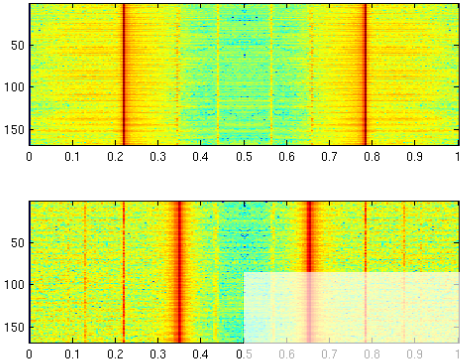
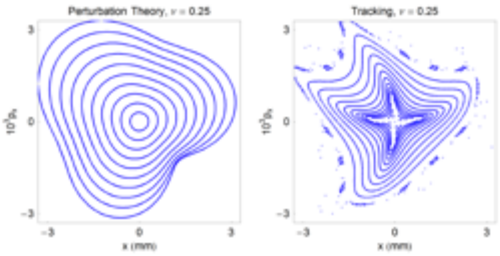
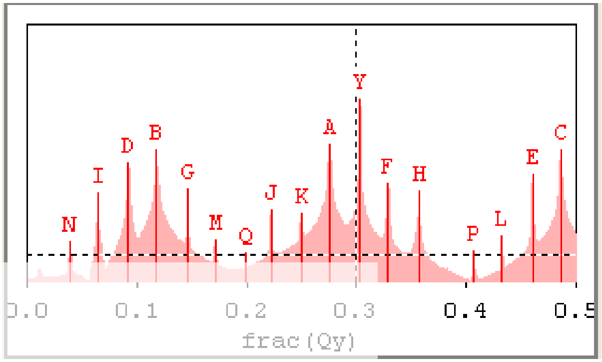
Methods and Tools to Simulate and Analyze non-linear beam Dynamics in Electron Storage Rings

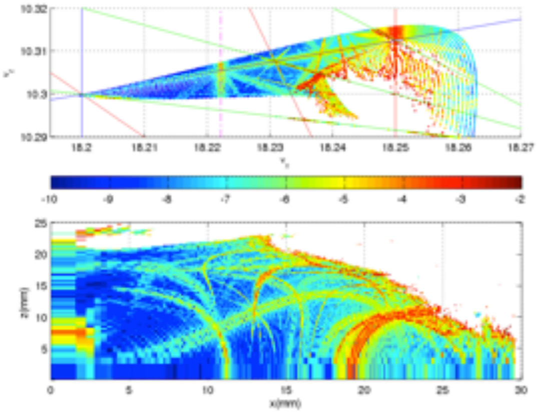


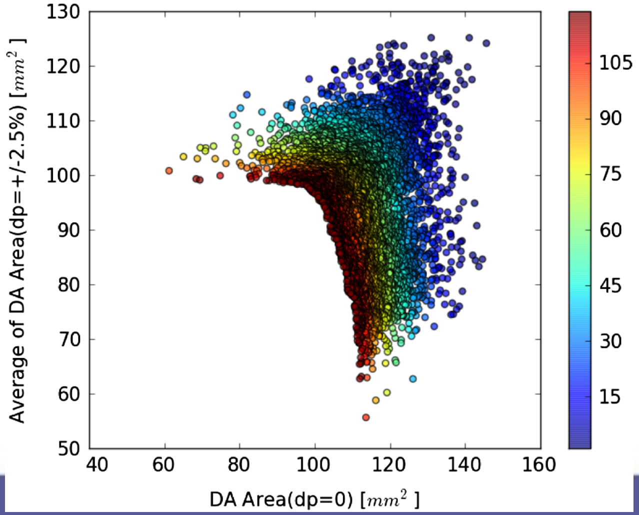


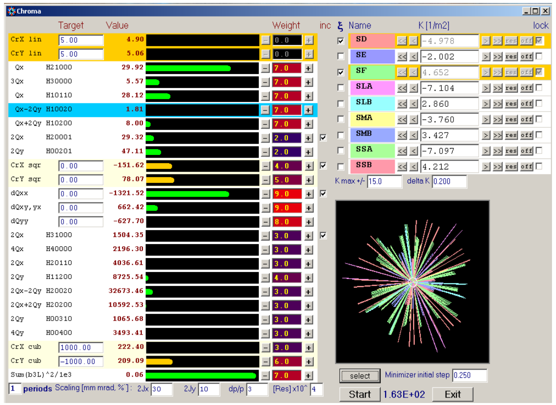


Laurent S. Nadolski

Synchrotron SOLEIL, Gif-sur-Yvette, France






Chroma

	Target	Value	Weight	inc
CrX lin	5.00	4.90	0.0	
CrY lin	5.00	5.06	0.0	
Qx H21000		29.92	7.0	
3Qx H30000		5.57	7.0	
Qx H10110		28.12	7.0	
Qx-2Qy H10020		1.81	7.0	
Qx+2Qy H10200		8.00	7.0	
2Qx H20001		29.32	2.0	☑
2Qy H00201		47.11	2.0	
CrX sqr	0.00	-151.62	4.0	☑
CrY sqr	0.00	78.07	5.0	
dQxx	0.00	-1321.52	9.0	☑
dQxy,yx	0.00	662.42	9.0	
dQyy	0.00	-627.70	8.0	
2Qx H31000		1504.35	3.0	☑
4Qx H40000		2196.30	3.0	
2Qx H20110		4036.61	3.0	
2Qy H11200		8725.54	4.0	
2Qx-2Qy H20020		32673.46	3.0	
2Qx+2Qy H20200		10592.53	3.0	
2Qy H00310		1065.68	3.0	
4Qy H00400		3493.41	3.0	
CrX cub	1000.00	222.40	3.0	
CrY cub	-1000.00	209.09	6.0	
Sum(b3L)^2/1e3		0.06	7.0	

1 periods Scaling [mm mrad, %]: 2Jx 30 2Jy 10 dp/p 3 [Res]x10^ 4

ξ	Name	K [1/m2]	lock
☑	SD	-4.978	☑
☐	SE	-2.002	☐
☑	SF	4.652	☑
☐	SLA	-7.104	☐
☐	SLB	2.860	☐
☐	SMA	-3.760	☐
☐	SMB	3.427	☐
☐	SSA	-7.097	☐
☐	SSB	4.212	☐

K max +/- 15.0 delta K 0.200

Minimizer initial step 0.250

1.63E+02

Layout

- **Challenging requirements for today and tomorrow synchrotron light sources**
- **Tools**
  - Tracking codes for storage rings
  - Frequency Map Analysis (FMA) like analysis
  - Momentum aperture & Touschek life time
- **Optimization methods**
  - New optimization method via genetics algorithms
  - Resonance Driving Terms (RDTs)
  - Tuning multipole magnets: sextupole and higher order
- **Perspectives**

Requirements for light sources

- **Low emittance storage ring**
  - **Route to diffraction limit in H-plane**
  - Complex lattices (TME, MBA lattices)
    - See Dr. Shimosaki's talks
  - Damping wiggler

Storage ring	Energy (GeV)	H-emittance
Petra III	6 Gev	1 nm.rad
PEPX	4.5 GeV	0.1 nm.rad
NSLS II	3 GeV	0.6 nm.rad
MAX IV	3 GeV	< 0.3 nm.rad
Spring 8 upgrade	6 GeV	10 pm.rad
APS upgrade	7 GeV	15 pm.rad

- A **Dynamic** Accelerator:
- **High ratio of straight sections to hosted tens of insertion devices**
  - Apple II, III, Figure 8
  - SC, CRYO undulator/wiggler
  - Controlled polarization undulator
  - Fast switching of B-field (ms scale)

- **High brilliance, flux**
  - Diffracted limited in both planes
- **Taylored filling pattern**
  - Short vs long bunches
  - Low alpha lattice
  - Multi-beam facility (MLS, SOLEIL)
    - M. Ries' s talk today
- **Large on dynamics aperture (15-20mm)**
  - Waiting for on-axis injection
- **Large momentum aperture (2-6%)**
  - Touschek lifetime
  - Reduce beam losses
  - Reduce activation
  - Reduce running cost
- **Top-up operation (MTBF 1 week)**
- **Ultra-low coupling operation**

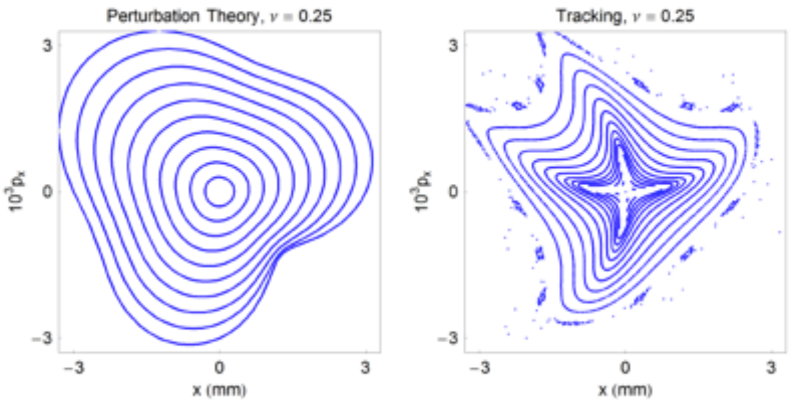
Figures of merit

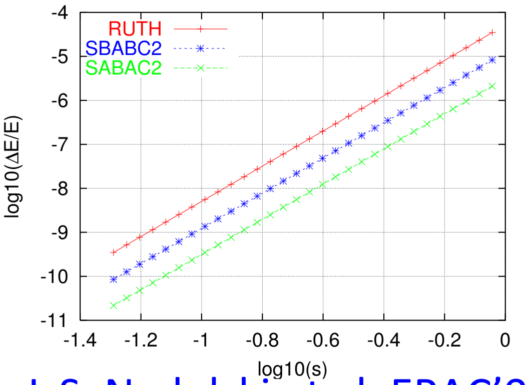
- **How to get there?**
  - High horizontal phase advance
  - Strong focusing lattices, low dispersion function
  - Strong chromatic sextupoles
  - Strong chromatic aberrations
  - Many sextupoles
    - Families
    - Individually powered
  - Higher multipoles
    - **Octupole** (Max IV)
    - Decapole (soon or later)

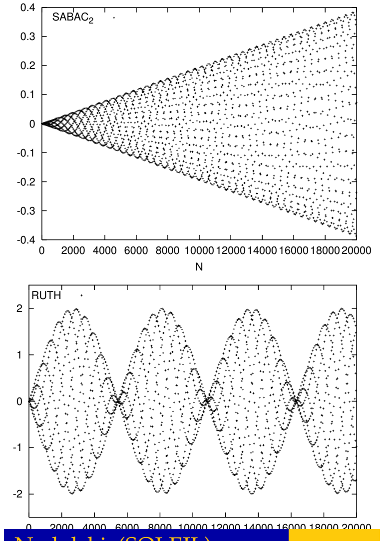
- **20 years after the first 3GLSs**
  - shift from simple lattice (ALS: 2 sextupole families, TBA based lattice) to highly complex and multi-parameter lattices
- **Optimization of non-linear parameters**
  - Amplitude/momentum tune dependence
  - Non-linear Twiss functions
  - Robust to IDs freely controlled by users

Tracking codes

- **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.





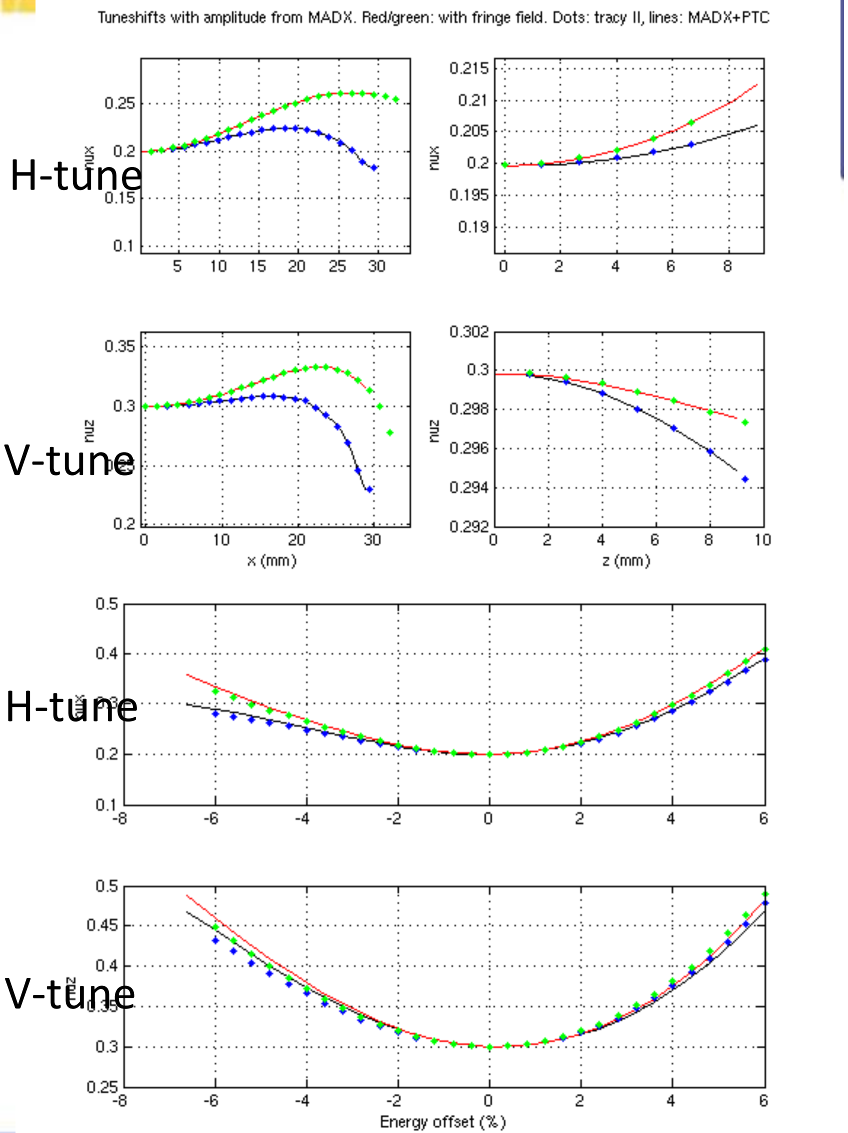


L S. Nadolski et al. EPAC'02

What is included in the Model?

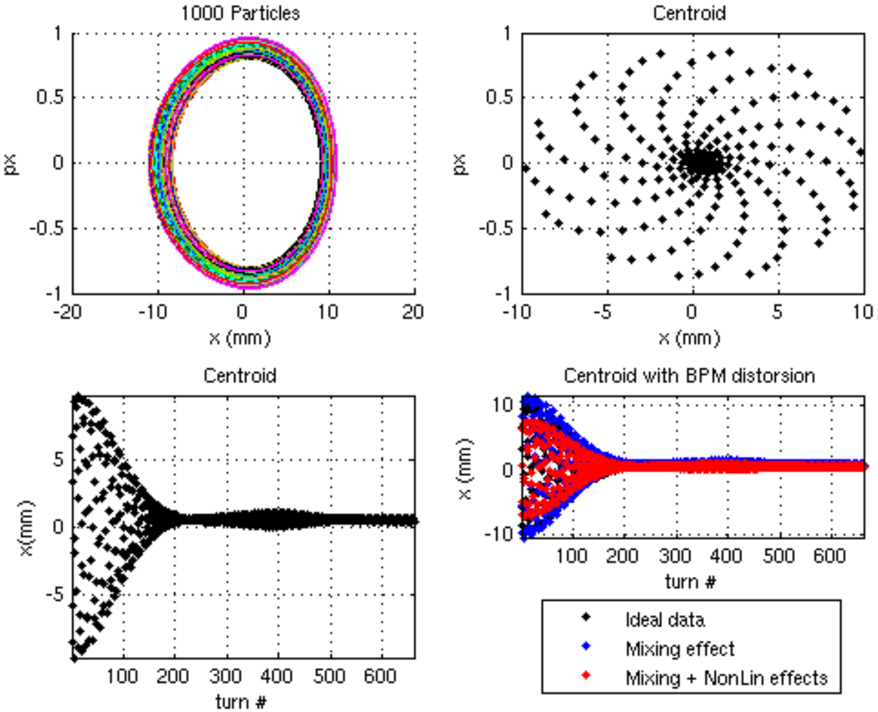
- Systematic multipole errors
  - Large momentum acceptance, large dispersion function → high order multipoles
- From magnetic measurements:
  - Add true m-poles (both systematic and non systematic)
  - Dipole: fringe field, gradient error, edge tilt errors
  - Quad.: fringe field
- Beam based
  - Multipoles 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

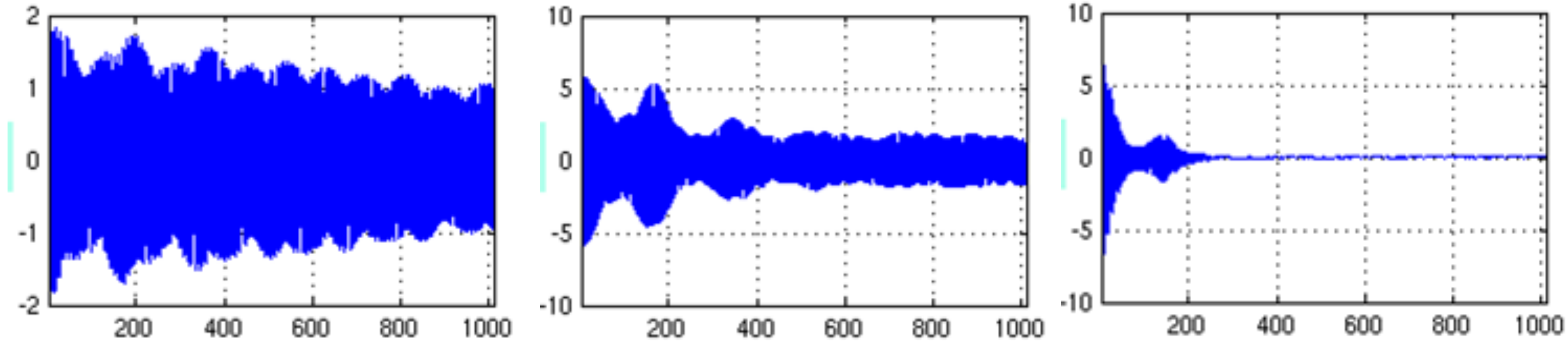
Tracy II & MADX/PTC_track exact (SOLEIL case)



Turn by turn (TbT)data beam smearing

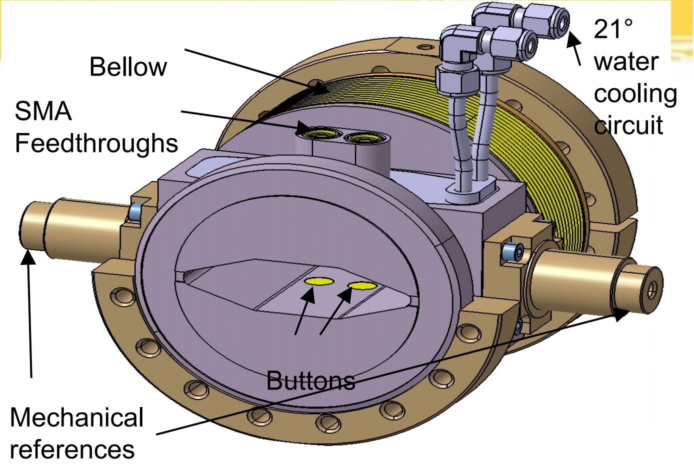
- **TbT BPM precision**: 10µm ~10 mA: limitative factor Frequency shift
- Algo. to precisely determine tune loose their precision *R. Bartolini et al. Part. Acc. 55, 247 (1995)*
- Lines excited by resonance of order (m+1) decohere m times faster than the tune line. *R. Thomas, PHd Thesis (2003)*
- Gain, coupling correction (LOCO based)

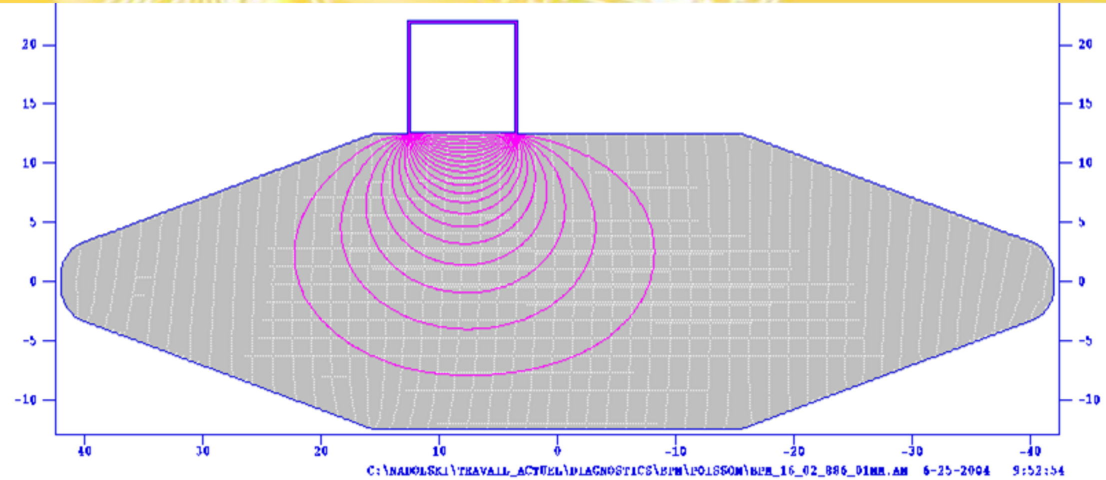


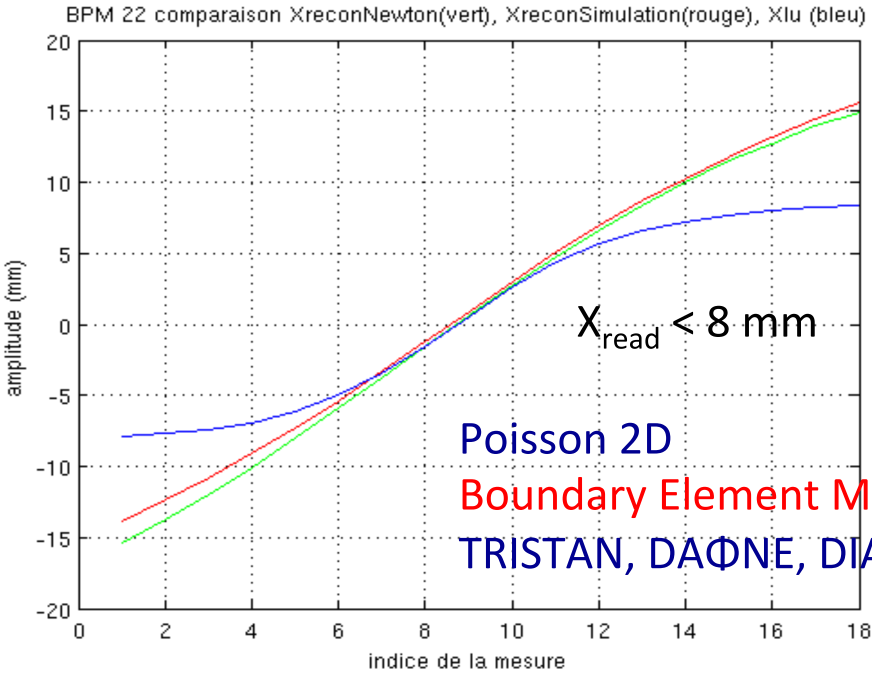


V (kicker H) :	2100 V	9000 V	12100 V
x (BPM) :	3.6 mm	15.2 mm	20.6 mm

BPM nonlinear response: SOLEIL case





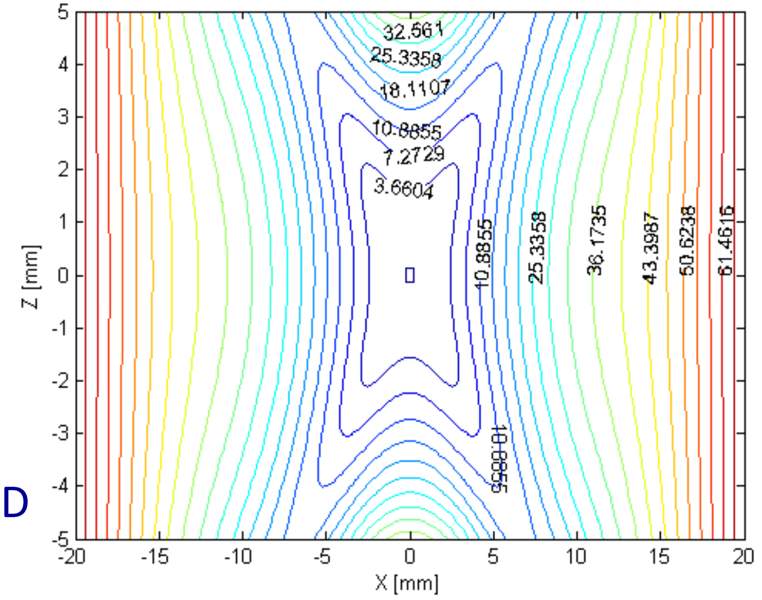


$X_{read} < 8$ mm

Poisson 2D

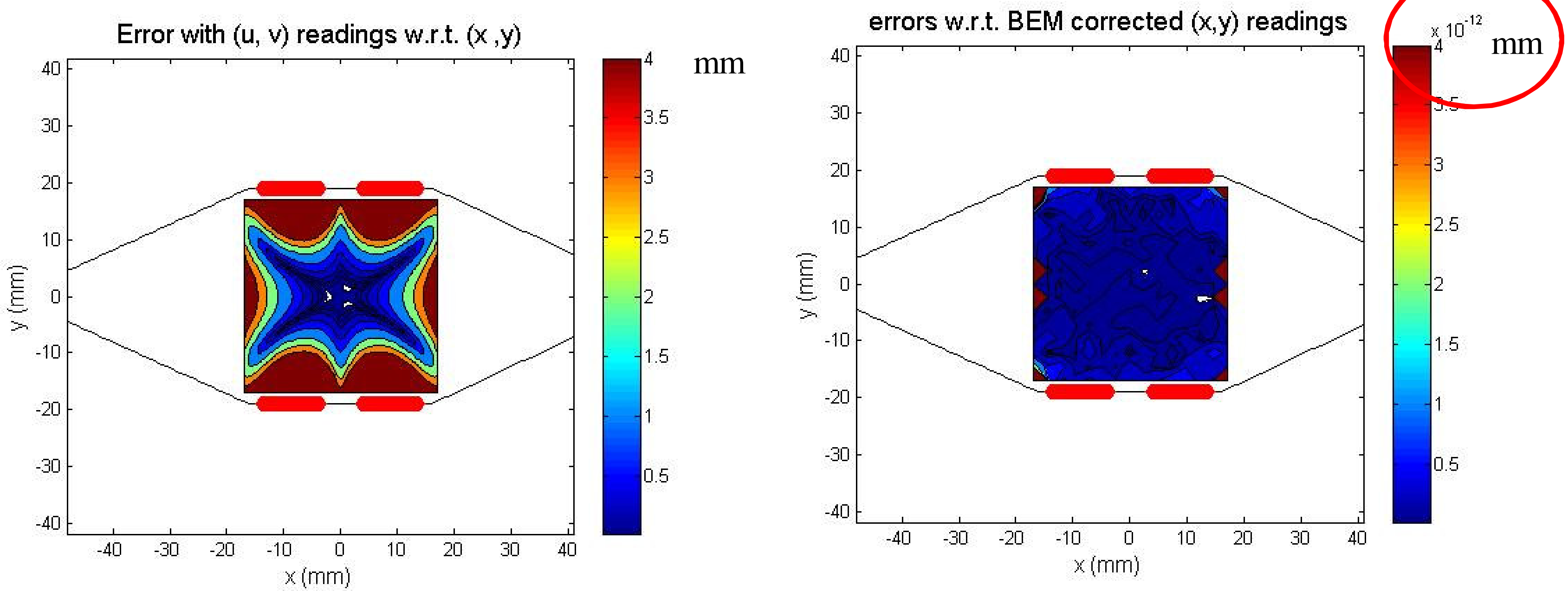
Boundary Element Method

TRISTAN, DAΦNE, DIAMOND



BPM signal reconstruction

R. Bartolini and J. Rowland, DLS internal note, AP-SR-REP-0171 (March 2010)



Numerical inversion of the map (x,y) -> (A,B,C,D) given by the electrostatic model

Use (x, y) as fit parameter to reproduce the four buttons readings (A, B, C, D)

3 buttons are sufficient to converge to machine precision

Courtesy of R. Bartolini

Frequency Map Analysis

Laskar A&A1988, Icarus1990 NATO-ASI 1996

- Construction of frequency map

$$\boxed{\mathcal{F}_\tau \ : \ \begin{array}{ccc} \mathbb{R}^n & \longrightarrow & \mathbb{R}^n \\ \boldsymbol{q}|_{\boldsymbol{p}=\boldsymbol{p}_0} & \longrightarrow & \boldsymbol{\nu} \end{array}}$$

with high precision: $\frac{1}{\tau^4}$ for Hanning Filter

- Refined Fourier technique
- Fast convergence (reduce tracking time)
- Give a global view of the transverse dynamics in a 2D map
- Mapping between DA/tune space using diffusion index

- Determination of tune diffusion vector

$$\boldsymbol{D}|_{t=\tau} = \boldsymbol{\nu}|_{t\in(0,\tau/2]} - \boldsymbol{\nu}|_{t\in(\tau/2,\tau]}$$

and construction of diffusion map

$$\boxed{\mathcal{D}_\tau \ : \ \begin{array}{ccc} \mathbb{R}^n & \longrightarrow & \mathbb{R}^n \\ \boldsymbol{q}|_{\boldsymbol{p}=\boldsymbol{p}_0} & \longrightarrow & \boldsymbol{D} \end{array}}$$

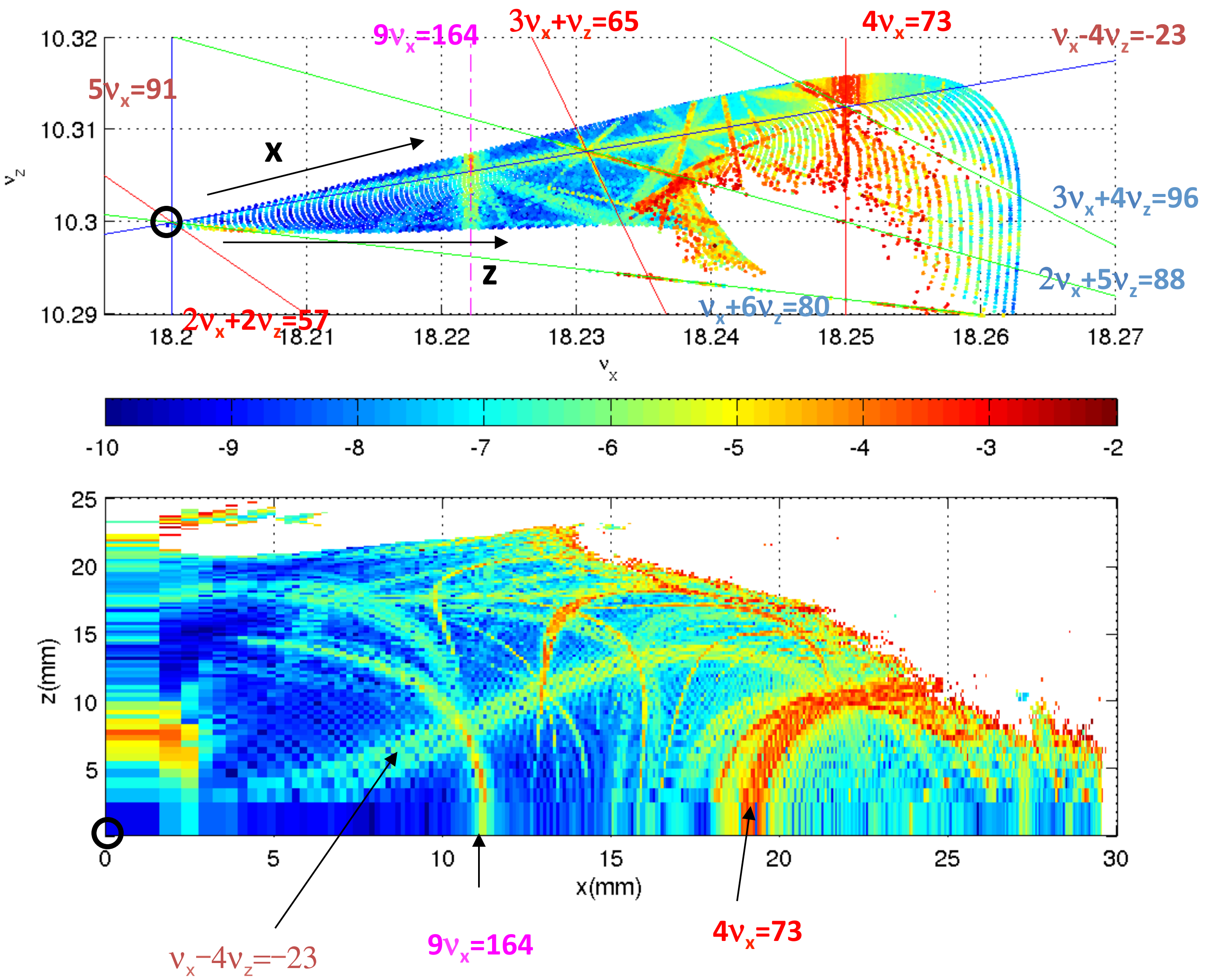
Does not provide a way to optimize

- Determination of resonance driving terms associated with amplitudes $a_{j,k}$

Bengtsson PhD thesis CERN88-05

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

Bare lattice (no errors)



WP sitting on Resonance node

$\nu_x + 6\nu_z = 80$

$5\nu_x = 91$

$\nu_x - 4\nu_z = -23$

$2\nu_x + 2\nu_z = 57$

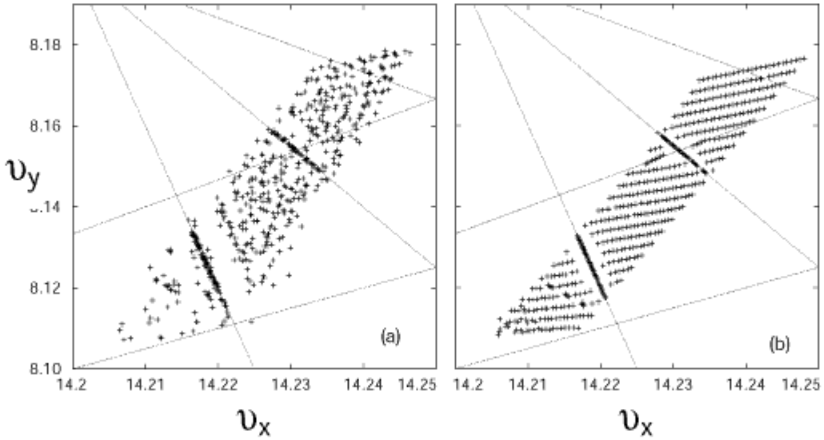
Frequency Map Analysis: ALS and BESSY-II

P. Kuske (BESSY-II)

ALS linear lattice corrected to 0.5% rms β-beating

BESSY-II with harmonic sextupole magnets, chromaticity, coupling

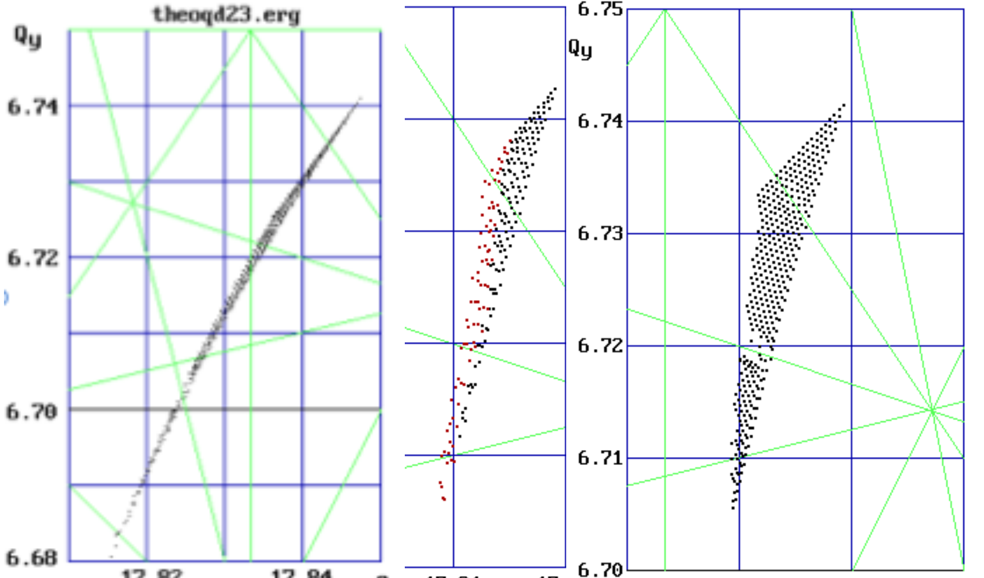
FM computed including residual β-beating and coupling errors



ALS measured

ALS model

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



BESSY-II measured

old/new model

BESSY-II model

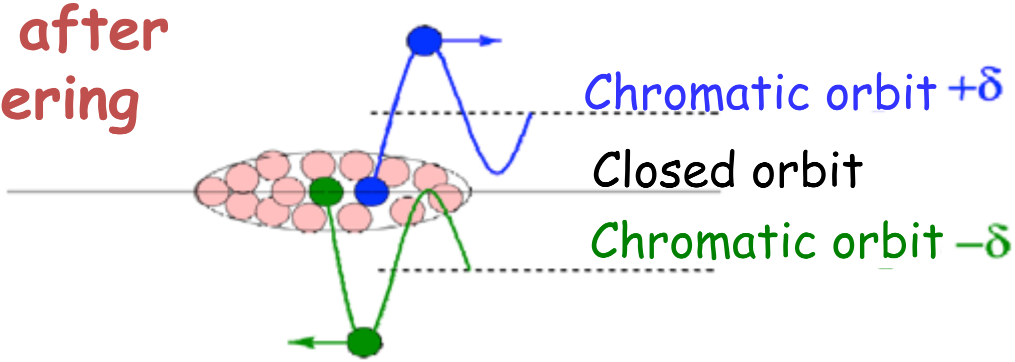
A very accurate description of machine model is mandatory

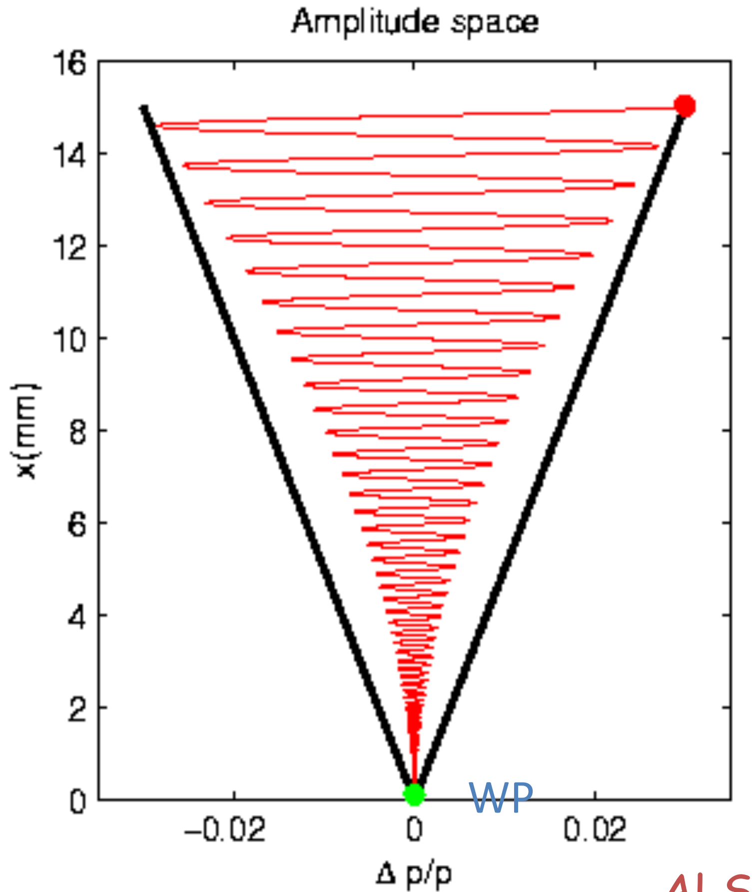
- Fringe fields: dipole, quadrupole (and sextupole) magnets
- Systematic octupole components in quadrupole magnets
- Decapoles, skew decapoles and octupoles in sextupole magnets

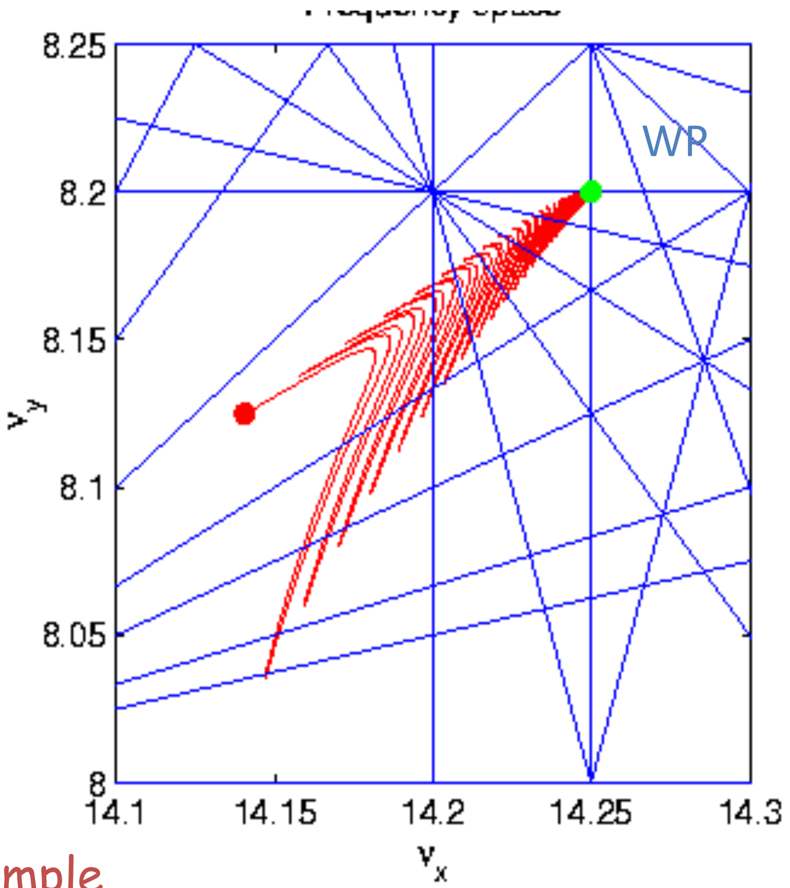
Particle behavior after Touschek scattering

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

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







ALS Example

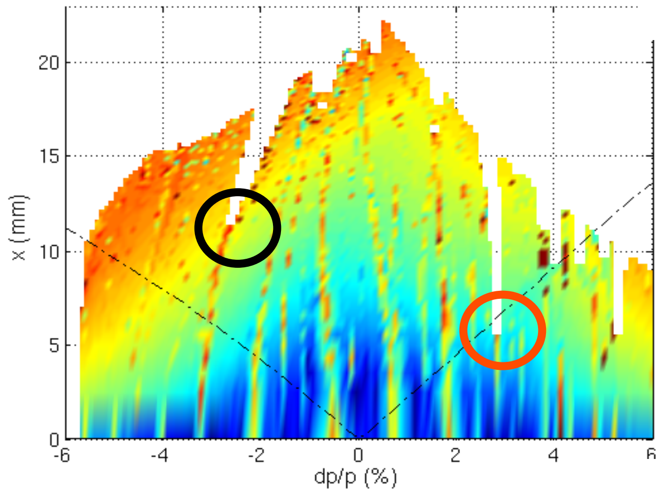
Large off-momentum DA to keep the Touschek scattered particule in its way back to WP

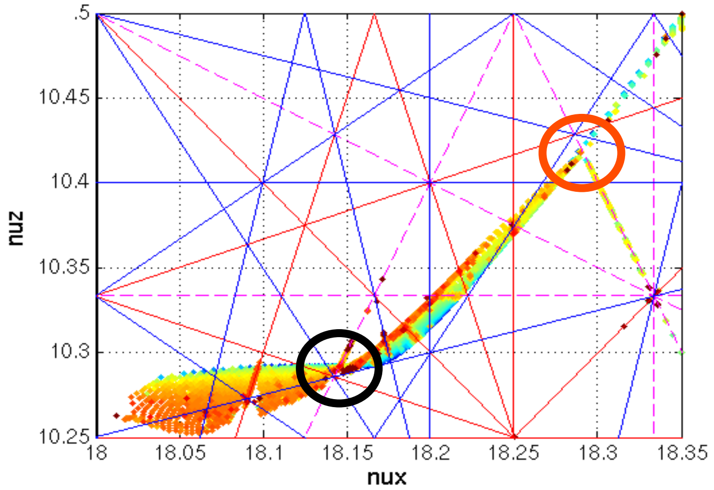
The SOLEIL energy acceptance of the bare machine is large : +/- 4%.

Agreement of a few percents (a factor 2 common 10 year ago)

Complete optimized linear and non-linear model

Simulations

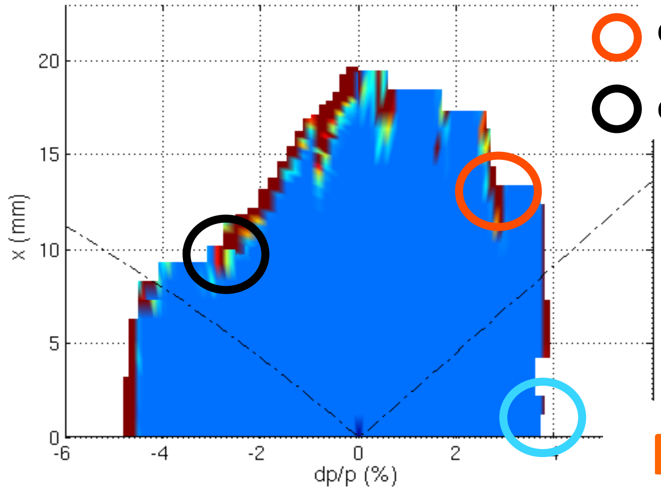


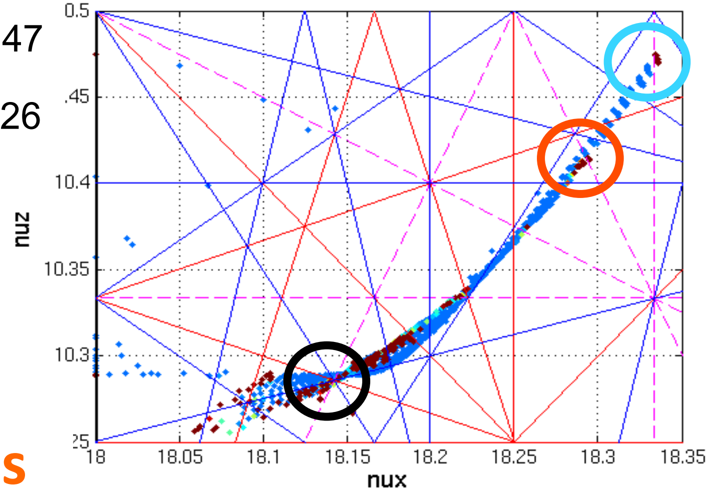


○ dp/p = + 4 % : $3v_x=55.$

○ dp/p = + 3 % : $2v_x+v_z=47$

○ dp/p = - 3 % : $2v_x–v_z=26$





Measurements

P. Brunelle et al, IPAC10

TOUSCHEK LIFETIME
LOCAL MOMENTUM ACCEPTANCE

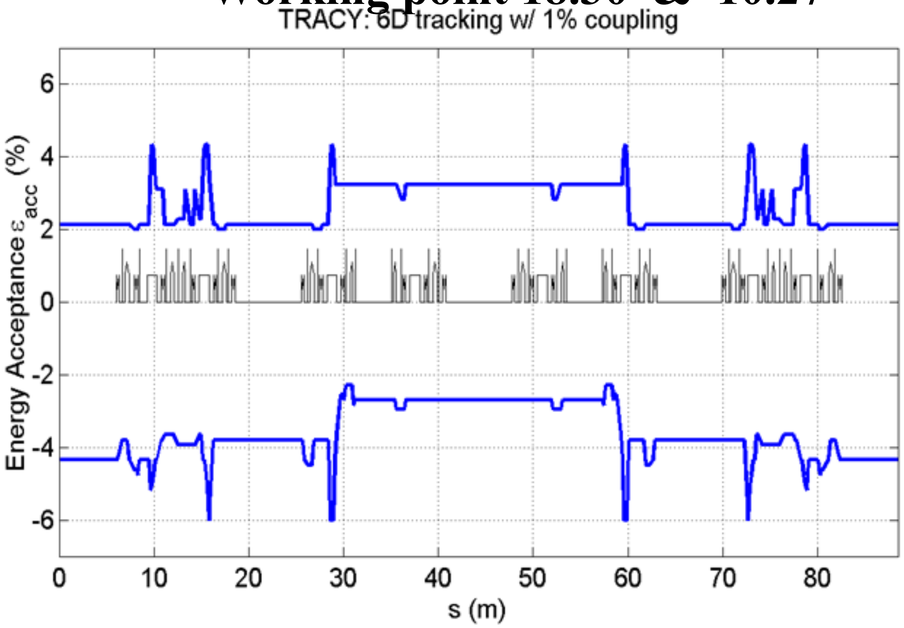
$$\frac{1}{\tau_{T_{1/2}}} = \left(\frac{r_e^2 c N}{8\pi \gamma^3 \sigma_l}\right) \cdot \frac{1}{L} \int_0^L \frac{C\left[\left(\frac{\varepsilon_{acc}(s)}{\gamma \sigma_x'(s)}\right)^2\right]}{\sigma_x(s) \sigma_z(s) \sigma_x'(s) \varepsilon_{acc}^2(s)} ds$$

Local $\varepsilon_{acc}(s)$ is determined by:

- RF bucket momentum height (longitudinal energy acceptance)
- aperture of the vacuum chamber, or by dynamic aperture (transverse)

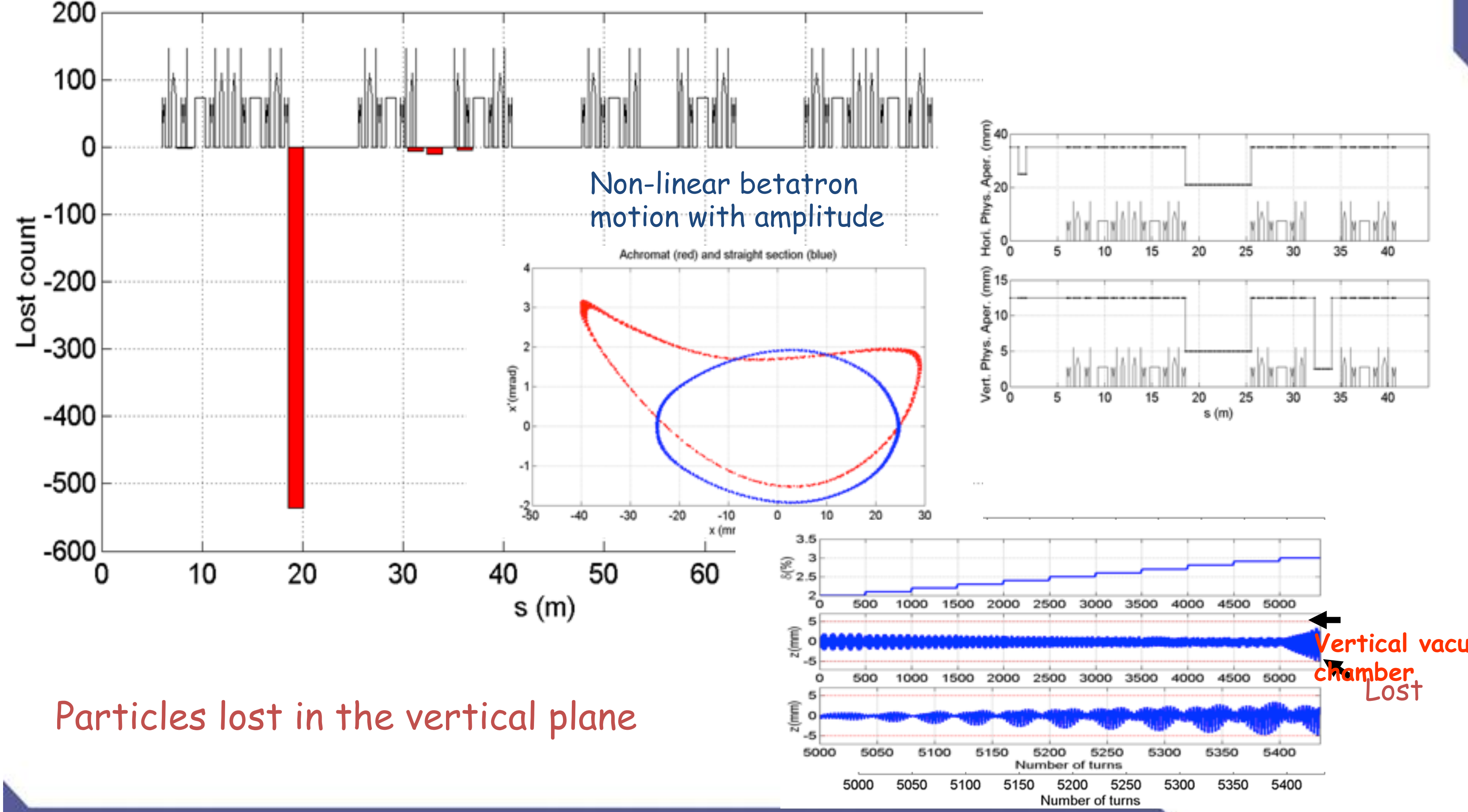
(if the induced amplitude after a Touschek scattering exceeds one of these two transverse limits).

SOLEIL
Working point 18.30 & 10.27



Beam loss location understanding to reducing activation

SOLEIL: Working point 18.30 & 10.27 ($\Delta\nu=0.03$)



Non-linear betatron motion with amplitude

Vertical vacuu chamber Lost

Particles lost in the vertical plane

Lattice optimization

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

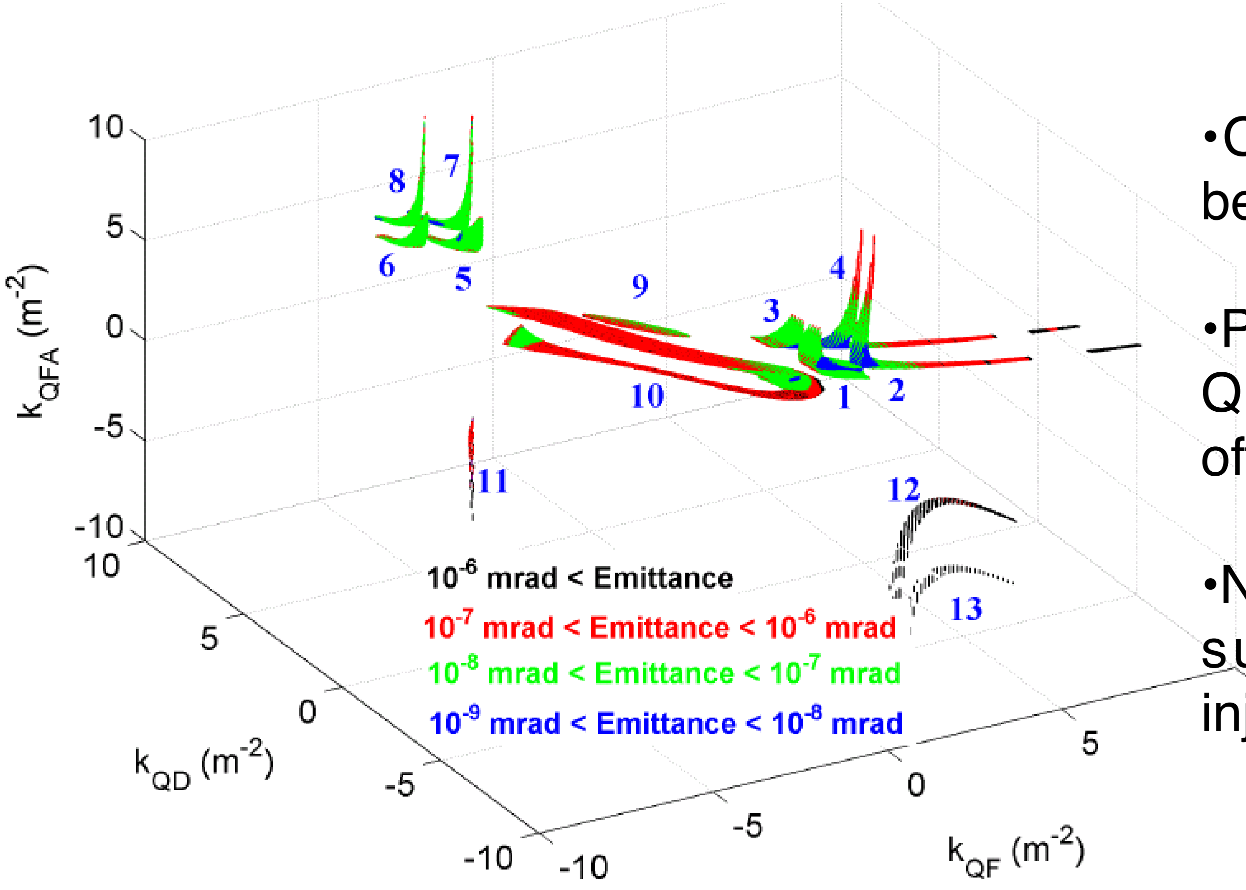
D. Robin, et al., Physical Review Special Topics 024002 (2008)

- 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**

13 areas of solutions identified counter intuitive and/or promising

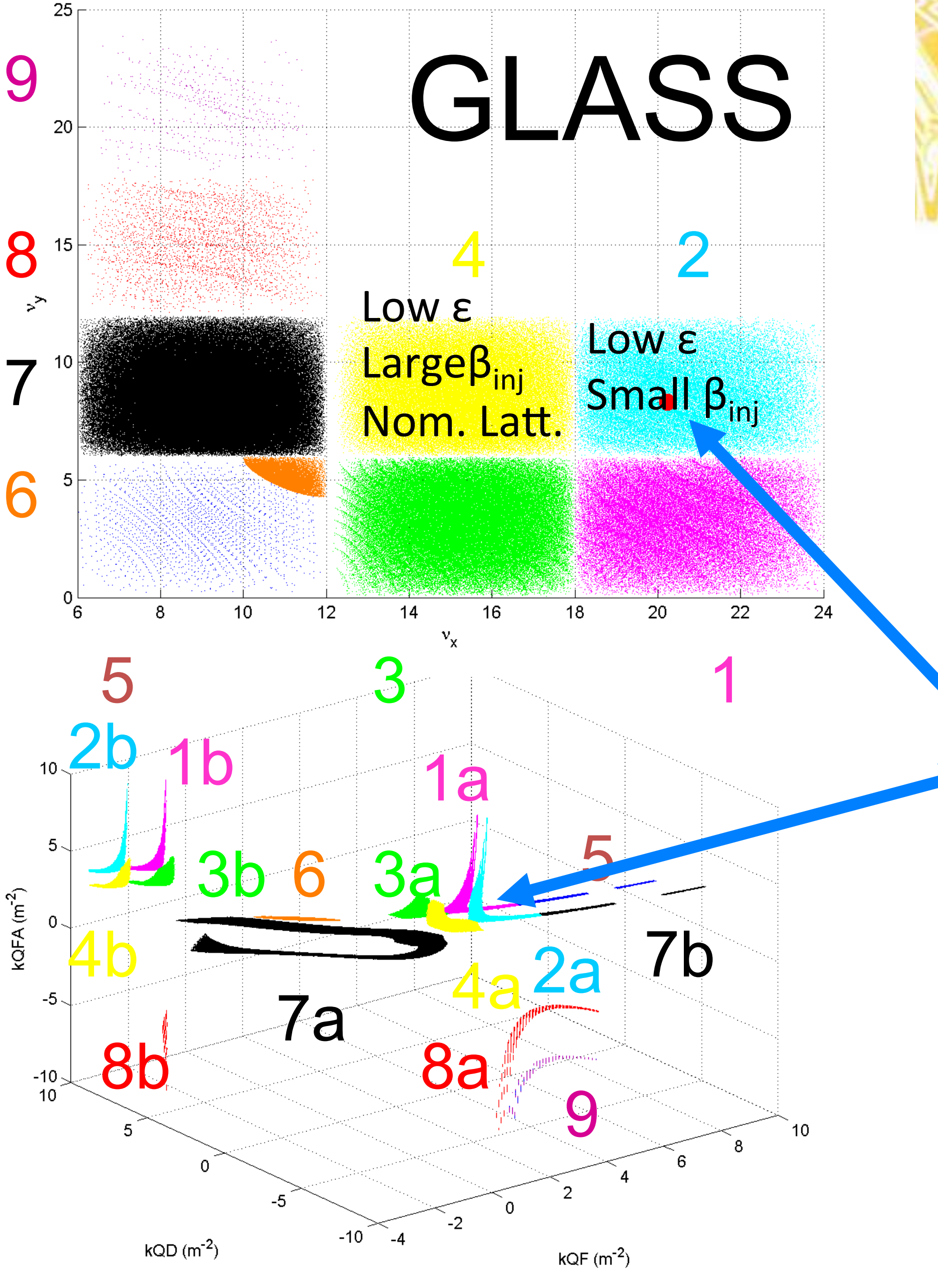


- Only 2 were known before!
- Possible operation with QF/QD off or QFA family off!
- New potential capabilities suggested if on axis injection is possible

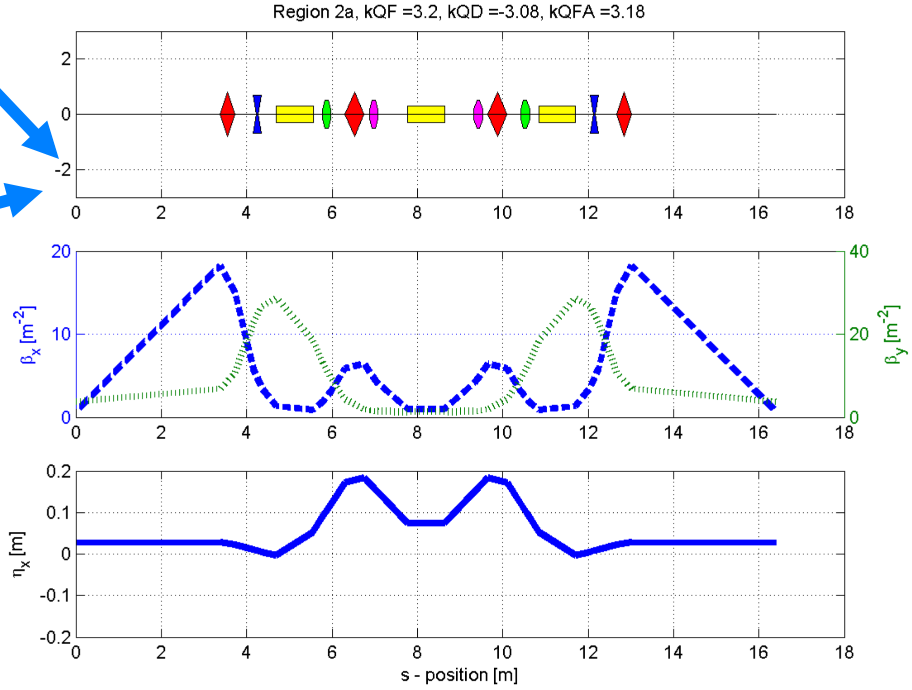
7 Regions with low (<10 nmrad) emittances

Courtesy of D. Robin,
NLBD workskop, Diamond 09

GLASS



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


Region 2a, kQF =3.2, kQD =-3.08, kQFA =3.18

Courtesy of C. Steier

Multi-Objective Genetics Algorithms MOGA

- Exhaustive and global scanning is not possible in a finite for most 3GLSs
- Indeed large number of parameters (~10 families of quadrupoles, of sextupoles)
- **Genetic algorithms** are a very promising solution
  1. Based on direct tracking
  2. Open new optimization windows
  3. Give solutions never thought about
  4. Beam-based checked
- Work started since almost 10 years at APS and followed by over labs and starts to give nice and practical results
- APS (M. Borland et al), ALS, BNL, LSLN, TPS, …

Merit functions

- NSLS II: Size of on (x> 15 mm) / off-momentum dynamics aperture (2-3 %)

$$f_1 = S(\delta = 0) \quad f_2 = S(\delta = -2.5\%) + S(\delta = 2.5\%),$$

- Adding tune shift with amplitude: faster convergence

$$f_1 = \sum_{\delta} S(\delta, y = 1\,\mu\mathrm{m})$$

$$f_2 = \left(\frac{\partial \nu_x}{\partial J_x}\right)^2 + \left(\frac{\partial \nu_x}{\partial J_y}\right)^2 + \left(\frac{\partial \nu_y}{\partial J_y}\right)^2,$$

- NSLSII: 3 harmonics + 6 chromatic sextupoles
- Tracking codes: Pelegant (APS), Tesla (BNL), …
- Small number of turns for DA tracking (64-128)
- Then results post filtered using FMA to select best and robust solutions

Maximal survival area in δ-x plane

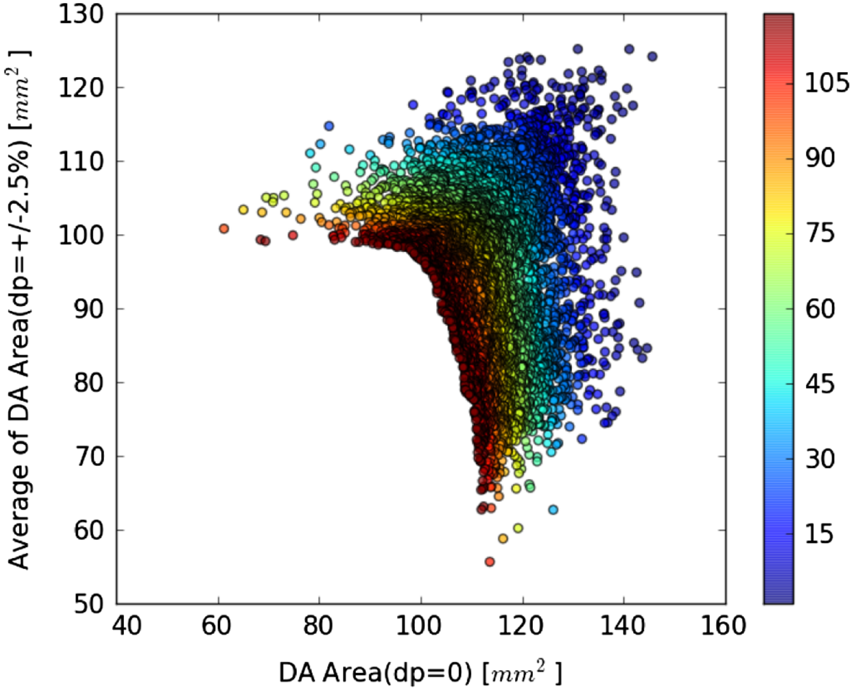
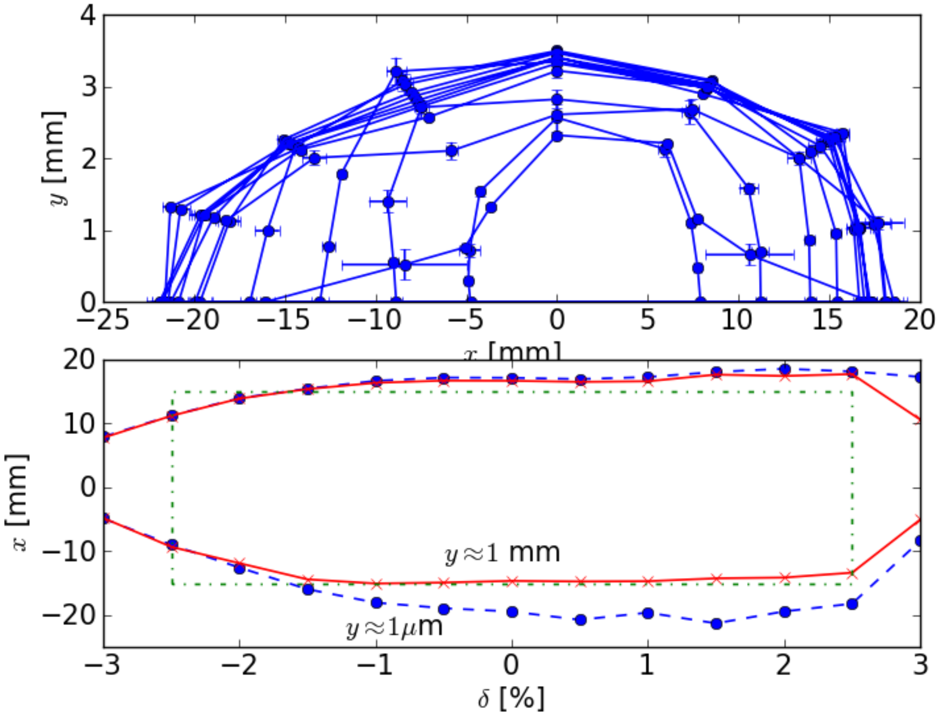


FIG. 1. The last generation of objective functions: DA of on-momentum (horizontal axis) and off-momentum (vertical axis) particles. Points are colored according to their rank.



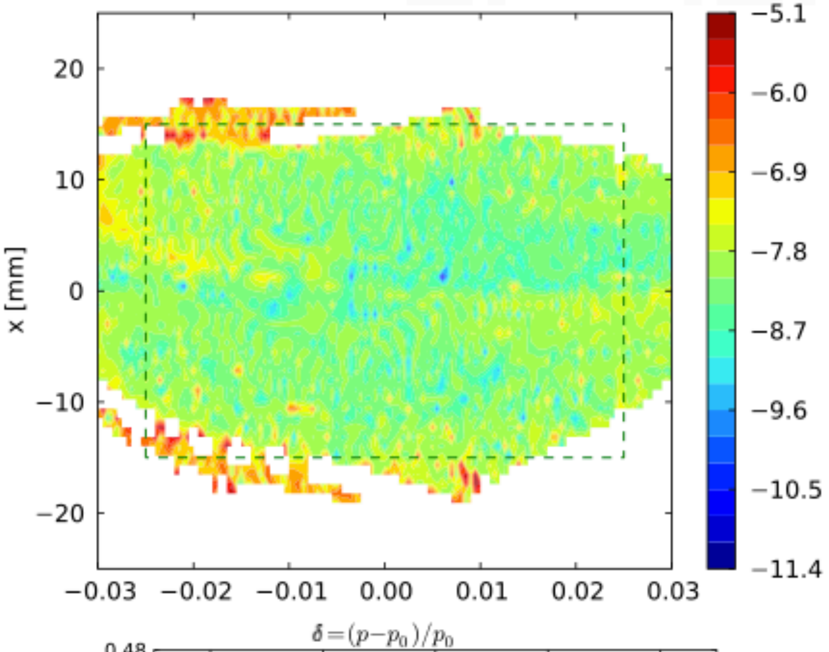
Population of 6000, computation of 300 generation take less than a week on 96 Xeon 2.33 GHz CPU in a Sun Grid Engine cluster.

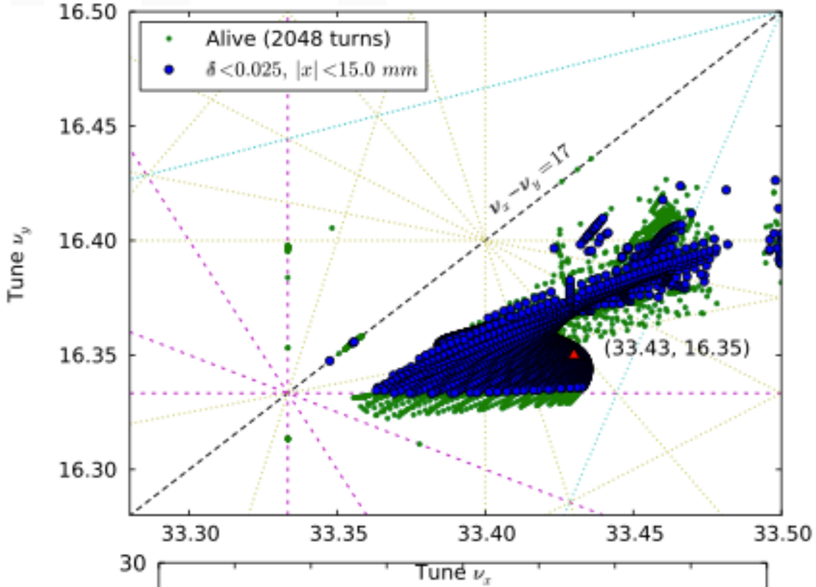
L Yang, PRSPAB 14 054001 (2011)

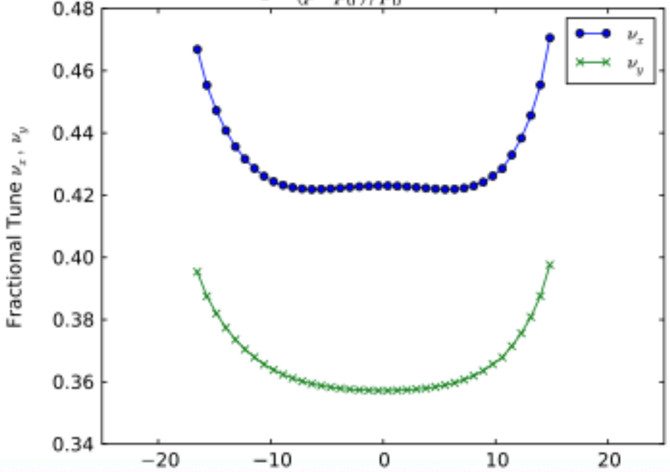
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 054001 (2011)

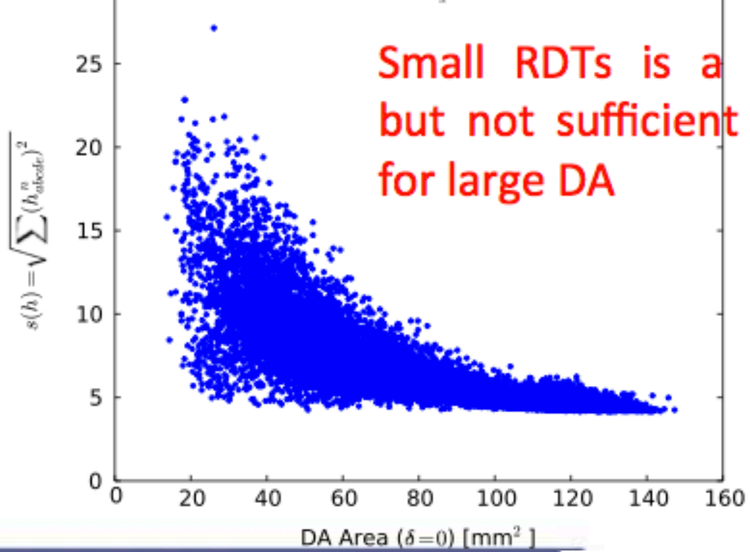
Multiobjective optimization of dynamic aperture

Lingyun Yang, Yongjun Li, Weiming Guo, and Samuel Krinsky
Photon Sciences Directorate, Brookhaven National Laboratory, Upton, New York 11973, USA





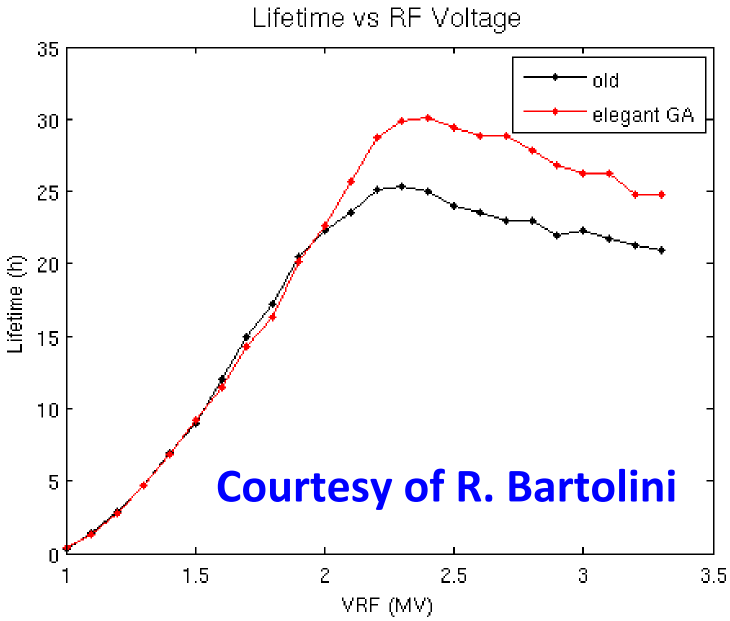




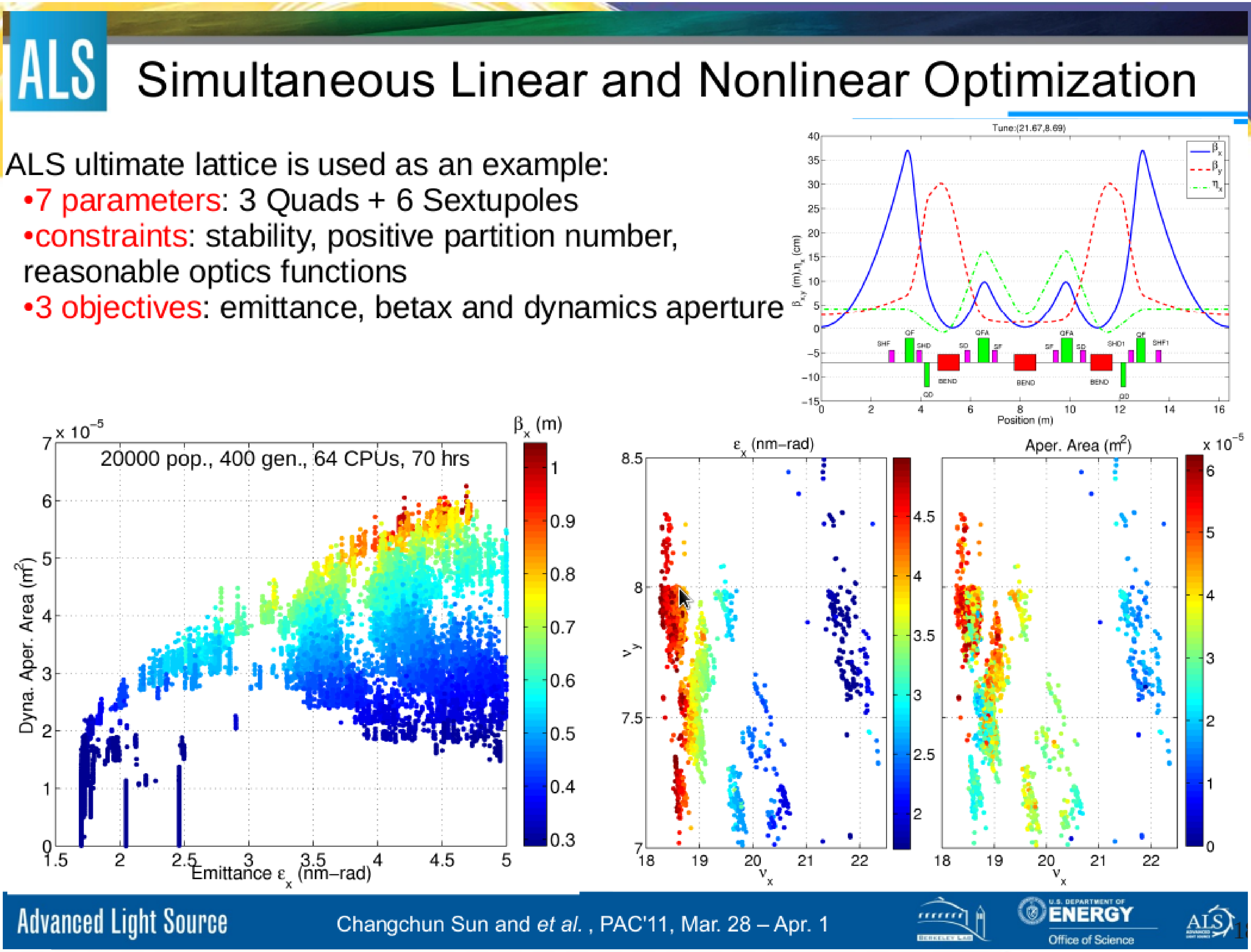
Small RDTs is a necessary but not sufficient condition for large DA

Amazing results verified by experiments

- Multi-objective optimization is effective, pretty robust to errors and very promising
- Experiment results at APS (M. Borland et al., PAC09)
  - Optimization of operation model
    - 24-bunch filling pattern (chro. 6): lifetime improved by 25%
    - Hybrid mode (chro. 11): lifetime improved by 10%
  - Breaking the symmetry of the sextupole: Lifetime 25% better APS slightly than operational lattice as predicted with the same injection efficiency (90-100%)
  - Application to Diamond Light Source: 25 % lifetime improvement.



Courtesy of R. Bartolini



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

20000 pop., 400 gen., 64 CPUs, 70 hrs

Advanced Light Source

Changchun Sun and *et al.* , PAC'11, Mar. 28 – Apr. 1

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:

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

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

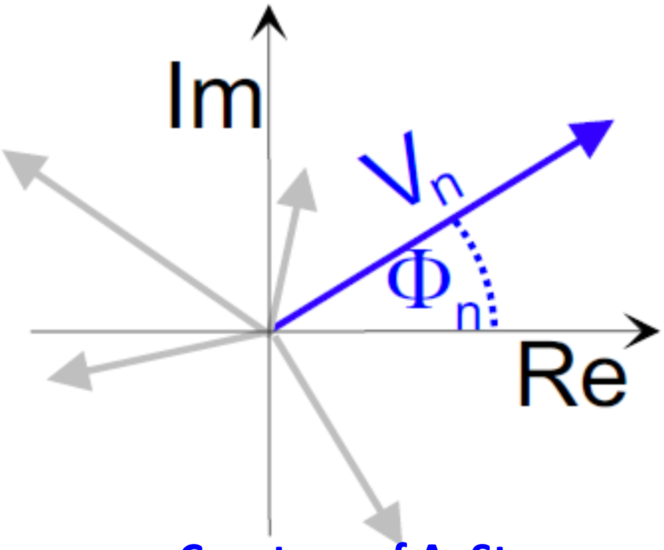
$$h = \sum_n^{N_{\text{sext}}} V_n e^{i\Phi_n}\ [\,+\ldots \text{quads for } p \neq 0 \ldots]$$

Sextupole$_n$ ↔ 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
- $\Phi_n \neq 0 \qquad \rightarrow$ resonances



Courtesy of A. Streun

b) ... 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, $N \rightarrow \infty \quad \Longrightarrow$

$$|h^{\infty}_{jklmp}| = \frac{|h_{jklmp}|}{2\sin\pi[a_xQ_x^{\text{cell}} + a_yQ_y^{\text{cell}}]}$$

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

$$h_{21000} = h^*_{12000} \longrightarrow \mathbf{Q_x}$$

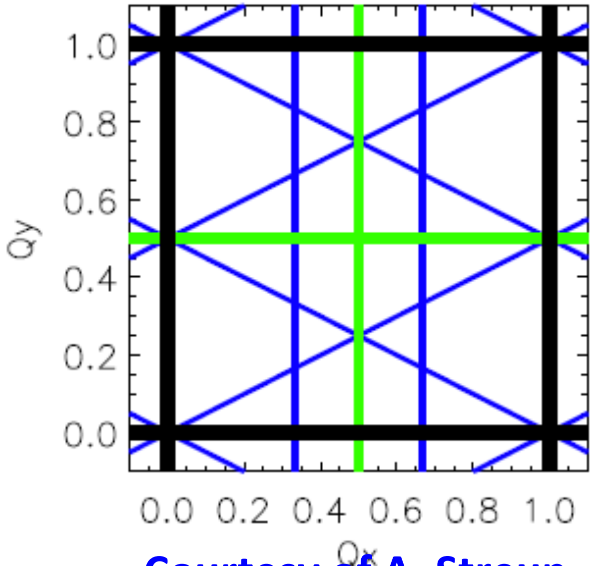
$$h_{30000} = h^*_{03000} \longrightarrow 3\,Q_x$$

$$h_{10110} = h^*_{01110} \longrightarrow \mathbf{Q_x}$$

$$h_{10200} = h^*_{01020} \longrightarrow Q_x + 2\,Q_y$$

$$h_{10020} = h^*_{01200} \longrightarrow Q_x - 2\,Q_y$$

$$\left.\begin{array}{l} h_{20001} = h^*_{02001} \longrightarrow 2\,Q_x \\ h_{00201} = h^*_{00021} \longrightarrow 2\,Q_y \end{array}\right\} \rightarrow d\beta/d\delta \;(\delta = \Delta E/E)$$



Courtesy of A. Streun

e) ... 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:**

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

- **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:

$h_{40000} \rightarrow 4Q_x$

$h_{00400} \rightarrow 4\,Q_y$

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

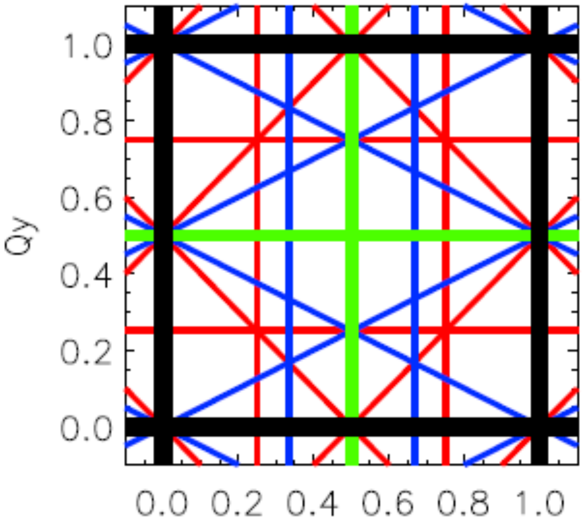
$h_{20020} \rightarrow 2Q_x - 2\,Q_y$

$h_{31000} \rightarrow 2\,Q_x$

$h_{20110} \rightarrow 2\,Q_x$

$h_{00310} \rightarrow 2\,Q_y$

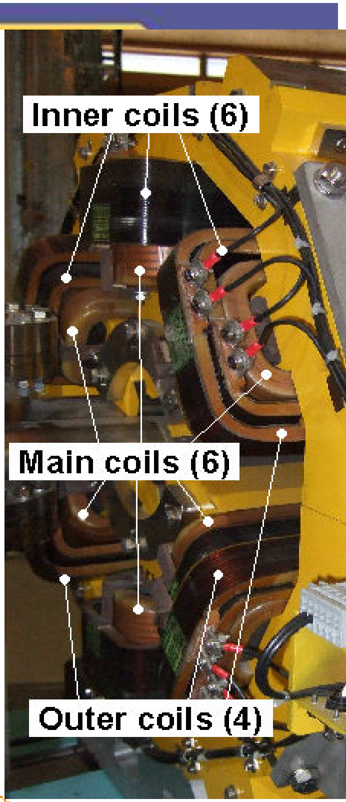
$h_{01110} \rightarrow 2\,Q_y$



Courtesy of A. Streun

Versatile Sextupoles

all 120 sextupoles were delivered with H&V corrector coils
⇨ make skew quadrupoles and auxiliary sextupoles



120 sextupoles in 9 families:

SF(24), SD(24), SE(24) → **chromaticities**

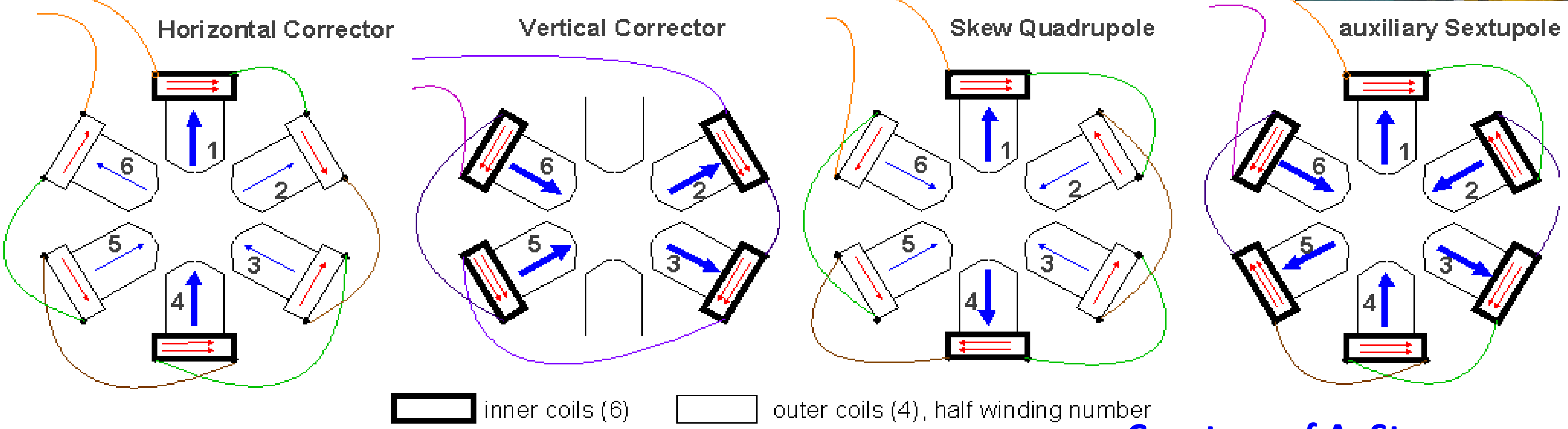
SSA(12), SSB(12), SMA(6), SMB(6), SLA(6), SLB(6) → **D.A.**

SD, SE, S∗B: **72** H&V correctors → **orbit correction**

S∗A: **24** skew quads ($\eta=0$) → **betatron coupling**

SF: **12** skew quads ($\eta>0$) → **vertical dispersion**

12 auxiliary sextupoles → **resonance suppression**



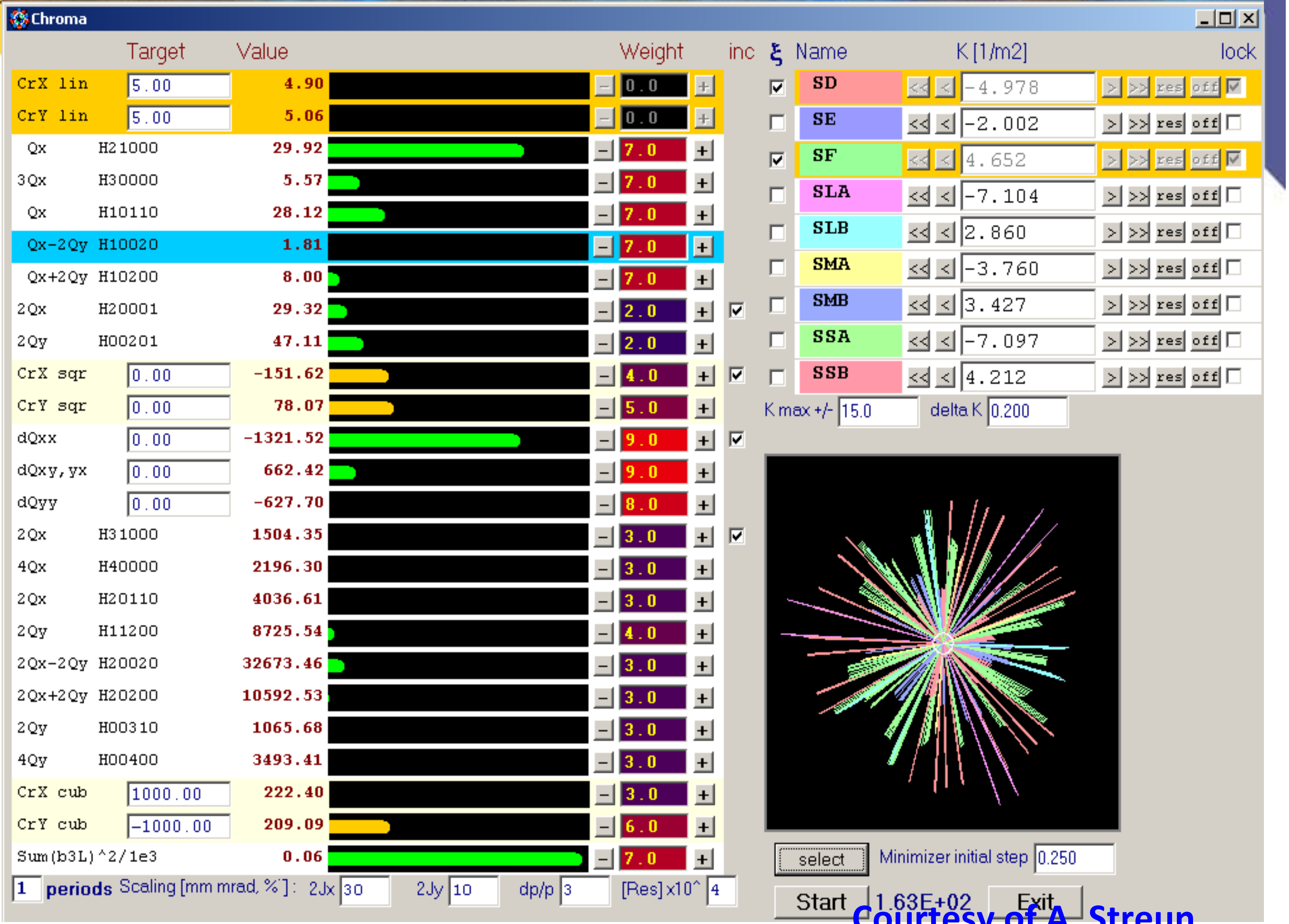
Courtesy of A. Streun

f) Tool for sextupole optimization (OPA)

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

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

$S(b_3 l)^2$ included in minimization



Chroma

	Target	Value	Weight	inc
CrX lin	5.00	4.90	0.0	
CrY lin	5.00	5.06	0.0	
Qx H21000		29.92	7.0	
3Qx H30000		5.57	7.0	
Qx H10110		28.12	7.0	
Qx-2Qy H10020		1.81	7.0	
Qx+2Qy H10200		8.00	7.0	
2Qx H20001		29.32	2.0	☑
2Qy H00201		47.11	2.0	
CrX sqr	0.00	-151.62	4.0	☑
CrY sqr	0.00	78.07	5.0	
dQxx	0.00	-1321.52	9.0	☑
dQxy,yx	0.00	662.42	9.0	
dQyy	0.00	-627.70	8.0	
2Qx H31000		1504.35	3.0	☑
4Qx H40000		2196.30	3.0	
2Qx H20110		4036.61	3.0	
2Qy H11200		8725.54	4.0	
2Qx-2Qy H20020		32673.46	3.0	
2Qx+2Qy H20200		10592.53	3.0	
2Qy H00310		1065.68	3.0	
4Qy H00400		3493.41	3.0	
CrX cub	1000.00	222.40	3.0	
CrY cub	-1000.00	209.09	6.0	
Sum(b3L)^2/1e3		0.06	7.0	

1 **periods** Scaling [mm mrad, %]: 2Jx 30 2Jy 10 dp/p 3 [Res]x10^ 4

ξ	Name	K [1/m2]	lock
☑	SD	-4.978	☑
☐	SE	-2.002	☐
☑	SF	4.652	☑
☐	SLA	-7.104	☐
☐	SLB	2.860	☐
☐	SMA	-3.760	☐
☐	SMB	3.427	☐
☐	SSA	-7.097	☐
☐	SSB	4.212	☐

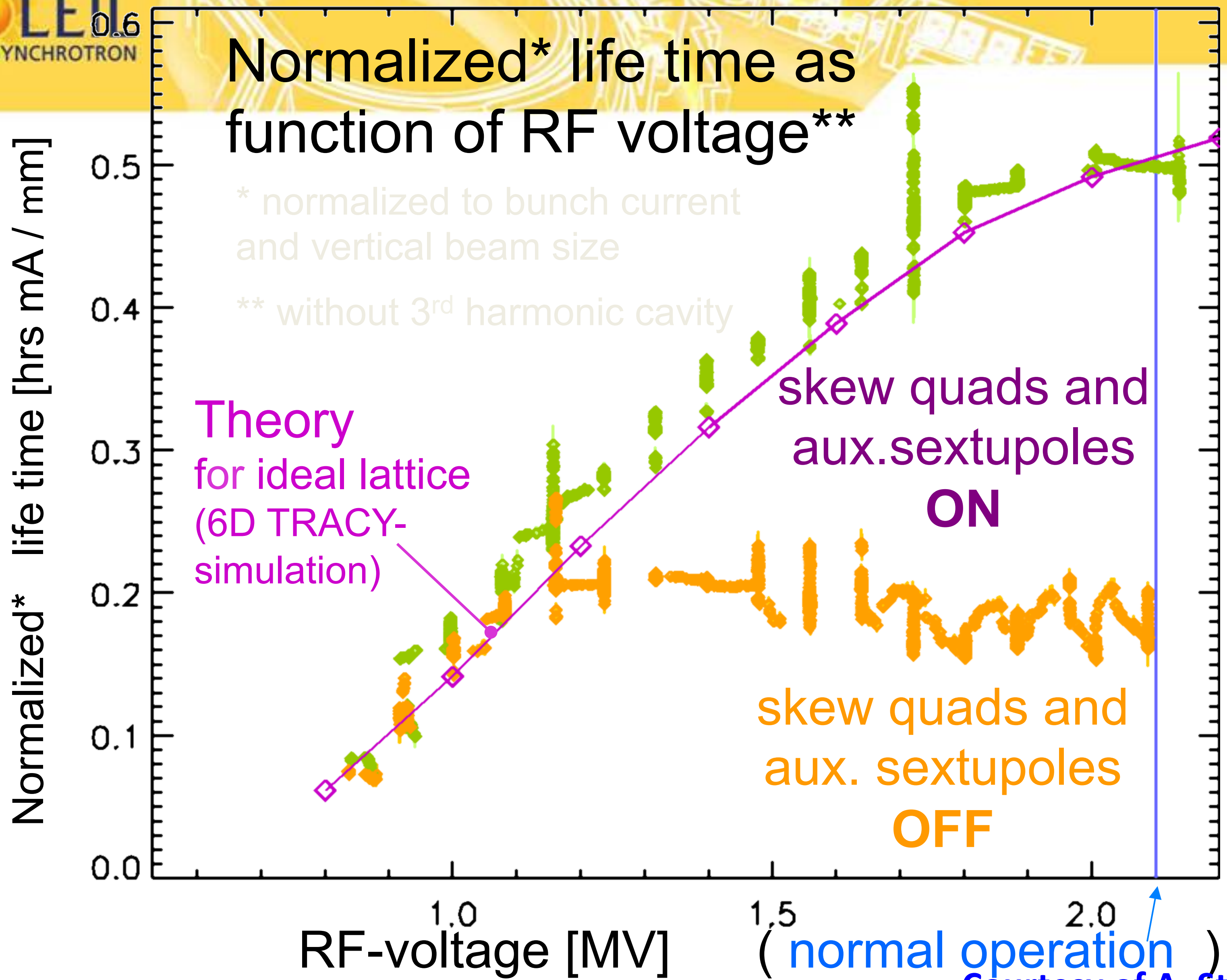
K max +/- 15.0 delta K 0.200

Minimizer initial step 0.250

1.63E+02

Courtesy of A. Streun

Lifetime in agreement with design



Normalized* life time as function of RF voltage**

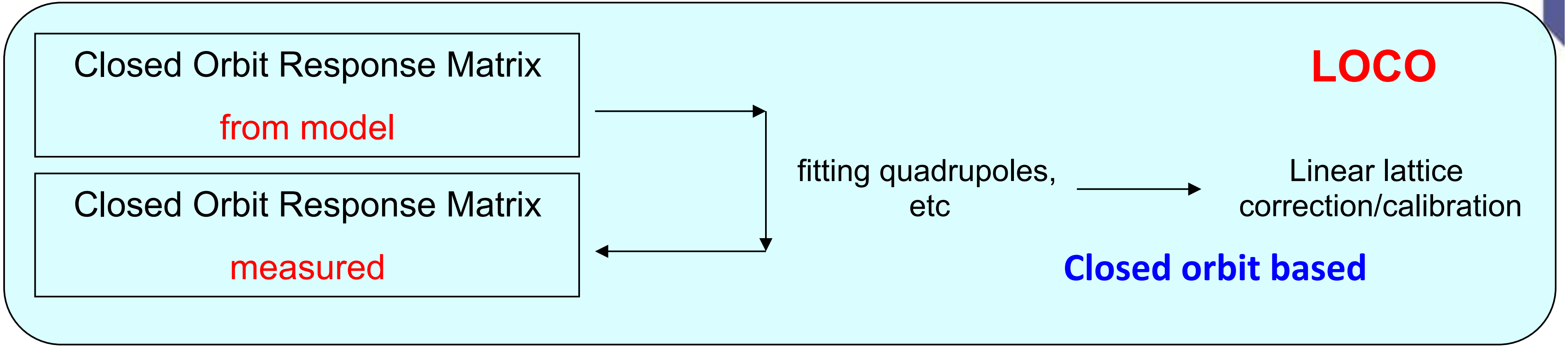
* normalized to bunch current and vertical beam size

** without 3rd harmonic cavity

Courtesy of A. Streun

Comparison real lattice to model
linear and nonlinear optics

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



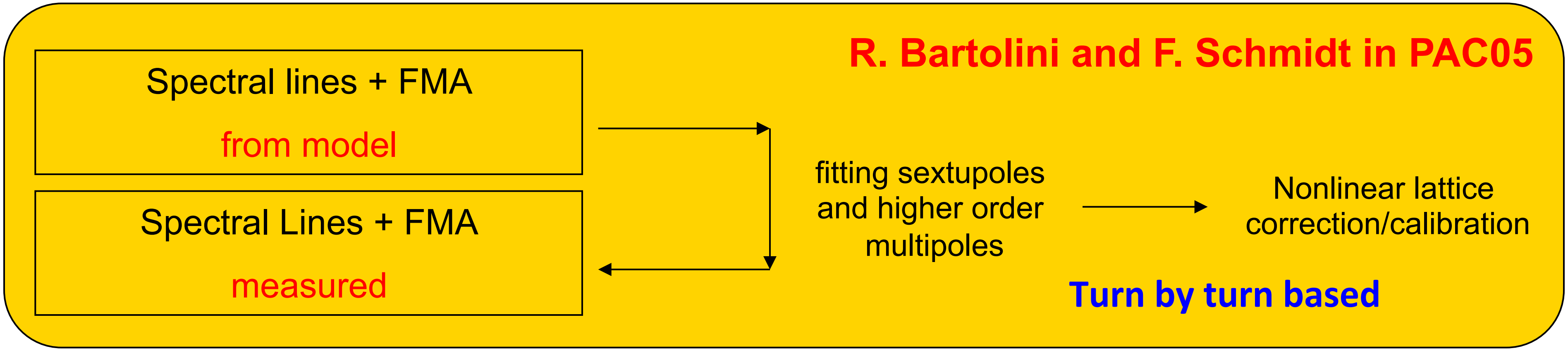
LOCO

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

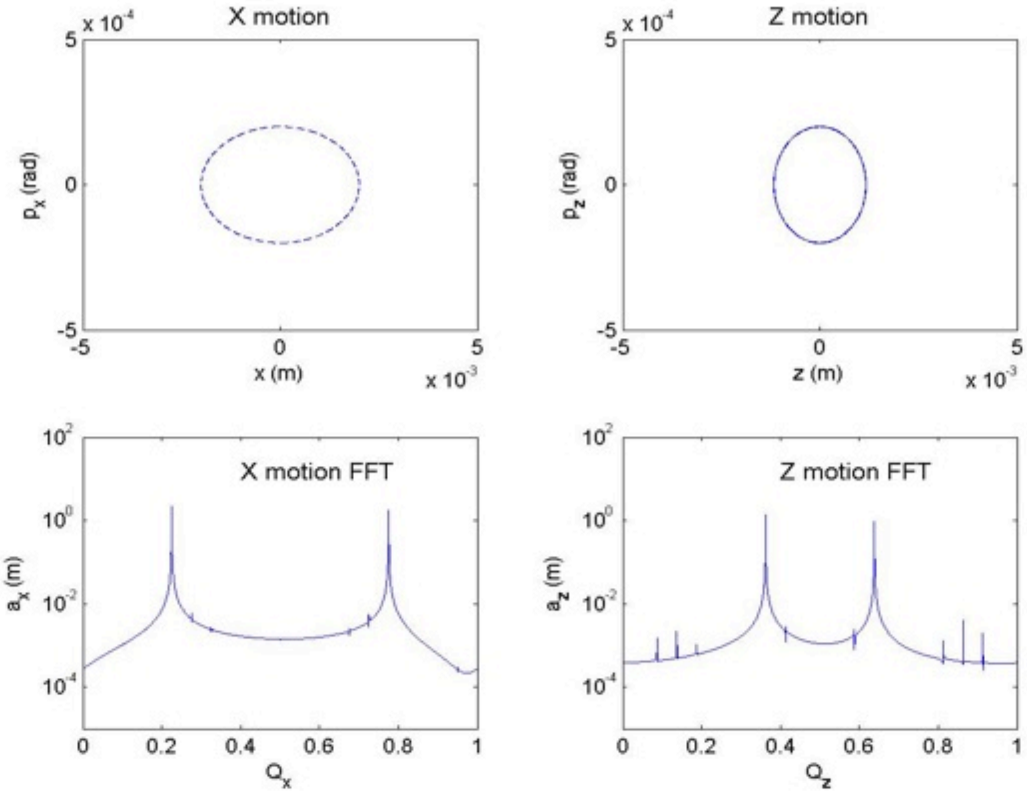
Turn by turn based

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

Courtesy of R. Bartolini

Frequency Analysis of betatron motion

Example: Spectral Lines for tracking data for the Diamond lattice



Spectral Lines detected with SUSSIX (NAFF algorithm)

e.g. in the horizontal plane:

• (1, 0)	$1.10\ 10^{-3}$	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

Frequency Analysis of Betatron Motion and Lattice Model Reconstruction

Using the measured amplitudes and phases of the spectral lines of the betatron motion we can build a fit procedure to calibrate the nonlinear model of the ring

Accelerator Model ↓

- tracking data at all BPMs
- spectral lines from model (NAFF)

Accelerator ↓

- beam data at all BPMs
- spectral lines from BPMs signals (NAFF)

e.g. targeting more than one line

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

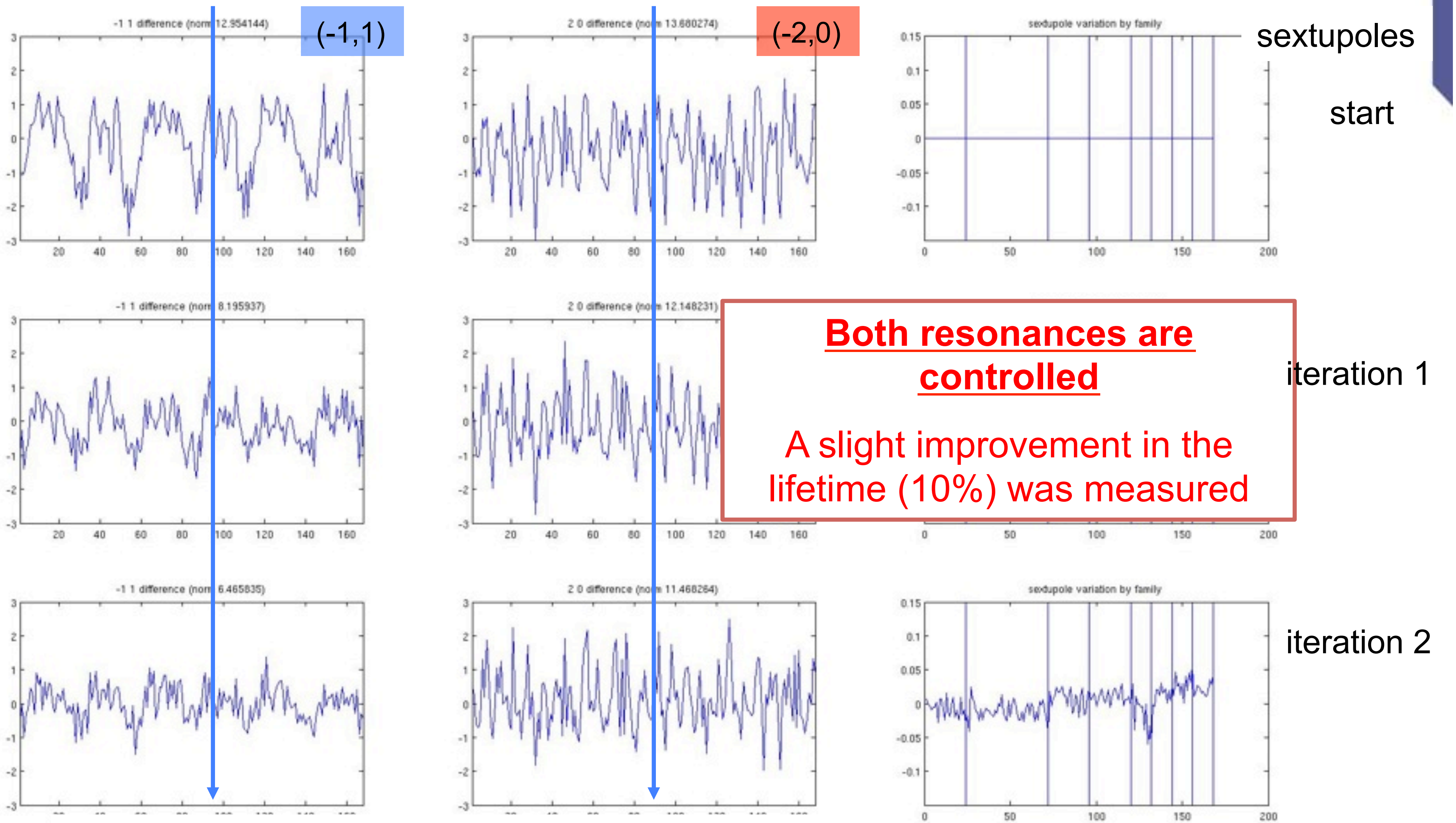
Define the distance between the two vector of Fourier coefficients

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

Least Square Fit of the sextupole gradients to minimize the distance χ2 of the two Fourier coefficients vectors

Courtesy of R. Bartolini

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



Both resonances are controlled

A slight improvement in the lifetime (10%) was measured

Both resonance driving terms are decreasing

Courtesy of R. Bartolini

Conclusion (1)

- Tracking codes trustable, long term tracking, parallelized
- Agreement between model and experience: tune shift with amplitude, DA, non-linear chromaticities are good providing a good linear and non-linear model
- Model efficiently used for predicting performance, impact of IDs using turn by turn data
- FMA like techniques give a global view of dynamics
  - Shift from 1D to 2D view
- Promising use RDTs based on TbT data (coupling correction[1], Non-linear LOCO like): will benefit from higher resolution TbT data
- MOGA enables us to optimize on/off dynamics aperture, use DAs, FMAs, RDTs in merit functions.
  - Shift from sequential to simultaneous

[1] talk by A. Franchi this afternoon

Conclusions (2)

- **3 GLSs run top-up operation mode**
  - MTFB >7 days
  - High injection efficiency (low beam loss rate, green technology, accelerators …)
- **Preserving high performances**
  - Need to monitor linear and non-linear dynamics (Twiss functions, RDTs, Tunes, Chromaticities, ..)
  - Soon ~100 pm RMS beam stability
  - Strong need for beam-based measurement
    - Beam based alignment, girder based alignment
    - Multi-pole beam based correction + Feedback syst.
    - Beam-based coupling correction + feedback syst.
    - …

Development of on-line continuous tools to measure beta-beats, chromaticity evolutions, local coupling, performance degradation but without perturbing the user experiments

Perspectives

- **Pushing high performance diagnostics**
  - TbT BPM performance, imaging, emittance measurement, …
- **Pushing ID optimization**
- **Wanted features**
  - To what extent can beam-based measurement replace magnetic measurements ?
    - RDT measurement A. Franchi, R. Thomas, F. Schmidt, PRSTAB 10, 074001 (2007)
  - SOLEIL: strong limitation for probing off-momentum dynamics (δ-x maps). Large RF frequency shifts make aging the cold tuning system of the superconductive cavities
    - A **special cavity for kicking** the beam energy over one turn would be very valuable

Conclusions and Perspectives

Over the years

New Techniques have come out

New tools have emerged

Mass computing has become affordable

New way of optimization

Open new horizon windows

Push limits of Accelerators

Makes us confident for the design and operation of ever brighter light sources, diffracted limited in H&V planes

Acknowledgments

- M. Borland and L. Emery (APS, USA)
- P. Kuske (HZB/Bessy II, Germany)
- X. Huang , Y. Cai, J. Safranek (SLAC, USA)
- C. Steier, D. Robin (ALS, USA)
- L. Yang (BNL, USA)
- K. Sotome (SPring8, Japan)
- S. C. Leemann, MAX-lab, Sweden
- A. Streun (PSI, Switzerland)
- R. Bartolini (Diamond/John Adams Institute, UK)
- A. Franchi (ESRF, France)
- R. Thomas, Y. Papaphillipou (CERN, Switzerland)
- A. Kling (Petra III, Germany)
- M. S. Chiu (TPS, Taiwan)
- SOLEIL Accelerator Physics Group

Mapped IDs *à la* ESRF

- Nonlinear maps of IDs are generated using the 3D RADIA code.
- To be read in a tracking code.
- BETA-ESRF does not take into account chromatic terms due to the edges of bending magnet.
- BETA-SOLEIL and TRACYII have been modified in order to read the IDs maps.
- Very good agreement between the two codes for ON and OFF momentum dynamic apertures.

- **The angular kicks experienced by the particle are derived from the function:**

$$\phi(x,z,s) = \left(\int_{-\infty}^{s} B_x \, ds'\right)^2 + \left(\int_{-\infty}^{s} B_z \, ds'\right)^2$$

- **f is integrated over 1 period resulting in a potential function U:**

$$U(x,z) = \int_{1\,period} \phi(x,z,s)\, ds$$

- **The angular kick experienced by a particle over the undulator period is:**

$$\boxed{\begin{aligned} \Delta x' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial x}(x,z) \\ \Delta z' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial z}(x,z) \end{aligned}}$$

P. Elleaume, EPAC'92

ID building strategy

- **Tolerances**

$$\int B_x ds = \int B_z ds = \pm 20\, G.cm \qquad \iint B_x ds ds' = \iint B_z ds ds' = \pm 1\, G.m^2$$

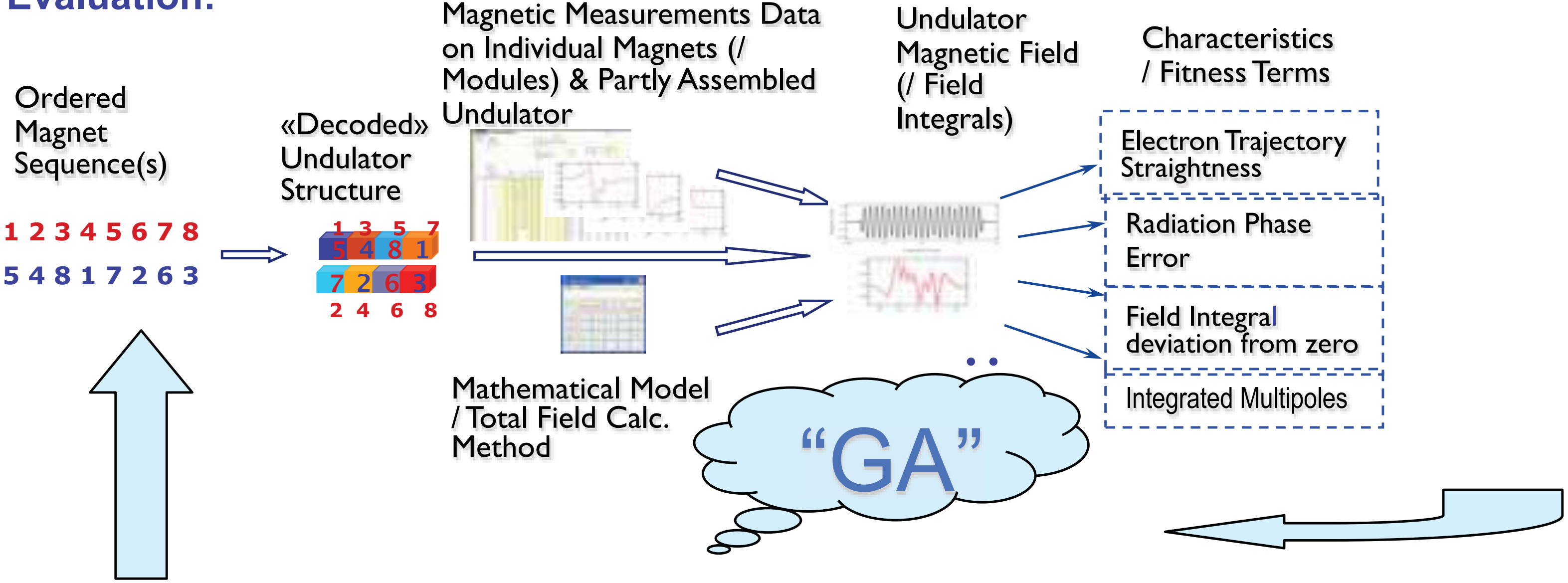
- **A 3 step-process using ID builder (O. Chubar)**
  1. **Assembly: Module sorting according to magnetic measurements**
     - → Minimization of first and second integrals
  2. **Shimming: using a merit function**
     - → Minimization at different gap and phase values with weight factor
       - i. On axis first & second integral (angle & position) in H & V plane
       - ii. Skew and normal gradient for new IDs
       - iii. Phase error < 0.2°
  3. **Magic fingers (different gap and phase values with weight factor)**
     - → Reduction of high field integral for large transverse amplitudes

- **Expected or unexpected effects depending on gap, phase, current values**
  - Orbit distortion (Feedforward)
  - Tune, chromaticity, coupling variations
  - Injection efficiency, lifetime variation (non-linearities, …)

IDbuilder

O.Rudenko and O.Chubar, Proc. of 9th Int. Conf. on PPSN IX, p.362 (2006)

Evaluation:



Variation Operators for Permutations:

Mutation : - e.g. swap items (magnets) at two randomly chosen positions - [5 4 8 1 7 2 6 3] ⟹

Crossover : - e.g. «order 1» - [1 2 3 4 5 6 7 8] [3 5 6 8 1 2 7 4] ⟹ [? ? ? 4 5 6 7 ?] ⟹

Advantages : object function, arbitrary search space, search from ap population, mutation and

Multi-Objective Genetic Algo.

```
Initialize population.
repeat
    crossover: $2 \rightarrow 2$
    mutation: change children.
    calculate obj. func. $f_m$
    natural selection: "sorting"
until should stop
```

① **Initialize**: the very first generation (random).
② **Crossover**: generate children from parents.
③ **Mutation**: change the children slightly.
④ **Natural selection**: keep population fixed from generation to generation.

Courtesy of L Yang

Mapped IDs *à la* ESRF

- Nonlinear maps of IDs are generated using the 3D RADIA code.
- To be read in a tracking code.
- BETA-ESRF does not take into account chromatic terms due to the edges of bending magnet.
- BETA-SOLEIL and TRACYII have been modified in order to read the IDs maps.
- Very good agreement between the two codes for ON and OFF momentum dynamic apertures.

- **The angular kicks experienced by the particle are derived from the function:**

$$\phi(x,z,s) = \left(\int_{-\infty}^{s} B_x\, ds'\right)^2 + \left(\int_{-\infty}^{s} B_z\, ds'\right)^2$$

- **fis integrated over 1 period resulting in a potential function U:**

$$U(x,z) = \int_{1\,period} \phi(x,z,s)\, ds$$

- **The angular kick experienced by a particle over the undulator period is:**

$$\boxed{\begin{aligned} \Delta x' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial x}(x,z) \\ \Delta z' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial z}(x,z) \end{aligned}}$$

P. Elleaume, EPAC'92

ID building strategy

- **Tolerances**

$$\int B_x ds = \int B_z ds = \pm 20\, G.cm \qquad \iint B_x dsds' = \iint B_z dsds' = \pm 1\, G.m^2$$

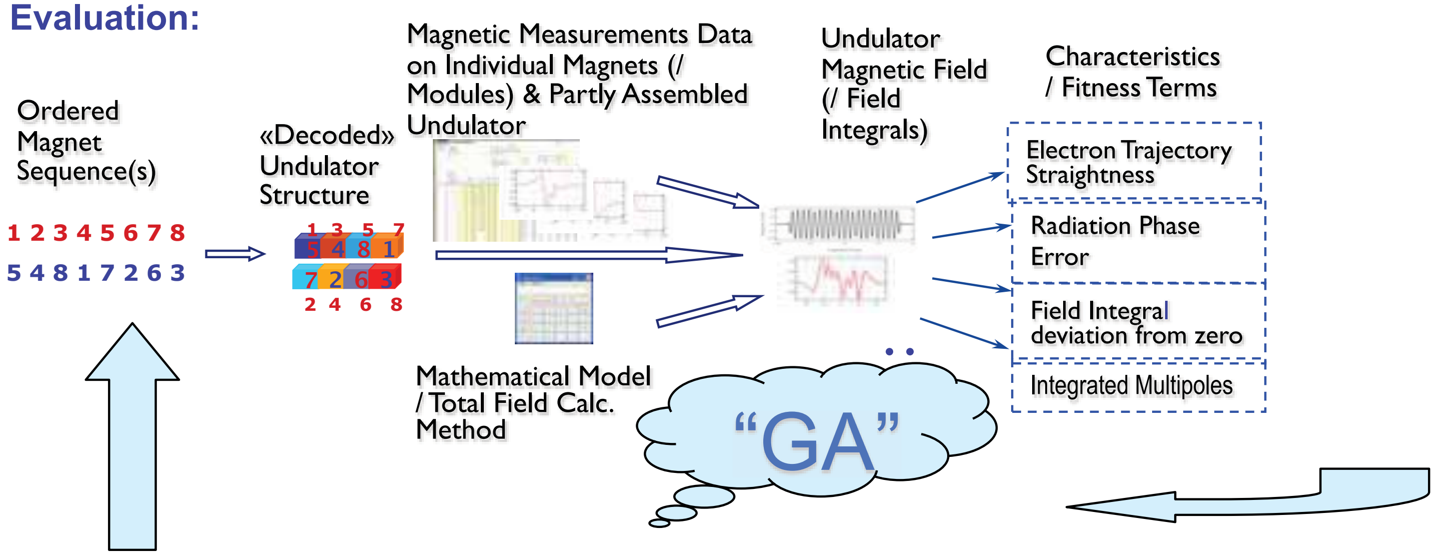
- **A 3 step-process using ID builder (O. Chubar)**
  1. **Assembly: Module sorting according to magnetic measurements**
     - → **Minimization of first and second integrals**
  2. **Shimming: using a merit function**
     - → **Minimization at different gap and phase values with weight factor**
       - i. **On axis first & second integral (angle & position) in H & V plane**
       - ii. **Skew and normal gradient for new IDs**
       - iii. **Phase error < 0.2°**
  3. **Magic fingers (different gap and phase values with weight factor)**
     - → **Reduction of high field integral for large transverse amplitudes**

- **Expected or unexpected effects depending on gap, phase, current values**
  - **Orbit distortion (Feedforward)**
  - **Tune, chromaticity, coupling variations**
  - **Injection efficiency, lifetime variation (non-linearities, …)**

ID builder

O.Rudenko and O.Chubar, Proc. of 9th Int. Conf. on PPSN IX, p.362 (2006)

Evaluation:



Variation Operators for Permutations:

Mutation : - e.g. swap items (magnets) at two randomly chosen positions - [5 4 8 1 7 2 6 3] ⟹

Crossover : - e.g. «order 1» -

[1 2 3 4 5 6 7 8]
[3 5 6 8 1 2 7 4] ⟹ [? ? ? 4 5 6 7 ?] ⟹

Advantages : object function, arbitrary search space, search from ap population, mutation and