LARP

Status of LHC AC Dipole Task

M. Bai, R. Calaga, R. Miyamoto, P. Oddo, G. Wang
Brookhaven National Laboratory

M. Syphers, A. Jansson
Fermi National Accelerator Laboratory

R. Tomas, J. Serrano, H. Schmickler
CERN, Geneva

LARP CM12 Collaboration Meeting, April 8th , 2009

BROOKHAVEN NATIONAL LABORATORY

Outline

LARP

- Overview
  - History and milestones
  - Current status
- Working status of the task
  - Dynamics tuning development: P. Oddo
  - Linear gradient error correction: G. Wang
  - Investigation of various diagnostics technique: R. Miyamoto
- Plans for FY2010 and beyond

BROOKHAVEN NATIONAL LABORATORY

History of the Task

- Proposed in April 2006
  - Task list
    - Identify possible scenarios for an AC dipole in the LHC
      - Specs for LHC AC dipole
        - » Operating frequency and strength: capable of generating a maximum driven oscillation of 4σ at 7 TeV
      - AGS/Tevatron approach: resonate a pinger: low Q but cheaper
      - RHIC approach: a dedicated ac dipole with high Q, expensive, tuning range
    - Explore the applications of using AC dipoles in the LHC for both linear optics measurement and non-linear beam dynamics studies
  - LARP collaboration with CERN instrumentation+ABP
    - Univ. of Texas, Austin: S. Kopp, R. Miyamoto
    - BNL: M. Bai, R. Calaga, P. Oddo
    - FNAL: A. Jansson, M. Syphers

History of the Task

LARP

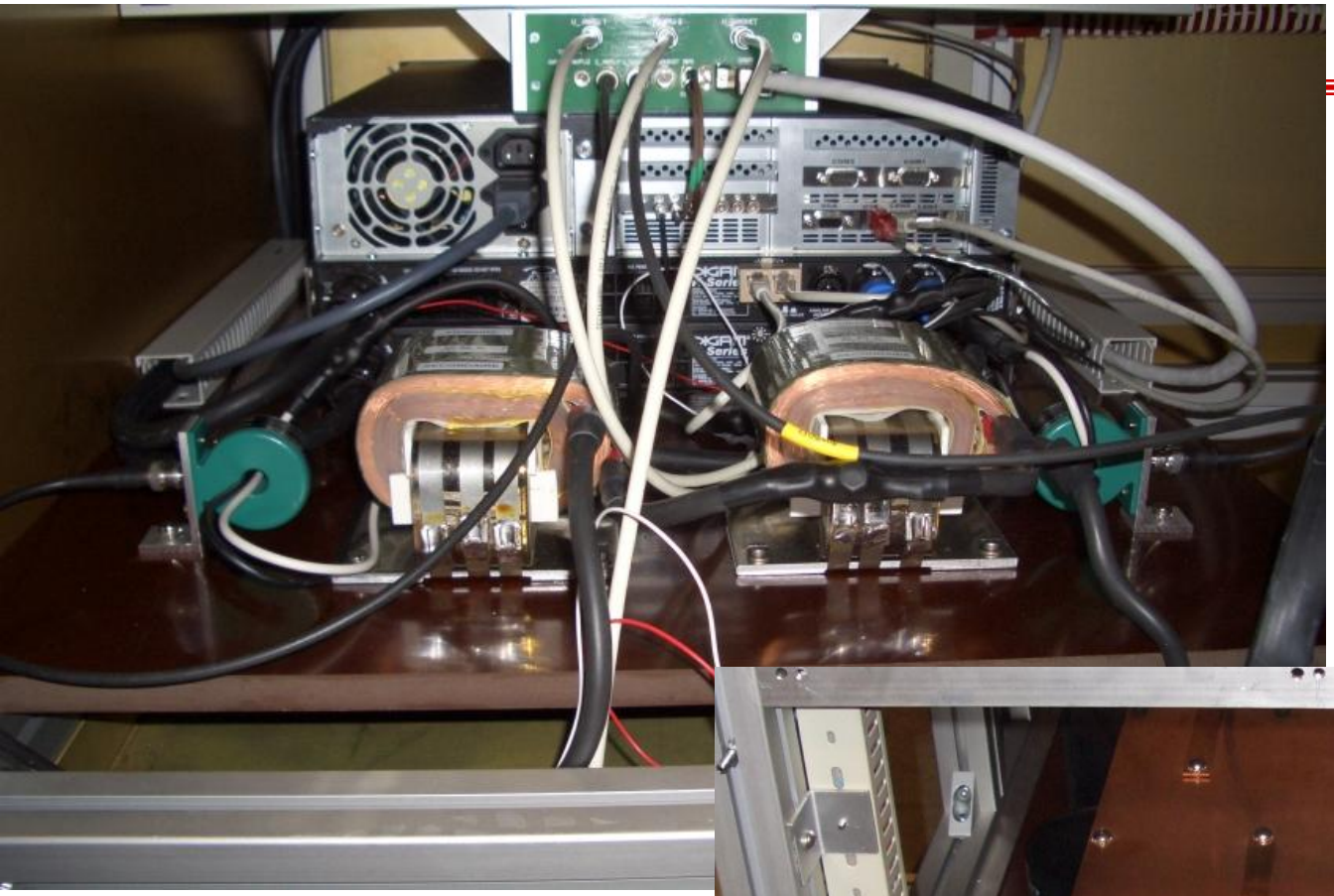
- At the end of FY2006
  - CERN decided to take the AGS/FNAL approach to build four ac dipoles by resonating 4 pingers
  - Estimate 1700A for 4σ at 7 TeV
- $80k allocated for FY2007
  - Additional amplifier for bridge test at FNAL and hardware purchase for exploring dynamic tuning technique
  - Labor and travel expense
- FY2008
  - Helped to design the tuning circuit to allow CERN ac dipole to achieve ± 0.01 tuning range: binary cap bank
  - Demonstrated the technique of using ac dipole to measure linear optics at both Tevatron and RHIC

BROOKHAVEN NATIONAL LABORATORY

Current status

- $35k allocated for FY2009
  - Support a BNL/LARP post-doc: G. Wang
  - Toohig fellow: R. Miyamoto
- Demonstrate the technique of linear gradient error correction based on the optics measurement using AC dipole at RHIC
  - G. Wang, M. Bai(100% BNL contribution)
- Demonstrate Dynamic tuning technique with RHIC high Q ac dipole
  - P. Oddo (100% BNL contribution)

4 AC dipoles have been installed in LHC!



2 magnetically coupled audio amplifiers

"Capacitor Bank" for frequency tuning.

(Courtesy of Javier Serran)

Status of the LHC AC Dipole Systems

LARP

- Specs:
  - Frequency: 2750 Hz - 4000 Hz
  - Amplitude: 1700 A peak (4σ)
  - Ramping: 200 ms ramp up, 200 ms flat top, 200 ms ramp down

- Status:
  - Amplitude and ramping specs tested and fulfilled.
  - Bandwidth spec fulfilled though manual capacitor bank configuration.

- Upcoming test:
  - Remote switching of capacitors in the bank using MOSFET switches (in the summer).

(Courtesy of Javier Serrano)

Status of Dynamic Tuning Development

AC-Dipole Comparison

LARP

	L µH	Ipk A	Max Field Gm	Frequency kHz	Pk Energy J	kVAR	Drive kW	Min sys Q
LHC	3.896	1800.0	190.0	2.90	6.312	115.00	27.0	4.26
Tevatron	8.300	450.0	115.0	20.00	0.840	105.60	8.0	13.20
AGS	2.340	270.0	20.0	106.00	0.085	56.81	2.2	25.82
RHIC	104.200	79.0	100.0	38.30	0.325	78.25	5.0	15.65
RHIC	26.360	158.0	100.0	60.84	0.329	125.78	5.0	25.16
Prototype	53.200	147.0	92.0	39.00	0.575	140.85	1.1	128.05
RHIC Spin Flipper	97.000	117.9	100.0	39.00	0.674	165.20	1.1	150.18

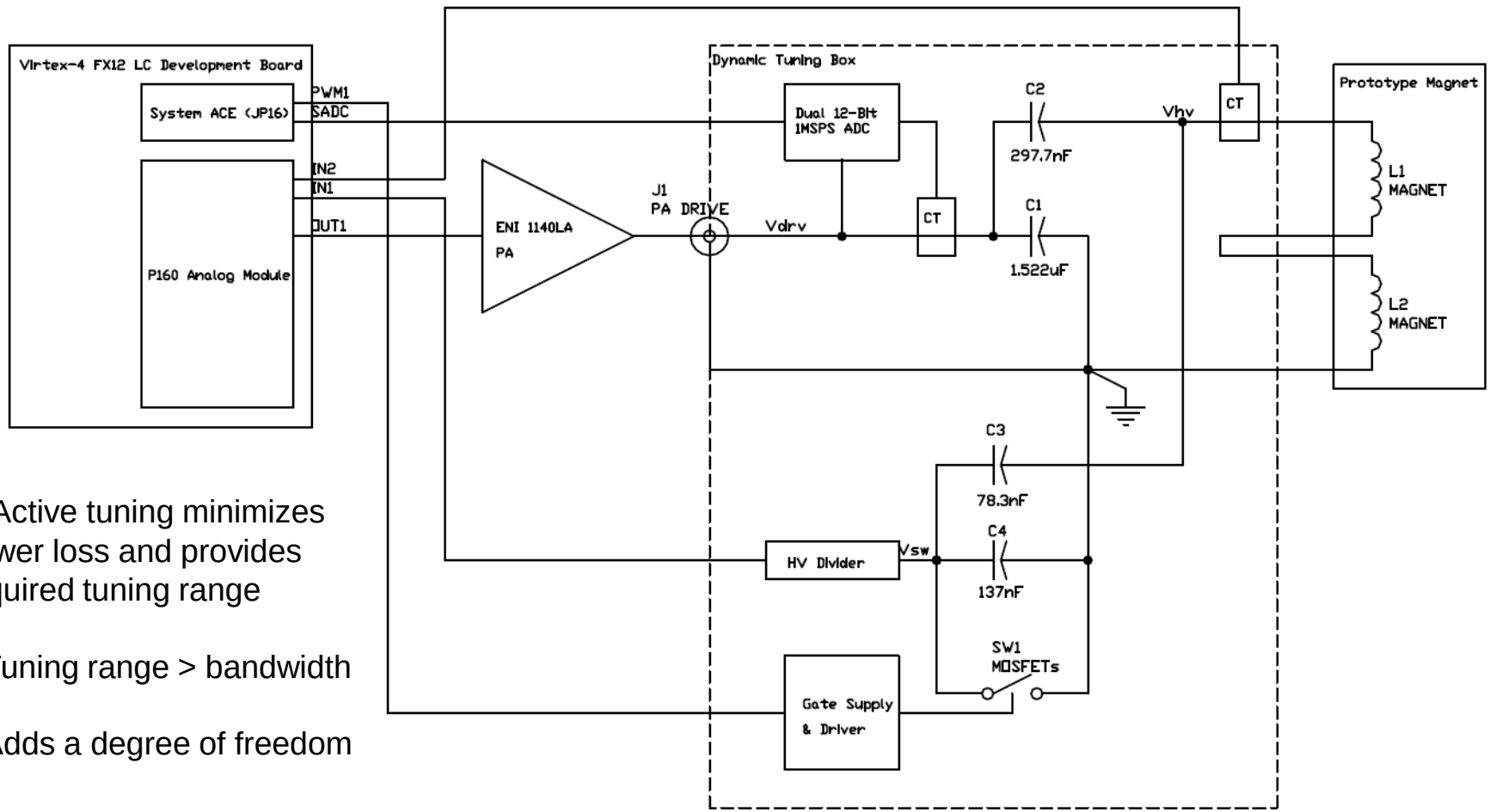
- Minimum System Q is the minim Q needed to achieve desired magnet current at a given drive power
- L is measured inductance and includes stray inductances

Prepared by P. Oddo

Email: poddo@bnl.gov

BROOKHAVEN NATIONAL LABORATORY

Prototype Dynamic Tuning Block Diagram



- Active tuning minimizes power loss and provides required tuning range

✓Tuning range > bandwidth

✓Adds a degree of freedom

$$P_{total} = \frac{VAR_{Magnet}}{Q_{Magnet}} + \frac{VAR_{Tuning}}{Q_{Tuning}}$$

Prepared by P. Oddo

Email: poddo@bnl.gov

BROOKHAVEN NATIONAL LABORATORY

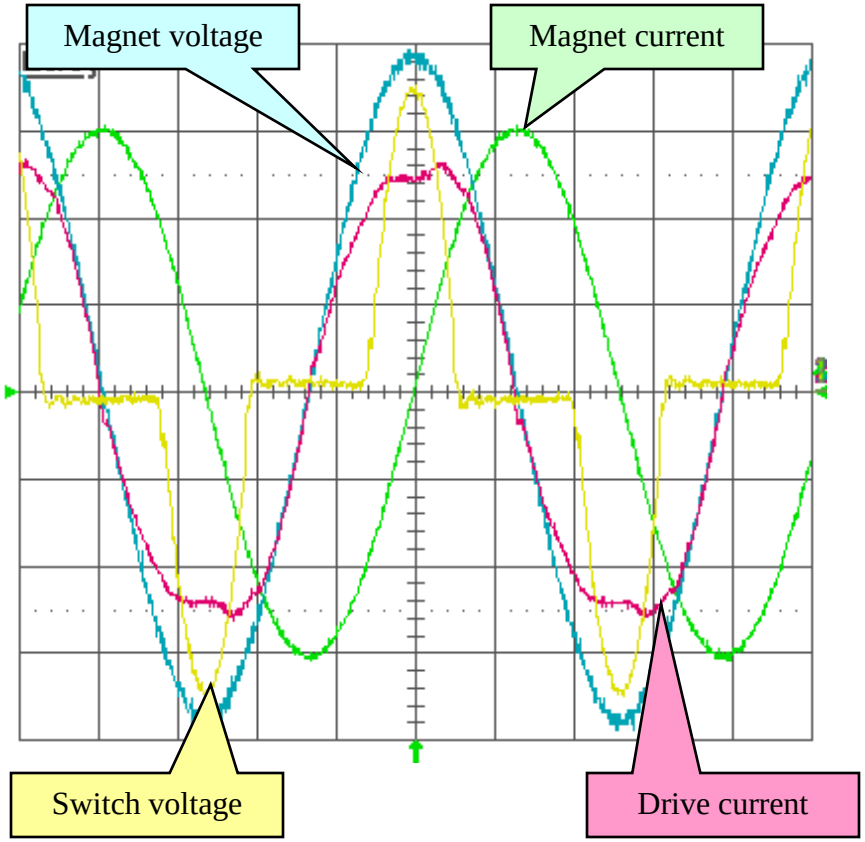
Prototype Tuning Results

Prepared by P. Oddo
Email: poddo@bnl.gov

LARP

Tuning range: 38.9kHz ±890Hz
Peak magnet current: $147A_{pk}$
Peak power: 880W
System Q: 135-158

- **Switched capacitor tuning is demonstrated to provide required tuning range with minimized power loss.**
  - It's possible to drive and tune a magnet via long cables without introducing significant losses
  - Due to time constrains, the RHIC Spin-Flipper Will initially use mechanical (inductor) tuning
    - Will complete switched tuning during summer shutdown



Correction Of Linear Gradient Errors

LARP

- Goal :

  Developing a technology to reduce the phase-beat / beta-beat due to linear optics gradient errors by using the ac dipole measured optics data.

- Basic concepts:

  The phase beat is related to the gradient errors by PRM

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

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

  By varying the gradients of some adjustable magnets (knobs) according to the measured optics, the phase beat can be reduced.

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

$$M = UWV^T$$

$$UU^T = I$$

$$VV^T = I$$

- Tools: ac dipole, fitting algorithm, trim quads (as knobs), SVD algorithm.

BROOKHAVEN NATIONAL LABORATORY

Status of gradient error correction

LARP

- Accurate optics measurement by using ac dipole excited coherent oscillation is demonstrated in RHIC and Tevatron.

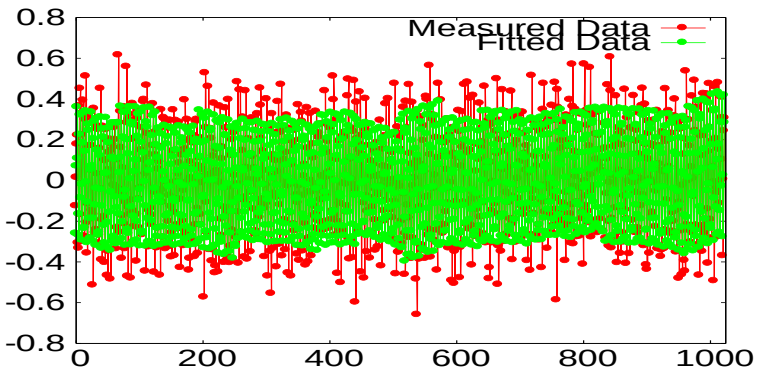
- The SVD algorithm for linear gradient error correction is verified by simulation.

- Data analysis of 2008 run data is in working progress. There are two chalenges in the processes of the linear gradient error correction.
  - Bpm data quality and the number of available bpms
  - The range of knobs.

BROOKHAVEN NATIONAL LABORATORY

Phase-beat measurement

- Implemented bpm data filters:
  - Status bit
  - Drive tune discrepancy
  - Suspiciously large χ^2 from fitting. (added in 2008)



(a) Fitting with large χ^2

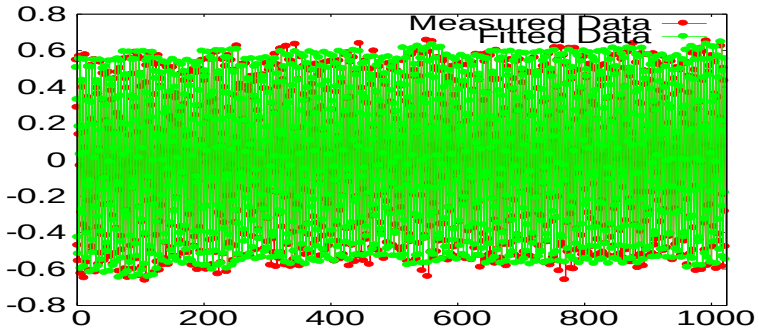
- Fitting formula

$$x_s(k) = A_m\{\cos(\psi_m)[\cos(2\pi Q_x^{ac}k) - r\cos(2\pi Q_x^{ac}k - 2\pi Q_x^{ac} + 2\chi_x^{ac})] - \sin(\psi_m)[\cos(2\pi Q_x^{ac}k) + r\sin(2\pi Q_x^{ac}k - 2\pi Q_x^{ac} + 2\chi_x^{ac})]\}$$

$$\psi_m = -\pi(Q_x^{ac} - Q_x) + \chi_x^{ac} - \Delta\psi_s \qquad r = \frac{\sin(\pi(Q_x^{ac} + Q_x))}{\sin(\pi(Q_x^{ac} - Q_x))}$$

Ac dipole initial phase

Betatron phase advance (fitting parameter)



(b) Fitting with reasonable χ^2

Noise Effects on Gradient Errors' Correction

LARP

- If the phase-beat caused by the known trim quads errors has large component in the small eigenvalue modes, the amplified noise due to bpms or the linear approximation could make the reconstruction very difficult. In order to demonstrate this effect, we did the following simulation.

$$\begin{pmatrix} \Delta kl_1' \\ \Delta kl_2' \\ \dots \\ \Delta kl_{n_{tq}}' \end{pmatrix} = \begin{pmatrix} 1/w_1 & 0 & 0 & 0 \\ 0 & 1/w_2 & 0 & 0 \\ 0 & 0 & \dots & \dots \\ 0 & 0 & \dots & 1/w_{n_{tq}} \end{pmatrix} \begin{pmatrix} \Delta\phi_1' \\ \Delta\phi_2' \\ \dots \\ \Delta\phi_{n_{tq}}' \end{pmatrix}$$

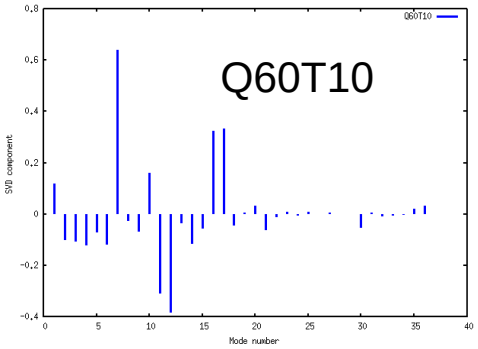
1 Set Known Gradient Errors. → 2 Calculate the Phasebeat → 3 Add Random Phasebeat Noise → 4 Use SVD code to calculate correction strength → 5 Calculate phasebeat after correction.

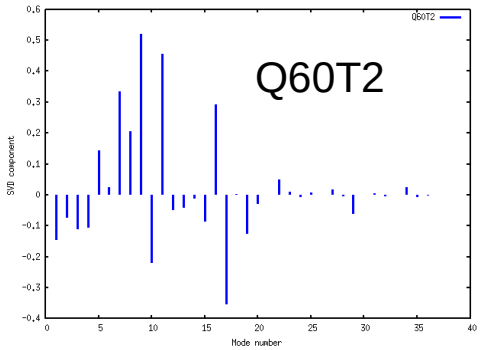
Without errors, step 4 should reconstruct the errors set in step 1.

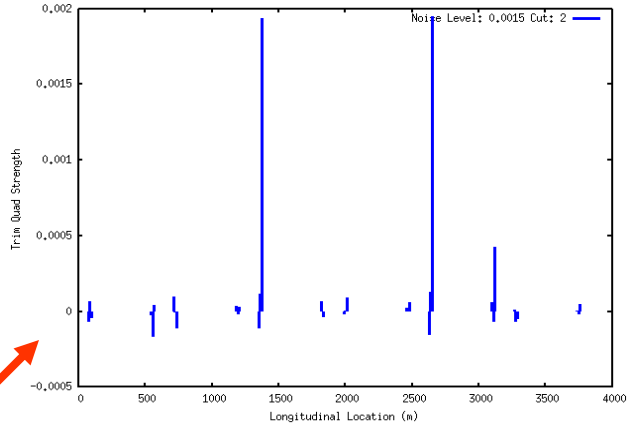
BROOKHAVEN NATIONAL LABORATORY

Noise Insensitive Trim Quads:

(Q60T10+Q60T2)*0.002



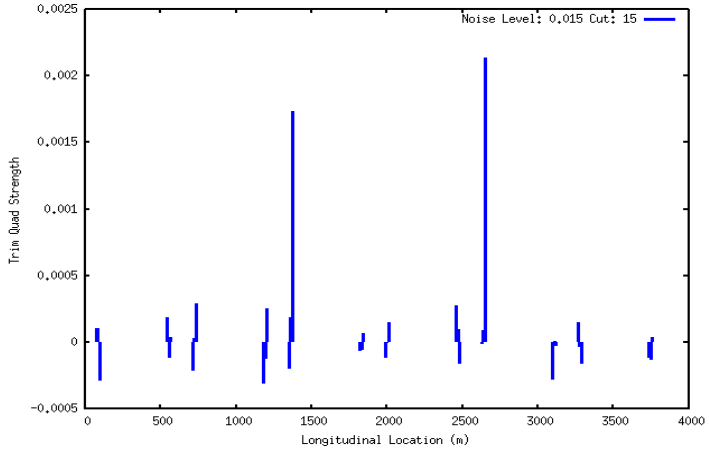




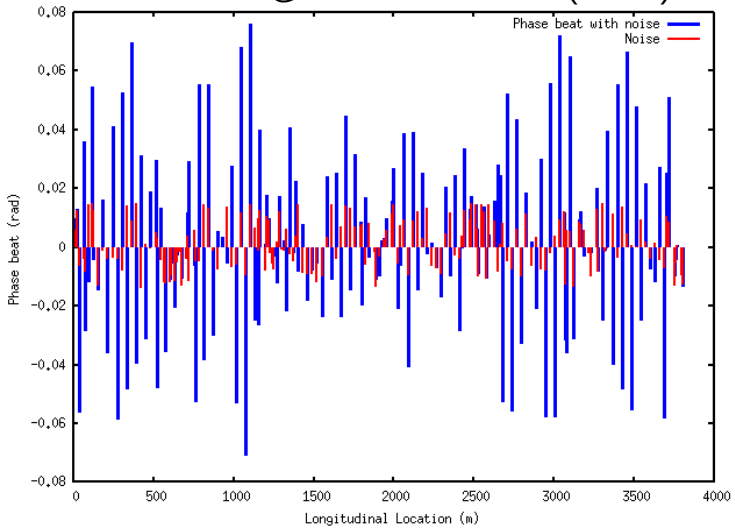
Noise ~2%

Trim Quads Error is Reconstruct able with Proper Cut

@ Noise Level: 0.015 (~20%)

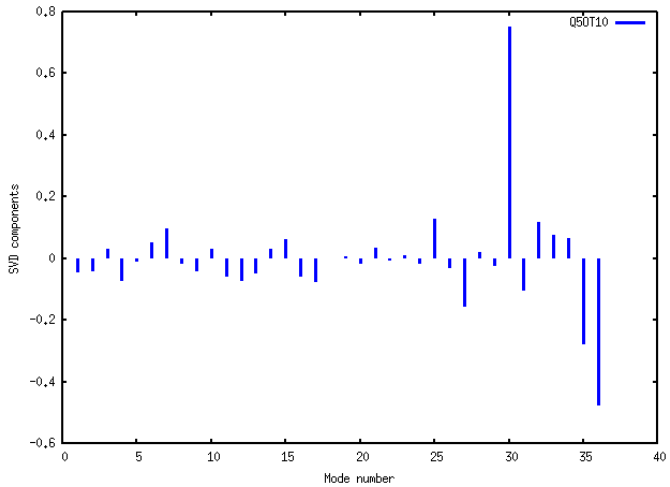


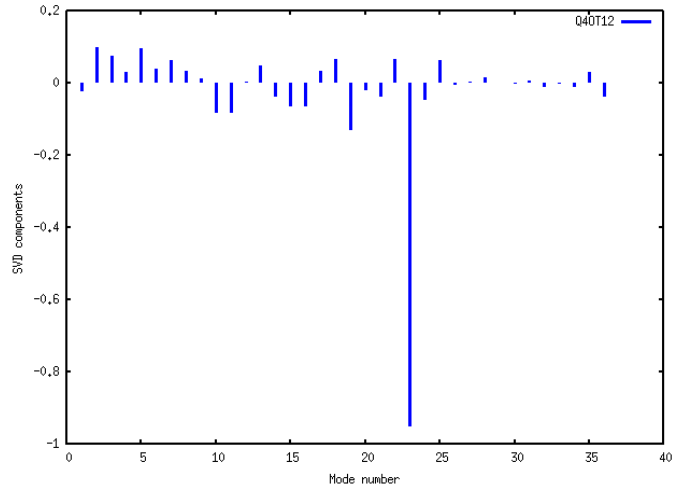
Phase beat @ noise level: 0.015 (~20%)



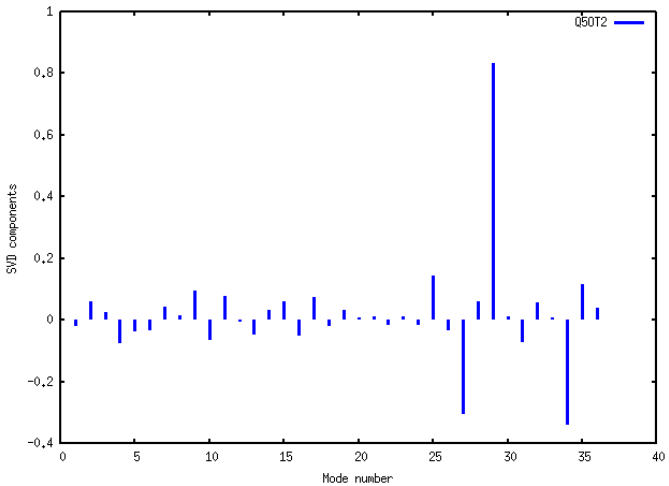
Noise Sensitive Trim Quads:

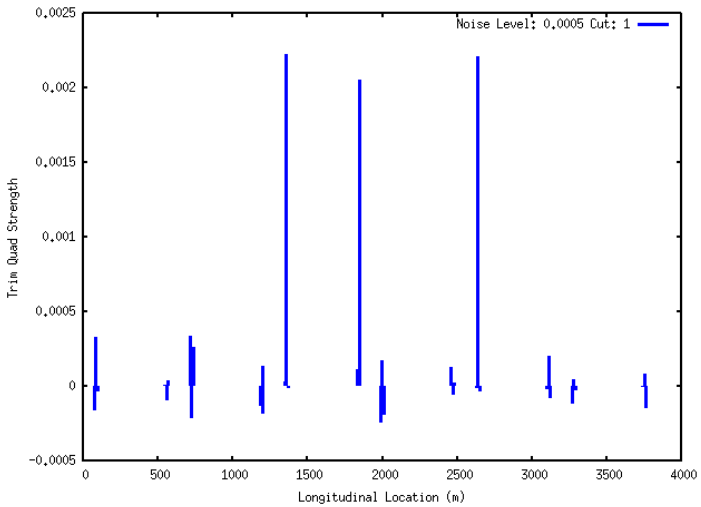
Example: (Q50T10+Q40T12+Q50T2)*0.002





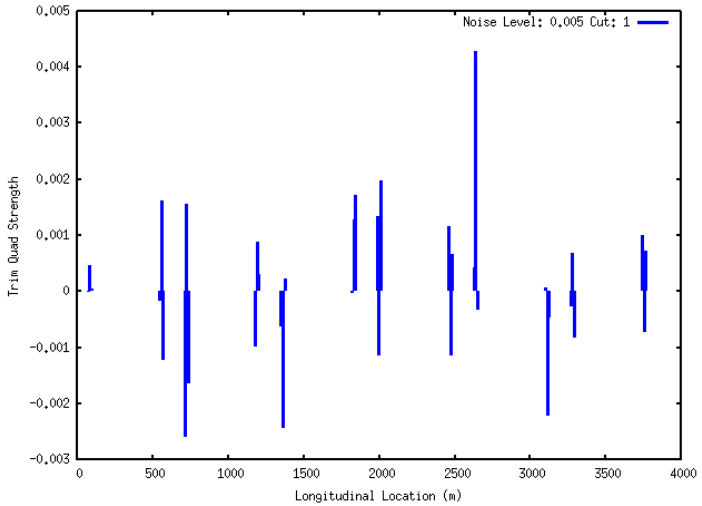
Noise ~1%

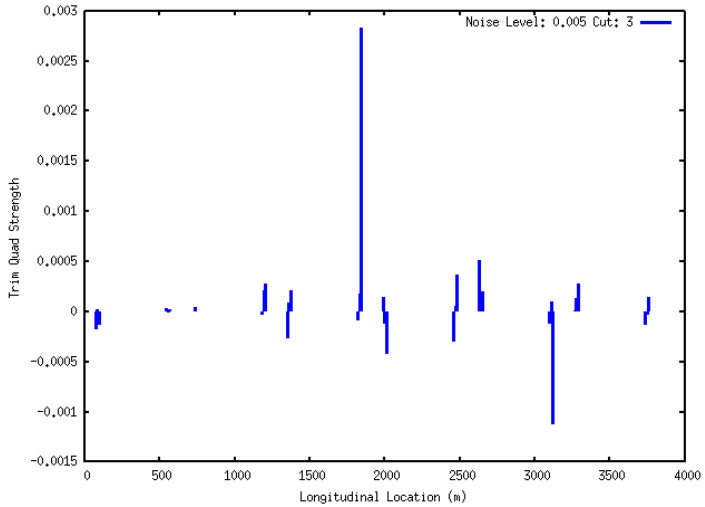


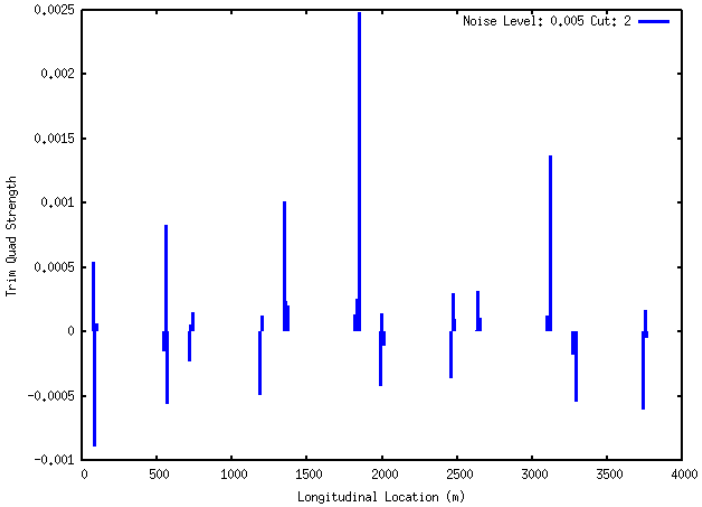


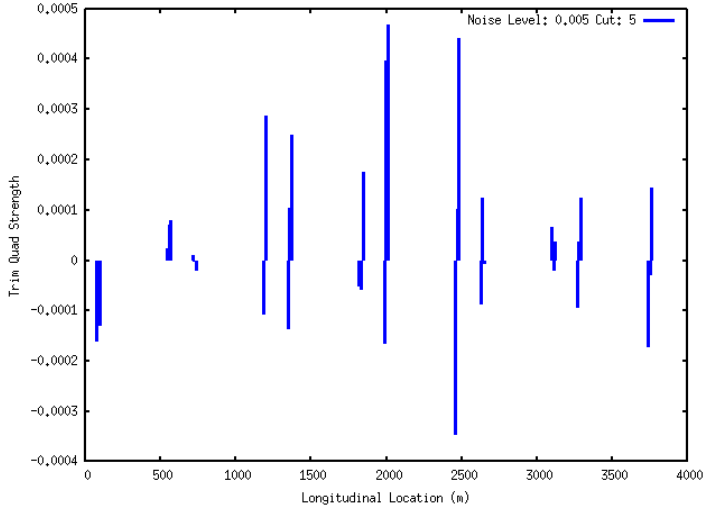
Trim Quads Error is Difficult to be Reconstructed

@ Noise Level: 0.005 (~10%)



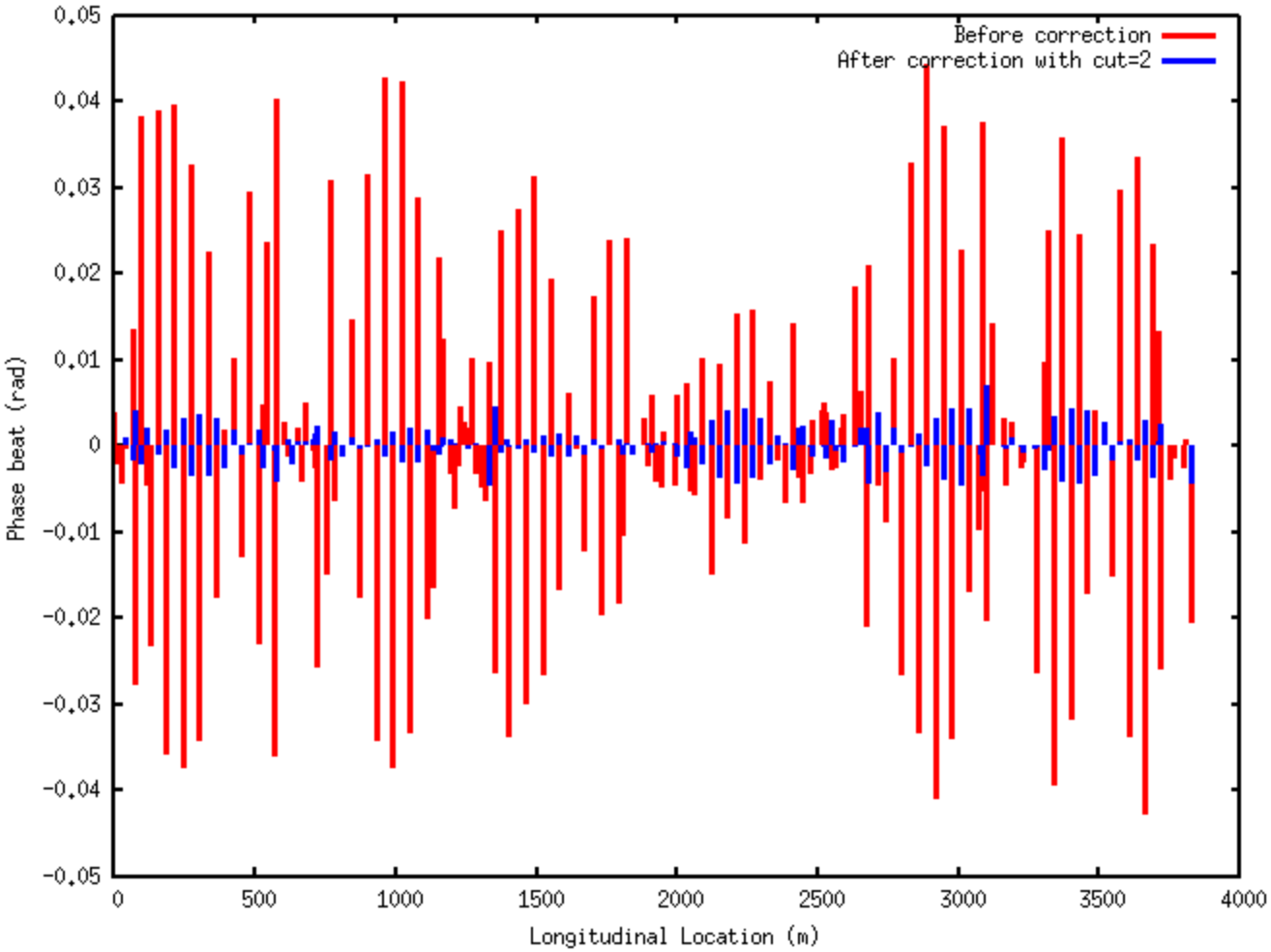






Phase-beat Correction is still working

@ Noise Level: 0.005 (~10%)



Demonstration of correction in Madx simulation

LARP

Procedures:

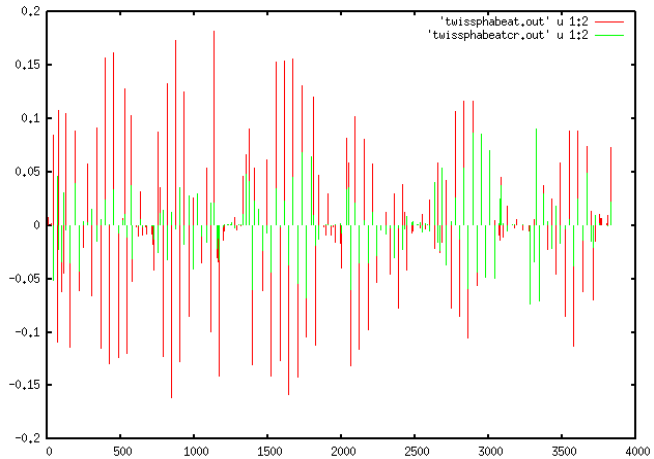
Set random quads errors in Madx and calculate phase beat

↓

Use our SVD codes to get knobs' strength

↓

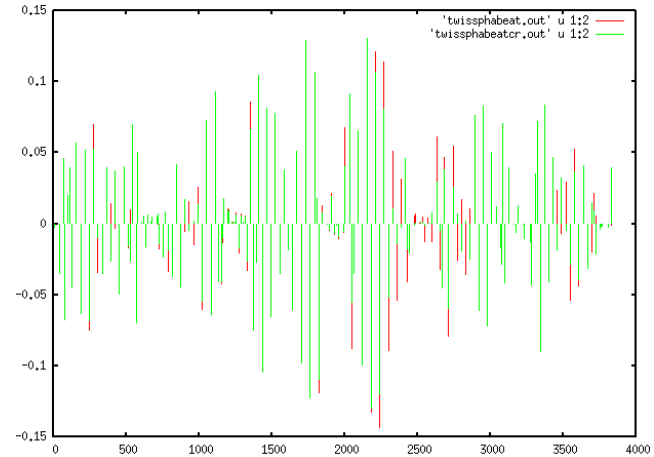
Apply the trim quads errors and calculate the phase beat again.



Random Relative QF errors

$$0.2 \times [Ranf() - 0.5]$$

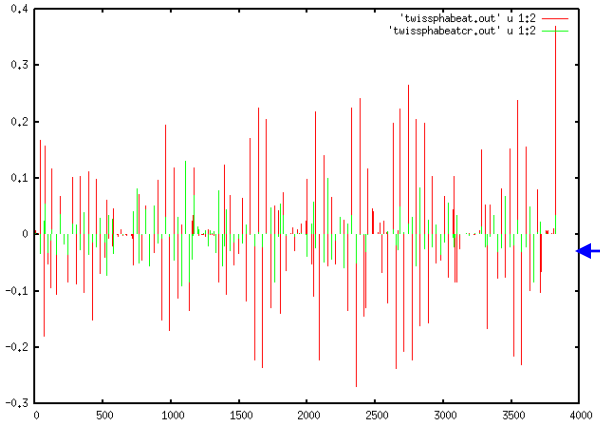
The phase beat reduced from rms 7.6% to rms 2.8%. Seed=123456789 generates phase beat within the knobs' range.



The phase beat increased slightly from rms 4.8% to rms 5.1%. Seed=123456789 generates phase beat beyond the knobs' range.

BROOKHAVEN NATIONAL LABORATORY

Demonstration of correction in Madx simulation

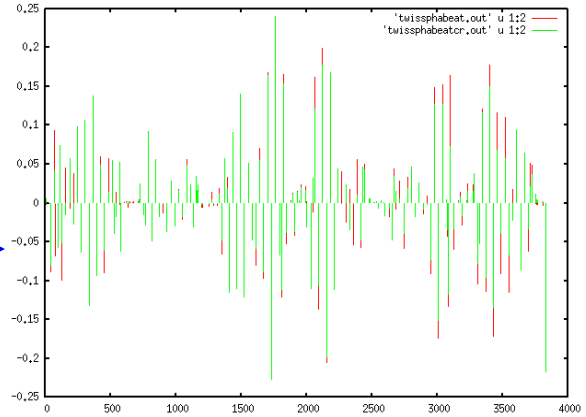


Seed=231456789, within the knobs' range.

Phase beat reduces from 11.5% to 3.6%.

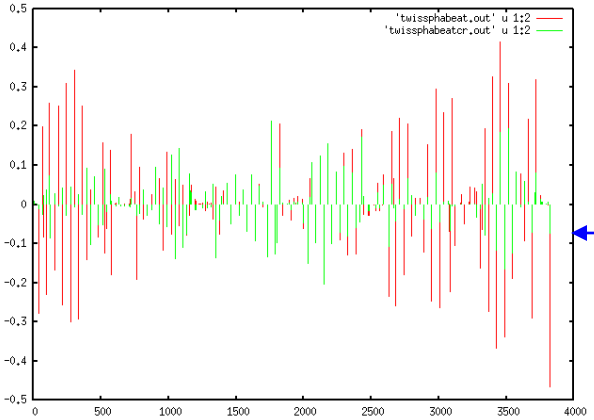
Random QD errors

$$0.05\times[Ranf()-0.5]$$



Seed=234156789, beyond the knobs' range.

Phase beat reduces from 7.4% to 6.6%.



Seed=345261789, within the knobs' range.

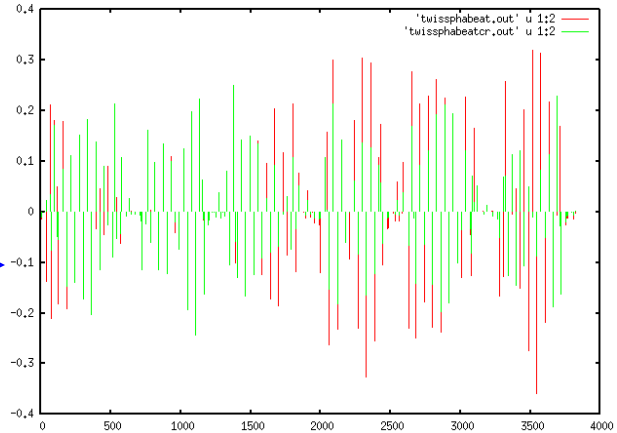
Phase beat reduces from 14.3% to 7.6%.

Ramdom QF+ QD errors

$$0.2\times[Ranf()-0.5]$$

$$+$$

$$0.05\times[Ranf()-0.5]$$



Seed=234561789, beyond the knobs' range.

Phase beat reduces from 13.8% to 10.5%.

Plan of linear gradient error correction

LARP

- We plan to demonstrate the SVD algorithm for linear gradient error correction in RHIC 2009 run during APEX time.

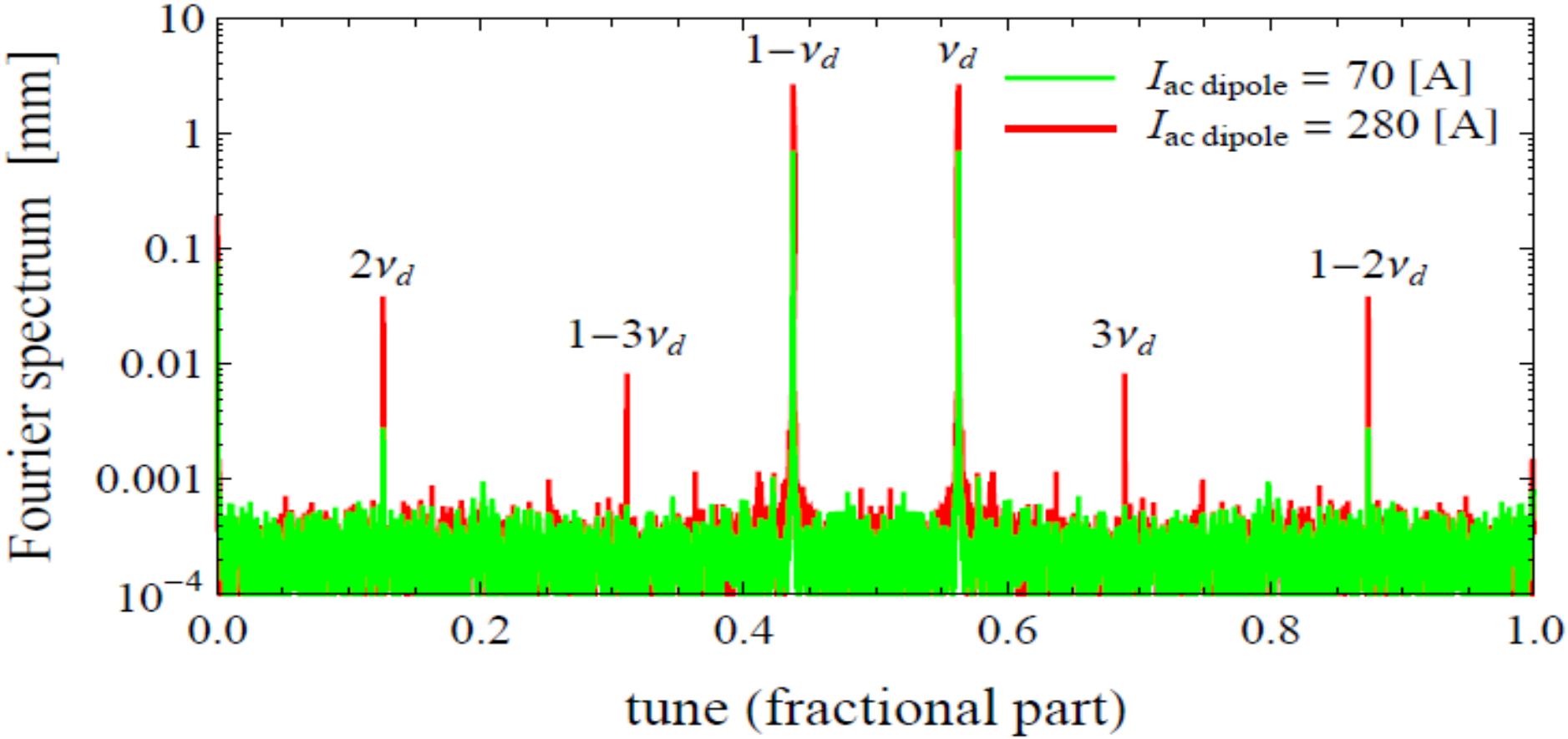
- Once demonstrated, we would like to work with our CERN collaborators to implement this technique to LHC.

BROOKHAVEN NATIONAL LABORATORY

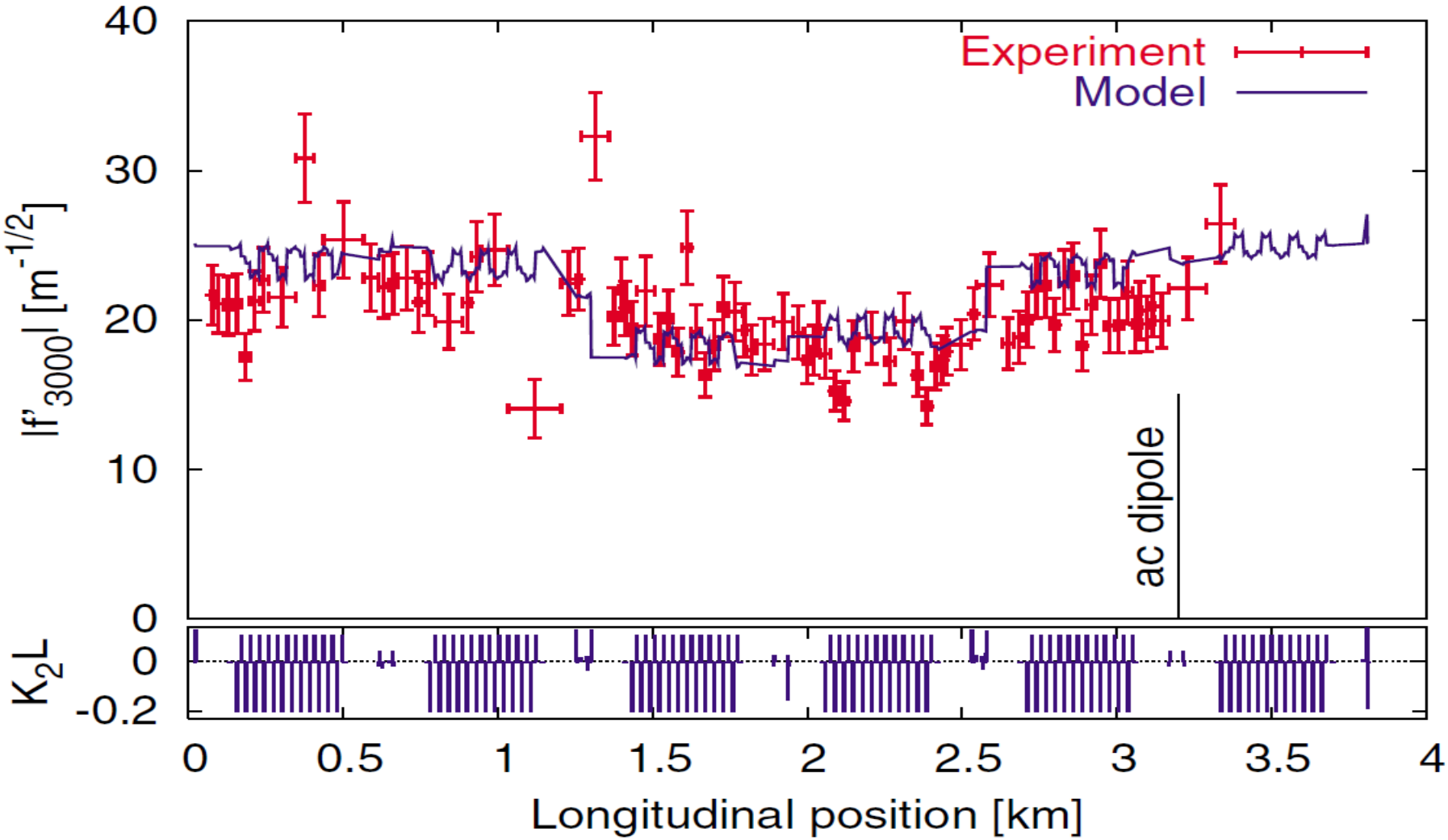
Nonlinearity Measurements Based on Spectrum

LARP

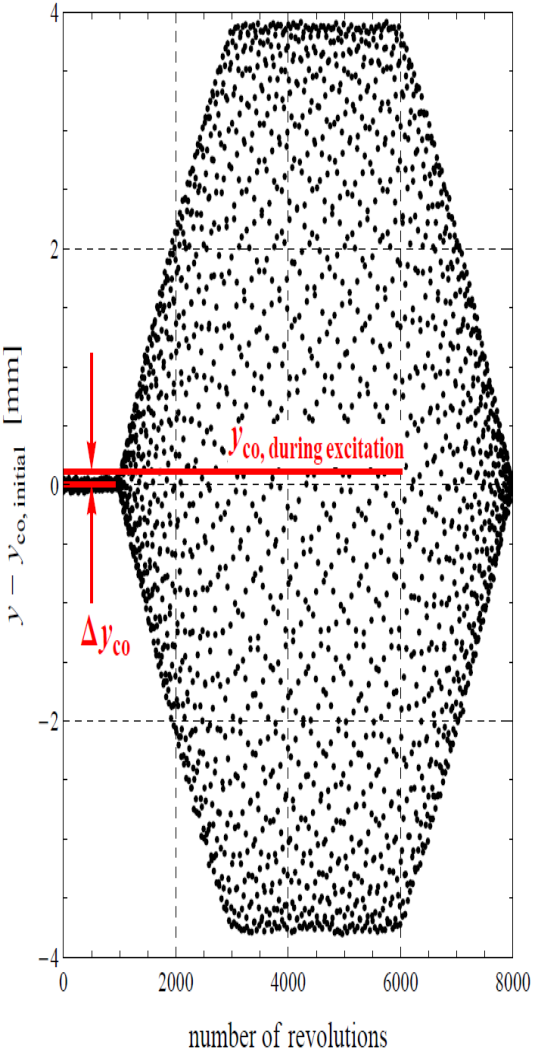
- Fourier spectrum contains information of nonlinear fields.
- All the higher betatron modes have tunes (integer)*ν_d.
- Interpolation is not necessary to determine amplitude.

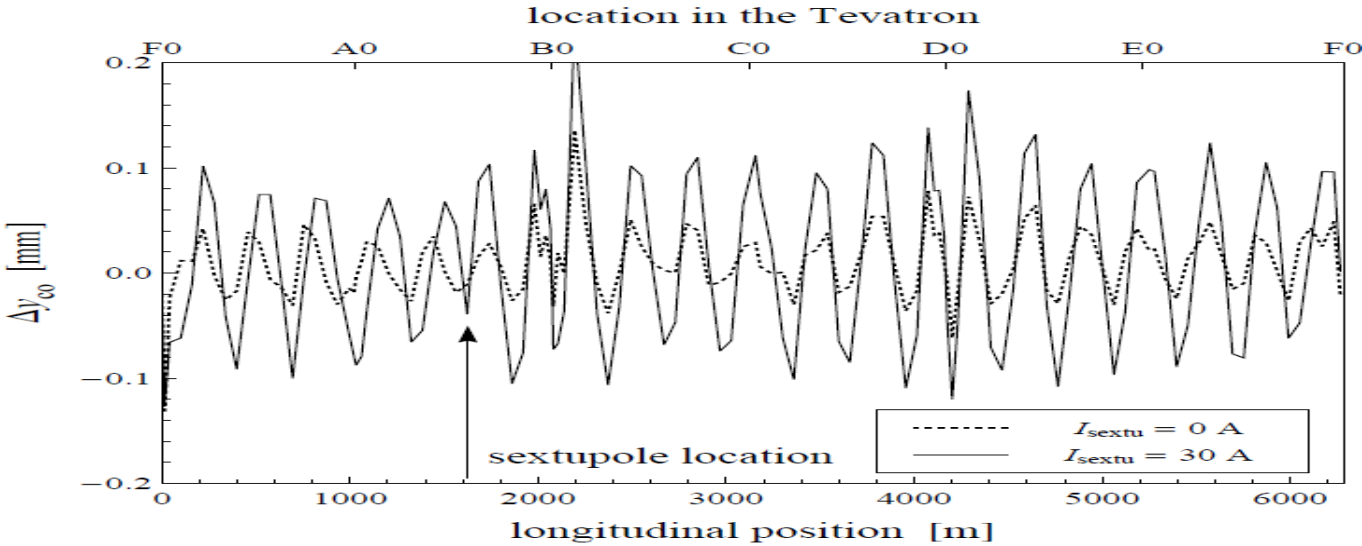


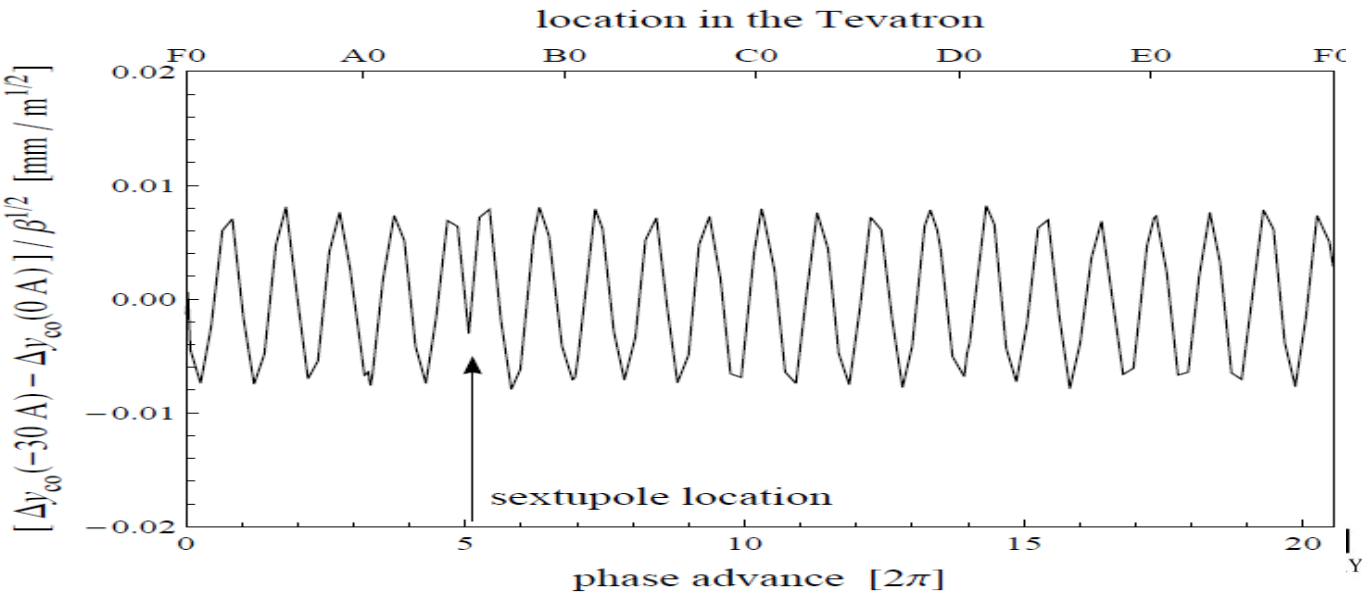
Sextupole Driving Term Measured in RHIC



Sextupole Measurements from Orbit Shifts

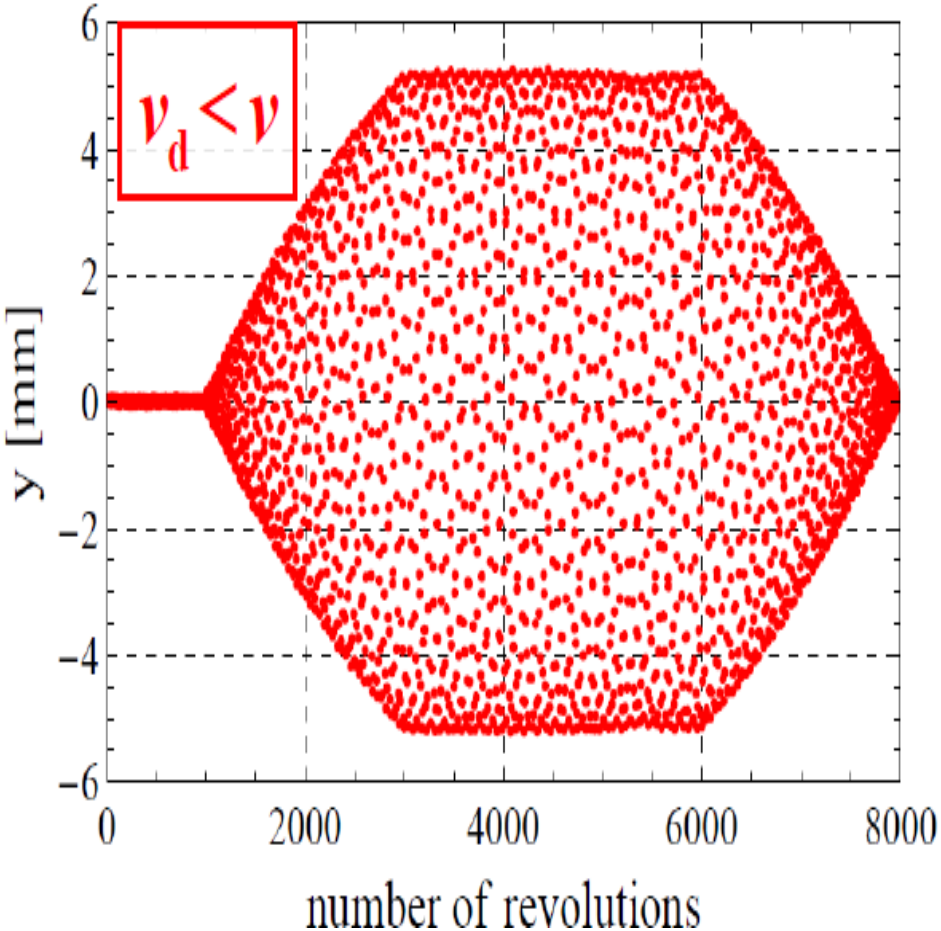


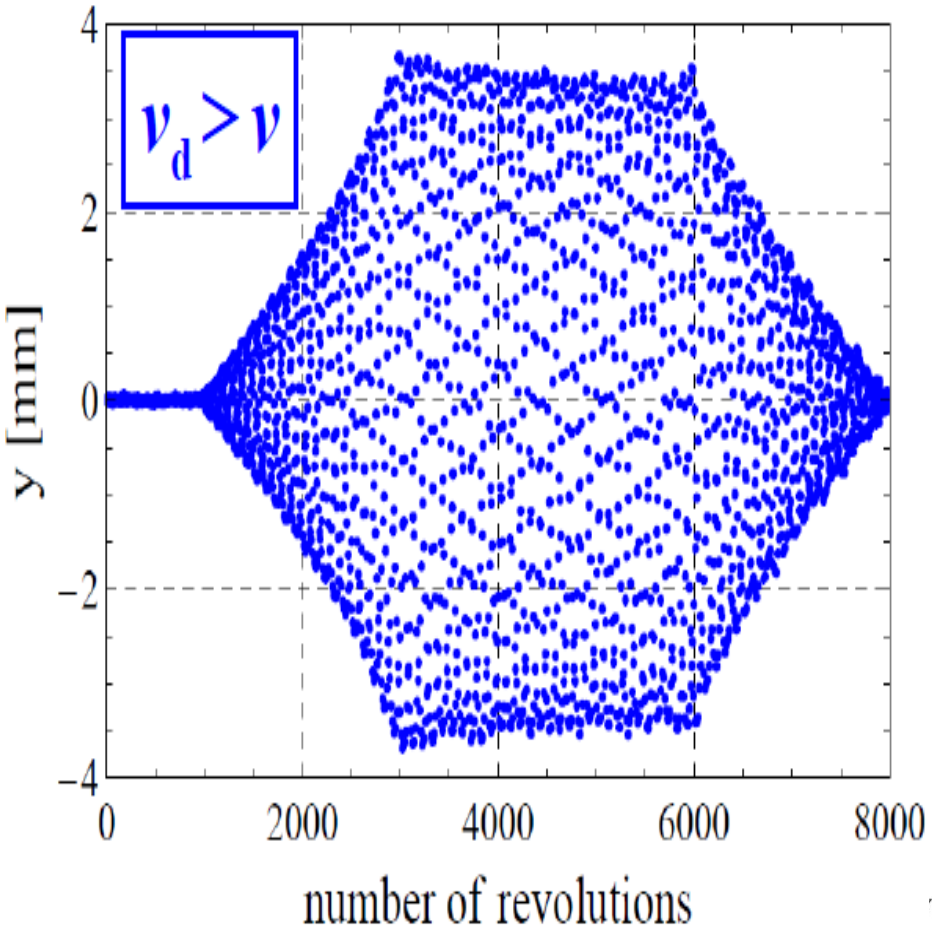




Detuning Measurements from Amplitude Response

$$\frac{\theta_{ac}\sqrt{\beta_{ac}\beta(s)}}{4\sin|\pi(\nu_d-\nu-\delta\nu(J))|}$$





Resonance Driving Terms for the Driven Motion

For the driven motion, Linear Coupling Driving Terms are modified from

$$C_{\mp}(s) = \oint d\bar{s}\, \frac{B_x'(\bar{s})\sqrt{\beta_x(\bar{s})\beta_y(\bar{s})}}{4(B\rho)\sin[\pi(\pm\nu_x - \nu_y)]} e^{-i[\pm\psi_x(\bar{s})-\psi_y(\bar{s})]-\pi i(\pm\nu_x-\nu_y)\mathrm{sgn}(s-\bar{s})}$$

to

$$C_{d,\mp}(s) = \oint d\bar{s}\, \frac{B_x'(\bar{s})\sqrt{\beta_{d,x}(\bar{s})\beta_y(\bar{s})}}{4(B\rho)\sin[\pi(\pm\nu_{d,x} - \nu_y)]} e^{-i[\pm\psi_{d,x}(\bar{s})-\psi_y(\bar{s})]-\pi i(\pm\nu_{d,x}-\nu_y)\mathrm{sgn}(s-\bar{s})}$$

Sextupole Driving Terms are modified from

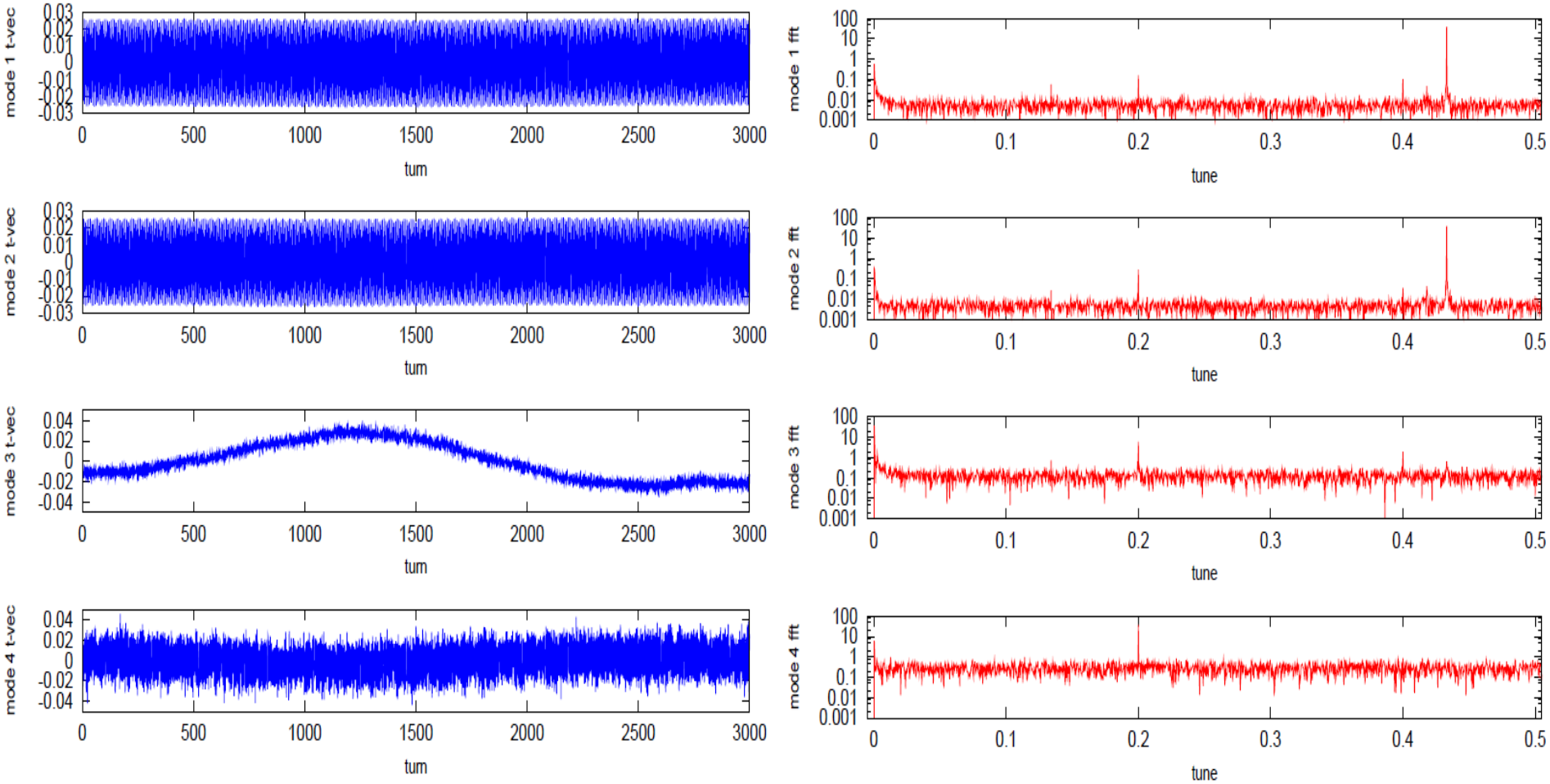
$$S_{\mp}(s) = \oint d\bar{s}\, \frac{B_y''(\bar{s})\beta_x(\bar{s})^{3/2}}{16(B\rho)\sin[\pi(\pm 2\nu_x - \nu_x)]} e^{-i[\pm 2\psi_x(\bar{s})-\psi_x(\bar{s})]-\pi i(\pm 2\nu_x-\nu_x)\mathrm{sgn}(s-\bar{s})}$$

to

$$S_{d,\mp}(s) = \oint d\bar{s}\, \frac{B_y''(\bar{s})\beta_{d,x}(\bar{s})\beta_x(\bar{s})^{1/2}}{16(B\rho)\sin[\pi(\pm 2\nu_{d,x} - \nu_x)]} e^{-i[\pm 2\psi_{d,x}(\bar{s})-\psi_x(\bar{s})]-\pi i(\pm 2\nu_{d,x}-\nu_x)\mathrm{sgn}(s-\bar{s})}$$

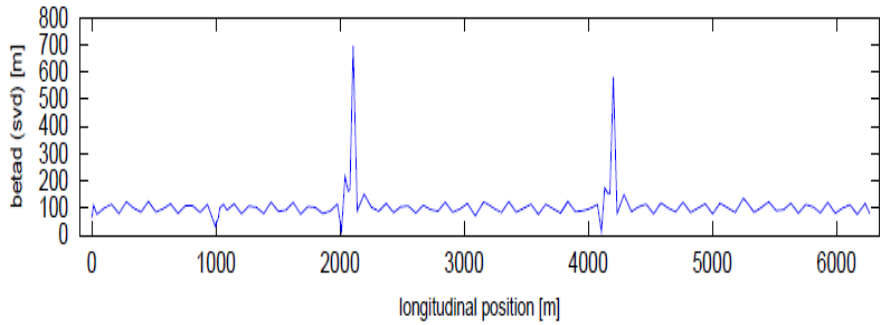
MIA Applied to the AC Dipole Excitation

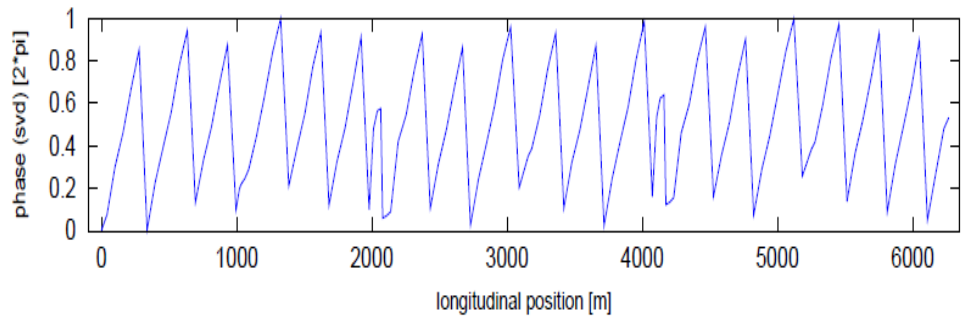
- Does MIA have an advantage for the AC dipole excitation?
- Residual modes for MIA.

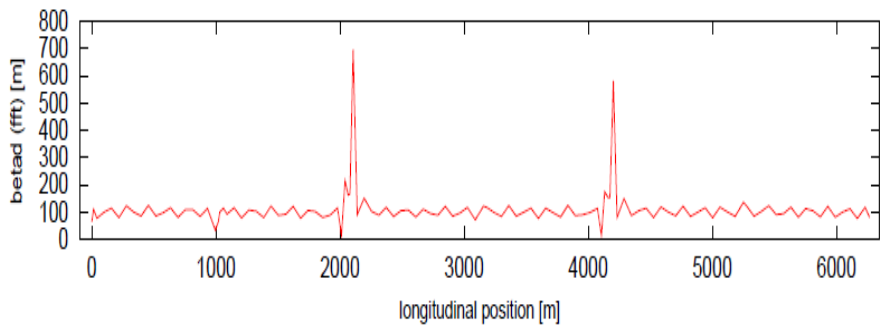


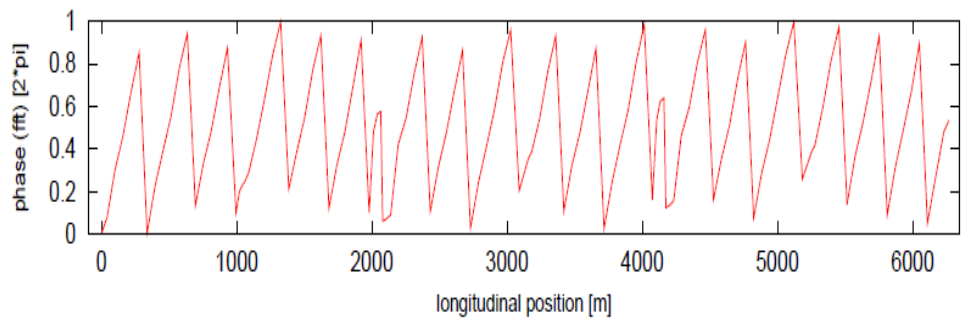
Beta and Phase: MIA vs. Fourier Analysis

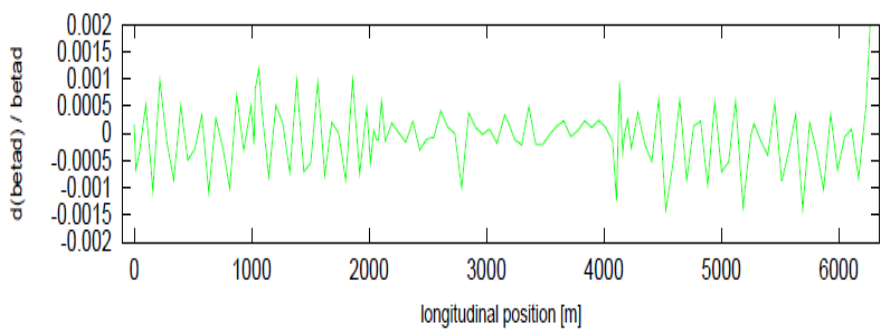
- Basically the same result for both techniques.

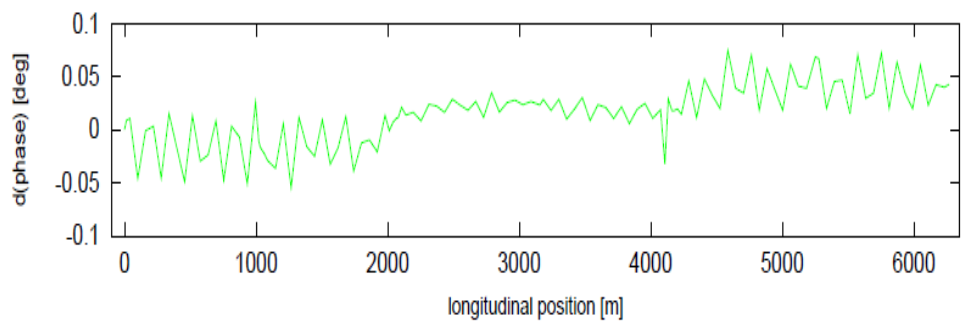












Budget plan for FY2010

LARP

- $60k for FY2010
  - Continue supporting the BNL/LARP post-doc: $35k
  - Travel expense for participating the commissioning: $20k
  - Miscellaneous like hardware: $5k

BROOKHAVEN NATIONAL LABORATORY

Plan for FY2010 and beyond

LARP

- FY2010-FY2011
  - Participate LHC AC dipole commissioning
  - Participate commissioning of AC dipole applications in beam dynamics
    - Measure optics
    - Linear gradient error correction
- Beyond FY2011
  - Participate accelerator physics experiment of applying ac dipole in non-linear beam dynamics studies
  - Design dedicated high Q ac dipole system with tuning range of ± 0.01 if the technique is demonstrated at BNL

BROOKHAVEN NATIONAL LABORATORY

LARP

Thank you!

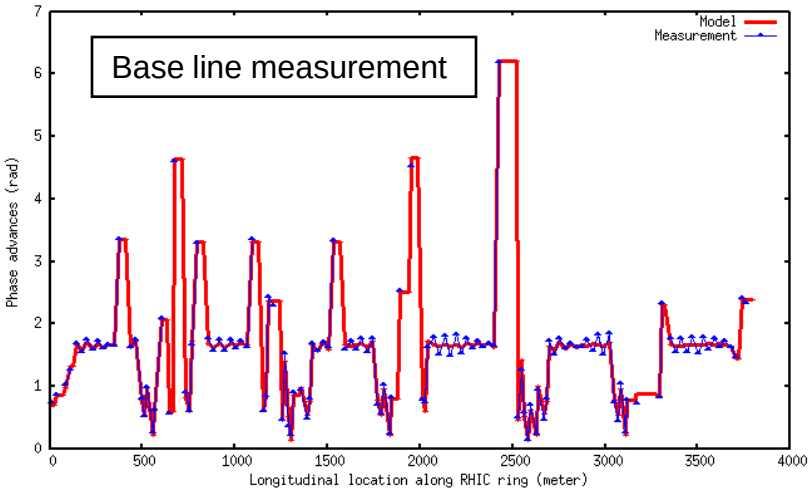
BROOKHAVEN NATIONAL LABORATORY

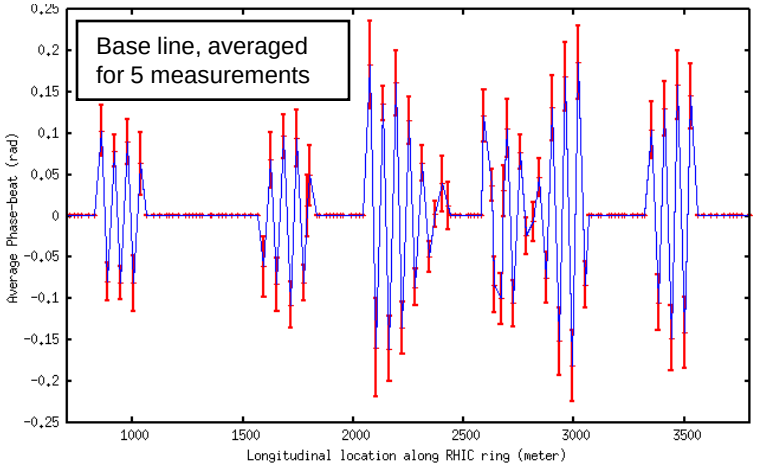
RHIC ac dipole optic data - 2008

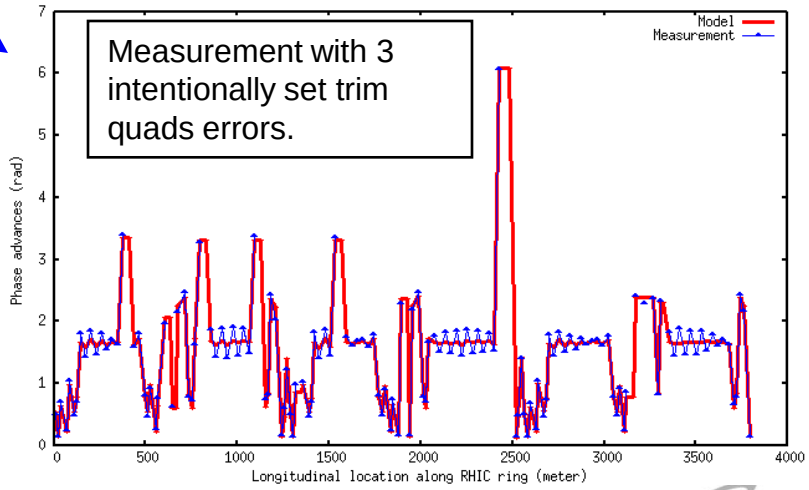
In order to verify the algorithm, known gradient errors have been intentionally set to a few trim quads (knobs).

After subtracting the unknown background gradient errors, these trim quads errors were expected to show up through data analysis.

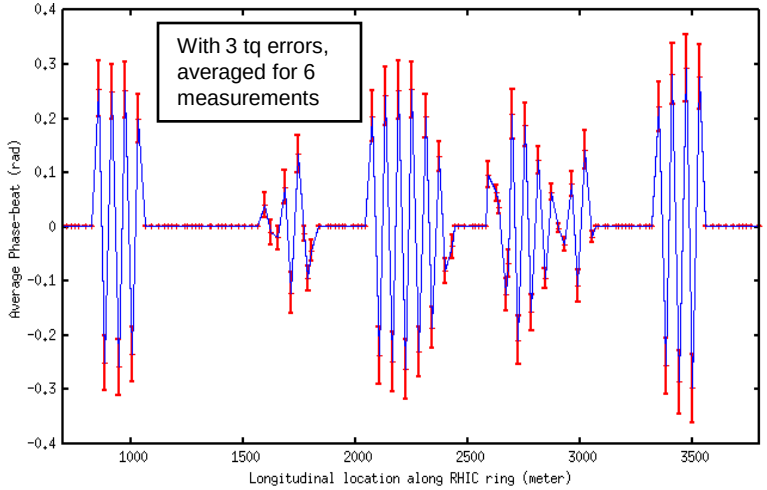
Typical fitting results of the base line measurement and measurement with trim quads errors.

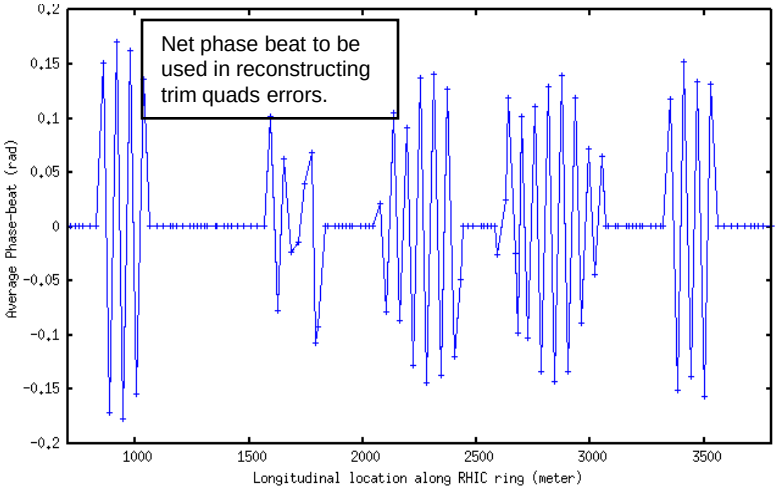






RHIC ac dipole optic data – 2008 (Continued)





- We analyzed 5 sets of base line measurement and 6 sets of measuremtns with known trim quads errors.

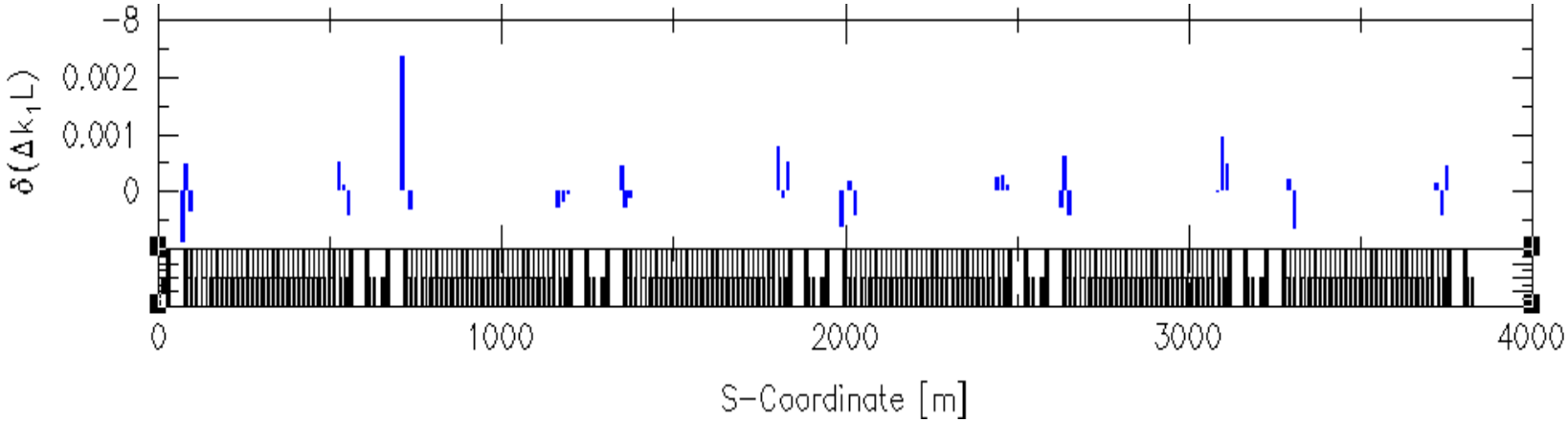
- After calculating the average and variance of both cases, we dropped sections with large variances from measurement to measurement (compared to their average values).

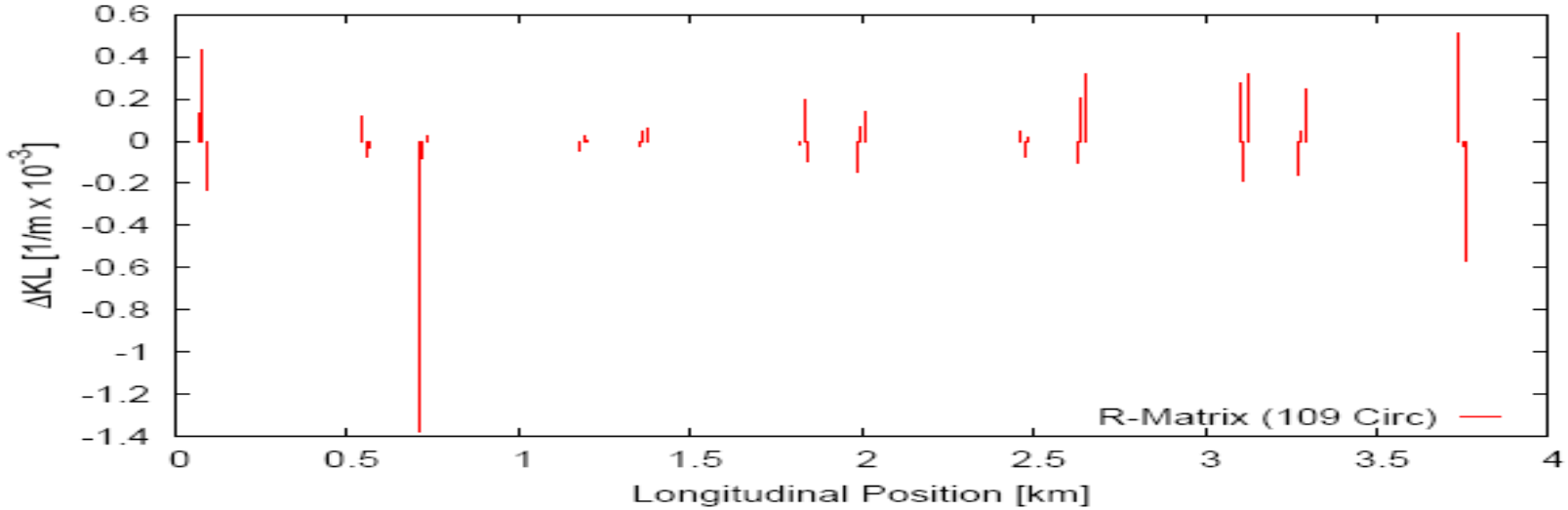
  As a result, we only used data from about 60 bpms to obtain trim quads strength.

- Although we only have 36 trim quads and in principal constraints more than 36 can over determine their strength, more constraints (or available bpm data) tend to increase the effectiveness of the knobs and reduce their vulnerabilities to noises.

RHIC ac dipole optics data – 2007

Analyzed by Mei and Rama

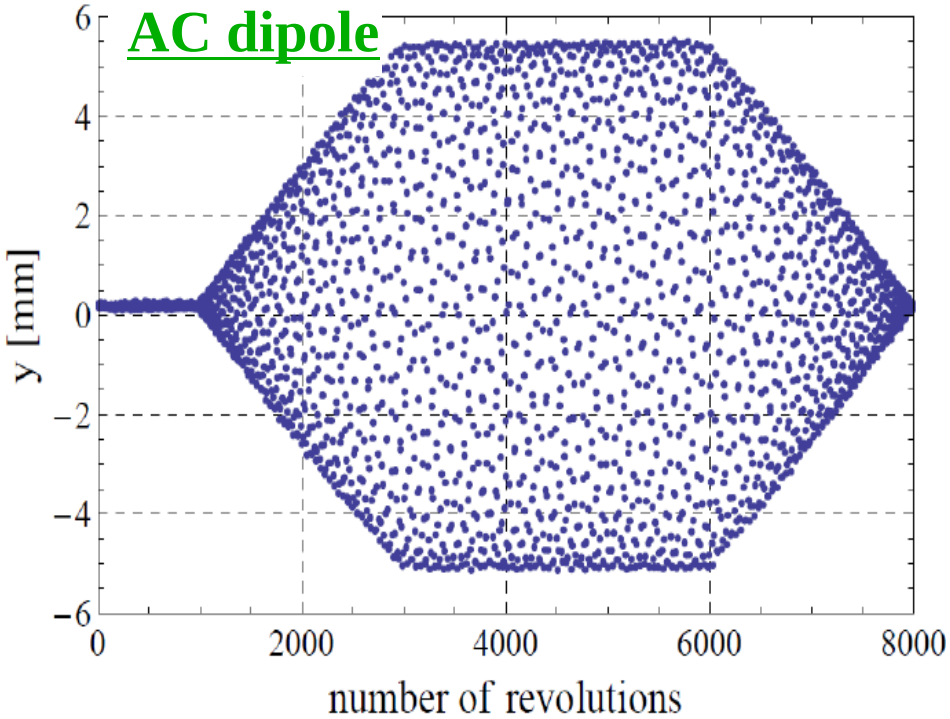


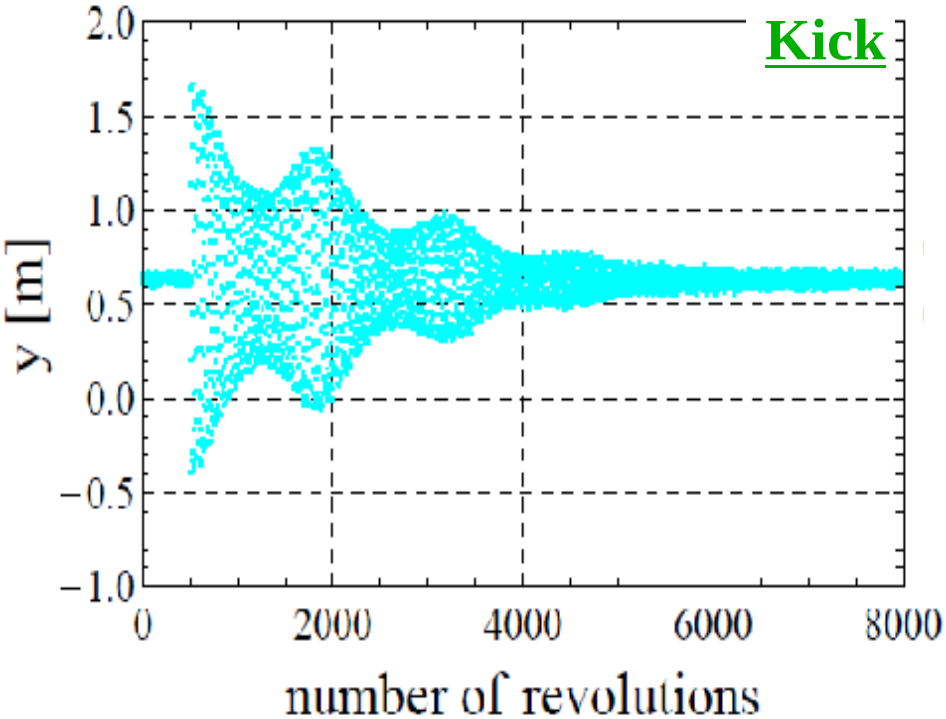


Introduction to the AC Dipole

- An oscillating dipole field (Qd ~ Q) drives the beam.
- Optics measurements from turn-by-turn data.
- 4 AC dipoles in LHC, 2 in RHIC, and 1 in the Tevatron.
- Advantages:

1. No decoherence
2. No emittance growth
3. Large excitation (in many cases larger than kicker/pinger)





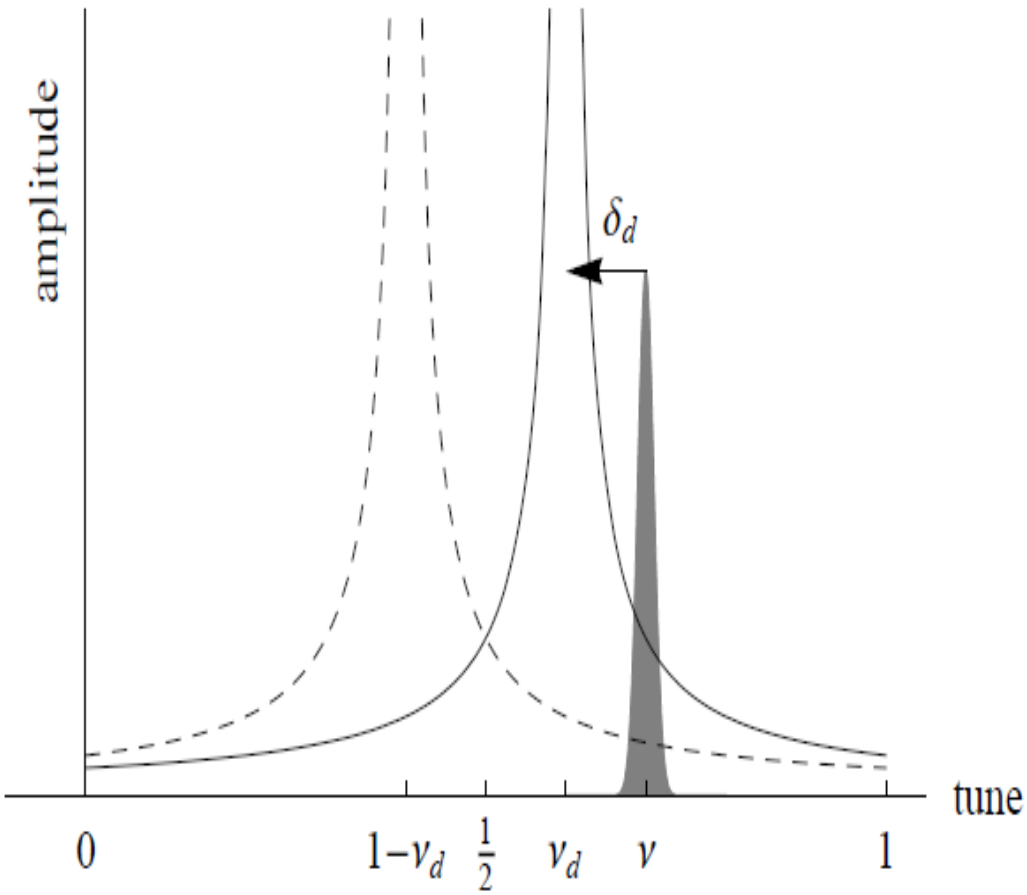
Difference & Sum Resonances of Driven Motion

$$x_d(n;s) = \frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}}{4(B\rho)\sin(\pi(Q_d-Q))}\cos[2\pi Q_d n + \psi(s) - \psi(s_{\rm ac}) + \pi(Q_d - Q)\,{\rm sgn}(s-s_{\rm ac}) + \chi]$$
$$- \frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})\beta(s)}}{4(B\rho)\sin(\pi(Q_d+Q))}\cos[2\pi Q_d n - \psi(s) + \psi(s_{\rm ac}) + \pi(Q_d + Q)\,{\rm sgn}(s-s_{\rm ac}) + \chi]$$

$$\lambda = \frac{\sin[\pi(Q_d - Q)]}{\sin[\pi(Q_d + Q)]} \simeq \frac{\pi\delta}{\sin(2\pi Q)}$$

Sum resonance produces artificial beta-beat and phase-beat:

- Amplitude of the beta-beat: 2λ (~6% for $|\delta| = 0.01$)
- Amplitude of the phase-beat: λ (~2 deg $|\delta| = 0.01$)



A Parametrization of Driven Motion

$$x_d(n;s) = A_d\sqrt{\beta_d(s)}\cos[2\pi Q_d n + \psi_d(s) - \psi_d(s_{\rm ac}) + \chi]$$

$$A_d = \frac{(B\ell)_{\rm ac}\sqrt{\beta(s_{\rm ac})(1-\lambda^2)}}{4(B\rho)\sin[\pi(Q_d - Q)]}$$

$$\frac{\beta_d(s)}{\beta(s)} = \frac{1+\lambda^2 - 2\lambda\cos[2\psi(s) - 2\psi(s_{\rm ac}) - 2\pi Q\,{\rm sgn}(s-s_{\rm ac})]}{1-\lambda^2}$$

$$\tan[\psi_d(s) - \psi_d(s_{\rm ac}) - \pi Q_d\,{\rm sgn}(s-s_{\rm ac})] = \frac{\tan(\pi Q_d)}{\tan(\pi Q)}\tan[\psi(s) - \psi(s_{\rm ac}) - \pi Q\,{\rm sgn}(s-s_{\rm ac})]$$

$$\psi_d(s) = \int_0^s \frac{d\bar{s}}{\beta_d(\bar{s})}\,, \quad \alpha_d(s) = -\frac{1}{2}\frac{d\beta_d(s)}{ds}\,, \quad \gamma_d(s) = \frac{1+\alpha_d(s)^2}{\beta_d(s)}$$

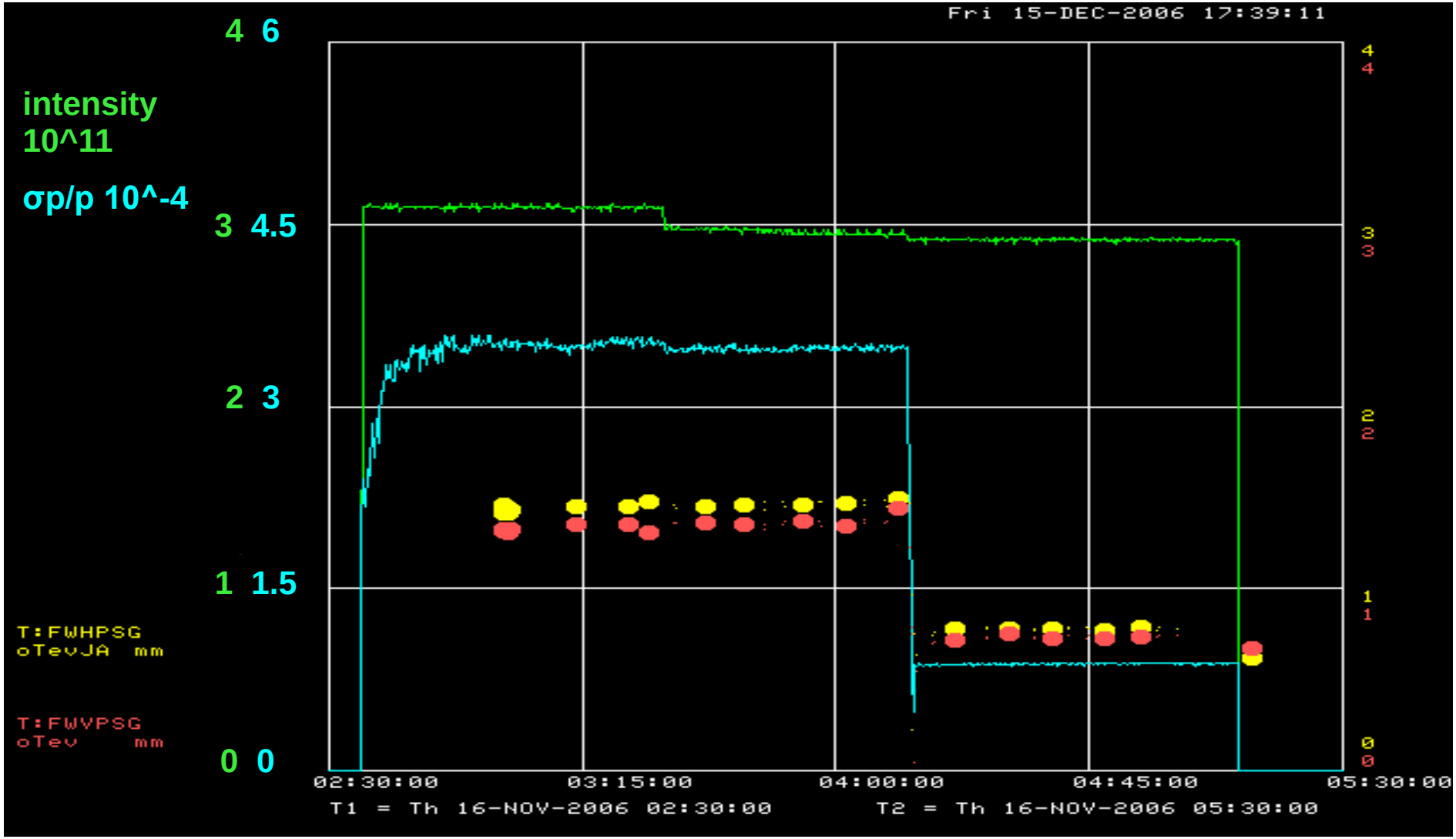
$$\gamma_d^2 x_d^2 + 2\alpha_d x_d x_d' + \beta_d x_d'^2 = A_d^2$$

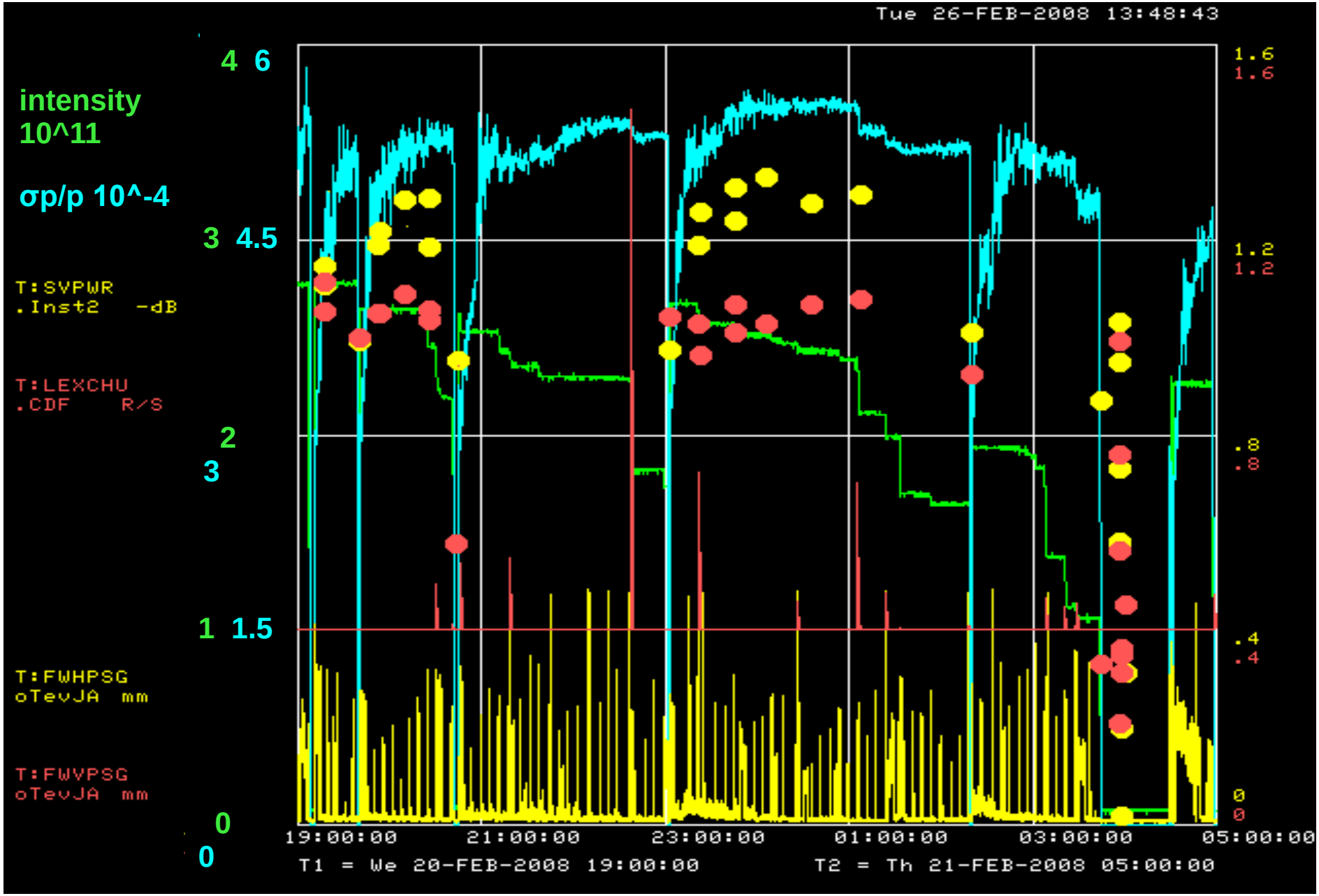
On the first order of λ (or δ)

$$\frac{\beta_d(s)}{\beta(s)} \simeq 1 - 2\lambda\cos[2\psi(s) - 2\psi(s_{\rm ac}) - 2\pi Q\,{\rm sgn}(s-s_{\rm ac})]$$

$$\psi_d(s) - \psi(s) \simeq \lambda\sin[2\psi(s) - 2\psi(s_{\rm ac}) - 2\pi Q\,{\rm sgn}(s-s_{\rm ac})] + \lambda\sin[2\psi(s_{\rm ac}) - 2\pi Q] + 2\pi\delta\Theta(s-s_{\rm ac})$$

A Typical Operation of an AC Dipole in the Tevatron



- $|\delta|$ must be larger than 0.015 @ 150 GeV and 0.01 @ 980 GeV
- So far the Tevatron AC dipole is used ~200 times and no abort or quench.

A Not So Typical Operation of an AC Dipole