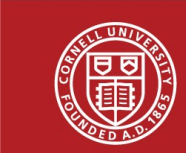

Cornell University
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Beam-Based Alignment of BPMs Using ORM and Coupling Measurements at CesrTA

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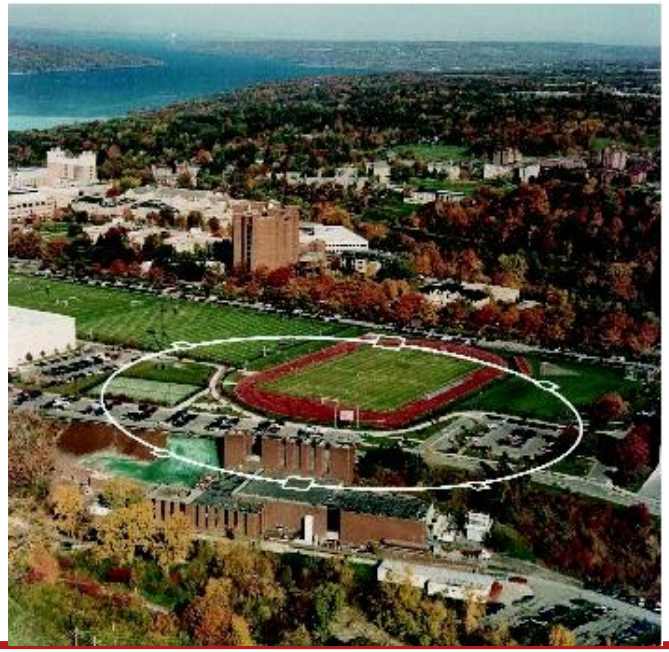
Accelerator-Based Sciences and Education



Outline

- Orbit Response Matrix – Method and Goals
- Simulation:
  - Orbit Response Measurement and Correction
  - Resolution Limit of BPM Tilts
- ORM Data Acquisition
- Analysis of ORM Measurements in Tao_Cesr
- Difference-Orbit Measurement Repeatability
- Incorporating Phase and Coupling Data with ORM Orbit Data

Orbit Response Matrix (Review)

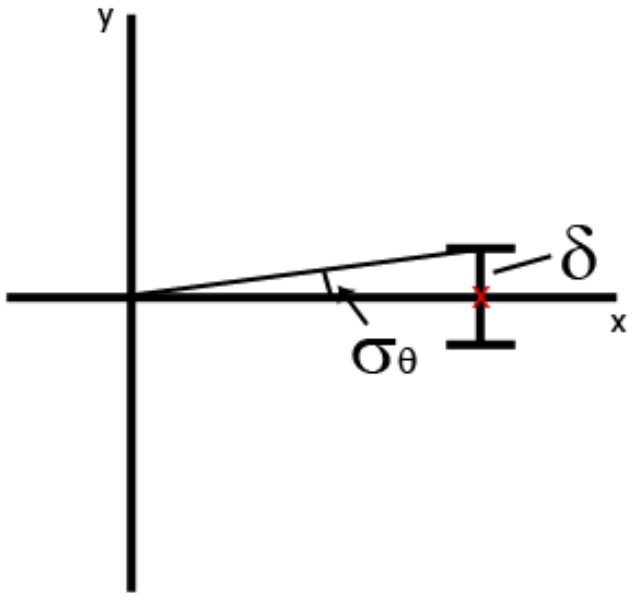
- Apply a kick θ to a closed orbit, and produce a new closed orbit
- For m steerings and n BPMs, repeating for all corrector magnets produces a 2nx2m matrix M such that:

$$\begin{pmatrix} x_1 \\ \vdots \\ x_n \\ y_1 \\ \vdots \\ y_n \end{pmatrix} = M \begin{pmatrix} \theta_{x_1} \\ \vdots \\ \theta_{x_m} \\ \theta_{y_1} \\ \vdots \\ \theta_{y_m} \end{pmatrix}$$

  - In CesrTA, we have m = 117 corrector magnets and n = 98 BPMs
- M is a function of a variety of fitting parameters (quad strength, corrector magnet kicks, etc.)
- Use least-squares methods to fit a model to the measured data
- Our strategy:
  - Use β-phase and coupling measurements to identify and correct optical errors
  - Use ORM analysis to measure BPM tilts, gain errors, etc.

Analysis of σ_θ

- How well can we expect to be able to measure BPM tilts?
- BPM tilt measurement resolution depends on the orbit displacement-- larger displacement means higher accuracy in measuring tilts
- Assuming an uncertainty δ in position for i measurements, error propagation yields an expected uncertainty σ_θ at each BPM:

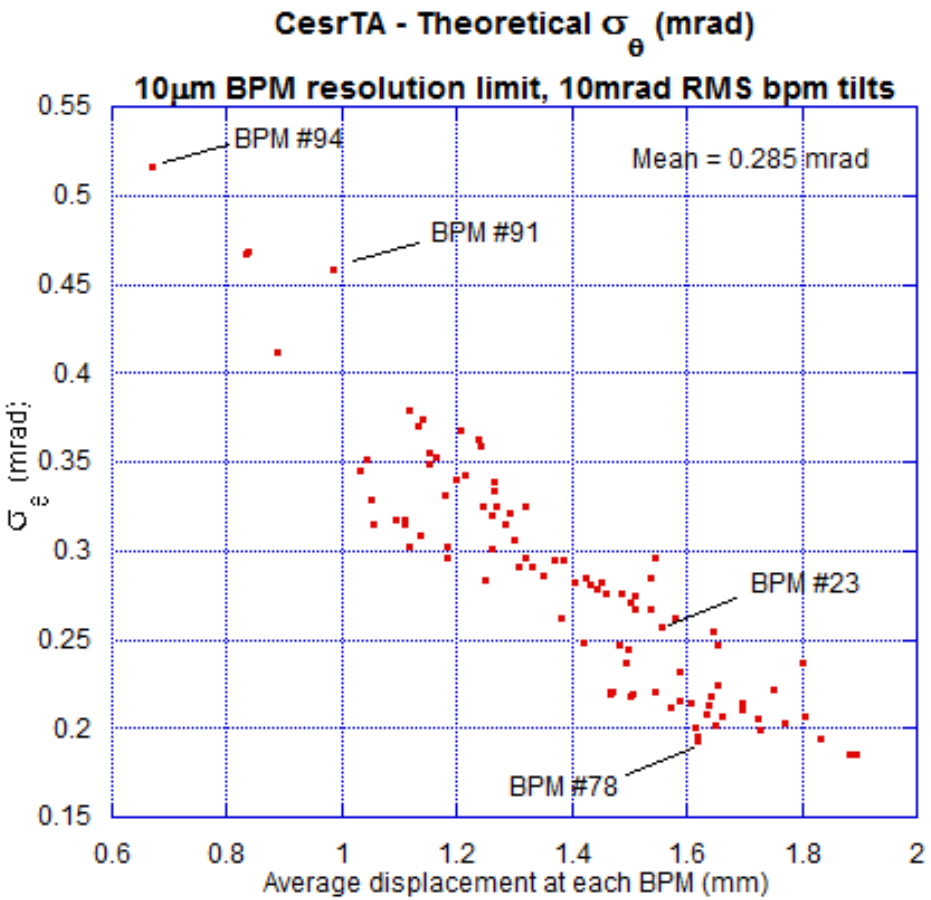


$$\sigma_\theta = \frac{\delta}{\sqrt{\sum (x_i{}^2 + y_i{}^2)}}, \quad i = 1, 2, \ldots$$

Simulation of ORM Data

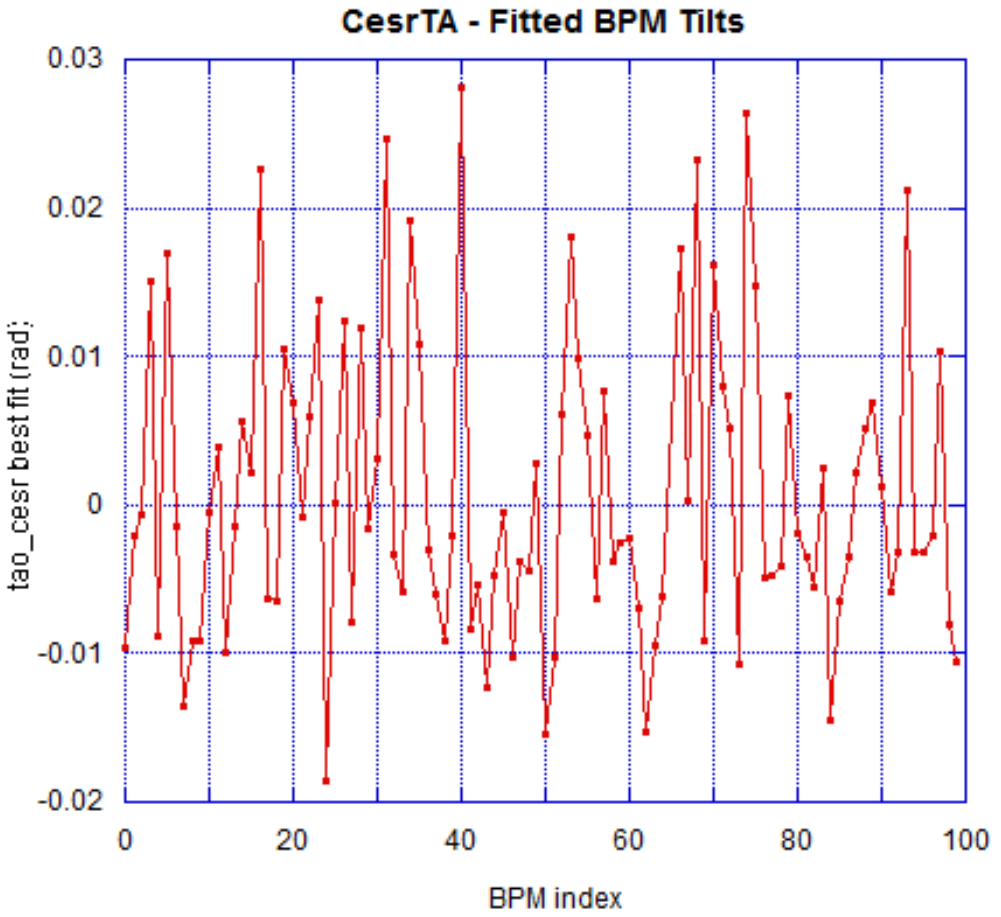
- Simulate ORM orbit files using BMAD accelerator library
  - Assuming:
    - BPM tilts with RMS of 10 mrad
    - BPM resolution of 10 microns in both x and y
- Find the average displacement at each BPM over all orbits taken
- Calculate σ_θ using method described
- Plotting σ_θ against the average displacement at each individual BPM yields 100 data points on this graph
- The average displacement over all BPMs and all orbits is 1.4mm, at which we expect

$$\sigma_\theta \approx \mathbf{0.29\ mrad}$$



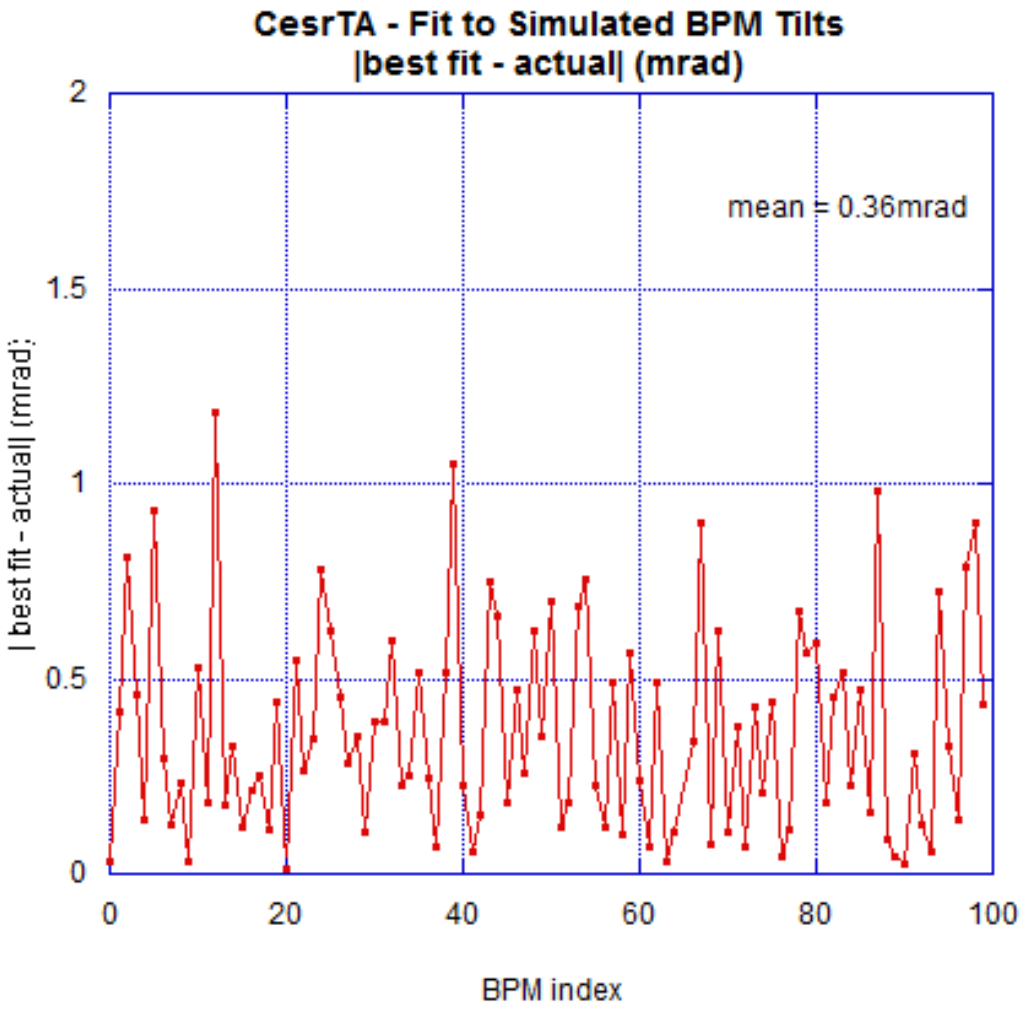
ORM Analysis of Simulated Data

- Perform ORM analysis on the same simulated data in Tao_Cesr
- Recall:
  - BPM tilts at RMS of 10mrad
  - BPM resolution = 10 micron
- Correct using Levenberg-Marquardt (LM) non-linear optimization algorithm



ORM Analysis of Simulated Data

- Mean difference between best fit and actual BPM tilt, across all BPMs: **0.36 mrad**
- Recall: expected mean σ_θ is 0.29mrad
  - Very close!



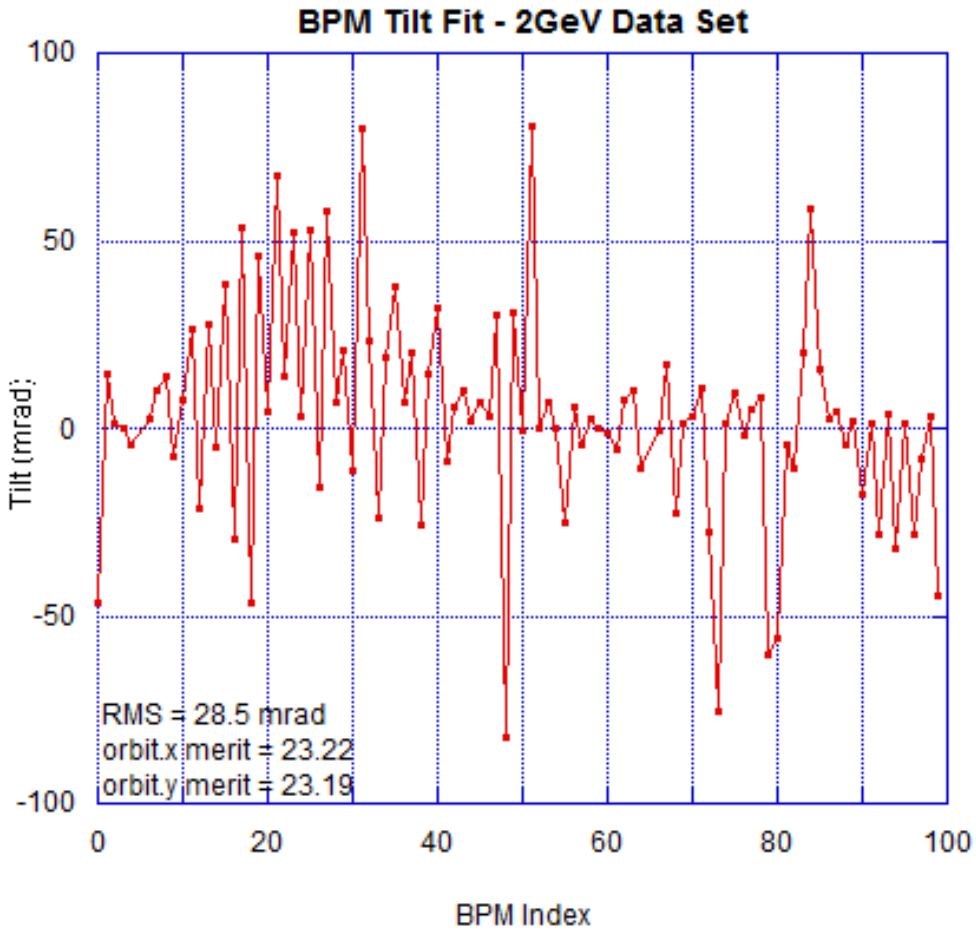
Data Acquisition - Details

- Data taken at two energies:
  - 5 GeV, 100nm ε_x
  - 2 GeV, 8nm ε_x
- Single-bunch, using 2.5mA at low energy, 5mA at high energy
- Prior to taking data, flatten orbit using steering magnets and correct betatron phase using quads/skew quads
- Data acquisition takes roughly 2 ½ hours for all 117 difference-orbits
- Beam lifetime in 5 GeV optics is many hours, therefore no need to top off the beam during measurements
- However, 2 GeV optics designed for low-emittance, and beam lifetime is poor (τ ~ 40 minutes at 2.5mA)
  - Need to top off 4-8 times during measurements at low energy, thus breaking the measurements into smaller subsets

Analysis in Tao_Cesr

- Once data is acquired, we can analyze it in Tao_Cesr
- Try to fit model ORM matrix to the measured ORM data
- Basic fitting procedure:
  - Primary errors are in the steering magnet kicks--calibration is not great
  - Start by fitting the single kick strengths used in each individual difference orbit
  - Then fit against kicks and BPM tilts combined
  - All optimizations done using LM non-linear optimizer
- Quad k's were fit to the betatron phase and corrected prior to taking ORM orbit data, therefore we do not fit them again

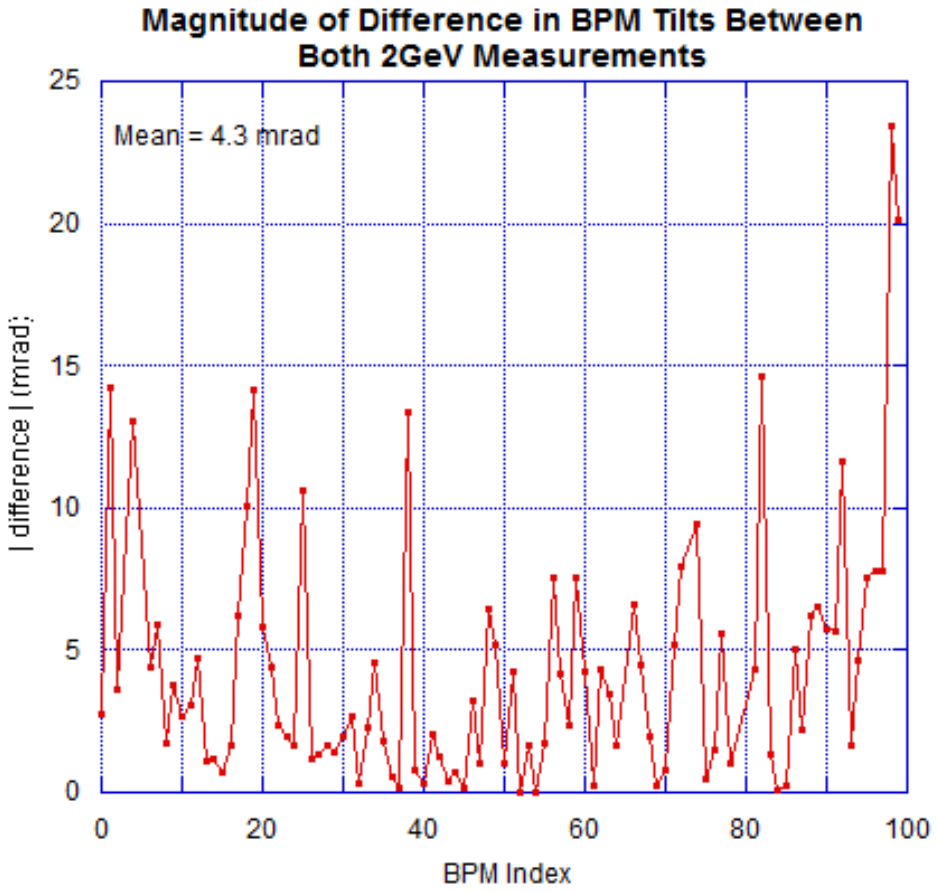
2GeV Measurements



Notable features:

- RMS BPM tilt is about 30 mrad
- E/W asymmetry (West = 0-49, East = 50-99)
  - Why are the fitted BPM tilts in the East much smaller than the West?
- Odd numbered BPMs are next to vertically-focusing quads
  - Why are the BPM tilts on most odd-numbered BPMs in the West much larger than the even BPMs in the same region?

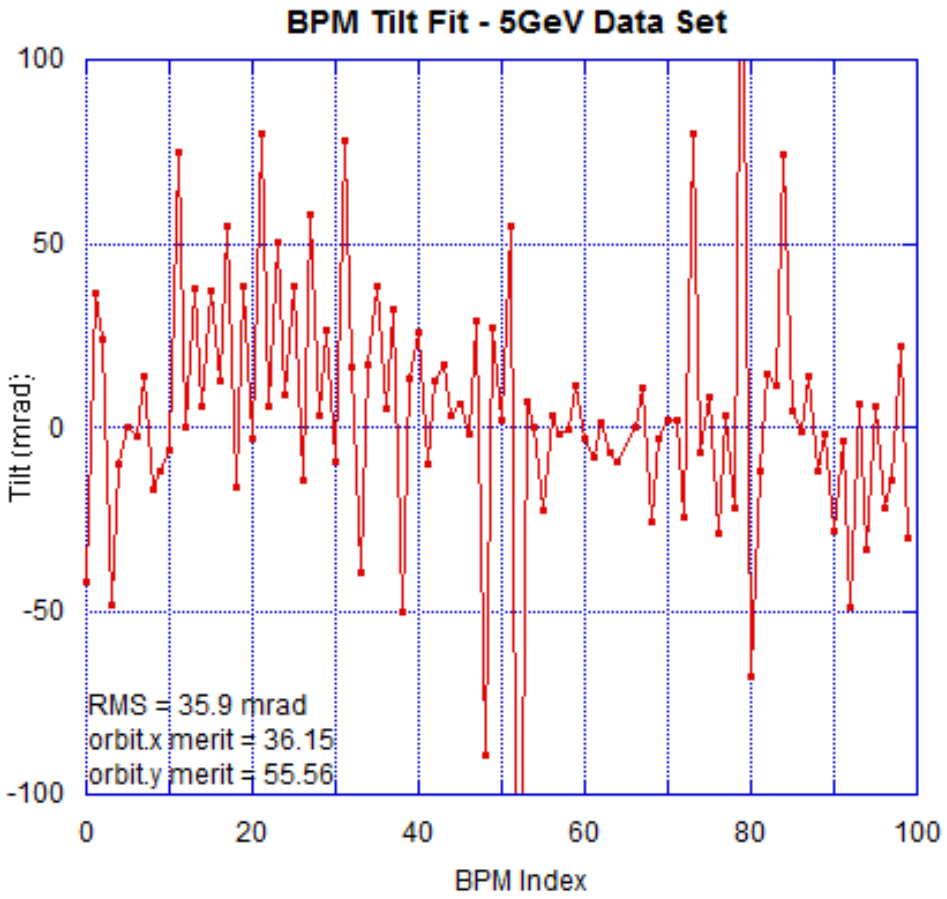
Difference Between 2GeV Fits

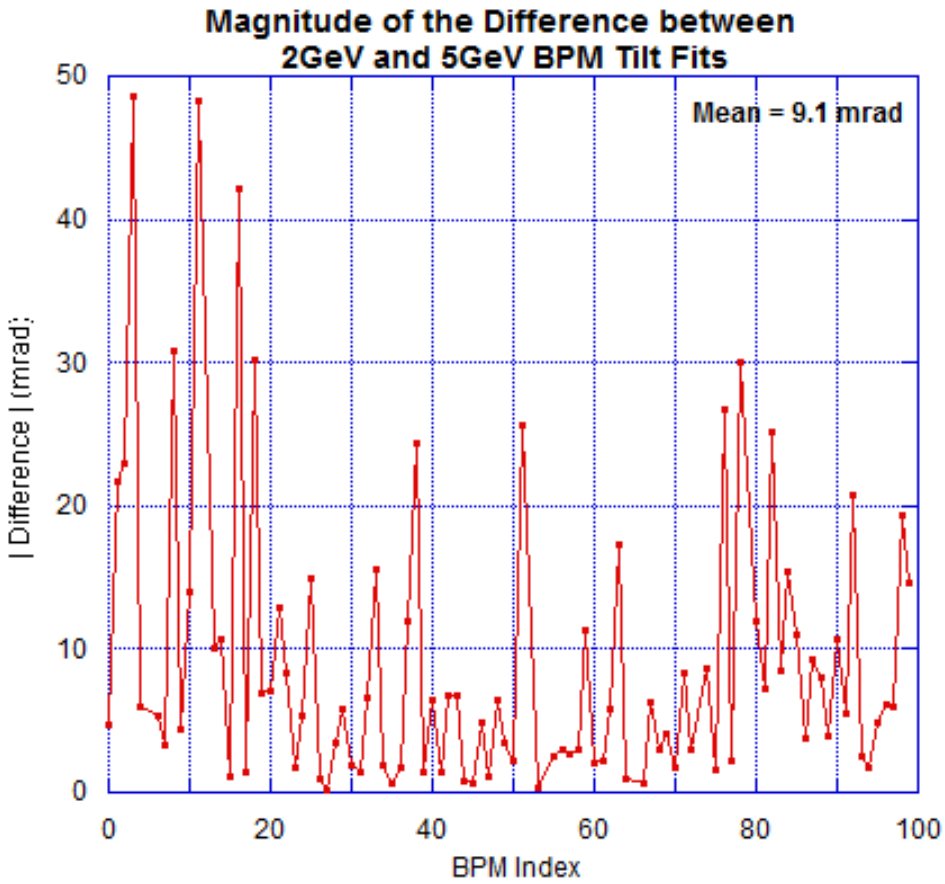


- Both data sets at 2 GeV, same optics
- Taken six days apart
- Orbit, β- phase, and coupling were corrected before both data sets were taken
- In the graph to the left, vetoed the three severe outliers (>25 mrad)
  - Mean difference in BPM tilts between the two data sets is **4.3 mrad**
  - Recall:
    - Analytic and simulated BPM tilt resolution was ~0.3 mrad for a 10-micron BPM resolution
    - To achieve our emittance target, we must know BPM tilts to better than 10mrad

5GeV Optics

Results of the same fitting procedure using ORM data from 5GeV measurements:





Difference between 2 GeV and 5 GeV BPM Tilt fits

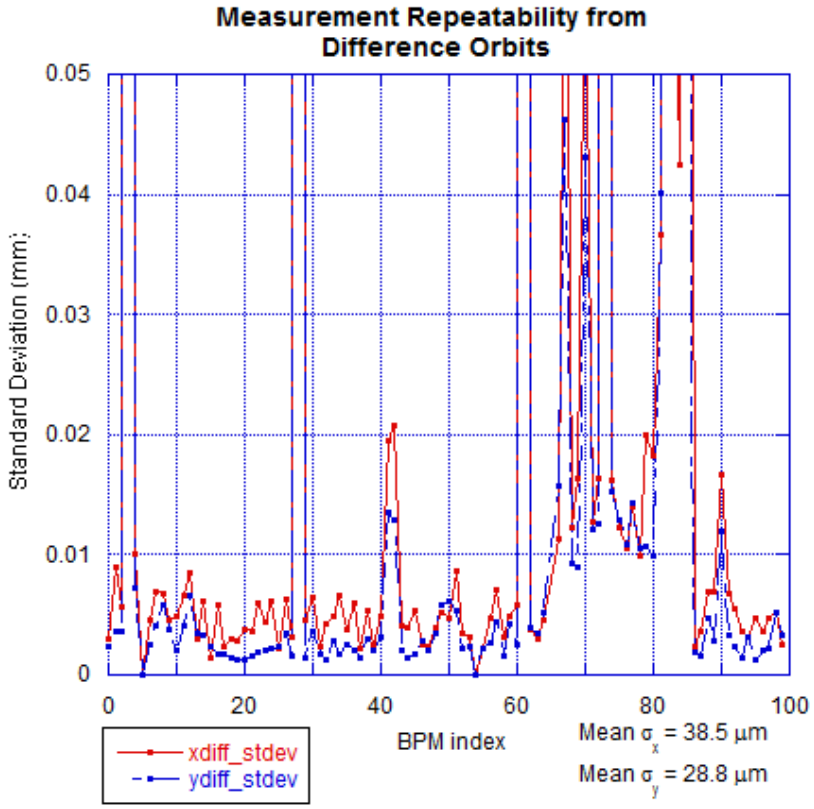
Summary Thus Far

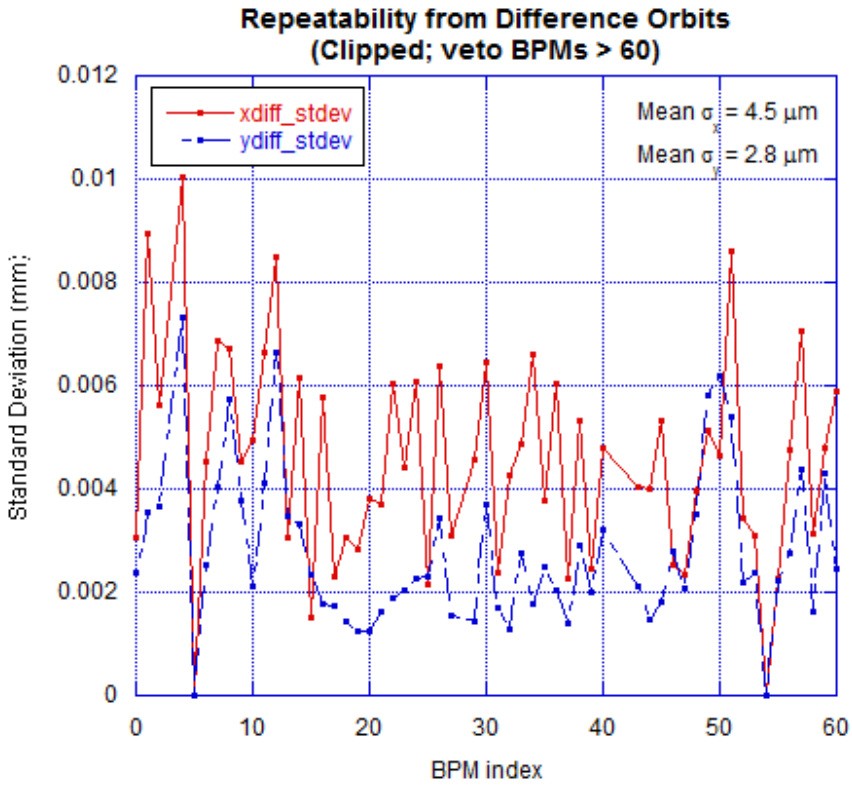
- Summary of results so far:

Energy	Fit	RMS BPM Tilt	orbit.x merit	orbit.y merit
2GeV	Kicks, BPM Tilts	28.5 mrad	23.22	23.19
5GeV	Kicks, BPM Tilts	35.9 mrad	36.15	55.56

- 5GeV fit has same general characteristics as 2GeV fit, however the quality of fit is not as good
- Difference between 2GeV and 5GeV fits is larger (**9.1 mrad**) than between the two 2GeV fits (**4.3 mrad**), however both are below the 10 mrad target
- Differences are larger than the analytic and simulated BPM tilt resolution (0.3mrad) for a BPM resolution of 10 microns
  - •We have overestimated the BPM resolution
  - •The tilts have changed significantly between measurements
  - •Orbit measurements are not reproducible
- To test reproducibility, take several difference-orbit measurements, and find the standard deviation at each BPM

Measurement Repeatability



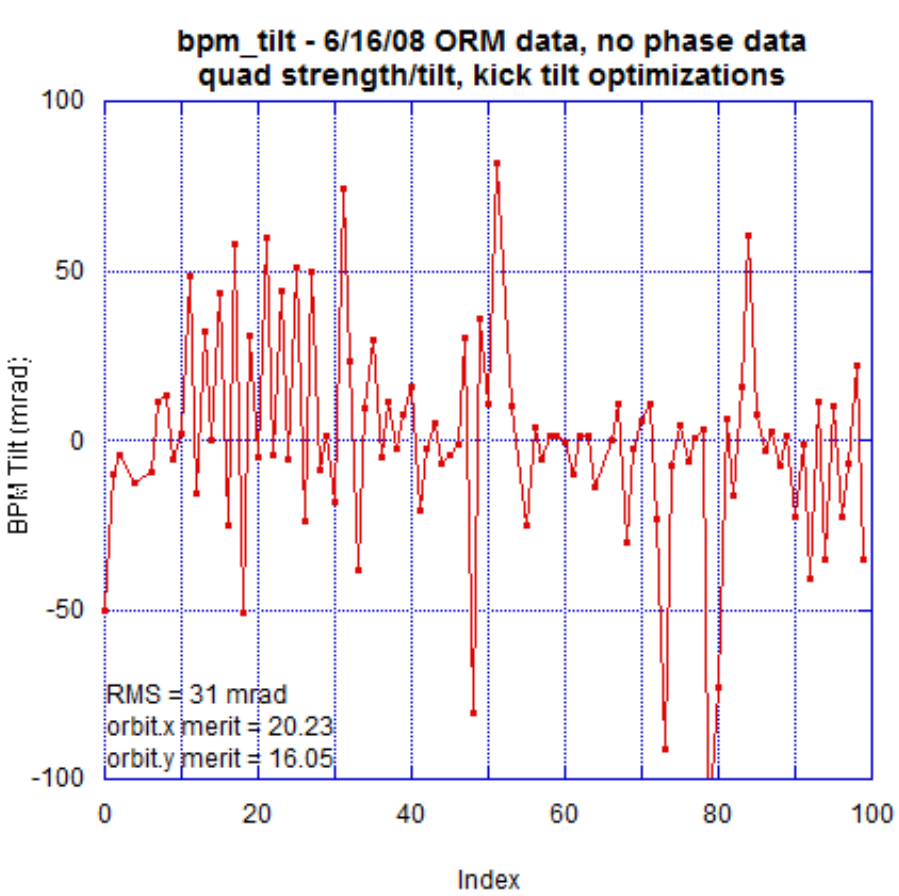


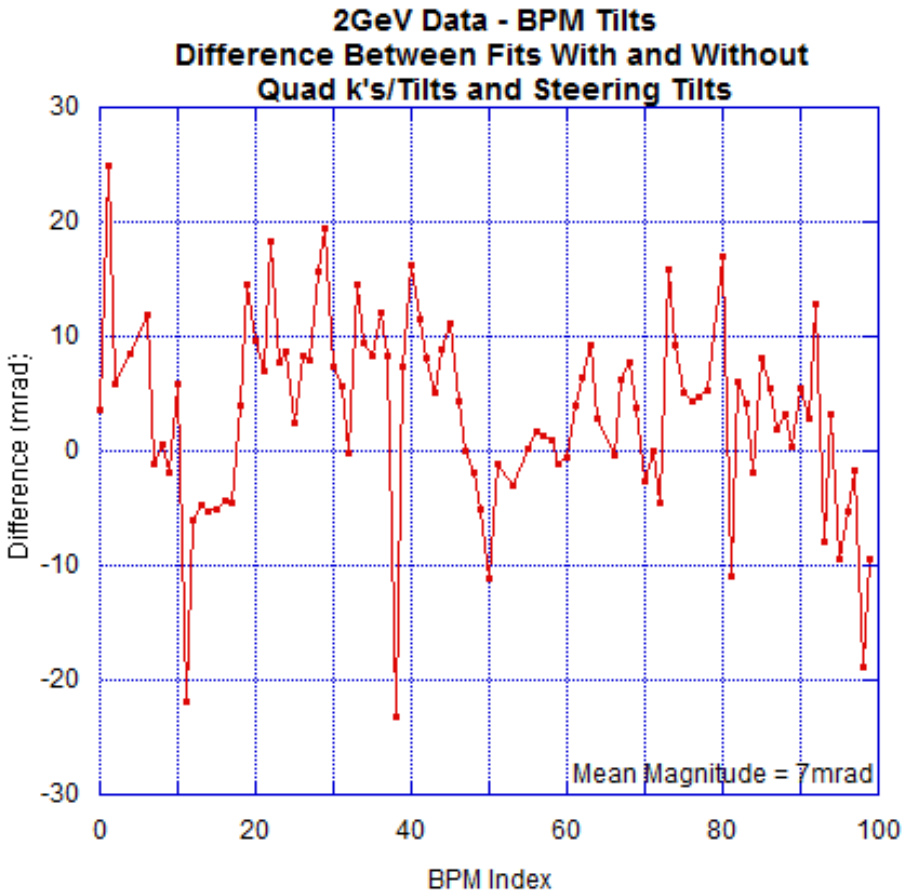
- Including all data points, repeatability is within 39 microns
- Looking at 0-60 and vetoing the four bad outliers, repeatability is now within 4.5 microns or better
- BPM repeatability does not appear to be a significant source of the discrepancy in BPM tilt fits among the three data sets

2GeV - Quad and Steering Tilts

- Recall: at this point, the 2GeV fit is significantly better than 5GeV fit
- What happens if we start using more variables in the model with 2GeV data?
  - Add in quadrupole strengths and tilts, and steering magnet tilts
- Fitting procedure: use several passes of optimization
  - Kick strengths
  - Quad strengths + quad tilts
  - Kick strengths + kick tilts
  - BPM tilts

2GeV - Quad and Steering Tilts

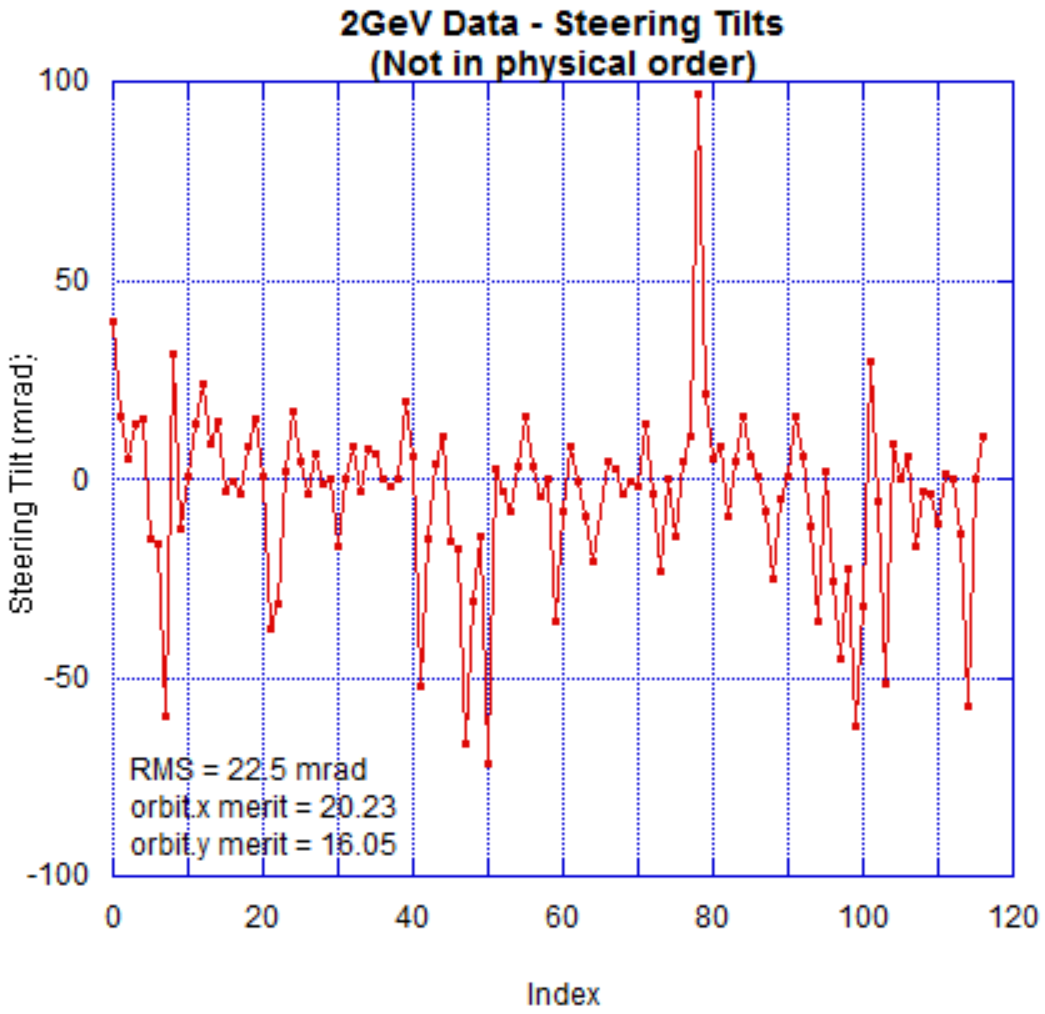




- Results:
  - Significantly better fit than when only using kicks and BPM tilts
  - RMS BPM tilt increased by 1.5 mrad from previous 2GeV fit
  - Still see unusual behavior in the West, and several of the same outliers throughout

2GeV - Quad and Steering Tilts

- Fitted steering tilts:



Incorporating Phase Data

- What happens if we try to incorporate the betatron phase and coupling measurements taken just before the ORM data set?
- Introduce phase/coupling data after correcting steering kicks, but before fitting BPM tilts
    - Set cbar.11 and cbar.22 data weights to zero for all phase/coupling fits
    - Relative weights between phase/coupling and orbit data can be problematic
        - Try weighting phase and coupling data such that after optimizing against kicks, sums of phase/coupling/orbit merits are within an order of magnitude of each other
- Try two different optimizations:
    - Fit only kicks and BPM tilts
    - Fit quad strengths and tilts, kicks and kick tilts, and BPM tilts

Summary

- Cumulative results (to date):

Energy	Fit	RMS BPM Tilt	orbit.x merit	orbit.y merit
2GeV	Basic Fit	28.5 mrad	23.22	23.19
5GeV	Basic Fit	35.9 mrad	36.15	55.56
2GeV	Advanced Fit	31 mrad	20.23	16.05
2GeV	Basic Fit (with phase/coupling data)	95 mrad	24.5	23.3
2GeV	Advanced Fit (with phase/coupling data)	60.6 mrad	70.6	66

Basic fit = only use kicks, BPM tilts
Advanced fit = use kicks/kick tilts, quad k's/tilts, and BPM tilts

Further Studies

- Still working on relative weights between orbit and betatron phase/coupling data
  - Phase / coupling data still weighted too heavily?
- Eventually, we will include dispersion measurements
- Need to formally define uncertainties in BPM tilts (and all other fit parameters)
- Causes of E/W asymmetry of fitted tilts and unusual behavior in the West must be explored further
- More optimizations must be explored:
  - Apparent BPM tilts may be caused by gain errors in individual buttons
  - Other possible degeneracies in the fit?
- Suggestions would be appreciated!