Low Emittance Rings Workshop 2011

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Non-linear dynamics optimization in low emittance rings: from model to experiments

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Outline

- Introduction
- Comparing Model and Measurements
  - – Orbit response matrix analysis
  - – Frequency map Analysis
    - On / Off energy
  - – RF scan / Touschek lifetime scan
  - – Tunescans
  - – Resonance Driving Terms
- Summary

Introduction

- *The dynamic aperture limits the performance in many current accelerators. To optimize the performance a good knowledge of the machine model is required. To achieve the required accuracy of the machine model, beam based measurements have proven to be essential.*
- Nonlinear dynamics (usually) limits the performance of low emittance storage rings
  - On-energy → Dynamic Aperture → Injection Efficiency, elastic Gas Lifetime
  - Off-energy → Momentum Aperture (limit is typically off-energy transverse dynamics!) → Touschek, inelastic Gas Lifetime, damping ring positron injection

Goals of Measurements

1. Calibrate Machine Model
    - Linear, Coupled
    - Nonlinear (potentially including fringe field, ID effects)
2. Predict performance, develop performance improvements
    - Lattice symmetrization, ID shimming, …
3. Provide model independent ideas for optimization direction

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

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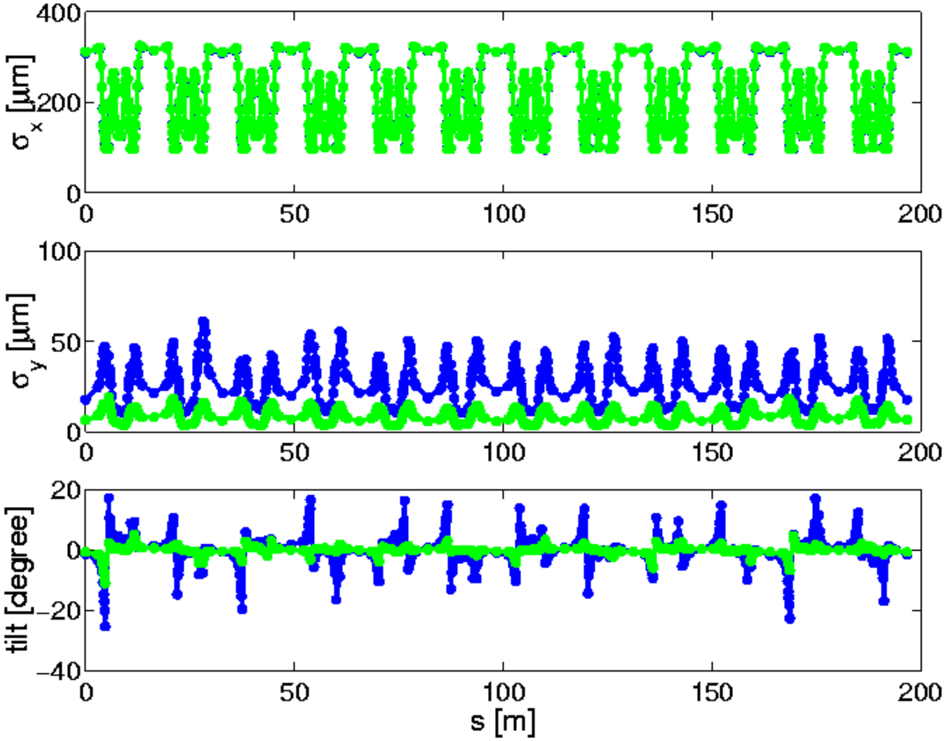
Orbit Response Matrix Analysis

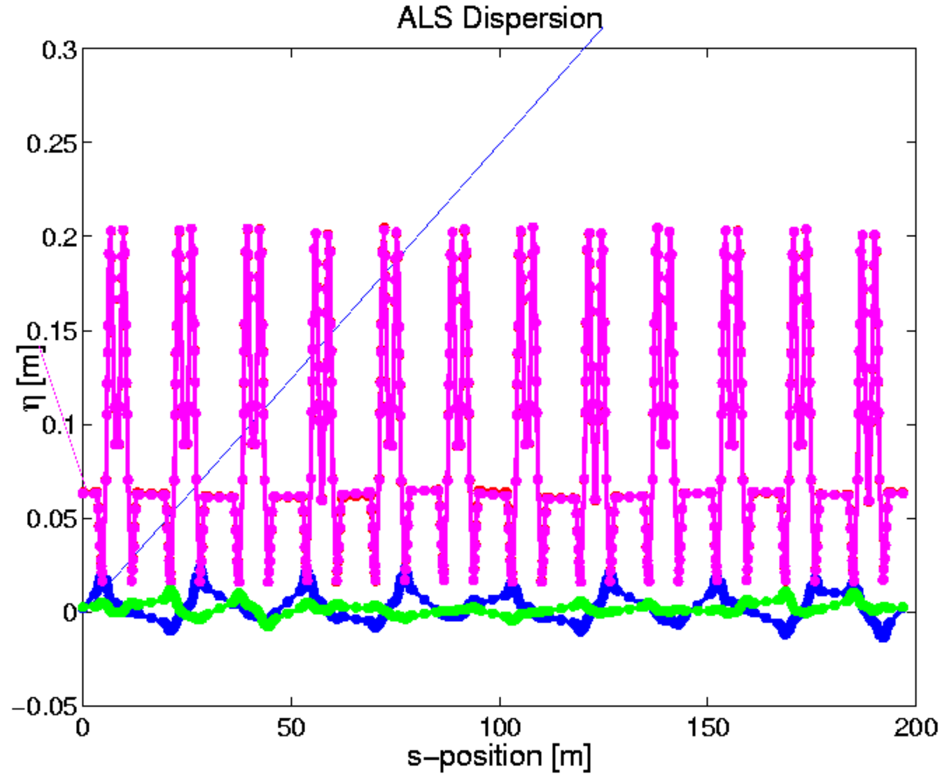
- Orbit response matrix analysis has been used for several years to quantify gradient and skew gradient errors using the beam
- Many local bay area experts (SLAC/SSRL, LBNL): Main code used nowadays is LOCO (Linear Optics from Closed Orbits), originally developed by J. Safranek (now at SSRL)
- Orbit response matrix analysis has been used with great success at nearly all light sources and many colliders.
- Measure a closed orbit response matrix, and adjust parameters in a lattice model to reproduce the measured matrix:

$$C_{12}^{ij} = \left[R^{ij}\left(1 - R^{jj}\right)^{-1}\right]_{12} - \frac{\eta_i \eta_j}{\left(\alpha - \frac{1}{\gamma^2}\right)C}$$

$$\hat{C}^{ij} = C^{ij} + \sum_k \frac{\partial C^{ij}}{\partial g_k}\delta g_k + C^{ij}\Delta x^i + C^{ij}\Delta y^j$$

Example: Emittance and Dispersion Correction





- **In this example vertical beamsize reduced by factor >4**
  —emittance by factor 20
- **Vertical dispersion reduced from 7 to below 3 mm rms**
- **Tilt of phase space reduced significantly everywhere**

Response Matrix Fit: Status

- Nowadays response matrix analysis is standard tool
  - Speed and memory restrictions are things of the past
  - Linear + coupled models, very high accuracy
    - <1% beta beating, <0.1% emittance ratio (1 pm)
  - Can be used for additional purposes
    - Local chromaticity
    - Distribution of broad band impedance
    - …

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Frequency Map Analysis

Originally developed by Jacques Laskar for celestial dynamics application – first accelerator applications in cooperation with ALS

The frequency analysis algorithm (NAFF) is a postprocessor for particle tracking data or turn-by-turn BPM data that numerically computes, over a finite time span, a frequency vector for any initial condition.

Frequency Map: Initial condition $\longrightarrow$ Frequency vector

Based on the KAM theorem frequency map analysis determines whether an orbit is regular or chaotically diffusing (in a phase space that is sufficiently close to an integrable conservative system, many invariant tori will persist. Trajectories starting on one of these tori remain on it thereafter, executing **quasiperiodic motion with a with a fixed frequency vector** depending only on the torus)**.**

Regular orbits $\longrightarrow$ Frequency vector remains fixed in time

Nonregular orbits $\longrightarrow$ Frequency vector changes in time

Allows quantitative analysis of how regular (or chaotic) particle motion is – important additional information beyond 'hard' dynamic aperture

Tunes and Diffusion Rates

TRACKING CODE + FREQUENCY ANALYSIS POSTPROCESSOR

Track particle for **N** turns

↓

Compute horizontal and vertical tunes
ν_{x1} and ν_{y1}

↓

Track particle for another **N** turns

↓

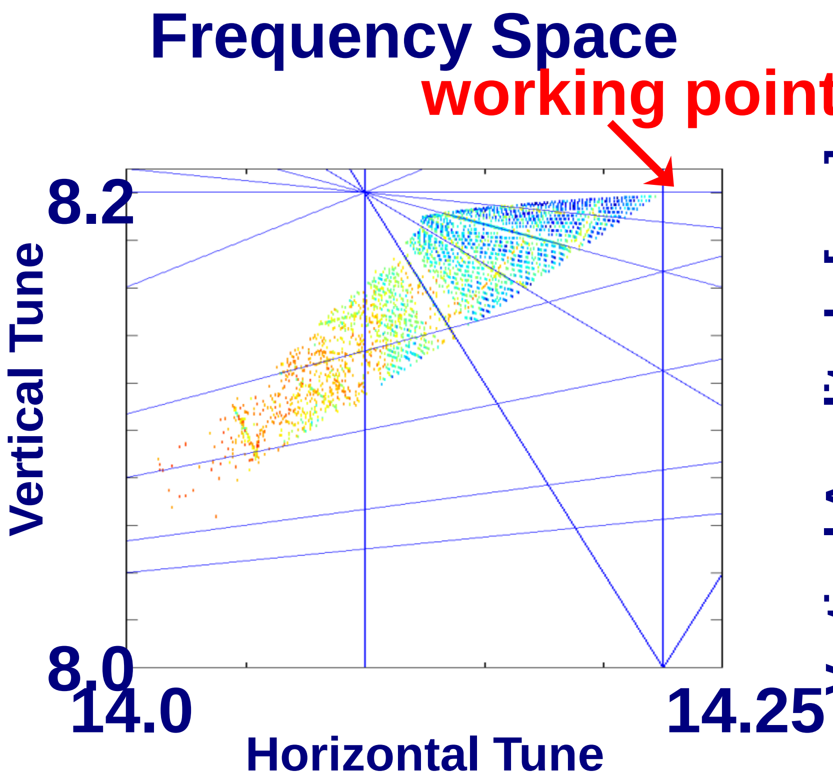
Compute horizontal and vertical tunes
ν_{x2} and ν_{y2}

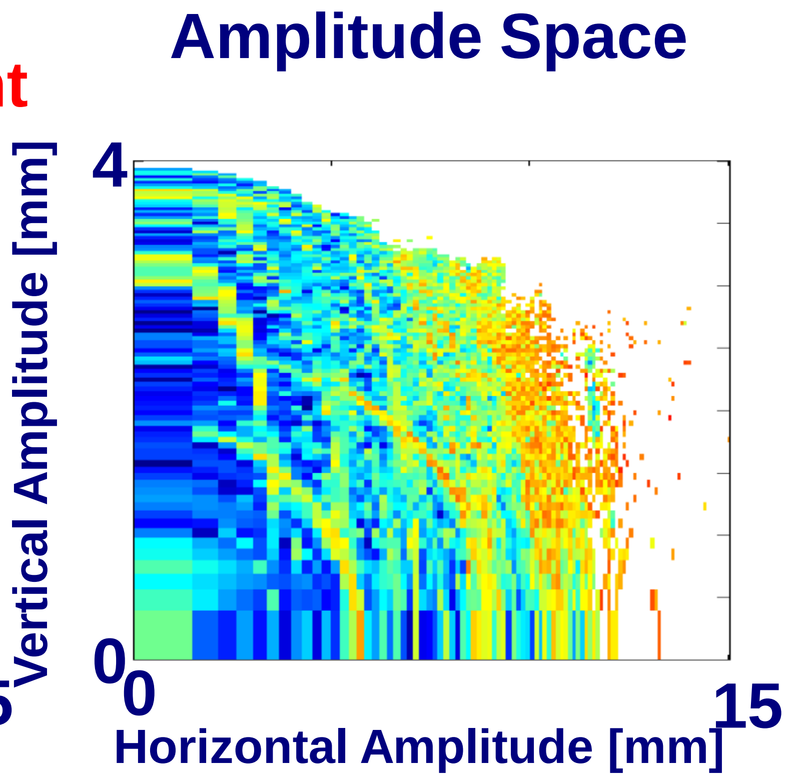
Compute diffusion rates

$$\frac{\partial \nu_x}{\partial \tau} \approx \frac{\nu_{x2} - \nu_{x1}}{N}$$

$$\frac{\partial \nu_y}{\partial \tau} \approx \frac{\nu_{y2} - \nu_{y1}}{N}$$

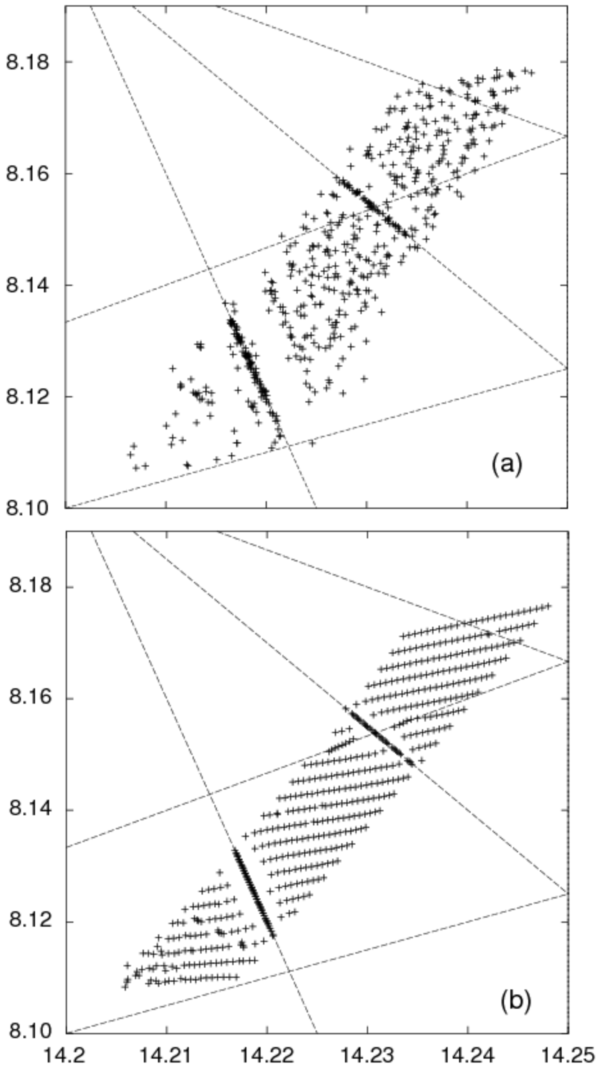
Frequency Map Analysis





- **Provides insight on**
  - —**why problem occurs**
  - —**How to improve dynamics**
  - —**Quantitative comparison**

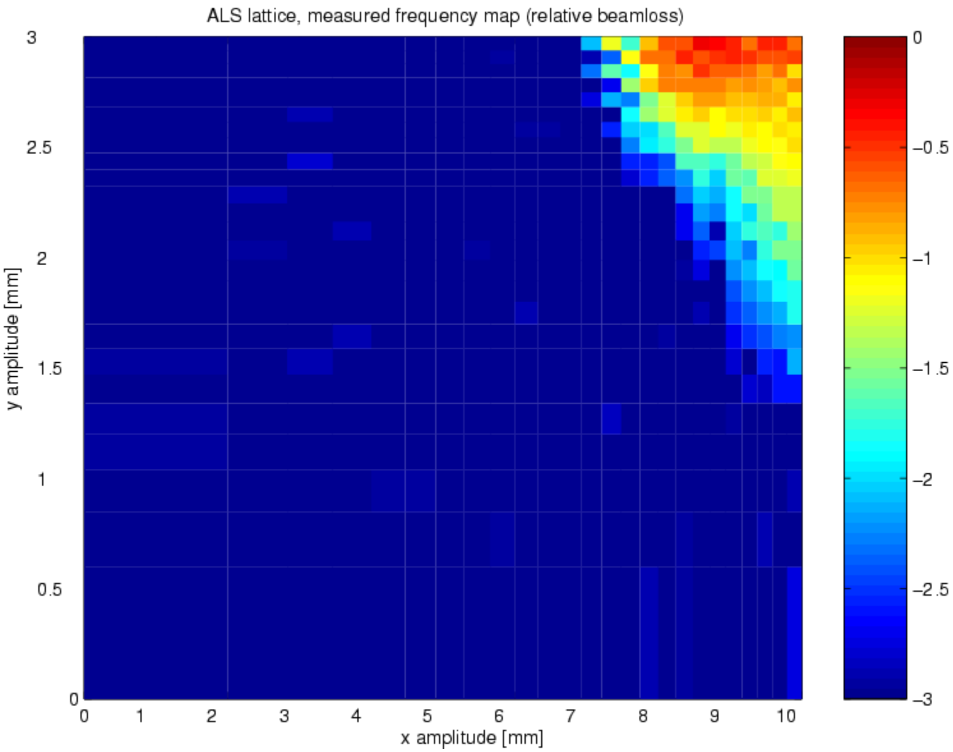
Measured Frequency Map

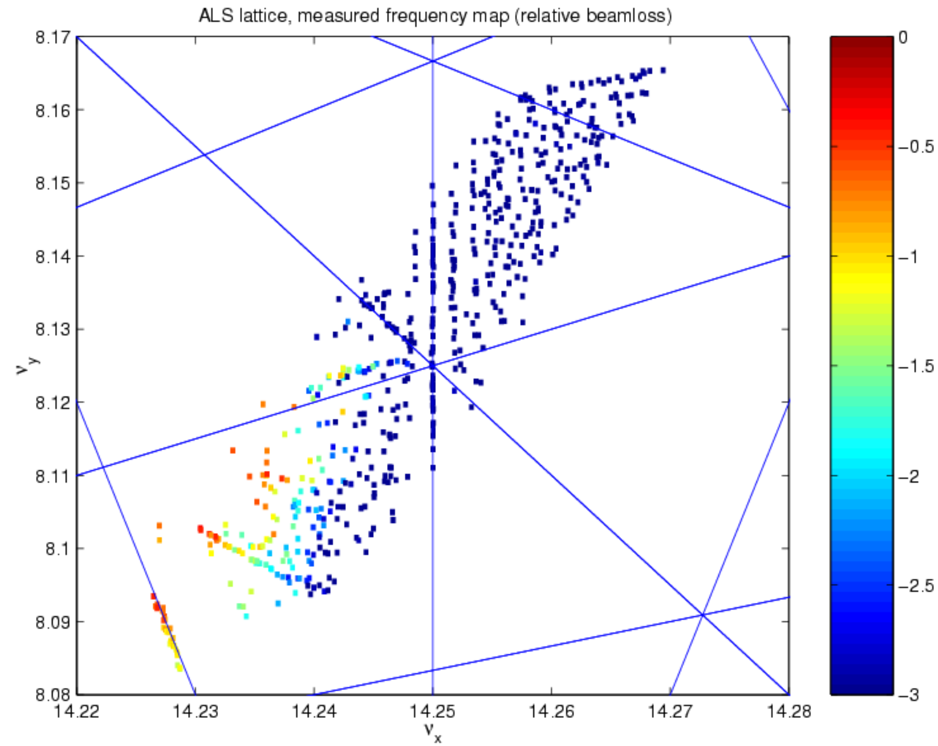


- Allows precise comparison of nonlinear model of lattice and real machine
- At ALS reached good agreement between measured and calculated frequency maps, using calibrated model (gradient and skew gradient errors) and nominal sextupolse
  - Later also included nonlinear maps of insertion devices (particularly elliptically polarizing undulators)
- Provides model independent evaluation of how good transverse nonlinear lattice properties are
- Provides guidance for optimization

Phys. Rev. Lett 85, 3 (2000), 558

Measured Frequency Map/Beam Loss

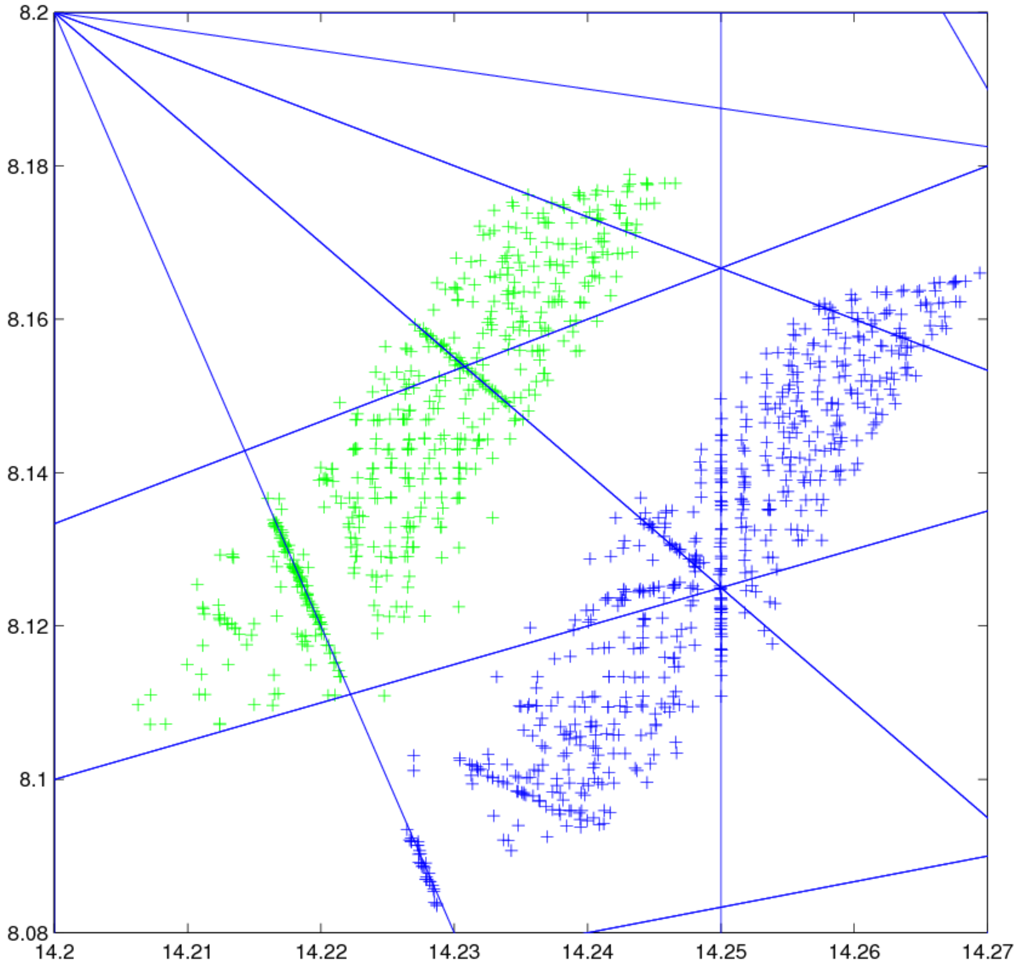




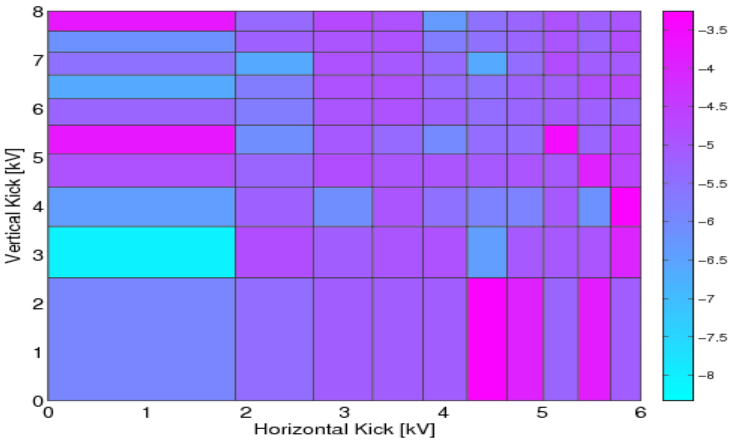
- Partial Beam Loss mostly if particles have to pass (radiation damping) through resonance intersection
- Isolated resonances not dangerous.

Side remark: Spectra contain more information than just fundamental frequencies – other resonance lines – resonance strength versus amplitude (see R. Bartolini, et al.).

Model independent evaluation of dynamics



- Frequency map analysis allows to model independently evaluate how regular beam motion is
- Recently also tried to measure diffusion rates (multi BPM) – remains challenging

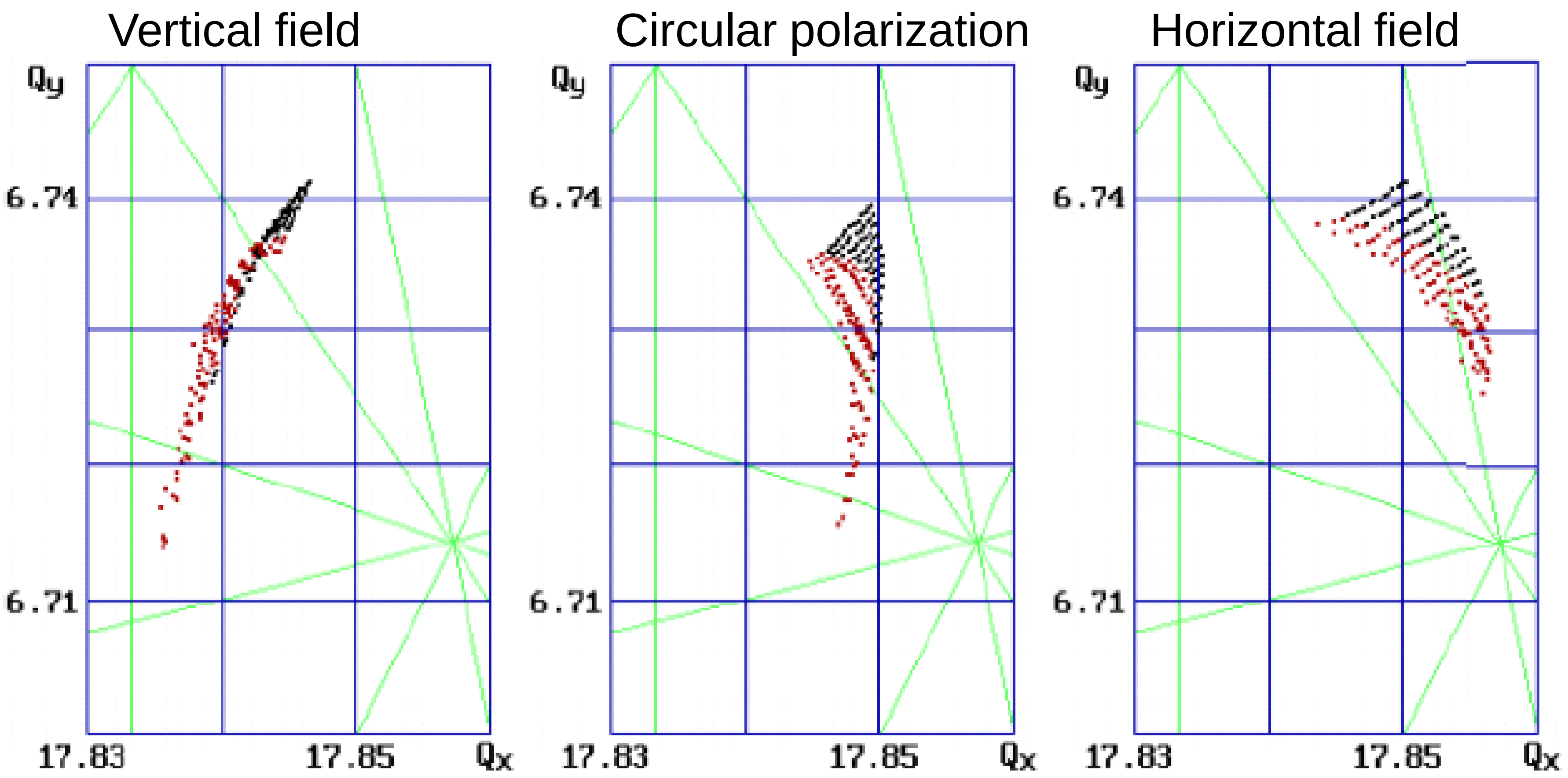


What needs to be included in model

- At ALS (and APS, many early 3^{rd} generation LS, which have large, systematic, uncompensated detuning with amplitude…), accurate, calibrated coupled linear model + design multipoles + simple ID models used to be enough
- Later on, needed to include accurate nonlinear insertion device models
- Other places need to include dipole (+multipole) fringe fields, other measured magnet properties …

Frequency map measurements at BESSY-II

- Beam dynamics highly dependent on EPU row phase.
- Dynamic aperture reduction induced injection losses



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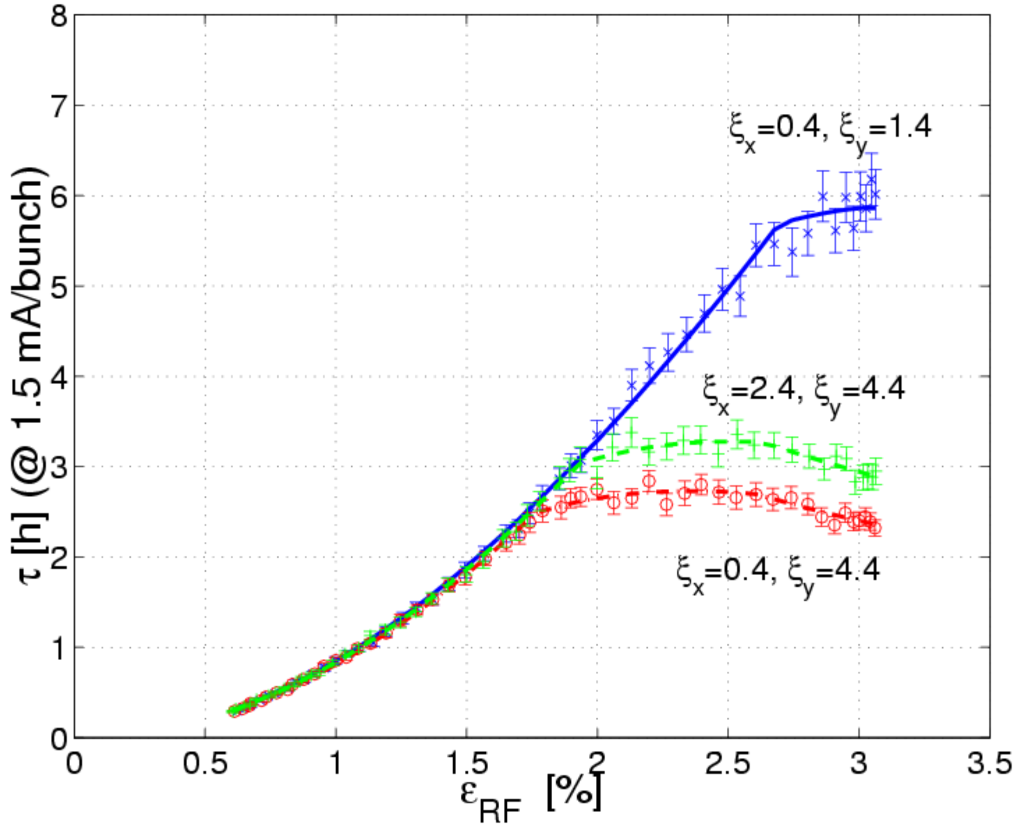
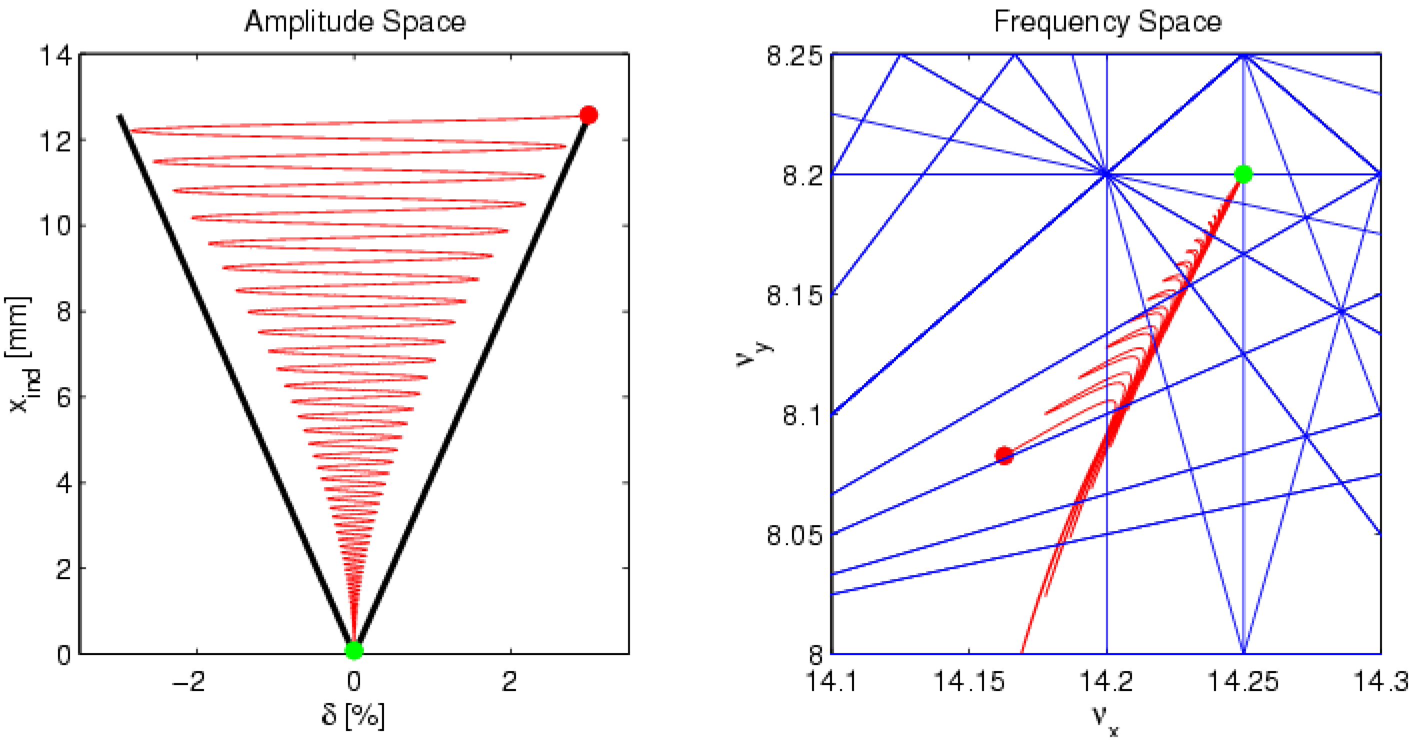
RF amplitude scans



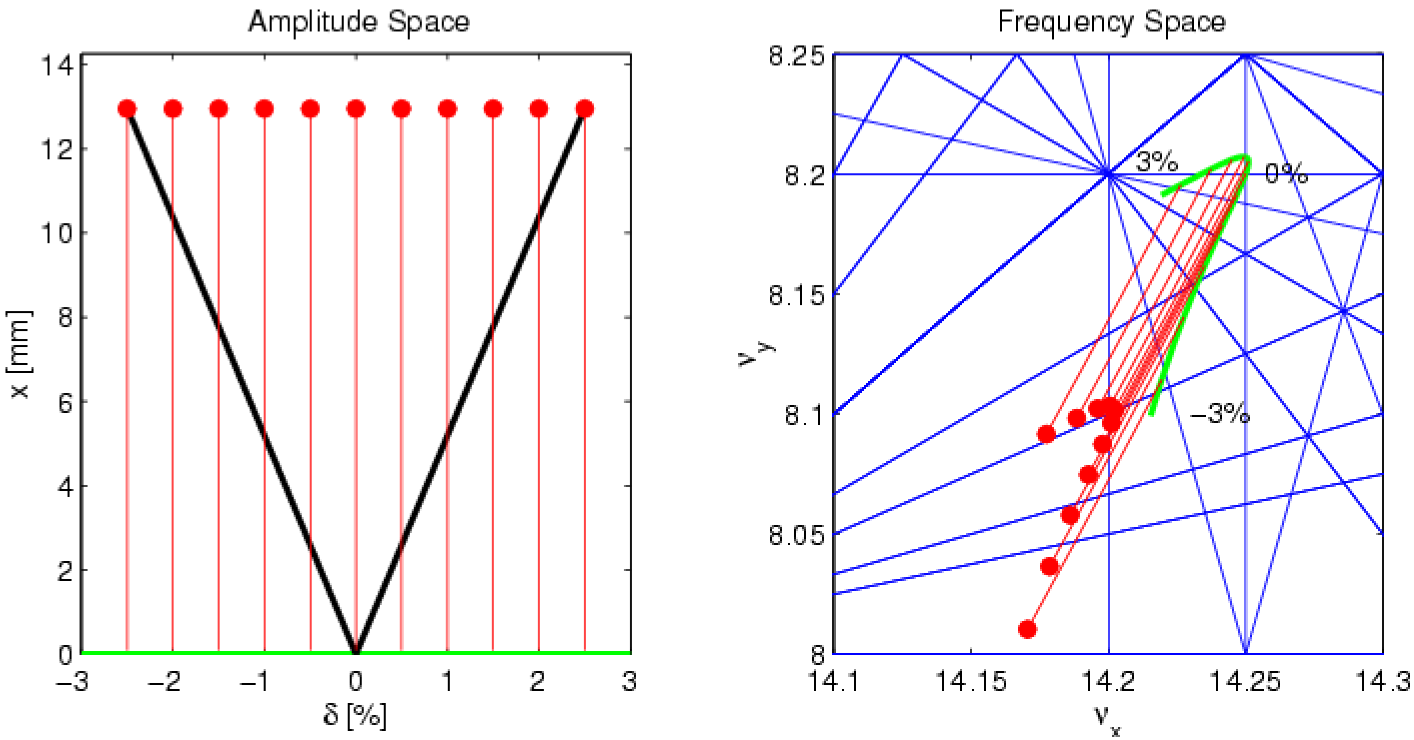
- Momentum aperture in ALS is clearly impacted by dynamics
- Sensitivity to chromaticity is at first surprisingly large (sextupole strength only different by a few percent).

Touschek Scattering – Tune Shift – Particle Loss



- Particle losing/gaining energy – horiz. oscillation (dispersion/H-function) + long. Oscillation
- Particle changes tune
  - Synchrotron oscillations (chromaticity)
  - Radiation damping (detuning with amplitude and chromaticity)
- During damping process particle can encounter region in tune space where motion gets resonantly excited.

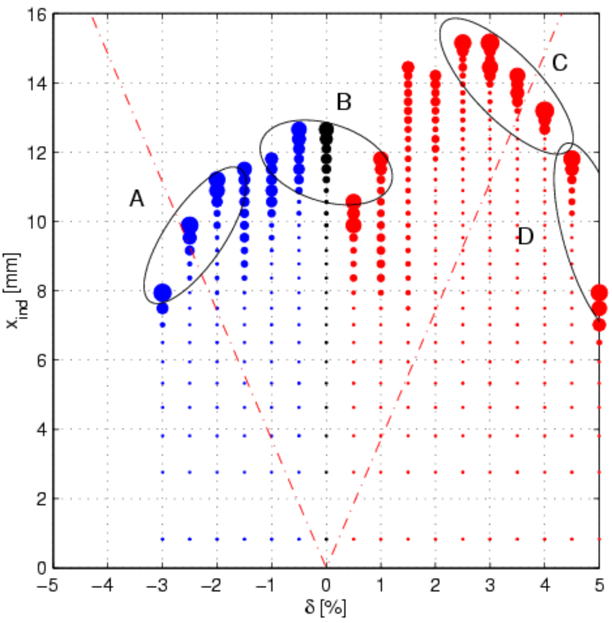
Measurement principle

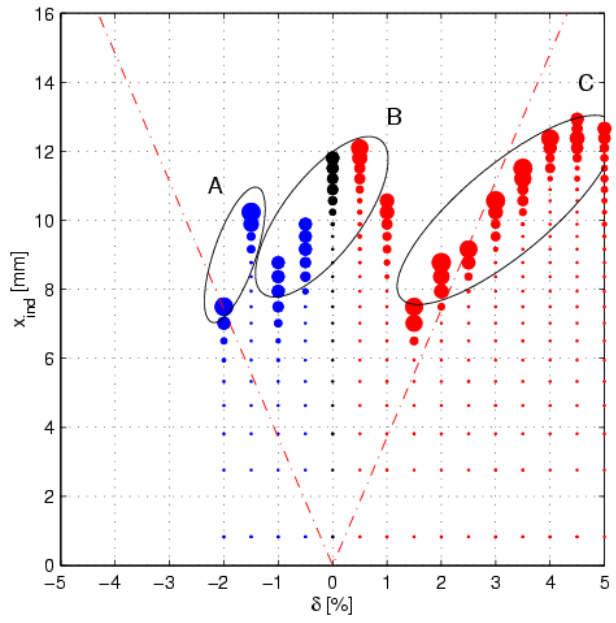


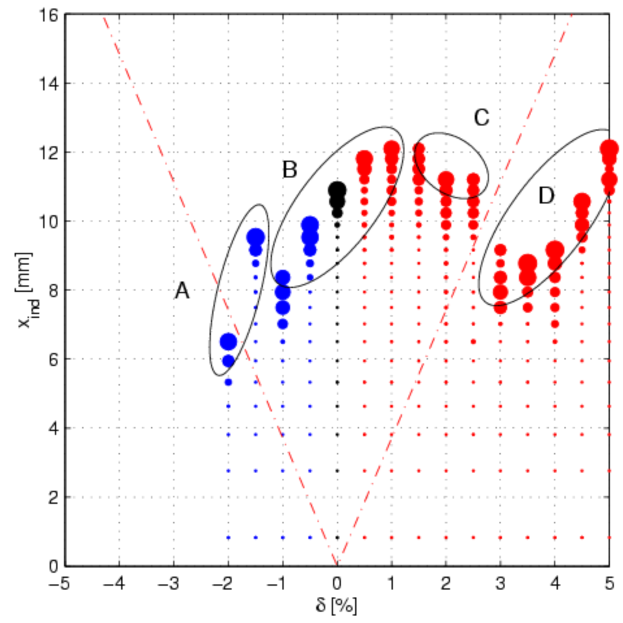
- **Experimentally very difficult to exactly simulate Touschek scattering (simultanous kicks) – also difficult to measure tunes during synchrotron oscillations**
  - **Some positive results (Y. Papaphilippou et al.)**
- **Still possible to locate loss regions when scanning only transverse amplitude while keeping energy offset fixed**

Aperture Scan for 3 Different Chromaticities

Small horiz. Chromaticity Small vert.	Small horiz. Large vert.	Large horiz. Large vert.



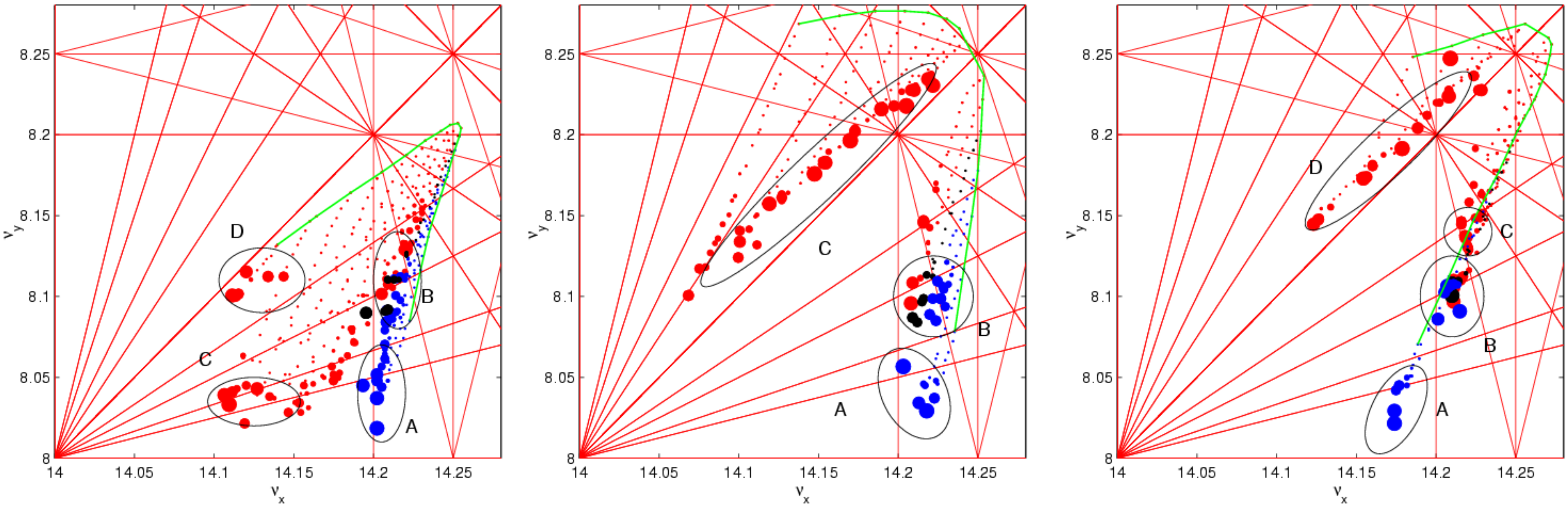




$\varepsilon > 3$ % straight 2.65 % arcs	$\varepsilon = 2.6$ % straight 1.75 % arcs	$\varepsilon = 2.6$ % straight 1.9 % arcs

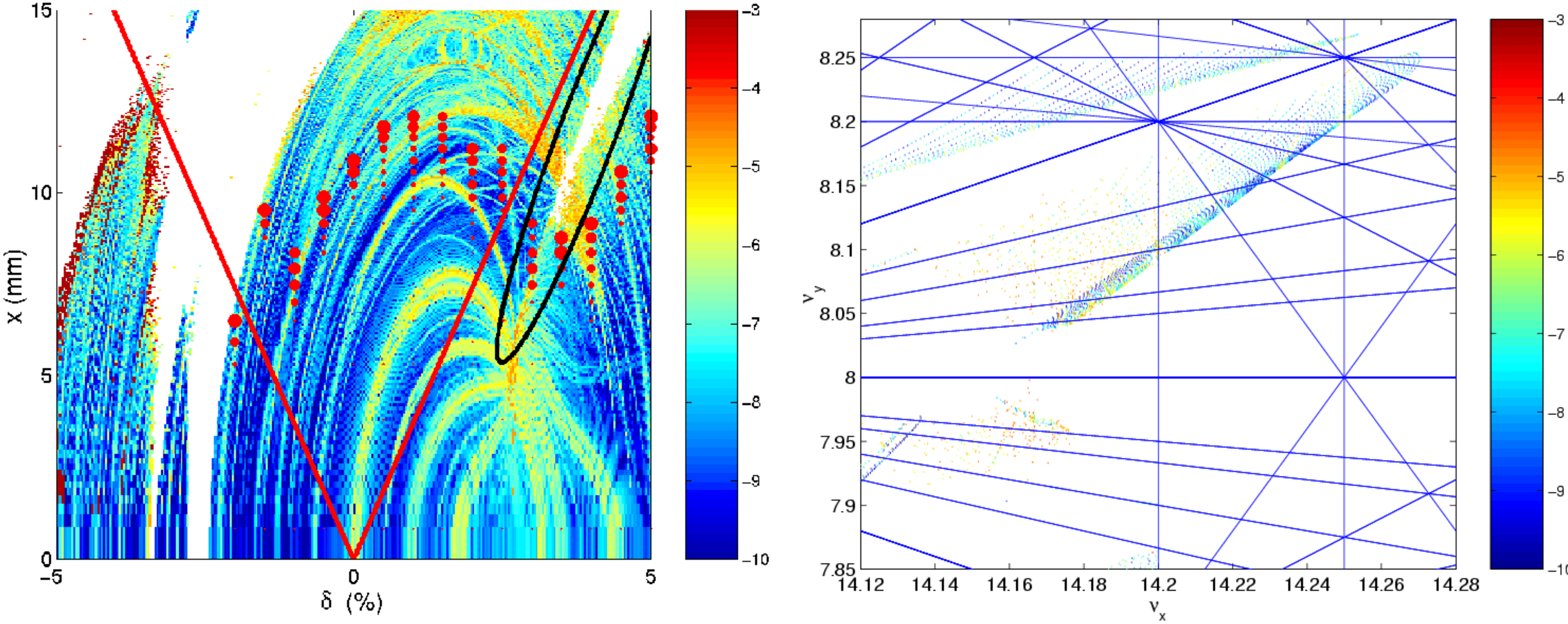
Aperture Scan for 3 Different Chromaticities

Small horiz. Chromaticity	Small horiz.	Large horiz.
Small vert.	Large vert.	Large vert.



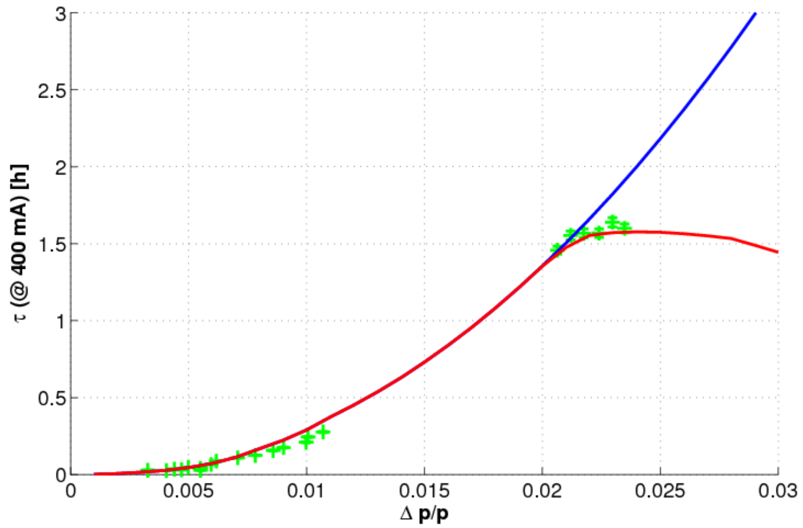
$\varepsilon > 3$ % straight	$\varepsilon = 2.6$ % straight	$\varepsilon = 2.6$ % straight
2.65 % arcs	1.75 % arcs	1.9 % arcs

Results agree well with Simulations



- Simulations reproduce shift of beam loss area caused by the coupling resonance to higher momentum deviations

Touschek lifetime scans



Again, iterate calculation by including additional effects (fringes, multipoles, IDs, …) until it matches measurement

- Touschek Lifetime calculation can be very accurate
- ALS example: Calculate RF voltage dependent Touschek lifetime based on calibrated machine model (emittance, beamsized, lattice function, s-position dependent dynamic momentum aperture all calculated from calibrated model)
- Interesting tidbit: Measurement above was at low energy in ALS, where we are already beyond minimum of Touschek form factor (a regime, which Max-4 and NSLS-II will probe routinely

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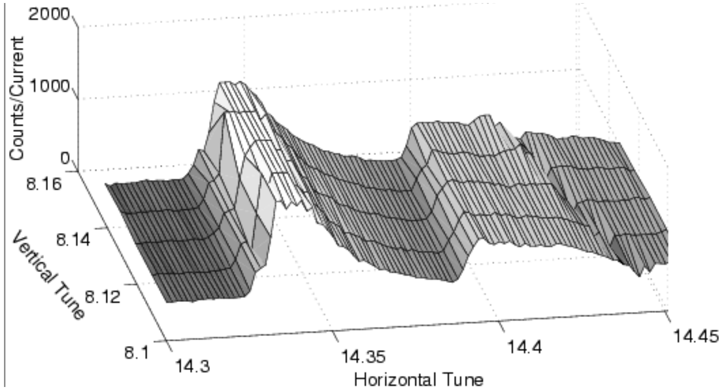
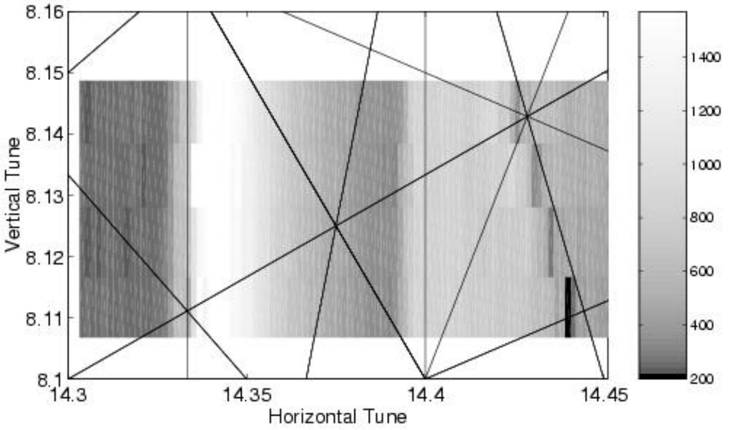
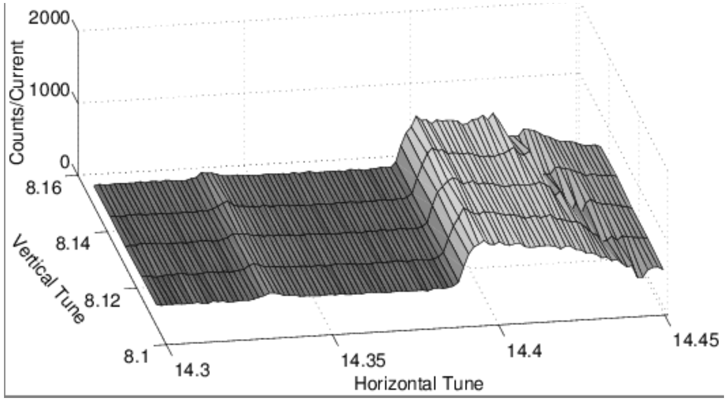
Tune scans (with and without large beta beating)

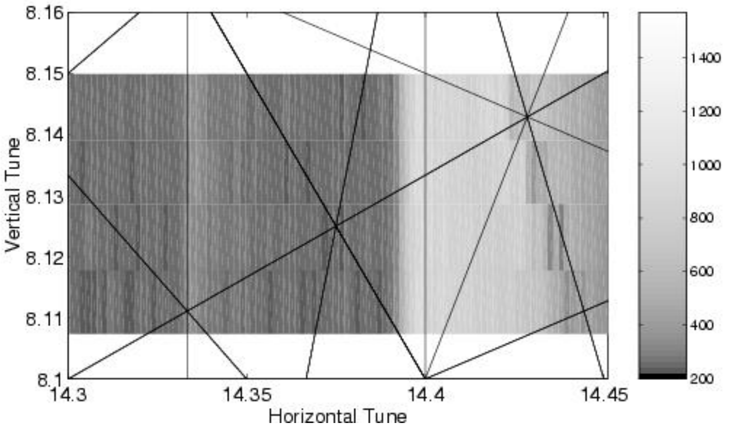
Uncorrected lattice





Corrected lattice





Three resonances are present:

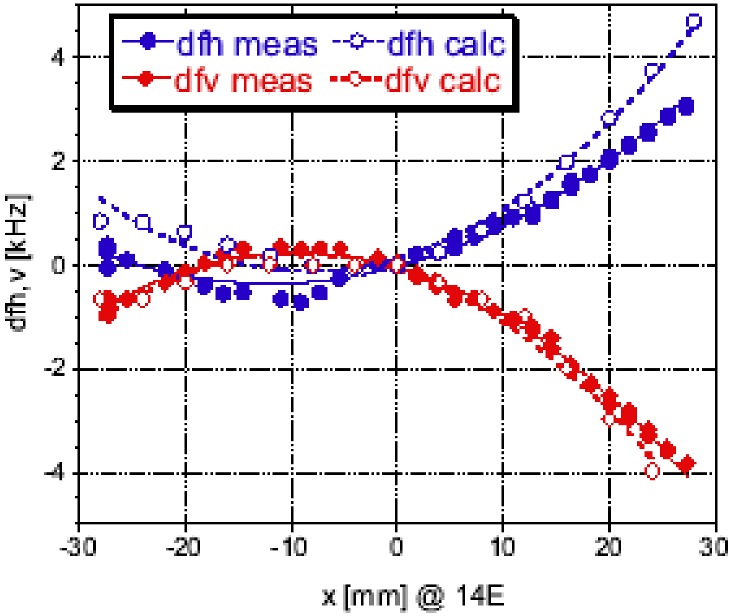
$5\nu_x = 72$ **(allowed)**

$3\nu_x = 43$ **(unallowed)**

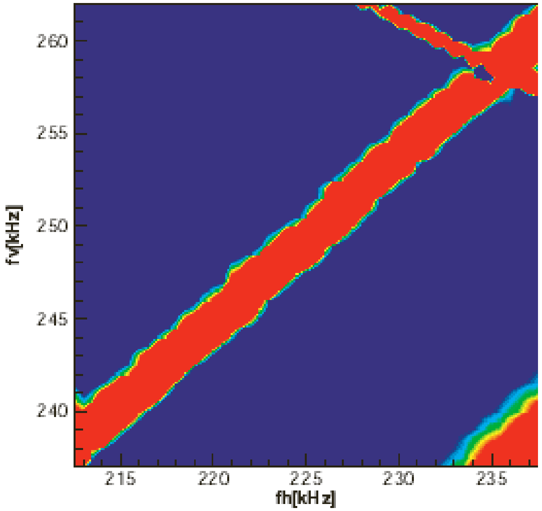
$2\nu_x - \nu_y = 37$ **(unallowed)**

CESR superconducting wiggler

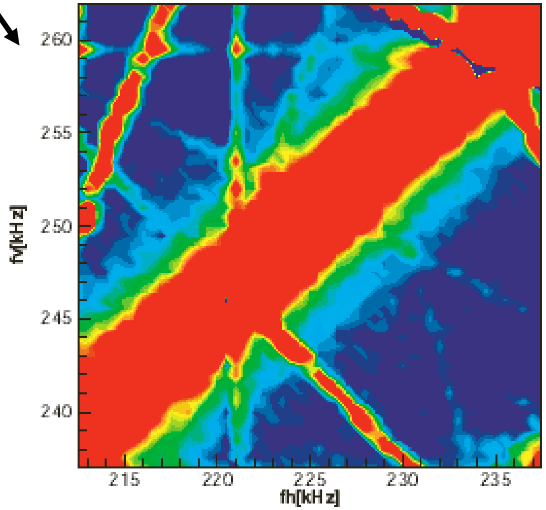
1. Tune vs. closed orbit measurements confirmed expected field integrals.
2. Vertical beam size as a function of (ν_x, ν_y) shows resonances excited by wiggler.



Temnykh et al., PAC03



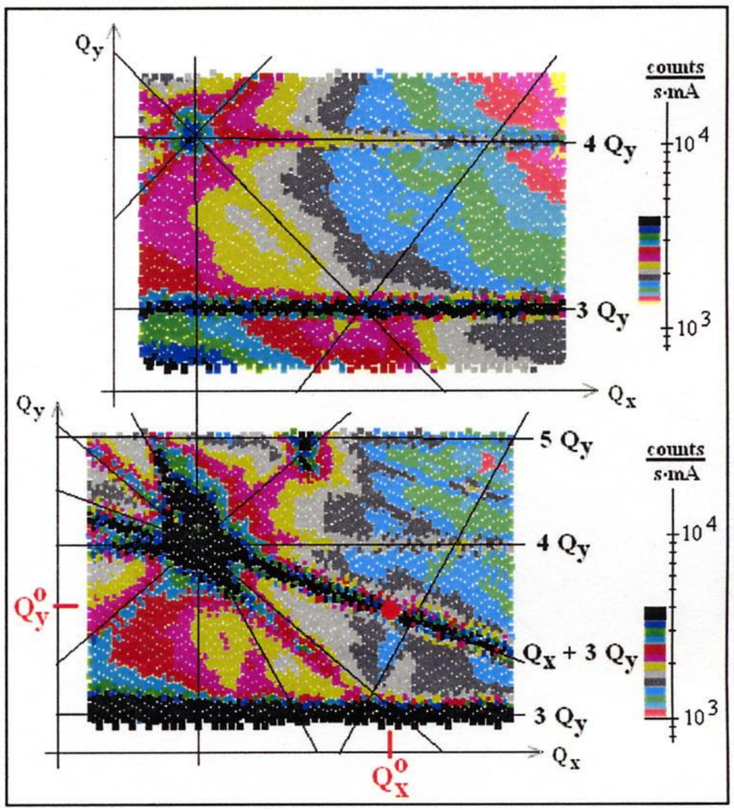
Wiggler off



Wiggler on

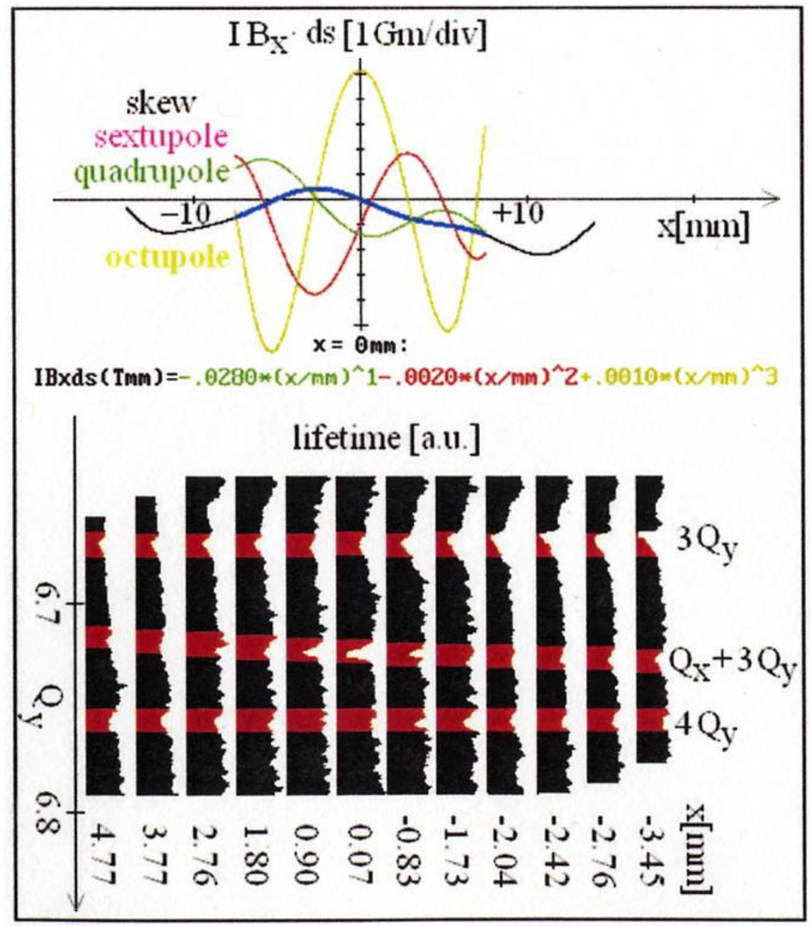
Bessy II measurements with EPUs (before shims)

Tune scans with beam loss monitor measurements can be used to identify resonances excited by IDs.



Kuske, Gorgen, Kuszynski, PAC'01

Scanning both tune and closed orbit while measuring lifetime gives a measure of multipole strengths vs. orbit.



More BESSY II measurements

- Resonance excitation seen in turn-by-turn BPM data.

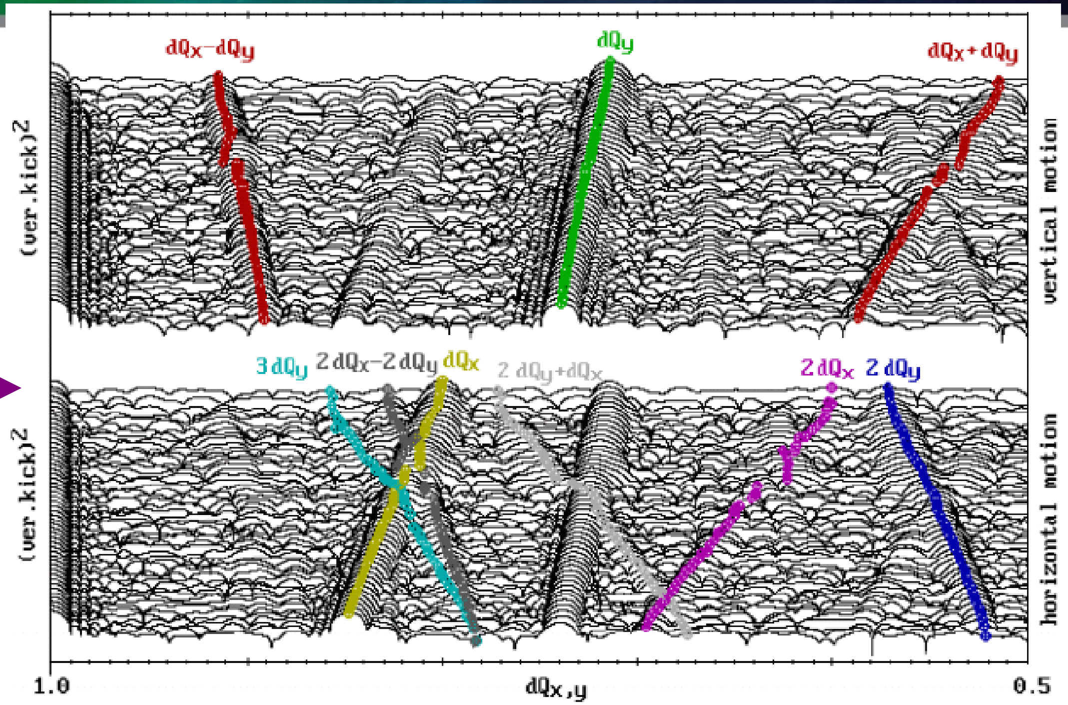
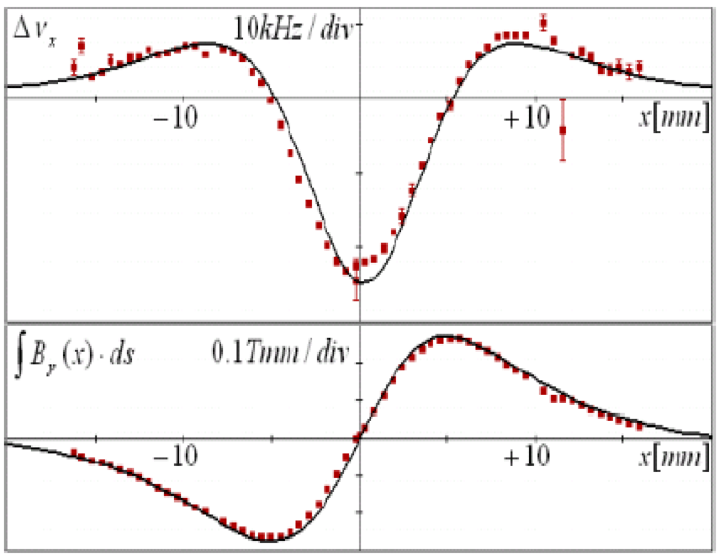


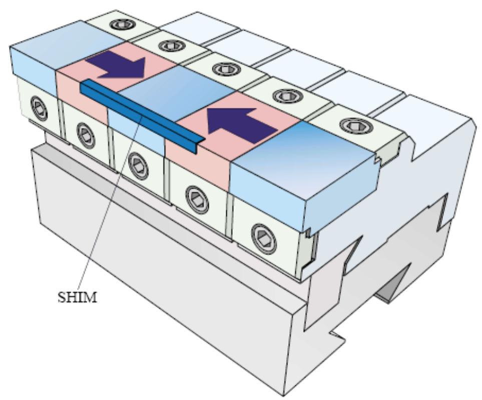
Figure 1: Spectra of the vertical and horizontal beam motion (top and bottom) with the fundamental tunes: dQ_x (yellow), dQ_y (green) and combinations of them.

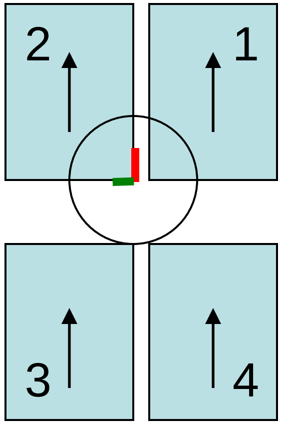


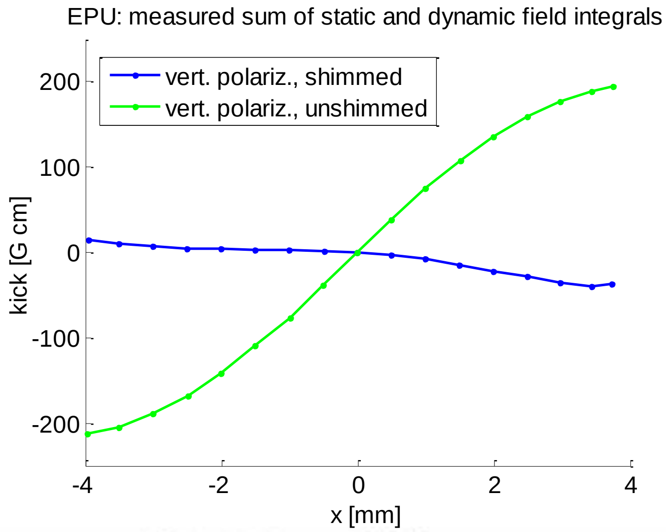
- Tune measurements vs. closed orbit bump confirm expected dynamic field integrals.

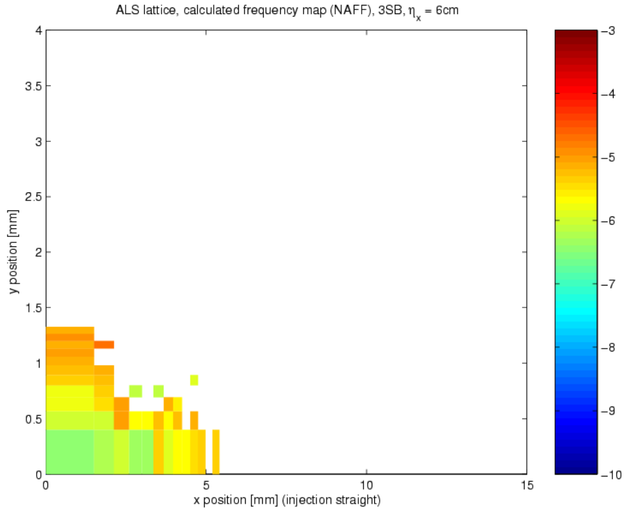
Correction via passive shims

- Dynamic multipoles compensated by magnetic shims

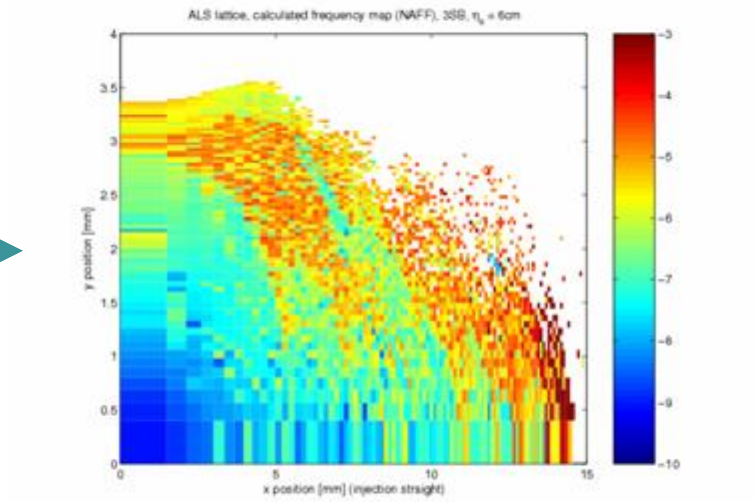








Shimming



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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

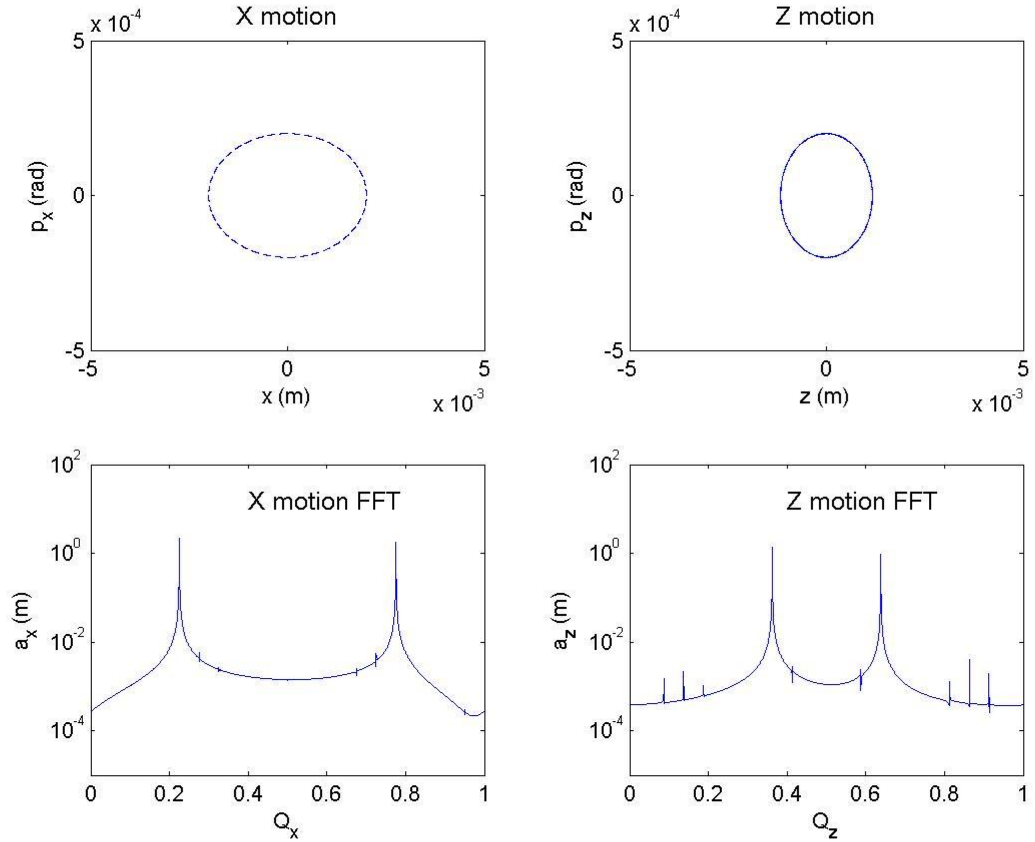
$$\overline{A} = \left(a_1^{(1)} \quad \ldots \quad a_{NBPM}^{(1)} \quad \varphi_1^{(1)} \quad \ldots \quad \varphi_{NBPM}^{(1)} \quad a_1^{(2)} \quad \ldots \quad a_{NBPM}^{(2)} \quad \varphi_1^{(2)} \quad \ldots \quad \varphi_{NBPM}^{(2)} \quad \ldots \right)$$

Define the distance between the two vector of Fourier coefficients

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

Riccardo Bartolini, et al.

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



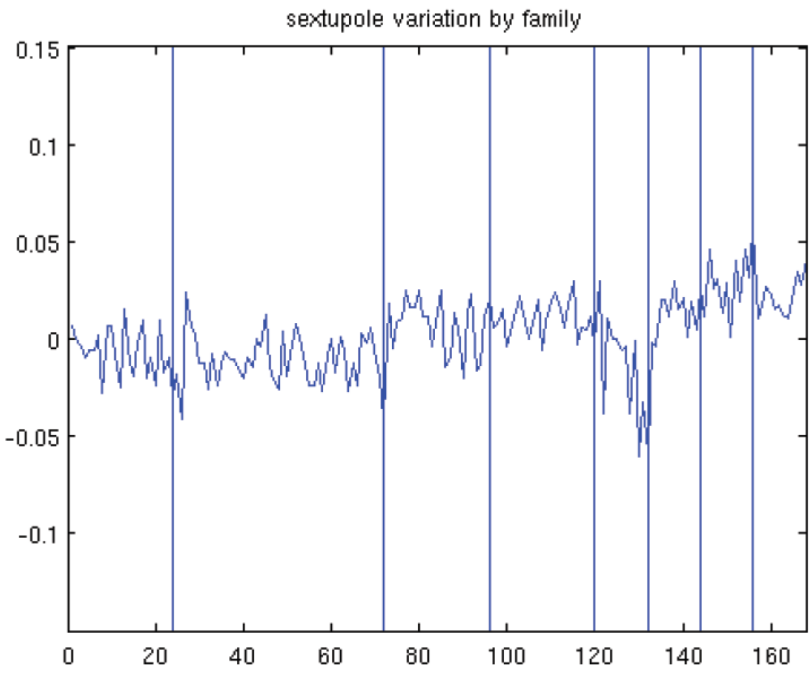
Spectral Lines detected with NAFF algorithm

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

Using multiple resonance lines simultabeously

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



Now the sextupole variation is limited to < 5%

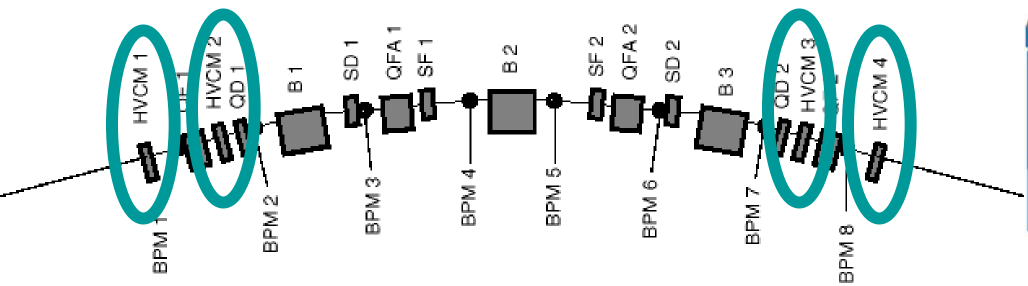
Both resonances are controlled

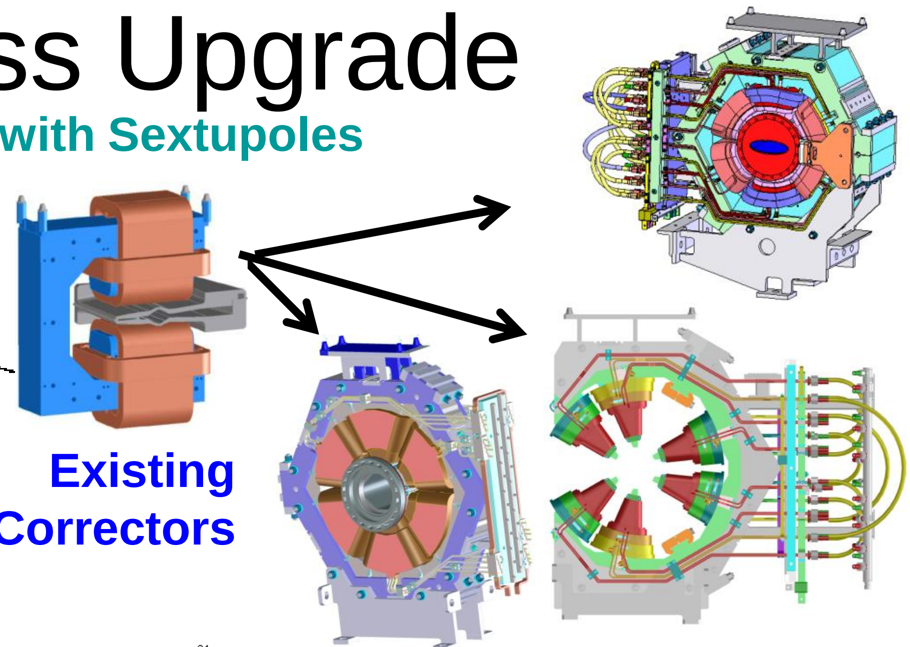
and the **lifetime improved by 10%**

Riccardo Bartolini, Diamond

ALS Brightness Upgrade

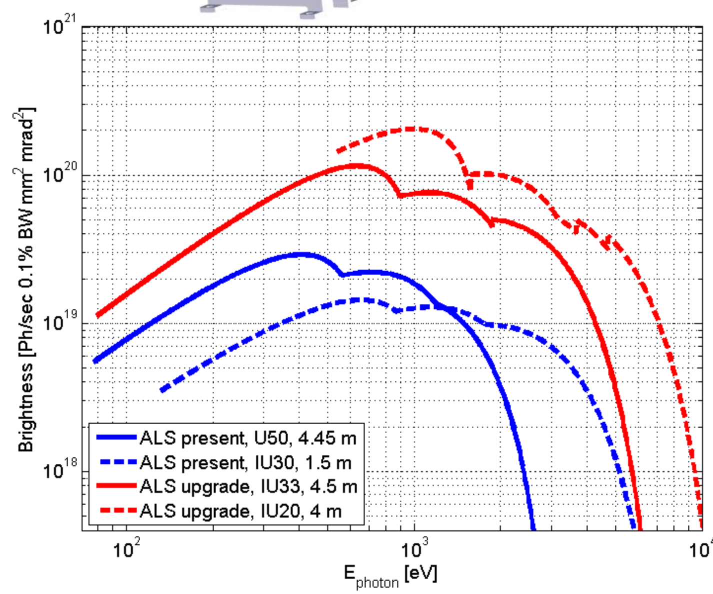
Replace Corrector Magnets with Sextupoles





Existing Correctors

- By changing magnet lattice, horizontal emittance is reduced from 6.3 nm rad to 2.2 nm rad
- Brightness is inversely proportional to emittance
- ***Of existing light sources, only PETRA-III has a lower emittance***



C. Steier, et al., NIM A, DOI: 10.1016/j.nima.2010.11.077.

Summary

- Beam based measurements are essential to improve performance of low emittance lattices
- Allow calibration of linear, coupled, nonlinear models
- Based on model predictions, can optimize lattices (symmetrization, coupling correction, …)
- Some measurements also provide model independent guidance for optmization (tune, chromaticity choice, …)
- Standard bag of tools
  - Response matrix analysis, frequency maps, tunescans, rf-scans, resonance driving terms, …