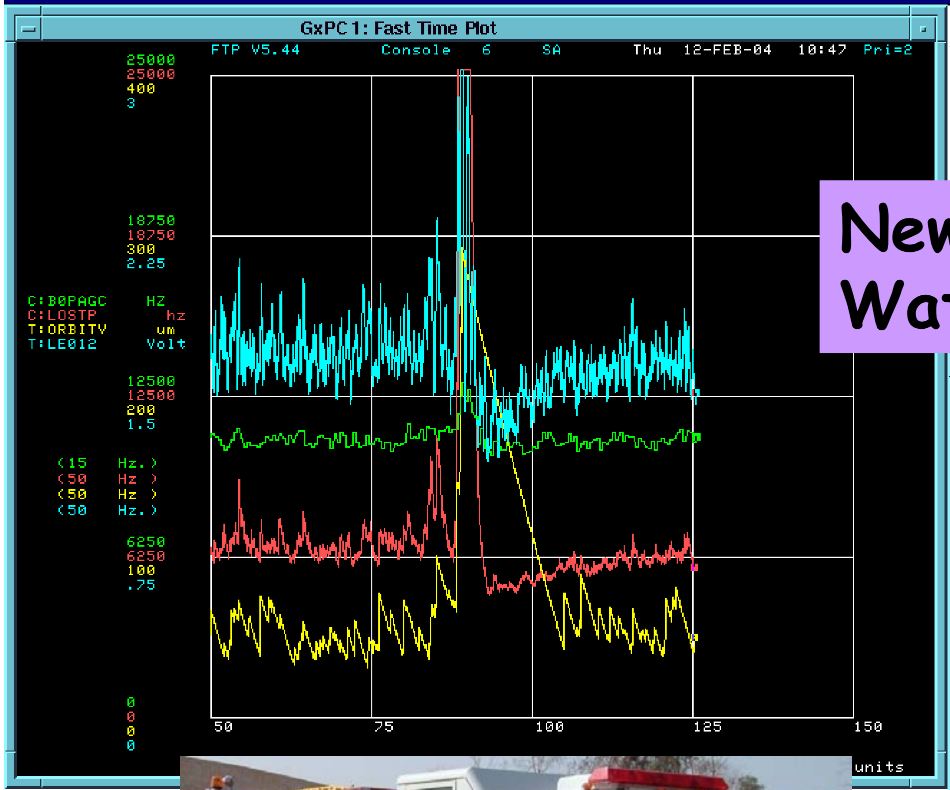
Drift of Quad Positions : 2 mos



Drift of Quad Positions : 1 week

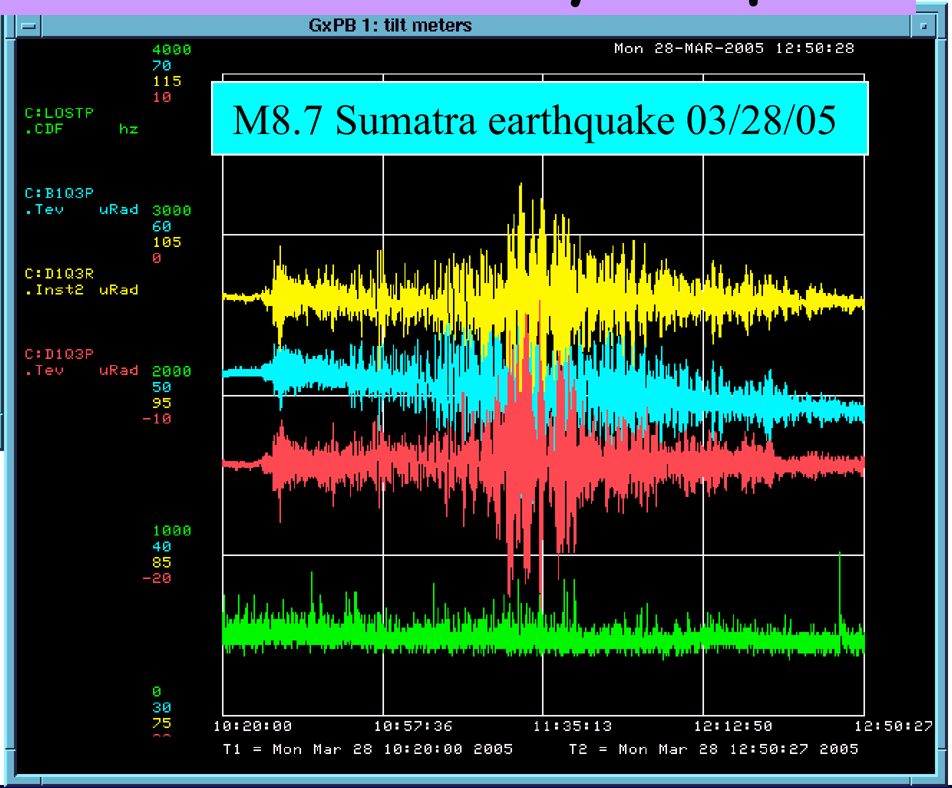


Sensitivity to "quakes" → Enforce LB quad support



←"Fire-truck-quake"
~200 um orbit jitter

New diagnostics: tiltmeters, Water Levels on every LB quad



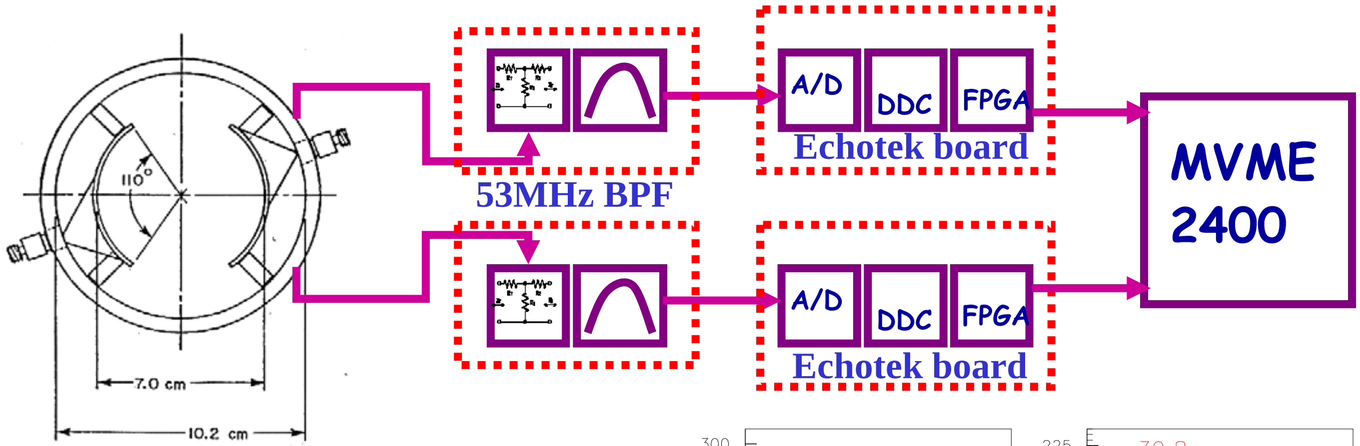
Having good magnets, well aligned, good vacuum (tons of stories), beam →

LET'S GO!

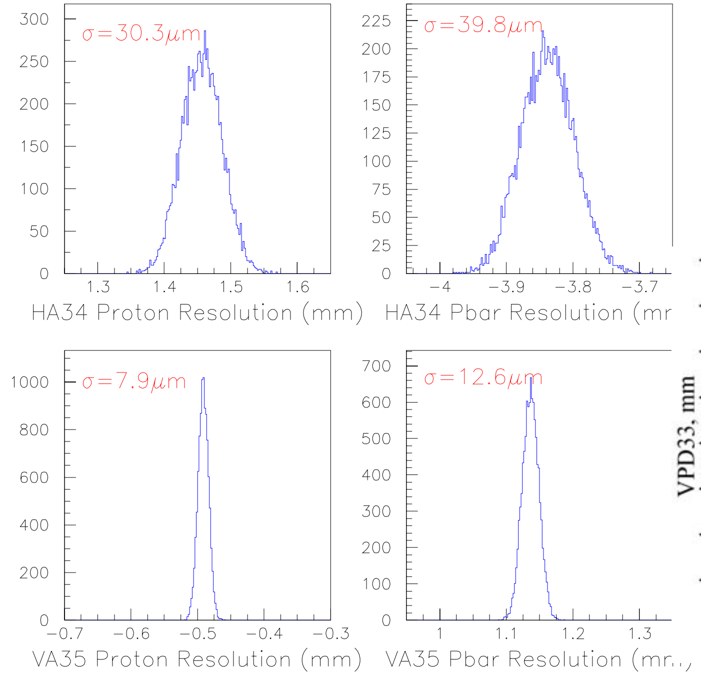
“Driver’s Nightmare”

You need very good eyes and ears to live in such a world…

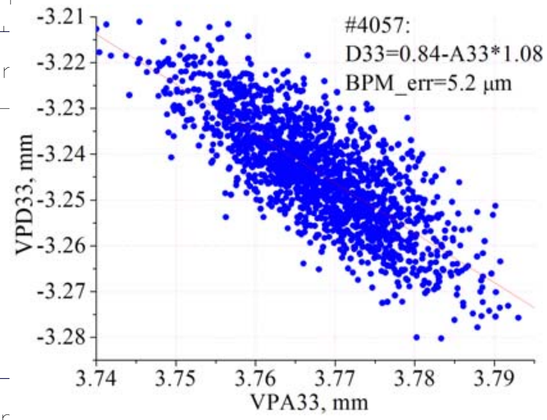
Beam Position Monitors: Old had problems…



- Existing BPMs fitted with new electronics based on *Digital Down-Conversion*
- Resolution ~5μm (previously LSB was 0.15mm)
- Eliminated difference between coalesced and uncoalesced beams.
- Measures pbar orbit,too

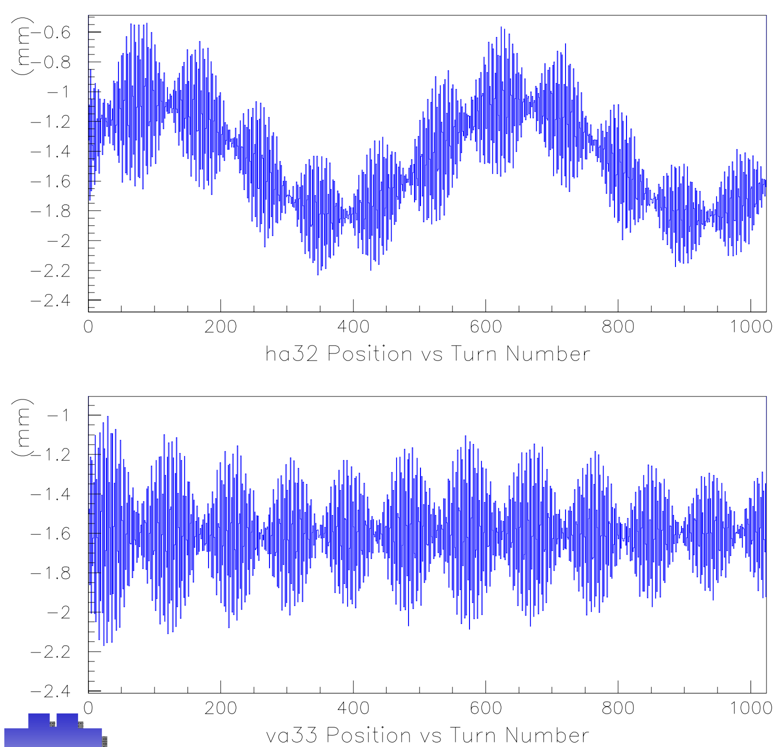


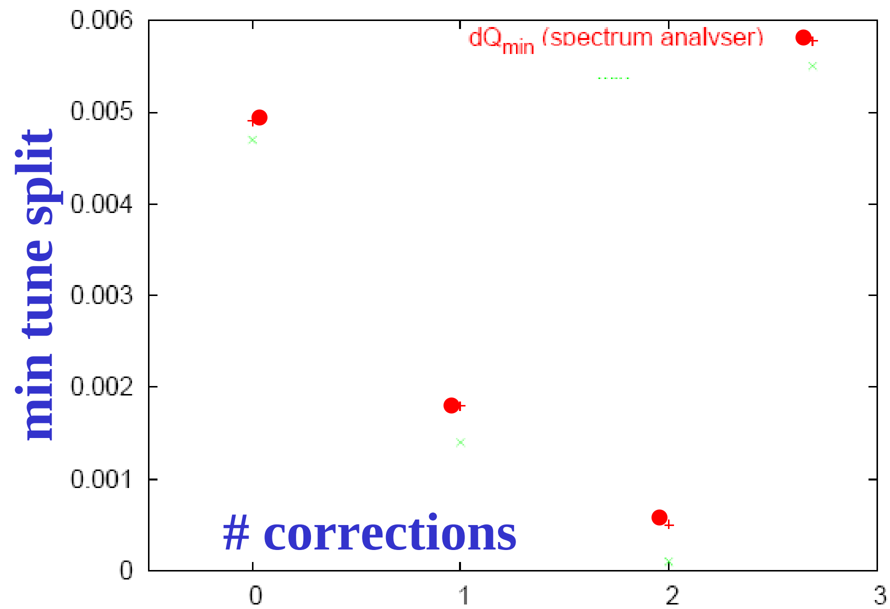
***Note that "resolution" includes real beam motion, mainly in the horizontal plane (synchrotron osc.)**



New BPMs → De-coupling and Lattice measurement

- Calculating all optics functions and coupling correction using TBT data from many BPMs

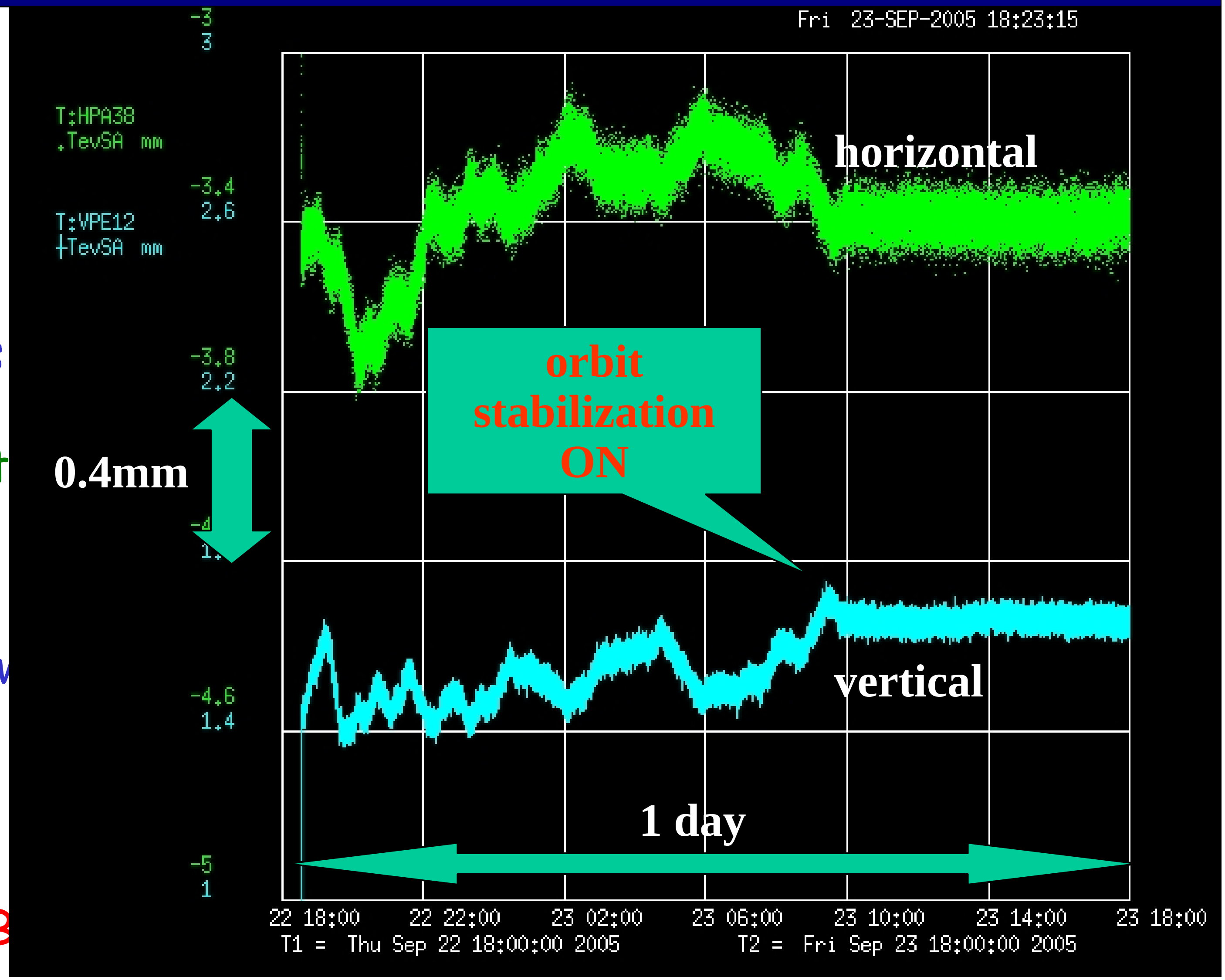




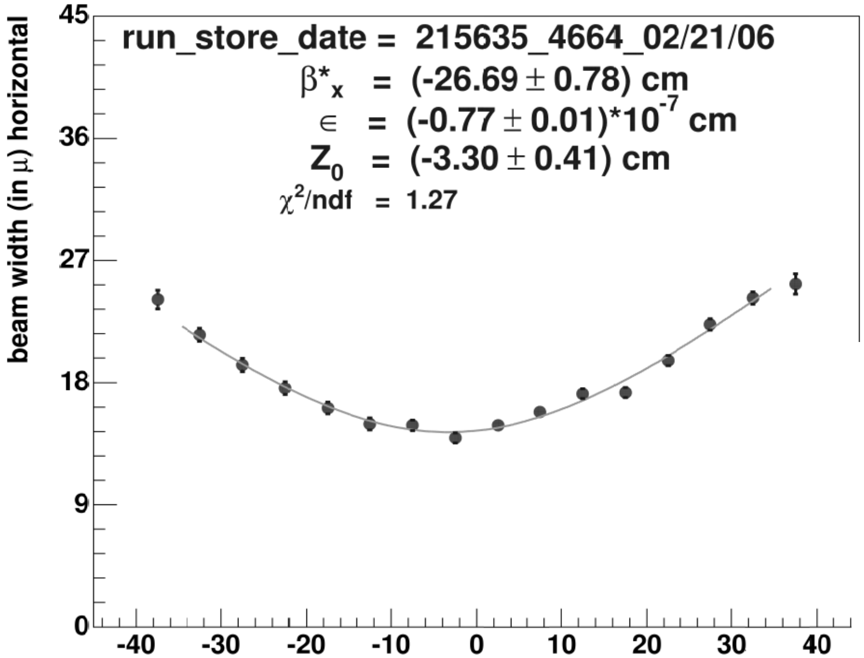
- Beta-functions measured to better than 5% accuracy on both helices, errors corrected, lattice modified so that β*=36cm→29cm, giving ~10% gain in Luminosity

Orbit stabilization

- Slow (~1/min) automatic continuous correction of orbit variations using several dipole correctors close to the IPs
- Standard at most Light Sources – only recently commissioned in Tevatron with new BPMs (old were too sensitive to bunch structure → quench fear)
- Now need fast FB



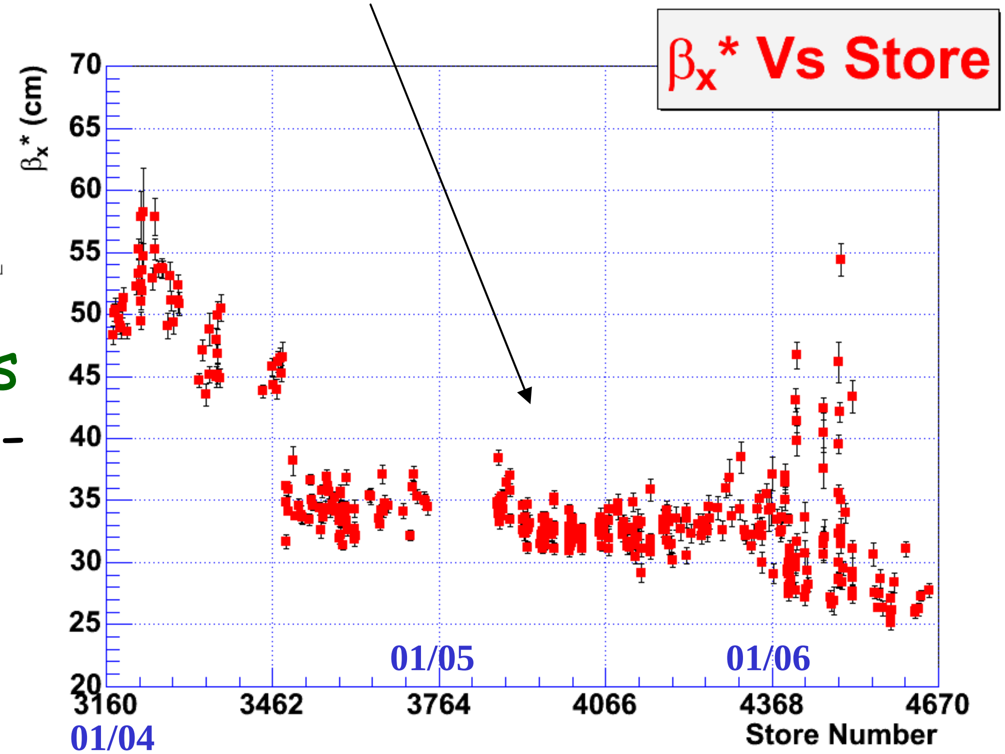
CDF and D0 IP Waist Diagnostics



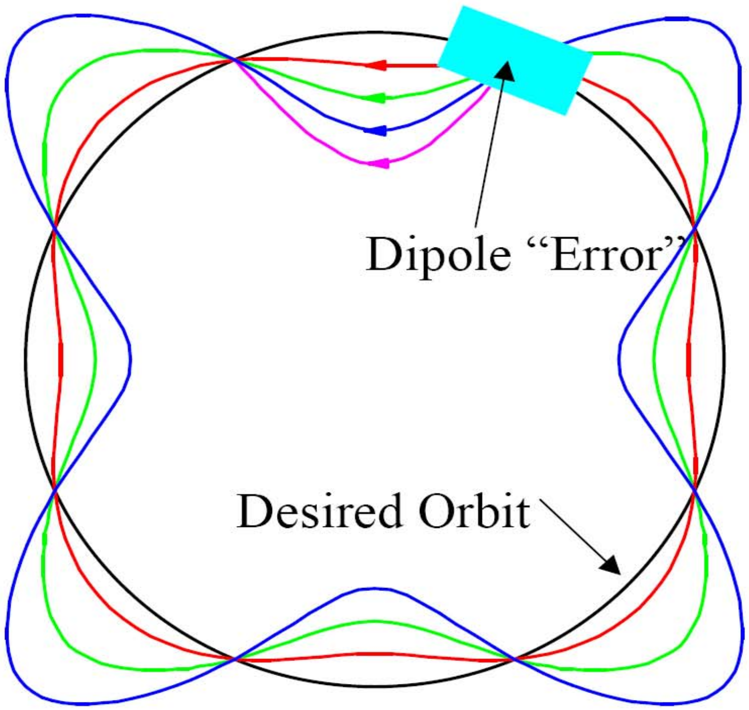
Vertices of p-pbar collisions analyzed and processed (on-line @ CDF , off-line with ~day delay @D0) → IP position, luminous region waist size vs z

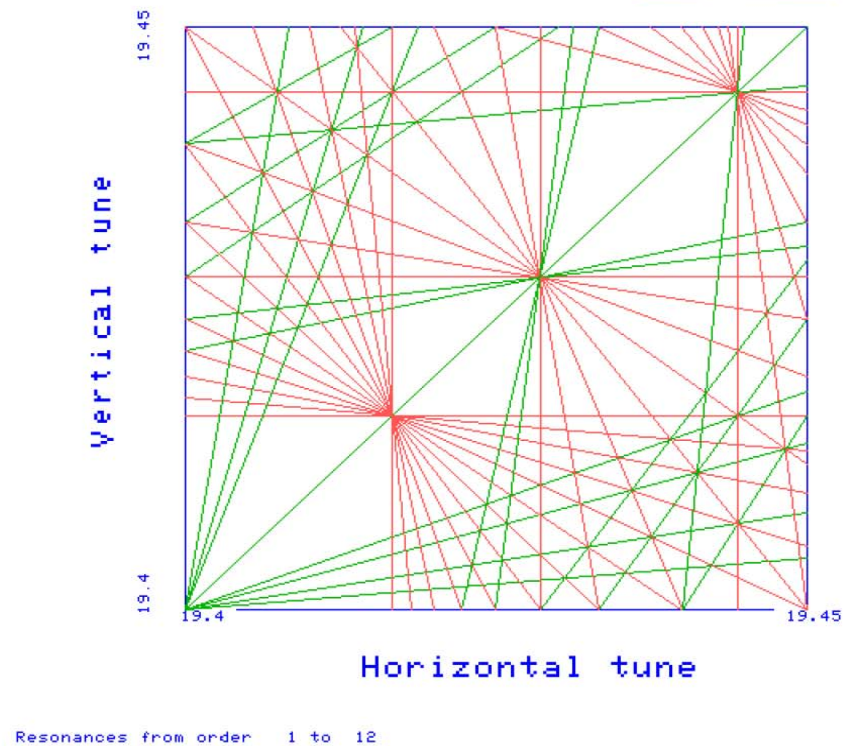
Vertical beta-function measured at D0 Jan'2004 to Mar'2006

("beam diagnostics for free")



Importance of Tunes

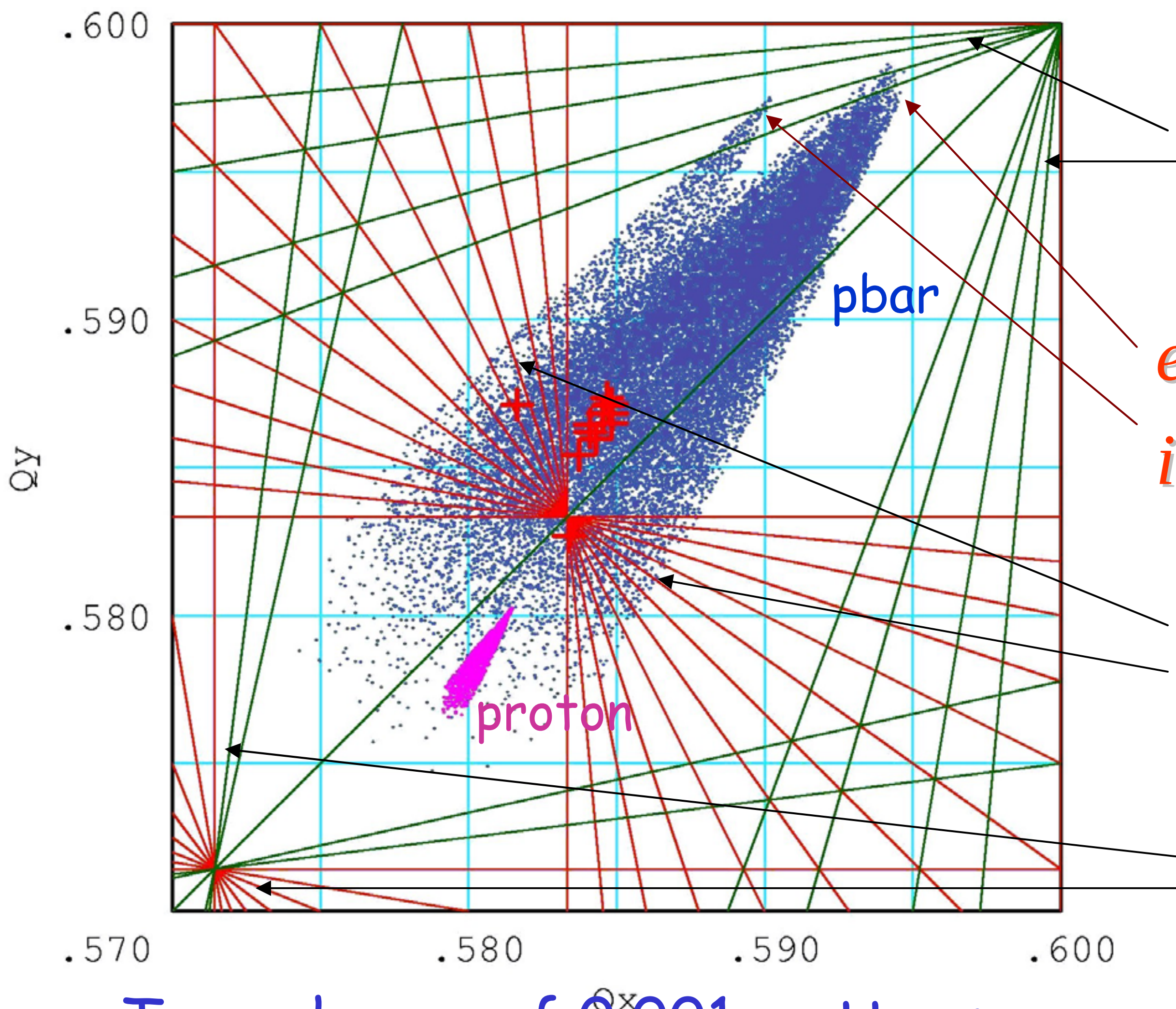




- Dipole errors affect tunes = 1, 2, 3…
- Quadrupole errors affect tunes 1/2, 1, 3/2, 2, 5/2 ...
- Sextupole errors affect tunes 1/3, 2/3, 1, 4/3...

Particles live 10^{10} turns →sensitive to very high orders

Tevatron: Life in the "Tune Box"



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

every bunch has its own tune!

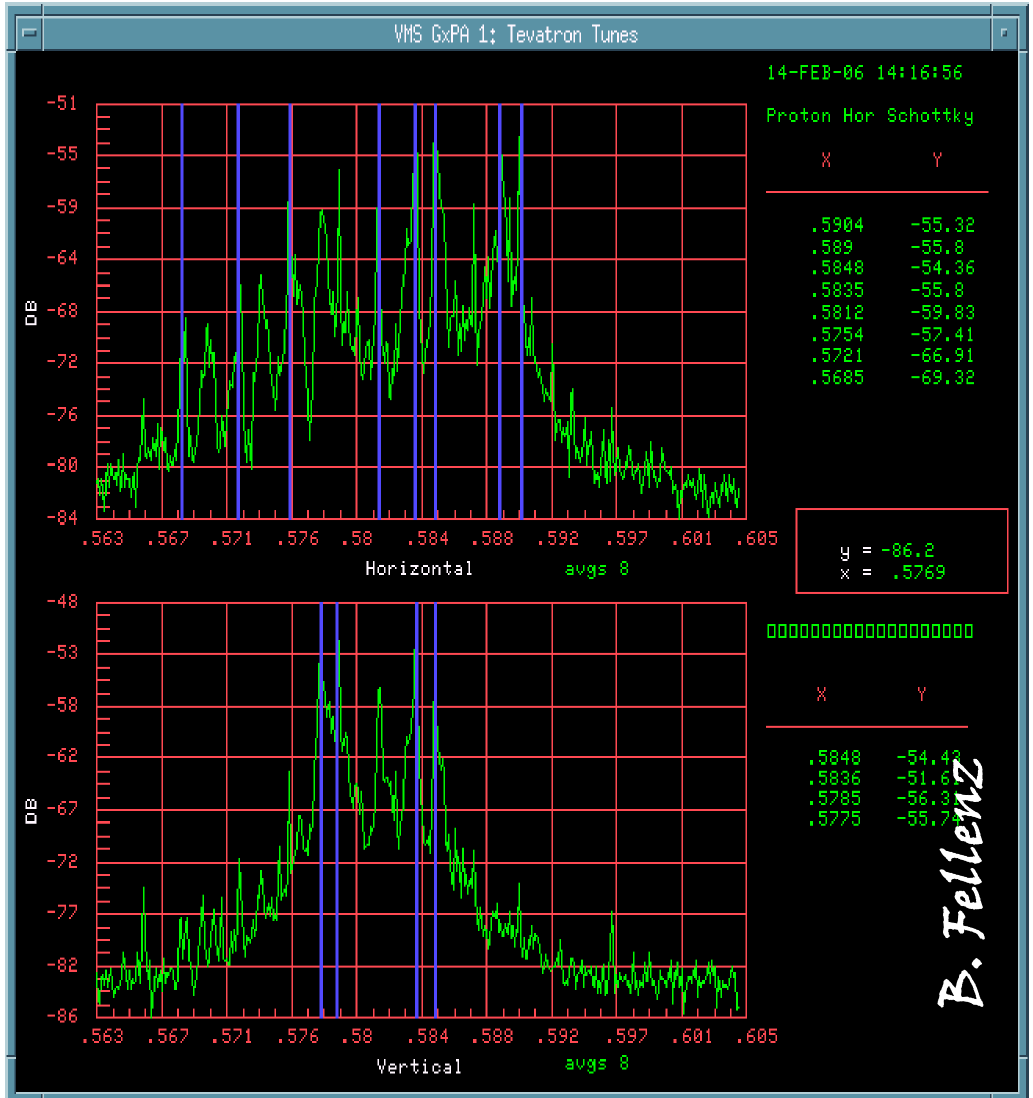
12th order resonances:
Q=7/12=0.583 -
Bad lifetime

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

Tune change of 0.001 matters

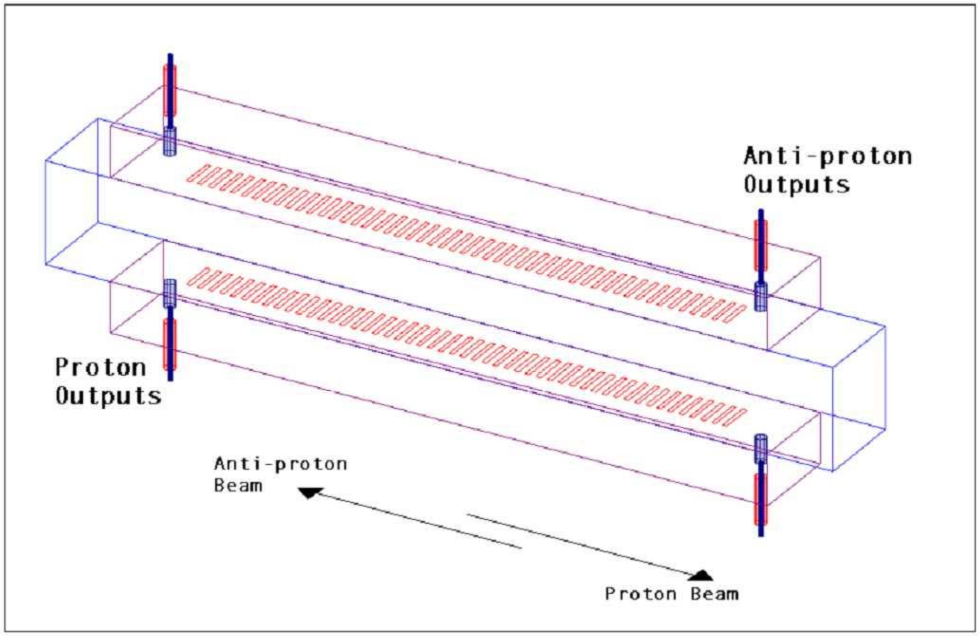
Tune Diagnostics: 21.4 MHz Schottky

- Workhorse for shot setup. Operators determine tune from spectrum peaks
- Often needs excitation (VTICK)
- **But:** a) does not see pbars anywhere, b) very complicated by coherent tune lines,
- c) does not see bunch-by-bunch tunes



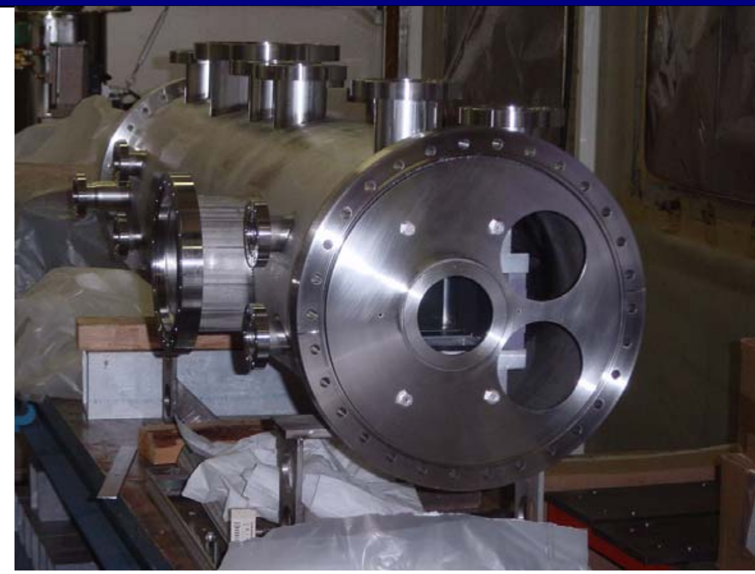
1.7 GHz Schottky Detector

Slotted Waveguide Pickup

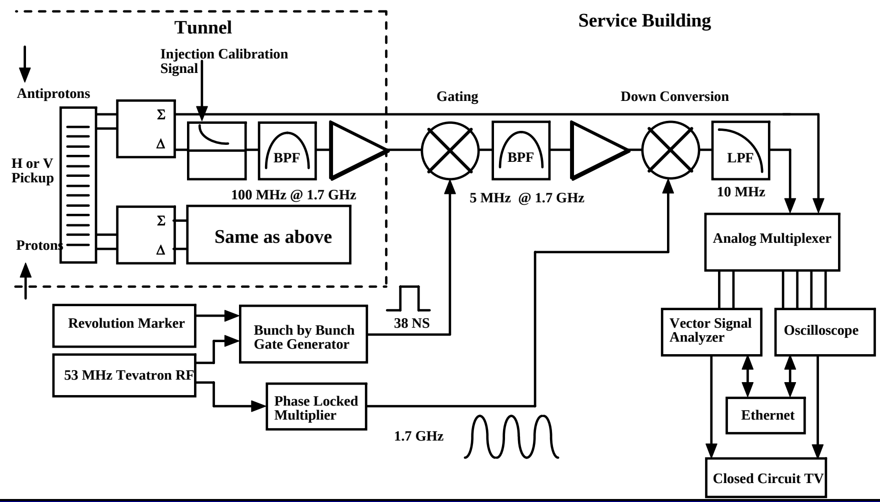


1.7 GHz 109 x 75 mm aperture

- Vertical and horizontal units
- Proton and pbar ports
- 100 MHz bandwidth



Tevatron Schottky Signal Processing

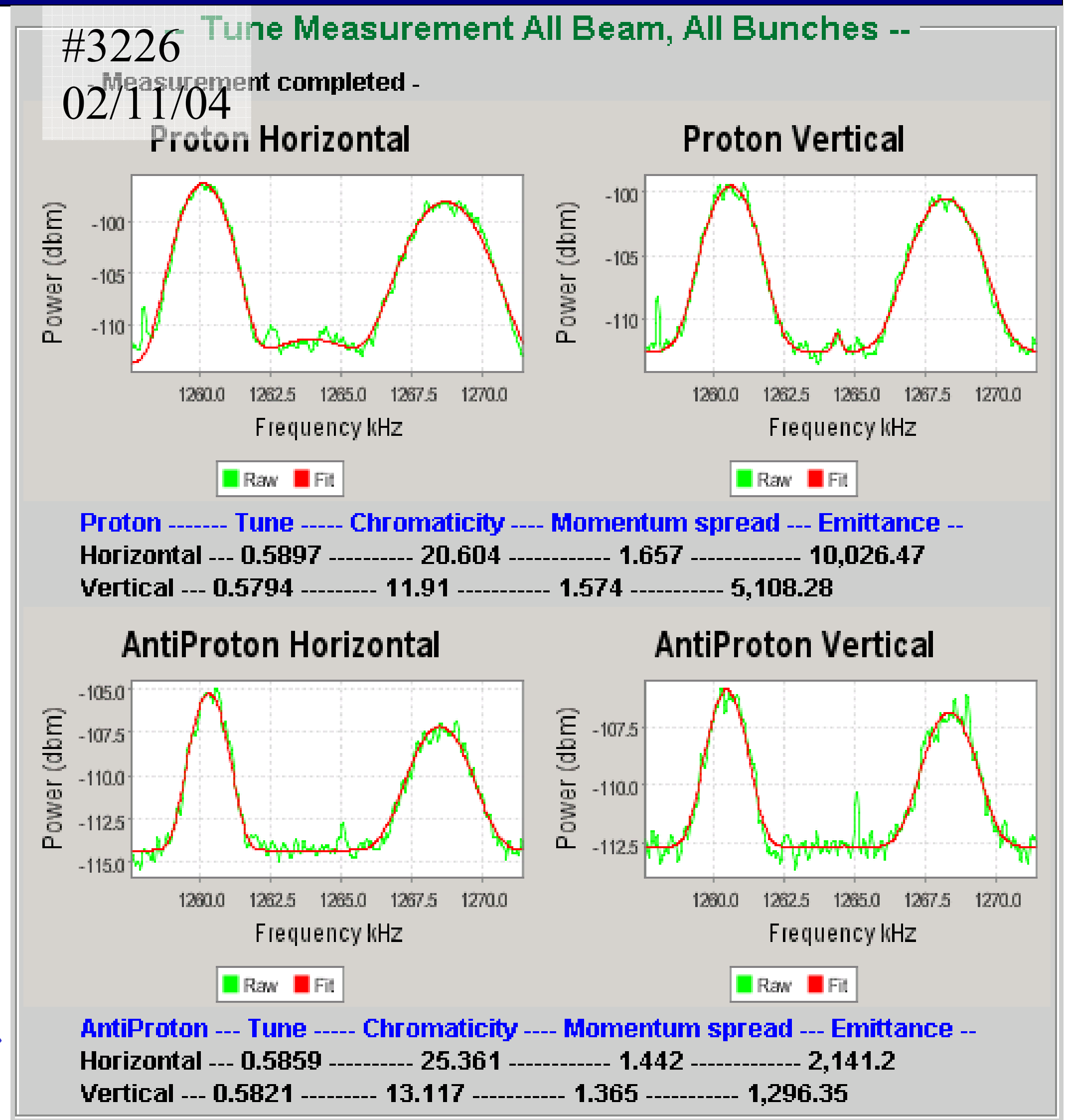


1.7GHz Schottky Spectra

- Q and 1-Q lines are seen
- Fit gives:
  - Betatron frequency (accuracy ~0.001)
  - dP/P ∝ sum of two widths
  - C_vh ∝ difference of two widths
  - Emittance ∝ area under the peaks
- For each bunch!

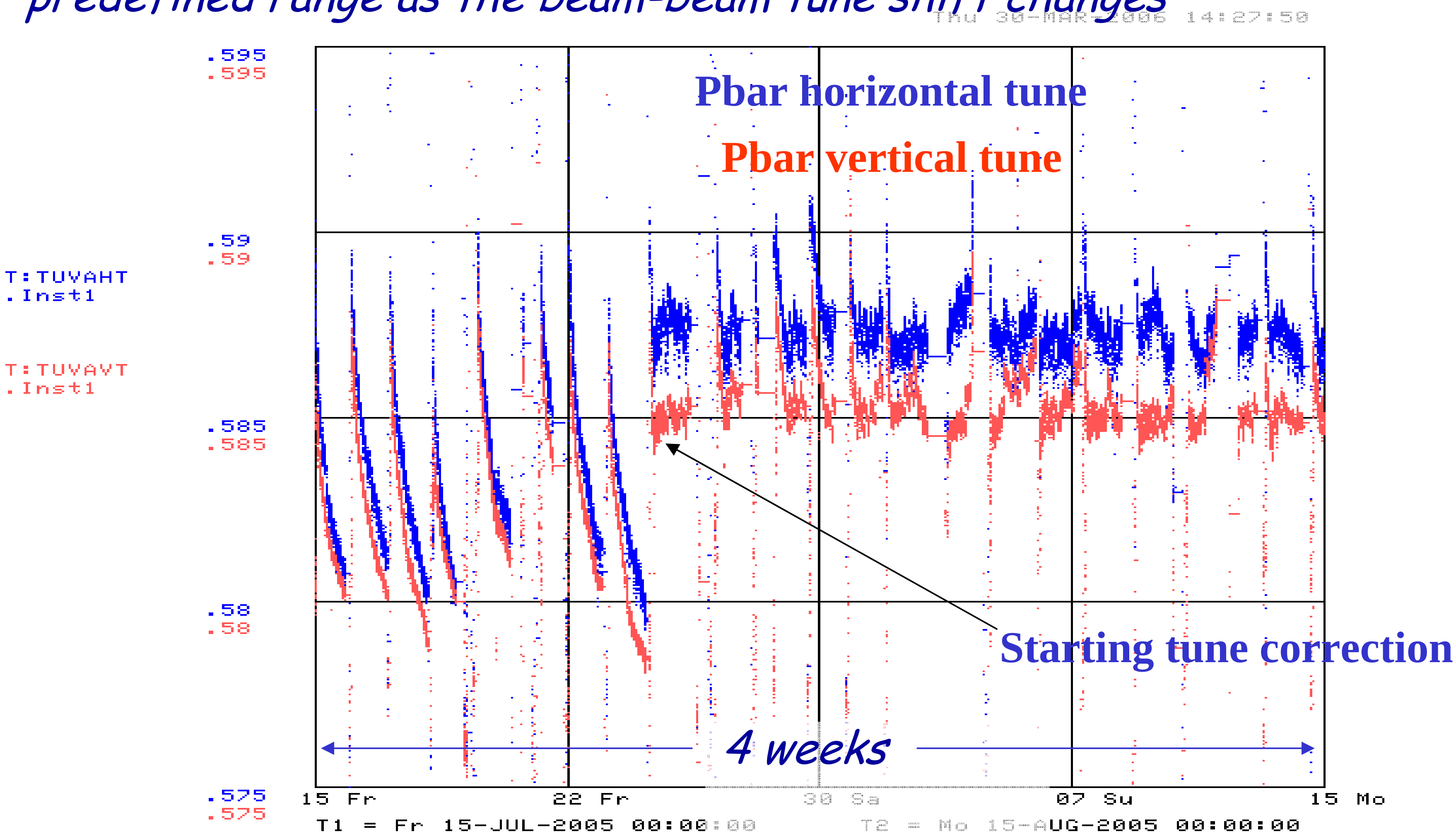
... non-invasive!

A.Jansson/P.Lebrun



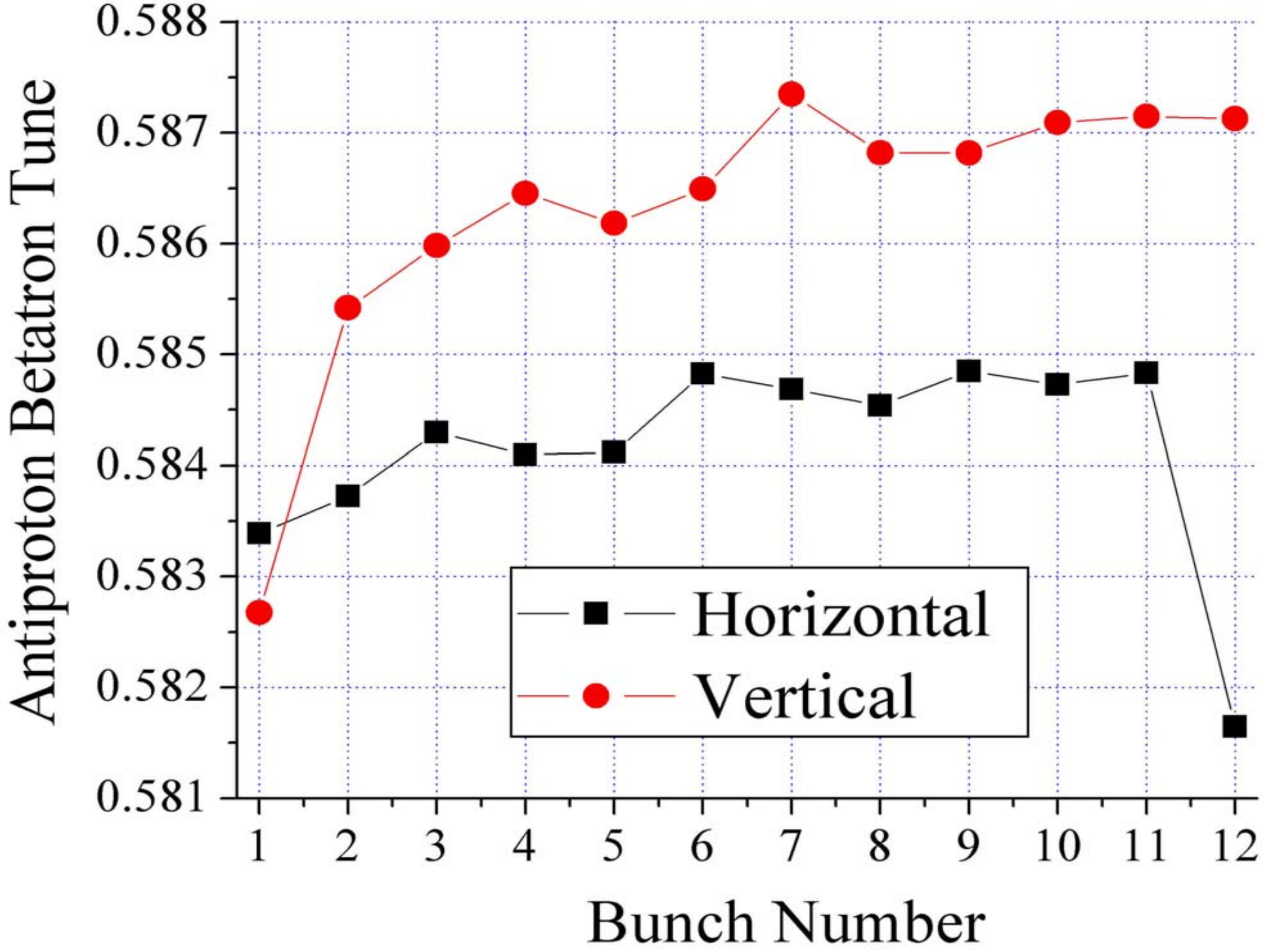
Tune stabilization

- *Operators use 1.7 GHz Schottky data to keep pbar tunes within a predefined range as the beam-beam tune shift changes*



1.7GHz Schottky Bunch Tunes

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

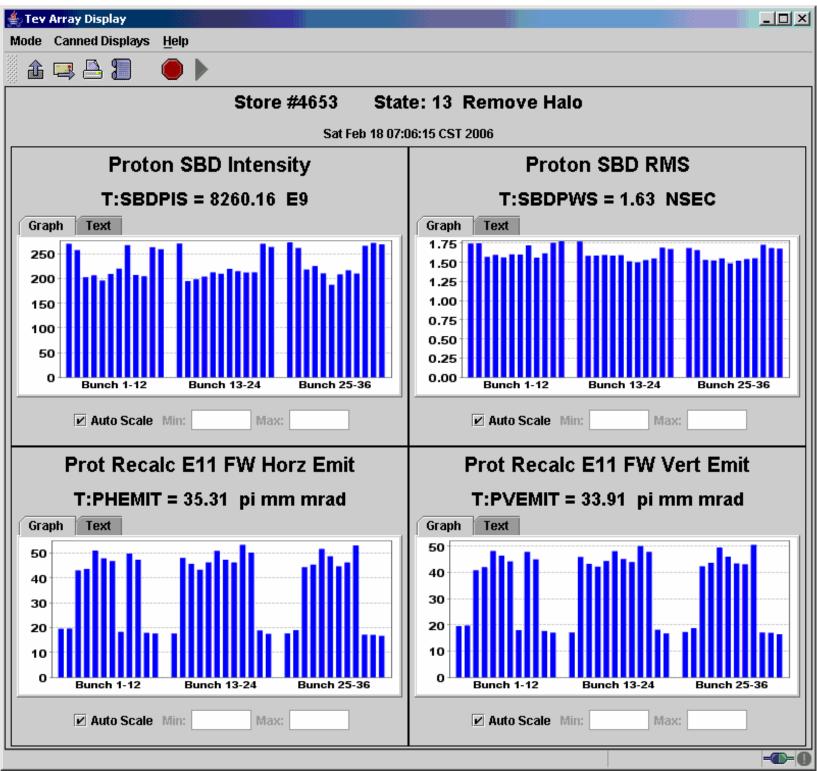


Plotting Bunch-by-Bunch Data
for each of 36 p + 36 pbar bunches

Observing differences in bunch-by-bunch behavior is very useful for understanding beam dynamics in the Tevatron

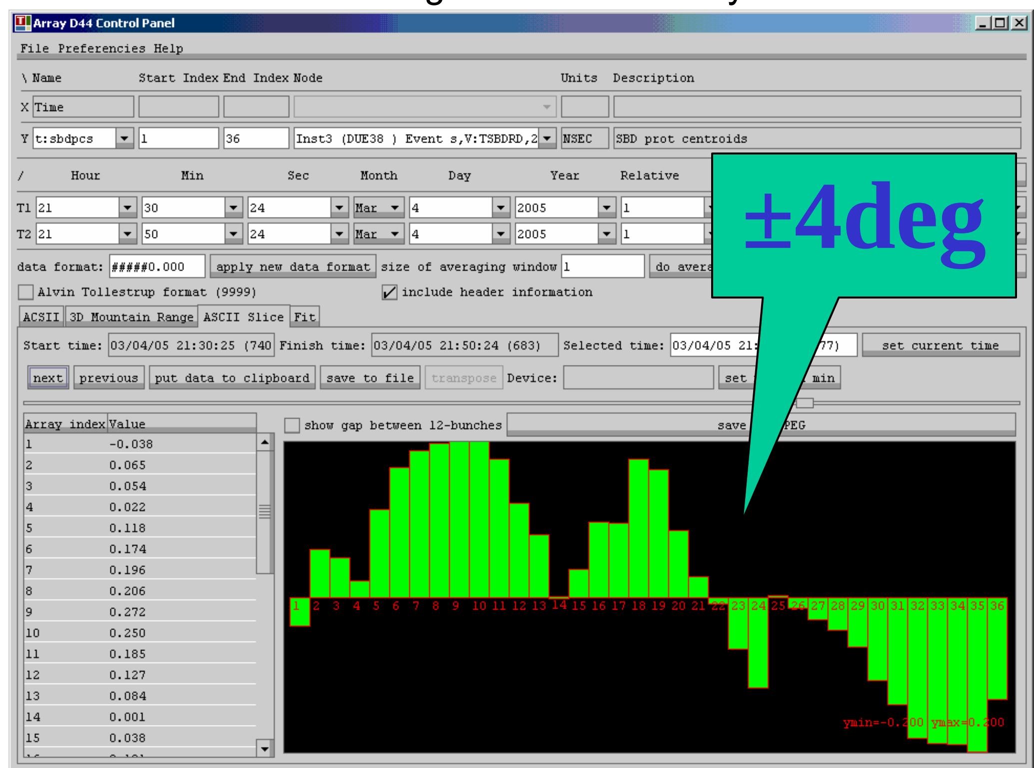
Live data

Instability @ 150 GeV resulted in interesting intensity and emittance patterns

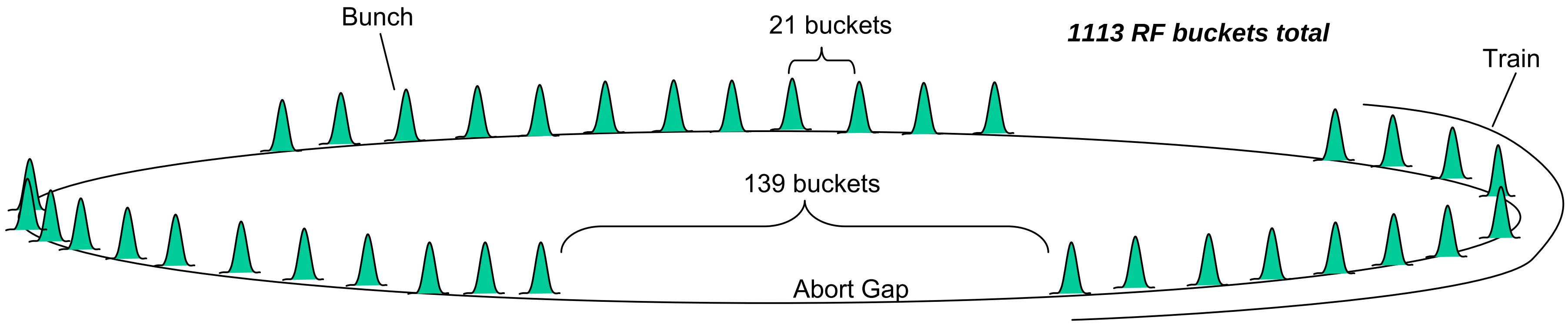


Logged data

Proton bunch centroid motion during longitudinal instabilitity



Intrabeam Scattering and Longitudinal Oscillations Lead to Generation of DC beam in Abort Gaps



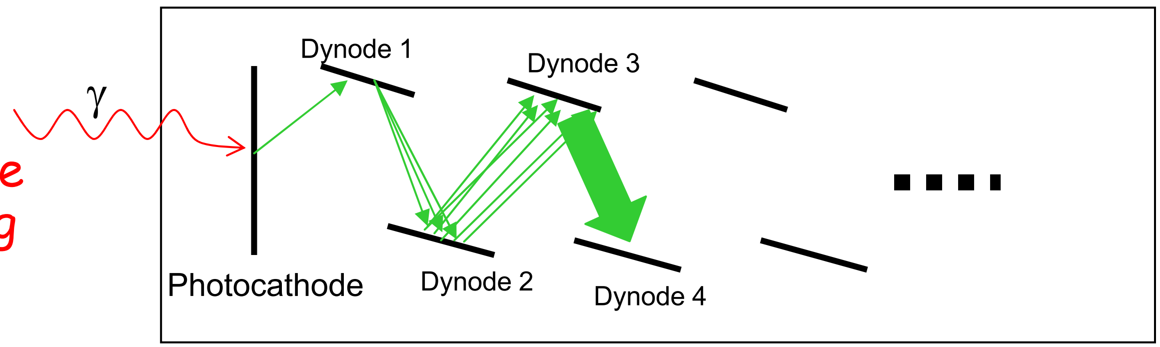
- The Tevatron operates with 36 bunches in 3 groups called trains
- Between each train there is an abort gap that is 139 RF buckets long
  - RF bucket is 18.8 ns → Abort gap is 2.6 μs
- Protons leak out of main bunches to the gaps. Tevatron is sensitive to few x 10^9 particles in the abort gaps (total beam ~ 10^{13}) as they lead to quench on beam abort (kicker sprays them)

Abort Gap Intensity Monitor

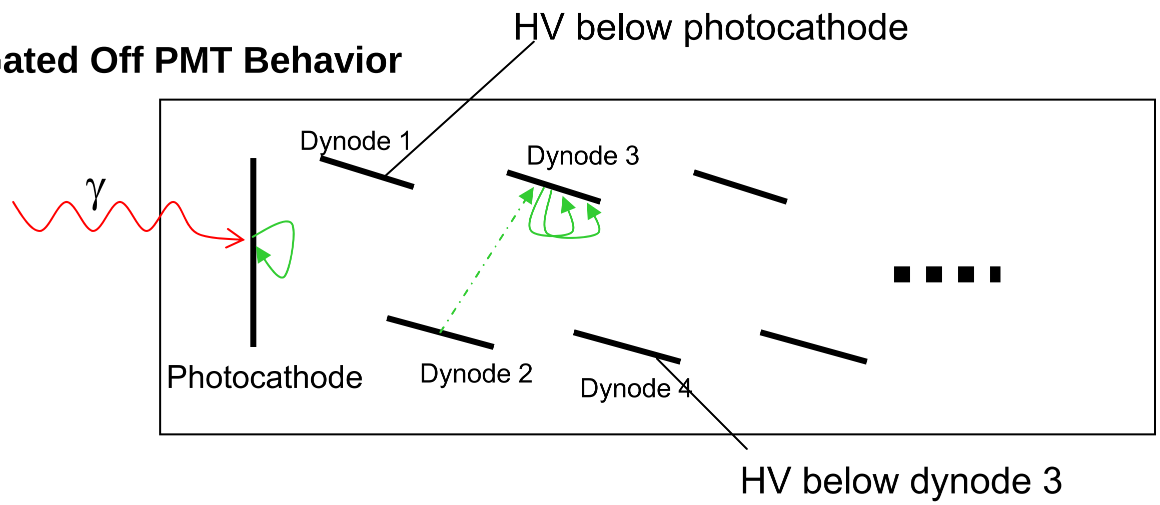
Hamamatsu gated MCP style PMT

- 5ns minimum gating time w/no noticeable settling time
- Very large extinction ratio
- Somewhat expensive (~$20K /tube)
- 2-stage Micro Channel Plate PMT – Gain of <= 10^6
- No sensitivity to pre-gate light

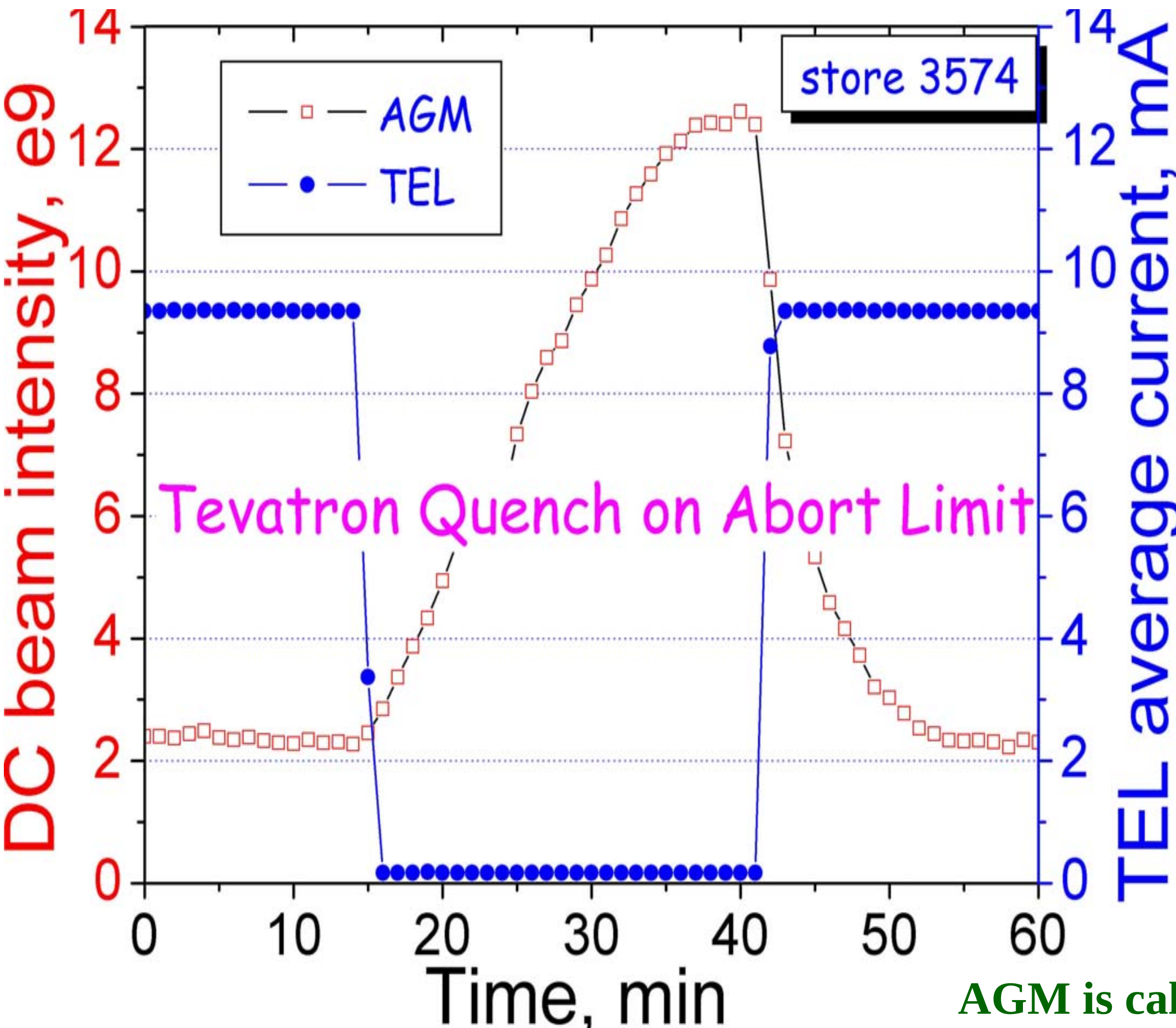
Nominal PMT Behavior (Gated On)

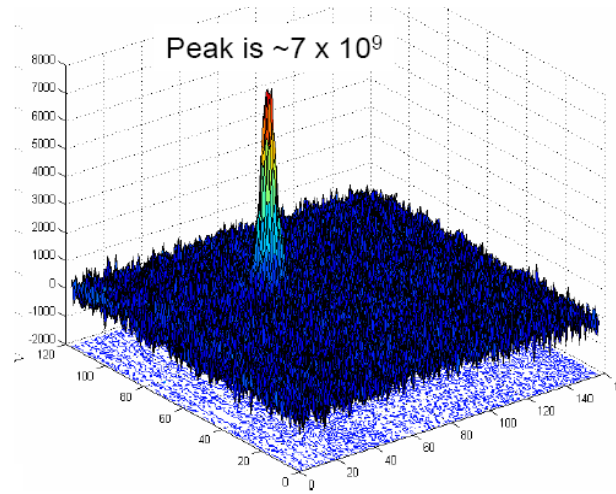


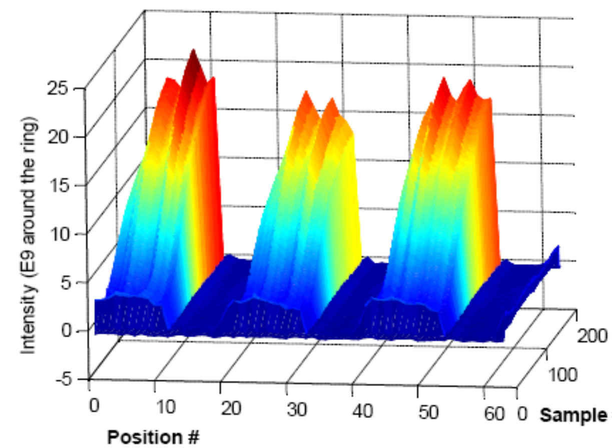
Gated Off PMT Behavior



DC Beam in Abort Gap:TEL On/Off/On



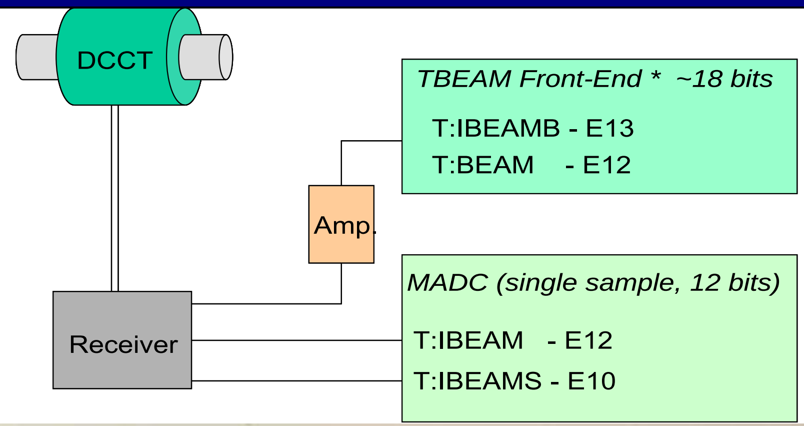




AGM is calibrated wrt to DCCT - the most precise Tev instrument.

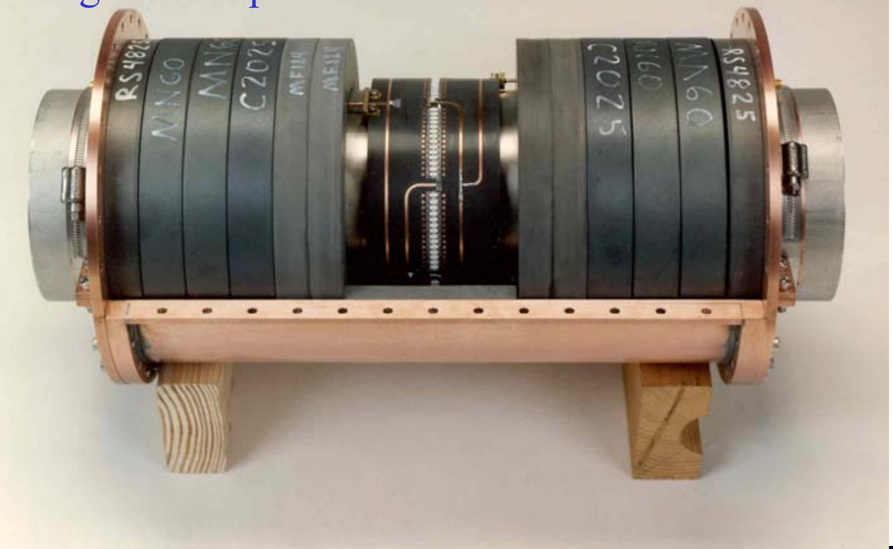
Intensity Measurements: DCCT and FBI

- DCCT (DC Current Transformer)
  - Typical intensities $10^9 \rightarrow 10^{13}$ p's
  - Noise ~0.5 e9 or ~0.005% max
  - 24-bit ADC samples @ 6.9 MHz
  - Output 128-sample average @ 54 kHz
  - Calibrate via external pulser
  - N_p+N_pbar together

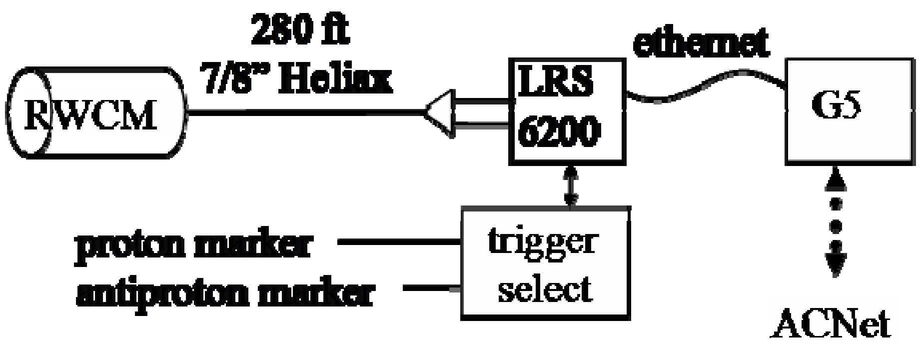


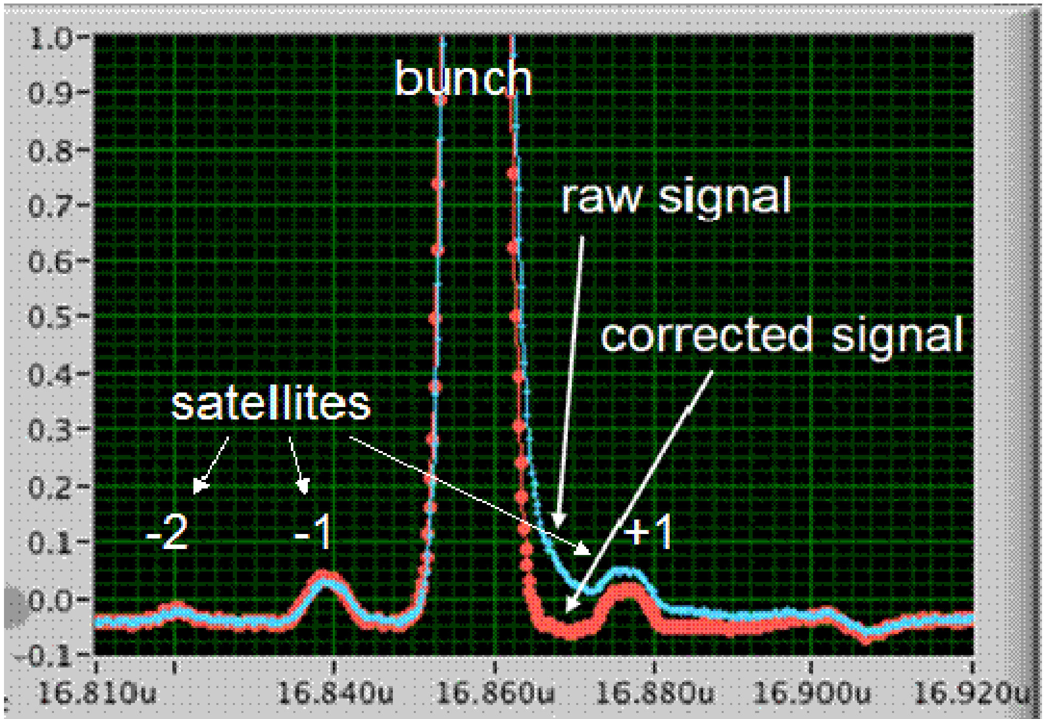
- FBI (Fast Bunch Integrator)
  - Bunch-by-bunch intensities via RWM
  - Narrow (1) & wide gates (5 buckets)
    - Main and satellite bunches
  - Updates @ up to few hundred Hz
  - Sensitivity to temperature improved
  - Calibrate via DCCT
    - Few % correction for satellites

Resistive Wall Monitor:
Ceramic break with 80 120Ω resistors.
Signals sampled at four locations are summed.



Sampled Bunch Display (SBD)

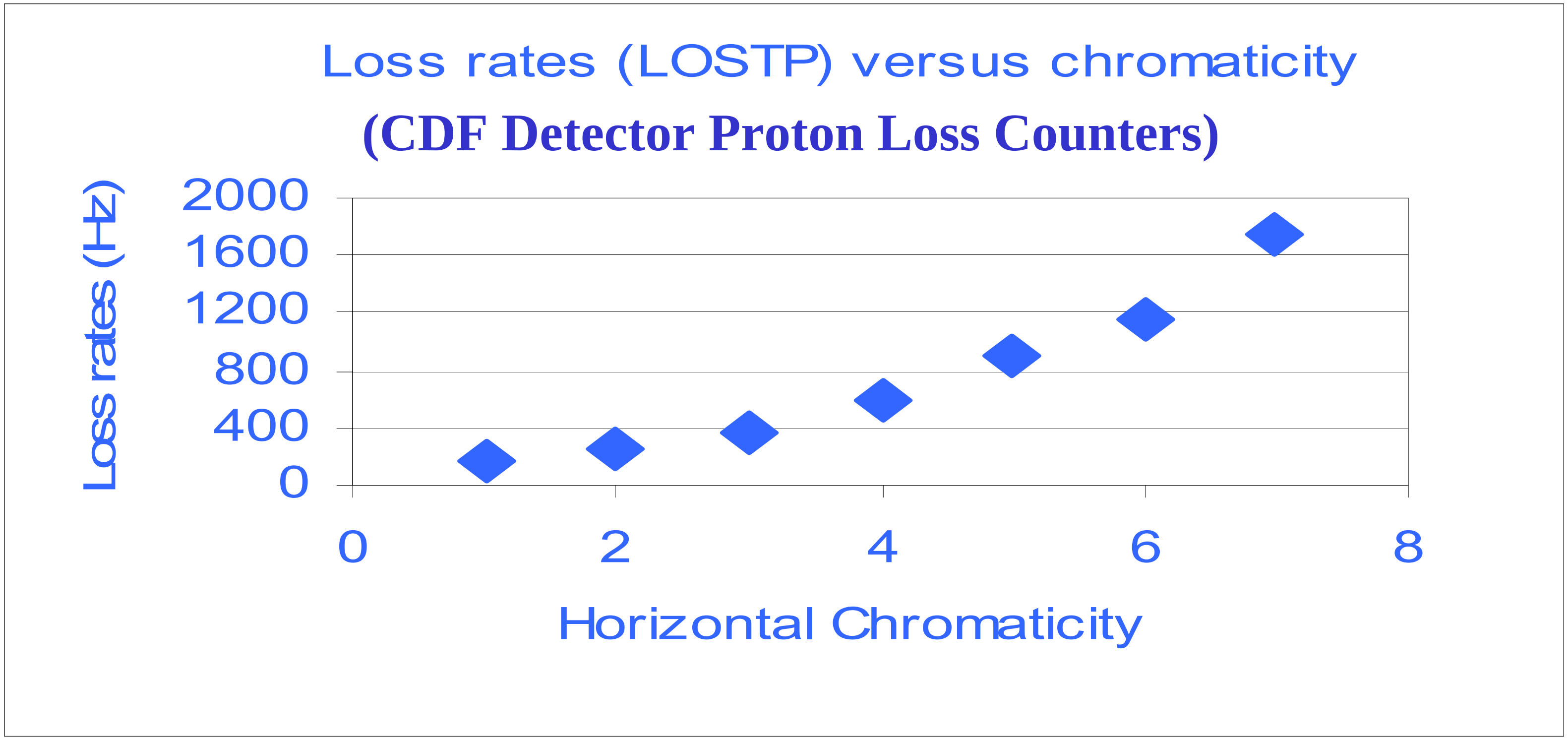




- Measure bunch intensities, lengths
  - Few – 350 × 10^9, 1-4 ns
  - Updates ≈ 1 Hz
- LeCroy WaveRunner 6200 captures waveforms over many turns in memory
  - 2 GHz bandwidth, 10 G-samples/sec
- Macintosh G5 does signal processing
  - 200 tap (0.5 ns/tap) FIR filter removes effect of dispersion in the long cable
- Resolution of intensity ~0.05% (5e9)
- Resolution of centroid position and RMS length ≈ 0.02 ns (RMS is ~2ns)

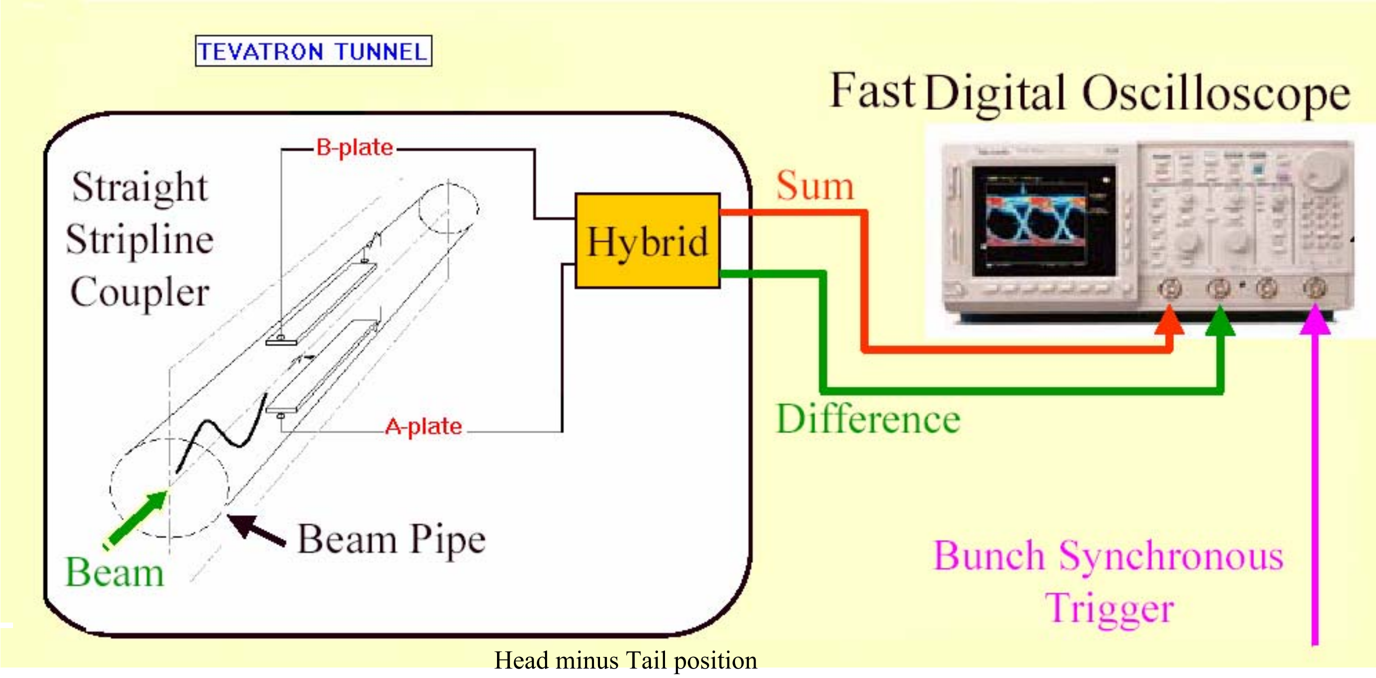
Figure 2: a proton bunch signal (raw) and after application of the FIR filter. The feature at the far right is a 3/4 % reflection. from one channel through the splitter to the other. Full height of the main bunch is ~5 amps.

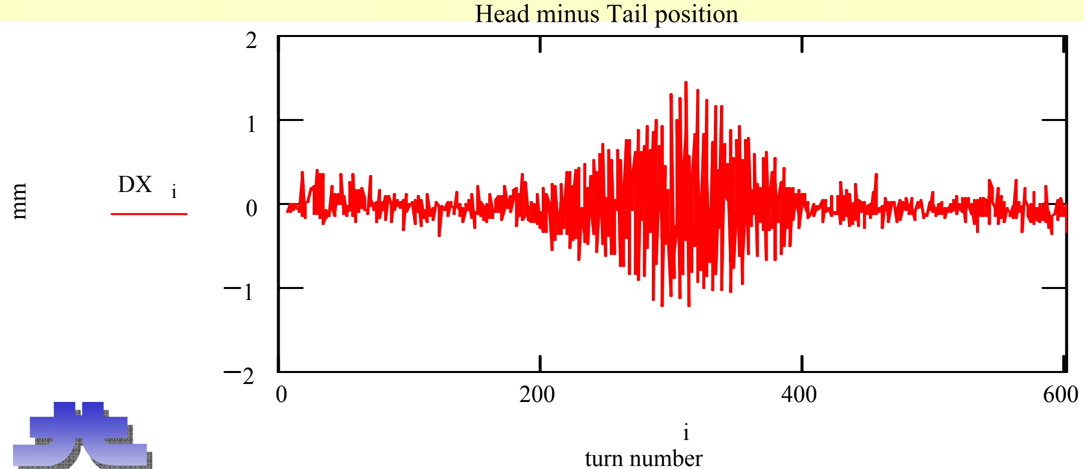
Beam Lifetime Depends on Chromaticity



- Two methods for fast Q' measurements:
  - Head-Tail Monitor
  - Fast and Accurate TuneTracker

Fast Q' Head-Tail Monitor





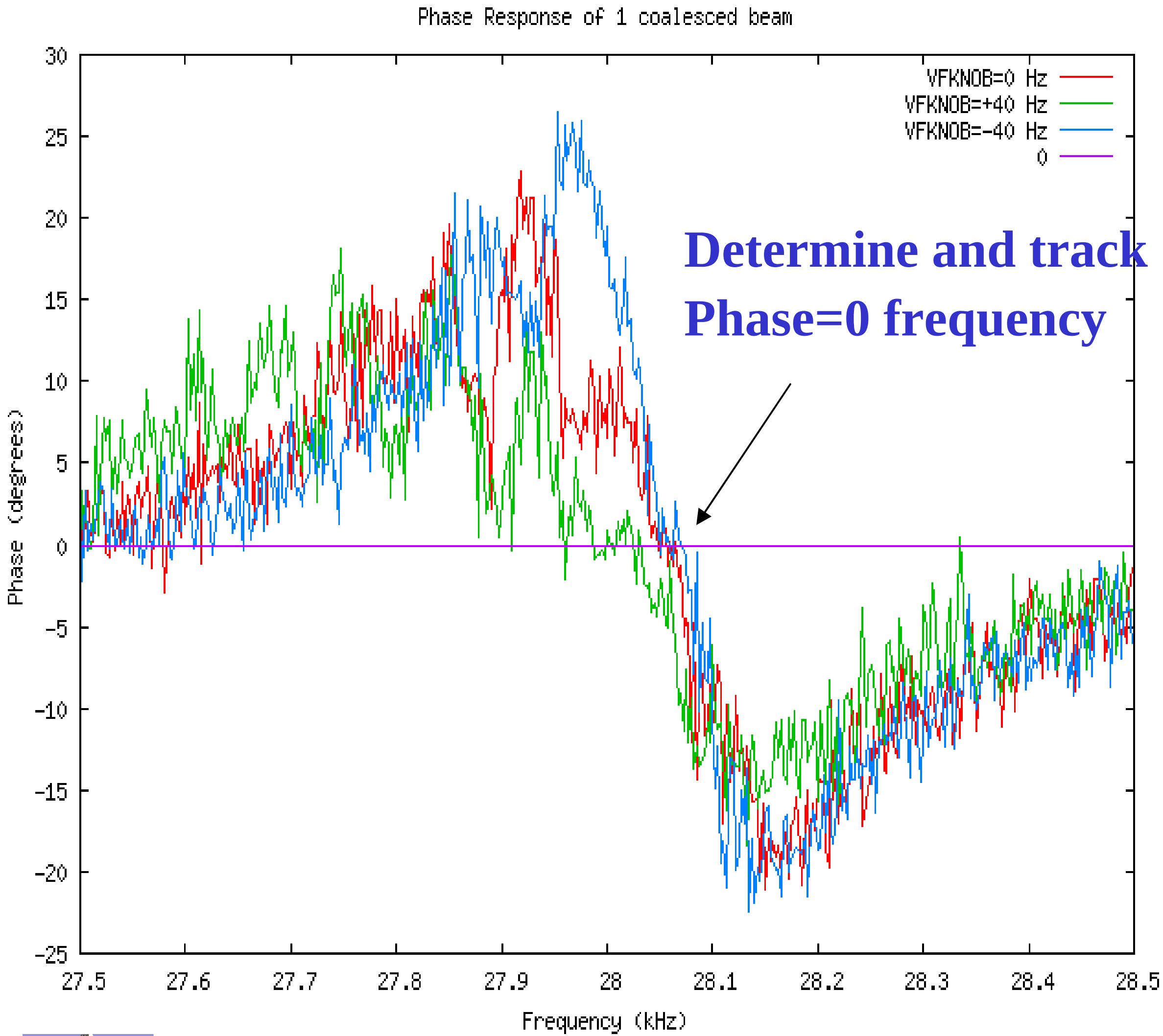
Particles with different dP/P have different tunes → head-tail phase difference ~Q'

Just few pi dε kick

Accuracy ~0.5 unit

- Very fast method
  - Ops like it!
- Currently used for monitoring
  - No difficulty to measure Q' with octupoles

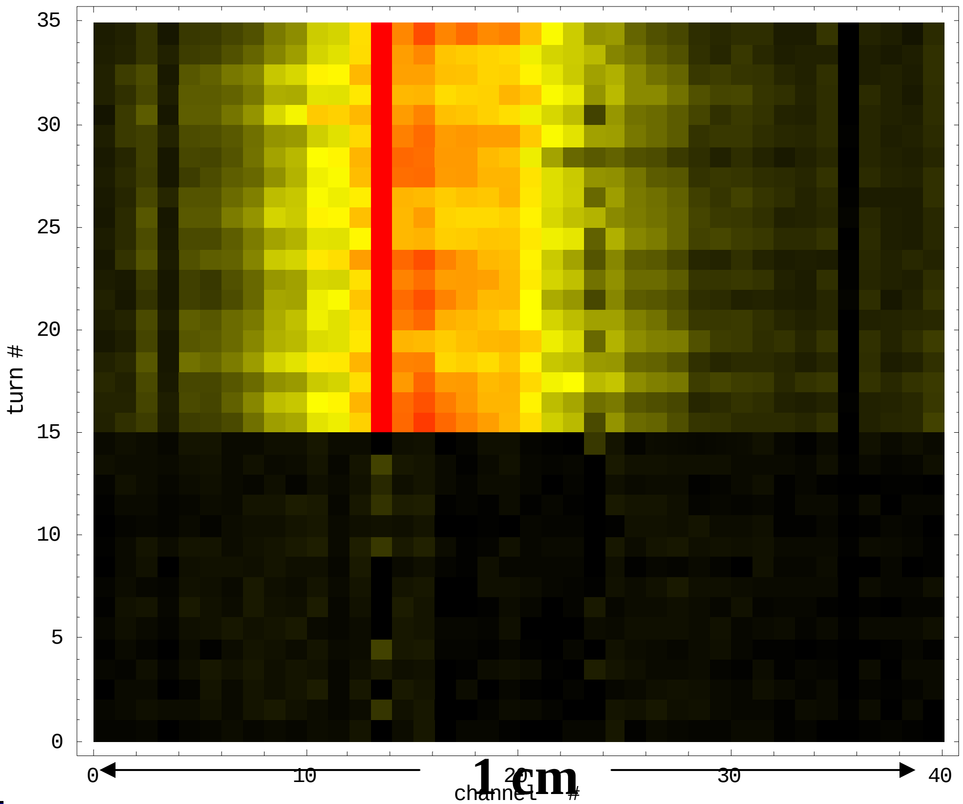
Fast and Accurate Tune Tracker

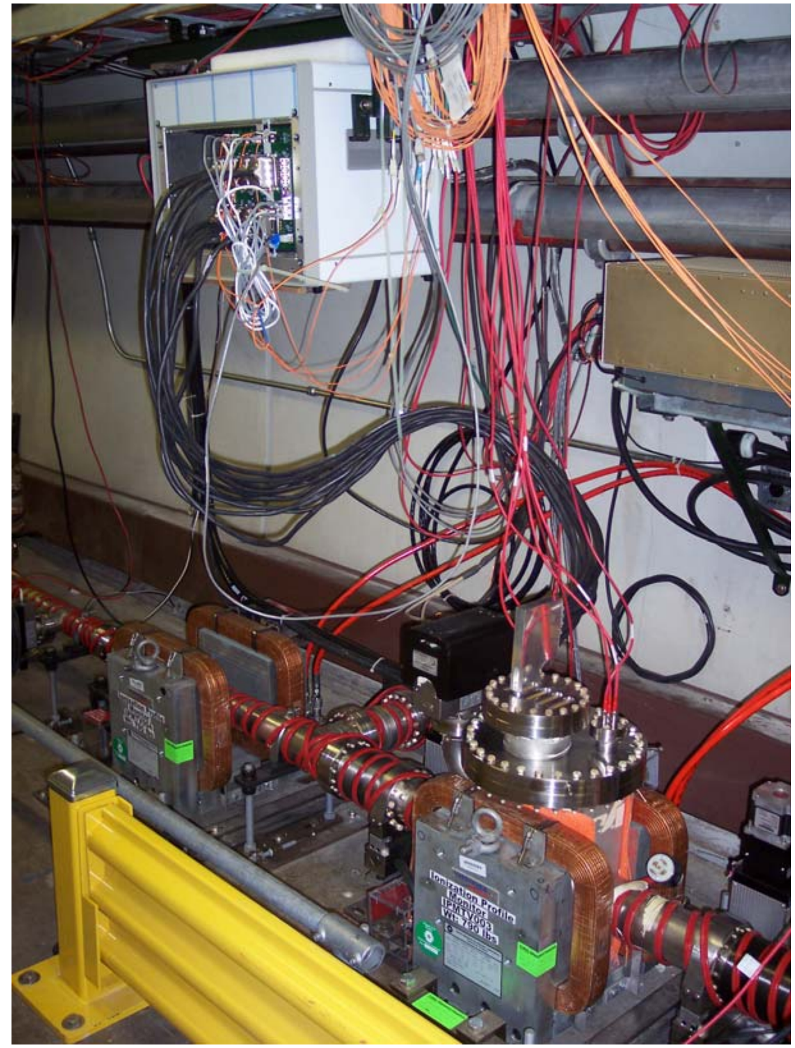


- Beam is slightly excited over a frequency range around f_betatron
- Zero phase response frequency declared =Q
- Accuracy in Q ~0.0001
- Very fast method (3Hz)
  - Works on every Tev ramp and in LB squeeze
- Change dP/P and determine Q'
  - Stat accuracy ~0.2
  - Syst error ~0.5 unit

Quadrupole Oscillations due to Lattice Mismatch: Ionization Profile Monitor

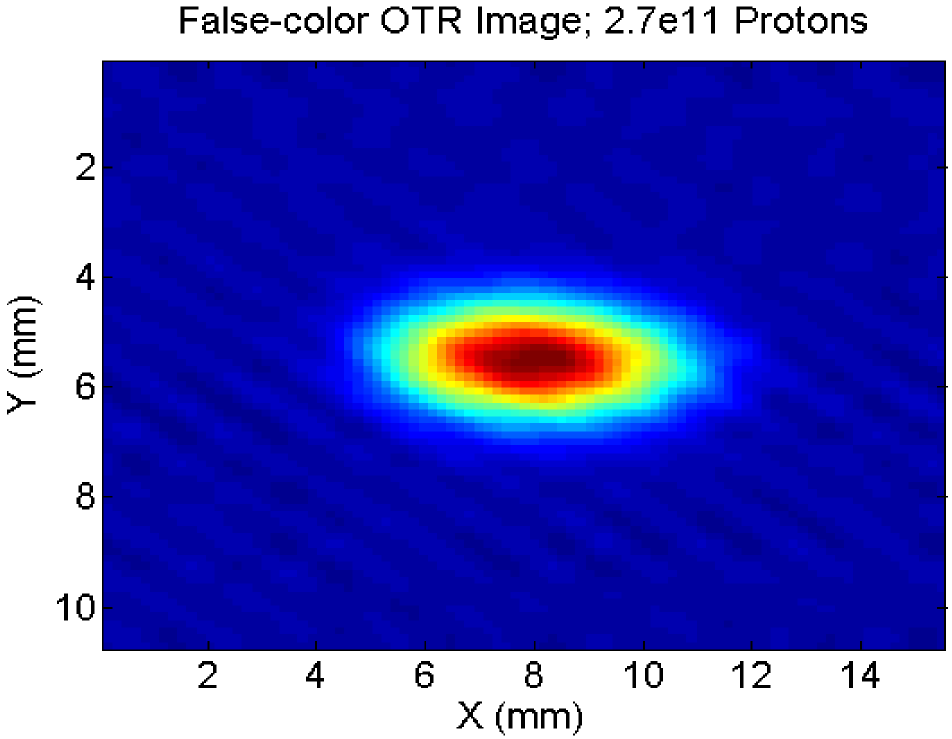
- Single bunch turn-by-turn beam size measurement.

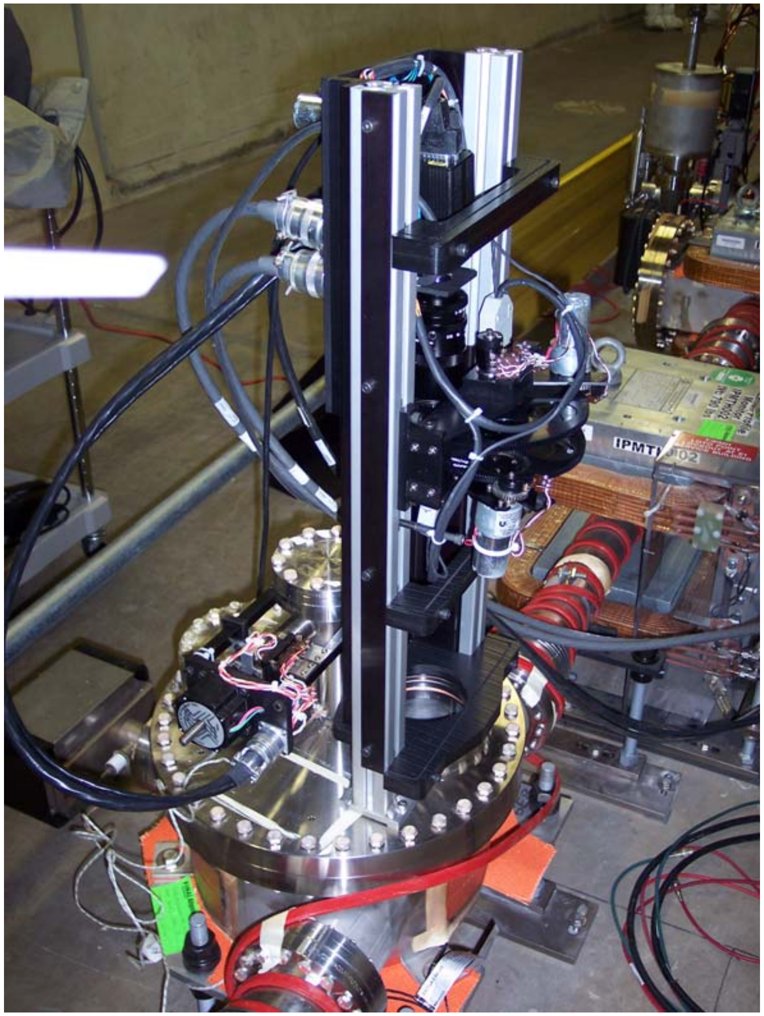




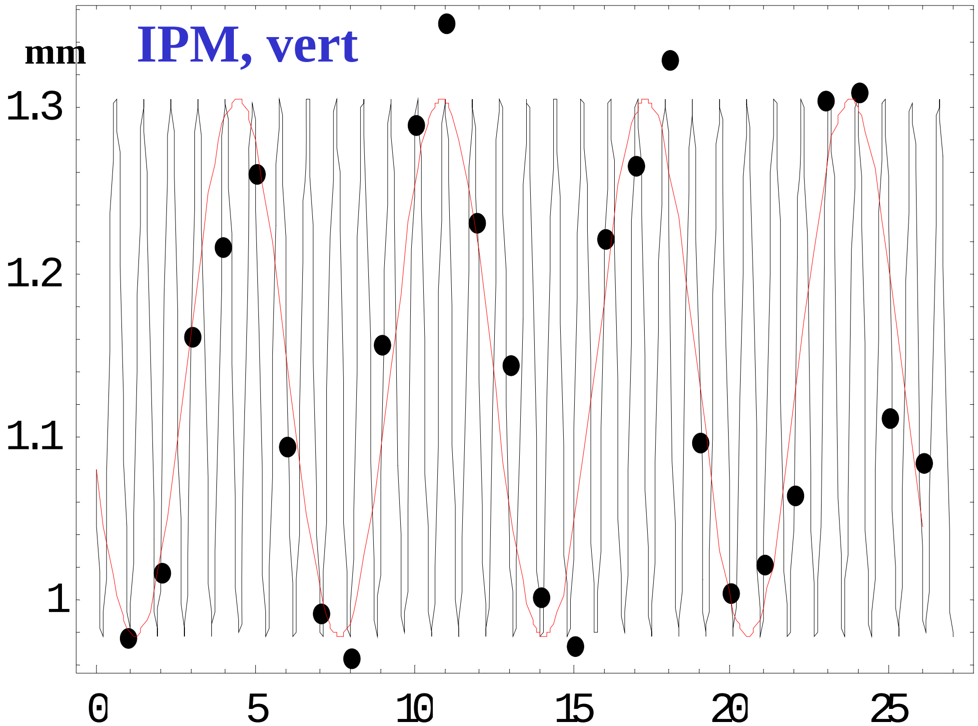
Optical Transition Radiation Monitor

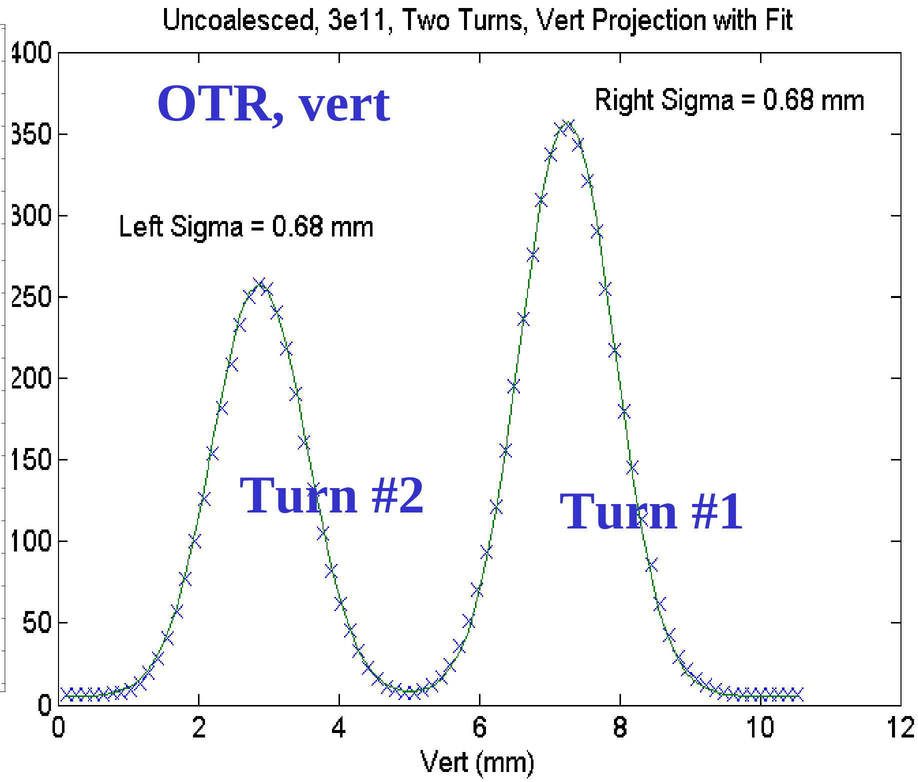
- 5 μm aluminized mylar foils
- Rad hard camera, 130x170μm size pixels





Both Instruments show mismatch





IPM shows significant (~30%) quadrupole oscillations

OTR shows no size change over 1 turn (#2 vs #1, note ampl.)

… just one example of importance of having several instruments for cross-checks →

Cross- Checks and -Calibration

- Intensity: DCCT and FBI and SBD
  - DCCT is most precise, but limited function
  - FBI and SBD within 1%, multi-functional
- Phase oscillations: SBD and LPM (slow and fast)
- Tunes: Schottky 21MHz, 1.7GHz, TuneTracker
  - All three in operations for different tasks
  - Absolute differences dQ~0.005, relative changes <0.001
  - TT fastest and precise, 1.7GHz most versatile
- Emittances: Flying Wires, SyncLite, Schottky
  - Tons of efforts to bring the three to within ~10%
  - FWs are ~main tool, used for 1.7 GHz Schottky calibr-n
- Luminosity: CDF and D0 different by ~5%

Beam Diagnostics: Lessons

- Due to peculiarities of SC synchrotron operation, non-invasive beam diagnostic instruments should be preferred, effects of intrinsically invasive ones minimized (FW 33→7um)
- Having two or more instruments for same beam parameter measurements (makes life more complicated to bring them together but) makes the data more trustworthy
- Fast data collection rate (at least 1 sec for all channels) is a must – at all stages, for all bunches, all the time – and saved for years (for postmortem)
- Detectors have tons of beam diagnostics, so good communication channels with them are important

Beam Diagnostics Lessons (2)

- Accept help/ideas from other groups/labs – many of them have invaluable expertise:
  - CD: BPM upgr; PPD: BLM upgr/SL/beta* monitors; LBL: Abort Gap Monitor MCP-PMT; ANL: e-cloud detectors, etc.
- An instrument development is fast, compared to time needed to make it "fully operational" and satisfactory for operators and physicists – a lot of efforts went into that →
- Team up diagnostics developers and users from the very beginning till commissioning of the instruments (and even beyond that – in operation)

Teaming Up for Instrument Development

Instruments	Developers	Commissioners, Users
Beam Line Tuner	D.McGinnis/V.Scarpine	J.Annala
dEmm@ Inj, "last sec"	V.Scarpine	A.Xiao/J.Annala
BPM upgrade	S.Wolbers/R.Webber	M.Martens/J.Steimel
21.4MHz Shottky	B.Fellentz	P.Lebrun/D.Still
1.7GHz Shottky	R.Pasquinelli	A.Jansson/V.Shiltsev
Tune Tracker	C.Y.Tan	C.Y.Tan/J.Annala
SyncLite/Abort Gap Monitor	R.Thurman-Keup	A.Valishev/V.Shiltsev
Flying Wires	J.Zagel/S.Pordes	A.Jansson/E.McCrory
IBEAM+SBD+FBI	R.Flora/S.Pordes	A.Tollestrup/J.Annala
Head-Tail Monitor	V.Ranjbar	V.Ranjbar
Baseband Schottky	A.Semenov/C.Y.Tan	V.Lebedev/J.P.Carneiro
Vacuum Diagnostics/RGA	B.Hanna	V.Shiltsev
HLS/Vibrations	J.Volk/T.Johnson	V.Shiltsev/J.Annala
Longitudinal Phase Monitor	A.Ibrahim	J.P.Carneiro/V.Shiltsev
Luminosity+IP diagnostics	CDF/D0	V.Papadimitriou/V.Shiltsev
IPMs/OTRs	A.Jansson/V.Scarpine	A.Jansson
Beam Loss Monitor upgrade	J.Lewis/S.Pordes	J.Annala/D.Still
Software (DLPlotter, OAC, SDA)	T.Bolshakov/Cntrls	R.Moore/J.Slaughter

As Collider Run is very long journey – special attention needed to maintenance & operation

6 yrs Statistics of Tevatron Run II

1292 High Energy Physics (HEP) stores in total

932 terminated intentionally; average store length: 22.4h

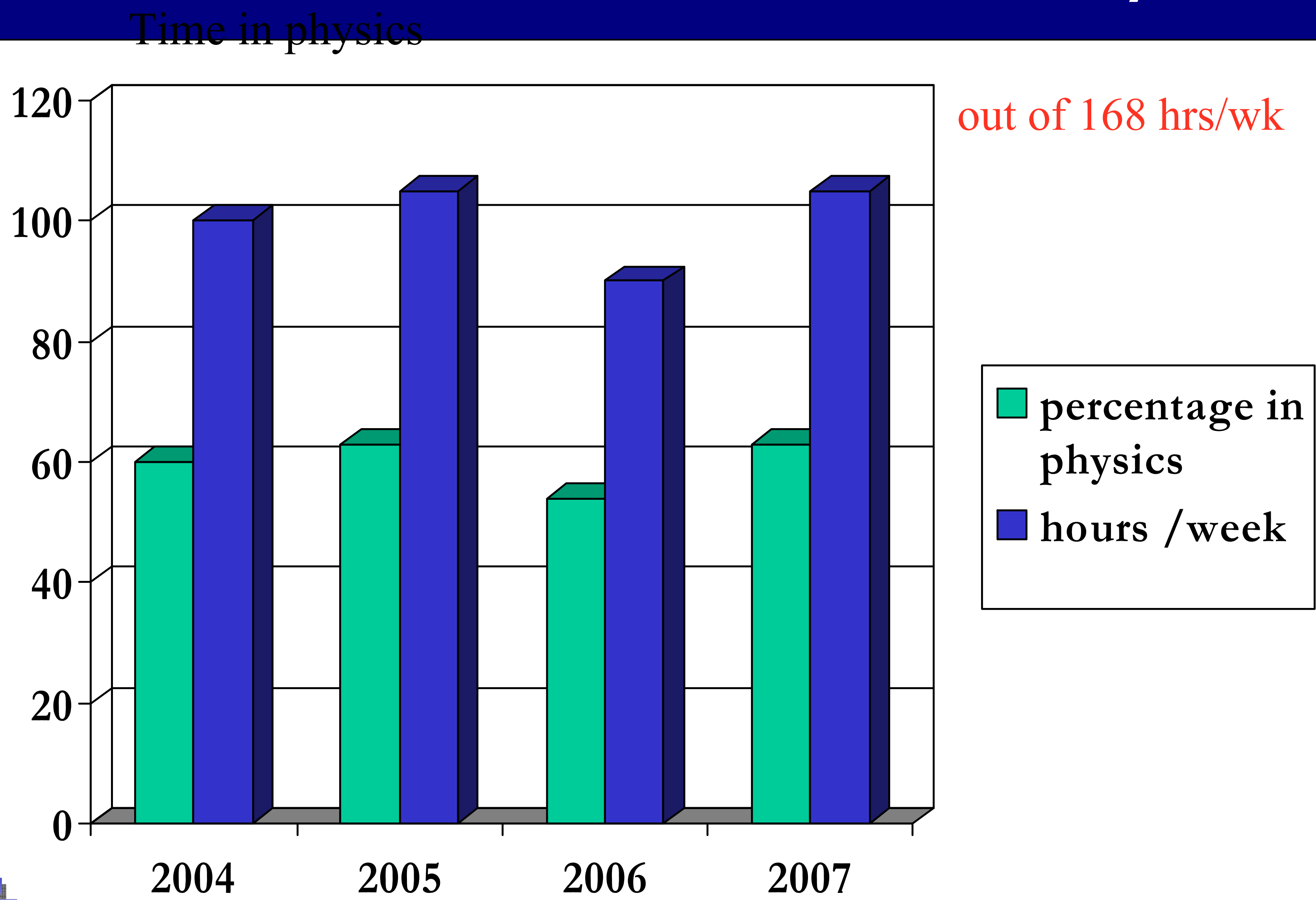
360 stores ended due to failures; average store length: 10.23h

Top 10 causes:

-cryogenics	49 →	13%
-lightening	40 →	11%
-quench protection	33 →	9%
-controls	29 →	8%
-separators	25 →	7%
-RF	25 →	7%
-low β quadrupoles	24 →	7%
-corrector magnets	20 →	5.5%
-human error	20 →	5.5%
-PC	20 →	5.5%

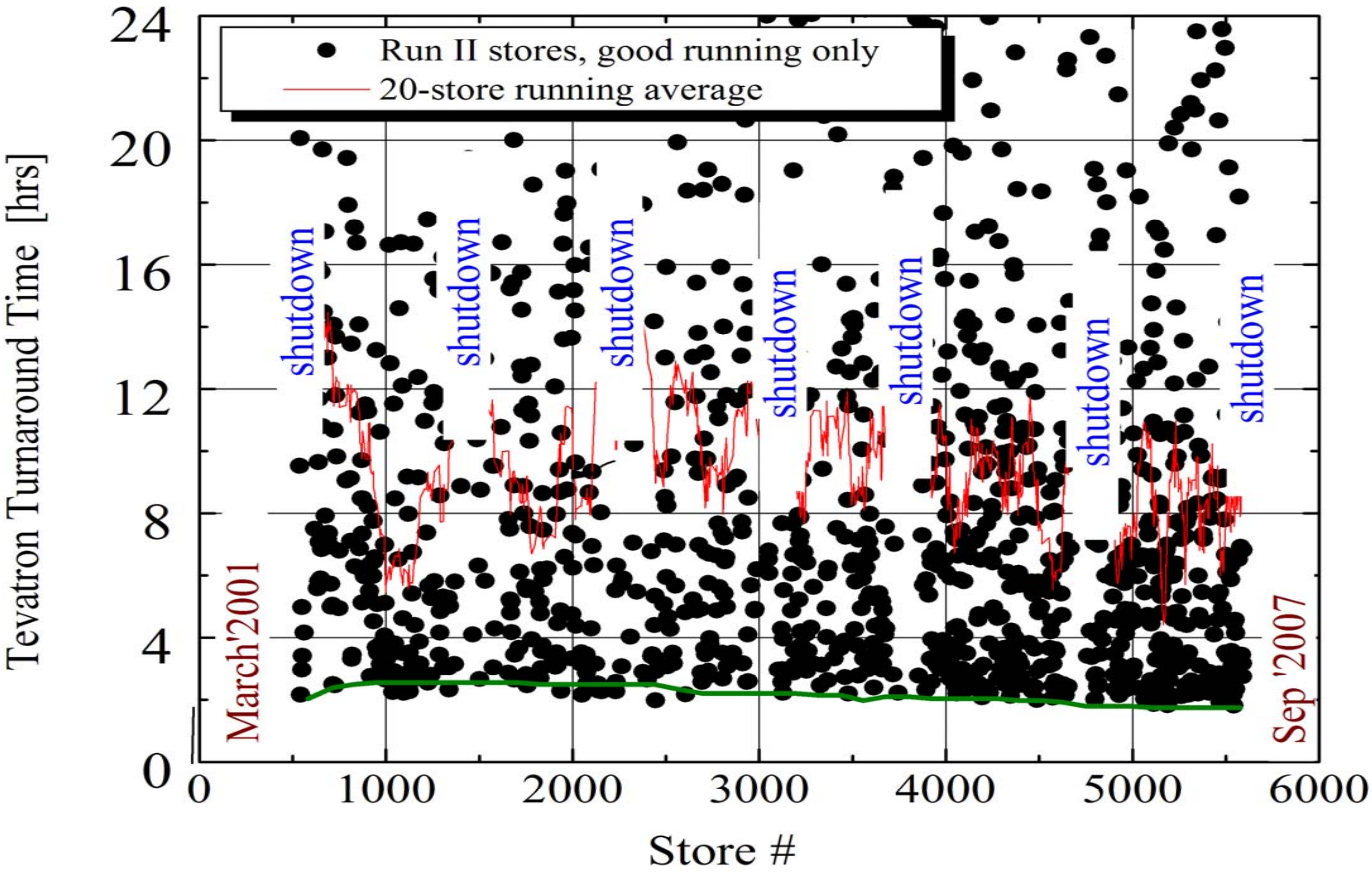
one can expect most of them also for the LHC operation!

Tevatron Collider: Time in Physics



out of 168 hrs/wk

Turn Around Time: ~2.5 hrs min



Maintenance and Reliability

- Trends in system failures and major vulnerabilities are tracked and mitigated as soon as possible. Examples of past problems:
  - Abort kicker prefires.
    - After extensive work, no prefires in over two years.
  - Quench Protection Monitor failures causing aborts.
    - Major overhaul of the system has resulted in 0 false aborts this past year due to the QPM system
  - Linac 7835 Power Amplifier tubes.
    - Working group formed that worked with the vendor and ultimately placed a “reserve stock” order for 12 tubes.

Tools to Track Problems

- The Primary tool available to all support departments is the Downtime log and the Downtime Summary.
- This is an electronic database in which any downtime is entered by the Operations Crew.
- The downtime is captured by machine and system.
- Available on the Beams Division Web Page for internal viewing.
- The system allows the compilation of downtimes to indicate developing fault trends.
- System failures are also discussed at daily 9:00 AM meeting to develop possible mitigation strategies.

Unpredictable: mouse incursion

Lets Talk Maintenance

- In the beginning of Collider (1980's) we ran until the wheels fell off then fixed them.
- Later we built in maintenance periods and often broke the machine in the process.
- Now we follow what is referred to by industry as: Reliability-Centered Maintenance (RCM)

Overview of the Concept

- Despite this commonly accepted view, Preventive Maintenance (PM) seemed to have *limited beneficial effects*. Indeed, in many cases, PM actually made things *worse* by providing more opportunity for maintenance induced failures.

What is RCM

- The objective of maintenance is to preserve the item's function(s).
- RCM focuses on the end system. (accelerator - for us)
- Reliability is the basis for decisions.
  - Failure characteristics of the item in question must be understood to determine the efficacy of preventive maintenance.

RCM cont.

- RCM is driven first by safety and then economics
  - Safety must always be preserved. When safety is not an issue, PM must be justified on economic grounds. Accelerator Performance for us.
- RCM acknowledges design limitations.
  - Maintenance cannot improve the inherent reliability – it is dictated by design.
- RCM is a continuing process.
  - Differences between the perceived and actual design life and failure characteristics are addressed through age (or life) exploration. Like the Cryogenic Wet Engine maintenance periods.

…no time left for horror stories… come tomorrow

Lecture 3 Thur: Beam Physics & Performance