Nonlinear resonances measurement and correction in storage rings

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Outline

- Introduction to the diamond storage ring
- Analysis of nonlinear resonances
  - Spectral lines analysis and resonance driving terms
  - Frequency Maps
  - Calibration of the nonlinear ring model
- Limits of the methods
- Conclusions and ongoing work
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

- 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): 24, 4.2 µrad (at centre of 5 m ID)

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
All BPMs have t-b-t- capabilities
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
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**

Accelerator Model → Accelerator

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

Each spectral line can be associated to a resonance driving term

All diamond BPMs have turn-by-turn capabilities

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

\[ Q_x = 0.22 \text{ H tune in H} \]
\[ Q_y = 0.36 \text{ V tune in V} \]

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

\[ m \, Q_x + n \, Q_y \]
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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

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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

$$\vec{A} = (a_1^{(1)} \ldots a_{NBPM}^{(1)} \ \varphi_1^{(1)} \ldots \varphi_{NBPM}^{(1)} \ a_1^{(2)} \ldots a_{NBPM}^{(2)} \ \varphi_1^{(2)} \ldots \varphi_{NBPM}^{(2)} \ldots)$$

Define the distance between the two vector of Fourier coefficients

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

Least Square Fit of the sextupole gradients to minimise the distance $\chi^2$ of the two Fourier coefficients vectors
Simultaneous fit of (-2,0) in H and (1,-1) in V

-1.1 difference (norm: 12.954144)

-2.0 difference (norm: 13.880274)

-1.1 difference (norm: 0.192037)

-2.0 difference (norm: 12.140231)

-1.1 difference (norm: 0.485539)

-2.0 difference (norm: 11.455264)

Sextupoles start

Iteration 1

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

Both resonance driving terms are decreasing

(-1,1)  (-2,0)
Sextupole variation

Now the sextupole variation is limited to < 5%

Both resonances are controlled

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

\[ \bar{A}_{\text{target}} = (Q_x[(x, y)_1],..., Q_x[(x, y)_n], Q_y[(x, y)_1],..., Q_y[(x, y)_n],...,) \]

The distance between the two vectors

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

can be used for a Least Square Fit of the sextupole gradients to minimise the distance \( \chi^2 \) of the two vectors.
Sextupole strengths variation less than 3%

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