Tevatron Optics Correction Experience

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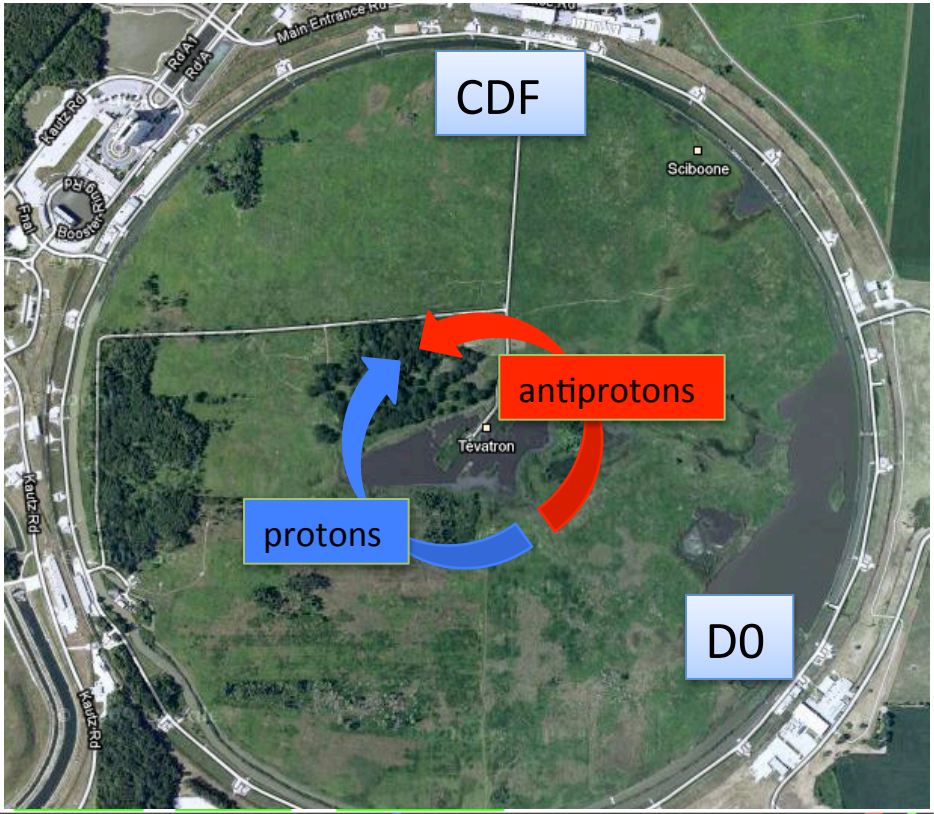
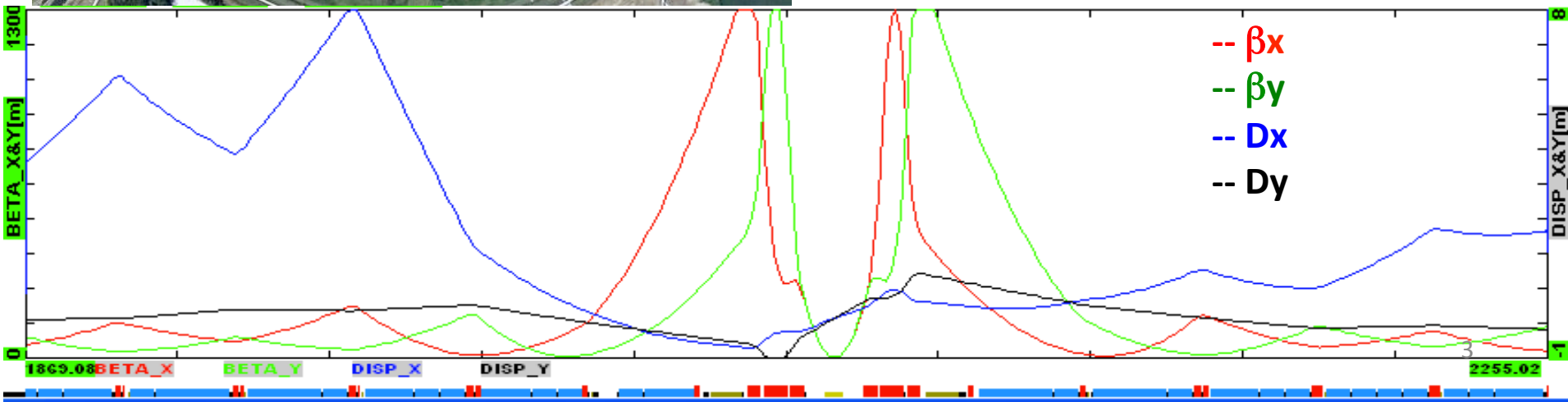
Outline

- Tevatron optics model
- LOCO
- Selected examples
  - Alignment errors
  - β^* reduction and correction of optics at IPs
  - Chromatic β-function
- Application to RHIC?

Tevatron Description



No. of dipoles	800
No. of quadrupoles	250
Quad circuits	52
Phase adv. per cell	60°
Betatron tunes	20.585/20.585
Coupling	<0.003
Interaction regions	2
β^*	0.28 m
βmax	1,400 m



Tevatron Lattice Model

- We use OptiM code[1] (Windows with GUI, Linux command line)
- Element currents (I) are extracted from control system
- Quadrupole gradient
  - Lattice quads have gradient $G=F(I)+\Delta G$
    - F(I) was measured at the time of manufacturing
    - ΔG – unknown error, determined from beam-based measurements
  - B1 component in dipoles – same for all
- Skew-quadrupoles
  - Lattice skew-quadrupoles
  - A1 component in dipoles – same for all
  - Unknown skew gradient ΔG_{sq} determined from beam-based measurements - attached to every quadrupole to account for quad tilt and/or orbit offset in sextupoles

[1] V.Lebedev, http://www-bdnew.fnal.gov/pbar/organizationalchart/lebedev/OptiM/optim.htm

Tevatron Lattice Model Continued

- Sextupoles
  - Lattice sextupoles
  - B2 component in dipoles – same for all (not right!)
    - Was not properly measured at the time of manufacturing
    - Because of this modeled chromaticity is incorrect
- Nonlinear errors in triplets not accounted for

LOCO: Linear Optics from Closed Orbit

- The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets. The response matrix is defined by the linear lattice of the machine

$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{\substack{measured \\ model}} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

- The main idea of the analysis is to adjust all the variables that the response matrix depends on in order to solve the equation

$$M_{measured} - M_{model}(z) = 0 \quad ,$$

$$\Delta z = \left(\frac{\partial M_{model}}{\partial z} \right)^{-1} \cdot \left(M_{measured} - M_{model}(z_0) \right)$$

- Orbit Response Matrix is a function of up to 1600 variables (depends on number of correctors used)
  - Quadrupole gradient errors (250)
  - Steering magnet calibrations (222, typically use 100)
  - BPM gains (236)
  - Quadrupole tilts (250)
  - Steering magnet tilts (222)
  - BPM tilts (236)
  - Energy shift associated with steering magnet changes (222)

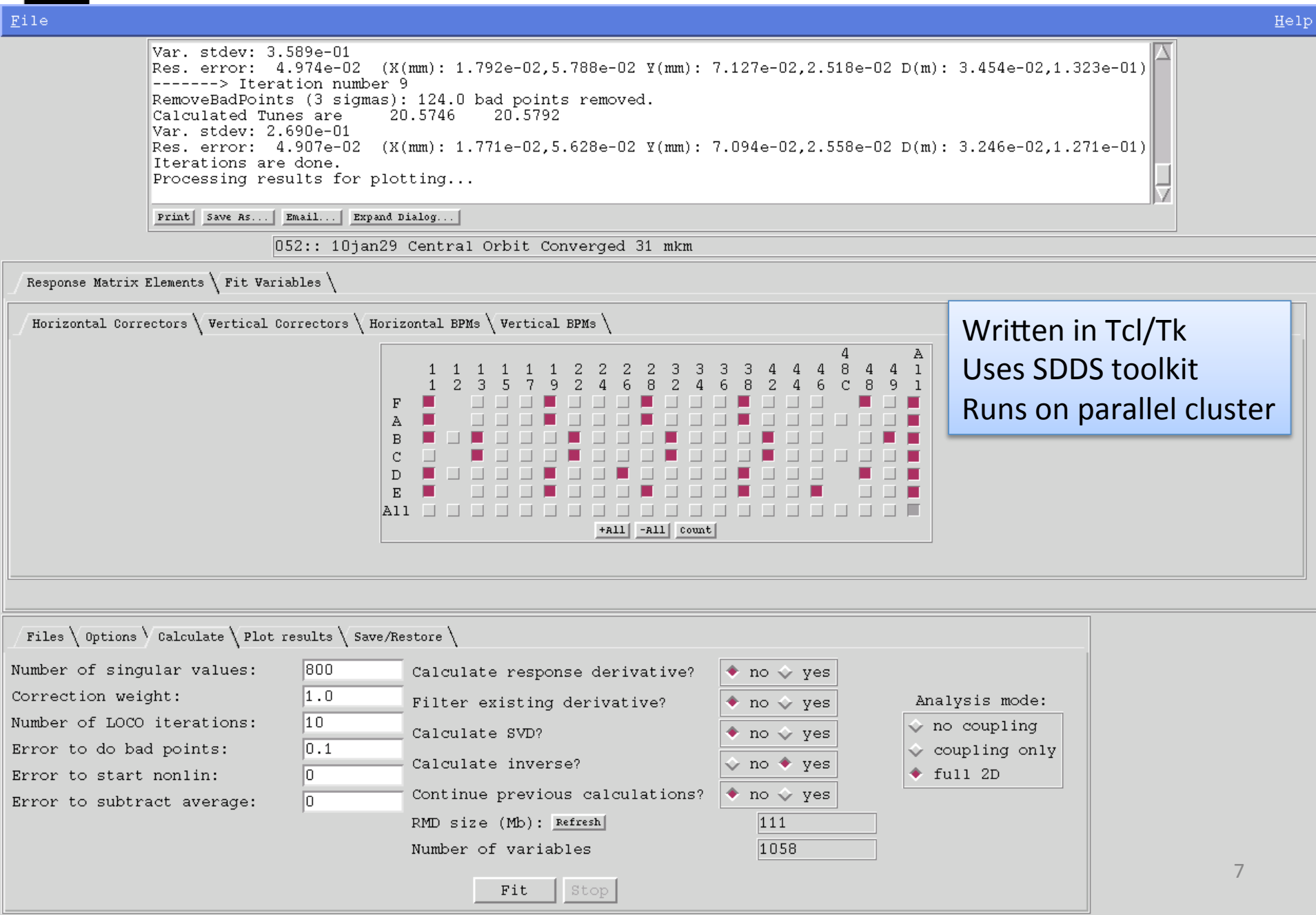
$$X = M^{-1} \cdot V$$

$$\begin{pmatrix} 1 \\ \times \\ 1270 \end{pmatrix} = \begin{pmatrix} 1270 \\ \times \\ 23600 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \times \\ 23600 \end{pmatrix}$$

- Many implementations. At Tevatron we used LOCO by V.Sajaev, ANL[1]

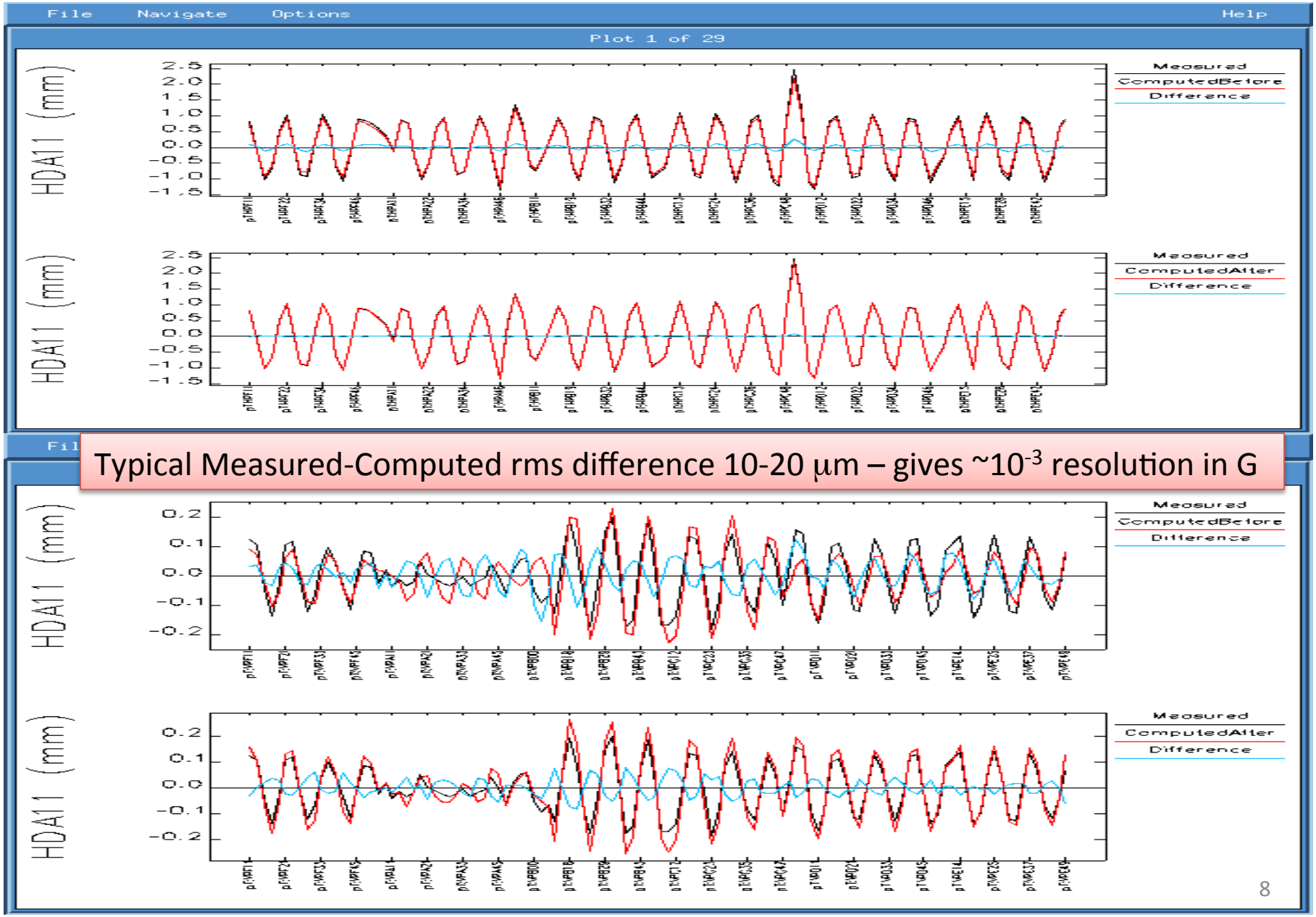
[1] V.Lebedev et al, NIM A 558 (2006)

LOCO GUI



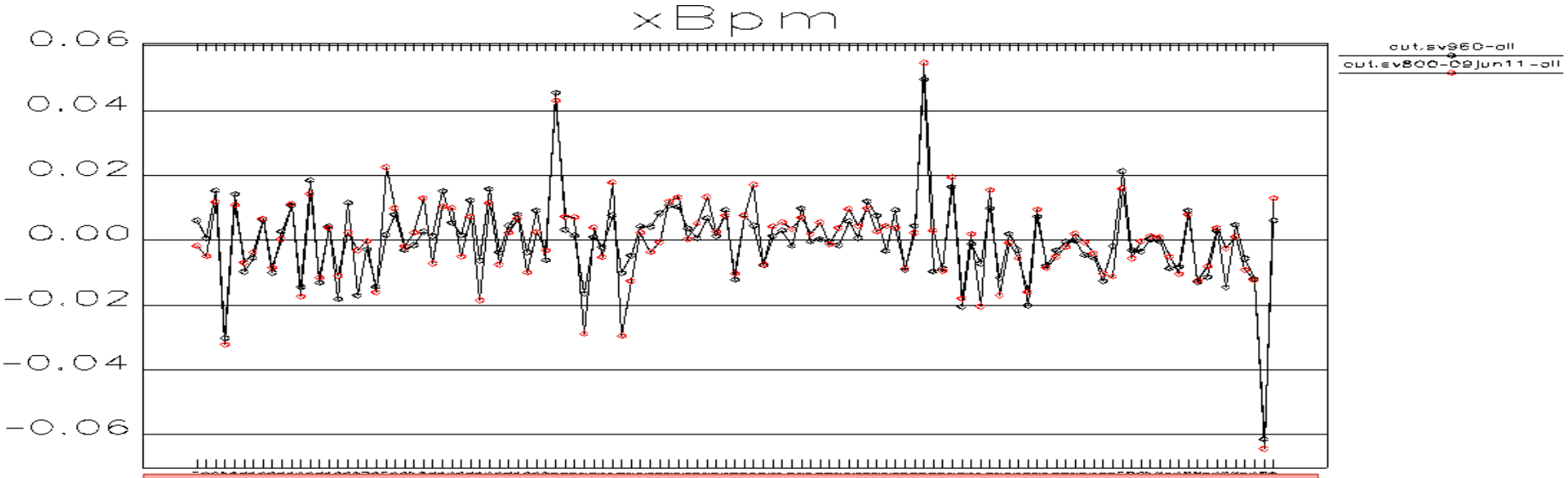
Written in Tcl/Tk
Uses SDDS toolkit
Runs on parallel cluster

LOCO: Measured and Computed Orbits

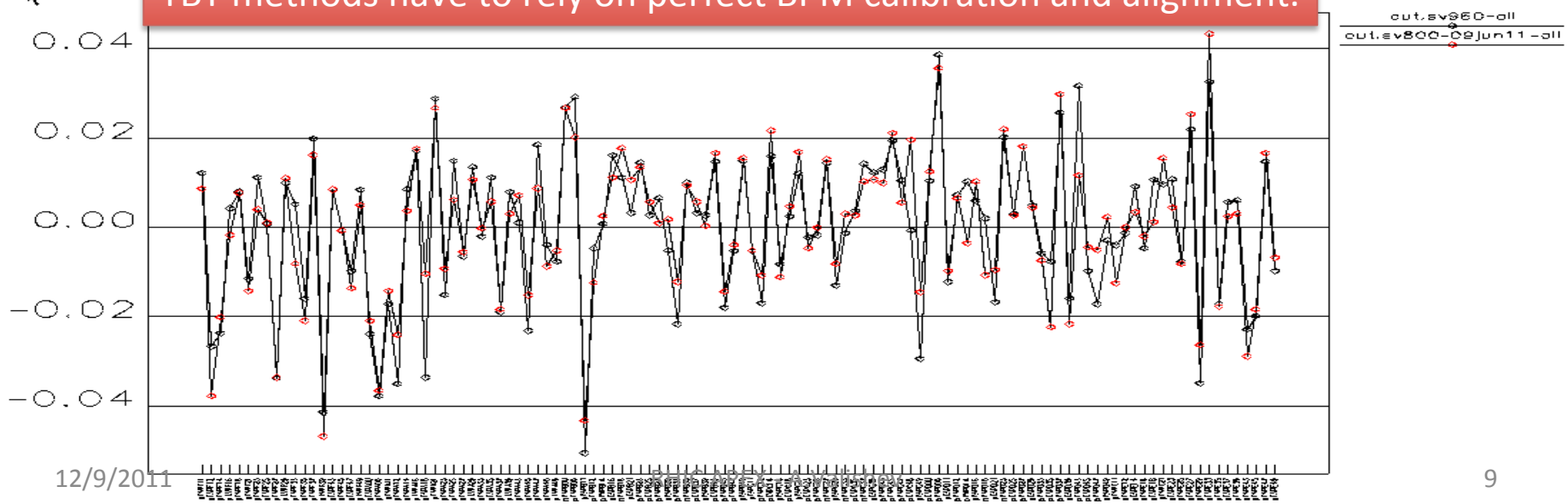


Typical Measured-Computed rms difference 10-20 μm – gives ~10^{-3} resolution in G

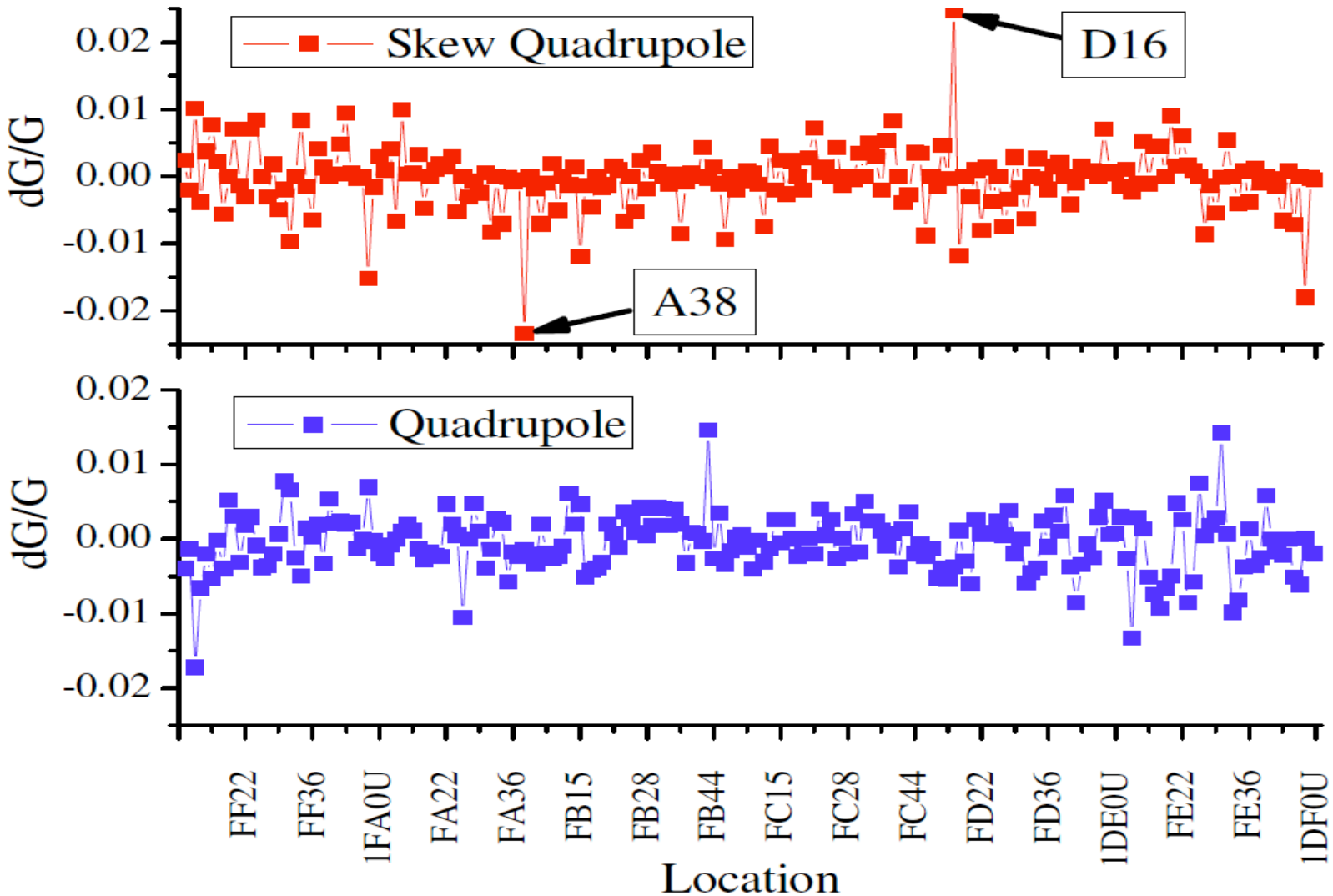
LOCO: BPM Calibration Errors and Tilts



Note: computation of these parameters is unique to LOCO.
TBT methods have to rely on perfect BPM calibration and alignment.

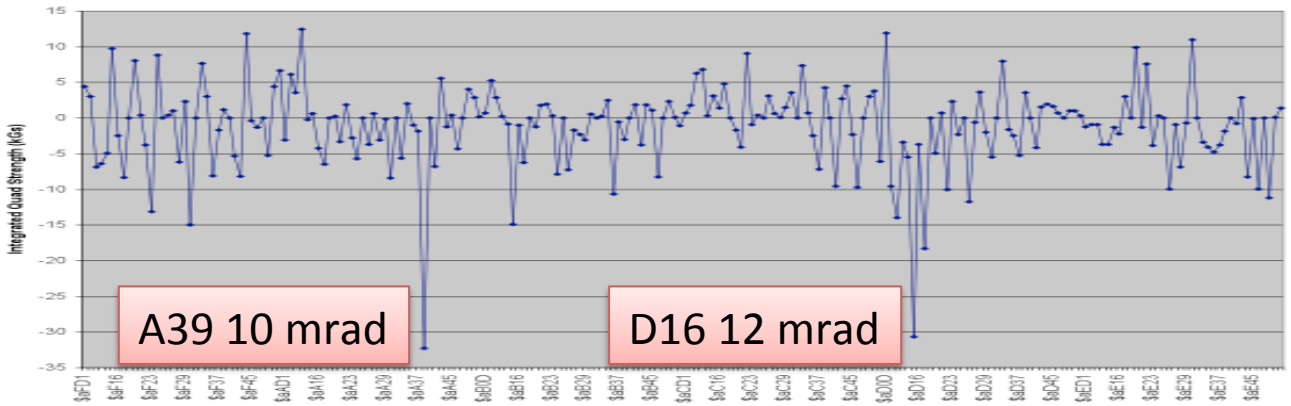


LOCO: Gradient and Skew Errors



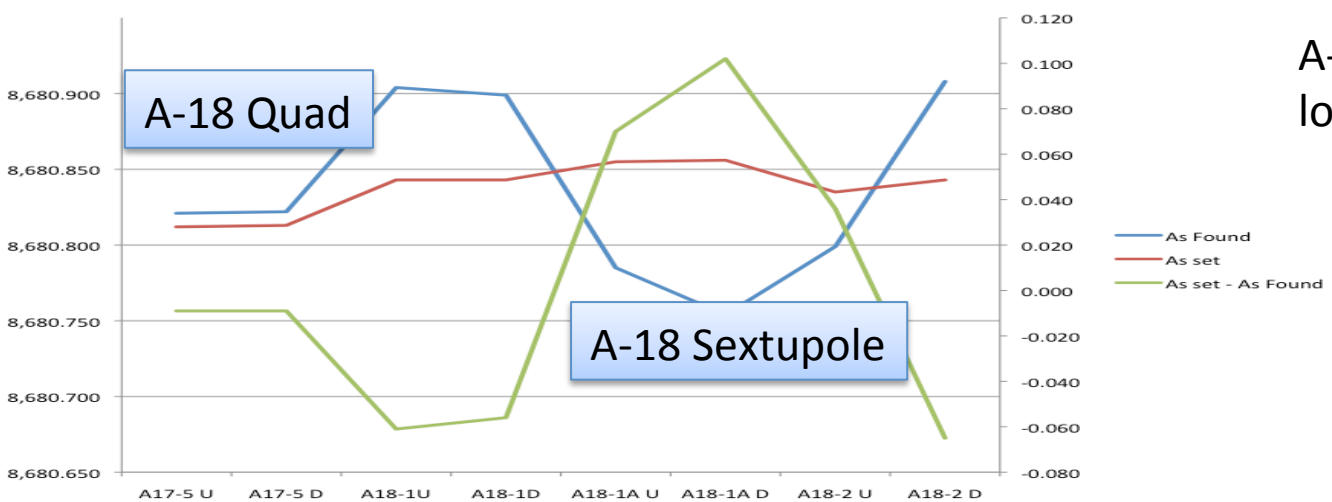
Example of Application: Alignment Errors

- Identified rolled quadrupoles



At D-16 and A-39, quadrupoles had the internal lugs set incorrectly for the roll angle

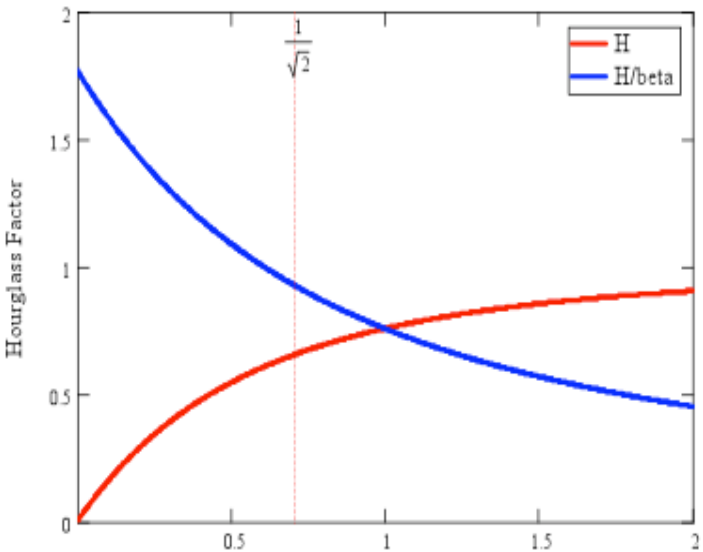
- Found alignment error resulting in offset sextupole



A-18 sextupole 2.5 mm lower w.r.t. A-18 quad

Example Application: Reduction of β^*

$$L = \frac{N_p N_a f \cdot H(\beta^*/\sigma)}{2\pi\sqrt{\sigma_{p,x}^2+\sigma_{a,x}^2}\sqrt{\sigma_{p,y}^2+\sigma_{a,y}^2}} = \frac{N_p N_a f \cdot H(\beta^*/\sigma)}{2\pi\sqrt{\varepsilon_{p,x}\beta_{p,x}+\varepsilon_{a,x}\beta_{a,x}}\sqrt{\varepsilon_{p,y}\beta_{p,y}+\varepsilon_{a,y}\beta_{a,y}}}$$

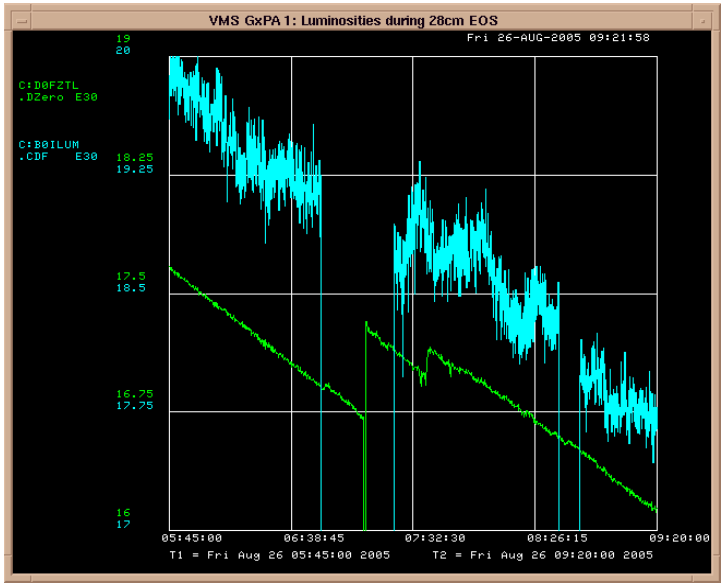


$$\rightarrow \frac{N_p N_a f \cdot H(\beta^*/\sigma)}{2\pi\left(\varepsilon_p\beta_p+\varepsilon_a\beta_a\right)}$$

$$\rightarrow \frac{N_p N_a f}{4\pi\varepsilon}\frac{H(\beta^*/\sigma)}{\beta^*}$$

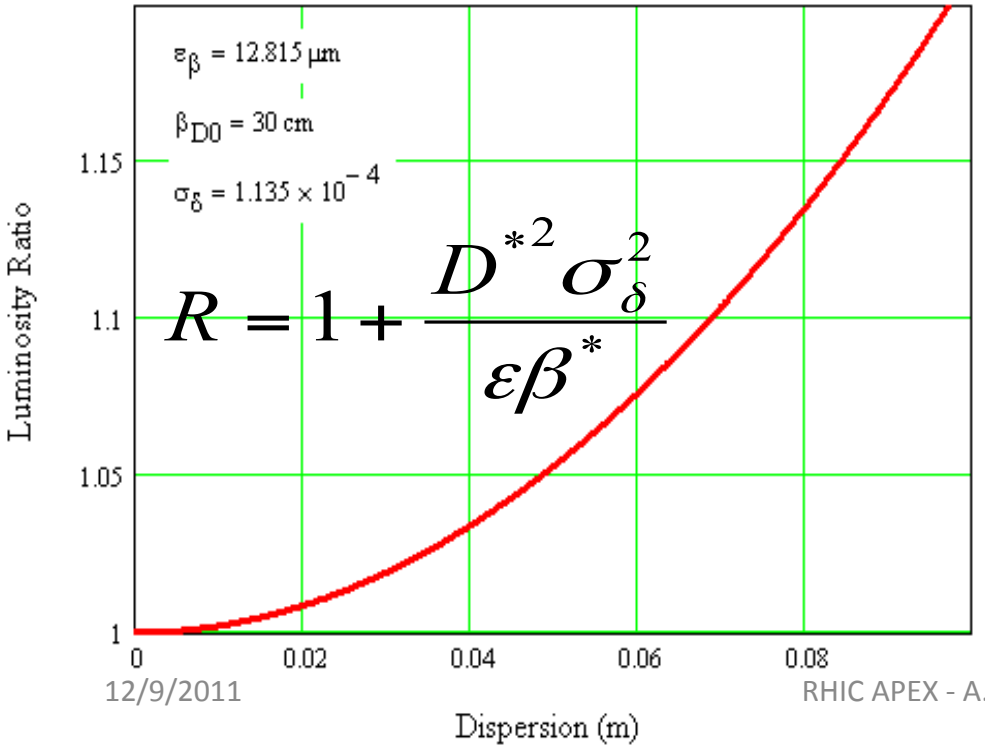
$$\beta(z) = \beta^* + z^2/\beta^*$$

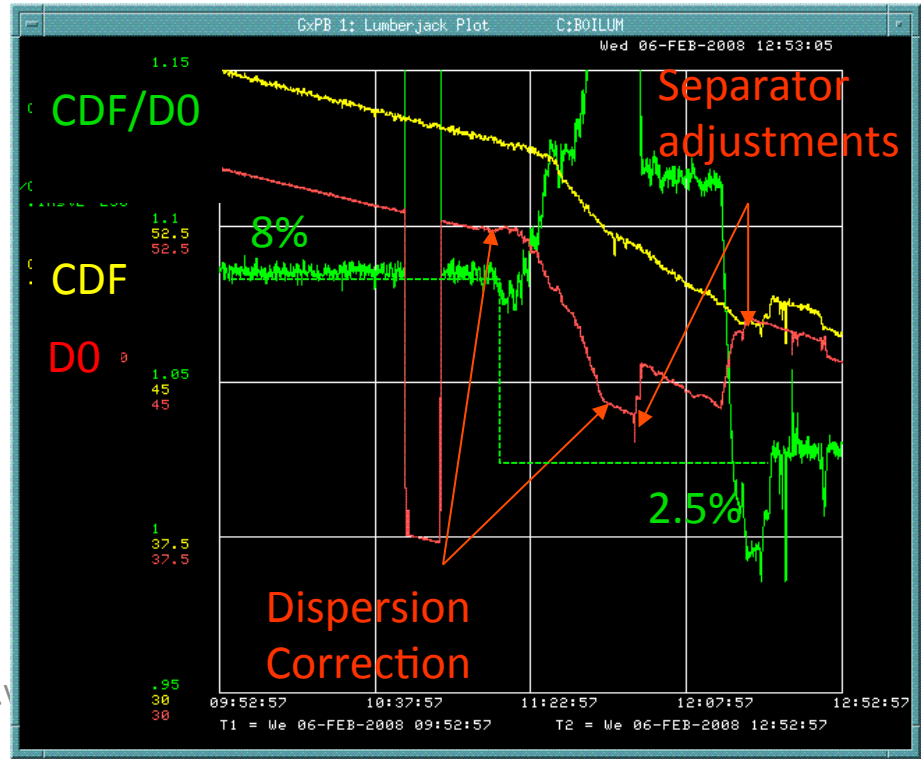
Beta* 35cm -> 28cm
gain is 11% not 25%!



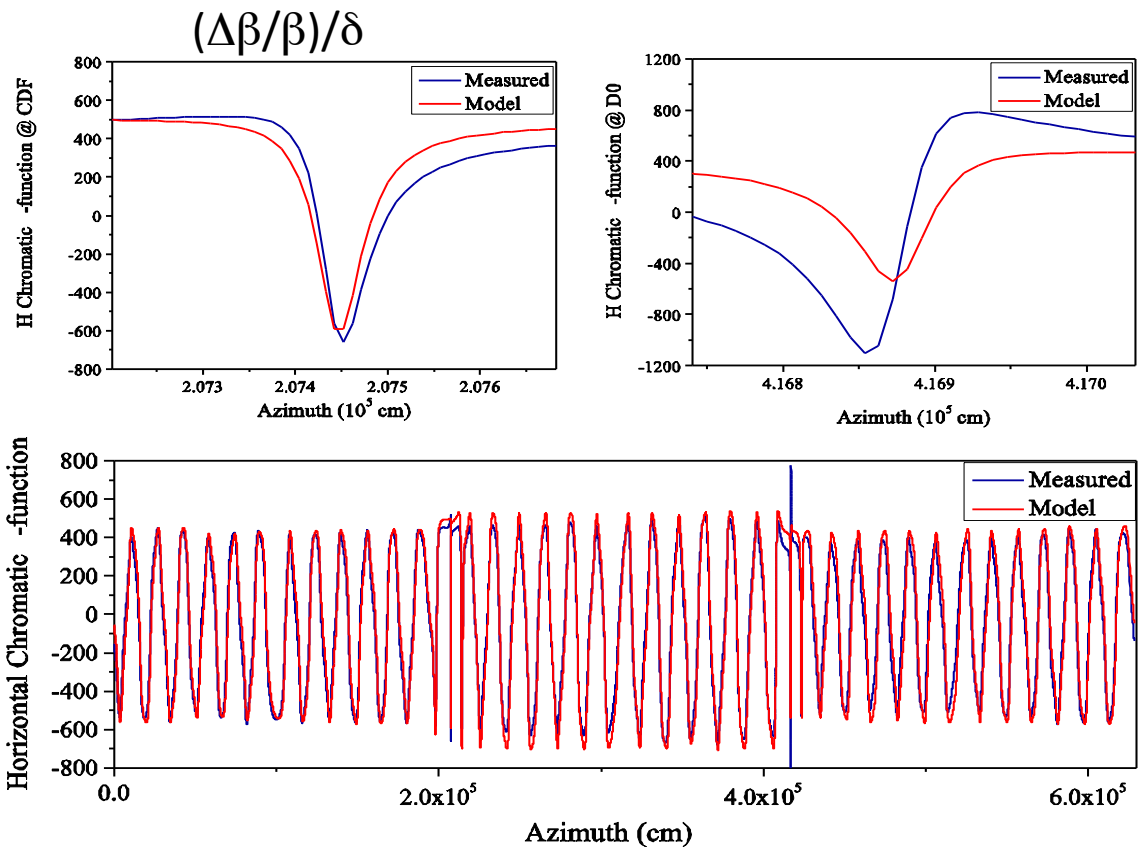
Example Application: CDF/D0 Luminosity

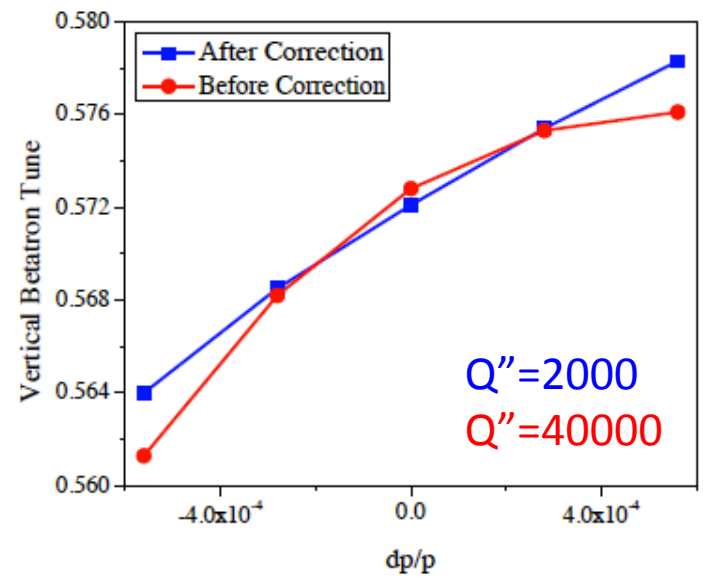
- The two experiments paid a lot of attention to the ratio of their luminosities. Desired difference < 2-3%
- LOCO measurements were used to regularly check the β* and D* values, and correct if necessary
- Example here: effect of D*





Example Application: Correction of β-function Chromaticity (Q”)





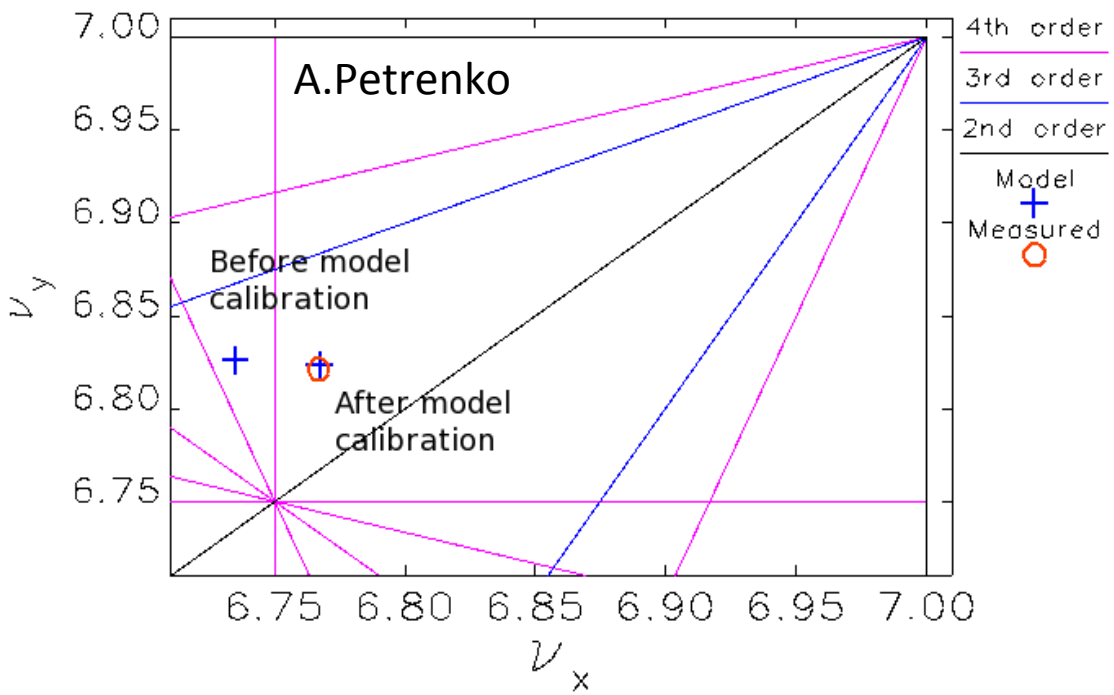
- Used LOCO to measure chromatic optics to verify model
- Created 12 additional sextupole circuits instead of just SF and SD

A. Valishev et al., FRPMS015, PAC’07

Other Applications at Fermilab

- Antiproton source (Accumulator and Debuncher)
  - Precise adjustment of slip factor for stochastic cooling improvement
- Recycler
  - Change of working point
- Transfer lines (A1 and P1)
  - Improvement of matching for emittance preservation

- Recently Booster (ramping machine!)



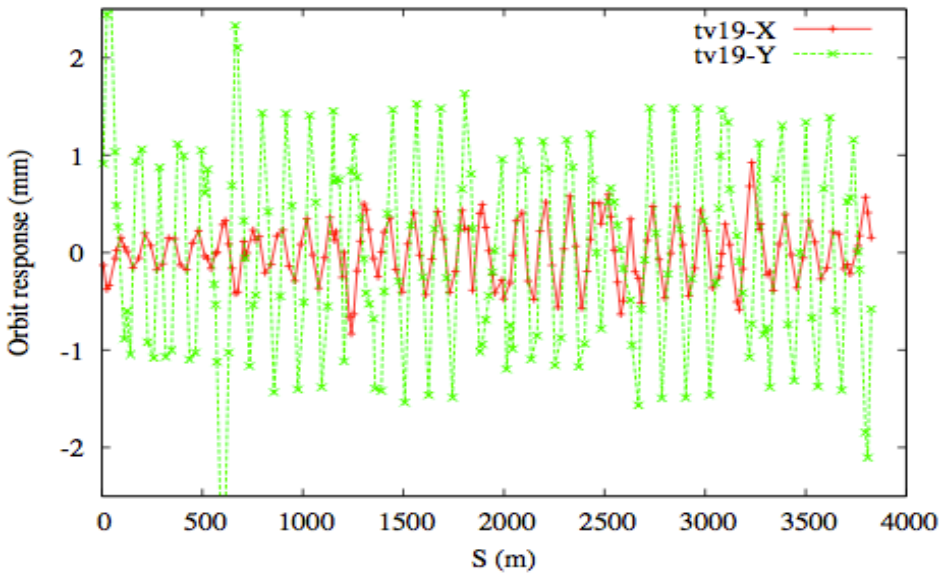
Lessons and Limitations

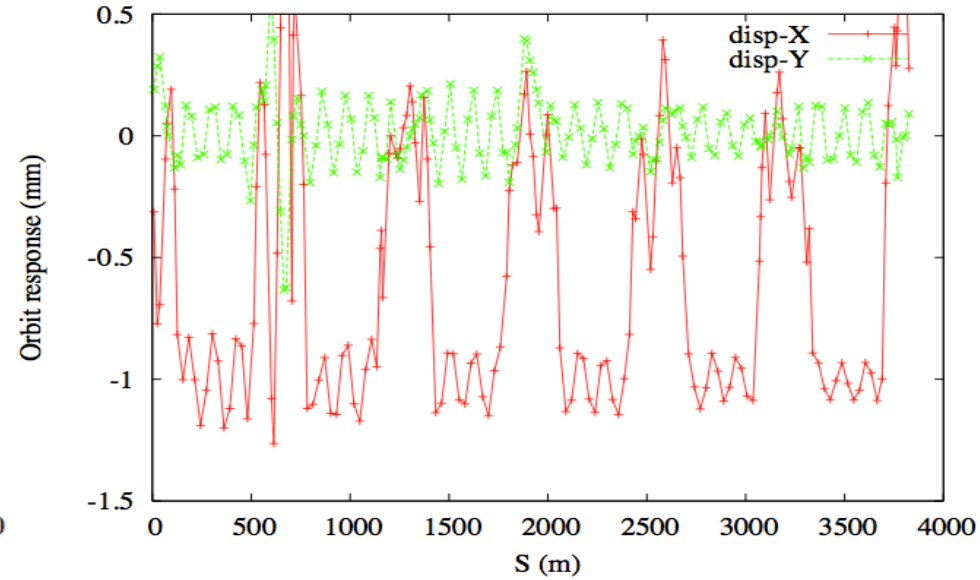
- Initial model fed with measured quad transfer functions drastically improved the data fit
- One MUST use the energy offset (dispersion) measurement along with the dipole correctors for the fit to converge! This also provides very accurate absolute calibration
- Weighted ORM helps to achieve good convergence

- Response matrix measurements are slow
  - Full measurement at Tevatron (200 correctors) took over 2 hours
  - However, a subset of correctors can be used with good results (still high redundancy with 60 correctors)
- Convergence depends on the closeness of initial model to the true solution
  - Initial fitting 'by hand' helps
- Solution for ΔG is not unique
  - Only large gradient errors are found reliably

Applying at RHIC?

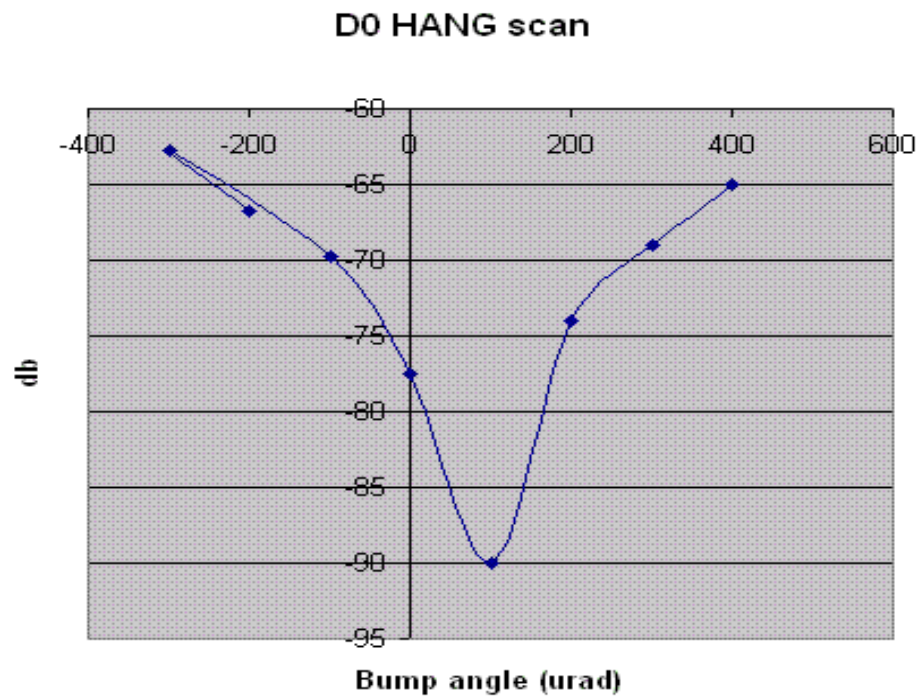
- First look: March 2011





- To use FNAL tools, one would need to
  - Measure the response matrix
    - Response matrix measurements were already implemented
  - Convert RHIC lattice files into OptiM or elegant
    - Tedious manual work
  - Modify LOCO configuration for RHIC

Doable in one week

Note on BBA

- Method called 'Quad Tickling' used at the Tevatron in 2001 for finding FF quad centers
  - Modulate quad current at low frequency 0.6Hz
  - Use network analyzer to observe peak at this frequency at a BPM spaced p/2
  - Vary orbit through the quad – minimum amplitude=center