SLS-2 conceptual design and SLS status

Andreas Streun, PSI Villigen, Switzerland

Status of the SLS

♦ layout ♦ beam lines ♦ achievements
♦ operation statistics ♦ BPM system aging

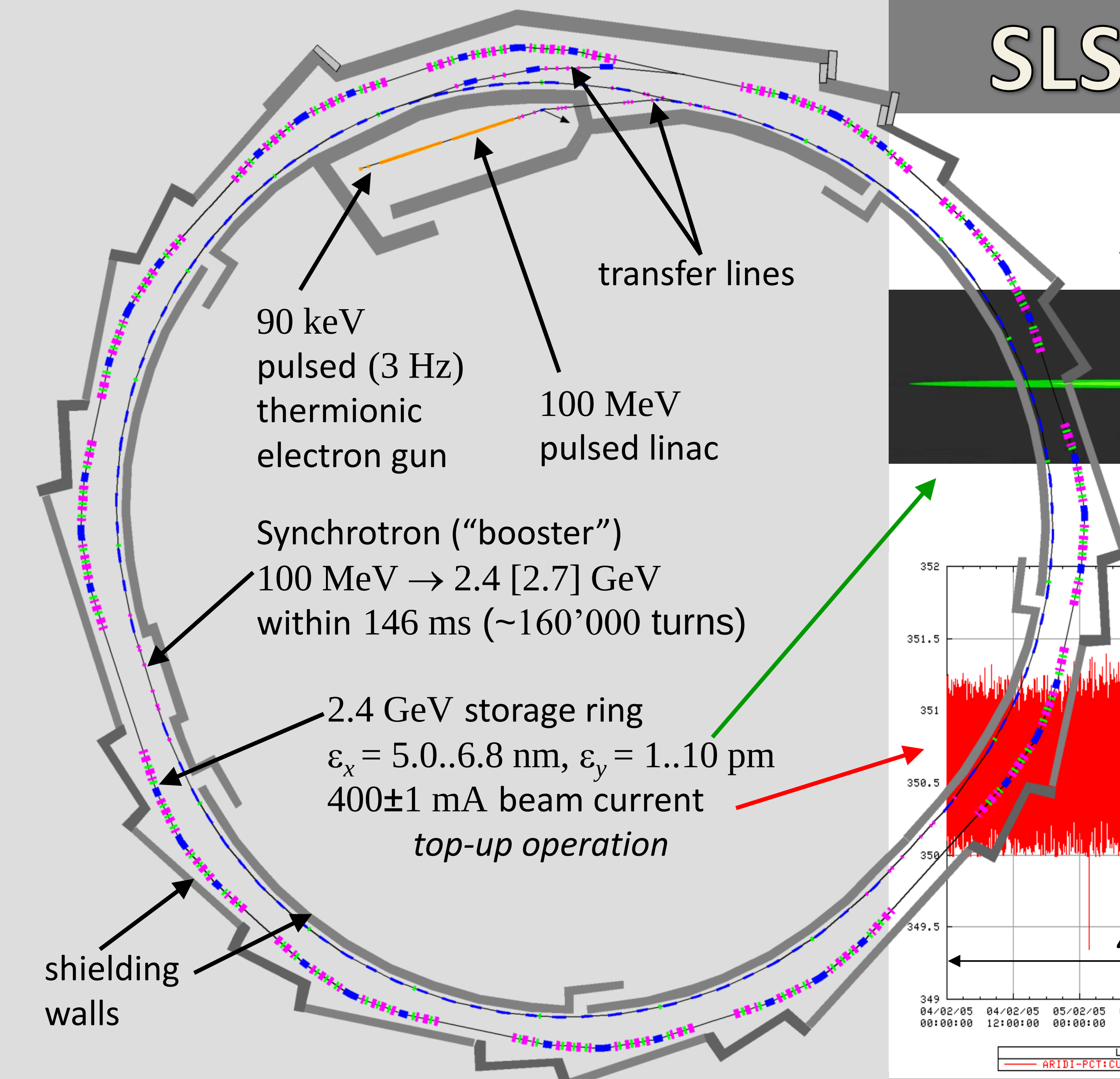
SLS-2 conceptual design

♦ conceptual design report ♦ time schedule and budget
♦ longitudinal gradient bends and anti-bends ♦ 7BA lattice
♦ source points and straight sections ♦ brightness and coherence
♦ dynamic aperture ♦ misalignments and corrections
♦ magnets ♦ vacuum ♦ injection

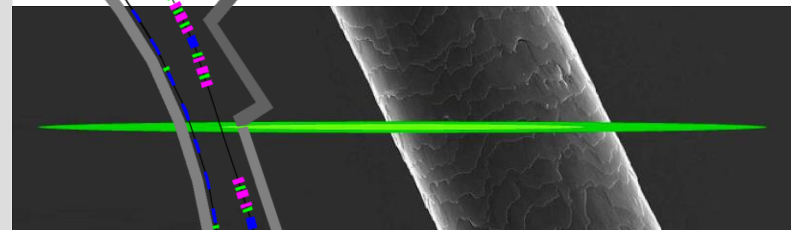
Summary and outlook

25th European Synchrotron Light Sources meeting
Nov. 21-22, 2017, Dortmund, Germany

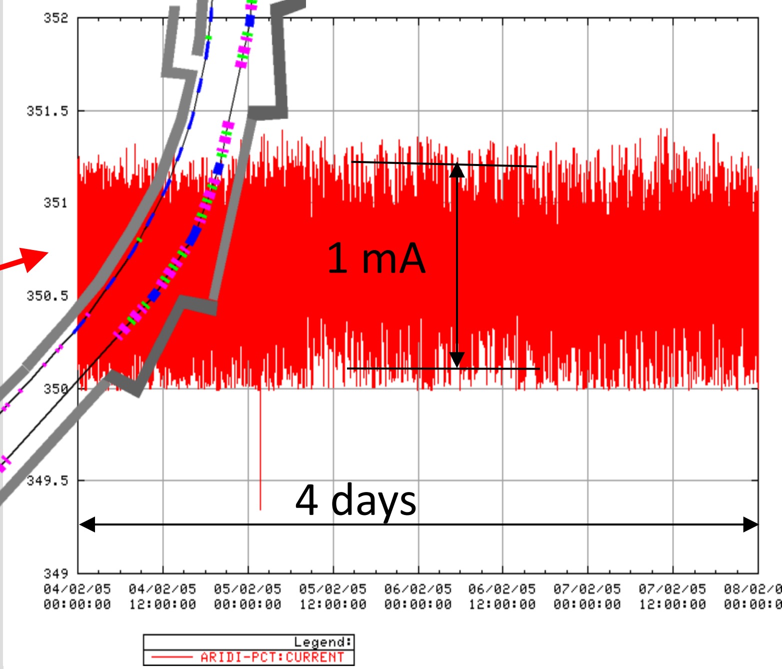
SLS status



Electron beam cross section in comparison to human hair



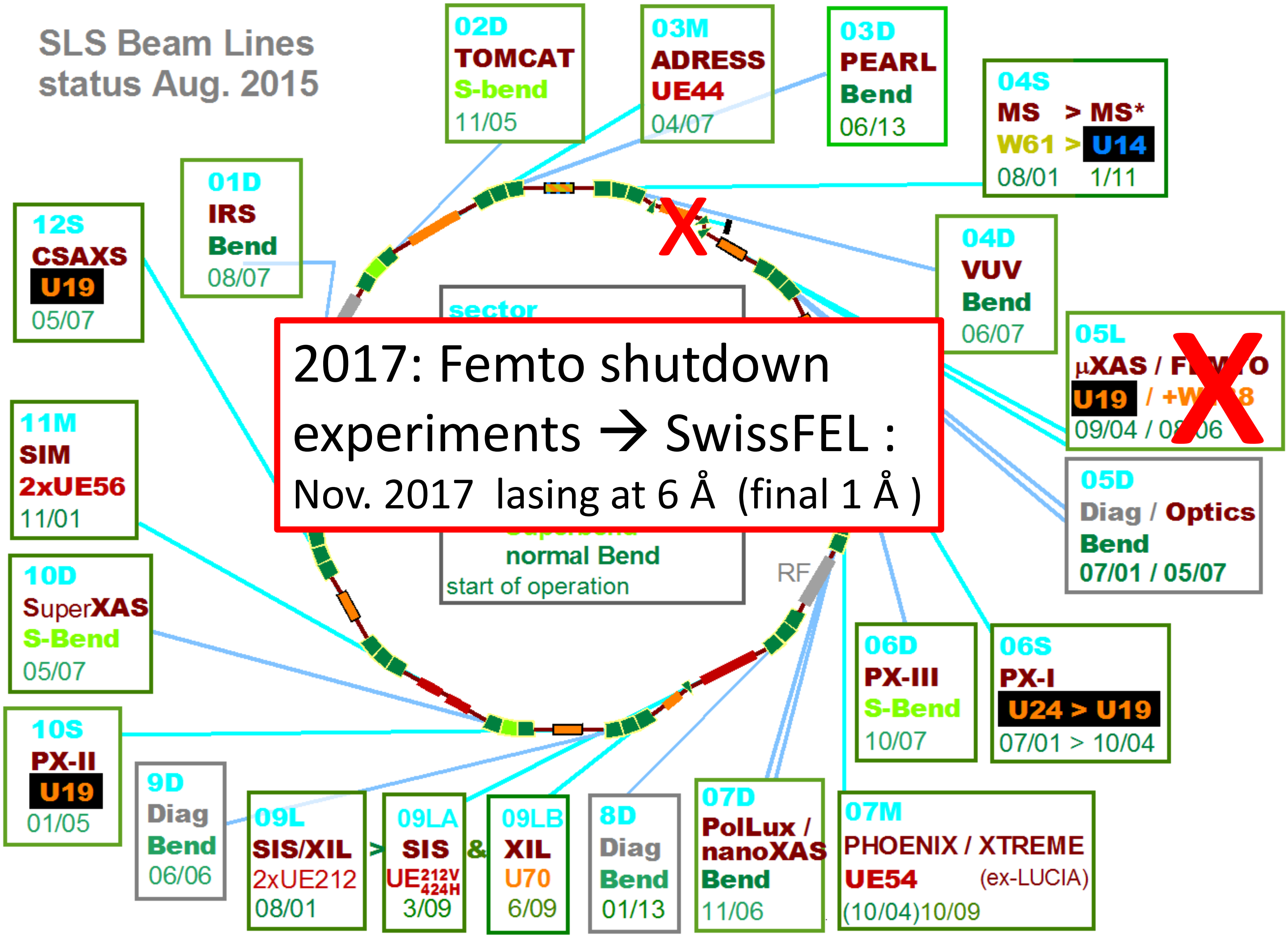
Current vs. time



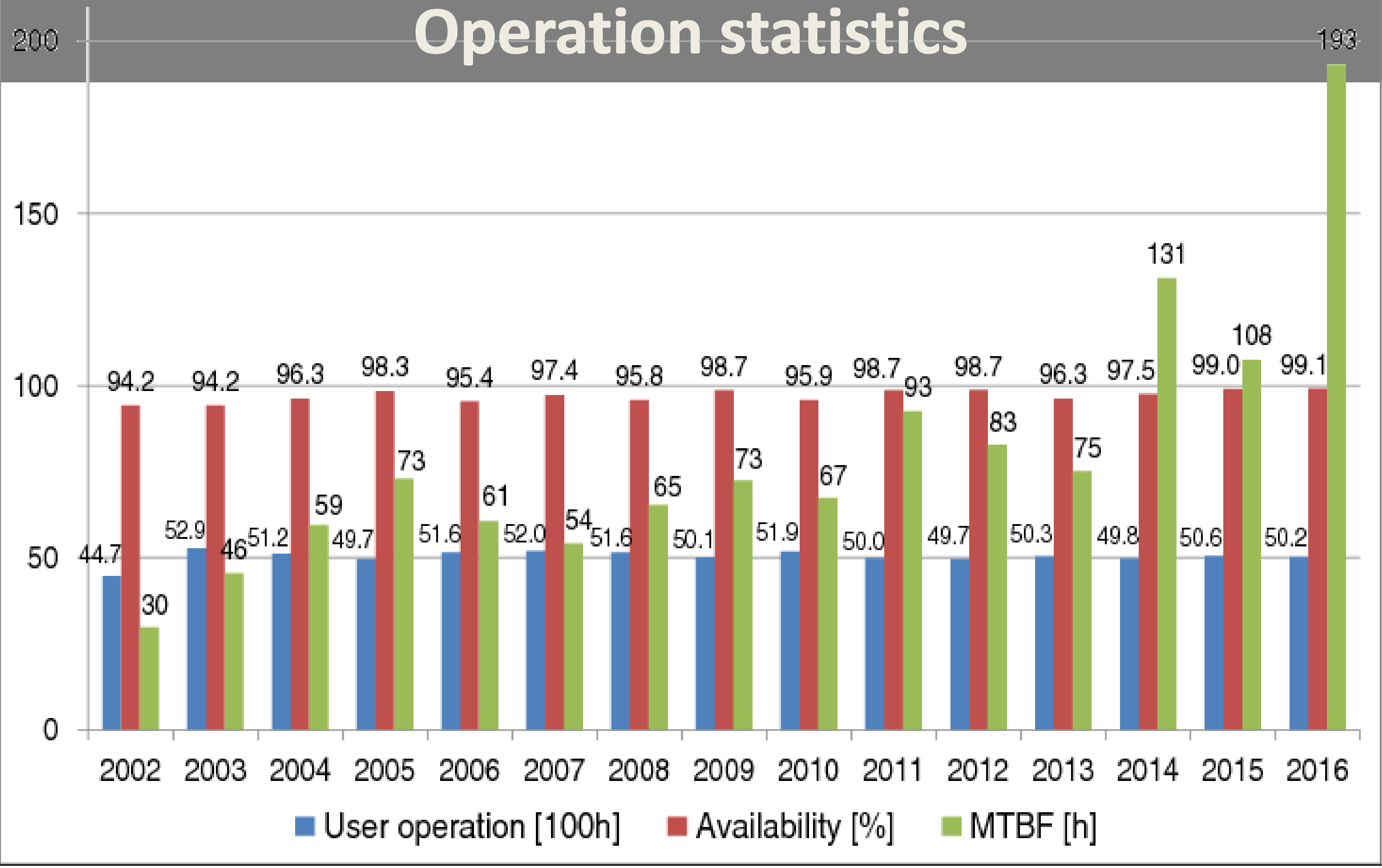
SLS major achievements

- **Reliability**
  - > 5000 hrs user beam time per year
  - 97.6% availability (2005-2016 average)
- **Top-up operation since 2001**
  - constant beam current 400-402 mA over many days
- **Photon beam stability $< 1\ \mu m$ rms (at frontends)**
  - fast orbit feedback system (< 100 Hz)
  - undulator feed forward tables, beam based alignment, dynamic girder realignment , photon BPM integration etc...
- **Ultra-low vertical emittance: 1.0 ± 0.3 pm**
  - model based and model independent optics correction
  - high resolution beam size monitor developments
- **150 fs FWHM hard X-ray source FEMTO**
  - laser-modulator-radiator insertion and beam line

SLS beam lines



Operation statistics



A. Lüdeke

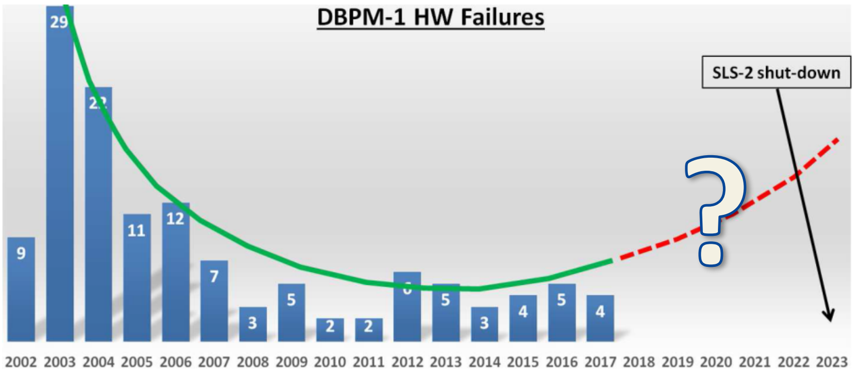
2017 (I-X): 4000 hrs Avail. 98.7% MTBF 150 h

BPM system

- 1st generation digital BPM system (Libera predecessor), design 1998.

  B. Keil, V. Schlott et al.

  - hardware failures per year →
  - maintenance/repair still possible but need substantial manpower
  - fading know-how (ASSEMBLER programming of DSP boards...)



- SLS upgrade
  - 2013: plan to upgrade BPM and FOFB (fast orbit feedback) electronics in 2015/16 using SwissFEL/E-XFEL BPM platform
  - postponed for budget reasons

→ **SLS-2 project:** SLS storage ring upgrade

- double number of BPMs, beam in 2024
- 2017: start development of new SLS-2 BPM platform with latest technology
  - motivation: much lower costs, longer availability
- will be used for SLS (1) upgrade ≥2020
- integration of SLS-2 photon monitors into FOFB

SLS-2 Conceptual design

SLS: > 16 years of very successful operation...

... but emittance **5 nm** at 2.4 GeV not competitive in near future

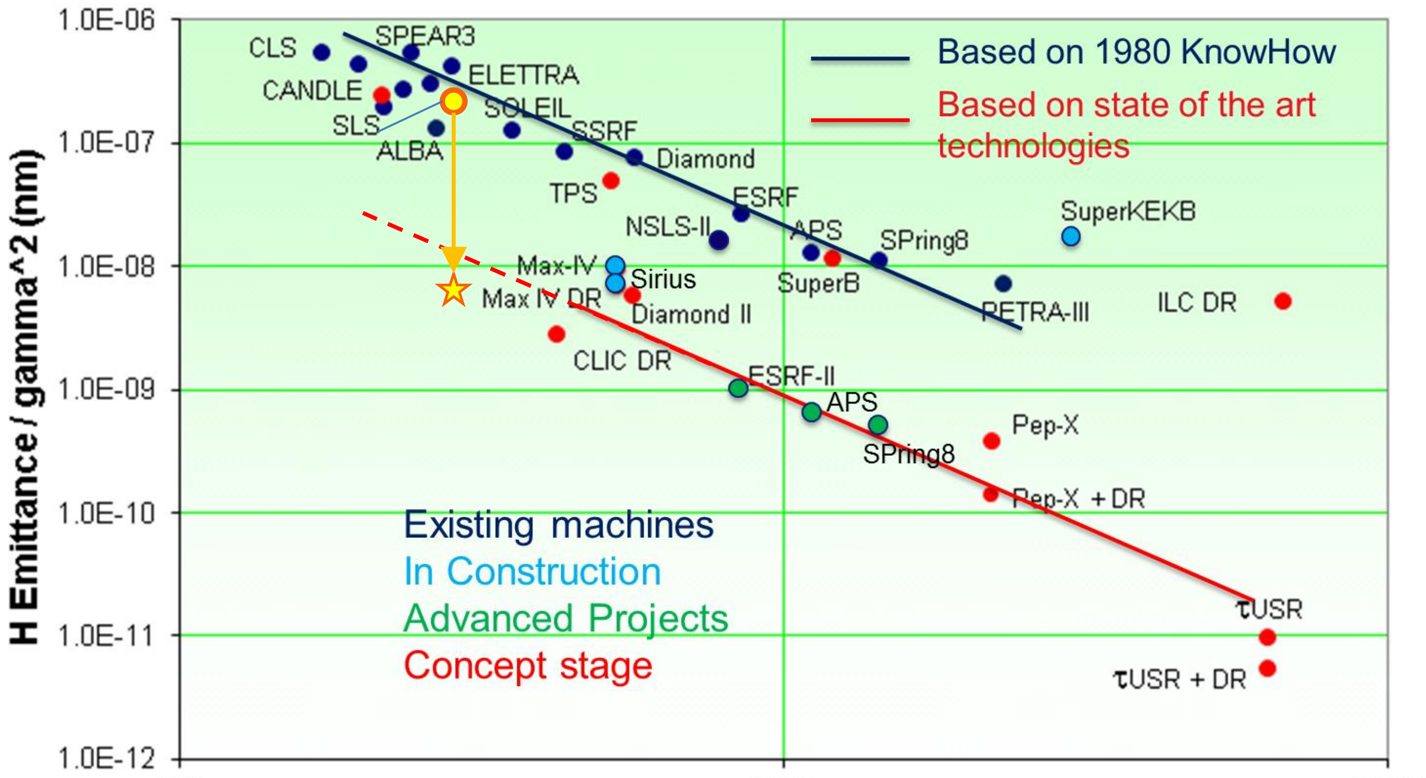


Figure from P. Raimondi, LELD-1 WS, Barcelona, April 2015

SLS

↓

SLS-2

Emittance scaling

$\varepsilon \propto \gamma^2 C^{-3}$

→ linear fit

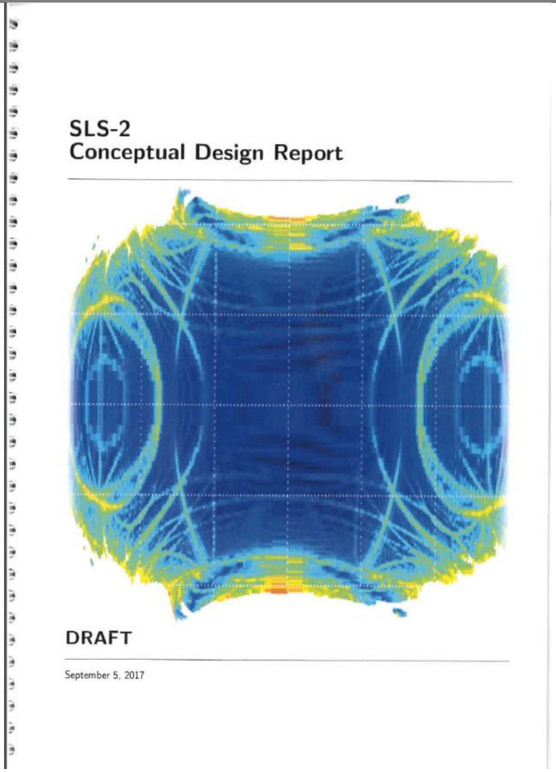
$$\log \frac{\varepsilon}{\gamma^2} = K - 3 \cdot \log C$$

$K \approx 1.5 \rightarrow \approx 0$

improvement ×30

Conceptual Design Report

- New storage ring: 12 × 7-BA
  - 100 pm (125 pm with IBS) at 2.4 GeV
  - 290.4 m circumference
  - 12 × 5½ m straight sections
- Conceptual Design Report
  - DRAFT Sep. 5, 2017 → final Dec. 22, 2017
  - http://ados.web.psi.ch/SLS2/CDR/Doc/cdr.pdf
- CDR review meeting, Sep. 26-27, 2017
- Submission to SNF (Swiss National Science Foundation) < 31.12.2017
  - Swiss research infrastructure roadmap 2021-24
  - total budget 100 MCHF (machine <u>and</u> beamlines, without salaries)



SLS-2 objective

Upgrade task: factor >30 lower emittance

+ harder X-rays

SLS challenge: small circumference

- No space for very many lattice cells (MBA)
- No space for damping wigglers

Scaling of new ring designs to SLS upgrade:

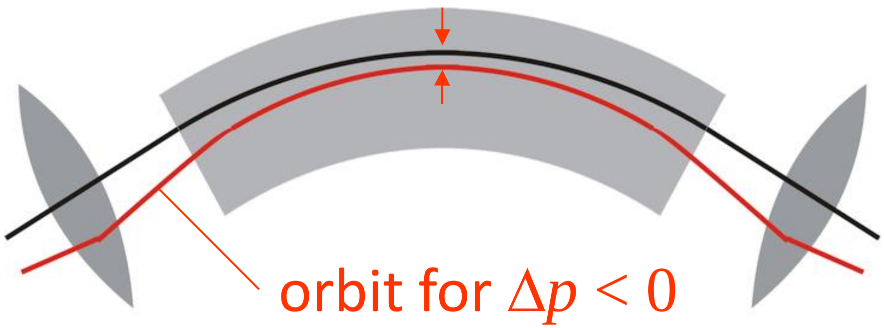
Approximate emittance scaling $\varepsilon_x \propto (\text{Energy})^2 / (\text{Circumference})^3$

SLS	E = 2.4 GeV	C = 288 m			
MAX IV	E = 3 GeV	C = 528 m	ε_x = 328 pm	$\rightarrow$	1290 pm
SIRIUS	E = 3 GeV	C = 518 m	ε_x = 240 pm	$\rightarrow$	950 pm
ESRF-EBS	E = 6 GeV	C = 844 m	ε_x = 147 pm	$\rightarrow$	590 pm

⇨ **SLS-2:** New lattice cell concept $\varepsilon_x \rightarrow$ **~100 pm**

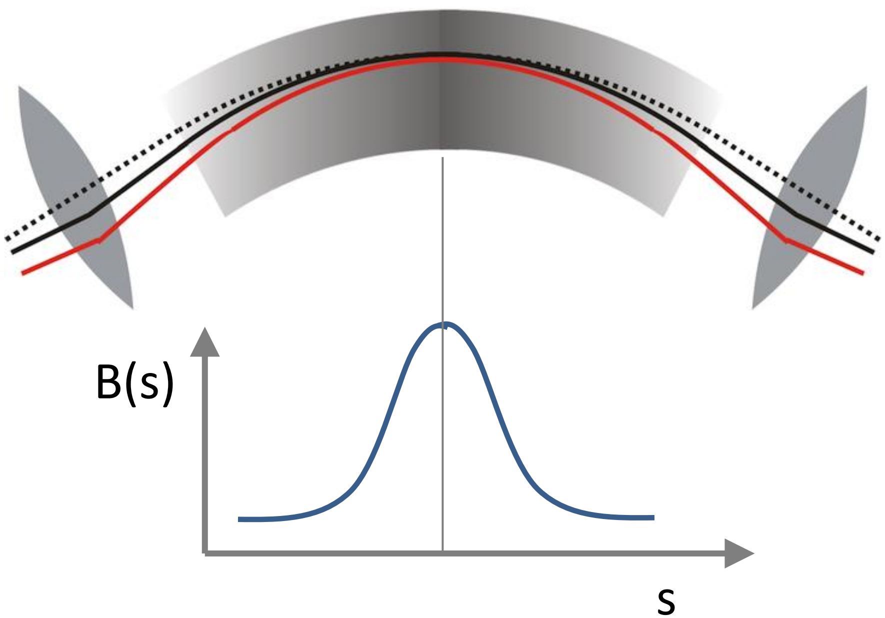
SLS-2 lattice cell

⇨ CDR page 10



Standard MBA cell

- quadrupoles (lenses) to focus dispersion
- dispersion at center > 0 (*"the dilemma of the TME cell"*)



SLS-2 modified MBA cell

- displaced quadrupoles = **reverse bending magnets (RB)**
- dispersion at centre $\rightarrow$ 0
- longitudinal field variation in dipole magnet: max. B at center = **longitudinal gradient bend (LGB)**

⇨ 5× lower emittance than conventional cell

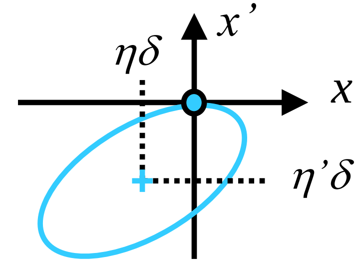
Quantum excitation

$$I_5 = \int |h|^3 \mathcal{H}\, ds$$

LGB

Minimization of I_5

$\eta \rightarrow \approx 0$ where $h \rightarrow$ max.



RB dispersion matching:

$\eta \rightarrow \approx 0$ at LGB center.

$$h = \frac{1}{\rho} = \frac{e}{p} B_y \qquad \mathcal{H} = \frac{\eta^2 + (\alpha\eta + \beta\eta')^2}{\beta}$$

Radiation integrals

$$\varepsilon_{xo}[\mathrm{m \cdot rad}] = \tilde{C}_q \, (E[\mathrm{GeV}])^2 \, \frac{I_5}{I_2 - I_4}$$

$$\tilde{C}_q = 1470 \frac{\mathrm{nm \cdot rad}}{\mathrm{GeV}^2}$$

Damping partitioning

$$I_4 = \int h\eta(h^2 + 2k)\, ds$$

$$k = \frac{e}{p} \frac{\partial B_y}{\partial x}$$

Increase of horizontal damping partition number $J_x = 1 - I_4/I_2$

traditional (combined function):

$k < 0$ where $h > 0,\ \eta > 0$

RB

$k > 0$ where $h < 0,\ \eta > 0$

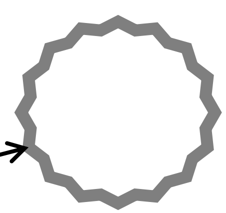
Damping

$$I_2 = \int h^2\, ds$$

Increase of radiation loss $\sim I_2$

LGB I_2 increase for $h = h(s)$

RB Σ|bend angles| > 2π



SLS-2 cell: how LGB and RB work together

⇨ CDR p. 12

SLS-2 Cell: 5° angle, 2.48 m length. $\nu_{x;y}$ = 0.428 (=3/7); 0.143 (=1/7)

LGB angle = 4.38°

VB angle = 0.31° $+\theta$

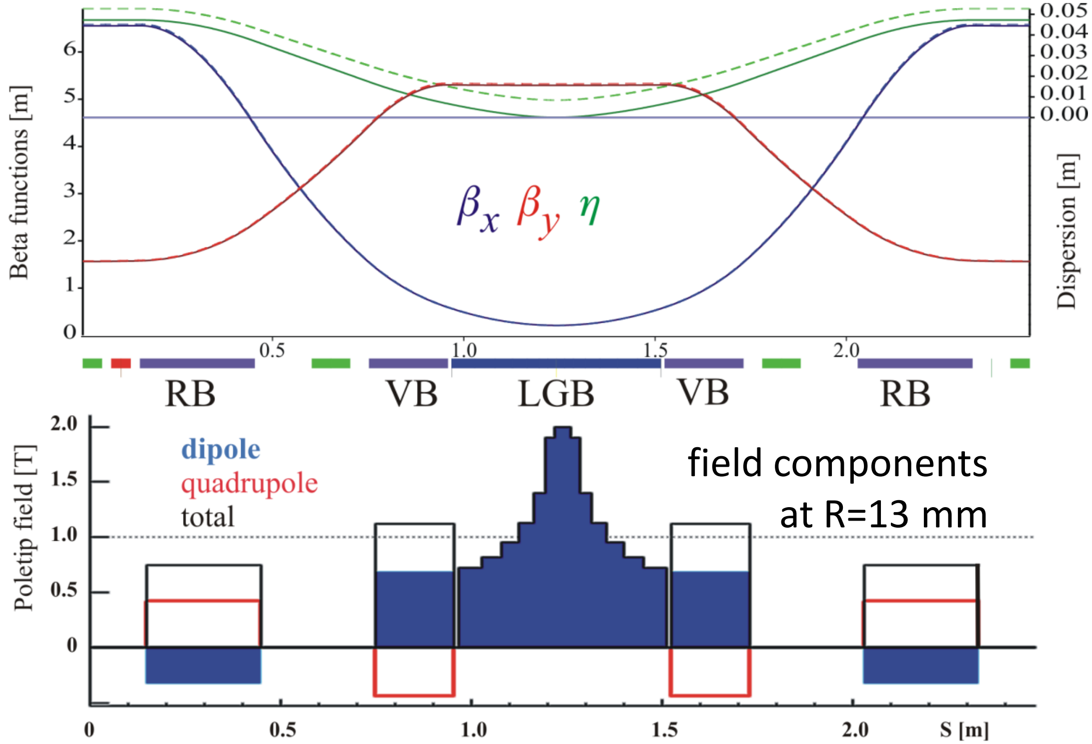
RB angle = $-\theta$

→ gain

$\theta = -0.7°$ (——) vs. $\theta = 0°$ (- - -)

$$\tilde{C}_q E^2 \frac{I_5}{I_2 \, J_x} = \varepsilon_{xo}$$

I_5: ÷ 2.30; I_2: ×1.30; J_x: ×1.53; ε_{xo}: ÷ 4.58

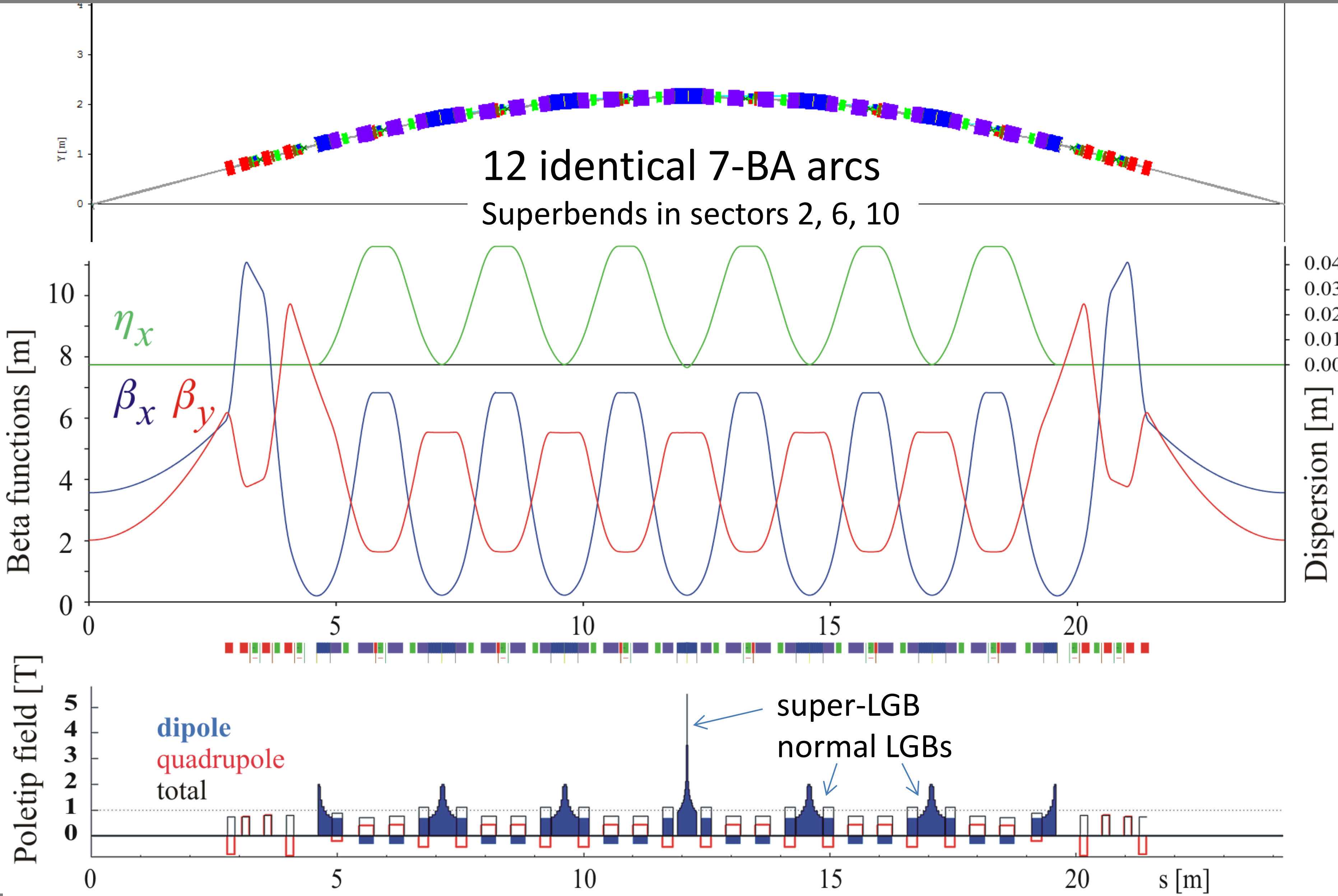


RB-angle θ	ε [pm]	J_x	ΔE [keV]	α
$-0.7°$ ——	100	1.75	7.6	$-0.21 \cdot 10^{-3}$
0 - - - -	458	1.14	5.8	$+0.40 \cdot 10^{-3}$

To get low emittance from an LGB requires RBs for dispersion matching! (in a periodic cell)

SLS-2 7-BA

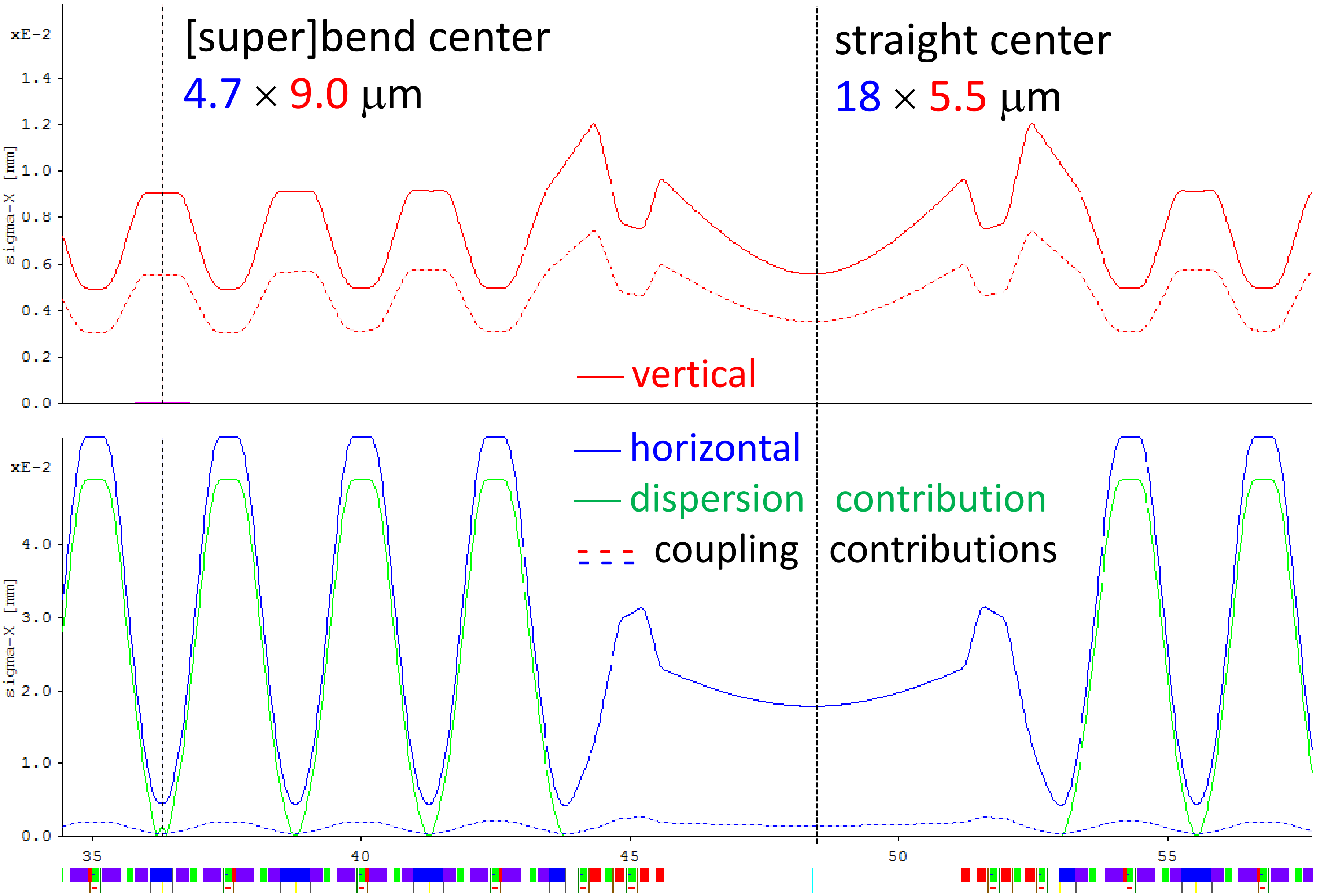
⇨ CDR p. 14



Beam size

rms envelopes for 10% emittance coupling (no IBS)

emittances 98 pm / 10 pm



Periods			3
Length	[m]		290.400
Angle	[deg]		360.000
AbsAngle	[deg]		561.600
TuneA			39.19298
TuneB			15.30746
ChromA			0.000
ChromB			0.000
Alpha	[xE-3]		-0.133
JA			1.66685
JB			1.04354
Energy	[GeV]		2.400
EmitA	[nm rd]		0.098
EmitB	[nm rd]		0.010
dE/turn	[keV]		554.4
Espread	[xE-3]		1.036
TauA	[ms]		5.031
TauB	[ms]		8.036
TauE	[ms]		6.503
Location			BSOM
Position	m		36.300
BetaA	m		0.209
AlphaA			0.0000
BetaB	m		5.318
AlphaB			0.0000
Disp X	m		-0.0012
Disp'X	rad		0.0000
Disp Y.	m		0.0000
Disp'Y	rad		0.0000
PhiA/2pi			4.8989
PhiB/2pi			1.9134
curly H	m		(to do)
Orbit X	mm		0.0000
Orbit X'	mrad		0.0000

Lattice parameters

⇨ CDR p. 15

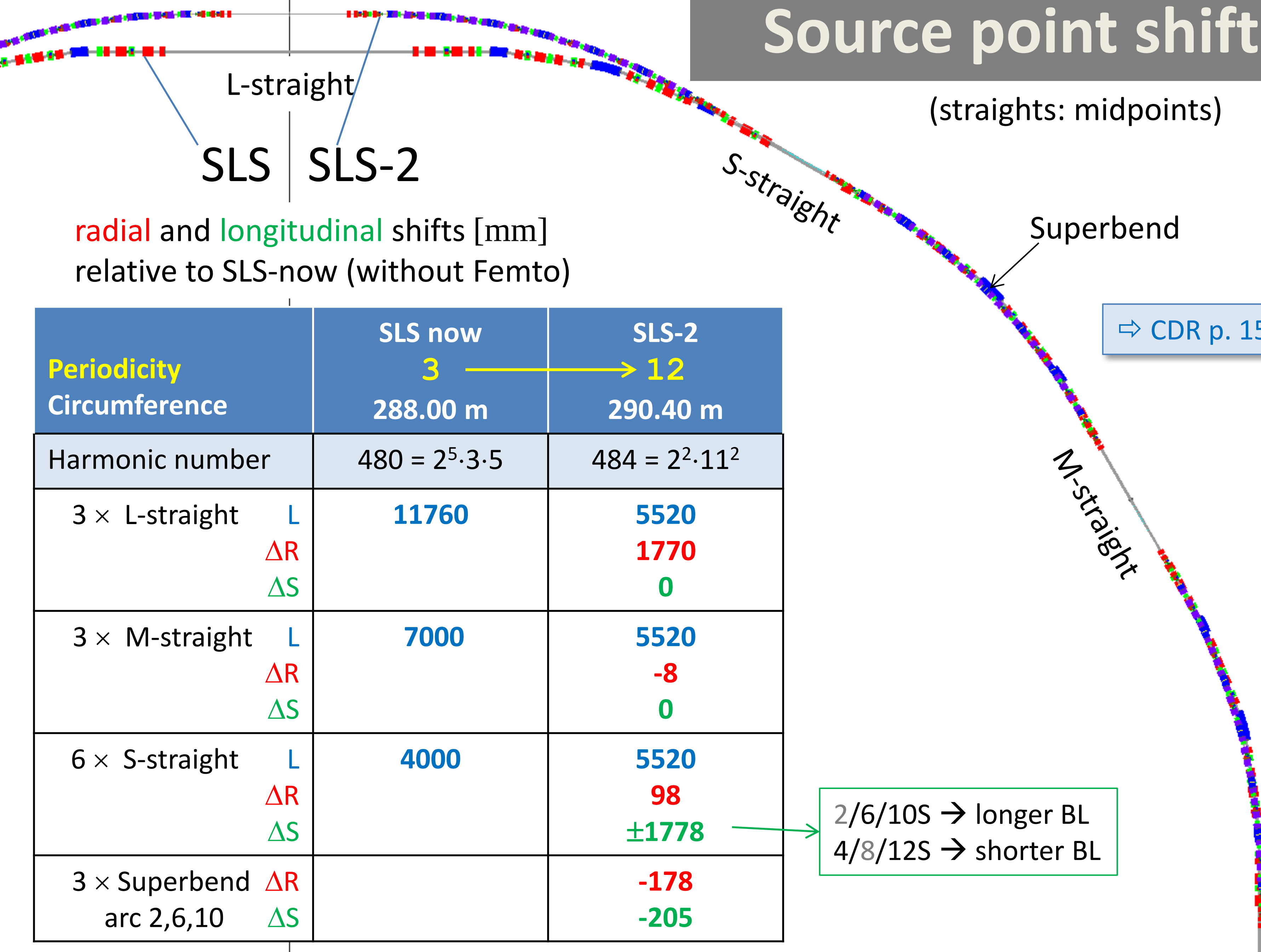
Name	SLS*)	SLS-2#)
Emittance at 2.4 GeV [pm]	**5069**	**102 → 126**♦)
Lattice type	12×TBA	12×**7**BA
Circumference [m]	288.0	290.4
Total *absolute* bending angle	360°	561.6°
Working point $Q_{x/y}$	20.43 / 8.22	39.2 / 15.30
Natural chromaticities $C_{x/y}$	–67.0 / –19.8	–95.0 / –35.2
Optics strain1)	7.9	5.6
Horizontal damping Partition J_x	1.00	1.71
Momentum compaction factor [10^{-4}]	6.56	–1.33
Radiated Power [kW] 2)	208	222
rms energy spread [10^{-3}]	0.86	1.03 → 1.07♦)
damping times x/y/E [ms]	8.9 / 8.9 / 4.4	4.9 / 8.4 / 6.5

1) product of horiz. and vert. normalized chromaticities C/Q
2) assuming 400 mA stored current, bare lattice without IDs
*) SLS lattice before FEMTO installation (<2005)
#) SLS-2 with 3 superbends

♦) including intra-beam scattering for 1 mA bunch current (400 mA in 400 of 484 buckets; 500 MHz), 10 pm vertical emittance, 1.4 MV RF voltage, 3rd harmonic cavity for 2.2×bunch length.

Source point shifts

(straights: midpoints)



radial and longitudinal shifts [mm]
relative to SLS-now (without Femto)

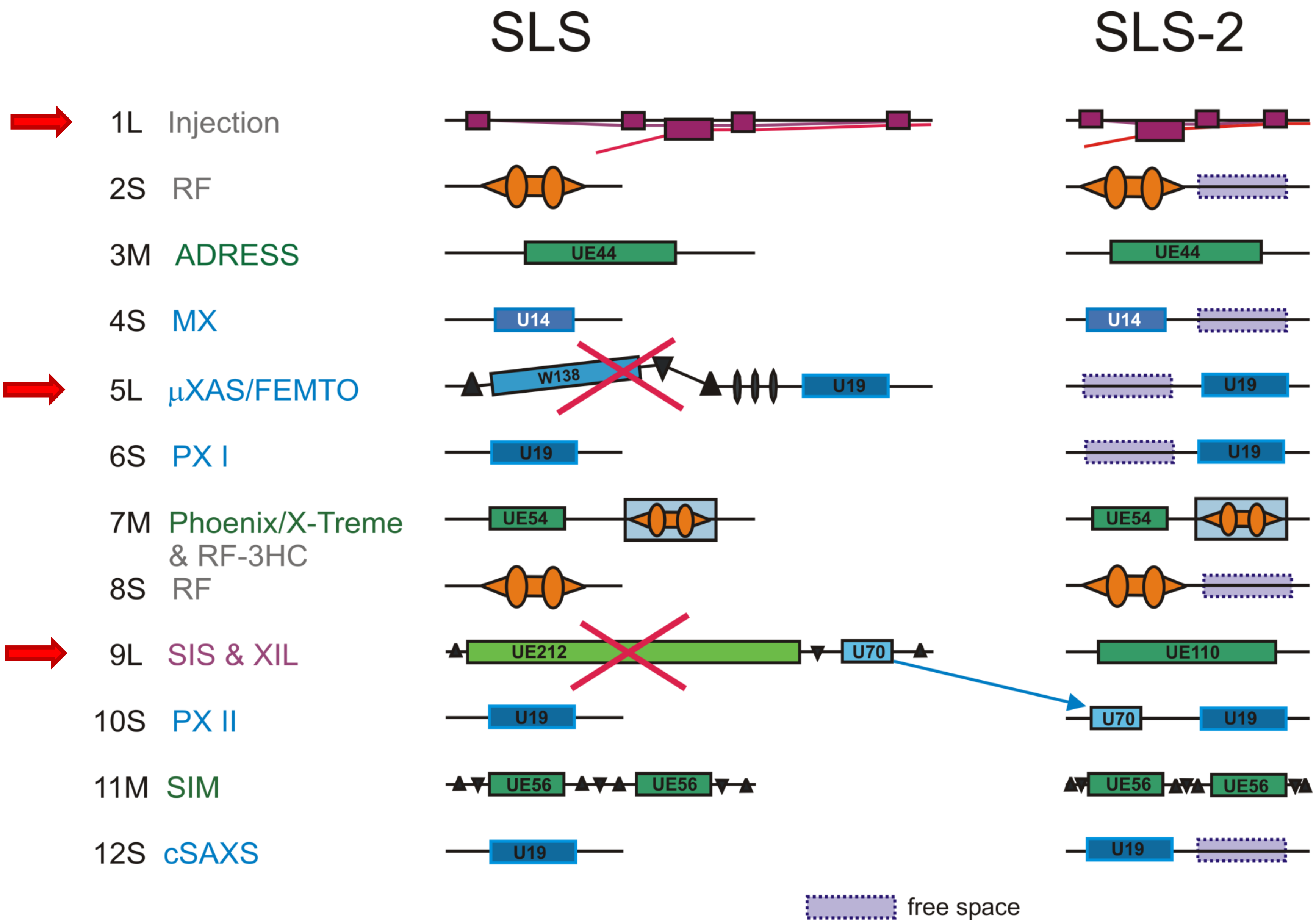
⇨ CDR p. 15,138

		SLS now	SLS-2
Periodicity		3 →	12
Circumference		288.00 m	290.40 m
Harmonic number		$480 = 2^5 \cdot 3 \cdot 5$	$484 = 2^2 \cdot 11^2$
3 × L-straight	L	11760	5520
	ΔR		1770
	ΔS		0
3 × M-straight	L	7000	5520
	ΔR		-8
	ΔS		0
6 × S-straight	L	4000	5520
	ΔR		98
	ΔS		±1778
3 × Superbend	ΔR		-178
arc 2,6,10	ΔS		-205

2/6/10S → longer BL
4/8/12S → shorter BL

Straight sections

⇨ CDR p. 128



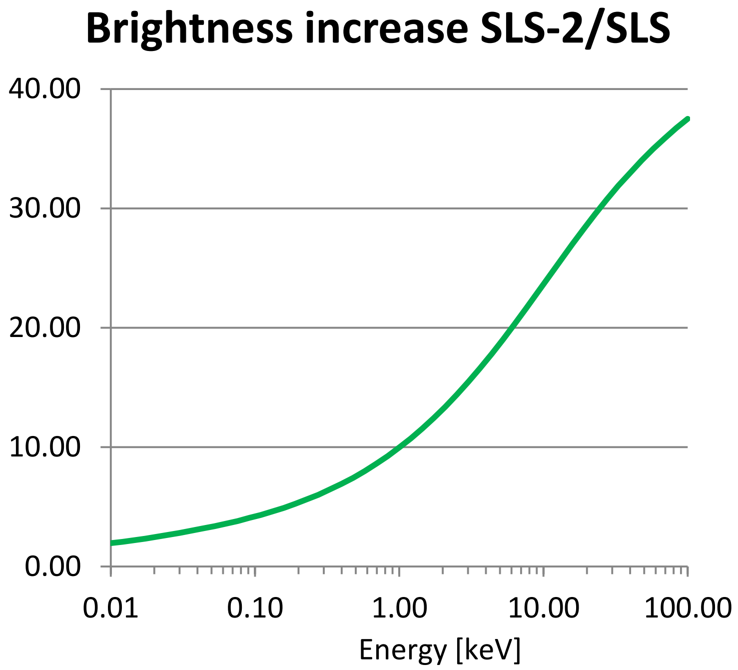
Undulator brightness and coherence

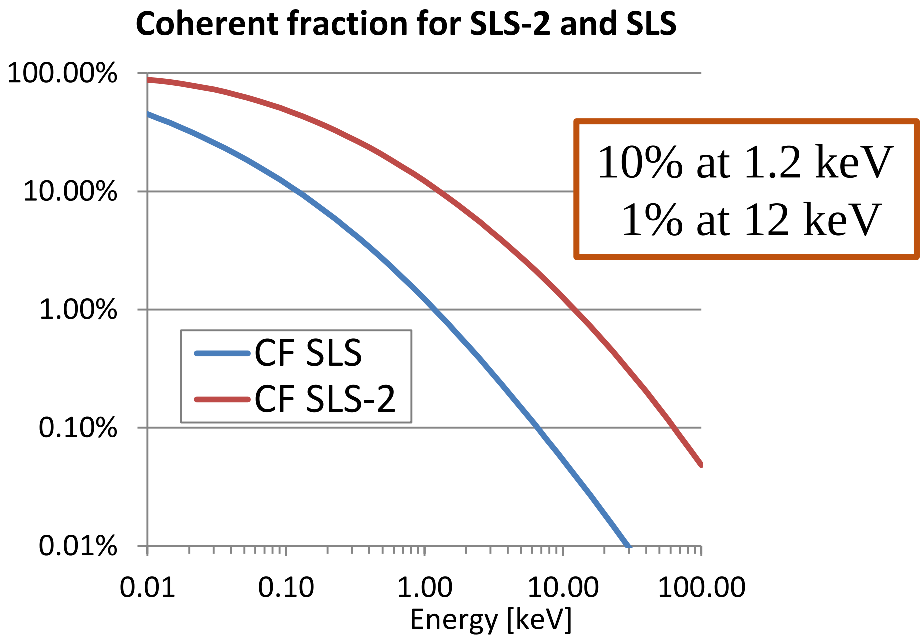
Photon energy range 0.01...100 keV ≅ 0.12...1240 Å

(Used energy range at SLS = 0.09...45 keV)

2 m long undulator from SLS short straight. Vertical emittance 10 pm.

Horizontal emittance: SLS 5500 pm (incl. Femto), SLS-2 126 pm (incl. IBS)





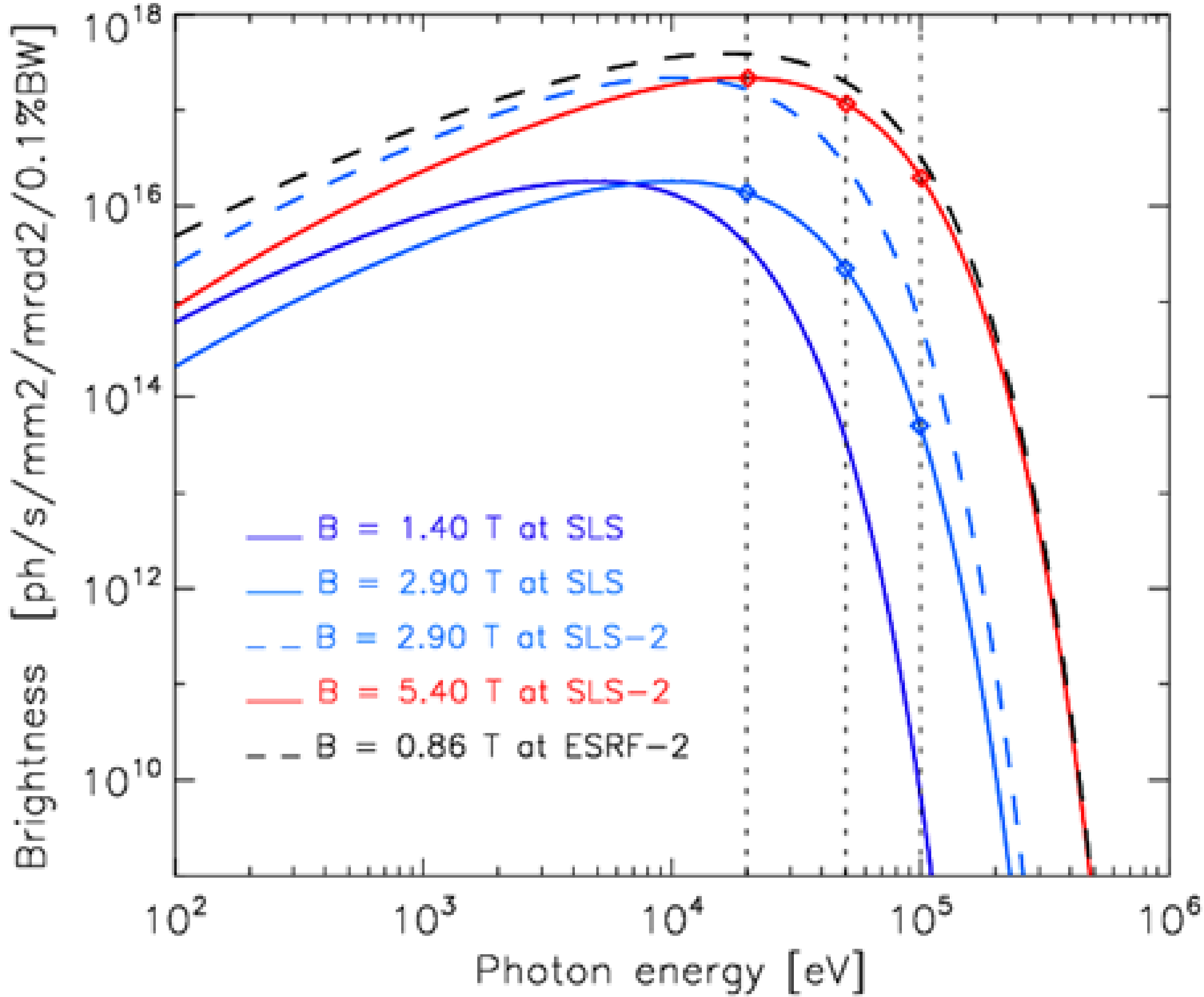
$$\left.\begin{array}{r} B(\lambda) \\ CF(\lambda) \end{array}\right\} = \frac{1}{\varepsilon_{\gamma x}(\lambda)\times\varepsilon_{\gamma y}(\lambda)} \times \left\{\begin{array}{c} \dot{N}(\lambda)/4\pi^2\mathrm{BW} \\ \left(\varepsilon_r(\lambda)\right)^2 \end{array}\right.$$

$\dot{N}(\lambda)$ spectral photon flux

BW bandwidth of experiment

$\varepsilon_{\gamma x,y}$ convoluted photon beam emittances, $\varepsilon_r = \lambda/4\pi$ diffraction emittance

Super-LGB brightness



Super-LGB brightness
for ±0.5 mrad fan angle &
full vertical acceptance

- 2.9 T at SLS
- 5.4 T at SLS-2

- - ESRF-EBS (6 GeV)
0.86 T 2-pole wiggler

Dynamic acceptance optimization

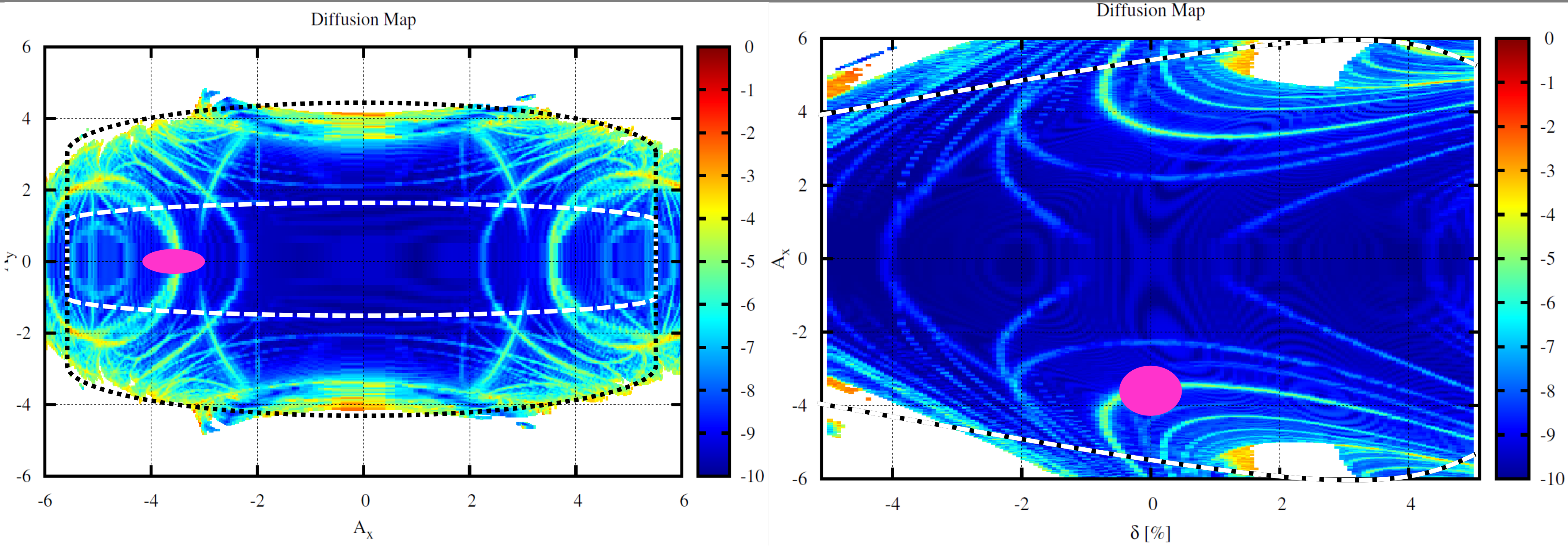
⇨ CDR p. 17/18

- Phase cancellation
  - cell tunes $\Delta\nu_x = 3/7 \approx 0.428$ and $\Delta\nu_y = 1/7 \approx 0.143$
    ⇨ cancellation of all regular sextupole and octupole resonances over 7 cells
    - cell tune $\Delta\nu_x \approx 0.43$ most effective for dispersion suppression by reverse bend.
- Minimization of higher order terms
  - amplitude dependent tune shifts (ADTS) (analytic)
  - 2^{nd} order sextupole / 1^{st} order octupole resonances
  - higher order chromaticities (numeric)
  - → 7 sextupole and 6 octupole families
- direct optimization of dynamic apertures
  - multi-objective genetic algorithm (MOGA)
    - used for previous lattice version, not yet for the CDR version.

J. Bengtsson, M. Aiba, M. Ehrlichman

Dynamic aperture

⇨ CDR p. 19



Diffusion maps (stable ↔ unstable) for bare (i.e. error-free) lattice

⇖ in {x,y} space in {Δp/p, x} space ⇗

color defines stable motion (4000 turns), white=unstable

· · · · physical aperture limit from $r = 10$ mm beam pipe

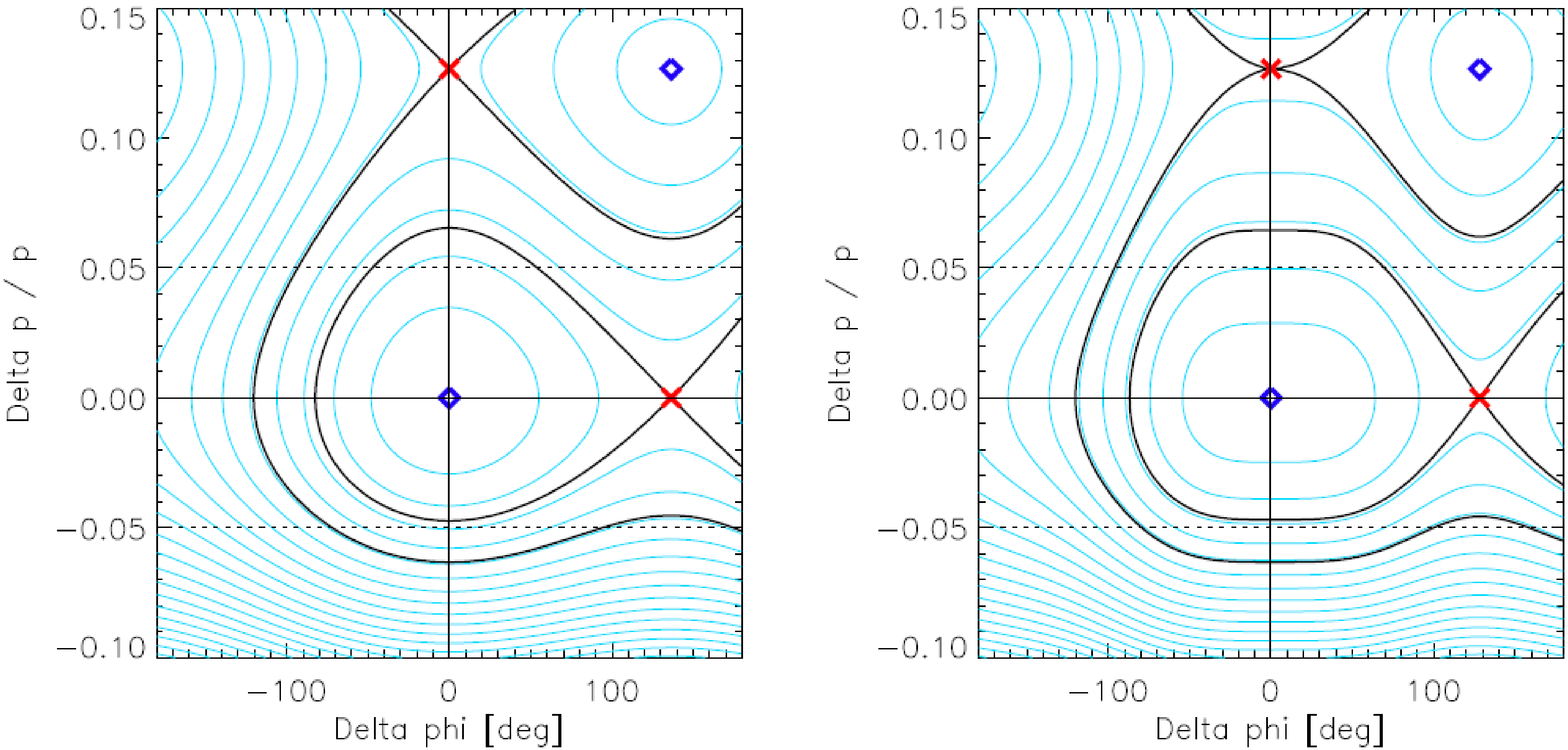
- - - - physical aperture with undulator gaps (4 mm gap on 2 m length)

approx. injected beam from booster (3σ)

M. Böge, J. Bengtsson, M. Aiba

RF bucket

⇨ CDR p. 20



RF bucket for 1.4 MV, 500 MHz, w/o and with 3HC

- small α_1 → transition to "alpha bucket" at 2 MV
- large α_2 → asymmetric momentum acceptance

Correlated misalignments

Girder train link. 3 types of misalignments (RMS, cut 2σ)

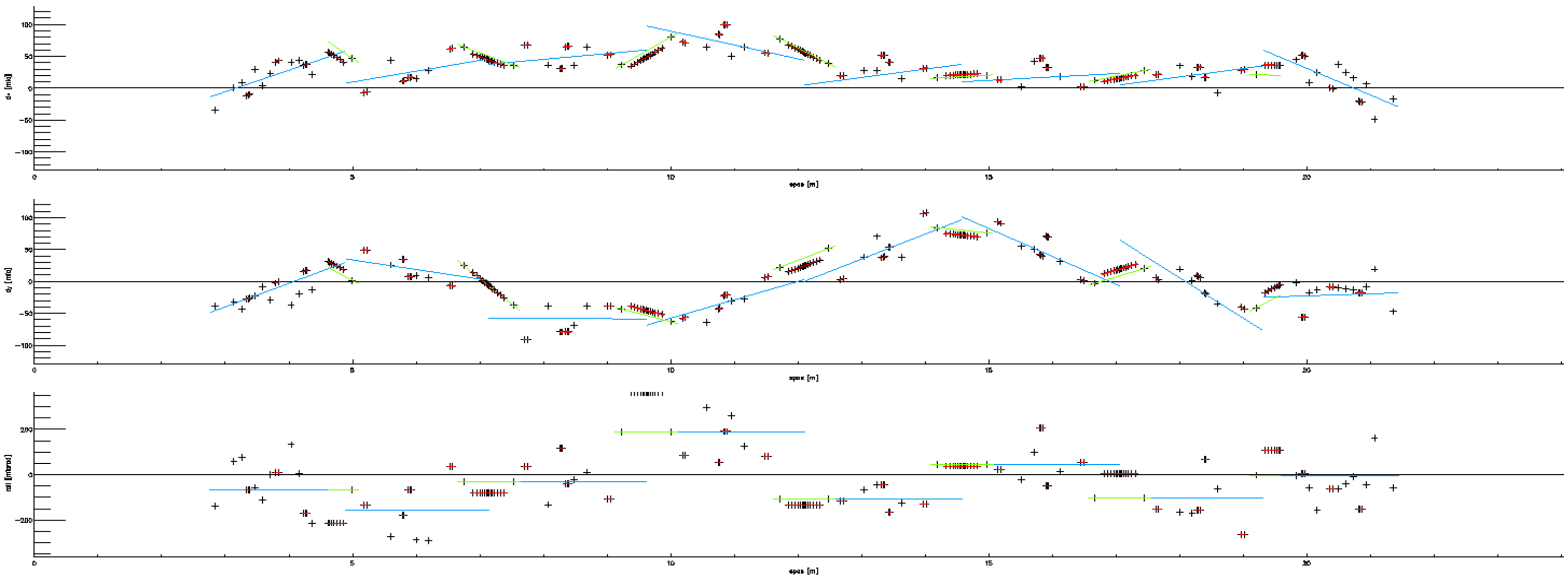
girder joints (60 μm) / joint play (20 μm) / elements on girders (30 μm)

+ define compound elements (i.e. common yoke magnets)

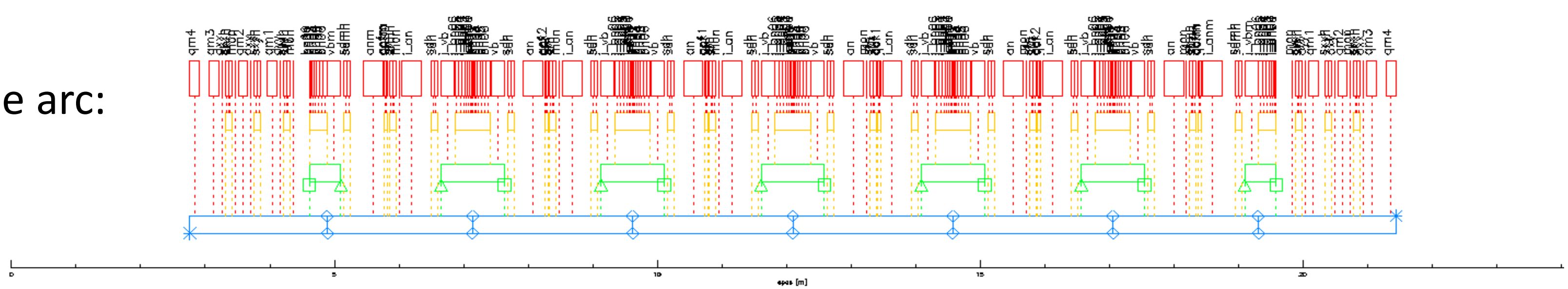
Δx

Δy

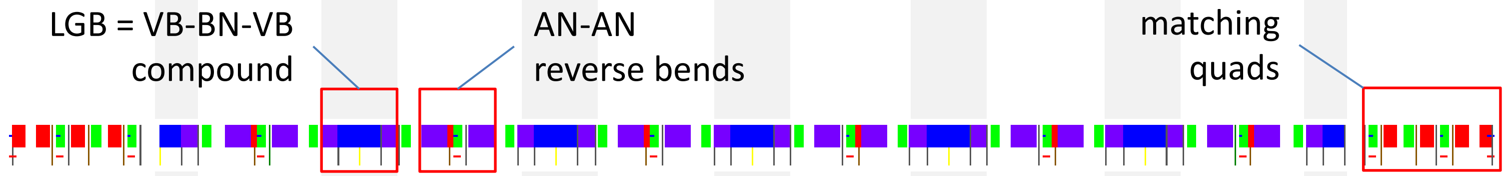
$\Delta \phi$



one arc:



Girder patterns under consideration

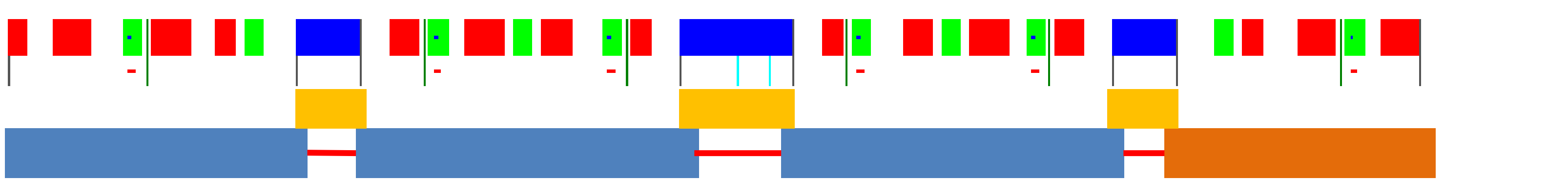


BD model: primary girder with joints (—), secondary girders passive like SLS

CDR model for normal and superbend arcs: movable girders and plinth with manual adjustments. Displaced virtual joints (—)

⇨ CDR p. 87

Movable long girders between plinth for every other LGB? Option to have 3 superbends in one arc. Double virtual joints in plinth (——)

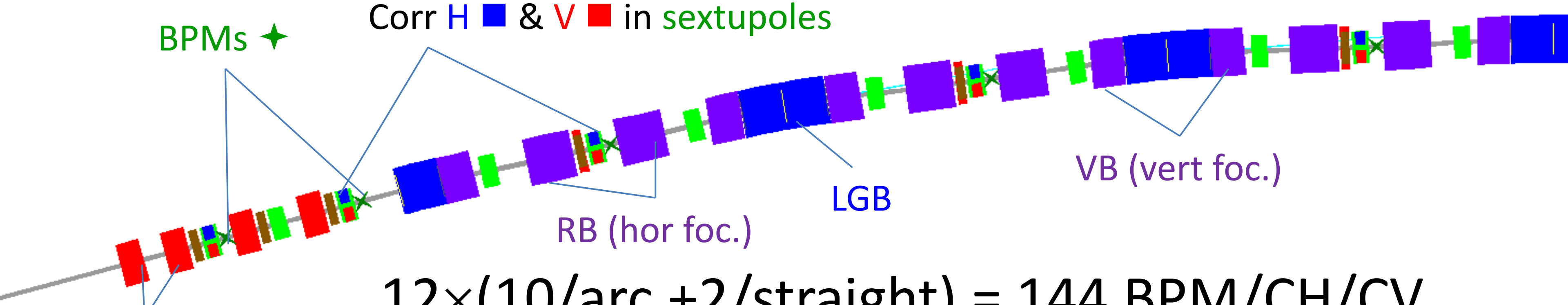


SLS now for comparison

S. Maag, M. Böge, K. Dreyer et al.

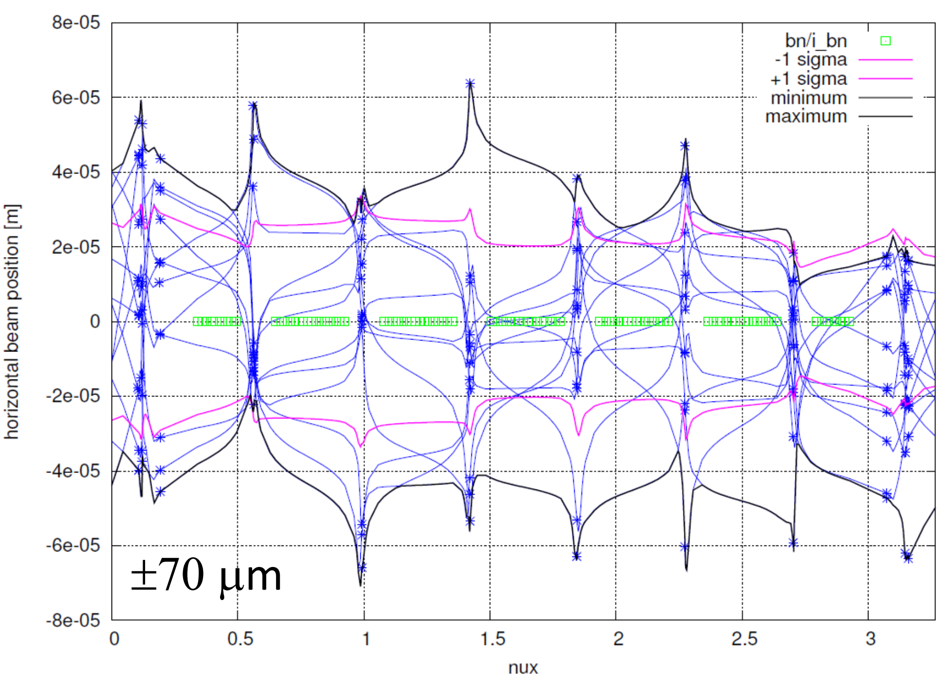
Orbit correction

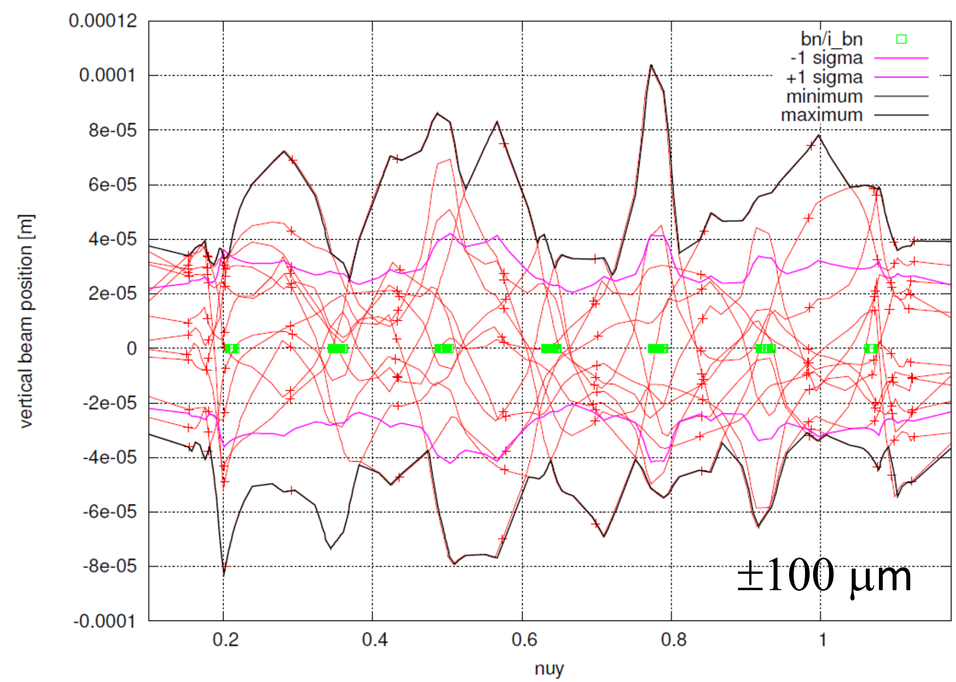
⇨ CDR p. 20



12×(10/arc +2/straight) = 144 BPM/CH/CV

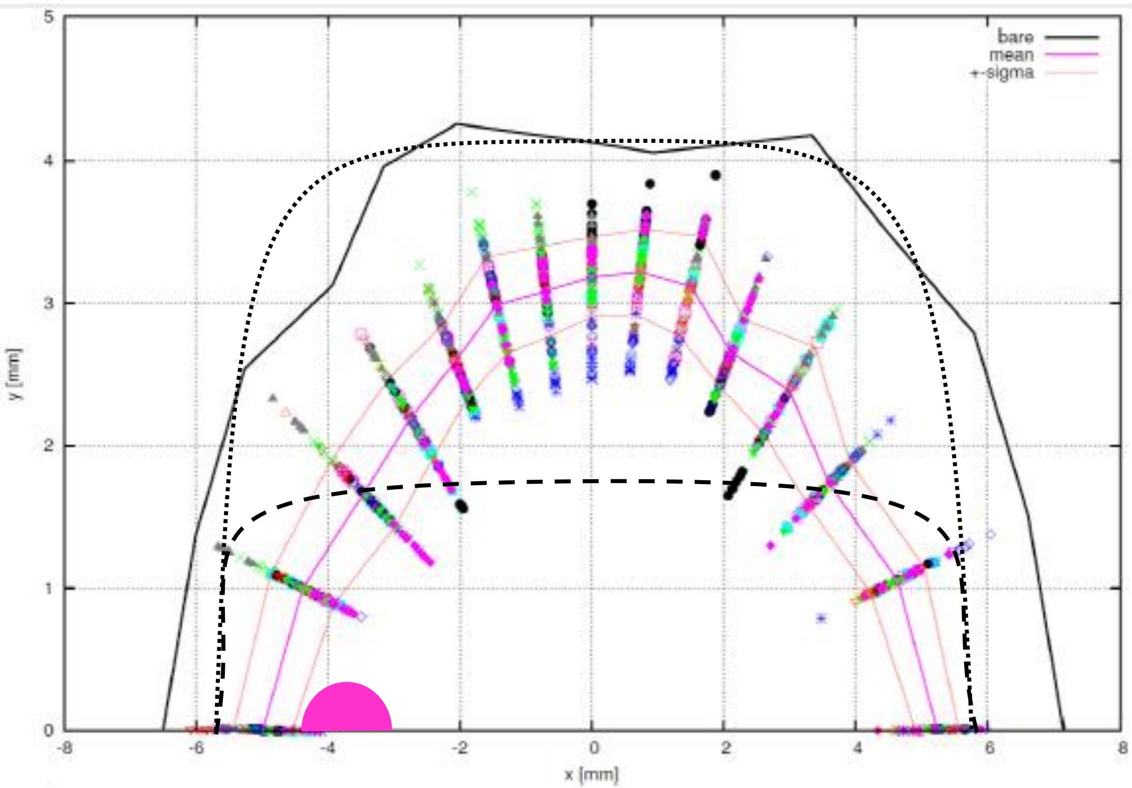
Orbit excursions between BPMs hor/vert (12 seeds):





Dynamic aperture with errors

⇨ CDR p. 25



Simulation included
- orbit correction
  - Corrector strength max. 400 μrad
- beam based alignment
- optics correction (LOCO style)
  - residual beta-beat H 1.0%, V 1.3 %
- no coupling correction
  - average vertical emittance ≈ 4.5 pm

120 seeds (12 misalignments × 10 multipole errors)

girders/joints/elements: 60/20/30 μm rms cut 2σ

M. Böge
J. Bengtsson
M. Aiba

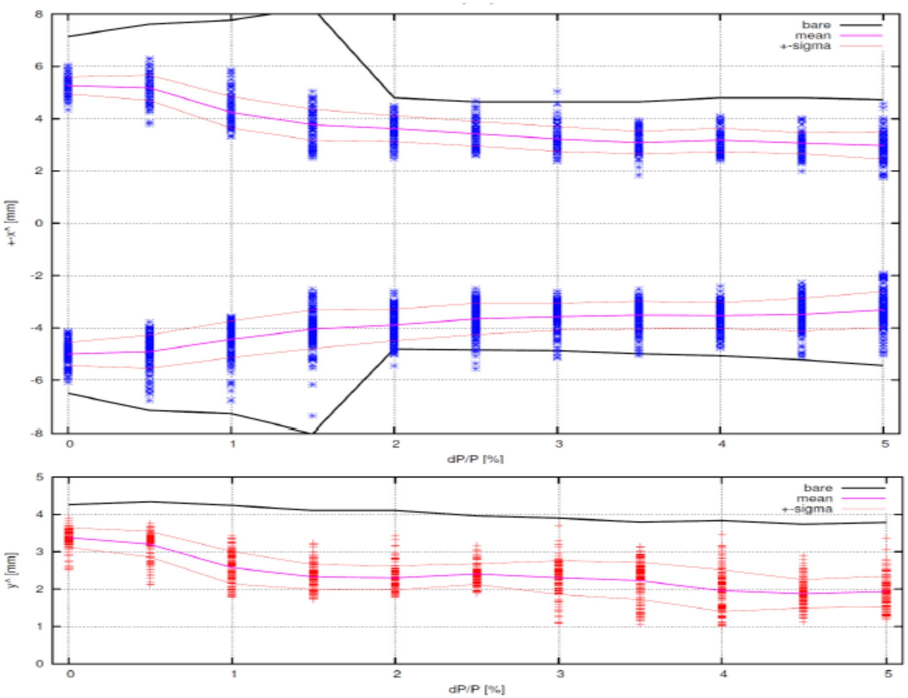
—— mean dynamic aperture —— +/- sigma

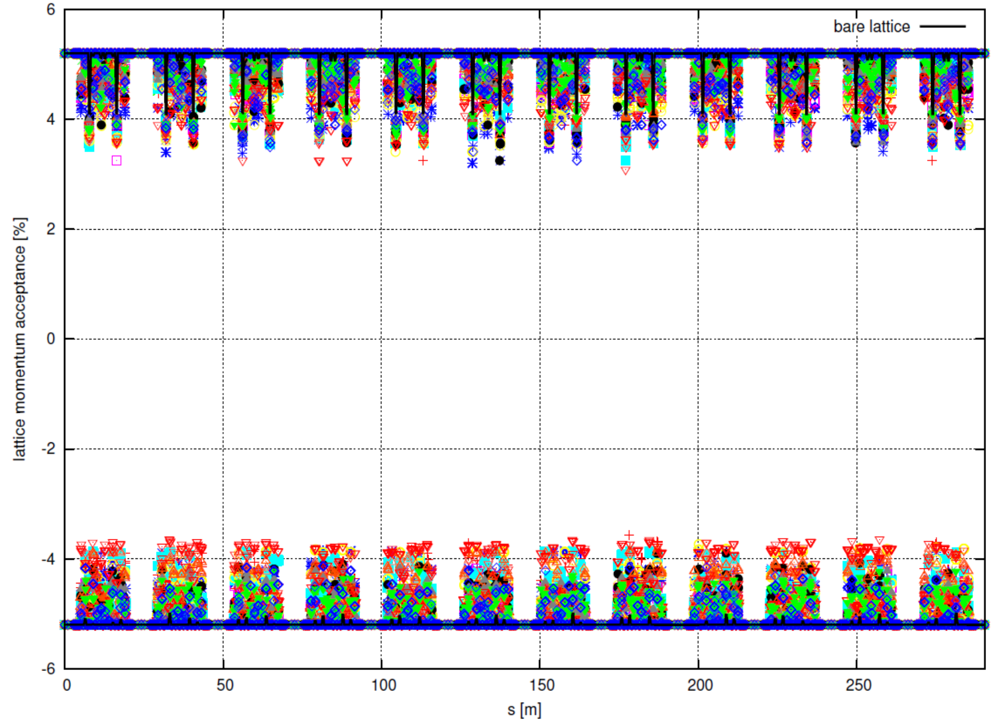
······ physical aperture limit from r = 10 mm beam pipe

- - - physical aperture with undulator gaps (4 mm gap on 2 m length)

⬬ approx. injected beam from booster (3σ)

Momentum acceptance and Touschek Lifetime





⇧ H and V dynamic aperture as function of momentum (120 seeds)

Local momentum acceptance (120 seeds) ⬀

Touschek Lifetime:	2.8±0.4 hrs	**9.3±1.4 hrs**
vertical emittance:	5 pm	10 pm
bunch length:	2.4 mm (no 3HC)	5.7 mm (with 3HC)

1 mA / bunch (400 mA total), IBS not included

linear RF-mom.acc. used: 1.4 MV → 5.2%

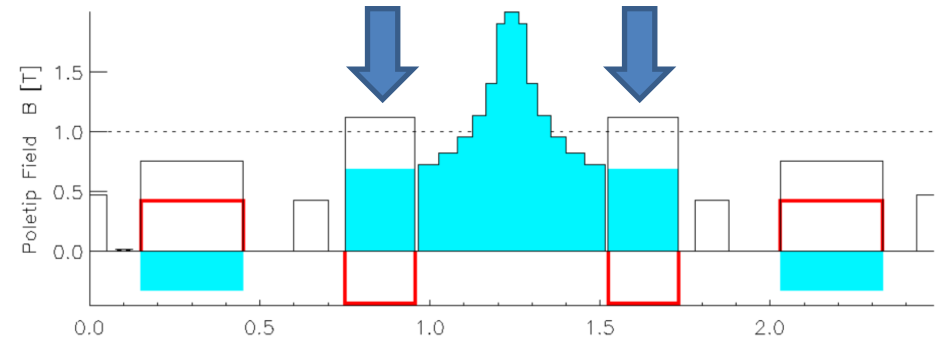
M. Böge, J. Bengtsson, M. Aiba

Magnets 1 - compound LGB

⇨ CDR p. 44

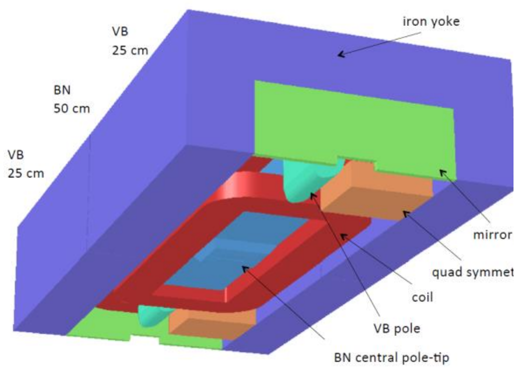
longitudinal/transverse gradient compound bend

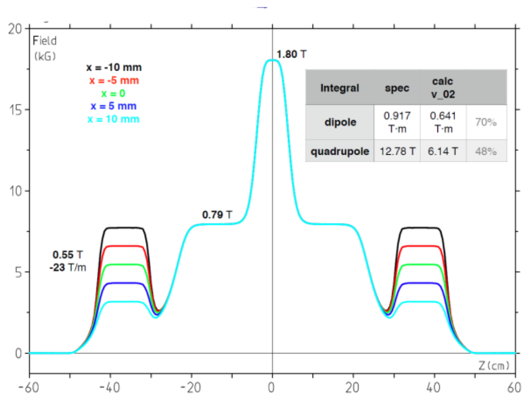
- use low field at LGB ends for vertical focusing gradient
- → save space, increase J_x



RC

resistive coil version

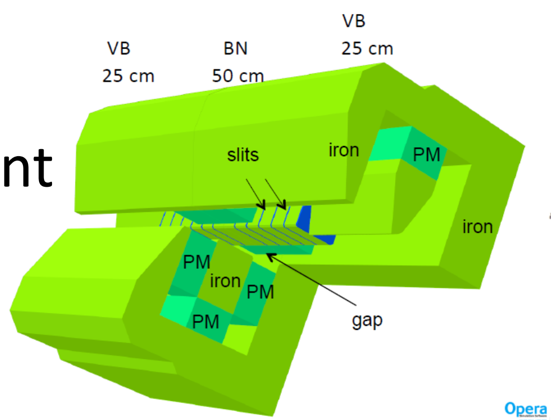


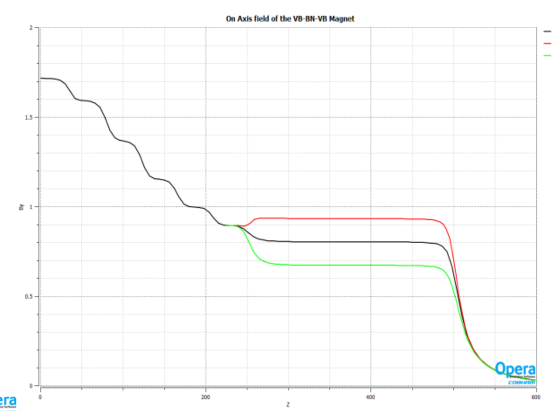


work in progress

PM

permanent magnet version





Alternatives:

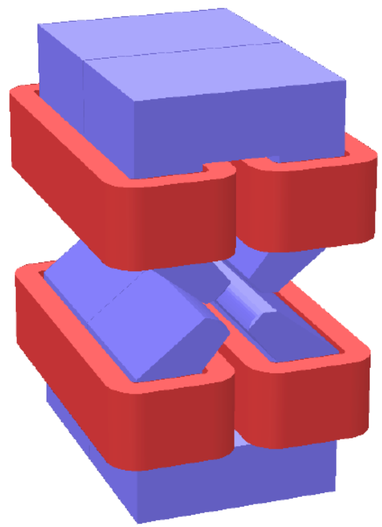
- discrete quadrupoles?
- distributed gradient?
- incorporation of sextupole component too?
- tunability?

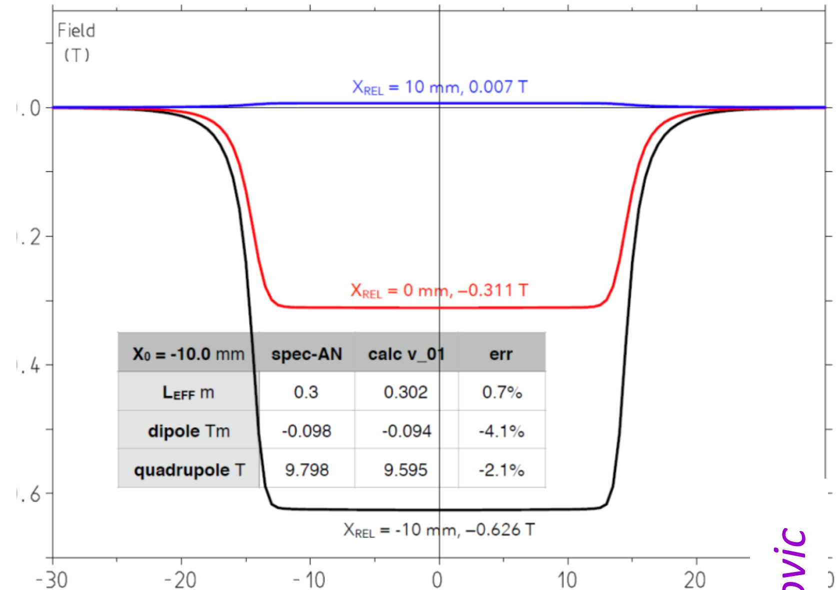
P. Lerch, M. Negrazus, V. Vrankovic

Magnets 2 - reverse bends and others

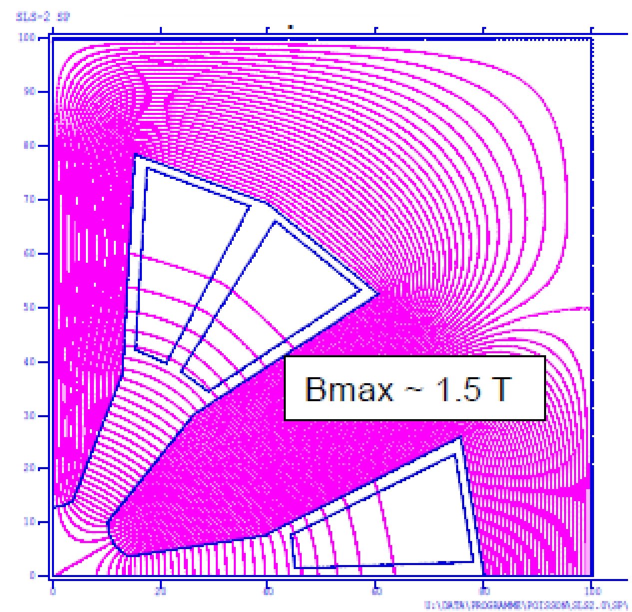
⇨ CDR p. 45

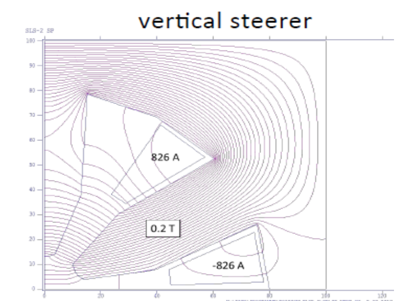
- Reverse bend →
  = quad off center
  - RC and PM versions
- Quadrupoles
  - 72 T/m
  - R = 13 mm
- Sextupoles →
  - including horizontal and vertical corrector coils → →
  - R = 13 mm
- Octupoles
  - including tuning quadrupoles and skew quadrupoles
  - R = 15 mm

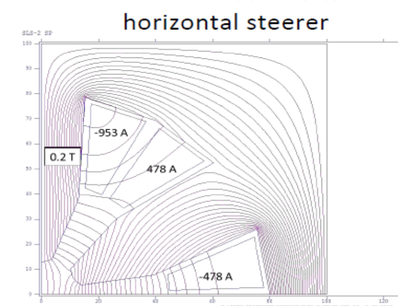




X_0 = -10.0 mm	spec-AN	calc v_01	err
L_{EFF} m	0.3	0.302	0.7%
dipole Tm	-0.098	-0.094	-4.1%
quadrupole T	9.798	9.595	-2.1%



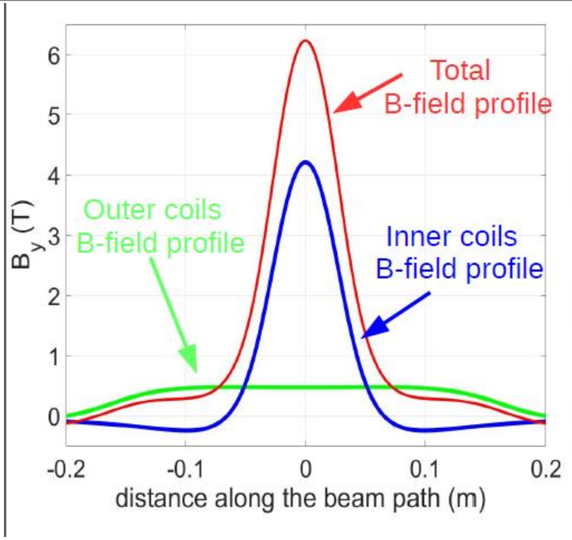




P. Lerch, M. Negrazus, V. Vrankovic

Magnets 3 - superbend

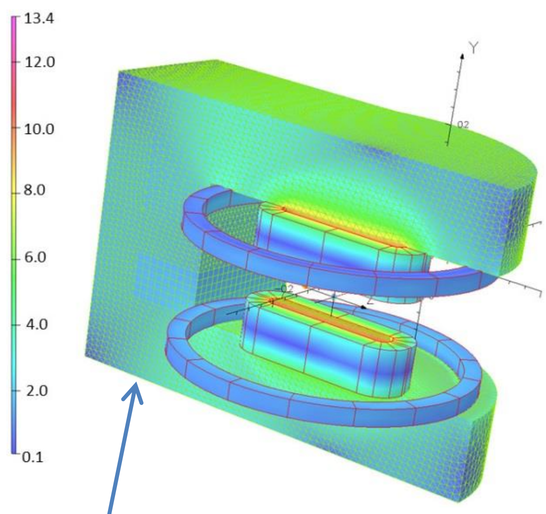
⇨ CDR p. 54



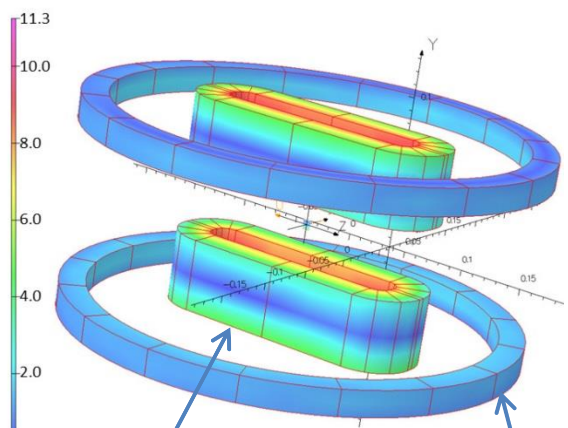
C. Calzolaio, S. Sanfilippo, A. Anghel, S. Sidorov

Longitudinal gradient superbend

- split racetracks + solenoids
- B-field profile full width half maximum (FWHM): 40-70 mm.
- B-field peak: ≈ 6 T.

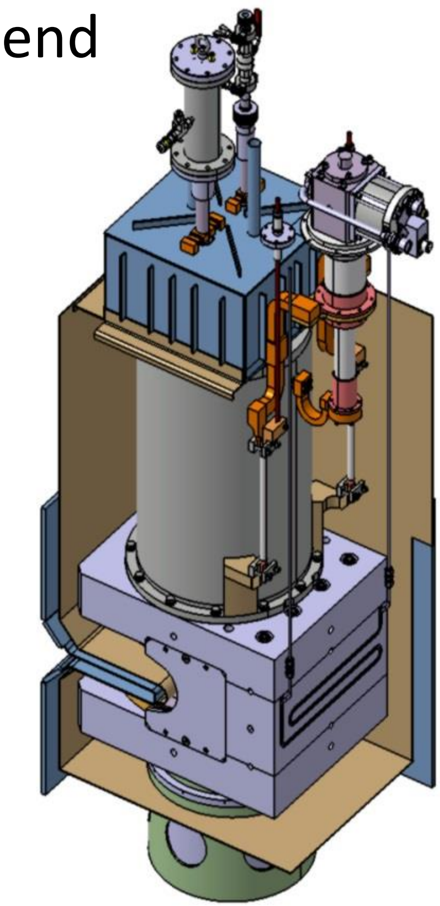


ARMCO^{R} or V-permendur) to enhance the field and reduce the stray field



Inner Nb_3Sn coils to produce the B-field peak

Outer NbTi coils to provide the field integral

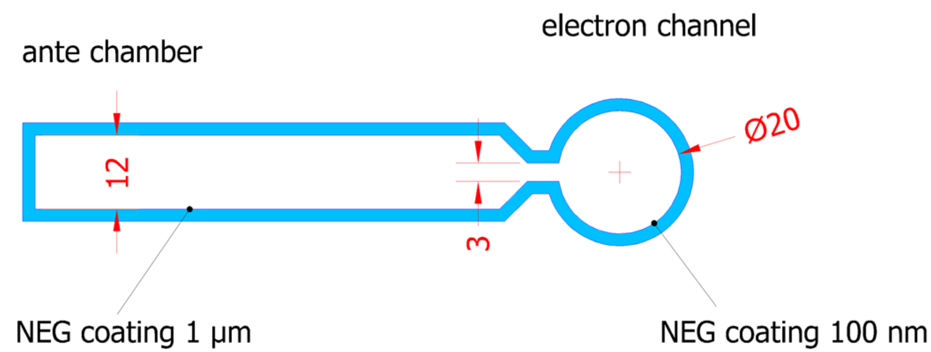


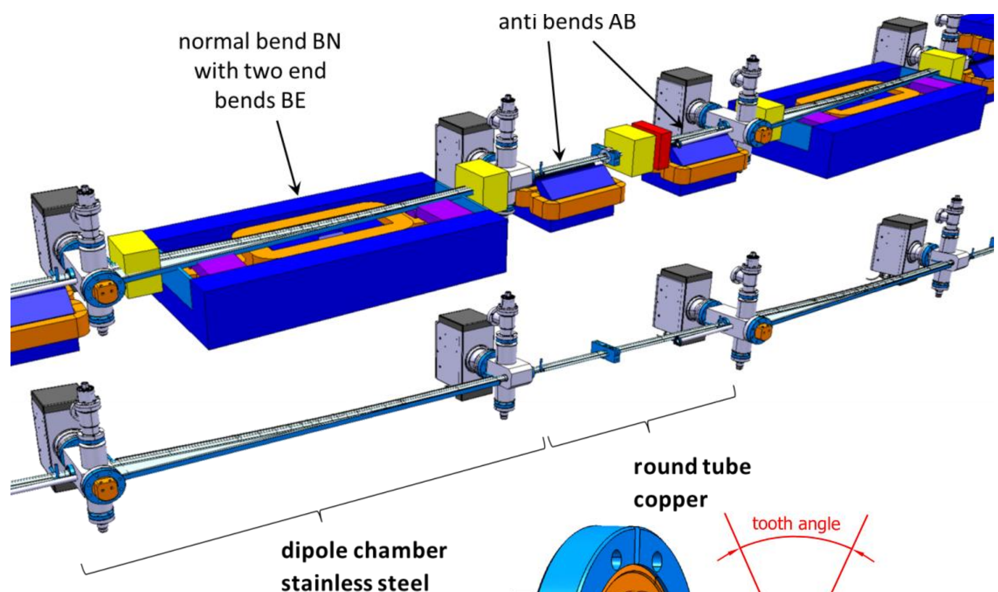
Cryostat assembly

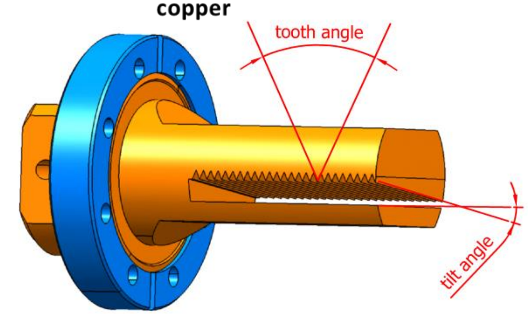
Vacuum system

⇨ CDR p. 70

- Alternating vacuum sections
  - antechambers in LGB areas →
  - copper tubes in RB areas ↘
- NEG coating
  - 1 μm in antechamber
  - 100 nm in beam pipe
    ➔ turbulent bunch lengthening threshold 2.5/4.0 mA without/ with 3rd harmonic cavity (required: >1 mA) (incl. resistive wall, tapers, BPMs)
  - < 10^{-9} mbar after 70 Ah
- High power density absorbers
  - ESRF design
  - CuCrZr material
    - flange knife edge machined from same material →





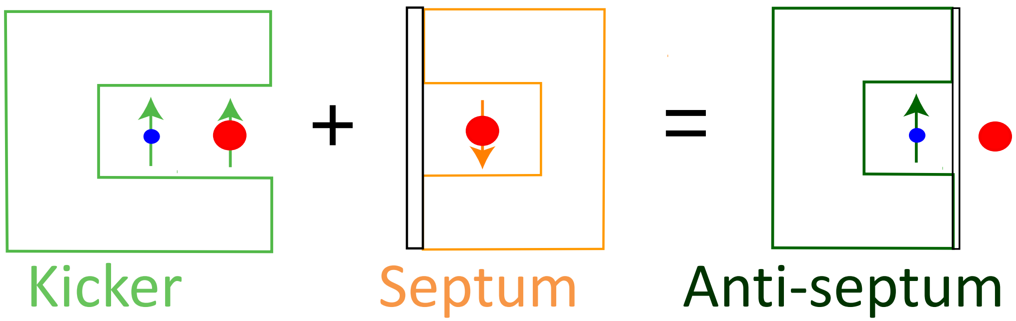


M. Hahn, L. Schulz et al.

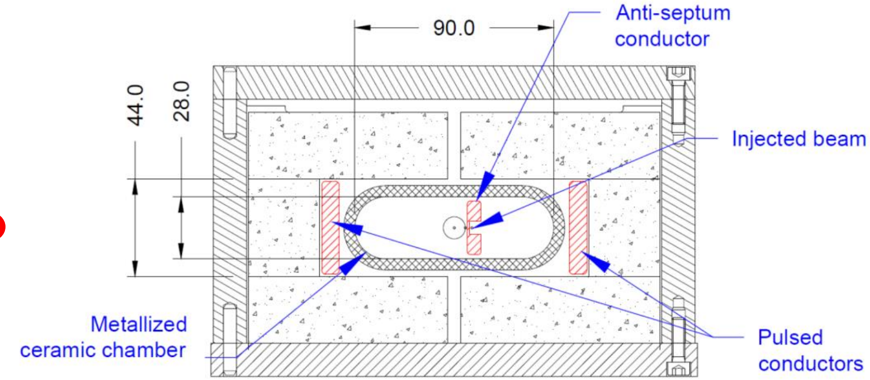
Injection

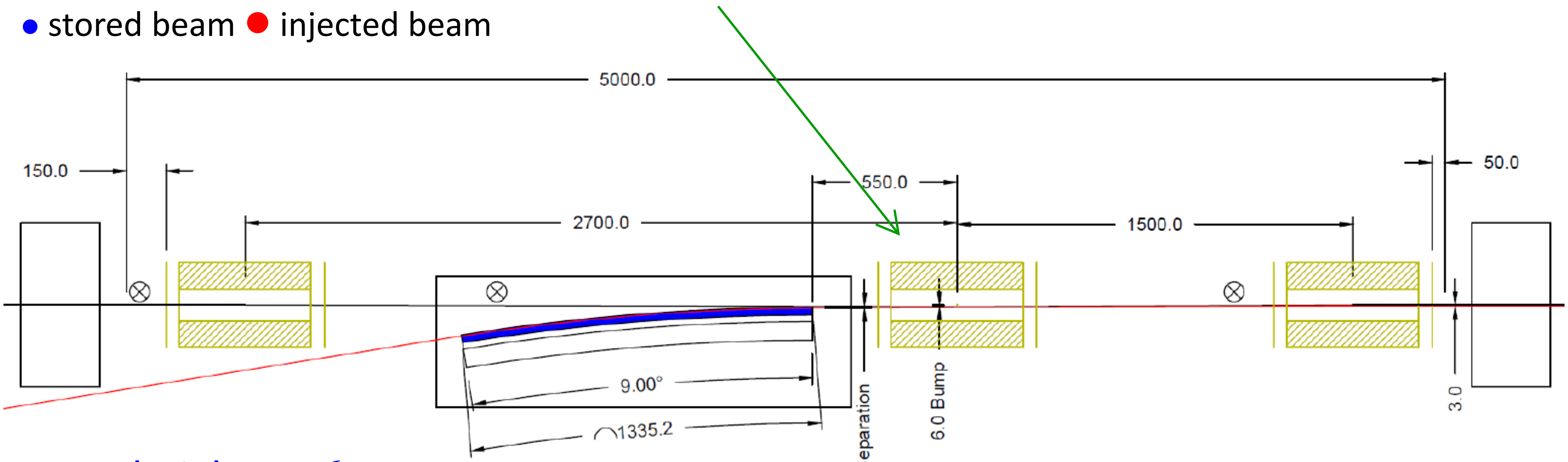
⇨ CDR p. 89

Off-axis injection with anti-septum



● stored beam ● injected beam





Bump height = –6 mm

Anti-septum wall = 1 mm

Separation = 3 mm

Dynamic aperture ≈ 5 mm ✓

Work in progress:

- alternative pulsed multipole off-axis
- longitudinal on-axis (off-phase)
- emittance exchange in booster

M. Aiba
C. Gough

Summary & Outlook

Status

- design of a competitive compact low emittance lattice
  - reverse bends AND longitudinal gradient bends required
- challenging magnet specs, very dense lattice
- confidence in off-axis injection and sufficient Touschek lifetime
- tight tolerances
  - advanced corrections already required in commissioning phase

Next steps

- submission of proposal < 31.12.2017
  - manpower and cost plans
  - final version of CDR
- technical design 2018-20
  - refinements of CDR lattice version
    wrt to magnet feasibility, dynamic apertures etc