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Tevatron Commissioning and Operating Experience

Mike Martens
Tevatron Dept, Fermilab
January 24, 2005

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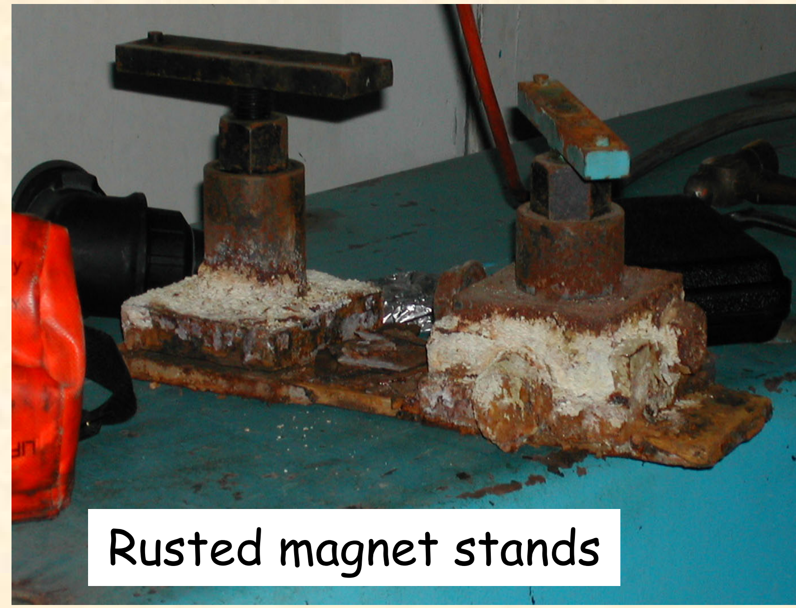
22 years of Tevatron

With a few hiccups…

Damaged spool piece



Rusted magnet stands

and signs of aging …

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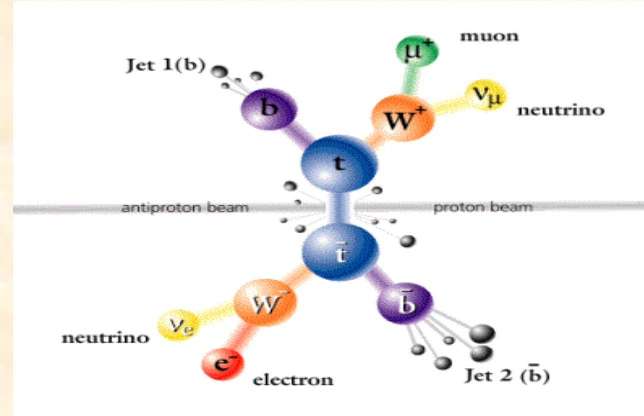
… but also success

Accelerator Division World Records for proton/antiproton collider operations:

- **980 GeV** proton/antiproton energy
- **1.05 E32 [1/cm^2/sec]** Initial Luminosity **(January 27, 2005)**
- **18.6 [1/pb]** integrated luminosity/week
- **246 E10** pbars stored in accumulator

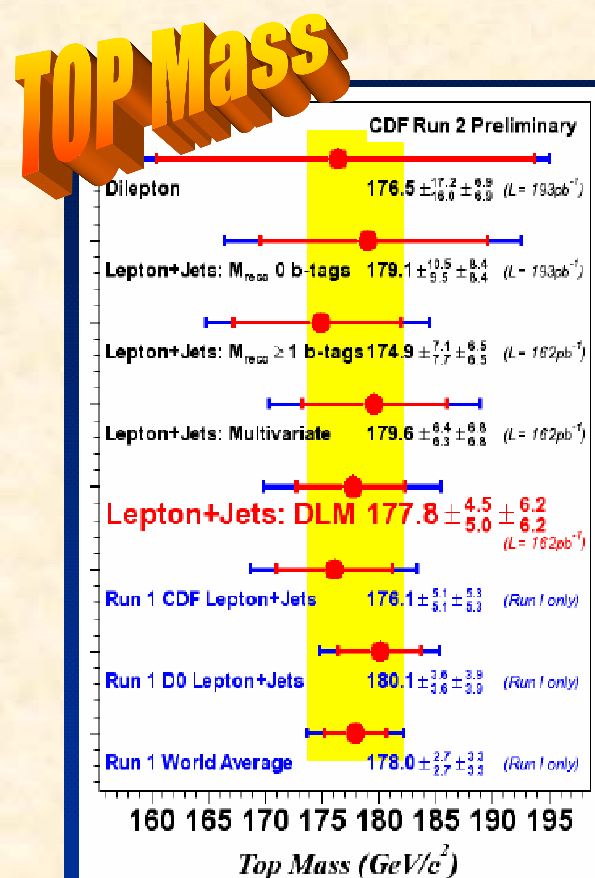
*The ISR acheived an initial proton-proton colliding beam luminosity of 1.4E32 [1/(cm**2 sec)] at 31 GeV in 1982.*

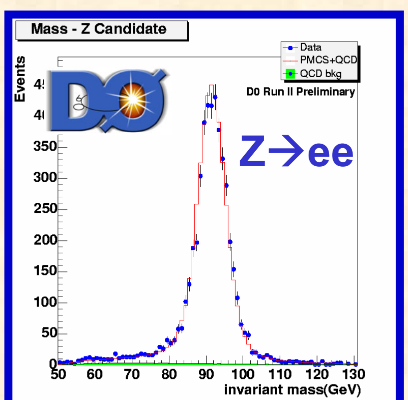
A Sample of New Results from CDF and DØ

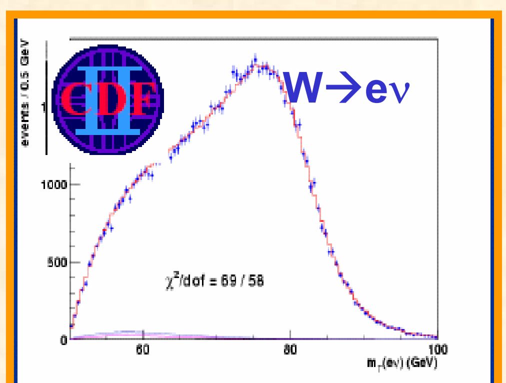


Recorded Lum ~ 0.5 fb^{-1}
Analyzed ~ 0.25 fb^{-1}

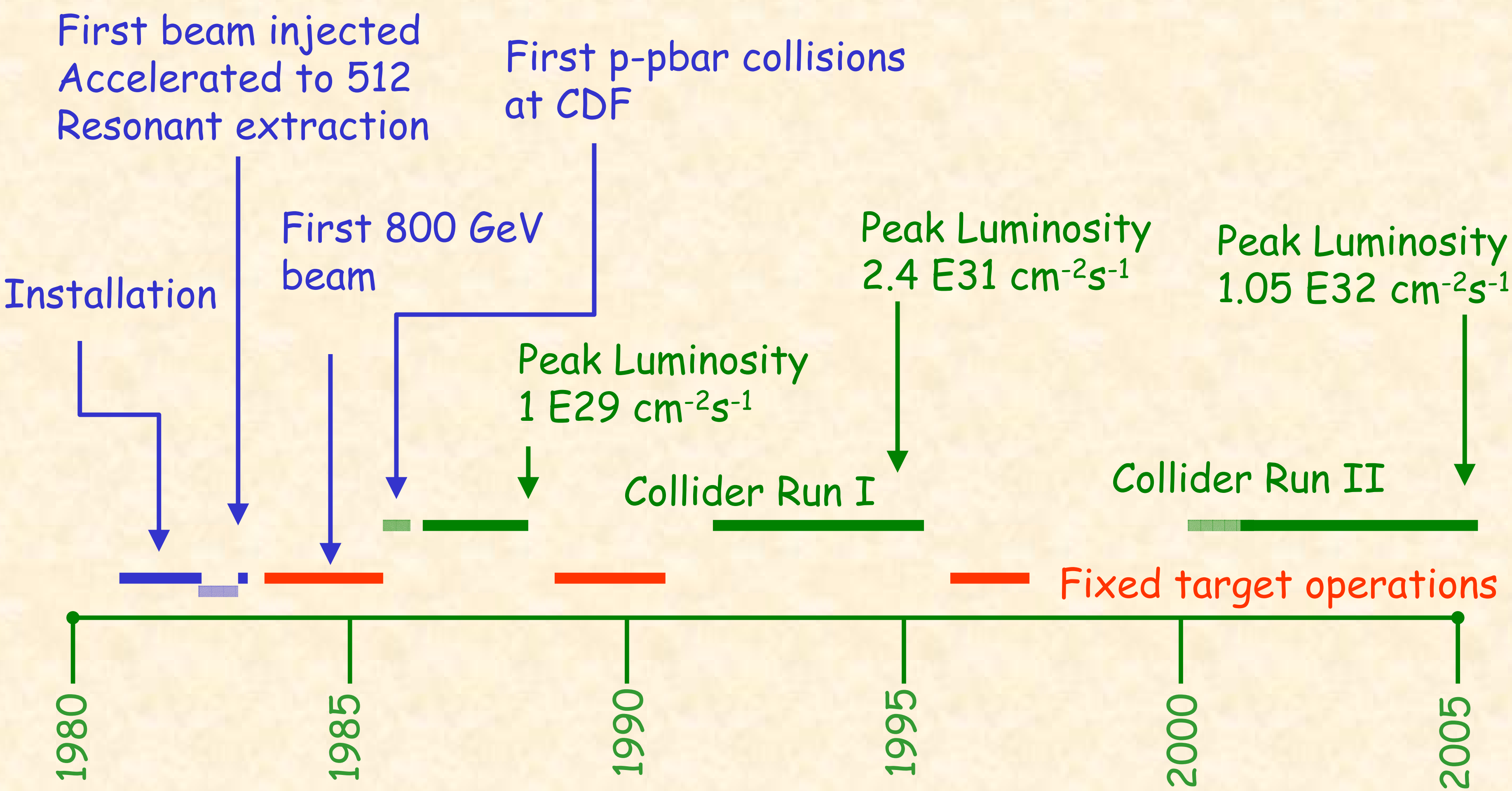
With 2 fb^{-1}, expect
→δm_{top}~2 GeV; δm_W~30 MeV; Prec. Meas.
→Observation of single top production
→SUSY ?? ED??



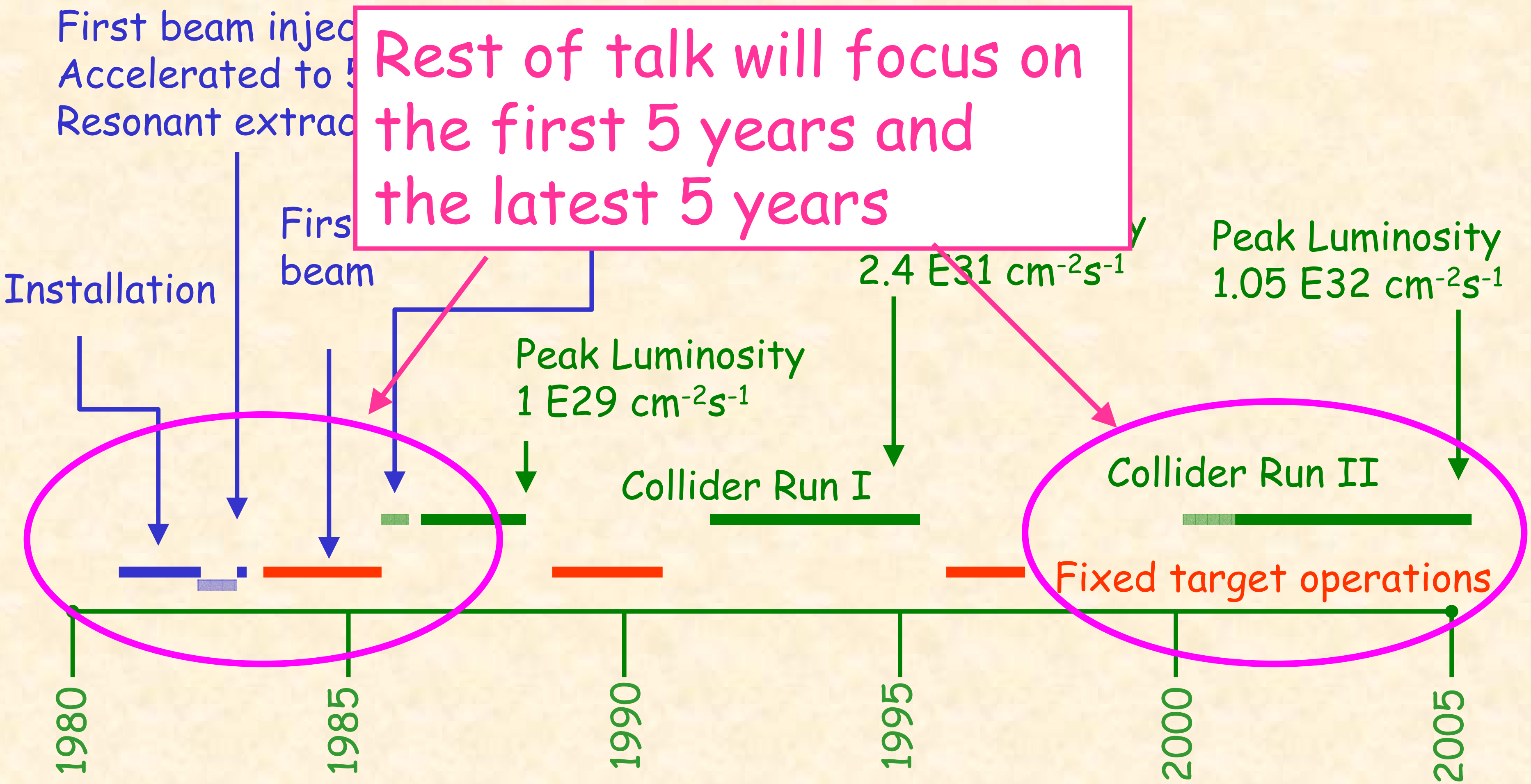




Fixed Target and Collider Operations



Fixed Target and Collider Operations



Fixed Target and Collider operations

- June 1981: Installation of Tevatron Begins
- June 2, 1983: First Injected Beam into the Tevatron
- July 3, 1983: First Accelerated Beam to 512 GeV
- Aug 2, 1983: Resonant Extraction to Switchyard
- Feb 1984: First 800 GeV beam in Tevatron.
- Oct 13, 1985: First p-pbar collisions at CDF
- 1988-89: Collider Run
- 1989-91: Fixed Target
- 1991-96: Collider Run I
- Sep 1996-97: Fixed Target Run.
- June 2000: Start of Collider Run II commissioning.
- March 1, 2001: Begin Collider Run II of the Tevatron.

My Experience

- 14 years in the Tevatron Group
- Divide my time
  - Accelerator Physics and Tevatron Improvement
  - Main Control Room Operations
- Roles
  - Collider Commissioning Team Member
  - Tevatron Coordinator
  - Fermilab Run Coordinator
- Witnessed
  - Commissioning of Collider Run I
  - Re-commissioning of Fixed Target Run
  - Planning and Commissioning of Run II

Tevatron Commissioning (1983)

- **Fixed Target commissioning was a success!**
- **Success was attributed to lots of preparation**

> "None of us who had gone through the startup of the Main Ring in 1971-72 wanted an experience like that again, so preparation was near-meticulous." – Don Edwards

- This part of the talk derives from comments & papers by Helen Edwards, Don Edwards, Rol Johnson, Bob Mau, Dave Augustine, Dave Finley, Mike Harrison, etc, …
- Useful Reference: **"The Energy Saver Test and Commissioning History"**, Helen Edwards, 12th International Conference on High-Energy Accelerators, 1983

First Commissioning

- Commissioning Steps
  - Magnet String Tests : Many from 1977 onwards
  - "3/4 A-sector Test" (1/8 of ring) : Six months in 1982
  - Installation Shutdown : Eight months in 82/83
  - Power Testing and 512 GeV ramp : Four months in 1983
  - First Injected beam to extraction : Two months in 1983
- Comparison between Beam and Magnet Measurements
- Operational Experience and Reliability

Magnet String Tests

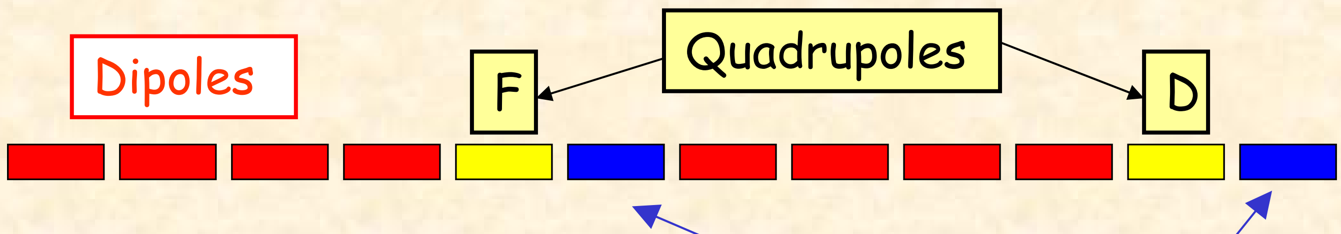
"The importance of the test efforts carried out during the Energy Saver R & D and construction phase cannot be emphasized enough" – from paper by H. Edwards

- Magnet String Tests (1978)
  - Five half-cells installed and cooled down
  - 100 GeV beam through 500 feet of cryogenic magnets
  - Learned about quenches from injection
- **"3/4 A-sector Test" representing 1/8 of ring (1982)**
  - Tested full potential of cryo systems and pressure piping, controls, power supplies, voltage to ground, and quench protection systems

Resulted in reliable enough operation during beam start-up

Six months of testing

Standard Tevatron Cell



774	Dipole
222	Quadrupole
206	Corrector package
26	Feedcan
22	Bypass
27	Turn-around box
11	Other

1293	**Cryo Components**

Corrector Packages Contain:

Trim quadrupoles
- T:QF focussing circuit
- T:QD defocussing circuit
- T:SQ skew quad circuit

Trim sextupole correctors
- T:SF at focussing locations
- T:SD at defocussing locations

Dipole correctors

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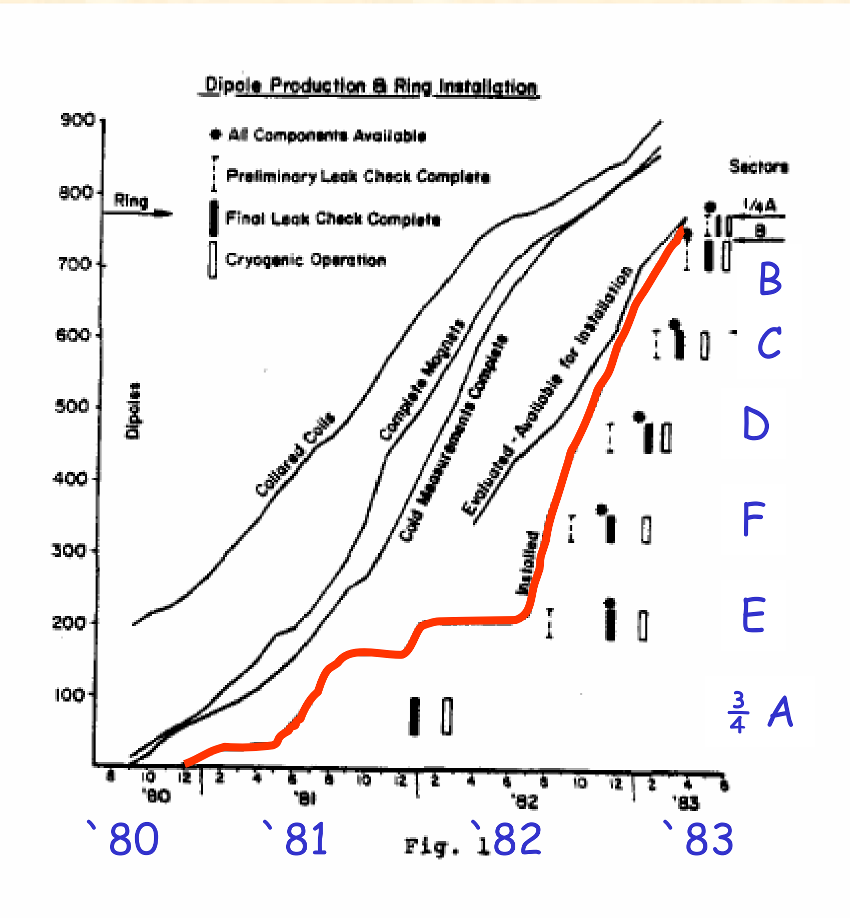
Installation



- 15 months total time period
- Peak of 54 people total
- Six months from time magnets ready till string was finally cold
- ~3 months from final leak check to cryogenics operations

Installation

- Handling Damage
  - 3% of dipoles with vacuum leaks
  - 13% of correctors and special components with vacuum leaks
  - Even though devices were leaked checked before installation
- High failure rate of vacuum seals (>25%)
  - New type of seal was used and failure rate was insignificant
- Largest effort went into interface connection and leak check
  - Four splice connections
  - Four small flange connections (beam pipe and cryo)
  - One large flange connection
  - **Estimated 50 man hours per interface X 1200 interfaces**

Problems requiring warm-up

- Two cryo sections had leaks because of broken ceramics
- One dipole with turn-to-turn short
  - The short disappeared when collared coil was removed from cryostat
- Two splices of the power bus were not soldered during installation
- Six beam detectors were in the wrong configuration
- Five beam detectors had internally broken connections
- Three corrector magnets with low impedance to ground
- Leaks at eight locations required additional external pumping

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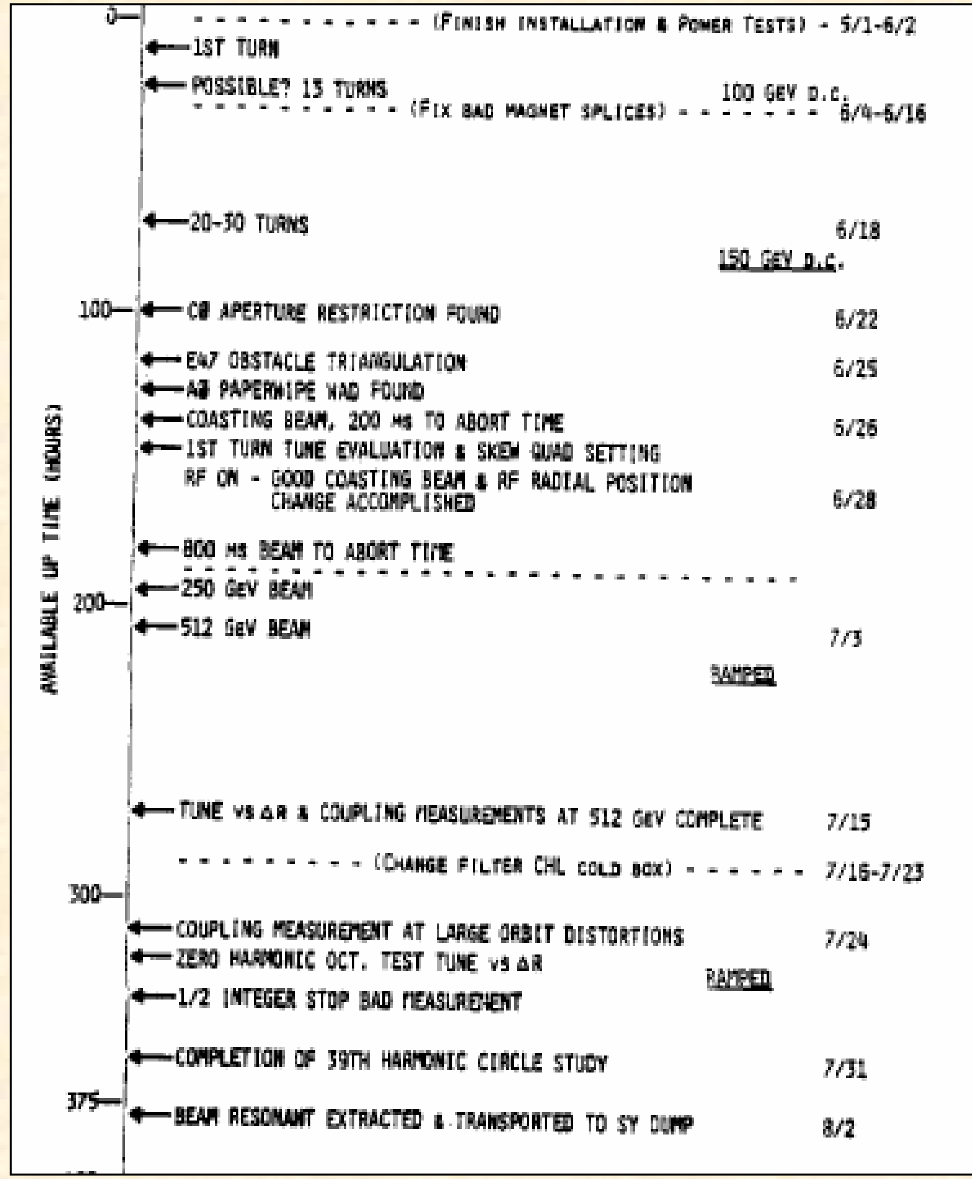
Beam Test and Commissioning

One month from first injection to 512 GeV. (210 hours of available uptime)

Three weeks of beam measurements (165 hours of uptime)

Several days for extraction

Two months from first injection till resonant extraction.



Aperture Restrictions

- At startup 3 aperture restrictions found
  - Error in beam pipe design
  - Wad of paper in the beam tube
  - Bumped around an unknown aperture restriction.
- BPM/BLM's crucial for locating aperture restrictions
  - One turn position and intensity information
  - Self-triggering on beam intensity
  - Circular buffer memory halted on an abort

Comparison to Magnetic Measurements

- Measured Tunes $\nu_x = 19.6$, $\nu_y = 19.2$
  - Expected tunes ($\nu_x = \nu_y = 19.4$) is avg. of measured $(\nu_x + \nu_y)/2$
  - Need $\langle b_1 \rangle = 1.5$ units in dipoles to explain tune shift
  - This is inconsistent with Magnet Test Data

Source is unknown

- Coupling reduced to $|\nu_x - \nu_y| \sim 0.01$ with skew quad correctors
  - Need $\langle a_1 \rangle = 1$ unit in dipoles to explain strength of skew quad
  - This is inconsistent with Magnet Test Data

More on this later

- Measured Chromaticity different than expected
  - Ideally the measured $\langle b_2 \rangle$ is corrected by correctors
  - About $\langle b_1 \rangle = 1$ unit of sextupole is unaccounted

Persistent currents were not understood at the time.

Success in Commissioning…

…was attributed to

- Lots of Preparation
- Paid attention to reliability
- Magnet string and A-Sector test of magnets were important
- A “focused” commissioning effort - daily meeting to plan the days events.

Early Operational Experience

- Useful Reference: “Operational Experience with Superconducting Synchrotron Magnets”, P.S. Martin, PAC 1987
- Biggest (but not only) problem was broken superconducting leads between magnets.
- Persistent Current Effects (Chromaticity Drift and Snapback) were a surprise for collider operations

Tevatron Magnet Leads

MAGNET ENDS AND FAILURE MODES

Figure 1 shows Tevatron dipole ends .

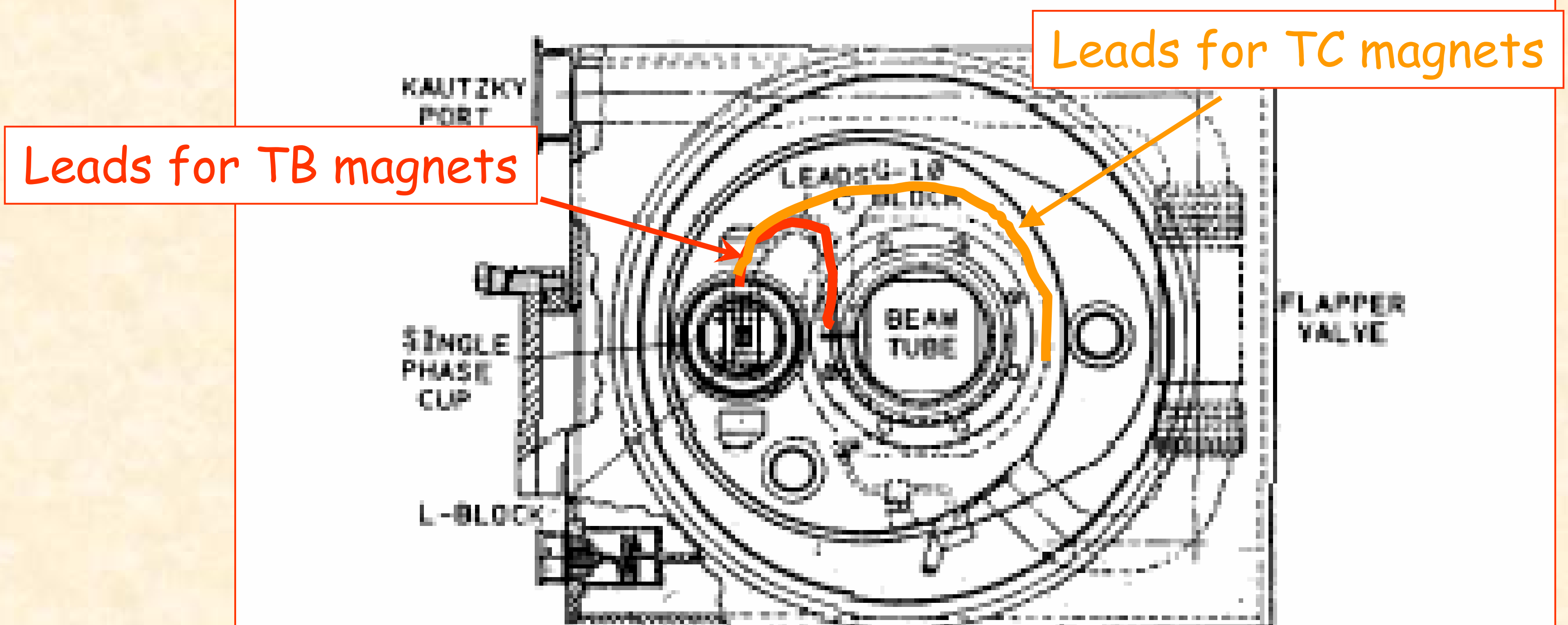
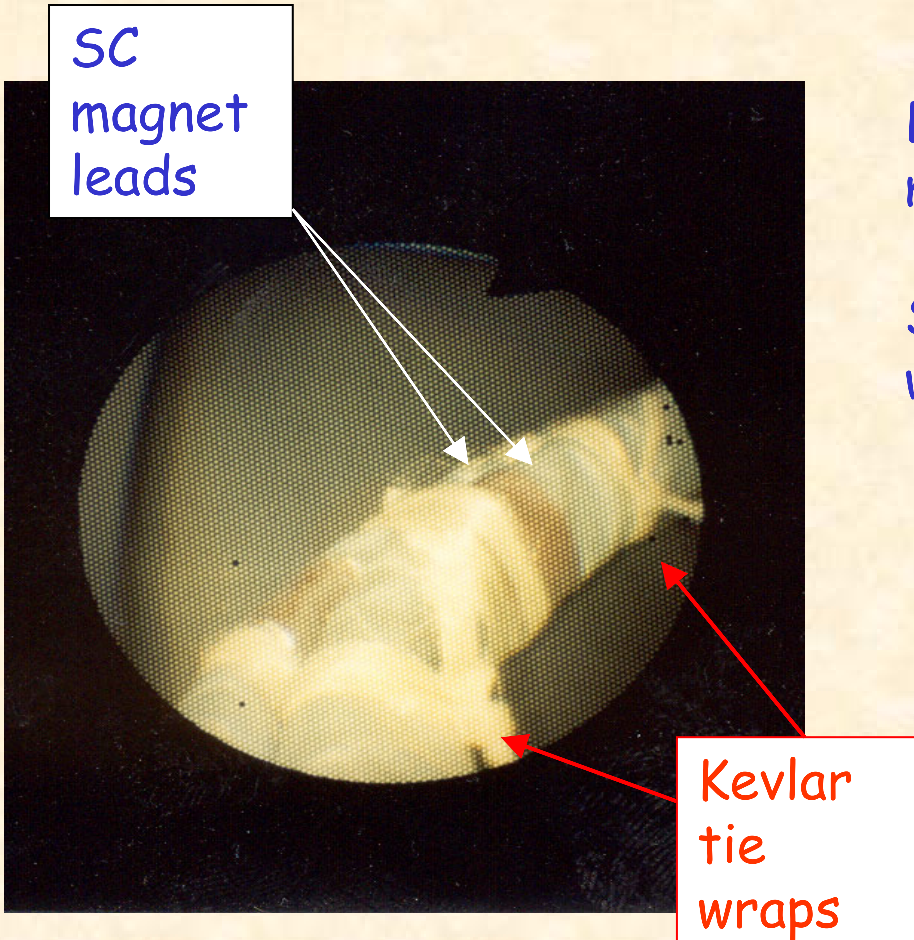


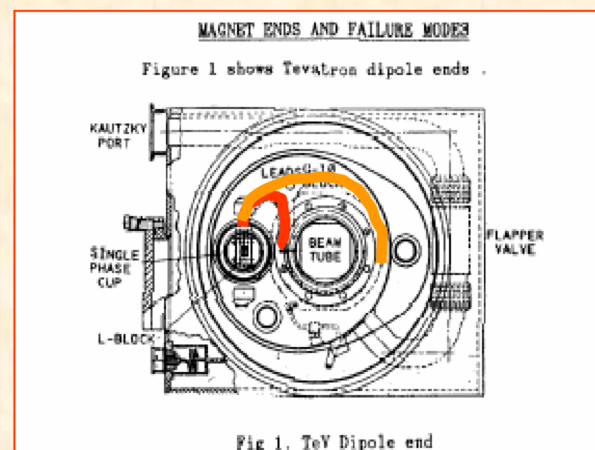
Fig 1. TeV Dipole end

Untied Magnet Leads



Bore scope picture of the magnet leads.

Shows two magnet leads tied with Kevlar tie wraps.



Broken Magnet Leads

- 1984: Opened the cryostats and secured leads with Kevlar. **All** upstream ends of TC magnets were repaired.
- **Everything is OK?**
- 1987: 8 magnet failures in 5 month during Fixed Target operations
  - TC-461 DN Broken Leads
  - TC-632 DN Broken Leads
  - TC-463 UP Cracked Weld
  - TC-550 DN Broken Leads

    } TC Downstream not OK
  - TC-767 DN Gnd Fault to beam tube
  - TB-341 UP Broken Leads
  - TB-359 UP Broken Leads
  - TB-280 UP Vacuum Leak

    } TB Leads not OK

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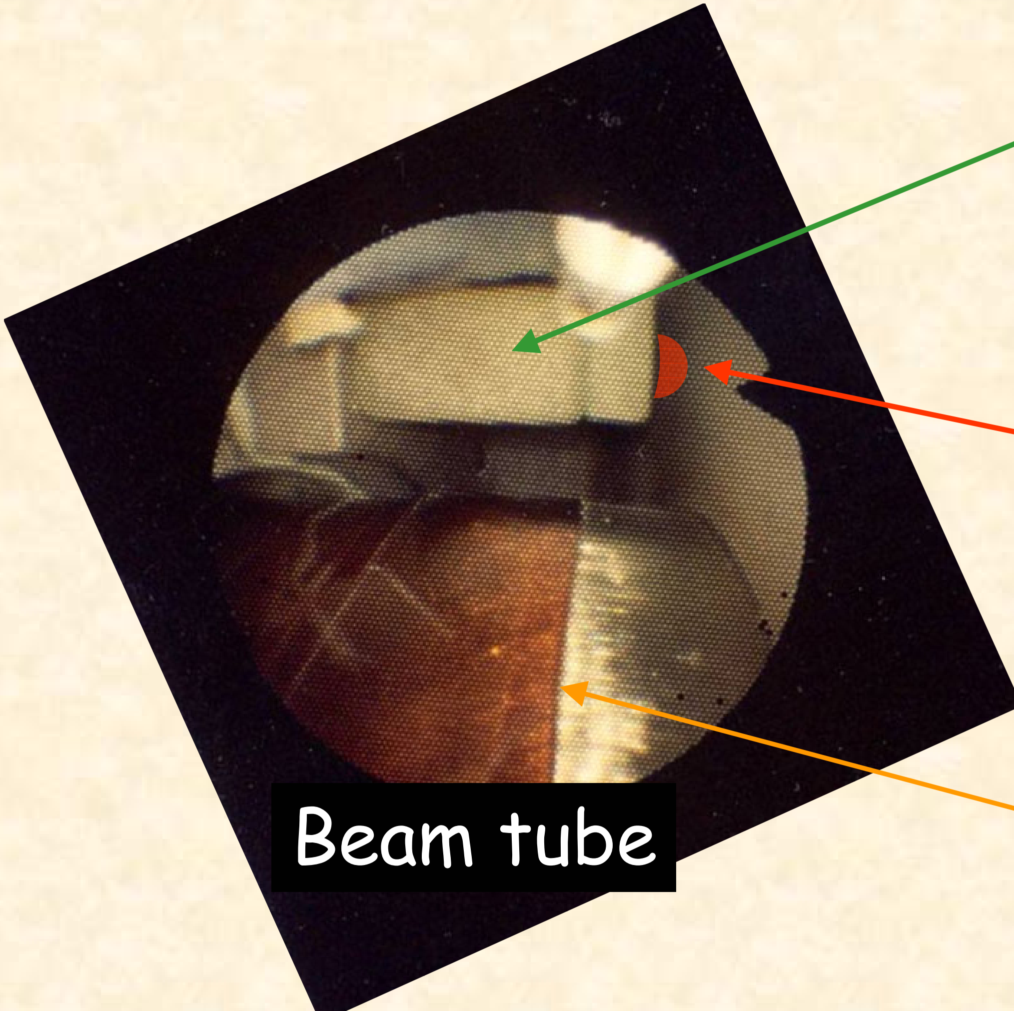
Ends of magnets were inspected using bore scope and x-rays.



G10-block:
Some were loose

Round head screw instead of flathead:
Reduce clearance

Kapton Tape:
unraveling caused magnet to beam tube short

Inspection Results

	TB Upstream	TB Downstream	TC Upstream	TC Upstream
# x-rayed	104	103	94	95
# bore scoped	104	84	8	78
Leads not tied	85	22	0	28
Broken Strands	7	0	0	0
L-block loose	13	8	2	11
G-10 block loose	22	25	24	12
G-10 clearance	21	29	21	25
Beam tune Kapton	48	0	0	0

A lot of time and effort for inspection and repair !

Operational Reliability
(Up to March 1987)

Fraction of Component Types Replaced in 4 years of Operations	
DIPOLES	12%
QUADRUPOLES	6%
SPOOL PIECES	16%
FEEDCANS	19%
ALL OTHERS	5%

About 1/6 of these were failures during operations

- **Of 24 proton/pbar stores only 8 were ended intentionally**
  - **RF station, QPS, vacuum, power supplies, etc. were cause of lost stores.**

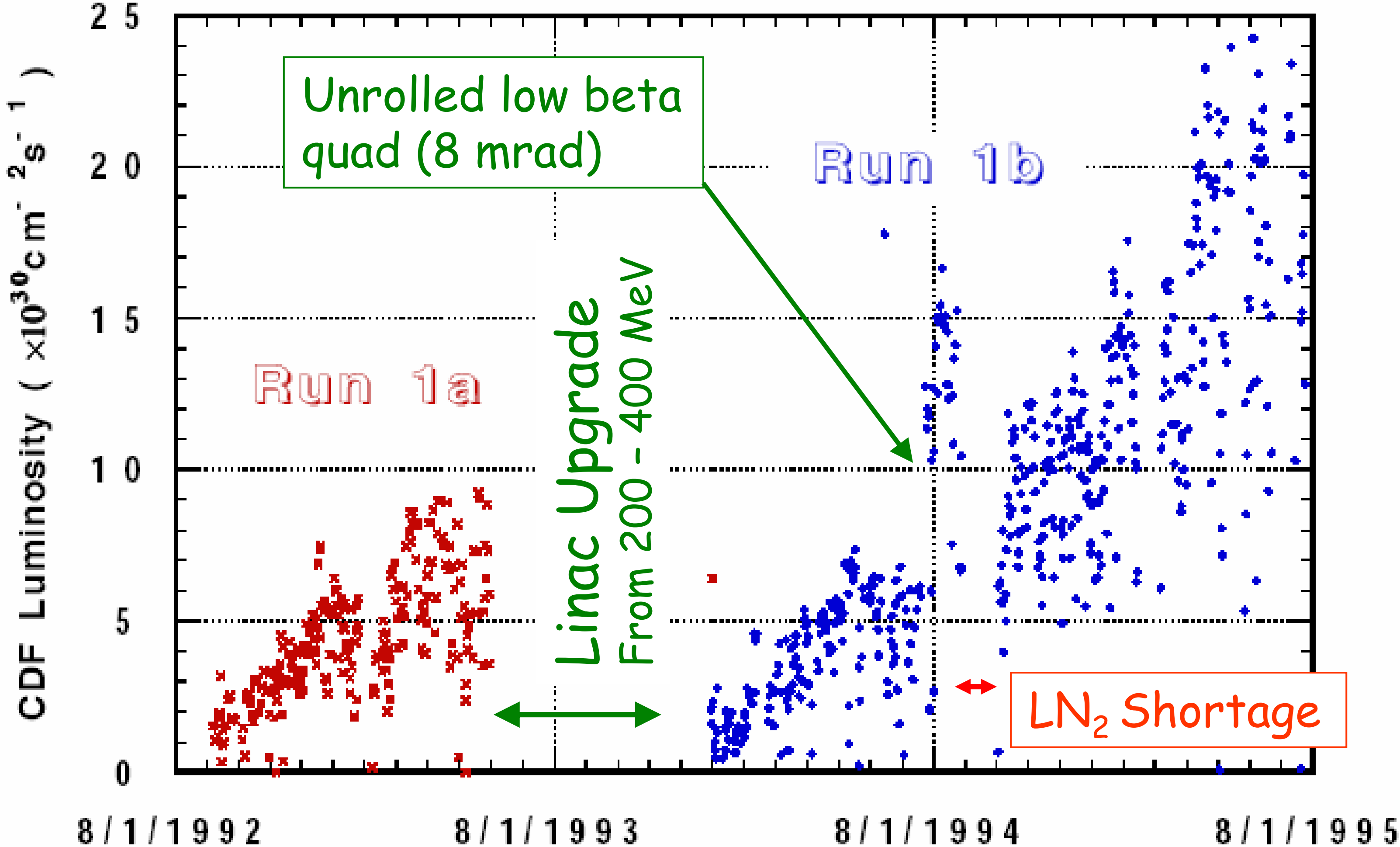
Summary of first 4 years

Not trouble free.

Lots of problems solved.

It Works !

Collider Run I



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Collider Run I

Table III
Tevatron Collider Reliability Summary

Collider Run 1b
12/15/93 - 07/24/95

Reasons for terminating stores	*Number of Stores Terminated*	*Store Hours*
Intentional	352	5294.74
Controls	20	182.35
Quench Protection System	19	129.57
Miscellaneous	12	89.91
Correction Magnet Systems	6	22.31
Cryogenics	11	64.37
Low Beta Quadrupoles	16	73.01
Utilities	9	48.24
Human Error	9	77.00
Tevatron Power Supplies	19	127.39
Glitches	6	50.30
Tevatron RF	10	105.20
Vacuum	3	25.39
Instrumentation	1	1.73
Experimental Areas	1	13.97
Magnet Failure	0	0.00
Kicker Pre-Fire	2	40.45
Total	***496***	***6345.93***

352/496 = 71% of stores ended intentionally

Lessons from Run I

- Reliability is still an issue: 30% of stores ended due to failure.
- Alignment of magnets is an issue.
- Even after “benign” shutdowns it takes time to get machine performing again.

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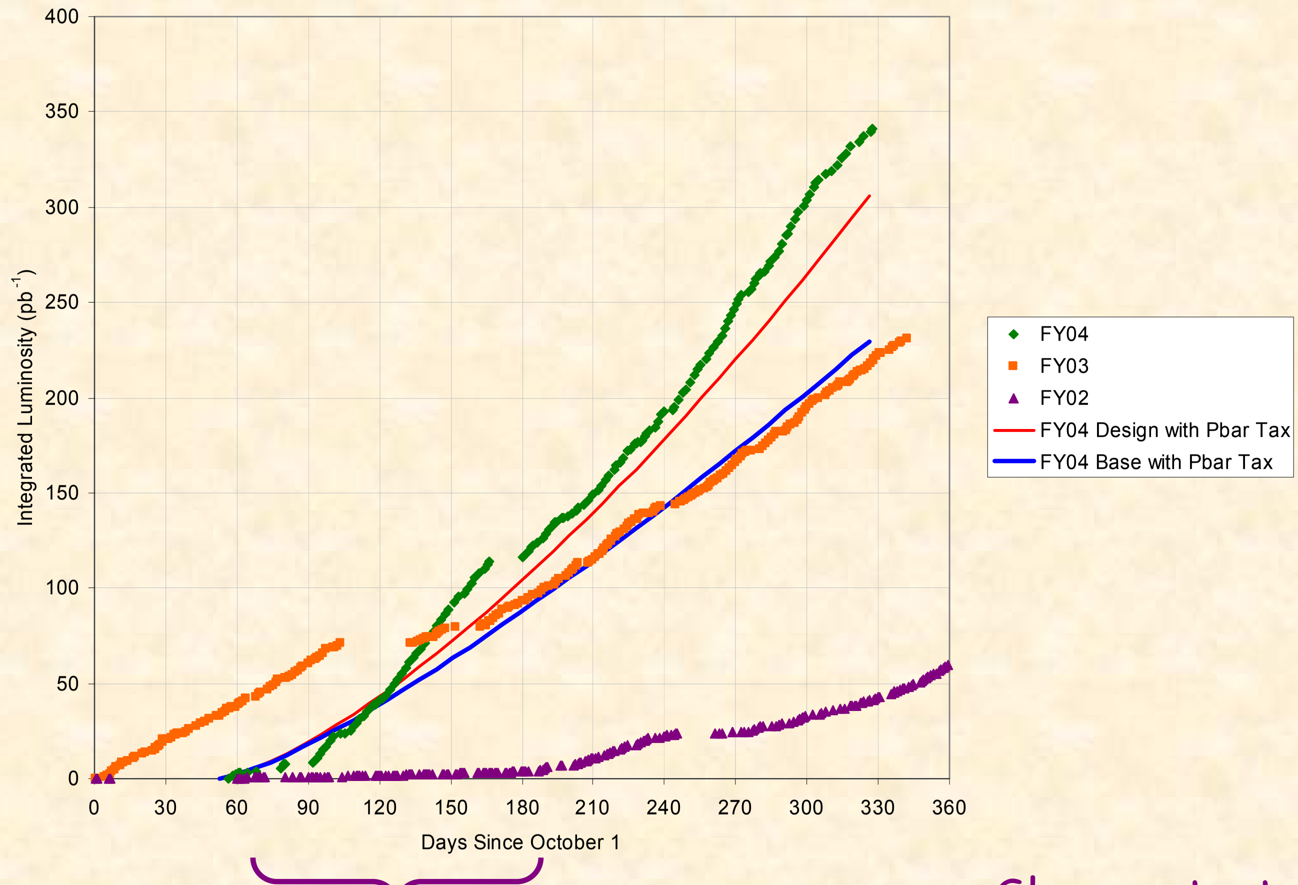
Collider Run II

Still learning after all these years



Slower start than anticipated in FY '02

Run II Reliability

Collider Run IIA
March 2001 – Oct 2002

200/292 = **68% ended intentionally**

Average store length = 17.3 hours

Average failed store length = 9.6 hours

Intentional	200
Controls	7
Correction Magnets	1
Cryogenics	14
Experimental Areas	3
Glitches/Lightning	13
Human Error	2
Instrumentation	0
Kickers	2
Low Beta Quads	4
Magnet Failures	2
Miscellaneous	3
Quench	9
Quench Protection System	19
Separators	3
Tevatron Power Supplies	6
Tevatron RF	3
Utilities	0
Vacuum	1

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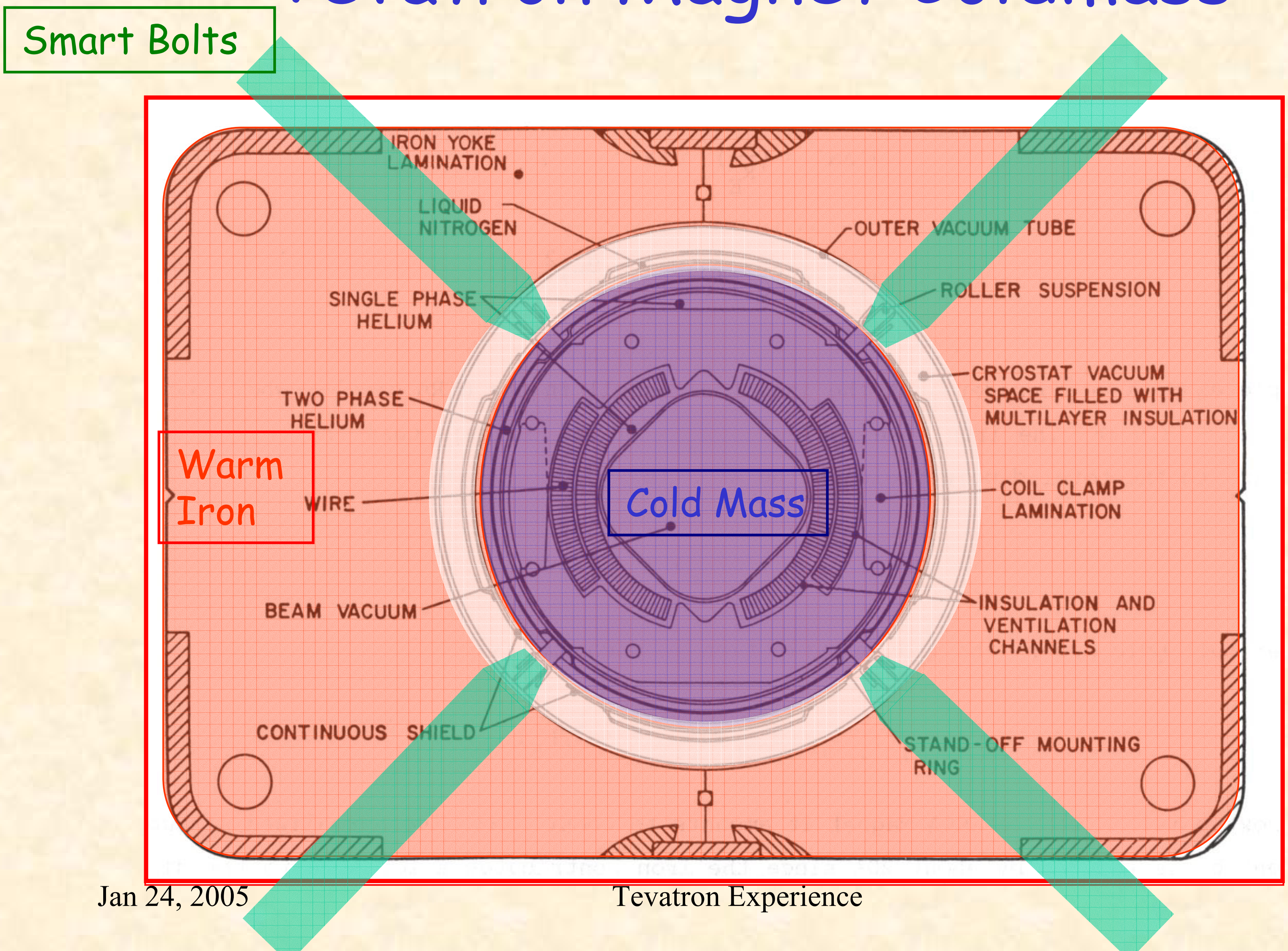
More on this later

Tevatron Magnet Coldmass



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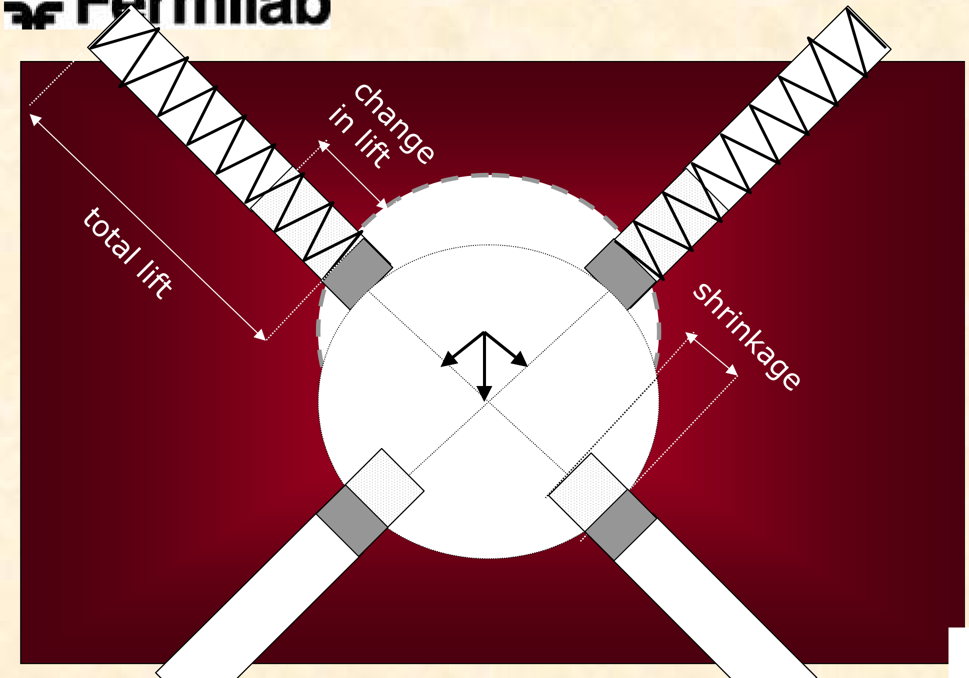
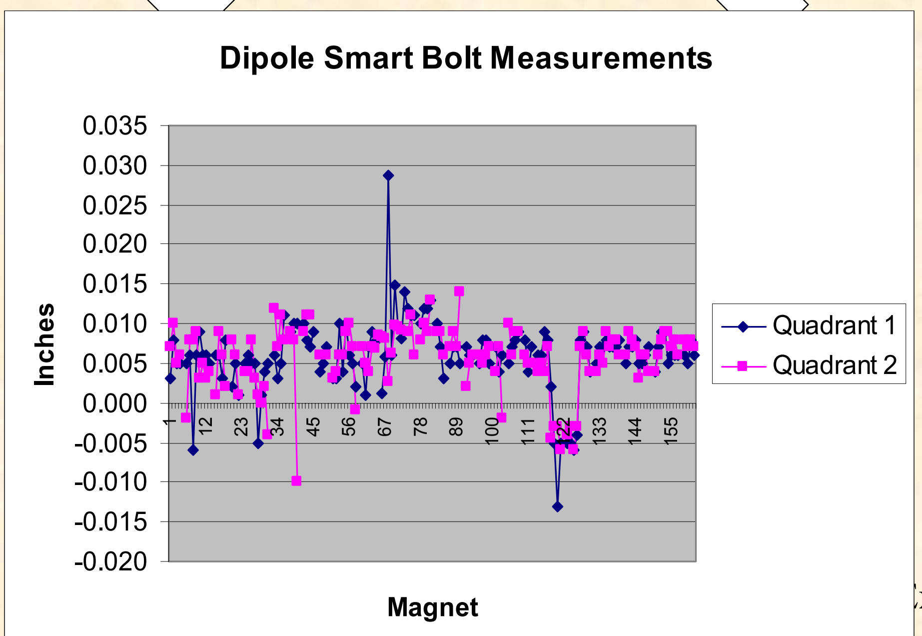


Re-shimmed ~500 Dipoles to move cold mass into center of the warm iron.

Strength of skew quad correctors reduced by ~50%



Creep in G11 suspensions → coils dropped ~3 mils in yoke → ~+1 unit of a1 (b1 unchanged → uniform creep)

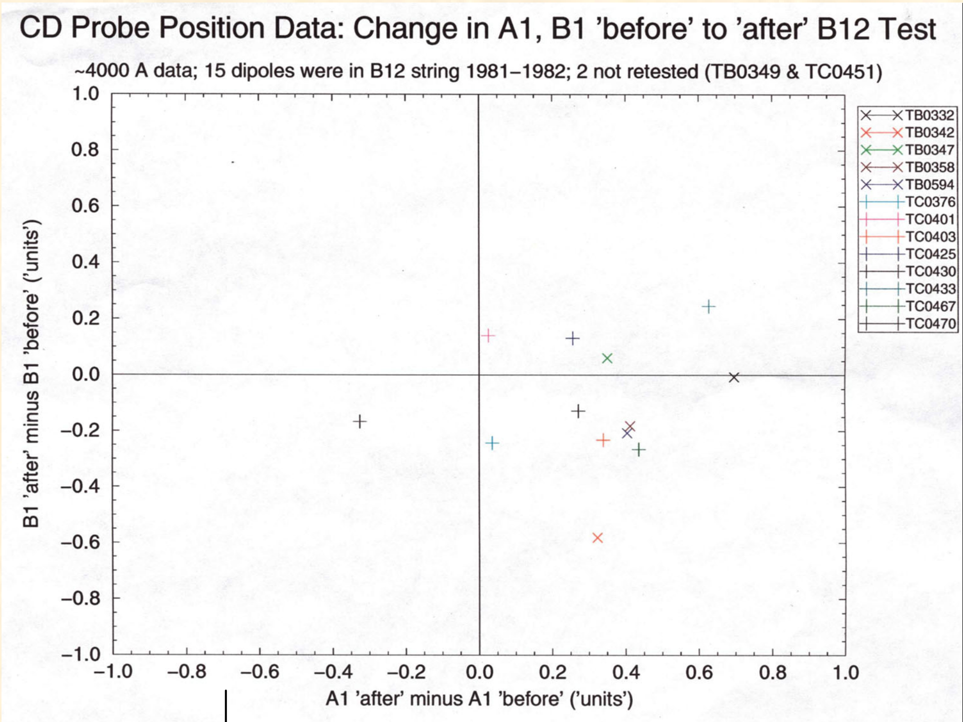
Tables: a1/b1 change in body of 8 Tevatron dipoles 1980 – recently (body position, ~0.8m / 2.4m probes used in 2003 / 1980s measurements)

TM-1182
1630.000

MAGNETIC FIELD PROPERTIES OF FERMILAB ENERGY SAVER DIPOLES

March 1983

R. Hanft, B. C. Brown, W. E. Cooper, D. A. Gross†, L. Michelotti, E. E. Schmidt, F. Turkot
Fermi National Accelerator Laboratory*
P. O. Box 500
Batavia, Illinois 60510



center-line of the yoke by adjusting the thickness of the shim packs on the preload screw ends. The iron yoke contributes about 18% of the total dipole field within the magnet bore. When the collared coil is off center with respect to the yoke, the iron can also modify the field harmonics. However since the iron is far away relative to 1 inch, it is only the quadrupole coefficients a_1 and b_1 that can be materially affected

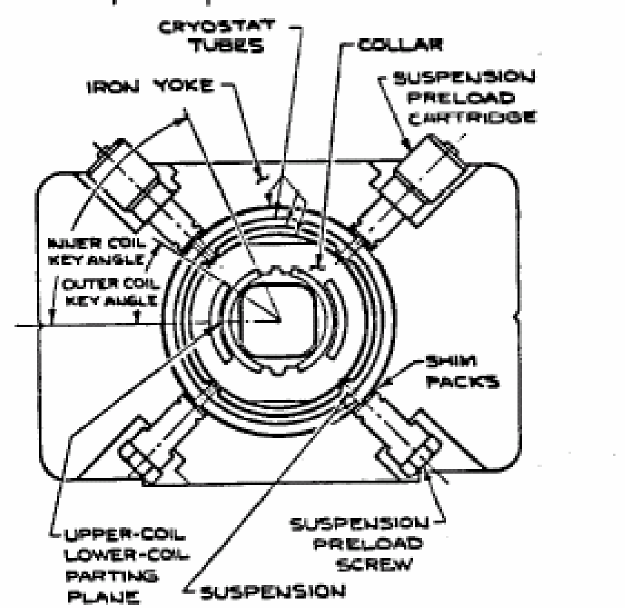


Fig. 1. Schematic cross section of dipole

in the region of interest for circulating beam. Moving the coil 0.0037 inches in the + x direction increases b_1 by 1 unit, while moving it 0.0037 inches in the + y direction decreases a_1 by 1 unit.

B12 test: early evidence of a1 problem

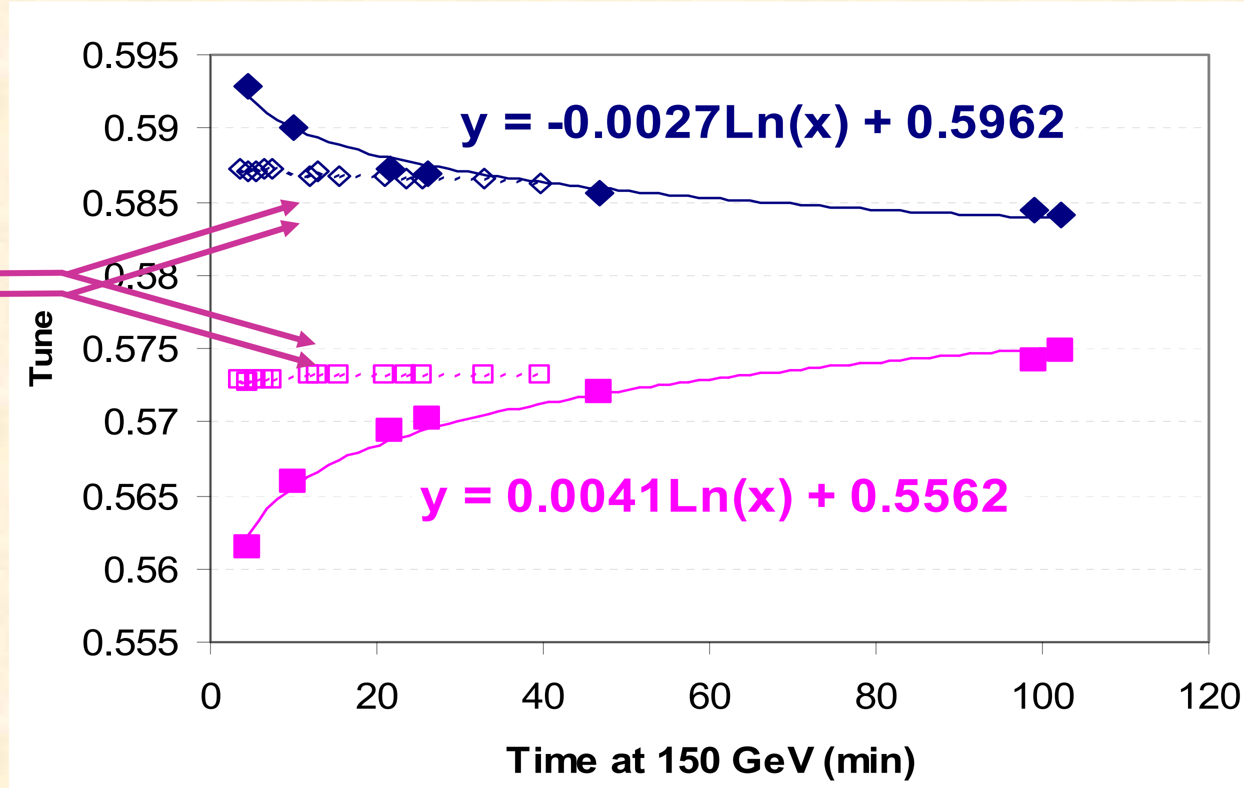
"It's all said… "

P. Bauer

Tune Drift @ 150 Gev

After correction algorithm was implemented

Tev needs $\Delta\upsilon(t) < 0.002$



Why does the tune drift?
Is it related to b_2 drift?
Noticed only in Run II?

Coupling drifts also.
$\Delta\nu_{min}$ = 0.02 tune units

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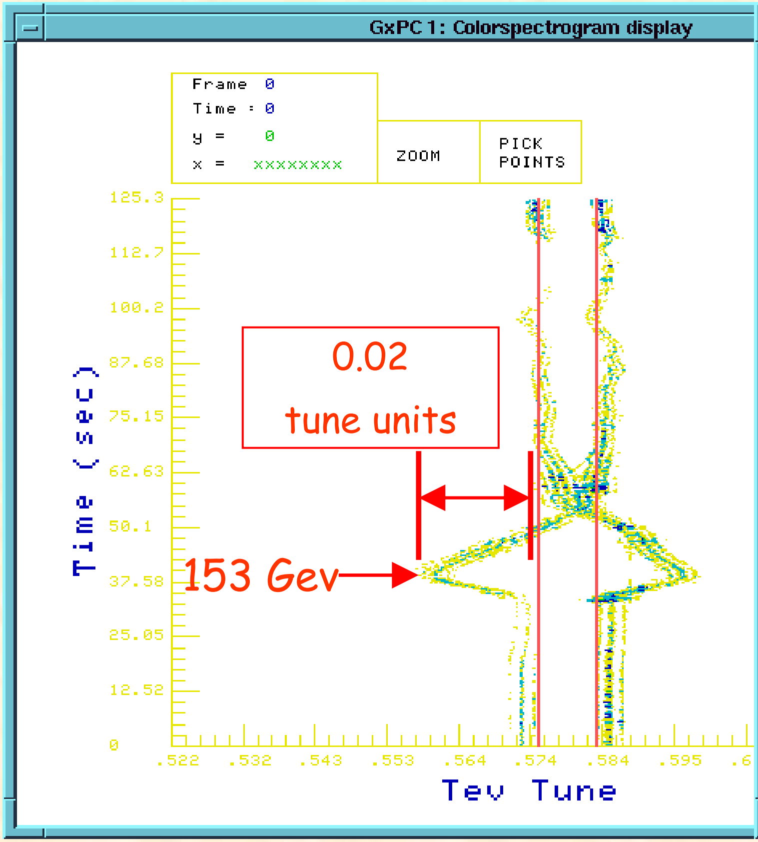
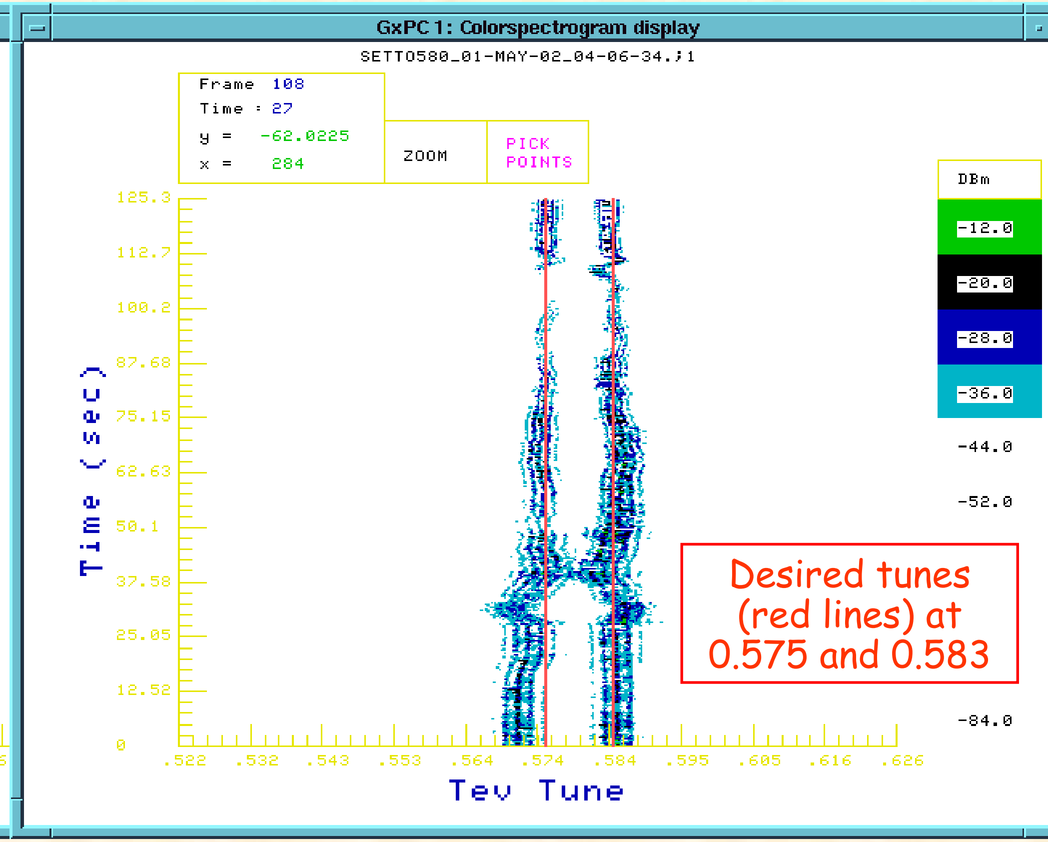
Tune Variations on the ramp





- Near start of ramp (150 → 153 Gev): large tune/coupling excursions
- Tune/coupling changes of (0.02 tune units, 0.02 minimum tune split)
- Variations fixed with additional breakpoint at 153 Gev and tune/coupling snapback correction at start of ramp.

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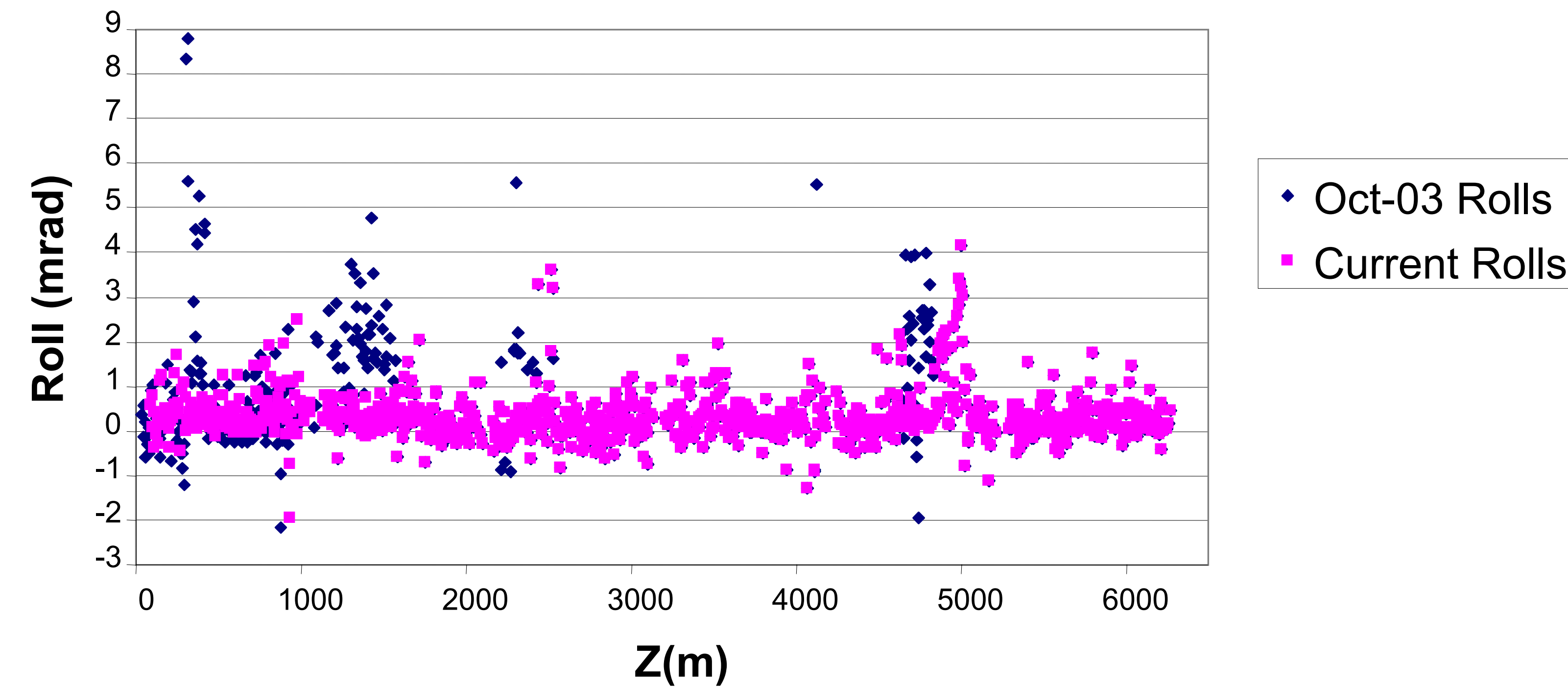
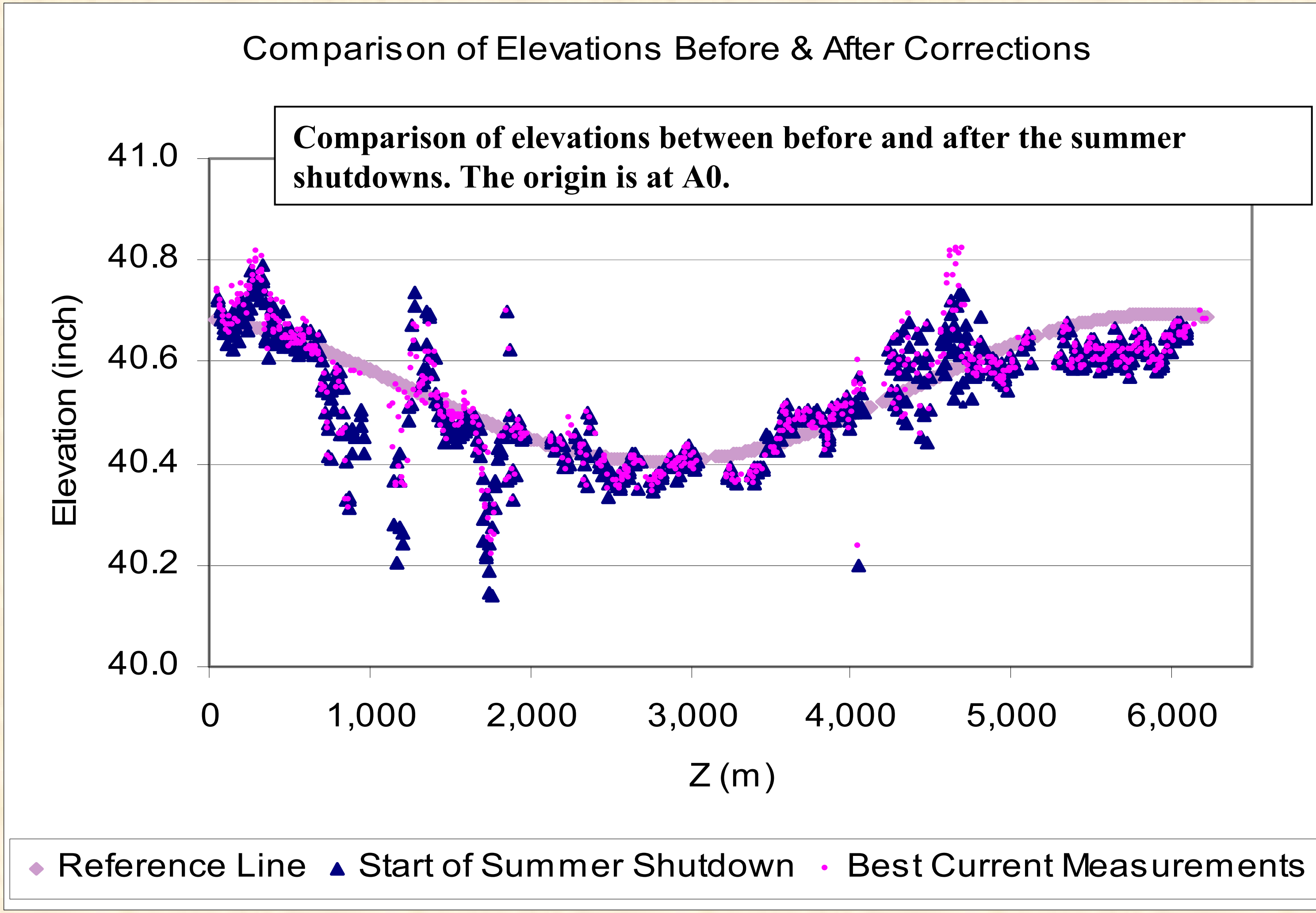
Correction in Rolls



Comparison of magnet rolls (Dipoles and Quadrupoles) around the entire Tevatron before and after the summer shutdown and the two December shutdowns. Current rolls are in purple, the corrected Oct-03 rolls are in dark blue. The origin is at A0.



Elevations – Before & After

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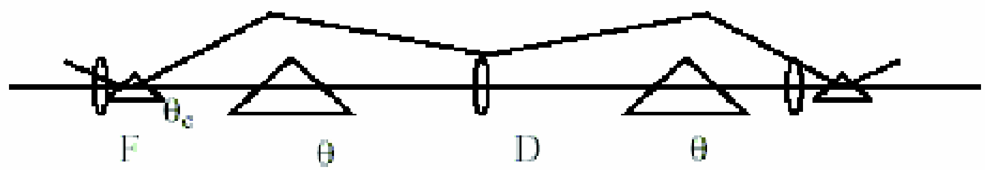
Estimate of magnitude of effect…



here, $\theta = \phi\theta_0$

Periodic solution:

$$M_0\begin{pmatrix}0\\ y'_0\end{pmatrix} + M_0 M_{L/2}^{-1}\begin{pmatrix}0\\ \phi\theta_0\end{pmatrix} + M_F M_{L/2}\begin{pmatrix}0\\ \phi\theta_0\end{pmatrix} + \begin{pmatrix}0\\ \theta_c\end{pmatrix} = \begin{pmatrix}0\\ y'_0\end{pmatrix}$$

$$\theta_c = -\phi\theta_0 \frac{2+\sin(\mu/2)}{1+\sin(\mu/2)}$$

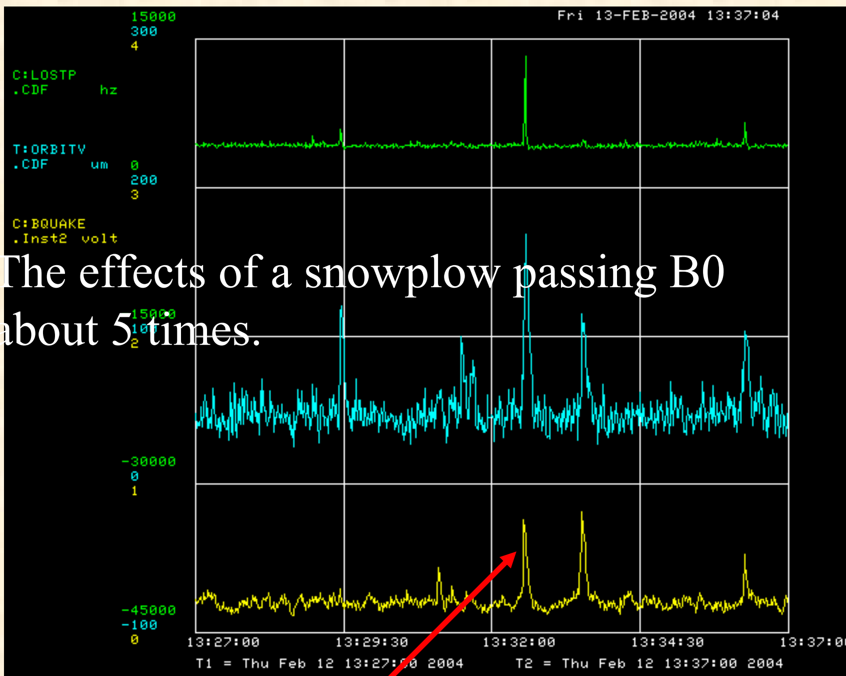
So, 80 μrad correction would correspond … –1.5 mrad

Orbit offset in dipoles + sextupole field drift can explain ~ 30% of tune and coupling drift

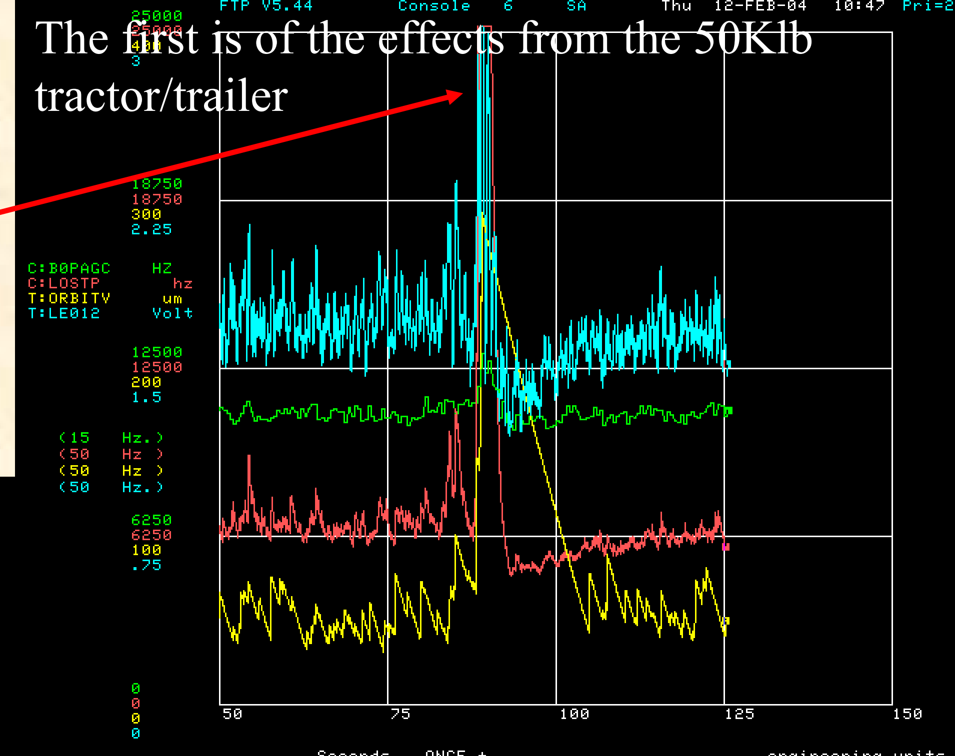
Accelerometer Measurements at B0

Measured by
Todd Joihnson
And Duane
Plant

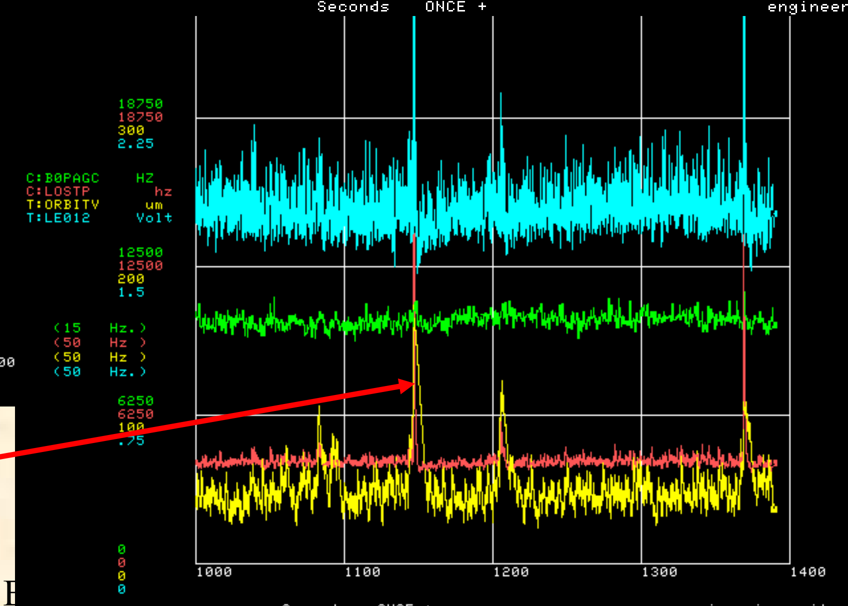
This would cause the collimators to stop during beam halo scraping!



The effects of a snowplow passing B0 about 5 times.



The first is of the effects from the 50Klb tractor/trailer



Explains the source of spikes on the BLMs

Collimator Damage

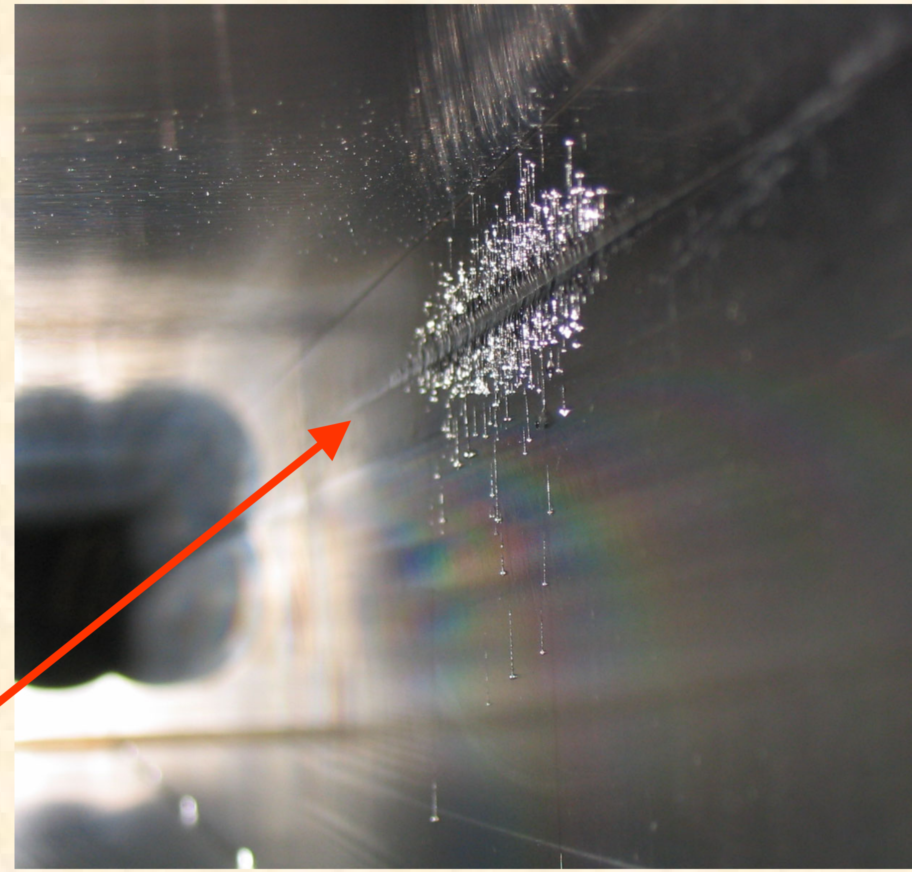
Mask out BLMs to prevent false aborts.

Magnetic fields decay slow enough to prevent rapid beam loss.

Quench detection will pull the abort before damage is done.

Conventional Wisdom:

We won't damage anything with beam in the Tevatron.



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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.

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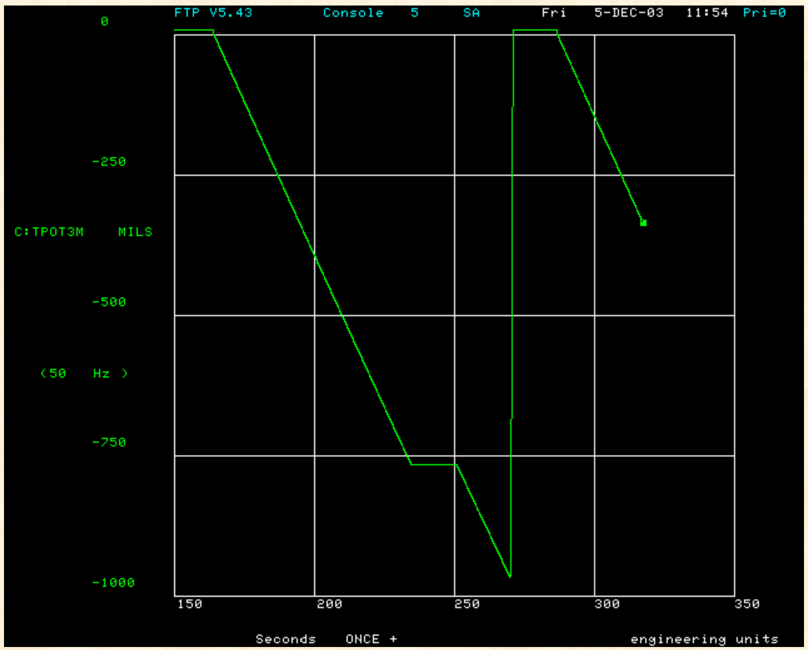
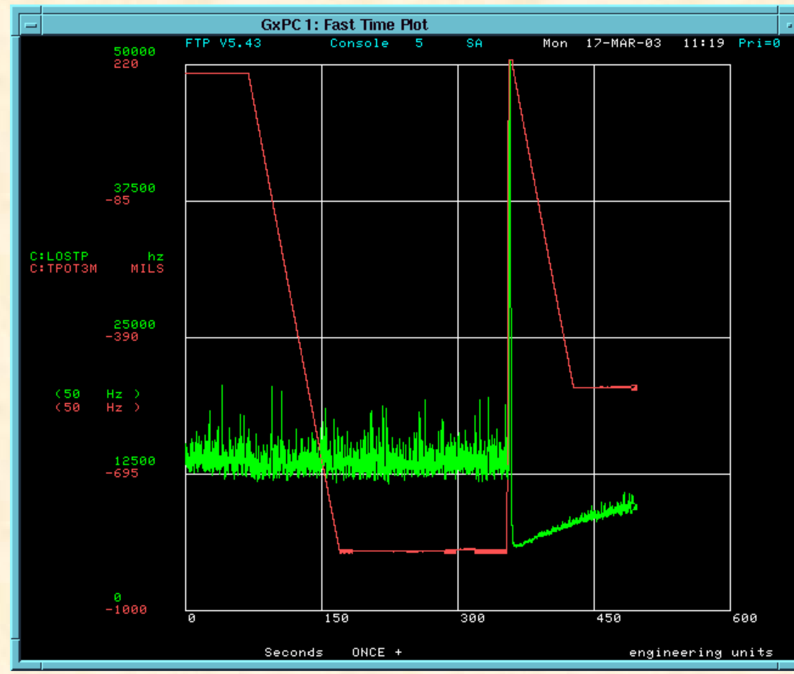
CDF Pot 3 Position

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



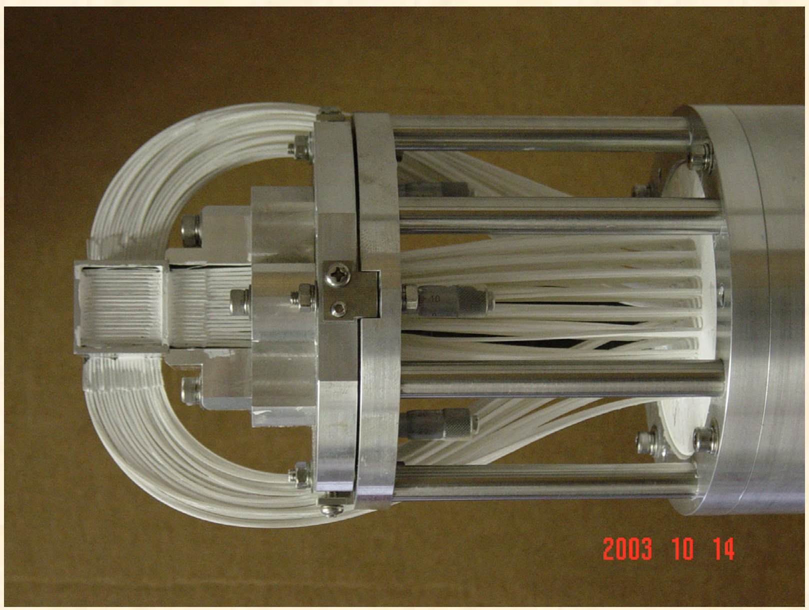
Reproduced after quench
On Dec 5, 2003

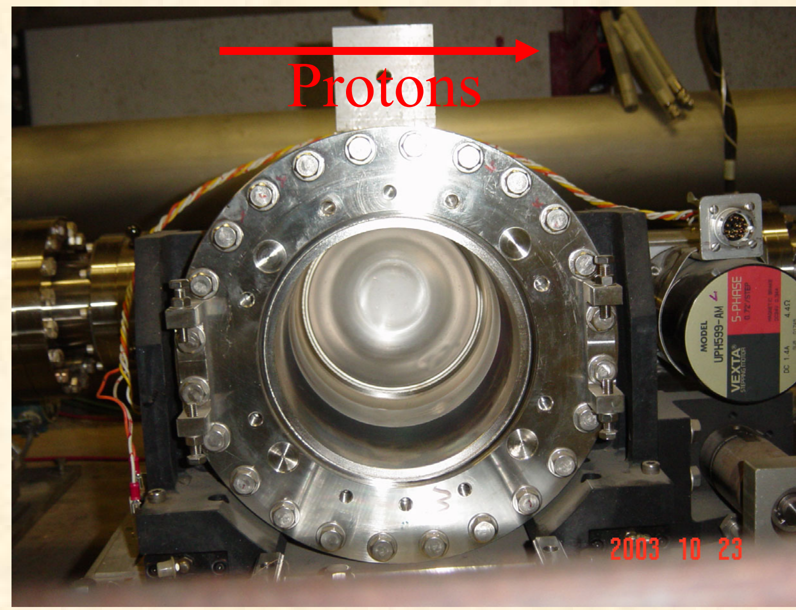


Similar incident on
~ 3/17/03

Pot 3 Pictures

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



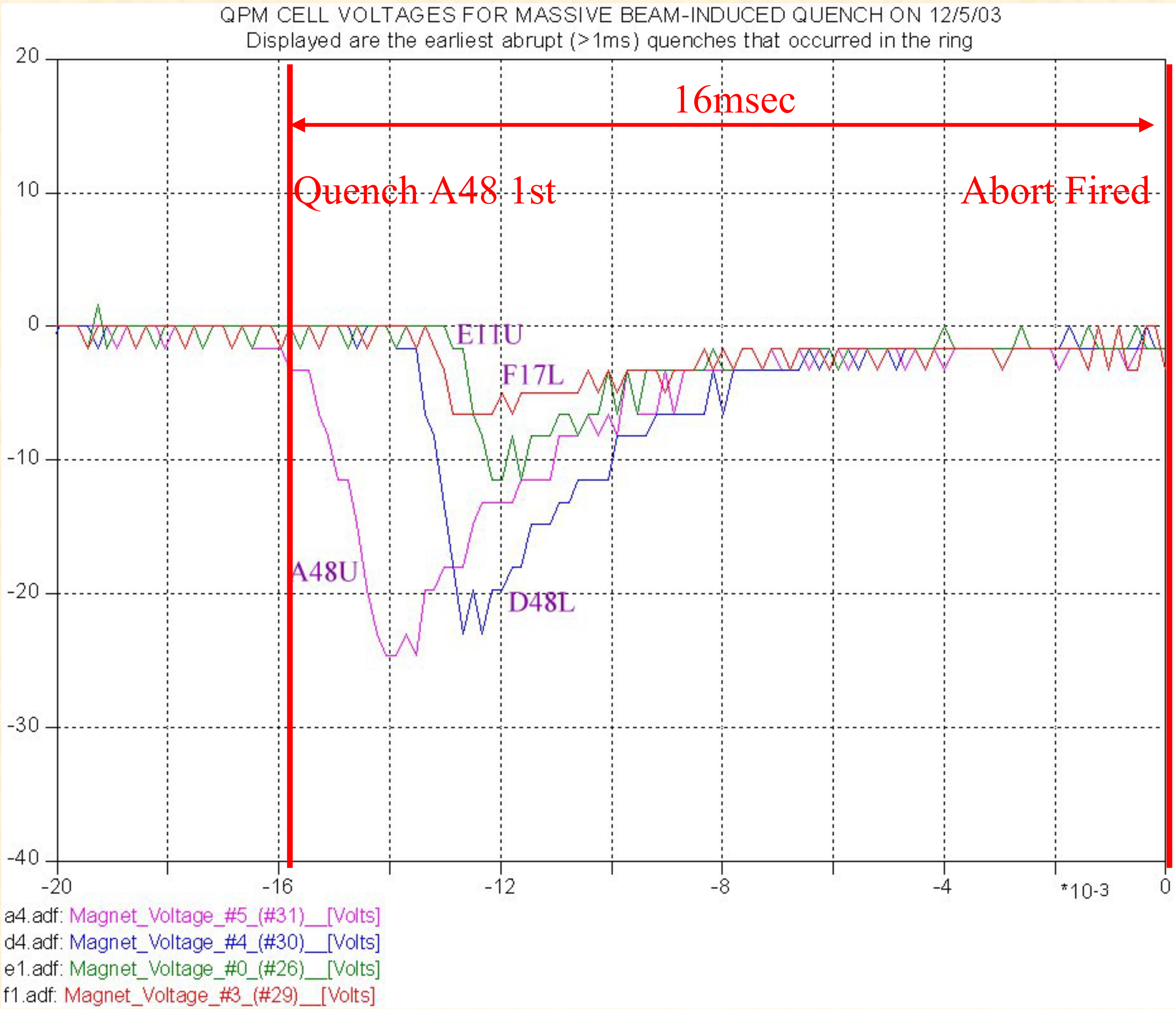


These are pictures before Dec 5,2003

(Courtesy CDF Pot Personnel)

T44 loss of Quench

QPM Over Sample Buffer



Development of Quench:

A48U 16msec

D48L 13.5msec

F17L 13msec

E11U 12.5 msec

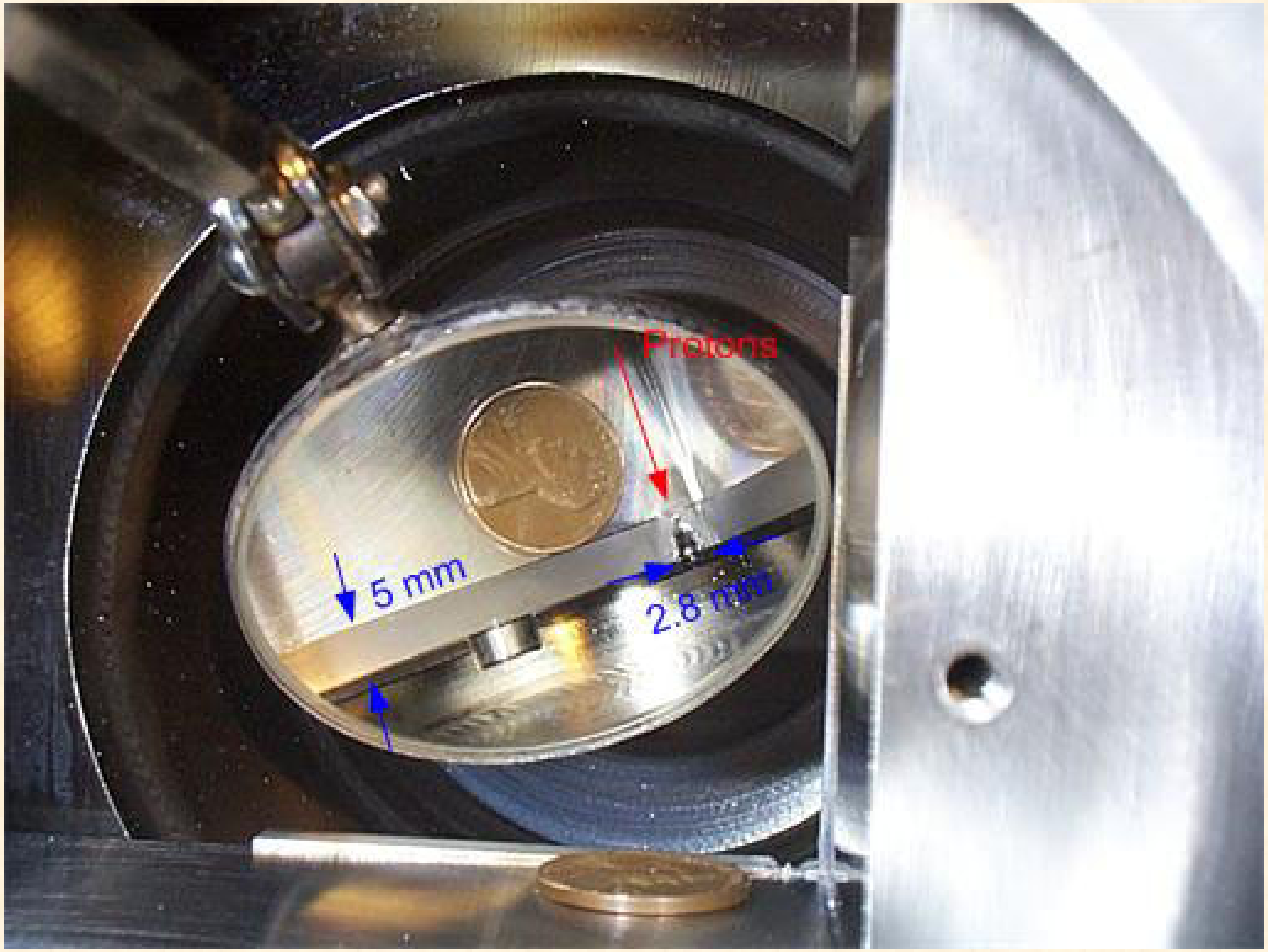
Before abort

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

(Courtesy D. Wolff & EE Support)

Fermilab

Damage to D49 Target



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

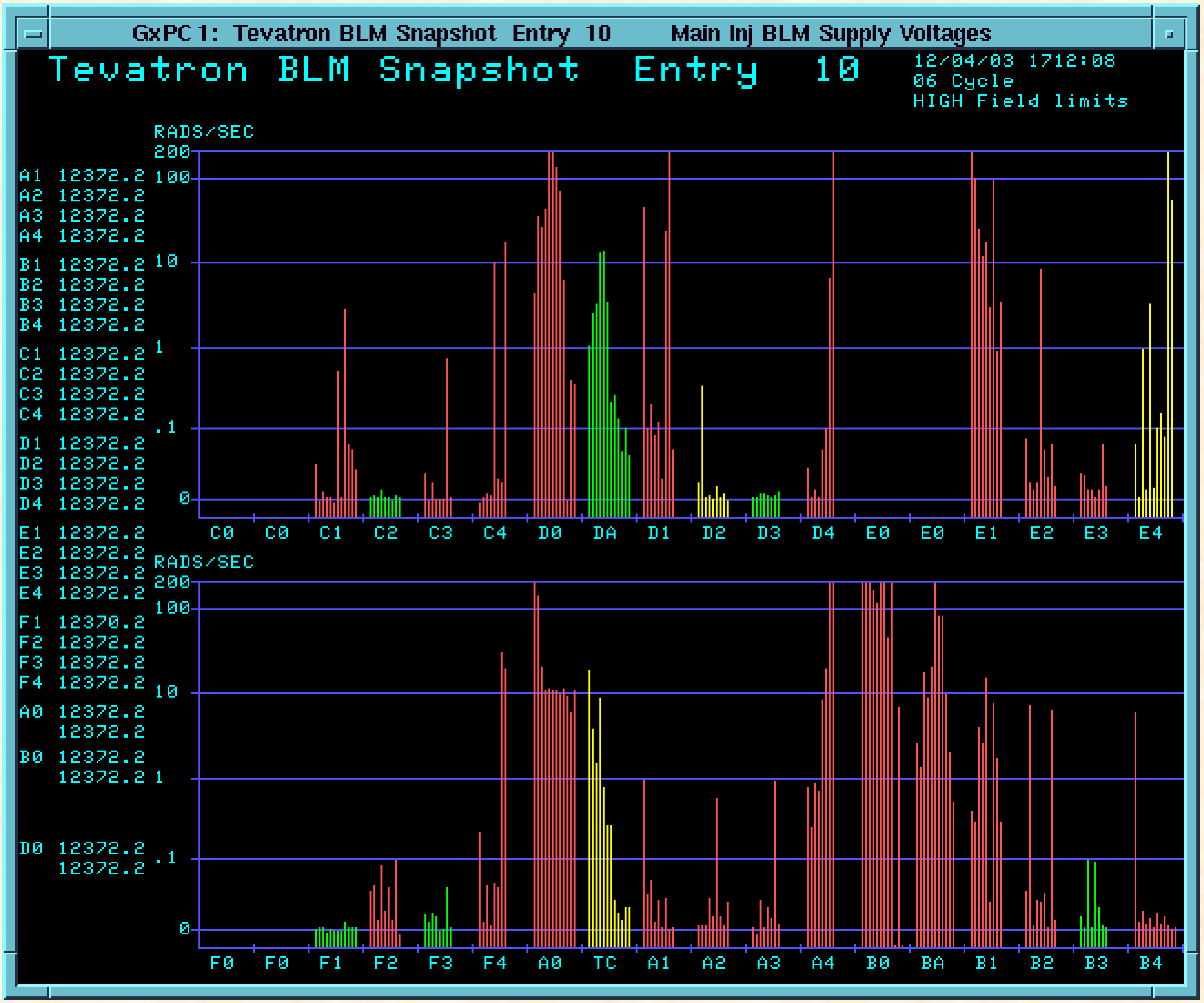
Once the hole
was open allowed
Beam to travel to
next limiting
horizontal aperture
which is E03

Fermilab

Damage to E03 1.5m Collimator

Protons

Tevatron Ring Wide Loss Plot



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.

Conclusions

- The Tevatron has had 22 good years so far.
- It wasn't always easy but it was a success.
- Still learning about the Tevatron even today.

From: Tevatron

To: LHC

Good luck to continue the tradition of the worlds highest energy superconducting synchrotron !