

# Nonlinear dynamics at the SLS storage ring

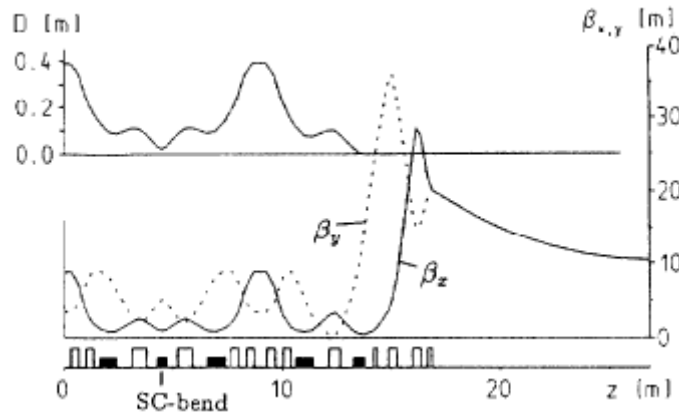
Andreas Streun, Paul Scherrer Institut, Villigen, Switzerland

- ◆ 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](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

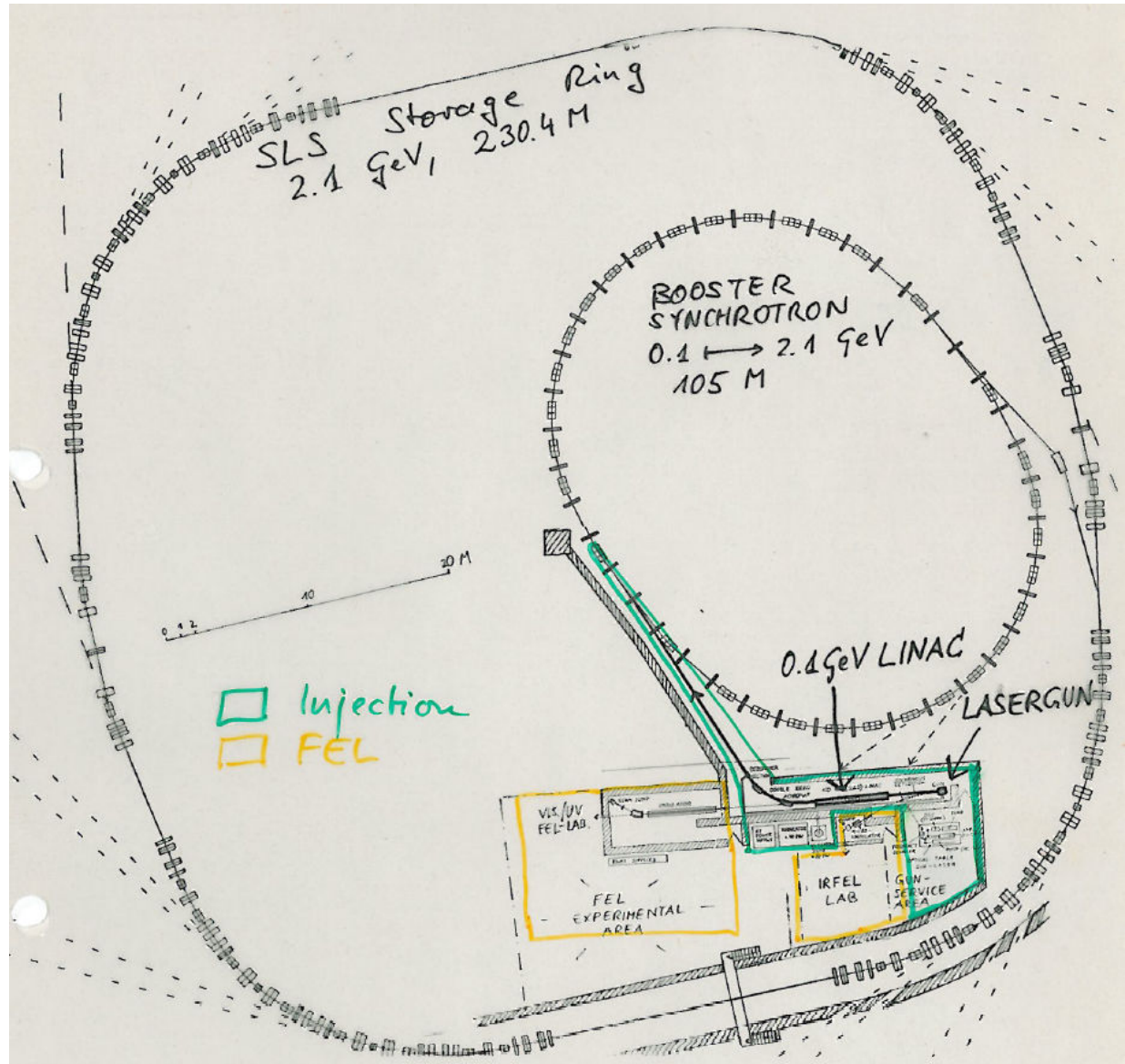
>20m straights

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

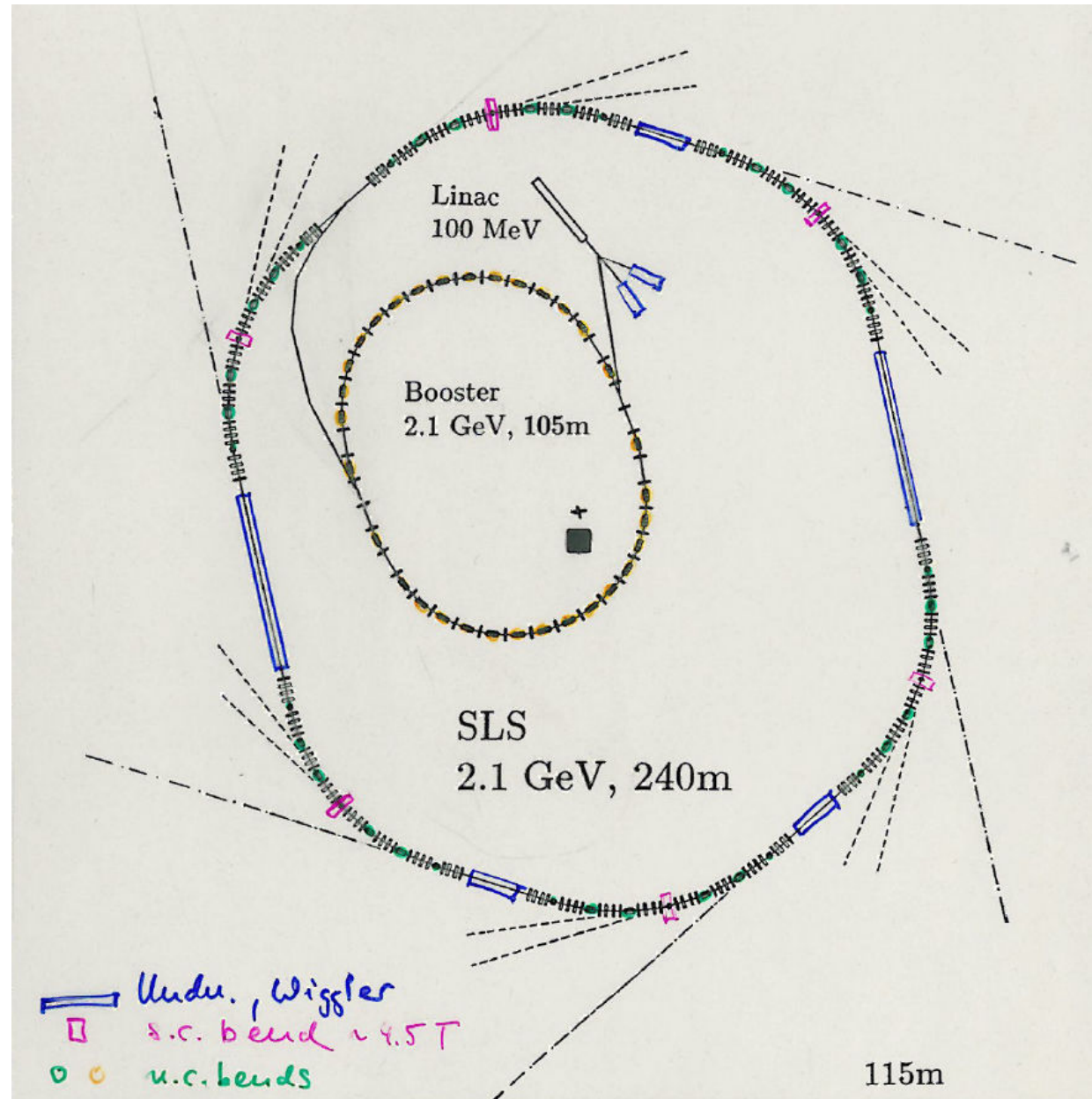
2 × 20 m

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

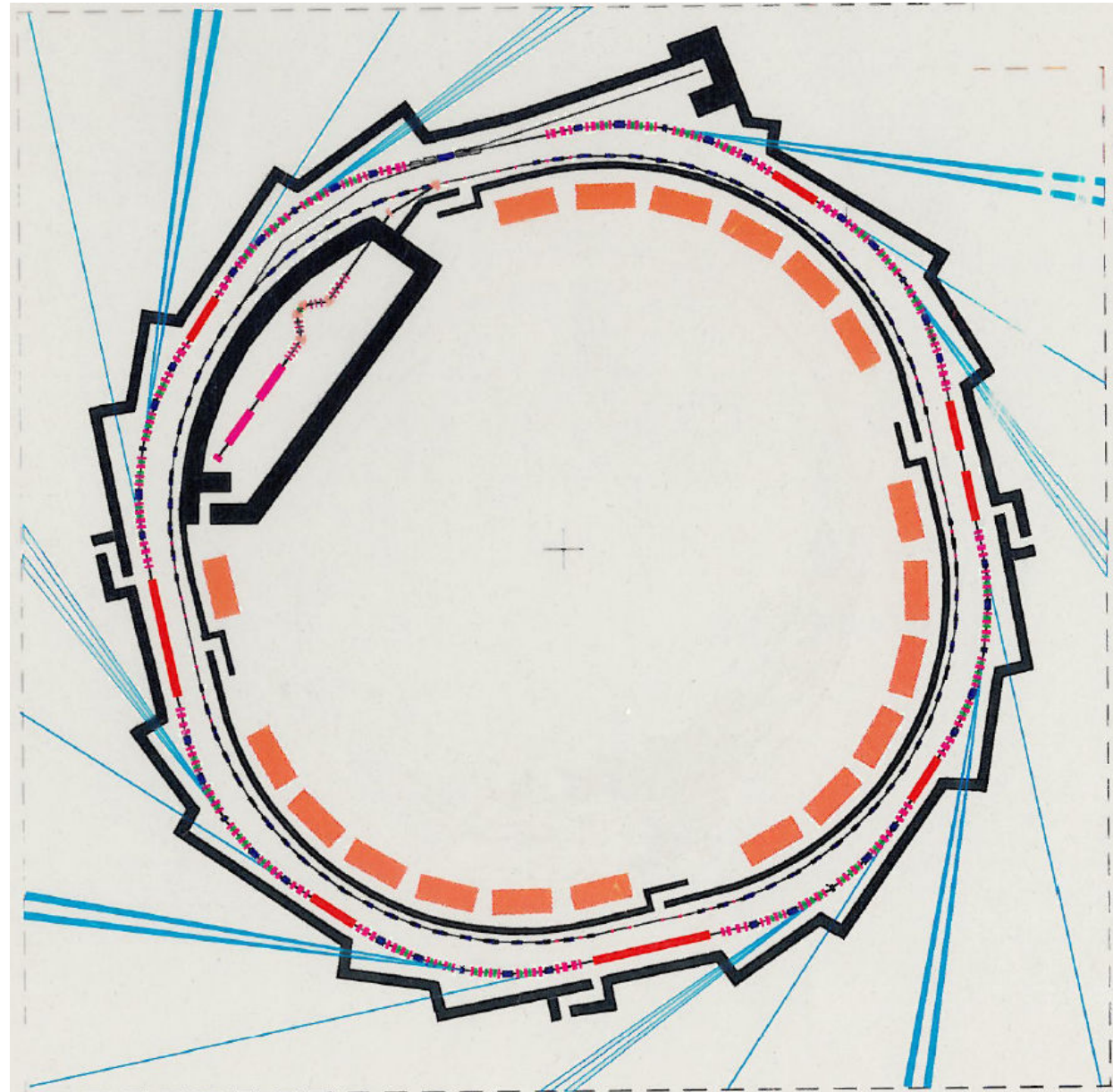
4 × 20m

**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

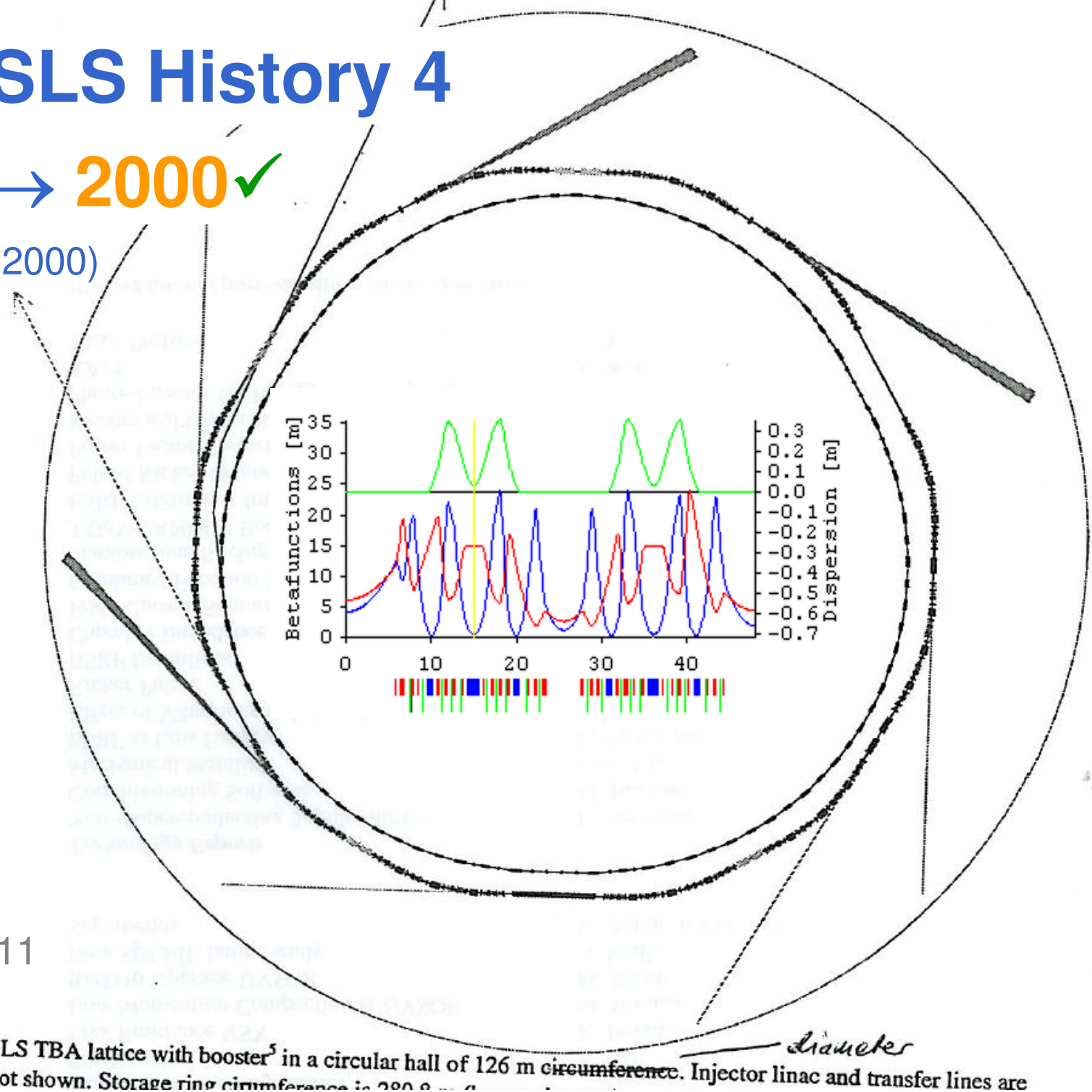
281 → 288 m

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<sup>5</sup> in a circular hall of 126 m circumference. Injector linac and transfer lines are not shown. Storage ring circumference is 288 m.

... beyond SLS:

2003 → 2009

12 → 20 × **7BA** arc

12 → 20 straights

12 × 4.6 m → 20 × 5 m

285 → 528 m

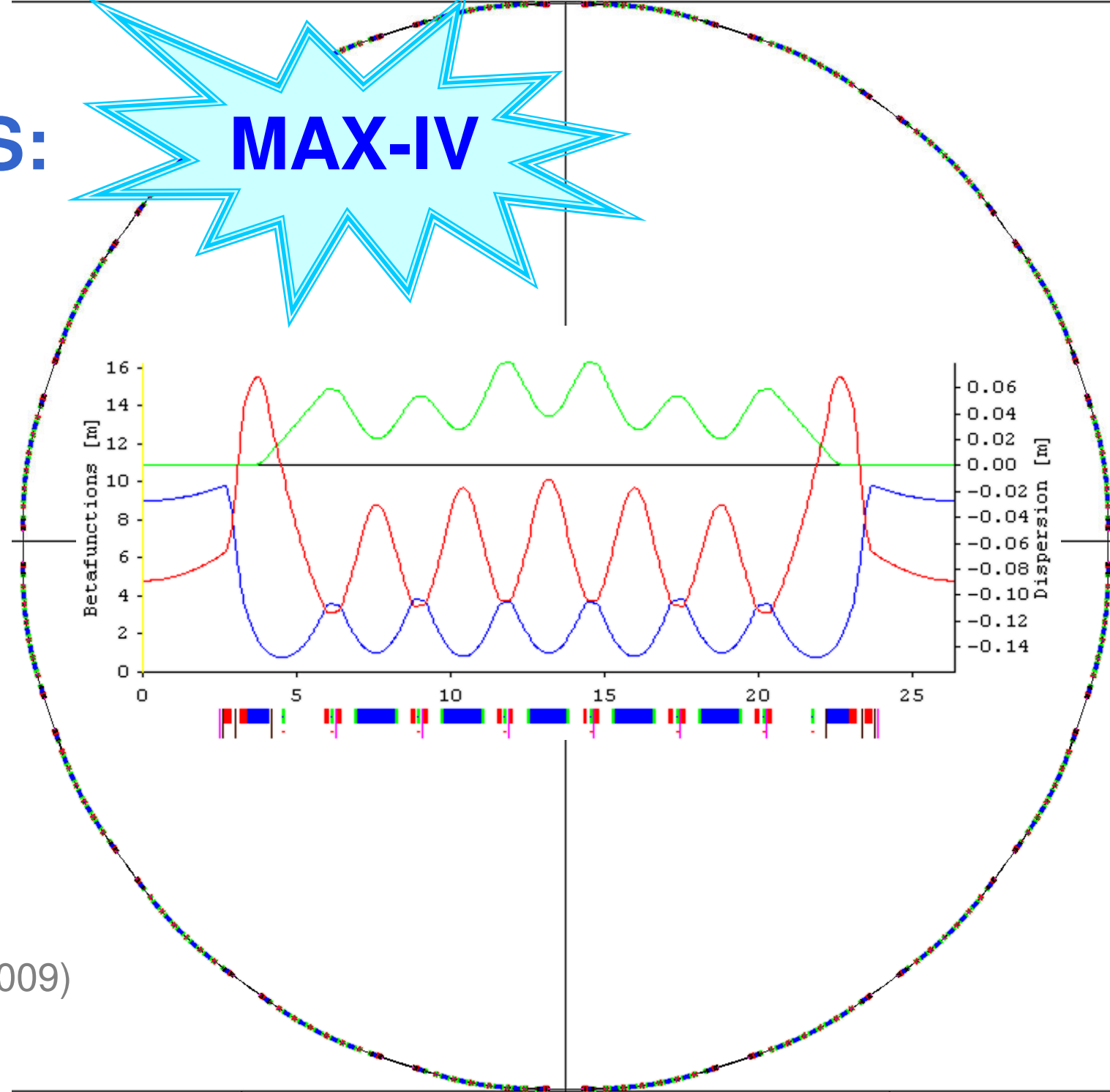
3.0 GeV

1.2 → 0.33 nm

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

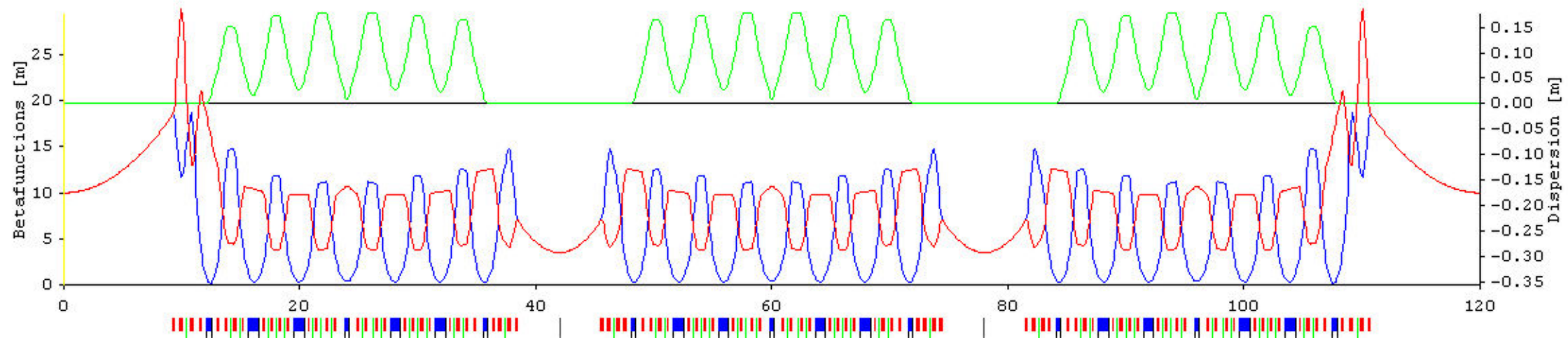
S. C. Leemann et al.  
PRST AB 12, 120701 (2009)

**MAX-IV**





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



- ◆  $6 \times 7BA$  arcs with centre s.c. bends
- ◆  $Q = 20.2 / 5.4$     $Q_{\text{cell}} \sim 0.44 / 0.09$     $\xi = -55 / -18$
- ◆  $E = 2.1 \text{ GeV}$     $C = 240 \text{ m}$     $\varepsilon = 3.2 \text{ nm}$
- ✗ Too few **user** straights:  $2 \times 20 + 4 [2] \times 6 \text{ m}$
- ✗ 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:

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

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

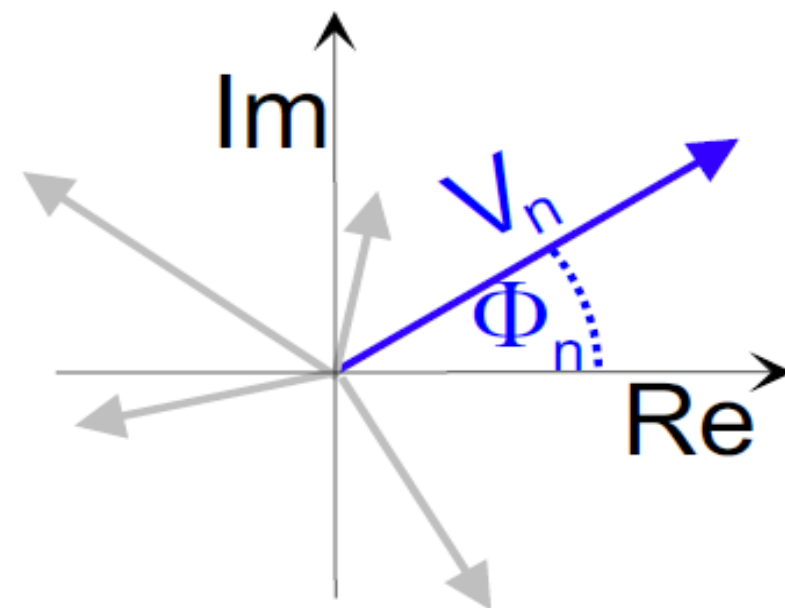
$$h = \sum_n^{N_{\text{sext}}} V_n e^{i\Phi_n} [ + \dots \text{quads for } p \neq 0 \dots ]$$

Sextupole<sub>n</sub> ↔ 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





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

## First order sextupole [+quadrupole] Hamiltonian

- 2 phase independent terms → chromaticities:

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

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

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

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

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

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

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

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

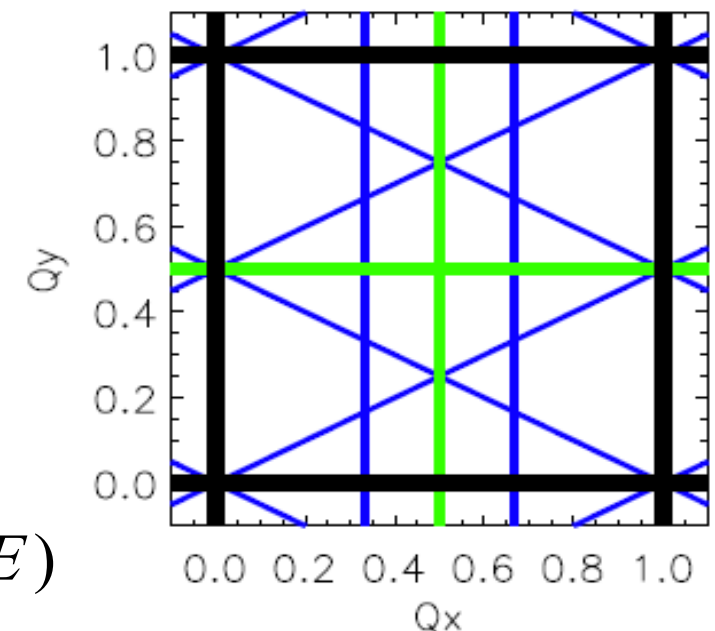
$$h_{10200} = h_{01020}^* \longrightarrow Q_x + 2 Q_y$$

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

$$h_{20001} = h_{02001}^* \longrightarrow 2 Q_x$$

$$h_{00201} = h_{00021}^* \longrightarrow 2 Q_y$$

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



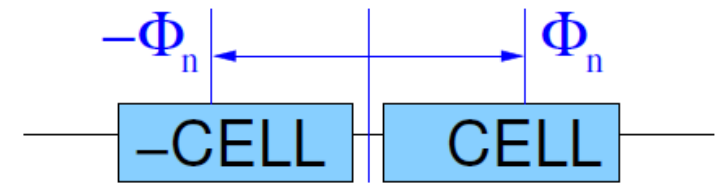
### c) a particular problem of multi-bend achromat (MBA) lattices

Systematic first order optimization:

9 terms  $h_{jklmp}$  (7 complex, 2 real)

→ **16** sextupole families

⇒ Symmetry:



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

Linear system for  $M$  families of sextupoles:

$$\left\{ \sum_{n \in \{Sm\}} \beta_n^{(\dots)} D_n^{(\dots)} e^{i\{(\dots)\phi_n\}} \dots \right\}_{9 \times M} \times \left\{ (b_3 L)_m \right\}_{M \times 1} = \left\{ \sum_{\text{Quad}} (b_2 L) \dots \right\}_{1 \times 9}$$

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

**SLS 6×7BA:**  
 $\Phi_x^{\text{cell}} = 159^\circ$

$2Q_x$  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  $\{(b_3 L)_m\} \implies$  suppression by  $\Delta\phi_x^{\text{straight}}$

J. Bengtsson et al., NIM A 404 (1998) 237

d) to optimize the sextupole strengths is not enough....

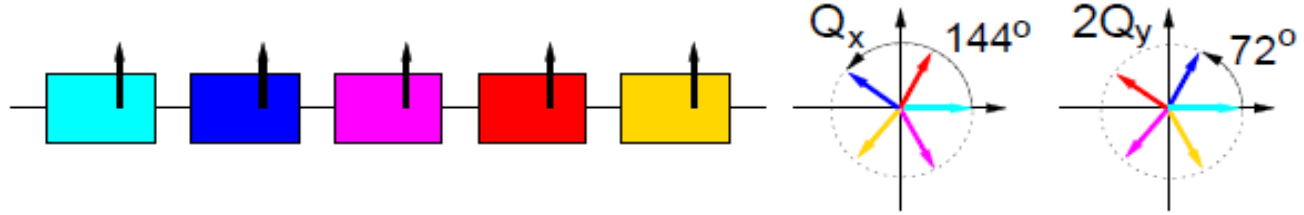
## Phase cancellation schemes

**Periodicity:**  $N$  cells

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

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

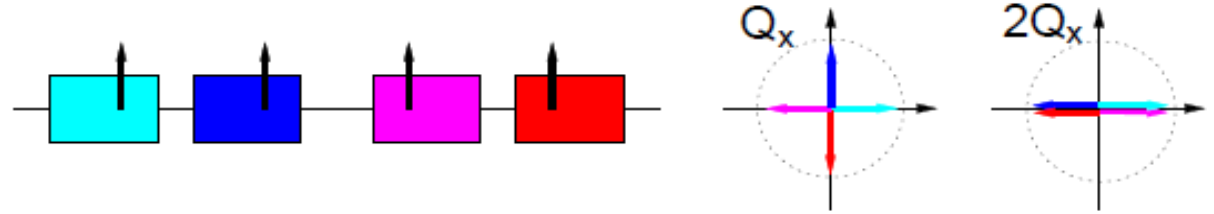
SLS  $6 \times 7$ BA (i.e. 5 cells)  
 ( $\epsilon = 3.2 \text{ nm @ } 2.1 \text{ GeV}$ )  
 $\Rightarrow \Delta Q_x^{\text{cell}} = 0.44 \quad \text{☹}$



**Symmetry:** Lattice section vs. mirror image

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

SLS  $12 \times$  TBA  
 ( $\epsilon = 4.9 \text{ nm @ } 2.4 \text{ GeV}$ )  
 $\Delta Q_x^{\text{cell}} \approx 7/4, \Delta Q_y^{\text{cell}} \approx 3/4 \quad \text{☺}$



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

$\Rightarrow$  Iterate: **linear**  $\iff$  **nonlinear** lattice design

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

## Second order sextupole [+first order octupole] Hamiltonian

$$\sum_n \sum_m (b_3 L)_n (b_3 L)_m \times (\beta_n, \phi_n \beta_m, \phi_m \dots) + \left[ \sum_q (b_4 L)_q \times (\beta_q, \phi_q \dots) \right]$$

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

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

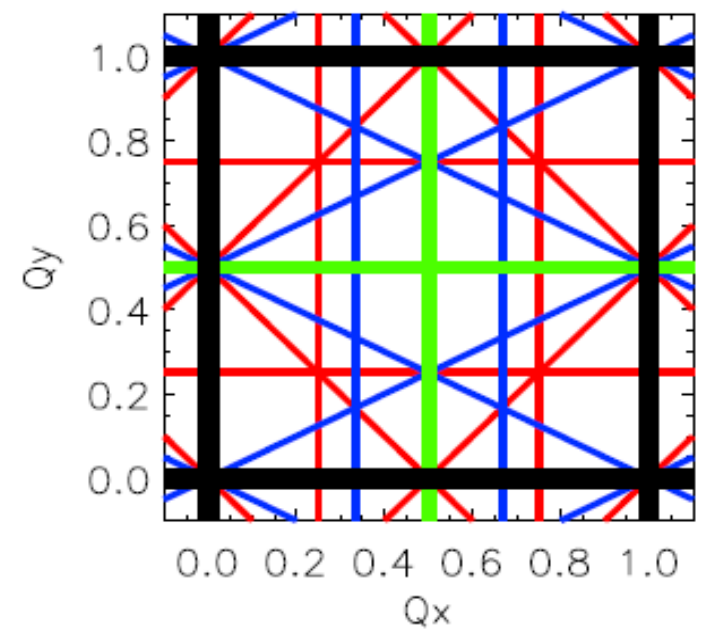
- **2 phase independant off-momentum terms** → **second order chromaticities:**

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

- **8 phase dependant terms**

→ **octupolar resonances:**

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





## f) Tool for sextupole optimization (OPA)

Analytical expressions for 1<sup>st</sup> and 2<sup>nd</sup> Hamiltonian modes. (J. Bengtsson)

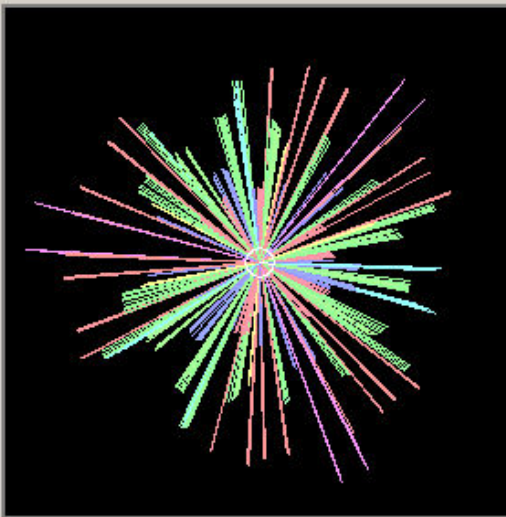
Numeric differentiation for 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> chromaticity

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

Chroma

	Target	Value	Weight	inc	Name	K [1/m <sup>2</sup> ]	lock
CrX lin	5.00	4.90	0.0	+	SD	-4.978	<input checked="" type="checkbox"/>
CrY lin	5.00	5.06	0.0	+	SE	-2.002	<input type="checkbox"/>
Qx H21000		29.92	7.0	+	SF	4.652	<input checked="" type="checkbox"/>
3Qx H30000		5.57	7.0	+	SLA	-7.104	<input type="checkbox"/>
Qx H10110		28.12	7.0	+	SLB	2.860	<input type="checkbox"/>
Qx-2Qy H10020		1.81	7.0	+	SMA	-3.760	<input type="checkbox"/>
Qx+2Qy H10200		8.00	7.0	+	SMB	3.427	<input type="checkbox"/>
2Qx H20001		29.32	2.0	+	SSA	-7.097	<input type="checkbox"/>
2Qy H00201		47.11	2.0	+	SSB	4.212	<input type="checkbox"/>
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	+			

K max +/- 15.0 delta K 0.200



select Minimizer initial step 0.250

Start 1.63E+02 Exit

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

# Performance of the SLS 12×TBA lattice

## Dynamic apertures

current SLS optics F6CWO

physical aperture

dynamic & phys. aperture

## Transverse: x vs. y

corresponding to

$A_x = 34 \text{ mm mrad}$

$A_y = 2 \text{ mm mrad}$

## Momentum: x vs. dp/p

corresponding to

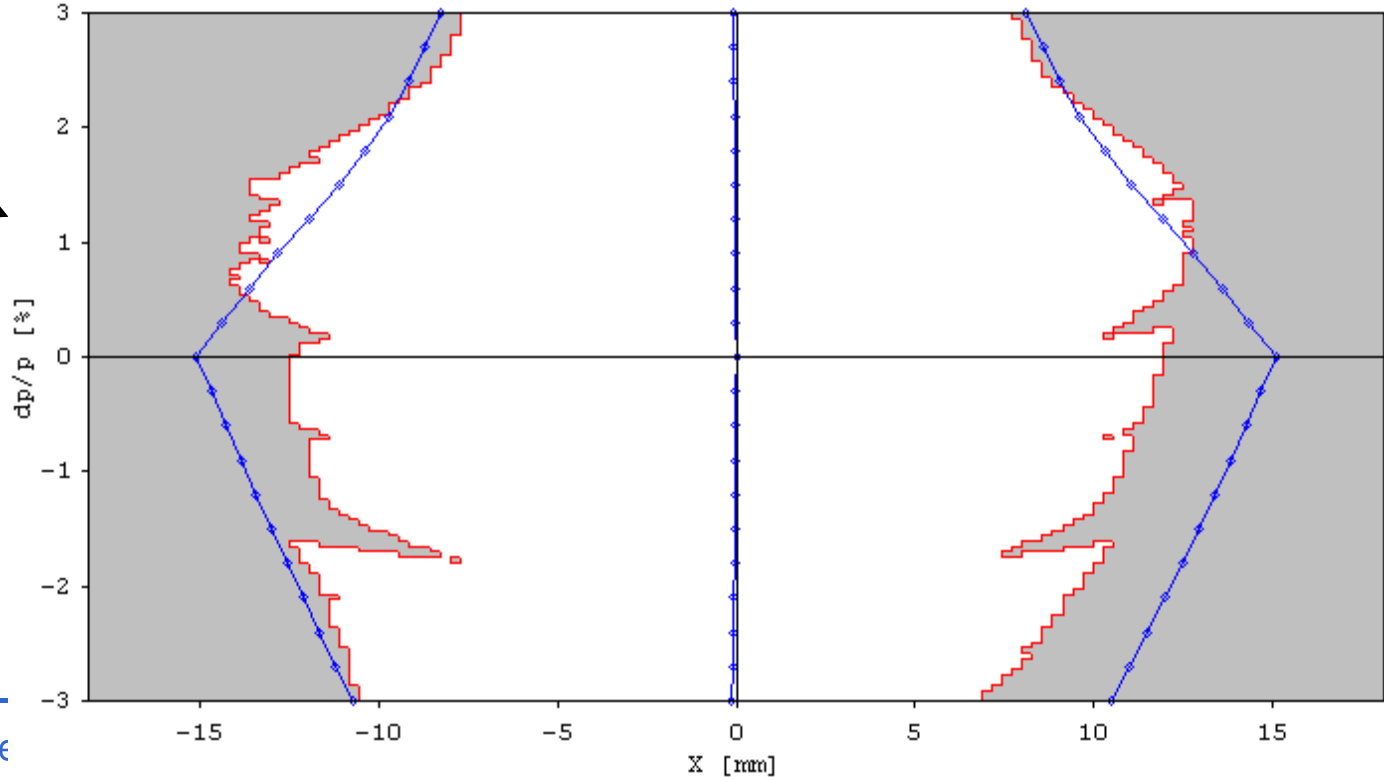
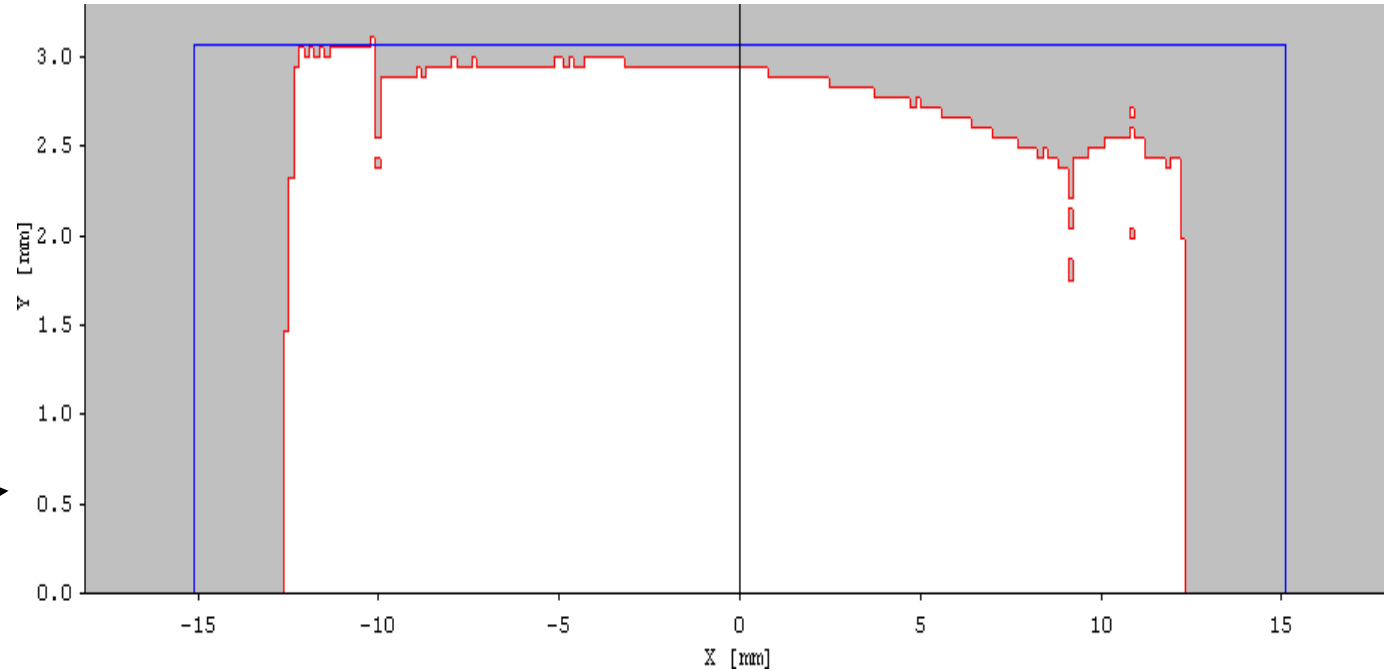
$T_{\text{Touschek}} = 9.7 \text{ hrs}$

in standard user mode.

(6D Tracy tracking)

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

→  $\sigma_y = 9 \text{ } \mu\text{m at monitor}$



# 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  $\rightarrow$  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  $\rightarrow 5 \cdot 10^{-4}$ ,  $\varepsilon_y \rightarrow 2.8$  pm

$\rightarrow$  M. Böge, *Reaching ultra-low vertical emittance in the SLS*

## ◆ Sextupole symmetrization...

# Sextupole symmetrization

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

Sextupoles in symmetric *families*:

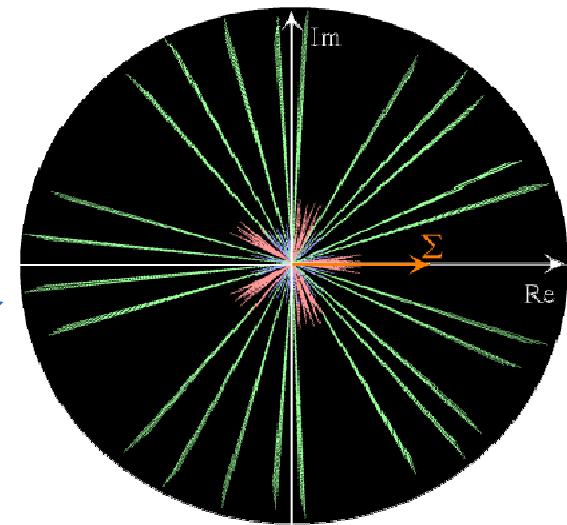
- $\text{Im}(h) = 0$  by lattice symmetry
- design: optimized for  $\text{Re}(h) \rightarrow 0 \forall h$ .

⇒ Auxiliary sextupoles breaking the symmetry

- compensate parasitic  $\text{Re}, \text{Im}(h) \neq 0$ .
- first step: do *empirical* optimization
- $\geq 9$  knobs required for  $\text{Re}$  and  $\text{Im}$  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  $\sim 3\%$  of SF strength



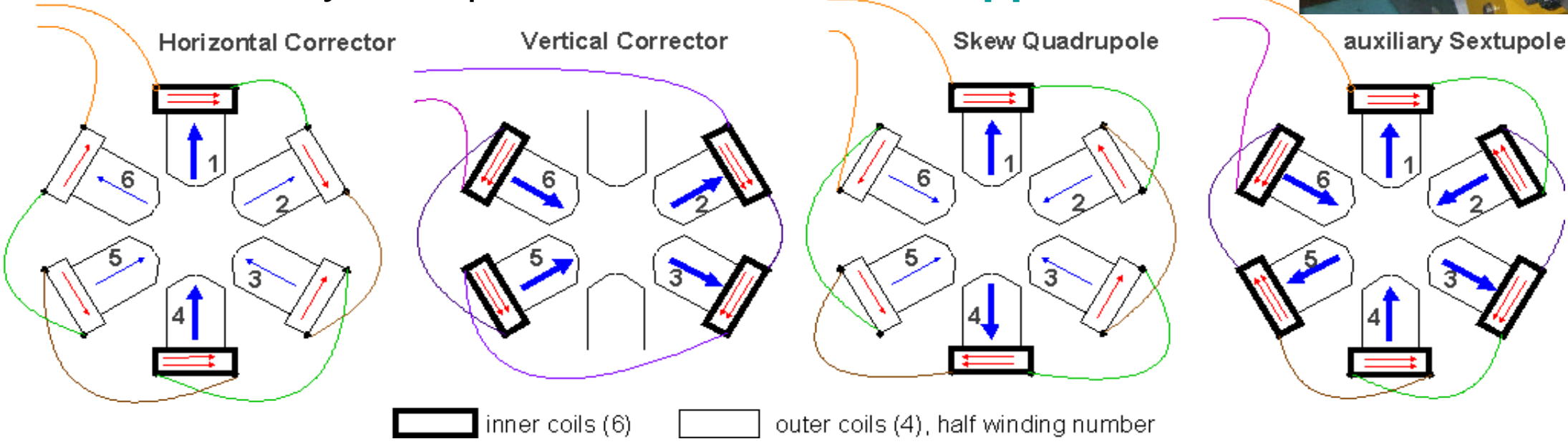
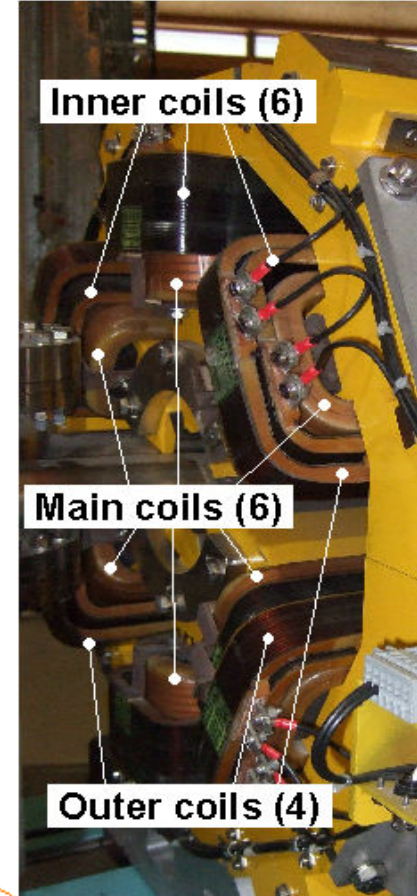


# Versatile Sextupoles

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 $\sigma_y/\tau$ 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

a2L	I-SET	status
CS-01LF	0.02705	0.882 ok
CS-02MF	0.00000	0.000 CA-error
CS-03MF	0.00343	0.112 ok
CS-04LF	0.05970	1.947 ok
CS-05LF	0.04432	1.445 ok
CS-06MF	0.03362	1.096 ok
CS-07MF	-0.00213	-0.069 ok
CS-08LF	-0.02322	-0.758 ok
CS-09LF	0.05919	1.930 ok
CS-10MF	0.00507	0.165 ok
CS-11MF	-0.02332	-0.761 ok
CS-12LF	-0.01008	-0.329 ok
CS-01LA	0.00512	0.102 ok
CS-01SA	0.00186	0.061 ok
CS-02SA	0.01576	0.514 ok
CS-02MA	0.00034	0.011 ok
CS-03MA	0.00535	0.175 ok
CS-03SA	0.01718	0.560 ok
CS-04SA	0.02677	0.873 ok
CS-04LA	-0.01623	-0.529 ok
CS-05LA	-0.00218	-0.071 ok
CS-05SA	-0.00196	-0.064 ok
CS-06SA	-0.00716	-0.234 ok
CS-06MA	0.00193	0.063 ok
CS-07MA	0.00000	0.000 excluded
CS-07SA	0.00000	0.000 CA-error
CS-08SA	0.00000	0.000 excluded
CS-08LA	-0.02039	-0.665 ok
CS-09LA	-0.00939	-0.306 ok
CS-09SA	0.01742	0.568 ok
CS-10SA	0.00186	0.061 ok
CS-10MA	-0.00606	-0.198 ok
CS-11MA	0.01560	0.509 ok
CS-11SA	-0.00287	-0.093 ok
CS-12SA	-0.01749	-0.570 ok
CS-12LA	0.01877	0.612 ok

b3L	I-SET	status
SC-01SF	-0.24927	0.943 ok
SC-02SF	0.00000	-0.000 ok
SC-03SF	-0.26235	0.992 ok
SC-04SF	0.00000	-0.000 ok
SC-05SF	-0.33209	1.256 ok
SC-06SF	0.17908	-0.677 ok
SC-07SF	-0.43960	1.663 ok
SC-08SF	0.19192	-0.726 ok
SC-09SF	0.06784	-0.257 ok
SC-10SF	0.27956	-1.057 ok
SC-11SF	0.12339	-0.467 ok
SC-12SF	0.44194	-1.671 ok

req.Amp	req.Ph	sol.Amp	sol.Ph	factor	
Qy	500	119	500	119	10000
Qx+Qy	500	-94	500	-94	1000
Qx-Qy	200	-30	200	-30	1000
Qx	800	-180	800	-180	100
3Qx	1100	40	1100	40	100
Qx+2Qy	400	-21	400	-21	100
Qx-2Qy	700	88	700	88	100
ChromX	0	0	0	0	1000

Auxiliary sextupoles

$h_{21000} \Rightarrow Q_x$

$h_{30000} \Rightarrow 3Q_x$

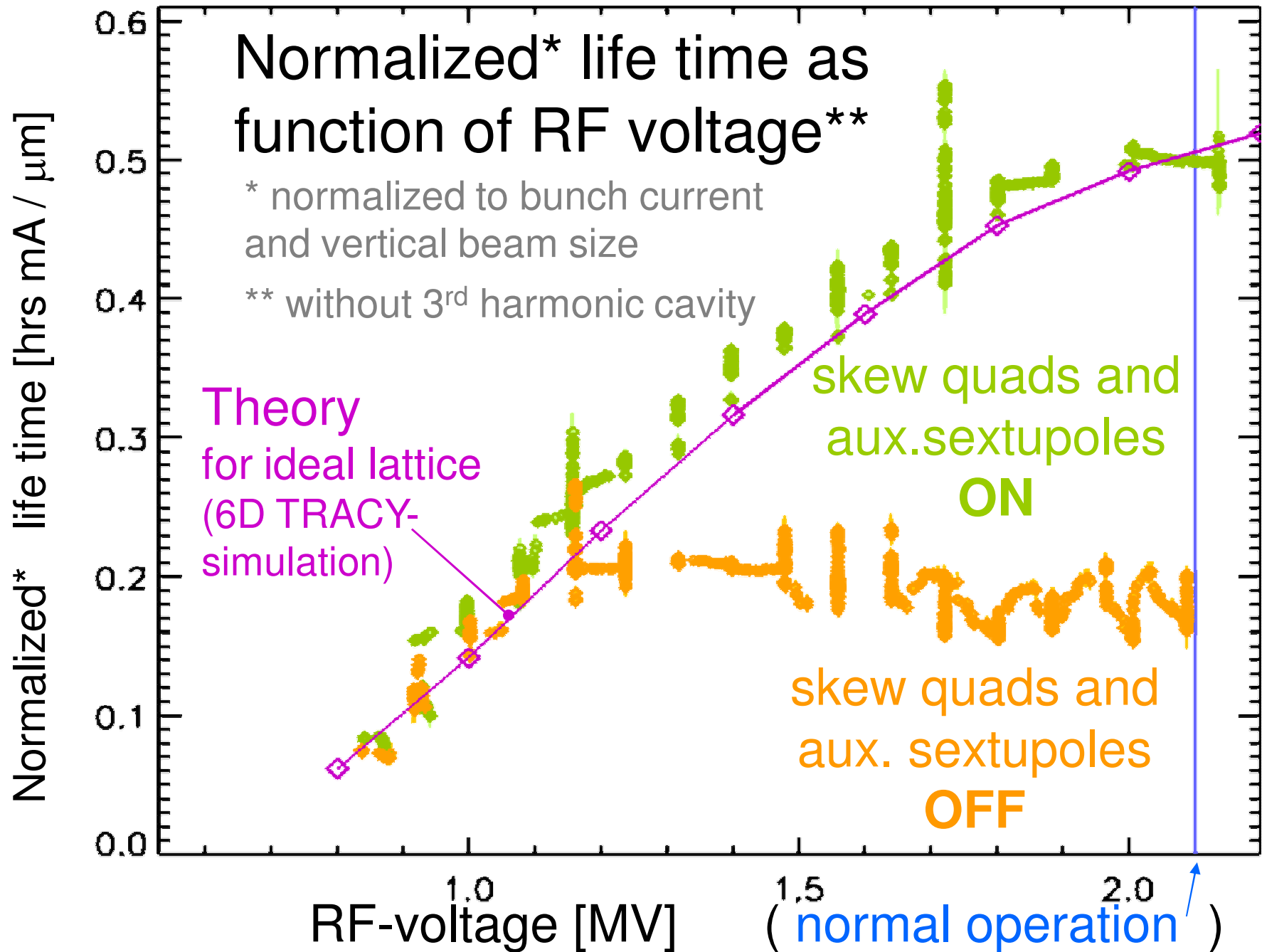
$h_{10200} \Rightarrow Q_x + 2Q_y$

$h_{10020} \Rightarrow Q_x - 2Q_y$

Empirical tuning

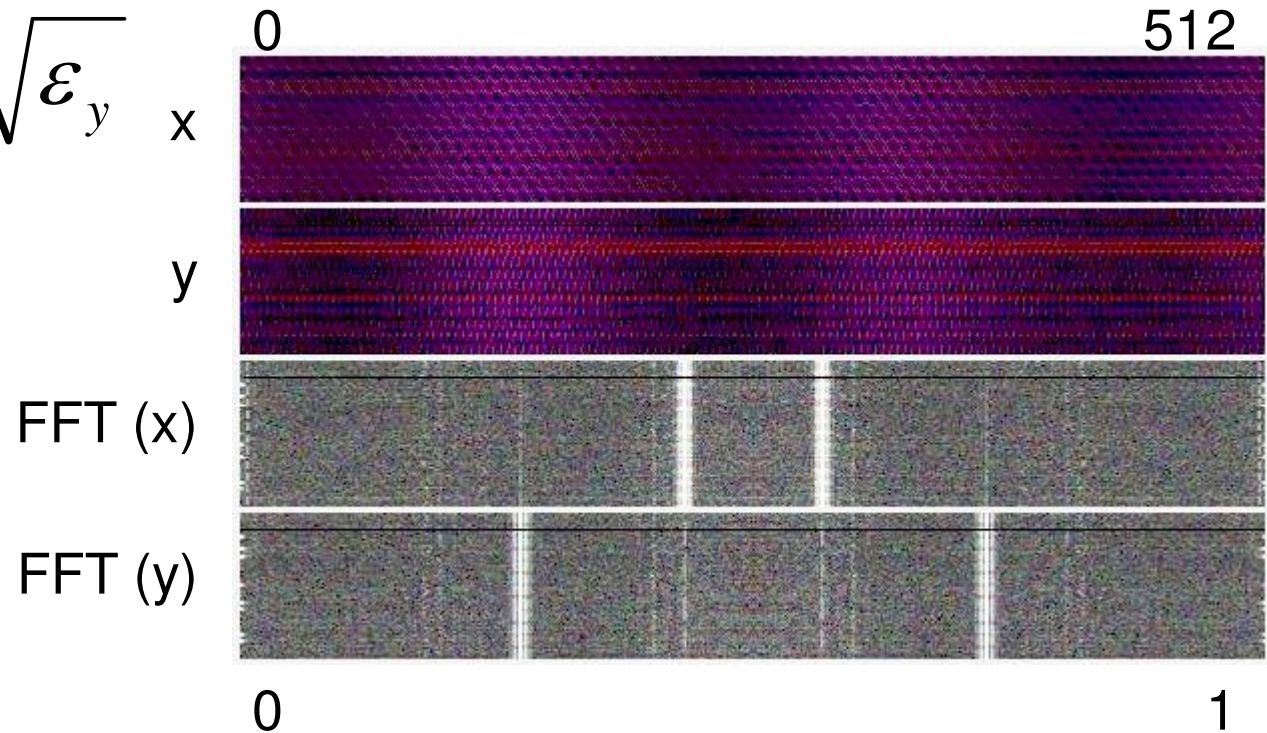
Ratio of vertical beam size to lifetime on stripchart

# Lifetime in agreement with design



# Future work on SLS ...

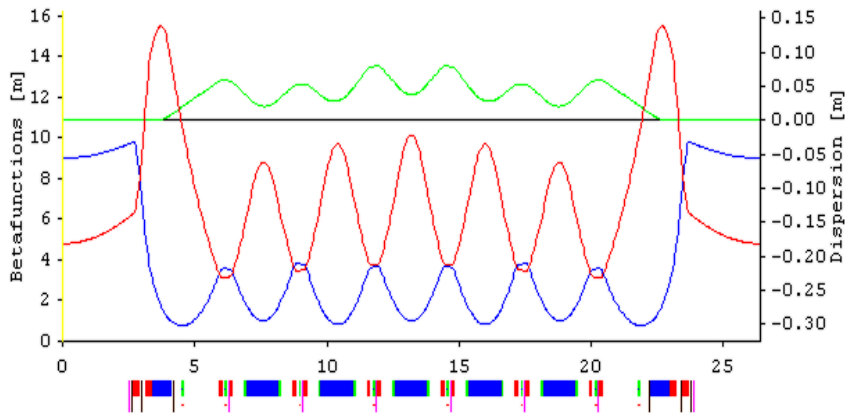
- ◆ Further suppression of betatron coupling:
  - eliminate steps between girders  $\Rightarrow$  girder realignment
  - centering of orbit in sextupoles  
 $\Rightarrow$  measurement of misalignments using skew quad coils
- ◆ controlled excitation of vertical dispersion:
  - set  $(T, \varepsilon_y)$  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.



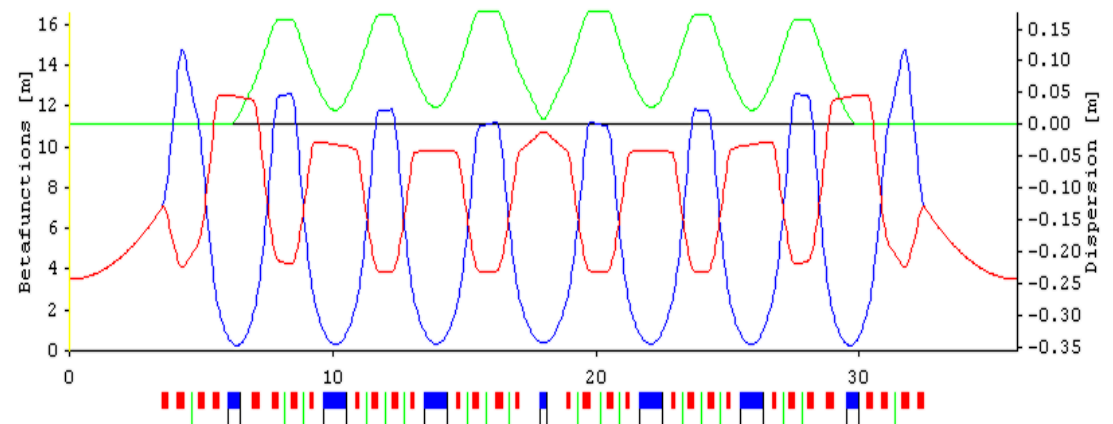


# MAX-IV – proper use of the 7BA

1/20 MAX-IV



1/6 SLS'93



7BA arcs

Energy  $E$

Emittance  $\varepsilon$

Tune  $Q$

norm. chrom.  $-\xi/Q$

Energy acceptance

Circumference

**MAX-IV**

20

3 GeV

**0.33 nm**

42.2 / 14.3

**1.2 / 3.1**

**> 5%**

**528 m**

**SLS'93**

6

2.1 GeV

3.2 nm

20.2 / 5.4

**2.7 / 3.4**

**~ 2%**

240 m

$\Rightarrow \Rightarrow$  scaled to

20

3 GeV

0.18 nm

67.3 / 18.0

> 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

◆ compact lattice

■ high gradients: short magnets

■ gradients in bending magnets

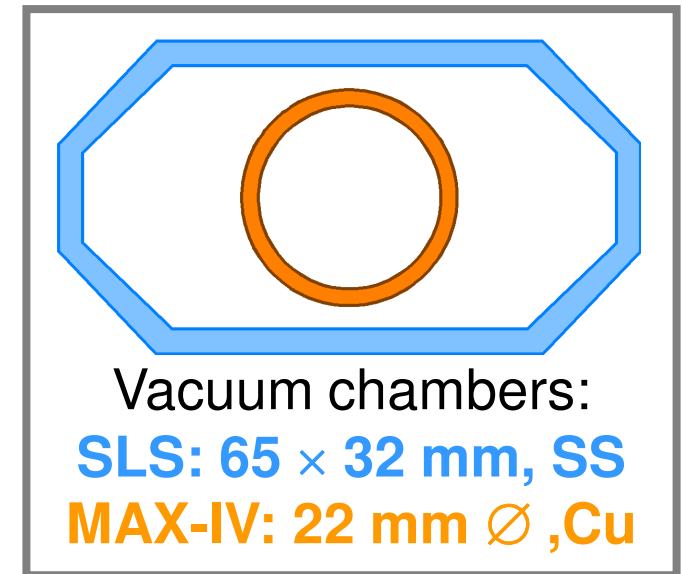
◆ nonlinear dynamics

■ 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 1<sup>st</sup> order phase-independent sextupole effects of 2<sup>nd</sup> and 3<sup>rd</sup> 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:

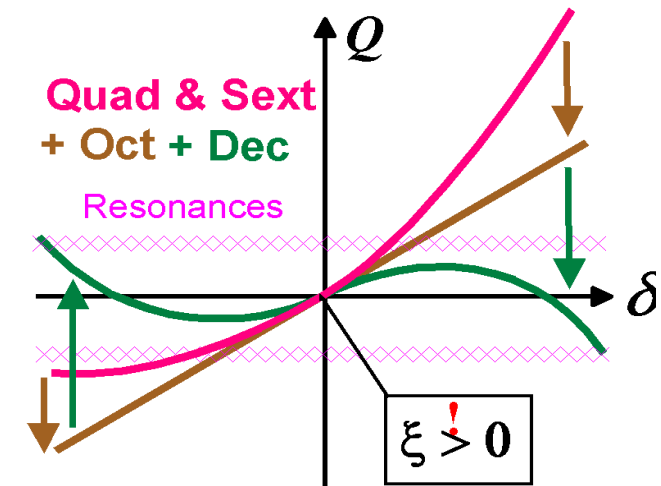
- cubic chromaticities:  $\partial^3 Q_x / \partial \delta^3$ ,  $\partial^3 Q_y / \partial \delta^3$
- quadratic ADTS and off-energy linear ADTS

### ◆ 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).

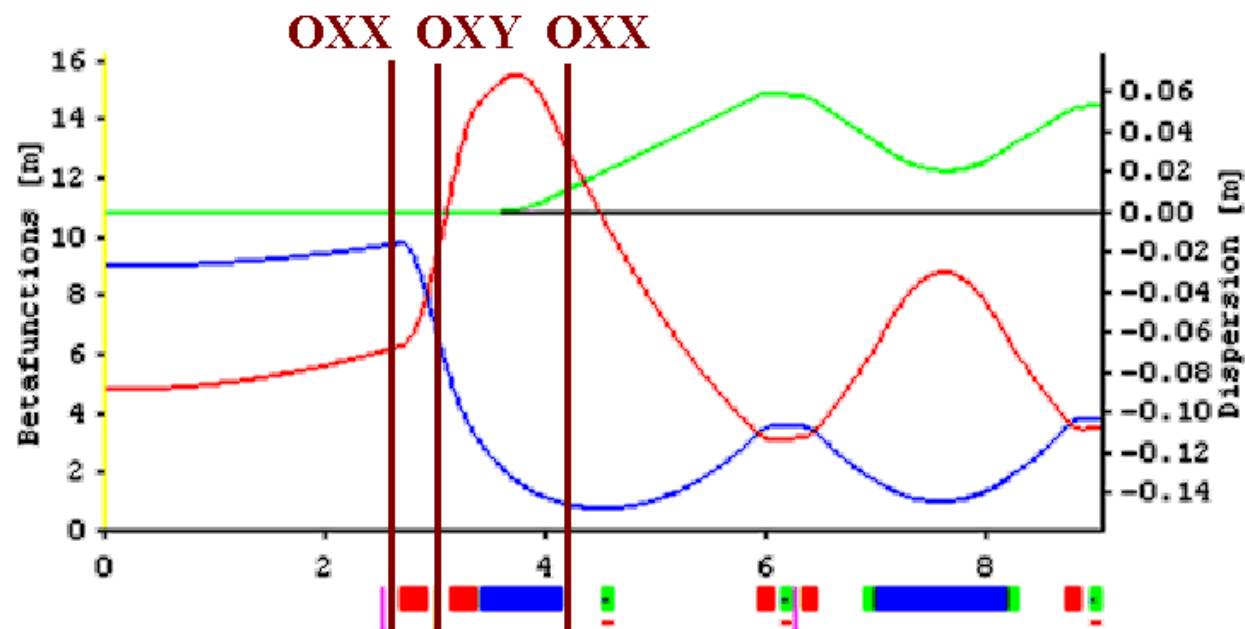


# h) ...tool upgrade and application

## 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:



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

2Qx	H20001	5.02						
2Qy	H00201	7.18						
CrX sqr		0.00	-20.25			-1.0	+	<input checked="" type="checkbox"/>
CrY sqr		0.00	-20.21			-1.0	+	<input type="checkbox"/>
dQxx		-2500.00	-2500.00			-1.0	+	<input checked="" type="checkbox"/>
dQxy, yx		4600.00	4600.00			-1.0	+	<input checked="" type="checkbox"/>
dQyy		6000.00	6000.00			-1.0	+	<input checked="" type="checkbox"/>
2Qx	H31000	1465.00				-1.0	+	<input checked="" type="checkbox"/>
4Qx	H40000	4434.18				-1.0	+	<input type="checkbox"/>
2Qx	H20110	34314.36				-1.0	+	<input type="checkbox"/>
2Qy	H11200	9873.73				-1.0	+	<input type="checkbox"/>
2Qx-2Qy	H20020	6557.55				-1.0	+	<input type="checkbox"/>



# Conclusions

- ◆ The  $12\times$ TBA lattice for the SLS was the right decision
  - compromise: number of straights, emittance, circumference
- ◆ Robust “standard method” of sextupole optimization
  - 1<sup>st</sup> and 2<sup>nd</sup> order sextupole Hamiltonian analytical
  - 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> 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