Resonance driving term analysis

Studies on Lattice Calibration With Frequency Analysis of Betatron Motion

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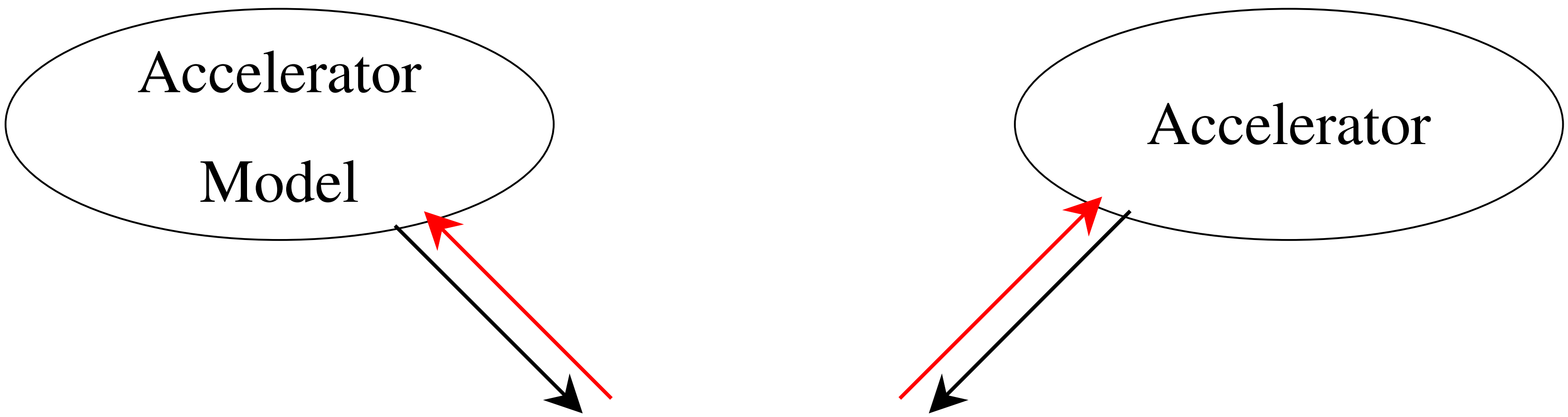
Most of the material in this lecture from

Ricardo Bartolini (Diamond),

Frank Schmidt, R. Tomas (CERN) , …

- Outline:
  - ❖ **Introduction**
    - **NAFF**
    - **perturbative theory of betatron motion**
    - **SVD fit of lattice parameters**
  - ❖ **DIAMOND Spectral Lines Analysis**
    - **Linear Model**
    - **Nonlinear Model**

Real Lattice to Model Comparison



- Closed Orbit Response Matrix (LOCO–like)
- Frequency Map Analysis
- Frequency Analysis of Betatron Motion (resonant driving terms)

Frequency Analysis of Betatron Motion and Lattice Model Reconstruction (1)

Accelerator Model

- tracking data at all BPMs
- spectral lines from model (NAFF)
- build a vector of Fourier coefficients

Accelerator

- beam data at all BPMs
- spectral lines from BPMs signals (NAFF)
- build a vector of Fourier coefficients

$$\overline{A} = \left(a_1^{(1)} \quad \ldots \quad a_{NBPM}^{(1)} \quad \varphi_1^{(1)} \quad \ldots \quad \varphi_{NBPM}^{(1)} \quad a_1^{(2)} \quad \ldots \quad a_{NBPM}^{(2)} \quad \varphi_1^{(2)} \quad \ldots \quad \varphi_{NBPM}^{(2)} \quad \ldots \right)$$

Define the distance between the two vector of Fourier coefficients

$$\chi^2 = \sum_k \left(A_{Model}(j) - A_{Measured}(j) \right)^2$$

Least Square Fit (SVD) of accelerator parameters θ

to minimize the distance χ^2 of the two Fourier coefficients vectors

- Compute the "Sensitivity Matrix" M $\qquad \Delta\overline{A} = M\overline{\theta}$
- Use SVD to invert the matrix M $\qquad M = U^T W V$
- Get the fitted parameters $\qquad \overline{\theta} = (V^T W^{-1} U)\,\Delta\overline{A}$

MODEL → TRACKING → NAFF →

Define the vector of Fourier Coefficients – Define the parameters to be fitted

SVD → CALIBRATED MODEL

DIAMOND Layout

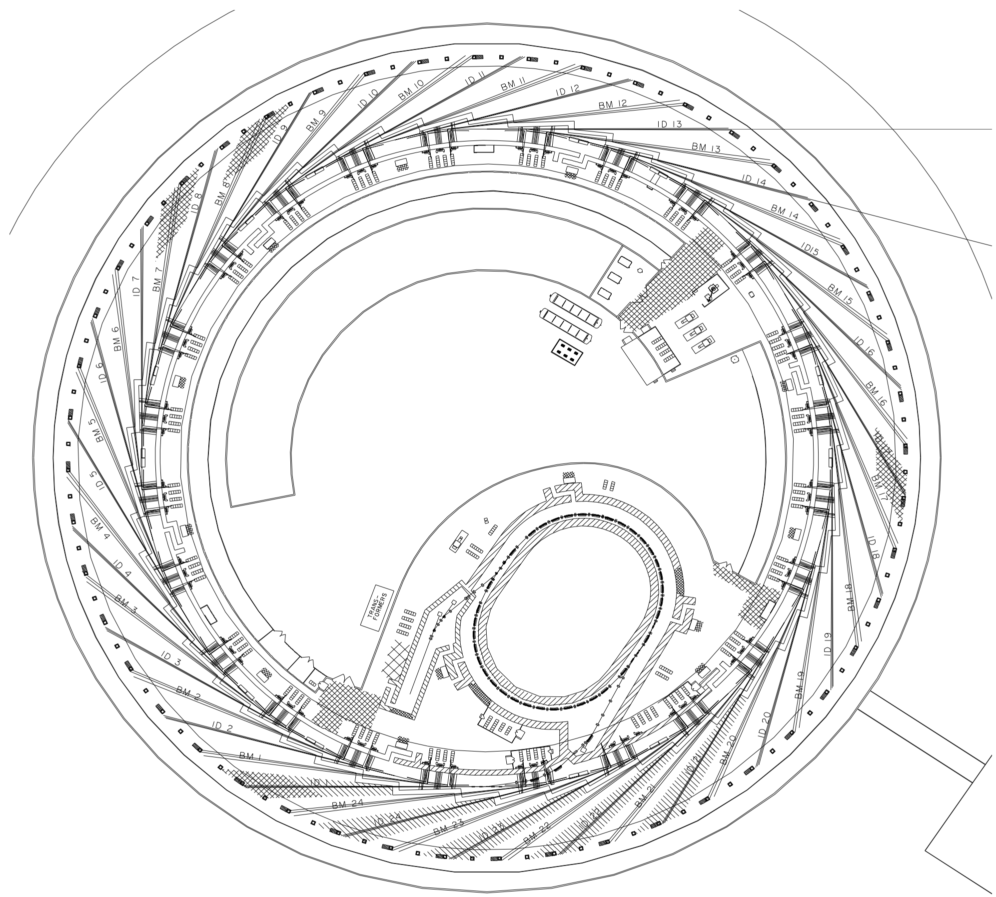
Main parameters:

100 MeV Linac

3 GeV Booster (158.4 m)

3 GeV Storage Ring (561.6 m)

- **24 cell DBA lattice**
- **2 + 1 SC RF cavities**
- **18 straight for ID (5 m)**
- **6 long straights (8 m)**



Commissioning end 2006

NAFF algorithm – J. Laskar (1988)
(Numerical Analysis of Fundamental Frequencies)

Given the quasi–periodic time series of the particle orbit (x(n); p_x(n)),

- Find the main lines with the previous technique for tune measurement

  $\Rightarrow \nu_1$ frequency, a_1 amplitude, ϕ_1 phase;

- build the harmonic time series

$$z_1(n) = a_1 e^{i\phi_1} e^{2\pi i \nu_1 n}$$

- subtract form the original signal
- analyze again the new signal z(n) – z_1(n) obtained

The decomposition $z(n) = \sum_{k=1}^{n} a_k e^{i\phi_k} e^{2\pi i \nu_k n}$ **allows the**

Measurement of Resonant driving terms of non linear resonances

The quasi periodic decomposition of the orbit

$$x(n) - ip_x(n) = \sum_{k=1}^{n} c_k e^{2\pi i \nu_k n} \qquad c_k = a_k e^{i\phi_k}$$

can be compared to the perturbative expansion of the non linear betatron motion

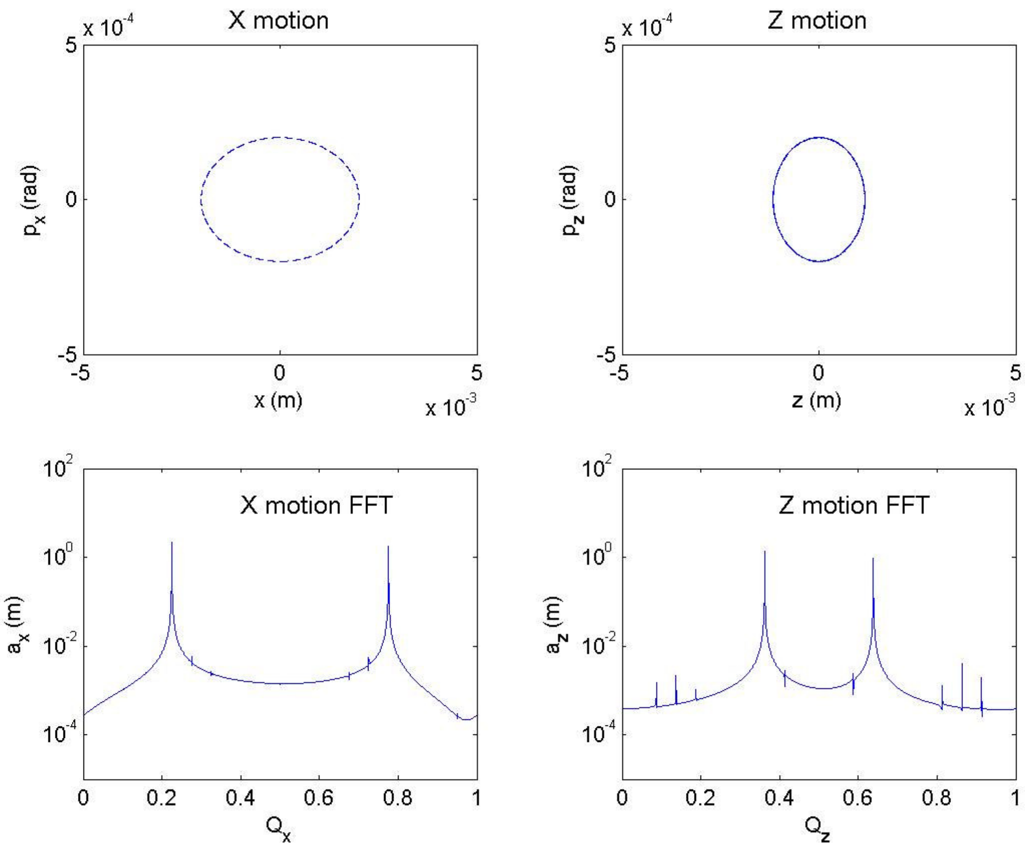
$$x(n) - ip_x(n) = \sqrt{2I_x}\, e^{i(2\pi Q_x n + \psi_0)} +$$

$$-2i \sum_{jklm} j s_{jklm} (2I_x)^{\frac{j+k-1}{2}} (2I_y)^{\frac{l+m}{2}} e^{i\left[(1-j+k)(2\pi Q_x n + \psi_{x0}) + (m-l)(2\pi Q_y n + \psi_{y0})\right]}$$

Each resonance driving term s_{jklm} contributes to the Fourier coefficient of a well precise spectral line

$$\nu(s_{jklm}) = (1 - j + k)Q_x + (m - l)Q_y$$

Spectral Lines for DIAMOND low emittance lattice (.2 mrad kick in both planes)

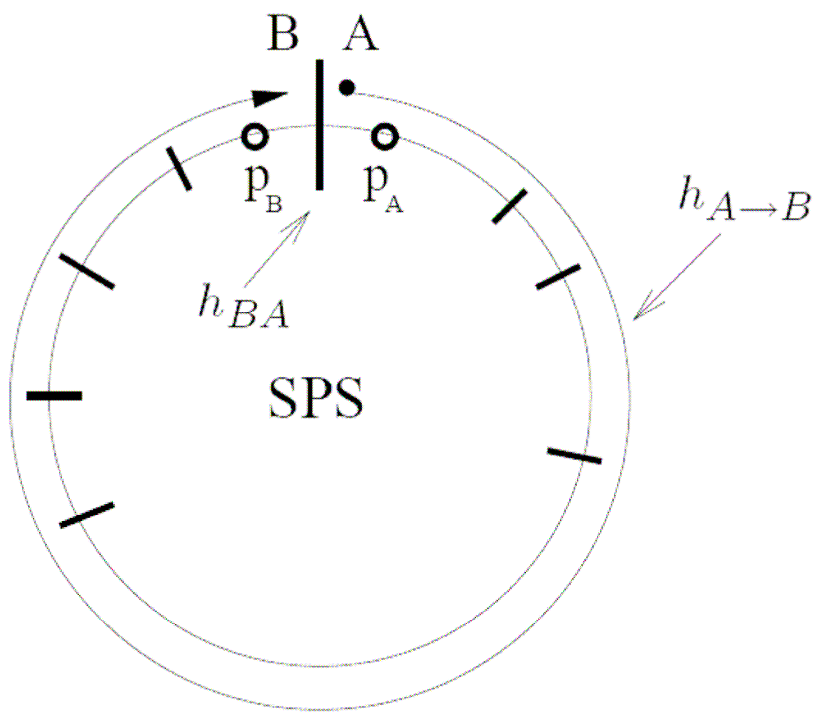


Spectral Lines detected with NAFF algorithm

e.g. Horizontal:

• (1, 0)	$1.10\ 10^{-3}$	horizontal tune
• (0, 2)	$1.04\ 10^{-6}$	$Q_x - 2\ Q_z$
• (–3, 0)	$2.21\ 10^{-7}$	$4\ Q_x$
• (–1, 2)	$1.31\ 10^{-7}$	$2\ Q_x + 2\ Q_z$
• (–2, 0)	$9.90\ 10^{-8}$	$3\ Q_x$
• (–1, 4)	$2.08\ 10^{-8}$	$2\ Q_x + 4\ Q_z$

Longitudinal Variation of Driving Terms

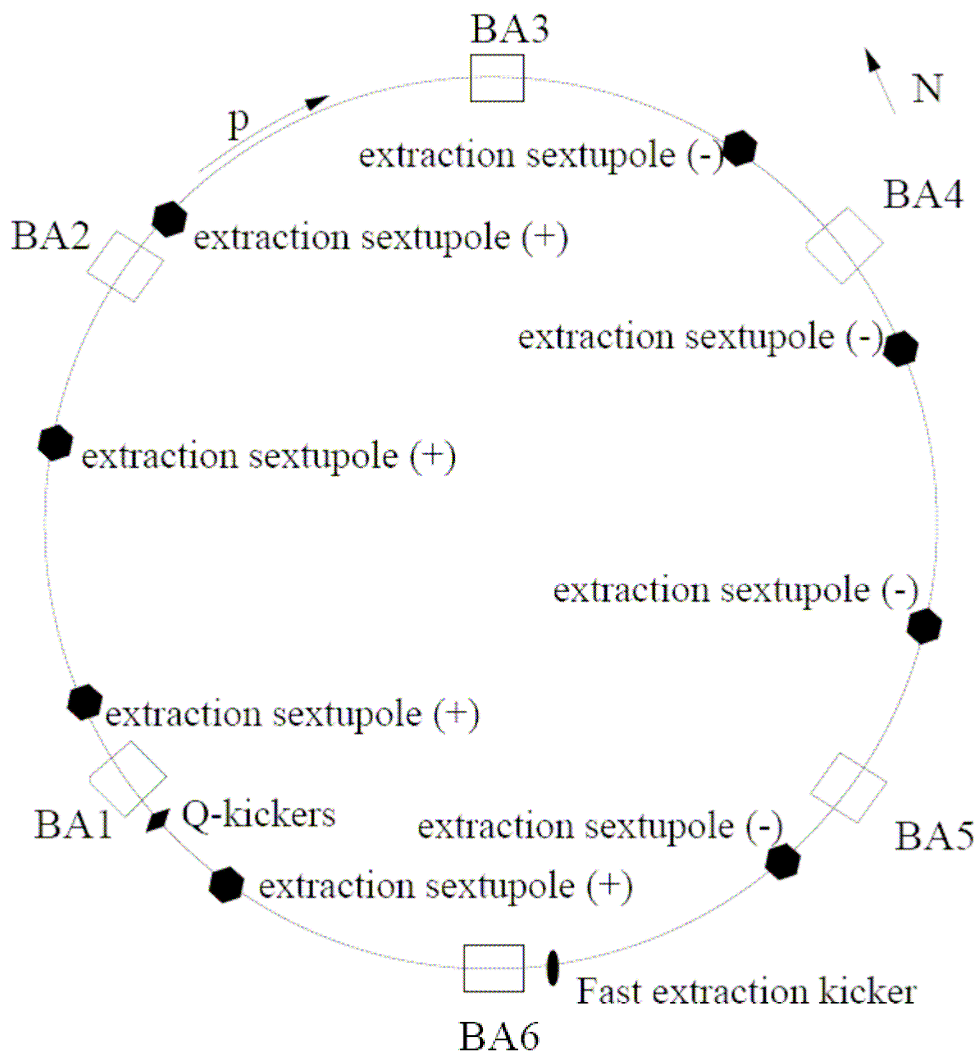


$$\left.\begin{array}{l} h_A = h_{A\to B} \circ h_{BA} \\ h_B = h_{BA} \circ h_{A\to B} \end{array}\right\} h_A \neq h_B$$

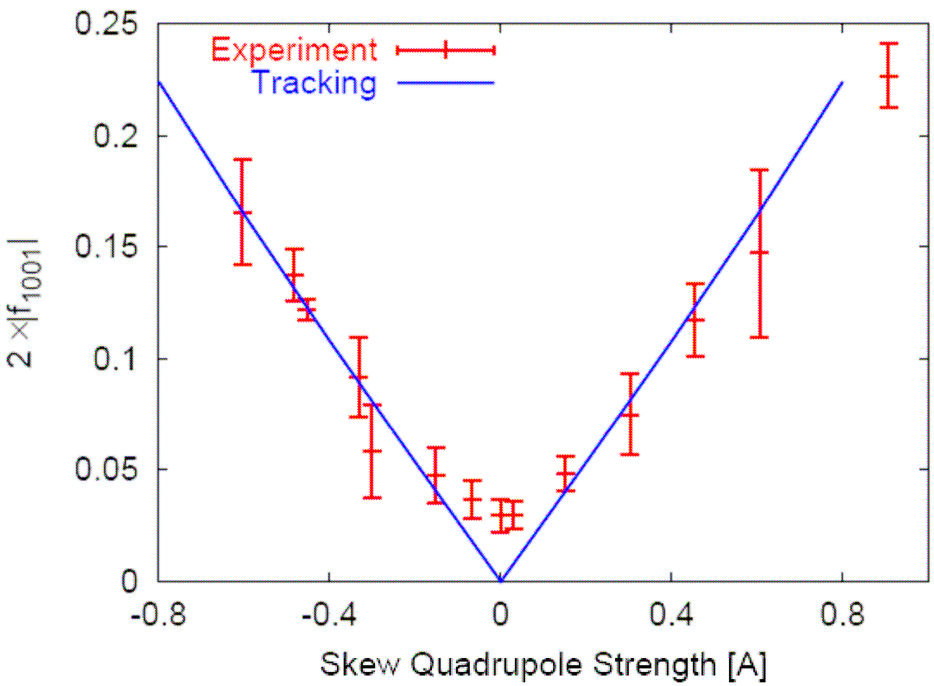
$\Rightarrow$ Amplitude of Driving Terms not the same

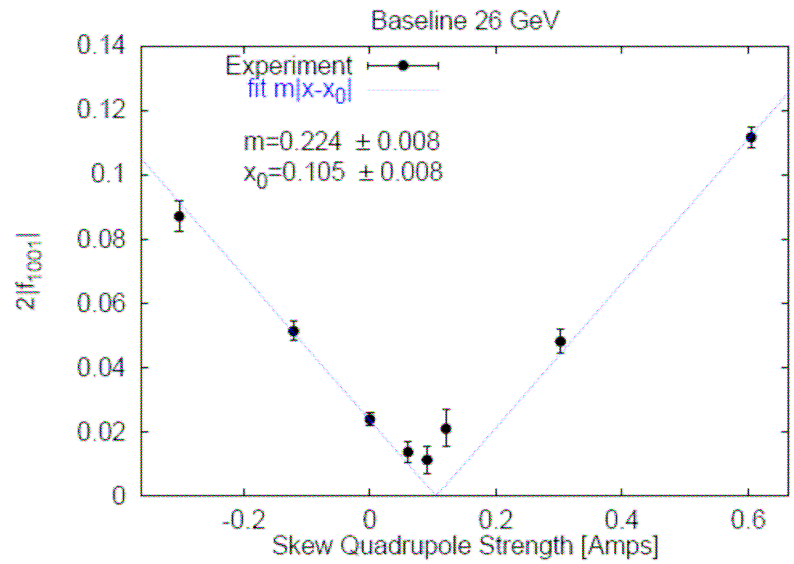
$\Rightarrow$ Amplitude constant between lattice errors

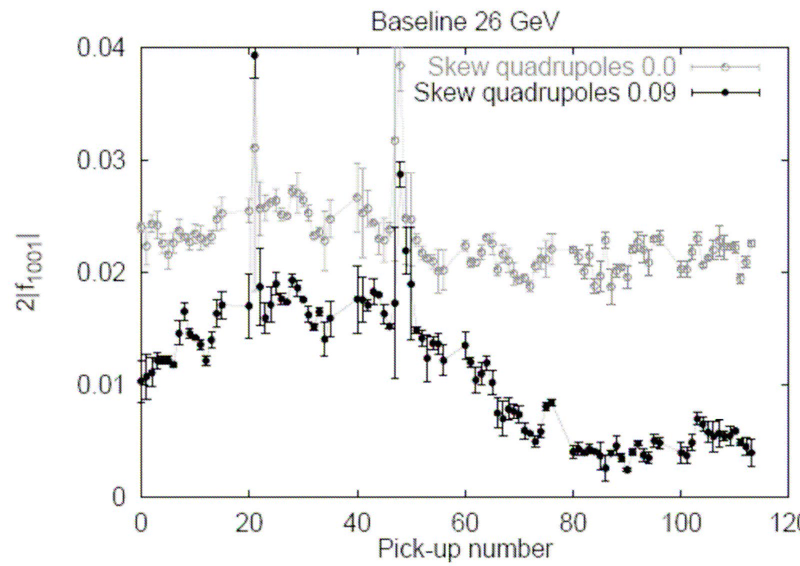
Early (2000-2002) Work: SPS experiments



Linear Coupling in SPS

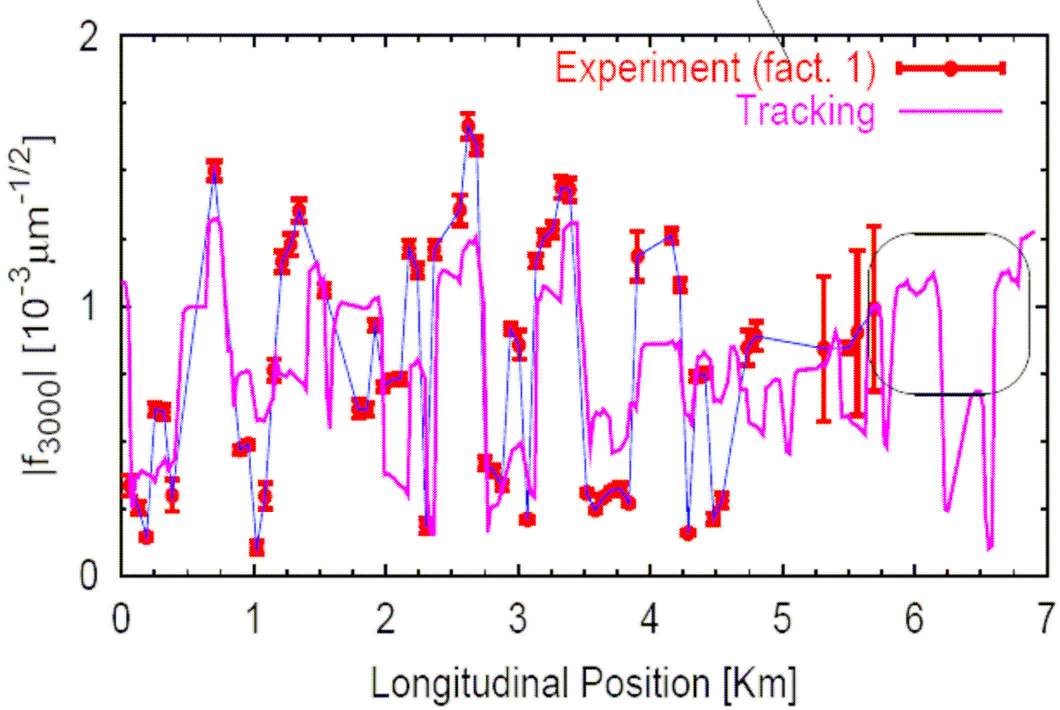






Sextupole Driving Terms

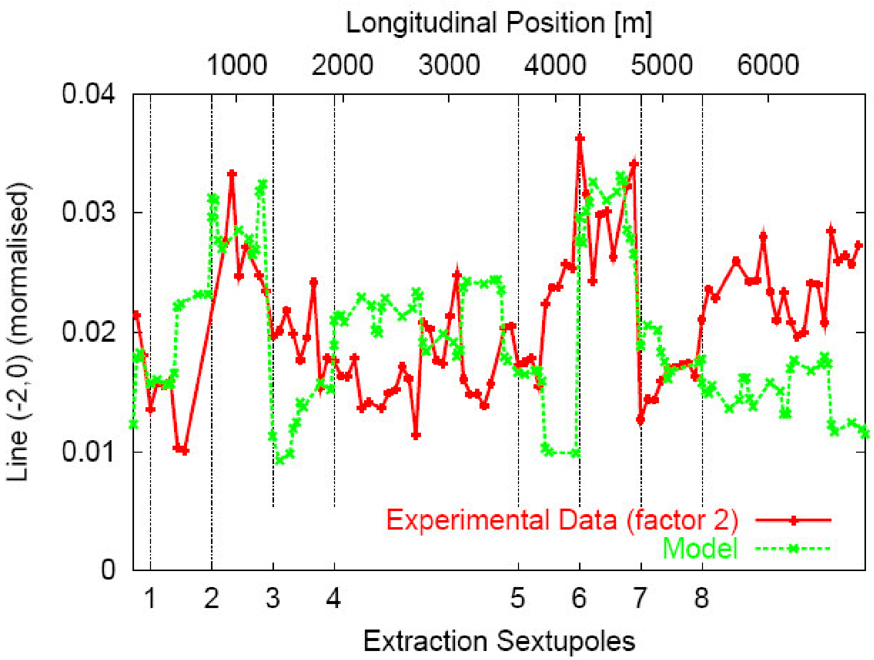
Bare SPS, Qx=26.62 (No decoherence).



$\Rightarrow$ Local discrepancies may be due to unknown sextupole sources.

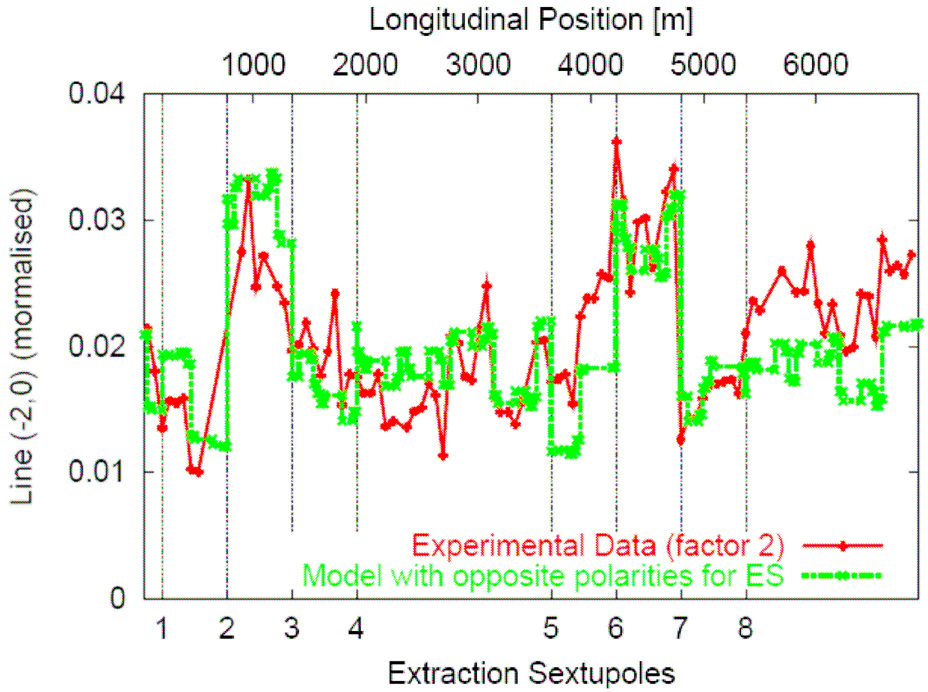
Sextupole Driving Terms with Extraction Sext.

The resonance (3,0) introduces the spectral line (-2,0).



⇒ We have a problem!

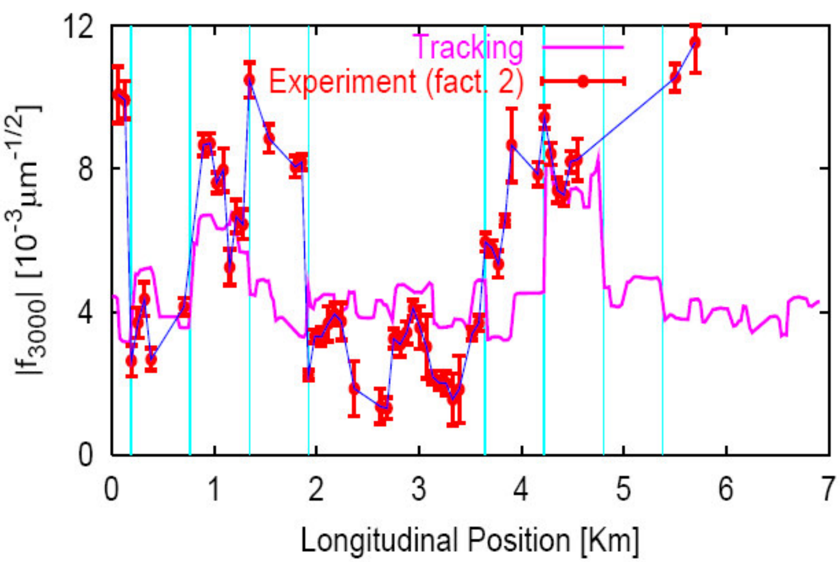
Change polarities of the extraction sextupoles?



Hardware checks confirmed that these sextupoles had opposite polarities.

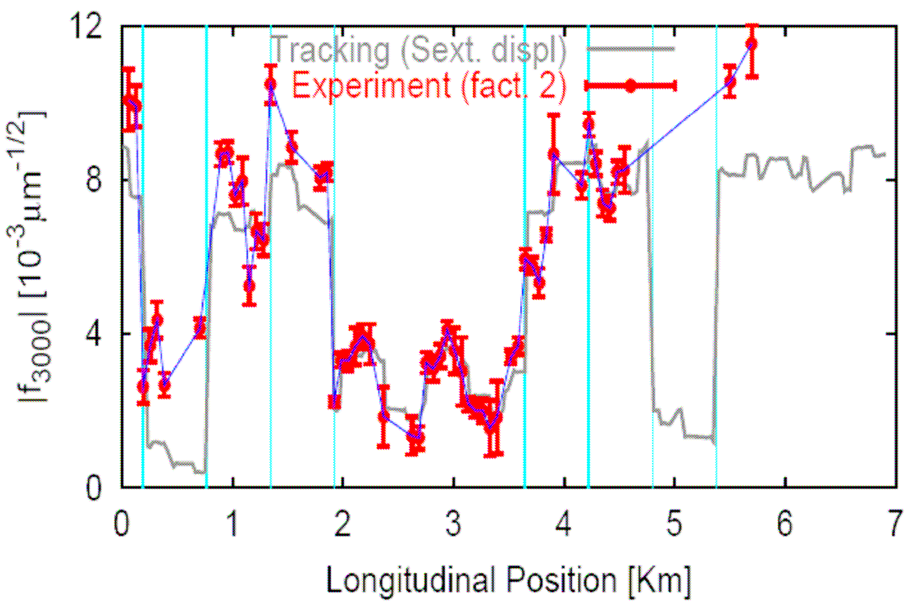
Sextupole Driving Terms with Extraction Sext.

Extraction Sextupoles powered to ++++−−−−30 A.
Data fully decohered ⇒ Line reduced by a factor 2.



⇒Large discrepancies: We have a problem!

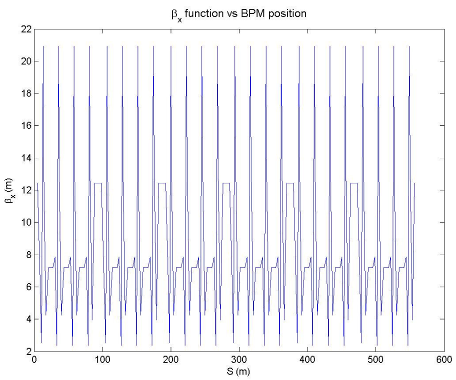
The closed orbit as measured from pick-ups is introduced at the extraction sextupoles in the model.

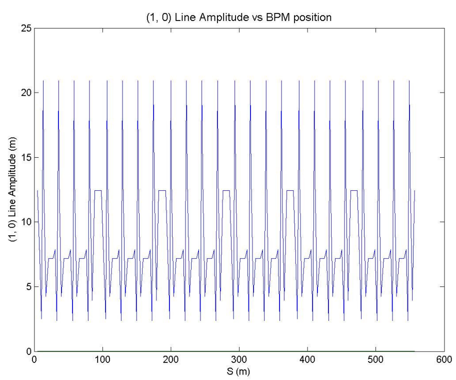


⇒ Improvement due to beta−beating and phase differences in the model.

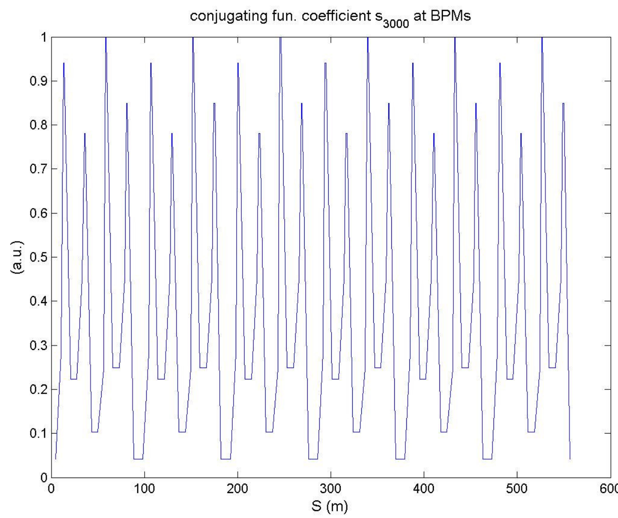
Amplitude of Spectral Lines for low emittance DIAMOND lattice computed at all the BPMs

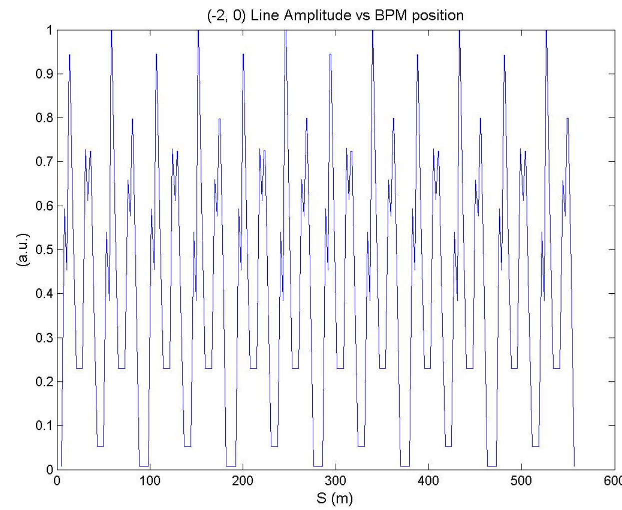
Main spectral line (Tune Q_x)





(-2, 0) spectral line: resonance driving term h_{3000} ($3Q_x = p$) at all BPMs





- The amplitude of the tune spectral line replicates the β functions
- The amplitude of the (– 2, 0) show that third order resonance is well compensated within one superperiod. Some residual is left every two cells ($5\pi/2$ phase advance)

Example: DIAMOND with random misalignments (100 μm r.m.s) in chromatic sextupoles to generate linear coupling

The coupled linear motion in each plane can be written in terms of the coupling matrix

$$C = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}$$

e.g. for the horizontal motion

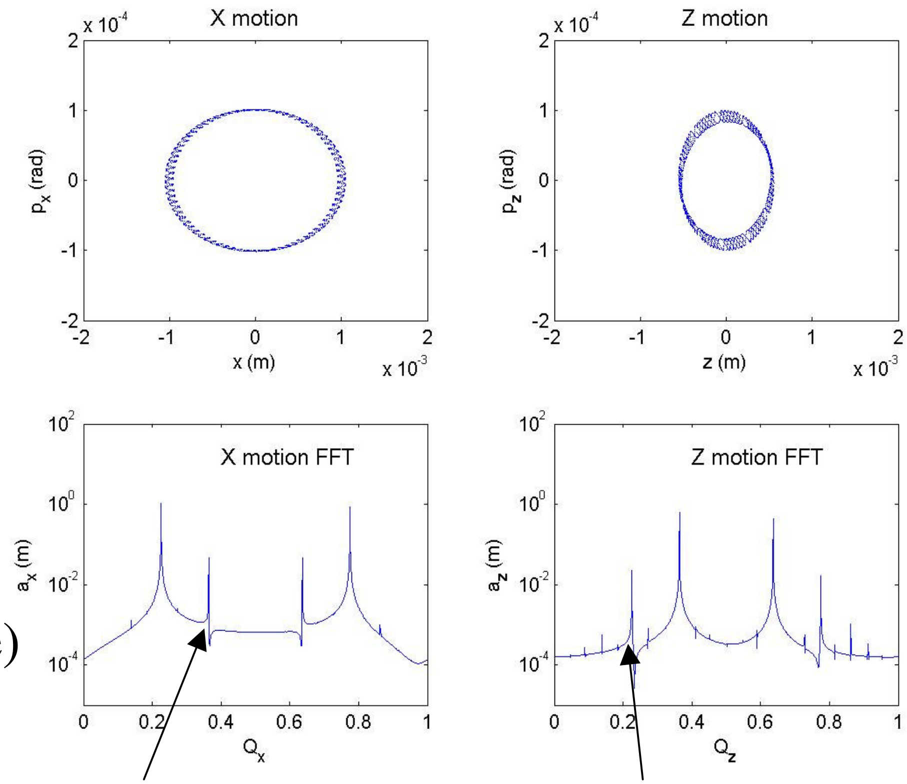
$$\zeta_x = x - ip_x = a_1 e^{i(\phi_u+\delta_u)} + a_2 e^{-i(\phi_u+\delta_u)} +$$

$$+ a_3 e^{i(\phi_v+\delta_v)} + a_4 e^{-i(\phi_v+\delta_v)}$$

a_3 and a_4 depend linearly on c_{ij}

- two frequencies (the H tune and V tune)
- no detuning with amplitude

0.1 mrad kick in both planes



Tune Z in horizontal motion

Tune X in vertical motion

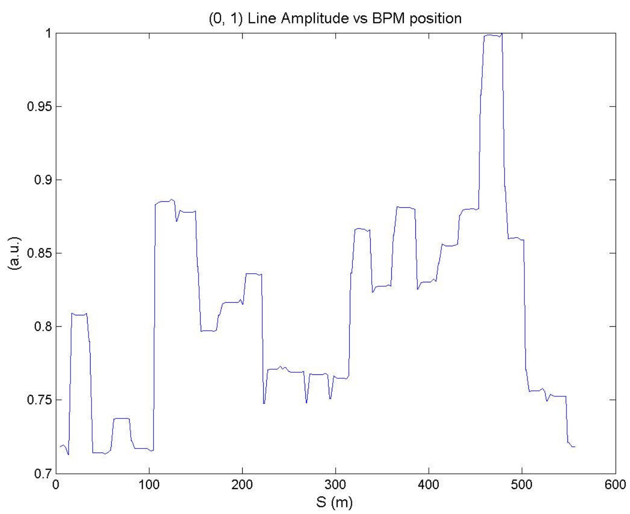
(0,1) spectral line for low emittance DIAMOND lattice computed at all the BPMs (V misalignment errors added to chromatic sextupoles)

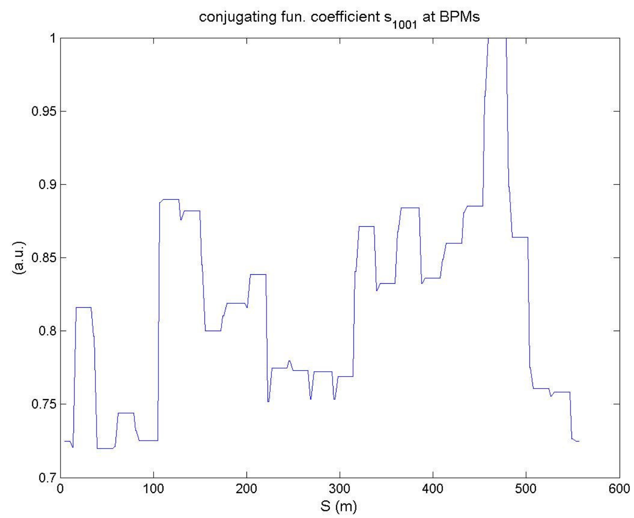
$$h_{1001p} = \frac{1}{2\pi}\int_0^{2\pi R} a_2(s)\left(\frac{\beta_x}{2}\right)^{1/2}\left(\frac{\beta_z}{2}\right)^{1/2} e^{i(W_x(s)-W_z(s))-i\frac{ps}{R}} ds$$

$$s_{1001p} = \frac{ih_{1001p}}{Q_x - Q_z + p} \qquad s_{1001}(s) = \frac{1}{2\pi R}\sum_{p=-\infty}^{\infty} s_{1001p} e^{ips/R}$$

The resonance driving term h_{1001} contributes to the (0, 1) spectral line in horizontal motion

from analytical formula





from spectral line

The amplitude of the (0, 1) spectral line replicates well the s dependence of the difference resonance $Q_x - Q_z$ driving term

DIAMOND Spectral Lines Analysis

❖ Horizontal Misalignment of sextupoles (β – beating)

❖ Vertical Misalignment of sextupoles (linear coupling)

❖ Gradient errors in sextupoles (non linear resonances)

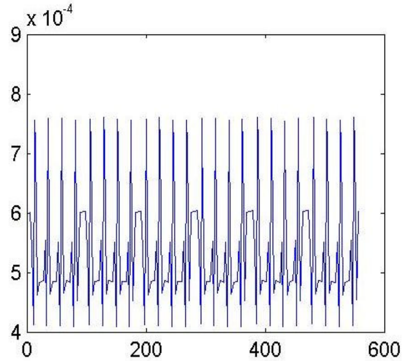
Horizontal misalignment of a set of 24 sextupoles with 100 μm rms (β - beating correction)

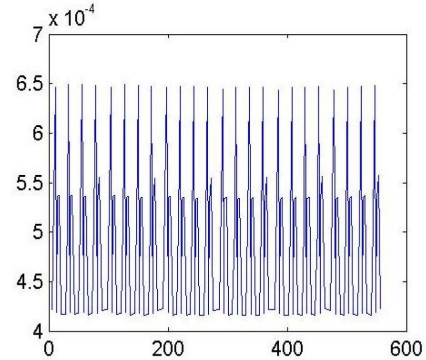
The generated normal quadrupole components introduce a β - beating.

- we build the vector of Fourier coefficients of the horizontal and vertical tune line
- we use the horizontal misalignments as fit parameters

H tune line

(no misalignments)



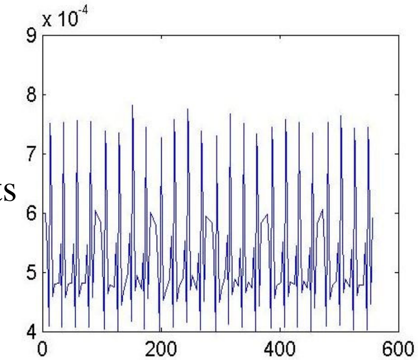


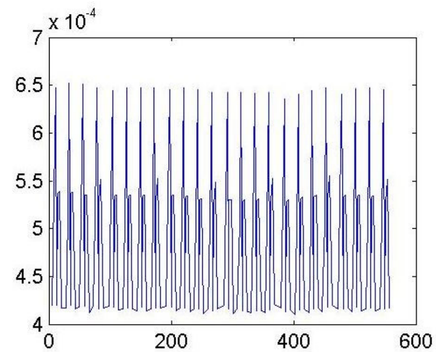
V tune line

(no misalignments)

H tune line

with misalignments





V tune line

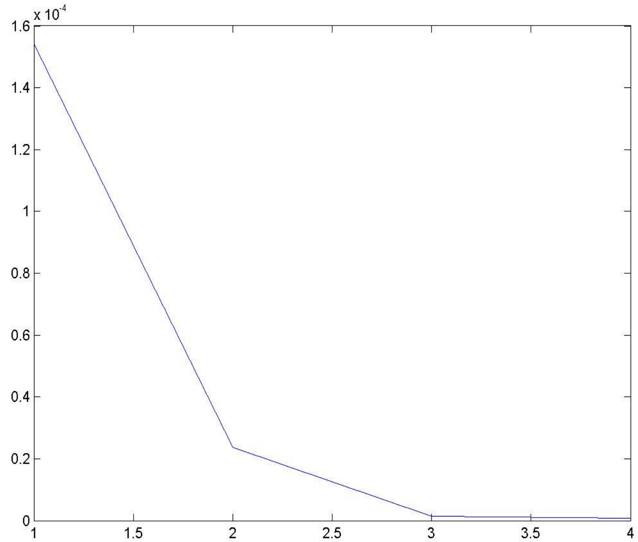
with misalignments

SVD on sextupoles horizontal misalignments

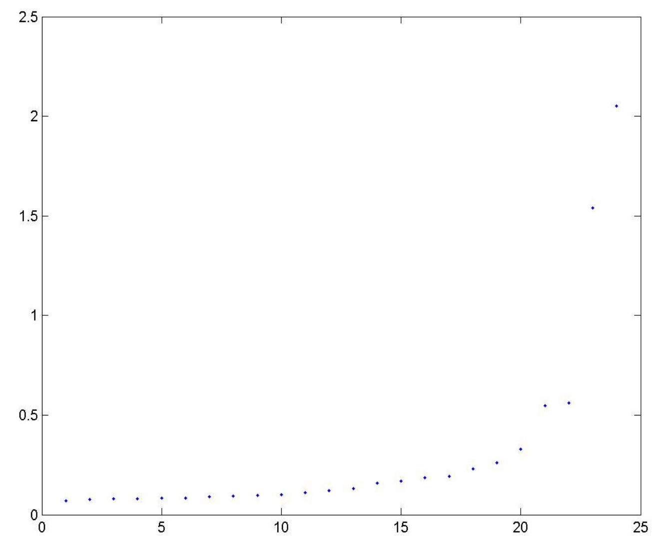
We build the vector $\overline{A} = \left(a_1^{H(1,0)} \quad \ldots \quad a_{NBPM}^{H(1,0)} \quad a_1^{V(0,1)} \quad \ldots \quad a_{NBPM}^{V(0,1)} \right)$

containing the amplitude of the tune lines in the two planes at all BPMs

We minimize the sum $\chi^2 = \sum_j \left(A_{Model}(j) - A_{Measured}(j) \right)^2$



χ^2 as a function of the iteration number

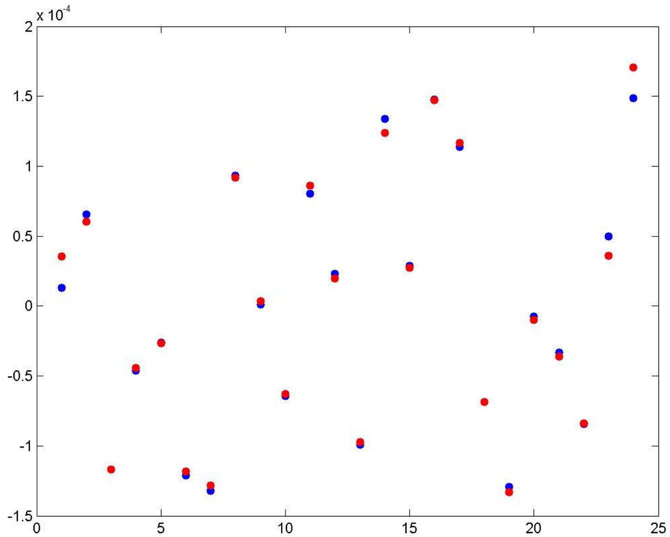


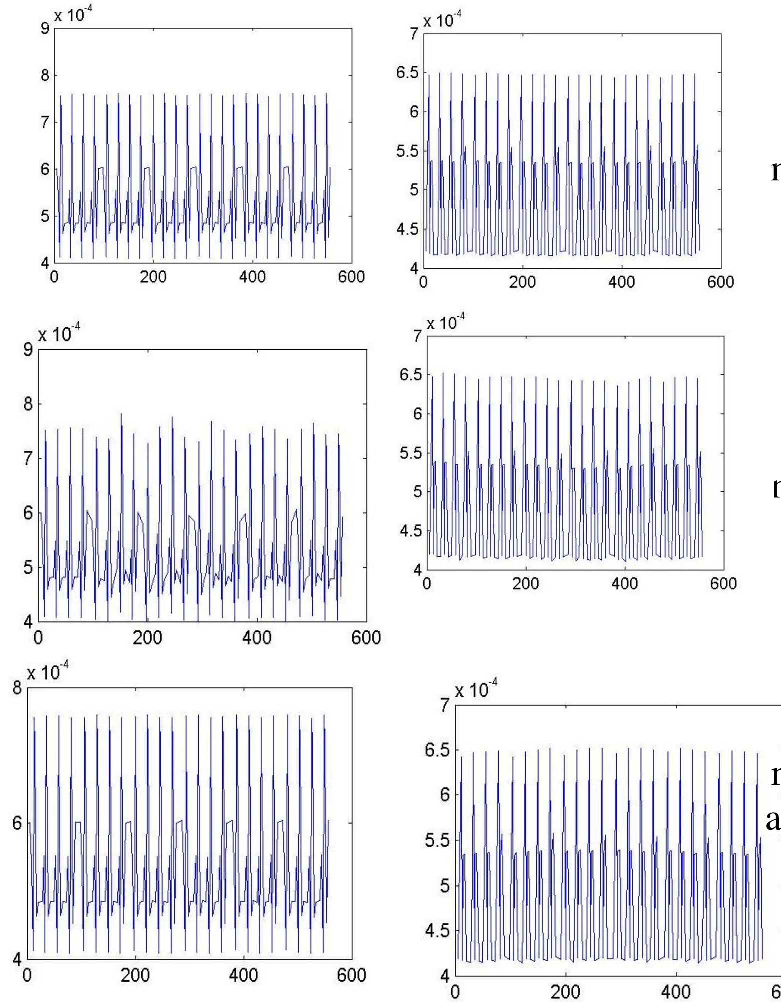
Example of SVD principal values

Fitted values for the 24 horizontal sextupole misalignments obtained from the SVD

Blu dots = assigned misalignments

Red dots = reconstructed misalignments





no misalignments

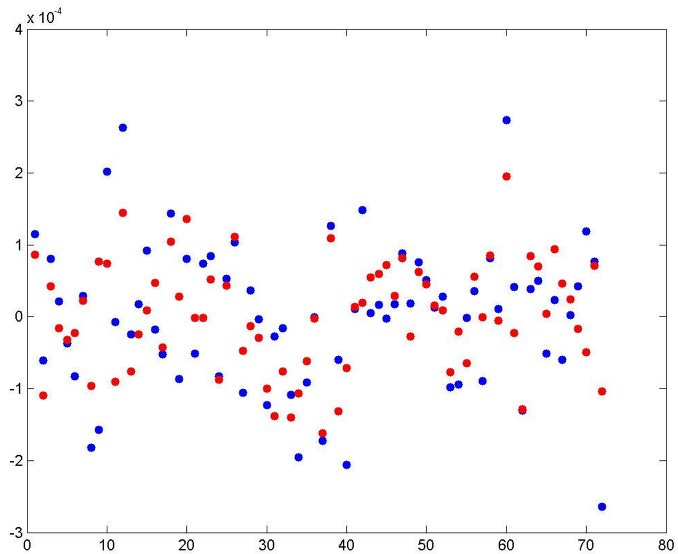
with misalignments

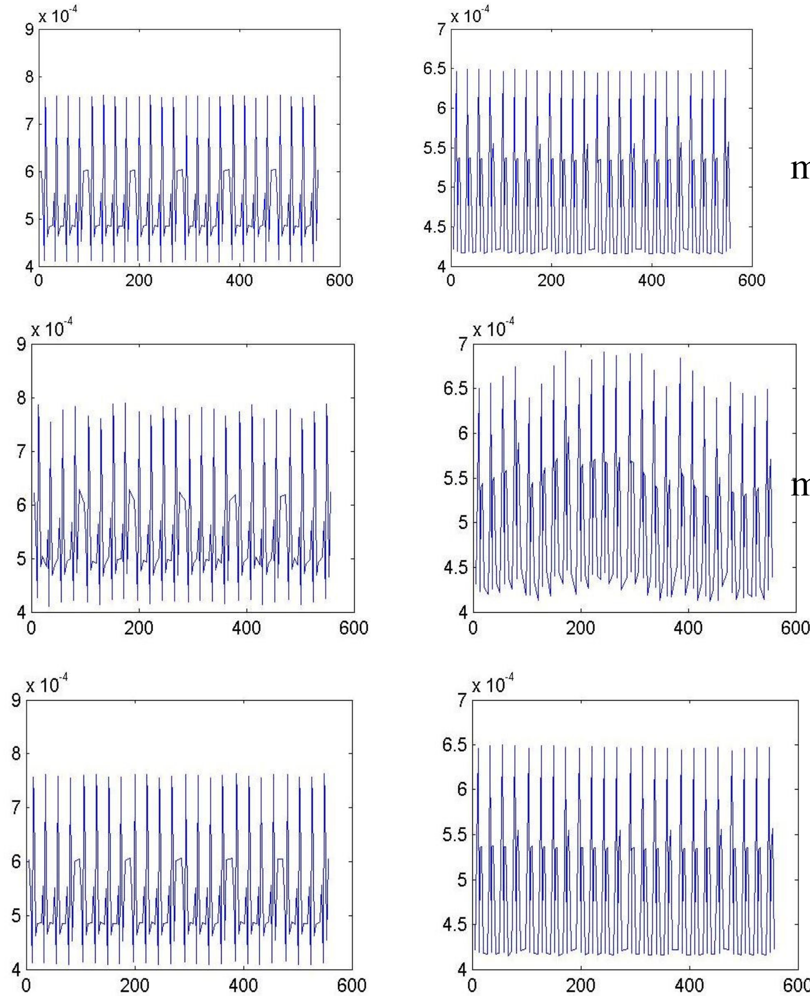
with misalignments and corrections

Fitted values for the 72 horizontal sextupole misalignments obtained from the SVD

Blu dots = assigned misalignments

Red dots = reconstructed misalignments





no

misalignments

with

misalignments

with

salignments

d corrections

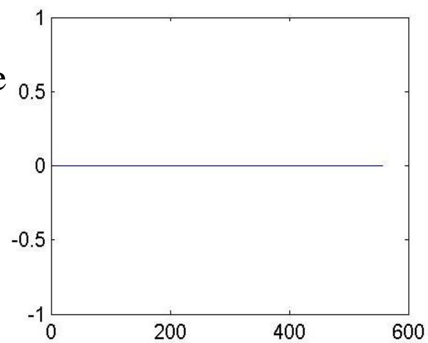
Vertical misalignment of a set of 24 sextupoles with 100 μm rms (linear coupling correction)

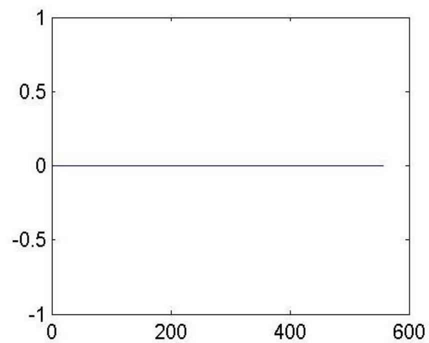
The generated skew quadrupole components introduce a linear coupling.

- we build the vector of Fourier coefficients of the (0, 1) line in the H plane
- we use the vertical misalignments as fit parameters

(0,1) line amplitude in H plane

(no misalignments)



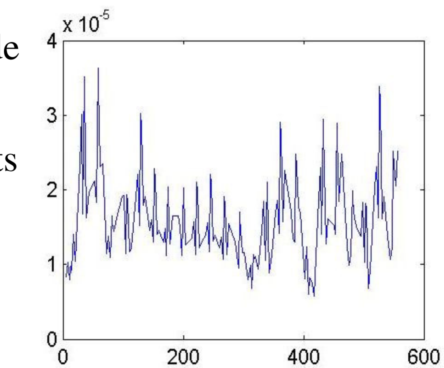


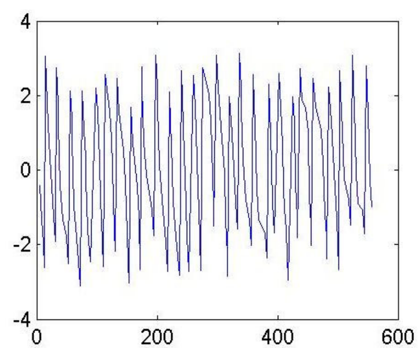
(0,1) line phase in H plane

(no misalignments)

(0,1) line amplitude in H plane

with misalignments





(0,1) line phase in H plane

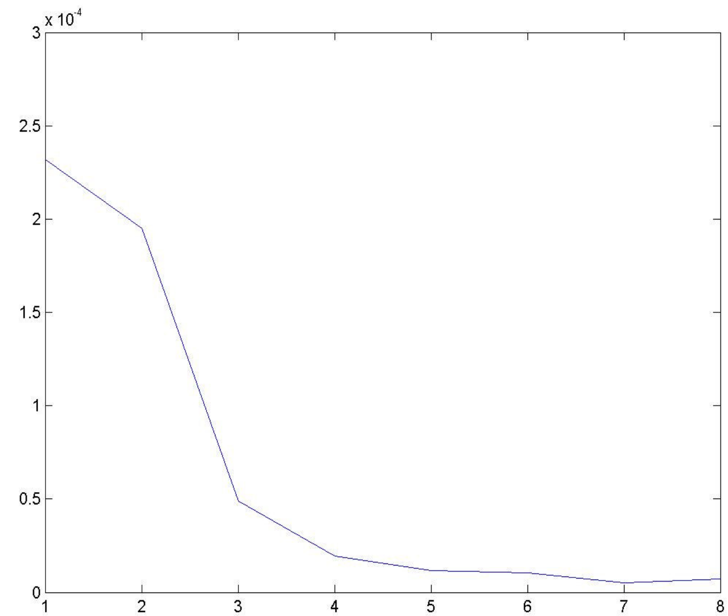
with misalignments

SVD on sextupole vertical misalignments

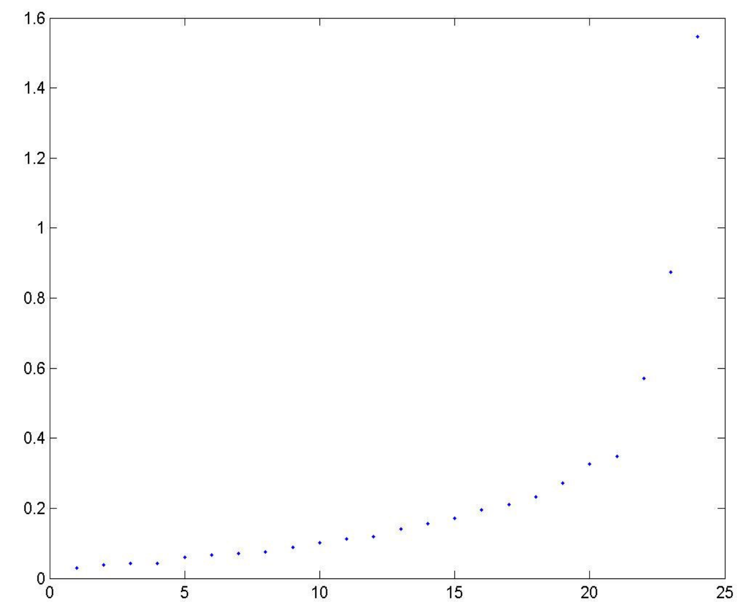
We build the vector $\overline{A} = \left(a_1^{H(0,1)} \quad \ldots \quad a_{NBPM}^{H(0,1)} \quad \phi_1^{H(0,1)} \quad \ldots \quad \phi_{NBPM}^{H(0,1)} \right)$

containing the amplitude and phase of the (0, 1) line in the H planes at all BPMs

We minimize the sum $\chi^2 = \sum_j \left(A_{Model}(j) - A_{Measured}(j) \right)^2$



χ^2 as a function of the iteration number

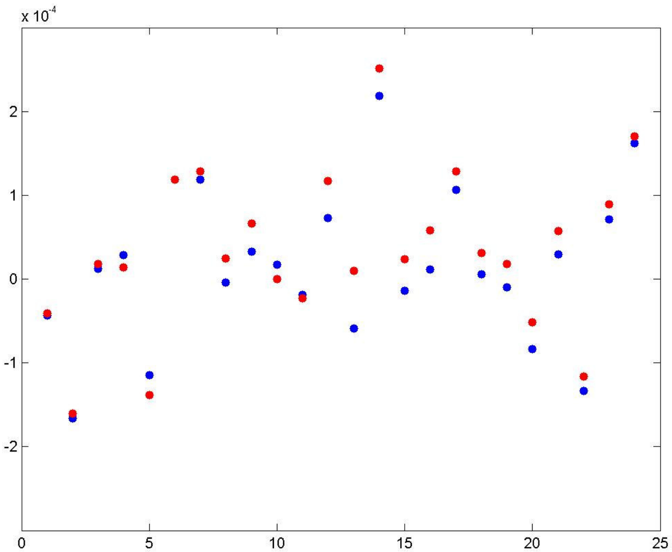


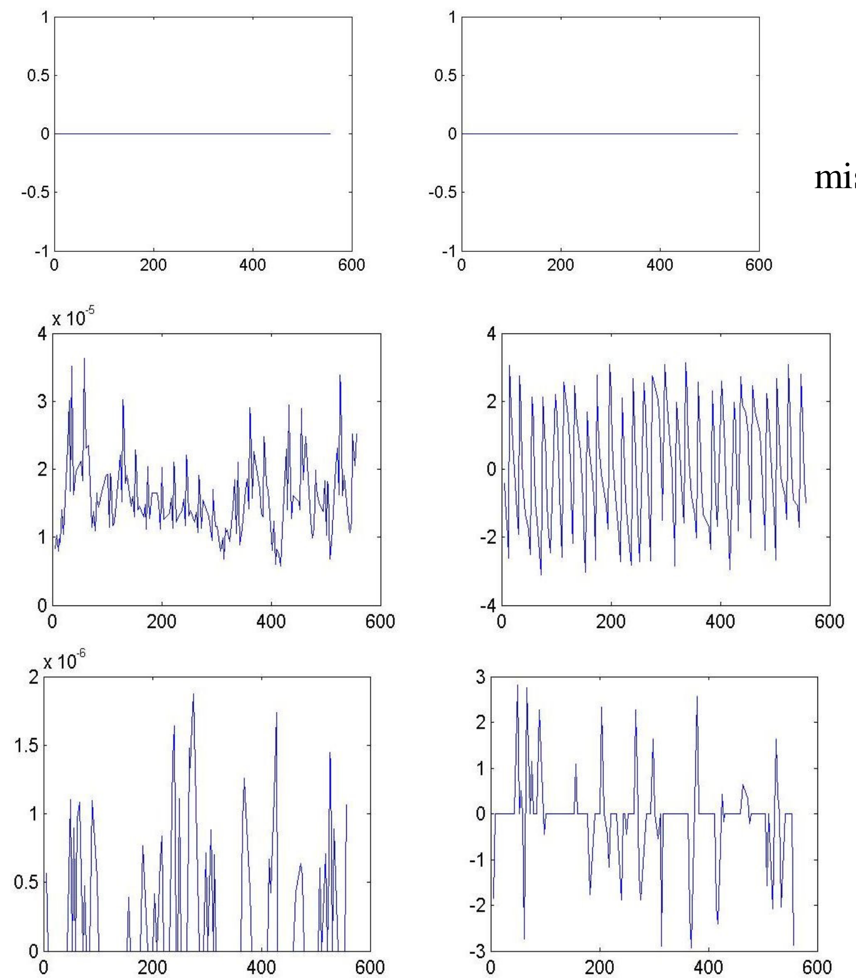
Example of SVD principal values

Fitted values for the 24 vertical sextupole misalignments obtained from SVD

Blu dots = assigned misalignments

Red dots = reconstructed misalignments





no

misalignments

with

alignments

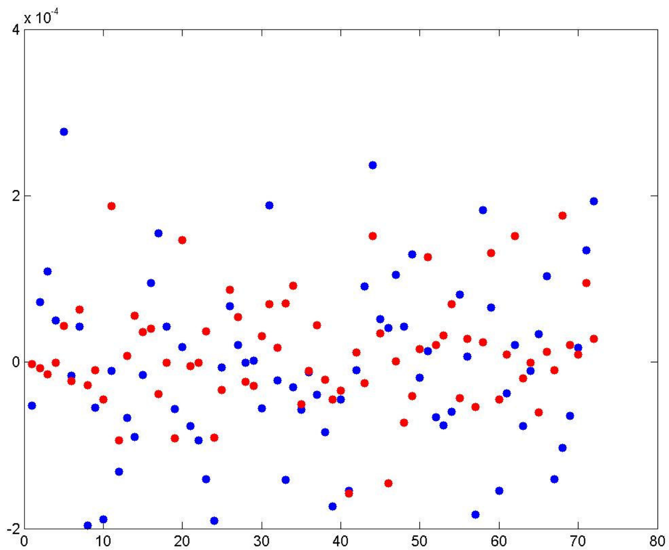
with

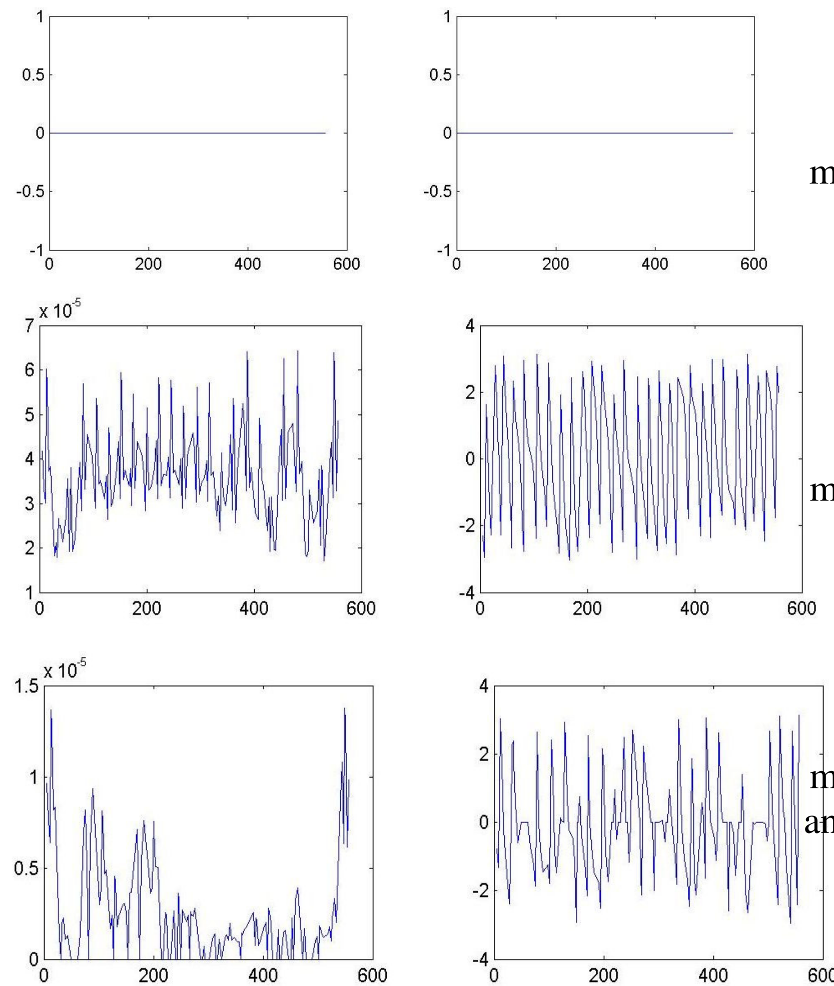
alignments
corrections

Fitted values for the 72 vertical sextupole misalignments obtained from SVD

Blu dots = assigned misalignments

Red dots = reconstructed misalignments





no misalignments

with misalignments

with misalignments and corrections

Sextupoles gradient errors applied to 24 sextupoles (dK_2/K_2 = 5%)

The sextupole gradient errors spoil the compensation of the third order resonances, e.g $3Q_x = p$ and $Q_x - 2Q_z = p$

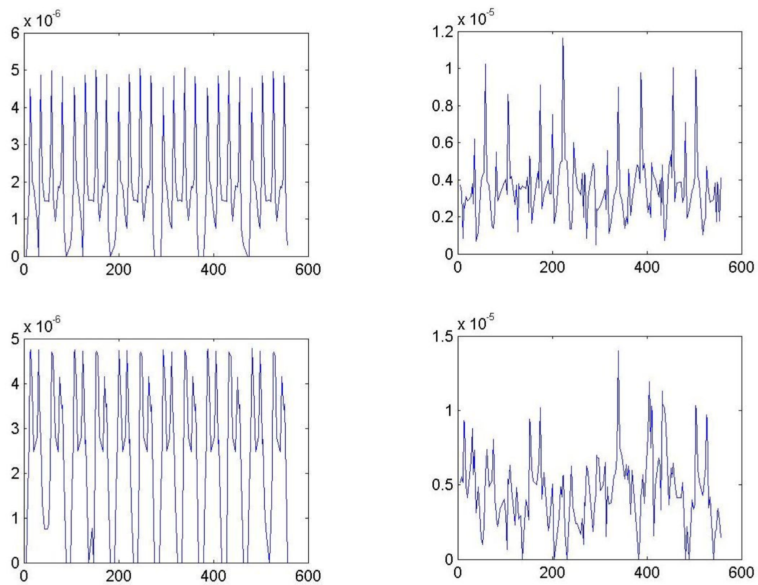
- we build the vector of Fourier coefficients of the H(-2,0) and H(0,2) line
- we use the errors gradients as fit parameters

(0,2) line amplitude in H plane

(no gradient errors)

(0,2) line amplitude in H plane

with gradient errors



(-2,0) line amplitude in H plane

(no gradient errors)

(-2,0) line amplitude in H plane

with gradient errors

SVD on sextupole gradient errors

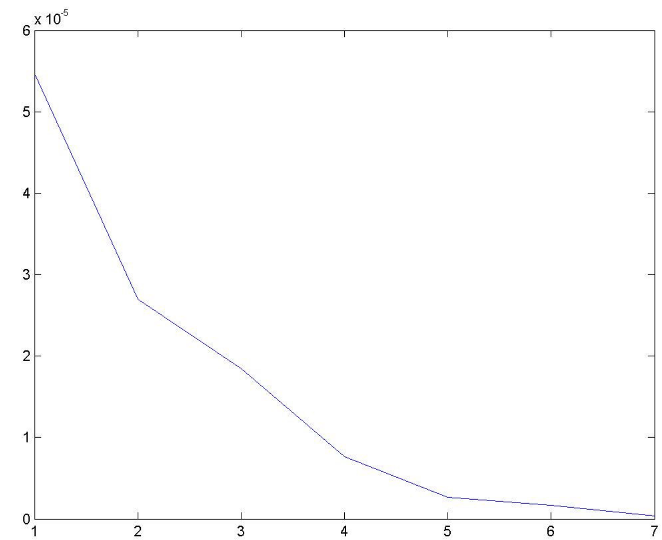
We build the vector $\overline{A} = \left(a_1^{H(-2,0)} \quad \dots \quad a_{NBPM}^{H(-2,0)} \quad a_1^{H(0,2)} \quad \dots \quad a_{NBPM}^{H(0,2)} \right)$

containing the amplitudes at all BPMs

- the (–2, 0) line in the H plane related to h_{3000}
- the (0, 2) line in the H plane related to h_{1002}

We minimize the sum

$$\chi^2 = \sum_j \left(A_{Model}(j) - A_{Measured}(j) \right)^2$$

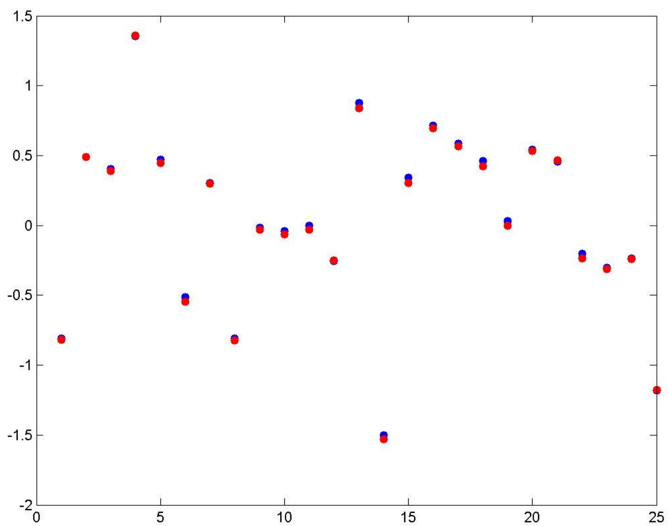


χ^2 as a function of the iteration number

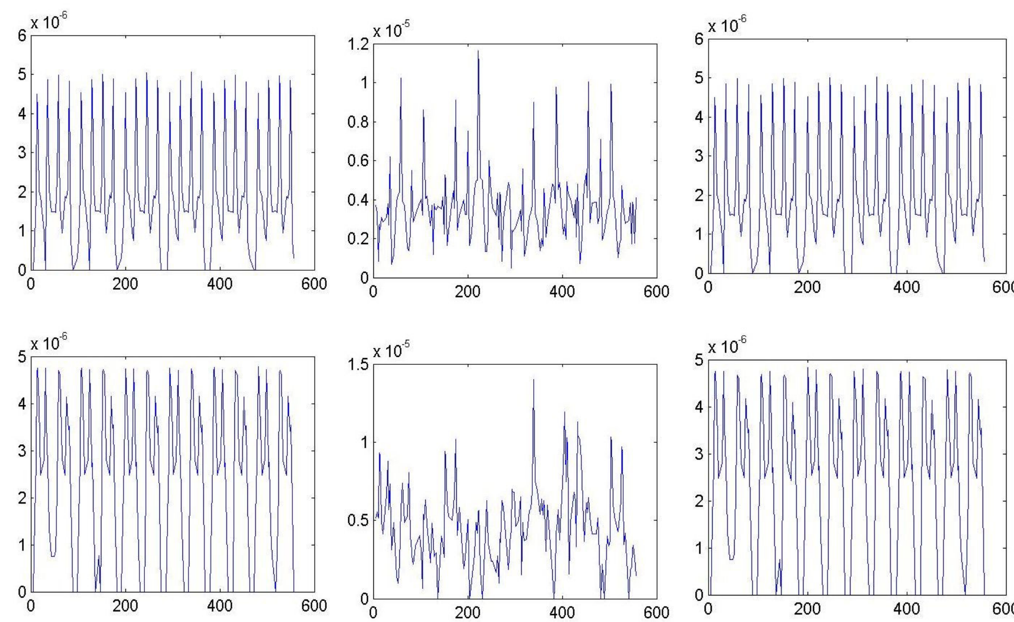
Fitted values for the 24 sextupoles gradients errors obtained from SVD

Blu dots = assigned misalignments

Red dots = reconstructed misalignments



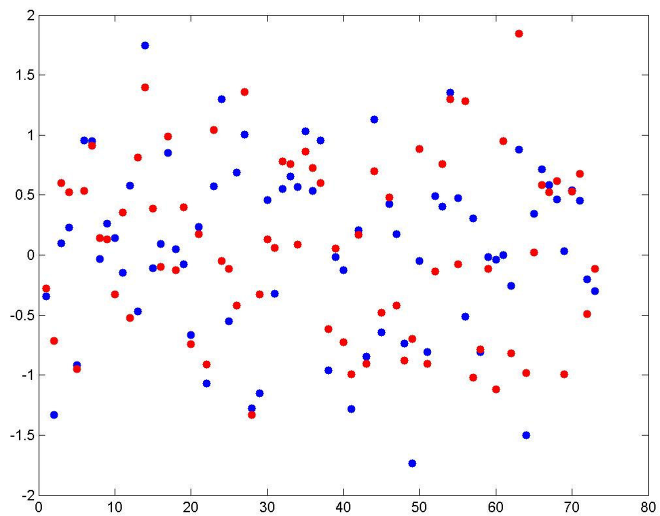
no gradient errors | with gradient errors | with gradient errors and corrections



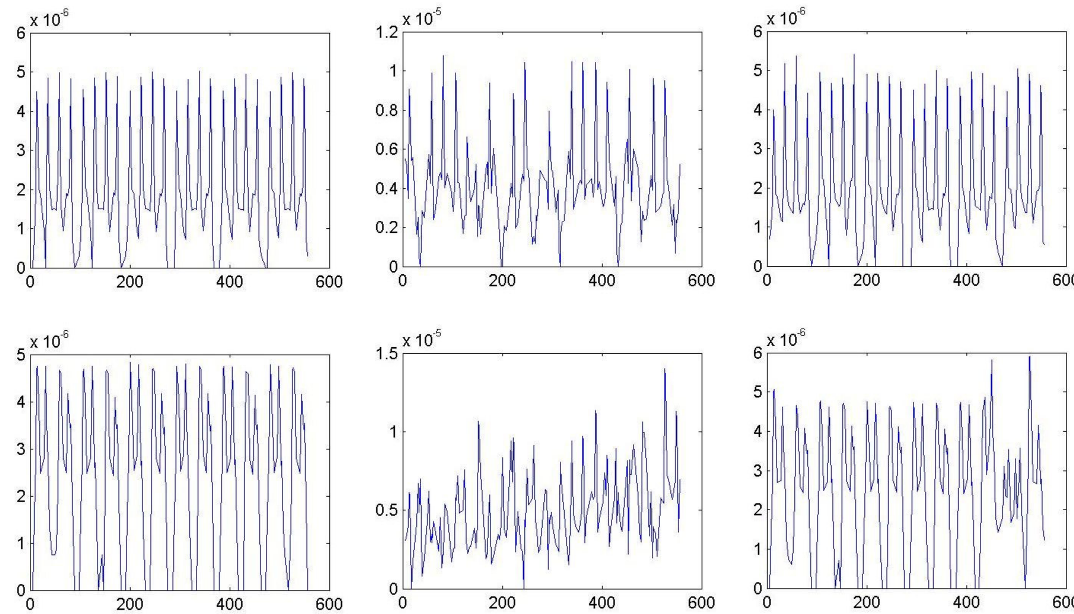
Fitted values for the 72 sextupoles gradients errors obtained from SVD

Blu dots = assigned misalignments

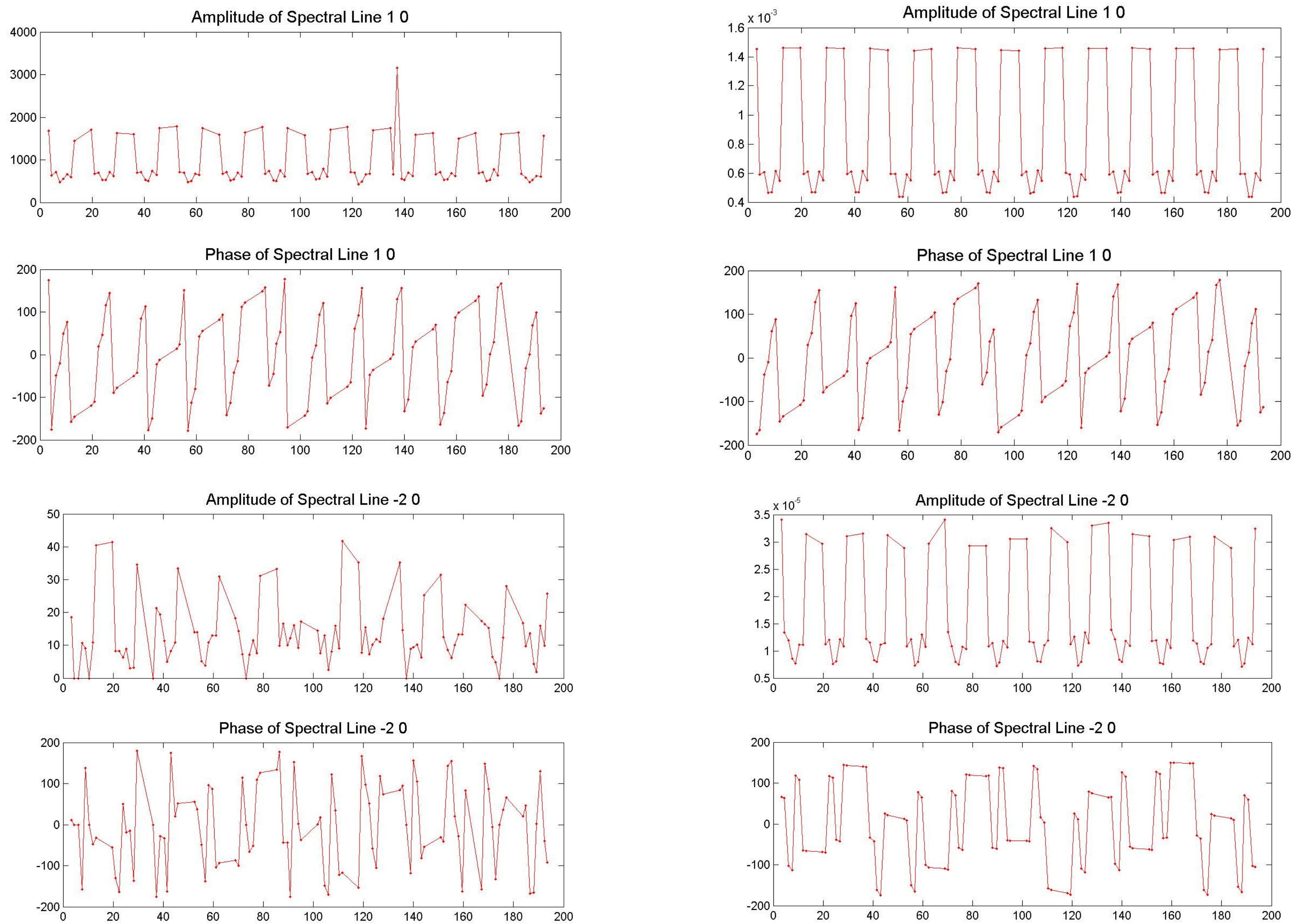
Red dots = reconstructed misalignments



no gradient errors	with gradient errors	with gradient errors and corrections



ALS example (very early results)



Summary

- **Resonance driving term analysis provides quantitative information about nolinearities in the machine**
- **It allows to measure the local distribution of the dominant nonlinearities**
- **However, it does not give a direct information about how harmful the nonlinearities are**
- **Theoretically it can provide a method similar to orbit response matrix analysis (or phase advance, …) to measure not just the gradient and skew gradient distribution, but also the setxupole, (octupole), … How well this will work experimentally is not quite clear, yet:**
    - **Can we use the spectral lines to recover the LINEAR and NON LINEAR machine model with a Least Square method?**
- SPS with a few very large nonlinearities worked well. Diamond simulations look encouraging. ALS measurements so far seem BPM resolution limited.

Further Reading

- R. Bartolini, et al. ‘Measurement of Resonance Driving Terms by Turn-by-Turn Data’, Proceedings of PAC 1999, 1557, New York (1999)
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- R. Bartolini and F. Schmidt, LHC Project note 132, Part. Accelerators. 59, pp. 93-106, (1998).
- F. Schmidt, R. Tom´as, A. Faus–Golfe, CERN-SL-2001-039-AP Geneva, CERN and IPAC 2001.
- M. Hayes, F. Schmidt, R. Tom´as, EPAC 2002 and CERNSL-2002-039-AP Geneva, 25 Jun 2002.
- F. Schmidt, CERN SL/94-56 (AP) Update March 2000.
- R. Bartolini and F. Schmidt, CERN SL–Note–98–017 (AP).