PAUL SCHERRER INSTITUT

Bernard Riemann :: SLS 2.0 :: Paul Scherrer Institut

Lattice concept of and news on the SLS 2.0 upgrade

XXVI ESLS Workshop, 2018-11-27, Krakow, Poland

Outline

- why Longitudinal Gradient Bends (LGBs) need reverse bends (RBs) to properly reduce emittance

  ➚ BR & Andreas Streun: *Low emittance lattice design from first principles: reverse bending and longitudinal gradient bends* arXiv:1810.11286 (submitted to PRAB)

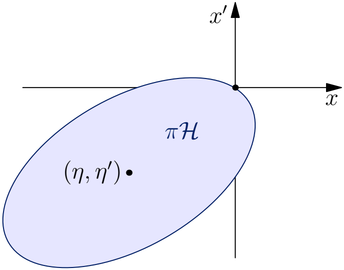
- SLS 2.0 lattice
- trajectories through combined-function magnets
- emittance coupling

Radiation integrals

↗ R.H. Helm et al., Proc. PAC 1973, p. 900

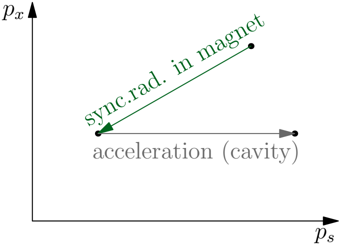
Equilibrium emittance $\varepsilon \propto I_5 / I_2$

Quantum excitation (I_5)



- oscillation around dispersive orbit after energy loss
- loss probability depends on orbit curvature $b(s)$.
- minimize $I_5 = \int |b^3(s)| \, \mathcal{H}(s) ds$

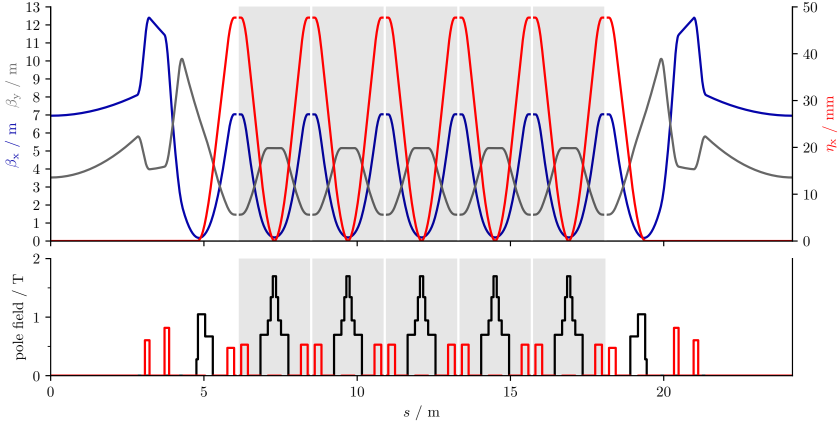
Radiation damping (I_2)



- damping of transverse momenta
- longitudinal acceleration
- maximize $I_2 = \int b^2(s) ds$

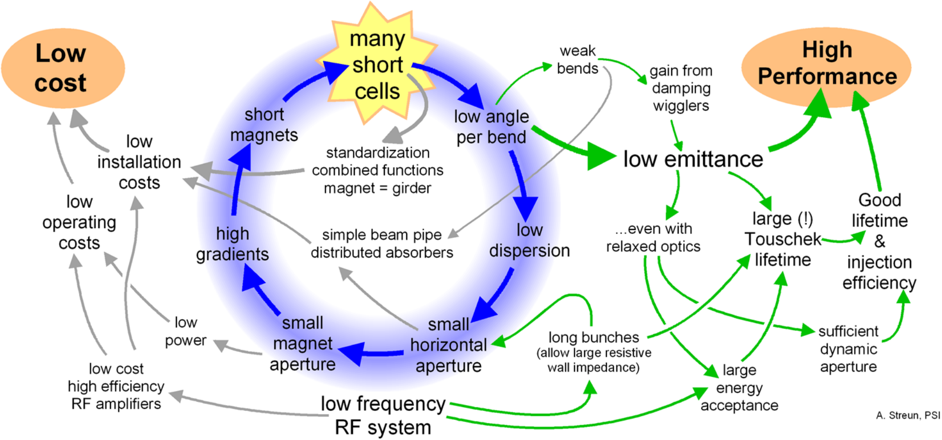
Multi-bend achromat (MBA)

historical review: ➚ D. Einfeld, Synchrotron Radiation News **27**(6), p.4 (2014).



- M bending magnets, $M-2$ **unit cells** with angle $2\theta_0$,
  2 matching cells with one bend (θ_0) each. $\rightarrow$ MBA angle $2(M-1)\theta_0$
- emittance $\varepsilon \propto \theta_0^3 \propto (\mathbf{M-1})^{-\mathbf{3}}$, increase M within technical limits.

MBA optimization cycle

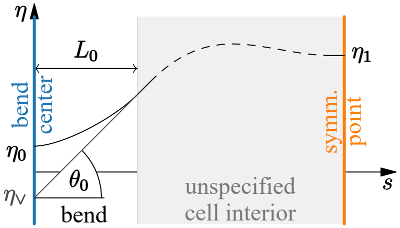


For large *M*, unit cells dominate the emittance.

Unit cell

Figures of merit

- Emittance for given bending angle
- Cell length, chromaticity
  $\Rightarrow$ low phase advance 2ϕ per cell
- moderate focusing (lower limits on β_0 in bend center)
- plot emittance as a function $\varepsilon(\beta_0, \phi)$.



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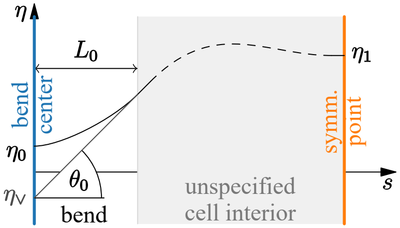
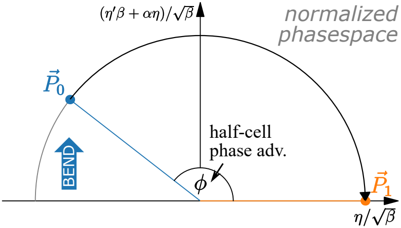


Half-cell model

- bend center: symmetry point of $\beta(s), \eta(s)$.
- For matching, model behaviour of $\eta(s)$ outside bend via $\eta_\vee$.

Unit cell

Half-cell model (continued)



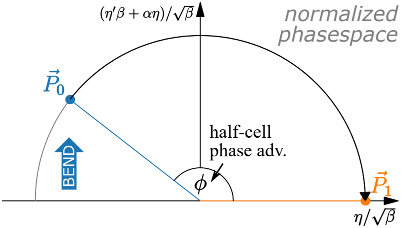
- Matching condition yields

$$\eta_0 = \underbrace{\eta_\vee(\beta_0, \phi)}_{\text{cell optics}} + \underbrace{\int_0^{L_0} s \cdot b(s)\,\mathrm{d}s}_{\text{magnet-specific}} .$$

- β_0, ϕ and magnet profile $b(s)$ fully define emittance.

Unit cell

Half-cell model (continued)



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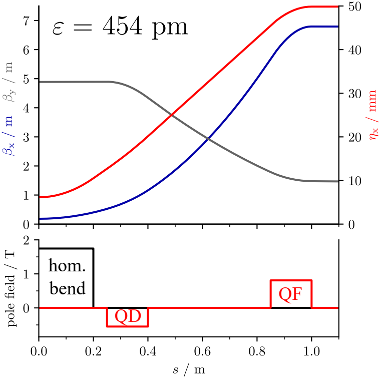
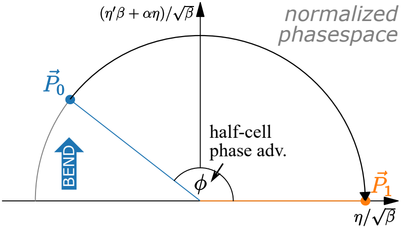
A typical example cell (at 2.4 GeV)



- emittance is ≈ 3.5-times larger than the theoretical minimum emittance ($\varepsilon_{\mathrm{TME}} = 121$ pm).

Half-cell model (continued)



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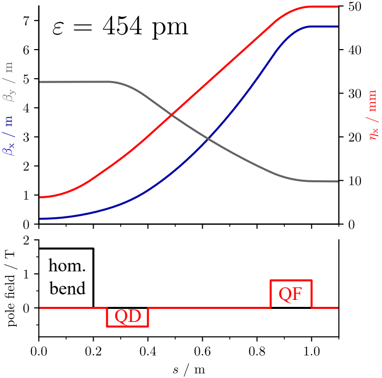

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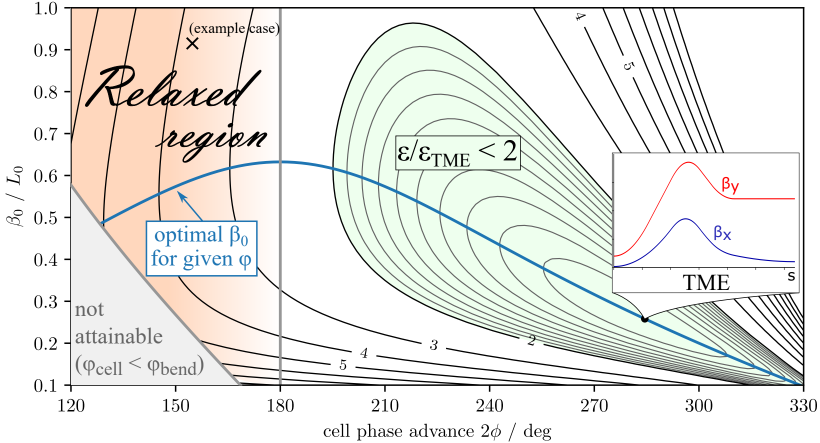
☹ Why?

(relaxed) TME cell

➚ L. C. Teng, Tech. Rep. ANL LS-17 (1987).



☞ Relaxed optics parameters and low-emittance region not overlapping.

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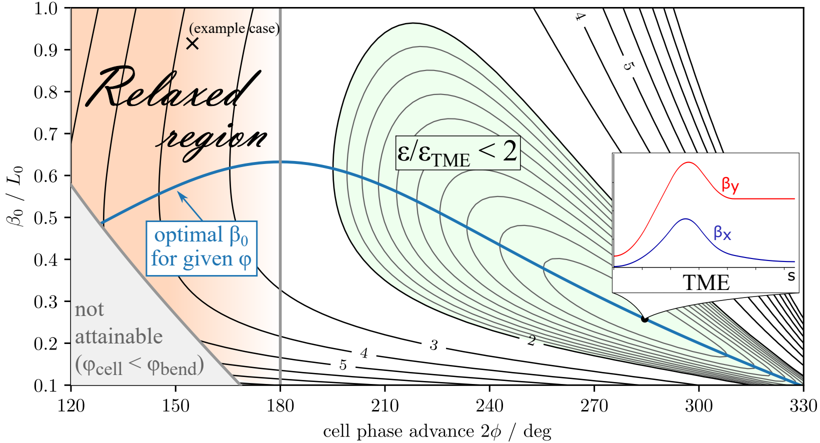

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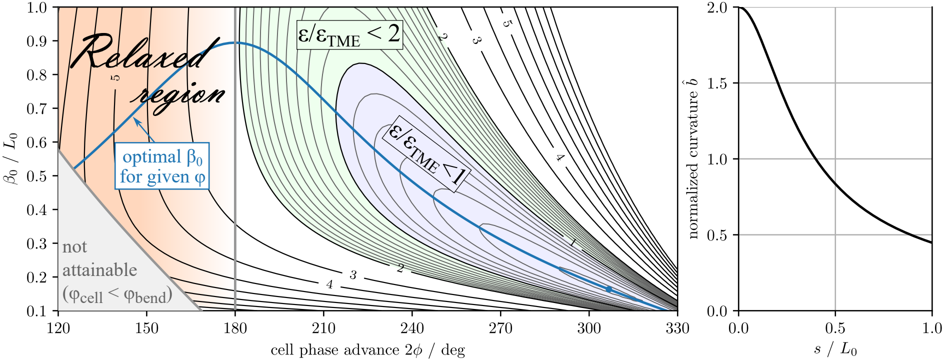
? What happens if magnet profile $b(s)$ is not constant?

cell with example LGB



- concentrated field in magnet center.
- low emittance at large phase advances, but cannot be used

☹ $\varepsilon > 2\varepsilon_{TME}$ **in relaxed region**.

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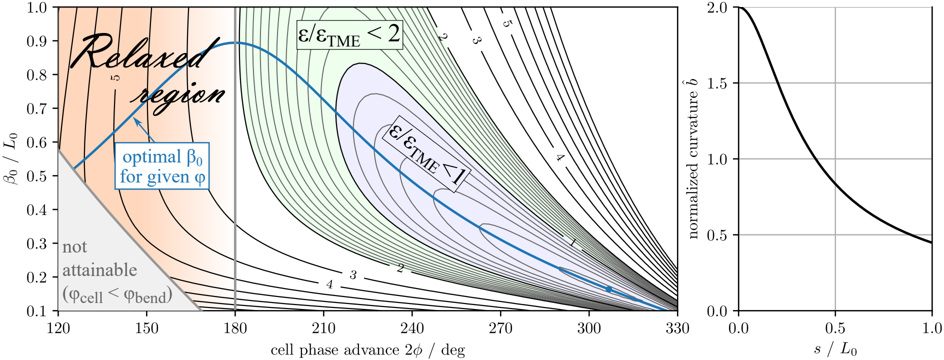

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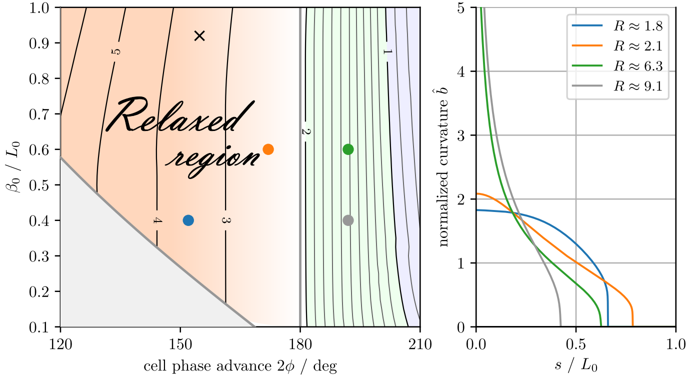
? What happens if magnet profile $b(s)$ is optimized for each β_0, ϕ?

Free-form LGB cell

positive curvature, $b(s) \geq 0$



☹ a principle performance limit seems to exist: $\varepsilon > 2\varepsilon_{\text{TME}}$ for $2\phi < 180°$.

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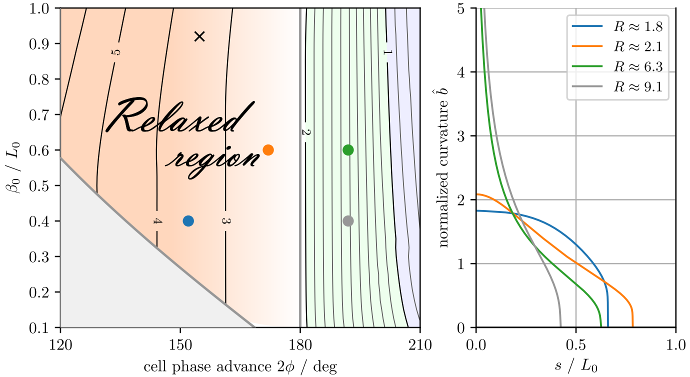

- ☹ a principle performance limit seems to exist: $\varepsilon > 2\varepsilon_{\mathrm{TME}}$ for $2\phi < 180°$.
- qualitative explanation: lower bound on $\eta_0 > \eta_\vee > 0$

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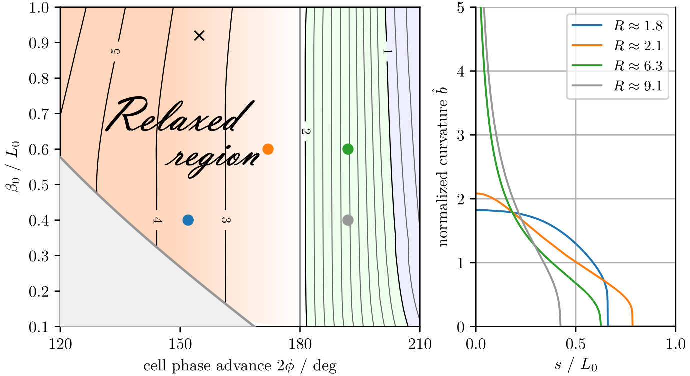

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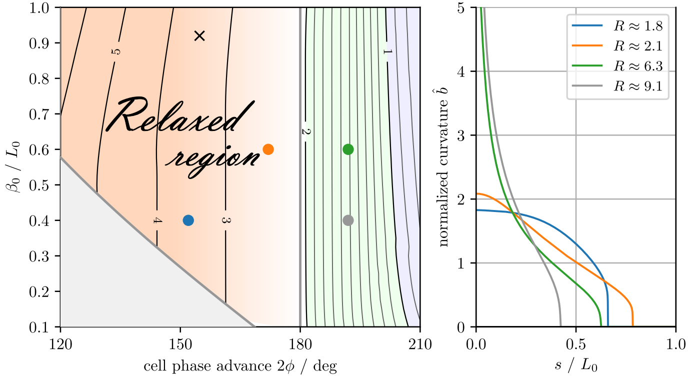

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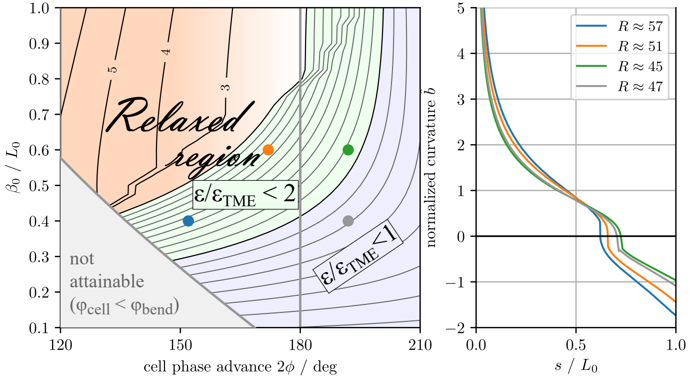
? many $b(s)$ shapes fall off to zero - what happens if the constraint $b(s) \geq 0$ is removed?

Free-form LGB cell

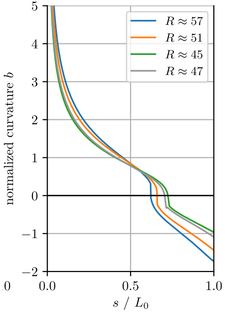
arbitrary curvature



- Constraint on polarity of magnetic field is lifted, $b(s) < 0$ is possible.
- ☺ *significant emittance reduction* $\varepsilon < 2\varepsilon_{TME}$ occurs with $2\phi < 180°$!
- ☞ near the end of the bending magnet, the polarity of the magnetic field is *reversed.*

(thin-lens) reverse-bend cell

↗ A. Streun, Nucl. Instrum. Methods Res. A **737**, p. 148 (2014)

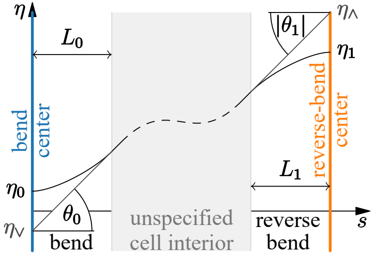


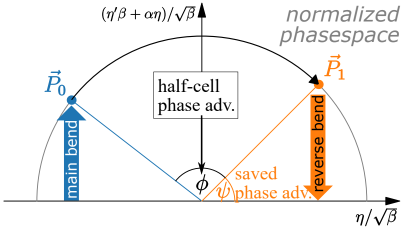
- Bend can interpreted as a combination of
  - main bend near magnet center
  - reverse bend near magnet end
- In this setup, focusing is applied at the end of the half-cell.

➫ Very similar to unit cell of above reference!

☞ Study a general setup, similar to (relaxed) TME cells.

A unit cell with two bends

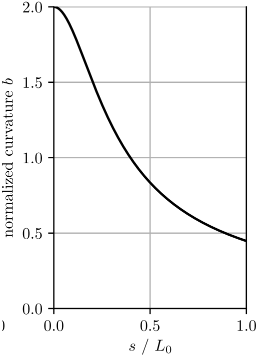


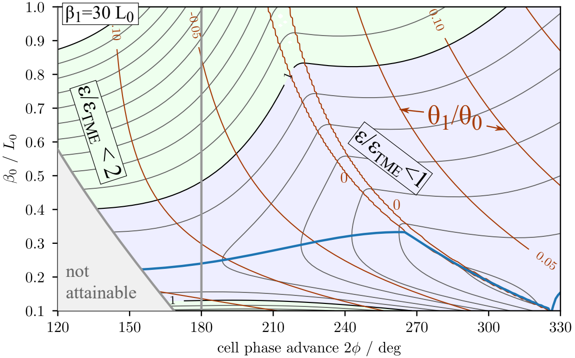


Half-cell model

- insert a homogeneous bend with half-kick angle $\theta_1 < 0$ at the half-cell end.
- phase advance relative to the one-bend case is *reduced*: $\phi = \phi_{oneBend} - \psi$.
- large β at the reverse bend end helps.

LGB/RB cell with moderate LGB shape





- Here, length of homogeneous reverse bend $L_1 \sim |\theta_1/\theta_0| L_0$.

☺ $\varepsilon < 2\varepsilon_{\mathrm{TME}}$ for relaxed region.

☺ Field enhancement OK (LGB not too strong).

☺ weak and small reverse bend.

Preliminary Conclusion

With reasonable focusing in unit cells
(cell phase advance $2\phi < 180^\circ \rightarrow$ short cells, low chromaticity)...

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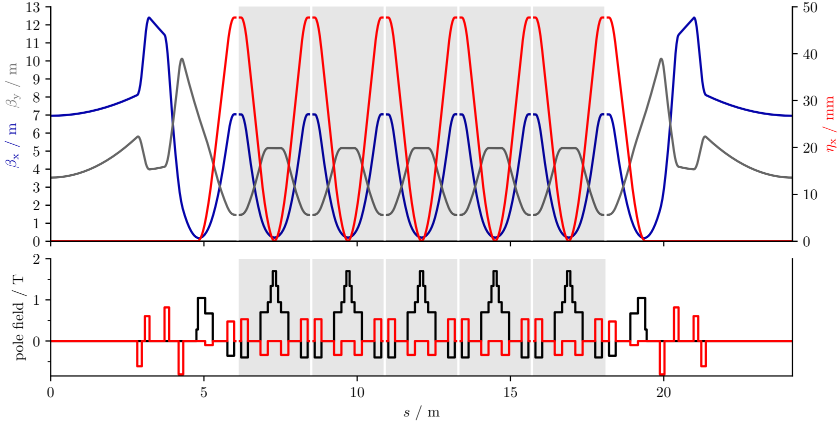
? Used only I_2, I_5 – what about the other radiation integrals?

- I_1 momentum compaction: this integral is small ☞ need for trading ε vs α, choose $\alpha < 0$ to suppress CBI (not shown here).
- I_3 closely related to I_2.
- I_4 manipulation via combined dipole and quadrupole fields (horizontal damping partition J_x)

the 7BA for SLS 2.0

see also ➚ A. Streun, T. Garvey et al., J. Synchrotron Radiat. **25**, 631 (2018)

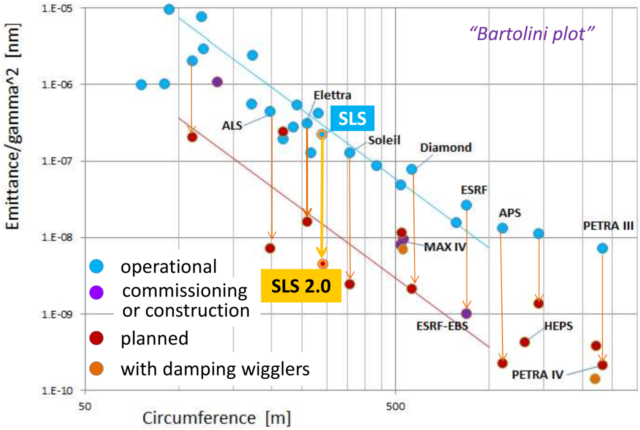


- LGB and RB merge with adjacent quadrupoles (combined-function lattice, damping partition $J_x \sim 1.7$).
- due to $\varepsilon \propto I_5 \big/ (I_2\, J_x)$, emittance is reduced to 99 pm $< \varepsilon_{\mathrm{TME}}$.

the new generation of SL sources

Emittance normalized to energy vs. circumference

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



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

storage ring parameters

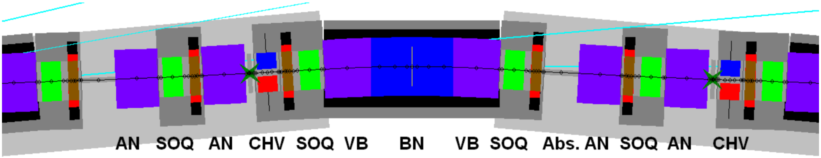
see also ➚ SLS-2 Conceptual Design Report (2017)

energy	2.4 GeV
max. current	400 mA
rf system	500 MHz, 3HC
vert. emittance	10 pm

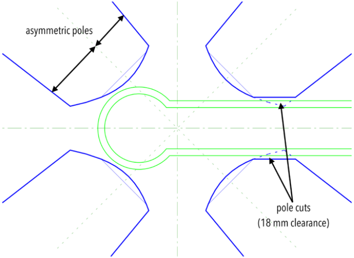
	SLS	SLS 2.0
circumference	288 m	290.4 m
buckets	480	484
periodicity	3	12
horiz. emittance @ 0 mA	5.5 nm	101 pm
@ 400 mA	5.5 nm	125 pm
rel. energy spread @ 0 mA	8.6×10^{-4}	1.04×10^{-3}
@ 400 mA	8.6×10^{-4}	1.08×10^{-3}
bunch length without 3HC	$\sim$ 40 ps	23 ps
– with 3HC	$\sim$ 100 ps	70 ps

SLS 2.0 unit cell

↗ A. Streun, Tech. Report SLS2-SA81-004 (Sep. 2018)

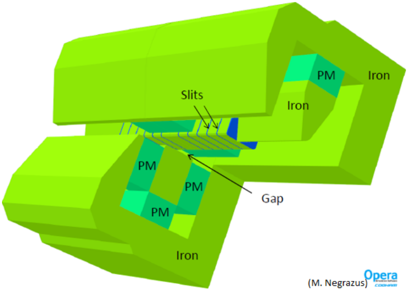


AN: hor. focusing reverse bend



- off-centered quadrupole yoke

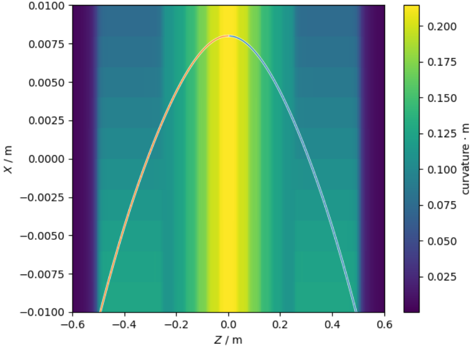
BN/VB: vert. focusing LGB



- stacked permanent magnets in iron yoke.

BN/VB magnetic field

continuation of ➚ M. Aiba et al., Nucl. Instrum. Methods Res. A **892**, p. 41 (2018)



- build continous field map from 'pixel input'
- compute closed-orbit trajectory by standard means (Runge-Kutta)
- compute focusing terms via derivatives of magnetic field and curvature

vertical emittance control using dispersion

M. Aiba, M. Böge

- Dispersion bump is excited with dispersive skew quads in the arc
- Coupling is excited at the same time but it is suppressed by non-dispersive skew quads in the straight section
- Possible setting:

	K1(m-2)
CSXX	-0.17983
CSXY	0.001074
CSYY	0.002835
CSYM	-0.19539
CSXM	-0.28117
CSY2	-0.24031
CSY2	-0.1748
CSX2	-0.19683
CSY2	-0.14275
CSY1	-0.13676
CSX1	-0.10322
CSY1	-0.1037
CSY1	-0.1037
CSX1	-0.10322
CSY1	-0.13676
CSY2	-0.14275
CSX2	-0.19683
CSY2	-0.1748
CSY2	-0.24031
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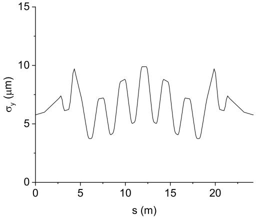
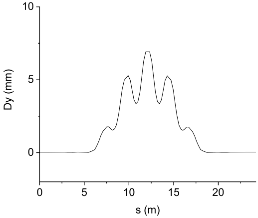
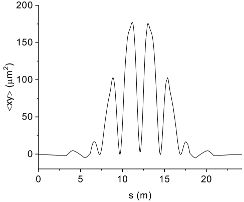
CSYY	0.002835
CSXY	0.001074
CSXX	-0.1748

288 skew Qs







Dispersion and its derivative along the straight section are zero. Actually, the coupling in the arc is rather large, and thus the emittance is increased through dispersion+coupling

Thank you for your attention!

Acknowledgments

- A. Streun
- M. Aiba
- M. Böge

and many others