Modelling experience at Diamond

R. Bartolini

Diamond Light Source Ltd
and
John Adams Institute, University of Oxford

J.A.I.

OMCM Workshop,
20th June 2011, CERN

diamond

Outline

- Introduction to the diamond storage ring
- Modelling and correcting the **linear optics**
- Modelling and correcting the **nonlinear optics**

  Frequency Maps

  Spectral lines analysis and resonance driving terms

  Limits of the methods

- Conclusions and ongoing work

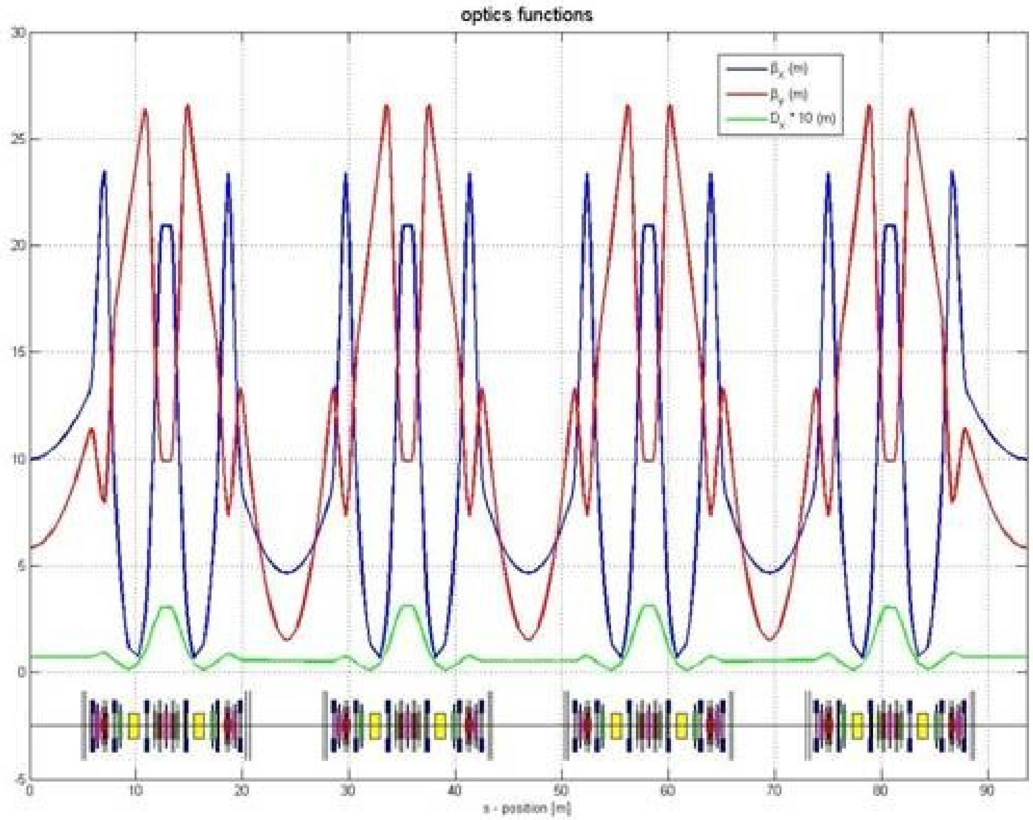
Diamond aerial view

Diamond is a third generation light source open for users since January 2007

100 MeV LINAC; 3 GeV Booster; 3 GeV storage ring

2.7 nm emittance – 300 mA – 18 beamlines in operation (10 in-vacuum small gap IDs)

Diamond storage ring main parameters
non-zero dispersion lattice



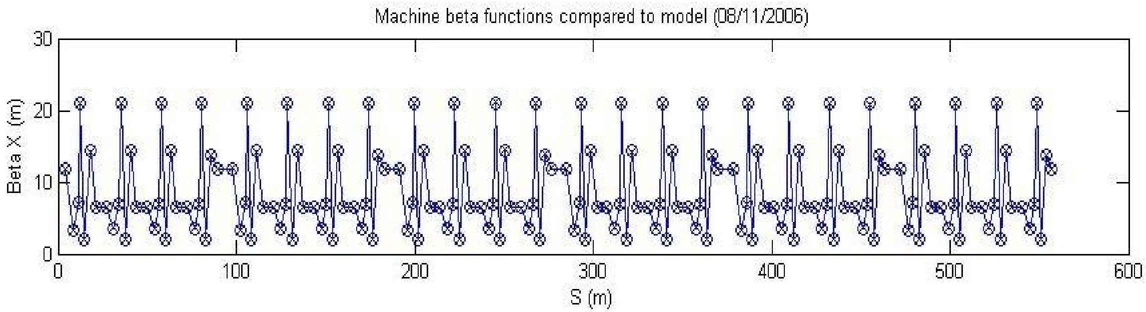
48 Dipoles; 240 Quadrupoles; 168 Sextupoles
(+ H and V orbit correctors + 96 Skew Quadrupoles)
3 SC RF cavities; 168 BPMs

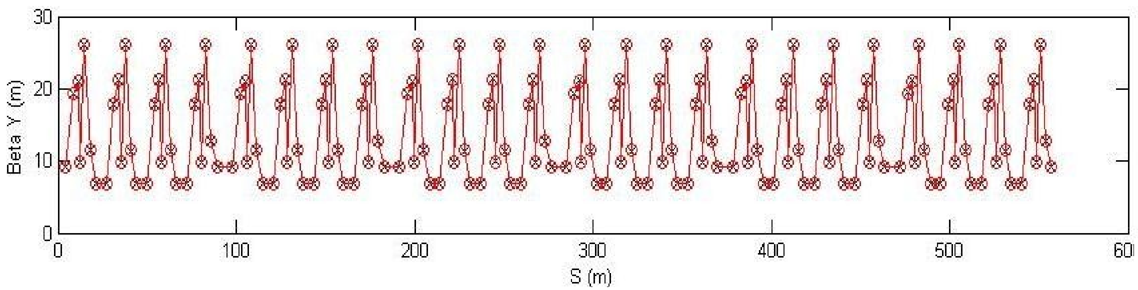
Quads + Sexts have independent power supplies

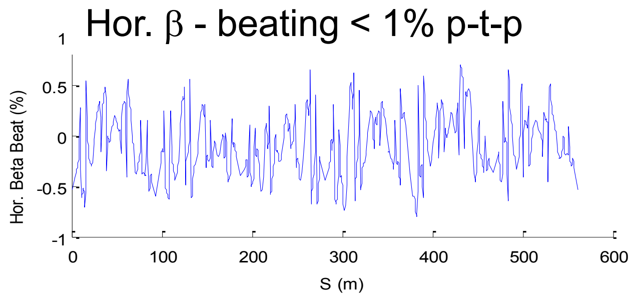
Energy	**3 GeV**
Circumference	**561.6 m**
No. cells	**24**
Symmetry	**6**
Straight sections	**6 x 8m, 18 x 5m**
Insertion devices	**4 x 8m, 18 x 5m**
Beam current	**300 mA (500 mA)**
Emittance (h, v)	**2.7, 0.03 nm rad**
Lifetime	**> 10 h**
Min. ID gap	**7 mm (5 mm)**
Beam size (h, v)	**123, 6.4 μm**
Beam divergence (h, v) ***(at centre of 5 m ID)***	**24, 4.2 μrad**
Beam size (h, v)	**178, 12.6 μm**
Beam divergence (h, v) ***(at centre of 8 m ID)***	**16, 2.2 μrad**

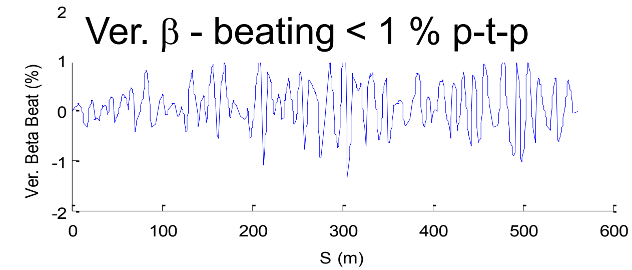
Linear optics modelling with LOCO

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





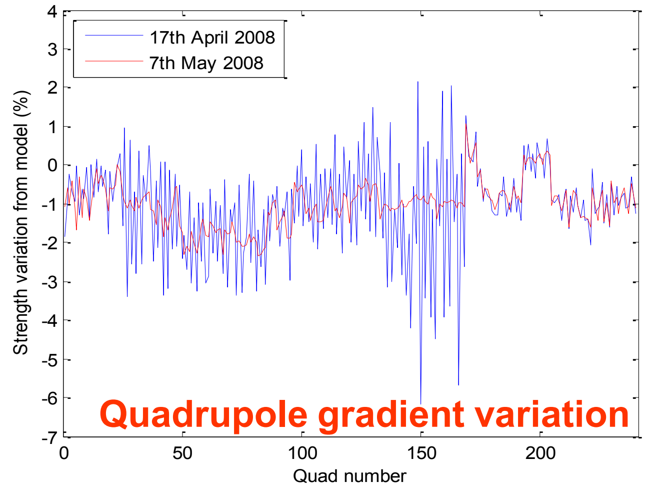




Modified version of LOCO with constraints on gradient variations **(see [ICFA Newsl, Dec'07])**

β - beating reduced to 0.4% rms

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

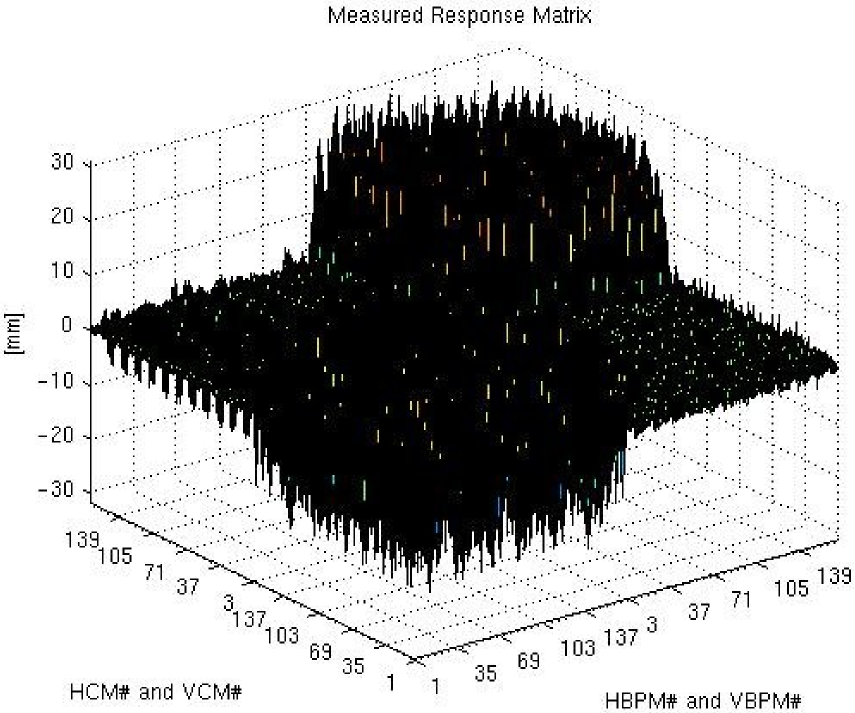


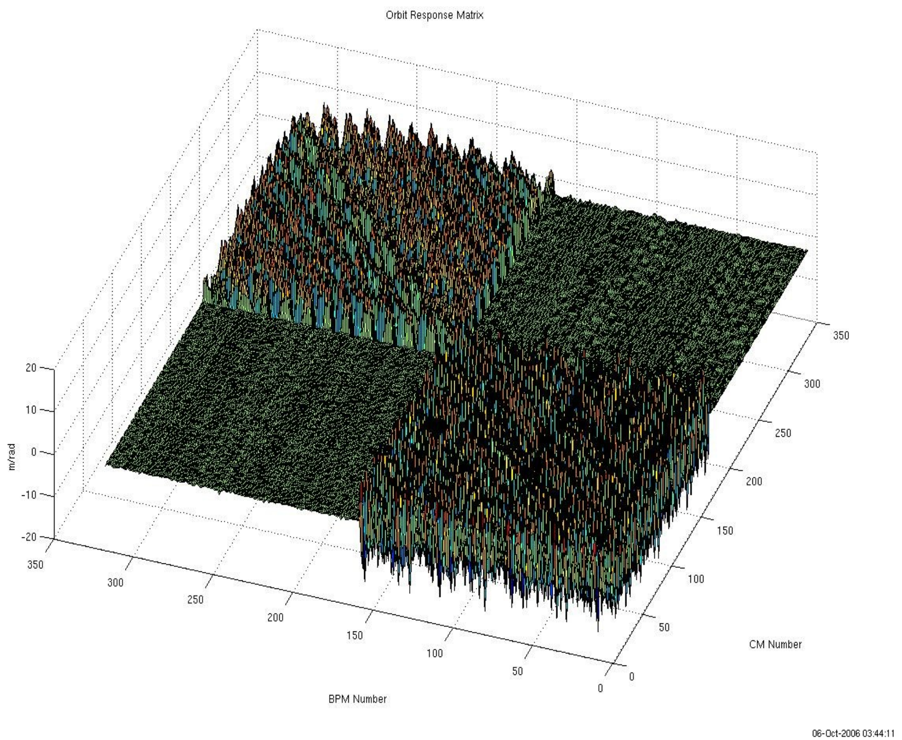
LOCO has solved the problem of the correct implementation of the linear optics

Linear coupling correction with LOCO

Skew quadrupoles can be simultaneously zero the off diagonal blocks of the measured response matrix and the vertical disperison

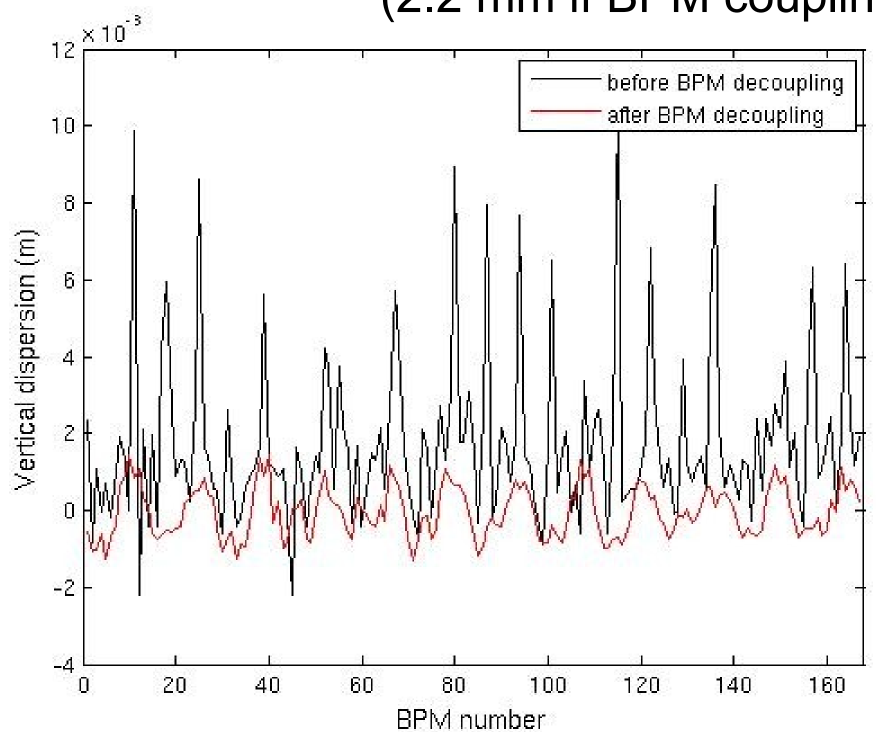
$$\chi^2(\overline{Q},\overline{G}_{BPMs},\overline{S}_q,\overline{k}_{BPMs},\ldots)=\sum_{i,j}\left(R_{ij}^{measured}-R_{ij}^{model}(\overline{Q},\overline{S}_q,\overline{G}_{BPMs},\overline{k}_{BPMs},\ldots)\right)^2$$





Residual vertical dispersion after correction

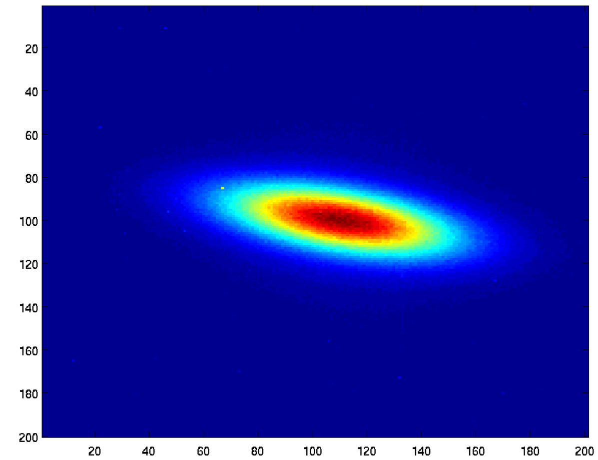
Without skew quadrupoles off	r.m.s. Dy = 14 mm
After LOCO correction	r.m.s. Dy = 700 µm
	(2.2 mm if BPM coupling is not corrected)



Measured emittances

Coupling without skew quadrupoles off K = 0.9%

(at the pinhole location; numerical simulation gave an average emittance coupling 1.5% ± 1.0 %)



Emittance [2.78 - 2.74] (2.75) nm

Energy spread [1.1e-3 - 1.0-e3] (1.0e-3)

After coupling correction with LOCO (2*3 iterations)

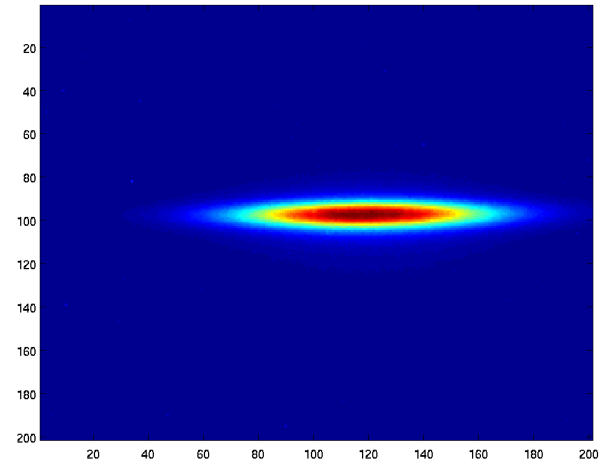
1st correction K = 0.15%

2nd correction K = 0.08%

V beam size at source point 6 μm

Emittance coupling 0.08% → **V emittance 2.2 pm**

Variation of less than 20% over different measurements

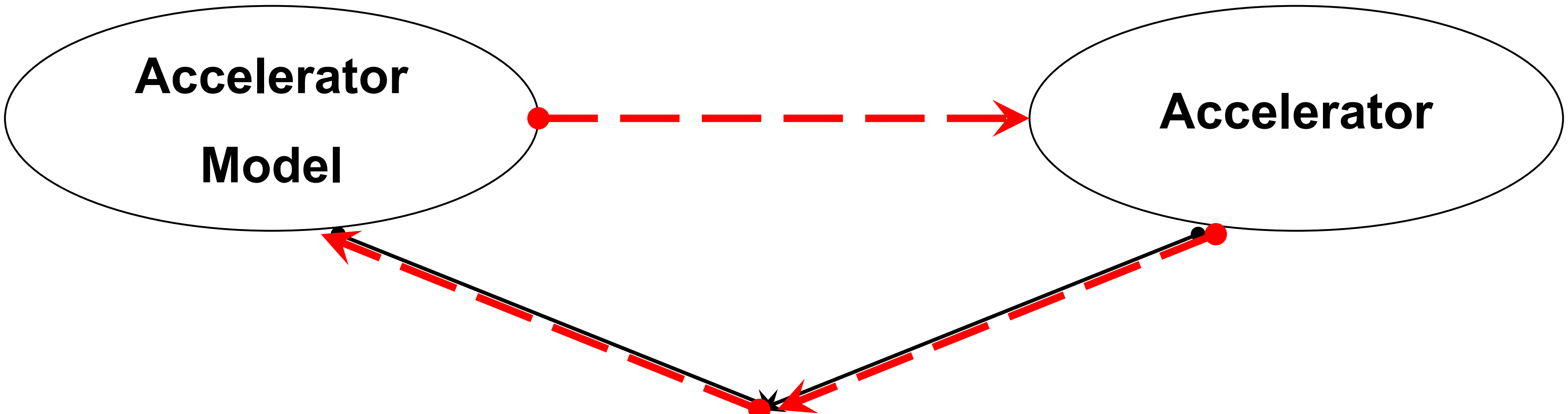


Comparison machine/model and Lowest vertical emittance

	Model emittance	Measured emittance	β-beating (rms)	Coupling* ($\varepsilon_y / \varepsilon_x$)	Vertical emittance
ALS	6.7 nm	6.7 nm	0.5 %	0.1%	4-7 pm
APS	2.5 nm	2.5 nm	1 %	0.8%	20 pm
ASP	10 nm	10 nm	1 %	0.01%	1-2 pm
CLS	18 nm	17-19 nm	4.2%	0.2%	36 pm
Diamond	2.74 nm	2.7-2.8 nm	0.4 %	0.08%	2.2 pm
ESRF	4 nm	4 nm	1%	0.1%	4.7 pm
SLS	5.6 nm	5.4-7 nm	4.5% H; 1.3% V	0.05%	2.0 pm
SOLEIL	3.73 nm	3.70-3.75 nm	0.3 %	0.1%	4 pm
SPEAR3	9.8 nm	9.8 nm	< 1%	0.05%	5 pm
SPring8	3.4 nm	3.2-3.6 nm	1.9% H; 1.5% V	0.2%	6.4 pm
SSRF	3.9 nm	3.8-4.0 nm	<1%	0.13%	5 pm

* best achieved

Comparison real lattice to model
linear and nonlinear optics



- Closed Orbit Response Matrix (LOCO)
- Frequency Map Analysis
- Frequency Analysis of betatron motion (resonance driving terms)

The calibrated nonlinear model is meant to **reproduce all the measured dynamical quantities,** giving us insight in which resonances affect the beam dynamics and possibility to **correct** them

Comparison real lattice to model
linear and nonlinear optics

Frequency Maps and amplitudes and phases of the spectral line of the betatron motion can be used to compare and correct the real accelerator with the model

LOCO

Closed Orbit Response Matrix
from model

Closed Orbit Response Matrix
measured

fitting quadrupoles, etc → Linear lattice correction/calibration

R. Bartolini and F. Schmidt in PAC05

Spectral lines + FMA
from model

Spectral Lines + FMA
measured

fitting sextupoles and higher order multipoles → Nonlinear lattice correction/calibration

Combining the complementary information from FM and spectral line should allow the calibration of the nonlinear model and a full control of the nonlinear resonances

Frequency map and detuning with momentum comparison machine vs model (I)

Using the measured **Frequency Map** and the measured **detuning with momentum** we can build a fit procedure to calibrate the nonlinear model of the ring

Accelerator Model	Accelerator
$\downarrow$	$\downarrow$
• tracking data	• BPMs data with kicked beams
• build FM and detuning with momentum	• measure FM and detuning with momentum

$$\overline{A}_{target} = (Q_x[(x,y)_1],\ldots,Q_x[(x,y)_n],Q_y[(x,y)_1],\ldots,Q_y[(x,y)_n],\ldots$$

$$\ldots,Q_x(\delta_1),\ldots,Q_x(\delta_m),Q_y(\delta_1),\ldots,Q_y(\delta_m))$$

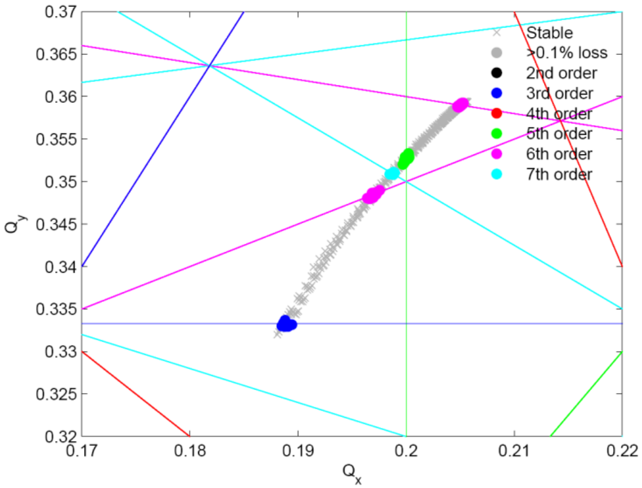
The distance between the two vectors

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

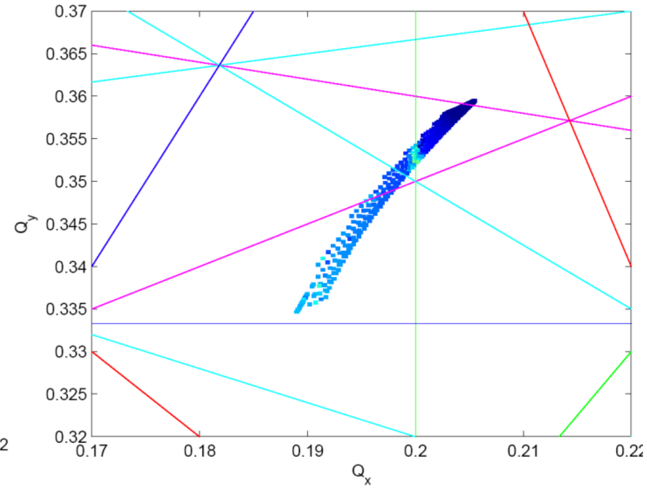
can be used for a Least Square Fit of the sextupole gradients to minimise the distance χ2 of the two vectors

Frequency map and detuning with momentum comparison machine vs model (I)

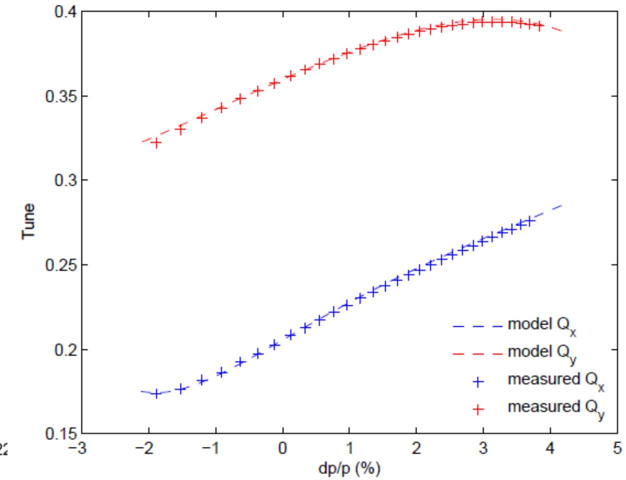
FM measured



FM model



detuning with momentum model and measured



Sextupole strengths variation less than 3%

The most complete description of the nonlinear model is mandatory !

Measured multipolar errors to dipoles, quadrupoles and sextupoles (up to b10/a9)

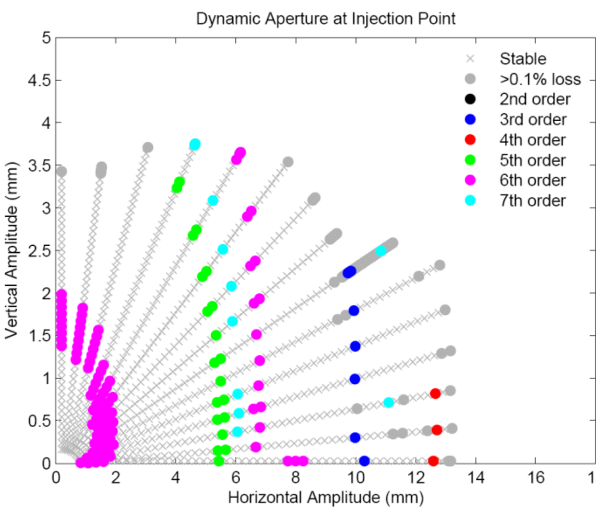
Correct magnetic lengths of magnetic elements

Fringe fields to dipoles and quadrupoles

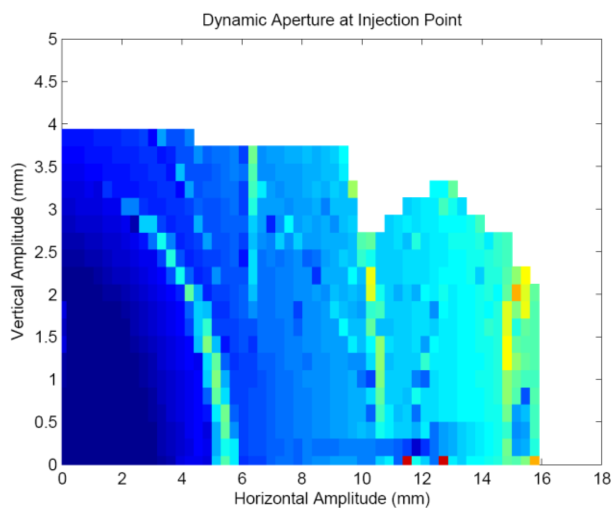
Substantial progress after correcting the frequency response of the Libera BPMs

Frequency map and detuning with momentum comparison machine vs model (II)

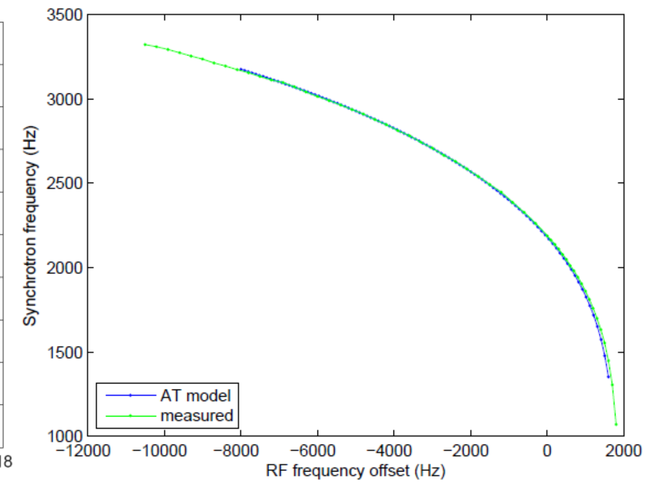
DA measured



DA model



Synchrotron tune vs RF frequency

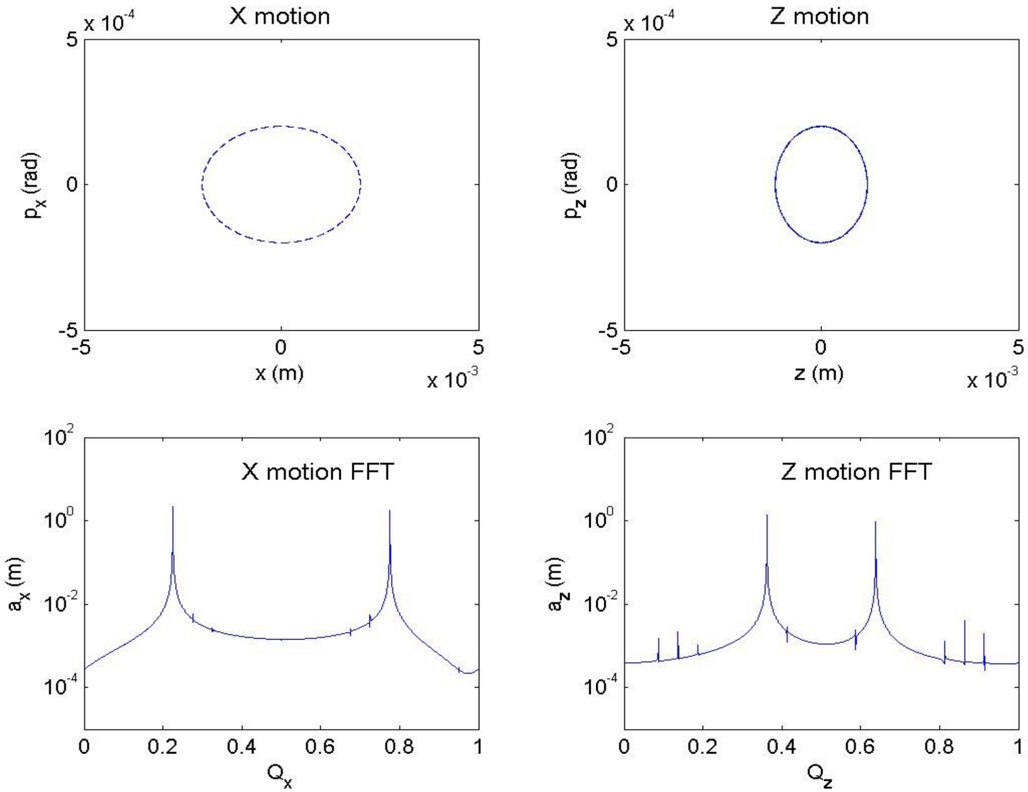


The fit procedure based on the reconstruction of the measured FM and detunng with momentum describes well the **dynamic aperture**, the **resonances excited** and the dependence of the **synchrotron tune vs RF frequency**

R. Bartolini et al. Phys. Rev. ST Accel. Beams 14, 054003

Frequency Analysis of betatron motion

Example: Spectral Lines for tracking data for the Diamond lattice



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

Each spectral line can be associated to a resonance driving term

J. Bengtsson (1988): CERN 88–04, (1988).
R. Bartolini, F. Schmidt (1998), Part. Acc., **59**, 93, (1998).
R. Tomas, PhD Thesis (2003)

All diamond BPMs have turn-by-turn capabilities

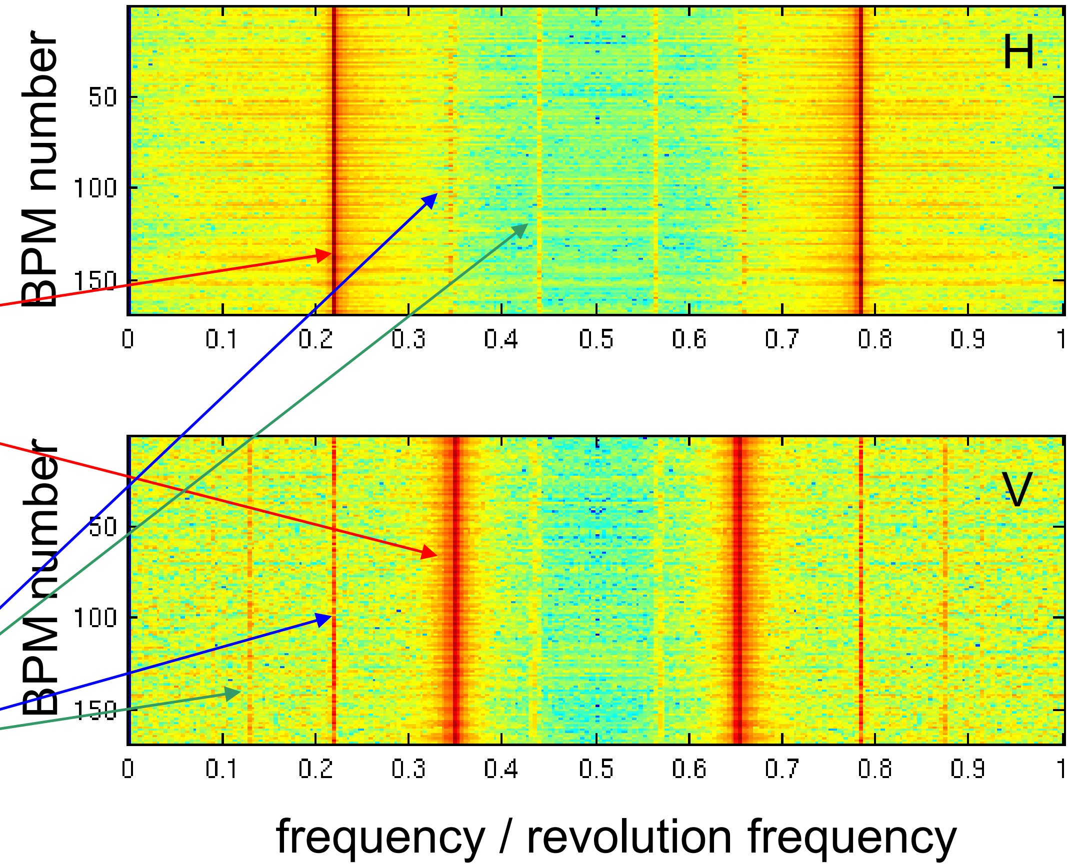
- excite the beam diagonally
- measure tbt data at all BPMs
- colour plots of the FFT

Q_X = 0.22 H tune in H

Q_y = 0.36 V tune in V

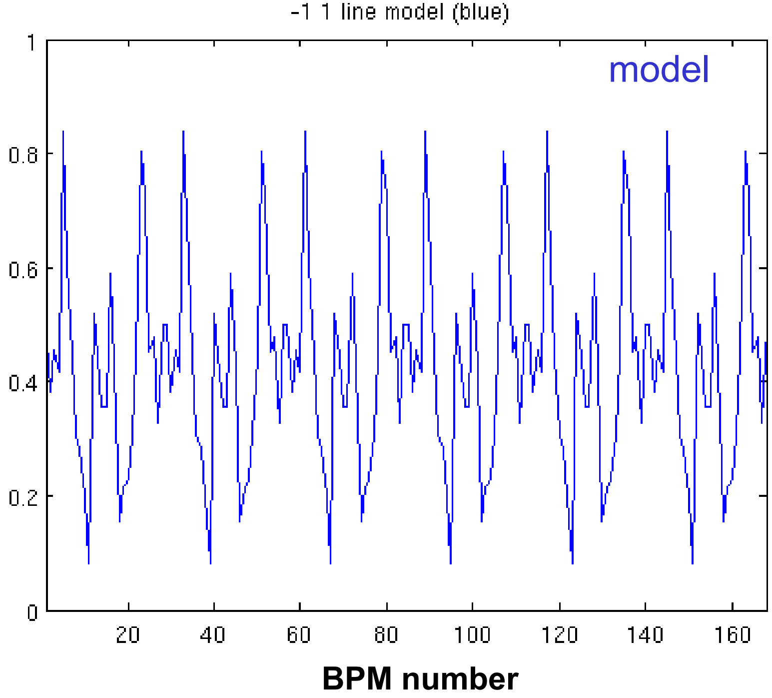
All the other important lines are linear combination of the tunes Q_x and Q_y

$m\,Q_x + n\,Q_y$

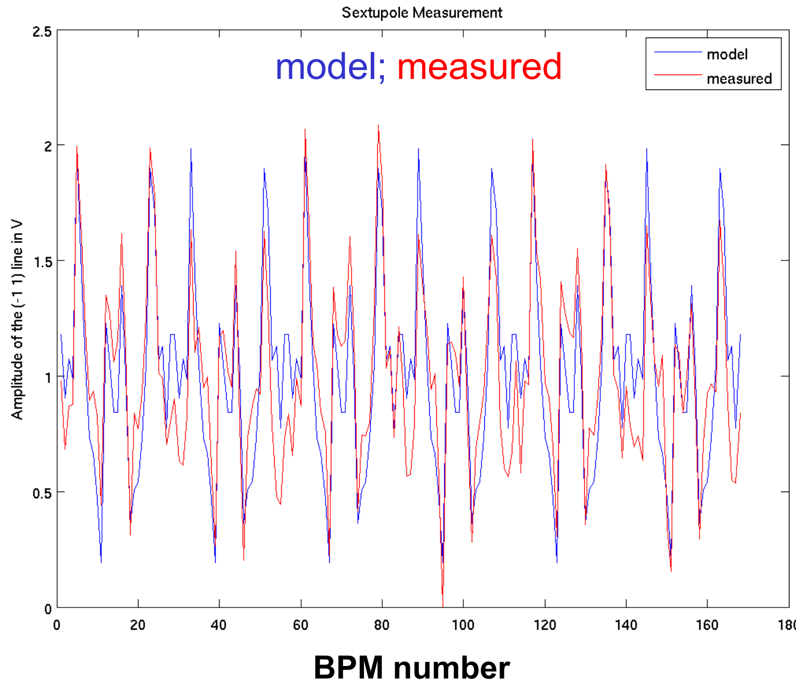


Spectral line (-1, 1) in V associated with the sextupole resonance (-1,2)

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



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



Frequency Analysis of Betatron Motion and Lattice Model Reconstruction

Using the measured amplitudes and phases of the spectral lines of the betatron motion we can build a fit procedure to calibrate the nonlinear model of the ring

Accelerator Model

- tracking data at all BPMs
- spectral lines from model (NAFF)

Accelerator

- beam data at all BPMs
- spectral lines from BPMs signals (NAFF)

e.g. targeting more than one line

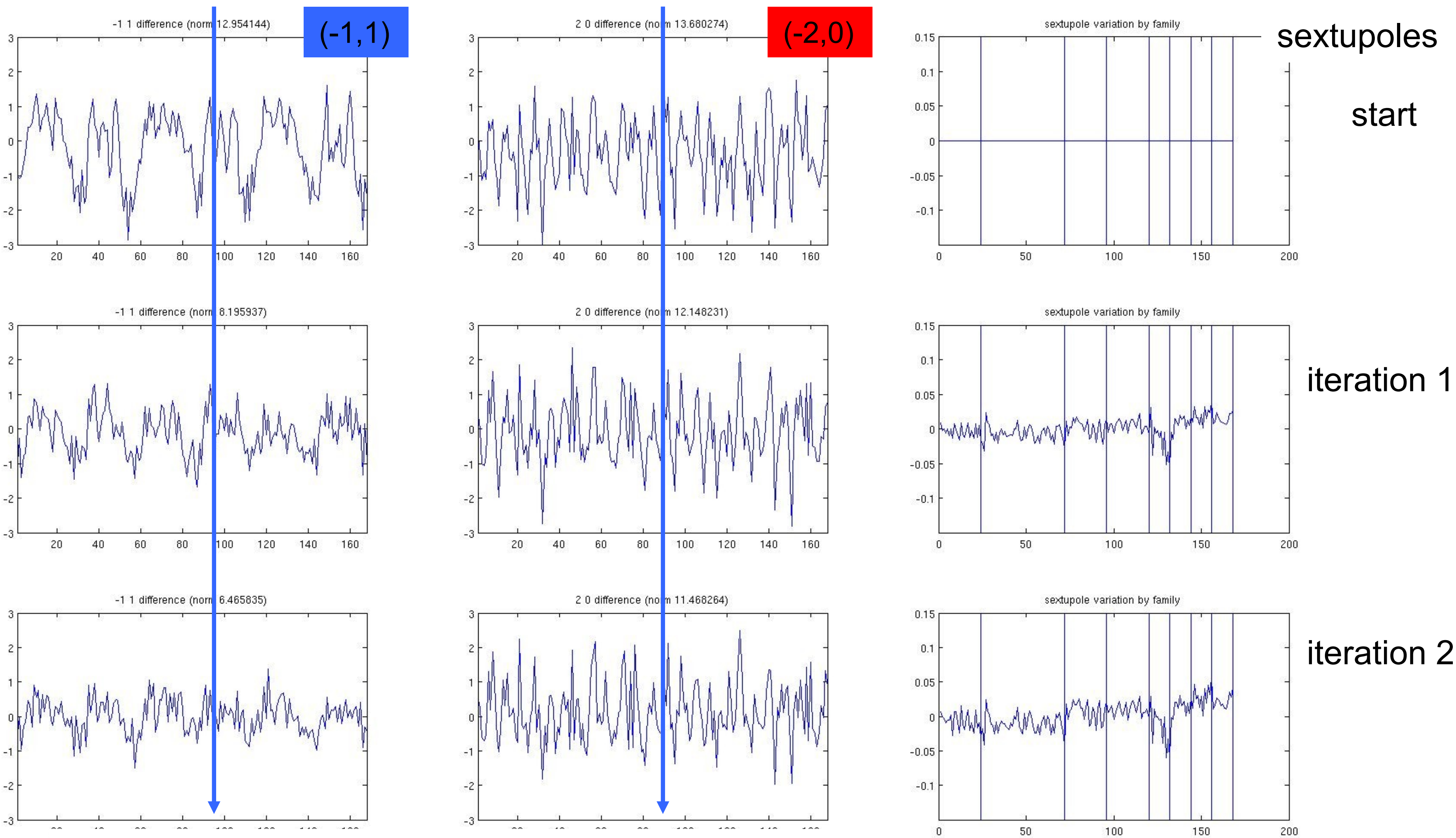
$$\overline{A} = \left(a_1^{(1)} \quad \ldots \quad a_{NBPM}^{(1)} \quad \varphi_1^{(1)} \quad \ldots \quad \varphi_{NBPM}^{(1)} \quad a_1^{(2)} \quad \ldots \quad a_{NBPM}^{(2)} \quad \varphi_1^{(2)} \quad \ldots \quad \varphi_{NBPM}^{(2)} \quad \ldots \right)$$

Define the distance between the two vector of Fourier coefficients

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

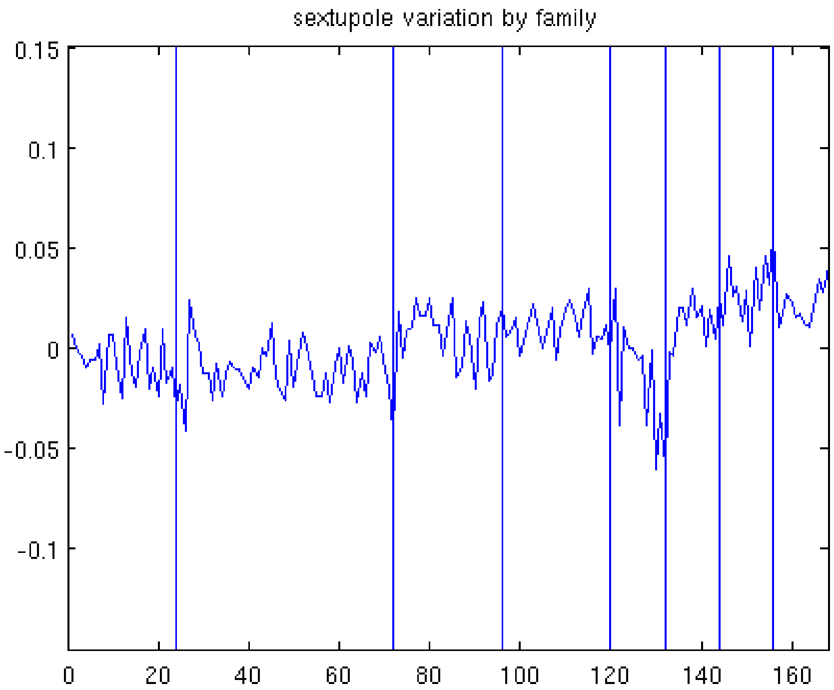
Least Square Fit of the sextupole gradients to minimise the distance χ2 of the two Fourier coefficients vectors

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%)

Limits of the Frequency Analysis techniques

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,

BPM nonlinearities corrected as per R. Helms and G. Hofstaetter PRSTAB 2005
BPM frequency response can be corrected with a proper deconvolution of the time filter used to built t-b-t data form the ADC samples R. Bartolini subm. to PRSTAB

Conclusions

A very good control of the linear optics was achieved at the diamond sto[illegible]ing

The ***beta-beating*** is corrected to less than 1% p-t-p and the ***line[illegible]ng*** reduced to less than 0.1% with a vertical emittance of abou[illegible]

Building upon this excellent correction of the lin[illegible], we have studied new techniques for the analysis and the correcti[illegible] nonlinear beam dynamics.

Frequency Map analysis and [illegible] ***lines analysis*** have been used to calibrate the nonlinear ring model of [illegible]ond storage ring.

The ***calibrate[illegible]*** [illegible]s capable of reproducing the measured values of the main dynamica[illegible]s that characterise the nonlinear beam dynamics .

Thank you for your attention