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Strong Transverse Coupling in the Tevatron*

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APS April Meeting
May 2, 2004

Outline:

Evidence of Strong Coupling
Investigations of Possible Source Terms
Source(s) Revealed and Remediation
Conclusions

*Work performed under Contract no. DE-AC02-76CH03000 with the U.S. Dept. of Energy

Initial Tevatron Operation

- **As-built and commissioned in 1983:**
  - **Quad Alignment:** d_{rms} **= 0.5 mm -->** θ_{rms} **~ 20** μ**rad**
  - **Quad Roll:** ϕ_{rms} **= 1 mrad -->** $\delta\nu_{min}$ **~ 0.01**
  - **Measured orbit distortions, tune separations agreed with predictions**
  - **Single distributed (0th harmonic) skew quadrupole circuit used to bring minimum tune separation to** $\delta\nu_{min}$ **~ 0.001**
    - **This "SQ" circuit ran at about 0.3 Amp at injection, or about 2 Amp at 800 GeV (out of 50 Amp supply)**

Evidence of Strong Coupling

Twenty years later …

- **Coupling Correctors Running Strong**
  - **SQ circuit running ~15x stronger than in 1984**
  - **If SQ were to be turned off, would result in $\delta\nu_{min}$ ~ 0.3 !!**
  - **Additional skew quads being used for tuning $\delta\nu_{min}$**
    - **in particular, use individual quads out of phase (ν_y-ν_x) with SQ**
- **Emittance Growth at Injection**
  - **Larger for larger momentum spread (coalesced bunches)**
  - **$\Delta\varepsilon_y = 5\pi$ mm-mrad consistent with $\Delta D_y \sim 1$ m and $\sigma_p/p \sim 7 \times 10^{-4}$**
- **Vertical Dispersion "*Pattern*" (not random)**
  - **Peak values ΔD_y ~ 0.8 m**
- **Hor/Ver Transverse Beam Dampers**
  - **Cross-talk between planes hindered their commissioning**

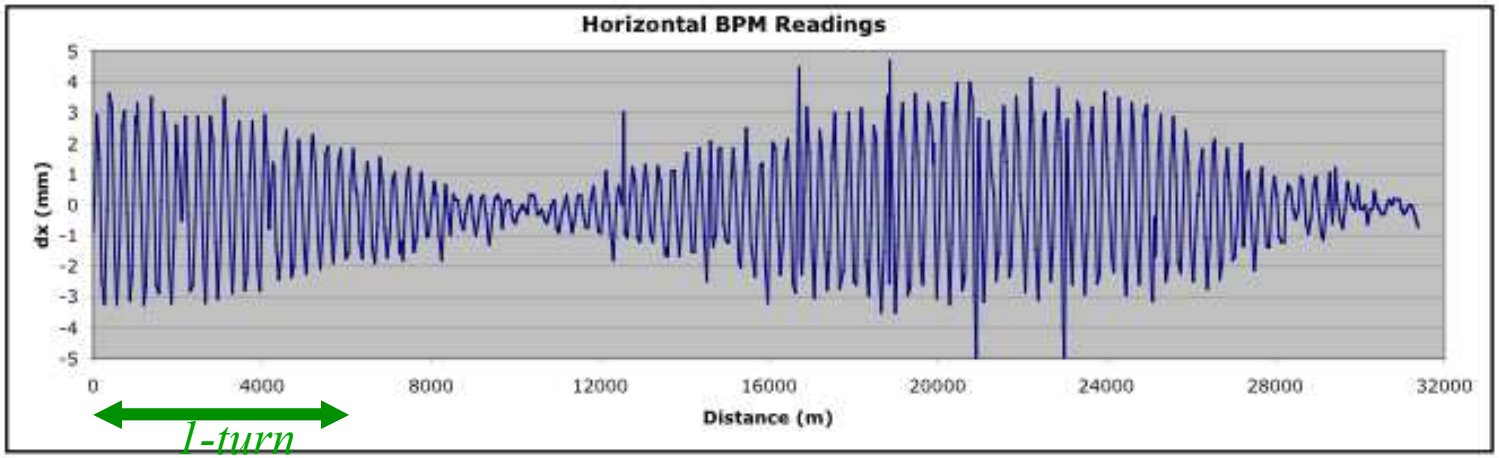
Estimates of Source Terms

- **Arc Quad alignment:**
  - **If take ϕ_{rms} ~ 2 mrad (large), then $\delta\nu_{min} \sim (2/\pi)\,\phi_{rms}\,\sqrt{N} = 0.02$**
  - **Not large enough to explain observations**
- **Was thought perhaps IR quads were an issue (as in Run I)**
  - **No direct evidence of largely rolled quads in IR's**
- **Also found regions of systematically rolled dipole magnets, which subsequently induced large vertical orbit excursions through large (1/2 km) regions of the Tevatron**
  - **Systematic vertical offsets through dipole magnets (with sextupole moments) could generating coupling**
  - **these effects could account for ~10% of the effect, at best**
- **One year ago (Feb 03), measurements performed which showed conclusively that source of coupling was distributed uniformly around the circumference…**

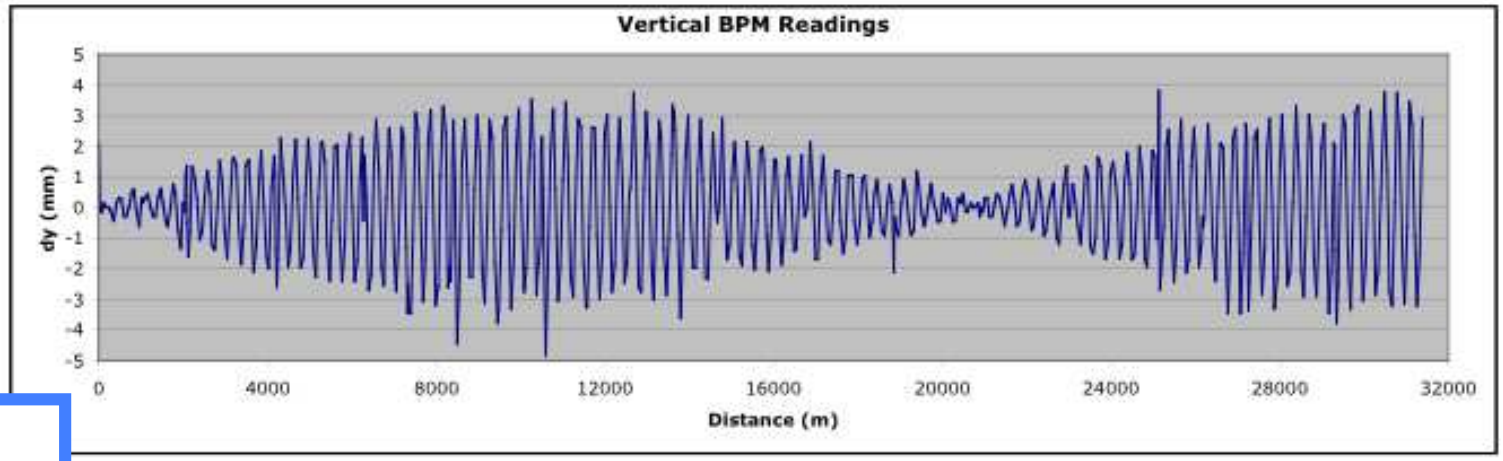
The Measurement …

Inject with horizontal oscillation and look for source of vertical oscillation…

Hor BPM's



Ver BPM's



The source is *everywhere*!

Interpretation

- **Suggested that skew quad term, a_1, in main dipoles had large systematic value**

  $\delta y'_n = 4\theta_0 a_1 (x_0 \cos n\mu)$ (at n^{th} half-cell, with 4 dipoles/half cell)

  so, $\Delta y_N = \Sigma\ (4x_0\theta_0 a_1 \cos n\mu) <\beta> \sin(N-n)\mu$ (*after N half-cellls*)

  which is an oscillation of amplitude

  $4<\beta>\theta_0 a_1 x_0 (N/2) = x_0$ when $N \sim 300$ (1.5 turns)

  ==> $a_1 = (\partial B_x/\partial x)/B_0 = (2\theta_0<\beta>N)^{-1} \sim 1 \times 10^{-4}$/in.

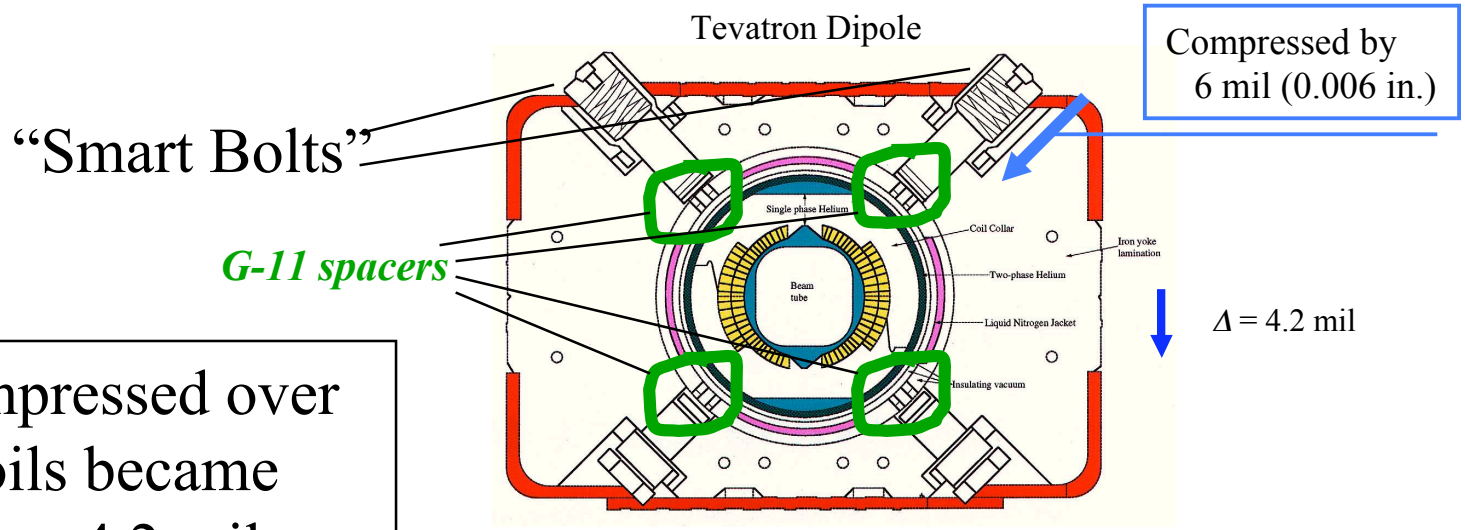
- **Similar value agreed with the observed corrector settings for minimizing tune split…**

  $\Delta\nu_{min} = 2 F a_1 \sim 2\ (25\ m)(1x10^{-4}/in.)(in./0.0254\ m) = 0.2$

The Smoking Gun

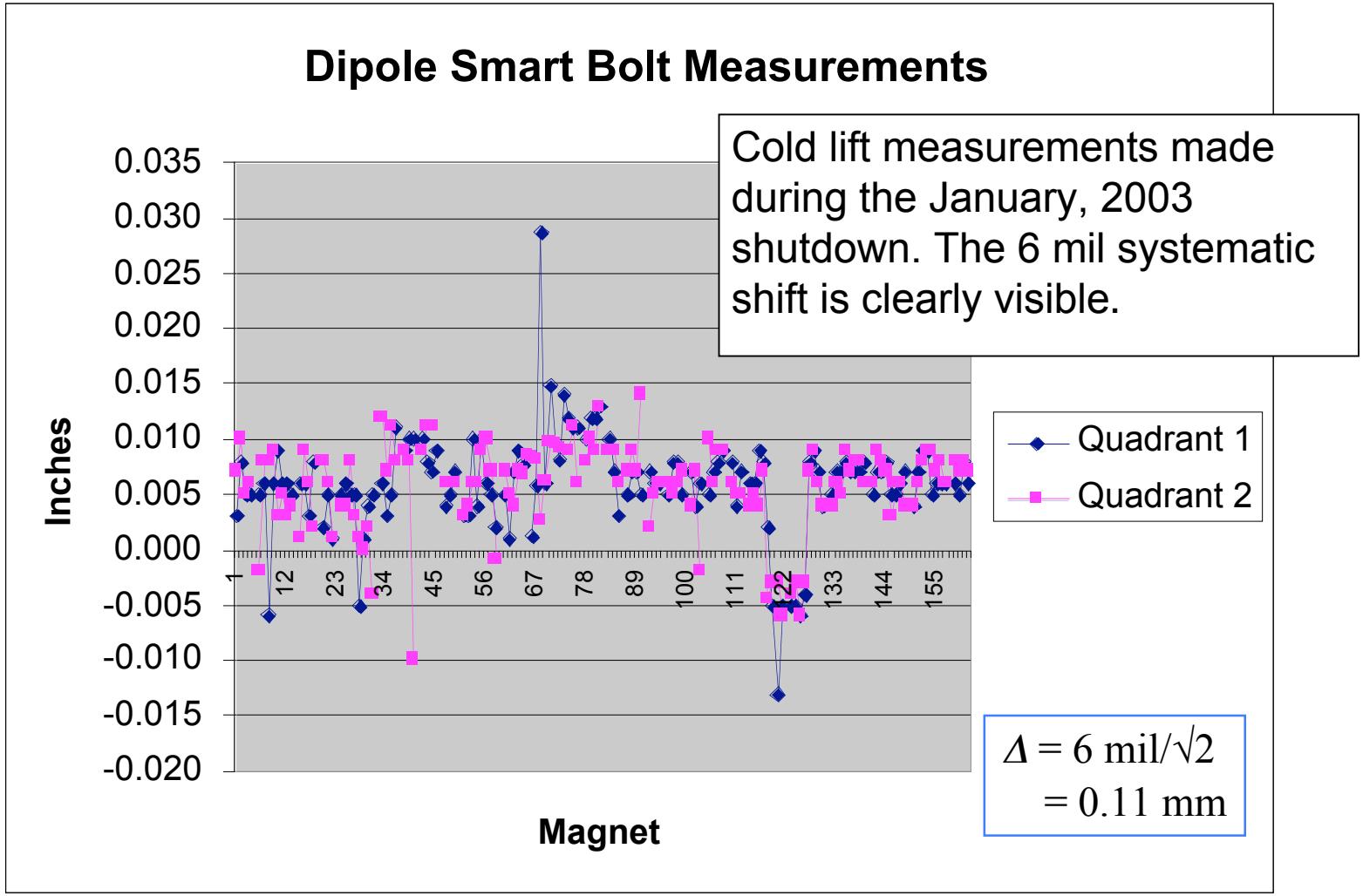
Just before the experiment, during a routine shutdown, technicians were sent to the Tevatron tunnel to measure coil placements (via "Smart Bolts") to look for rotations inside the iron yoke.

What they found: *vertical* coil *displacements*!

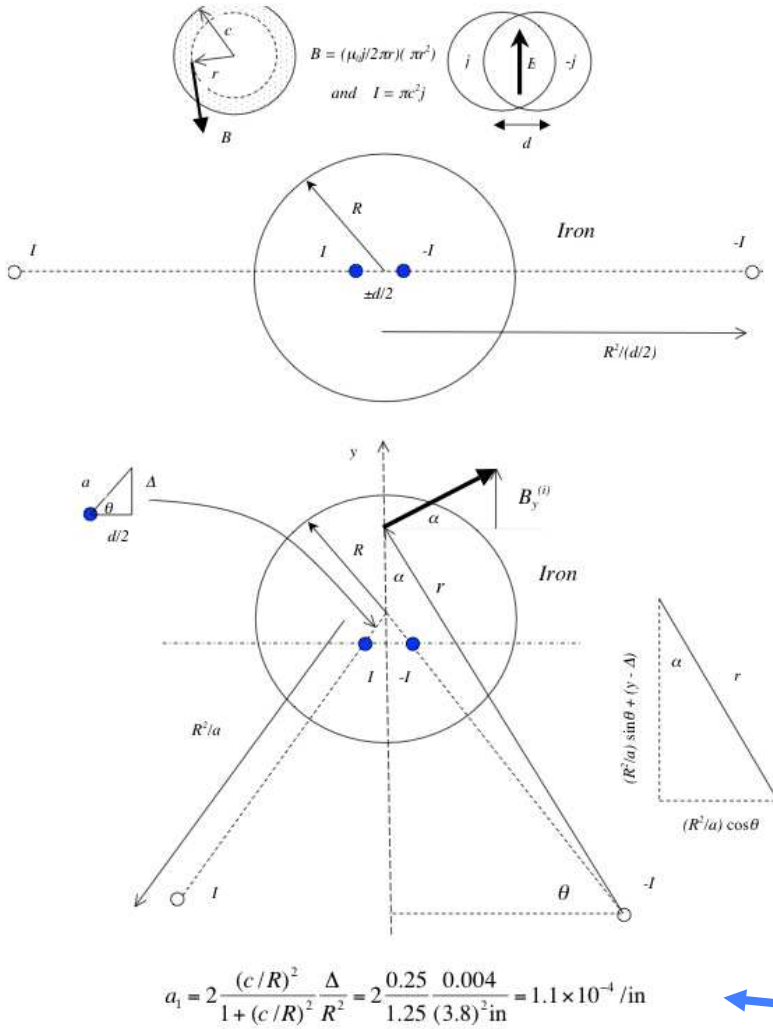


Spacers compressed over time, and coils became displaced by ~ 4.2 mil

Coil Measurements



Estimate of Skew Quad Field



$$a_1 = 2\frac{(c/R)^2}{1+(c/R)^2}\frac{\Delta}{R^2} = 2\frac{0.25}{1.25}\frac{0.004}{(3.8)^2\text{in}} = 1.1\times10^{-4}\ /\text{in}$$

Result

Start with uniform current density within a cylindrical cross section; look at field from 2 such cross sections, separated by distance *d*, and with equal/opposite current densities

--> pure dipole field, B_c

Next, add an iron yoke of radius *R* and compute magnetic images, which will be located left and right, and which enhance the field in the center:

$$B_0 \sim B_c\,[\,1+(c/R)^2\,]$$

Finally, displace the center of the yoke with respect to the center of the coil by a distance Δ, and compute the resulting skew quadrupole component,

$$a_1 = (dB_x/dx)/B_0$$

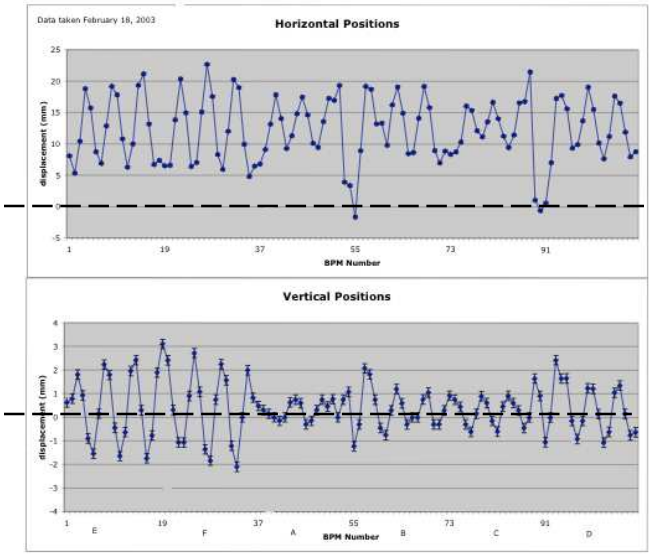
Local Coupling due to Non-local Correction

- During low-beta optics upgrade in Run Ib, several (6 out of 48) skew quadrupole correctors were removed to make room for IR tuning quads; thus, there are "holes" of missing correctors on each side of each IR -- nominally would correct for ~53 dipoles at each IR (asymmetric w.r.t. center of straight section); felt was "OK" for $\delta\nu_{min}$ adjustments, but …
- The centers of these regions are not in phase with the main SQ circuit (remaining 42 quads); thus an additional skew quad circuit -- 2 quads in the A0 straight -- which is out of phase with the main SQ circuit is effective at further reducing $\Delta\nu_{min}$.
- A0 straight section has horizontal dispersion, and thus these correctors represent new sources of vertical dispersion, accounting for the observed pattern

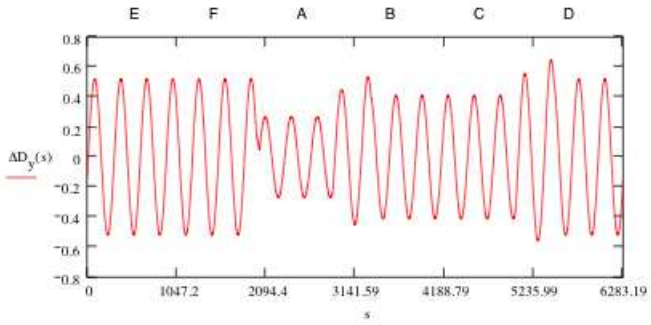
(measured)

H dispersion

V dispersion



Vertical Dispersion from Simple model of Tevatron Corrector Settings and missing SQ correctors



First Pass at Remedial Action

- **Winter 03/04 Shutdown allowed some work to be done, though with limited manpower would take months to fix all 776 dipole magnets**
- **During this shutdown, the 106 dipole magnets in the 2 IR regions where skew quad correctors no longer exist had their cold masses shimmed *in situ* to make their $a_1 = 0$.**
- **Additional 12 dipole magnets at ends of other 4 Tevatron straight sections, also out of phase with main circuit, later shimmed as well.**

- **The skew quad circuits now running at lower currents, though not optimal.**
- **Vertical dispersion was reduced by ~50%.**
- **Further optimization in skew circuits may be possible; have not had appropriate Tevatron study time to pursue.**

Conclusions

- Strong coupling due to displaced coils within dipole magnets led to large systematic skew quad terms throughout the Tevatron
- Skew quad correctors in IR regions had been removed from main circuit during IR upgrades in Run I
  - This eventually led to non-local correction of minimum tune split, generating vertical dispersion, and
  - generated large regions of local coupling
    - emittance growth at injection from optics mismatch
    - "coupled" transverse damper system
- Over past few months, Tevatron dipole magnet coils in regions without appropriate correctors have been shimmed to reduce a_1
  - Reduced coupling corrector strengths proportionately
  - Vertical dispersion reduced by 50%, emittance growth reduced 75%
- Looking at plans to gradually correct remaining 658 magnets
  - Must fix magnets in a pattern consistent with corrector system
- *Thanks to many:* D. Edwards, G. Annala, N. Gelfand, J. Johnstone, M. Martens, T. Sen, D. Harding, J. Carson, J. Volk, R. Stefanski, …