PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

A. Streun :: on behalf of SLS-2 project team :: Paul Scherrer Institut

SLS-2 : Upgrade of the Swiss Light Source

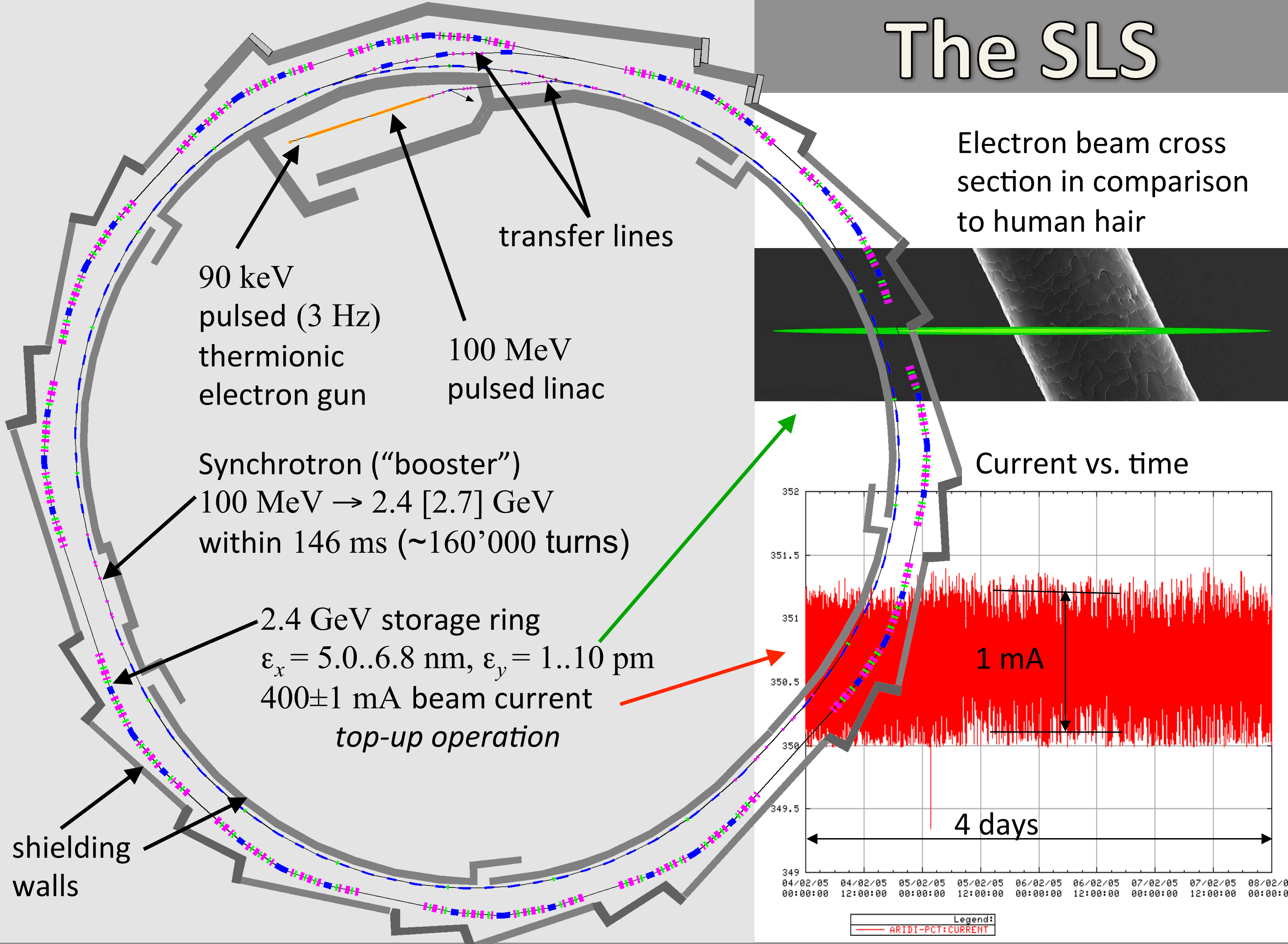
PHANGS workshop, Dec. 4-5, 2017, Trieste

Outline

- SLS - the Swiss Light Source
  - Layout, History and Achievements
- SLS-2 Concept
  - Radiation equilibrium and Multi-Bend Achromats
  - Longitudinal Gradient Bends and Reverse Bends
- SLS-2 Lattice design
  - Optics, Layout, Emittance and Acceptance
- SLS-2 Components
  - Magnets, Vacuum Chambers, Injection
- Summary & Outlook

- SLS-2 sources: Undulators, Brightness etc.
  → presentation by Thomas Schmidt

The SLS



transfer lines

90 keV
pulsed (3 Hz)
thermionic
electron gun

100 MeV
pulsed linac

Synchrotron (“booster”)
100 MeV → 2.4 [2.7] GeV
within 146 ms (~160’000 turns)

2.4 GeV storage ring
$\varepsilon_x = 5.0..6.8$ nm, $\varepsilon_y = 1..10$ pm
400±1 mA beam current
top-up operation

shielding
walls

Electron beam cross
section in comparison
to human hair

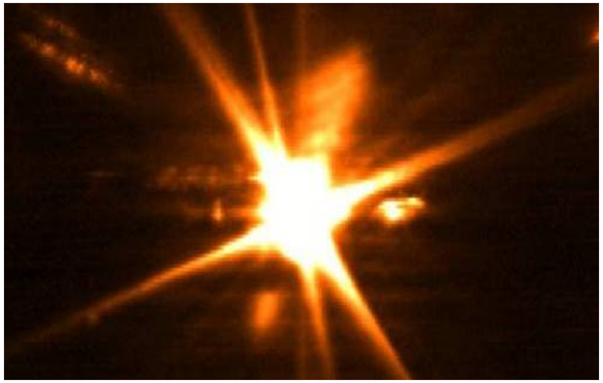
Current vs. time

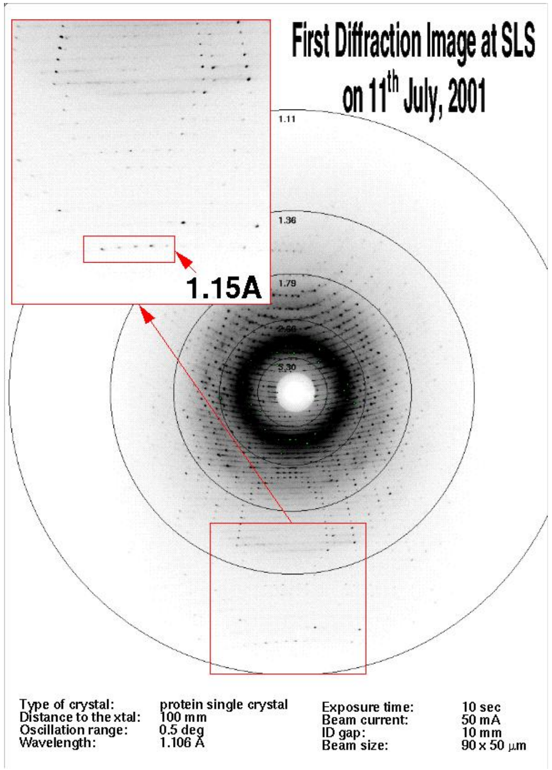
1 mA

4 days

SLS history

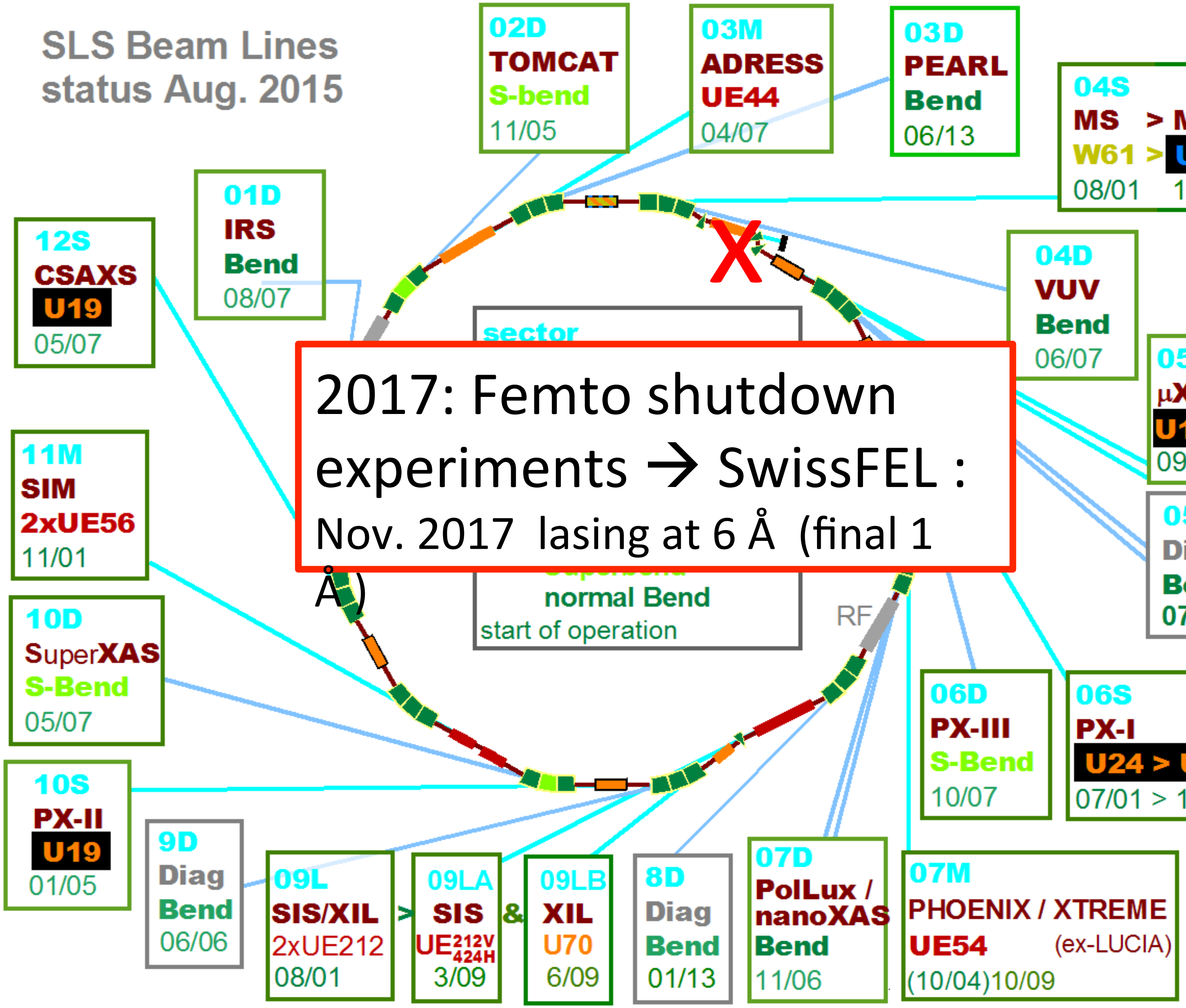
	1990	First ideas for a **Swiss Light Source**
	1993	Conceptual **Design** Report
June	**1997**	**Approval** by Swiss Government
June	**1999**	Finalization of **Building**
Dec.	**2000**	First **Stored Beam**
June	**2001**	Design current **400 mA** reached **Top up** operation started
July	**2001**	First **experiments**
Jan.	**2005**	**Laser beam slicing "FEMTO"**
May	**2006**	**3 Tesla super bends**
	2010	**~completion: 18 beamlines**




First Diffraction Image at SLS on 11th July, 2001

Type of crystal: protein single crystal
Distance to the xtal: 100 mm
Oscillation range: 0.5 deg
Wavelength: 1.106 Å
Exposure time: 10 sec
Beam current: 50 mA
ID gap: 10 mm
Beam size: 90 x 50 µm

SLS beam lines



2017: Femto shutdown experiments → SwissFEL :
Nov. 2017 lasing at 6 Å (final 1 Å)

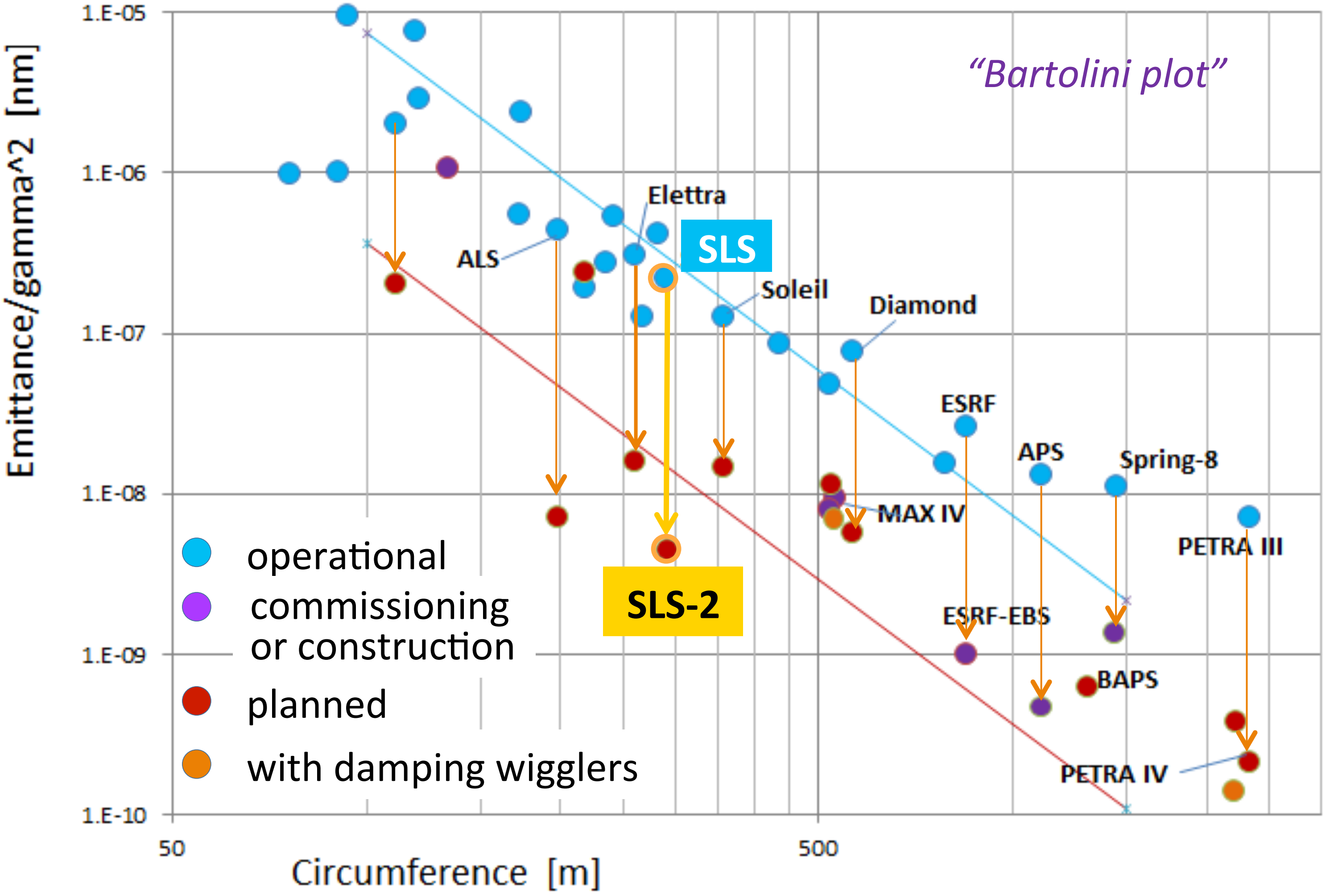
SLS major achievements

- **Reliability**
  - > 5000 hrs user beam time per year
  - 97.6% availability (12 year average 2005-16; 99.1 % in 2016)
- **Top-up operation since 2001**
  - constant beam current 400-402 mA over many days
- **Photon beam stability $< 1\ \mu\mathrm{m}$ rms (at frontends)**
  -) fast orbti feedback system ($< 100\ \mathrm{Hz}$ ▪
  - 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

The new light sources generation

SLS: 17 years of very successful operation...

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



Theoretical Emittance scaling

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

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

$K \approx 2 \rightarrow \approx -1$

improvement ×20

↓ upgrade projects

⇨ SLS-2

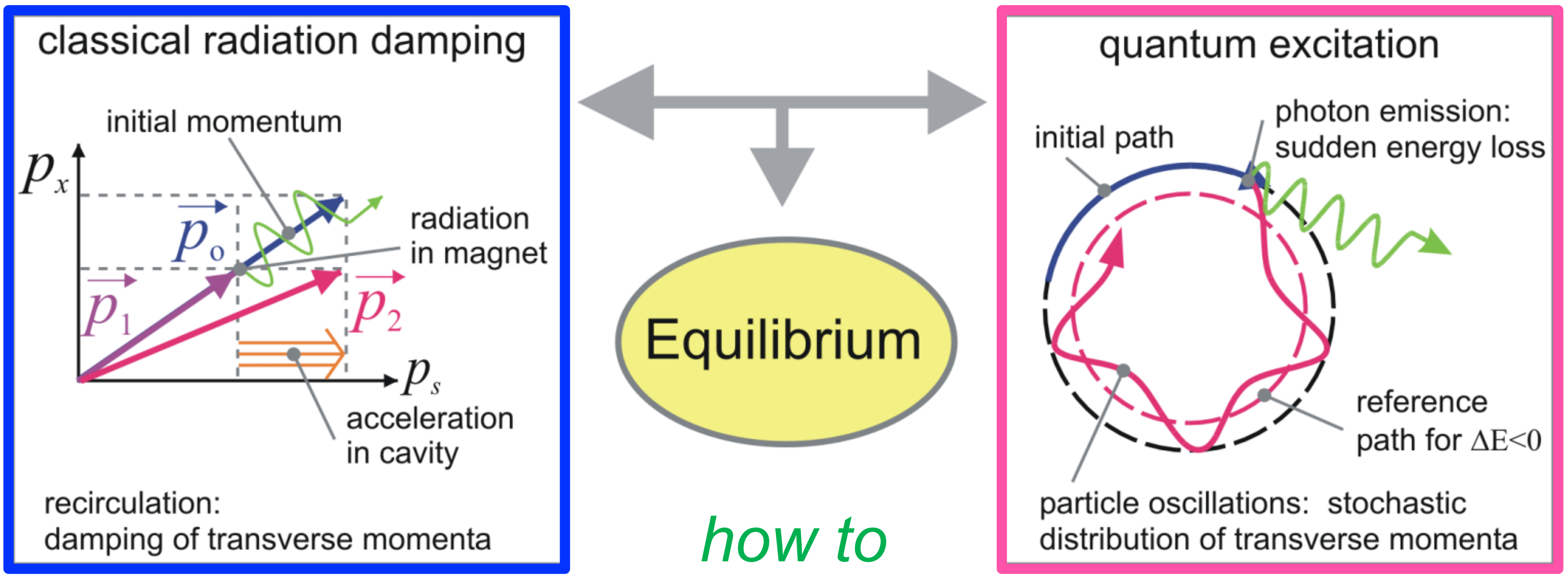
how to ?

Basics: how to get low emittance ?

Electron storage ring:

Radiation Equilibrium

- independent of initial conditions



classical radiation damping

recirculation:
damping of transverse momenta

Equilibrium

quantum excitation

particle oscillations: stochastic distribution of transverse momenta

how to

⇧ maximize this -- and -- minimize this ⇧

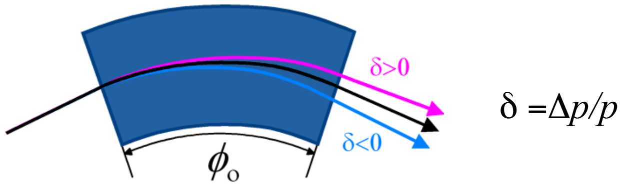
?

Minimum equilibrium emittance

- Maximal radiation damping
  - increase radiated power ⇨ pay with RF-power

    ⇨ **Damping wigglers**: $\Sigma\,|\text{deflection angles}| > 360^\circ$
- Minimal quantum excitation
  - keep off-momentum orbit close to nominal orbit

$$\text{Dispersion} = \frac{\text{orbit}}{\text{momentum}} = \frac{X}{\Delta p/p}$$



⇨ minimize dispersion at locations of radiation (= bending magnets)

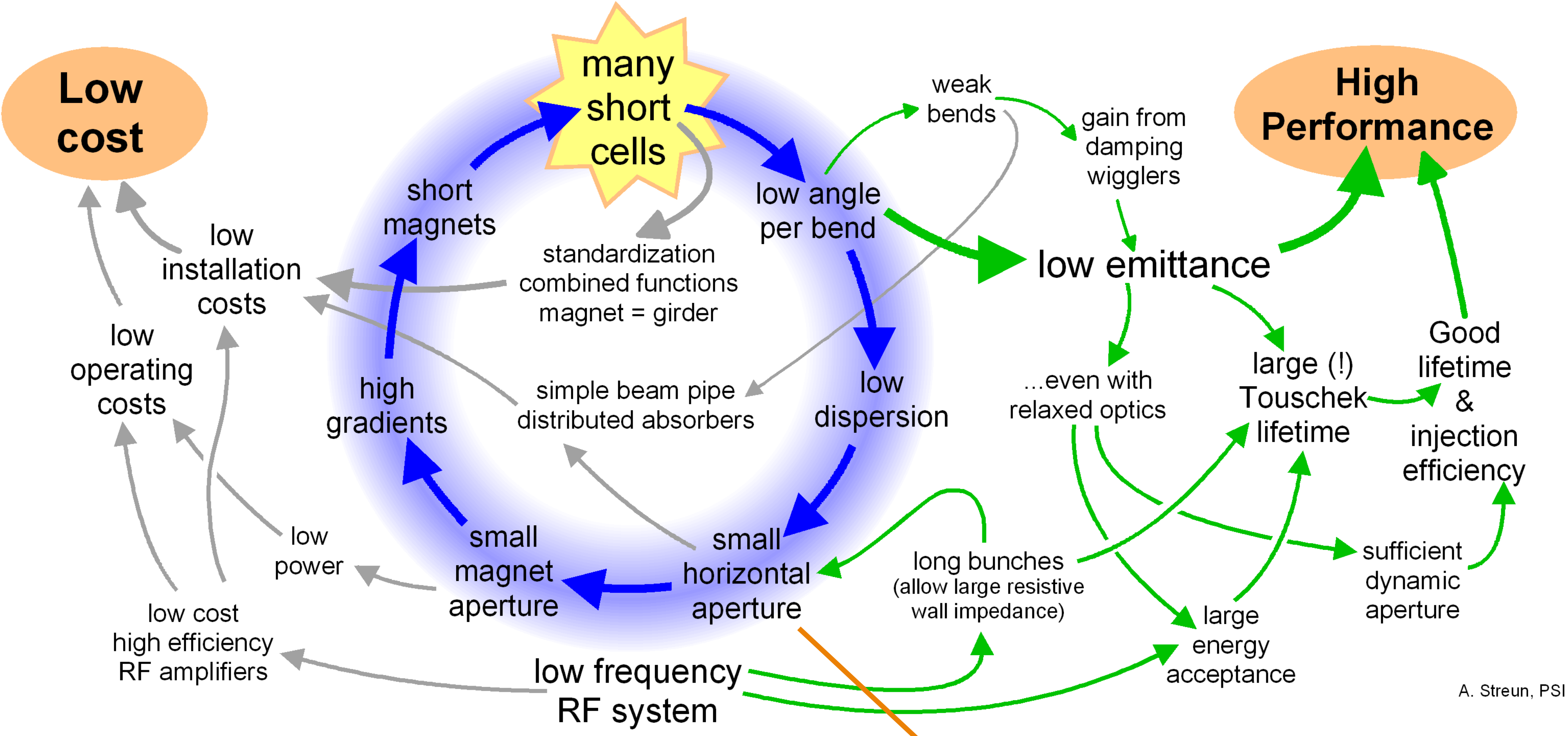
- Focusing into bending magnet to suppress dispersion.
- Many short bending magnets (= small angle ϕ) to limit dispersion growth: $\varepsilon \sim \phi^3$

$$\phi = 2\pi / N_{\text{cell}} \text{ and } N_{\text{cell}} = C / L_{\text{cell}} \rightarrow \varepsilon \sim C^{-3}$$

⇨ **Multi-Bend Achromat (MBA)**

⇨ Miniaturization of components: reduce cell length L_{cell}

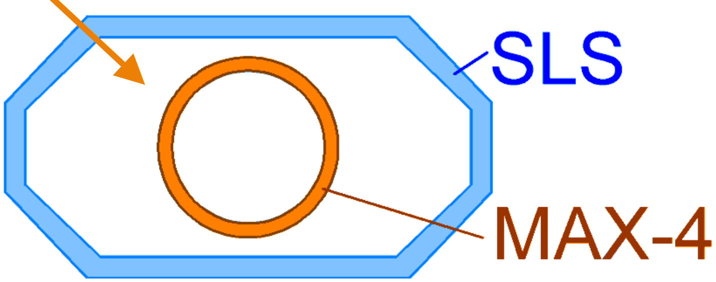
The Multi-Bend Achromat (MBA)



A. Streun, PSI

Miniaturization

- ⇨ small vacuum chambers
- ⇨ high magnet gradients
- ⇨ more cells in given circumference



Application of MBA to SLS-2

Upgrade task: factor >30 lower emittance $(< 150\ \mathrm{pm})$

+ harder X-rays $(> 50\ \mathrm{keV})$

SLS challenge: small circumference $(288\ \mathrm{m})$

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

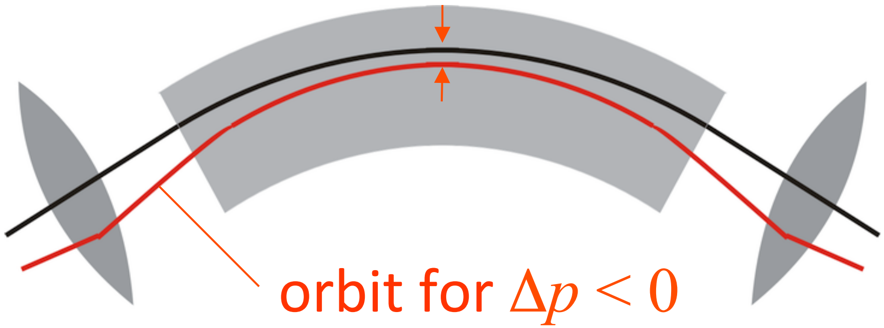
Scaling of new ring designs to SLS upgrade:

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

SLS	$E = 2.4\ \mathrm{GeV}$	$C = 288\ \mathrm{m}$				
MAX IV	$E = 3\ \mathrm{GeV}$	$C = 528\ \mathrm{m}$	$\varepsilon_x = 328\ \mathrm{pm}$	→	$1290\ \mathrm{pm}$	✗
SIRIUS	$E = 3\ \mathrm{GeV}$	$C = 518\ \mathrm{m}$	$\varepsilon_x = 240\ \mathrm{pm}$	→	$950\ \mathrm{pm}$	✗
ESRF-EBS	$E = 6\ \mathrm{GeV}$	$C = 844\ \mathrm{m}$	$\varepsilon_x = 147\ \mathrm{pm}$	→	$590\ \mathrm{pm}$	✗

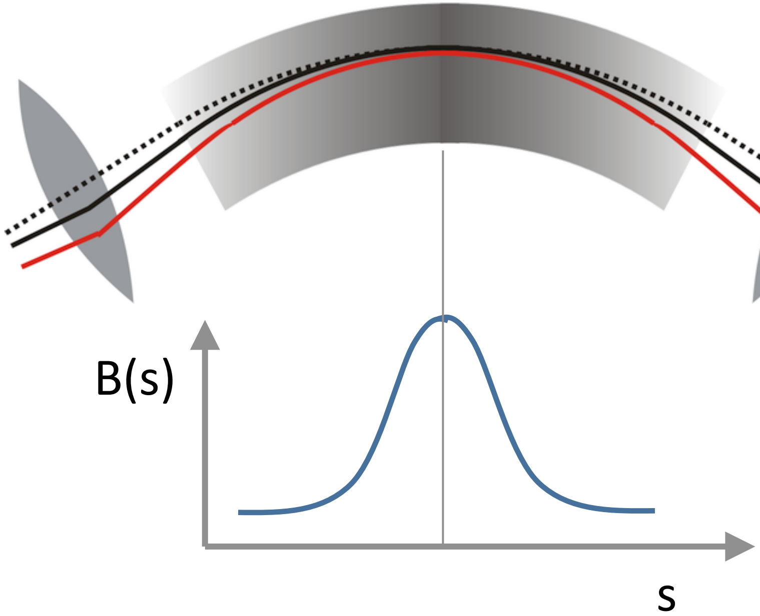
⇨ **SLS-2:** New lattice cell concept $\varepsilon_x \rightarrow \sim\!100\ \mathrm{pm}$ ✓

SLS-2 novel lattice cell



Standard MBA cell

- quadrupoles to focus dispersion
- dispersion at center > 0 (in periodic cell)



SLS-2 modified MBA cell

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

⇨ up to 5× lower emittance than conventional cell

...in a nutshell - the way to minimum emittance

Quantum excitation

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

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

Radiation integrals

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

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

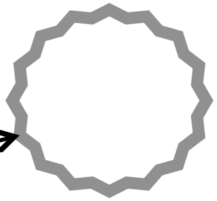
Damping

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

Increase of radiation loss ~ I_2

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

RB Σ|bend angles| > 2π



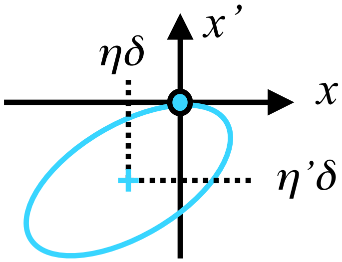
LGB

Minimization of I_5

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

RB dispersion matching:

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



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 $J_x = 1 - I_4/I_2$

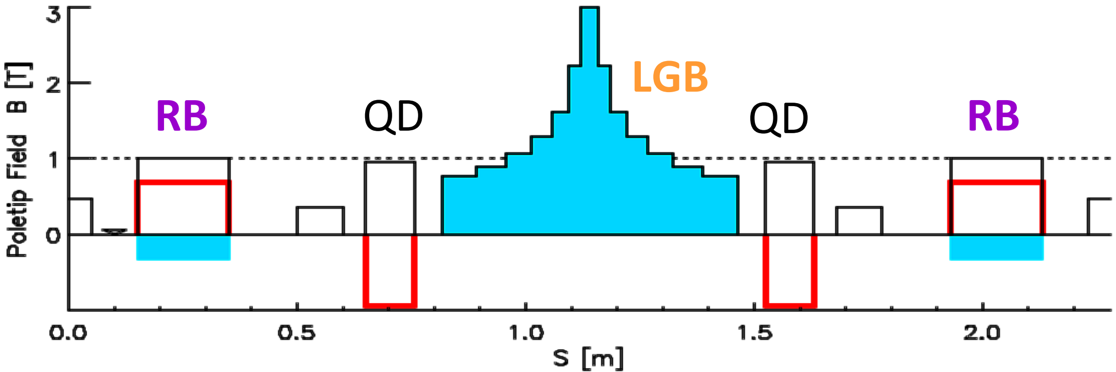
traditional (combined function):

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

RB

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

How LGB and RB work together



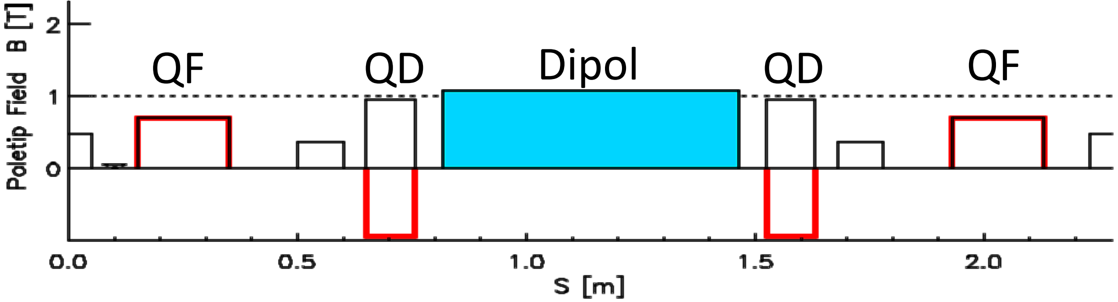
LGB-RB cell (SLS-2 *alternative* lattice)

ε_{xo}= 103 pm

5° *net* deflection, 2.48 m length.

$\nu_{x;y}$ = 0.428 (=3/7); 0.143 (=1/7)

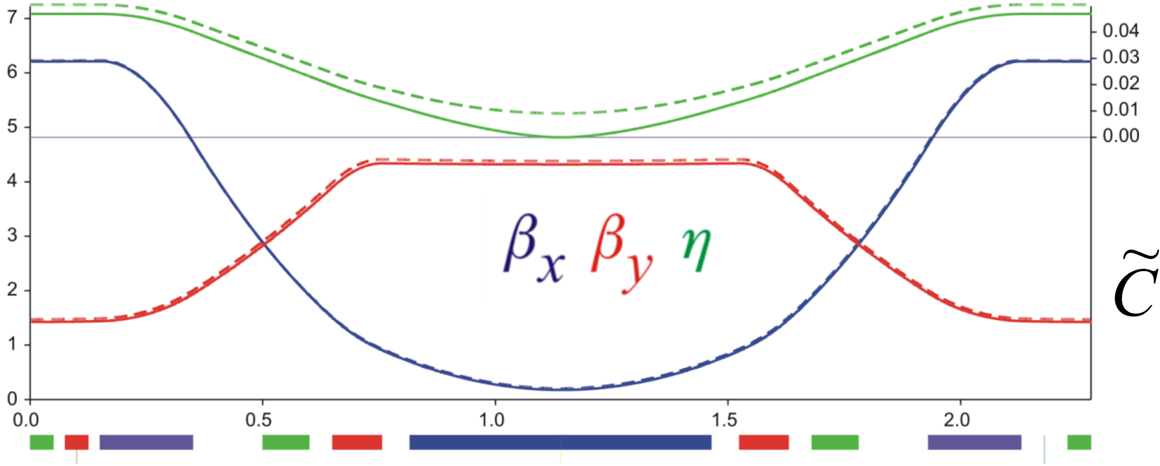
B_y at $x = 13$ mm: **dip**, quad, **total**



Conventional cell

ε_{xo}= 427 pm

same deflection, length and tunes



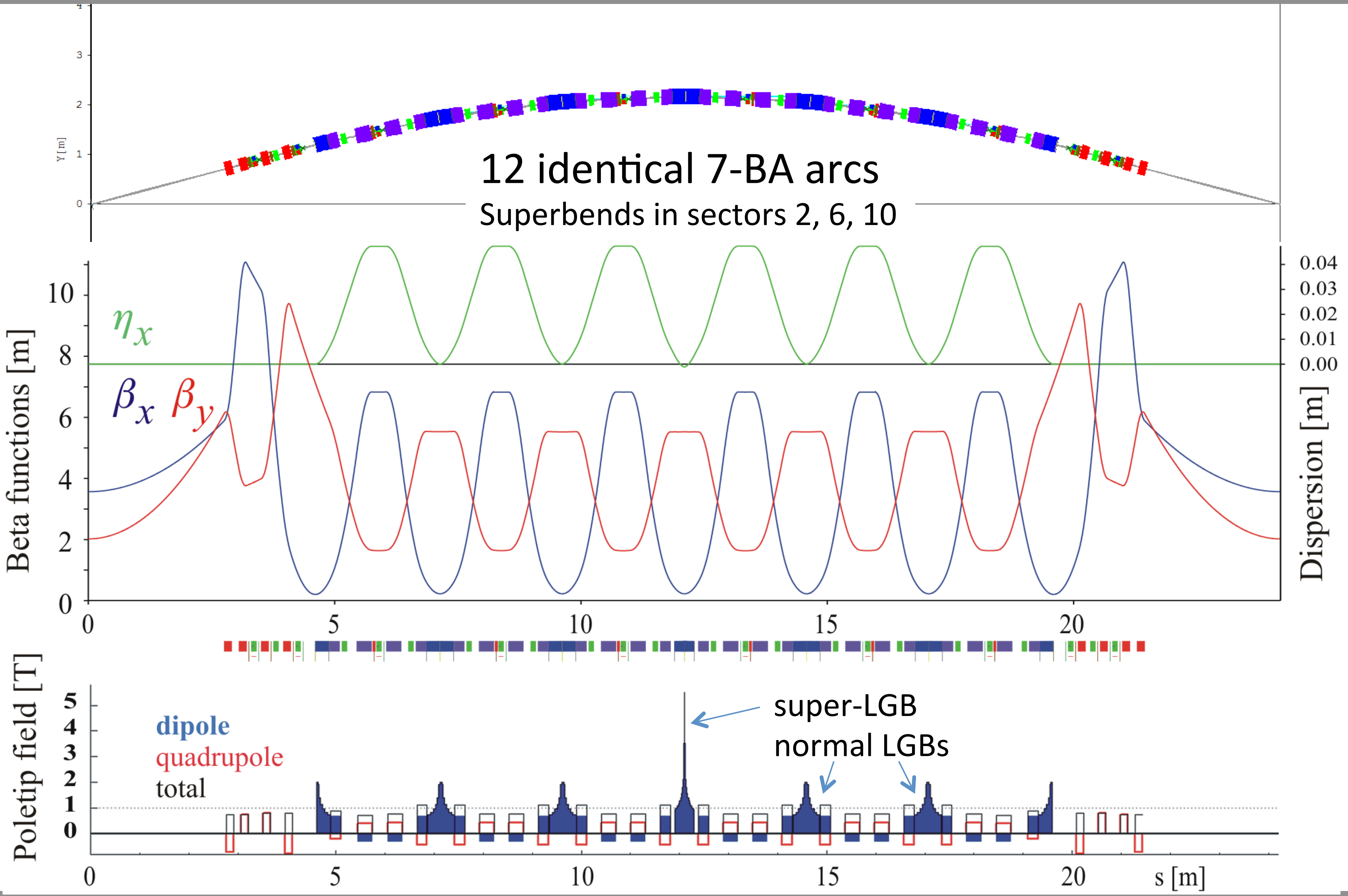
Optical functions

LGB-RB —— Conventional - - -

Gain in radiation integrals:

$$\tilde{C}_q E^2 \frac{\overset{\div 1.61}{I_5}}{\underset{\times 1.76}{I_2}\;\underset{\times 1.45}{J_x}} = \varepsilon_{xo} \quad \div 4.14$$

SLS-2 7-BA



12 identical 7-BA arcs

Superbends in sectors 2, 6, 10

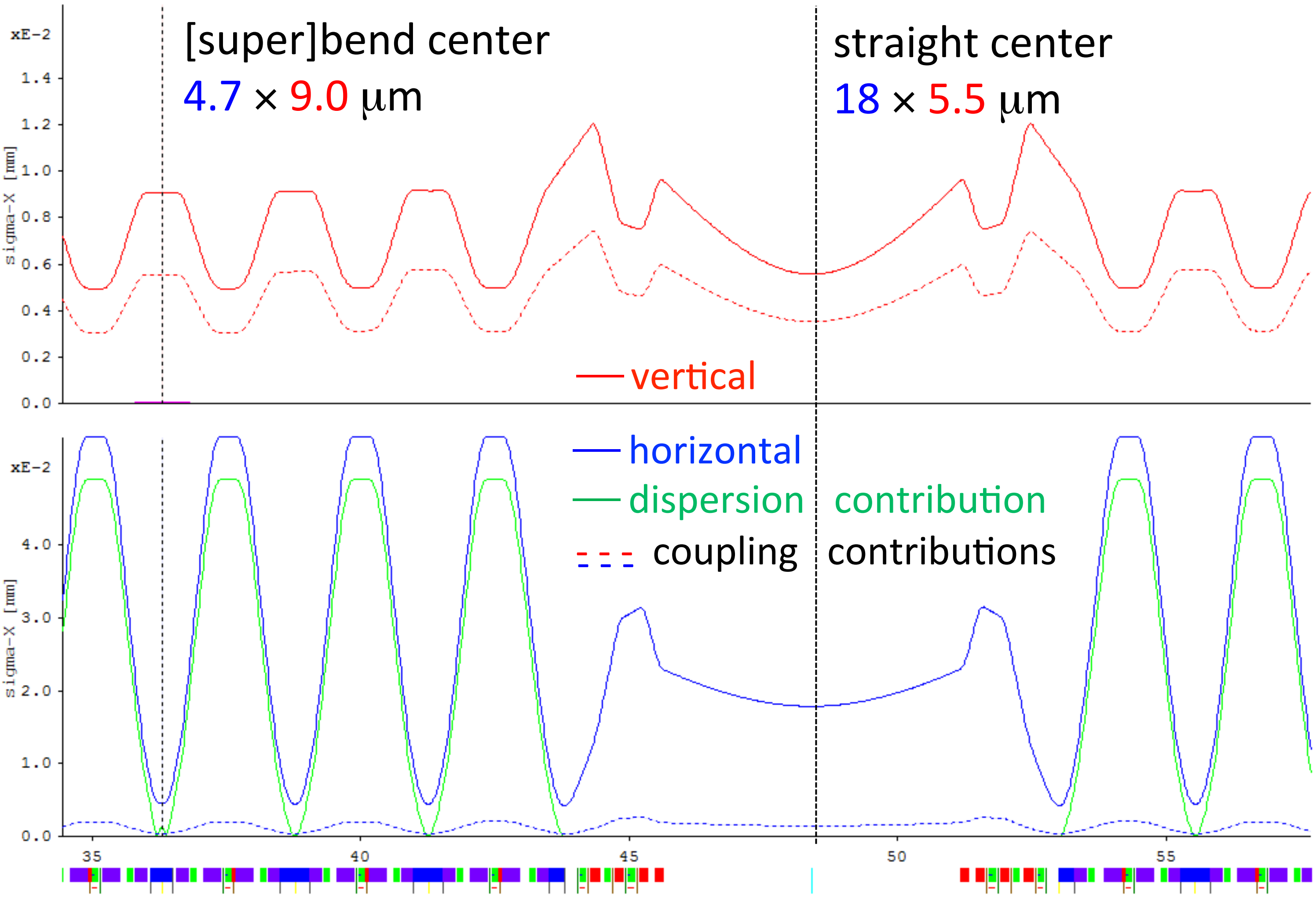
super-LGB

normal LGBs

Beam size

rms envelopes for 10% emittance coupling (no IBS)

emittances 98 pm / 10 pm



[super]bend center

4.7 × 9.0 μm

straight center

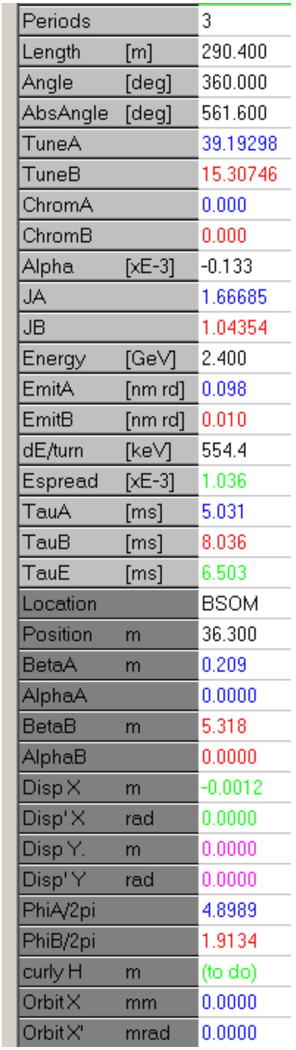
18 × 5.5 μm

— vertical

— horizontal

— dispersion contribution

- - - coupling contributions



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

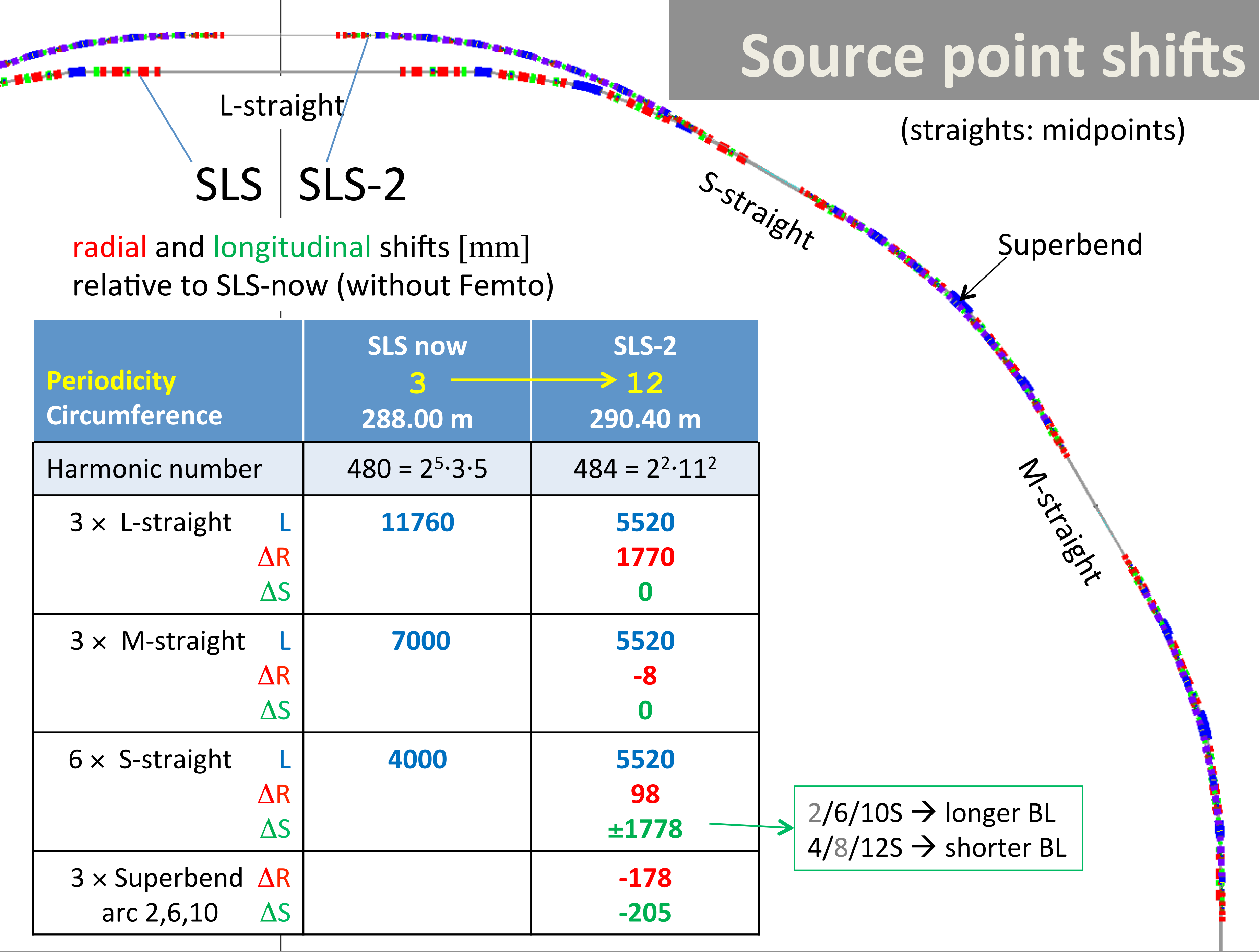
Name	SLS*)	SLS-2#)
Emittance at 2.4 GeV [pm]	**5069**	**102 → 126♦)**
Lattice type	12×TBA	12×**7**BA
Circumference [m]	288.0	290.4
Total *absolute* bending angle	360°	561.6°
Working point $Q_{x/y}$	20.43 / 8.22	39.2 / 15.30
Natural chromaticities $C_{x/y}$	−67.0 / −19.8	−95.0 / −35.2
Optics strain1)	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)

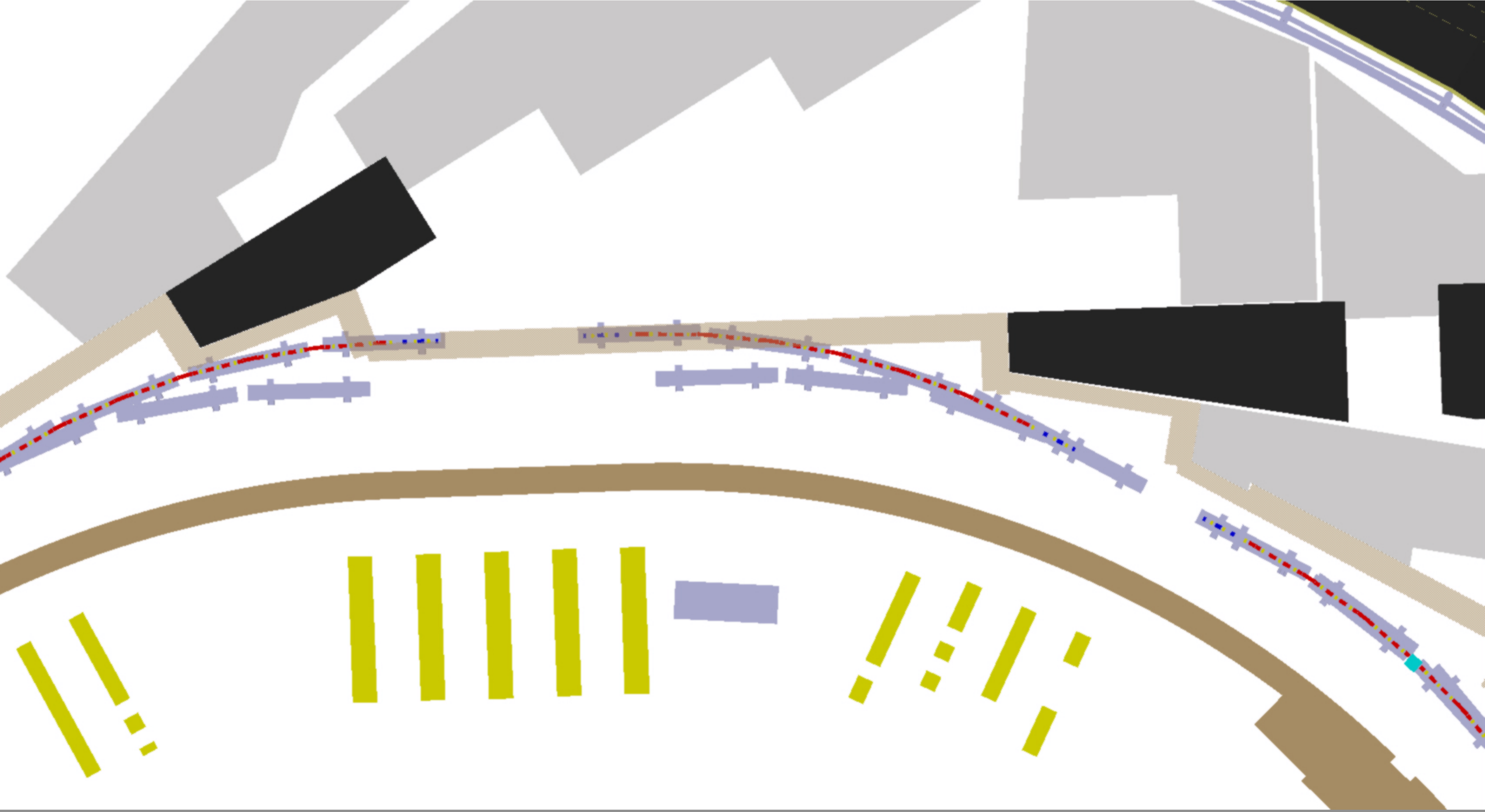


radial and longitudinal shifts [mm]
relative to SLS-now (without Femto)

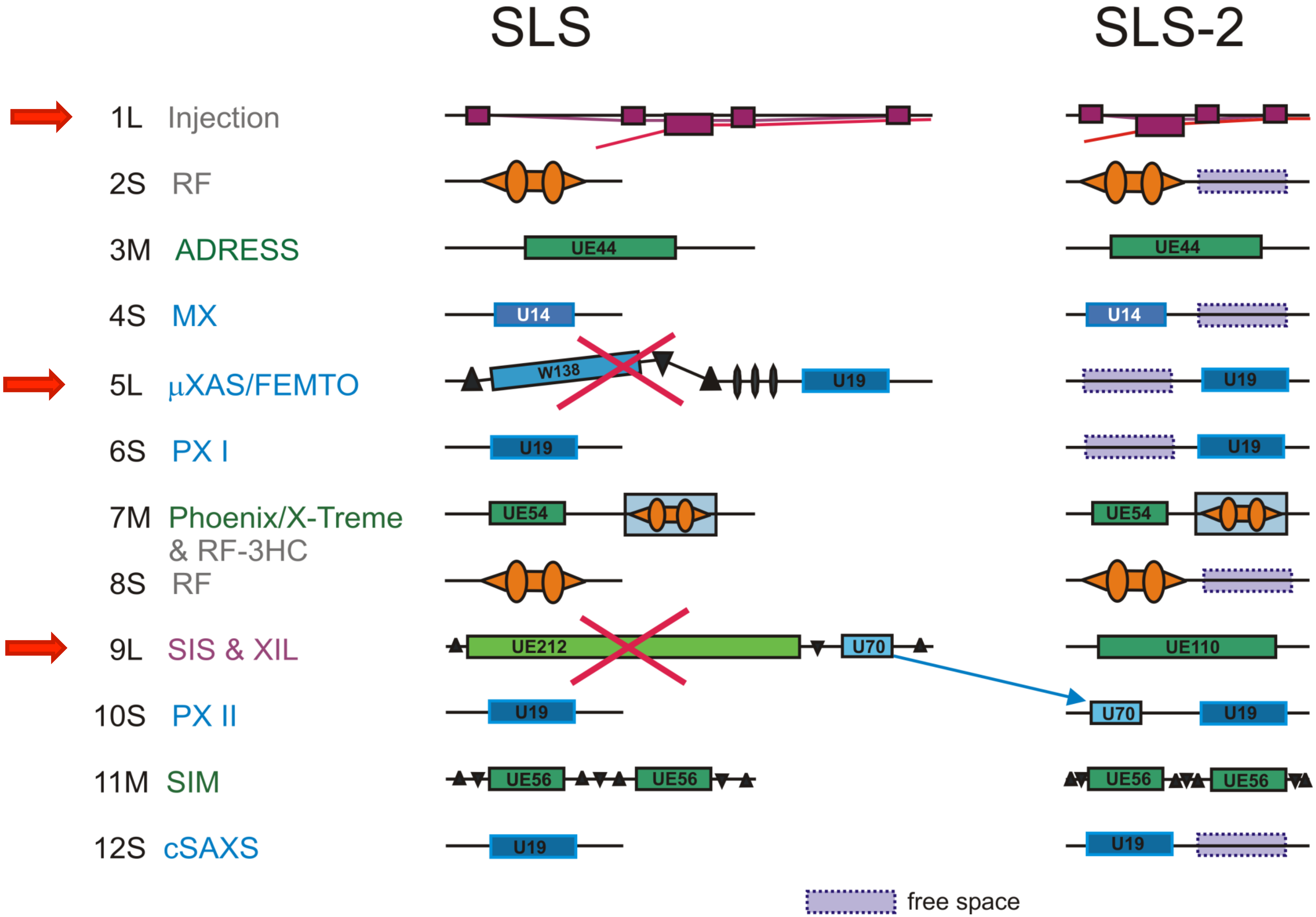
		SLS now	SLS-2
Periodicity		**3** →	**12**
Circumference		**288.00 m**	**290.40 m**
Harmonic number		$480 = 2^5 \cdot 3 \cdot 5$	$484 = 2^2 \cdot 11^2$
3 × L-straight	L	**11760**	**5520**
	ΔR		**1770**
	ΔS		**0**
3 × M-straight	L	**7000**	**5520**
	ΔR		**-8**
	ΔS		**0**
6 × S-straight	L	**4000**	**5520**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

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

Tunnel modification in 3 long straights
SLS-2 lattice and existing SLS girders



Straight sections



SLS

SLS-2

1L Injection

2S RF

3M ADRESS

4S MX

5L µXAS/FEMTO

6S PX I

7M Phoenix/X-Treme & RF-3HC

8S RF

9L SIS & XIL

10S PX II

11M SIM

12S cSAXS

▨ free space

Dynamic Acceptance

a challenge for low emittance lattices

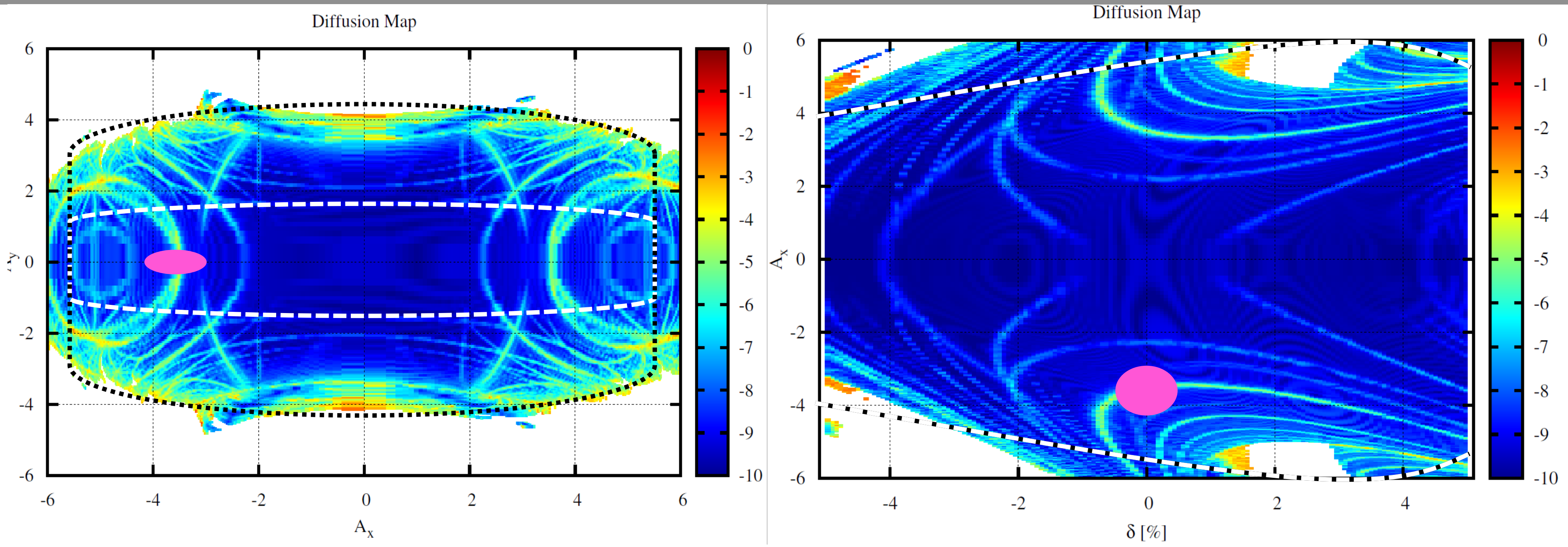
- Dynamic acceptance (for low coupling) =
  - horizontal dynamic aperture including physical limitations (beam pipe)
    → off-axis injection efficiency / possibility
  - lattice momentum acceptance
    = momentum dependent horizontal dynamic aperture
    → Touschek lifetime
  - vertical limit ≈ physical aperture (mini gap undulators)
    → Coulomb scattering lifetime

Dynamic acceptance optimization method

- 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)
  - 2nd order sextupole / 1st 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



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

⬁ in $\{x,y\}$ space in $\{\Delta p/p, x\}$ space ⬀

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

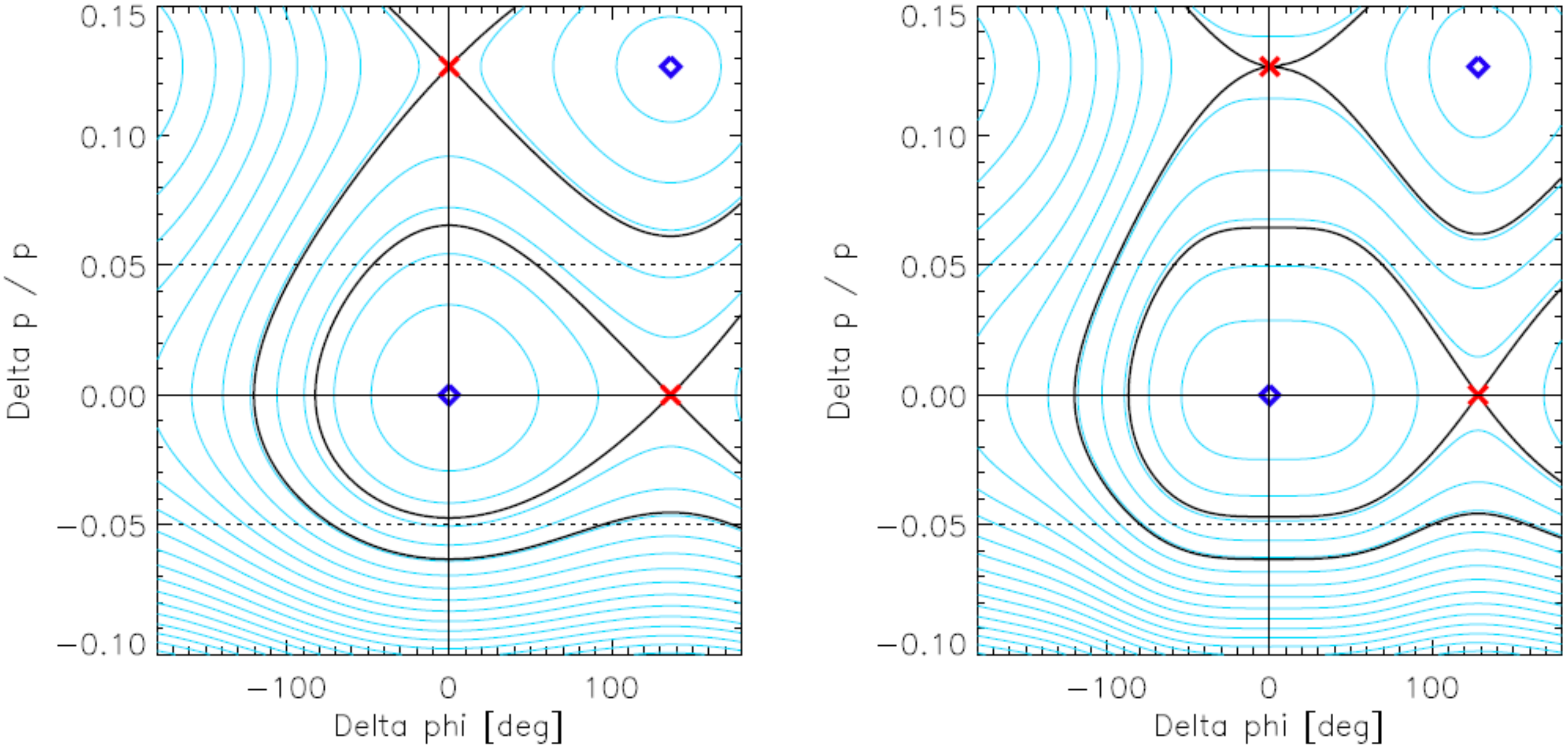
· · · · physical aperture limit from $r = 10$ mm beam pipe

- - - - 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

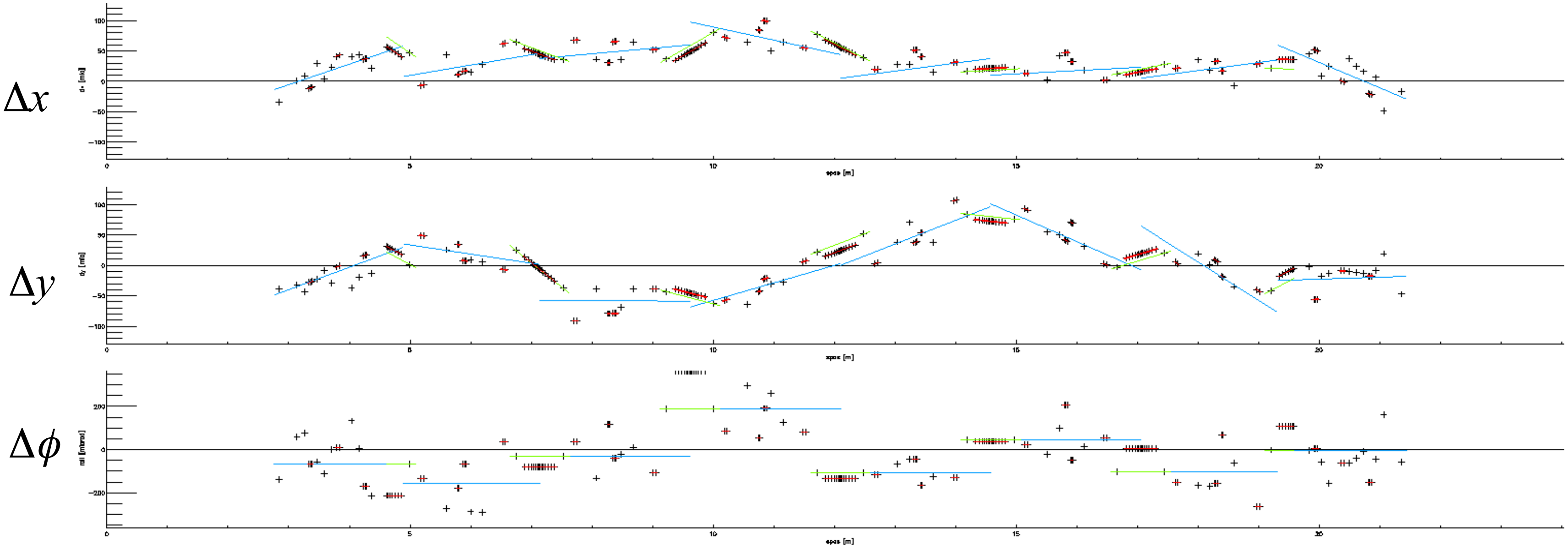


RF bucket for 1.4 MV, 500 MHz, w/o and with 3HC

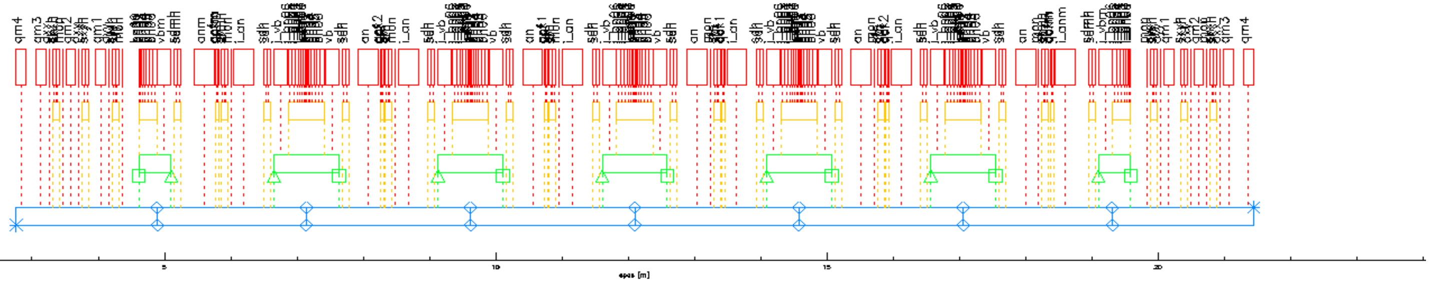
- small α_1 → transition to "alpha bucket" at 2 MV
- large α_2 → asymmetric momentum acceptance

Correlated misalignments

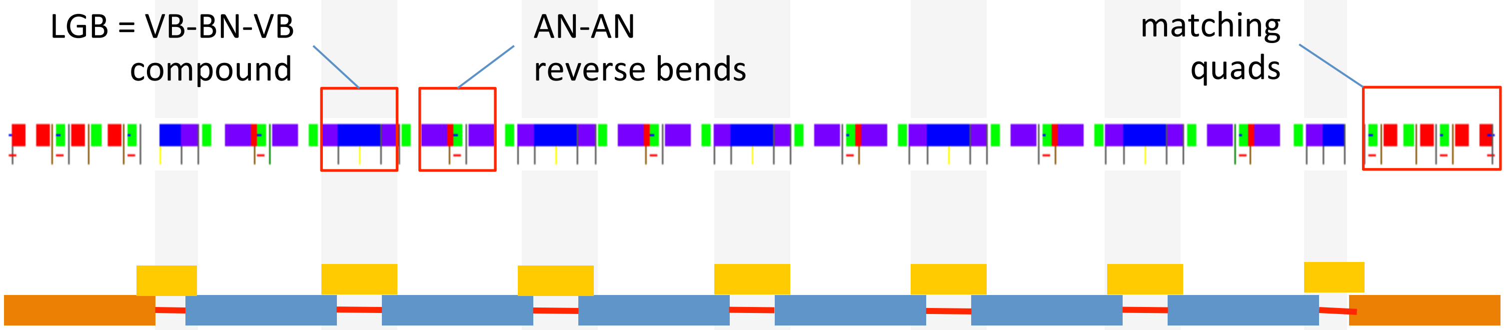
Girder train link. 3 types of misalignments (RMS, cut 2σ)
girder joints (60 μm) / joint play (20 μm) / elements on girders (30 μm)
+ define compound elements (i.e. common yoke magnets)



one arc:



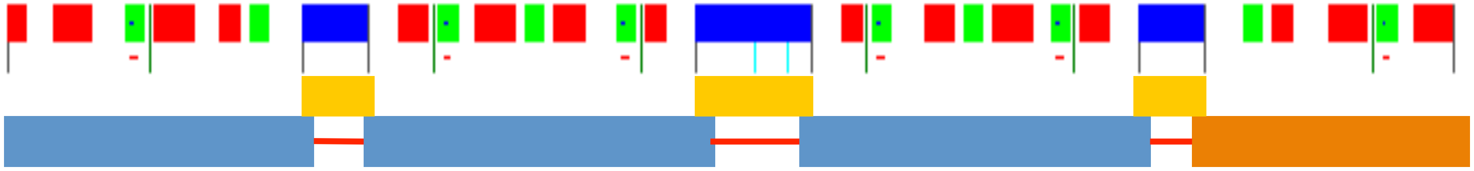
Girder patterns under consideration



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 (—)

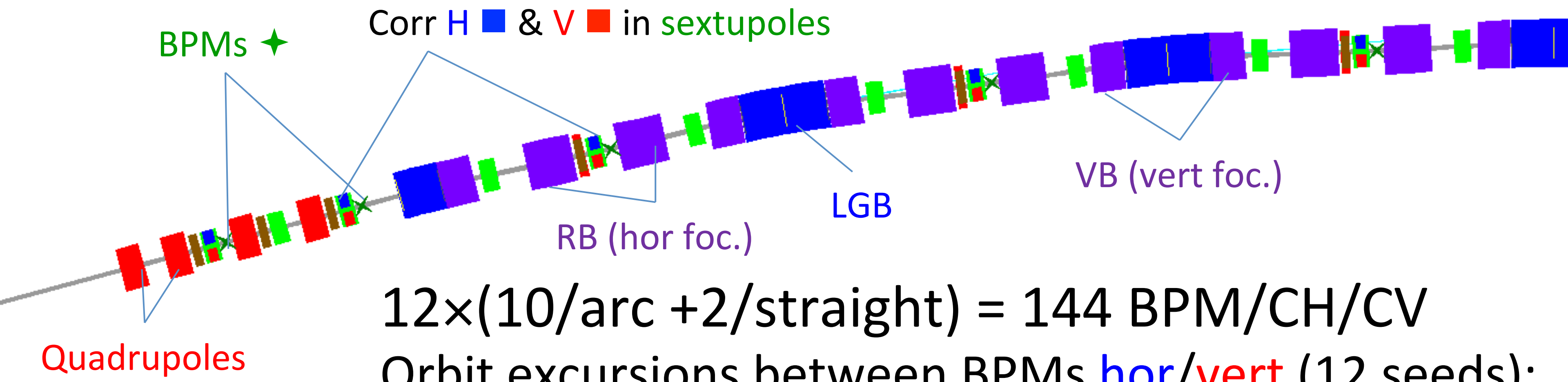
Movable long girders between plinth for every other LGB? Option to have 3 superbends in one arc. Double virtual joints in plinth (—— ——)



SLS now for comparison

S. Maag, M. Böge, K. Dreyer et al.

Orbit correction



BPMs ✦

Corr H 🟦 & V 🟥 in sextupoles

Quadrupoles

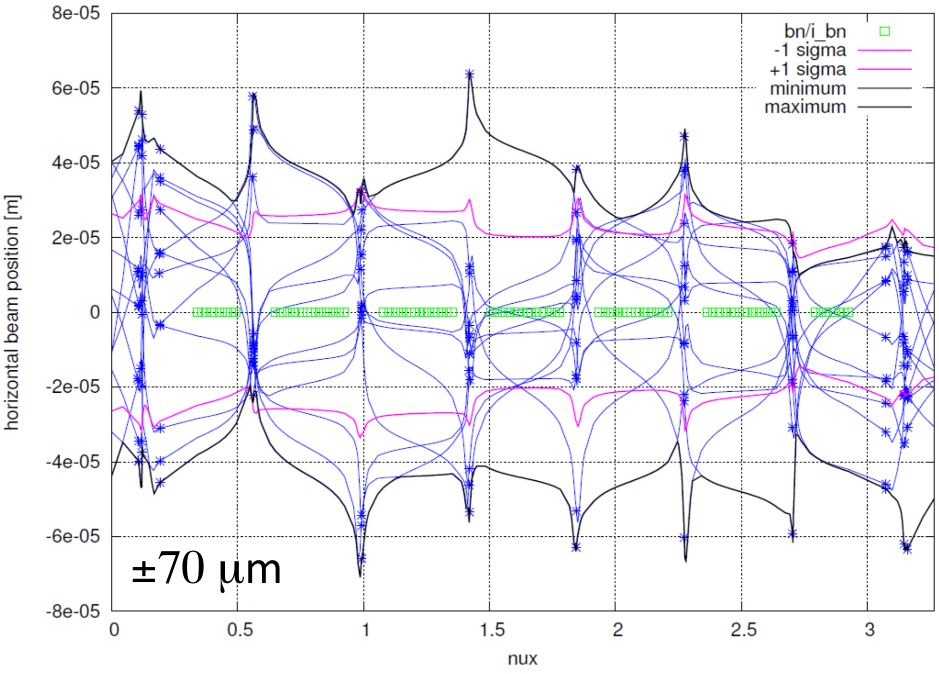
RB (hor foc.)

LGB

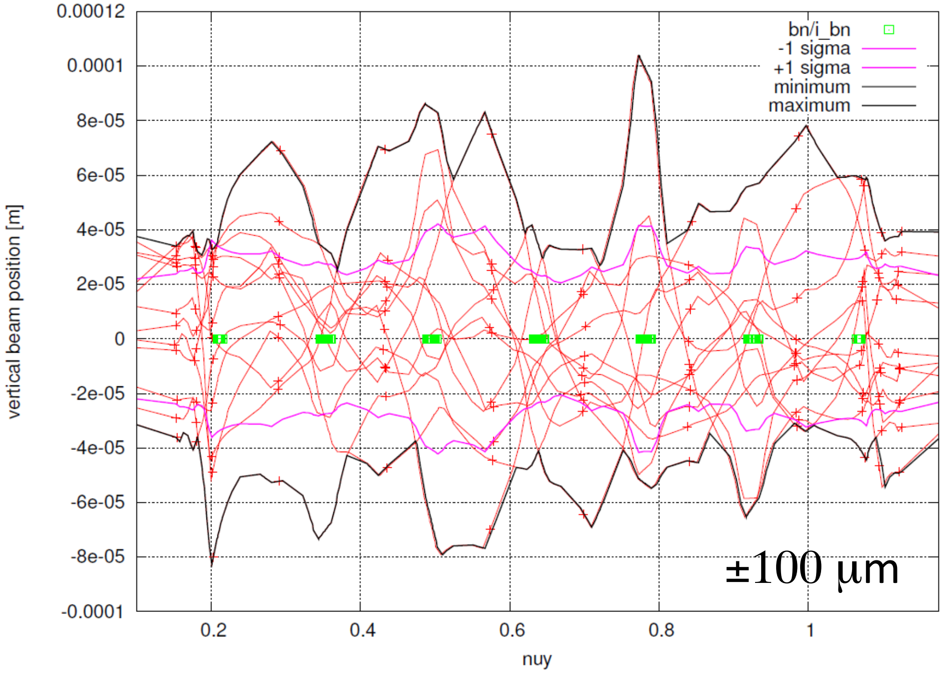
VB (vert foc.)

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

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

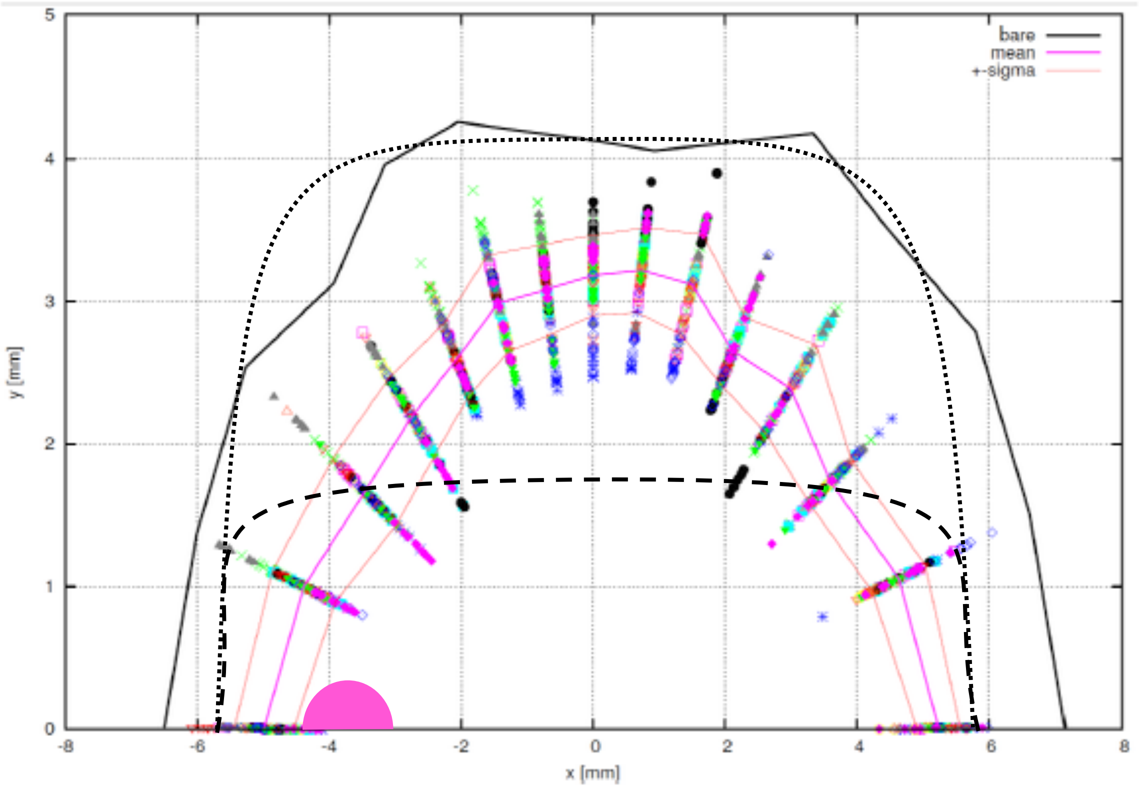


±70 µm



±100 µm

Dynamic aperture with errors



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

—— mean dynamic aperture —— +/- sigma

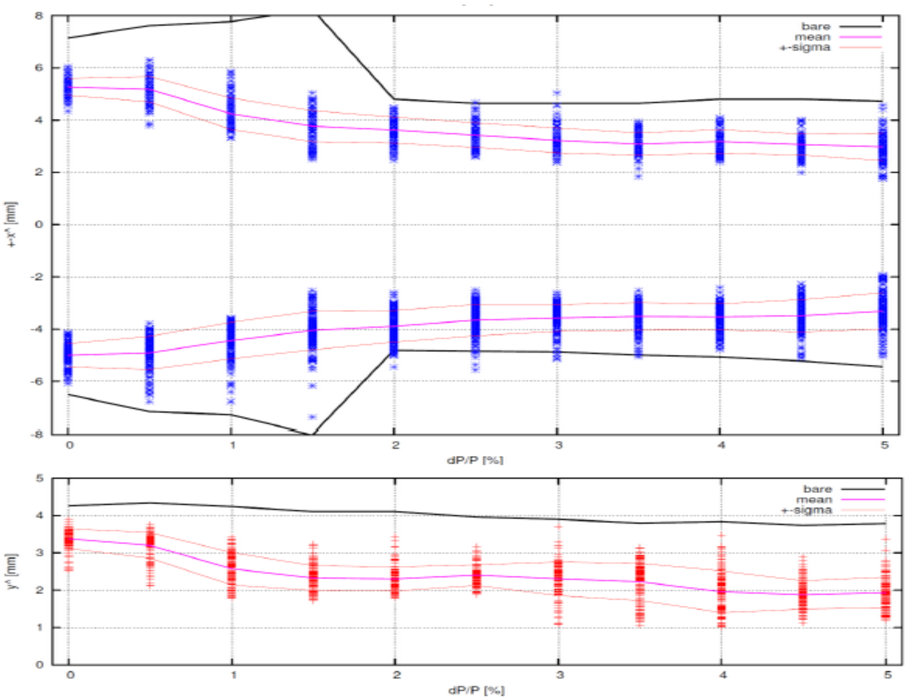
…… physical aperture limit from r = 10 mm beam pipe

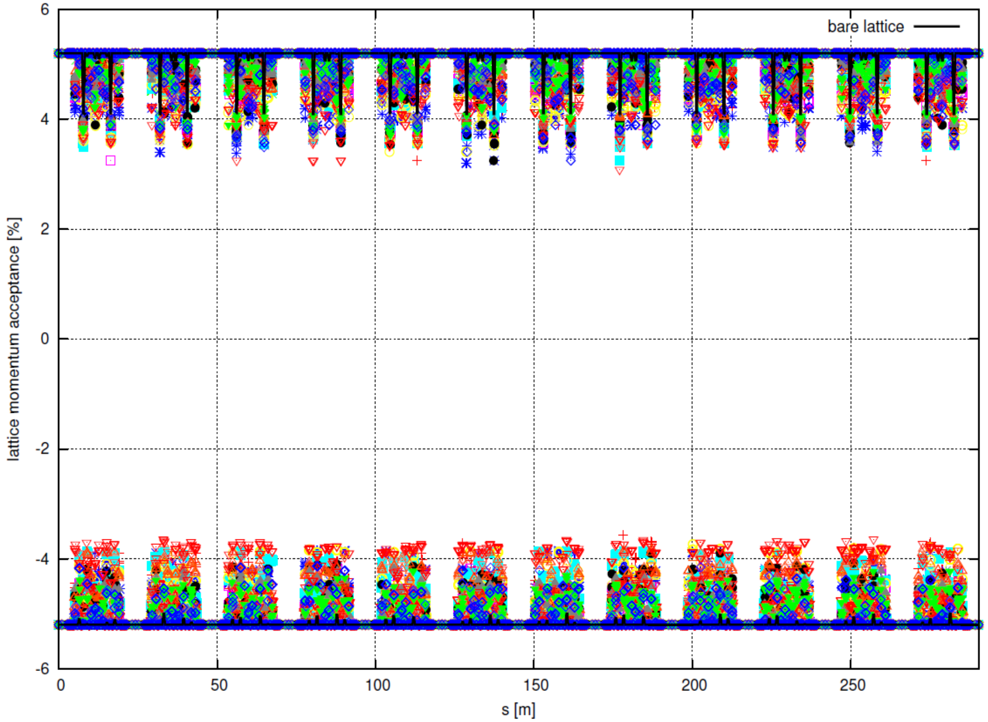
- - - physical aperture with undulator gaps (4 mm gap on 2 m length)

● approx. injected beam from booster (3σ)

M. Böge
J. Bengtsson
M. Aiba

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

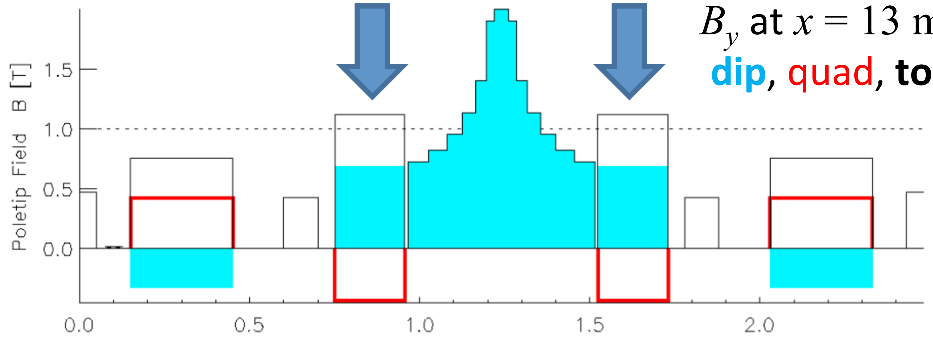
linear RF-mom.acc. used: 1.4 MV → 5.2%

M. Böge, J. Bengtsson, M. Aiba

Magnets 1 - compound LGB

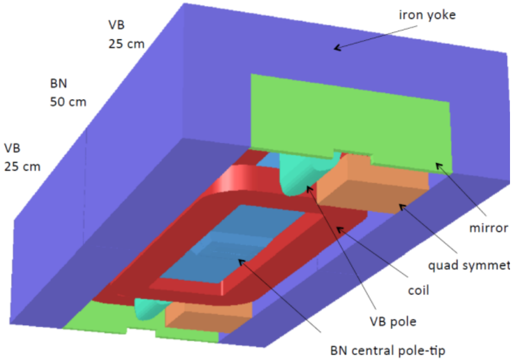
longitudinal/transverse gradient compound bend

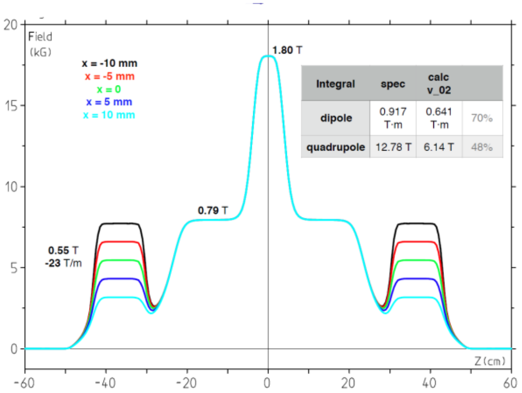
use low field at LGB ends
for vertical focusing gradient
→ save space, increase J_x



RC

resistive coil version

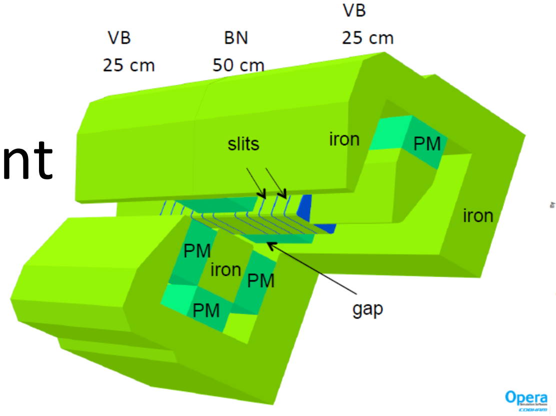


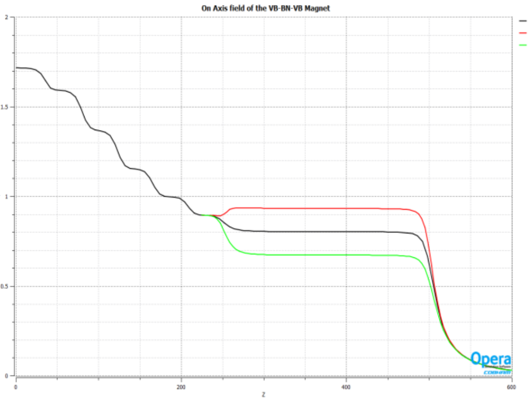


Integral	spec	calc v_02	
dipole	0.917 T·m	0.641 T·m	70%
quadrupole	12.78 T	6.14 T	48%

PM

permanent magnet version





work in progress

Alternatives:

- discrete quadrupoles?

- distributed gradient?

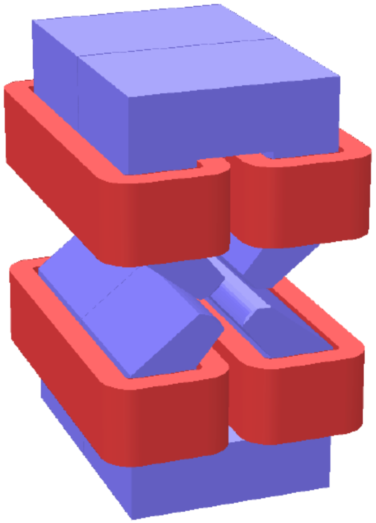
- incorporation of sextupole component too?

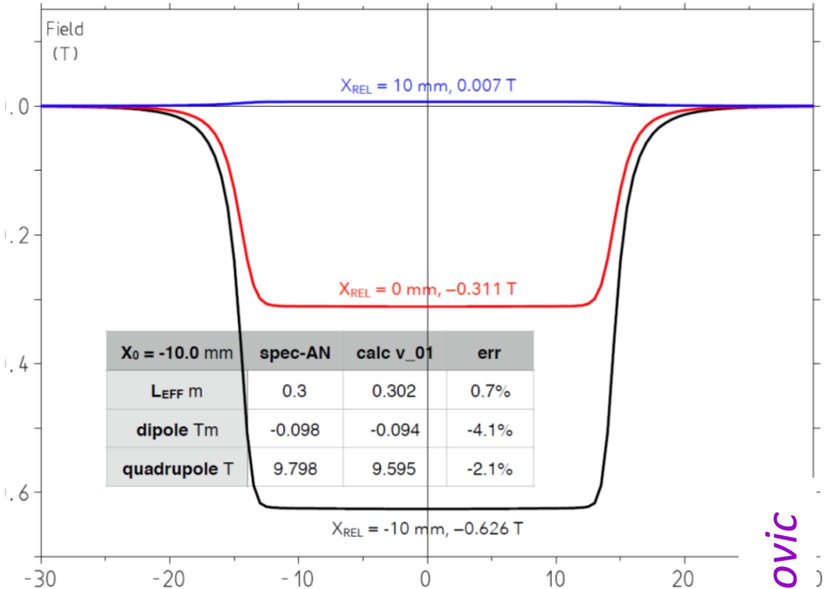
- tunability?

P. Lerch, M. Negrazus, V. Vrankovic

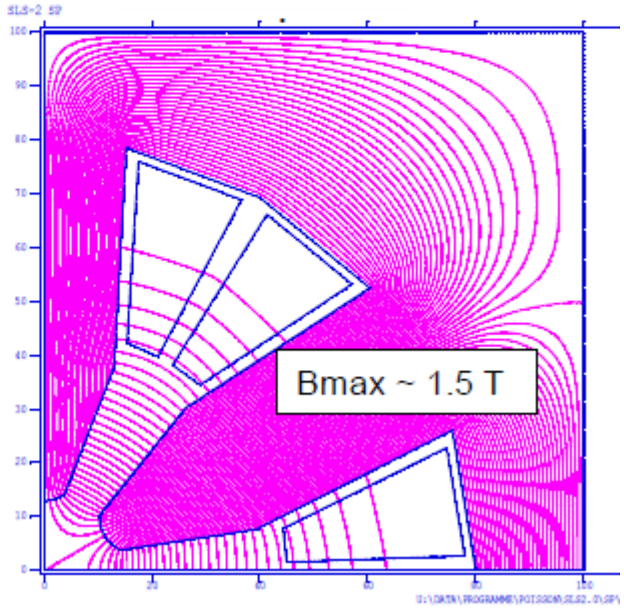
Magnets 2 - reverse bends and others

- 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

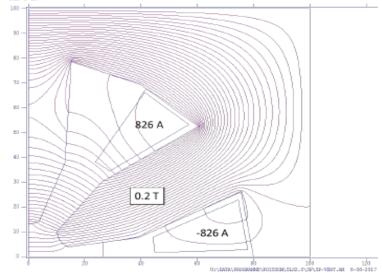




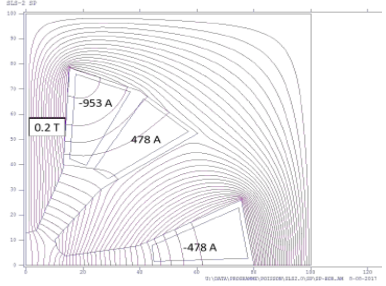
X_0 = -10.0 mm	spec-AN	calc v_01	err
L_{EFF} m	0.3	0.302	0.7%
dipole Tm	-0.098	-0.094	-4.1%
quadrupole T	9.798	9.595	-2.1%



vertical steerer

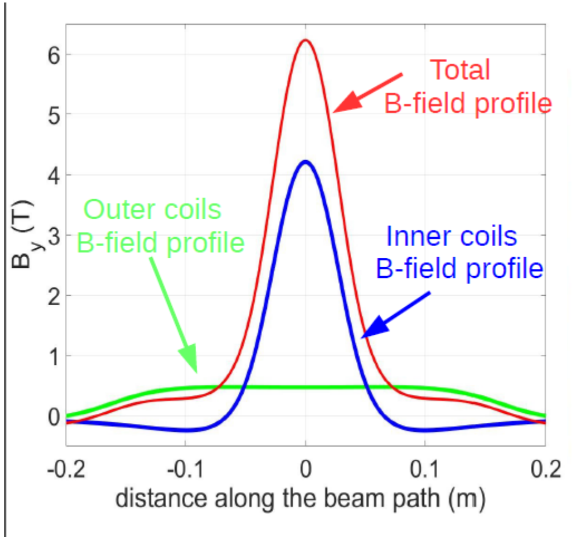


horizontal steerer



P. Lerch, M. Negrazus, V. Vrankovic

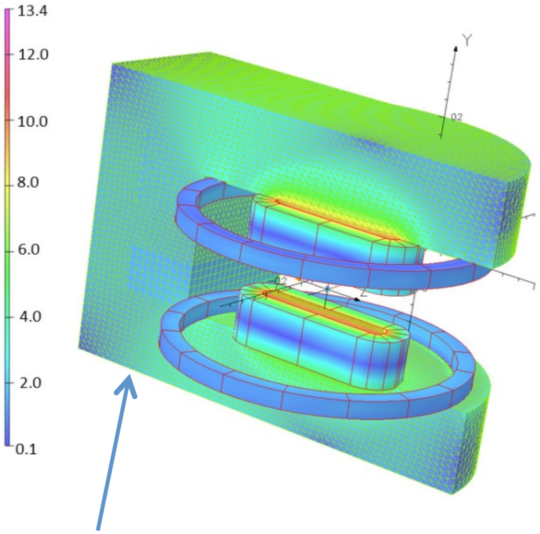
Magnets 3 - superbend

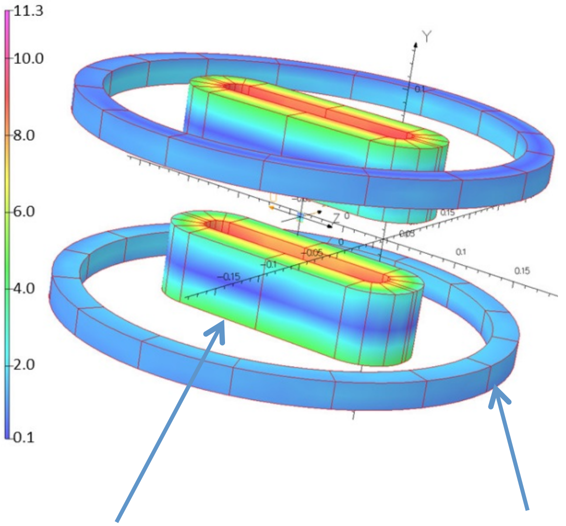


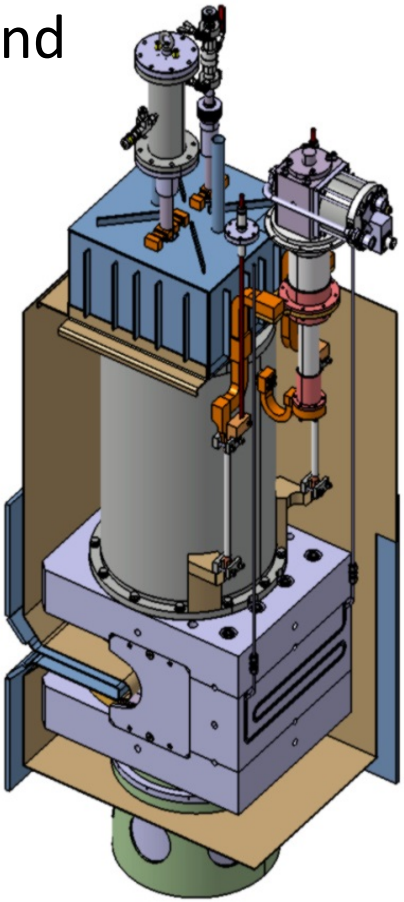
C. Calzolaio, S. Sanfilippo, A. Anghel, S. Sidorov

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

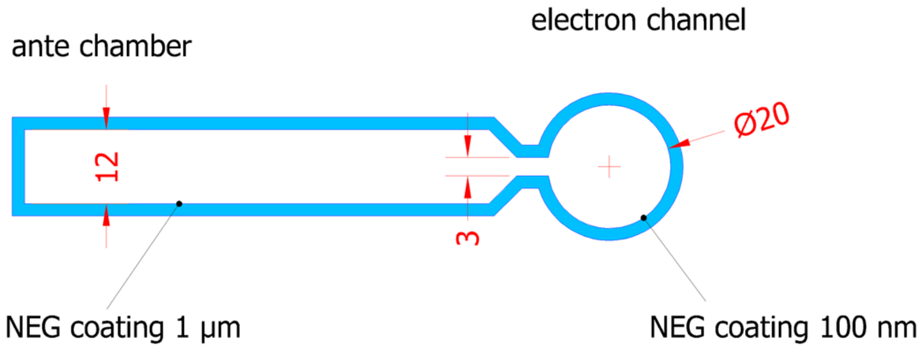
Inner Nb_3Sn coils to produce the B-field peak

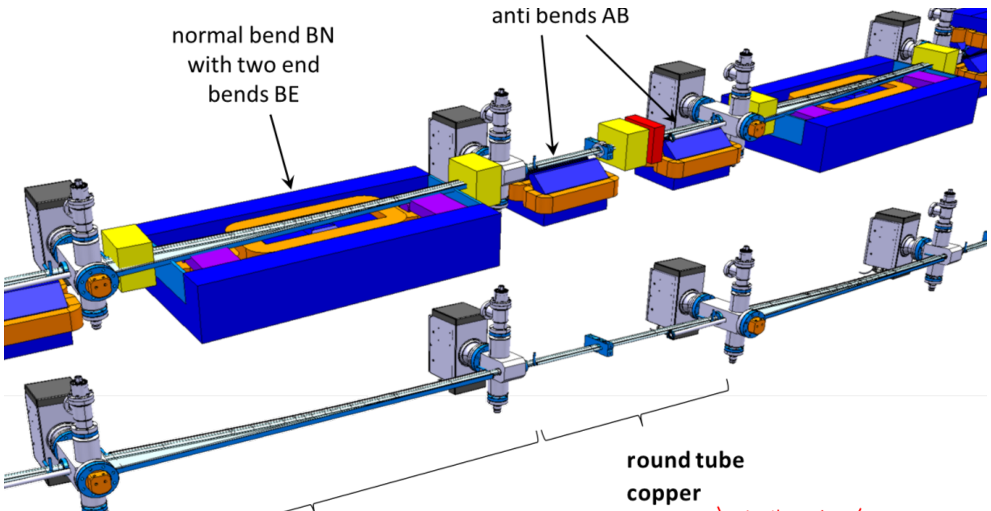
Outer NbTi coils to provide the field integral

Cryostat assembly

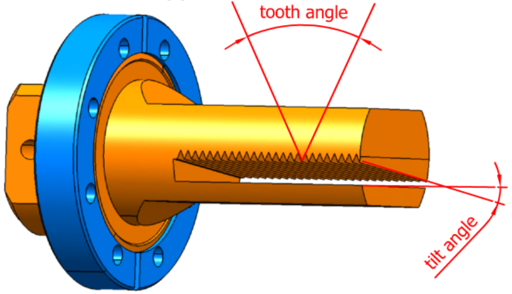
Vacuum system

- Alternating vacuum sections
  - antechambers in LGB areas →
  - copper tubes in RB areas ↘
- NEG coating
  - 1 μm in antechamber
  - 500 nm in beam pipe
    → turbulent bunch lengthening threshold 2.0/3.5 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 →





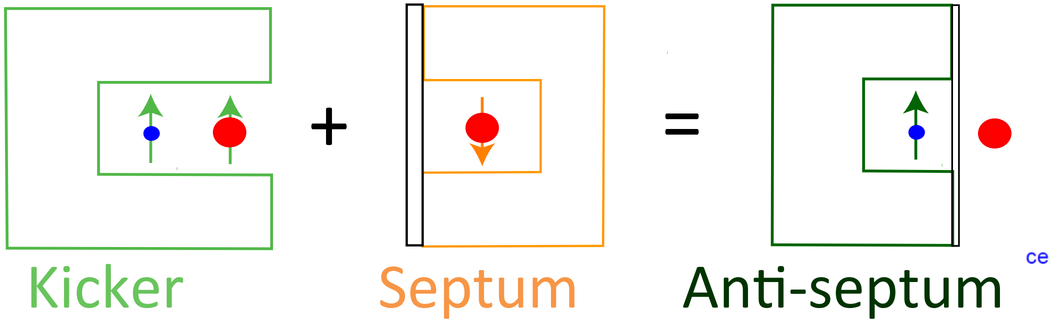
dipole chamber stainless steel

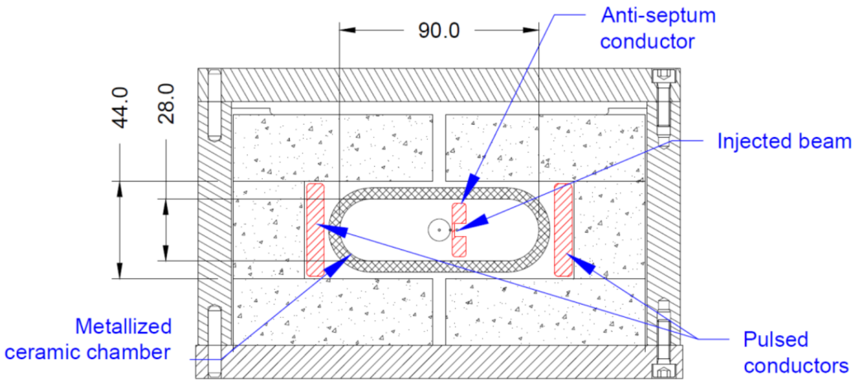


M. Hahn, L. Schulz et al.

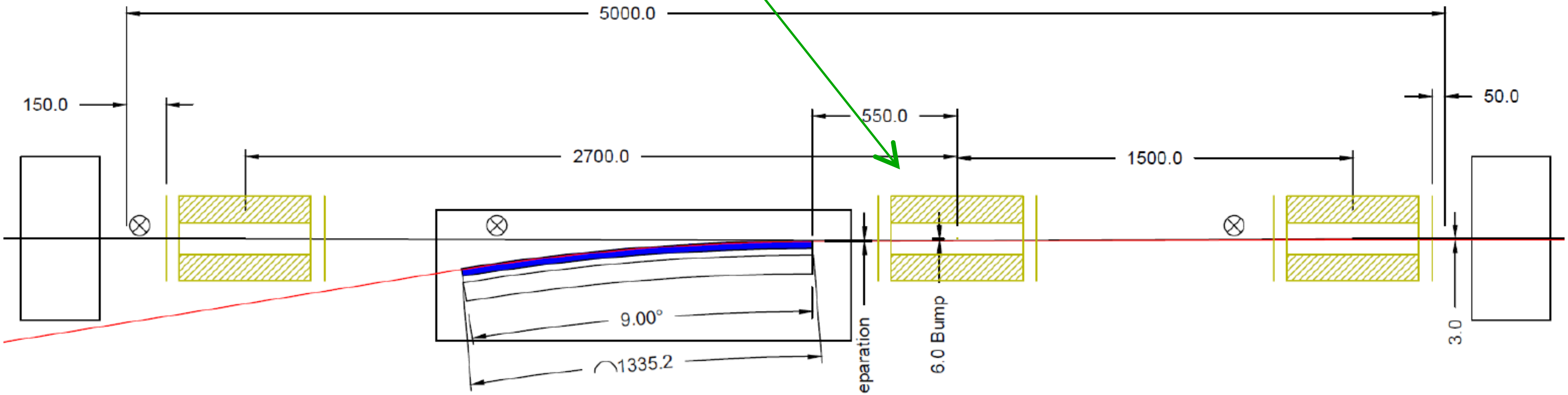
Injection

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 ✓

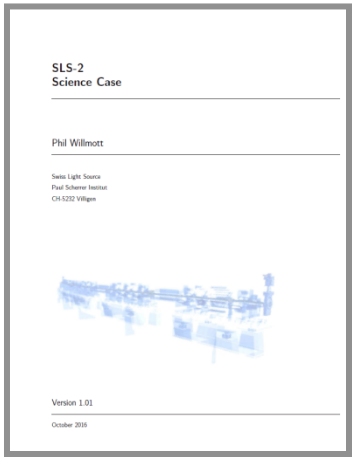
Work in progress:

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

M. Aiba
C. Gough

SLS-2 status

- Science Case
  - Version 1.0, Nov. 2016
    - http://ados.web.psi.ch/SLS2/CDR/Science_Case/bookmain.pdf
- Conceptual Design Report
  - DRAFT Sep. 5, 2017
    - http://ados.web.psi.ch/SLS2/CDR/Doc/cdr.pdf
  - CDR review meeting, Sep. 26-27, 2017
  - Final version < 22.12.2017 ⇨ PSI-report 17-03
- Submission to SNF < 31.12.2017
  (Swiss National Science Foundation)
  - Swiss research infrastructure roadmap 2021-24
  - total budget 100 MCHF
    - (83 machine + 17 beamlines, without salaries)



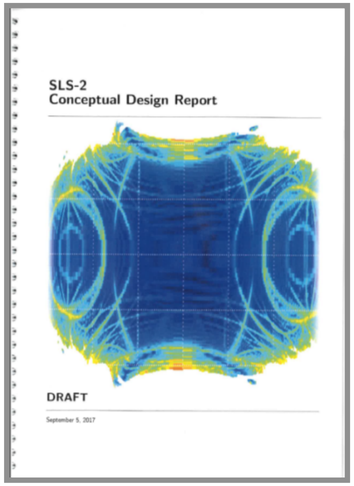
SLS-2
Science Case

Phil Willmott

Swiss Light Source
Paul Scherrer Institut
CH-5232 Villigen

Version 1.01

October 2016

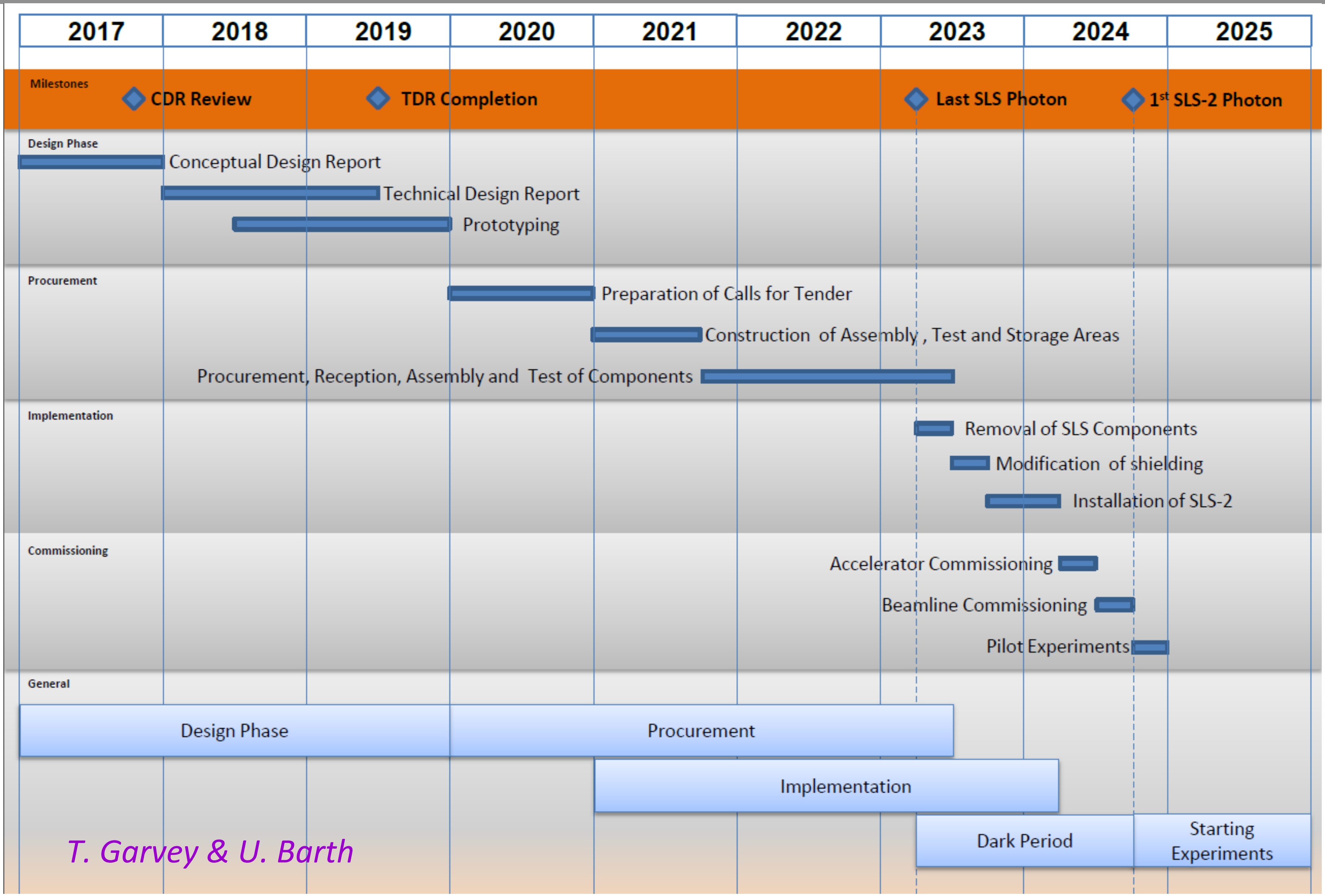


SLS-2
Conceptual Design Report

DRAFT

September 5, 2017

SLS-2 schedule



T. Garvey & U. Barth

Summary

Design of a...
- **competitive**
- **compact**
- **novel**
- **low emittance**

Lattice

Confidence in...
- **off axis injection**
- **beam lifetime**

Challenging...
- **magnet design**
- **tolerances**
- **time schedule**

Thank you !