Lifetime and dynamics of particles at large amplitudes

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Outline

- **Motivation**
- **Lifetime**
- **Particle motion at large amplitudes**

Concepts

Want to touch on a number of concepts including:

- **Scraper measurements**
- **RF scans**
- **Tune scans**
- **Pinger measurements**
- **Frequency Map Analysis**

Motivation

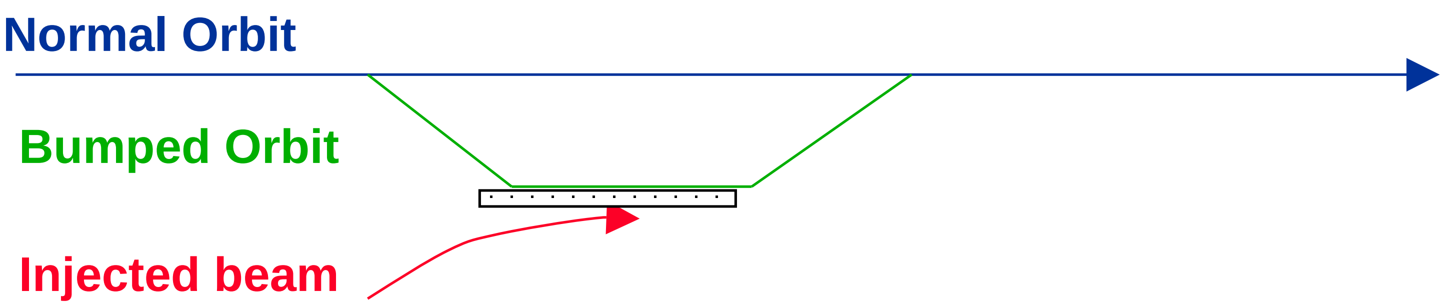
Motion of particles at large amplitudes impacts the performance of the storage ring.

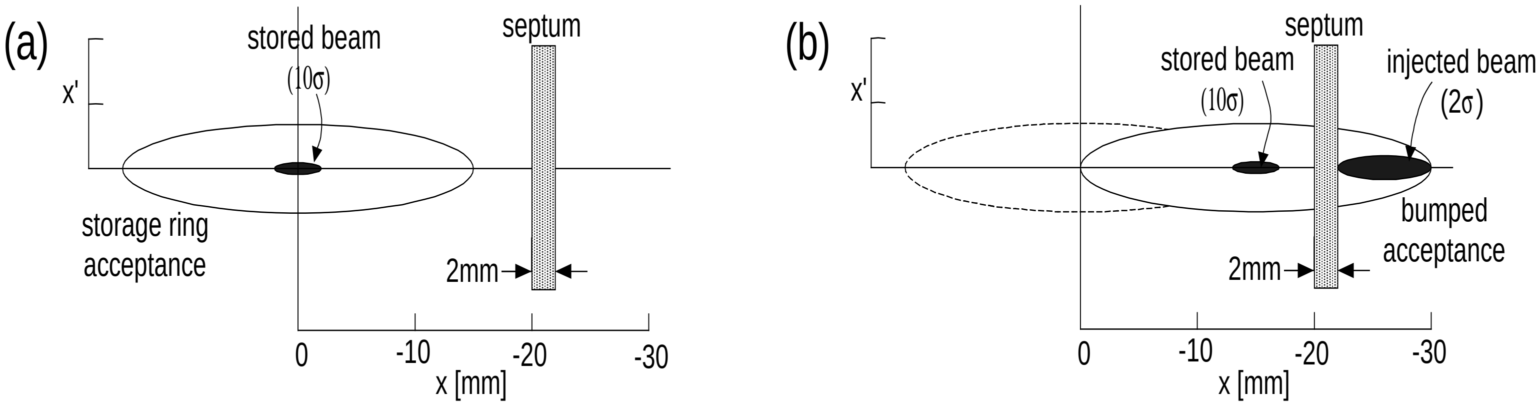
Particle loss

- **Injection efficiency**
  - **Longer injection times**
  - **Increased radiation levels**

- **Lifetime**
  - **More frequency fills**
  - **Faster current loss → changing brightness**

Injection Efficiency





Storage ring acceptance has to be large enough to capture sufficient amount of injected beam.

Lifetime and beam loss

Why is there a finite lifetime?

- Electron undergoes a scattering event
- Change in angle or energy gives increased amplitude of oscillation
- If a boundary is hit (physical or dynamic) then the electron is lost
- Gradually all electrons are lost

Types of scattering

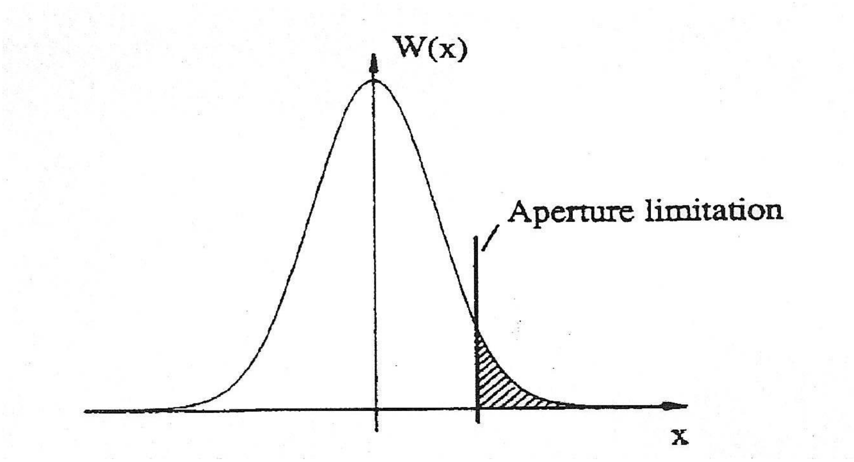
- Electron-Photon Scattering
  - Quantum Lifetime
- Electron-Gas Scattering
  - Gas Lifetime
- Electron-Electron Scattering
  - Touschek Lifetime

Quantum Lifetime

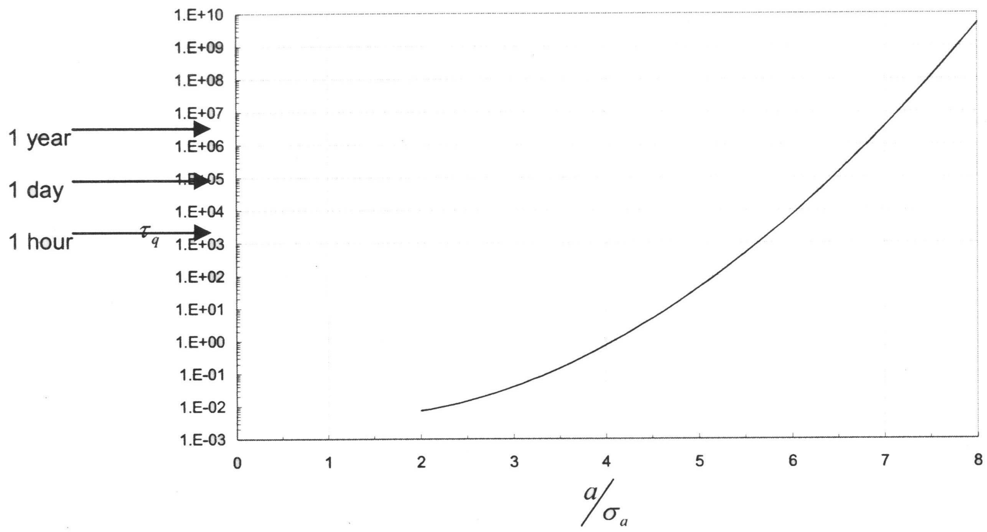
- Emission of synchrotron radiation is quantised
- Distribution of radiation is approximately Gaussian
- A Gaussian distribution of particles is produced
- Tails of distribution are lost
- Redistribution on time scale of damping time

- Quantum lifetime is typically more important for colliders than for light sources

Quantum Lifetime



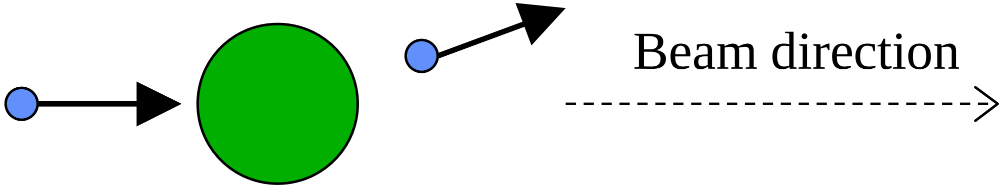
Beam distribution, W(x)



Quantum Lifetime versus aperture-to-beamsize ratio

Gas-scattering lifetime

Particles scatter elastically or inelastic with residual gas atoms.
This introduces betatron or synchrotron oscillations.



The scattering process can be described by the classical Rutherford scattering with differential cross section per atom in cgs units

$$\frac{d\sigma}{d\Omega} = \left(\frac{zZe^2}{2\beta cp}\right)\frac{1}{\sin^4\frac{\theta}{2}}$$

If the new amplitudes are outside the aperture the particles are lost.

The elastic scattering lifetime is proportional to the square of the transversal aperture *A*:

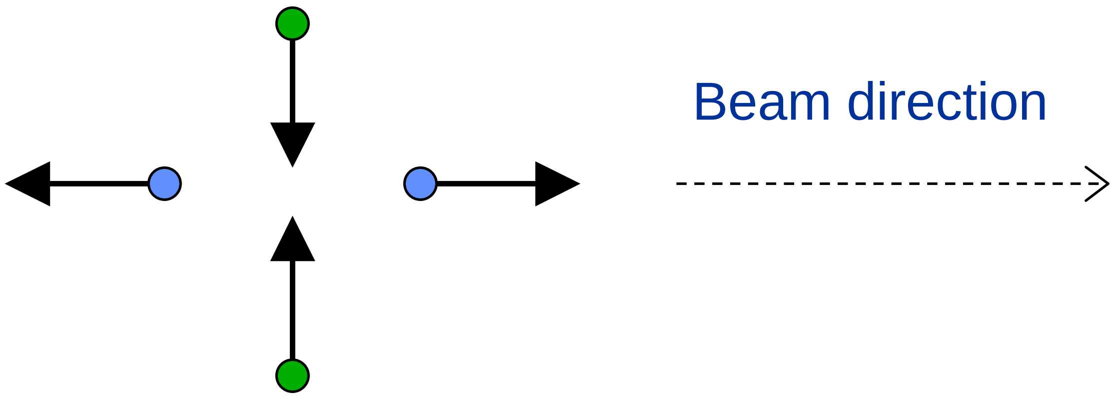
$$\frac{1}{\tau_{el}} \propto \frac{1}{E^2} \times \left(\frac{\beta_x}{A_x^2}\langle P\beta_x\rangle + \frac{\beta_y}{A_y^2}\langle P\beta_y\rangle\right)$$

The inelastic scattering lifetime is proportional to the logarithm of the longitudinal aperture e:

$$\frac{1}{\tau_{inel}} \propto \langle P\rangle \times \ln(\varepsilon)$$

Touschek Lifetime

Particles inside a bunch perform transverse betatron oscillations around the closed orbit. If two particles scatter they can transform their transverse momenta into longitudinal momenta.



Touschek Scattering

- **Large angle electron-electron scattering**
  - **Single scattering event leads to loss**
- **Calculate scattering cross-section**
  - **Möller cross section**
  - **which reduces to**

$$d\sigma \prec \frac{1}{\beta^2}\left(\frac{1}{\sin^4\theta} - \frac{1}{\sin^2\theta}\right) d\Omega$$

  - **For non relativistic velocities and no average polarization**
    - **Effect of polarization is not negligable (see Christoph's talk on Friday)**

- **If the new momenta of the two particles are outside the momentum aperture, ε, the particles are lost. The lifetime is proportional to the square of ε**

$$\frac{1}{\tau_{tou}} \propto \frac{1}{E^3}\frac{I_{bunch}}{V_{bunch}\sigma_x'}\frac{1}{\varepsilon^2} f\left(\varepsilon, \sigma_x', E\right)$$

Lifetime Limiting Processes

$$\frac{1}{\tau_{el}} \propto \frac{1}{E^2} \times \left(\frac{\beta_x}{\Delta_x^2} \langle P\beta_x \rangle + \frac{\beta_y}{\Delta_y^2} \langle P\beta_y \rangle \right) \qquad (1)$$

- ❑ Elastic Scattering

$$\frac{1}{\tau_{tou}} \propto \frac{1}{E^3} \frac{I_{bunch}}{V_{bunch}\sigma'_x} \frac{1}{\varepsilon} f\left(\varepsilon, \sigma'_x, E\right) \qquad (2)$$

- ❑ Touschek Effect

- ❑ Quantum Lifetime

$$\frac{1}{\tau_q} \propto \frac{\Delta^2}{\sigma^2} \times \exp\left(-\frac{\Delta^2}{2\sigma^2} \right) \qquad (3)$$

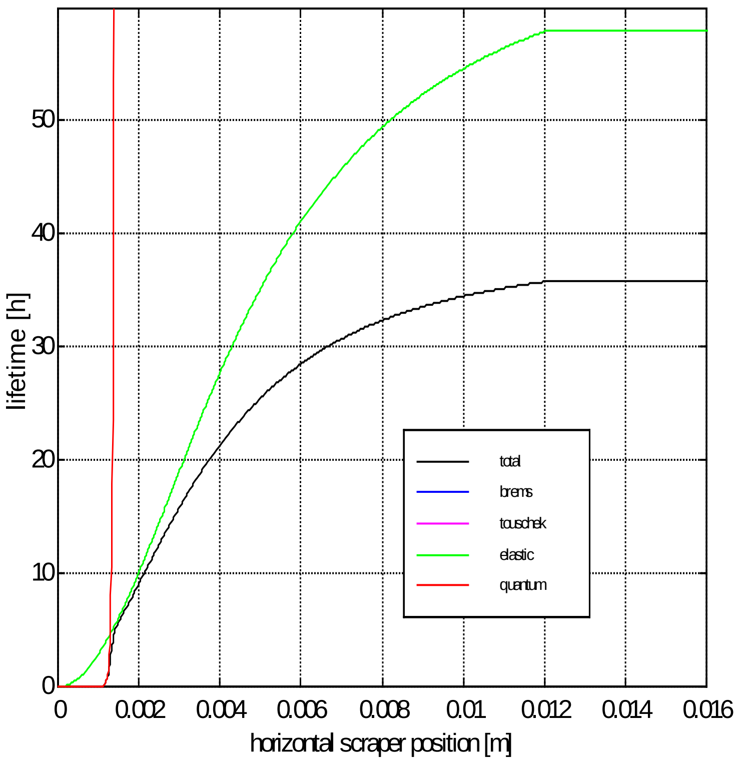
- ❑ Inelastic Scattering

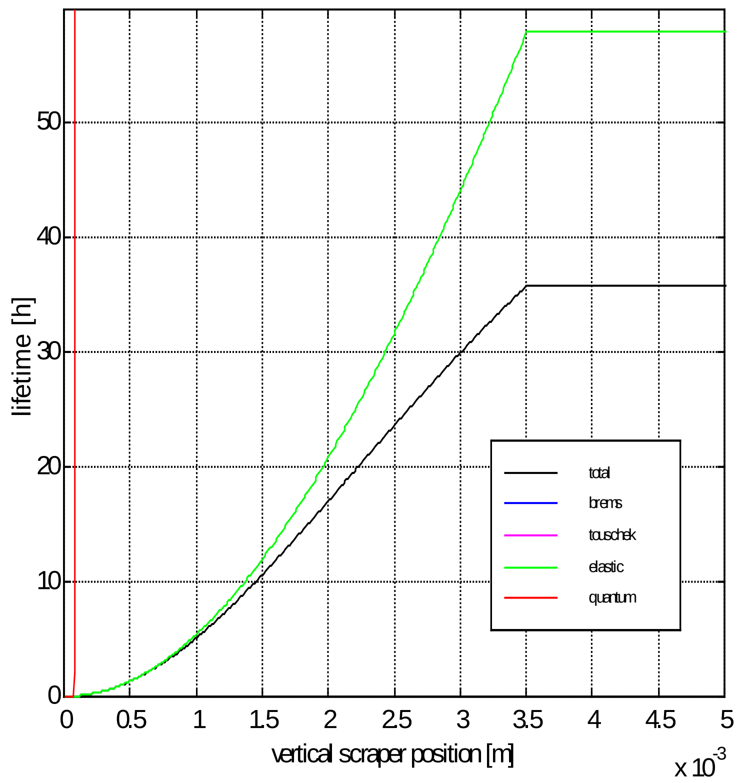
$$\frac{1}{\tau_{inel}} \propto \langle P \rangle \times \ln(\varepsilon) \qquad (4)$$

$$\frac{1}{\tau} = \frac{1}{\tau_{el}} + \frac{1}{\tau_{tou}} + \frac{1}{\tau_{ql}} + \frac{1}{\tau_{inell}}$$

Dependency of Lifetime on Transverse Aperture

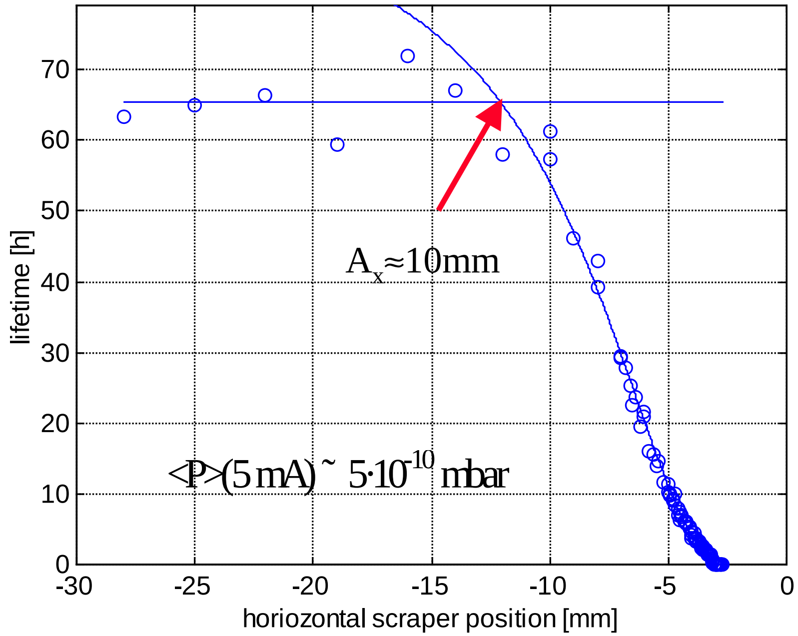
Theoretical Results

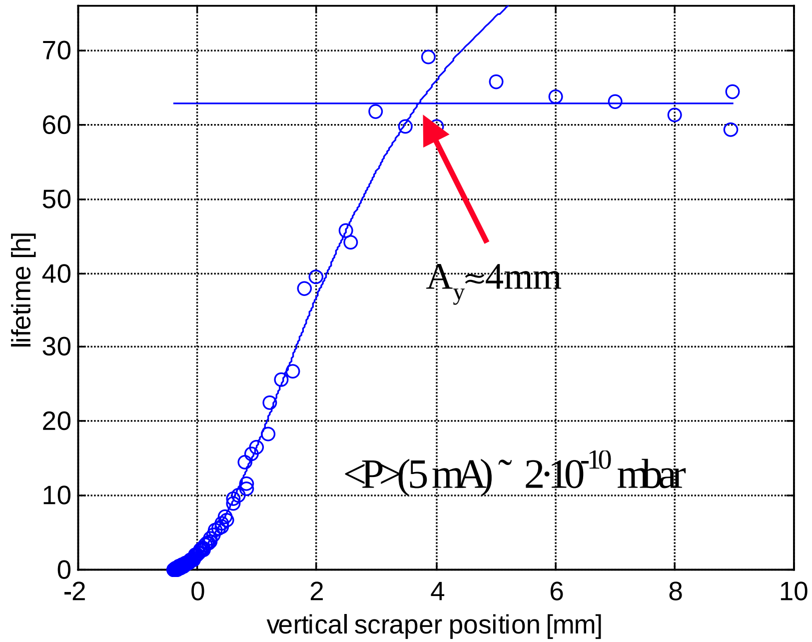




Transverse Acceptance and Gas Lifetime

• move scraper into beam and record lifetime: acceptance, gas pressure





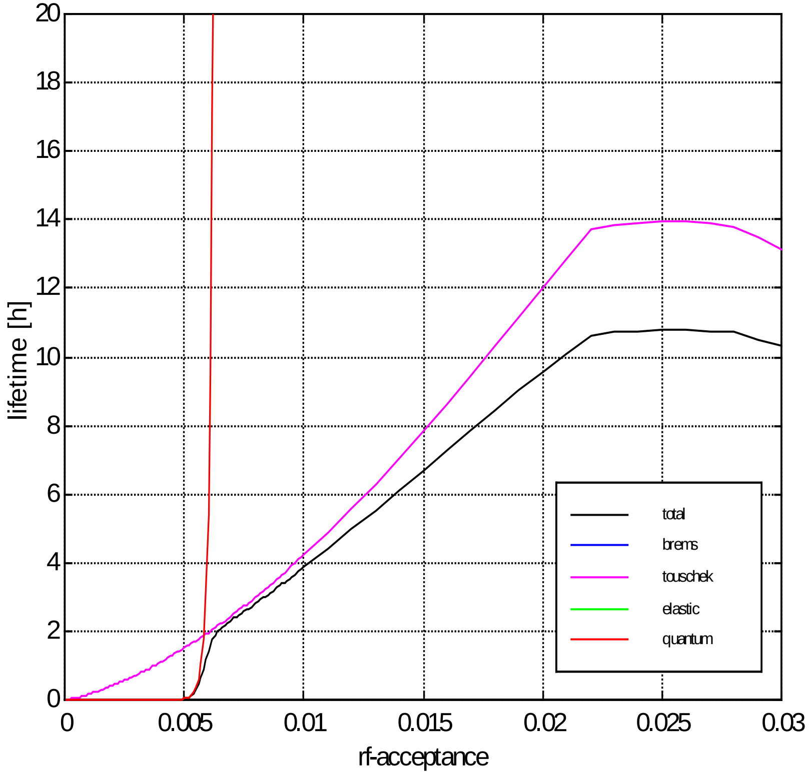
$$\frac{1}{\tau}(\Delta_x) = \begin{cases} const. & \text{if } \Delta_x > A_x \\ \frac{1}{\tau_{tou+inel}} + C_{el}\frac{1}{E^2}\langle P\rangle\left(\langle\beta_x\rangle\frac{\beta_x}{\Delta_x^2} + \langle\beta_y\rangle\frac{\beta_y}{A_y^2}\right) & \text{if } \Delta_x < A_x \end{cases}$$

Assuming different distribution of the gas, i.e. higher pressure in the straight sections: **$3*10^{-10}$ mbar**

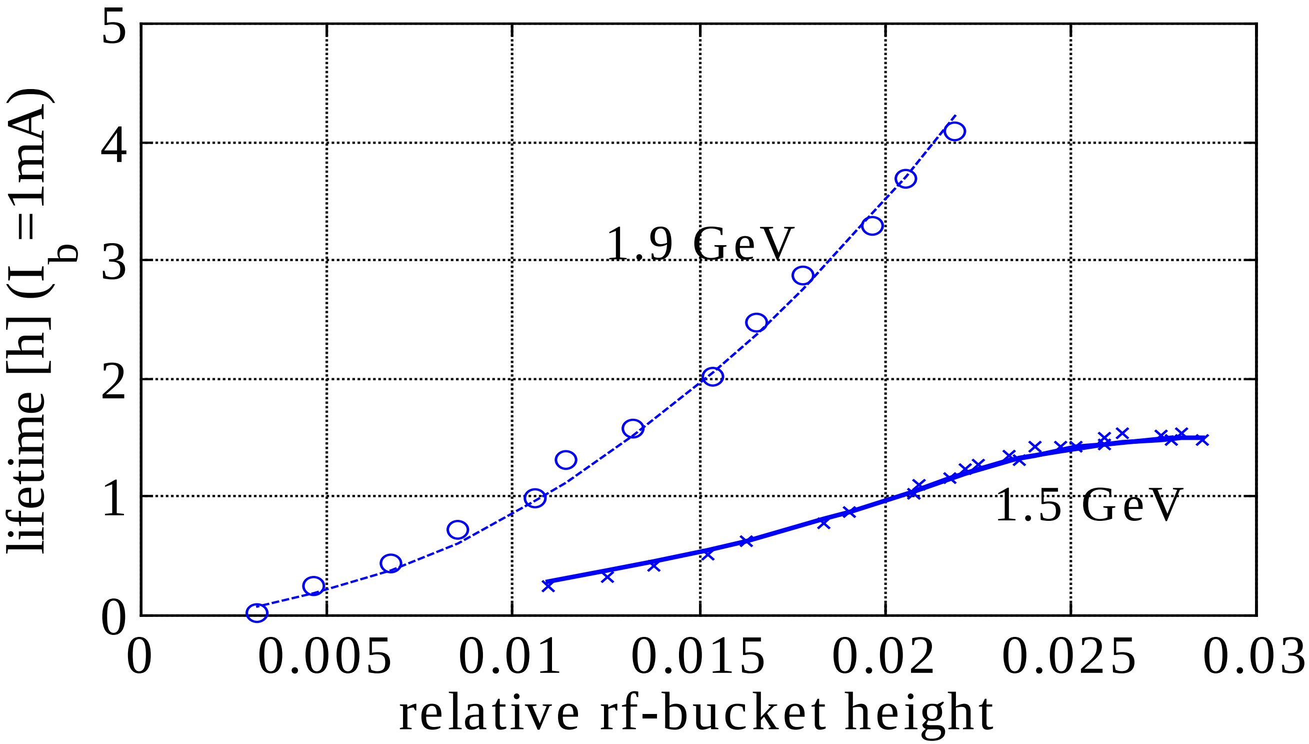
Desorption coefficient: $1.75*10^{-12}$ mbar/mA

Dependency of Lifetime on Longitudinal Aperture

Theoretical results including bunch length change



Lifetime versus RF-Bucket Height



Summary of Lifetime Contributions

	5mA	400mA
elastic scattering	85	≈18
inelastic scattering	265	≈60
Touschek	≈150	1.8
total	≈45	≈1.6

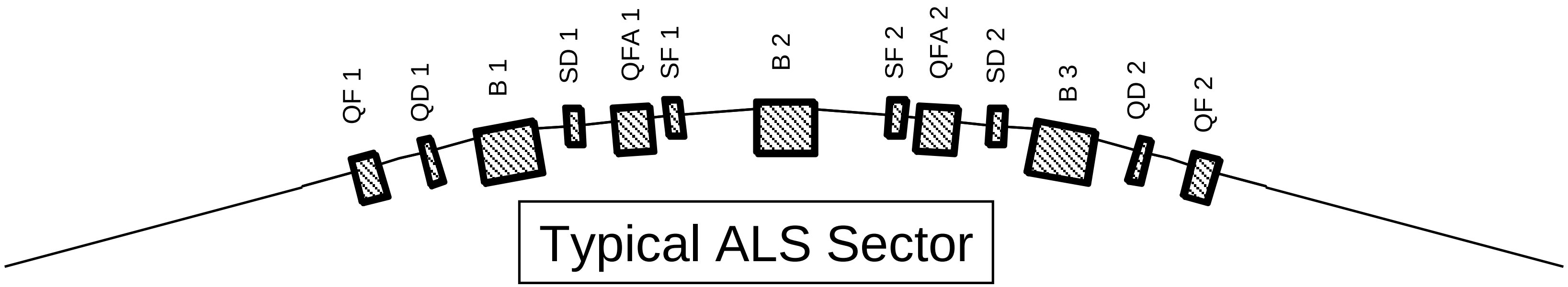
Motion at large amplitudes

The stability of the motion of particles at large amplitudes is clearly important for a good performance of the storage ring.

- Lifetime
- Injection efficiency

Need to understand the beam dynamics

Advanced Light Source



- ALS consists of 12 sectors
  - 12-fold periodicity $\Longrightarrow$ *Suppression of resonances*

$$m\nu_x + n\nu_y = \mathbf{12} \times q$$

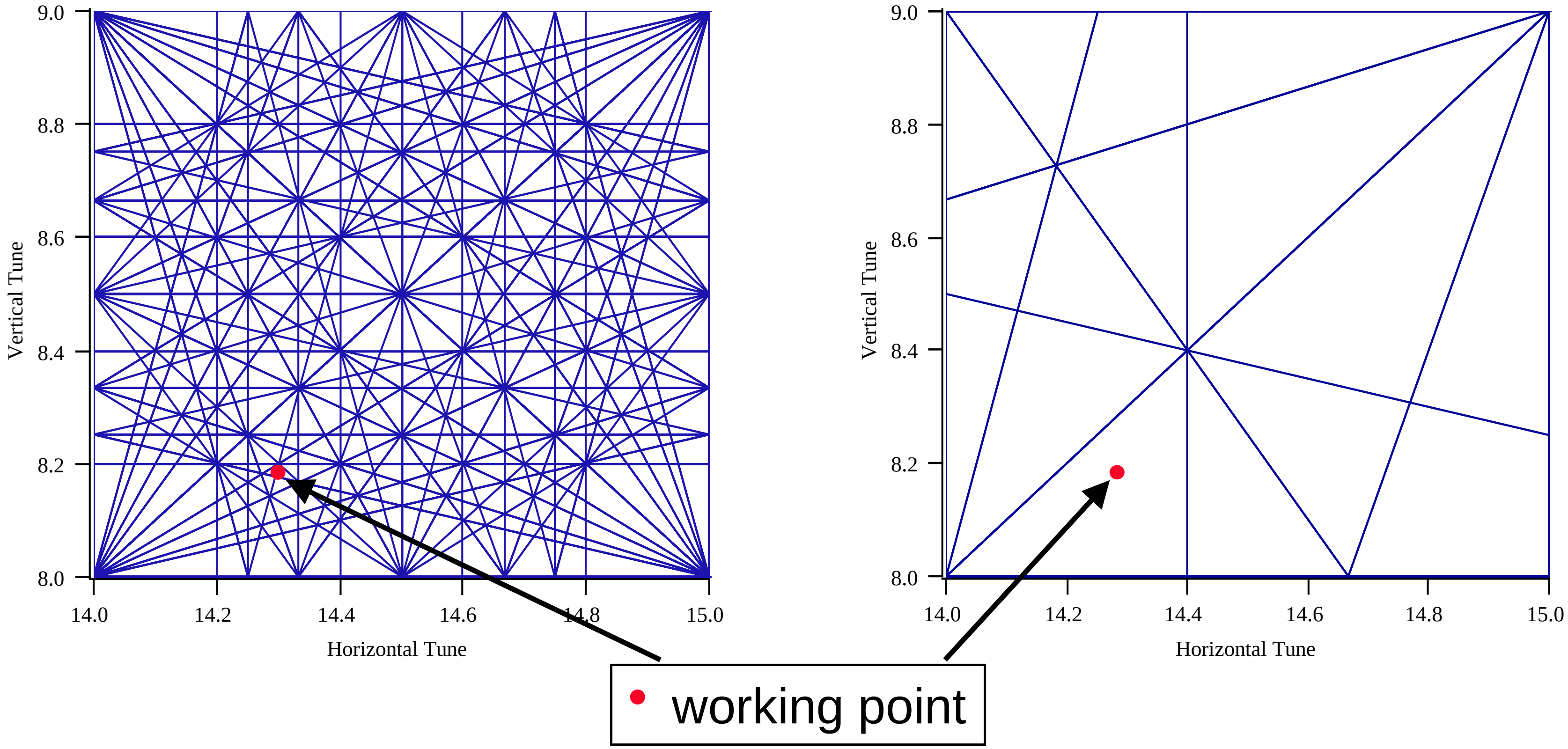
where m, n and q are integers

Benefits of Periodicity

Tune plane - *resonances up to 5th order*

All resonances

Allowed resonances



Resonance Excitation

Resonances can lead to irregular and chaotic behavior for the orbits of particles which eventually will get lost by diffusion in the outer parts of the beam.

Rule of thumb => Avoid low order resonances

Unfortunately there is no simple way to forecast the real strength of a resonances without using a tracking code or through measurements

=> Tune scans
=> Frequency Map Analysis

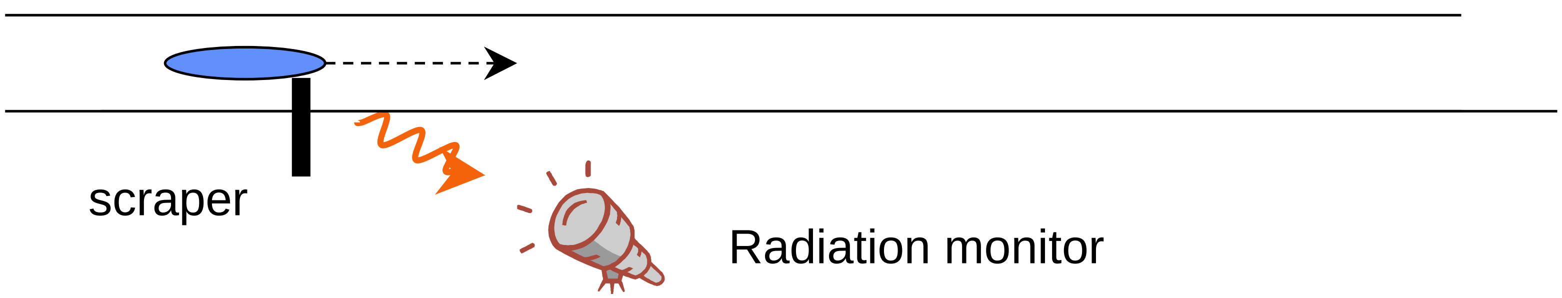
Tune scan

When resonances are present they may change the distribution of the beam at large amplitudes.

- In the case of a resonance island →particles may get trapped at large amplitudes

Technique:

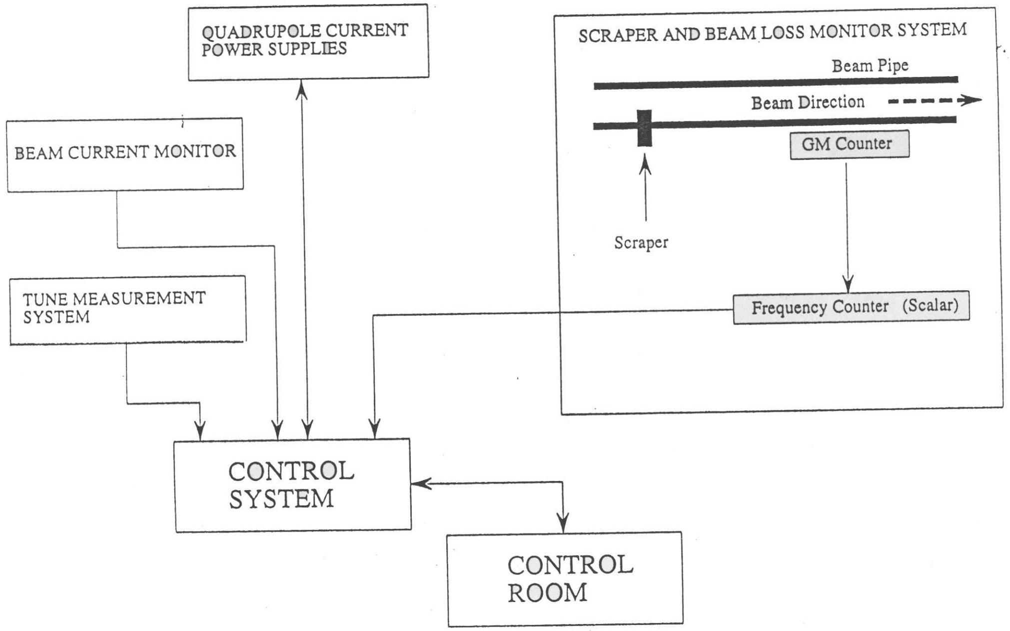
- By Introducing a scraper and a loss monitor



- Scan the tunes and measure the change in the count rate

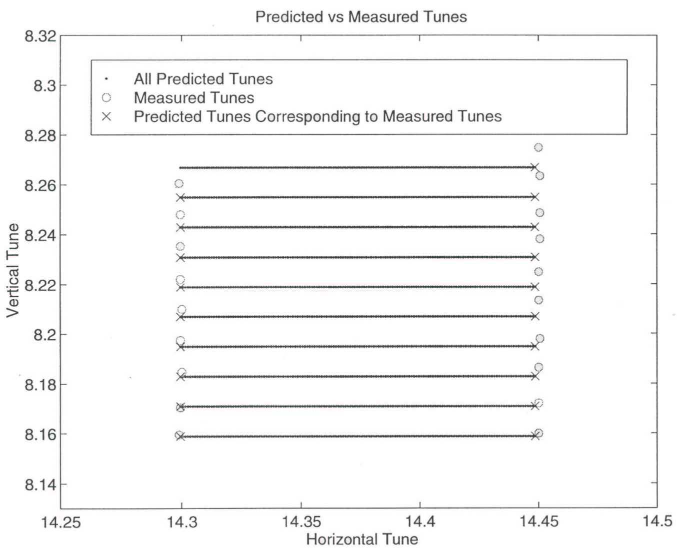
Developed by A. Temnykh (Proc. Of the IXth ALL-Union Meeting on Accelerators of Chaged Particles, Dubna, 1984, INP Peport No. INP 84-131

ALS tunescan system



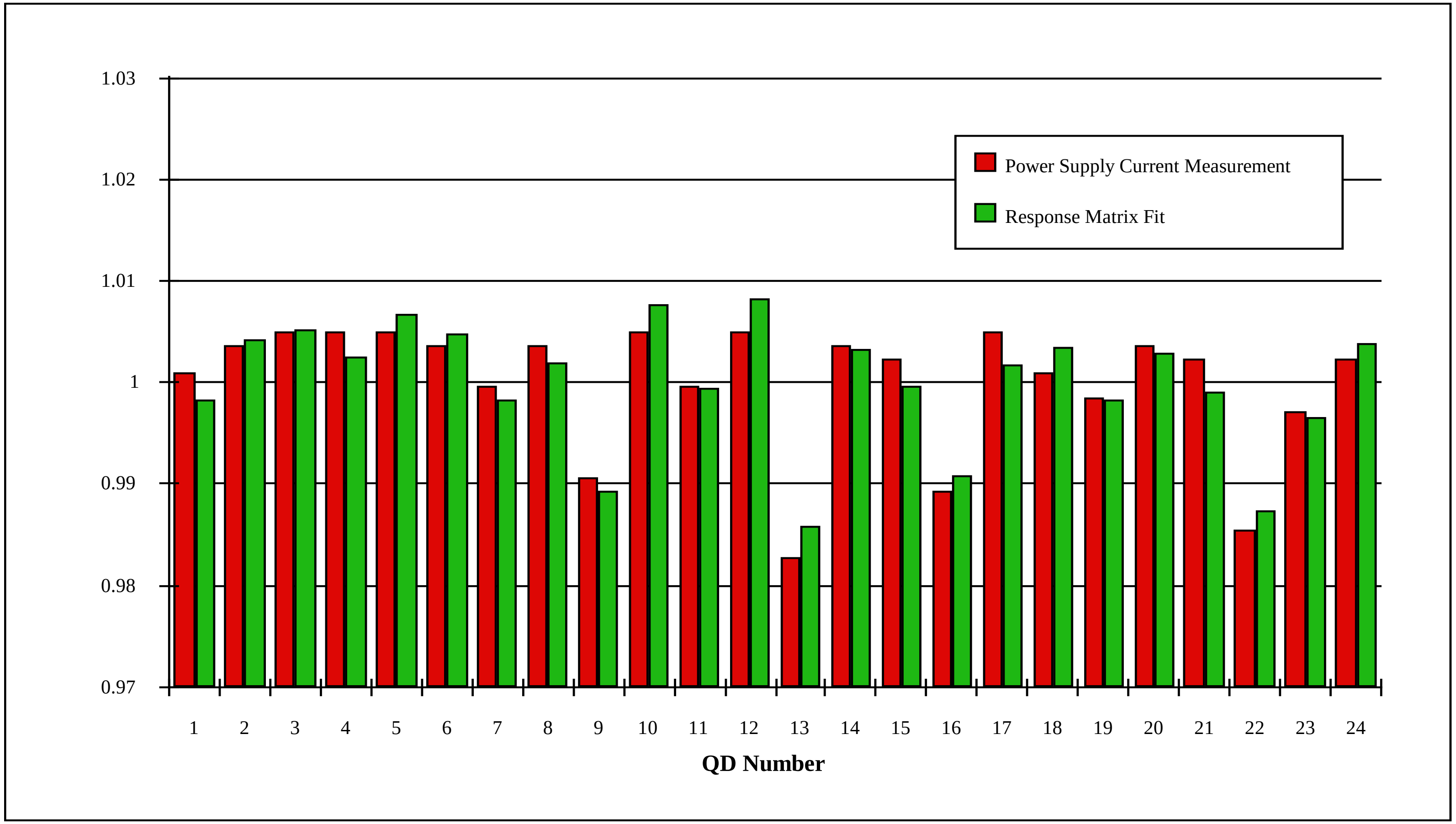
Experimental system

Raster scans



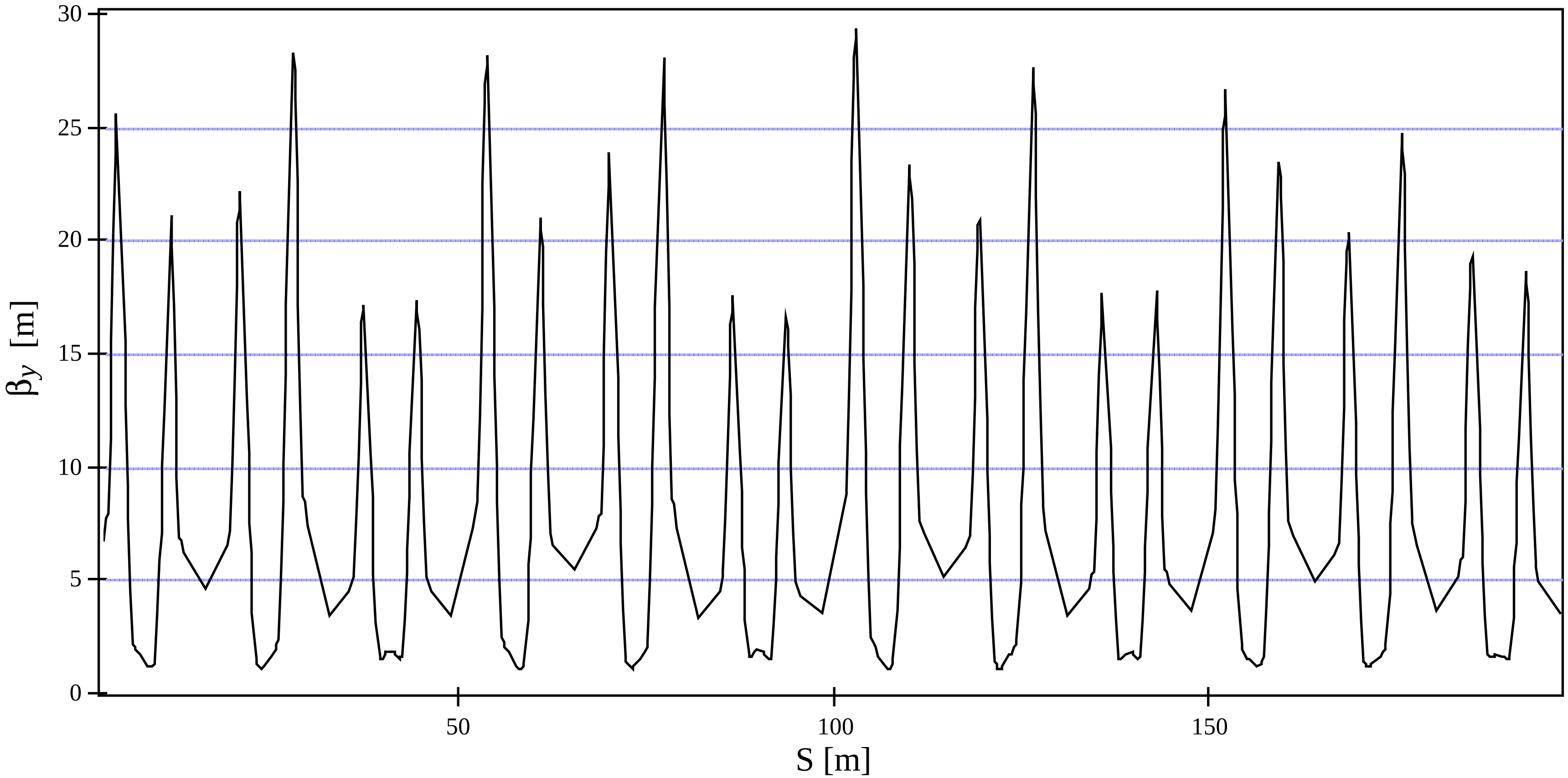
Measured Quadrupole Gradient Errors*

Normalized QD Quadrupole Field Strengths
(measured in two independent ways)



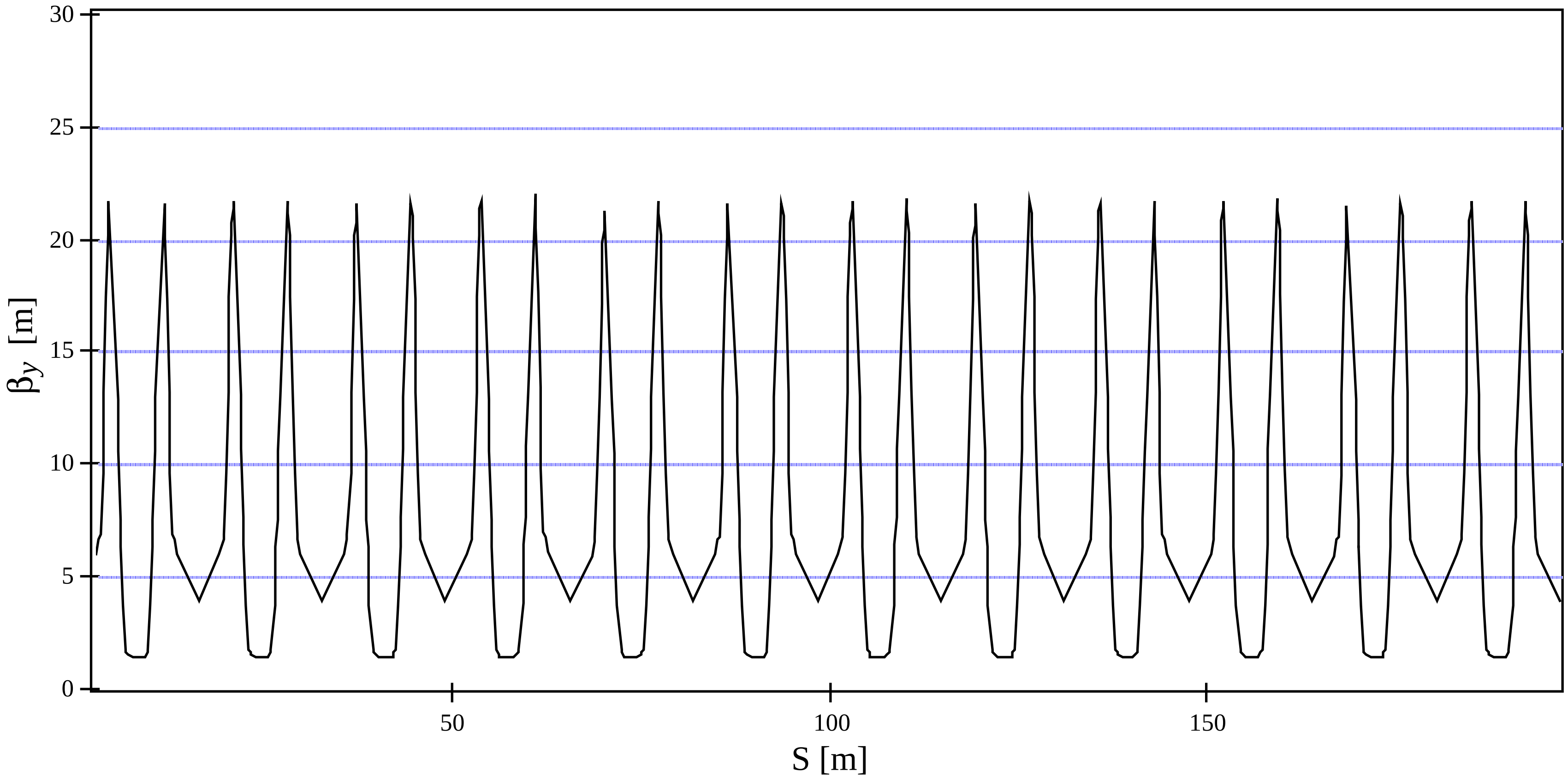
**ALS staff in collaboration with James Safranek of BNL*

Vertical Beta-Function Including Errors



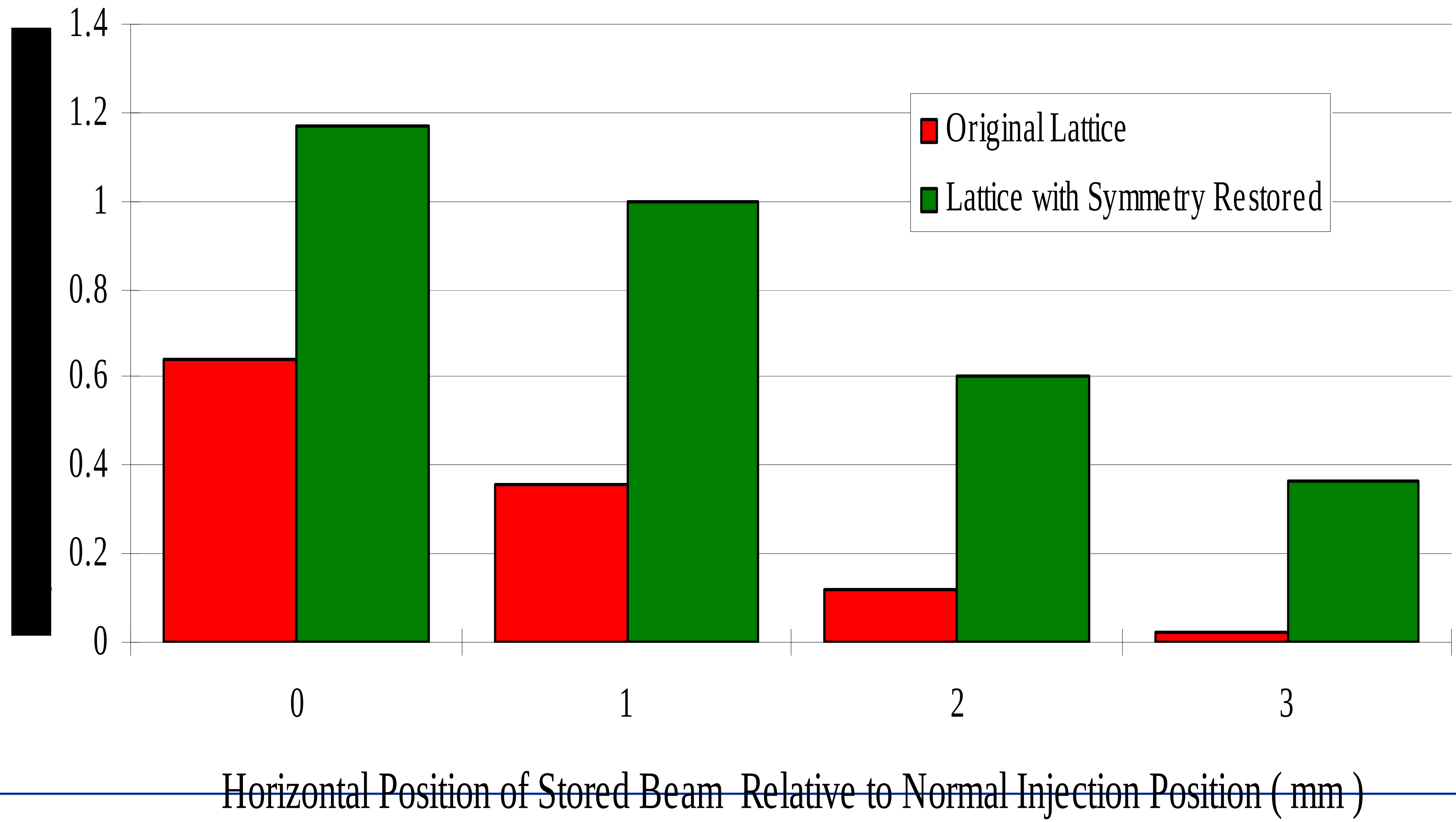
Vertical beta-beating is 19% (rms)

Vertical Beta-Function with Restored Symmetry



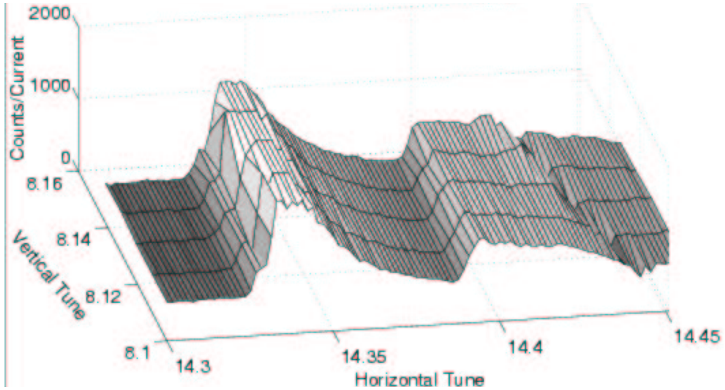
Vertical beta-beating is 1% (rms)

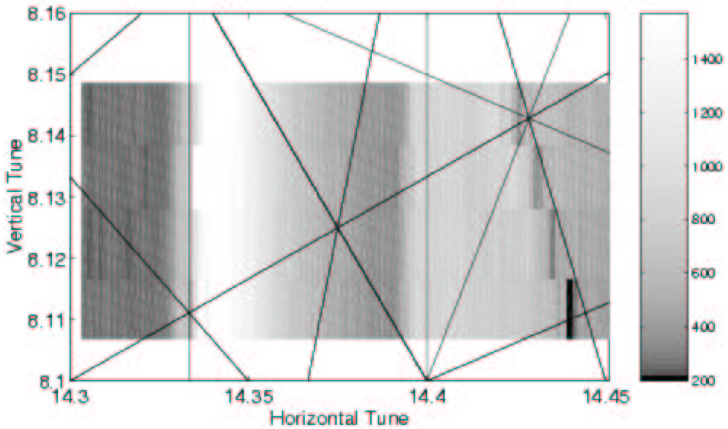
Improved Injection Efficiency



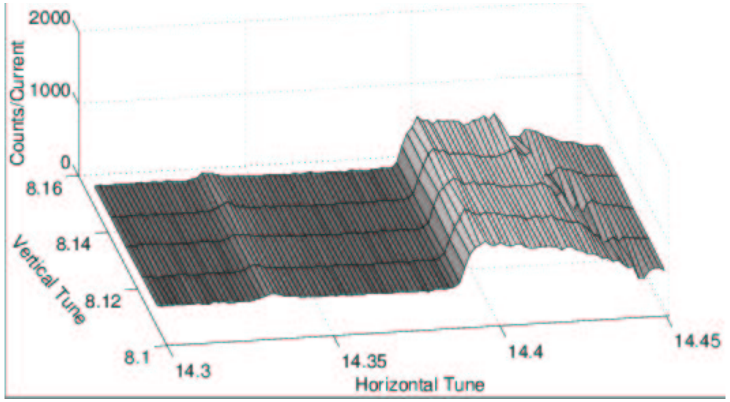
Tune scans (with and without large beta beating)

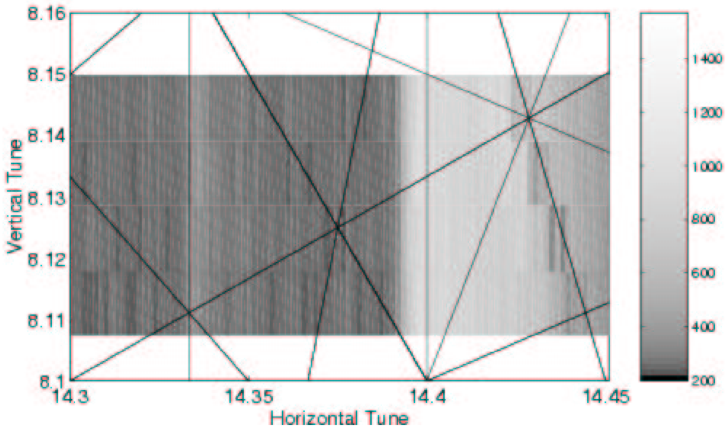
Uncorrected lattice





Corrected lattice





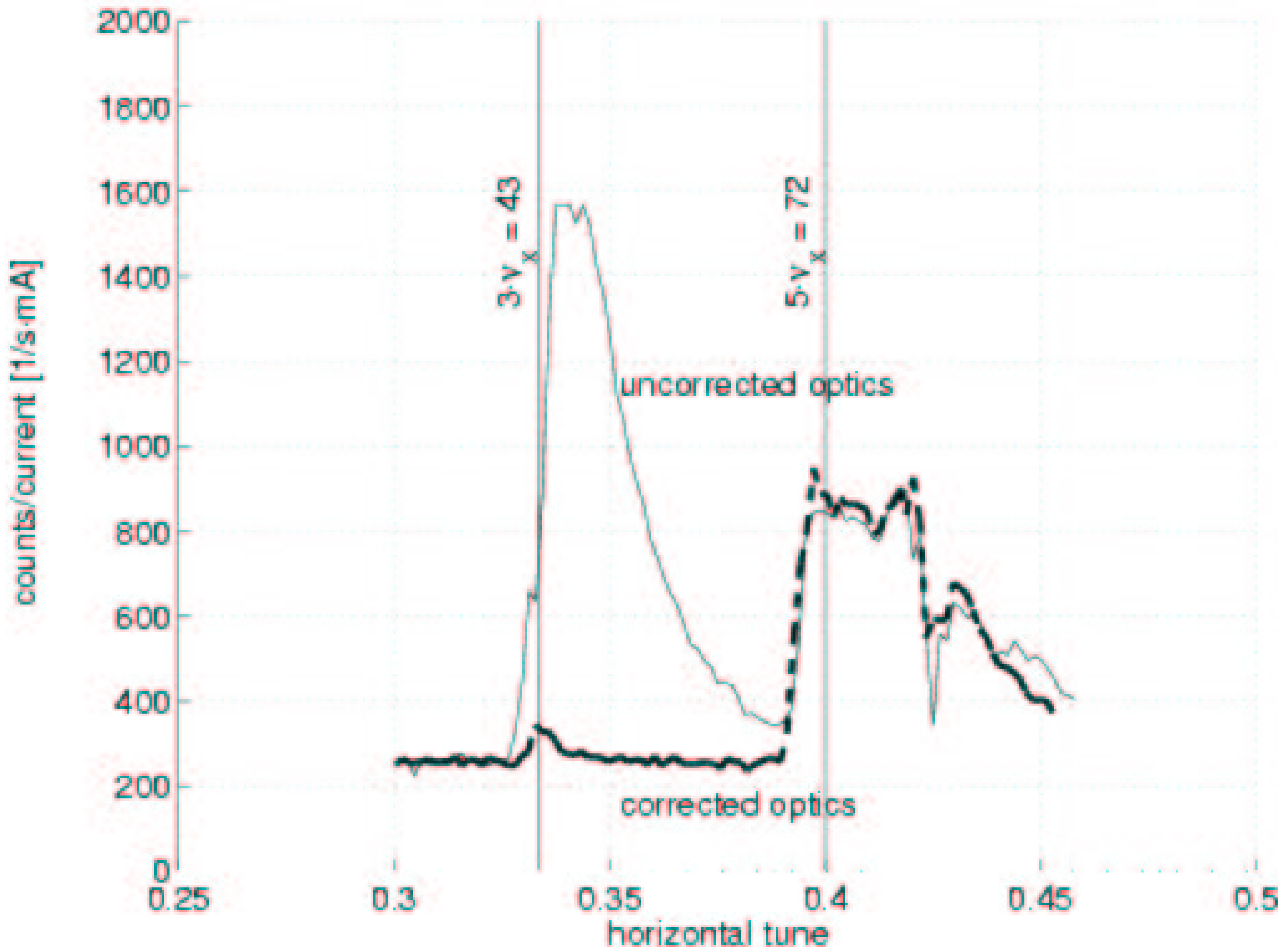
Three resonances are present:

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

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

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

Large reduction in the unallowed resonances

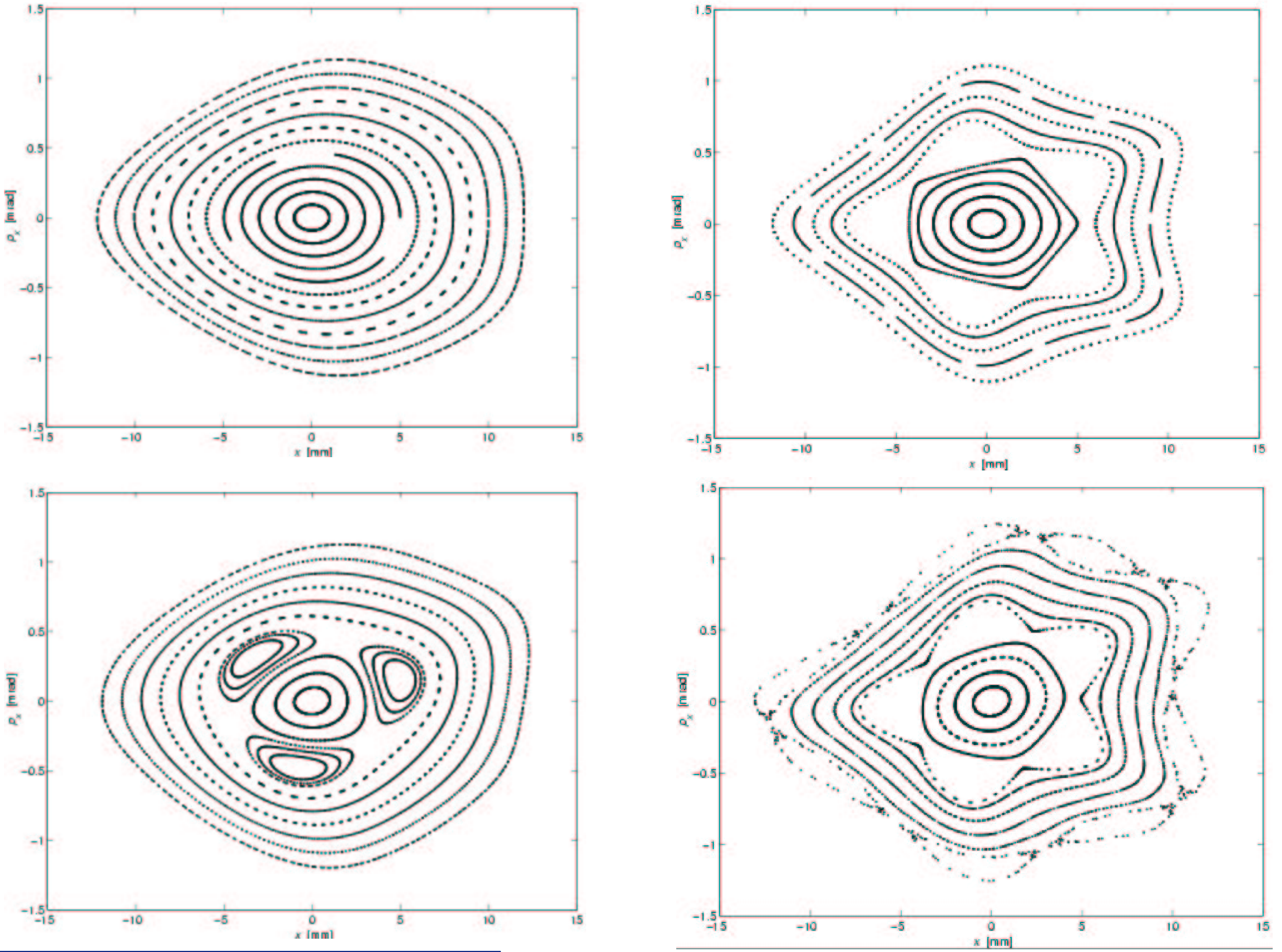


Large reduction in the unallowed resonances

Near 3rd order resonance | Near 5th order resonance

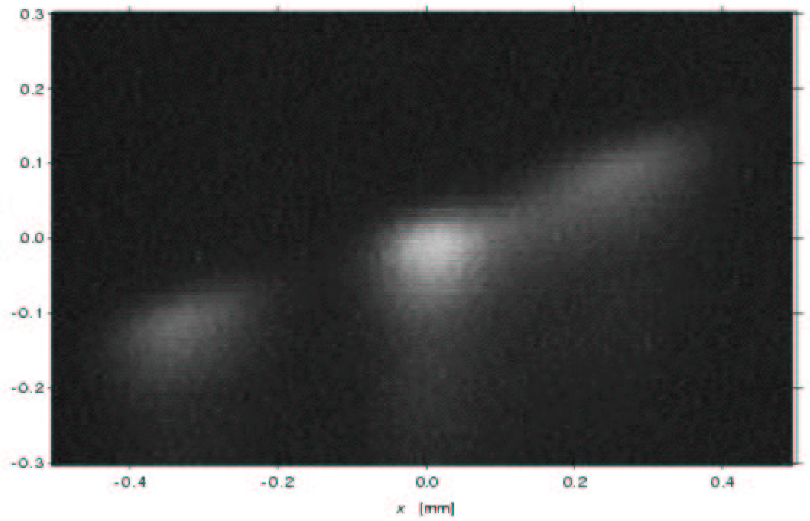
corrected

uncorrected

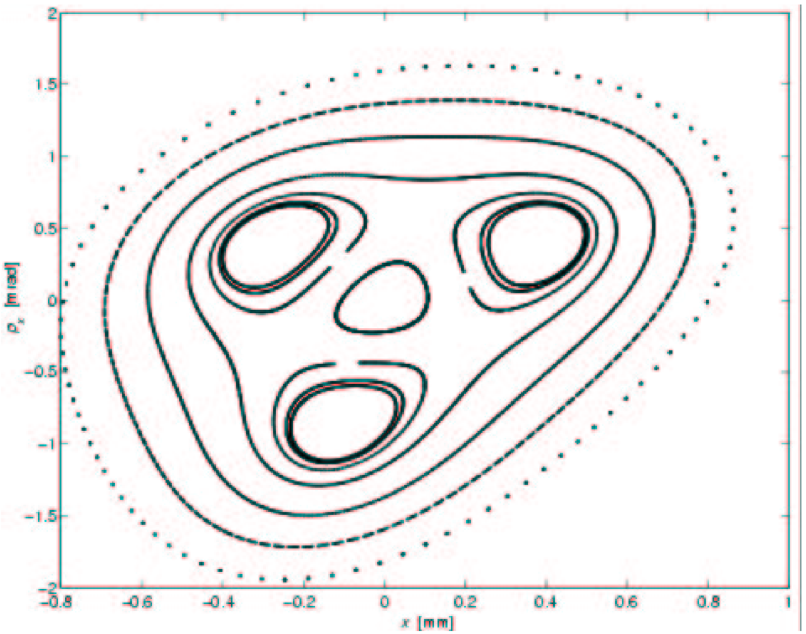


Profile measurement near 3rd order resonance

Profile measurement



Horizontal phase space



Tune scan summary

Advantages

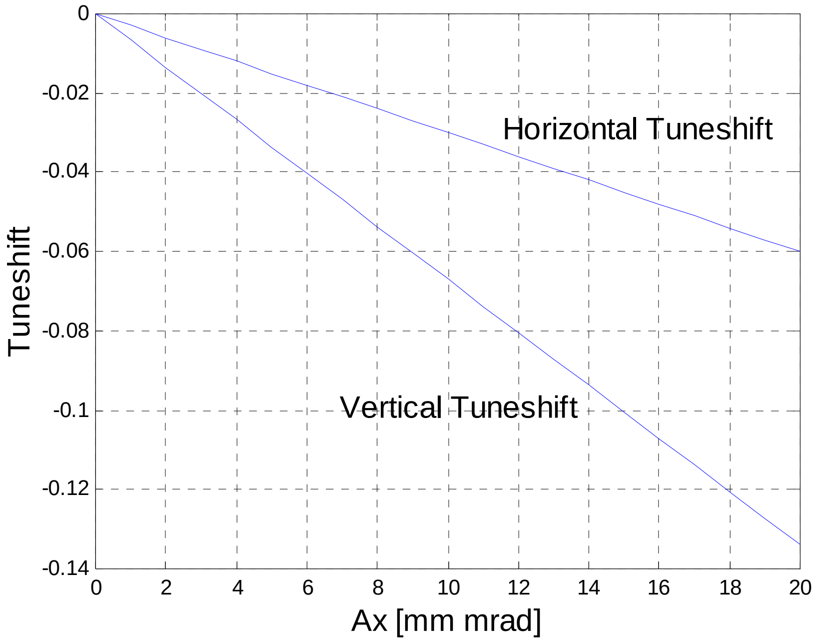
Quickly and sensitively see excited resonances in the tails and core of the beam as a function of different tunes

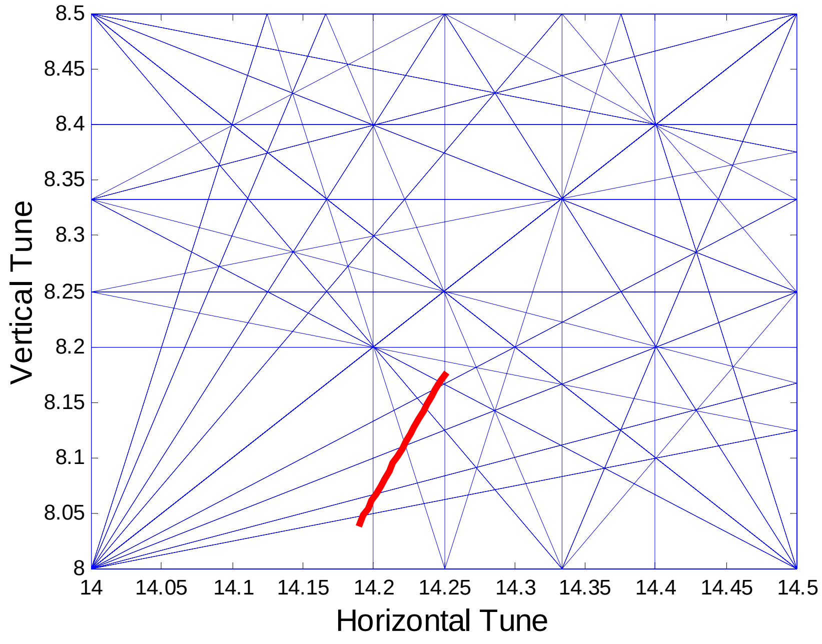
Disadvantages

Probing different machines and not looking at the effect of resonances on one working point and at different amplitudes. This is what one really would like to see.

Tune shift with amplitude

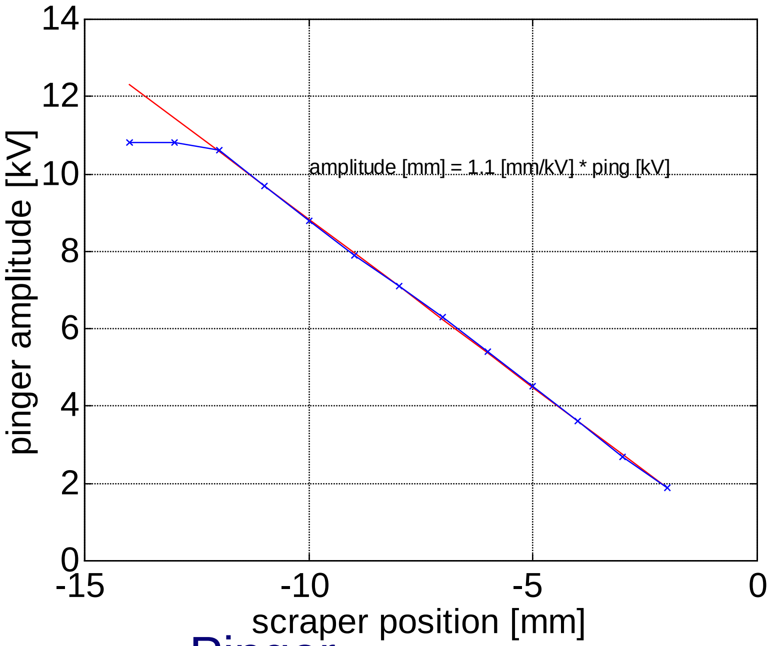
Particle tune get shifted with amplitude



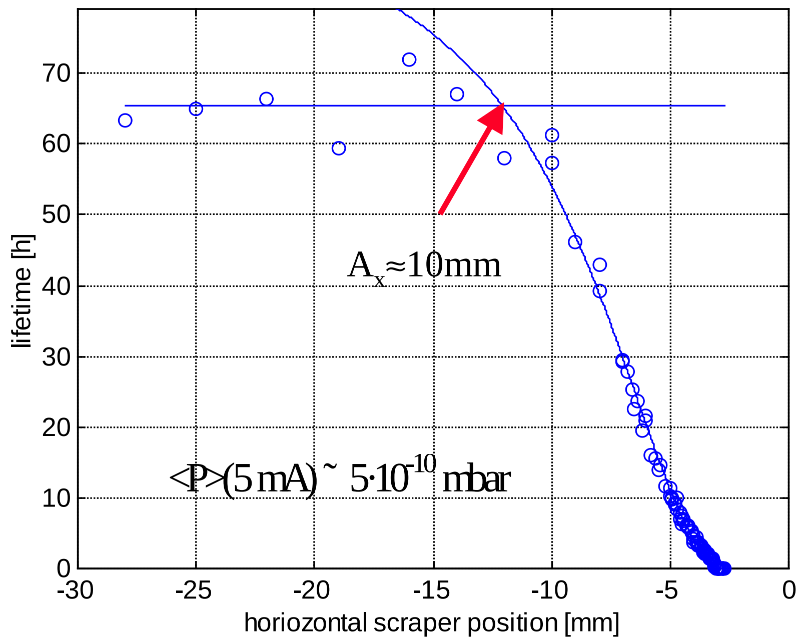


Aperture Measurements with Pinger Magnet

- Pinger magnet applies single kick ('ping') to beam each second
- Increase 'Ping' until beam is lost ==> DA
- Calibration of HV versus amplitude:



Pinger



Comparison with scraper

KAM Theorem (the basis of frequency map analysis)

According to the KAM theorem, in the 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.

Frequency Map Analysis

Developed by Jacques Laskar

The frequency analysis algorithm (NAFF) is a postprocesser for particle tracking data that numerically computes, over a finite time span, a frequency vector for any initial condition.

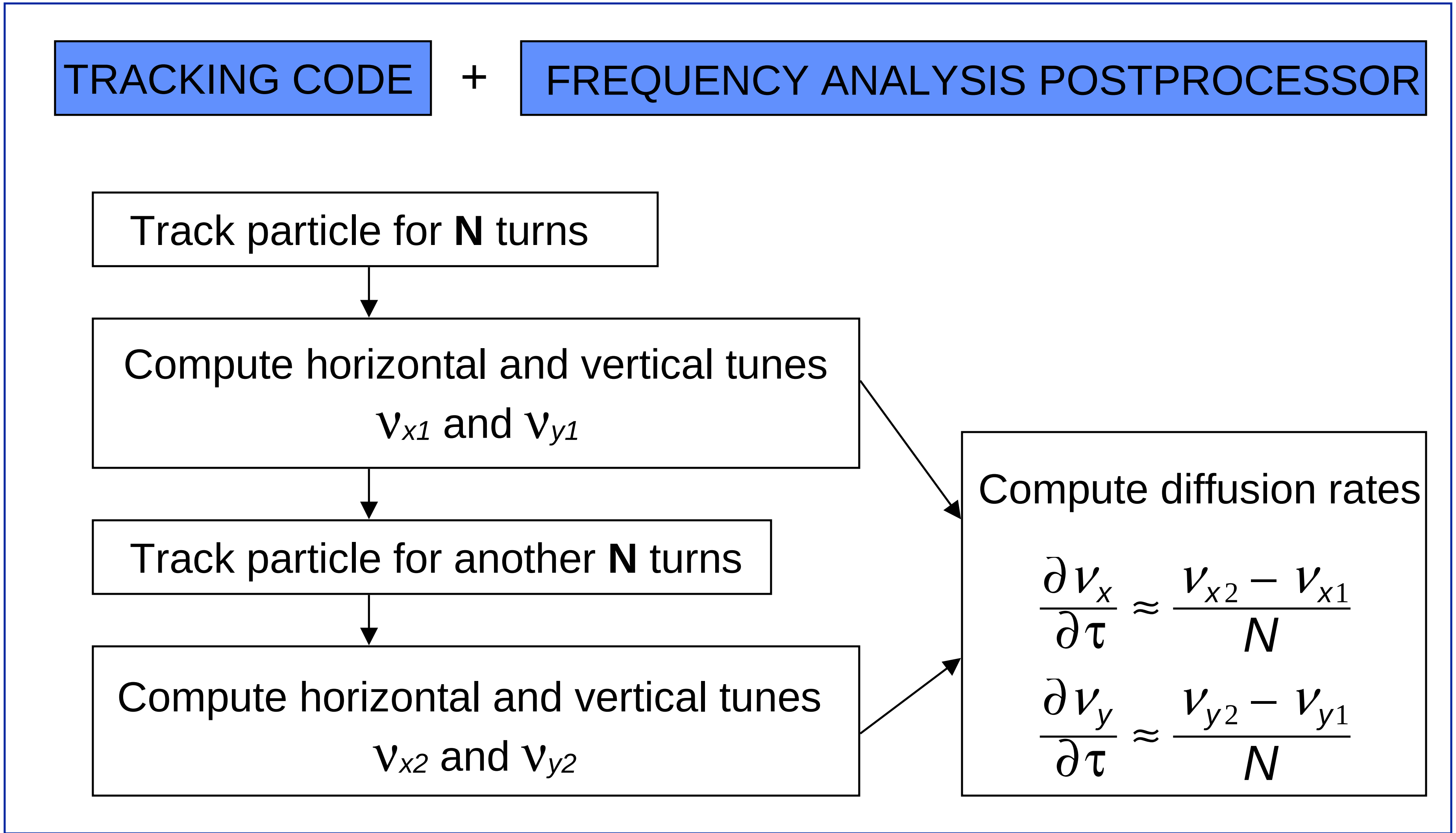
Frequency Map: Initial condition → Frequency vector

Based on the KAM theorem, frequency map analysis determines whether an orbit is regular or chaotically diffusing.

Regular orbits → Frequency vector remains fixed in time

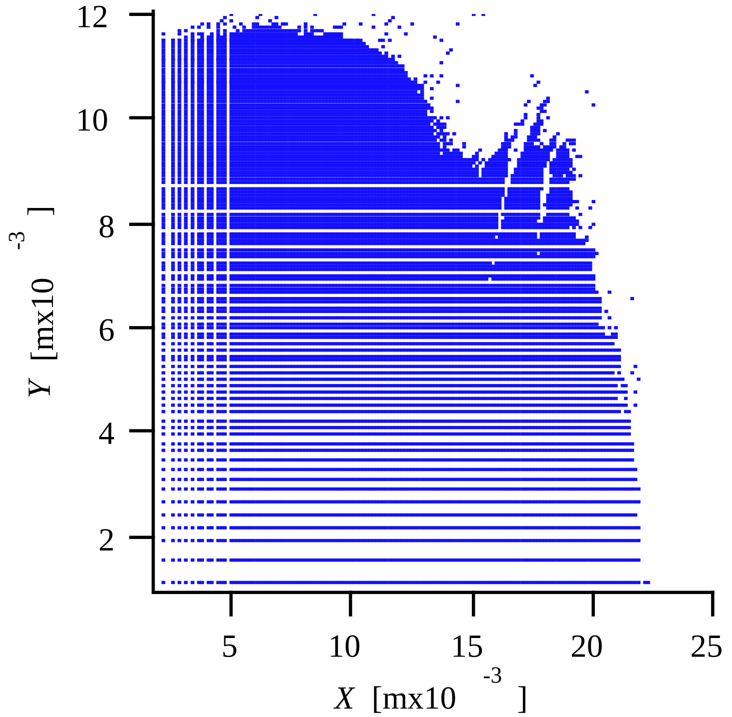
Nonregular orbits → Frequency vector changes in time

Tunes and Diffusion Rates

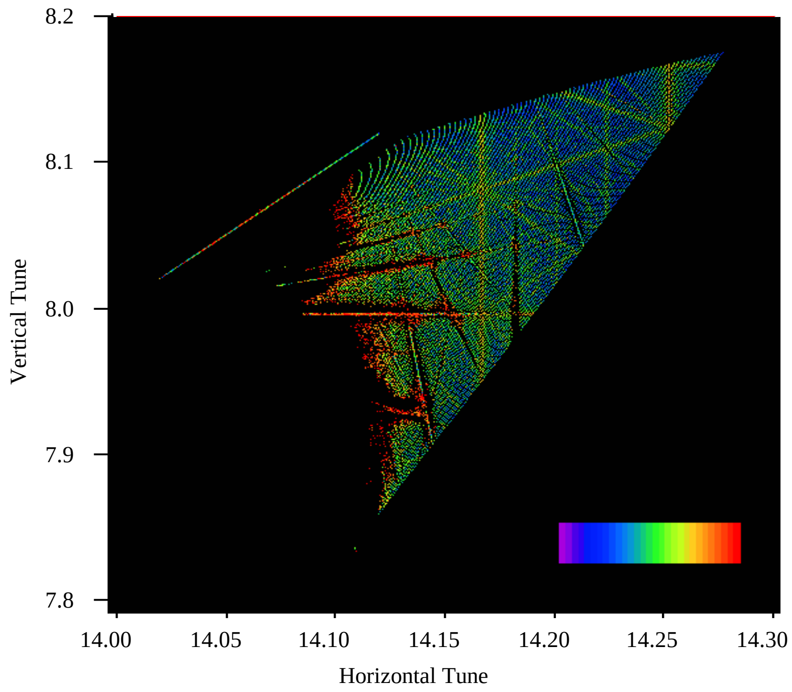


Dynamic Aperture and Frequency Map

Dynamic Aperture



Frequency Map



Summary

Various different techniques have been shown to probe the dynamics at large amplitude.

Christoph Steier will elaborate more on applying frequency map analysis towards understanding of the dynamics of large amplitude particles.