Correction of resonance in storage rings

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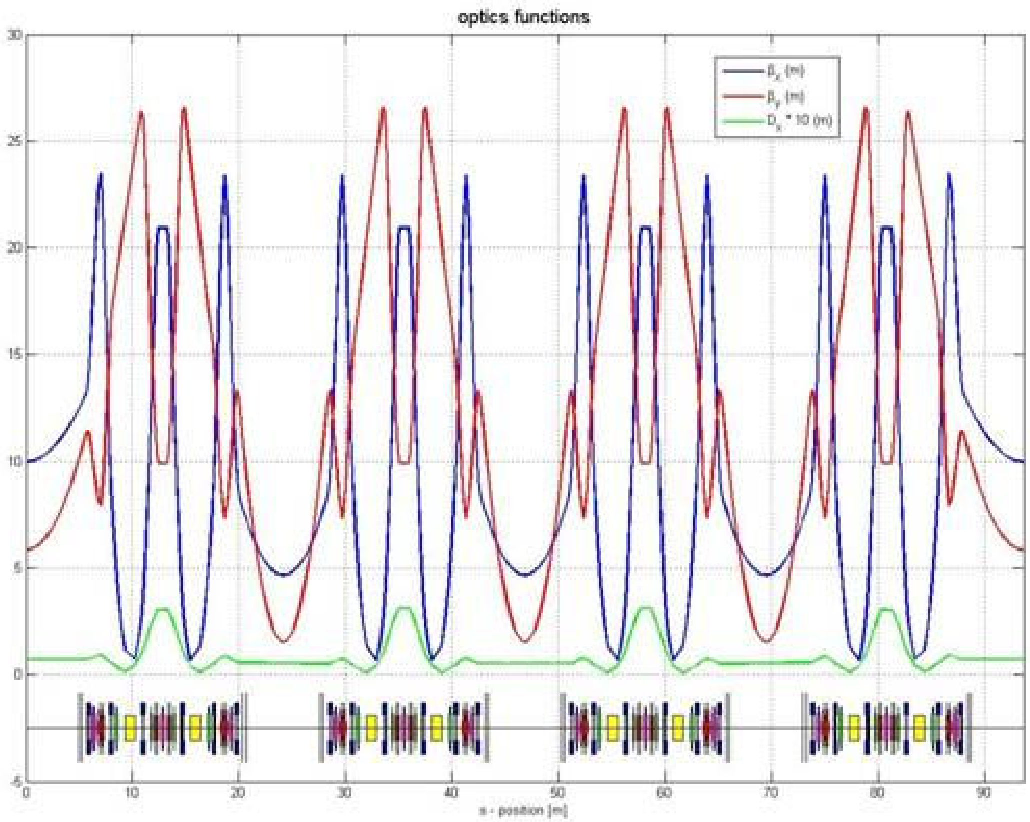
Outline

- Introduction
- Frequency analysis of betatron motion and resonance driving terms
- Comparison of nonlinear machine to nonlinear model
- Conclusions

Diamond storage ring main parameters
non-zero dispersion lattice



Energy	3 GeV
Circumference	561.6 m
No. cells	24
Symmetry	6
Straight sections	6 x 8m, 18 x 5m
Insertion devices	4 x 8m, 18 x 5m
Beam current	300 mA (500 mA)
Emittance (h, v)	2.7, 0.03 nm rad
Lifetime	> 10 h
Min. ID gap	7 mm (5 mm)
Beam size (h, v)	123, 6.4 μm
Beam divergence (h, v) *(at centre of 5 m ID)*	24, 4.2 μrad

48 Dipoles; 240 Quadrupoles; 168 Sextupoles (+ H and V orbit correctors + Skew Quadrupoles); 3 SC RF cavities; 168 BPMs

Quads + Sexts have independent power supplies

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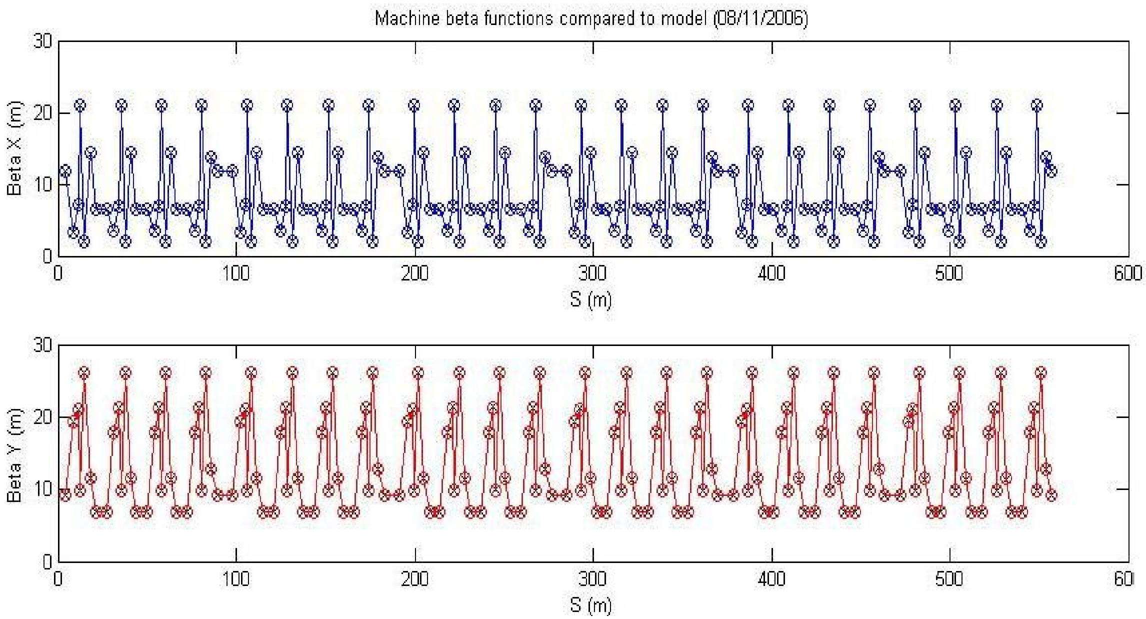
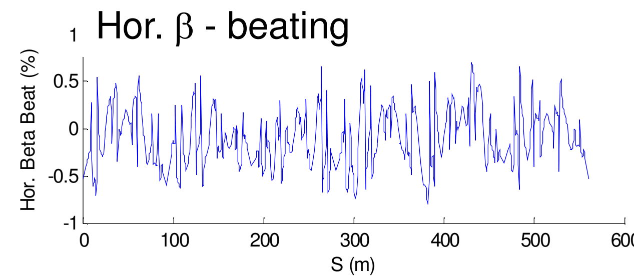
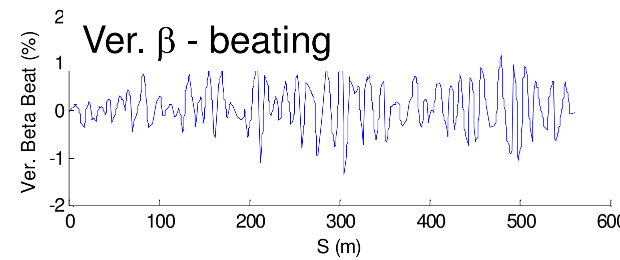
Linear optics modelling with LOCO

Linear Optics from Closed Orbit response matrix – J. Safranek et al.



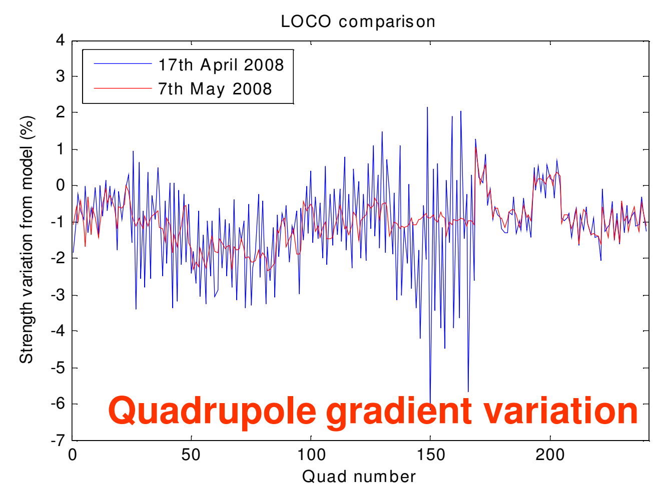




Modified version of LOCO with constraints on gradient variations **(see [ICFA Newsl, Dec'07])**

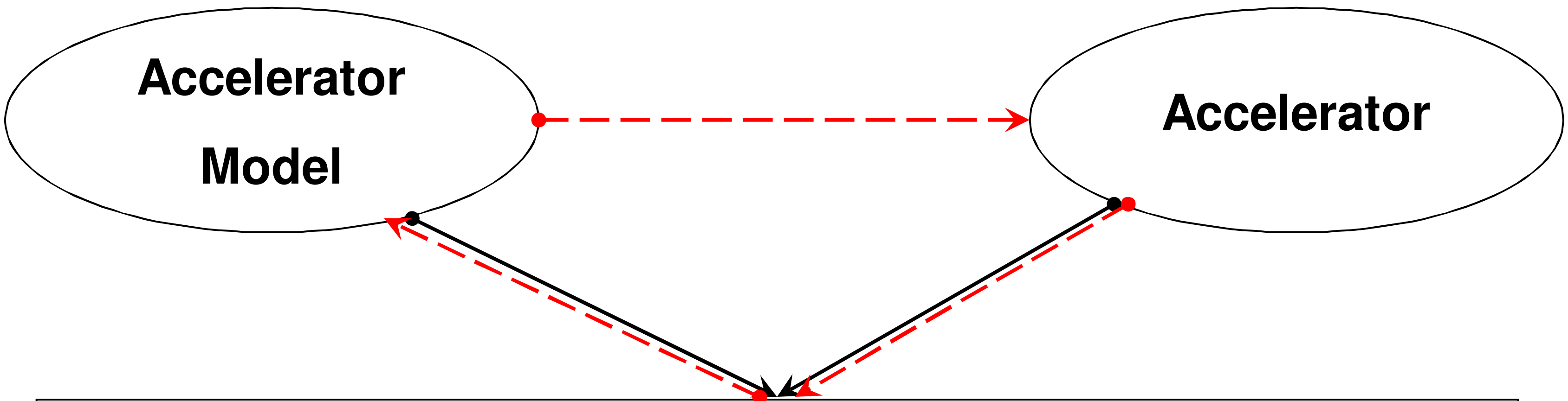
β - beating reduced to 0.4% rms

Quadrupole variation reduced to 2%
Results compatible with mag. meas.



LOCO allowed remarkable progress with the correct implementation of the linear optics

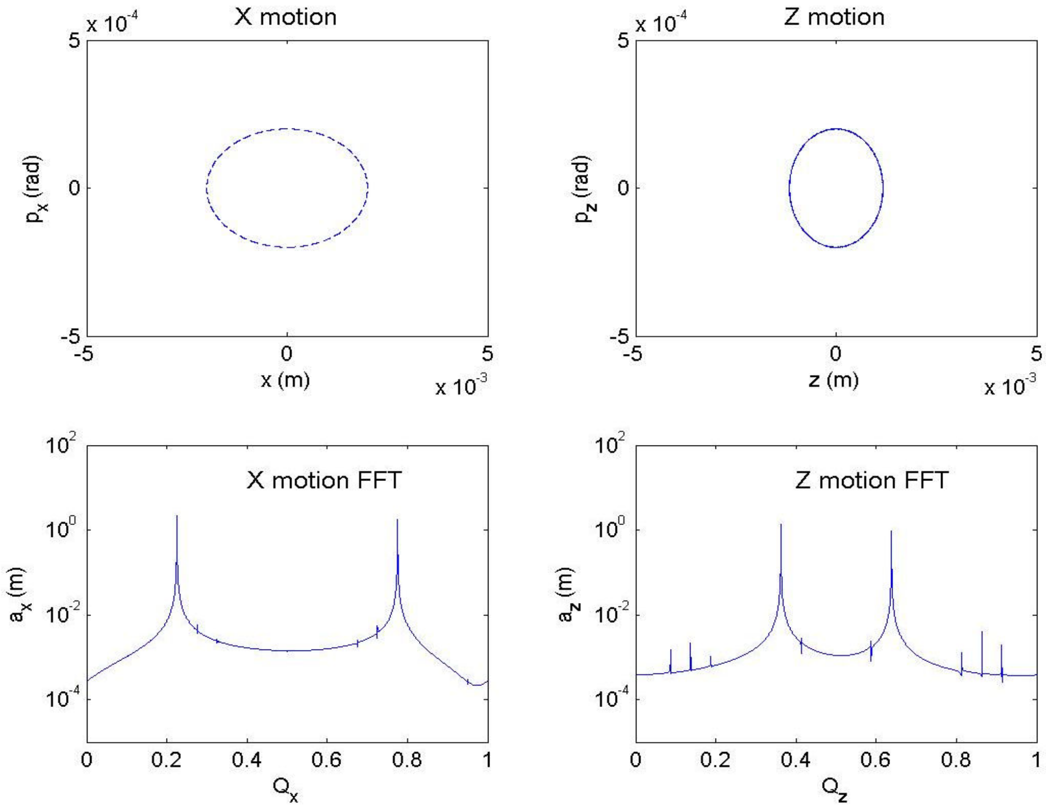
Comparison Real Lattice to Model



- **Closed Orbit Response Matrix (LOCO)**
- Detuning with amplitude (and with momentum)
- Apertures and Lifetime
- Frequency Map Analysis
- **Frequency Analysis of Betatron Motion (resonance driving terms)**

Frequency Analysis of betatron motion

Example: Spectral Lines for Diamond lattice
(.2 mrad kick in both planes – tracking data)



Spectral Lines detected with SUSSIX (NAFF algorithm)

e.g. in the horizontal plane:

- (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) $2.08\ 10^{-8}$ $2\,Q_x + 4\,Q_z$

Spectral lines and nonlinear resonances

J. Bengtsson (1988): CERN 88–04, (1988).
J. Laskar's work: Physica D 56, 253, (1992)
R. Bartolini, F. Schmidt (1998), Part. Acc., **59**, 93, (1998).
R. Tomas, PhD Thesis (2003)

• The main spectral lines appear at frequencies which are linear combinations of the betatron tunes;

• Each resonance driving term f_{jklm} contributes to the Fourier coefficient of a definite spectral line; to the lowest perturbative order there's a one-to-one correspondence

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

e.g the (3,0) resonance driving term f_{3000} excites the (-2,0) spectral line

• The amplitude and phase of spectral lines (and driving terms) vary along the ring;

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

A possible scheme: R. Bartolini and F. Schmidt (PAC05)

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

e.g. targeting more than one line

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

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 of the sextupole gradients to minimise the distance χ^2 of the two Fourier coefficients vectors

Comparison with LOCO-type of machine modelling

LOCO

Closed Orbit Response Matrix
from model

Closed Orbit Response Matrix
measured

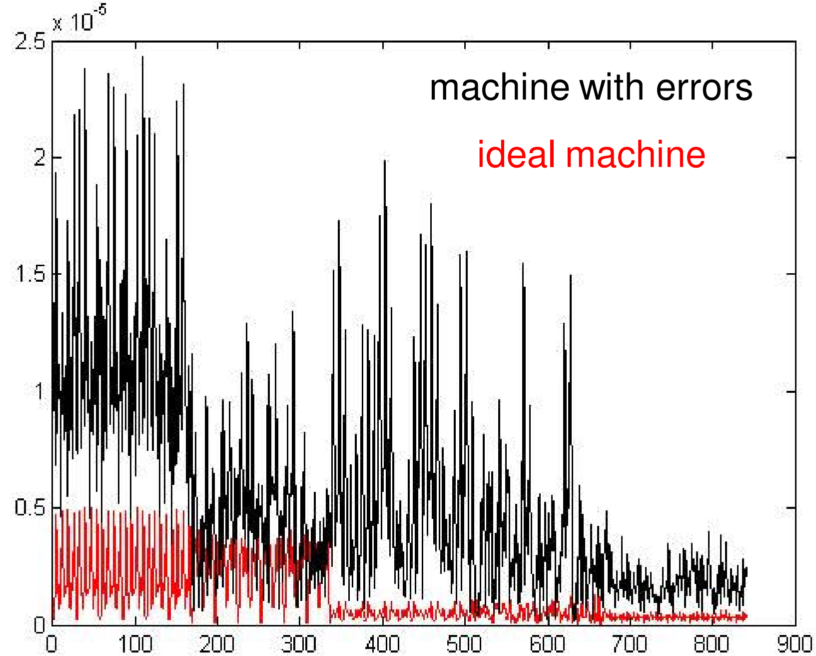
fitting quadrupoles, etc → Linear lattice correction/calibration

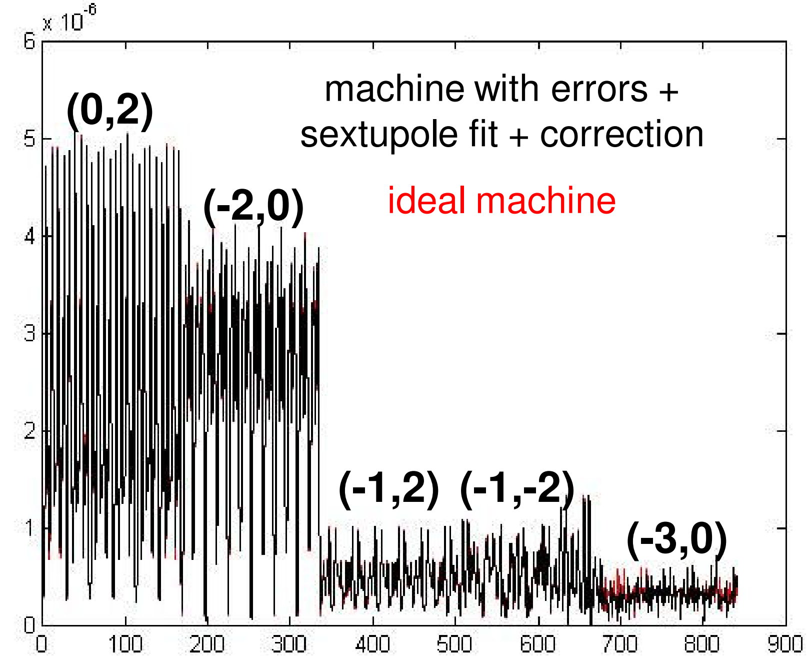
Spectral lines
from model

Spectral Lines
measured

fitting sextupoles → Nonlinear lattice correction/calibration

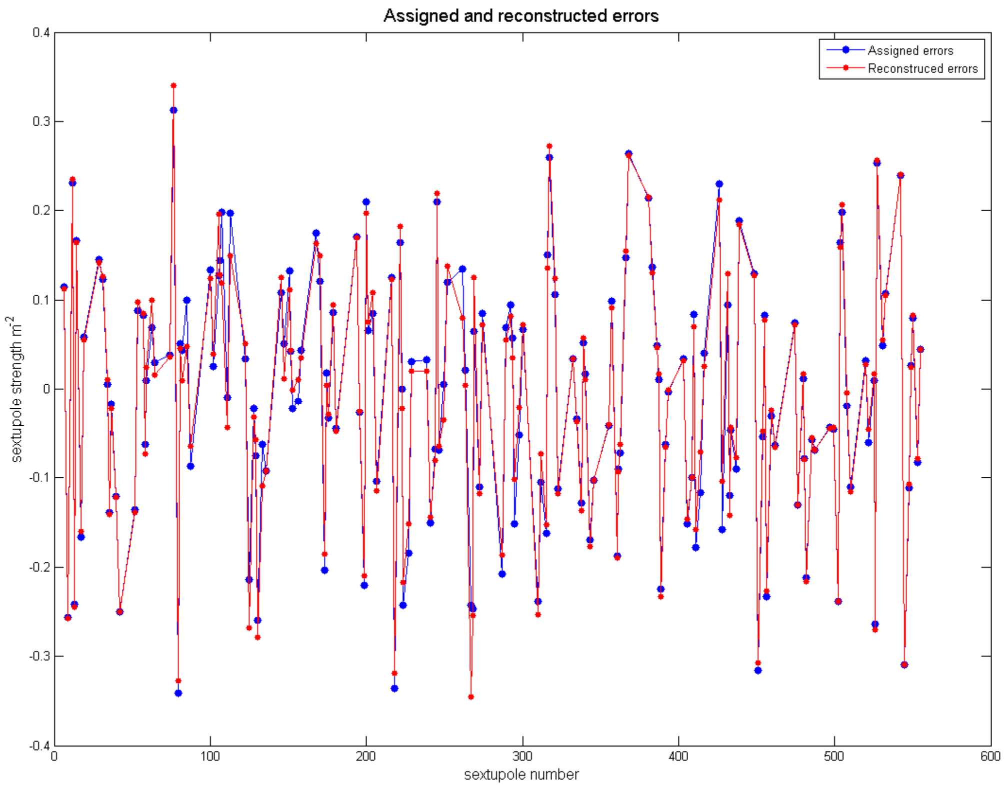
Fitting sextupole gradients to correct the s-dependence of the amplitude of the spectral lines





Given a machine with random sextupole errors, generating noisy spectral lines (black-left), the sextupole were fitted to reproduce the target vector (red-left) given by the ideal model. In this way we can correct the nonlinear model of the ring

Errors reconstruction from tracking data



Blue dots are the originally assigned random errors

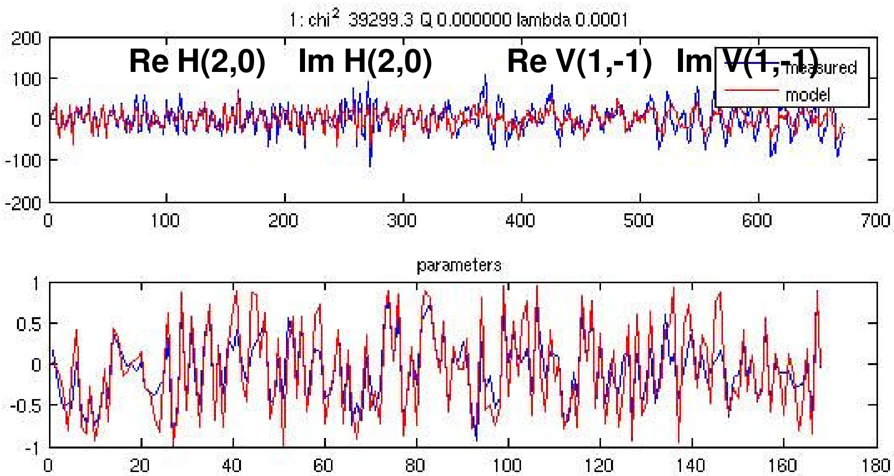
Red dots are the reconstruction of the errors obtained from the sextupole fit

Using also the pahse infomration of the spectral lines the fit procedure is fast and allows

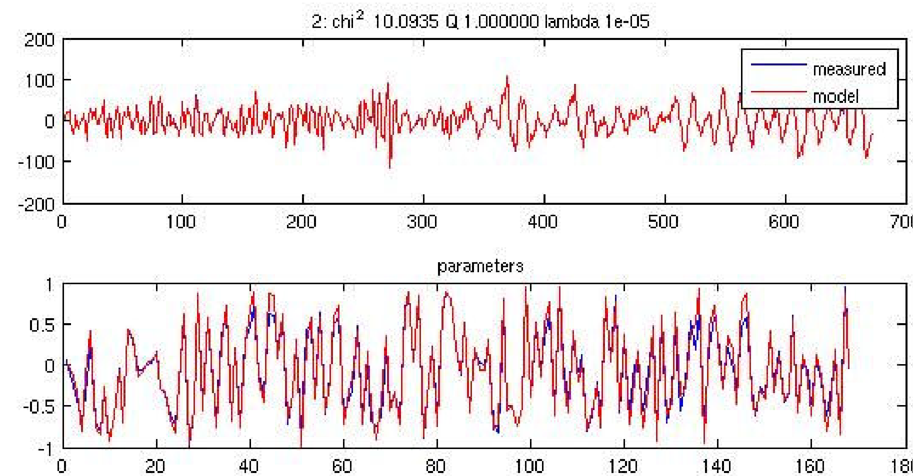
a detail reconstruction of the machine model and its correction is possible on tracking data

Phase information

No need to recover the phase explicitly: real and imaginary part of the spectral lines are sufficient and the fit is numerically more stable !



Iteration 1

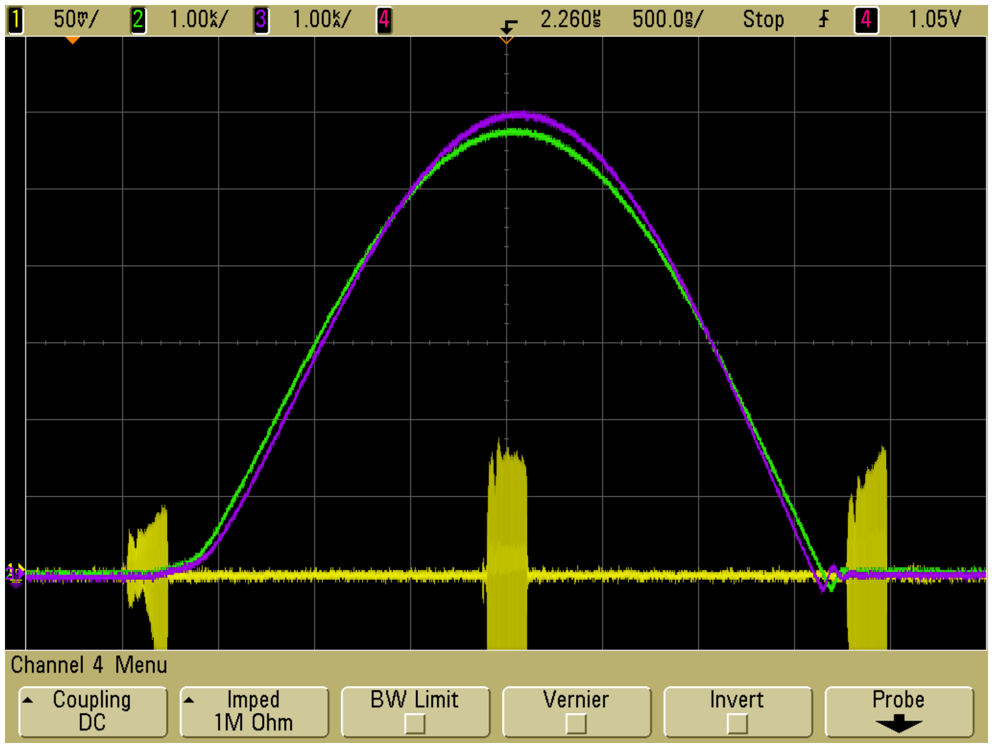


Iteration 2

This fit of the sextupole gradient errors takes 1 minute per iteration

This allows a much faster reconstruction of the nonlinear model

Pinger Experiments at Diamond



Experiments were performed using a fill with 100 bunches (~1/10 fill) and 25-50 mA, with slighlty positive chromaticity 0.5-1

All BPMs have turn-by-turn capabilities

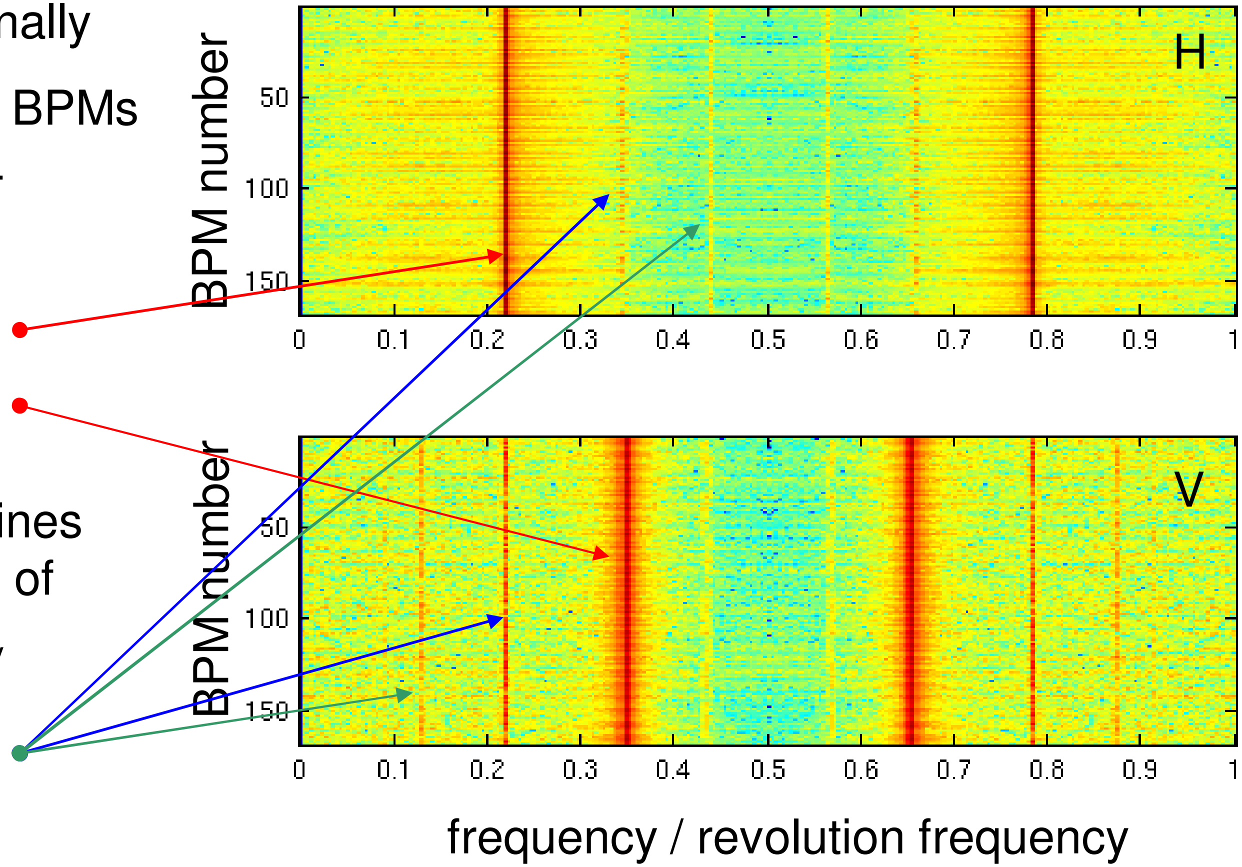
- excite the beam diagonally
- measure tbt data at all BPMs
- colour plots of the FFT

Q_X = 0.22 H tune in H

Q_y = 0.36 V tune in V

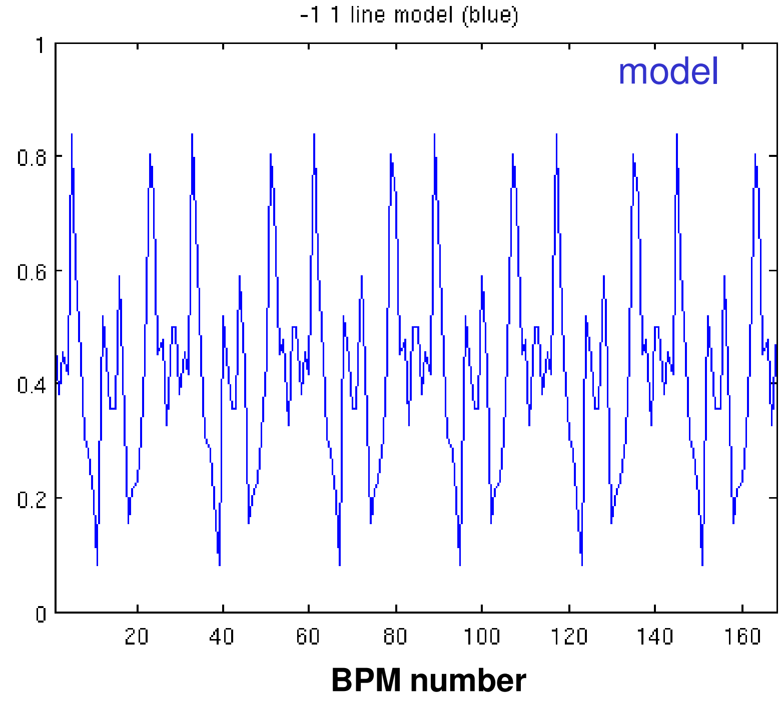
All the other important lines are linear combination of the tunes Q_x and Q_y

$m\,Q_x + n\,Q_y$

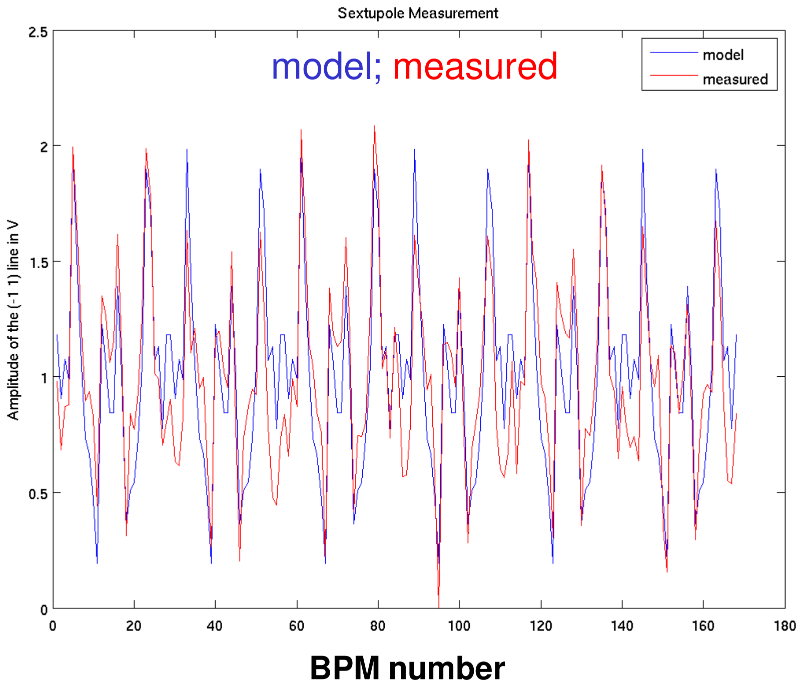


Spectral line (-1, 1) in V associated with the sextupole resonance (-1,2)

Spectral line (-1,1) from tracking data observed at all BPMs

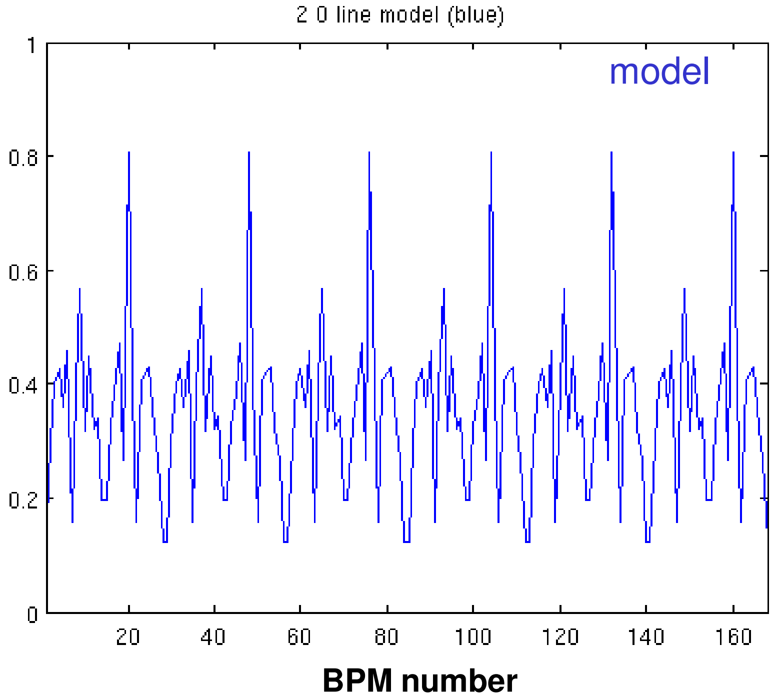


Comparison spectral line (-1,1) from tracking data and measured (-1,2) observed at all BPMs

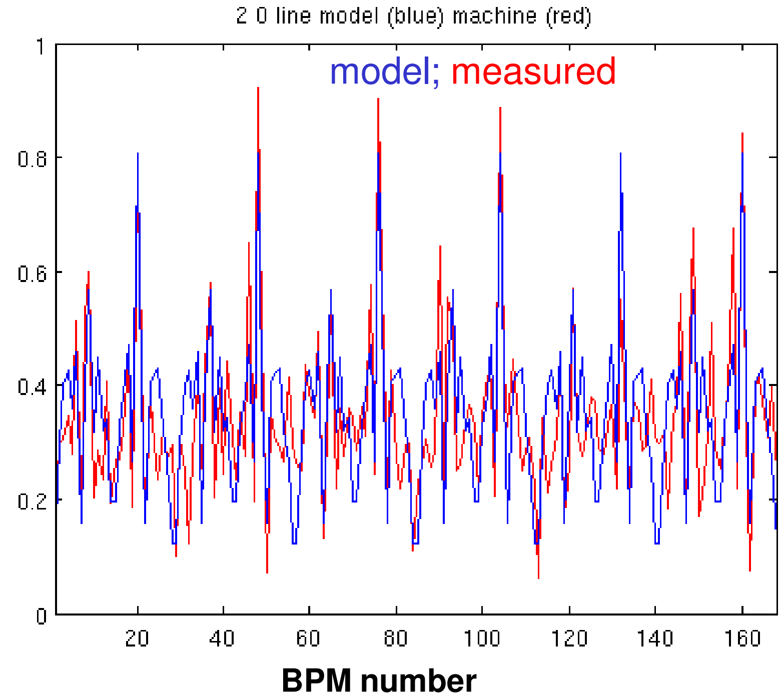


Spectral line (-2, 0) in H associated with the sextupole resonance (3,0)

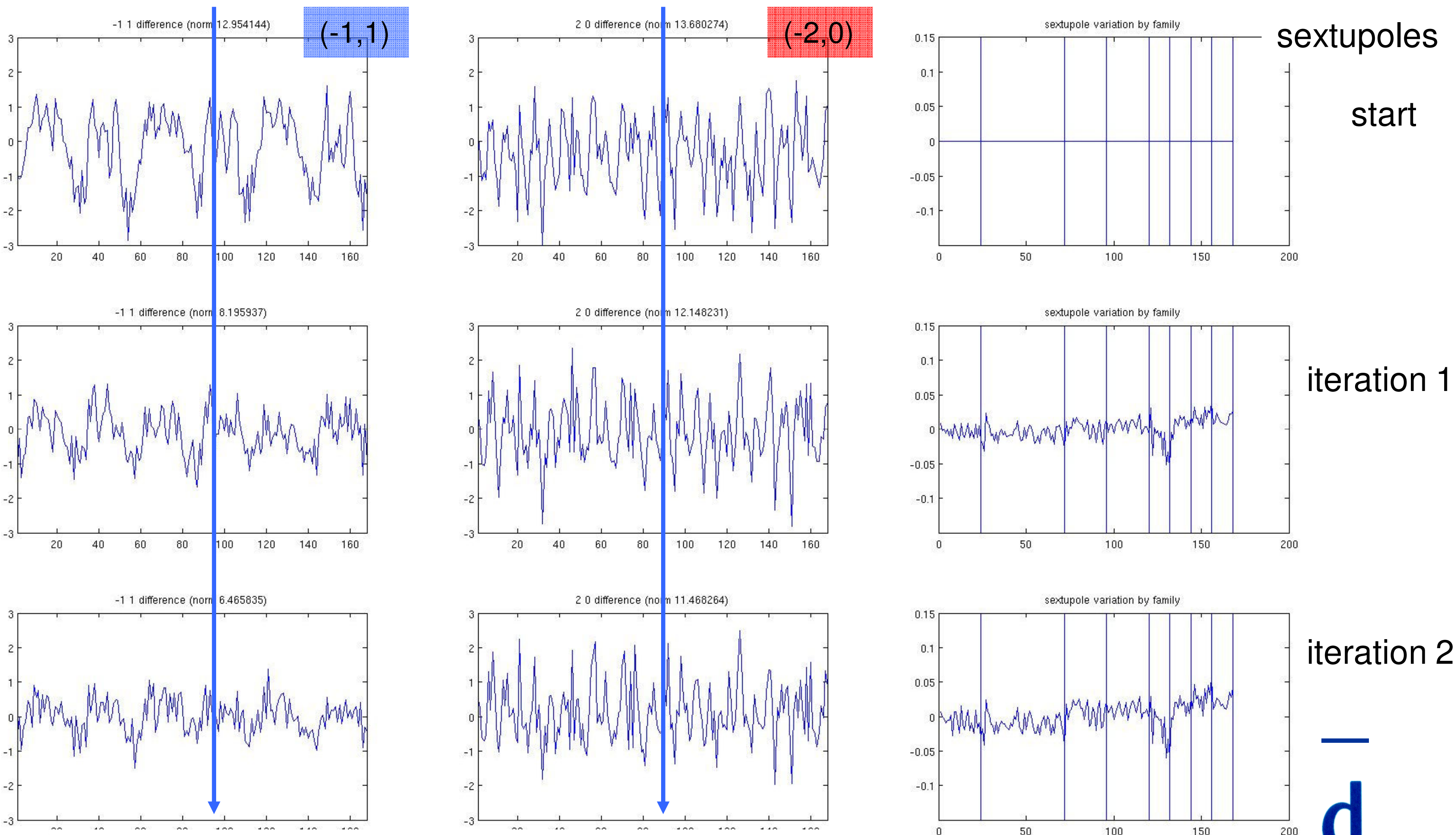
Spectral line (-2,0) from tracking data observed at all BPMs



Comparison spectral line (-2,0) from tracking data and measured (-2,0) observed at all BPMs

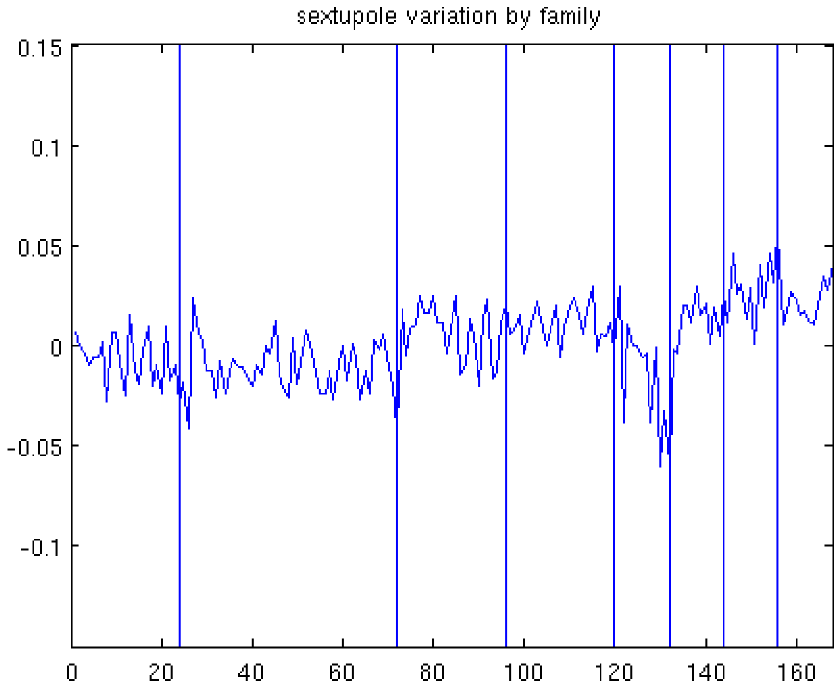


Simultaneous fit of (-2,0) in H and (1,-1) in V



Both resonance driving terms are decreasing

Sextupole variation



Now the sextupole variation is limited to < 5%

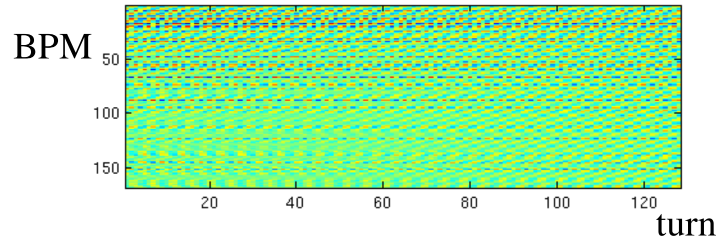
Both resonances are controlled

We measured a slight improvement in the lifetime (10%)

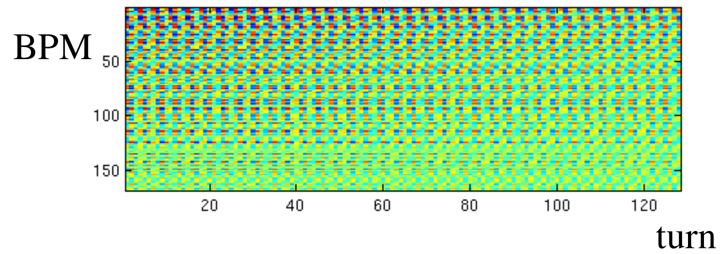
PRSTAB, 11, 104002, (2008)

Time alignment of turn by turn data

The use of the phase information from all BPMs requires a careful alignment of the turn by turn signals



Xmod - Xmeas



Ymod - Ymeas

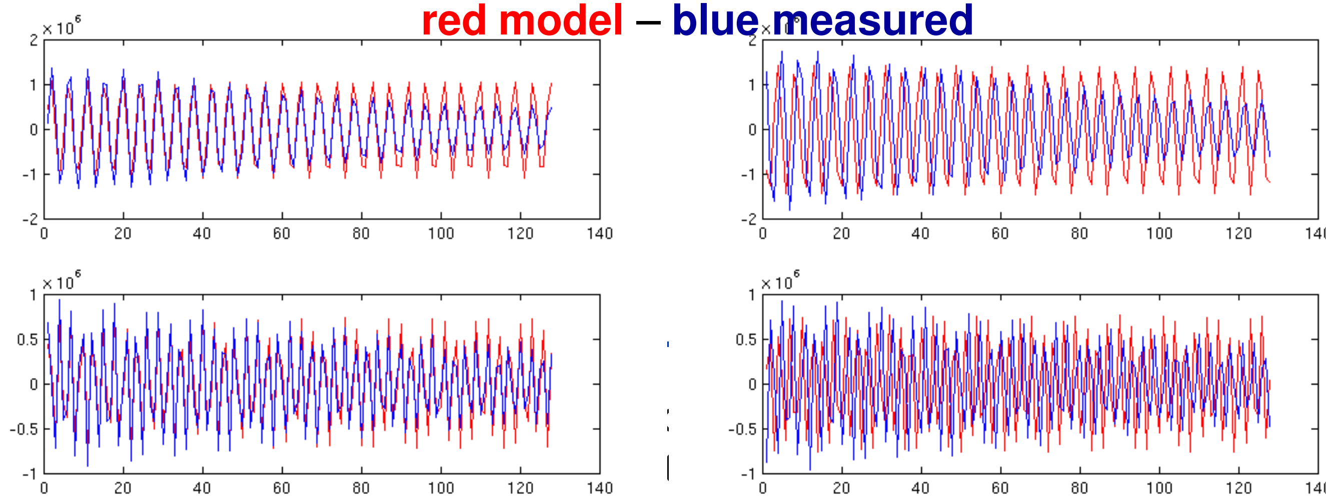
Problems met

- Pinger position and sign in model
- time alignment of BPMs signals
- time of flight of the beam to the BPMs
- frequency response of BPMs

red model – **blue measured**

BPM 1

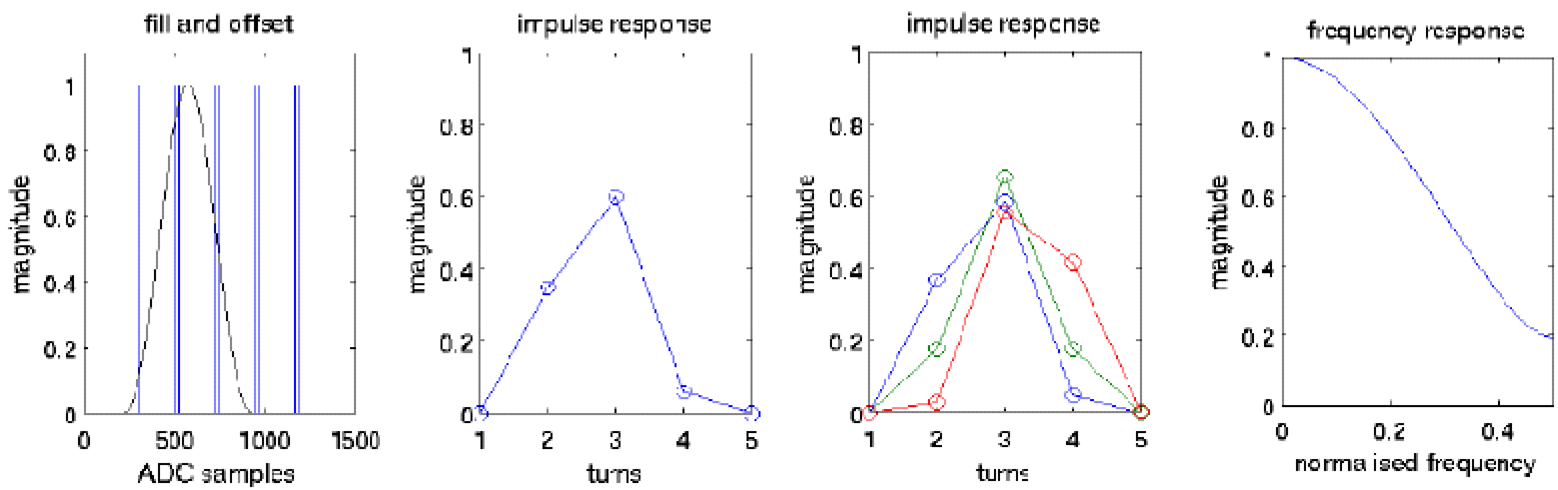
BPM 109



Frequnecy response of the BPMs

Feedback between modelling and experiments (Diamond and SOLEIL) highlighted several important issues in the functioning of Libera BPMs, which need to be take in account to get meaningful results, e.g.

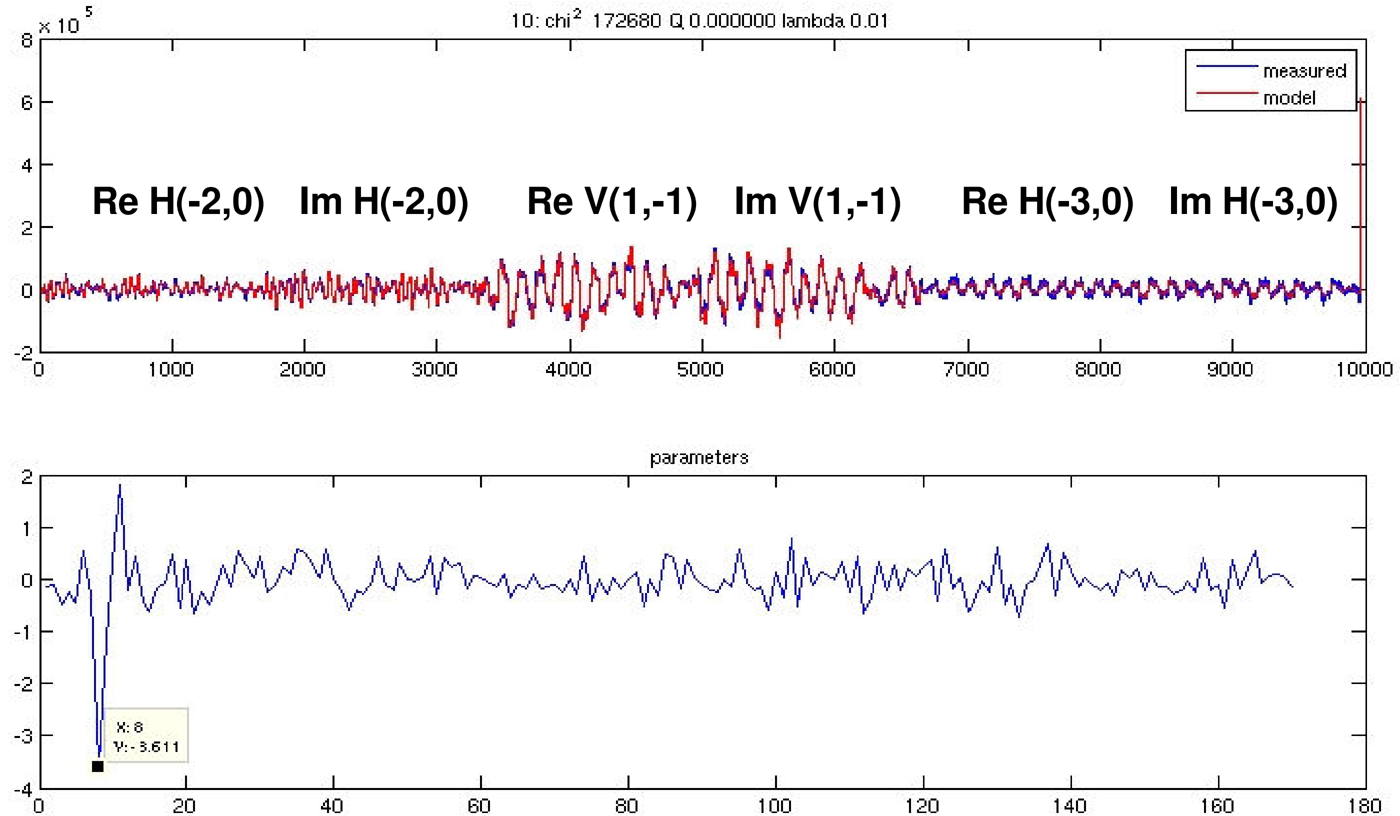
frequency response of the BPMs due to the mixing of more than one turn into the singal read for a single tune (convolution of up to three turns into one turn reading)



Detection of a sextupole variation

We repeated the test powering a sextupoles and let the fit algorithm find it

Lines analysed were H(-2,0), V(1,-1) and the octupole resonance H (-3, 0)



This method has the potential to generate a **fast resonance correction** (ping + fit + correct ~ 1 minute) and the reconstruction of the nonlinear model of the ring.

Limits of the Frequency Analysis technique

BPMs precision in turn by turn mode (+ gain, coupling and non-linearities)

10 μm with ~10 mA

very high precision required on turn-by-turn data (not clear yet is few tens of μm is sufficient); Algorithm for the precise determination of the betatron tune lose effectiveness quickly with noisy data. R. Bartolini et al. Part. Acc. 55, 247, (1995)

Decoherence of excited betatron oscillation reduce the number of turns available Studies on oscillations of beam distribution shows that lines excited by resonance of order m+1 decohere m times faster than the tune lines. This decoherence factor m has to be applied to the data R. Tomas, PhD Thesis, (2003)

The machine **tunes are not stable**! Variations of few 10^{-4} are detected and can spoil the measurements

BPM gain and coupling can be corrected by LOCO, but **BPM nonlinearities** (especially for diagonal kicks) and the **BPM frequency response** remain

Conclusions

Characterisation of the non-linear beam motion is ongoing: a wealth of information can be obtained from the turn-by-turn data

Several dynamical quantities are available (apertures, FM, Spectral lines, ...) and they provide complementary information on the nonlinear beam dynamics

Spectral line analysis has the potential to reconstruct the nonlinear machine model. Multiple resonances correction and improvement in Touschek lifetime was achieved.

Building of the correct nonlinear machine model is a highly non trivial task and lots of work still need to be done.