Effects of Systematic Rolls of Tevatron Magnets

Mike Syphers

BD/Beam Physics

Steering by Errors/Misalignments

- Typical Steering Errors
  - Transverse Displacements $\Delta\theta_{x,y} = d_{x,y}/F$
  - Roll Misalignment $\Delta\theta_{y} = \theta_0\, \phi$
  - Field Strength Error $\Delta\theta_{x} = \theta_0\, \Delta(BL)/(BL)$
- Closed Orbit Distortion

$$\Delta x = \frac{\Delta\theta\sqrt{\beta_0\beta}}{2\sin\pi\nu}\cos[\phi - \pi\nu]$$

- Linear Coupling due to rolled quad

$$\Delta\nu_{\min} = \frac{1}{2\pi}\sqrt{\beta_x\beta_y}\left(\frac{1}{F}2\phi\right)$$

Some History…

- Tevatron Design Report (1979)
  - Corrector Specification
    - Dipole $d = 0.5$ mm; $\theta = 1.4$ mrad; $\Delta B/B = 1.4\text{x}10^{-3}$
      (rms #'s)
    - Skew Quadrupole = standard tune quad, rotated 45°
- Commissioning (1983-84)
  - Alignment -- $\theta_{\text{rms}} \approx 1$ mrad or better; $d_{\text{rms}} \approx 0.5$ mm
  - Closed Orbit Correction
    - Observed $\theta_x \approx \theta_y \approx 30$ μrad (rms); $\theta_{max} \approx 110\text{-}130$ μrad
    - $<\theta_x> \approx 30$ μrad (energy offset) $<\theta_y> \approx 1.5$ μrad
  - Coupling Correction
    - Observed ~ 1-2 A correction in skew quad circuit (T:SQ) @ 800 GeV

History… (cont'd)

- Check:
  - Expected dipole correction:

$$\theta_c = \sqrt{\frac{2\langle J\rangle}{\hat{\beta}\sin^2\pi\nu}}\,\frac{1}{F}\left[d^2 + 2\,\frac{4\pi^2F^2}{774^2}\,\theta^2\right]^{1/2} = 32\ \mu\text{rad}$$

  - Expected skew quad correction:

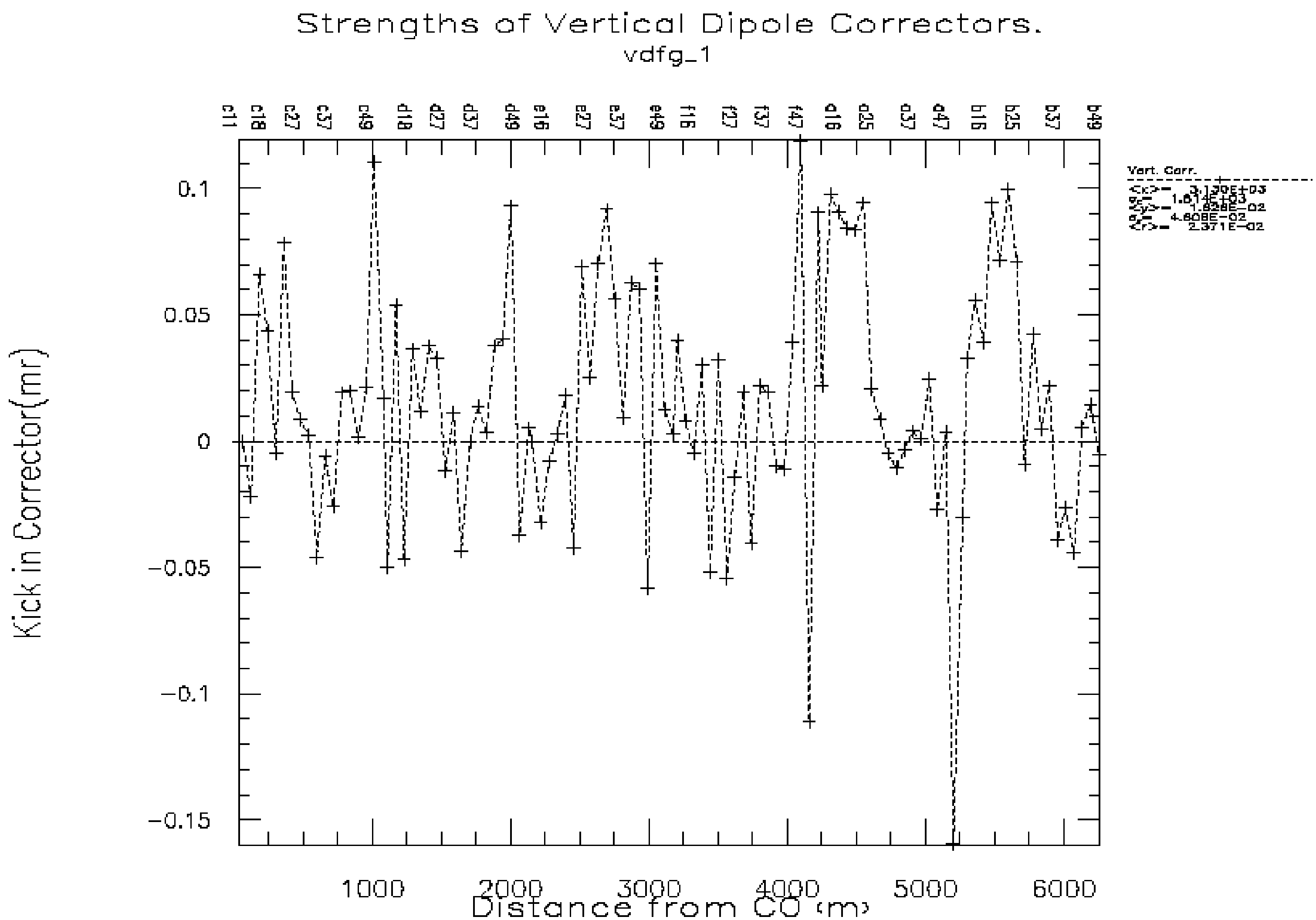
$$\Delta\Delta\nu_{\min}^{(typ)} = \frac{1}{2\pi}k_{rms}\sqrt{\beta_x\beta_y}\sqrt{N} = \frac{2}{\pi}\theta_{rms}\sqrt{N} = \frac{2}{\pi}(1\text{mrad})\sqrt{200} = 0.01$$

$$\frac{\Delta B'L}{B'L}\times(50\,\text{A}) = \frac{2\pi\Delta\Delta\nu_{\min}(B\rho)}{N_c F\,(B'L)}(50\,\text{A}) = \frac{2\pi(0.01)\left(\frac{10}{3}800\right)T\cdot m}{40(25m)(6T)}(50\,\text{A}) \sim 1\,\text{A}$$

…2002

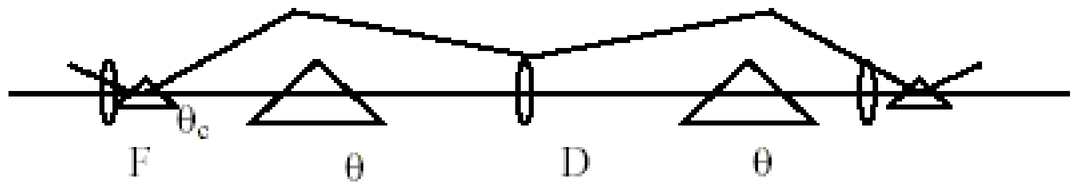
- Observed:
  - Systematic offset of H correctors
    - Energy error -- fixed
    - $\langle \theta_x \rangle = 0.7$ μrad now
  - Systematic offset of V correctors after orbit smoothing…
    - Ring-wide: $\langle \theta_y \rangle = 16$ μrad
    - Regions: $\langle \theta_y \rangle = 80$ μrad!
    - suspected systematic steering due to rolled dipoles

…2002 -- Dipole Correctors



…2002 (cont'd)

Estimate of magnitude of effect…



here, $\theta = \phi\theta_0$

Periodic solution:

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

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

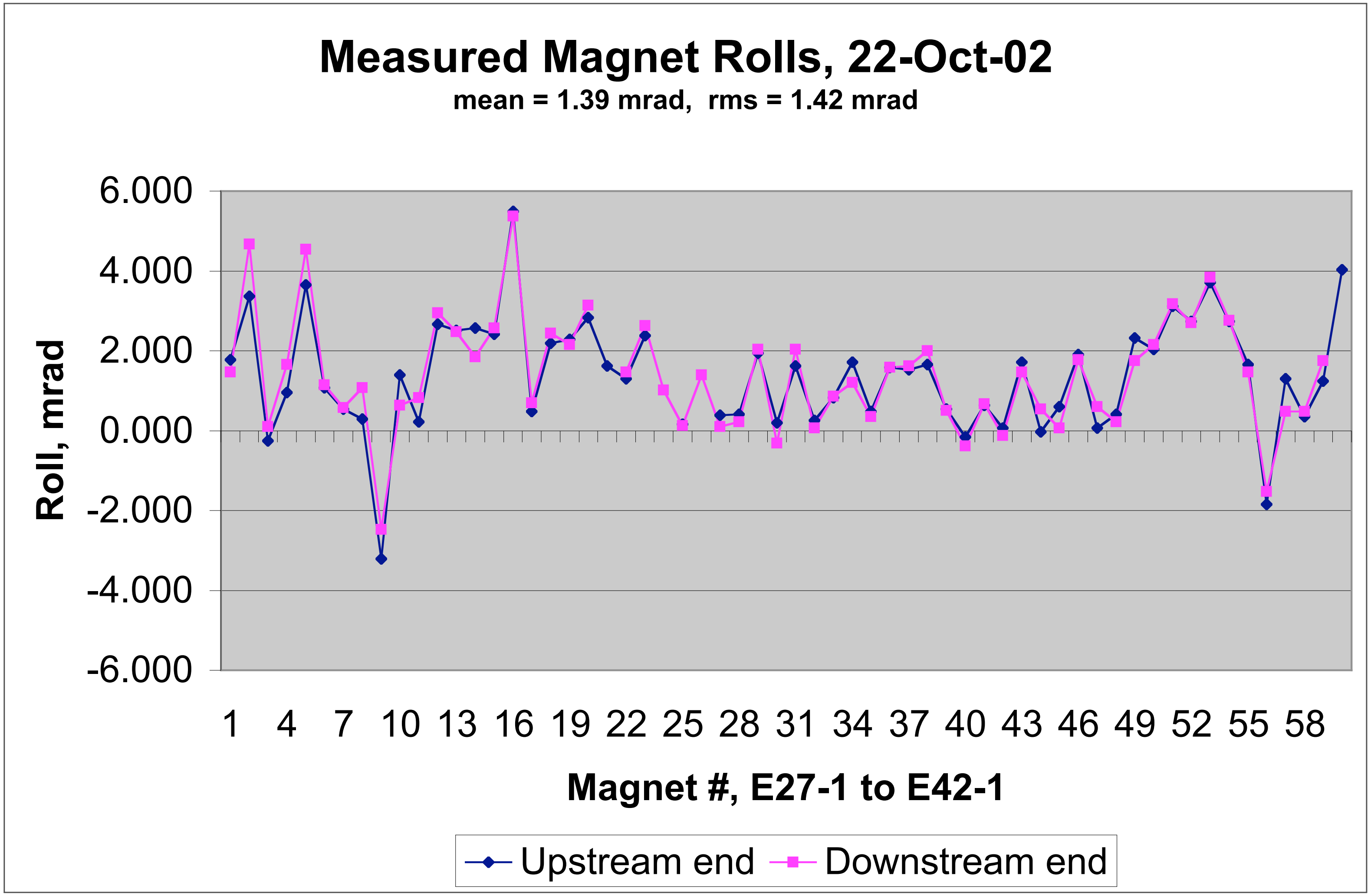
$$y'_0 = \theta_c/2$$

where $\sin(\mu/2)=L/(2F)$

So, 80 μrad correction would correspond to a systematic roll angle of…

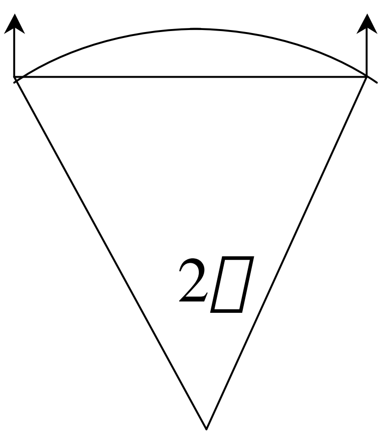
$$\phi = \pm\frac{80\,\mu rad}{(2\pi/774)\cdot 4}\cdot\frac{2.6}{1.6} = \pm 1.5\ \text{mrad}$$

…2002 (cont'd)



Measured Magnet Rolls, 22-Oct-02
mean = 1.39 mrad, rms = 1.42 mrad
Roll, mrad
6.000
4.000
2.000
0.000
-2.000
-4.000
-6.000
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
Magnet #, E27-1 to E42-1
Upstream end
Downstream end

- Note: the magnets in the tunnel should be tilted, and this is taken into account during survey…

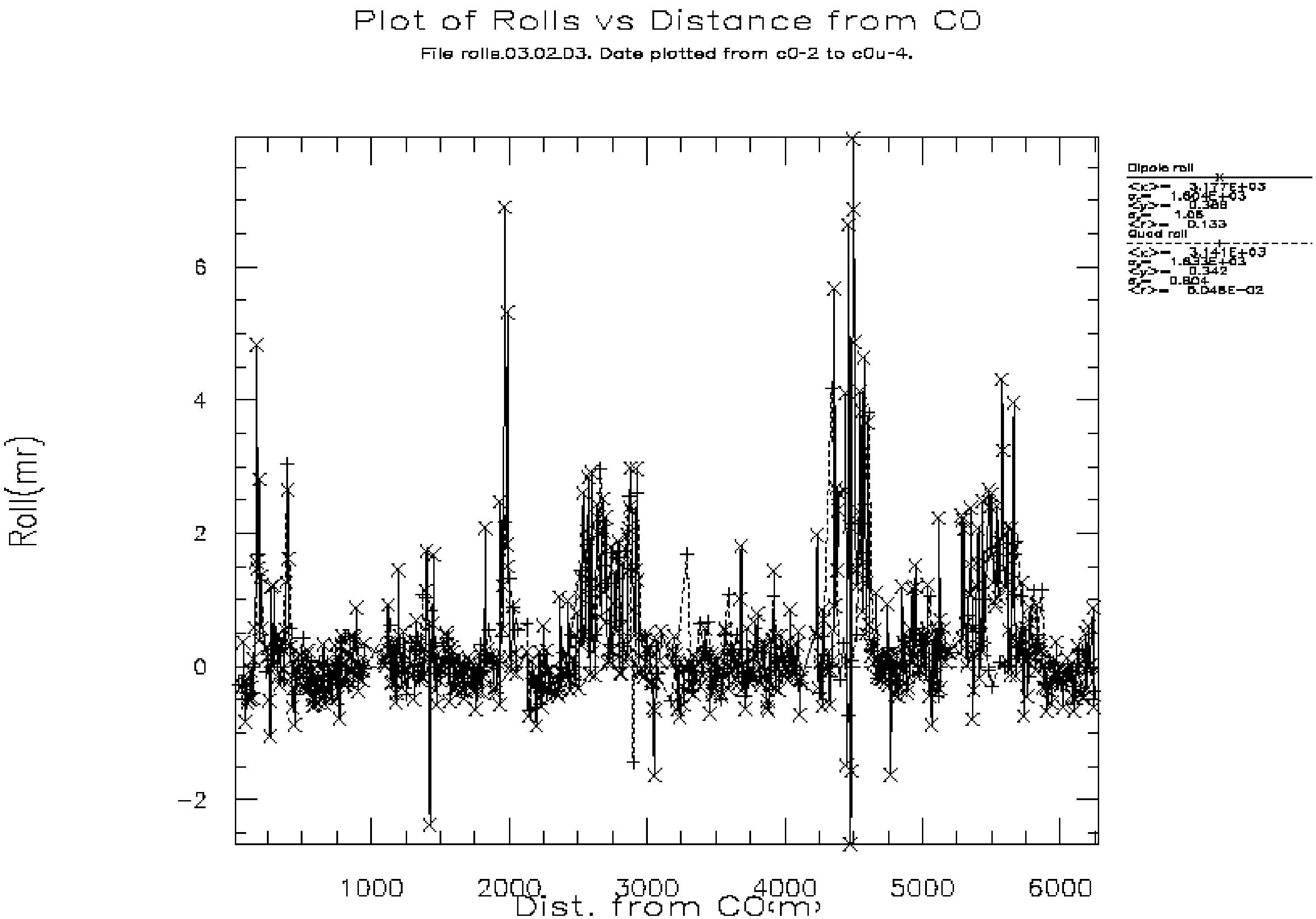


$\theta \approx 1 \text{ km} / 6400 \text{ km} = 0.16 \text{ mrad}$

So, in the noise; we see much larger roll angles

January 03 Shutdown

Tiltmeter Measurements

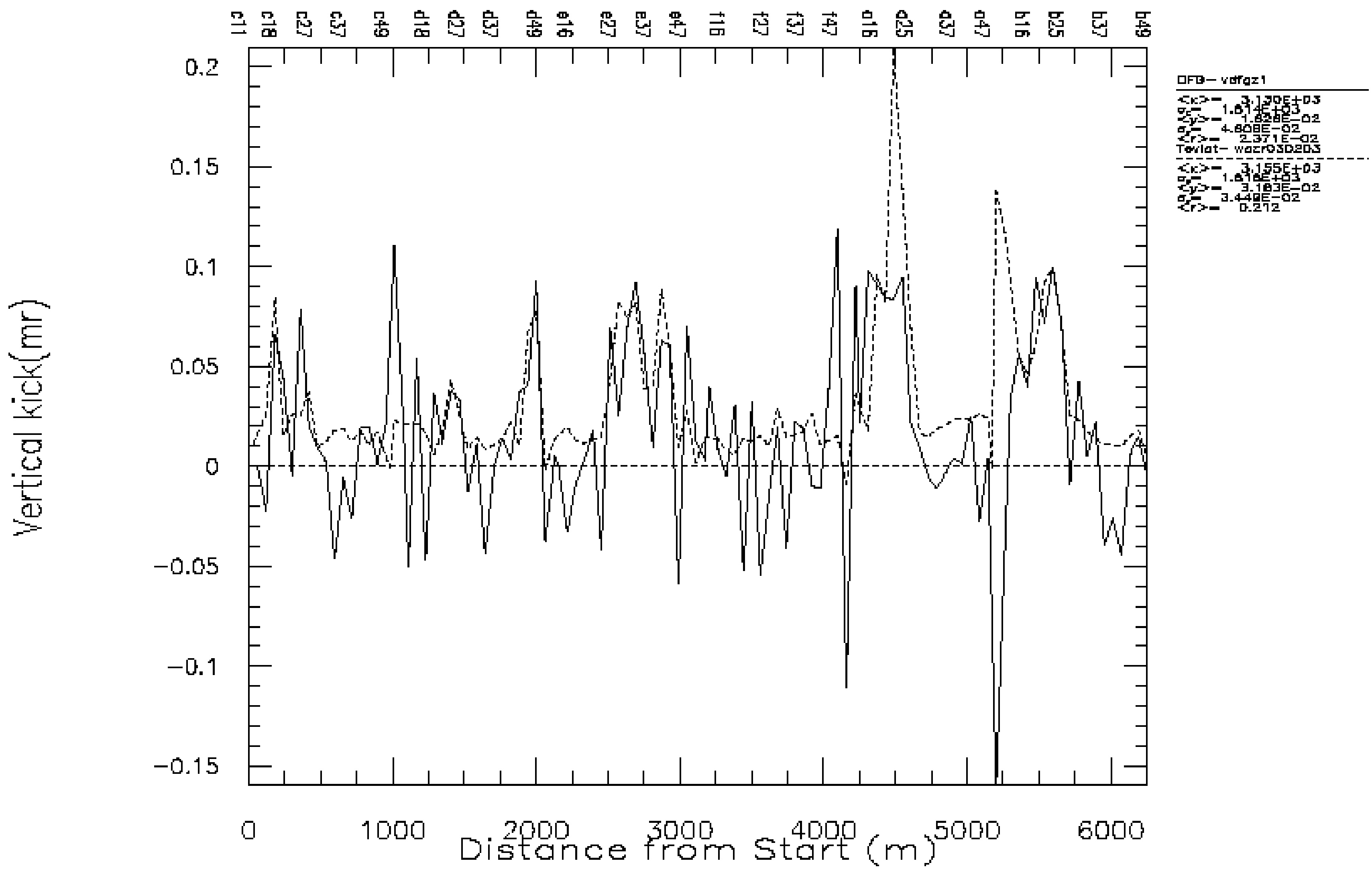


Modeling Effort

- TEVLAT modeling (N. Gelfand)
  - Magnet Database input (multipole data)
  - Survey information (via AMG, B. Hanna, R. Stefanski, et al.)
  - Corrector settings (via C49, etc.)
  - Looking for effects on lattice, optical properties due to field and alignment errors, etc.

Vertical

Comparison of dfg file [vdfg_1] with tevlat calculation in file [wc.r030203]



Coupling due to Feed down

- A corrected Systematic roll through a region…
  - Positive corrections indicate a roll to the radial inside
  - After correction, BPM's = 0, but orbit "scallops" vertically on order of (80 mrad/2)(15 m) = 0.6 mm
  - Average vertical position is less, but still ~0.4 mm.
  - Average vertical offset will feed down into linear coupling due to b_2 in the dipole magnets…

$$B_y = B_0[1 + b_2(x^2 - y^2)], \quad Bx = 2B_0 b_2 xy$$

skew quad field:

$$\partial B_x / \partial x = -\partial B_y / \partial y = 2B_0 b_2 y$$

Coupling Feed down (cont'd)

- Thus, a corrected systematic roll would produce…

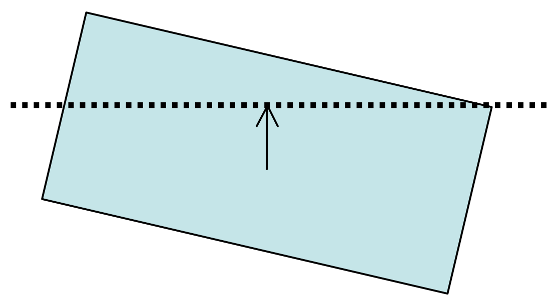
$$\Delta\nu_{\min} = \frac{1}{2\pi}\sqrt{\beta_x\beta_y}\left(\frac{2B_0 b_2\langle y\rangle\ell}{B\rho}\right)N_{dip} \approx \frac{2}{\pi}F\theta_0 b_2\langle y\rangle N_{dip}$$

- Suppose have ~3 sections, as seen in the data, where: $\theta \approx$ 1.6 mr over 7 cells, ≈ 3 mr over 4 cells, ≈ 1.6 mr over 7 cells (E, A, B sectors), and all add coherently to the minimum tune split. Then,

$$\Delta\nu_{\min} \approx \frac{2}{\pi}(25m)(64mr)\left(4\times\frac{1}{2.54^2}m^{-2}\right)(0.4mm)\left(7\cdot\frac{1.6}{1.4}+4\cdot\frac{3}{1.4}+7\cdot\frac{1.6}{1.4}\right)= 0.006$$

Feed down coupling…

- Simple “roll” may not be the whole story; the dipoles are tilted, but perhaps tilt axis is not about their centers…

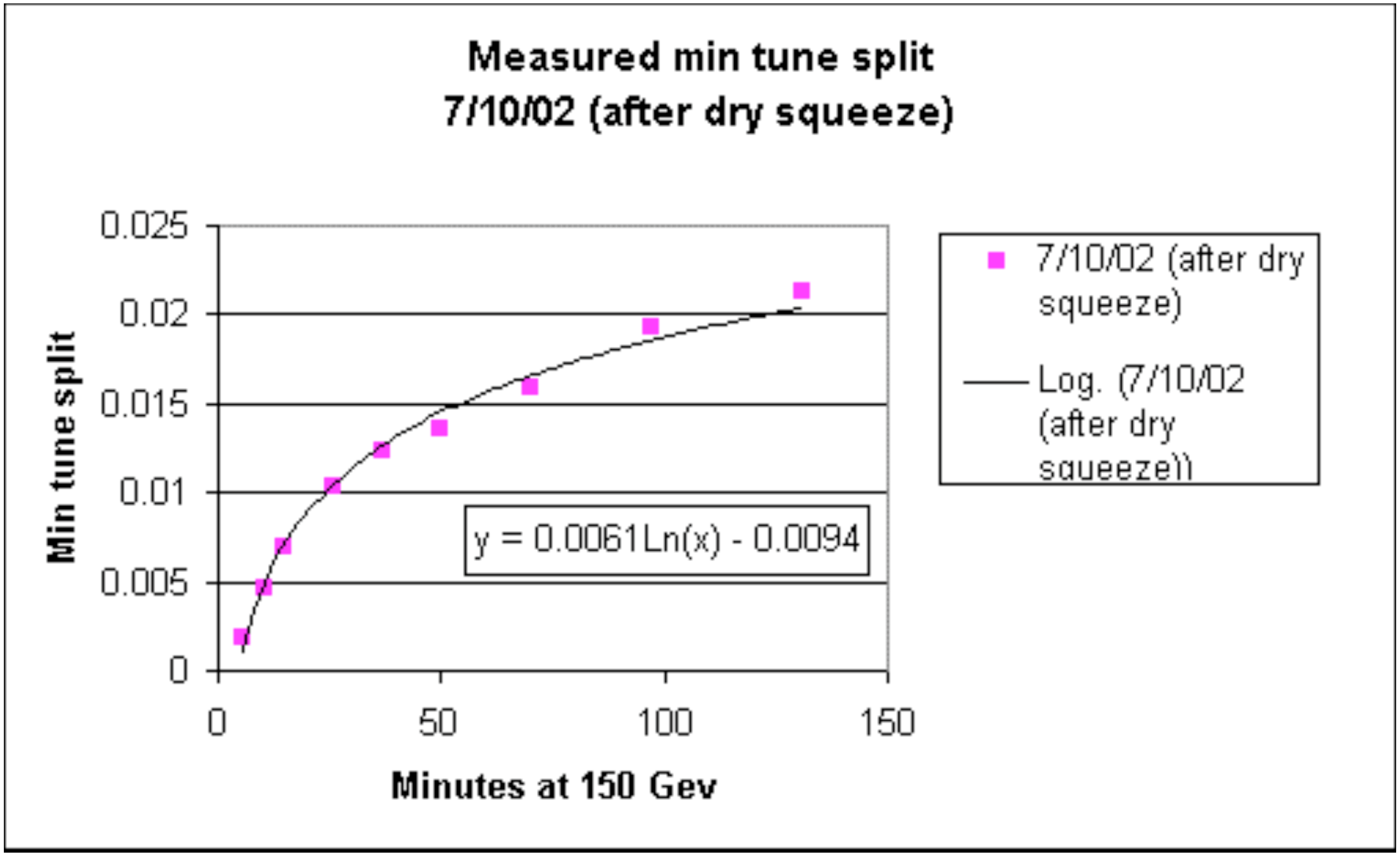


1.4mrad (27”/2) = 20 mil = 0.5 mm

Historically, quadrupole alignment (x,y,roll) has been better tracked than dipole alignment; thus, could imagine (better) aligned quads, with beam centered on BPMs, but dipole magnets misaligned producing coupling due to this effect.

Time variation of Sextupole Moment

- We know that chromaticity drifts in the Tevatron due to (logarithmic) time-varying persistent currents in the superconductor --
  - $□□_{x,y} = \pm <b_2(t)□D> = 25$ units   per unit of b_2
- We see drifting coupling with similar time behavior, with $□□_{min} \approx 0.02$ over 2 hours, during which time $□b_2 \approx 2$ units
- The "feed down" effect probably does not explain the major sources of coupling seen in the Tevatron, but may explain the time varying coupling observed at 150 GeV, taking into account all magnet misalignments.
- Will continue to examine, using latest roll information, etc.



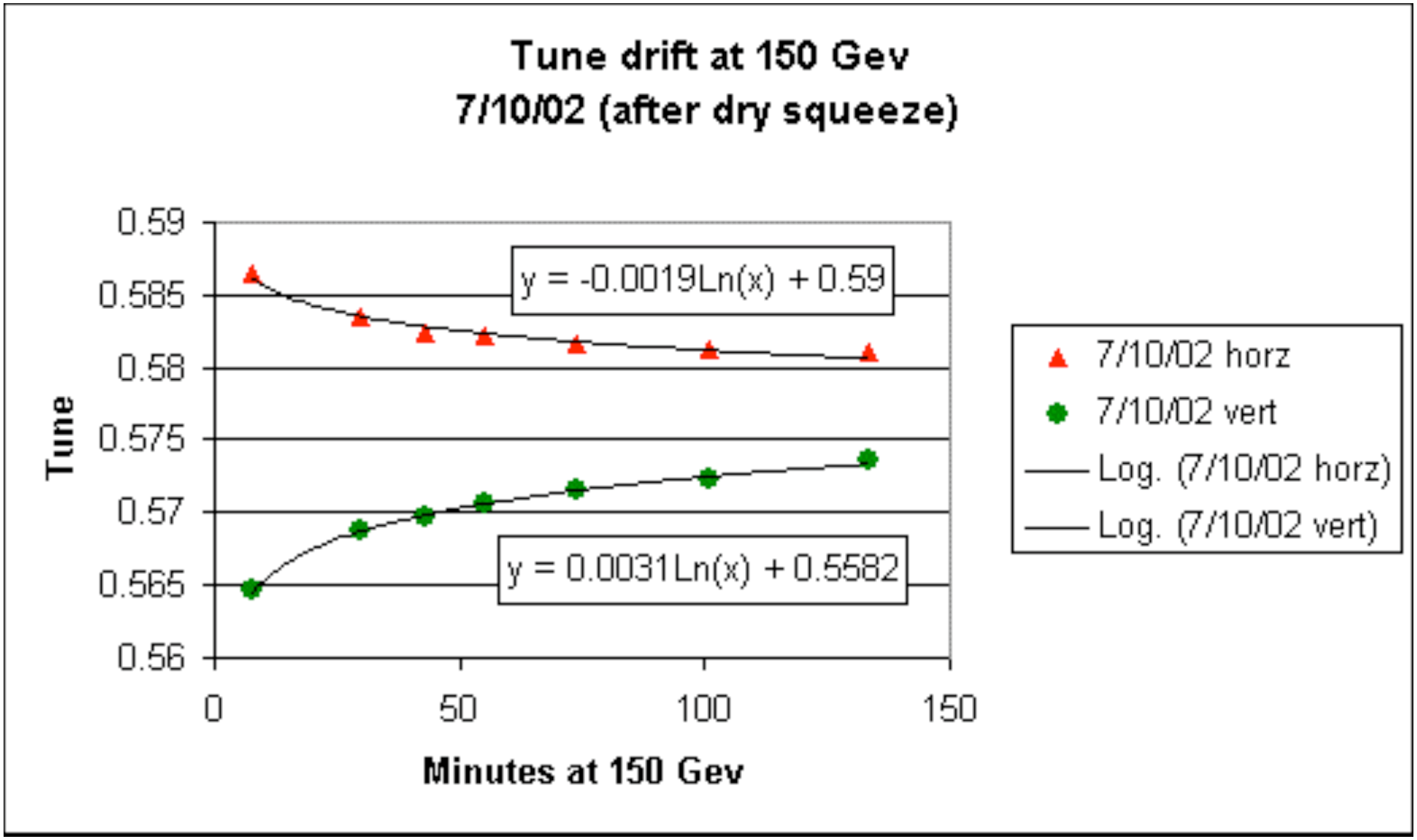
Courtesy M. Martens, P. Bauer

More words on Coupling in the Tevatron

- Tune quads are running harder than desired; if took decoupled Tevatron and turned off all the skew quad correctors, would have $\Delta\nu_{min}$ = 0.2! Thus, large coupling source(s) in the ring.
- Skew quad circuits can correct $\Delta\nu_{min}$, a ***global*** parameter, but still can be large ***local*** variations in amplitude functions, dispersion, etc. -- *local* coupling. (e.g., SynchLite monitor signals for pbars on helix)
- Can affect β, D:
  - injection match, emittance growth
  - β^*, luminosity

Tune Drift at 150 GeV

- The tunes are also observed to drift logarithmically at injection; can misalignments of dipoles explain this?
- For tune shift, would need horizontal offset in the dipole magnets
  - Similar argument as above holds if either (a) energy offset is corrected by the horizontal correctors, or (b) systematically misaligned (horizontal) elements
  - But, correctors (H) do not show systematic offsets as in the vertical correctors (0.7 μrad --> $dE/E = -1.3\text{x}10^{-5}$)



Courtesy M. Martens, P. Bauer

Tune Drift at 150 GeV (cont'd)

- Another observation -- if center the orbit through the SF sextupole family, the beam is not centered through the SD sextupole family (by about +0.25□mm, on average); currently running this way
- These families are used to control chromaticity, i.e., they vary according to the logarithmic time variation of b_2 in order to keep □ under control at 150 GeV…

$\Delta p/p = -1/\eta \; \Delta f/f$

$\sim -18^2 \, (20/53) \, 10^{-6}$

$= \; -0.12 \times 10^{-3}$

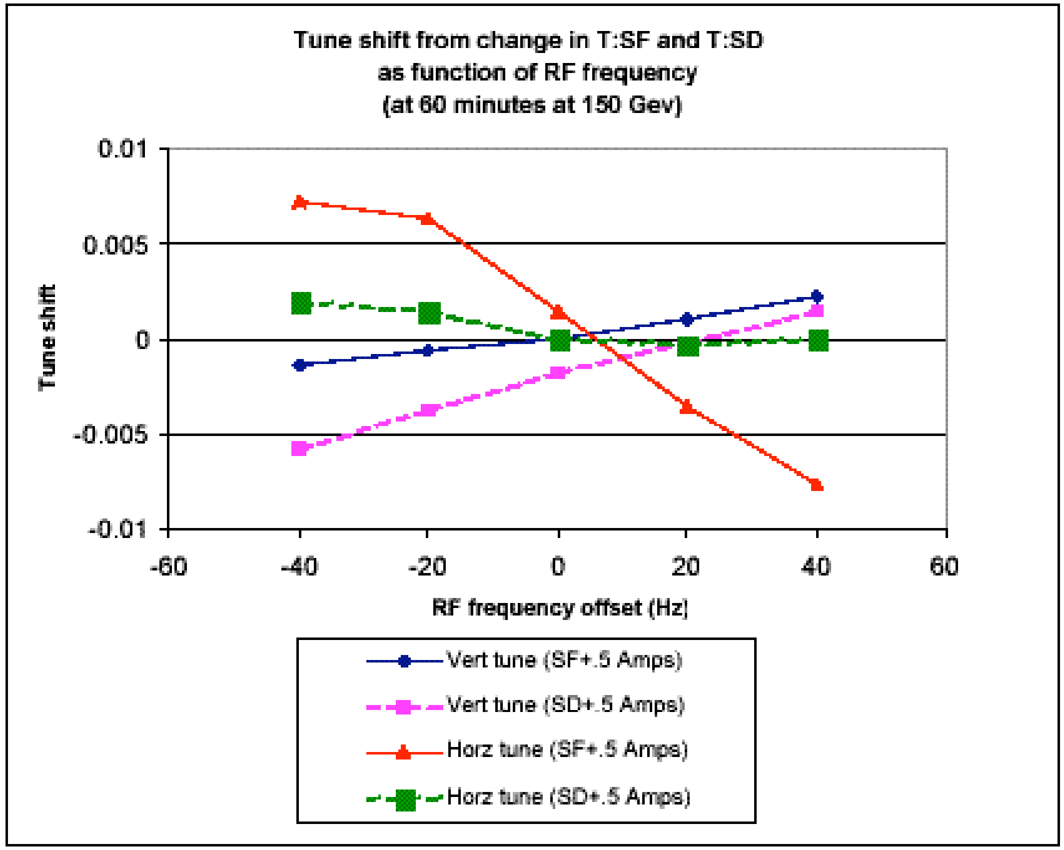
-->

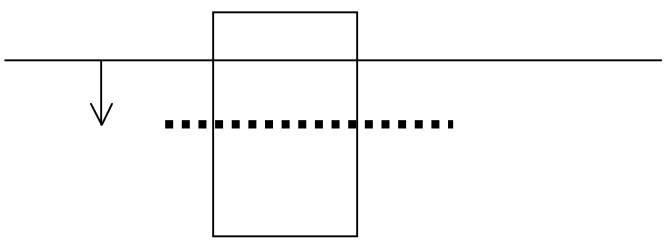
$<\Delta x>$

$\sim -(2m)(0.12 \times 10^{-3})$

~ -0.25 mm

--> +0.25 offset from center of sextupoles





Courtesy M. Martens, P. Bauer

Tune Drift (cont'd)

- Suppose beam centered at SF's, off by +0.25 mm at SD's, and SF/SD's play out "b_2 drift" program; then,

$$\Delta\nu_x \approx \frac{1}{2\pi}\breve{\beta} S_D N_D \langle x \rangle \approx \frac{1}{2\pi}\breve{\beta}\frac{4\pi\Delta\xi_y}{\hat{\beta}\breve{D}}\langle x \rangle$$

$$= 2\frac{\breve{\beta}}{\hat{\beta}}\Delta\xi_y \frac{\langle x \rangle}{\breve{D}} = 2(25/100)(-50)(0.25mm/2m)$$

$$= -0.003$$

and $\Delta\nu_y = -\Delta\nu_x(\beta_{max}/\beta_{min}) = +0.012$

- These tune changes would occur as $\Delta\xi = 50$ during 120 minute dwell time; appear similar to observations…

Conclusions

- Alignment Issues
  - Some Correctors running @ or near limits
  - Magnets move around; re-tune orbit ~2weeks
  - Systematic vertical orbit correction
    - Stronger correctors
    - Vertical offsets through dipoles
      - Feed down of b_2 --> coupling
      - Not large source, but may explain $\Delta\nu_{min}(t)$
    - Modeling so far reproduces corrector dipole settings
    - Still investigating, w/ latest roll/alignment data
  - Tune drift -- misaligned sextupoles, dipoles (b_2), etc.?

Conclusions (cont'd)

- Other strong coupling source(s) out there
- Horizontal orbit goes through SF's centered, but not through SD's
  - May explain $\square(t)$
  - Systematic correction of energy error does not explain this offset at SD's -- requires $dE/E =$ -0.005, which would require $<\square_c>$ = 250 □rad to correct -- not observed!
- Still looking…