Dynamic Aperture/Dynamic Momentum Aperture

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- ❑ *How the transverse single particle dynamics limits the dynamic aperture (injection efficiency) and the momentum aperture and therefore the beam lifetime in Light Sources (also applicable to colliders, damping rings, ...)*

Topics

- ❑ Motivation/Introduction
- ❑ Dynamic Aperture/Injection Efficiency
  - ❐ Machine Model Calibration
  - ❐ Frequency Map Analysis
  - ❐ Measurements of Frequency Maps
- ❑ Dynamic Momentum Aperture
  - ❐ RF-Amplitude Scan
  - ❐ Off-Energy Frequency Maps
- ❑ Summary

I will discuss three different examples (one injection efficiency and two Touschek lifetime examples), where the insight gained by frequency map analysis was applied directly to significantly improve the performance of the ALS.

Motivation

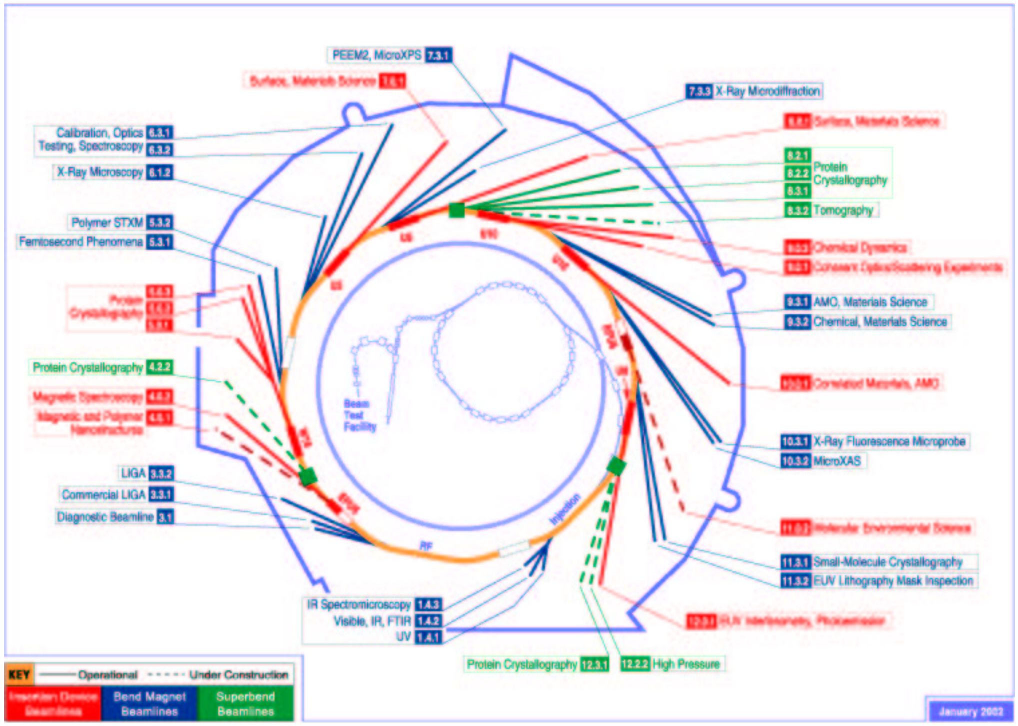
One performance limitation of ALS (like for other 3rd generation synchrotron radiation sources) is single particle dynamics

- ❑ Beam lifetime (dynamic momentum aperture)
- ❑ Injection efficiency (dynamic aperture)
- ❑ Transverse beam profile (resonant tail generation)

Gaining a good model (ideal machine with random errors is insufficient) and understanding of beam dynamics at high amplitudes can provide

- ❑ Diagnostic of problems
- ❑ Improvement of actual performance
- ❑ Prediction what will happen due to future expansions (superbends, distributed dispersion, lower beta functions, mini gap IDs, femtosecond)

ALS Parameters

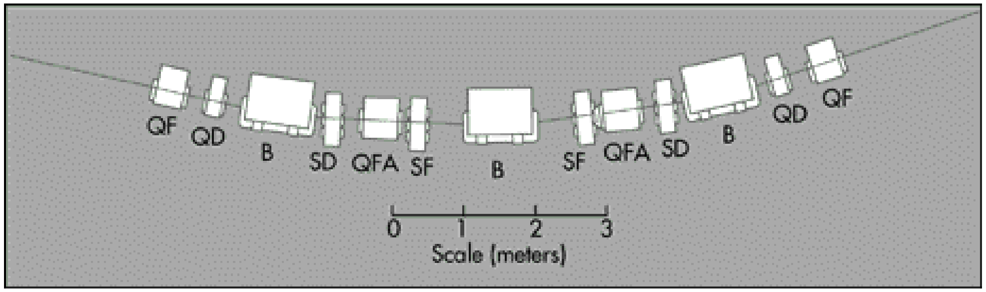


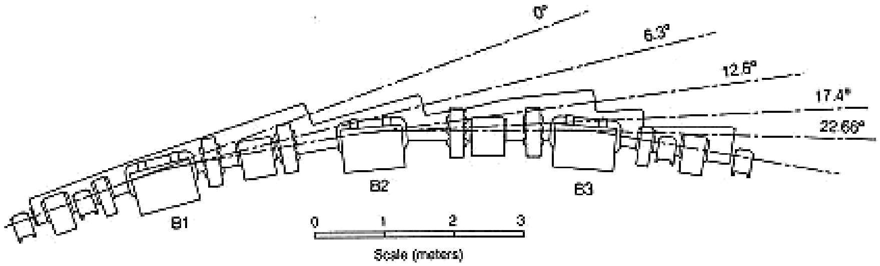
Nominal energy	1.5–1.9 GeV
Circumference	196.8 m
RF frequency	500 MHz
Harmonic number	328
Revolution freq.	1.5 MHz
Bunch current	1–2 mA or 5–35 mA
Energy spread	6–8 (8–10) $\times 10^{-4}$
Bunch length	15 – 20 ps

$1\text{ mA} = \frac{2}{3}\text{ nC} = 4.2 \times 10^9$ electrons

About 1 day a week available for accelerator physics studies (most studies directly related to user operation)

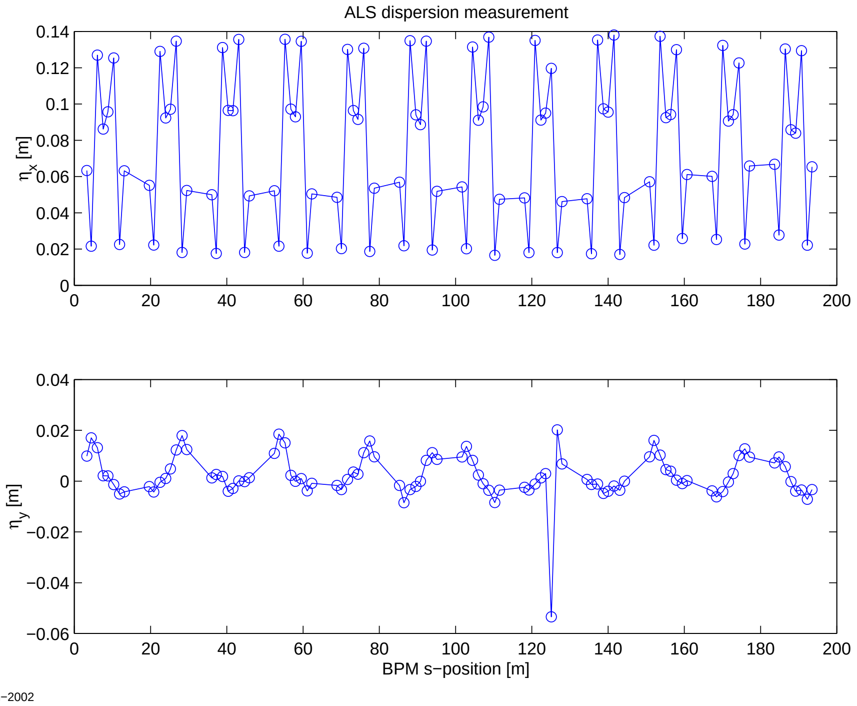
The ALS Lattice





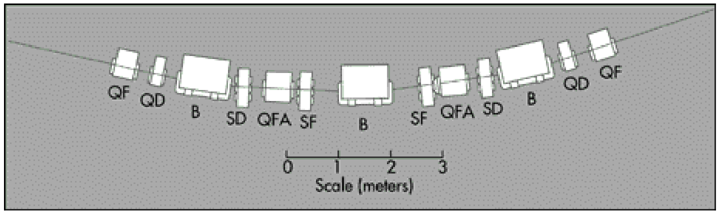
- 12 nearly identical arcs → TBA
- 8 fast beam position monitors per arc, 1024 turn recording capability; additional slow straight section IDBPMs
- 8 horizontal, 6 vertical corrector magnets per arc
- no individual skew quadrupoles so far, only 4 families
- TBA lattice very insensitive to dipole kicks (vertical dispersion)
- x-ray diagnostic beamline on bending magnet

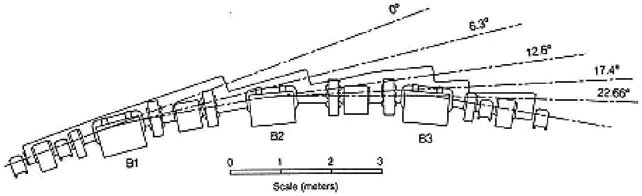
Vertical Dispersion/Coupling



- ❑ With normal orbit correction (BBA) spurious vertical dispersion typically 5 mm rms, with coupling correction about 2 mm rms
- ❑ Betatron coupling small ⇒ vertical emittance dominated by dispersion (at 1.5 GeV $\frac{\varepsilon_y}{\varepsilon_x}$ routinely below 1%, achieved values below 0.1% (5 pm rad))
- ❑ With Superbends (2001) change to distributed dispersion lattice

Response Matrix/Machine Model





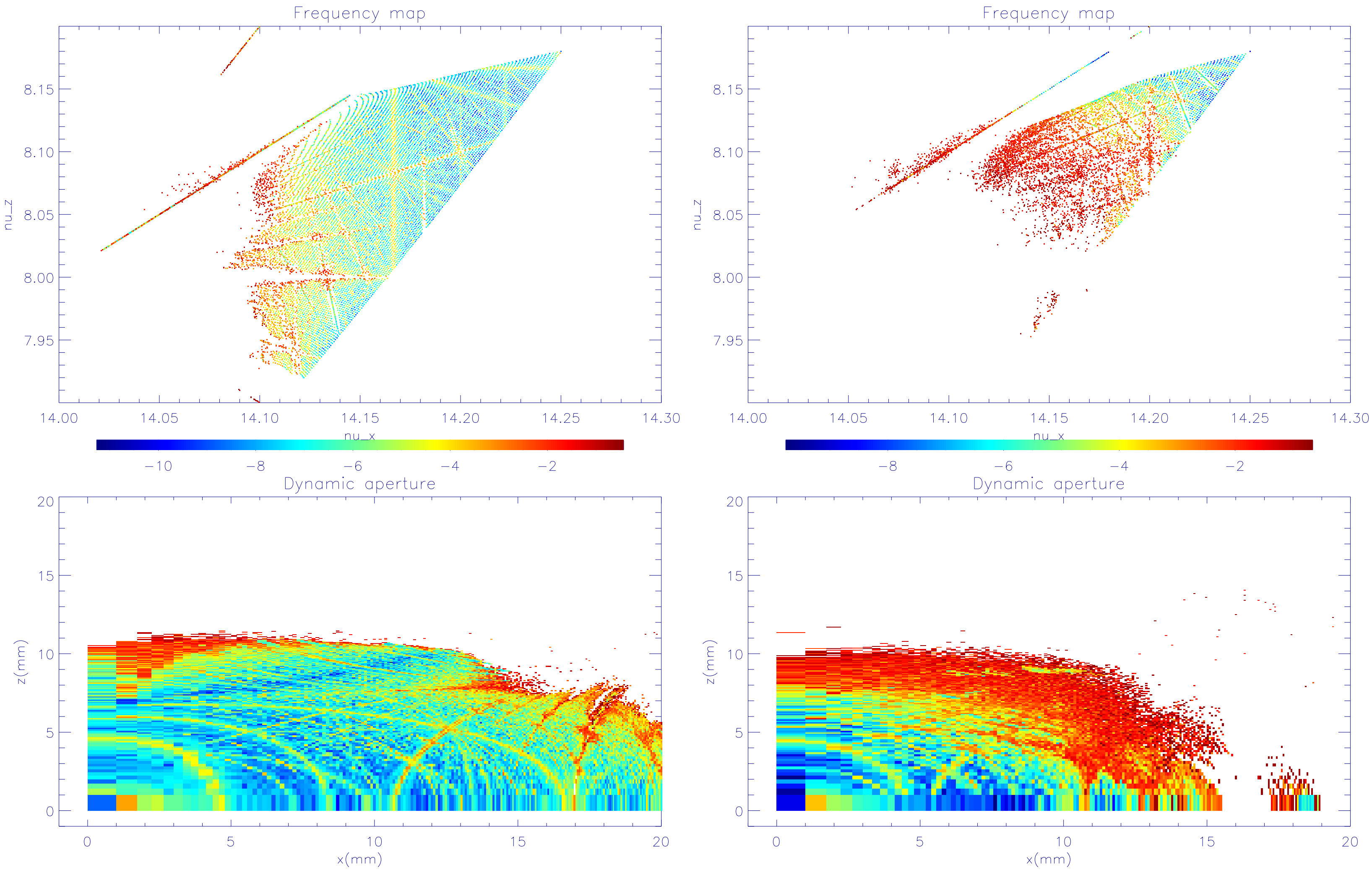
- fitting a machine model to the response matrix (SVD, LOCO)

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

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

- can determine individual quadrupole strengths
- can determine localized coupling strengths

ALS: Ideal Lattice/Calibrated Model



Ideal versus Calibrated Model

Linear lattice errors fundamentally change the beam dynamics

Ideal model:

- Dynamic aperture is large
- Chaotic zones at high amplitudes are small
- Particle loss is fast
- Particle loss due to allowed high order resonances

Calibrated model (linear errors):

- Dynamic aperture is smaller
- Large chaotic zones
- Particle loss is slow (diffusion)
- Particle loss due to unallowed lower order resonances

Is either of these models an accurate description of dynamics at high amplitudes in real ring? ⇒ test possible with Measured Frequency Maps

Experimental Procedure

Experimental Hardware

- ❑ horizontal + vertical single turn kicker
- ❑ 96 turn by turn monitors (1024 turns)

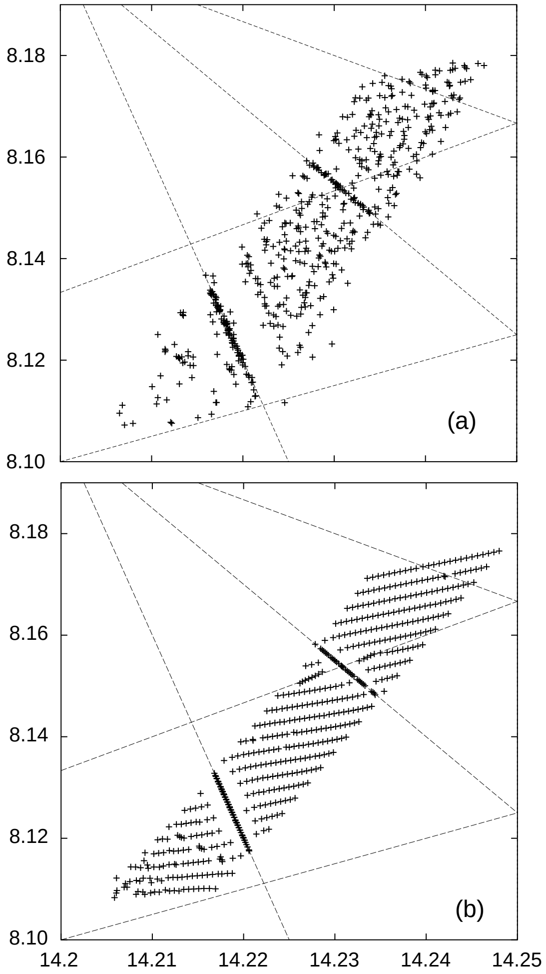
Experimental Procedure

- ❑ Electron beam (single bunch or small bunch train) gets simultaneously a horizontal and a vertical kick
- ❑ Beam centroid oscillations are recorded turn by turn for 1024 turns
- ❑ Repeat with different initial conditions (hor. + vert. kick amplitude) $\rightarrow$ 400-600 total points per map

Data Analysis

- ❑ turn by turn data is analyzed with frequency analysis post processor (NAFF) and results plotted in tune plane

ALS: Measured Frequency Map



- excellent agreement, using calibrated model (gradient errors), random skew errors, nominal sextupoles

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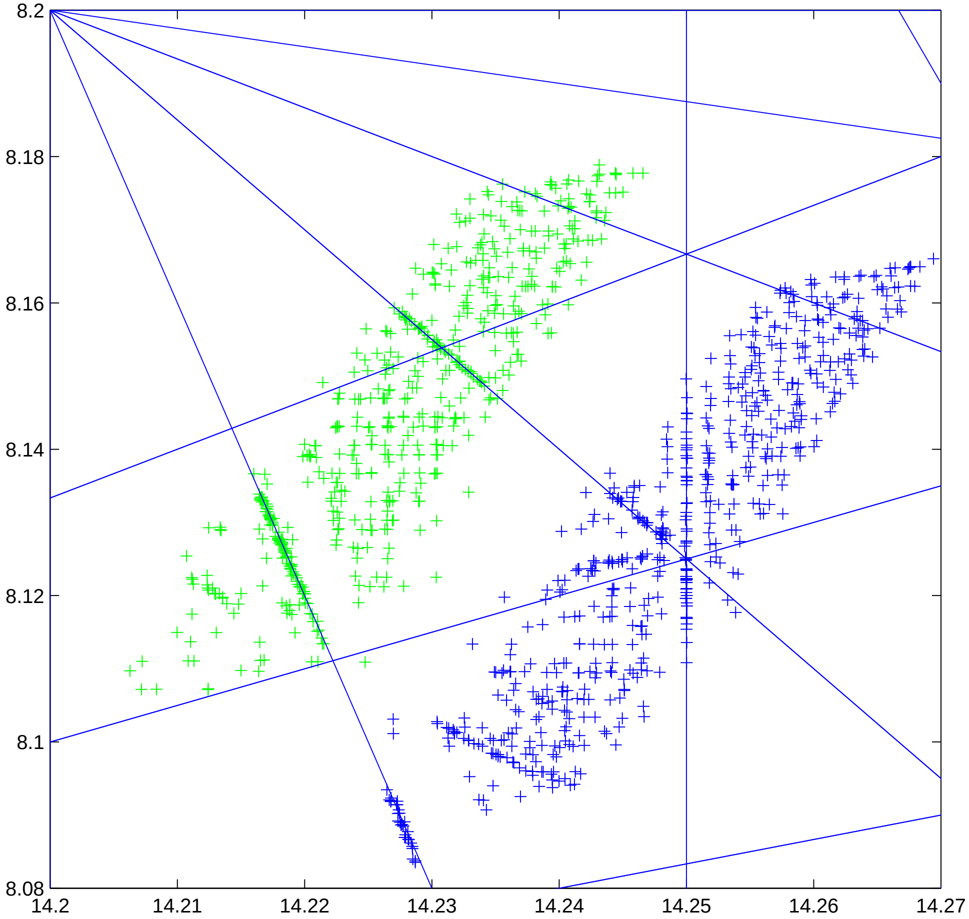
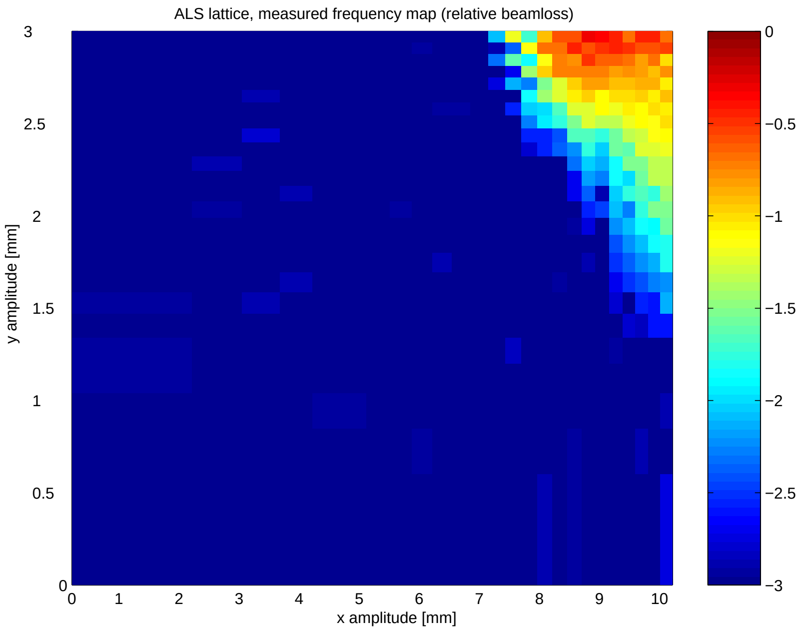
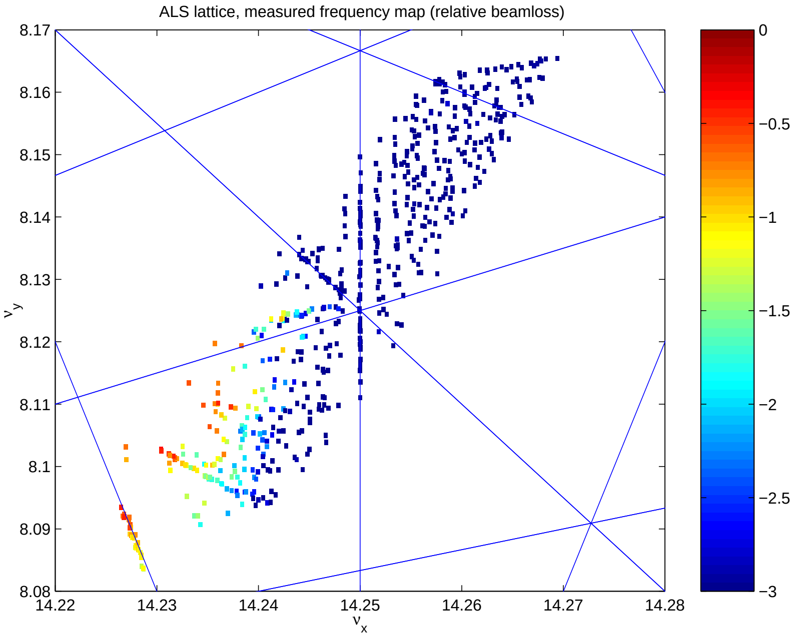
ALS: Measured Frequency Maps



- measurement → model independent diagnostic: (isolated, weak resonances + regular regions versus intersecting, strong resonances + large chaotic regions)

ALS: Measured Frequency Map with Measured Beam Loss





- Partial beam loss mostly if particles have to pass (radiation damping) through resonance intersection

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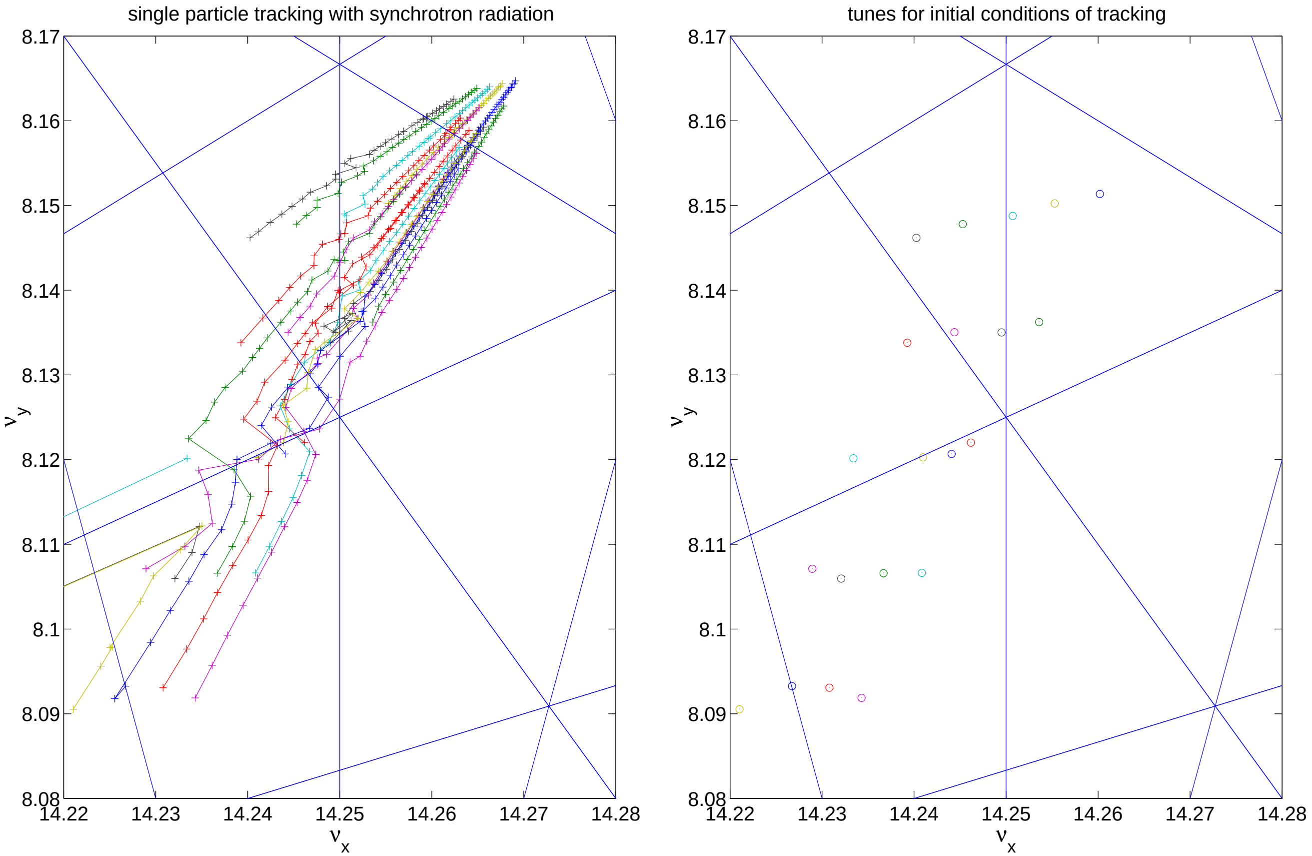
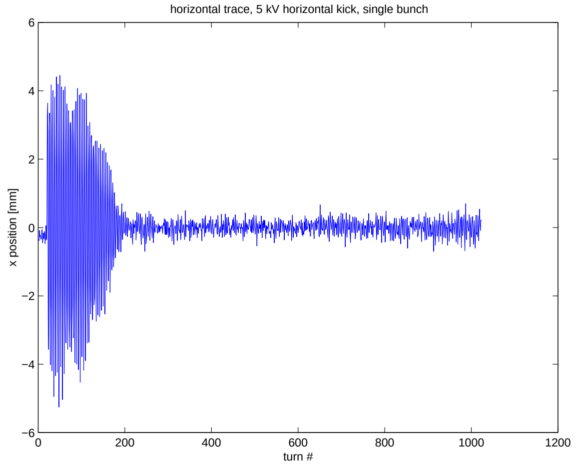
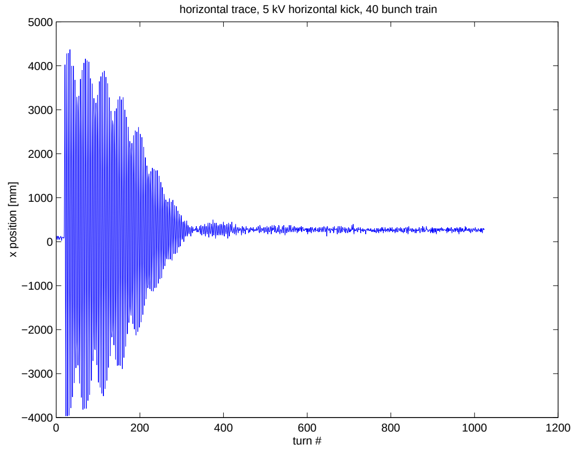
Tracking Individual Particles in Tune Space (with radiation)



- Fraction of particles damping through resonance intersection gain enough vertical oscillation amplitude to get lost on physical vertical aperture

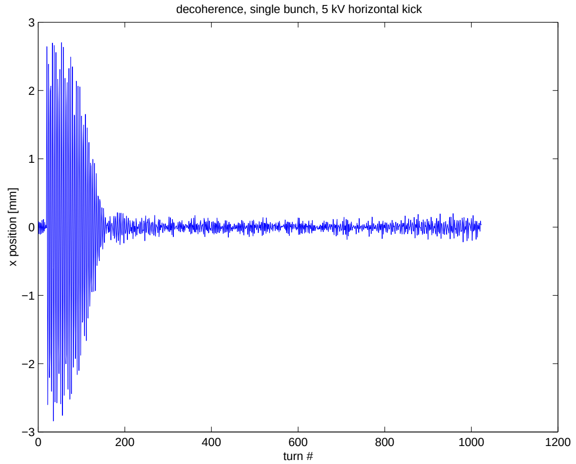
Experimental Difficulties: BPM noise

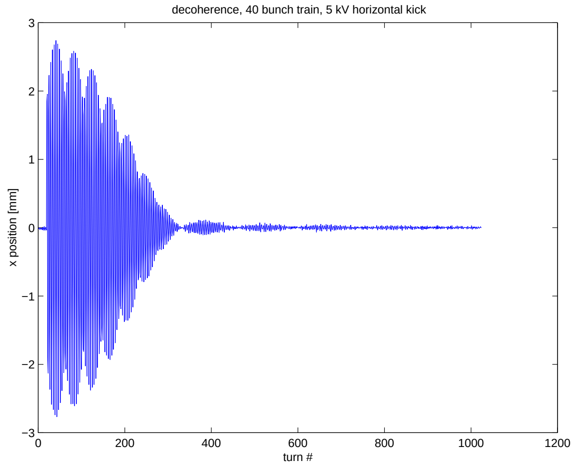




- FADs only have 8 Bit resolution
- input Bandpass filter has a transient step response time of about 60-80 ns ⇒ single bunch data very noisy
- use 40 bucket train instead ⇒ possible problems: additional decoherence, multibunch instabilities, resonance broadening
- noise level in 40 bucket case mainly determined by digitization resolution

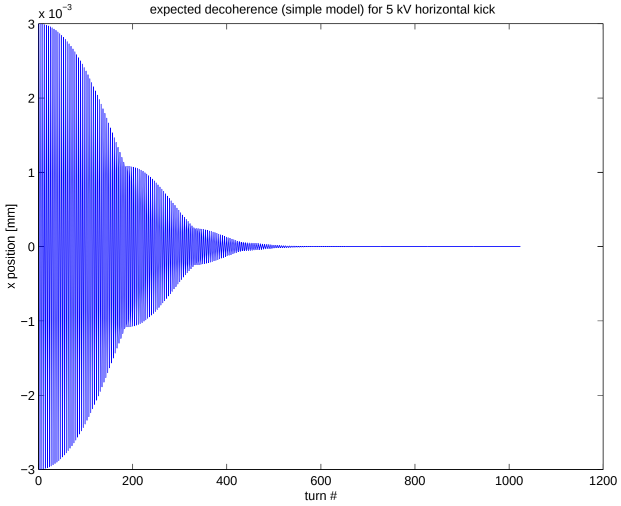
Decoherence


decoherence, single bunch, 5 kV horizontal kick


decoherence, 40 bunch train, 5 kV horizontal kick

- horizontally the additional decoherence due to the bunch train is small
- vertically it is significant (kick to about same amplitude, beamsizes different by factor of 10)
- decoherence changes not only amplitude but also oscillation phase ⇒ signals are not quasiperiodic after about 10-50 turns
- one needs fast converging frequency calculation algorithms (NAFF) and low noise position data → 2 dedicated, fast BPMs

Decoherence II



- simple model of decoherence: detuning proportional to betatron amplitude ($\Delta\nu \propto x^2$), no cross terms ⇒ analytic formula

$$
\begin{aligned}
A(N) &= \frac{1}{1+\theta^2}\exp\left(-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}\right)\\
\Delta\phi(N) &= -\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2} - 2\arctan\theta\\
\theta &= 4\pi\mu N\\
A_s(N) &= \exp\left(-\frac{\alpha^2}{2}\right)\\
\alpha &= 2\sigma_s\xi\nu_s^{-1}\sin\left(\pi\nu_s N\right)
\end{aligned}
$$

- problems: cross terms, resonances, BPM nonlinearities

Summary (Frequency Maps)

- *For the first time frequency maps have been measured on a storage ring*
  - The network of coupling resonances is clearly visible (Arnold Web)
  - The observed dynamics is complex
  - Model independent information about quality of lattice
- *Remarkable agreement between the measured and simulated maps*
  - ⇒ Confidence in our machine model (orbit response matrix analysis)
- *Outlook*:
  - Reduction in measurement time (to about 15 minutes) for frequency map planned ⇒ diagnostic tool for routine operation
  - Touschek lifetime ⇒ off energy frequency maps and measurements → studies started

Motivation (Dynamic Momentum Aperture)

Laurent Nadolski, David Robin, Christoph Steier, Ying Wu (LBNL);

Winfried Decking (DESY); Jacques Laskar(IMC-CNRS)

- ❑ Lifetime is a crucial performance parameter for all light sources ⇒ for 3rd generation light sources lifetime dominated by Touschek effect ⇒ Touschek lifetime strong function of momentum aperture ε

$$\tau_{\text{tou}} \propto E^3 \frac{V_{\text{bunch}} \sigma'_x}{I_{\text{bunch}}} \varepsilon^2 f\left(\varepsilon, \sigma'_x, E\right)$$

⇒ Momentum aperture ε influenced/limited by single particle dynamics

- ❑ Design momentum aperture for current light sources: $\geq$3%; achieved: about $\geq$2% ⇒ Need to understand current limitations

- ❑ For ALS: understand+minimize impact of future expansions (Superbends, distributed dispersion, lower beta functions, mini gap IDs, femtosecond)

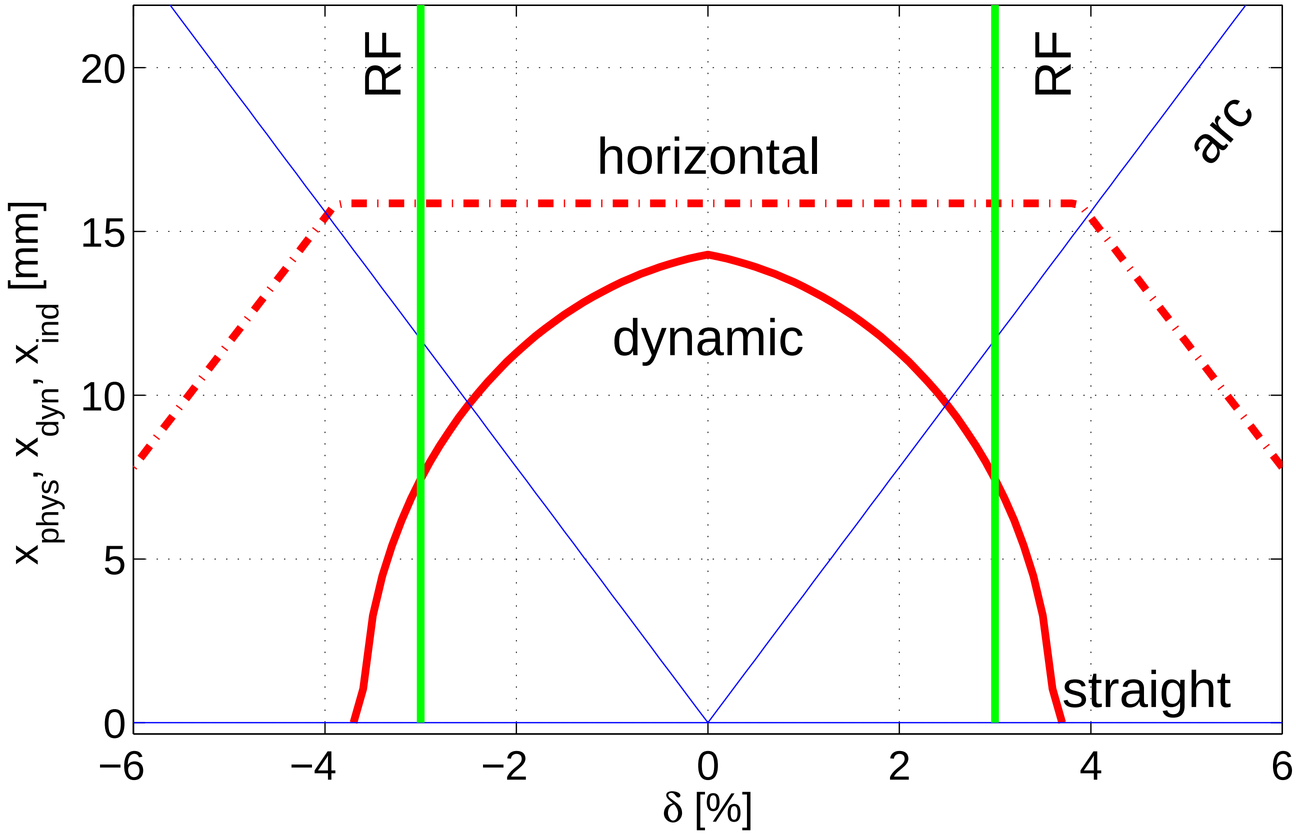
Motivation/Outline (Momentum Aperture)

- ❑ Design momentum aperture for future light sources (e.g. Soleil) 5–6% (necessary for reasonable lifetimes).

  ⇒ Application of some methods of Frequency Map Analysis can help understand the off-energy single particle dynamics.

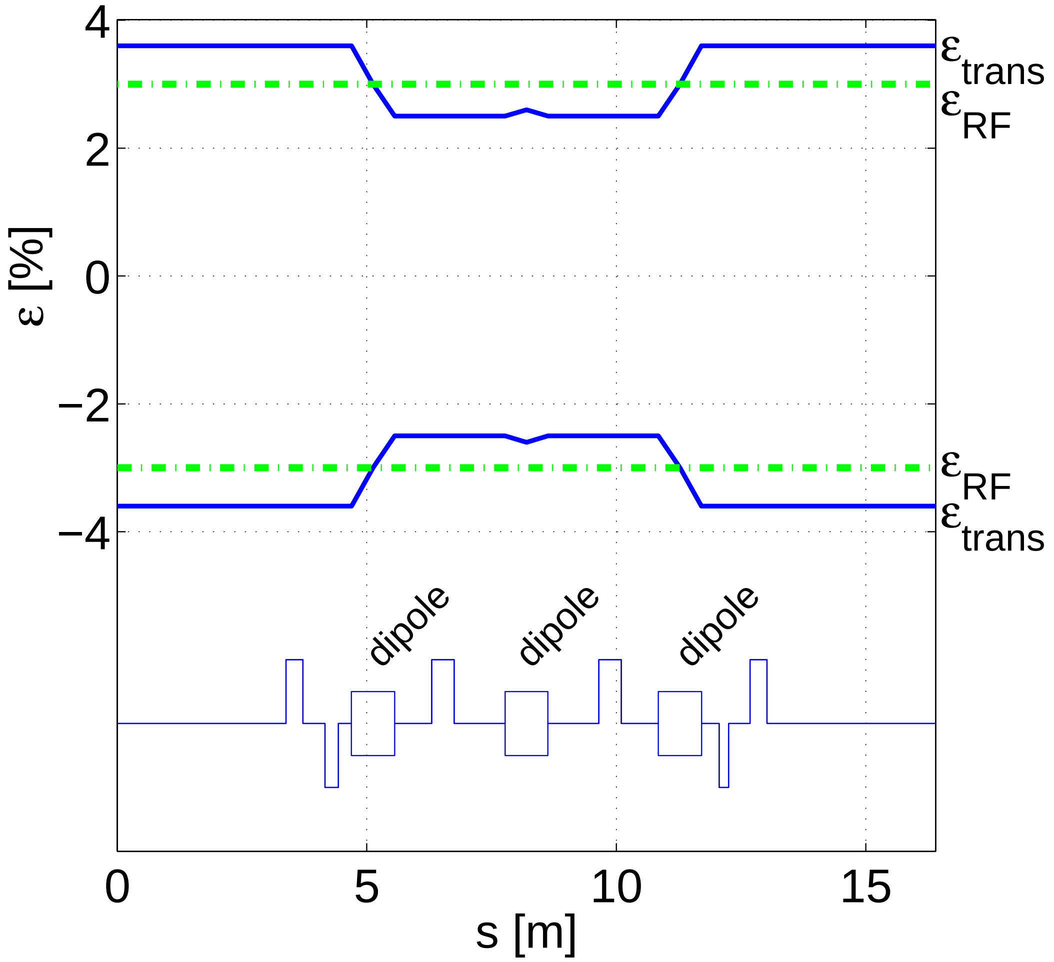
- ❑ Outline:
  - ◆ What limits momentum aperture
  - ◆ ALS limited by dynamic momentum aperture
  - ◆ Loss mechanism/Frequency Map Analysis (on-energy ⇒ off-energy)
  - ◆ Measurements can serve as model independent debugging tool
  - ◆ Agreement with simulations ⇒ tool for predictions for expansions/future machines

What Determines Momentum Aperture ?



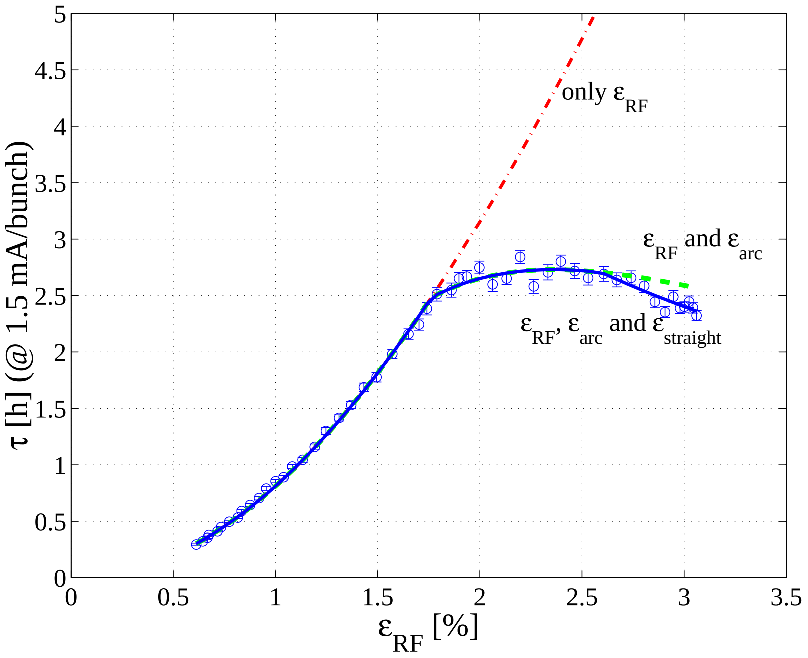
⇒ Possibility to study momentum aperture by scanning rf-voltage

Dependence of Momentum Aperture on Position in Lattice



⇒ for the ALS the momentum aperture is (nearly) constant in the straights and in the arcs, respectively

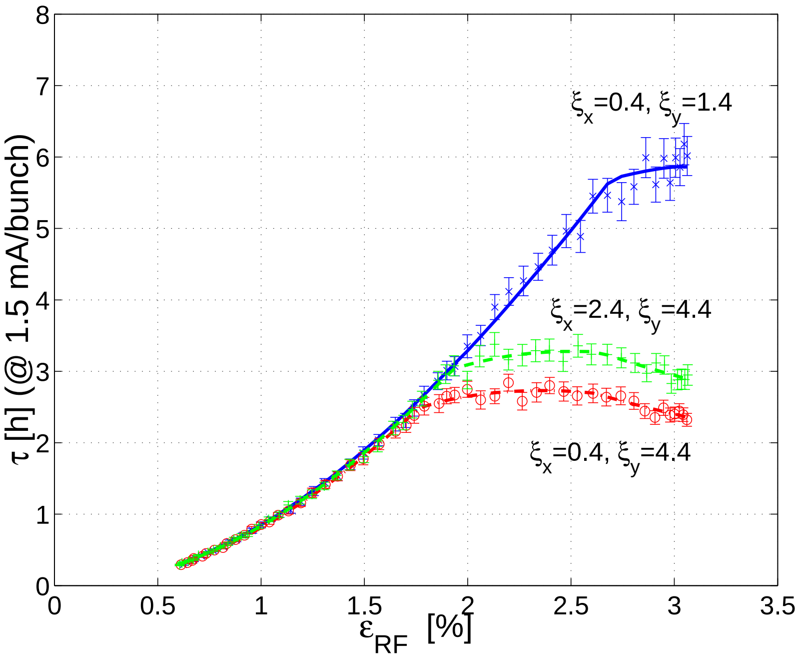
ALS: RF-amplitude scan



- Data can be fit with just three parameters:

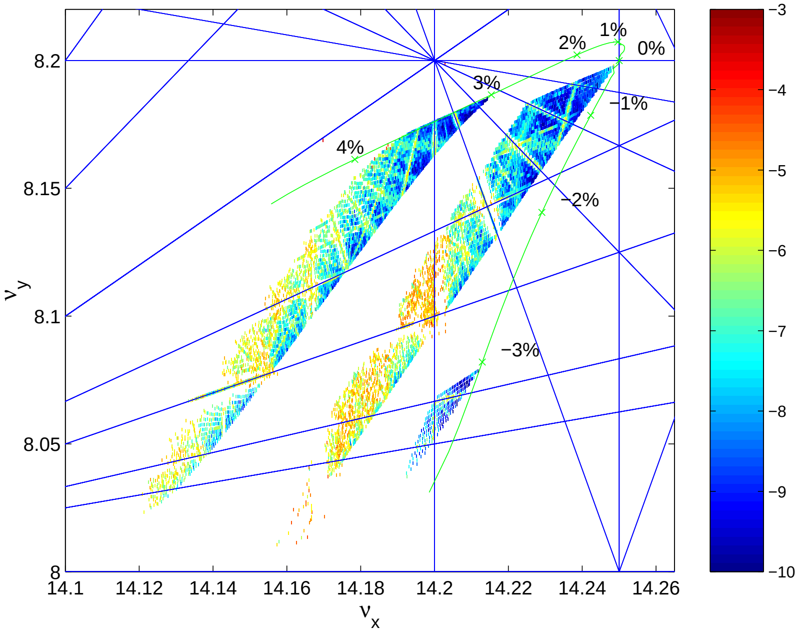
$$\tau_{tous} = \frac{A E_0^3 \sigma_L(\nu_s)}{L I_b}\left[\varepsilon_{arc}^2 \int_{arc} \frac{\sigma_x(s)\sigma_y(s)\sigma'_x(s)}{\ln\left(\frac{1}{1.78}\frac{\sigma'_x(s)^2 E_0^2}{\varepsilon_{arc}^2}\right)} ds + \varepsilon_{straight}^2 \int_{straight} \frac{\sigma_x(s)\sigma_y(s)\sigma'_x(s)}{\ln\left(\frac{1}{1.78}\frac{\sigma'_x(s)^2 E_0^2}{\varepsilon_{straight}^2}\right)} ds\right]$$

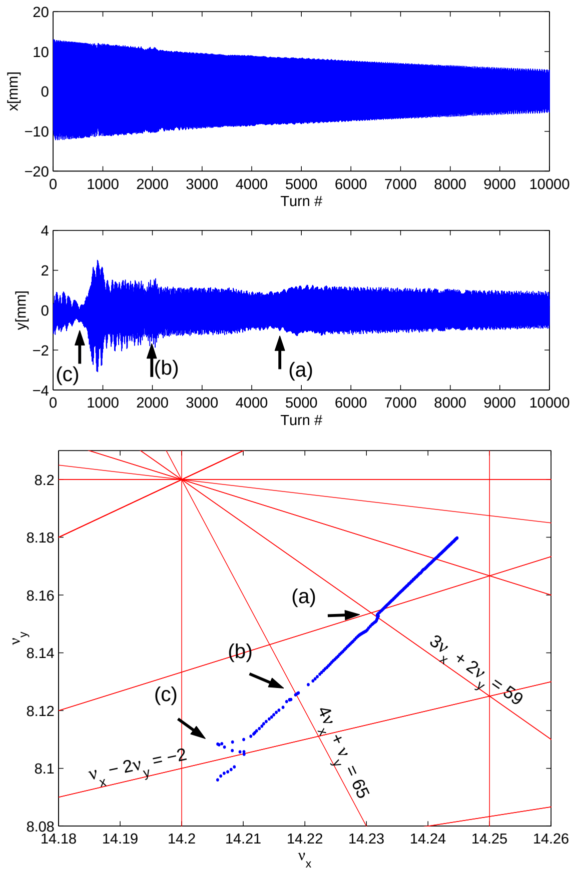
ALS: RF-amplitude scan



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

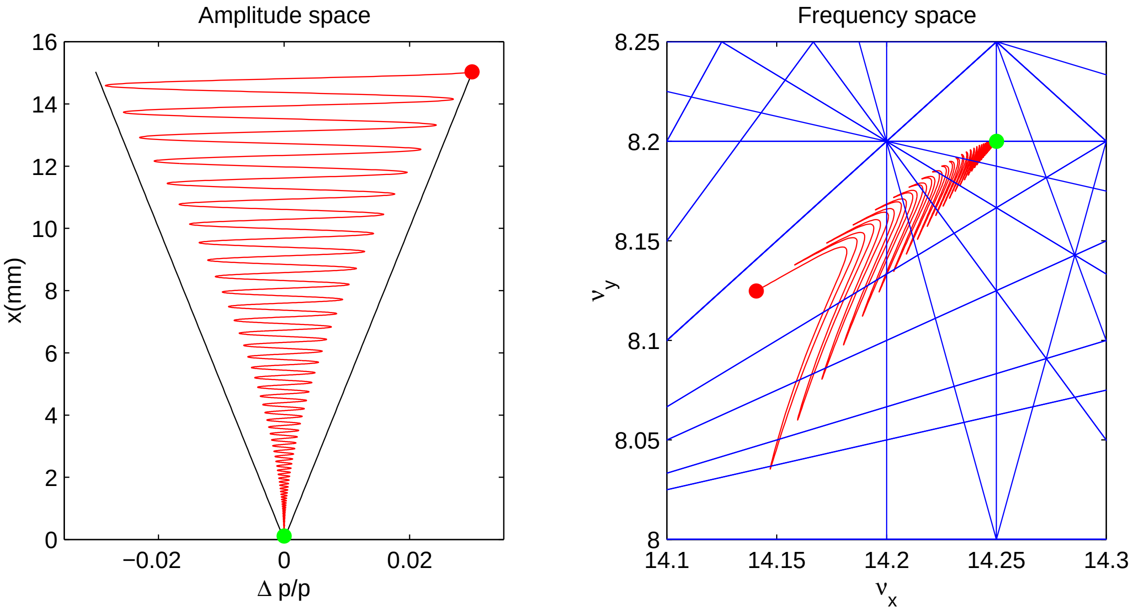
Off Momentum Frequency Map Analysis





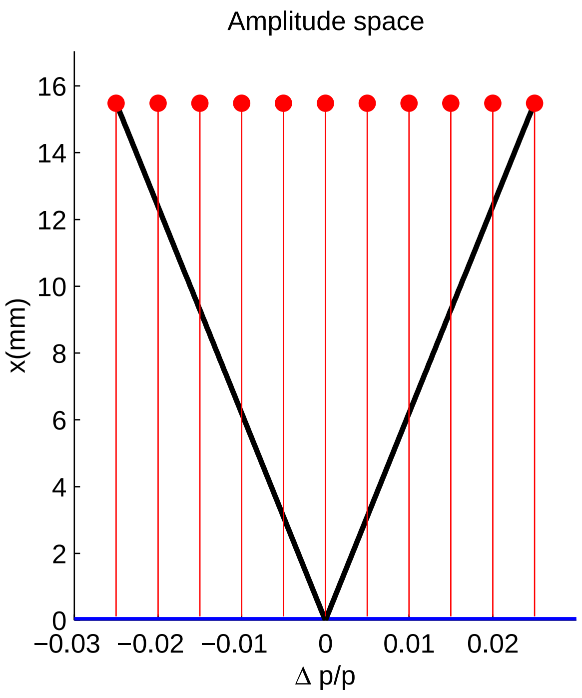
- ❑ Knowledge of off-momentum dynamics is sufficient to understand the full six dimensional dynamics

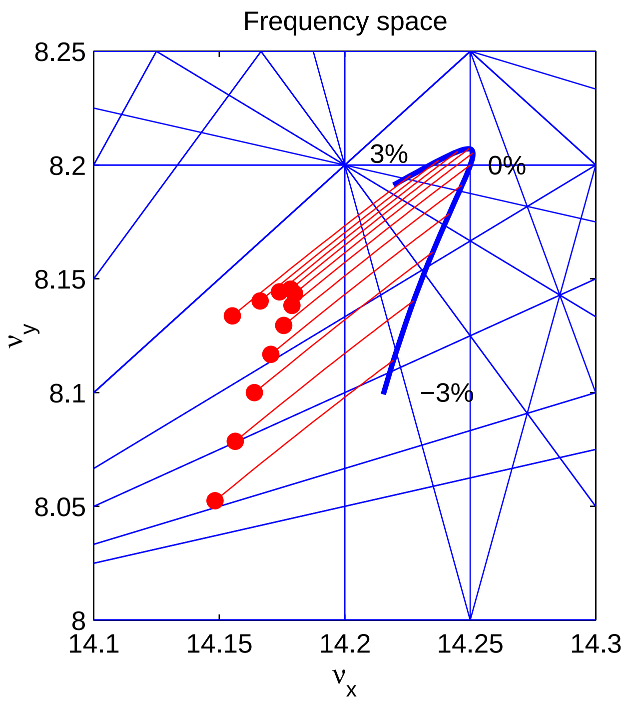
Touschek Scattering → Tuneshift → Particle Loss



- Particle loosing/gaining energy → hor. (dispersion/H-function) + long. oscillation
- Change in particle's betatron tune due to
  - Synchrotron oscillation (change in Δp, chromaticity)
  - Radiation damping ($\Delta p/p$ and A_x, chromaticity, detuning with amplitude)
  - Particle can get into regions of tune space where the motion gets chaotic or resonantly excited

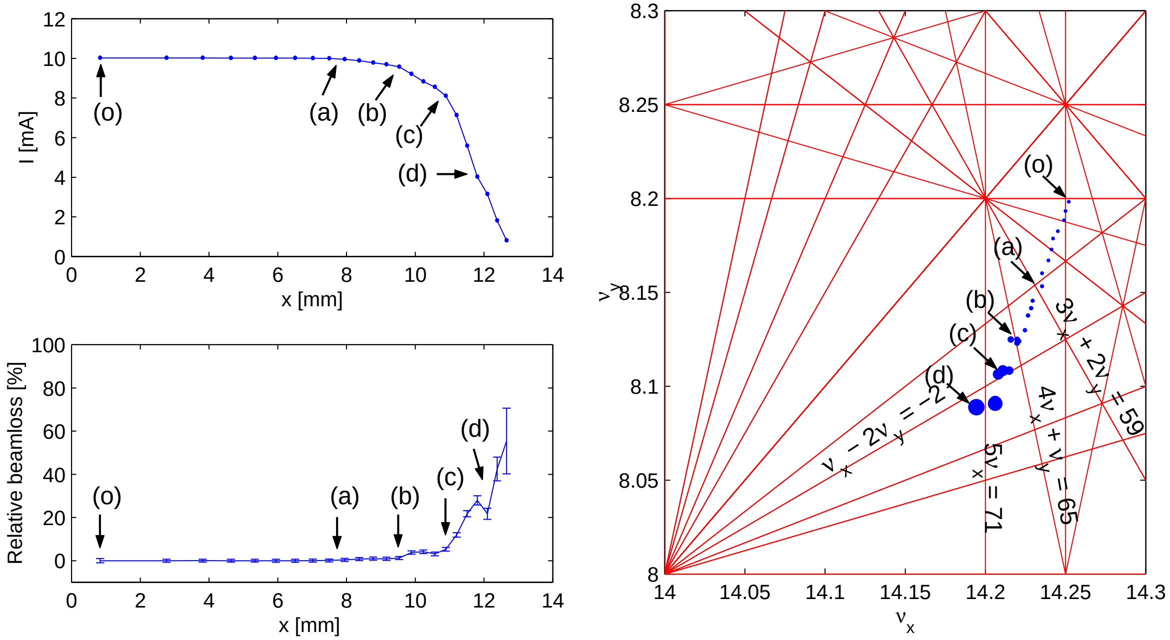
Measurement Principle


Amplitude space


Frequency space

- Experimentally very difficult to apply simultaneous transverse and longitudinal kick
- Still possible to locate loss regions when scanning only transverse amplitude while keeping energy offset constant

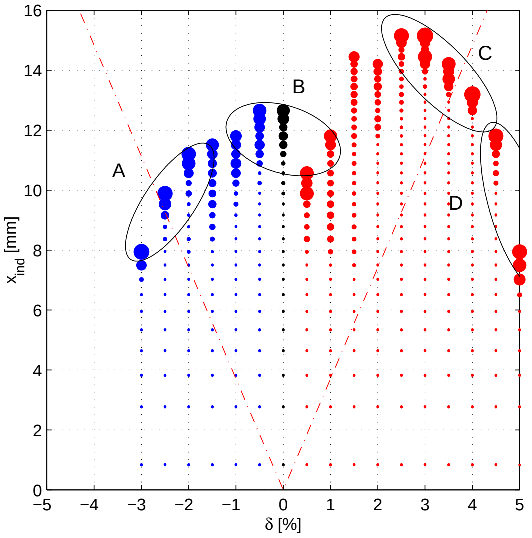
Measurement Method



- Use pinger magnet to kick/excite the beam with increasing amplitude
- Use DCCT to record relative beam loss after each kick
- Use turn-by-turn BPMs to record oscillation frequencies

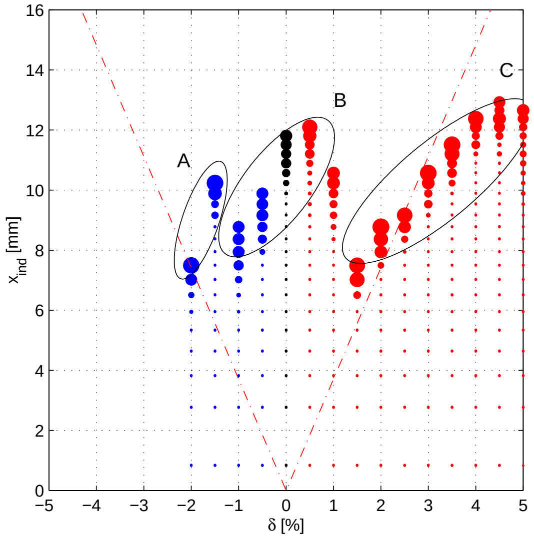
Aperture Scan – Three Different Chromaticities

Small Horizontal +
Small Vertical
Chromaticity



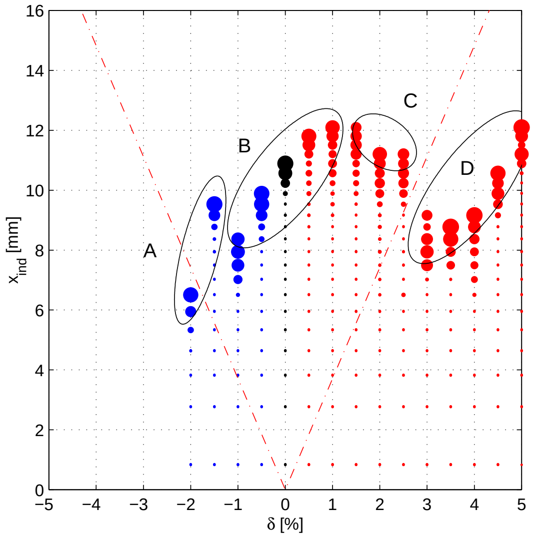
$\varepsilon > 3\%$ in the straights
2.65% in the arcs

Small Horizontal +
Large Vertical
Chromaticity



$\varepsilon = 2.6\%$ in the straights
1.75% in the arcs

Large Horizontal +
Large Vertical
Chromaticity

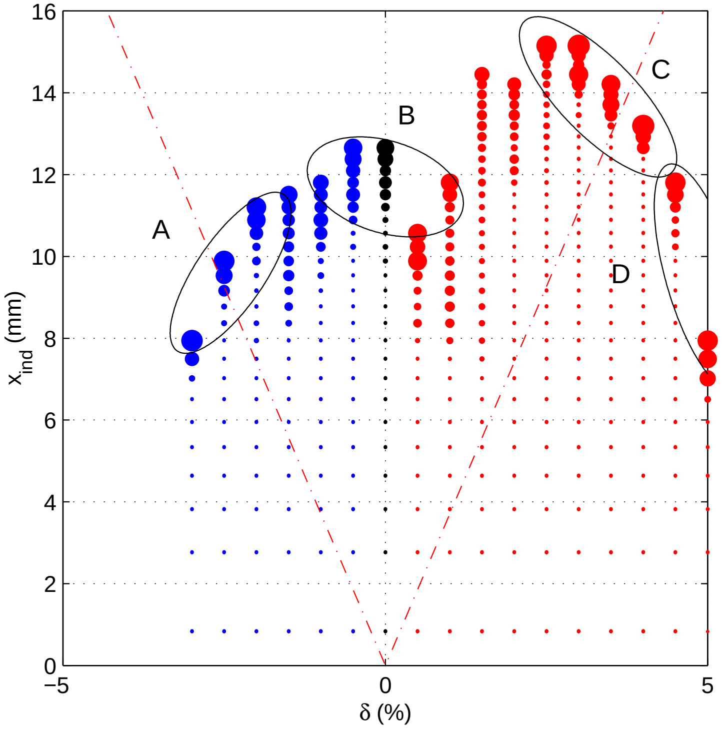


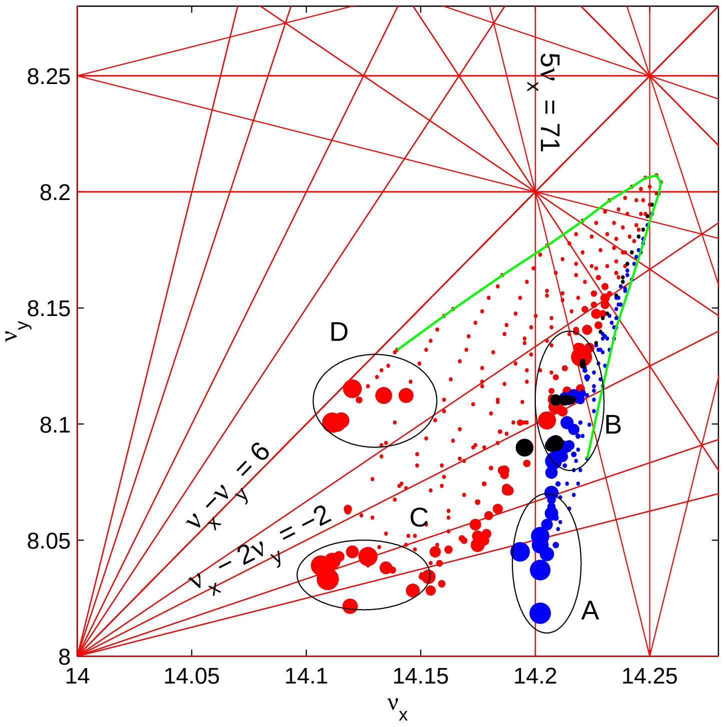
$\varepsilon = 2.6\%$ in the straights
1.9% in the arcs

Experimental Difficulties: Damping Partition

- Changing the RF-frequency to statically change the center beam energy is quite different from a particle undergoing synchrotron oscillations.
- The combination of quadrupole plus dipole field in all quadrupoles if the frequency is changed from the central frequency changes the damping partition numbers.
- The magnitude of change (for a given percentage energy change) depends on the size of the machine.
- For large machines a moderate beam energy change (changing the rf-frequency) can make the beam antidamped in one plane (typically horizontal).
- This limits how useful this (directly applied) method is for large accelerators (APS for example).

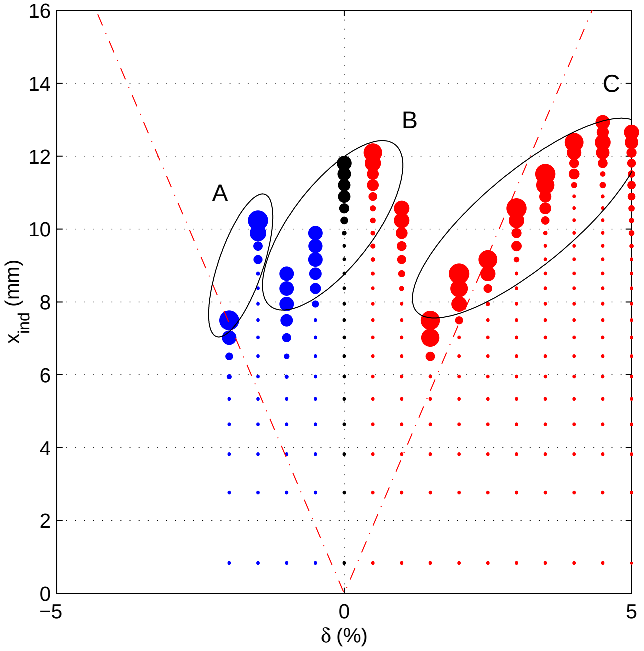
Aperture Scan – Small Chromaticity Case

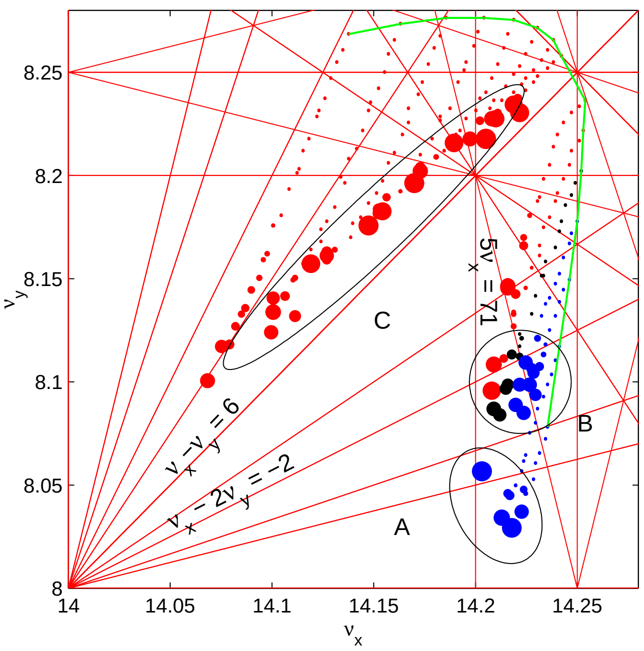




- Measured momentum aperture: $> 3\%$ (straight), 2.65% (arc)
- Ultimate limitation in both energy directions is vertical integer resonance

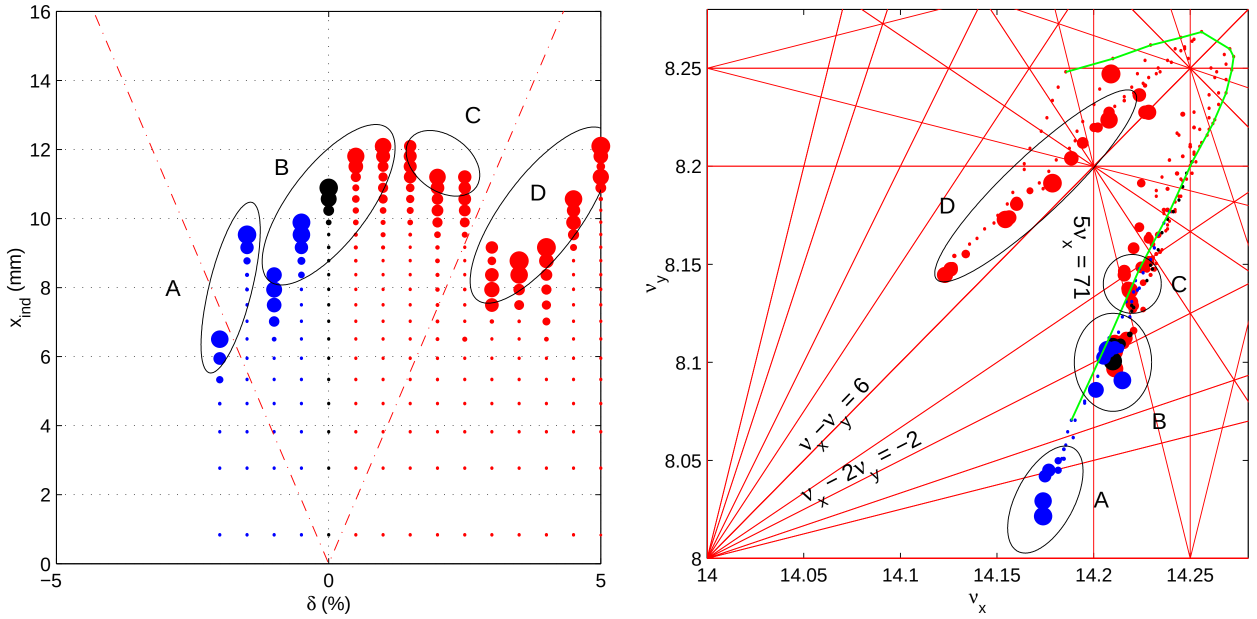
Large Vertical Chromaticity Case





- Measured momentum aperture: 2.6% (straight), 1.75% (arc)
- Limitation in negative direction is vertical integer resonance
- Limitation in positive direction is coupling resonance (used to control vertical beamsize at ALS)

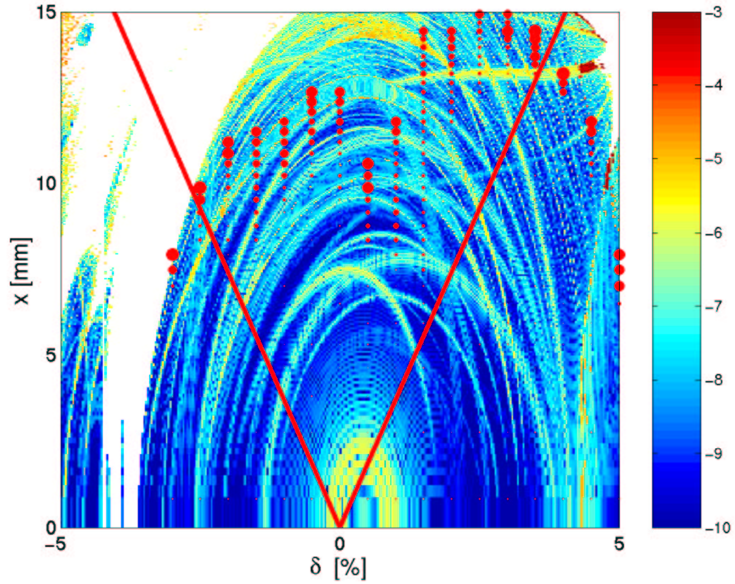
Large Horizontal+Vertical Chromaticity Case

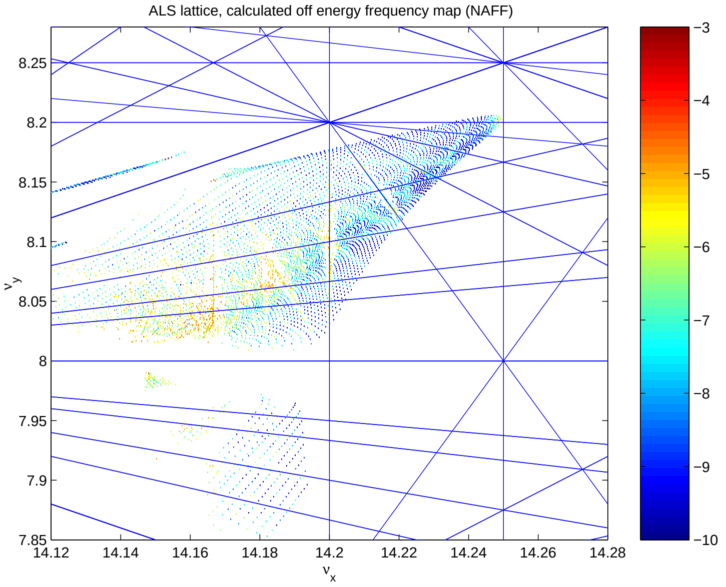


- Measured momentum aperture: 2.6% (straight), 1.9% (arc)
- Limitation in negative direction is still vertical integer resonance
- Limitation in positive direction is coupling resonance ⇒ shifted to larger energy deviation by additionally raising horizontal chromaticity

Comparison: Experiment - Simulation

Small Horizontal + Small Vertical Chromaticity

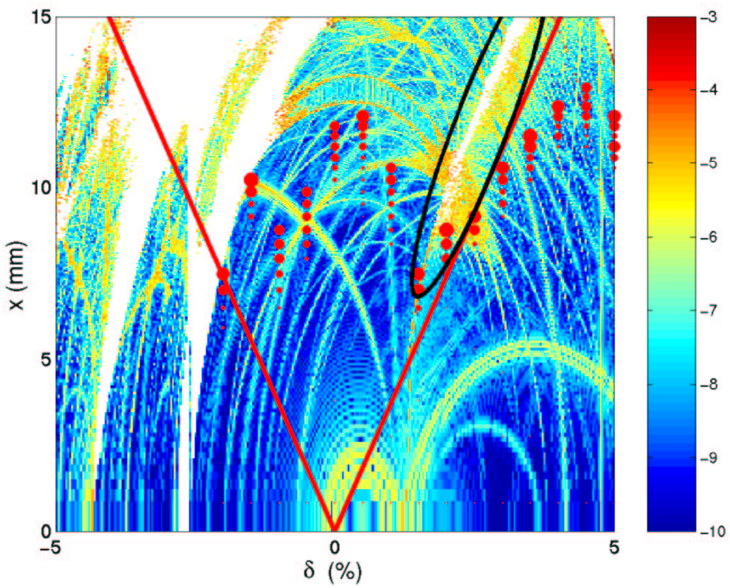


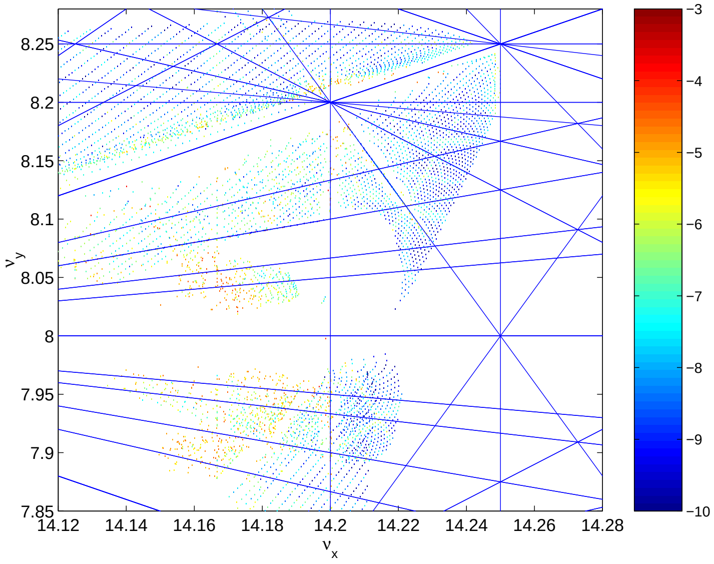


Agreement with simulations is good (though interpretation is not trivial and additional tools are necessary - plots in frequency space; comparison with experiments; off energy frequency maps, ...) ⇒ predict impact of new projects at ALS and performance of new light sources (and help to optimize them)

Comparison: Experiment - Simulation

Small Horizontal + Large Vertical Chromaticity

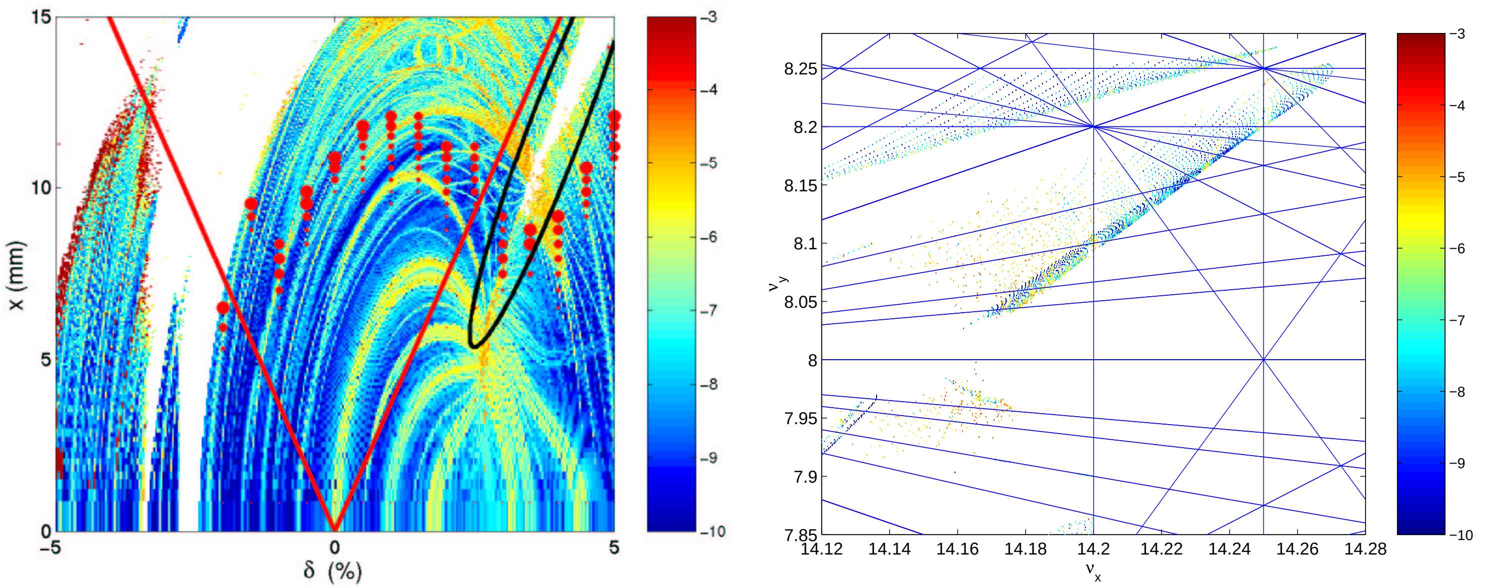




Simulations clearly reproduce reduction in momentum aperture due to coupling resonance (at positive delta) and integer resonance (at negative)

Comparison: Experiment - Simulation

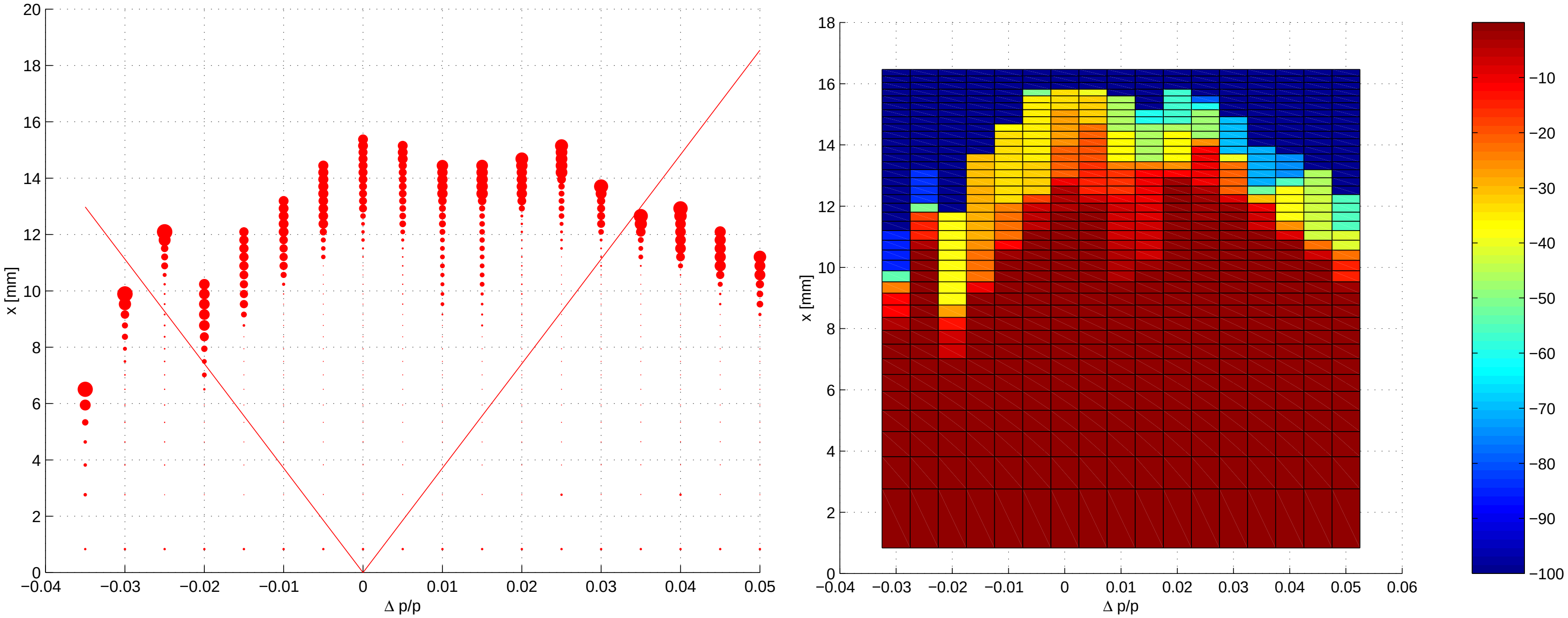
Large Horizontal + Large Vertical Chromaticity



Simulations show shift of beam loss area due to coupling resonance to higher positive momentum deviations.

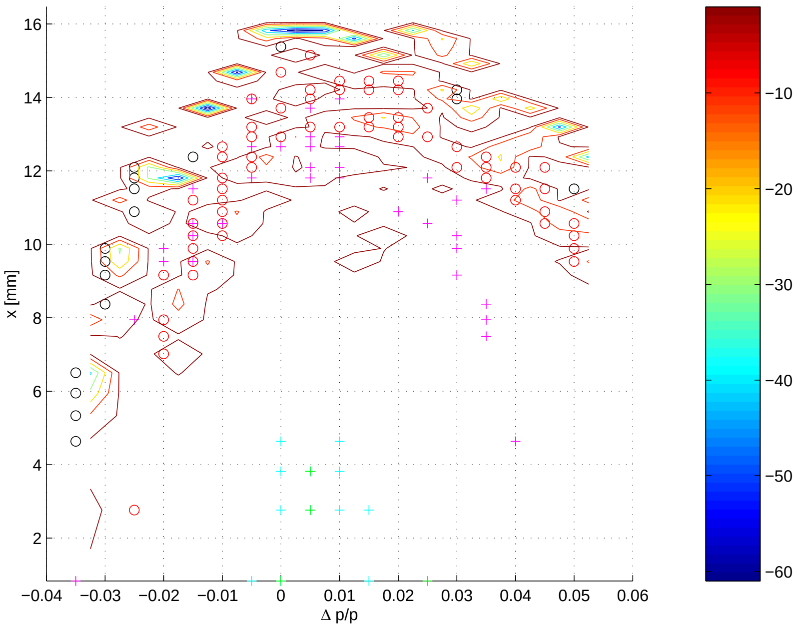
Off energy aperure studies/frequency maps

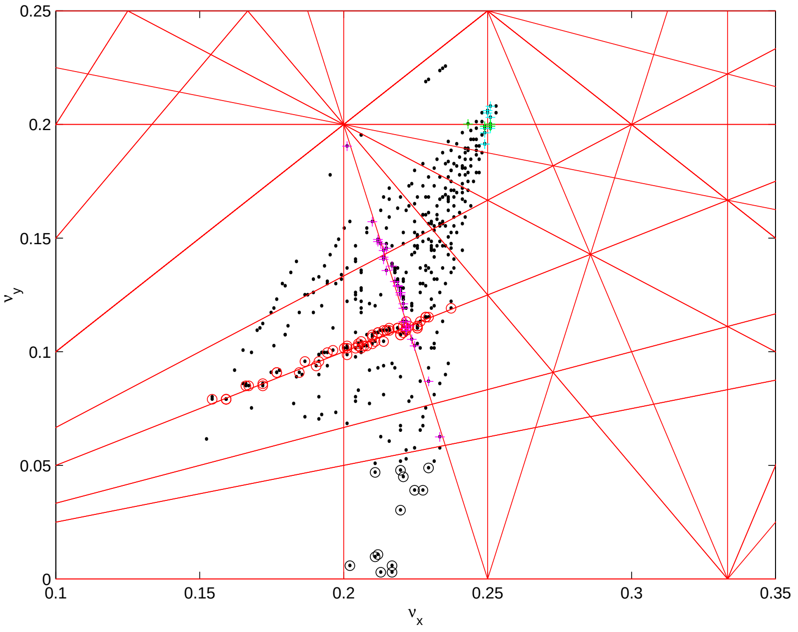
Winfried Decking, Jacques Laskar, David Robin, Christoph Steier, Ying Wu



- again some regions with partial beam loss ⇒ resonances
- short term dynamic aperture is not a smooth function of energy deviation

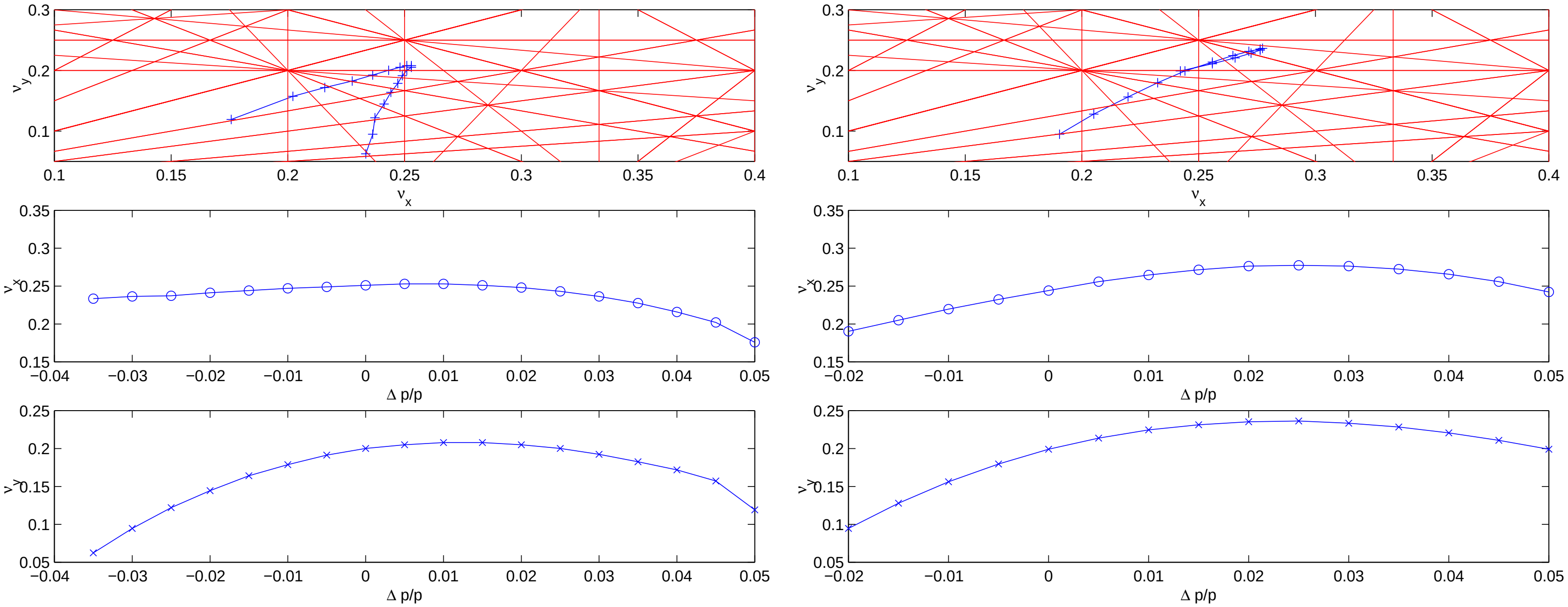
Off energy aperture studies/frequency maps II





- structures in dynamic aperture can be identified with resonances
- chromaticity (even the linear one) is important

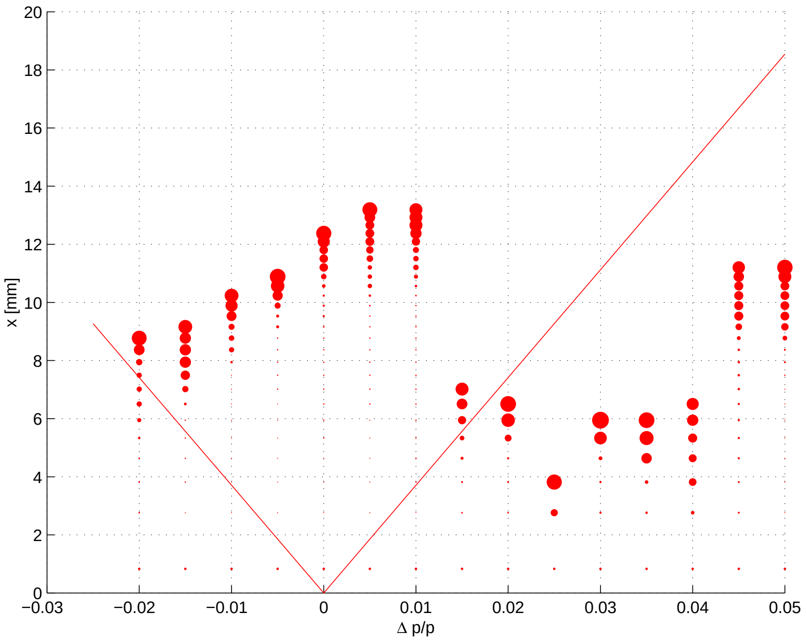
Off energy aperture studies/chromaticity

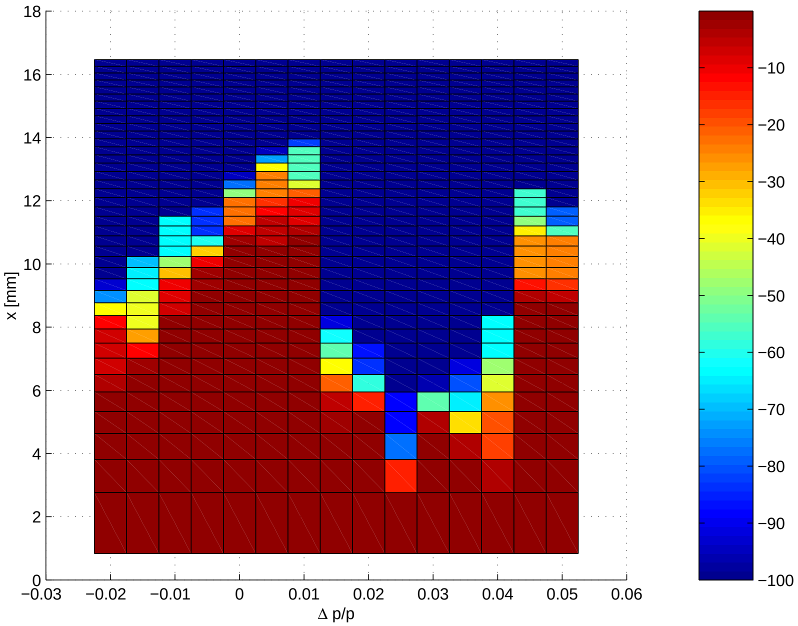


- with different linear chromaticity, off energy particles are influenced by different resonances ⇒ off energy dynamics can be very different

- effect can be fairly large

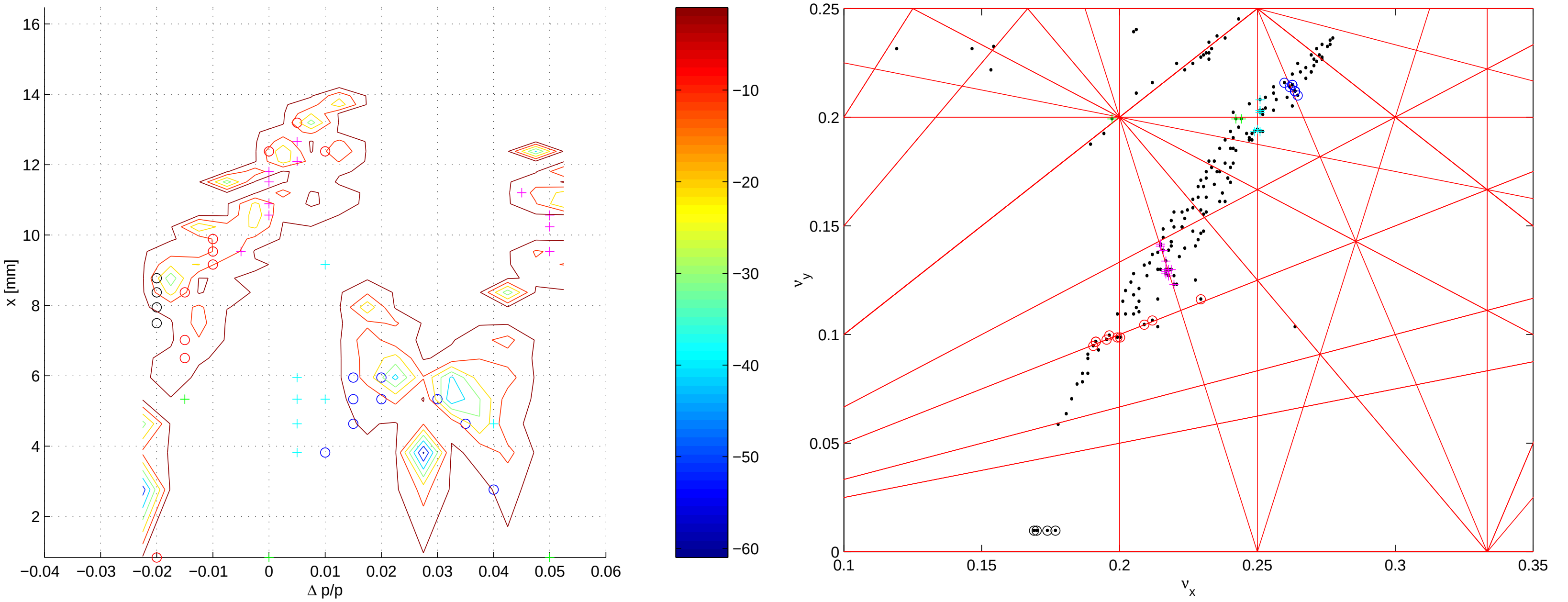
Off energy aperture studies/chromaticity II





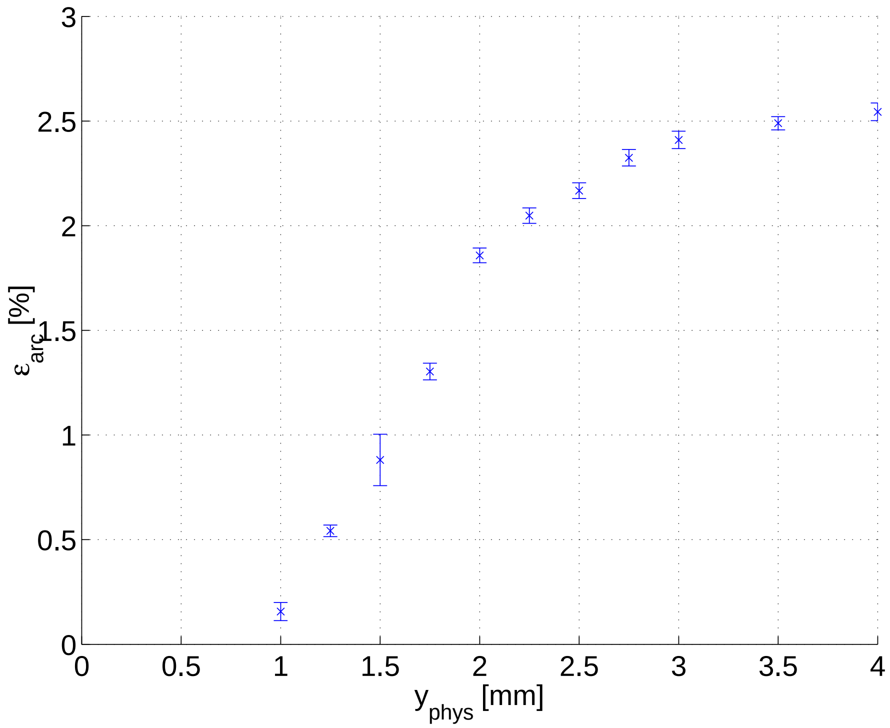
- due to linear chromaticity a region with strongly excited resonances is probed
- in current case they were especially strong because symmetry was broken (three-fold)

Off energy aperture studies/chromaticity III



- lossy regions in phase space can be easily identified with resonances (enhanced by periodicity breaking
- explains why ALS lifetime is very sensitive to vertical chromaticity

Impact of Vertical Physical Aperture



- Vertical physical aperture has big impact on momentum aperture
- For ALS lifetime collapses at aperture of about 40-50 σ_y

Summary (Momentum Aperture)

- *Dynamic momentum aperture is important/dominant effect for Touschek lifetime*
  - Measurement method using frequency analysis provides a very powerful model independent diagnostic tool
  - Improvement possibilities limited in ALS (two sextupole families), but large potential in newer light sources
- *Agreement between the measurement and simulation is good*
  - ⇒ Confidence in machine model ⇒ can be used to predict performance of upgrades or new machines
- *Outlook*:
  - Reduction in measurement time
  - Apply transverse and longitudinal kick simultaneously