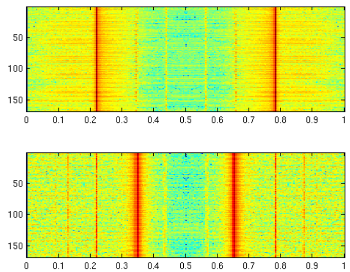
"Beam Dynamics meets Diagnostics" Workshop 4-6 November 2015, Florence, Italy.

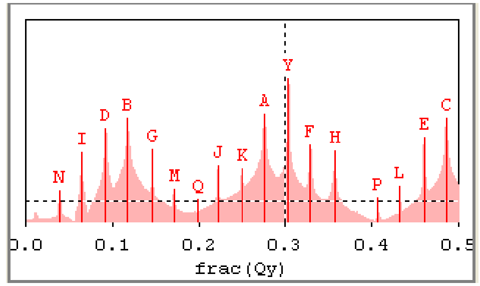
Session Storage Ring and lepton machines

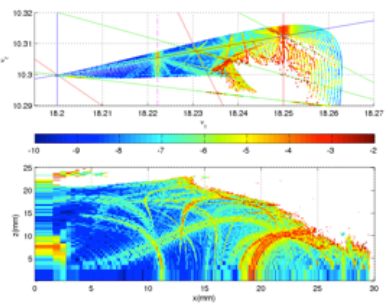
Analytical and numerical non-linear beam dynamics optimization

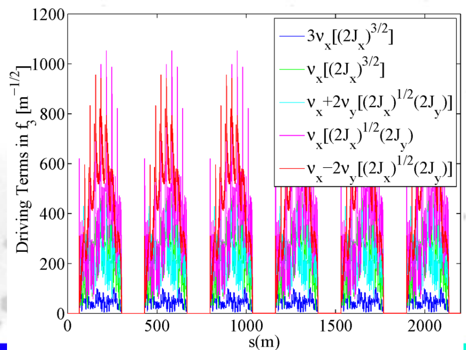
Laurent S. Nadolski

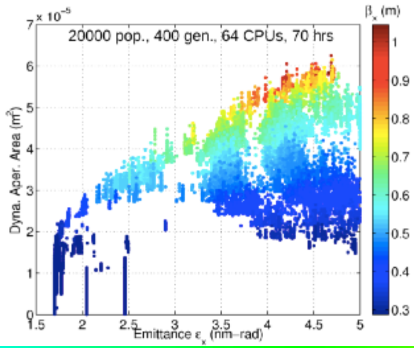
Synchrotron SOLEIL

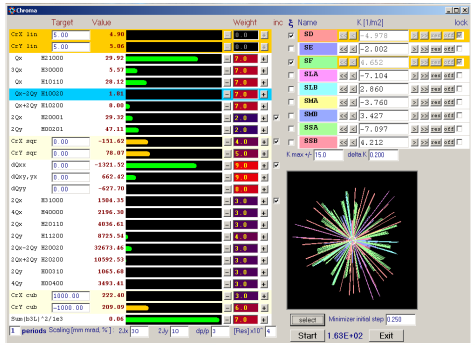












Contents

- **Ultra-Low Emittance Ring**
  - Quick overview
  - Challenges in term of beam dynamics
  - Figures of Merit

- **Tools and methods for Optimization of nonlinear dynamics**

  <u>Focus: Single particle dynamics and transverse beam dynamics</u>

  - Tracking codes for storage rings
  - Frequency Map Analysis (FMA)
  - Momentum aperture & Touschek lifetime
  - Resonance Driving Terms (RDTs)
  - New optimization method via genetic algorithms (GA)

- **Conclusions and perspectives**

Beam Diagnostics
Dreams of
Accelerator Physicists

Quick overview

Challenges in term of beam dynamics

Figures of Merit

LOW-EMITTANCE RINGS

Ultra-Low Emittance Ring: reducing the horizontal emittance

<u>Transverse emittance control</u>

- **H-emittance** given by lattice
- **V-emittance** control by coupling

Light Sources	Colliders	Damping Rings
High flux Spectral brightness High transverse coherence 5-500 pm•rad/1 pm•rad B > 10^{22}-10^{23} ph/s/mm^2/mrad^2/0.1%BW	Increase luminosity ~2 nm•rad (SuperB HER, superKEKB) L > 10^{36} cm^{-2}s^{-1}	Low emittance for injecting in colliders ILC (500pm/2 pm•rad), CLIC (100 pm•rad/1 pm) ...

$$B \propto \frac{N_{ph}}{dt\,\epsilon_x \epsilon_z\, 0.1\% \Delta\lambda/\lambda} \qquad L \propto \frac{n_b f_{rev} N_1 N_2}{\epsilon_x k \beta^*}$$

BRILLANCE = Figure of Merit for a new class of light Sources: Diffraction Limited Light Sources (DLSR)

$$B_n(\lambda) = \frac{F_n(\lambda)}{(2\pi)^2(\Sigma_x \Sigma_z)(\Sigma'_x \Sigma'_z)}$$

$$F_n = \frac{\pi}{2} \alpha N_u Q_n\left(\frac{nK^2}{4+2K^2}\right) \frac{\Delta\omega}{\omega} \frac{I}{e}$$

$$\Sigma_{x,z} = \sqrt{\sigma_r^2 + \sigma_{x,z}^2(e-)} \qquad \Sigma'_{x,z} = \sqrt{\sigma'^2_r + \sigma'^2_{x,z}(e-)}$$

$$\varepsilon_r(\lambda) = \sigma_r(\lambda)\sigma'_r(\lambda) = \frac{\lambda}{4\pi}$$

$$\varepsilon_{x,z}(e-) = \sigma_{x,z}(e-)\sigma'_{x,z}(e-)$$

$$\sigma_{x,z} = \sqrt{\varepsilon_{x,z}\beta_{x,z}} \qquad \sigma'_{x,z} = \sqrt{\frac{\varepsilon_{x,z}}{\beta_{x,z}}}$$

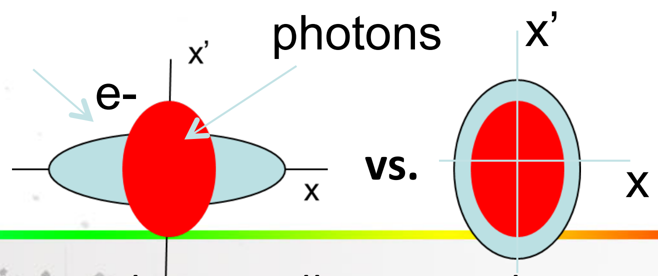
Single electron emittance:
Diffraction limit

(Gaussian beam) 8 pm∘rad – 10 keV

(cas le plus simple.)

Optimum brilliance is obtained when electron beam and photon beam ellipses match In both planes (specific β function for adaptation))

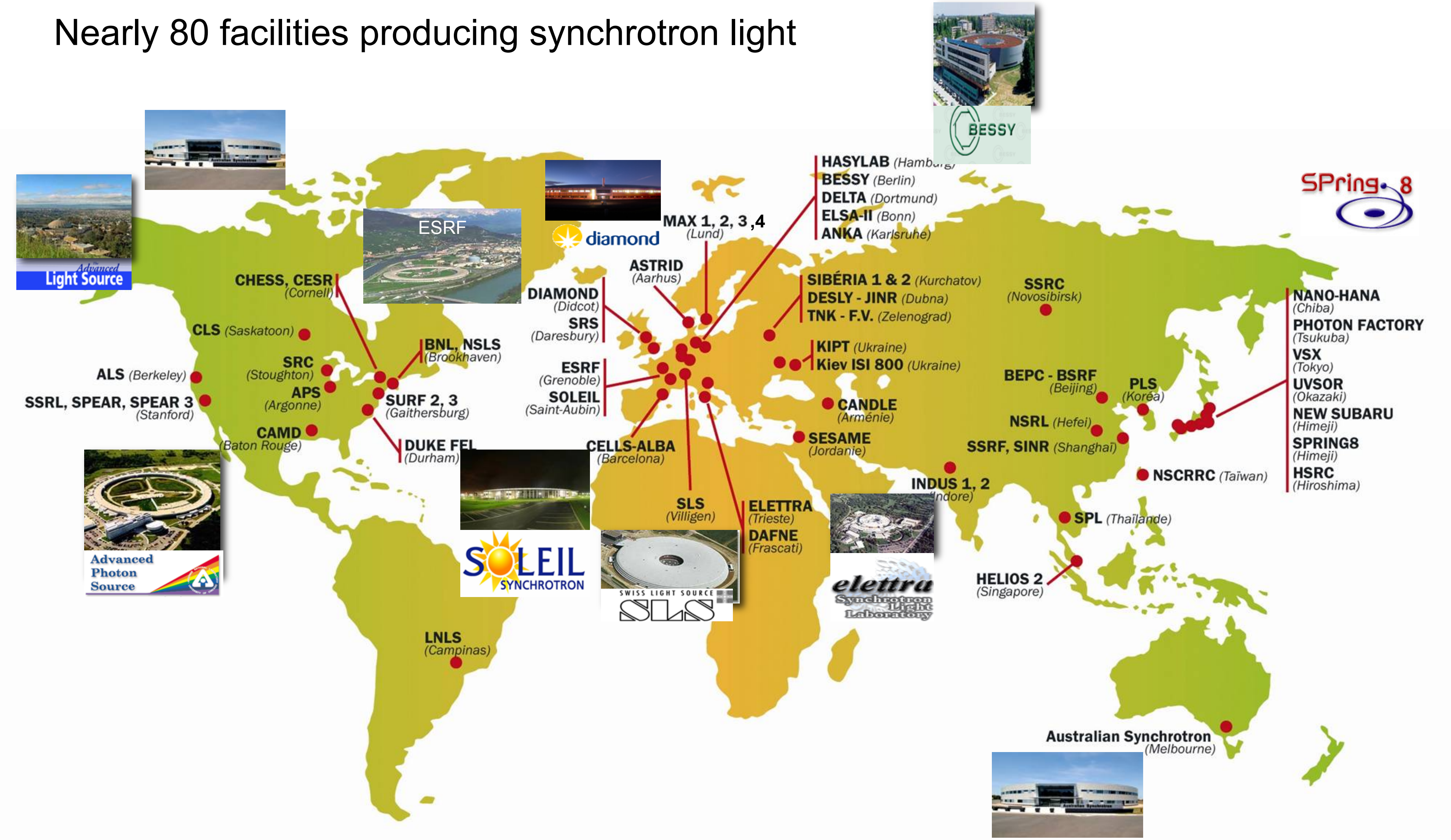
$$B_n(\lambda) = \frac{F_n(\lambda)}{4\pi^2(\varepsilon_x + \lambda_n/4\pi)(\varepsilon_z + \lambda_n/4\pi)}$$



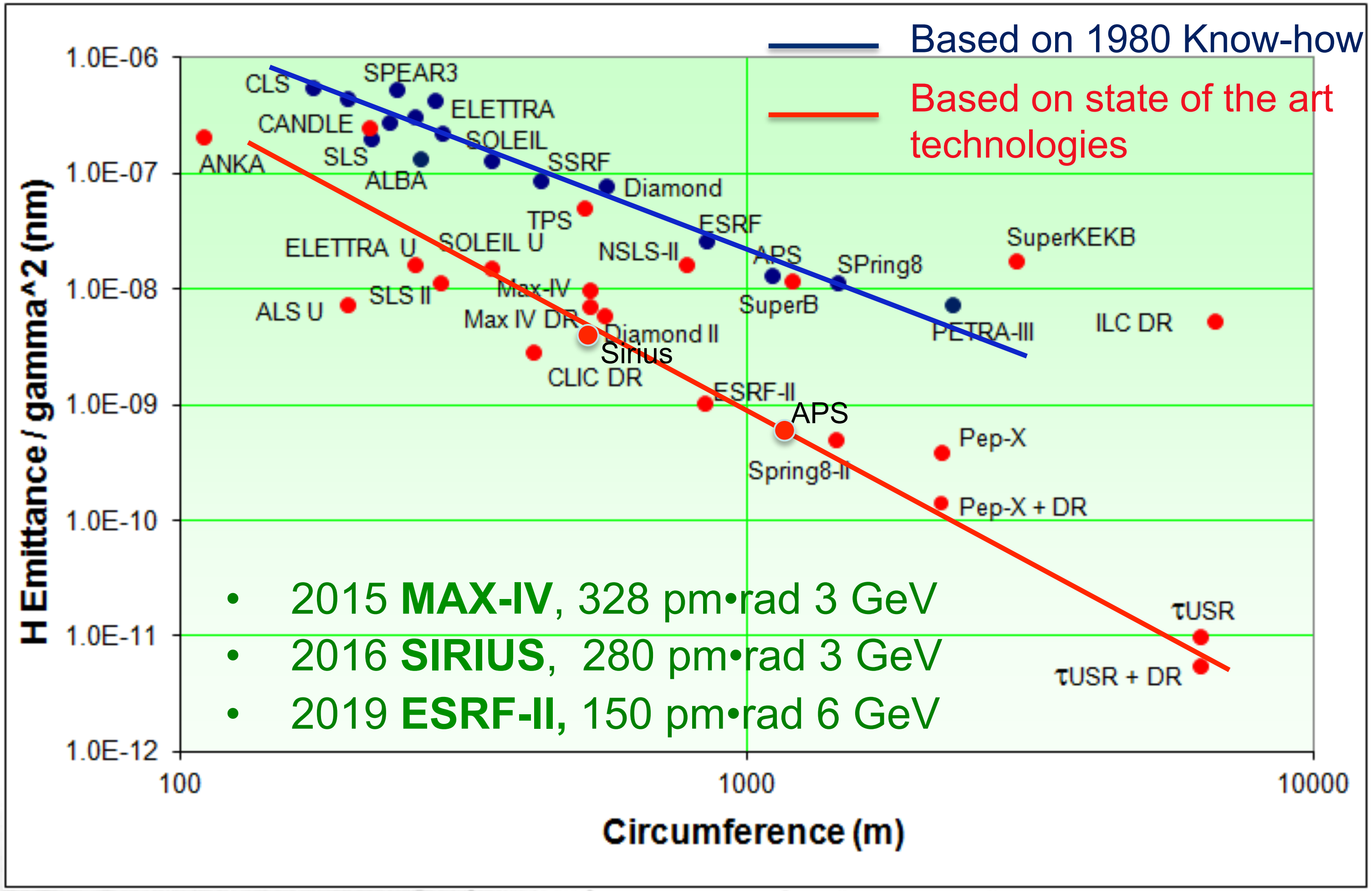
Electron-photons ellipse matching

Today's light source chart

Nearly 80 facilities producing synchrotron light



Survey of low emittance lattices



Update from R. Bartolini LER 2014

$$\epsilon_x^{iso} = F(lattice) C_q \gamma^2 \theta^3 \propto \frac{1}{N_d^3}$$

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint H(s)/\rho(s)^3\, ds}{\oint 1/\rho(s)^2\, ds}$$

Lattice Design for LER

Linear lattice unit cell

FODO — w/ and w/o h-dispersion

DBA — Double Bend Achromat

TBA — Triple Bend Achromat

TME — Theoretical Minimum Emittance

Hybrid

MBA (1993, Einfeld)

5BA

7BA — Multi Bend Achromat

9BA

HMBA — Hybrid Multi Bend Achromat

Magnets types

K-dipole — Gradient dipole

SuperBend — SC dipole

L-dipole — Long. Gradient dipole

PM — PM dipole

Anti-bend — Negative dipole

Nonlinear lattice

Chromatic Sextupoles (2)

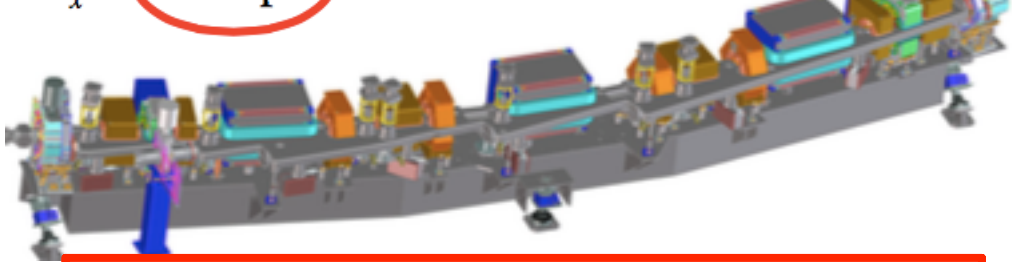
Harmonic Sextupoles > 5-10

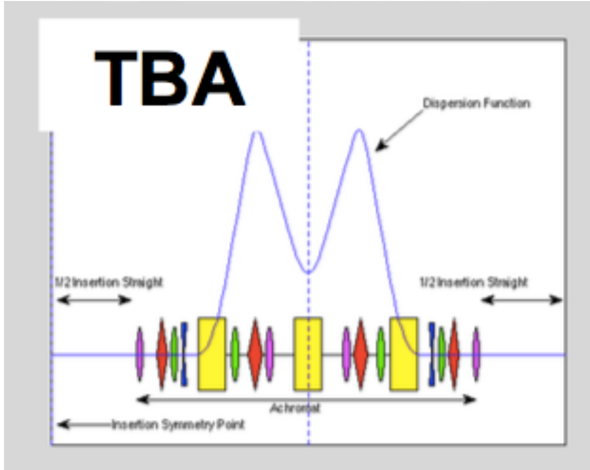
Octupoles (MAX-IV, ESRF-II, etc.)

Higher multipoles

From Simple to Complex and Compact lattices ALS case

$\varepsilon_x = 2000\ \text{pm} @ 1.9GeV$

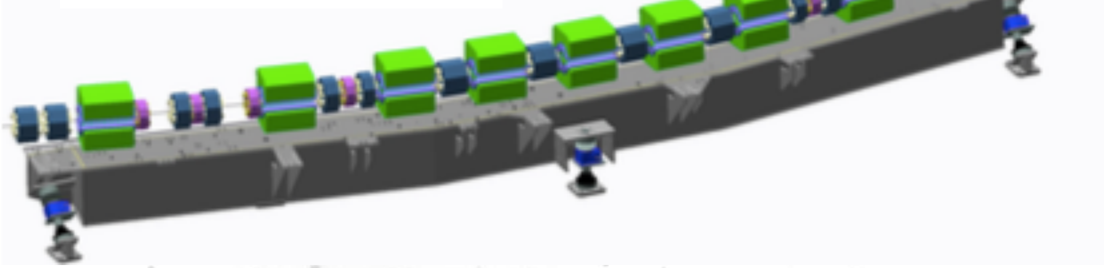


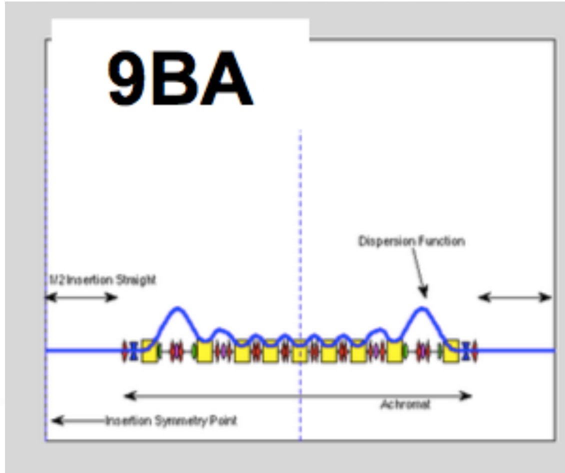


$$\varepsilon_x = C_L \frac{E^2}{N_D^3}, \qquad \varepsilon_x \propto \frac{E^2}{C^3}$$

C_L = lattice constant
N_D = # dipoles
C = Circumference

$\varepsilon_x = 52\ \text{pm} @ 2.0GeV$





Simple lattice with **2 independent families** of sextupole magnets to lattices with many families or individual of sextupoles, n-poles (octupole, …) → strong nonlinearities

Criteria for optimization

Large
Beam current

Twiss function control

High brilliance, transverse coherence

Small emittance

Small eff. emittance

Compactness
Number of straight sections
All magnets in one

Lattice Robustness

Magnetic, alignment errors

ID Configurations

Strong focusing
Chromaticities wall

Small or zero
dispersion in SS

Low dispersion
(strong Sextupole)

Resonances

Non-linearities

Injection efficiency
Dynamic aperture (DA)
Top-up

Touschek Lifetime
(Momentum aperture, MA)

Optimizing together On & Off momentum Dynamics

Criteria for optimization and limitations

Round beam

Local control of emittance
beam size

Time resolved, flux, brilliance
Based experiment

Diffraction limited

Photons

Coupling

Multi-purpose facility
Lattice flexibility

Coherence (V, H, L)

Adaptation photon
electron ellipse

Bunch length
(Short/long)

Dipole-based
beamline

IBS

Low-Z

Single/multibunch

Ion driven Inst.

Collective effects

New injection schemes
(On axis, swapping out, MIKs…)

Microwave

TMCI, RW

Minimize & localize
Top-up beam losses

Momentum compaction-wall (High current)
(instabilities threshold, Longitudinal dynamics)

Non-linear
On and off momentum dynamics

Linear optics for High charge, and increased the instabilities thresholds

Transverse and longitudinal dynamics

Optimization tool progress of the last decades

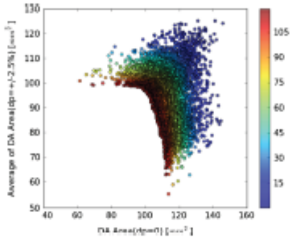


FIG. 1. The last generation of objective functions: DA of on-momentum (horizontal axis) and off-momentum (vertical axis) particles. Points are colored according to their rank.

Symplectic Tracking based methods

DA, MA separated

DA, MA together

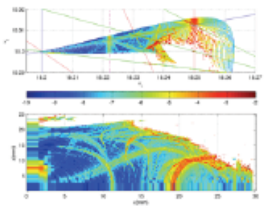
from L. Nadolski, ICFA LowEring, Oxford 7/13

Direct tracking based optimization

GLASS

Analytical based method

Genetic Algorithm
MOGA



Lie Algebra/Differential Algebra

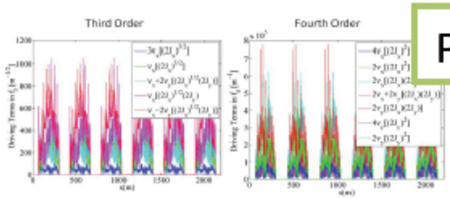
Resonance Driving Terms
RDT minimization

Amplitude Tuneshift
minimization

Frequency Maps
FMA
Diffusion factor

Nonlinear
"LOCO"

Canceling
Sextupole
Resonances



K.L. Brown & R.V. Servranckx
Nucl. Inst. Meth., A258:480–502, 1987
There are still three tune shift terms.

Yunhai Cai
Nucl. Inst. Meth., A645:168–174, 2011.

Phase advances

Interleaved
sextupoles

Resonance identification

Robustness to magnetic, alignment errors

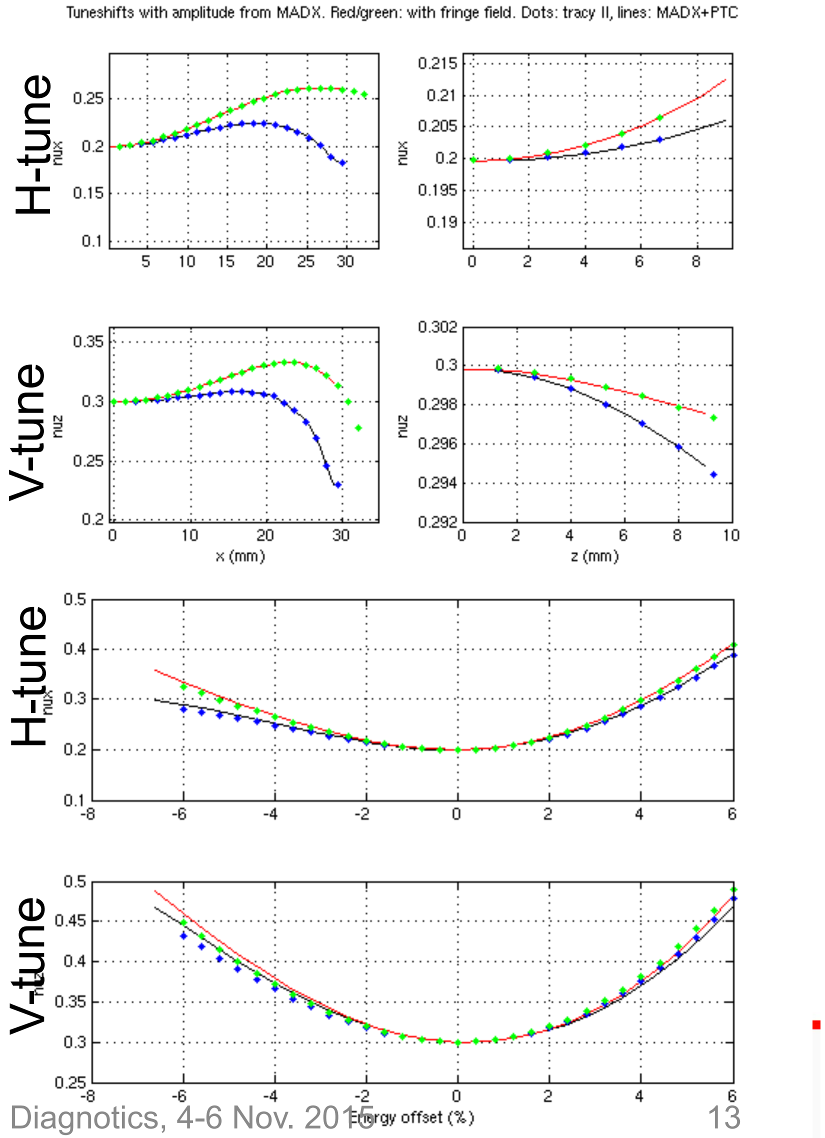
Robustness ID configurations

Tracking codes: **PTC MADX TRACY AT LEGO OPA ELEGANT**

Non-linear dynamics
What is included in the Model?

Tracy II & MADX/PTC_track exact (SOLEIL)

- Systematic multipole errors
  - Large momentum acceptance, large dispersion function → high order multipoles
- From magnetic measurements:
  - Add true m-poles (both systematic and non systematic)
  - Dipole: fringe field, gradient error, edge tilt errors
  - Quad.: fringe field
- Beam based
  - Multipoles deduced from turn by turn measurement, off-axis field integrals
  - Coupling errors
- Insertion devices
  - Taylor expansion
  - Radia kick maps
  - Sorting magnets: Genetics algo.
- Collective effects

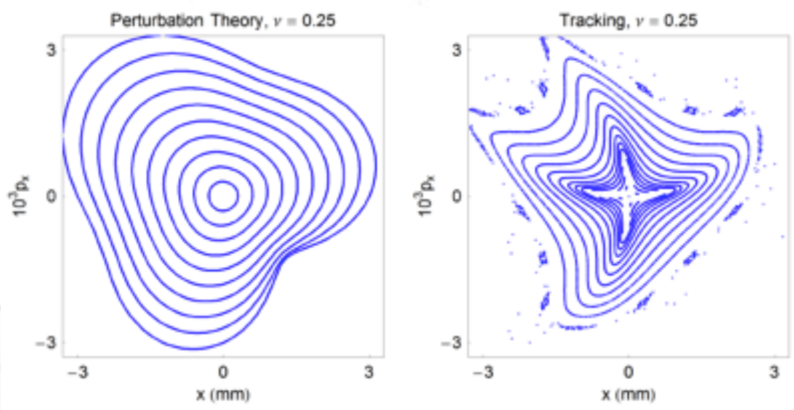


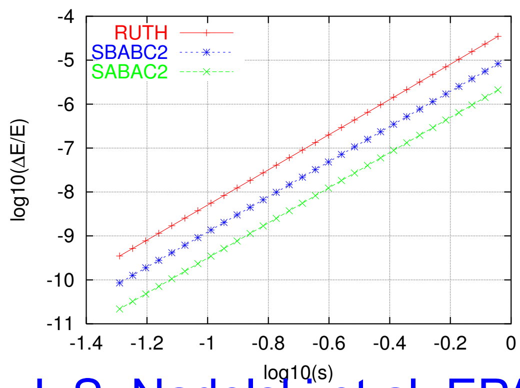
- Tracking codes for storage rings
- Frequency Map Analysis (FMA): concept true for model and online measurements

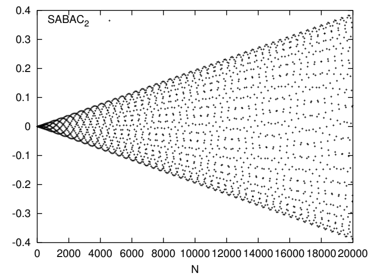
TOOLS AND FOR OPTIMIZATION OF NONLINEAR DYNAMICS

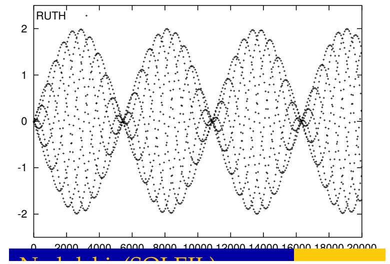
Tracking codes for numerical simulations

- **Long term tracking based on symplectic integrators**
  - Implicit or explicit schemes
- **Popularized by Ruth and Forest 1983-1990, use of Lie Algebra (Neri, 1988), Yoshida techniques (1990), Channel and Scovel (1990), Mclachlan (1995), Sanz-Serna (1998), Laskar integrators (2001)**
  - Preserves energy, bounded errors,
  - Phase stability
  - Used by MADX/PTC, Tracy, OPA, LEGO, ELEGANT, etc









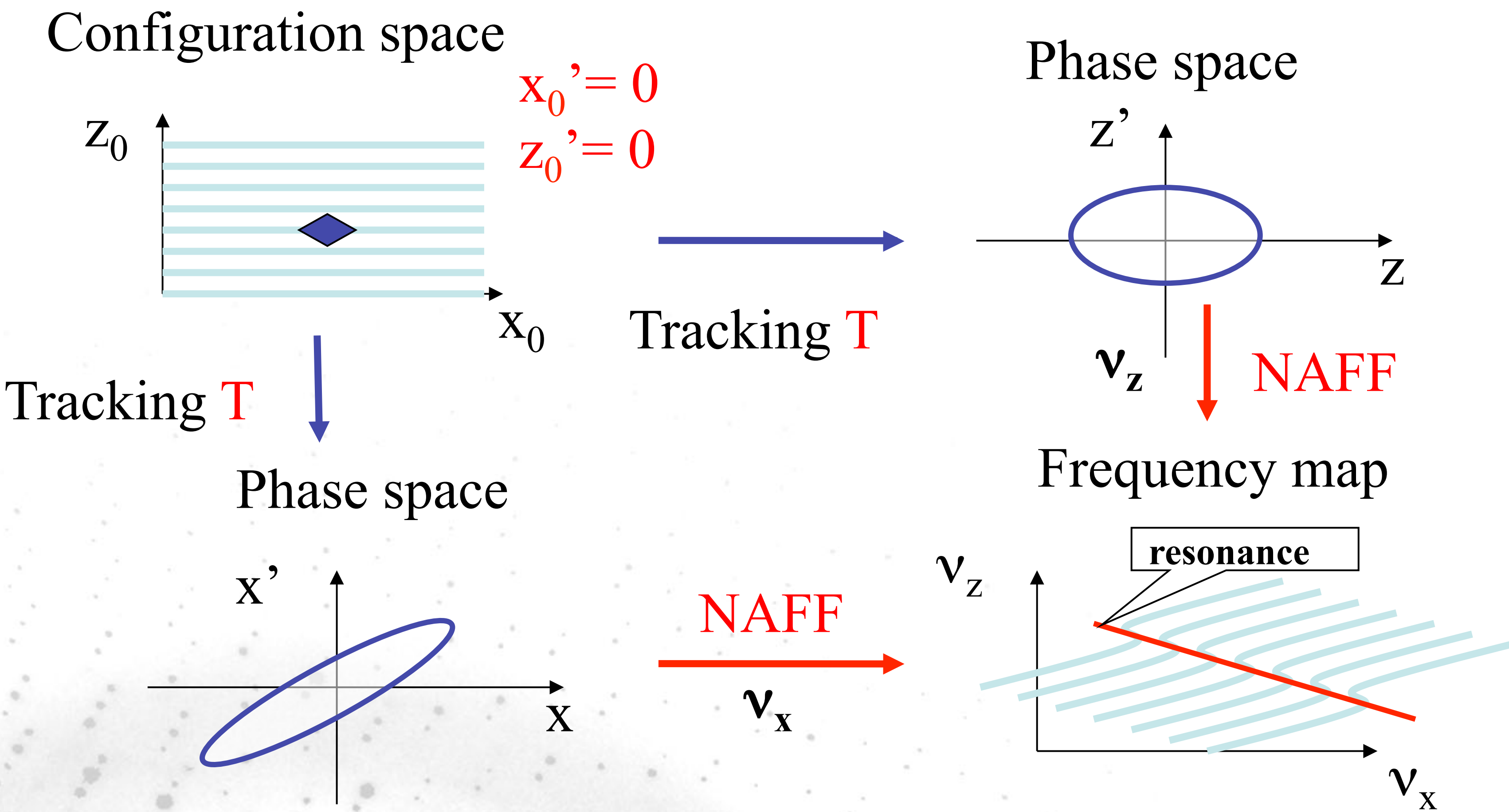
L S. Nadolski et al. EPAC'02

A brief History of Frequency Map Analysis (FMA)

- For many centuries, the motion of planets in the Solar System was considered as **perfectly regular.**
- In 1988, J. Laskar (Paris Observatory) published evidence of chaotic motion in the Solar Systems using a new method called Frequency Map Analysis (FMA).
- FMA was successively applied to the study of dynamics systems such as (short list)
  - Stability of Earth Obliquity and climate stabilization (Laskar, Robutel, 1993)
  - Standard application (Laskar, Floeschlé, Celleti, 1992, Laskar and Carletti 2000)
  - Galactic Dynamics (Papaphilippou et Laskar, 1996 and 1998)
  - Accelerator beam dynamics: lepton and hadron storage rings (Dumas, Laskar, 1993, Laskar, Robin, 1996, Papaphilippou, 1999, ...)

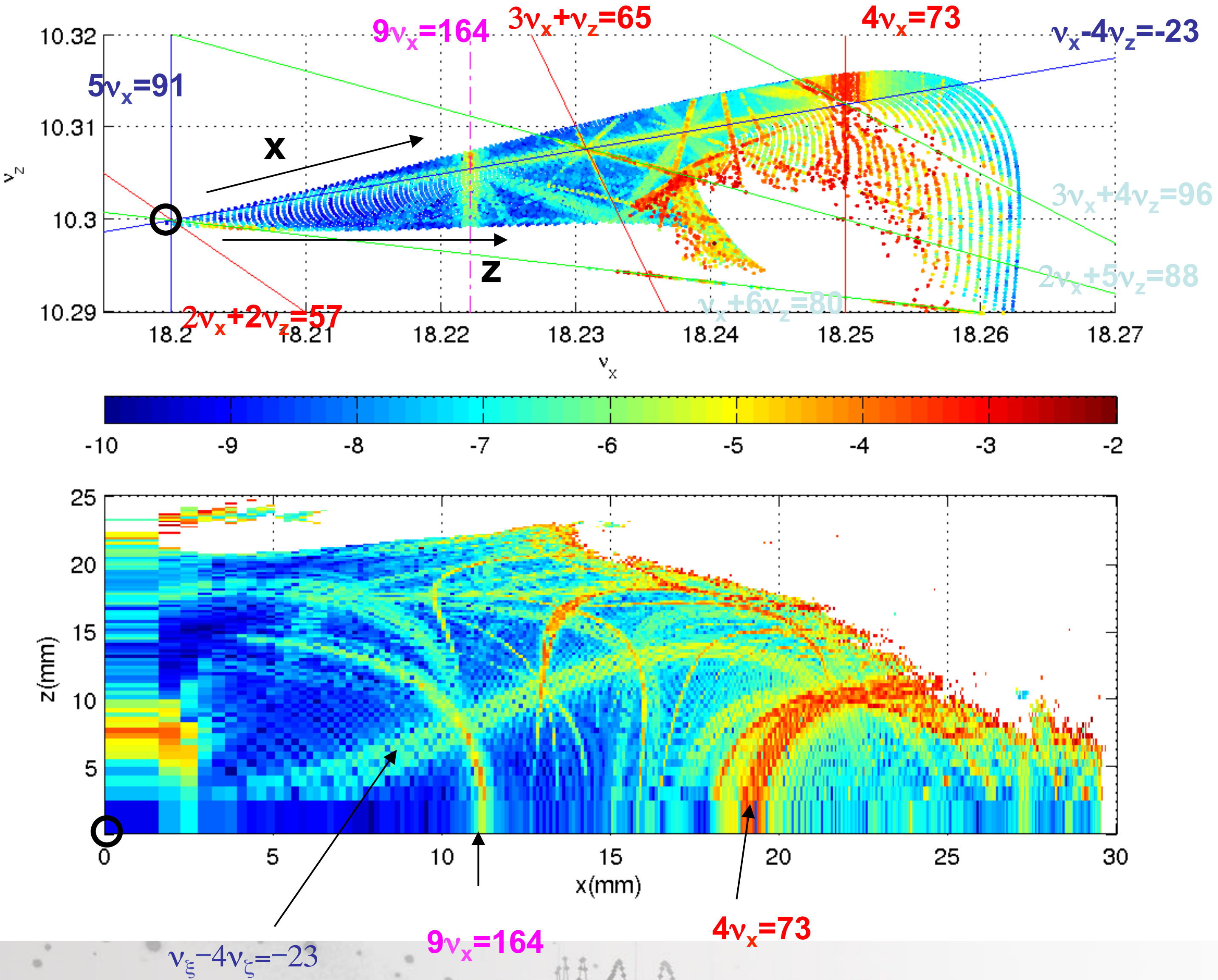
Computing a frequency map

Frequency map: $\boxed{F^T : (x_0, z_0) \longrightarrow (\nu_x, \nu_z)}$



On-momentum Dynamics --Working point
SOLEIL lattice (18.2,10.3)

Bare lattice (no errors)



WP sitting on resonance node

$\nu_x + 6\nu_z = 80$

$5\nu_x = 91$

$\nu_x - 4\nu_z = -23$

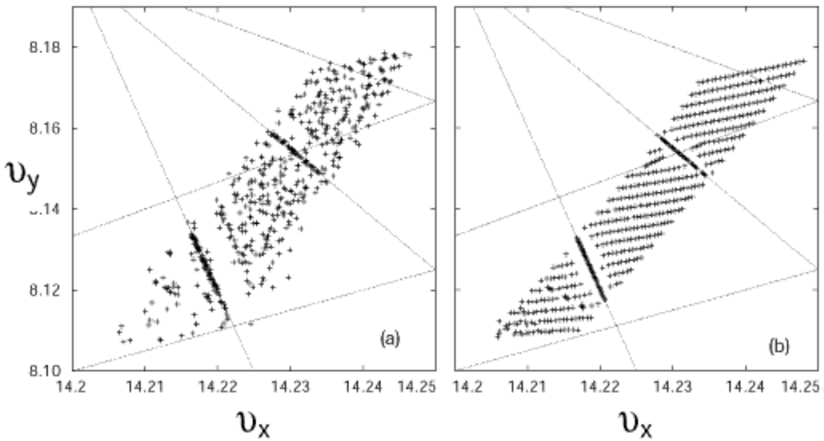
$2\nu_x + 2\nu_z = 57$

Frequency Map Analysis: ALS and BESSY-II

P. Kuske (BESSY-II)

ALS linear lattice corrected to 0.5% rms β-beating

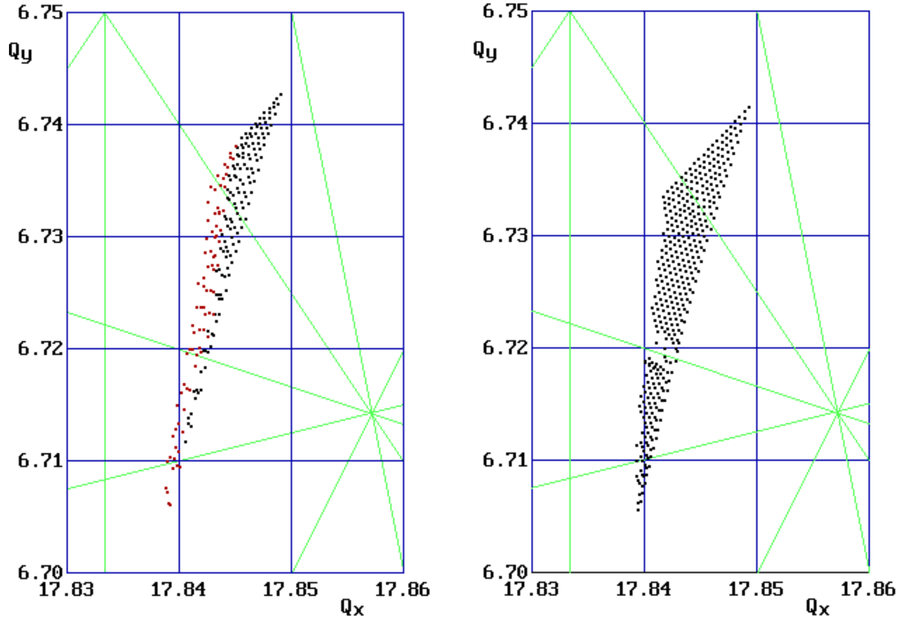
FM computed including residual β-beating and coupling errors



ALS measured ALS model

D. Robin et al PRL 85, 3 (2000)

BESSY-II with harmonic sextupole magnets, chromaticity, coupling



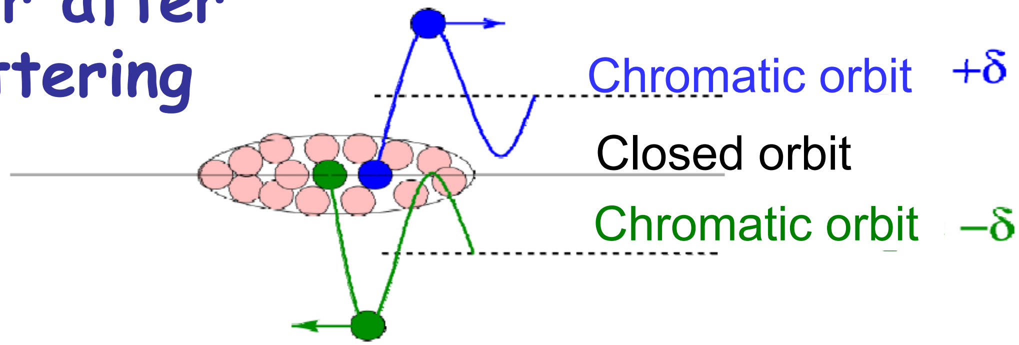
BESSY-II measured BESSY-II model

A very accurate description of machine model is mandatory

- fringe fields: dipole, quadrupole (and sextupole) magnets
- systematic octupole components in quadrupole magnets
- decapoles, skew decapoles and octupoles in sextupole magnets

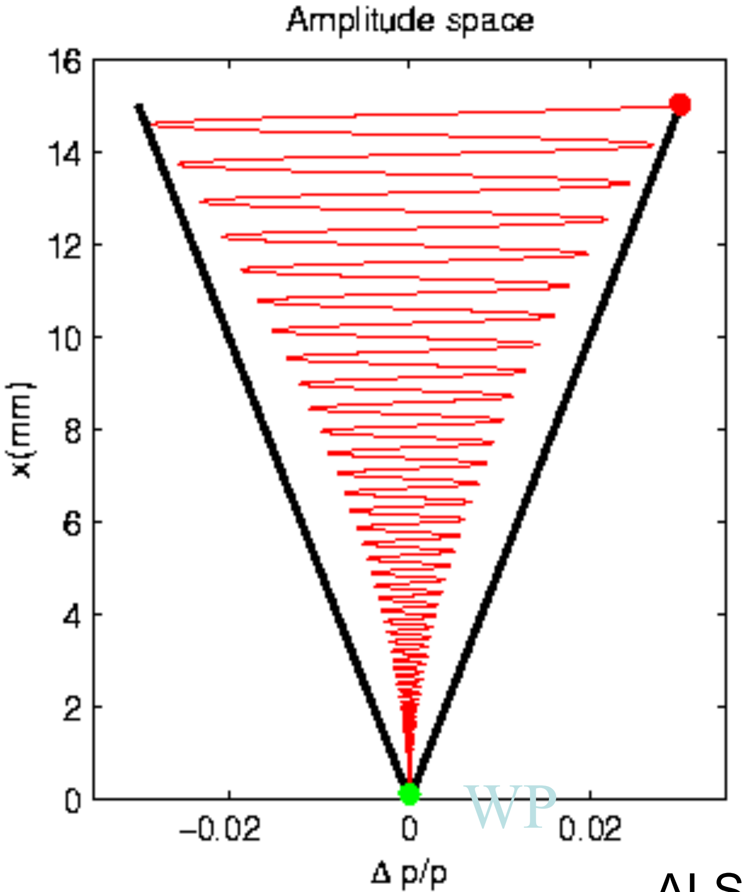
Courtesy C. Steier (ALS) P. Kuske (BESSY-II)

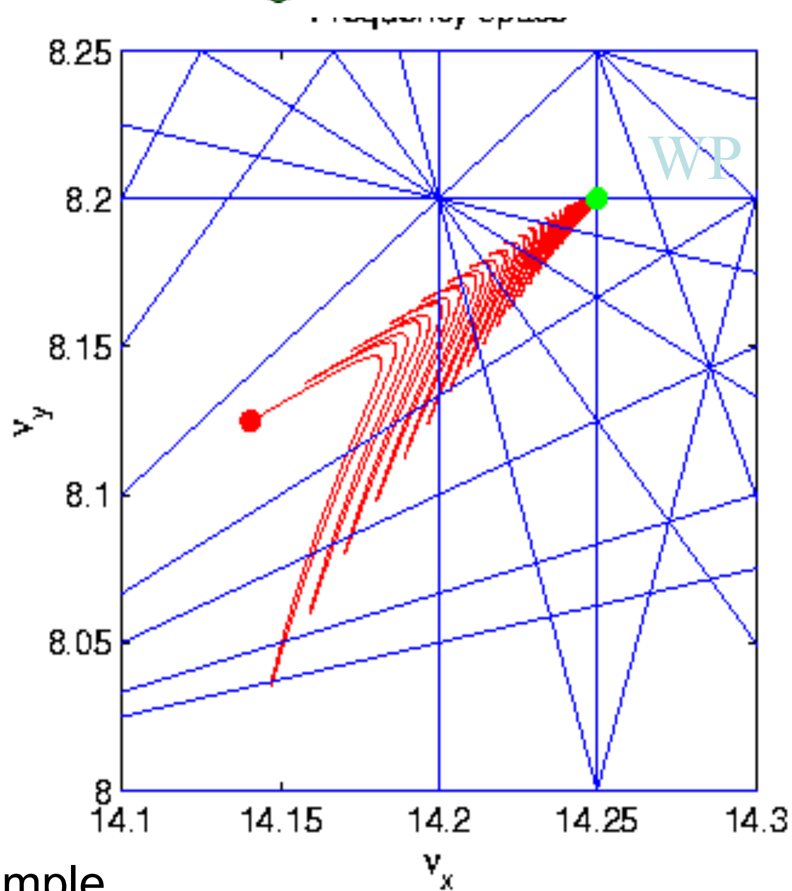
Particle behavior after Touschek scattering



$$x = \sqrt{A_x \beta_{x_1}} + \eta_0 \delta$$

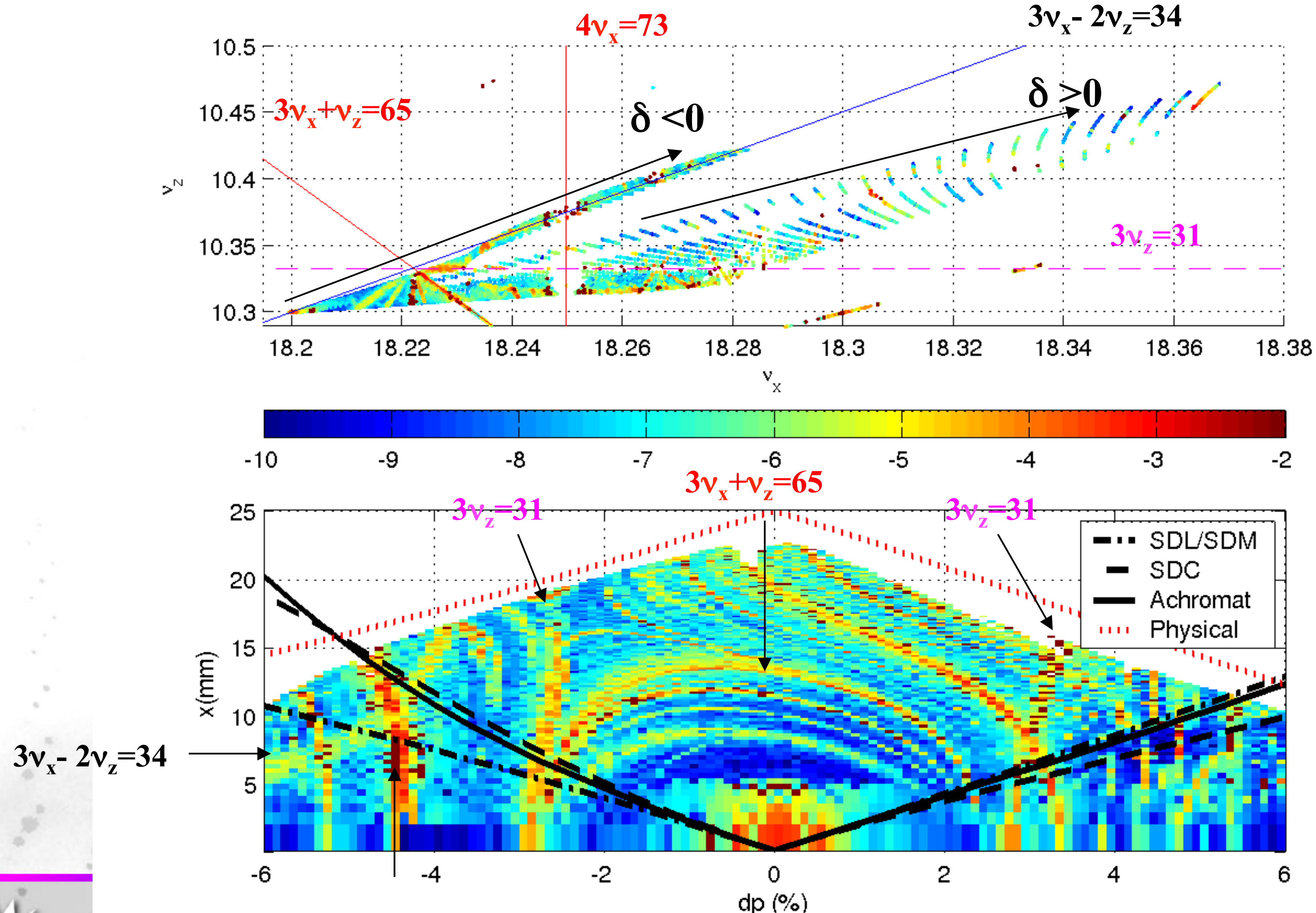
$$A_x = \gamma_{x_0} (\eta_0 \delta)^2 + 2\alpha_{x0} (\eta_0 \delta)(\eta_0^{'} \delta) + \beta_{x0} (\eta_0^{'} \delta)^2$$





ALS Example

Off momentum dynamics



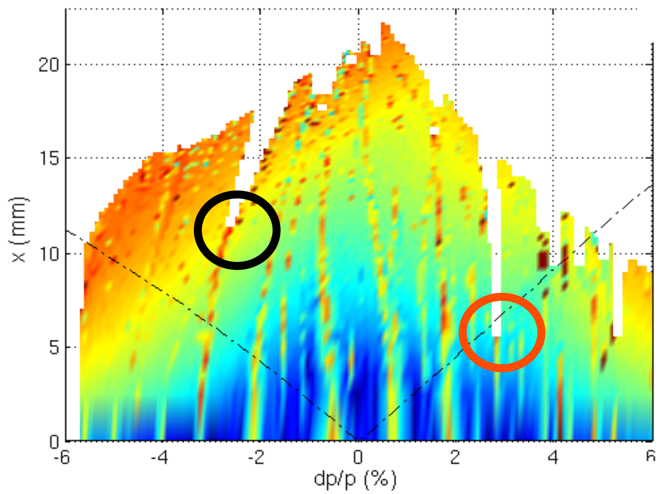
$z_0 = 0.3\text{mm}$

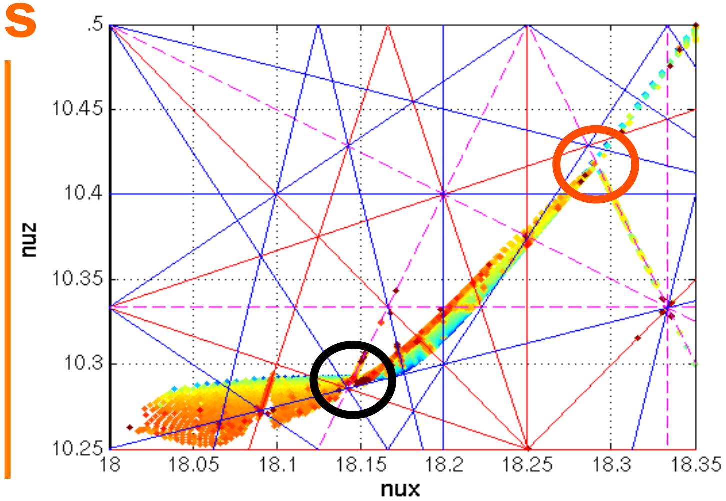
The SOLEIL energy acceptance of the bare machine is large : +/- 4%.

Agreement of a few percents (typically a factor two 20 years ago)

Complete optimized linear and non-linear model

Simulations

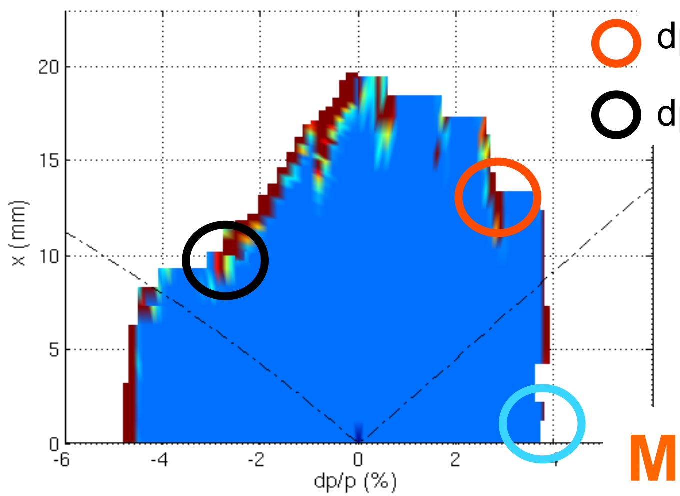


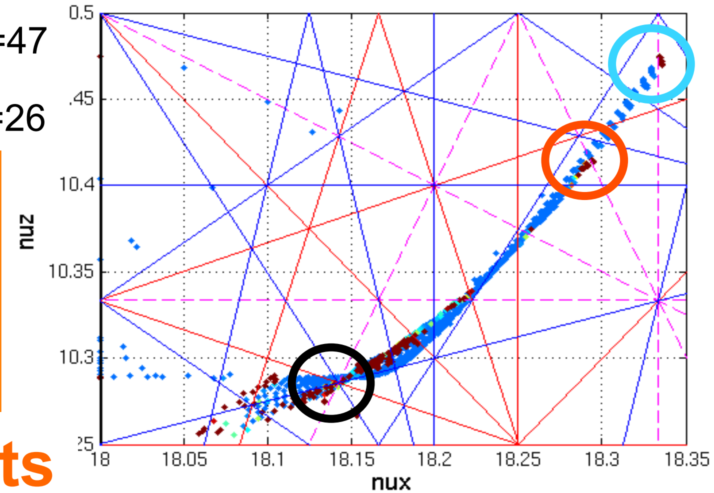


dp/p = + 4 % : $3v_x$=55.

dp/p = + 3 % : $2v_x+v_z$=47

dp/p = - 3 % : $2v_x-v_z$=26





Measurements

P. Brunelle et al, IPAC10

Resonance Driving Terms (RDTs)

ANALYTICAL OPTIMIZATION

The "standard method" for sextupole optimization

J. Bengtsson, *The sextupole scheme for the SLS: an analytic approach,* Internal report SLS-TME-TA-1997-12

a) get the sextupole [+quadrupole] Hamiltonian:

$$\Longrightarrow \quad \int_{\text{cell}} [H_2(s) + H_3(s)]\, ds = \sum h_{jklmp} \text{ with}$$

Resonances

$$h_{jklmp} \propto \sum_n^{N_{\text{sext}}} (b_3\, L)_n\, \beta_{xn}^{\frac{j+k}{2}}\, \beta_{yn}^{\frac{l+m}{2}}\, D_n^p\, e^{i\{(j-k)\phi_{xn}+(l-m)\phi_{yn}\}} - \left[\sum_n^{N_{\text{quad}}} (b_2\, L)_n\, \beta_{xn}^{\frac{j+k}{2}}\, \beta_{yn}^{\frac{l+m}{2}}\, e^{i\{(j-k)\phi_{xn}+(l-m)\phi_{yn}\}} \right]_{p\neq 0}$$

Resonant Driving Terms (RDTs)

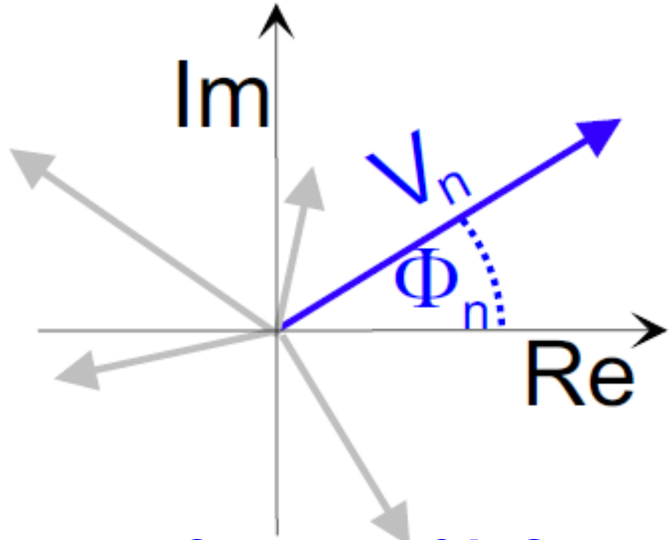
$$h = \sum_n^{N_{\text{sext}}} V_n e^{i\Phi_n} \; [\, + \ldots \text{quads for } p \neq 0 \ldots]$$

Sextupole$_n$ $\leftrightarrow$ complex vector:

Length $V_n = V_n\,(b_3, L, \beta_x, \beta_y, D)$

Angle $\Phi_n = \Phi_n\,(\phi_x + \phi_y)$

- $\Phi_n = 0 \;\forall\; n \rightarrow$ tune shifts
- $\Phi_n \neq 0 \rightarrow$ resonances



Courtesy of A. Streun

... 9 first order sextupole terms: adjust 2 real, suppress 7 complex...

First order sextupole [+quadrupole] Hamiltonian

- **2 phase independant terms → chromaticities:**

$$h_{11001} = +J_x\delta\left[\sum_n^{N_{sext}}(2b_3\,L)_n\beta_{xn}D_n - \sum_n^{N_{quad}}(b_2\,L)_n\beta_{xn}\right] \quad \rightarrow \quad \xi_x$$

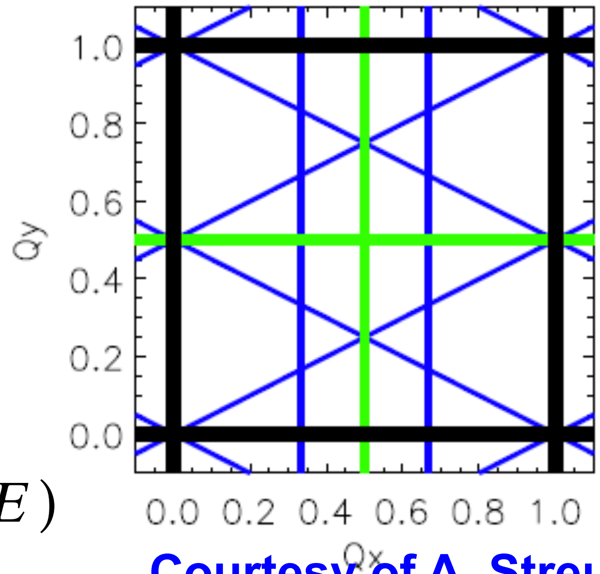
$$h_{00111} = -J_y\delta\left[\sum_n^{N_{sext}}(2b_3\,L)_n\beta_{yn}D_n - \sum_n^{N_{quad}}(b_2\,L)_n\beta_{yn}\right] \quad \rightarrow \quad \xi_y$$

- **7 phase dependant terms → resonances:** $h^N := h$ for N cells, $\quad N \rightarrow \infty \quad \Longrightarrow$

$$|h^{\infty}_{jklmp}| = \frac{|h_{jklmp}|}{2\sin\pi[a_x Q_x^{\text{cell}} + a_y Q_y^{\text{cell}}]}$$

$a_x = (j-k) \quad a_y = (l-m)$

$$h_{21000} = h^*_{12000} \longrightarrow \mathbf{Q_x}$$
$$h_{30000} = h^*_{03000} \longrightarrow 3\,Q_x$$
$$h_{10110} = h^*_{01110} \longrightarrow \mathbf{Q_x}$$
$$h_{10200} = h^*_{01020} \longrightarrow Q_x + 2\,Q_y$$
$$h_{10020} = h^*_{01200} \longrightarrow Q_x - 2\,Q_y$$
$$\left.\begin{aligned} h_{20001} &= h^*_{02001} \longrightarrow 2\,Q_x \\ h_{00201} &= h^*_{00021} \longrightarrow 2\,Q_y \end{aligned}\right\} \rightarrow d\beta/d\delta \quad (\delta = \Delta E/E)$$



Courtesy of A. Streun

... still not the end: 13 more terms in 2nd order: 5 real, 8 complex
(Pandora's box has a false bottom!)

Second order sextupole [+first order octupole] Hamiltonian

$$\sum_n \sum_m (b_3L)_n (b_3L)_m \times (\beta_n,\, \phi_n\, \beta_m,\, \phi_m\, \ldots) + \left[\sum_q (b_4L)_q \times (\beta_q,\, \phi_q\, \ldots)\right]$$

- **3 phase independant terms → amplitude dependant tune shifts:**

$$\frac{\partial Q_x}{\partial J_x} \quad \frac{\partial Q_x}{\partial J_y} = \frac{\partial Q_y}{\partial J_x} \quad \frac{\partial Q_y}{\partial J_y}$$

- **2 phase independant off-momentum terms → second order chromaticities:**

$$\xi^{(2)}_{x/y} = \frac{\partial^2 Q_{x/y}}{\partial \delta^2}$$

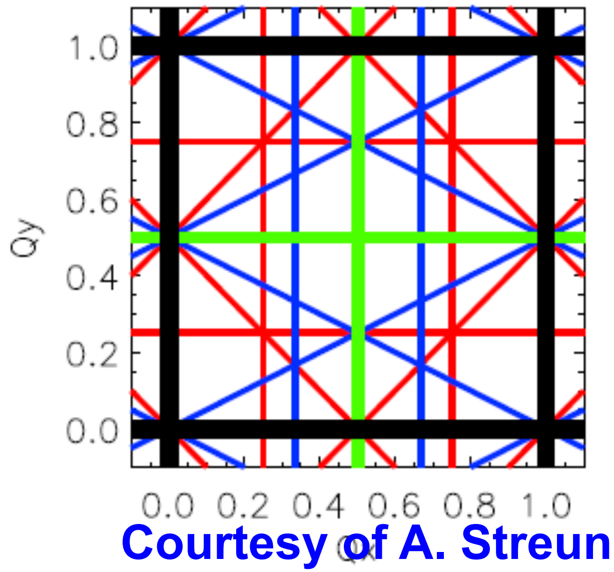
- **8 phase dependant terms**
  → octupolar resonances:

$h_{40000} \rightarrow 4Q_x$ $\qquad h_{31000} \rightarrow 2\,Q_x$

$h_{00400} \rightarrow 4\,Q_y$ $\qquad h_{20110} \rightarrow 2\,Q_x$

$h_{20200} \rightarrow 2Q_x + 2\,Q_y$ $\qquad h_{00310} \rightarrow 2\,Q_y$

$h_{20020} \rightarrow 2Q_x - 2\,Q_y$ $\qquad h_{01110} \rightarrow 2\,Q_y$



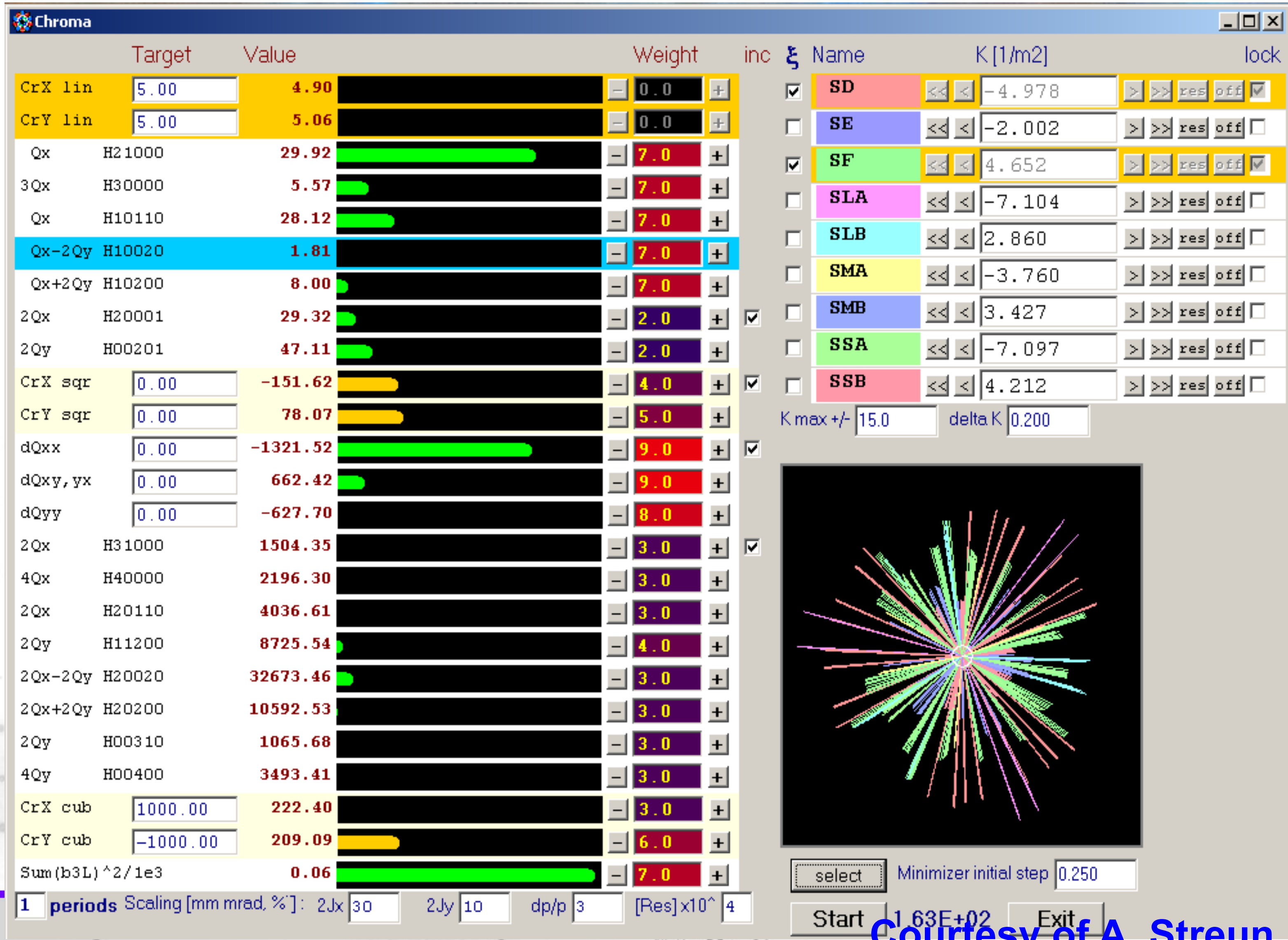
Courtesy of A. Streun

Tool for sextupole optimization (OPA)

Analytical expressions for 1st and 2nd Hamiltonian modes. *(J.Bengtsson)*

Numeric differentiation for 1st,2nd,3rd chromaticity

$\Sigma\ (b_3 l\ )^2$ included in minimization



Courtesy of A. Streun

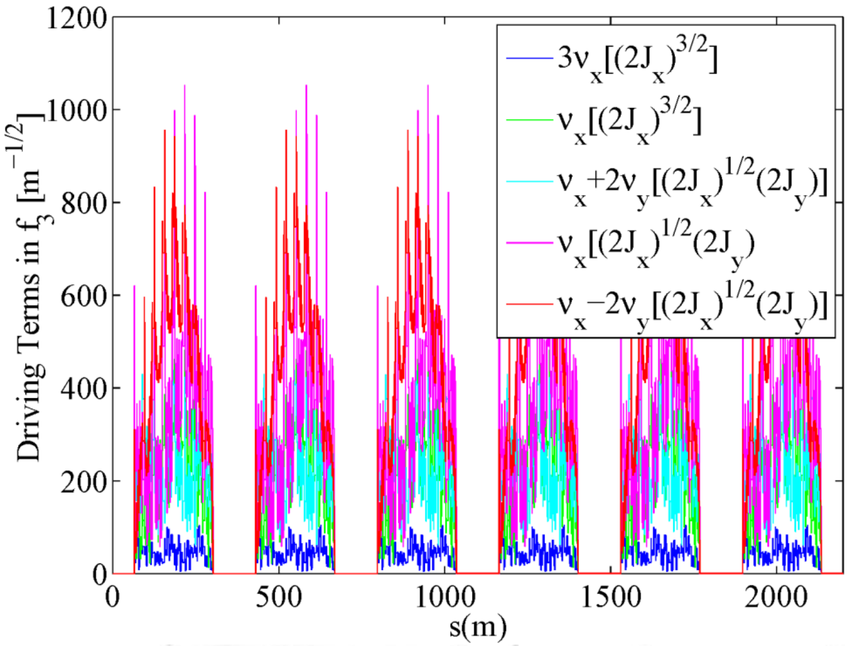
Cancellation of All Geometric 3rd and 4th at design level Resonances Driven by Strong Sextupoles

except $2\nu_x - 2\nu_y$

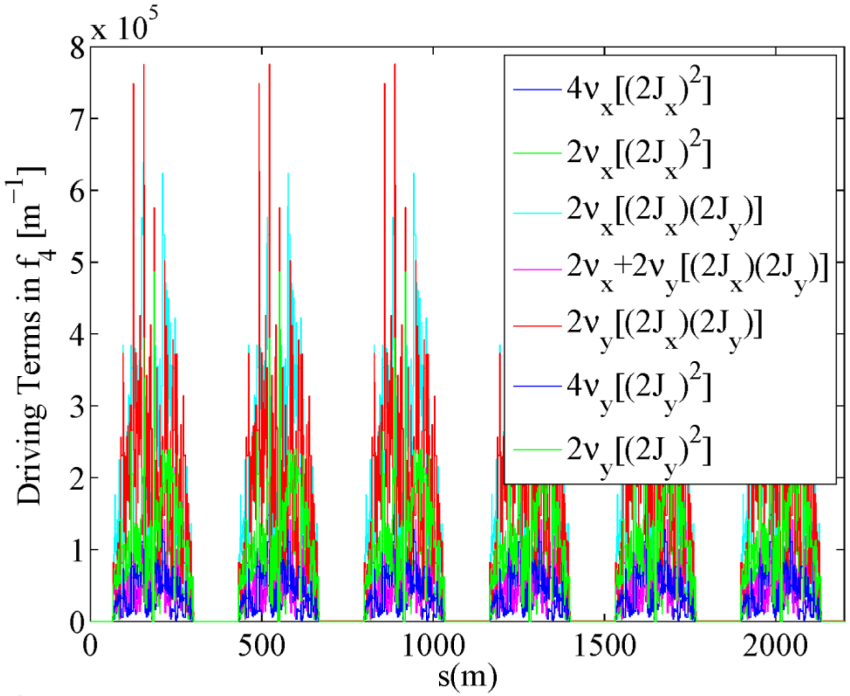
PEPX lattice

Key: Phase advance between sextupoles

Third Order



Fourth Order



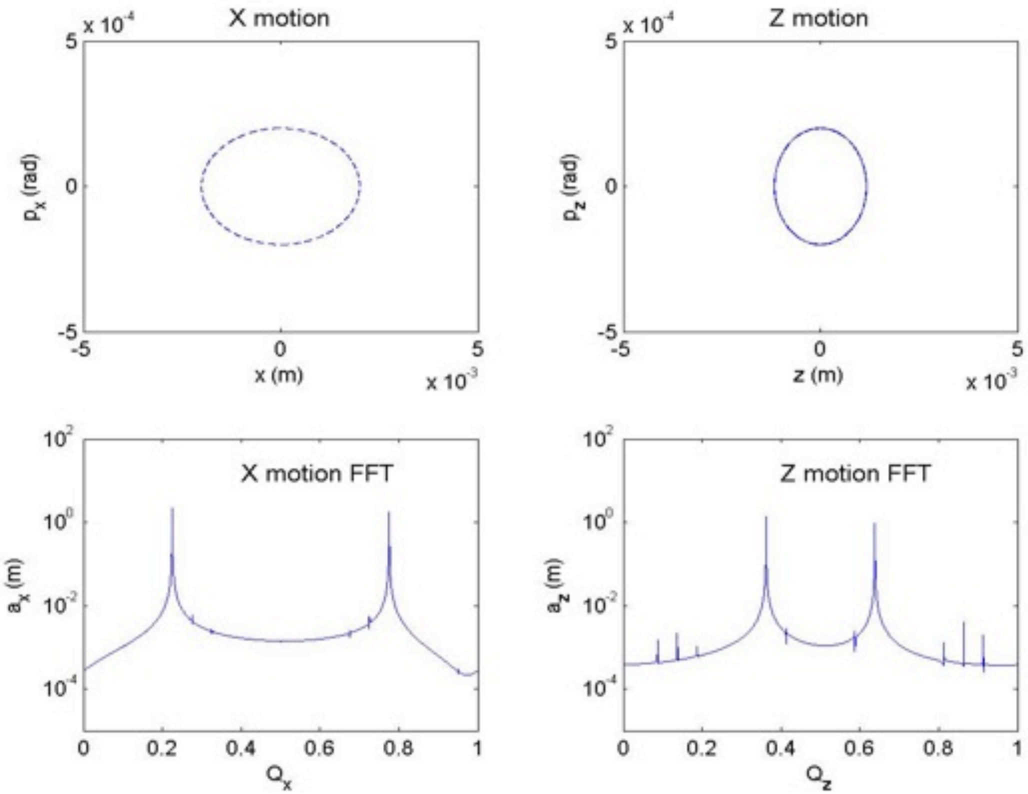
K.L. Brown & R.V. Servranckx
Nucl. Inst. Meth., A258:480–502, 1987

Yunhai Cai
Nucl. Inst. Meth., A645:168–174, 2011.

There are still three tune shift terms.

Frequency Analysis of betatron motion

Example: Spectral Lines for tracking data for the Diamond lattice



Spectral Lines detected with <u>SUSSIX</u> (NAFF algorithm)

e.g. in the horizontal plane:

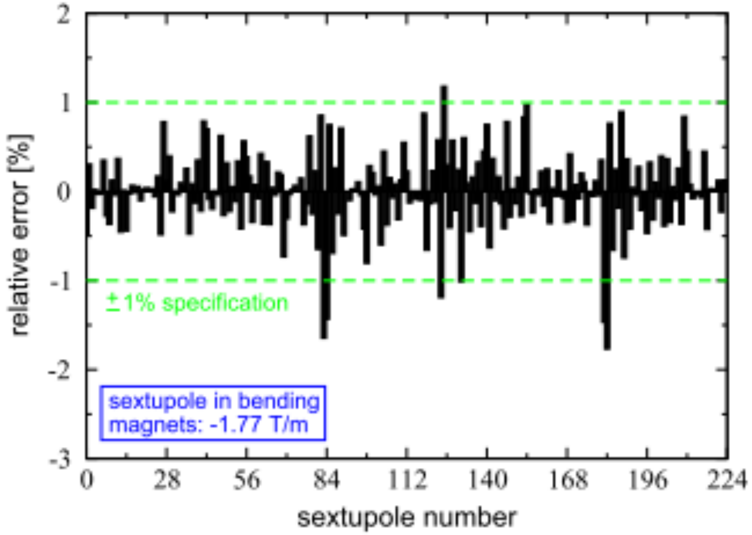
- (1, 0) $1.10\ 10^{-3}$ horizontal tune
- (0, 2) $1.04\ 10^{-6}$ $Q_x + 2\ Q_z$
- (–3, 0) $2.21\ 10^{-7}$ $4\ Q_x$
- (–1, 2) $1.31\ 10^{-7}$ $2\ Q_x + 2\ Q_z$
- (–2, 0) $9.90\ 10^{-8}$ $3\ Q_x$
- (–1, 4) $2.08\ 10^{-8}$ $2\ Q_x + 4\ Q_z$

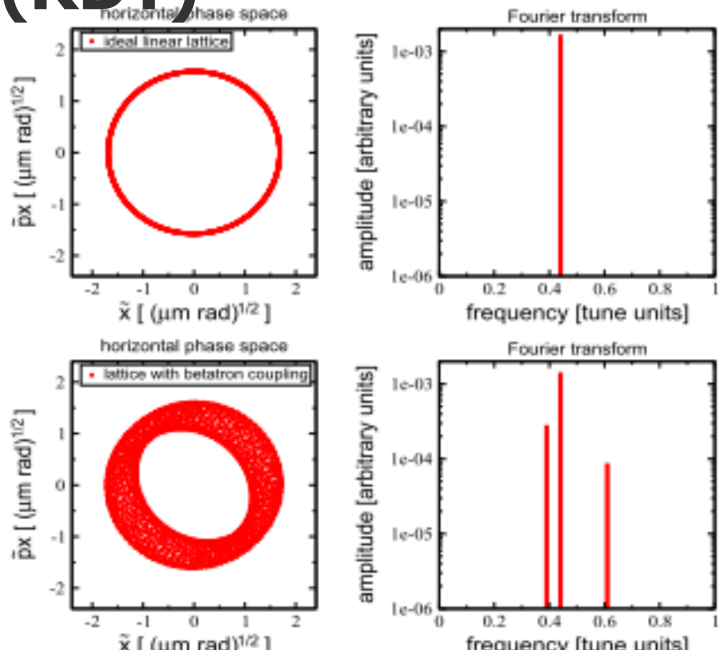
Each spectral line can be associated to a resonance driving term

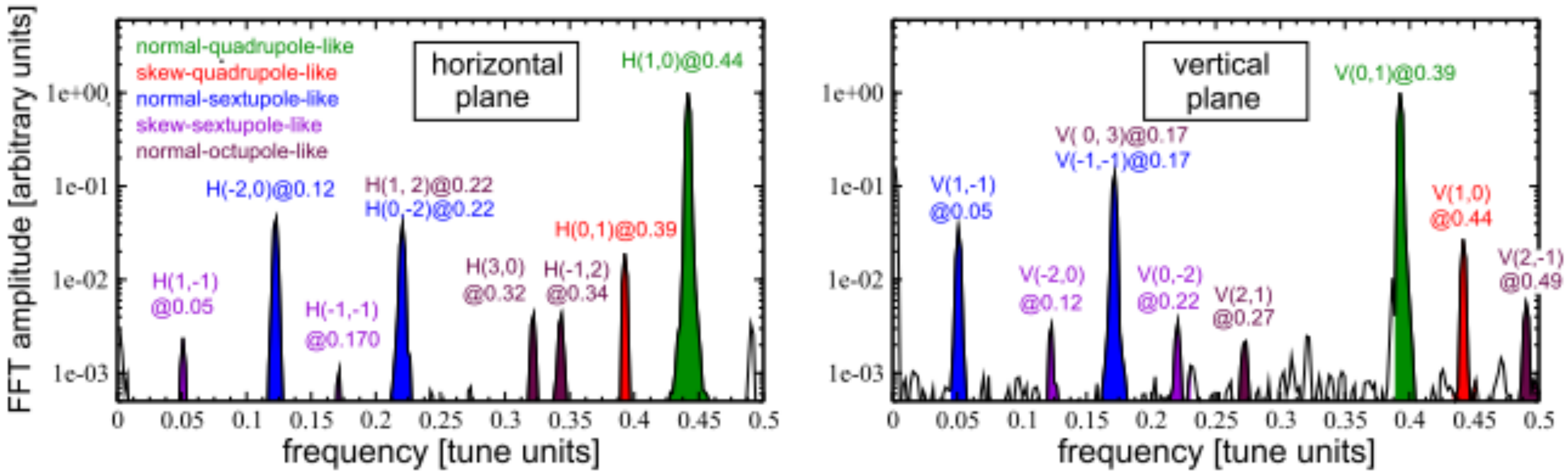
J. Bengtsson (1988): CERN 88–04, (1988).
R. Bartolini, F. Schmidt (1998), Part. Acc., **59**, 93, (1998).
R. Tomas, PhD Thesis (2003)

Courtesy of R. Bartolini

Resonance Driving Term (RDT) measurements







A. Franchi et al., Phys. Rev. ST Accel. Beams 17, 074001 (2014)

Comparison real lattice to model
linear and nonlinear optics

Courtesy R. Bartolini

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

Closed orbit based

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

Turn by turn based

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

Optimization:

Parameter space large (ten-hundreds of parameters)

How to ensure the optimal solution was found?

Analytical is often a first step in the optimization process

Subtleties of beam dynamics (on/off-momentum, symmetry)

1. Exhaustive search for all stable solutions
2. Genetic Algorithm based optimization

NUMERICAL OPTIMIZATION

Lattice optimization

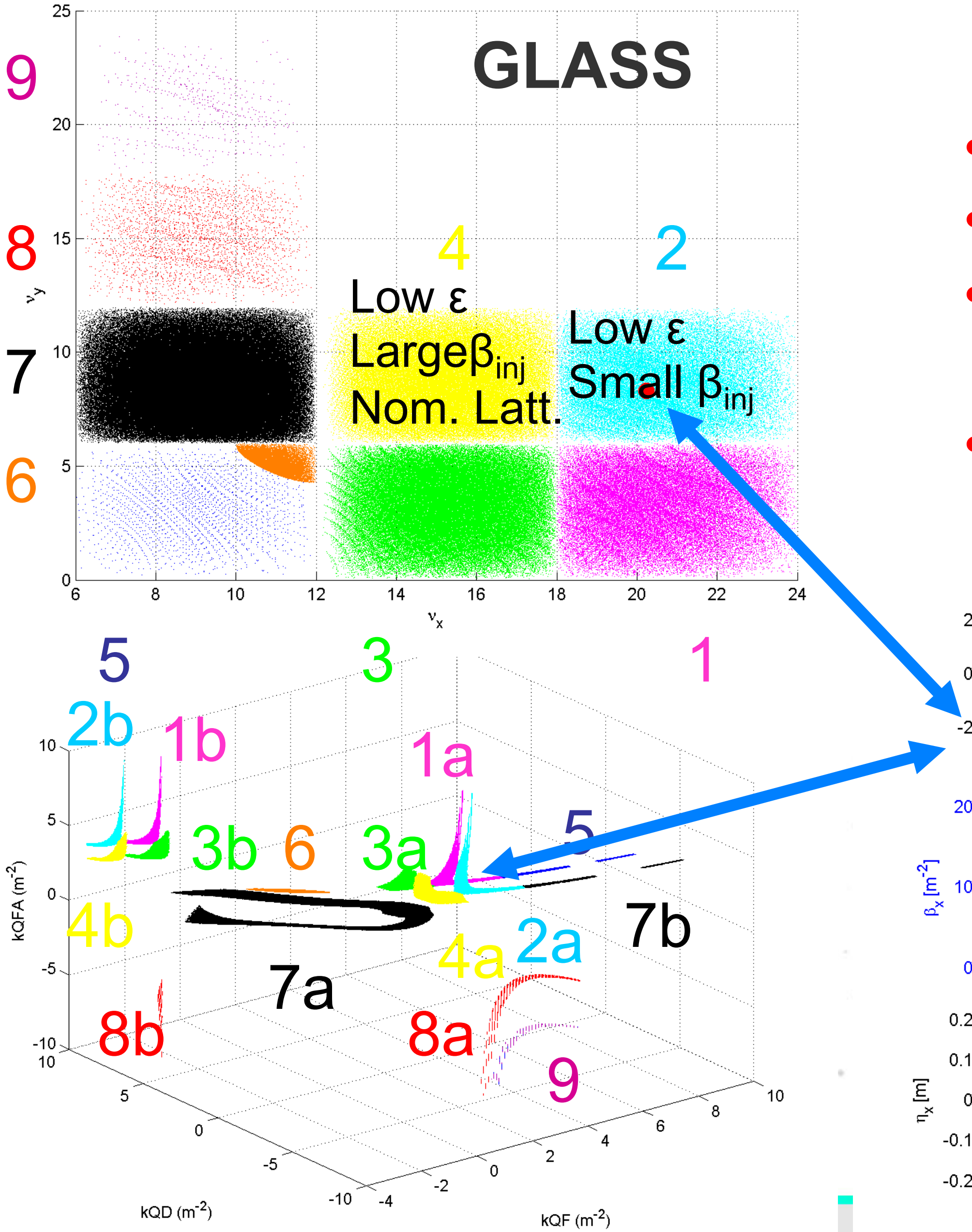
- **GLASS – Global Linear Analysis of All Stable Solutions**
  - •Scan for optimum lattice solution for highly periodic lattices (few parameters)

D. Robin, et al., Physical Review Special Topics 024002 (2008)

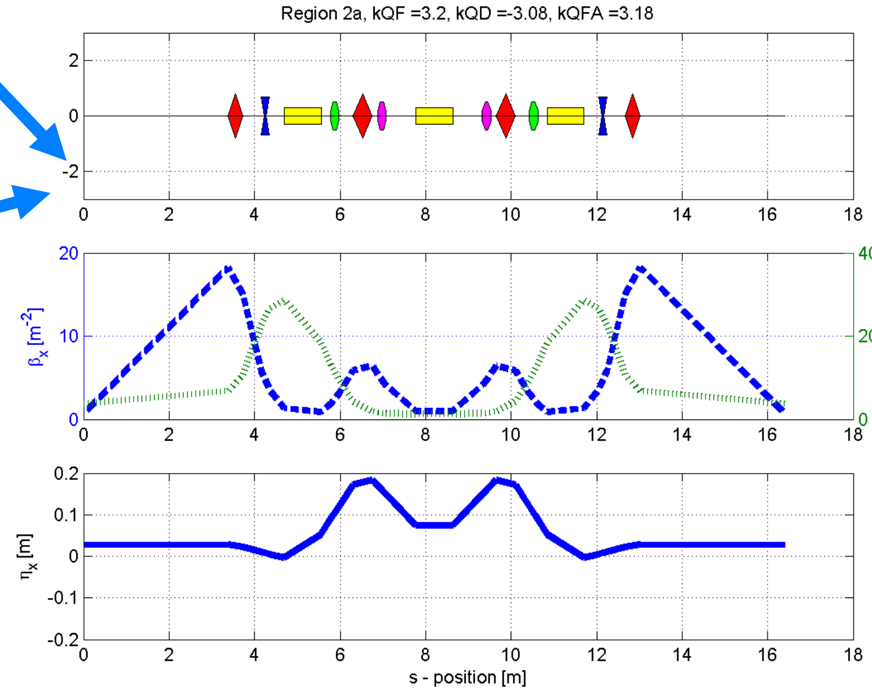
•A billion of lattices scanned with 3 quadrupole and 2 sextupole families

•After 1 day of computation, 1 million of stable solutions
  - •Then compute main properties of these solutions to build up a large exhaustive database
  - •Solutions sorted by emittance values, tunes, DA sizes, momentum apertures but also brilliance

Give a global view of the lattice, very practical



- *Low emittance*
- *Low momentum compaction*
- *Small beta functions in center bend*
- *Small horizontal beta in straights*



Courtesy C. Steier

Genetics Algorithms based optimization

- Exhaustive and global scanning is not possible in a finite for most 3GLSs

- Indeed large number of parameters (~tens families of quadrupoles, of sextupoles, individual. Power supplies)

- **Genetic algorithms** are a very promising solution
  1. Based on direct tracking or real tracking
  2. Open new optimization windows
  3. Give solutions never thought about
  4. Beam-based checked

- **Early work started since around 10 years at APS** and followed by over laboratories and starts to give practical results in simulation and/or online.

- APS (M. Borland et al), ALS, BNL, SIRIUS, SOLEIL, SLS, …(all facilities)

Genetic algorithm based optimizations for accelerators

- **Evolutionary algorithms** (1971-today)

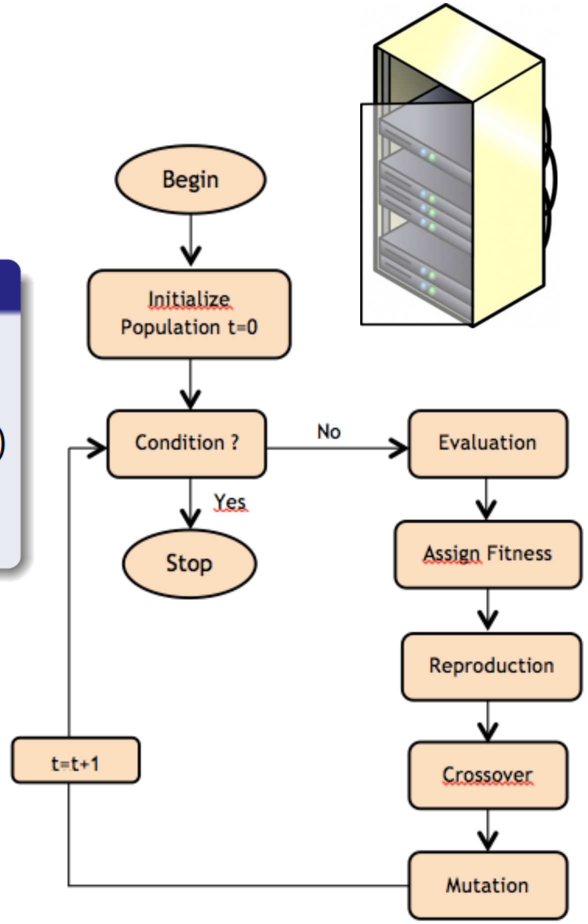
- **Various classes of algorithms**
  - Single/multi-objective types
  - Dominant/non dominant sorting (SPEA2, PESA, NGSA-II, …)
  - Pareto front optimality
    - Multi-objective Genetic Algorithm (MOGA)
    - Multi-objective Particle Optimization Algorithm (MOPSOA) 1995
  - Modern GA implementation (OPAL)

<u>Interesting Recent PhD dissertations</u>

- O. Roudenko, Application des algorithmes ́évolutionnaires aux problèmes d’optimisation multi-objectif avec contraintes pastel-00000967 (2010).
- Y. Ineichen,Toward Massively Parallel Multi-Objective Optimization With Application To Particle Accelerators DISS. ETH NO. 21114 (2013)

Principal of GA

CPU, GPU farms



Objectives: MA, DA, emiitance…

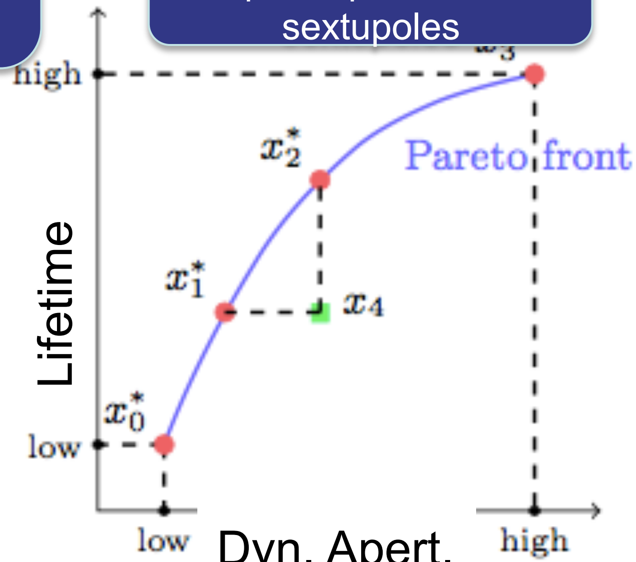
The general form of an optimization probl s:

Optimization

$$
\begin{aligned}
&\textbf{Minimize}/\text{Maximize} && f_m(x), && m = 1, 2, \ldots, M; \\
&\text{subject to} && g_j \geqslant 0, && j = 1, 2, \ldots, J; \\
& && h_k(x) = 0, && k = 1, 2, \ldots, K; \\
& && x_i^{(L)} \leqslant x_i \leqslant x_i^{(U)}, && i = 1, 2, \ldots, N;
\end{aligned}
\qquad (1)
$$

Constraints: beta-function, phase advance, tunes, chromaticities

Variables: strength of quadrupoles and sextupoles



Contradictory objectives

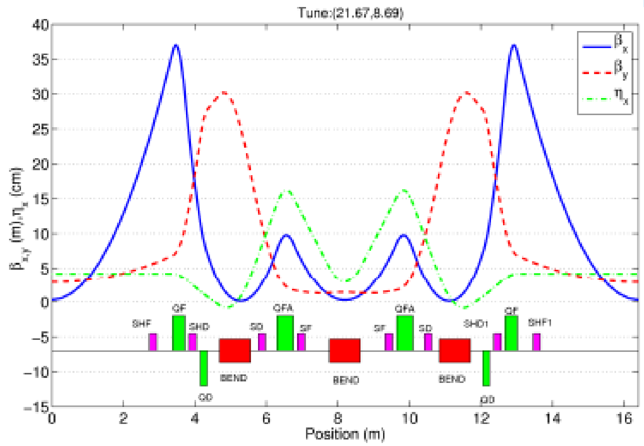
Optimal solution

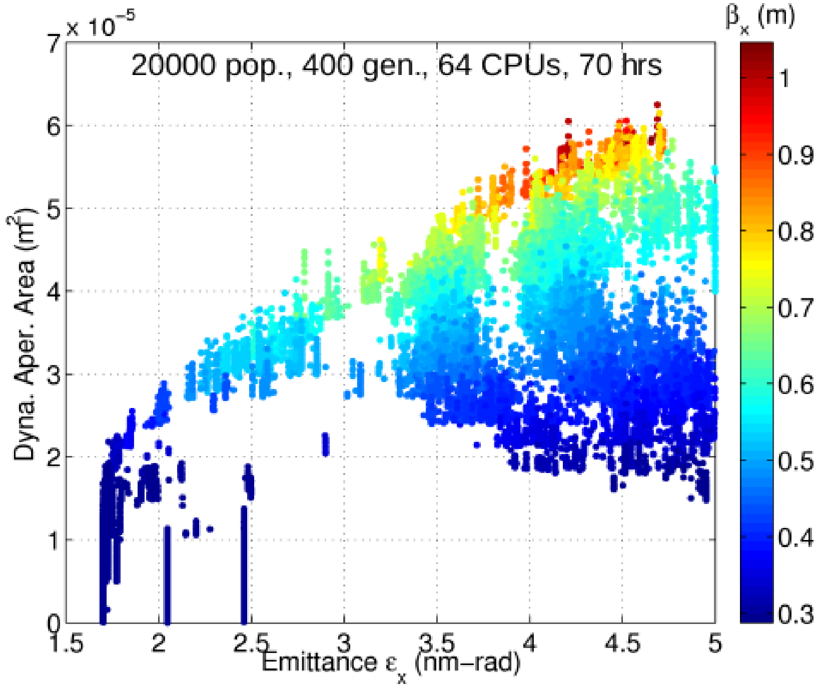
Y. Ineichen ETH-Diss 21114, 2013

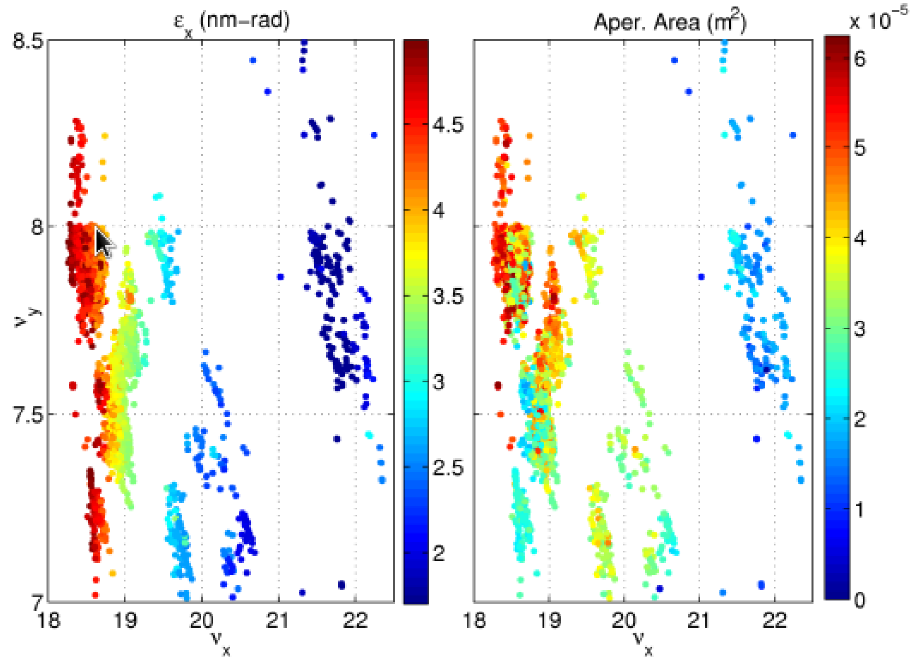
Simultaneous Linear and Nonlinear Optimization

ALS ultimate lattice is used as an example:

- 7 parameters: 3 Quads + 6 Sextupoles
- constraints: stability, positive partition number, reasonable optics functions
- 3 objectives: emittance, betax and dynamics aperture

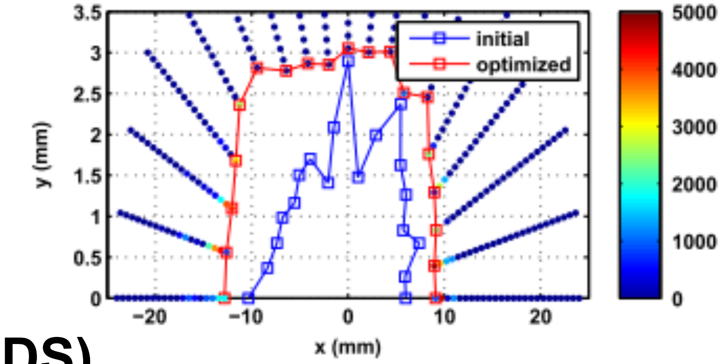






Online optimization for nonlinear dynamics

- **Diagnostics: proxies for dynamic aperture and lifetime**
  - Injection efficiency
  - Lifetime
  - Beam loss rate
  - …



- **Robust Conjugate Direction Search (RCDS)**
  - **SPEAR 3**
    - Applied to coupling, top-off transient, LCLS undulator taper, etc...
    - *X. Huang, J. Corbett, J. Safranek, J. Wu, NIMA (2013*)
    - Dynamic aperture increase >3.5 mm X. Huang et al., PRSTAB 18, 084001 (2015)
  - **ESRF (N. Carmignani, LER2015)**
    - 16 bunch operation: Improvement of lifetime 16.5 →20 h
    - Single bunch in hybrid mode: bunch current threshold 4 → 8 mA/bunch

Conclusion and perspectives

- **Nonlinear beam dynamics optimization is still a challenging task**

- **Theory**
  - Mature and modern tools
  - Refined and accurate models (based on magn. measurements, alignment)

- **Beam based Experiments and** quality of diagnostics (ease of use)
  - Mandatory to **cross-check/benchmark** our model vs experiment
    - Model upgrade, unexpected effects, difficult to model quantities, etc.
  - Online capability to explore nonlinear dynamics (tune shift, DA, MA, etc.)
    - **BPMs are our eyes**
      - Single, collective beam dynamics
      - TbT BPMs, Bunch per Bunch
      - Small/large beam charge, off-axis beam position, many/few turns
  - Online optimization (RDTs, GA, Injection, Lifetime)
  - Continuous monitoring (feedback, alive machine with insertion devices free controlled by users for instance)

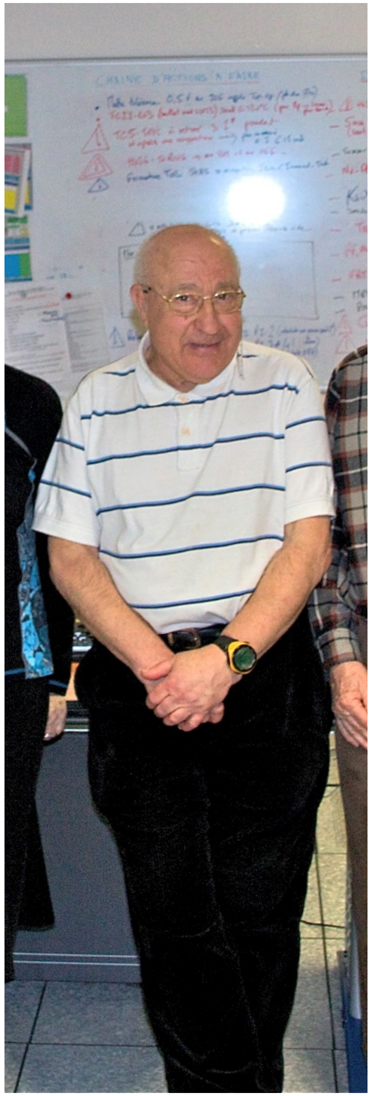
Tribute to Michel SOMMER

We have the very big sadness to announce you the death of Michel SOMMER, arisen on August 4th, 2015, at the age of 80.

He was an accelerator physicist of international renown, expert in electron beam dynamics in storage rings and in synchrotron radiation production.

He was working in the French LURE laboratory, and was involved in the design, construction and operation of many storage rings in France : ACO, DCI, ESRF, Super-ACO, SOLEIL, but also in other countries : Italy, Germany, Brazil, Taiwan, Korea, Jordan…

Above all, Michel Sommer was an open and cultivated man.



Thank you for your attention