Linear Optics Measurements and Corrections

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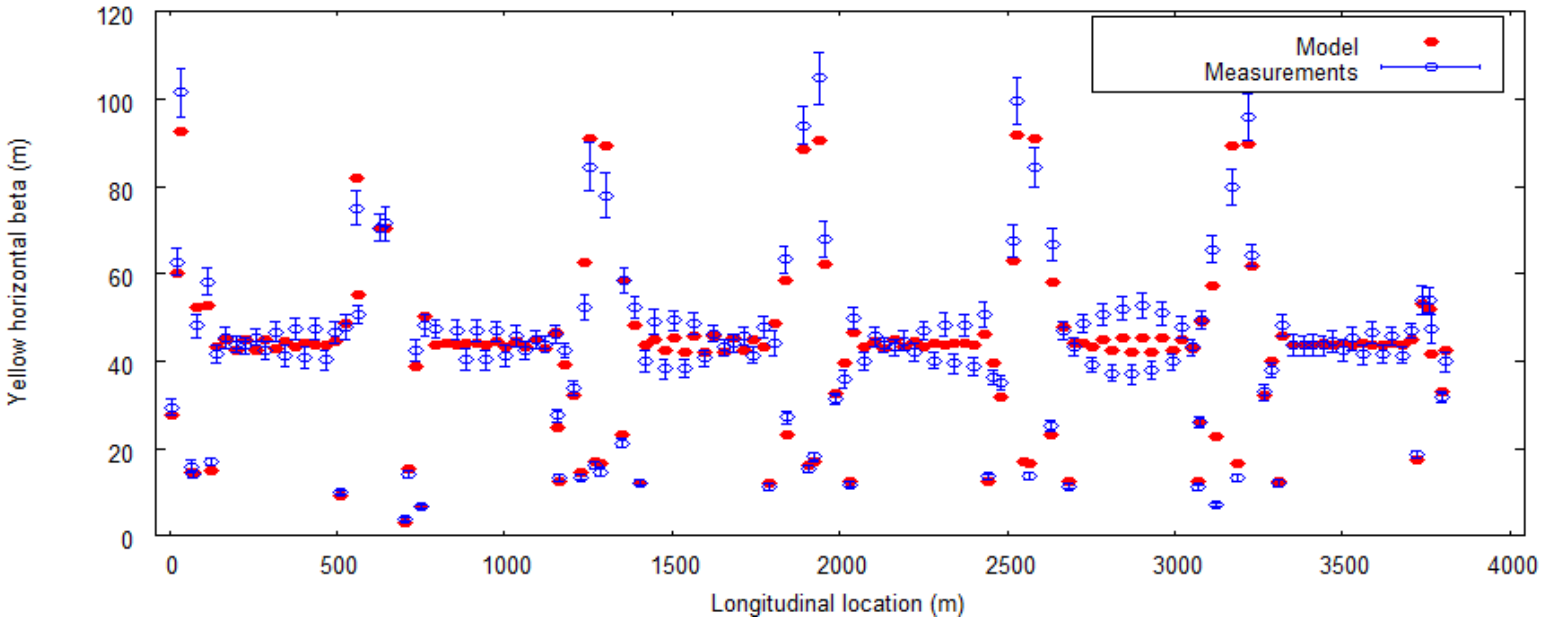
Outline

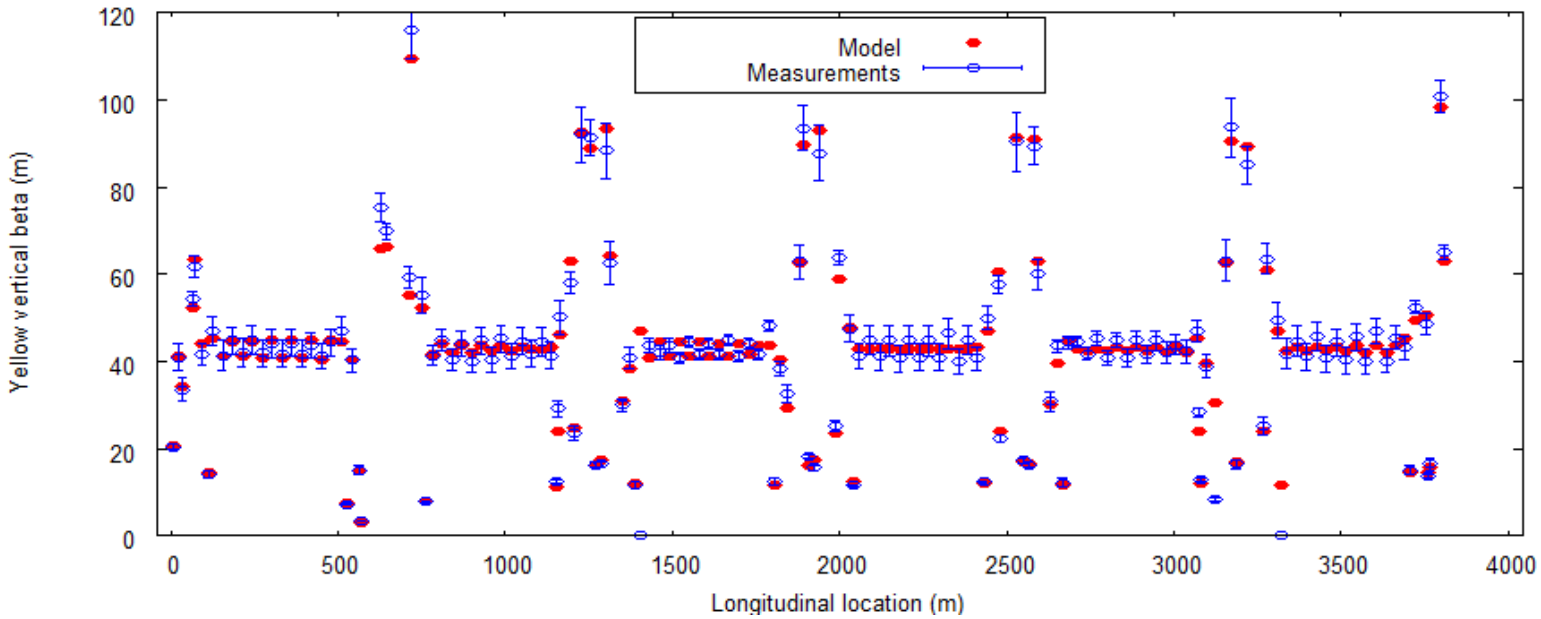
- Results of APEX Run-9
  - RHIC pp2pp optics measurements
  - Linear gradient error corrections
- Plan of optics correction experiments
  - Improve existing SVD algorithm: Verify range of knobs, iteration, multiple errors correction.
  - Investigate new algorithm: Multi-Objective Generic Algorithm (MOGA).

pp2pp yellow optics measurement: Ac dipole data

Rms beta-beat: 8.5%

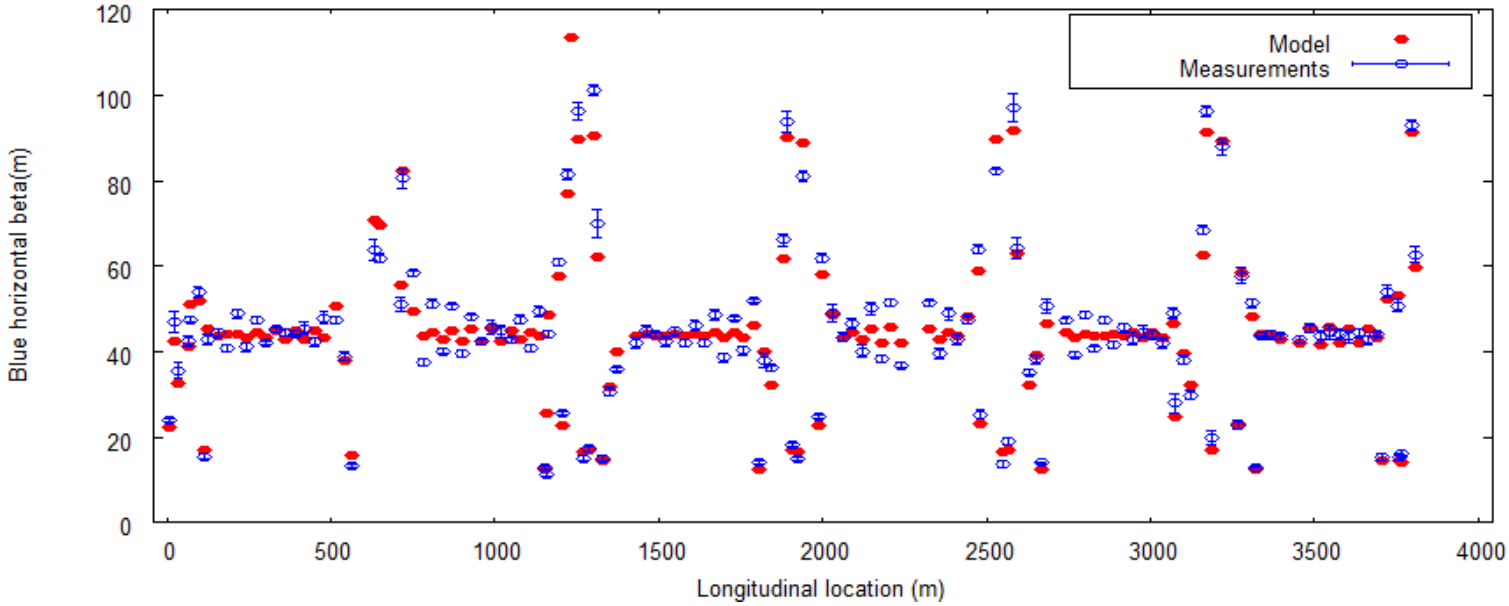


Rms beta-beat: 5.6%

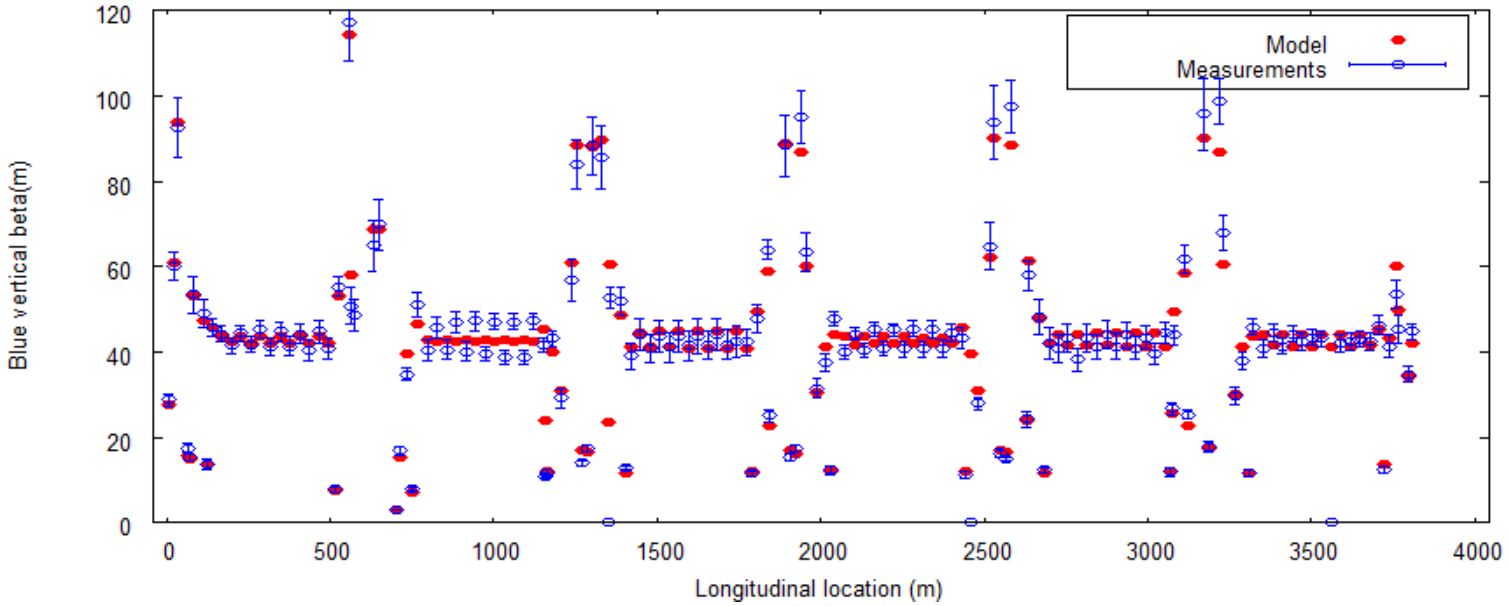


pp2pp blue optics measurement: Ac dipole data

Rms beta-beat: 7.6%



Rms beta-beat: 6.7%



Courtesy of T. Satogata

IR6 β^*, α_0, s*

- β^* and s* are minima, not necessarily located at s=0
  - Indeed, design optics have about s*=+/-4m
  - Calculate β^*, α_0, s* from quadratic fits of DX/Q1 BPM optics

Method	β^*(bh) [m]	β^*(bv) [m]	β^*(yh) [m]	β^*(yv) [m]	s*(bh) [m]	s*(bv) [m]	s*(yh) [m]	s*(yv) [m]
mad	22.18	21.41	22.05	20.74	3.88	-4.28	-3.88	4.09
OptiCalc	22.24	20.25	21.88	19.25	6.01	-2.66	-2.53	6.96
quad tweak	19.3(1.4)	24.0(3.2)	21.0(2.2)	17.4(0.7)	4.36(0.25)	-4.93(0.82)	-4.36(0.73)	5.32(0.24)
AC dipole	22.75	21.00	21.82	19.77	3.13	-3.92	-5.02	4.68

Method	α_0(bh)	α_0(bv)	α_0(yh)	α_0(yv)
mad	0.18	-0.21	-0.18	0.21
OptiCalc	0.27	-0.13	-0.12	0.36
quad tweak	0.23	-0.21	-0.21	0.31
AC dipole	0.16	-0.19	-0.23	0.24

- Some quad tweak error bars in β^* are large, 5-10% (bv β^* is 20%!)
- Variations in β^* measurements are on this order, 5-10%
- AC dipole optics errbars mostly ~5%
- All s*, α_0 are right levels/signs
- DX BPM scoords are important!!

Courtesy of T. Satogata

Raw optics comments

- β^*, α_0, s* measured two ways, modeled two ways
  - Barely consistent within quad tweak error bars
  - Quad tweak appears to be outlier but expected to be best method
    - Consider and investigate systematics in quad tweak/AC dipole
  - Why are mad and OptiCalc calculations so different?

- AC dipole measured beta waves of 5-10% in all planes
  - Optics seem pretty good: 100 GeV, only one β^*=1m insertion
  - Yellow horizontal needs further study; bad data set?
  - Data should be good enough for beta beat correction tests

- Next steps
  - AC dipole data also includes (more accurate) phases
  - Calculate transport, compare to model and fitted transport
  - Include full 4D transport, measured rolls, known errors (SteveT)
  - Extrapolate on-axis measured transport to near-aperture transport

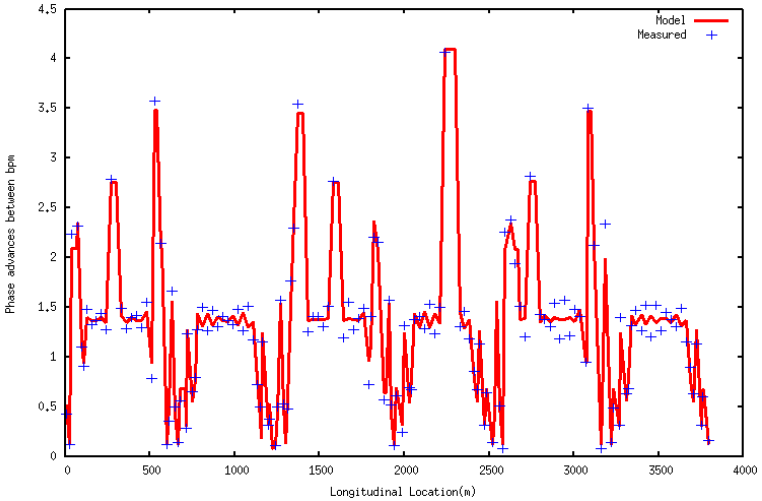
Status of gradient error correction

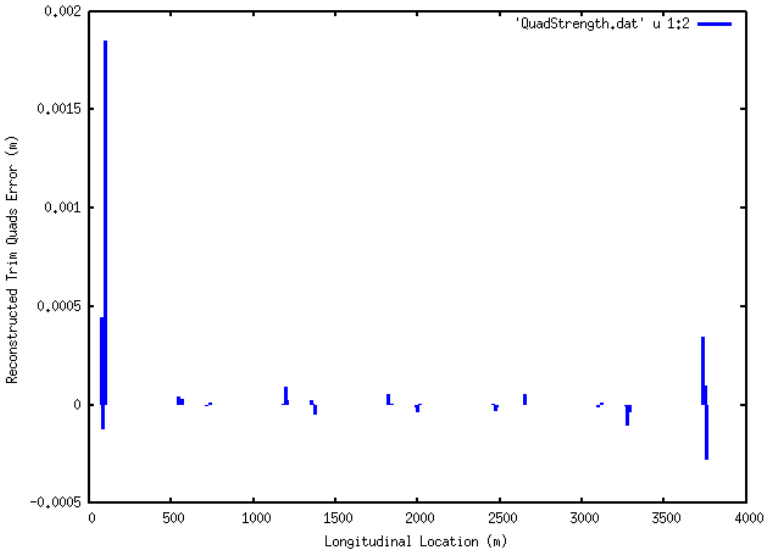
- Three experimental sessions were devoted to Linear optics corrections in RHIC 2009 run. The SVD algorithm was verified from these experiments. As a result of corrections, the rms phase beat was reduced by 40% and 30% respectively for two preset quadrupole errors.

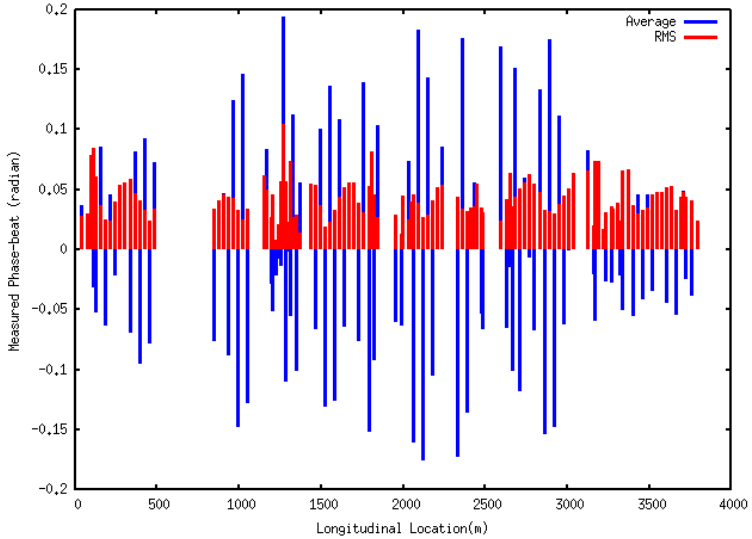
- Substantial variations of measured phases were observed, possibly due to the slow magnets variation.

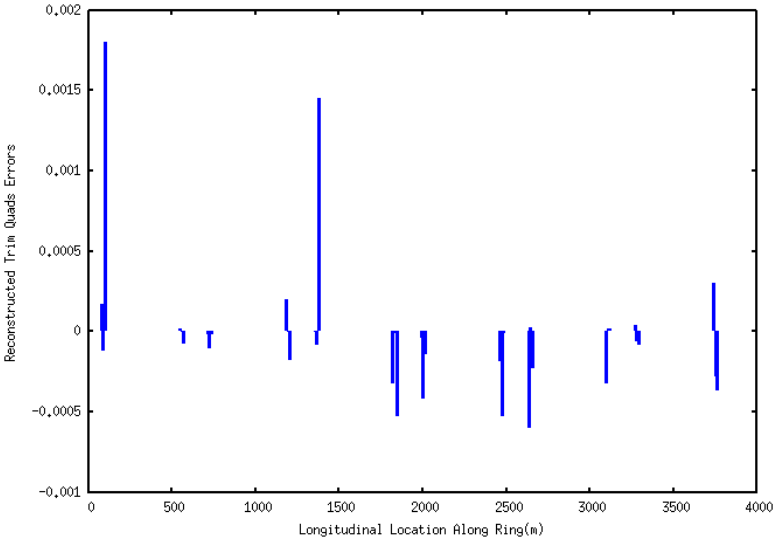
- New algorithm needs to be developed in order to improve the noise tolerances and identify qudrupole errors.
  - Bpm data quality and the number of available bpms
  - The range of knobs.

Experiment of Linear Optics Correction

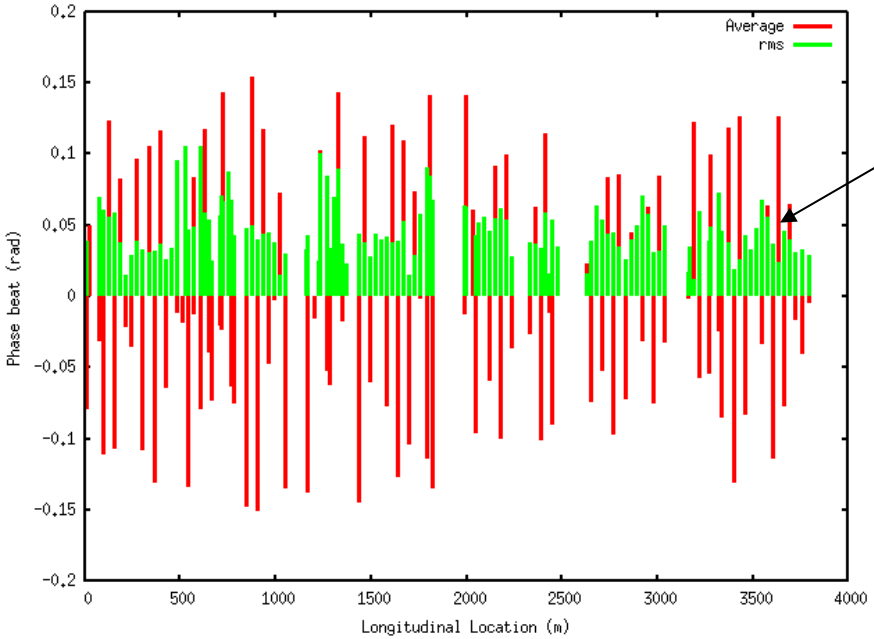








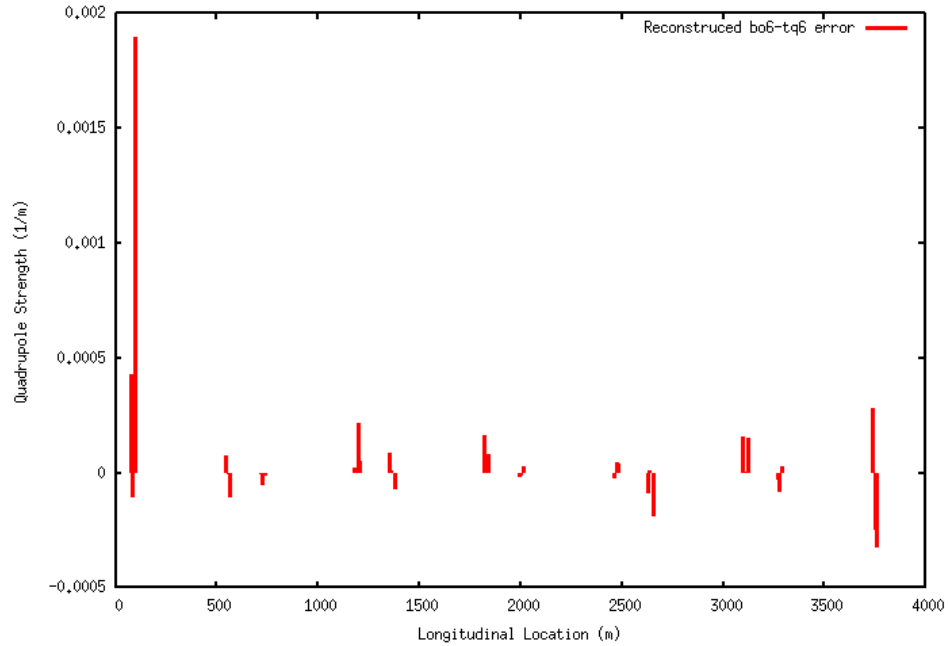
Experiment of Linear Optics Correction Continued 1



Substantial variation from measurement to measurement, possibly due to magnets oscillation.

The data for SVD analysis was obtained by averaging 12 sets of measurements

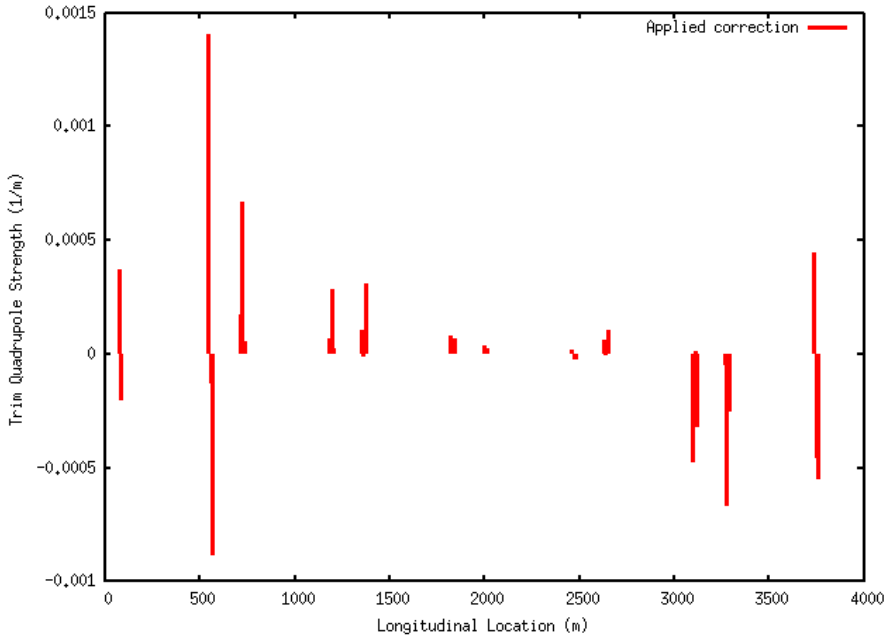
Reconstructed Quad Errors



Typical phase beat measurement (Drive at $1-Q_x-0.01$ for baseline.)

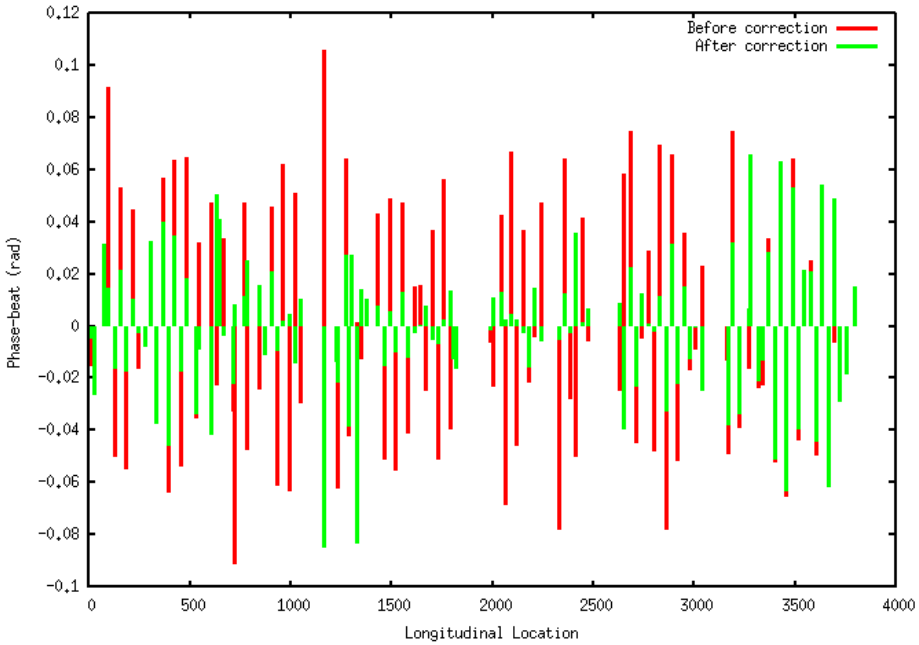
Experiment of Linear Optics Correction Continued 2

Rms phase beat reduced from 0.0454 rad (2.6 degrees) to 0.0279 rad (1.6 degrees), i.e. 40% of reduction

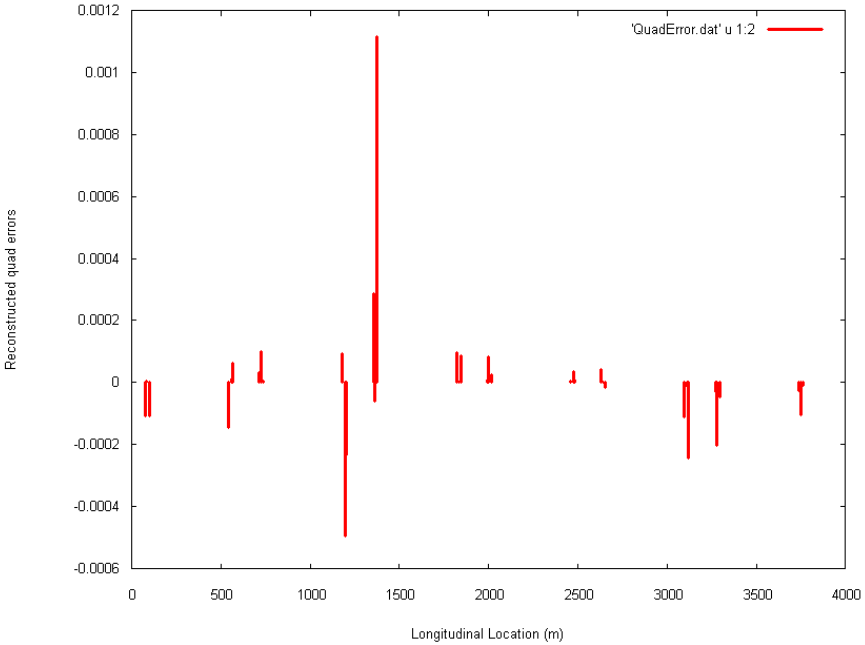


Applied Correction

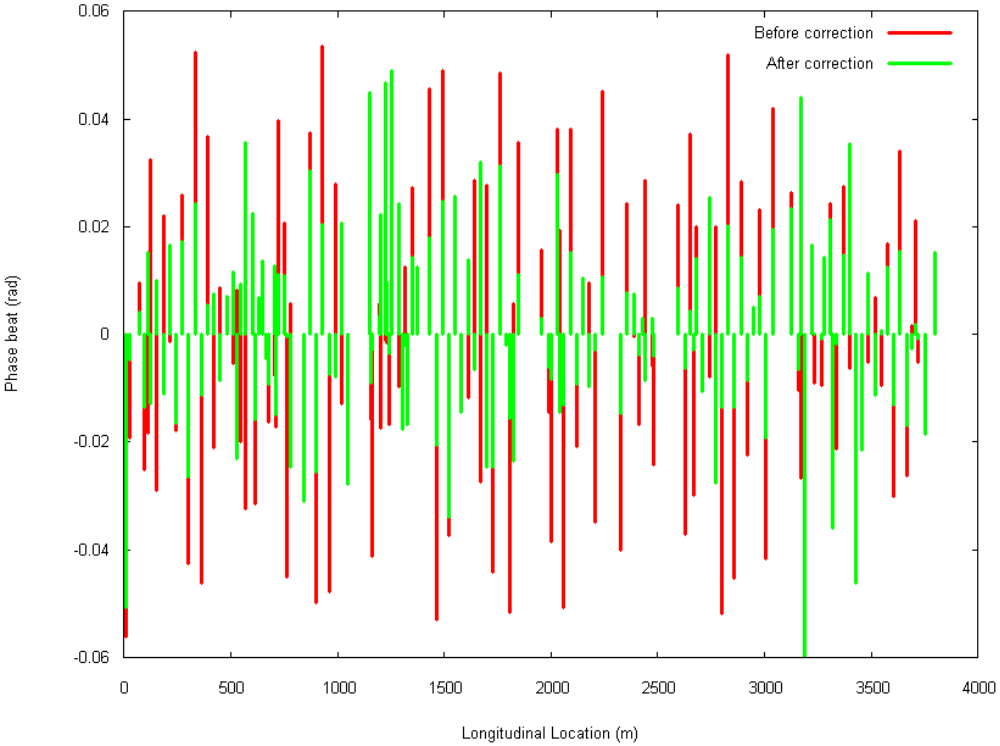
Comparison of phase beat



Experiment of Linear Optics Correction Continued 3



The rms phase beat went down from 0.027 rad to 0.019 rad, i.e. 30% reduction.



Reconstructed Quad errors are noisy and the amplitude is 40% less compared with the pre-set error.

Plan for APEX Run_10

- Applying SVD algorithm iteratively to test the effective range of the 36 trim quads on multiple gradient errors correction.

- Another algorithm for searching the optimum correction strength, MOGA, is under study. It has been investigated and confirmed in ALS optimization by Lingyun Yang. (L. Yang et al, NIM A 609 (2009) 50-57)

What is MOGA?

- Multi-objective: optimize multiple functions simultaneously.
  - Solution A is ‘better’ than B means that A is no worse than B for all objectives and is strictly better than B in at least one objective.
  - Search for a set of solutions: Pareto optimal
- Genetic searching:

Genetic searching:

1. **Initialize**: uniformly generate random solutions in variable space
2. **Cross-over**: generate next generation (children) based on initial solutions (parents). (2 parents generate 2 children)
3. **Mutation**: change the children slightly
4. **Nature selection**: calculate objective and take the top half of parents and children (so never worse from generation to generation)

SVD searching:

1. **Start from one specific solution:** assume the optimum is not far from the starting point.
2. **Calculate the gradient in variable space:** Phase response matrix
3. **Inverse Phase response matrix:** obtain one specific solution

Advantages:

Global: don’t rely on the assumption that the starting point is close to optimum.

Constraints: constraints on variable ranges can be easily added.

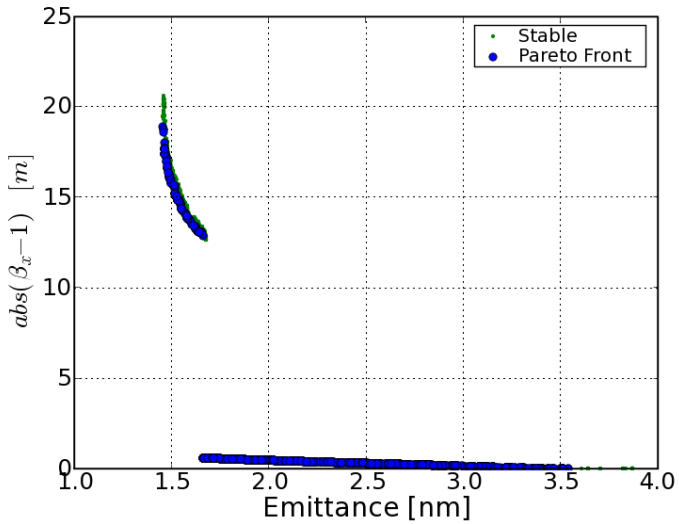
Multi-objective: can be used to optimize multiple lattice functions.

The Evolution of Optimization

Our optimization problem [Yang et al., 2008, Robin et al., 2008]:

- Optimize:
  1. Emittance ϵ.
  2. $\min(|\beta_x - 1.0|)$.
- Constraint:
  - $|\mathrm{Tr}(M_x)| \leqslant 2$, $|\mathrm{Tr}(M_y)| \leqslant 2$
  - $\max(\beta_x) \leqslant 35\ m$, $\max(\beta_y) \leqslant 35\ m$
  - $\max(\eta_x) \leqslant 0.4\ m$
- Parameters:
  1. QF,QD,QFA in one cell.

ϵ_x and $|\beta_x - 1|$



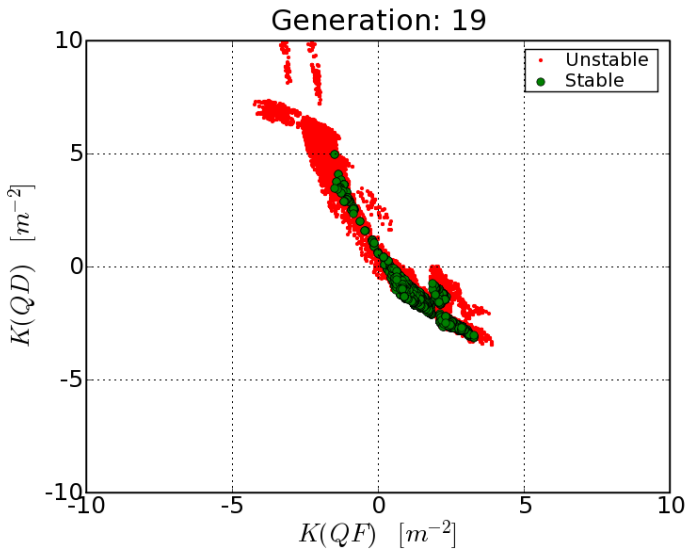
1. Evolution of objective functions. ϵ, $|\beta_x - 1|$

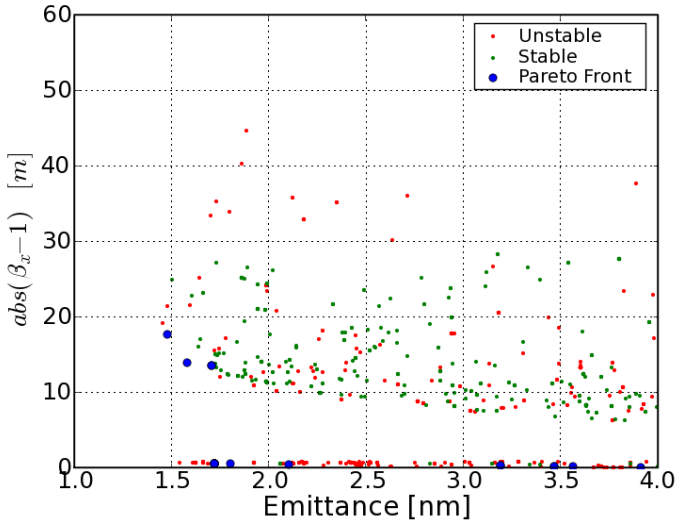
3 Parameters, optimize ϵ and $\beta_x \rightarrow 1m$

By tuning k_{QF}, k_{QD}, k_{QFA} we can optimize emittance ϵ_x and $|\beta_x - 1|$ at the center of straight.

- Red: violate the constraints, or no physical solution.
- Green: meet the constraints.
- Blue: Pareto optimal set, the best solutions so far.

1. Generation 19





3 Parameters, optimize ϵ and $\beta_x \rightarrow 1m$

By tuning k_{QF}, k_{QD}, k_{QFA} we can optimize emittance ϵ_x and $|\beta_x - 1|$ at the center of straight.

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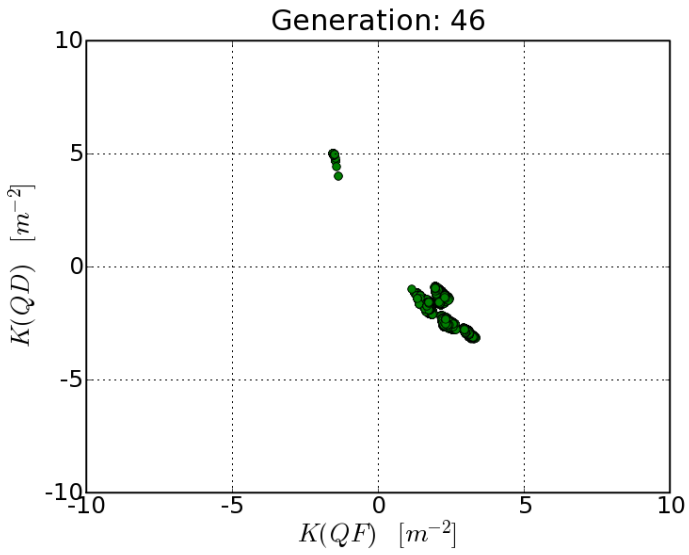
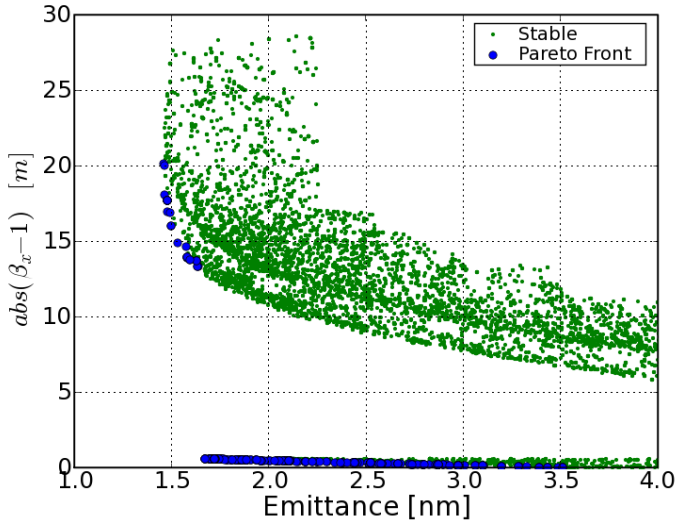
- Blue: Pareto optimal set, the best solutions so far.

1. Generation 19
2. Generation 46





3 Parameters, optimize ϵ and $\beta_x \rightarrow 1m$

By tuning k_{QF}, k_{QD}, k_{QFA} we can optimize emittance ϵ_x and $|\beta_x - 1|$ at the center of straight.

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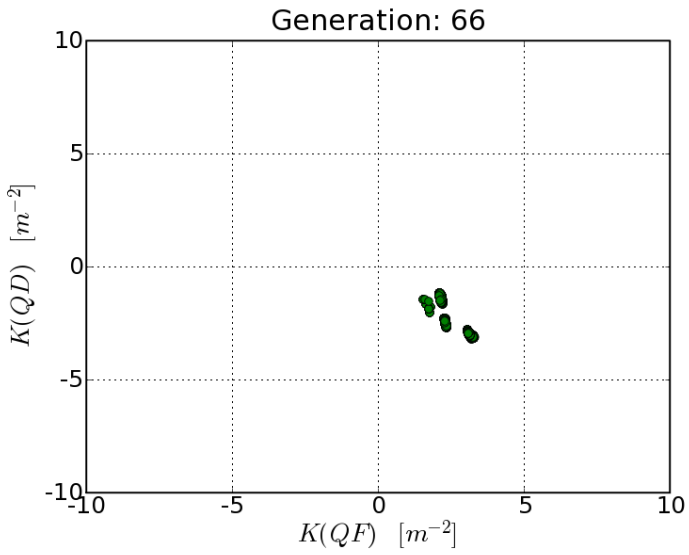
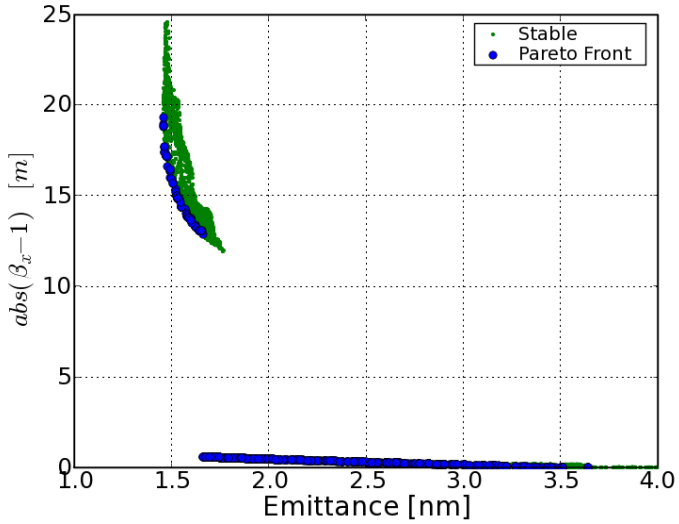
- Green: meet the constraints.
- Blue: Pareto optimal set, the best solutions so far.

1. Generation 19
2. Generation 46
3. Generation 66





3 Parameters, optimize ϵ and $\beta_x \rightarrow 1m$

By tuning k_{QF}, k_{QD}, k_{QFA} we can optimize emittance ϵ_x and $|\beta_x - 1|$ at the center of straight.

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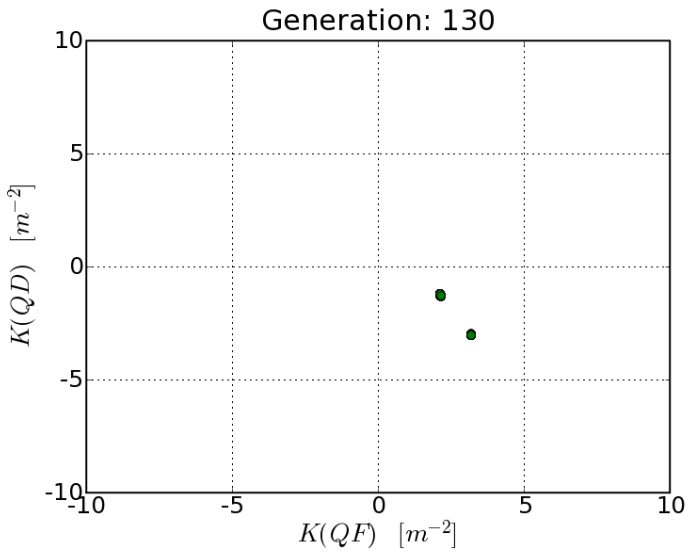
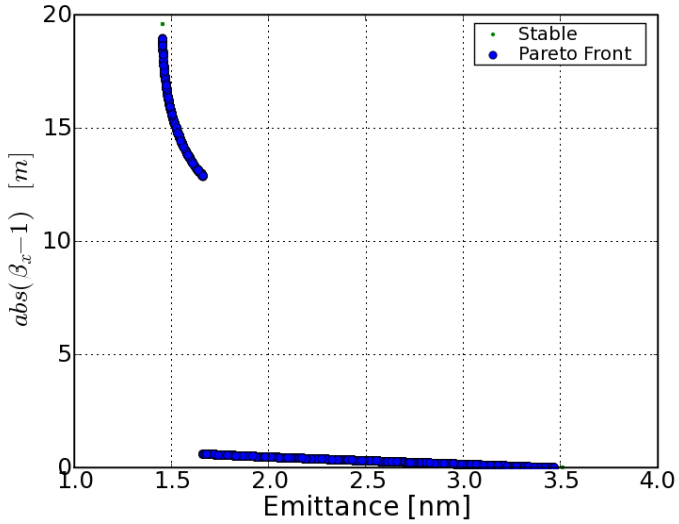
- Green: meet the constraints.
- Blue: Pareto optimal set, the best solutions so far.

1. Generation 19
2. Generation 46
3. Generation 66
4. Generation 130





Plan of Implementing MOGA

- Implement MOGA into linear optics correction code and test it by simulation.
  - For linear optics correction, the function to be minimized at the moment will be the rms phase beat in both planes and the variables will be the strengths of the trim quadrupoles.
  - It has the potential to optimize other lattice functions such as ORM and dispersion function simultaneously.
- Once the algorithm is confirmed by simulation, we would like to test it in RHIC APEX session.

- Thank you!

Determination of trim quads strength

- If the phase-beat is small (about 10% or less), the response of phase-beat to trim quads strength can be expressed into the following linear equation

$$\begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \cdots \\ \Delta\phi_{n_{bpm}} \end{pmatrix} = M \begin{pmatrix} \Delta kl_1 \\ \Delta kl_2 \\ \cdots \\ \Delta kl_{n_{tq}} \end{pmatrix}$$

, where M is the phase response matrix determined by the following expression

$$M_{i,j} = \frac{\beta_j}{4\sin(2\pi Q)} \left\{ \sin(2\pi Q) + \sin(2\psi_j - 2\pi Q) + sign(\psi_i - \psi_j) \left[\sin(2\pi Q) + \sin(2|\psi_i - \psi_j| - 2\pi Q) \right] \right\}$$

- Usually, the number of bpm is larger than the number of knobs (trim quads) , i.e. $n_{bpm} > n_{tq}$, and the system is over determined. It is known that for an over determined linear system, the SVD algorithm gives least χ^2 solution.

Determination of trim quads strength continued 1

- Thus we use the following equation to determine trim quads strength.

$$\begin{pmatrix} \Delta kl_1 \\ \Delta kl_2 \\ \dots \\ \Delta kl_{n_{tq}} \end{pmatrix} = V \begin{pmatrix} 1/w_1 & 0 & 0 & 0 \\ 0 & 1/w_2 & 0 & 0 \\ 0 & 0 & \dots & \dots \\ 0 & 0 & \dots & 1/w_{n_{tq}} \end{pmatrix} U^T \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \dots \\ \Delta\phi_{n_{bpm}} \end{pmatrix} \qquad (1)$$

, where U , V and w_i are determined by the unique singular vector decomposition of the phase response matrix, i.e.

$$M = U \begin{pmatrix} w_1 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 \\ 0 & 0 & \dots & \dots \\ 0 & 0 & \dots & w_{n_{tq}} \end{pmatrix} V^T \qquad U^T U = 1 \qquad V^T V = 1$$

- The SVD technique expands trim quads and bpms into n_{tq} orthogonal modes

. Explicitly, one can rewrite (1) into the following form,

Determination of trim quads strength continued 2

$$\begin{pmatrix} w_1 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 \\ 0 & 0 & \dots & \dots \\ 0 & 0 & \dots & w_{n_{tq}} \end{pmatrix} \cdot \begin{pmatrix} \Delta kl_1' \\ \Delta kl_2' \\ \dots \\ \Delta kl_{n_{tq}}' \end{pmatrix} = \begin{pmatrix} \Delta\phi_1' \\ \Delta\phi_2' \\ \dots \\ \Delta\phi_{n_{tq}}' \end{pmatrix}$$

, where $\begin{pmatrix} \Delta kl_1' \\ \Delta kl_2' \\ \dots \\ \Delta kl_{n_{tq}}' \end{pmatrix} = V^T \begin{pmatrix} \Delta kl_1 \\ \Delta kl_2 \\ \dots \\ \Delta kl_{n_{tq}} \end{pmatrix}$ and $\begin{pmatrix} \Delta\phi_1' \\ \Delta\phi_2' \\ \dots \\ \Delta\phi_{n_{tq}}' \end{pmatrix} = U^T \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \dots \\ \Delta\phi_{n_{bpm}} \end{pmatrix}$

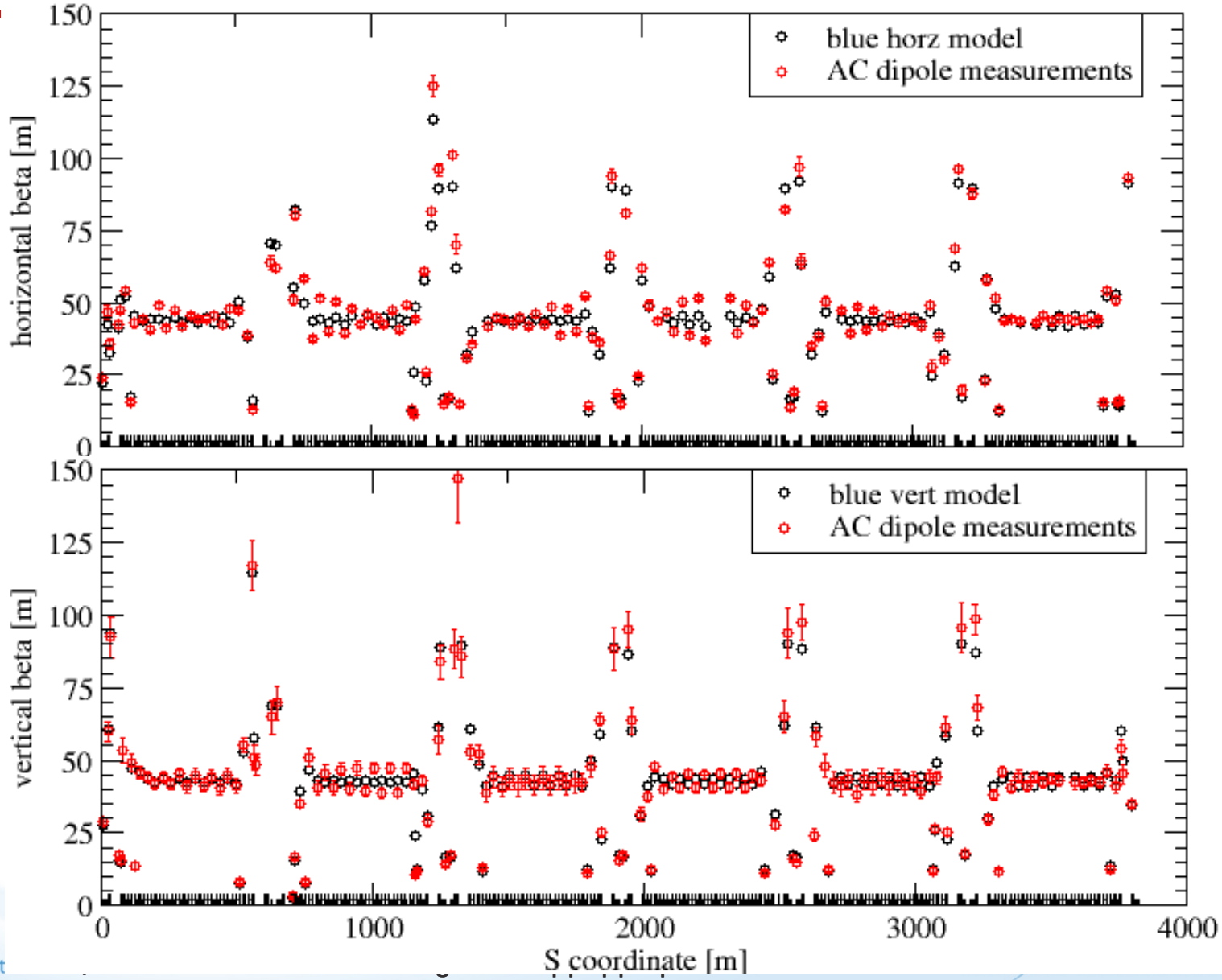
- Phase-beat components orthogonal to these 36 combination will not be corrected.
- If a eigenvalue w_i is zero or is comparable to the noise errors (due to linear approximation of model, bpm noise or computer round off errors), the corresponding mode of phase-beat is out of the knobs' range as well.
- Since the orthogonal condition, the corresponding combination of knobs for very small eigenvalue modes is not effective.
- Furthermore, noise and errors can be significantly amplified for the small eigenvalue modes.

Courtesy of T. Satogata

Blue AC dipole data

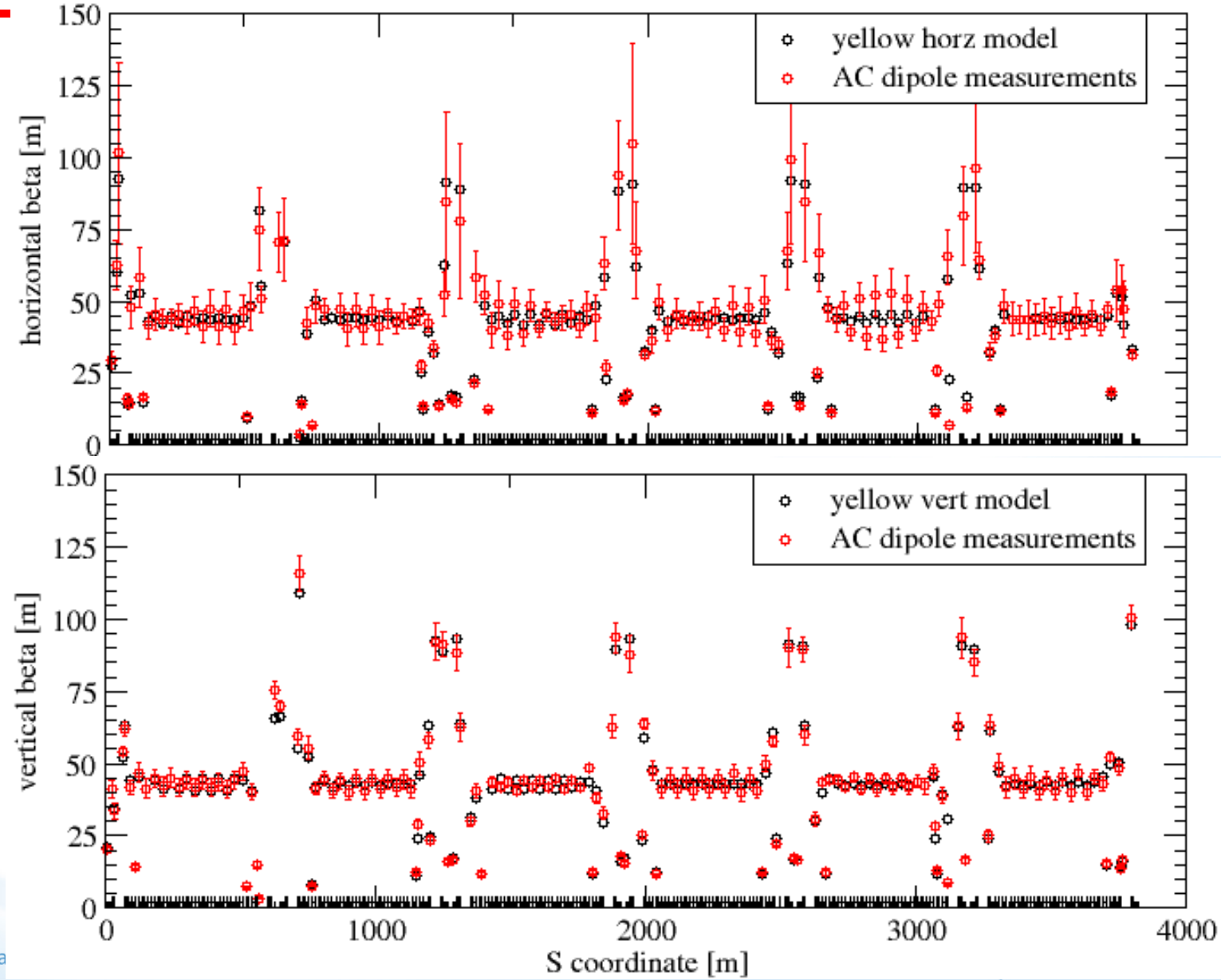
12.6% beta wave
7.6% after 3σ cut

20.9% beta wave
5.4% after 3σ cut



Courtesy of T. Satogata

Yellow AC dipole data

22.0% beta wave
8.4% after 3σ cut

21.3% beta wave
5.3% after 3σ cut