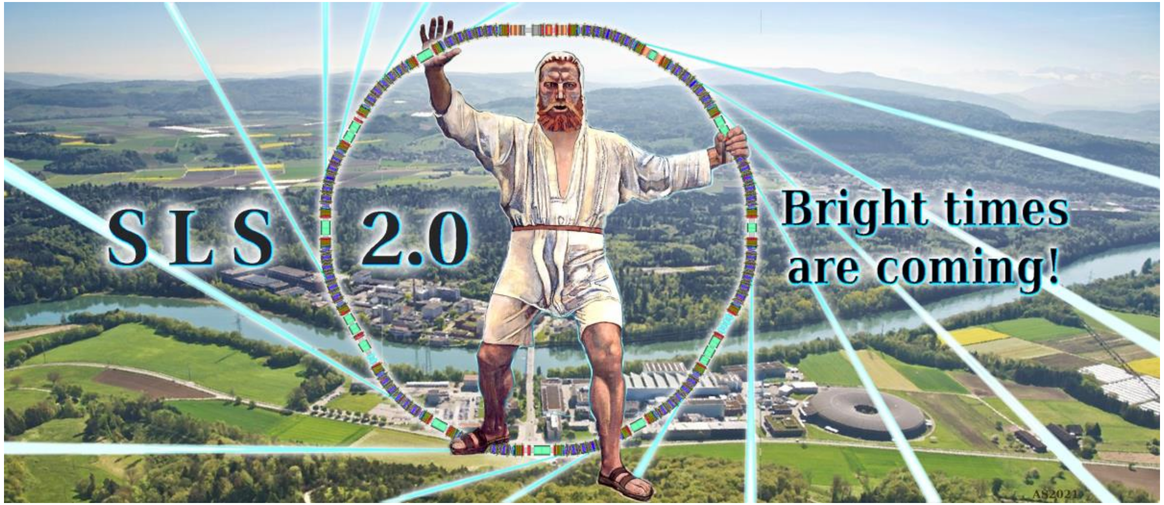
PAUL SCHERRER INSTITUT

PSI



Andreas Streun :: Synchrotron Beam Dynamics :: Paul Scherrer Institut

Machine Overview

SLS 2.0 User Information Workshop, PSI, Feb. 28, 2022

Outline

- Introduction
  - Diffraction limited storage ring
  - Multi-bend achromat
- Storage ring design
  - History
  - Concept
  - Performance
  - Lattice Layout
- Realization
  - Technology
  - Planning
- Conclusion and Outlook

Experiments with synchrotron light

- ***energy range***

$$E_\gamma = 10\ \text{eV (UV)} \ldots\ 100\ \text{keV (X-ray)}$$

$$E_\text{crit} = 665\ \text{eV}\cdot B\ [\text{T}]\cdot(E\ [\text{GeV}])^2 \rightarrow E_\gamma = 10\ \text{keV},\ B = 2\ \text{T} \rightarrow \boldsymbol{E = 2.7\ \text{GeV}}$$

- ***brightness***

Flux

$$B = \frac{\text{photons}}{(\text{time}) \times (\text{energy interval}) \times (\textbf{area}) \times (\textbf{solid angle})}$$

6-dimensional *invariant* photon phase space density

- ***coherence***
  coherent fraction
  transverse (spatial)

$$CF = \frac{\text{phase space (diffraction only)}}{\text{phase space (diffraction } \textbf{+ source}\text{)}}$$

"diffraction limited light source"

DLSR = diffraction limited storage ring

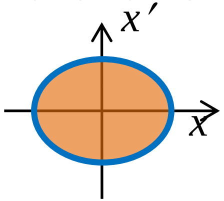
Diffraction limit

Diffraction limited source : source phase space (electron beam) **<<** diffraction phase space

Gaussian approximation for transverse 2D-phase spaces (horizontal and vertical)

- **emittance** = phase space *area* $\varepsilon = \sigma_x \cdot \sigma_{x'}$
- **beta function** = phase space *aspect ratio* $\beta = \sigma_x / \sigma_{x'}$

(= *Rayleigh length* in optics)



neglecting correlations $\langle xx' \rangle$

Diffraction limit

wave property

single photon emittance

$$\varepsilon_r = \frac{\lambda}{4\pi}$$

$$\sigma_{px} = p\,\sigma_{x'}$$

$$p = E/c = h/\lambda$$

uncertainty principle

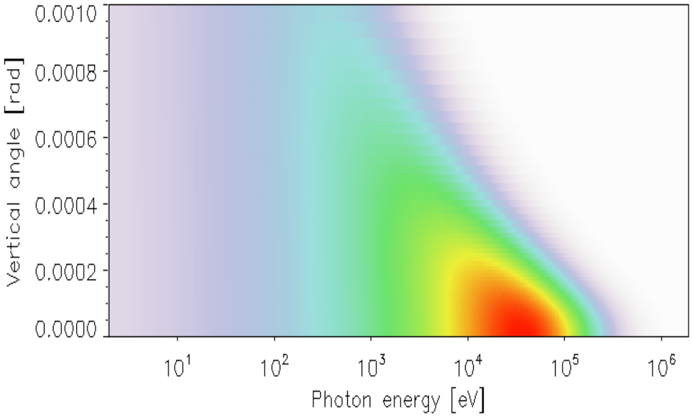
$$\sigma_x \sigma_{px} \geq \frac{\hbar}{2}$$

Photon beam emittance = convolution of electron beam (ε_y , β_y) and diffraction (ε_r , β_r)

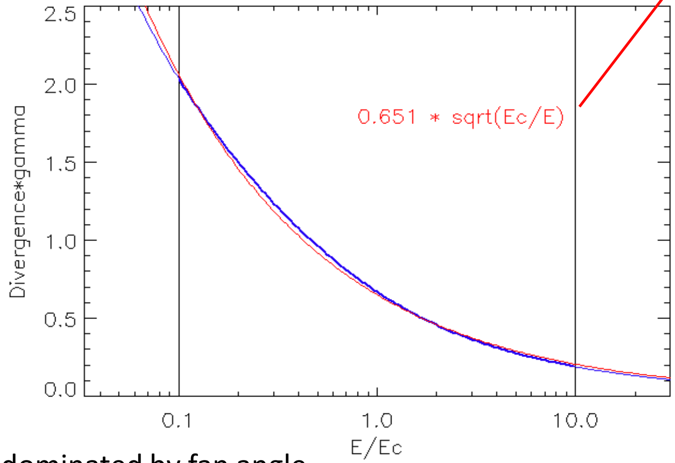
$$\varepsilon_{\gamma y} = \varepsilon_y \oplus \varepsilon_r = \sqrt{\varepsilon_y^2 + \varepsilon_r^2 + \varepsilon_y \varepsilon_r \left(\frac{\beta_r}{\beta_y} + \frac{\beta_y}{\beta_r} \right)} \xrightarrow{\beta_y = \beta_r} \varepsilon_y + \varepsilon_r$$

Diffraction: dipole magnet

Total power density (σ + π polarization) vs. vertical angle and photon energy for 5 Tesla dipole at 2.4 GeV



Vertical* divergence vs. photon energy:
Gauss fit to vertical profile
and
square root fit



*horizontal divergence dominated by fan angle

Diffraction emittance

$$\varepsilon_r = \frac{\lambda}{4\pi}$$

Vertical divergence

$$\sigma_{r'} = \frac{0.65}{\gamma}\sqrt{\frac{E_{\text{crit}}}{E_\gamma}}$$

$$E_{\text{crit}} = 665\ \text{eV}\ \ B\,[\text{T}]\,(E\,[\text{GeV}])^2$$

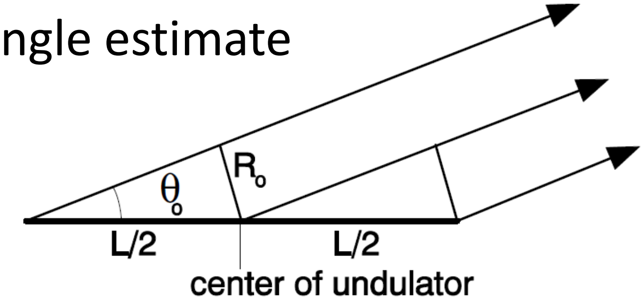
⇨ dipole diffraction beta function

$$\boxed{\sigma_{r'} = \sqrt{\frac{\varepsilon_r}{\beta_r}} \;\rightarrow\; \beta_r = \frac{1.34\ \text{mm}}{B[\text{T}]}}$$

- independant of photon energy
- independant of electron energy
- small ! (<< electron beta function)

Diffraction: undulator

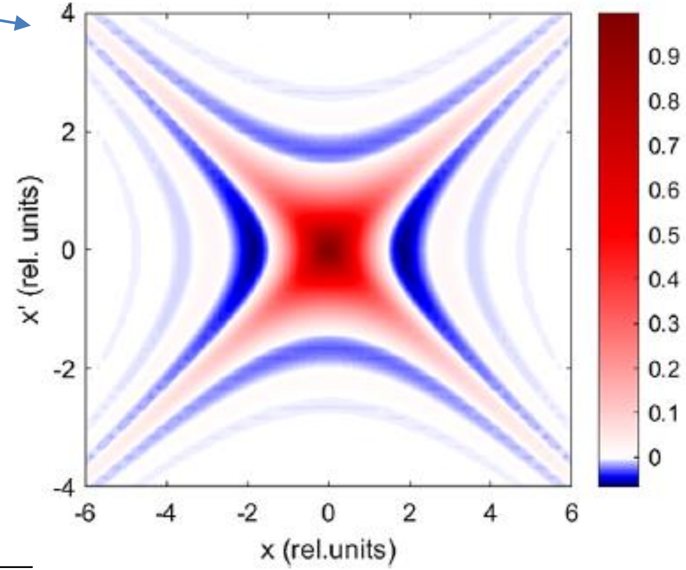
- Undulator beam is not Gaussian
  - different approximations...
  - depending on type of experiment
- Divergence angle estimate [Joho]



destructive interference for

$$\frac{\lambda}{2} = \frac{L}{2}(1 - \cos\theta_o) \rightarrow \sigma_{r'} = \theta_o \approx \sqrt{2\lambda/L}$$

Undulator brightness [Walker]



- Undulator diffraction beta-function

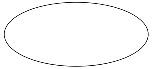
$$\sigma_{r'} = \sqrt{\frac{\varepsilon_r}{\beta_r}} \rightarrow \beta_r = \frac{L}{2\pi}$$

comparable to electron beta function

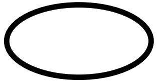
W. Joho, Radiation properties of an Undulator, SLS-Note 4/95

R. P. Walker, Undulator radiation brightness and coherence near the diffraction limit, Phys. Rev. Accel. Beams 22, 050704 (2019)

Phase space and beam cross section for SLS 2.0 and SLS



electron beam



photon beam

= electron beam

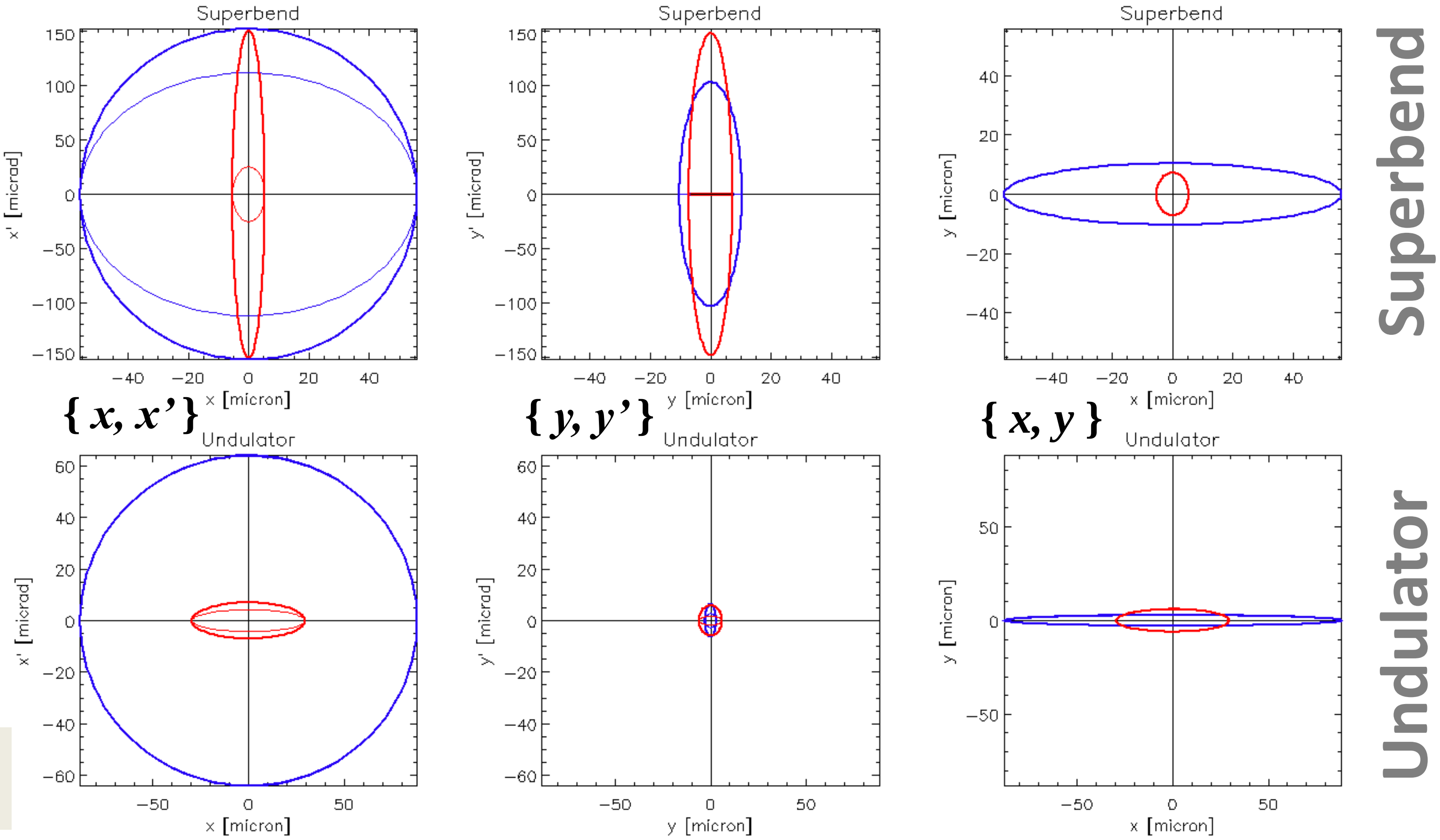
⊕ diffraction

$E_\gamma = 20$ keV

(superbends:

$B = 2.9$ T / 6.0 T,

zero fan angle)



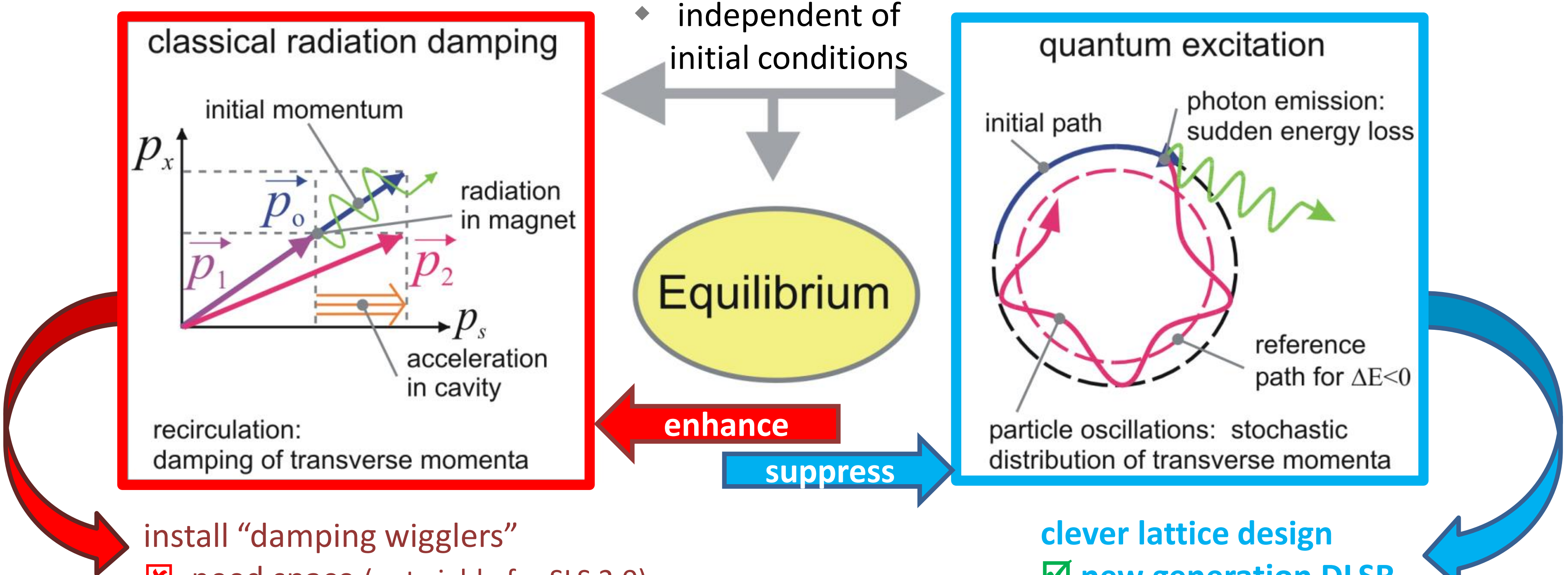
P-SAC 2018

(not the latest data)

How to get low electron emittance ?

Electron storage ring:

Radiation Equilibrium



- independent of initial conditions

Equilibrium

enhance

suppress

install “damping wigglers”

☒ need space (not viable for SLS 2.0)

clever lattice design

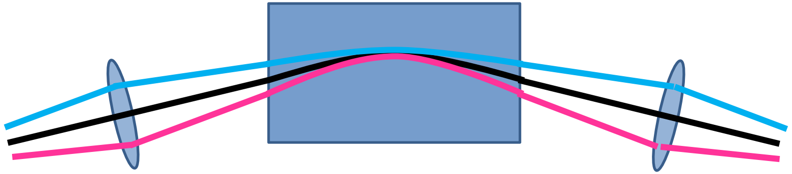
☑ **new generation DLSR**

Minimum Quantum Excitation

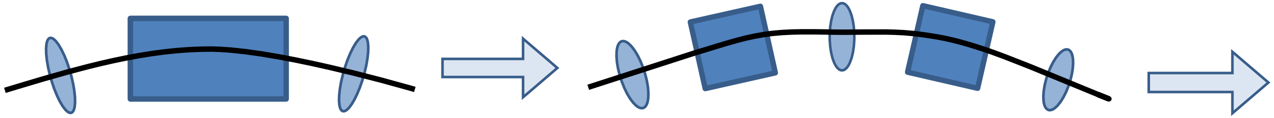
- keep off-momentum orbit close to nominal orbit

⇨ ***minimize dispersion*** at locations of radiation (dipoles)

- **Horizontal Focusing** into bends to suppress dispersion.

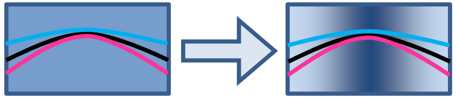


- **Multi-Bend Achromat lattice (MBA)**
  many short (small angle) dipoles to limit dispersion growth.



⇨ Miniaturization of components and/or large ring size

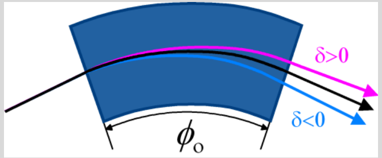
- **Longitudinal Gradient Bend (LGB)**
  highest radiation at lowest dispersion and v.v.



Storage ring is made from dipole magnets

Dipole = spectrometer

$\delta = \Delta p/p$



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

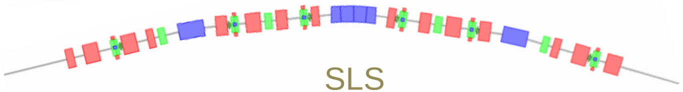
MBA = base for new

light source generation.
Pioneered by MAX IV.

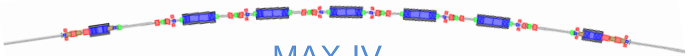
Multibend-achromat Lattices

MAX-I

ESRF



SLS



MAX-IV

ESRF-EBS

SLS 2.0

3rd generation light sources

DBA or TBA lattice arcs

(= double/triple bend achromat)

magnet bore ~ 60 mm

4th generation light sources

MBA lattice arcs (e.g. 7-BA)

(= multi-bend achromat)

magnet bore ~ 20 mm

M. Eriksson et al., Some small-emittance light-source lattices with multi-bend achromats, Nucl. Instr. and Meth. A587, 221 (2008)

D. Einfeld, Multi-bend Achromat Lattices for Storage Ring Light Sources, Sync. Rad. News 27.6, 4 (2014)

MBA Emittance

Minimum emittance achievable

(classical cell without combined functions, longitudinal gradients and reverse bending)

$$\varepsilon_{\mathrm{min}} \approx 1/6\ \mathrm{pm}\ (E\ [\mathrm{GeV}])^2\ (\phi\ [^\circ]\ )^3$$

N arcs made as ***M***-BA

angle per cell (dipole) $\phi = 360^\circ / [\ N \times (M-1)\ ]$

SLS $N = 12,\ M = 3\ ,\ E = 2.41\ \mathrm{GeV}$

$\varepsilon_{\mathrm{min}} = 3270\ \mathrm{pm}$

$\varepsilon_{\mathrm{xo}} = \mathbf{5030\ pm}$ (without FEMTO chicane and superbends)

SLS 2.0 $N = 12,\ M = 7\ ,\ E = 2.70\ \mathrm{GeV}$

$\varepsilon_{\mathrm{min}} = 152\ \mathrm{pm}$

$\varepsilon_{\mathrm{xo}} = \mathbf{149\ pm}$ (without superbends, 158 pm with s.b.)

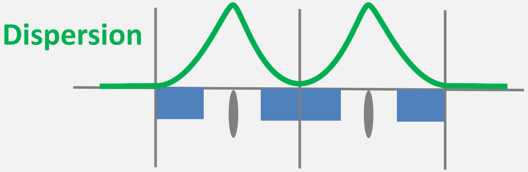
A-chromat

= no dispersion in straights

→ avoid widening due to energy spread

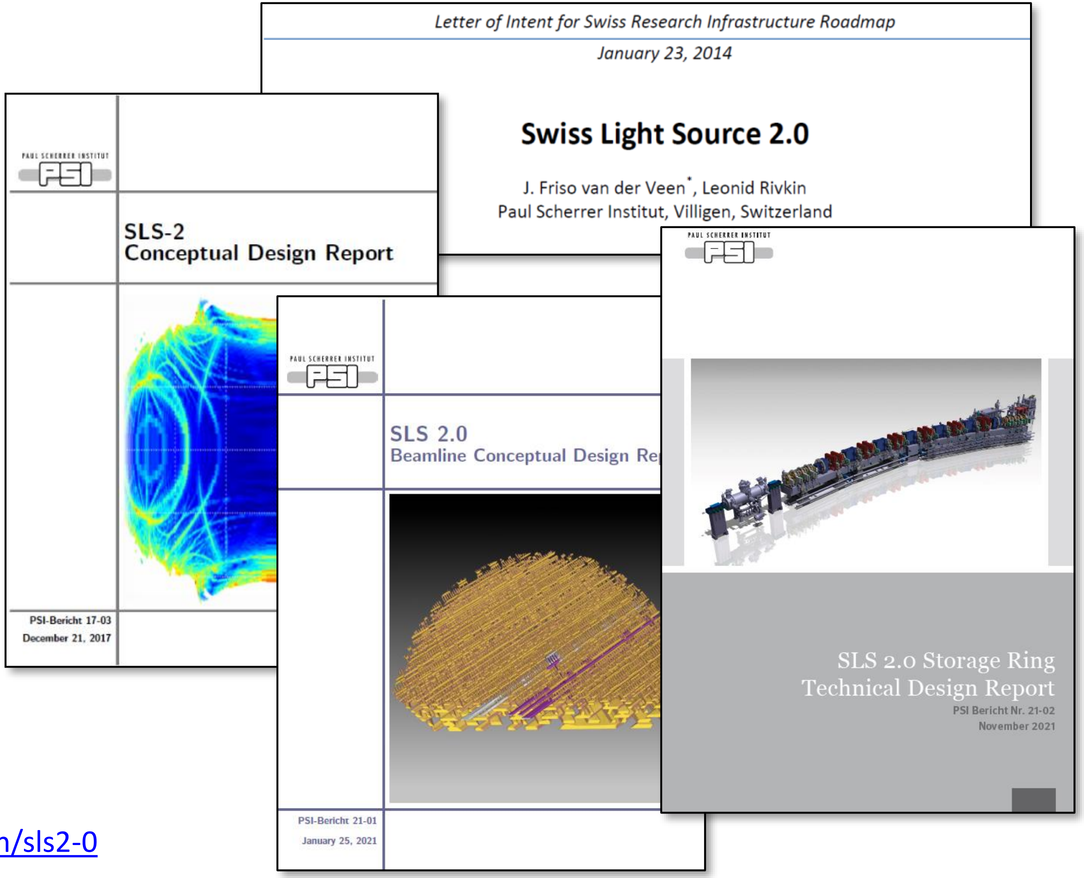
→ avoid jitter due to energy fluctuations

arc terminated by half dipoles:



SLS 2.0 upgrade: History

- First thoughts ~2012
- 1/2014 Letter of Intent
- 12/2017 Conceptual Design Report*
- 1/2018 Submission to SNF
- 12/2018 ETH board: on “roadmap”
- 4/2019: 1st Beamline CDR Adv. Comm.
- 6/2019: 1st Machine Adv. Comm. meeting
- 2/2020: increase energy to 2.7 GeV
- 3-6/2020: lattice review and finalization
- 12/2020: Funding secured: 129 MCHF
- 1/2021: Beamline CDR*
- 11/2021: Technical Design Report*



Letter of Intent for Swiss Research Infrastructure Roadmap

January 23, 2014

Swiss Light Source 2.0

J. Friso van der Veen*, Leonid Rivkin

Paul Scherrer Institut, Villigen, Switzerland

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SLS-2
Conceptual Design Report

PSI-Bericht 17-03
December 21, 2017

PAUL SCHERRER INSTITUT PSI

SLS 2.0
Beamline Conceptual Design Re

PSI-Bericht 21-01
January 25, 2021

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SLS 2.0 Storage Ring
Technical Design Report
PSI Bericht Nr. 21-02
November 2021

*available at https://www.psi.ch/en/sls2-0

SLS 2.0 Upgrade: Charge

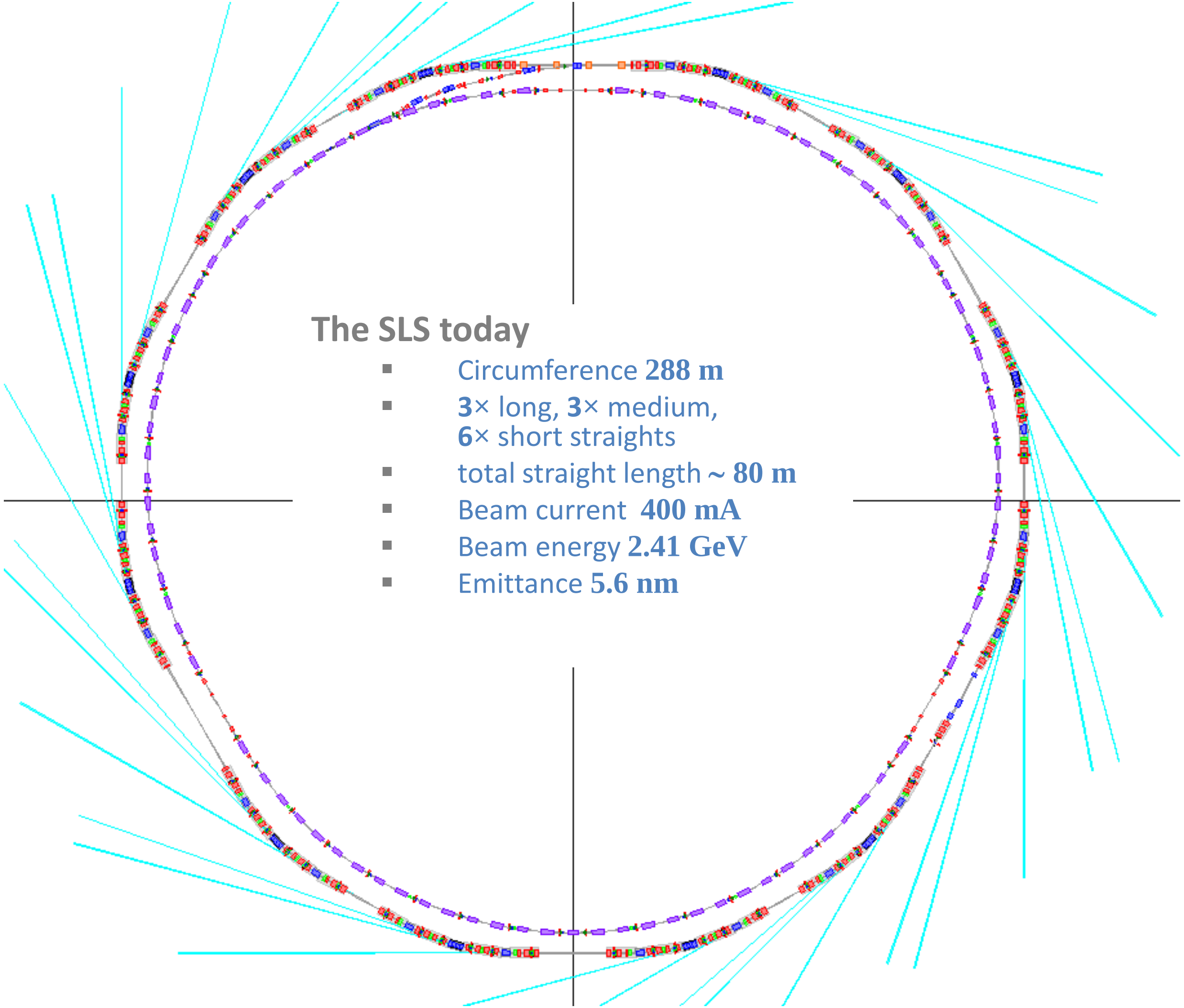
- **User demands**

  heterogeneous
  user community

  - Imaging and RIXS: brightness
    - TOMCAT beamline: high energy > 50 keV ⇨ superbends
  - Ptychography: coherent flux
  - Spectroscopy (hard and soft): flux
  - VUV: no deterioration of present situation, low energy (10 eV)
  - All: top-up operation, < 1% current fluctuation → beam lifetime
  - All: sub-micron beam stability and >99% availability
  - Hard X-ray: **brightness increase by factor ~ 40**

- **Constraints**
  - Re-use existing building and avoid tunnel modification
    - Tunnel size: maintain circumference of 288 m,
      period-3 layout: 12 arcs and short/medium/long straights
    - Beamline ports: source point shifts within ±70 mm

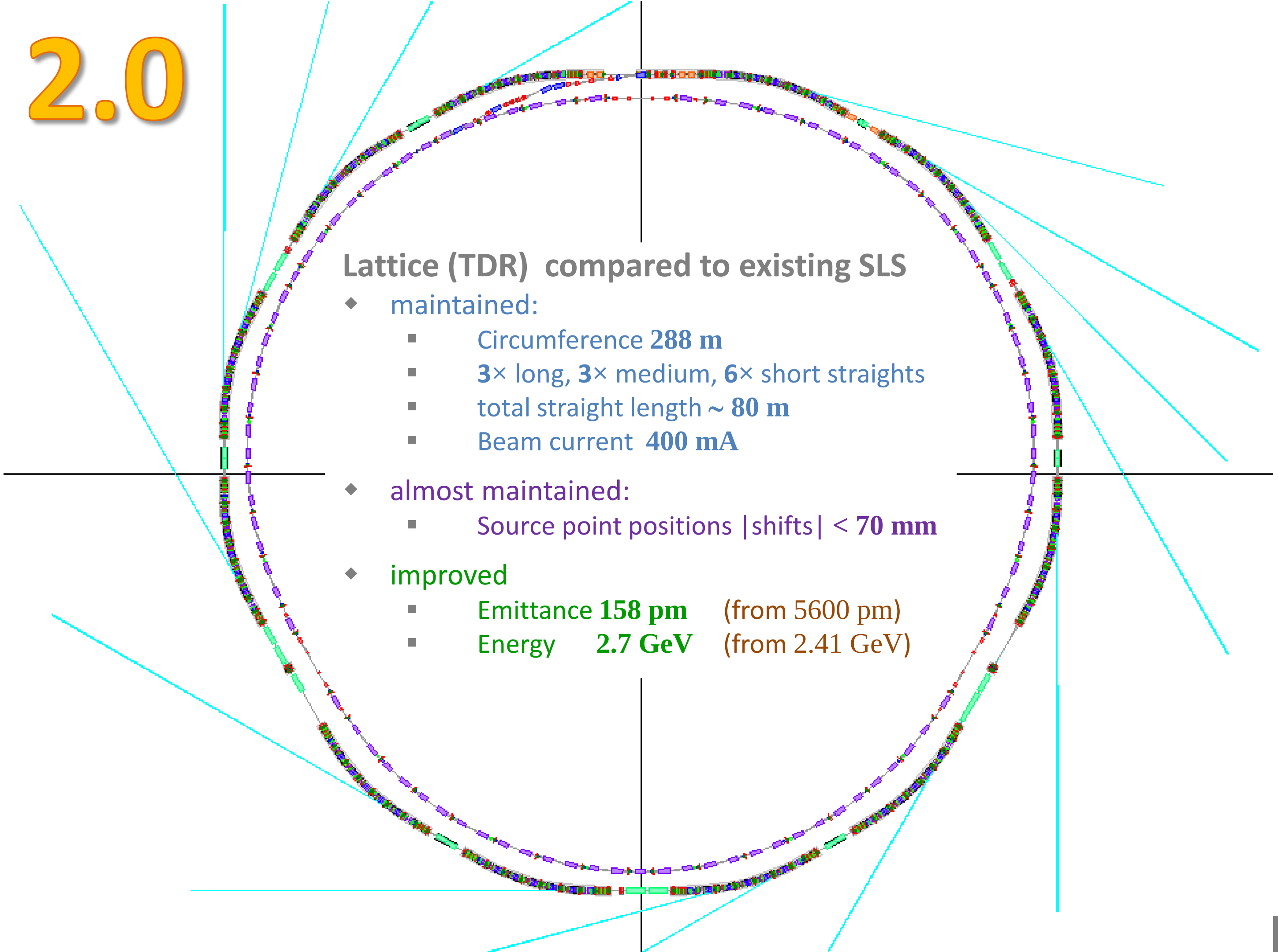
SLS



The SLS today

- Circumference **288 m**
- **3**× long, **3**× medium,
  6× short straights
- total straight length **~ 80 m**
- Beam current **400 mA**
- Beam energy **2.41 GeV**
- Emittance **5.6 nm**

SLS 2.0



Lattice (TDR) compared to existing SLS

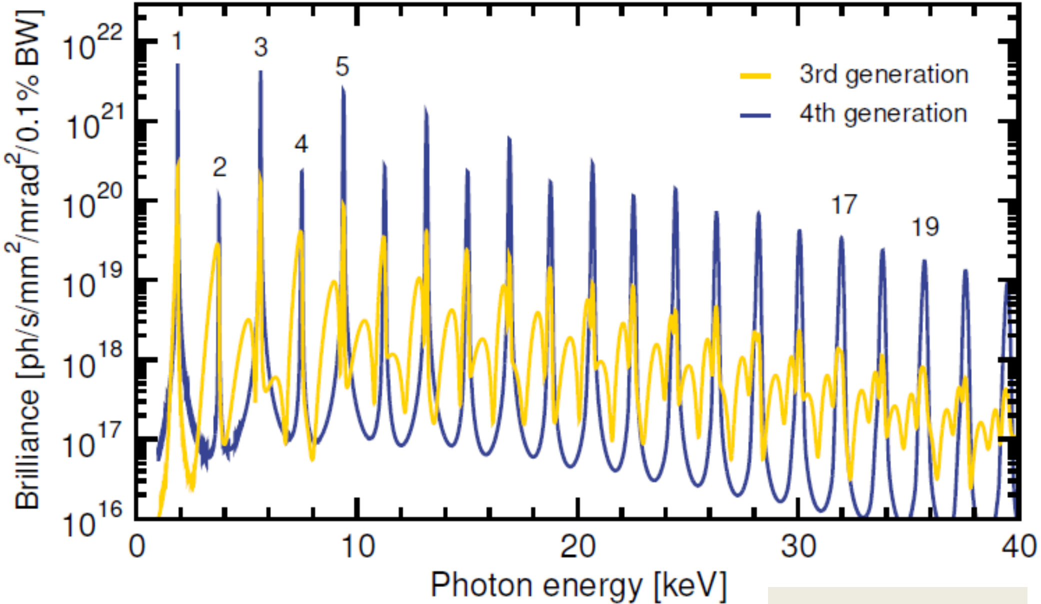
- maintained:
  - Circumference **288 m**
  - **3**× long, **3**× medium, **6**× short straights
  - total straight length ~ **80 m**
  - Beam current **400 mA**
- almost maintained:
  - Source point positions |shifts| < **70 mm**
- improved
  - Emittance **158 pm**   (from 5600 pm)
  - Energy   **2.7 GeV**   (from 2.41 GeV)

SLS 2.0 parameters

	SLS 2.0	**SLS**
◆ Lattice type	12 × 7BA, LGB/RB cell	12 × 3BA, conventional
◆ Circumference	288 m	288 m
◆ Straights (for IDs)	6× 4.3 m → 5× 4.1 m + 2.0 m 3× 6.5 m → 3× 5.0 m 3× 13.7 m → 6.6 m + 5.0 m + 3.0 m	6 (→ 4) × 3.9 m 3 (→ 2½) × 6.9 m 3 (→ 2) × 11.7 m
◆ Superbends	2 × 5.0 T, 2 × 2.1 T	3 × 2.9 T
◆ Energy	2.7 GeV	2.41 GeV
◆ hor. emittance	**158 pm** $\to^{\text{IBS}}$ ≈162 pm $\to^{\text{all IDs}}$ ≈134 pm	5630 pm (with Femto chicane)
◆ vert. emittance	10 pm (tunable)	5...10 pm (tunable)
◆ Energy spread	1146 ppm $\to^{\text{IBS}}$ ≈1160 ppm $\to^{\text{all IDs}}$ ≈1040 ppm	878 ppm
◆ Radiation loss	689 keV $\to^{\text{all IDs}}$ ≈900 keV	549 keV
◆ Current	400 mA	400 mA
◆ Beam Lifetime	≈11 h (ideal lattice, with 3HC; and 10^{-9} mbar CO)	≈10 h
◆ Lattice version	`b072`	`f6cwo`

Upgrade summary

- The upgrade mainly will reduce horizontal emittance by factor 35
  - everything else will change not or little: circumference, straight lengths, vertical emittance, beam current, source point positions etc.
  - side effect: energy spread will be 30% larger
  - beam energy increased by 13% in favor of hard X-rays
- Lower horizontal emittance
  - → increases brightness and coherent fraction
  - → gives clean undulator spectra and enables new undulator developments



SLS 2.0 BL-CDR

SLS 2.0 brightness

Improvement relative to SLS:

reduced emittance:

× 24 (10...20 keV)

+ higher energy (2.7 GeV):

× 59 (10...20 keV)

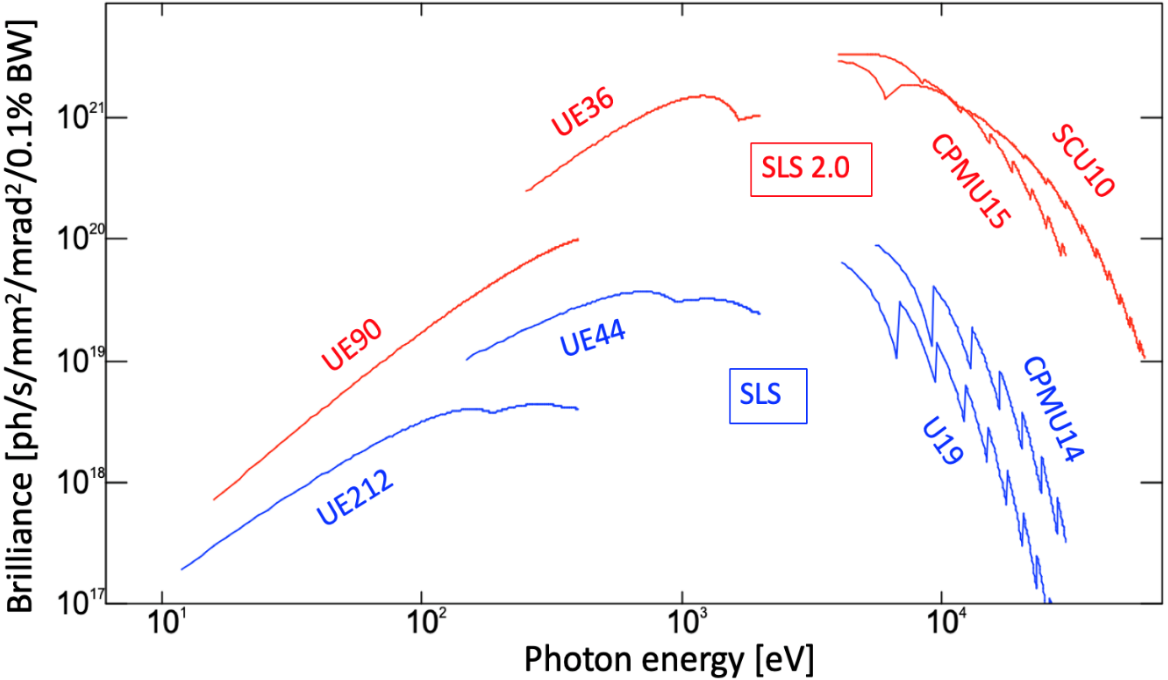
+ new undulators

(CPMU15 instead of U19):

× 140 (10 keV) ... 870 (20 keV)

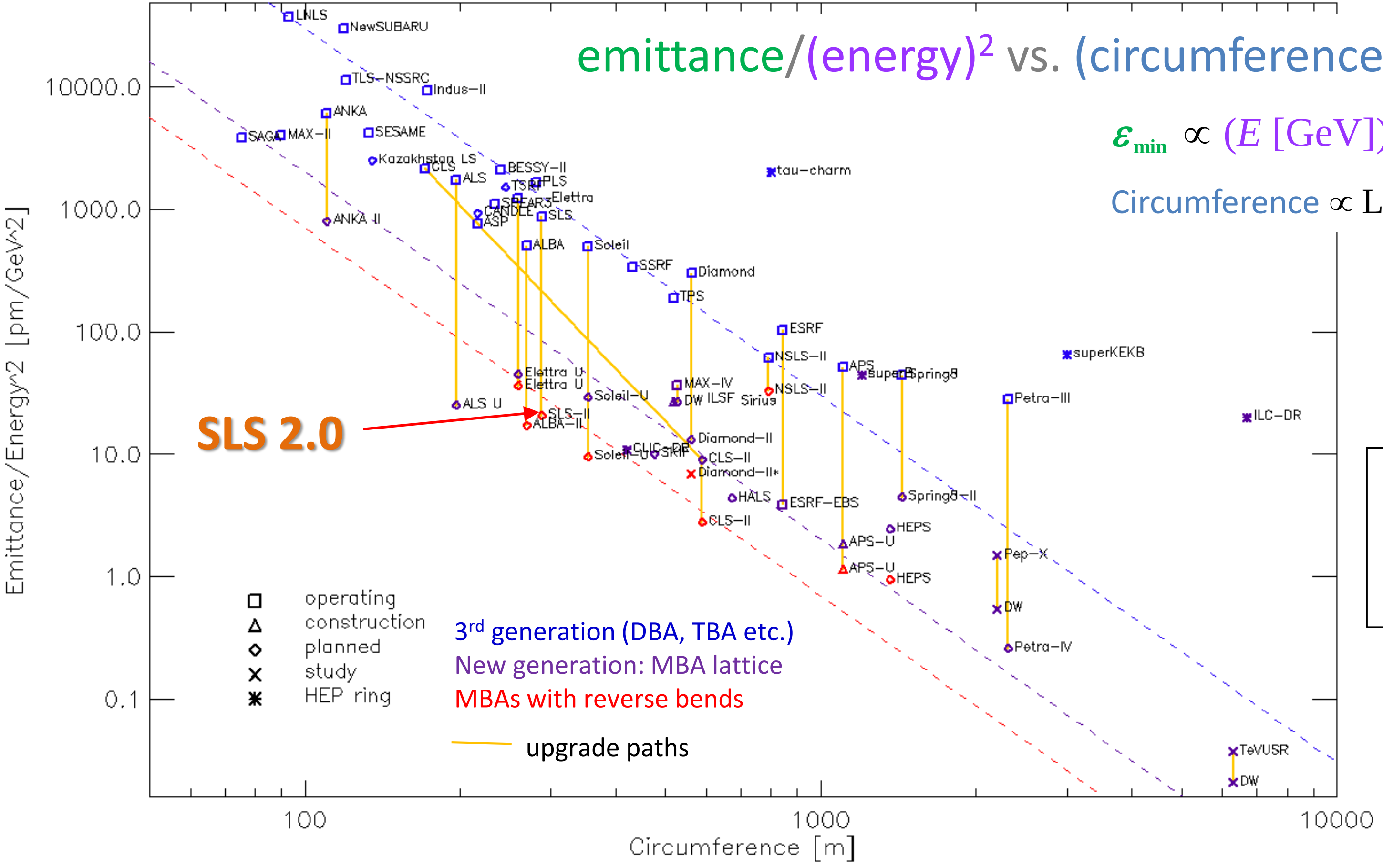
+ upgrade to SCU10:

× >1000 above 20 keV



from Beamline CDR, Jan. 2021
(not the latest data)

SLS 2.0 and other light sources



emittance/(energy)^2 vs. (circumference)^3

$\varepsilon_{\min} \propto (E\,[\mathrm{GeV}])^2\,(\phi\,[°]\,)^3$

Circumference $\propto L_{\text{cell}} \times 360°/\phi$

SLS 2.0

3rd generation (DBA, TBA etc.)

New generation: MBA lattice

MBAs with reverse bends

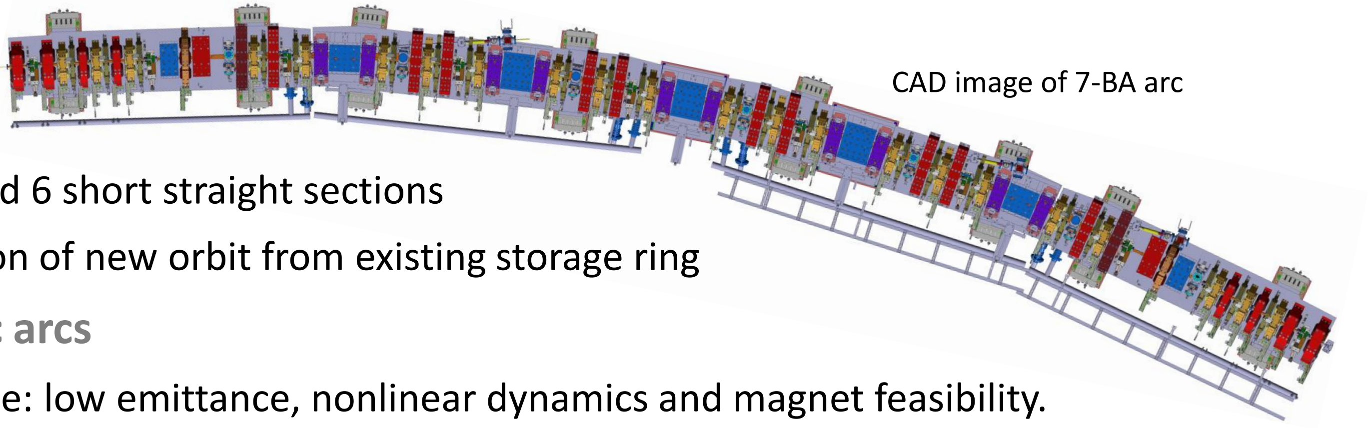
upgrade paths

Collected data courtesy of Riccardo Bartolini

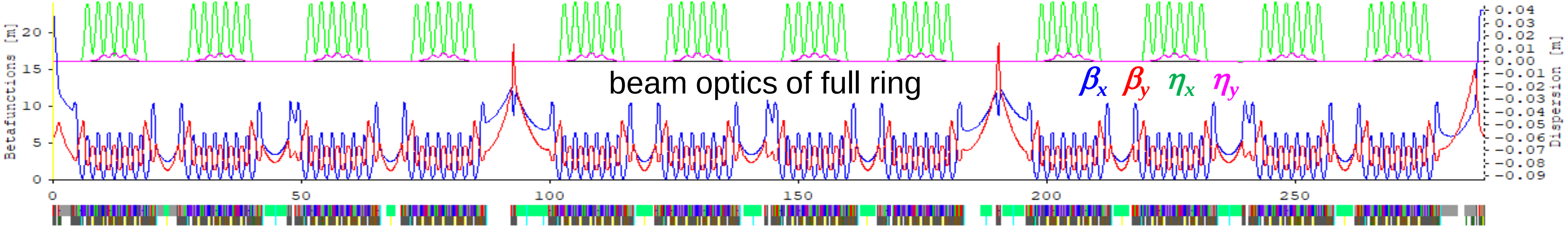
+ some additions (errors excepted)

Lattice concept 1

- **Layout**
    - 12 achromatic arcs
    - 3 long, 3 medium and 6 short straight sections
    - max. 70 mm deviation of new orbit from existing storage ring
- **Multi-bend achromatic arcs**
    - **7**BA best compromise: low emittance, nonlinear dynamics and magnet feasibility.
    - Novel "LGB/RB" unit cell design for lower emittance.
- **Energy increase from 2.4 to 2.7 GeV**
    - Shift of undulator harmonics gains more in brightness than loss due to larger emittance



CAD image of 7-BA arc



beam optics of full ring

β_x β_y η_x η_y

Lattice concept 2

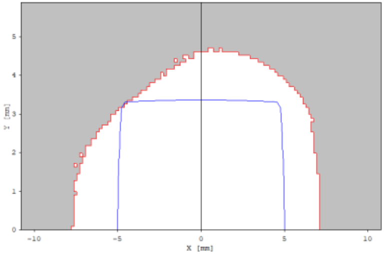
Dynamic aperture = transverse and momentum range where electrons are stable

- challenge for low emittance rings due to strong non-linear magnets.
- affects injection efficiency (or even possibility!) and beam life time.

➔ Pseudo-symmetry of lattice: symmetry-12 of non-linear optics despite symmetry-3 of lattice layout.

dynamic aperture

beam pipe silhouette



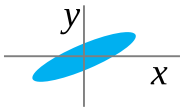
Brightness: matching of electron beam to diffraction phase space (emittance convolution)

➔ Small beta-functions in hard X-ray undulators (short straight sections)

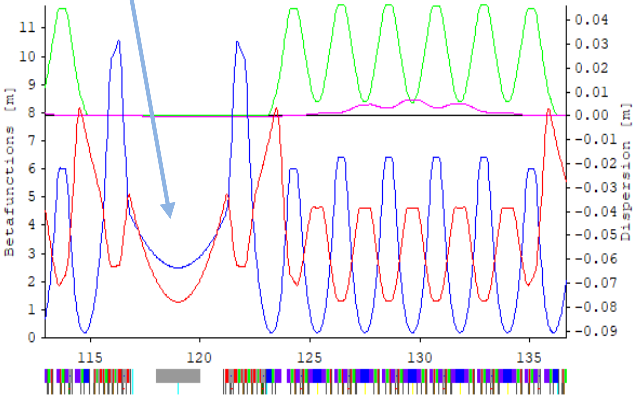
Vertical emittance and coupling control

- ε_y small in storage rings (no vertical dispersion)
  - world record $\varepsilon_y = 0.9 \pm 0.4$ pm [SLS 2012]
- compromise brightness vs. lifetime: $\varepsilon_y = 10$ pm to get ~10 hrs of beam lifetime.

➔ closed vertical dispersion wave in arcs to avoid coupling and beam tilt in straights



horizontal and vertical dispersions



The novel LGB-RB unit cell

Systematic control of quantum excitation = source of emittance

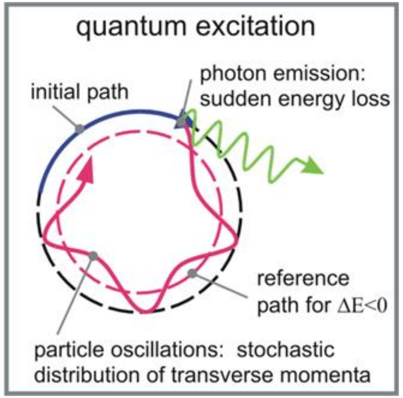
- function of magnet field strength (→ photon emission), and
- function of dispersion (→ translation of energy loss to transverse amplitude)

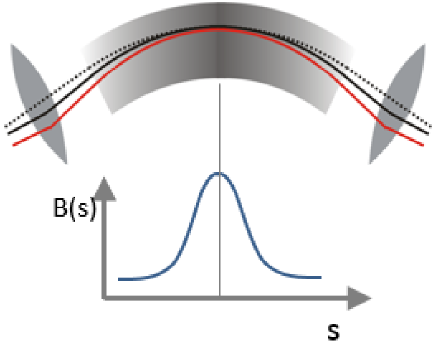
⇨ **LGB-RB lattice cell** = combination of

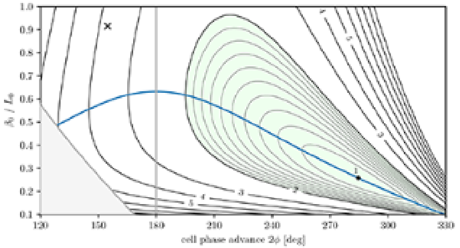
- **longitudinal gradient bend (LGB)**
  → high field (high emission) at location of low dispersion and v.v.
- and **reverse bending magnets (RB)** (= off-centered quadrupoles)
  → suppression of dispersion at LGB center
  not possible with quadrupoles only as in conventional lattice cells

⇨ ***factor 2-3 lower emittance !***

☝ developed for SLS 2.0 , adopted by several other projects







EDITORS' SUGGESTION

Low emittance lattice design from first principles: Reverse bending and longitudinal gradient bends

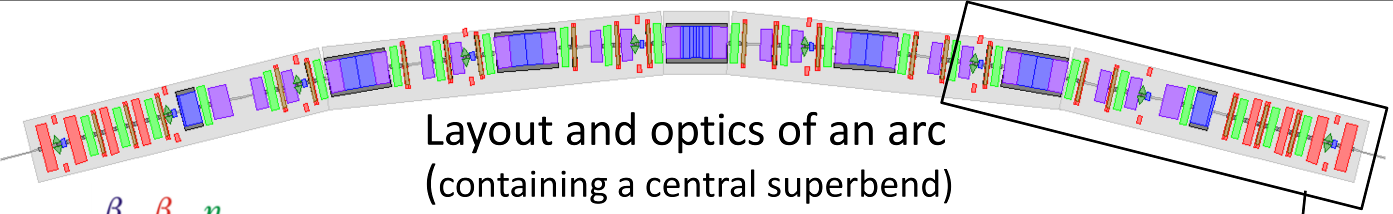
B. Riemann and A. Streun

Phys. Rev. Accel. Beams **22**, 021601 (2019)

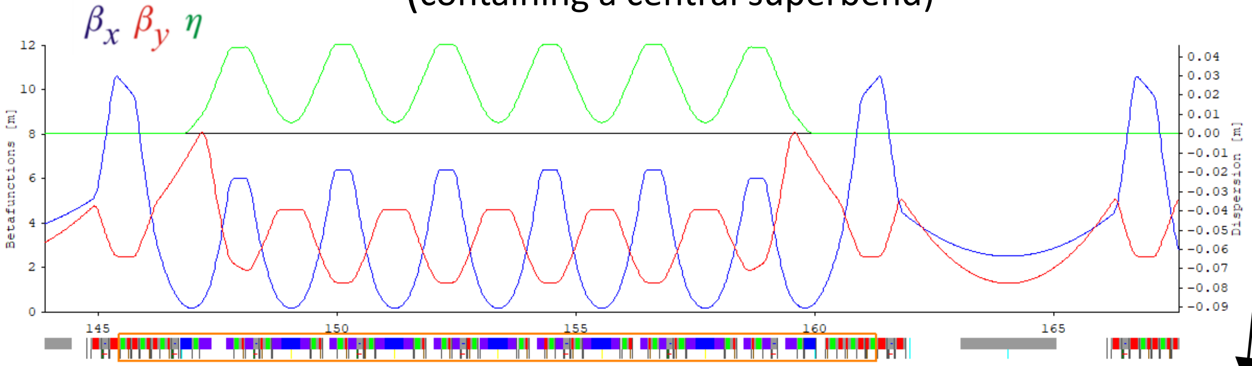
→ link

Combinations of standard and reverse bending magnets with distributed curvature can significantly reduce the horizontal emittance of future electron storage rings.

7BA arc



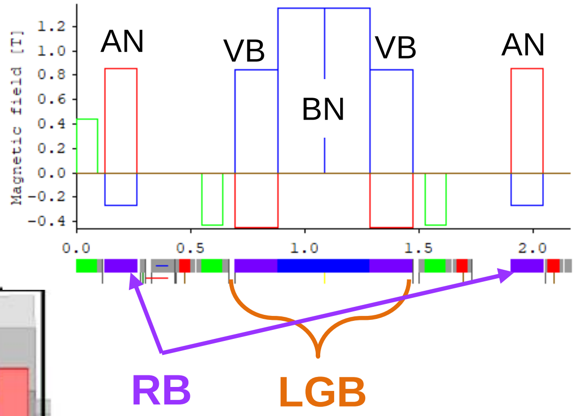
Layout and optics of an arc
(containing a central superbend)

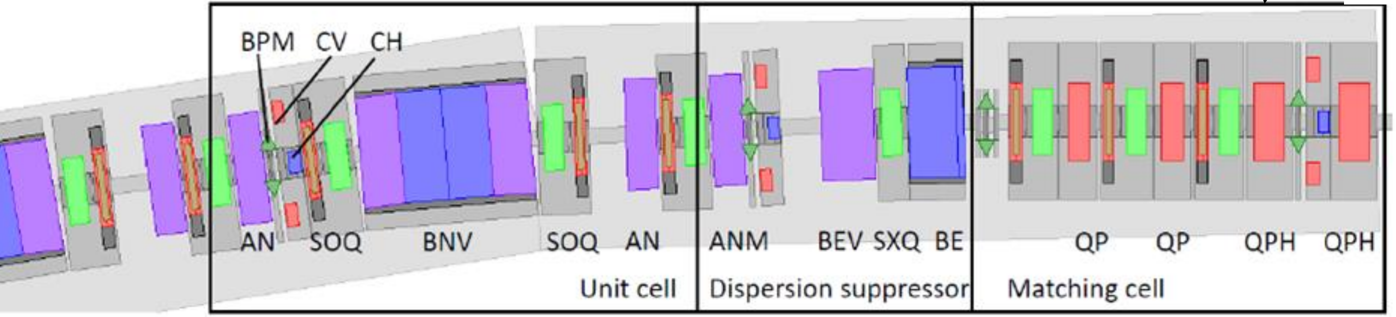


Magnetic fields
in LGB/RB unit cell

Pole-tip field at $R = 11$ mm

B $B'R$ $\frac{1}{2}B''R$

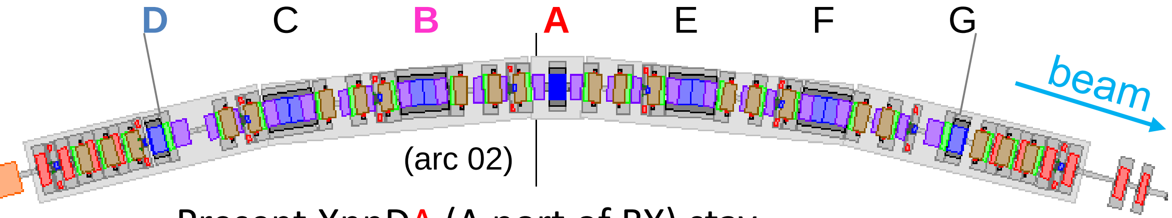


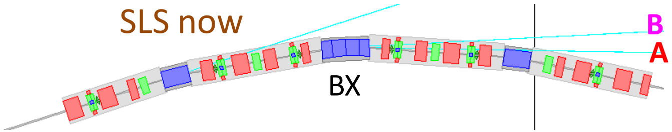


AN, VB, BN are permanent magnets.

Bends and superbends

Naming of dipoles / beam lines, for compatibility with existing beam lines:





Present XnnDA (A port of BX) stay

Present XnnDB (B-port of BX, 4° upstream)
move one dipole upstream (5°)

Radiation from C,E,F,G dipoles never used.

X01DD	**BE**	Diagnostics
X01DA	**BS5**	DEBYE
X02DA	**BS5**	s-TOMCAT
X04DB	**BN**	VUV
X05DA	**BN**	Optics
X05DB	**BN**	Diagnostics
X06DA	**BS2**	PX III
X07DA	**BN**	PolLux
X07DB	**BN**	nanoXAS
X09DA	**BN**	NAPP (2027)
X10DA	**BS2**	superXAS

Bending magnets

56×**BN**, 1.35 T permanent   2×**BS5**, 3..5 T supercond.

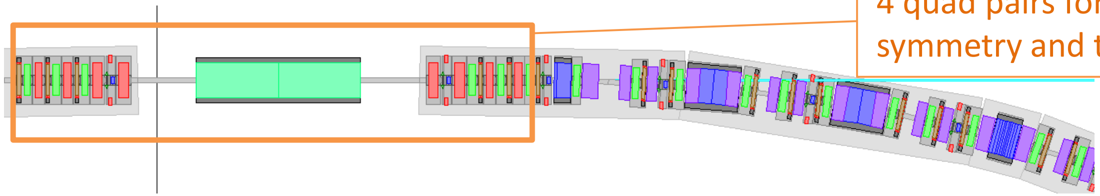
24×**BE**, 1.23 T permanent   2×**BS2**, 2.1 T permanent

Source point shift vs. SLS-1:

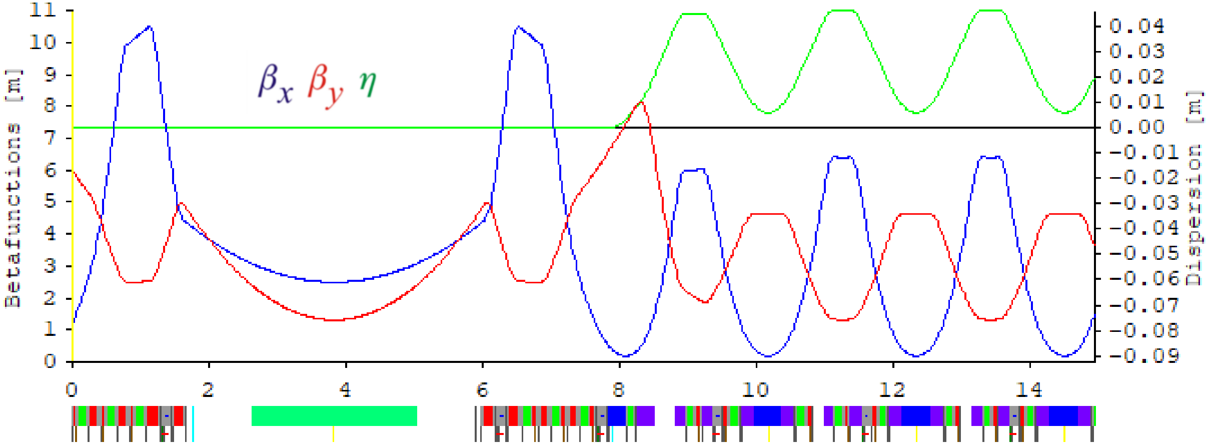
$\Delta R = -63$ mm, $\Delta S = \pm 135$ mm (XnnDA, + for nn even)

$\beta_{x/y} = 0.18 / 4.6$ m, $\eta = 4.0$ (5 T)…5.8 (1.35 T) mm

Short straights



4 quad pairs for matching symmetry and tunes



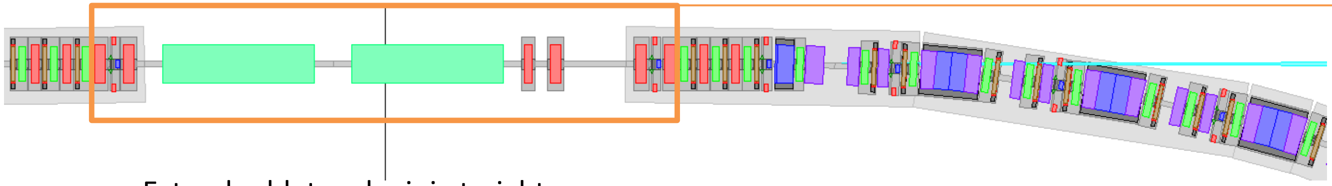
X02SA	**SCU10**	i-TOMCAT
X04SA	**CPMU14**	MS
X06SA	**U17**	PX I
X08SA	**U17**	µXAS
X10SA	**U17**	PX II
X12SA	**U17**	cSAXS

[2S] 4S 6S 8S 10S 12S Gross / net length: 4.31 / 4.11 m

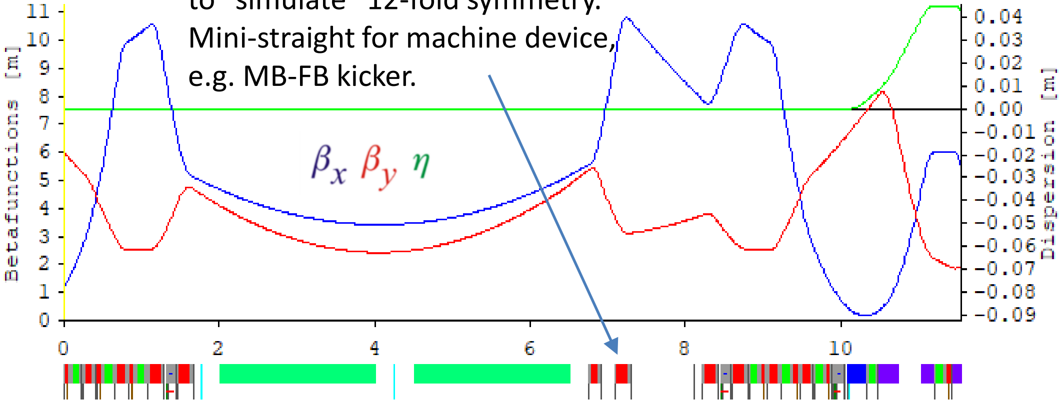
Source point (midpoint) shift vs. SLS-1: $\Delta R = -2.2$ mm, $\Delta S = 0$ mm

$\beta_{x/y} = 2.52 / 1.30$ m ⇨ Four hard X-ray beam lines can stay

Medium straights



6 quads to match optics ($\alpha_{x/y}$, $\beta_{x/y}$) and tunes without affecting optics in sextupoles.



Extra doublet and mini-straight to “simulate” 12-fold symmetry. Mini-straight for machine device, e.g. MB-FB kicker.

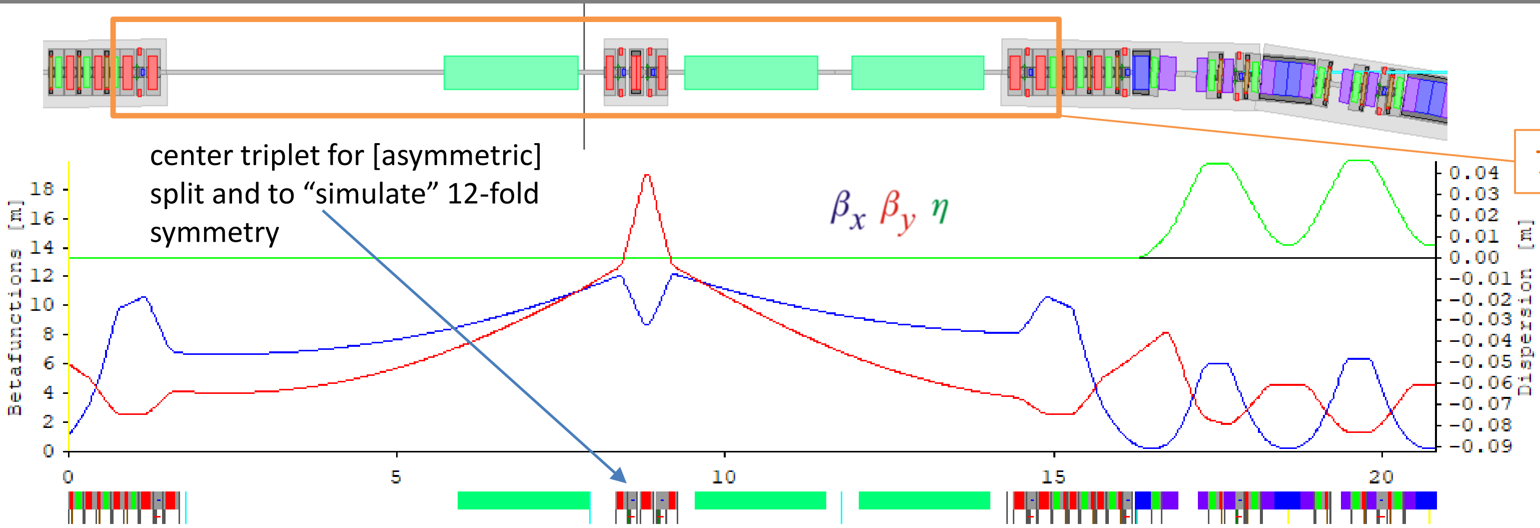
X03MA	**2×UE36**	RIXS
X07MA	**UE44**	Phoenix/Xtreme
X11MA	**2×UE36**	SIM

3M, 7M, 11M Gross / net length: 6.55 m / 4.98 + 0.82 m

Source point shift vs. SLS-1: $\Delta R = +67$ mm, $\Delta S = -685$ mm

$\beta_{x/y} = 3.40 / 2.40$ m

Long straights



center triplet for [asymmetric] split and to “simulate” 12-fold symmetry

7 quads for matching

5L, 9L Gross / net length: 12.71 m / 5.00 + 6.56 m (or v.v.)

5L: 4 x RF cavity ||| -- UE36 - UE36 - U70 --

9L: 3rd HC -- UE36 -- ||| --- UE90 -- UE90 --- (plot ⇧)

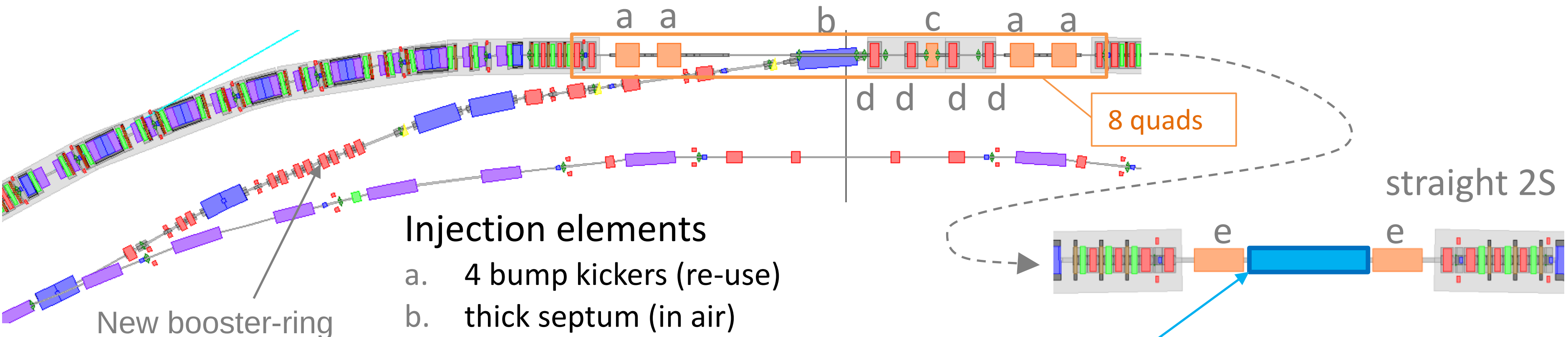
X05LA	**2×UE36** SX-ARPES
X05LB	**U70** XIL
X09LA/B	**UE36+2×UE90** QUEST

Source point shift $\Delta R = +67$ mm, $\Delta S = -2975 / +3755$ mm (5L)

vs. SLS-1 (mid of sub-straights) $\Delta S = -3755 / +2975$ mm (9L)

$\beta_{x/y} = 7 \ldots 12 / 4 \ldots 13$ m

Injection straight 1L

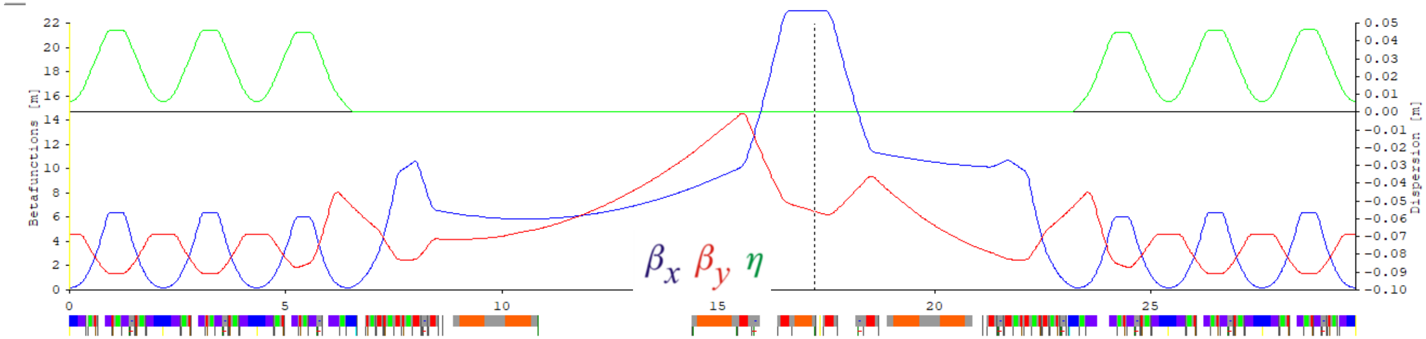


New booster-ring transfer line

SCU10 for iTOMCAT

Injection elements

a. 4 bump kickers (re-use)
b. thick septum (in air)
c. thin septum (1 mm in vacuum)
d. 4 large aperture quadrupoles (re-use)
e. fast kicker for on-axis injection in 2S



Injection schemes

1. start/fallback: classic 4-bump
2. aperture sharing with fast (10-20 ns) kicker in 2S
3. on-axis with superfast (< 2ns) strong kicker in 2S

Re-use of SLS injector

The SLS booster synchrotron

- Design was ahead of the times
  - G. Mülhaupt, 1994
- Includes features of modern MBA lattices:
  - many small combined function magnets
  - small beam pipe (30 × 20 mm)
  - large circumference

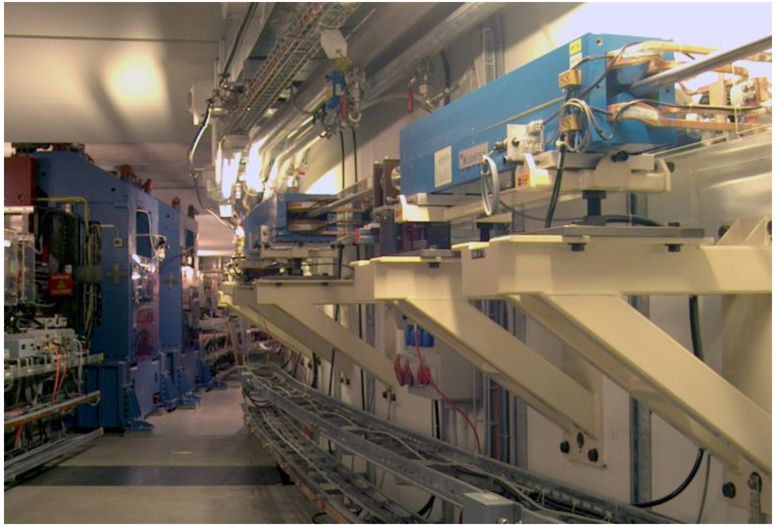
➔ Low emittance of **10 nm**

  - Further reduction to **1-2 nm** by emittance exchange
- **2.7 GeV** top energy
  - (0.1 → 2.7 GeV every 0.32 sec)
- **Perfectly suited for top-up at SLS 2.0 !**
  - (other upgrade projects build new boosters...)

➔ Re-use of booster and linac

➔ Modification of booster-to-ring transfer line

  - new endpoint, improved diagnostics



Booster mounted to inner tunnel wall

G. Mülhaupt, A few design considerations for injector synchrotrons for synchrotron light sources, Int. Rep. ESRF/MACH-INJ/94-13, Grenoble 1994.

J. Kallestrup and M. Aiba, Emittance exchange in electron booster synchrotron by coupling resonance crossing, Phys. Rev. Accel. Beams 23, 020701 (2020)

W. Joho, M. Muñoz, A. Streun, The SLS booster synchrotron, NIM A 562 (2006)

SLS 2.0 Realization

Key technologies, developments and challenges for SLS 2.0

Selected show case examples

- Magnets
- Vacuum systems
- RF systems
- Pulsed Magnet development
- Impedances and Instabilities
- Diagnostics development
- Installation and planning

Not presented today

- Insertion devices
- Stability and feedback
- Power supplies
- Mechanical engineering
- Collimation
- Radiation safety
- Computing and controls
- and much more...

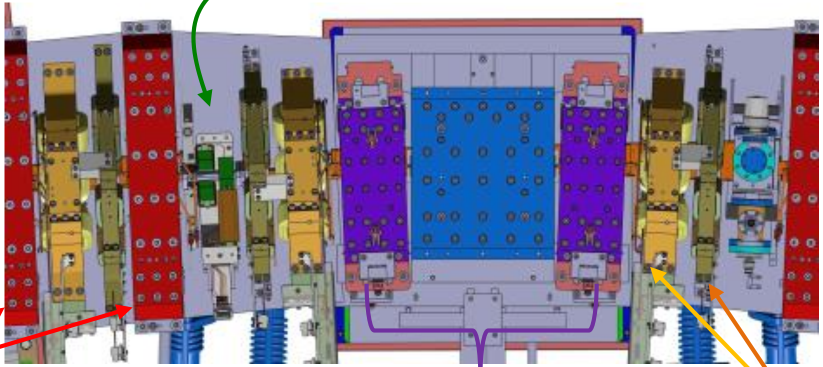
→ Technical Design Report

Magnets

Challenges

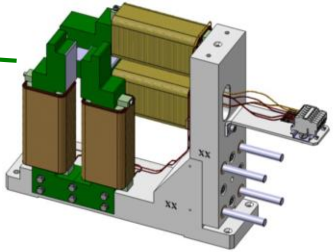
- High fields and gradients (> 1T)
- Combined functions
- Tight tolerances
  - field quality ~ 0.01..0.1 %
  - alignment < 30 μm
- Dense packing → cross-talk between adjacent magnets

Lattice unit cell



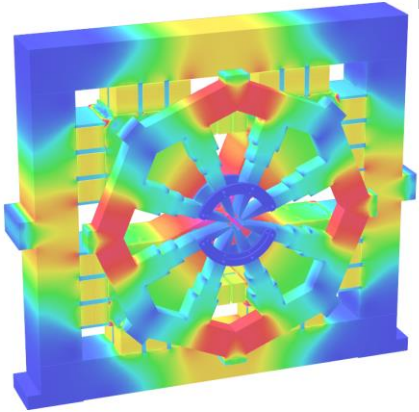
Reverse bends

VB-BN-VB LGB triplet

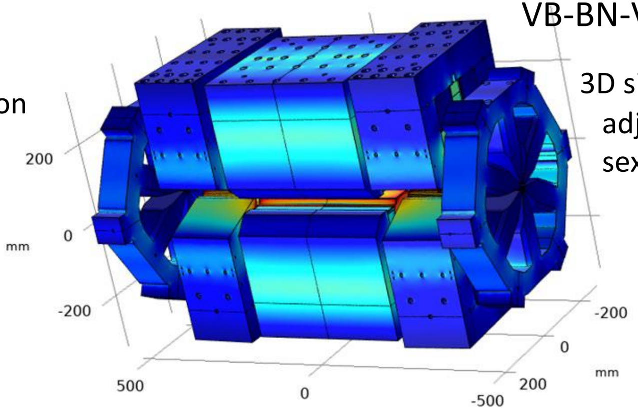


Vertical/horizontal fast corrector

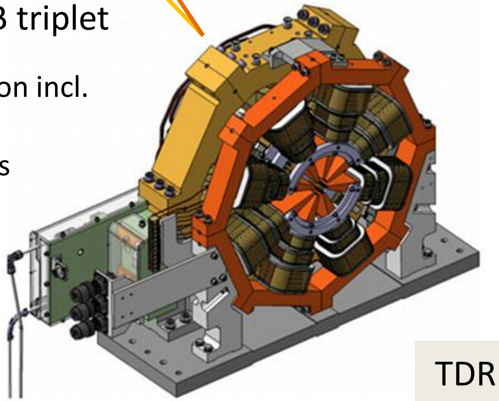
Sextupole/octupole magnet



3D simulation of crosstalk rev. bend to octupole



3D simulation incl. adjacent sextupoles

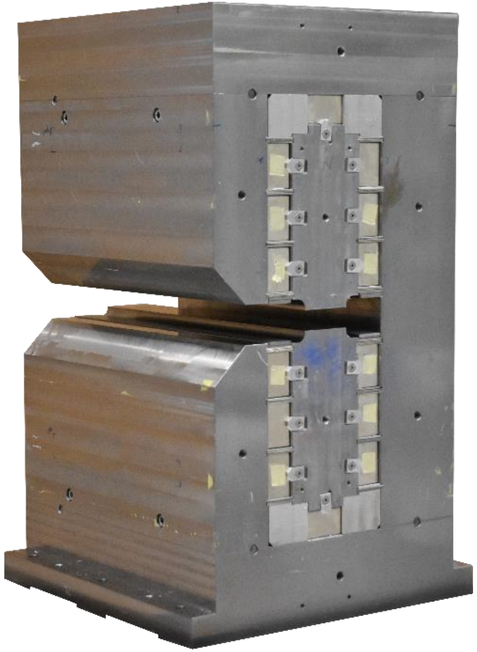


TDR

Magnet prototypes

BN

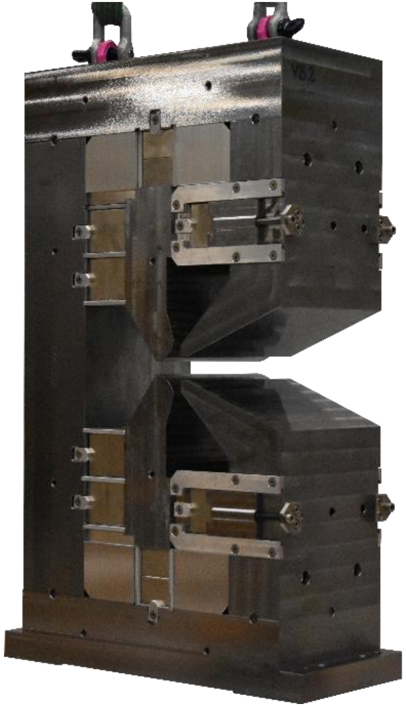
main dipole magnet



courtesy of Ciro Calzolaio

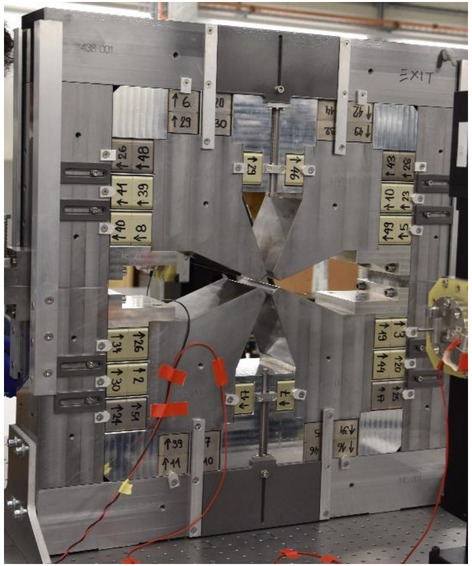
VB

dipole and vertically focusing quadrupole



ANM

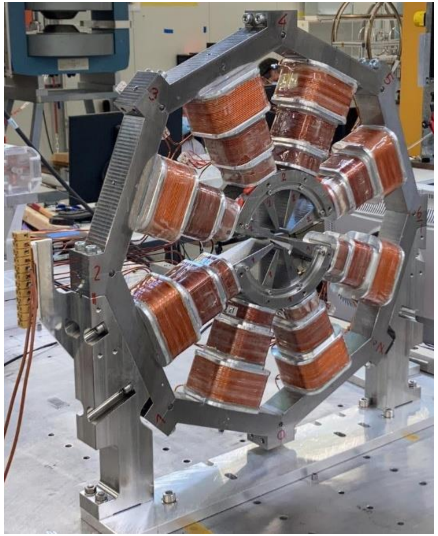
reverse bend and horizontally focusing quadrupole



permanent

OC

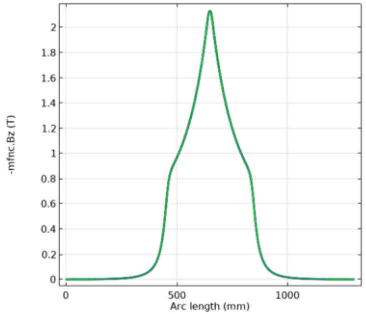
octupole with quadrupole and skew quadrupole

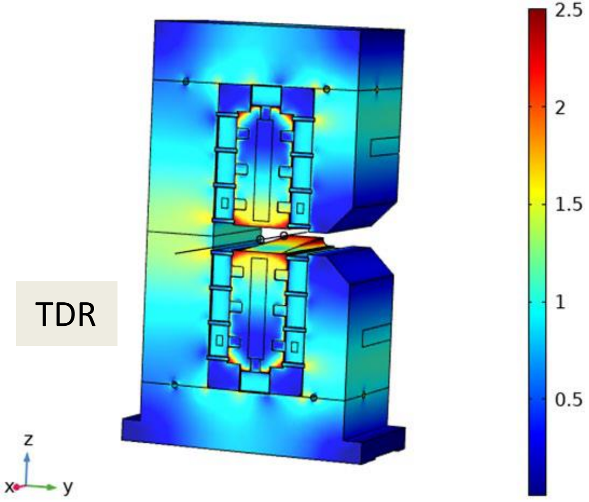


electric

Superbend design

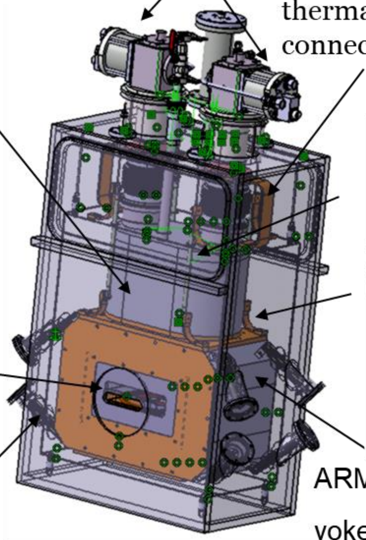
Permanent 2.1 T peak





TDR

Superconducting tunable 3..5 T peak



Gifford-McMahon cryocoolers

50 K thermal connection

LHe vessel (~15 l)
~8 hours autonomy in case of cryocooler's failure

Vacuum chamber

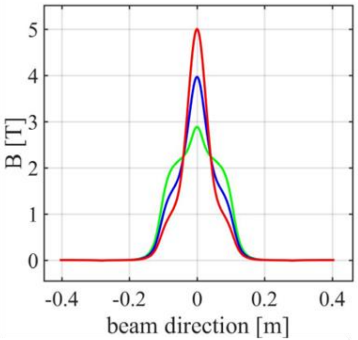
anchoring

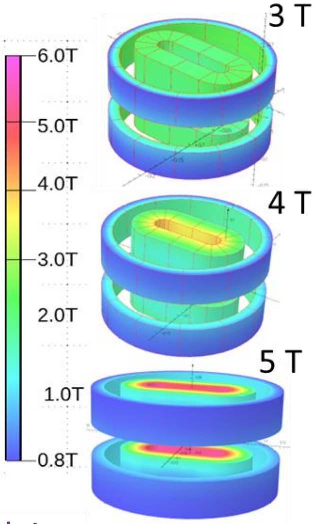
Suspension straps (x8)

ARMCO

yoke

Nb-Ti prototype coil and aluminum pre-compression structure





courtesy of Ciro Calzolaio

Magnet and power supply inventory

SLS 2.0 288 m circumference = 83.6 m straights + 204.4 m arcs

80 dipole bends (56 BN + 24 BE) 0 (PM)

144 combined function bends (112 VB + 8 VBS + 24 VE) 0 (PM)

144 reverse bends (120 AN + 24 ANM) 0 (PM)

112 quadrupoles (55 QP + 53 QPH + 4 QA-SLS) 112

288 sextupoles (264 SX + 24 SXQ) 62

264 octupoles [incl. quad+skewquad] (OC) 3×264

115 twin correctors (112 CHV + 3 CHV-SLS) 2×115

2+2 superbends (2 BS2, 2.1T PM + 2 BS5, 5.0 T SC) 0 (PM) + 2×2 (SC)

➔ **1151 magnets** (779 RC + 370 PM+ 2 SC), **~1200 power supplies**

SLS 288 m circumference = 80 m straights + 208 m arcs

36 bending magnets BX, BE 2

174 quadrupoles QA/B/C[W] 174

120 sextupoles SR[W] {sext.+{CH+CV}(72),skewquad(36),aux.sext.(12)} 9+2×72+36+12

upgrade: 3 superbends BXS: +3/-3 bends, +6 PS

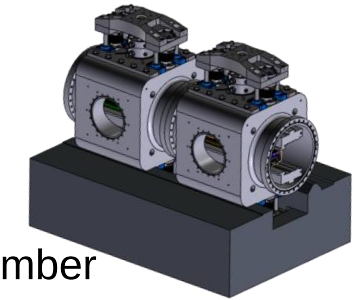
upgrade: Femto insertion: +3 bends, +4 quads, +1 corr.H/V, +9

➔ **338 magnets, 392 power supplies**

Vacuum system

Challenges and key technologies:

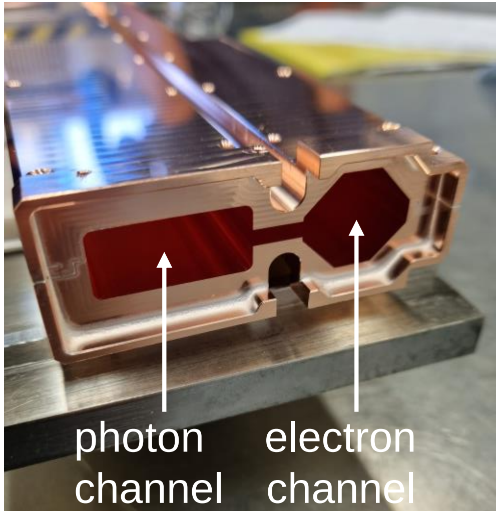
- CNC milling and lathing
- UHV soldering
- Wire erosion
- NEG coating

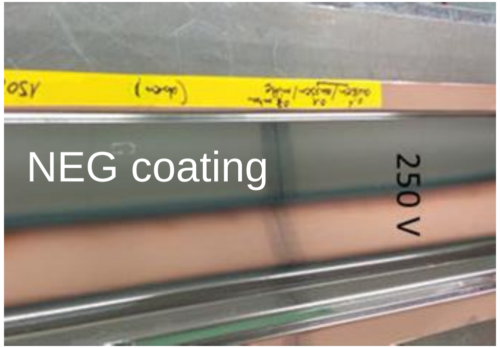


modular undulator chamber

courtesy of René Sieber

clamped milling





NEG coating

vacuum chamber prepared for soldering

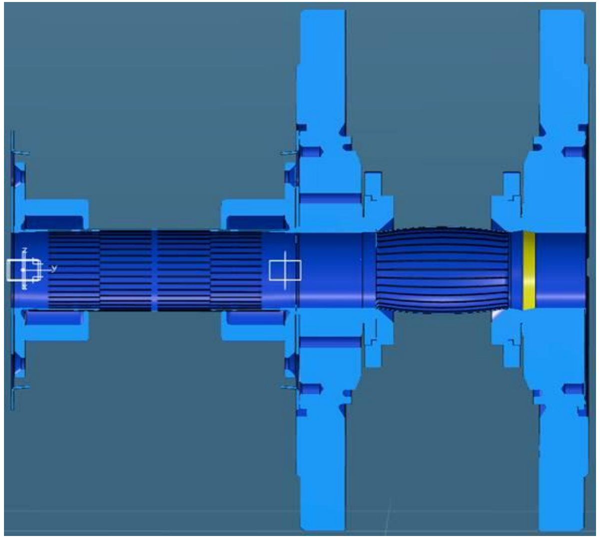
Impedances and Instabilities

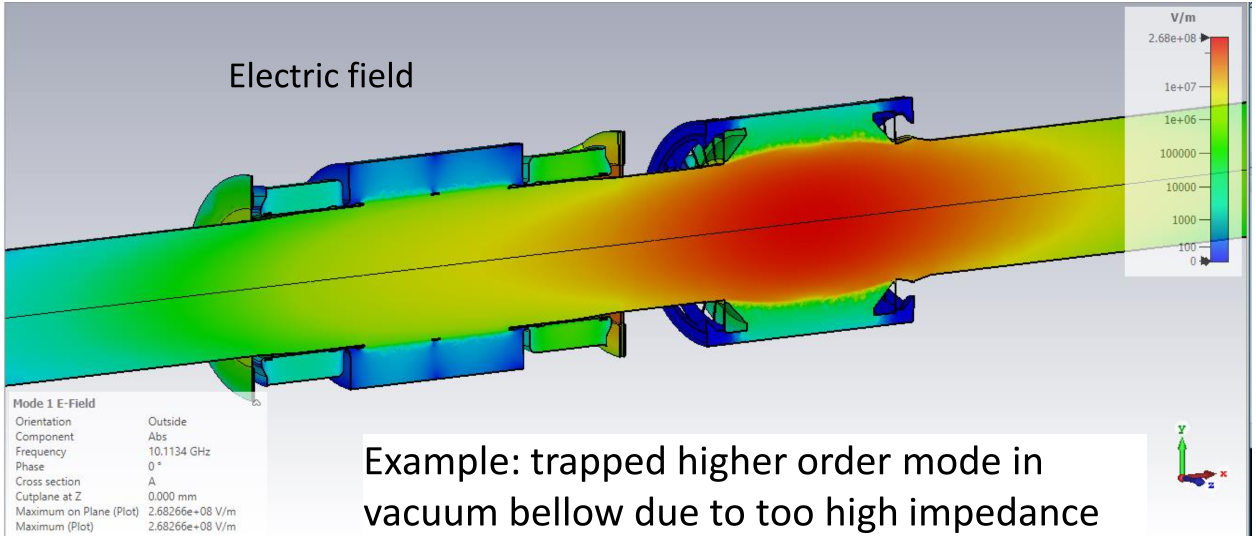
Challenge

Electromagnetic interaction of electron beam with narrow or discontinuous vacuum chamber.

→ Possible beam instabilities above some threshold current; energy loss heating chamber.

→ Design/simulations of bellows and valves (and all other chambers...) to avoid trapped modes.





Mode 1 E-Field

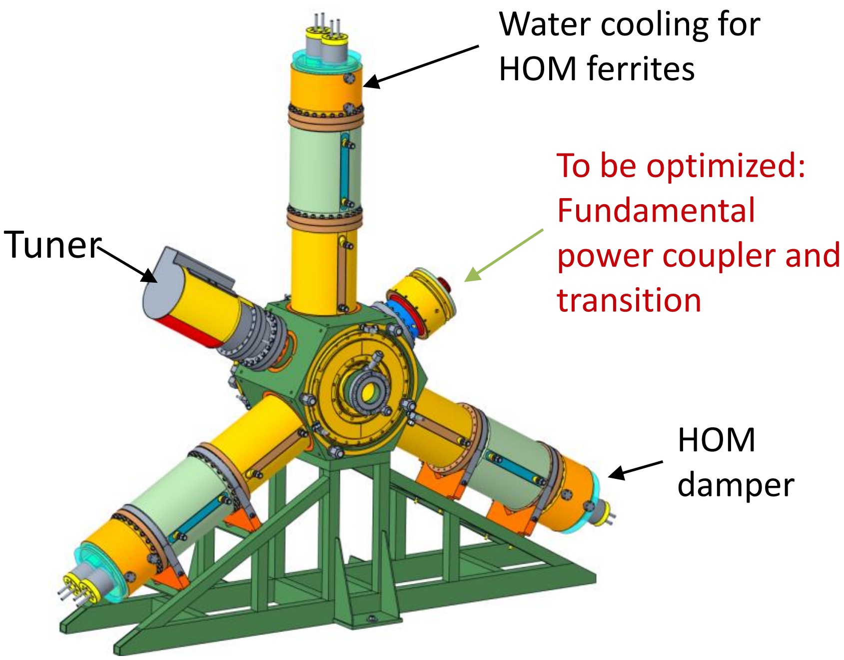
Orientation	Outside
Component	Abs
Frequency	10.1134 GHz
Phase	0 °
Cross section	A
Cutplane at Z	0.000 mm
Maximum on Plane (Plot)	2.68266e+08 V/m
Maximum (Plot)	2.68266e+08 V/m

Example: trapped higher order mode in vacuum bellow due to too high impedance
→ optimization required

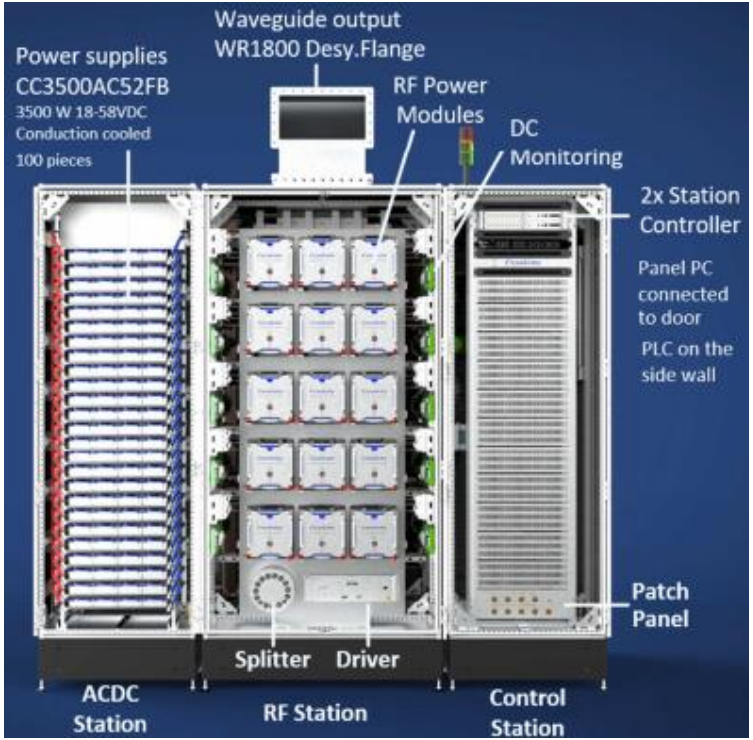
courtesy of Micha Dehler

Radio frequency systems

Procurement and Integration of new 500 MHz RF Cavities and Amplifiers



4+1 higher order mode (HOM) damped accelerating cavities

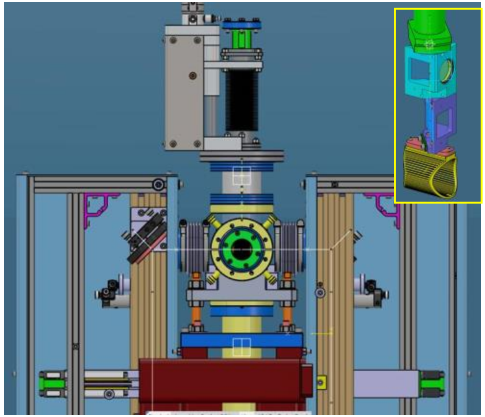


4 high power solid state UHF 150kW amplifiers and spares

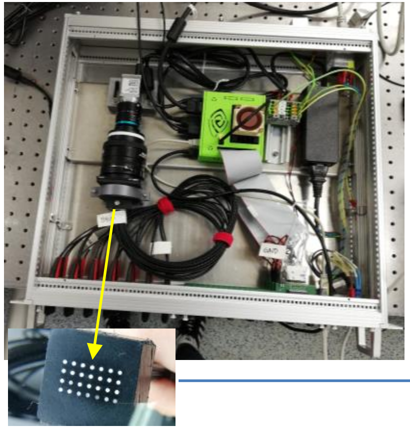
courtesy of Lukas Stingelin

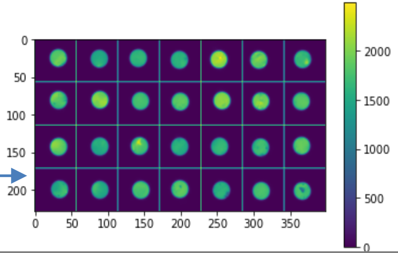
Diagnostics development

Booster-to-ring transfer line screen monitor



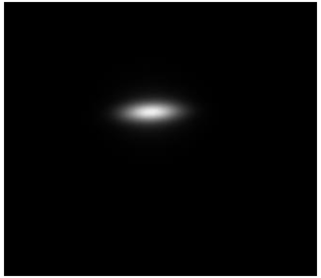
Beam loss monitor development (based on glass fibers and CCD)



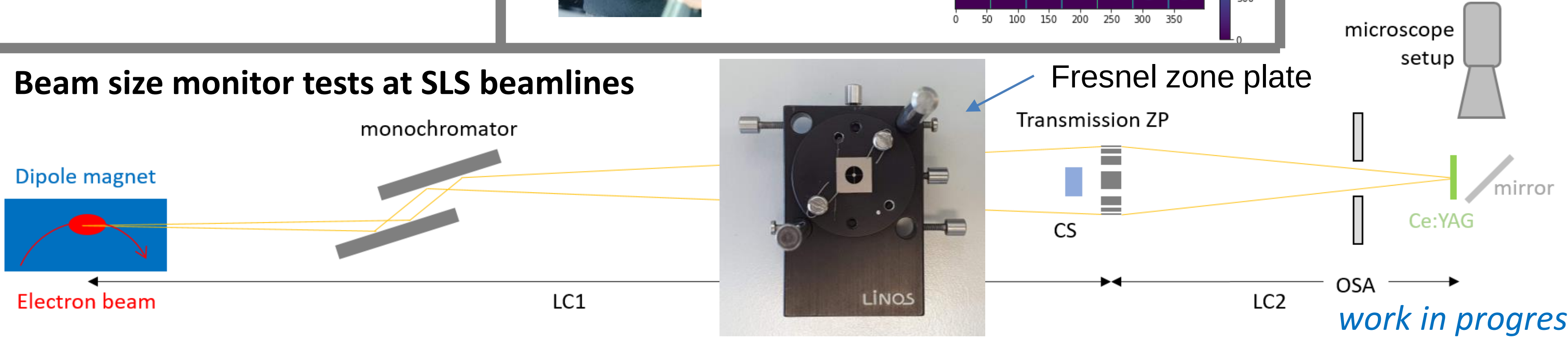


courtesy of Cigdem Ozkan Loch

Beam spot @ FZP focus

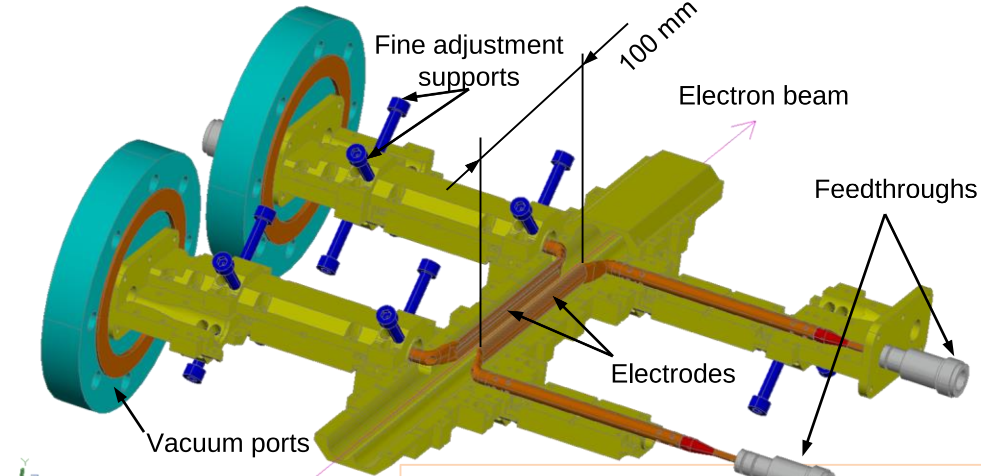


Beam size monitor tests at SLS beamlines

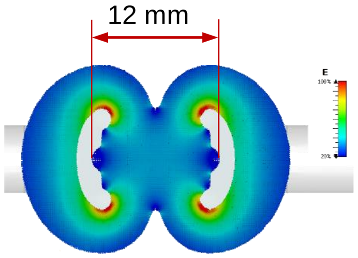


work in progress...

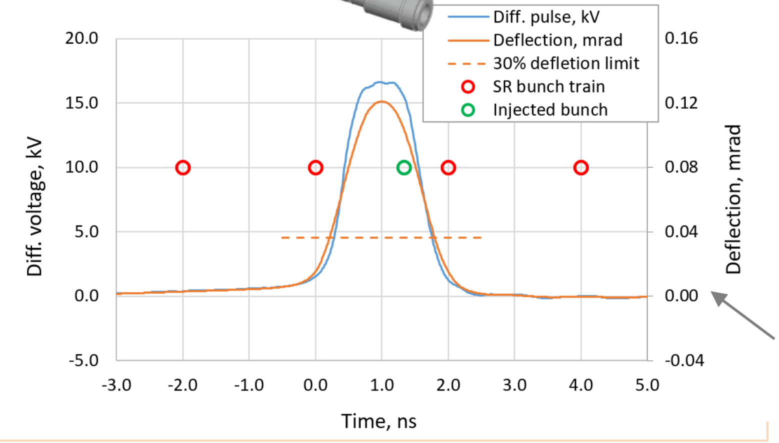
Fast injection kicker development



Electrodes' cross section



courtesy of Martin Paraliev



"Fast" injection: 10..20 ns pulse

aperture sharing mode

(= injected beam kicked half in, stored bunches kicked half out, both captured)

→ 5..10 bunches (1-2% of beam) are perturbed

"Super fast" injection: ~1.5 ns pulse

a) aperture sharing mode:

5 kV pulse

→ 1 bunch perturbed

b) on-axis mode:

(= injection "between" bunches, and longitudinal capture)

10 kV pulse

→ no perturbation of stored beam

○ injected bunch ○ stored bunches

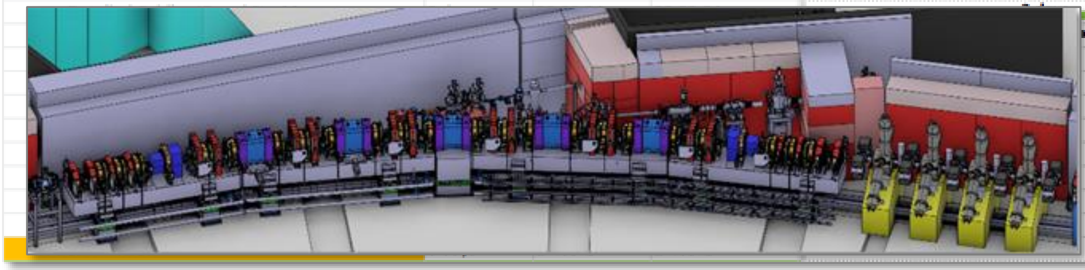
SLS 2.0 installation & planning

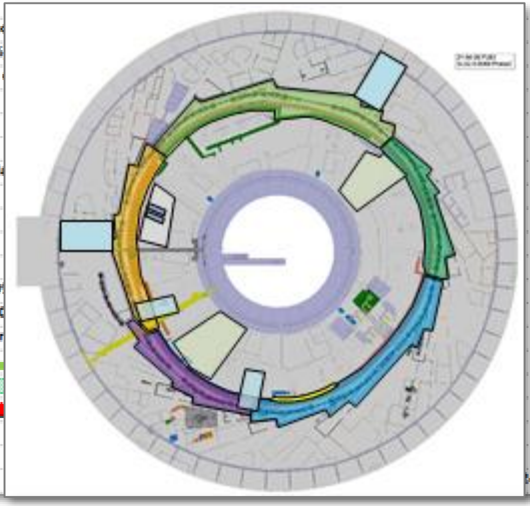
courtesy of Johan Wickström

Challenges

- Darktime duration, finding the optimum sequence. Today 1300 listed task.
- Verifying each step with the technical groups to confirm the working order.
- Safely opening and closing ~800 magnets and handling of 18m vacuum chambers.
- Preparing infrastructure and finding areas for storage and pre-assembly.

1 Area (57-07) 09-10	**142.9 days**	**10.10.23**	**14.05.24**
Dismounting	**19.1 days**	10.10.23	07.11.23
CE Work + Stammrohr	**42.5 days**	07.11.23	17.01.24
Installation New Machine	81.3 days	17.01.24	14.05.24
Basic Cabling	30 days	17.01.24	28.02.24
10 ARC	22.7 days	07.02.24	08.03.24
Start	0 days	07.02.24	07.02.24
Install Girders 4pc	1 day	07.02.24	08.02.24
[illegible]	[illegible]	[illegible]	[illegible]
Alignment Girder	2 days	08.02.24	12.02.24
[illegible]	[illegible]	[illegible]	[illegible]
Cabling of Arc (Detailed)	[illegible]	[illegible]	[illegible]
Cooling connect Detailed (1.5W/Arc)	8 days	12.02.24	22.02.24
[illegible]	[illegible]	[illegible]	[illegible]
Install BPM Pick ups und Thermoelemente	1 day	23.02.24	26.02.24
[illegible]	[illegible]	[illegible]	[illegible]
Close Magnets 6 st	4 days	26.02.24	01.03.24
Cooling Connection to Vacuum Chamber	2 days	01.03.24	05.03.24
Test Magnet Cool.& Elec. Connect.	2 days	05.03.24	07.03.24
VCS Inst & Commissioning	3 days	05.03.24	08.03.24
~~Hardware Commissioning~~	~~5 days~~	~~08.03.24~~	~~15.03.24~~
10 STR / CPMU16	**27.6 days**	**08.02.24**	**18.03.24**
Start	0 days	08.02.24	08.02.24
Install ID Mover Feet 4 st (2d/ID)	2 days	08.02.24	12.02.24
Mover Cabling	0.5 days	12.02.24	12.02.24
Install Undulators (1w+1wk BO)	7 days	12.02.24	**21.02.24**
Install Str. Magnets + Support (3pc) 0pc	0.1 days	21.02.24	**21.02.24**
Detailed Cooling ID and Str. Magnets	2 days	22.02.24	26.02.24





Conclusion

- Innovative storage ring design
  - High performance under severe constraints (circumference, symmetry etc.)
  - Novel low emittance lattice concept.
- Boost for synchrotron radiation experiments
  - Factor 60 hard X-ray brightness increase (even more with new undulators).
  - $\sim 52\ \mathrm{m}$ of straight section available for undulators.
  - Integration of superbends up to 5 Tesla.
- Economic upgrade
  - No modification of storage ring tunnel.
  - 30% lower power consumption than SLS now.
  - Re-use of injector complex.
- Forward-looking technological developments in many areas

Outlook

Milestones

■■■■■■■■ ■ = 1 month

- Oct. 19, 2022 ready for dark time

■■|■■■■■■■■■ SLS operation

- Oct. 2, 2023 start dark time

■■■|■■■■■■■■■■■■|

- Dec. 20, 2024 installation completed, tunnel closure

■■■■ commissioning

- May 1, 2025 beam available

■■■ beamline commissioning

- Aug. 1, 2025 start user operation phase 1

■■■■■| phase 1 operation

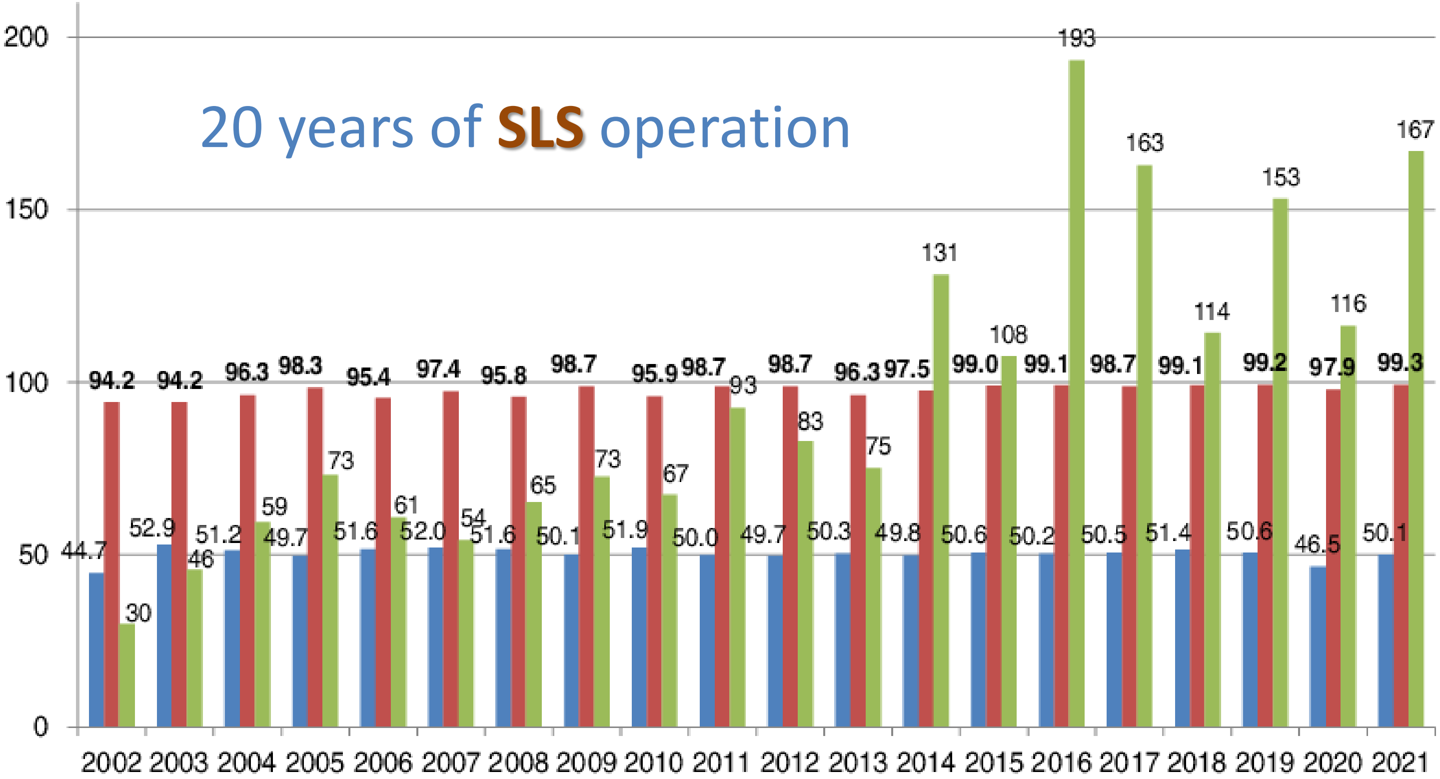
- Dec. 21, 2025 start shutdown

■■■■■

- June 1, 2026 start user operation phase 2

■■■■■■■|■■■■■■■■■■■■... phase 2 operation

Operation



20 years of **SLS** operation

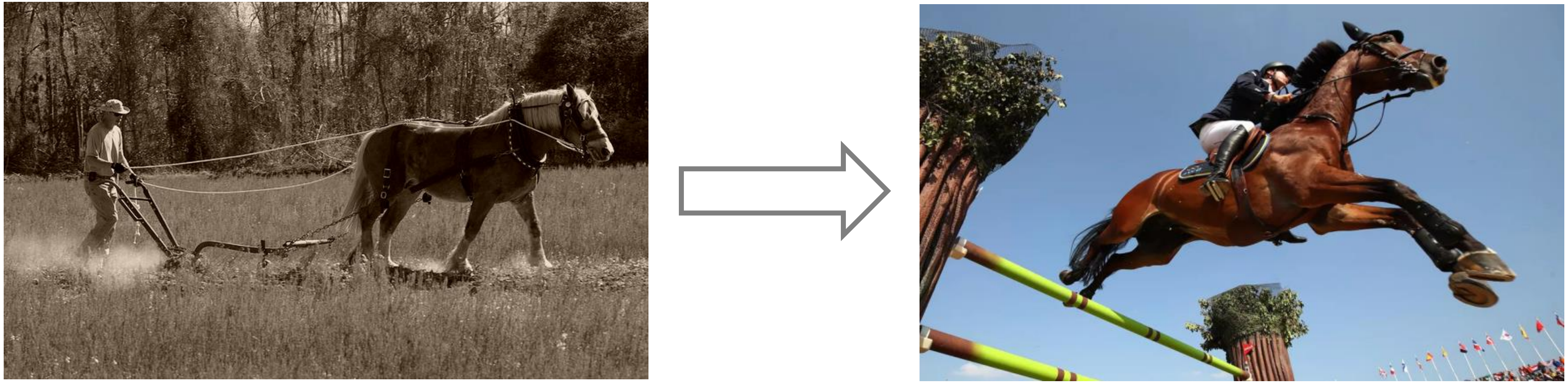
User operation [100 hrs]

Availability [%]

Mean time between failures [hrs]

⇒ great challenge for **SLS 2.0** to reproduce that in 2026-2045...

from SLS to SLS 2.0 ...



... a big leap for PSI !

Many thanks to the colleagues who provided material and input for this presentation!

Thanks for your attention !