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Strong Transverse Coupling in the Tevatron*

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Outline:

Evidence of Strong Coupling

Investigations of Possible Source Terms

Source(s) Revealed and Remediation

Conclusions

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Initial Tevatron Operation

- **As-built and commissioned in 1983:**
  - **Quad Alignment:** d_{rms} = 0.5 mm --> θ_{rms} ~ 20 μrad
  - **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)**
  - **$\Delta\varepsilon_y$ = 5π mm-mrad consistent with ΔD_y ~ 1 m and σ_p/p ~ 7 x 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**

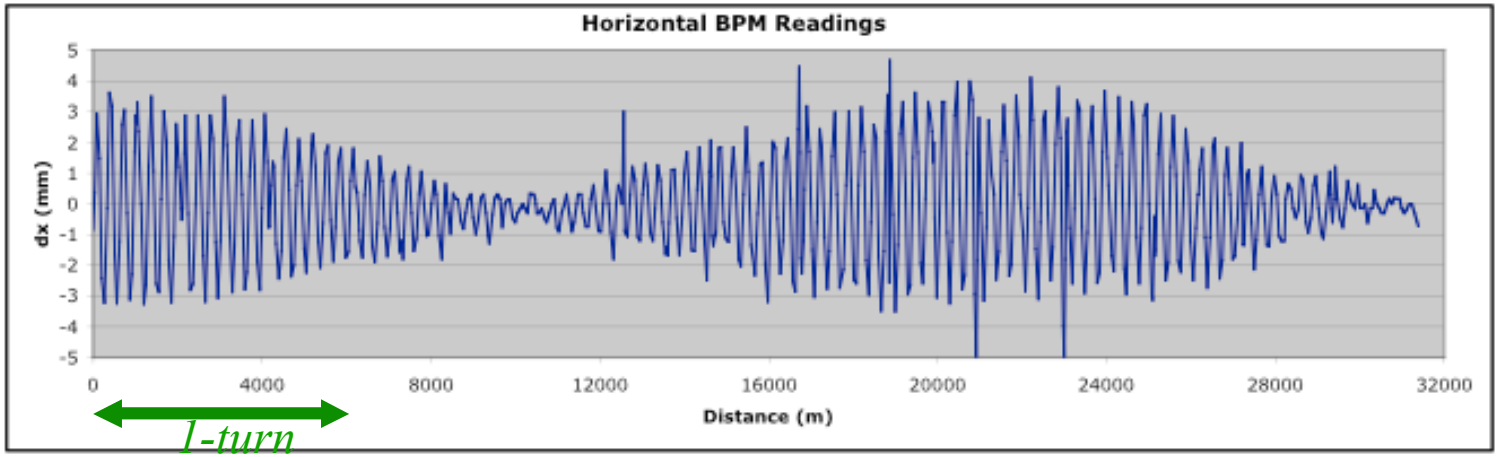
Estimates of Source Terms

- **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…**

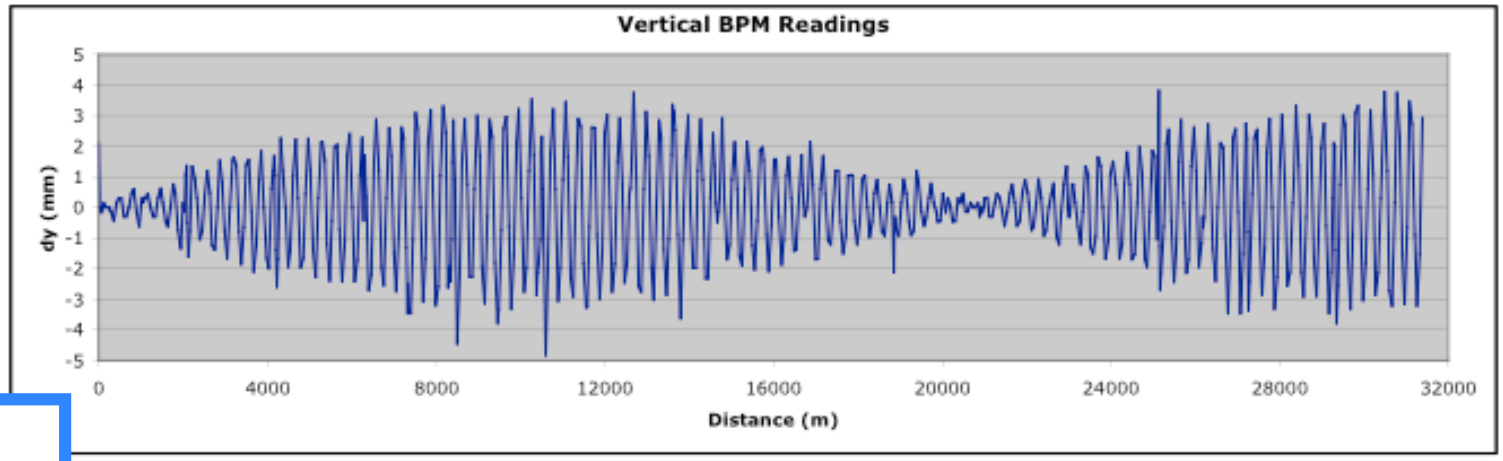
The Measurement …

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…**

  $\Delta\nu_{min} = 2\, F\, a_1 \sim 2\,(25\text{ m})(1\text{x}10^{-4}/\text{in.})(\text{in.}/0.0254\text{ m}) = 0.2$

The Smoking Gun

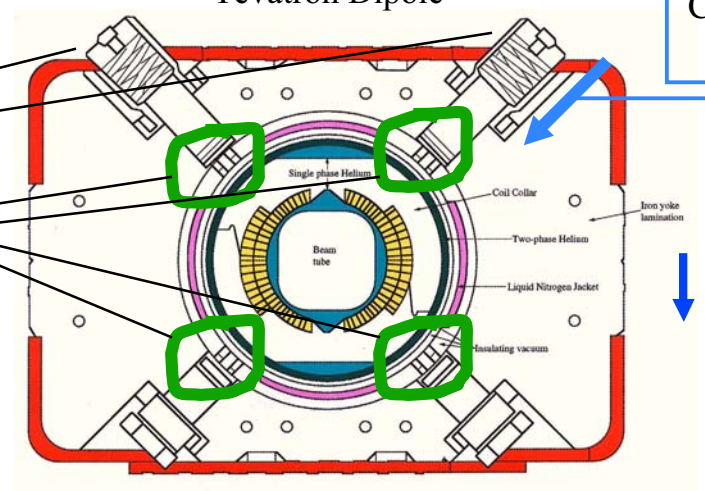
Just before the experiment, during a routine shutdown, technicians were sent to the Tevatron tunnel to measure coil placements (via "Smart Bolts") to look for rotations inside the iron yoke.

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

Tevatron Dipole

"Smart Bolts"

G-11 spacers

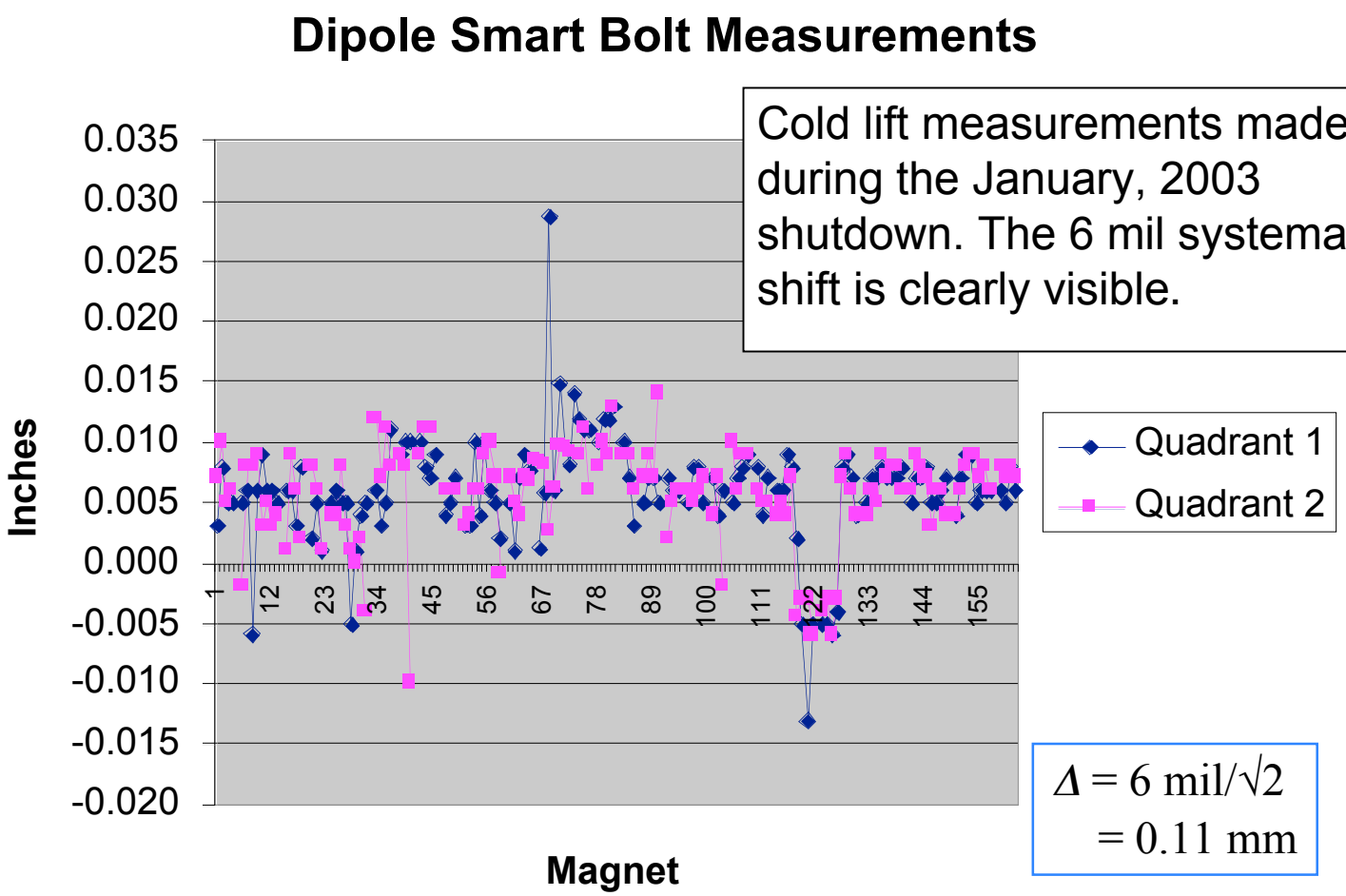


Compressed by 6 mil (0.006 in.)

Δ = 4.2 mil

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

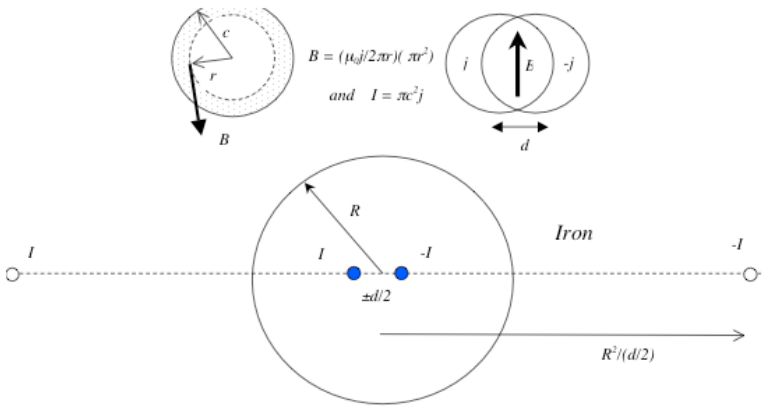
Coil Measurements

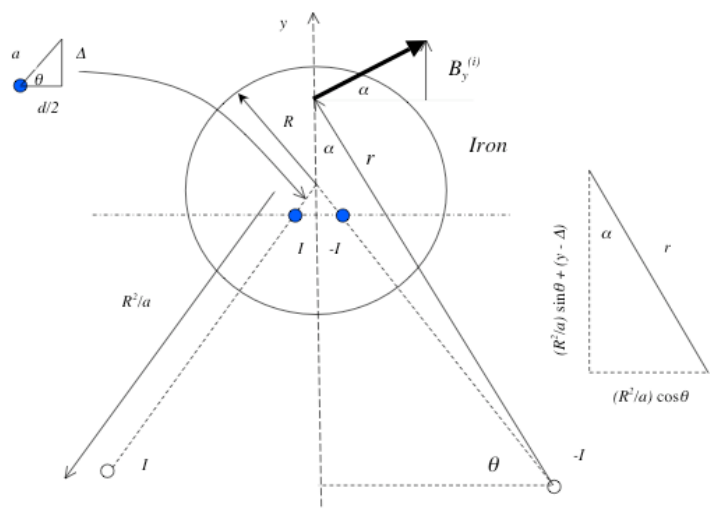


Cold lift measurements made during the January, 2003 shutdown. The 6 mil systematic shift is clearly visible.

$\Delta = 6\ \text{mil}/\sqrt{2}$
$= 0.11\ \text{mm}$

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,

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

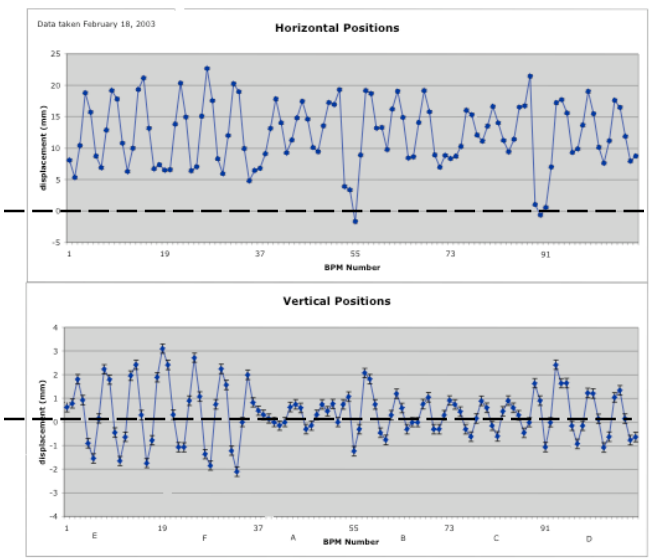
Local Coupling due to Non-local Correction

- **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**

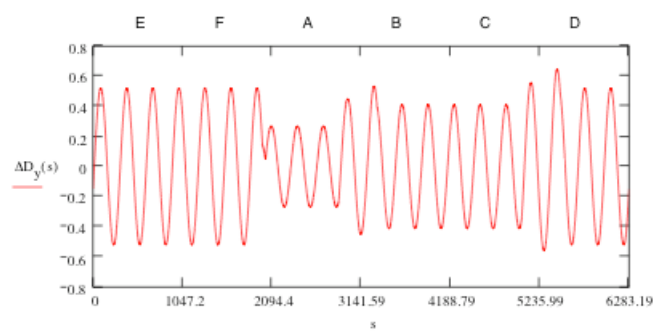
(measured)

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, …**