PAUL SCHERRER INSTITUT PSI

SWISS LIGHT SOURCE SLS

Nonlinear dynamics at the SLS storage ring

Andreas Streun, Paul Scherrer Institut, Villigen, Switzerland

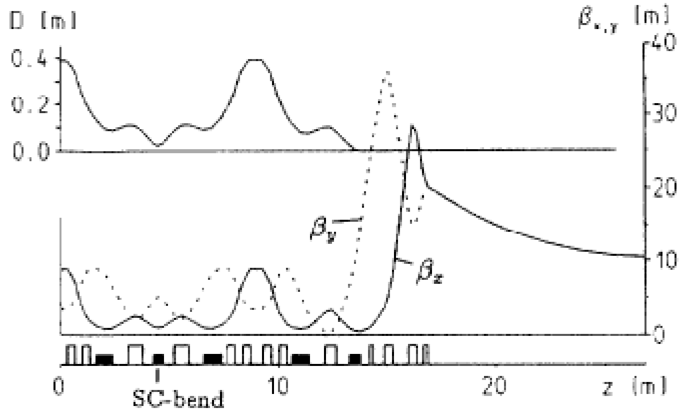
- History of SLS design: 7BA vs. TBA
- The method of sextupole optimization
- SLS performance: auxiliary sextupoles*
- The next generation: MAX-IV

* more at NBD-2 WS, DIAMOND, Nov.2-4, 2009
http://www.diamond.ac.uk/Home/Events/Past_events/NBD_workshop.html

coupling issues: → M. Böge, *Reaching ultra-low vertical emittance in the SLS*

SLS History 1

1991

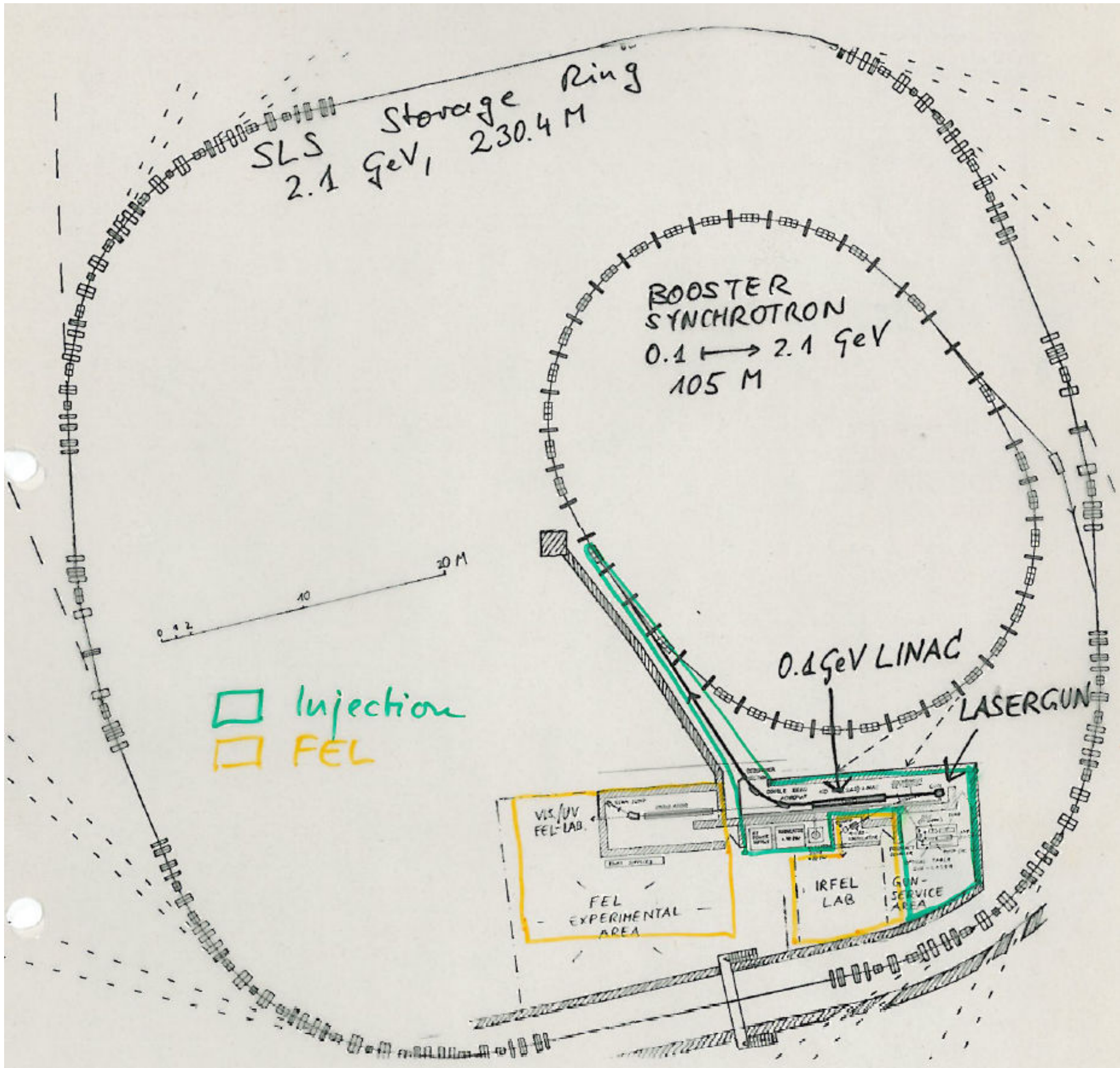


4 × “swiss arc”
(s.c.bend)

2 × DBA
>20m straights

230.4 m
1.5 / 2.1 GeV
3.6 / 7.0 nm

R.Abela et al.,
EPAC 1992, p.486



SLS History 2

1993 (CDR)

6 × **7BA** arc

6 straights:

4 × 6 m

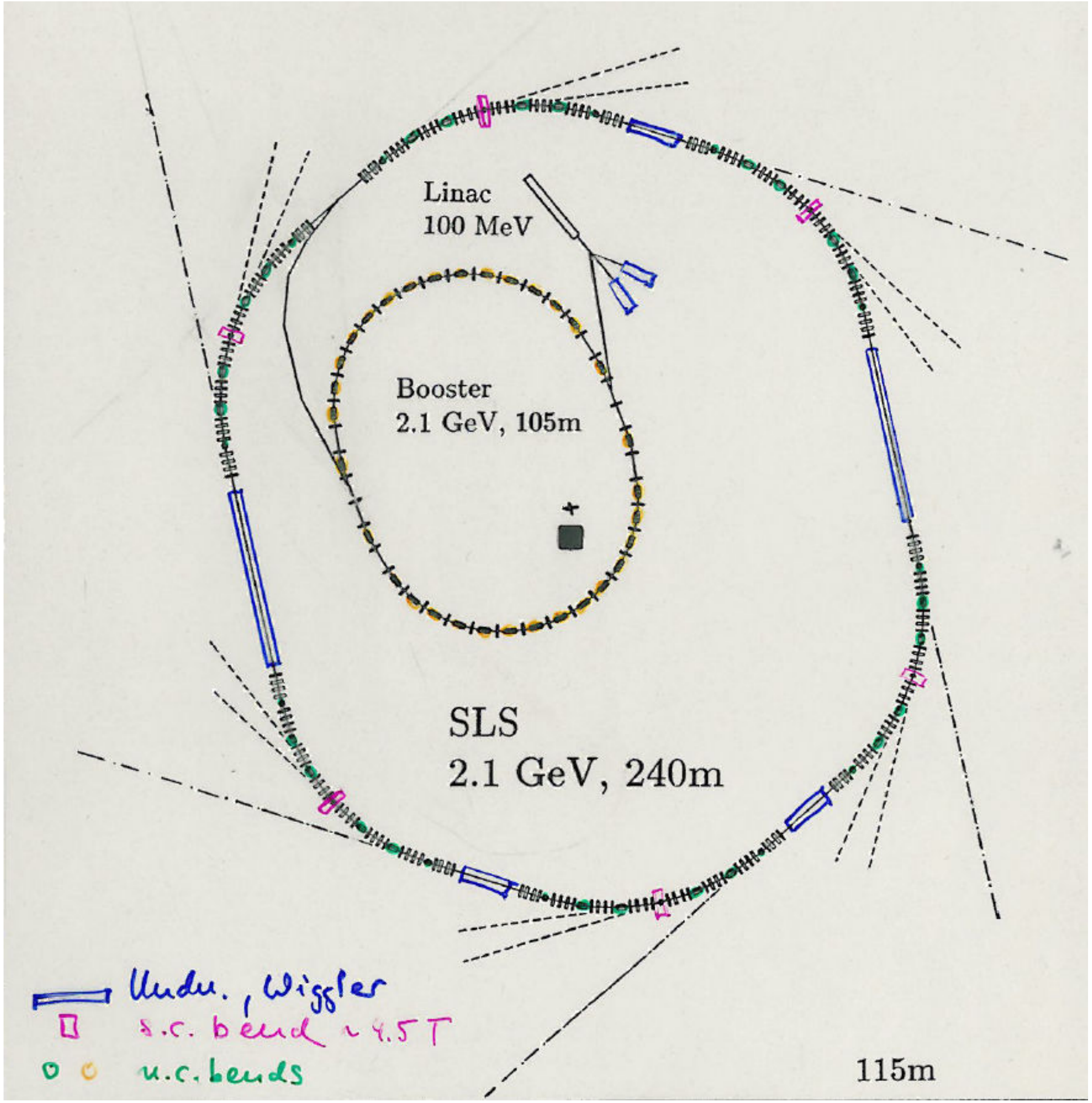
2 × 20 m

240 m

2.1 GeV

3.2 nm

W. Joho et al.,
EPAC 1994, p.627



SLS History 3

1995

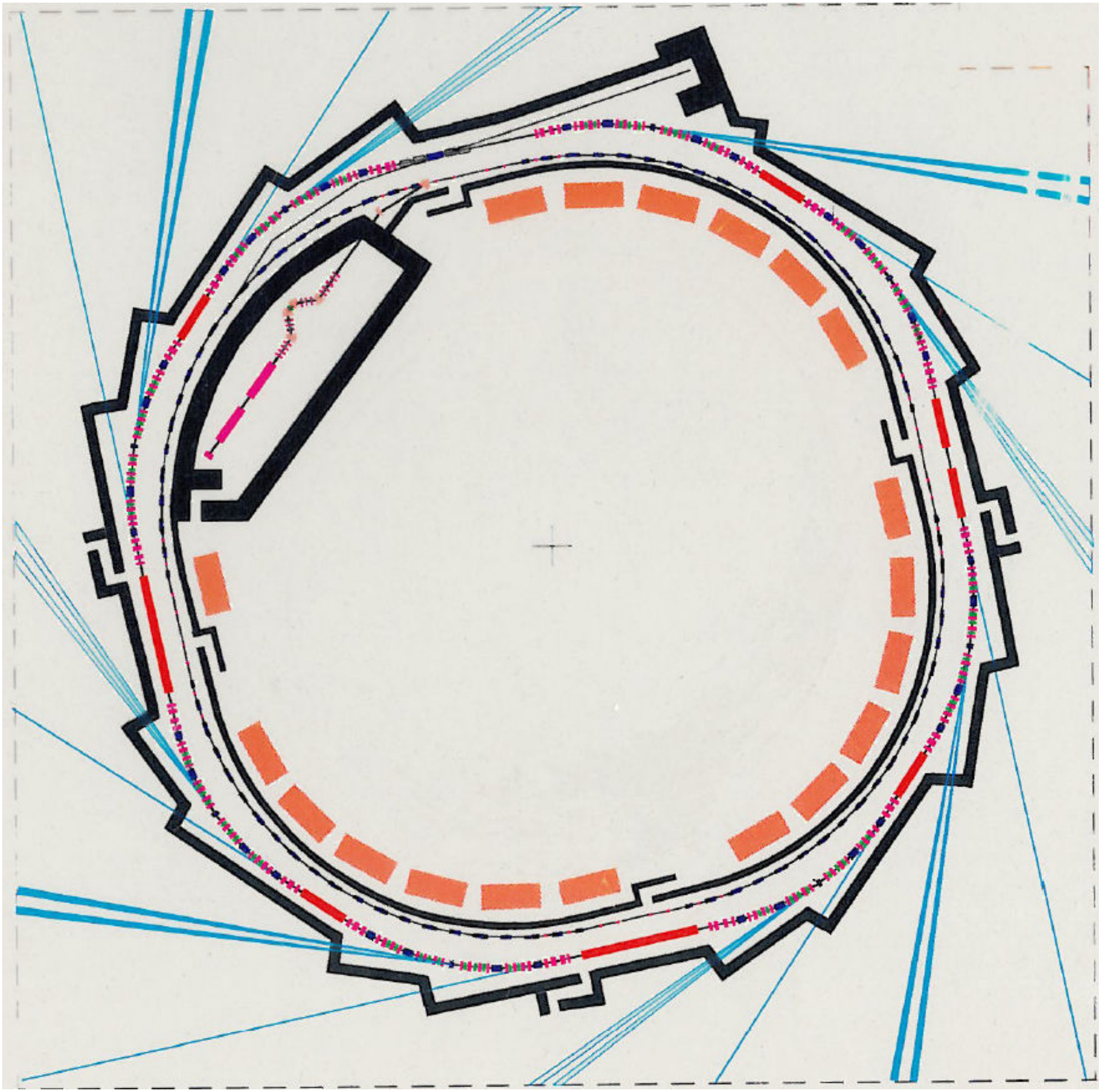
(PSI-TRIUMF collab.)

8 × **5BA** arcs

8 straights:
4 × 6m
4 × 20m

270 m
2.1 GeV
~ 2 nm

D. Kaltchev et al.,
PAC 1995, p.2823



SLS History 4

1996 → 1997 → 2000✓

(approval 1997, operation 2000)

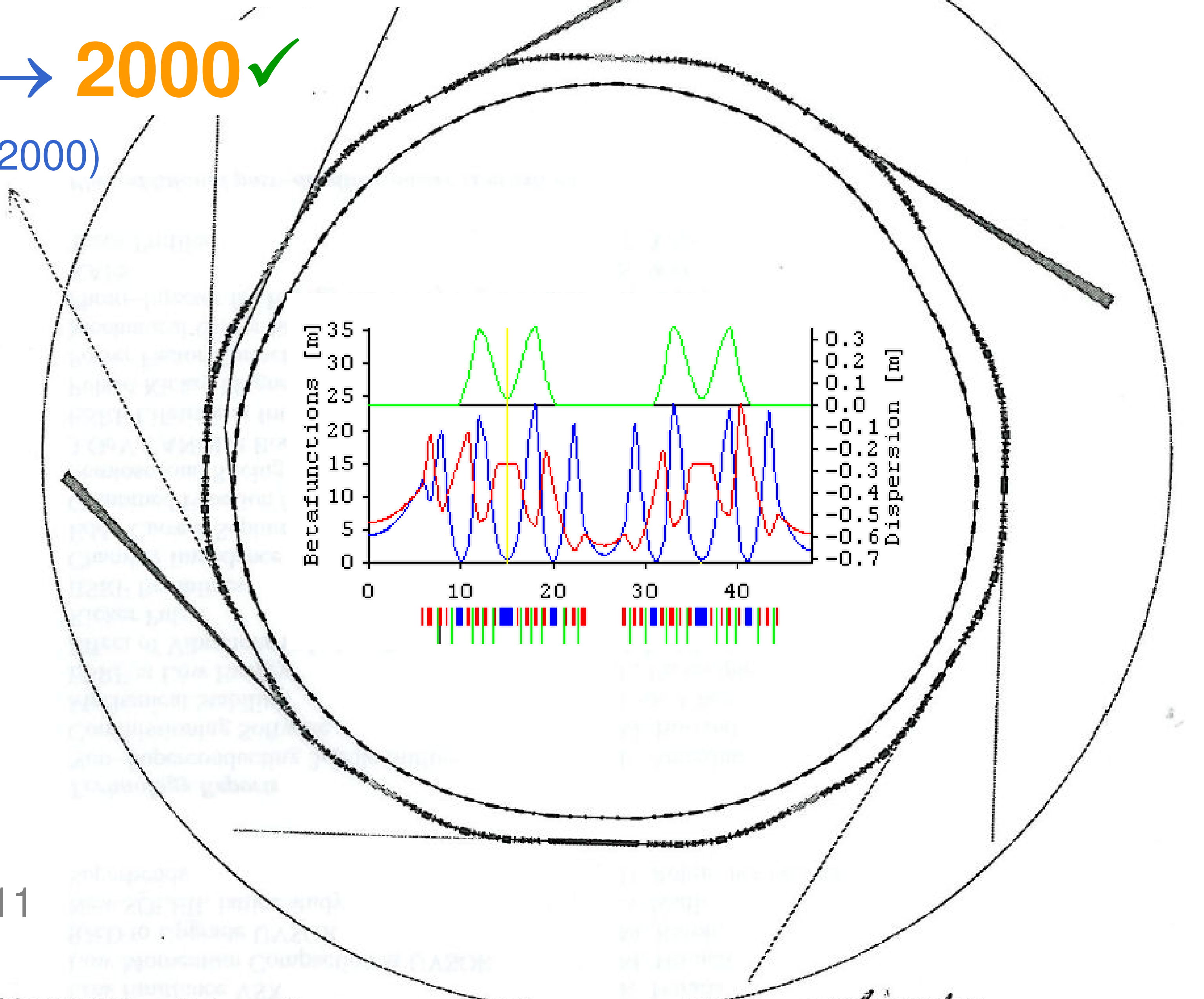
12 × **TBA** arc

12 straights
6 × 4 m
3 × 7 m
3 × 11.5 m

281 → 288 m
2.1 → 2.4 GeV
2.9 → 4.8 nm

A. Streun,
SLS-TME-TA-1996-0011

M. Böge et al.
EPAC 1998, p.623



SLS TBA lattice with booster[5] in a circular hall of 126 m circumference. Injector linac and transfer lines are not shown. Storage ring circumference is 280.8 m ...

... beyond SLS: MAX-IV

2003 → 2009

12 → 20 × **7BA** arc

12 → 20 straights

12 × 4.6 m → 20 × 5 m

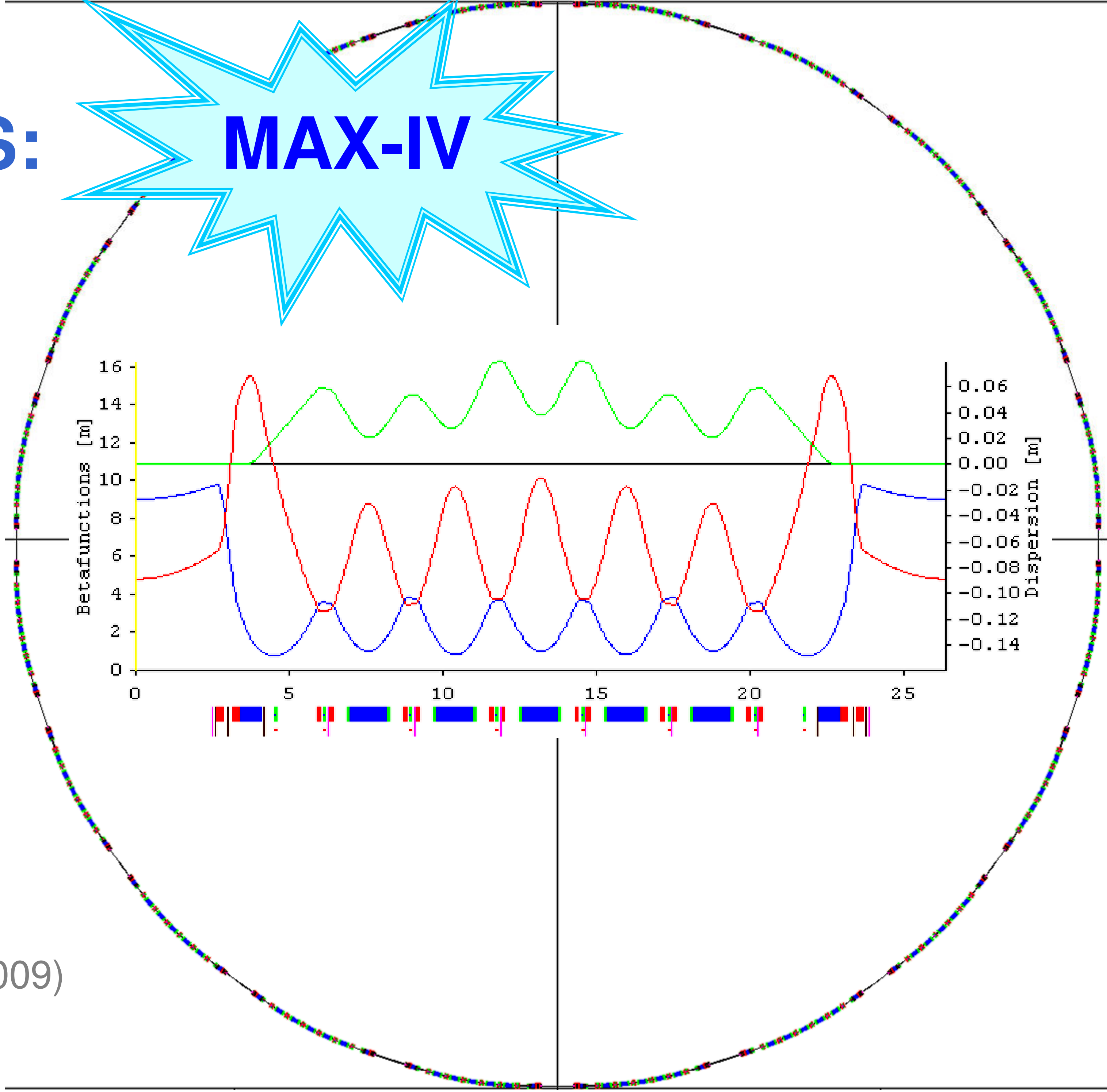
285 → 528 m

3.0 GeV

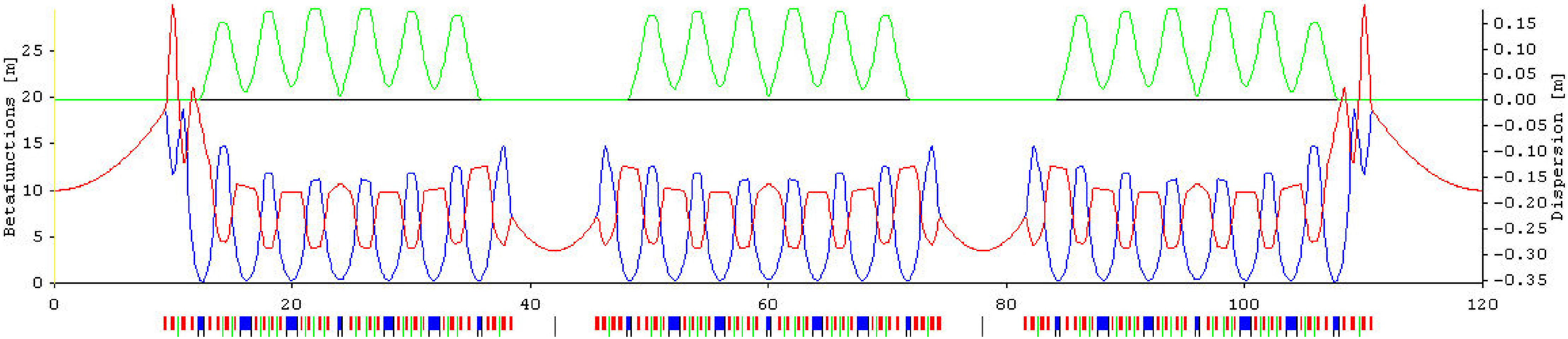
1.2 → 0.33 nm

H. Tarawneh et al.
NIM A 508 (2003) 480

S. C. Leemann et al.
PRST AB 12, 120701 (2009)



The 1993 (CDR) 7BA SLS lattice, *rejected*



- 6 × 7BA arcs with centre s.c. bends
- $Q = 20.2 / 5.4$ $Q_{cell} \sim 0.44 / 0.09$ $\xi = -55 / -18$
- $E = 2.1$ GeV $C = 240$ m $\varepsilon = 3.2$ nm

✗ Too few user straights: 2 × 20 + 4 [2] × 6 m

✗ Problems with energy acceptance

↳ *tool developments...*

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:

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

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

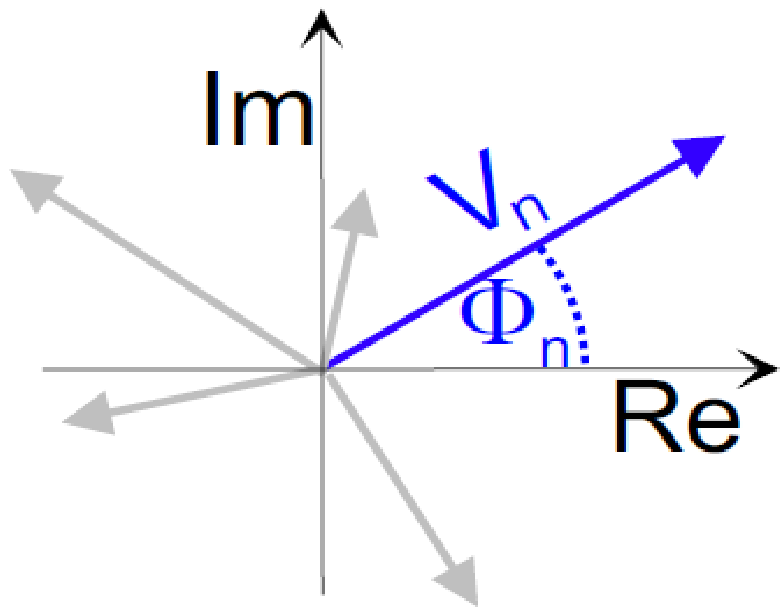
$$h = \sum_n^{N_\text{sext}} V_n e^{i\Phi_n} \; [\, + \ldots \text{quads for } p \neq 0 \ldots]$$

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



First order sextupole [+quadrupole] Hamiltonian

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

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

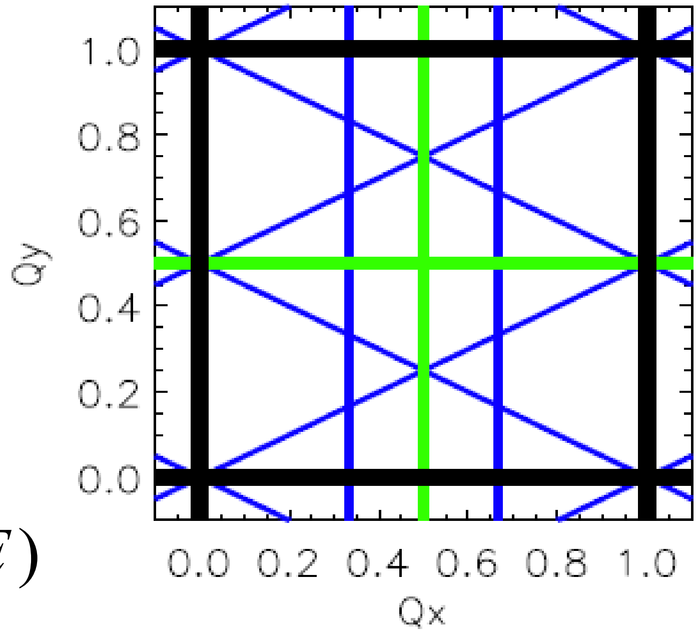
$$h_{00111} = -J_y\delta\,[\textstyle\sum_n^{N_{sext}}(2b_3\,L)_n\beta_{yn}D_n - \sum_n^{N_{quad}}(b_2\,L)_n\beta_{yn}\,] \quad\rightarrow\quad \xi_y$$

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

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

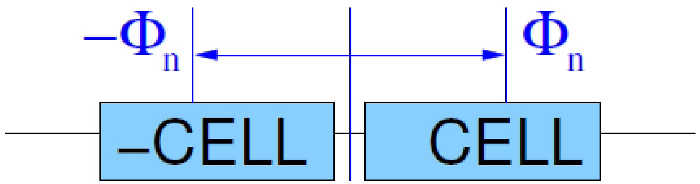
$a_x = (j-k) \quad a_y = (l-m)$

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



c) a particular problem of multi-bend achromat (MBA) *lattices*

Systematic first order optimization:



9 terms h_{jklmp} (7 complex, 2 real) $\Longrightarrow$ Symmetry:

$\rightarrow$ **16** sextupole families $\quad Im(h_{jklmp}) = 0 \rightarrow$ **9** sextupole families.

Linear system for M families of sextupoles:

$$\left\{ \sum_{n\in\{Sm\}} \beta_n^{(\dots)} D_n^{(\dots)} e^{i\{(\dots)\phi_n\}} \dots \right\}_{9\times M} \times \left\{ (b_3L)_m \right\}_{M\times 1} = \left\{ \sum_{\mathrm{Quad}} (b_2L) \dots \right\}_{1\times 9}$$

Light source problem: $\epsilon \downarrow \Longrightarrow \Delta\phi_x^{\mathrm{cell}} \rightarrow 180^\circ \Longrightarrow e^{i2\phi_x} \approx 1$

SLS 6×7BA:
$\Phi_x^{\mathrm{cell}} = 159^{\mathrm{o}}$

$2Q_x$ resonance driving term h_{20001} proportional to chromaticity $\xi_x \propto h_{11001}$

$$2Q_x \rightarrow \frac{\partial \beta_x}{\partial \delta} \rightarrow \xi_x^{(2)} = \frac{\partial^2 Q_x}{\partial \delta^2} \rightarrow \text{energy acceptance} \downarrow$$

No solution for $\{(b_3L)_m\} \Longrightarrow$ suppression by $\Delta\phi_x^{\mathrm{straight}}$

J. Bengtsson et al., NIM A 404 (1998) 237 *d) to optimize the sextupole strengths is not enough....*

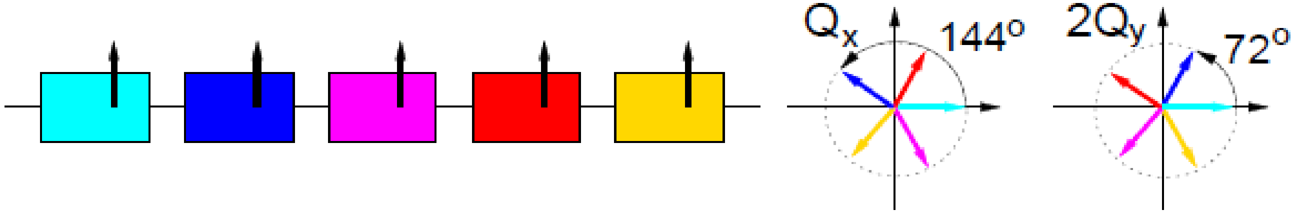
Phase cancellation schemes

Periodicity: N cells

$$N\Delta Q_x^{\rm cell}, \quad [3N\Delta Q_x^{\rm cell}, \quad 2N\Delta Q_x^{\rm cell}], \quad 2N\Delta Q_y^{\rm cell} \quad \longrightarrow \text{integer!}$$

e.g. $N = 5,\ \Delta Q_x^{\rm cell} = 0.4\,(=144^\circ),\ \Delta Q_y^{\rm cell} = 0.1\,(=36^\circ)$

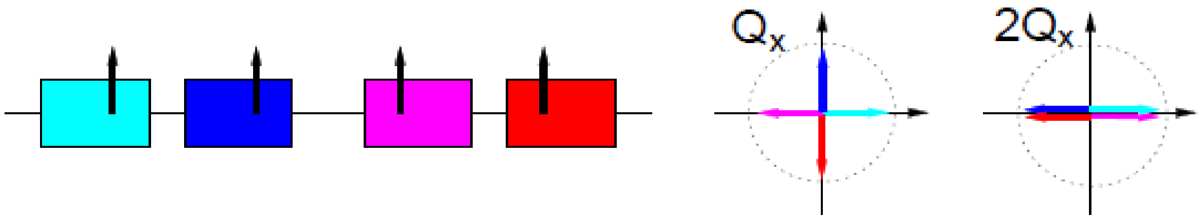
SLS 6 × 7BA (i.e. 5 cells)
(ε = 3.2 nm @ 2.1 GeV)
$\Rightarrow \Delta Q_x^{\rm cell} = 0.44$ ☹



Symmetry: Lattice section vs. mirror image

$$\Delta Q_x^{\rm cell} = \frac{2n_x+1}{4}, \quad \Delta Q_y^{\rm cell} = \frac{2n_y+1}{4} \quad (n_x, n_y \text{ integers}):$$

SLS 12 × TBA
(ε = 4.9 nm @ 2.4 GeV)
$\Delta Q_x^{\rm cell} \approx 7/4,\ \Delta Q_y^{\rm cell} \approx 3/4$ ☺



$\rightarrow$ phase advances over straight sections $\rightarrow \beta_x, \beta_y$ in straights.

$\Longrightarrow$ Iterate: linear $\Longleftrightarrow$ nonlinear lattice design

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:**

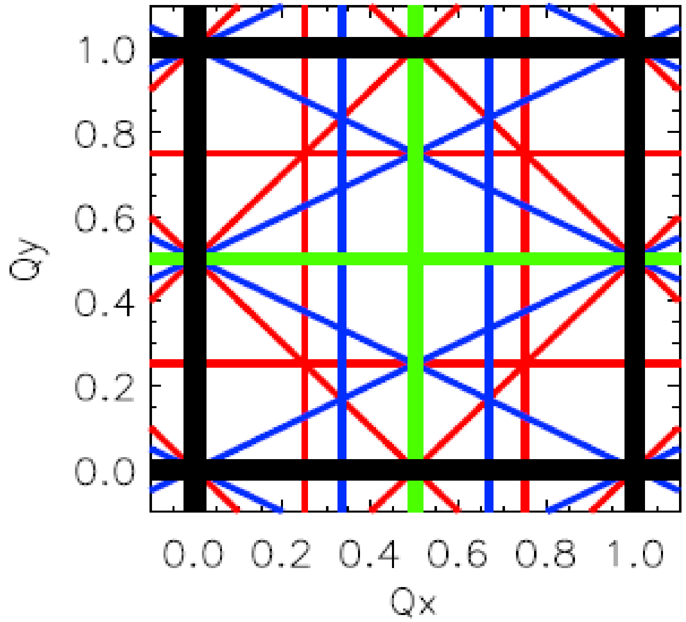
$$\frac{\partial Q_x}{\partial J_x} \qquad \frac{\partial Q_x}{\partial J_y} = \frac{\partial Q_y}{\partial J_x} \qquad \frac{\partial Q_y}{\partial J_y}$$

- **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:

$$h_{40000} \to 4Q_x \qquad h_{31000} \to 2\,Q_x$$
$$h_{00400} \to 4\,Q_y \qquad h_{20110} \to 2\,Q_x$$
$$h_{20200} \to 2Q_x + 2\,Q_y \qquad h_{00310} \to 2\,Q_y$$
$$h_{20020} \to 2Q_x - 2\,Q_y \qquad h_{01110} \to 2\,Q_y$$

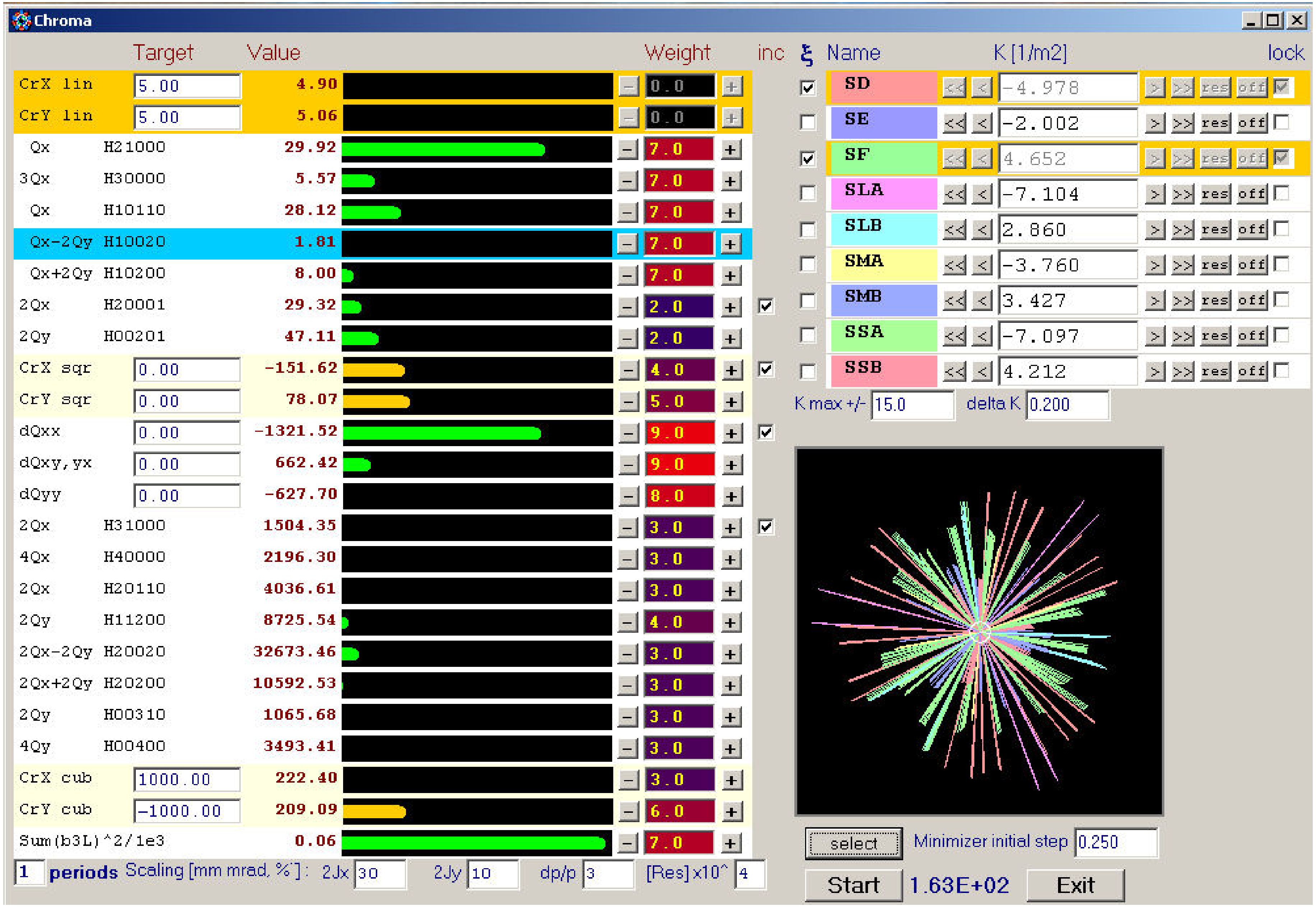


f) Tool for sextupole optimization (OPA)

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



Performance of the SLS 12×TBA lattice

Dynamic apertures

current SLS optics F6CWO

physical aperture

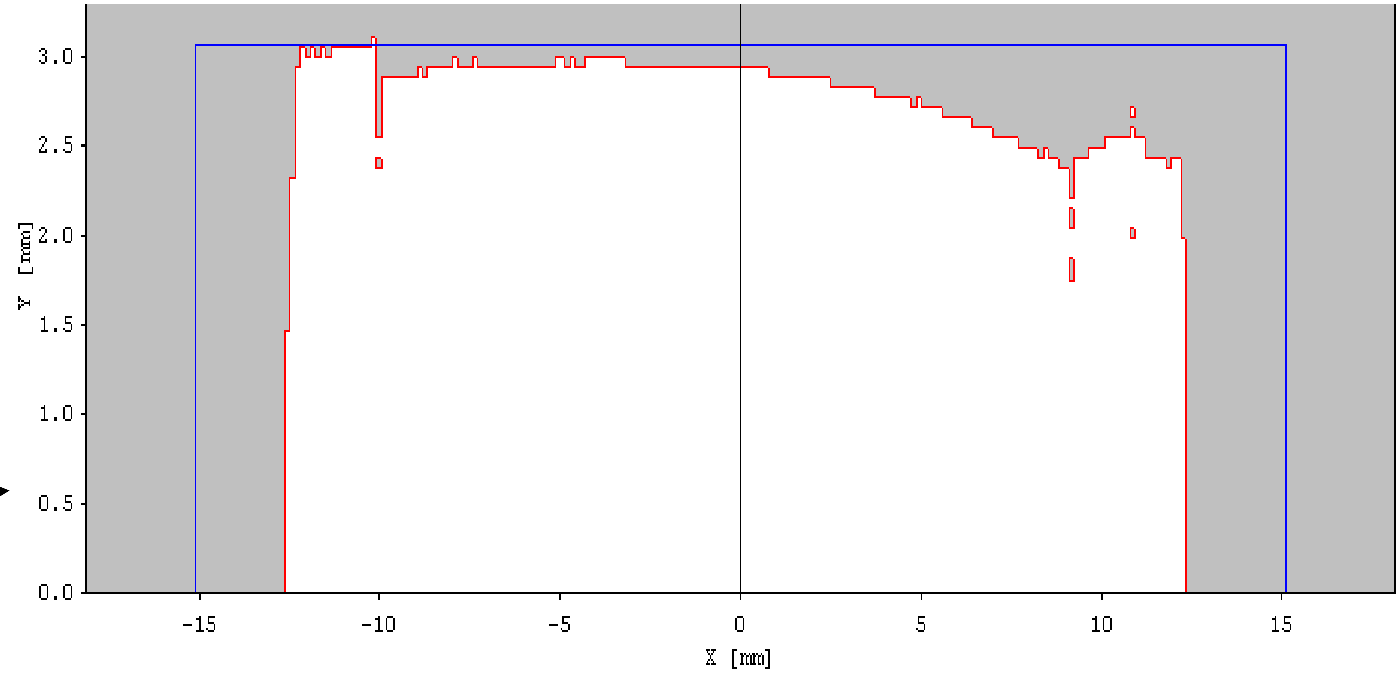
dynamic & phys. aperture

Transverse: x vs. y

corresponding to

A_x = 34 mm mrad

A_y = 2 mm mrad



Momentum: x vs. dp/p

corresponding to

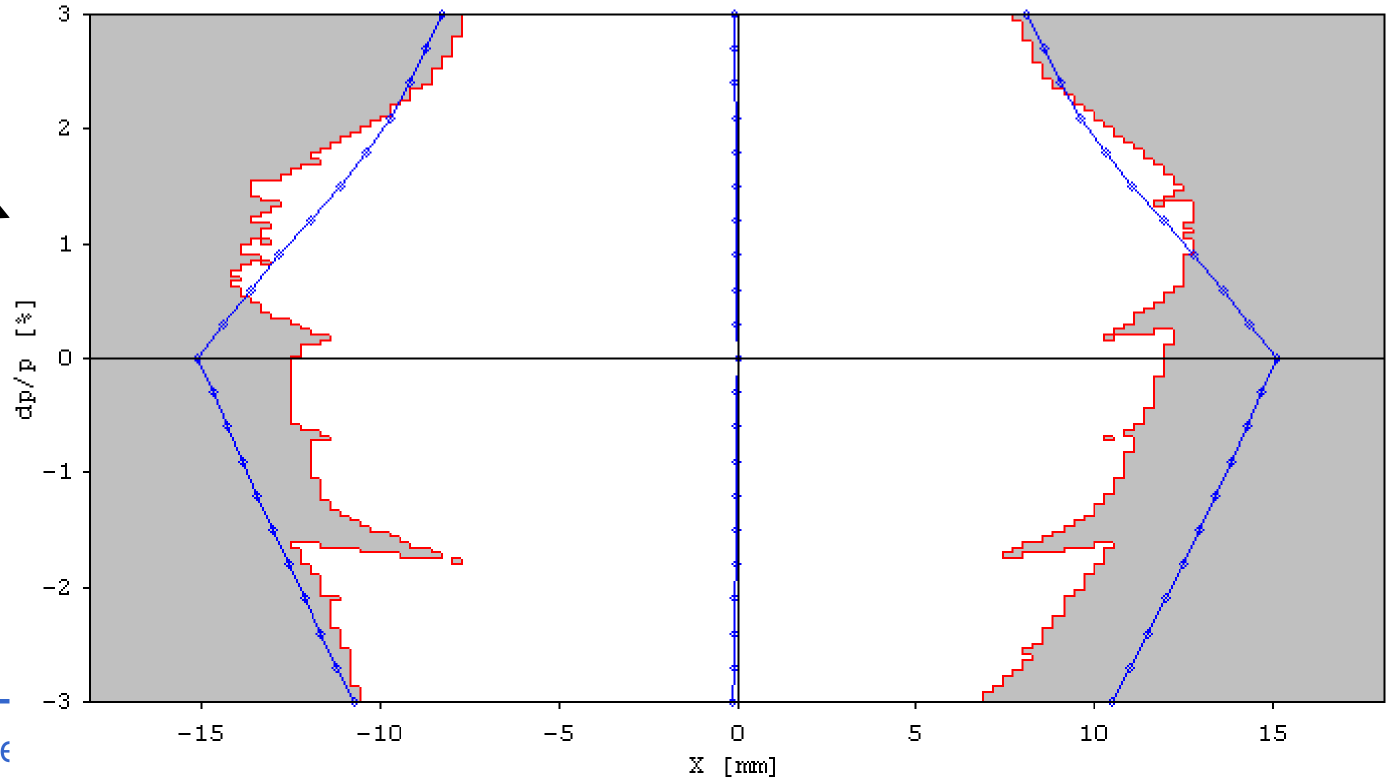
$T_{Touschek}$ = 9.7 hrs

in standard user mode.

(6D Tracy tracking)

- 400mA in 390 bunches
- 2.1 MV RF (500 MHz)
- 3rd HC for 2.2 x bunch length
- 0.1% emittance coupling

→ **σ_y = 9 μm at monitor**



Realization of performance (2001-2008)

(in terms of lifetime and energy acceptance)

- Complications:
  - $\xi = +1/+1 \rightarrow +5/+5$ for suppression of instabilities
  - Lattice modification for laser slicing: period 3 → 1
- Orbit correction
  - removal of bumps for users, girder realignments
  - beam based BPM calibration ("BB alignment")
- Optics correction: $\Delta\beta/\beta \rightarrow 3\%$ rms
  - 177 quadrupoles with individual power supplies
- Coupling suppression
  - 12 dispersive & 24 non-disp. skew quadrupoles
  - emittance coupling $\rightarrow 5\cdot10^{-4}$, $\varepsilon_y \rightarrow 2.8$ pm

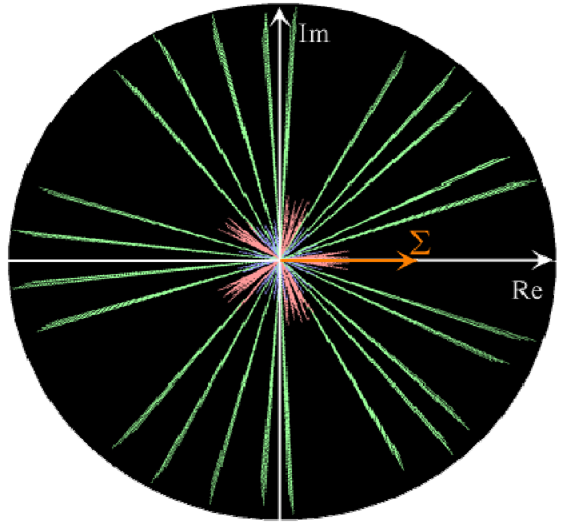
    → M. Böge, *Reaching ultra-low vertical emittance in the SLS*
- Sextupole symmetrization...

Sextupole symmetrization

$$h_{jklmp} \propto \sum_n^{N_{sext}} (b_3 L)_n \, \beta_{xn}^{\frac{j+k}{2}} \, \beta_{yn}^{\frac{l+m}{2}} \, D_n^p \, e^{i\{(j-k)\phi_{xn}+(l-m)\phi_{yn}\}}$$

Sextupoles in symmetric *families*:

- $\mathrm{Im}\,(h) = 0$ by lattice symmetry
- design: optimized for $\mathrm{Re}\,(h) \to 0 \;\forall\; h$.



⇨ Auxiliary sextupoles breaking the symmetry

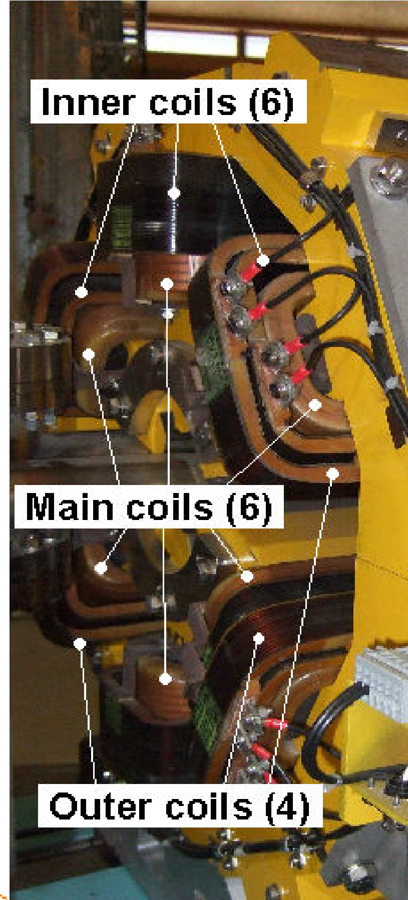
- compensate parasitic $\mathrm{Re},\mathrm{Im}\,(h) \neq 0$.
- first step: do *empirical* optimization
- ≥9 knobs required for Re and Im of h_{21000}, h_{30000}, h_{10200} and h_{10020} and $\Delta\xi_x = 0$
- $h_{10110} \propto h_{21000}$ and $\Delta\xi_y \propto \Delta\xi_x$ (SLS: all aux. sext. at same $\beta_x \, \beta_y \, \eta$)
- 12 auxiliary sextupoles installed

⇨ energy acceptance 2% → 3%

- auxiliary sextupole strength ~ 3% of SF strength

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**

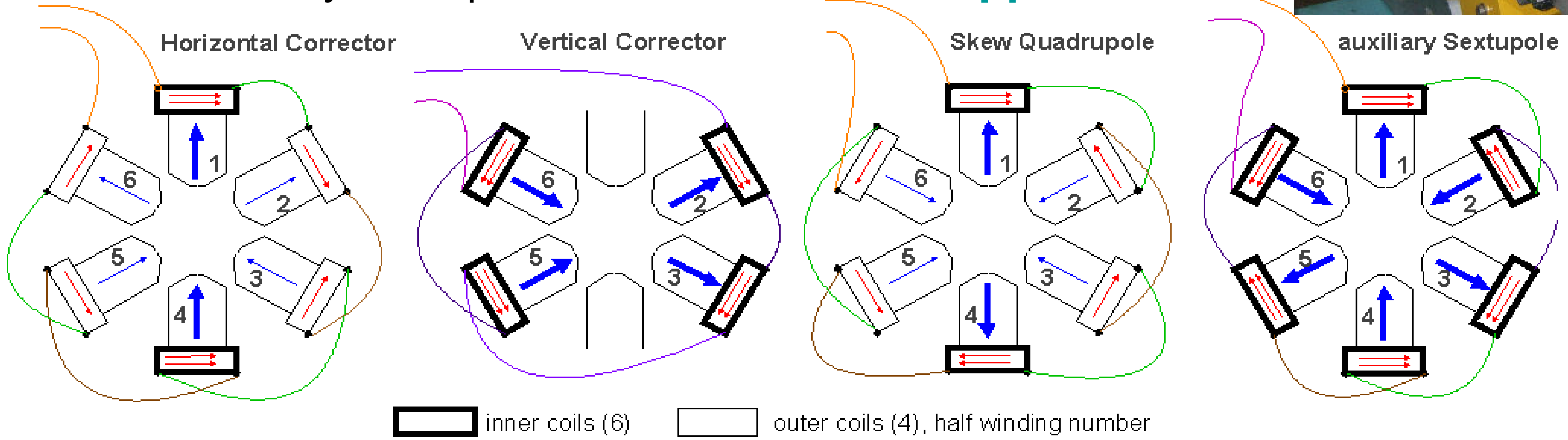
SSA(12), SSB(12), SMA(6), SMB(6), SLA(6), SLB(6) → **D.A.**

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**

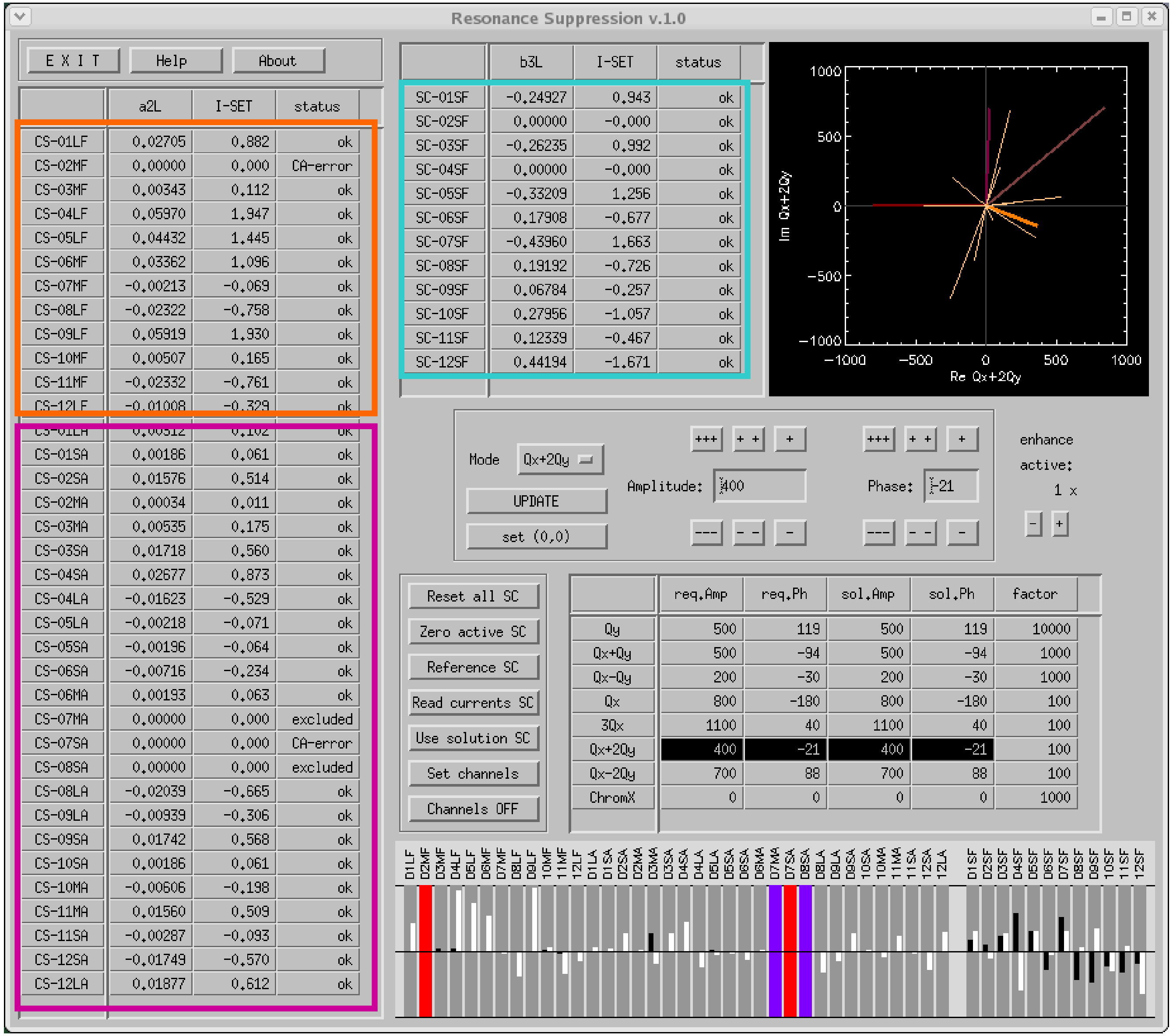


The σ_y/τ operator tool

Dispersive and **non-dispersive** skew quads

h_{00101}
$\Rightarrow Q_y \Rightarrow \eta_y$
h_{10100}
$\Rightarrow Q_x + Q_y$
h_{10010}
$\Rightarrow Q_x - Q_y$

Settings based on vertical dispersion and response matrix measurements
+
some empirical fine tuning



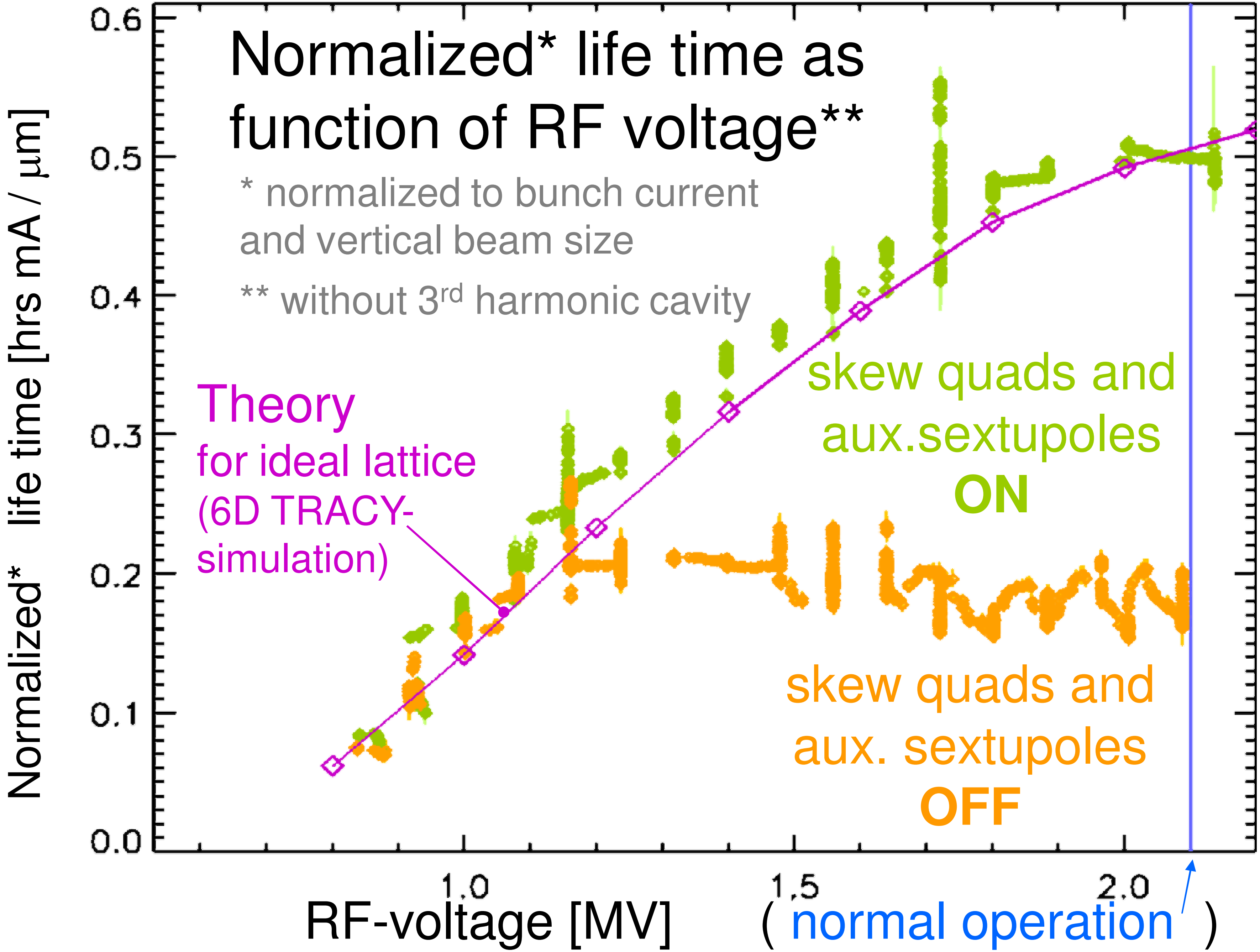
Ratio of vertical beam size to lifetime on stripchart

Auxiliary sextupoles

h_{21000}
$\Rightarrow Q_x$
h_{30000}
$\Rightarrow 3Q_x$
h_{10200}
$\Rightarrow Q_x + 2Q_y$
h_{10020}
$\Rightarrow Q_x - 2Q_y$

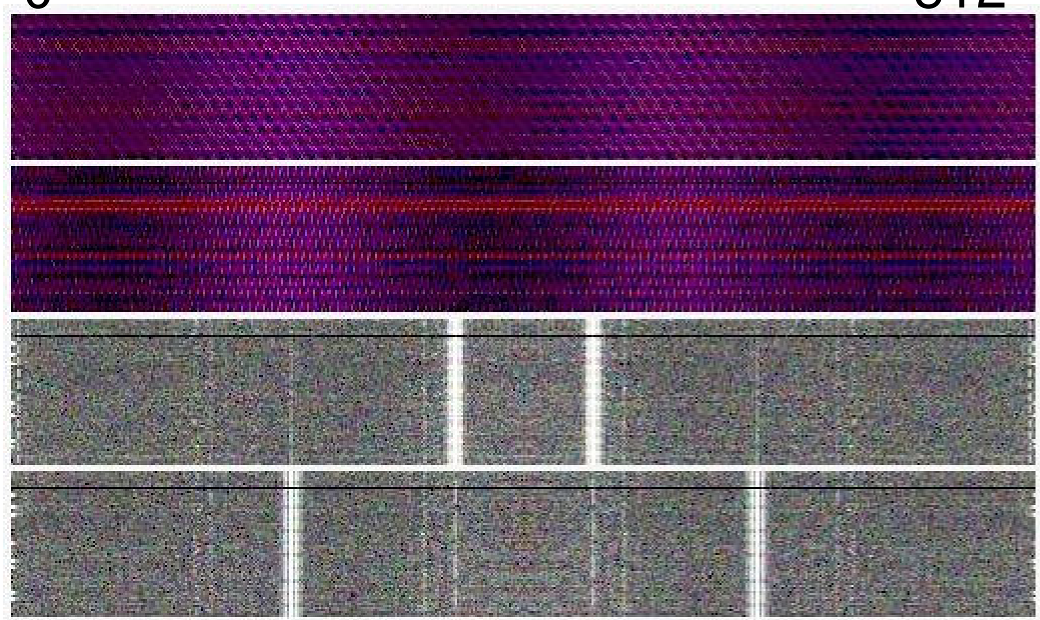
Empirical tuning

Lifetime in agreement with design



Future work on SLS ...

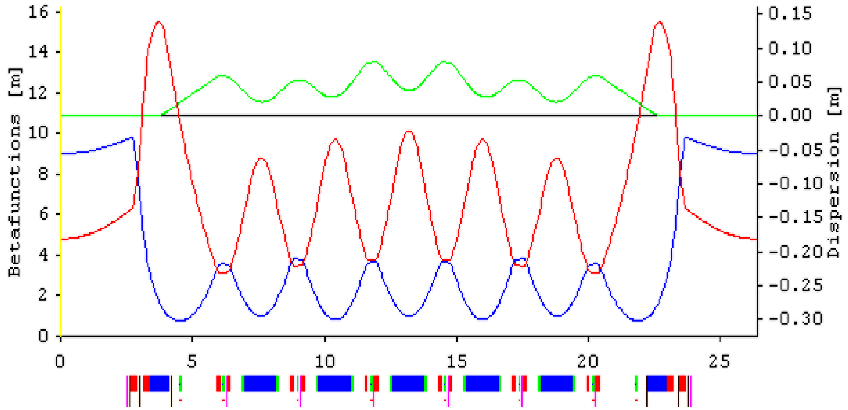
- Further suppression of betatron coupling:
  - eliminate steps between girders $\Rightarrow$ girder realignment
  - centering of orbit in sextupoles
    $\Rightarrow$ measurement of misalignments using skew quad coils
- controlled excitation of vertical dispersion:
  - set (T, ε_y) working point $T \propto \sqrt{\varepsilon_y}$
- set auxiliary sextupoles based on spectra from all BPMs in turn $\times$ turn mode.



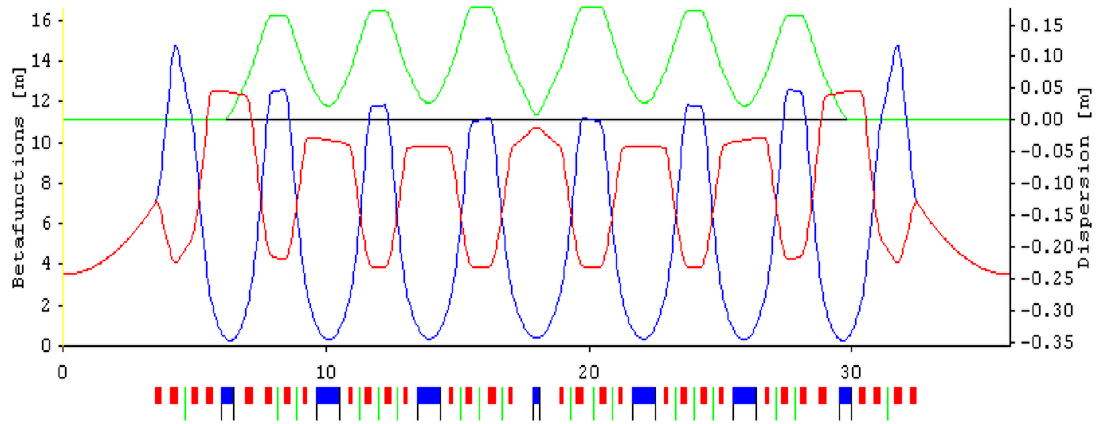
- automatize skew quad. & auxiliary sext. tuning.

MAX-IV – proper use of the 7BA

1/20 MAX-IV



1/6 SLS'93

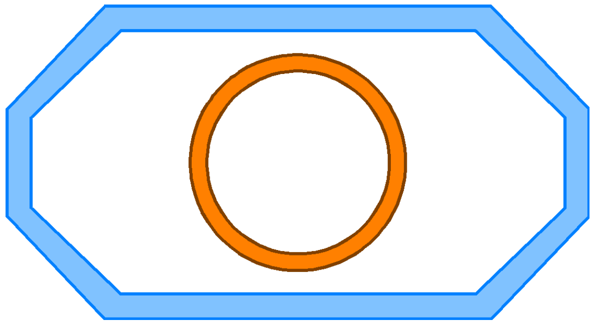


	MAX-IV	SLS'93 ⇒ ⇒	scaled to
7BA arcs	20	6	20
Energy E	3 GeV	2.1 GeV	3 GeV
Emittance ε	**0.33 nm**	3.2 nm	0.18 nm
Tune Q	42.2 / 14.3	20.2 / 5.4	67.3 / 18.0
norm. chrom. $-\xi/Q$	**1.2 / 3.1**	2.7 / 3.4	
Energy acceptance	**> 5%**	**~ 2 %**	
Circumference	**528 m**	240 m	> 800 m

MAX-IV concept

→ S. Leemann, *MAX-4 lattice design*

- many (140) small bends → low dispersion
  - ⇒ low emittance with relaxed optics
  - ⇒ small magnet apertures: high gradients



Vacuum chambers:
SLS: 65 × 32 mm, SS
MAX-IV: 22 mm ∅ ,Cu

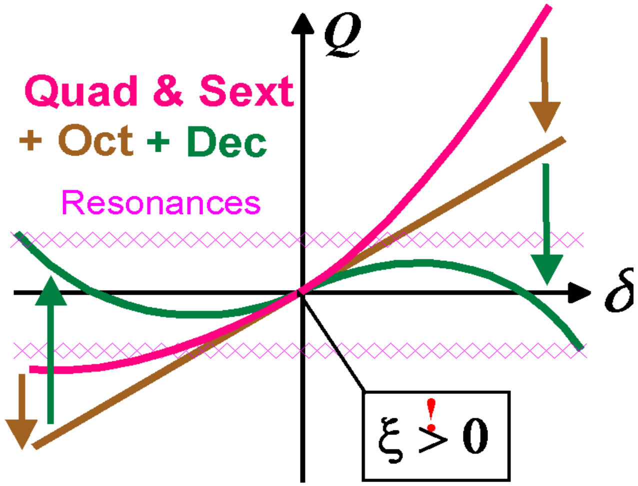
- compact lattice
  - high gradients: short magnets
  - gradients in bending magnets
- nonlinear dynamics
  - low dispersion: very strong sextupoles
  - sextupoles insufficient to control ADTS $\partial Q / \partial J$
  - ⇒ installation of octupoles

↳ *tool developments ctn'd...*

... g) include octupoles and decapoles

Use higher multipoles to control in 1st order
phase-independent sextupole effects of 2nd and 3rd order

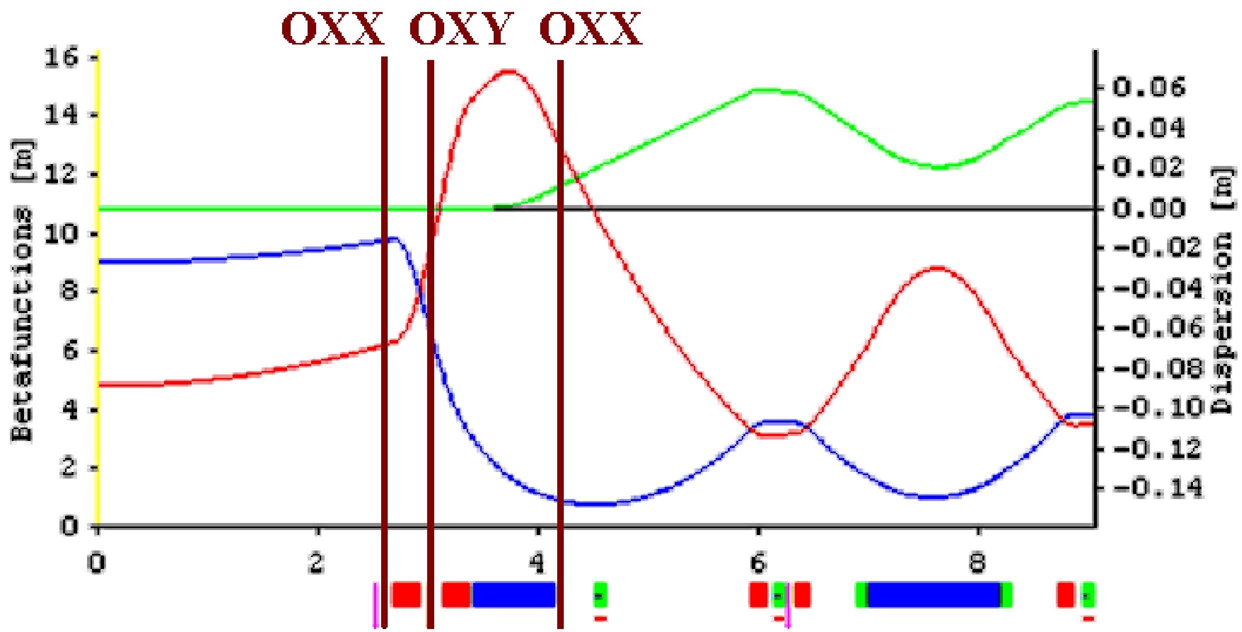
- **Octupoles:**
  - linear ADTS: $\partial Q_x/\partial J_x$, $\partial Q_x/\partial J_y = \partial Q_y/\partial J_x$, $\partial Q_y/\partial J_y$
  - quadratic chromaticities: $\partial^2 Q_x/\partial\delta^2$, $\partial^2 Q_y/\partial\delta^2$
- **Decapoles:**
  - cubic chromaticities: $\partial^3 Q_x/\partial\delta^3$, $\partial^3 Q_y/\partial\delta^3$
  - quadratic ADTS and off-energy linear ADTS
- Side-effects (resonances) tolerable [hopefully] if multipoles are rather weak...



➔ Taylor (minimize) beam footprint in tune space
- ➔ provide sufficient horizontal dynamic aperture for injection.
- ➔ provide sufficient energy acceptance for Touschek lifetime.

➔ Provide knobs for control room (linear systems).

h) ...tool upgrade and application

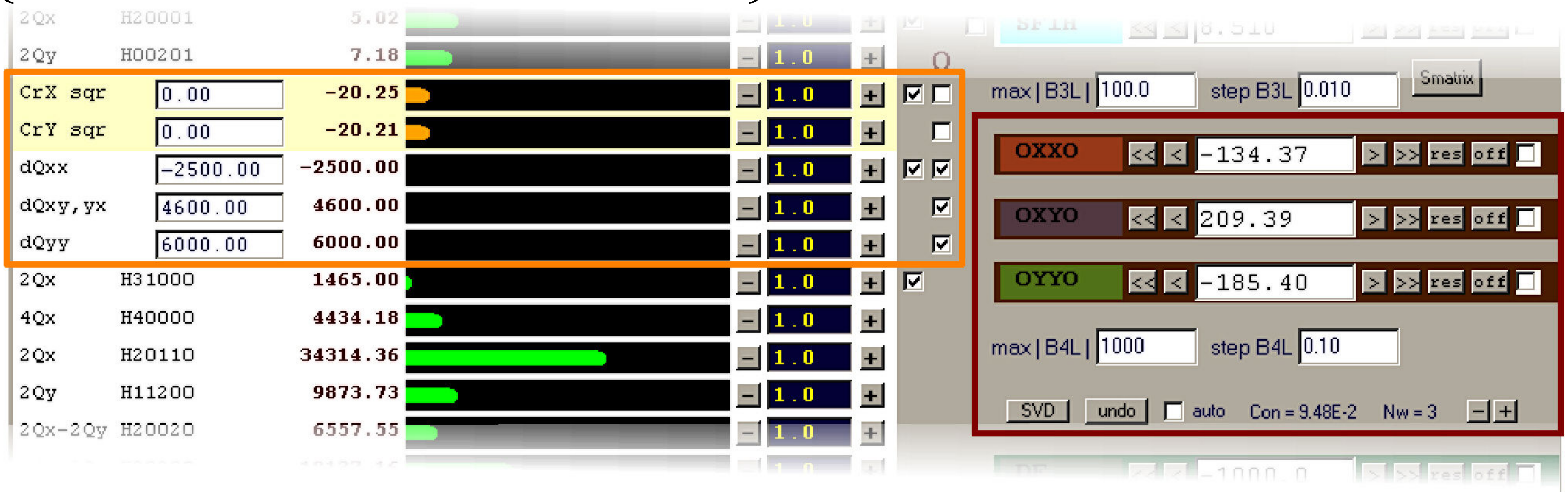


3 octupole families for **MAX-IV**

S. C. Leemann et al.
PRST AB 12, 120701 (2009)

SVD solver for linear system for N octupole families:

$$\left\{\frac{\partial Q_x}{\partial J_x},\frac{\partial Q_x}{\partial J_y},\frac{\partial Q_y}{\partial J_y},\frac{\partial^2 Q_x}{\partial \delta^2},\frac{\partial^2 Q_x}{\partial \delta^2}\right\}^T = \mathrm{M}_{5\times N}\cdot\{\ldots(b_4 l)_k\ldots\}_N^T$$



Conclusions

- The 12×TBA lattice for the SLS was the right decision
  - compromise: number of straights, emittance, circumference
- Robust "standard method" of sextupole optimization
  - 1st and 2nd order sextupole Hamiltonian analytical
  - 1st, 2nd and 3rd order chromaticities numerical
- SLS reached design performance
  - coupling control with 36 skew quadrupoles
  - nonlinear tuning using 12 auxiliary sextupoles
  - there is still room for further improvement
- Next generation low emittance rings
  - come-back of multi bend achromat lattice: compact & relaxed
  - reduced vacuum chamber and magnet dimensions
  - octupoles [and decapoles] included in lattice design