Beam dynamics and lattice proposal for SLS-2

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2nd workshop “Beam Dynamics meets Magnets”

Bad Zurzach, Dec. 1-4, 2014

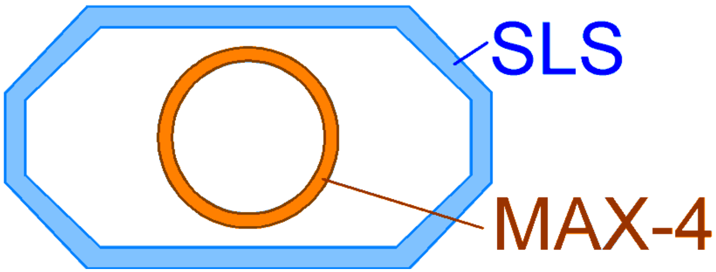
Contents

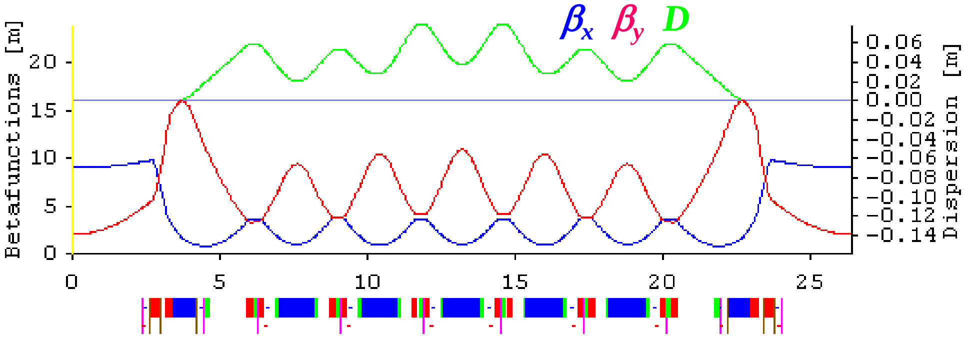
- The new generation of storage rings
- The SLS and the SLS-2 upgrade charge
- A compact low emittance lattice concept: Longitudinal gradient bends and Anti-bends
- Lattice designs – work in progress
- Magnets for SLS-2
- Design tasks, challenges and perspectives
- Conclusion

A revolution in storage ring technology

Pioneer work: MAX IV (Lund, Sweden)

Aperture reduction ⟷ **Multi-Bend Achromat (MBA)**





Technological achievement:

NEG* coating of small vacuum chambers.

⇨ Small magnet bore.

⇨ High magnet gradient.

*Non Evaporable Getter

short & strong multipoles

⇨ short lattice cells

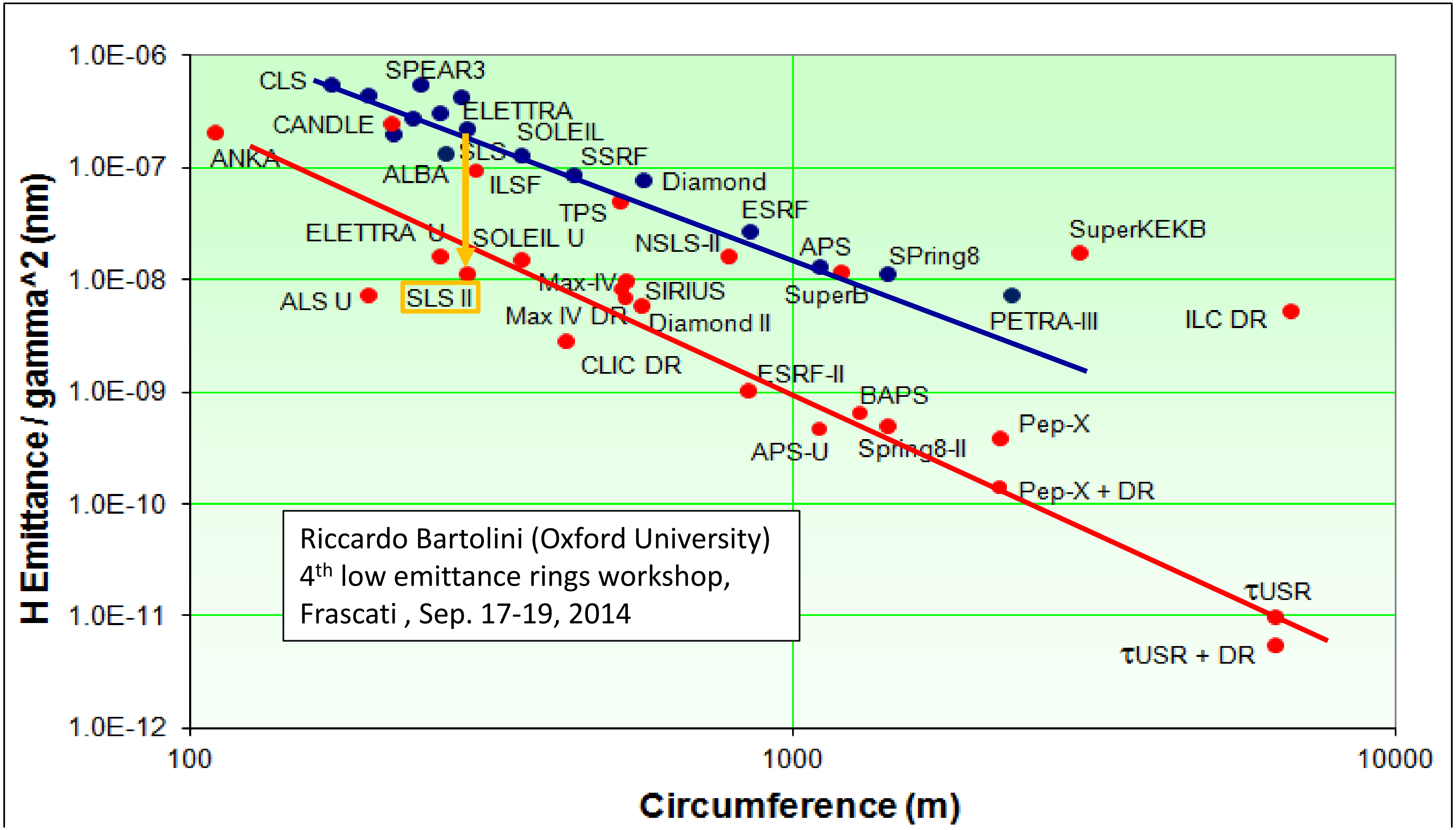
⇨ many lattice cells

⇨ low angle per bend (= dipole)

emittance $\varepsilon \propto (\text{energy})^2 \times (\text{bend angle})^3$

⇨ Emittance reduction from nm to 10...100 pm range

The storage ring generational change



Riccardo Bartolini (Oxford University)
4th low emittance rings workshop,
Frascati , Sep. 17-19, 2014

Storage rings in operation (●) and planned (●).

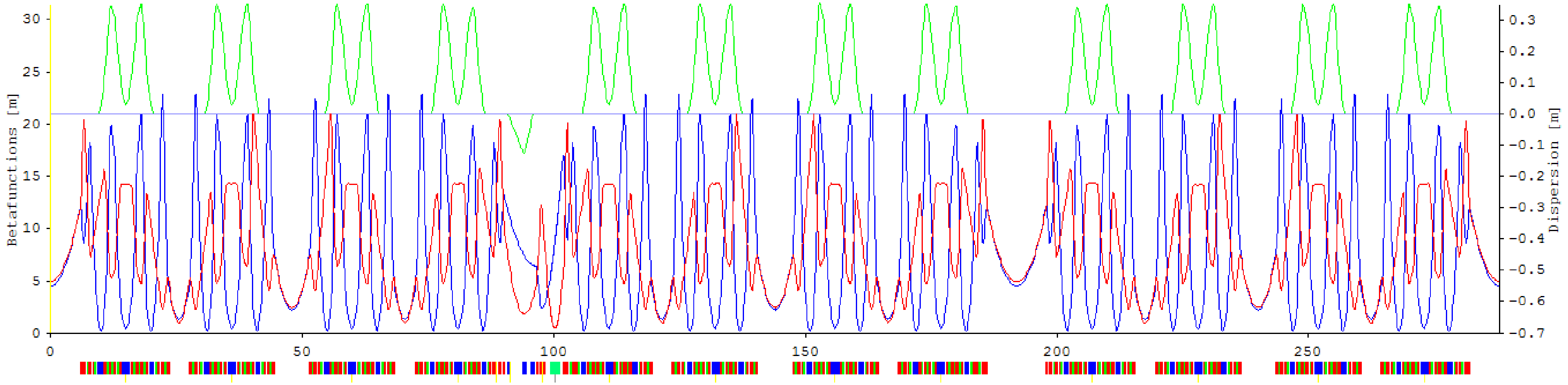
The old (—) and the new (—) generation.

New storage rings and upgrade plans

Name	Energy [GeV]	Circumf. [m]	Emittance* [pm]	Status
PETRA-III	6.0 3.0	2304	4400 → 1000 85 (round beam)	operational
MAX-IV	3.0	528	328 → 200	2015
SIRIUS	3.0	518	280	2016
ESRF upgrade	6.0	844	147	2019
DIAMOND upgrade	3.0	562	275	started
APS upgrade	6.0	1104	65	study
SPRING 8 upgrade	6.0	1436	68	study
PEP-X	4.5	2200	29 → 10	study
ALS upgrade	2.0	200	100	study
ELETTRA upgrade	2.0	260	250	study
SLS now	**2.4**	**288**	**5500**	**operational**
SLS-2	**2.4 (?)**	**288**	**100-200 ?**	**2024 ?**

*Emittance without → with damping wigglers

The SLS



- 288 m circumference
- 12 × TBA (triple bend achromat) lattice
- straight sections: 6 × 4 m, 3 × 7 m, 3 × 11.5 m
- FEMTO chicane for laser beam slicing
- 3 normalconducting 3T superbends
- Emittance 5.5 nm at 2.4 GeV (5.0 nm without FEMTO)
- User operation since June 2001
- 18 beam lines in operation

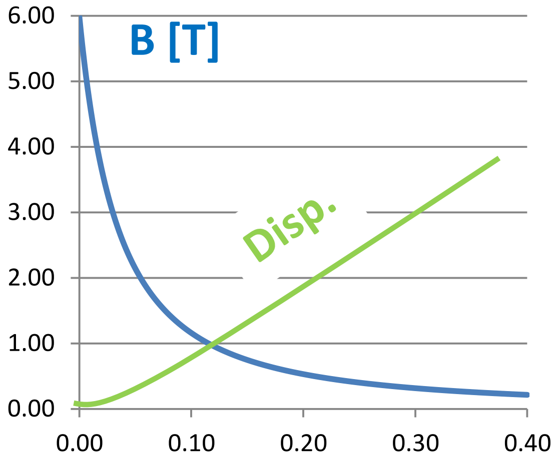
SLS-2 design constraints and the main challenge

- Constraints
  - keep circumference: hall, tunnel.
  - re-use injector: booster, linac.
  - keep beam lines: avoid shift of source points.
  - limited “dark time” for upgrade.
- Challenge: small circumference
  - Multi bend achromat: $\varepsilon \propto (\text{number of bends})^{-3}$
  - Damping wigglers (DW): $\varepsilon \propto \dfrac{\text{ring}}{\text{ring} + \textbf{DW}}$ radiated power
  - ⇨ Low emittance from MBA and/or DW requires space !
  - ⇨ Scaling MAX IV to SLS size and energy gives $\varepsilon \approx 1\ \text{nm}$.

Compact low emittance lattice concept

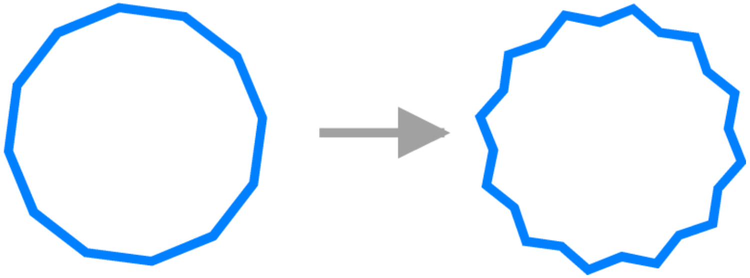
- Longitudinal gradient bends (LGB): field variation $B = B(s)$
  - $\boldsymbol{\varepsilon} \propto \int (\text{dispersion}^2 \ldots) \times (\text{B-field})^3\, ds$

  $\rightarrow$ high field at low dispersion and v.v.
- Anti-bends: $B < 0$
  - matching of dispersion to LGB



⇨ factor ≈ 5 lower emittance

compared to a conventional lattice



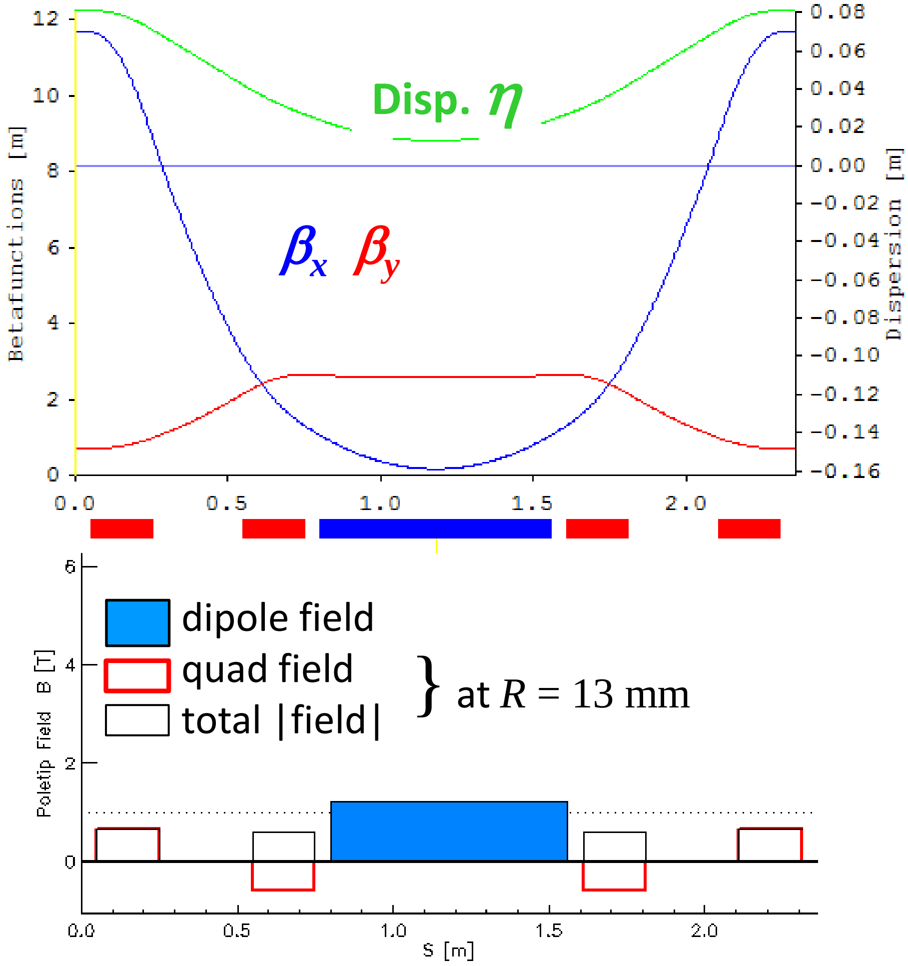
- Additional benefits
  - Hard X-rays (≈ 80 keV) from B-field peak (≈ 5 Tesla)
  - $\boldsymbol{\varepsilon}$-reduction due to increased radiated power from high field and from $\Sigma|\text{angle}| > 360°$ ("wiggler lattice")

AS & A. Wrulich, NIM A770 (2015) 98–112; AS, NIM A737 (2014) 148–154

A compact low emittance cell

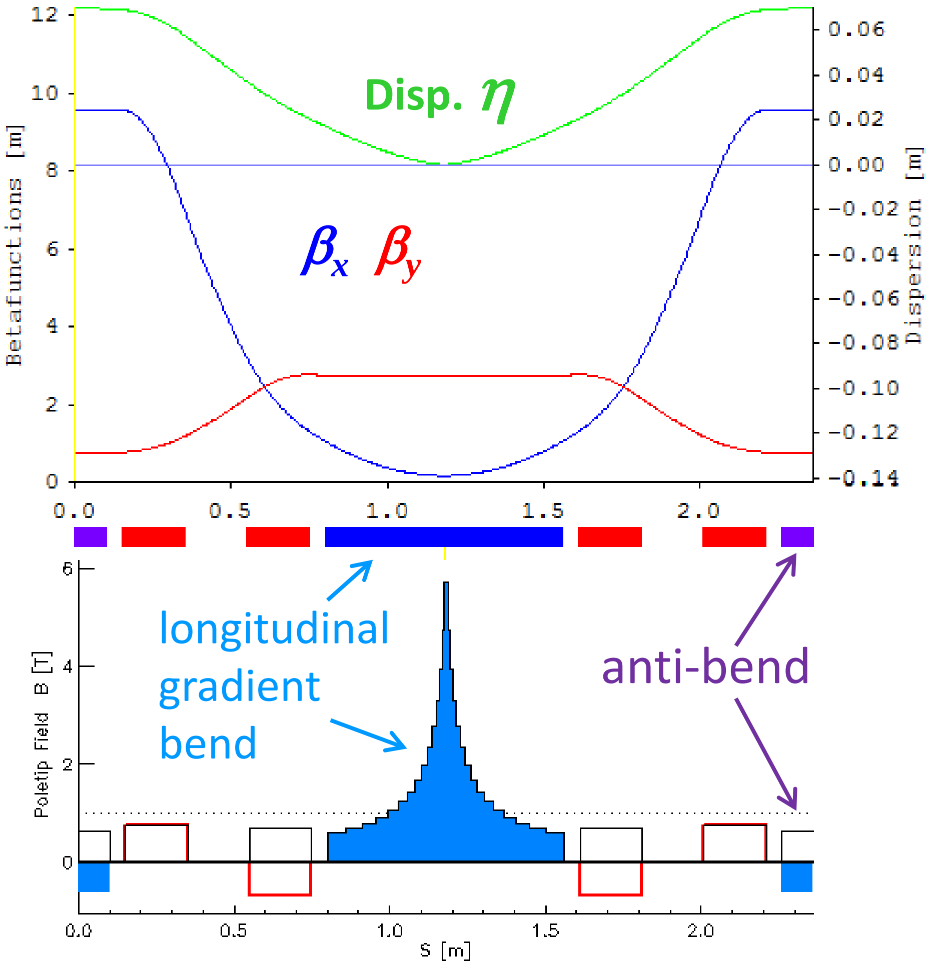
- Conventional cell vs. longitudinal-gradient bend/anti-bend cell
  - both: angle 6.7°, E = 2.4 GeV, L = 2.36 m, $\Delta\mu_x$ = 160°, $\Delta\mu_y$ = 90°, $J_x \approx 1$

conventional: ε = 990 pm



} at R = 13 mm

LGB/AB: ε = 200 pm



longitudinal gradient bend

anti-bend

Longitudinal gradient bends

$$\varepsilon \propto I_5 = \int_L |b(s)|^3 \mathcal{H}(s)\,ds \qquad \mathcal{H} = \frac{\eta^2 + (\alpha\eta + \beta\eta')^2}{\beta}$$

orbit curvature
$b(s) = B(s)/(p/e)$

- Longitudinal field variation $b(s)$ to compensate $\mathcal{H}(s)$ variation
- Beam dynamics in bending magnet
  - Curvature is source of dispersion: $\eta''(s) = b(s) \rightarrow \eta'(s) \rightarrow \eta(s)$
  - Horizontal optics ~ like drift space: $\beta(s) = \beta_0 - 2\alpha_0 s + \frac{1+\alpha_0^2}{\beta_0} s^2$
  - Assumptions: no transverse gradient ($k = 0$); rectangular geometry
- Variational problem: find extremal of $\eta(s)$ for

$I_5 = \int_L f(s,\eta,\eta',\eta'')\,ds \rightarrow \min$ with functional $f = \mathcal{H}(s,\eta,\eta',\eta'')\,|\eta''|^3$

  - too complicated to solve
    - mixed products up to η'''' in Euler-Poisson equation...

→ special functions b(s), simple (few parameters):
variational problem → minimization problem

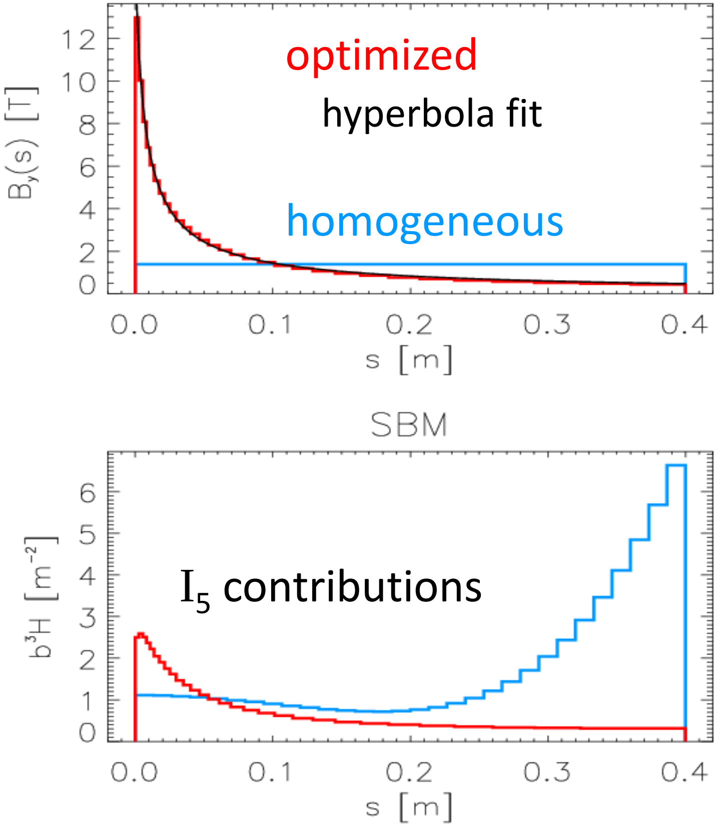
→ numerical optimization

Numerical optimization

- Half bend in N slices: curvature b_i, length Δs_i
- Knobs for minimizer: $\{b_i\}, \beta_0, \eta_0$
- Objective: I_5
- Constraints:
  - length: $\Sigma\Delta s_i = L/2$
  - angle: $\Sigma b_i \Delta s_i = \Phi/2$
  - [field: $b_i < b_{max}$]
  - [optics: β_0, η_0]
- Results:
  - hyperbolic field variation
    (for symmetric bend, dispersion suppressor bend is different)
  - Trend: $b_0 \to \infty$, $\beta_0 \to 0$, $\eta_0 \to 0$

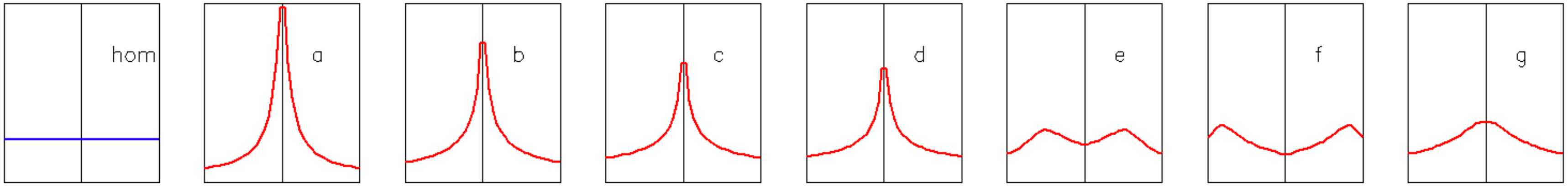
I

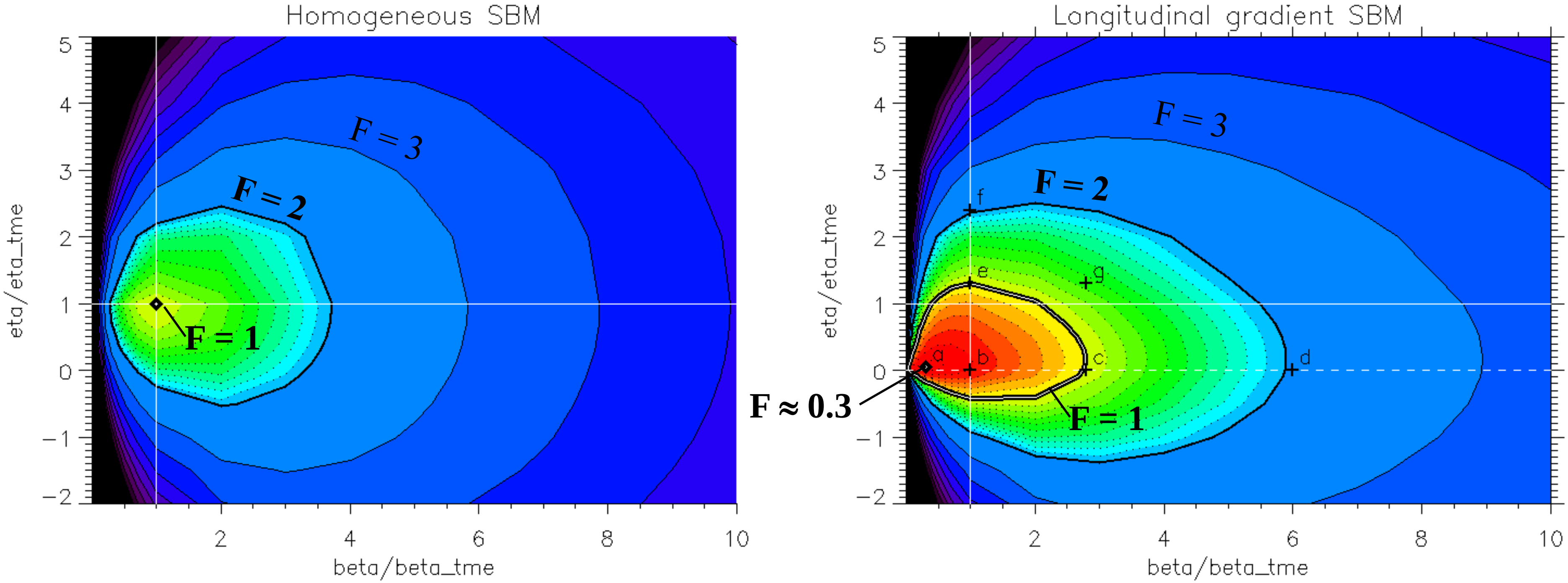
Results for half symmetric bend
(L = 0.8 m, Φ = 8°, 2.4 GeV)



Optimization with optics constraints

- Numerical optimization of field profile for fixed β_0, η_0
  - Emittance (F) vs. β_0, η_0 normalized to data for TME of hom. bend





small (~0) dispersion at centre required, but tolerant to large beta function

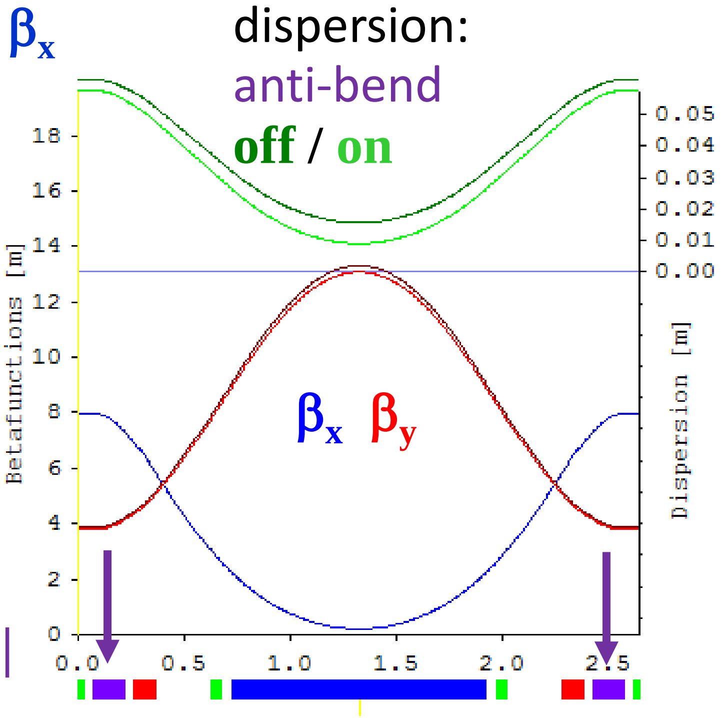
Anti-bends

- General problem of dispersion matching:
  - dispersion is a horizontal trajectory
  - dispersion production in dipoles → “defocusing”: $\eta'' > 0$
- Quadrupoles in conventional cell:
  - over-focusing of horizontal beta function β_x
  - insufficient focusing of dispersion η

⇨ disentangle η and β_x !

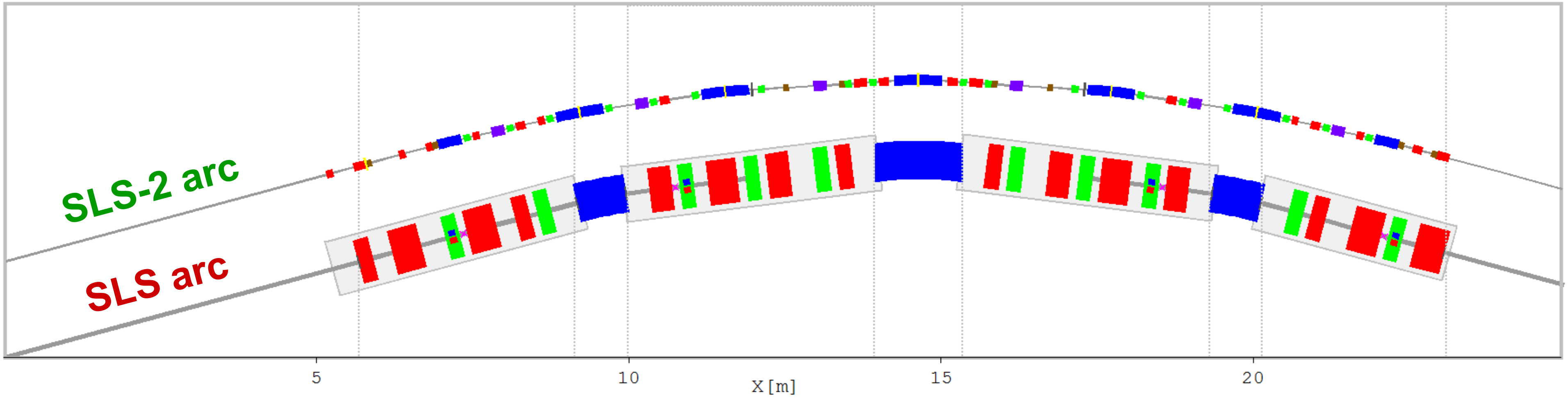
- use negative dipole: ***anti-bend***
  - kick $\Delta\eta' = \psi$, angle $\psi < 0$
  - out of phase with main dipole
  - negligible effect on β_x , β_y
- Side effects on emittance:
  - main bend angle to be increased by $2|\psi|$
  - anti-bend located at large $\mathcal{H}$

→ in total, still lower emittance →



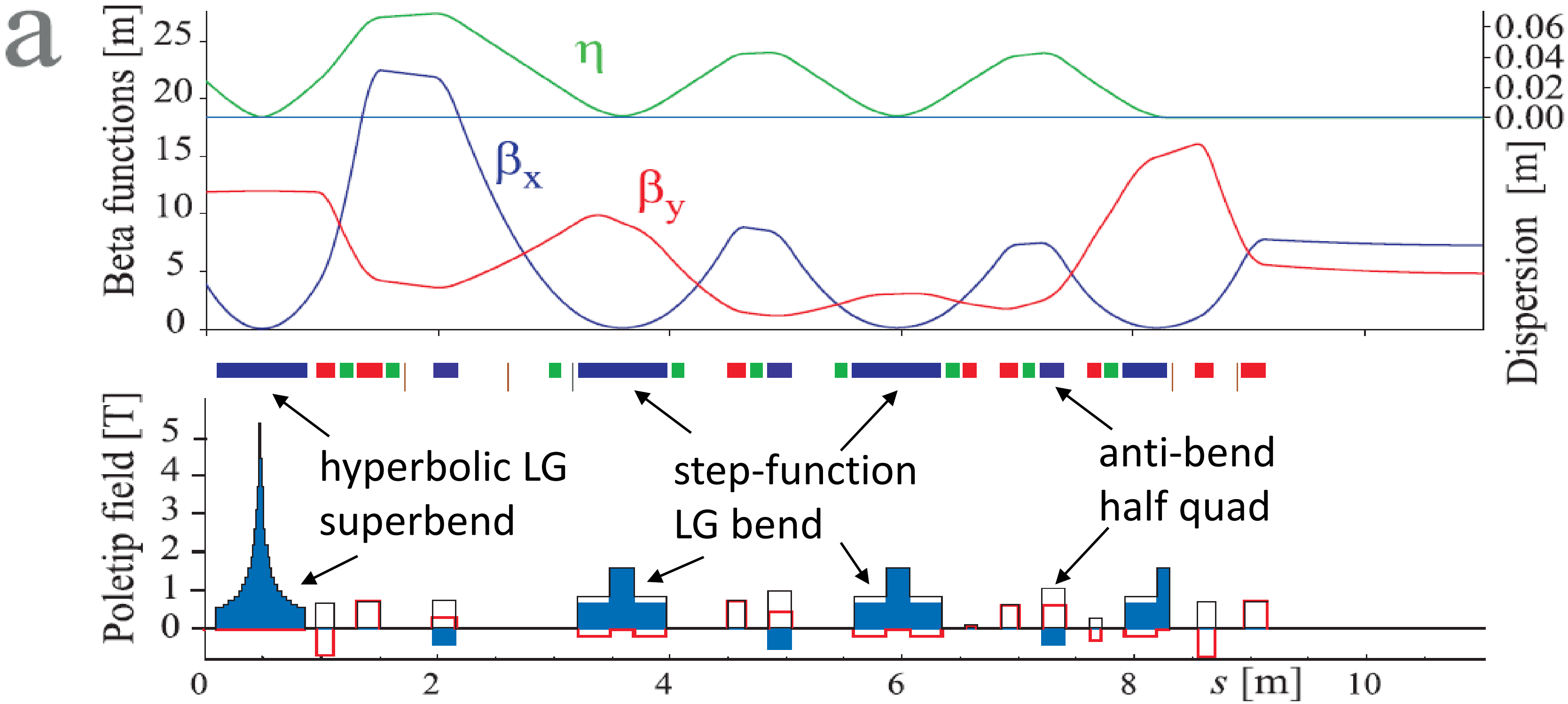
relaxed TME cell, 5°, 2.4 GeV, $J_x \approx 2$
Emittance: **500 pm** / **200 pm**

SLS-2 lattice design status



- Various concept lattice designs for 100-200 pm
  - based on a 7-bend achromat arc.
  - longitudinal gradient superbends of 4-6 T peak field.
  - anti-bends for dispersion matching.
  - small octupoles for acceptance optimization.
  - beam pipe / magnet bore ∅ 20 / 26 mm.

a) ultra-low emittance lattice



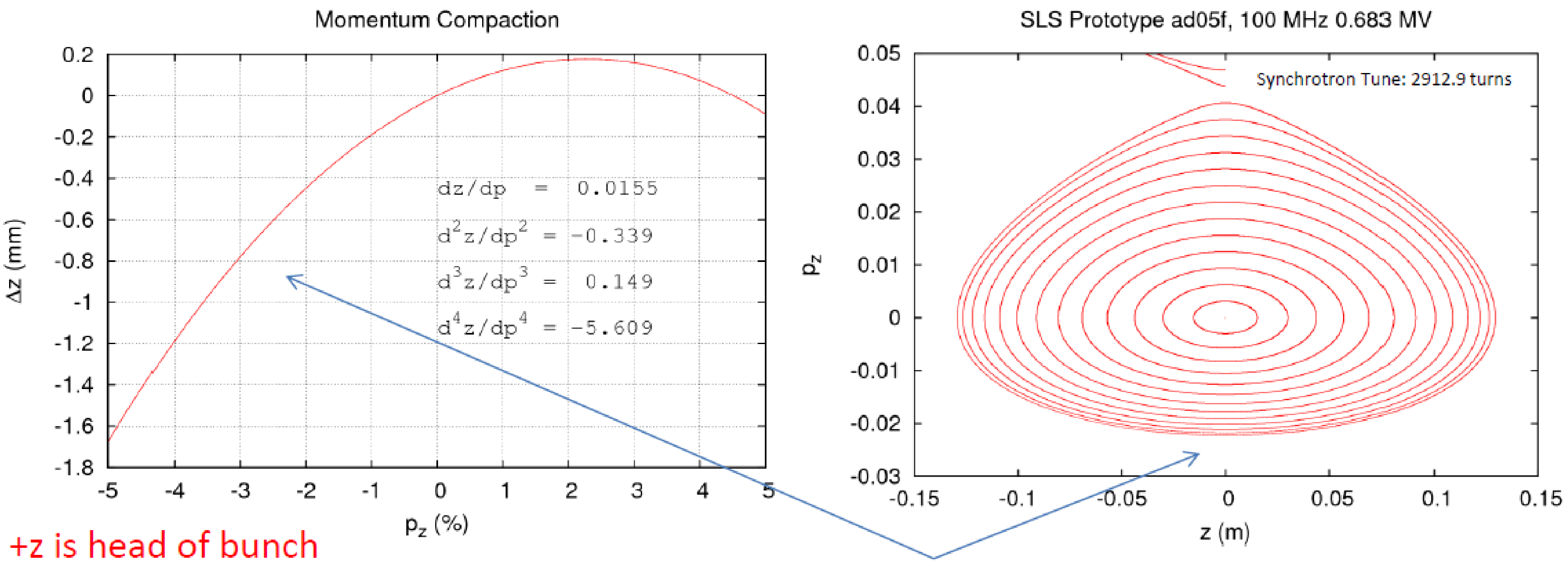
hyperbolic LG superbend

step-function LG bend

anti-bend half quad

- ☑ ultra-low emittance: **ε = 73 pm** ! (≈18 m / 30° arc at 2.4 GeV)
- ☑ ≈ feasible magnets, ≈ sufficient dynamic aperture
- ☒ large normalized chromaticities $-\xi/Q = 3.9 / 4.3$
- ☒ quasi isochronous (MCF $\alpha = -5\cdot 10^{-5}$) and nonlinear
- ➔ too short bunches, insufficient energy acceptance

Longitudinal Dynamics

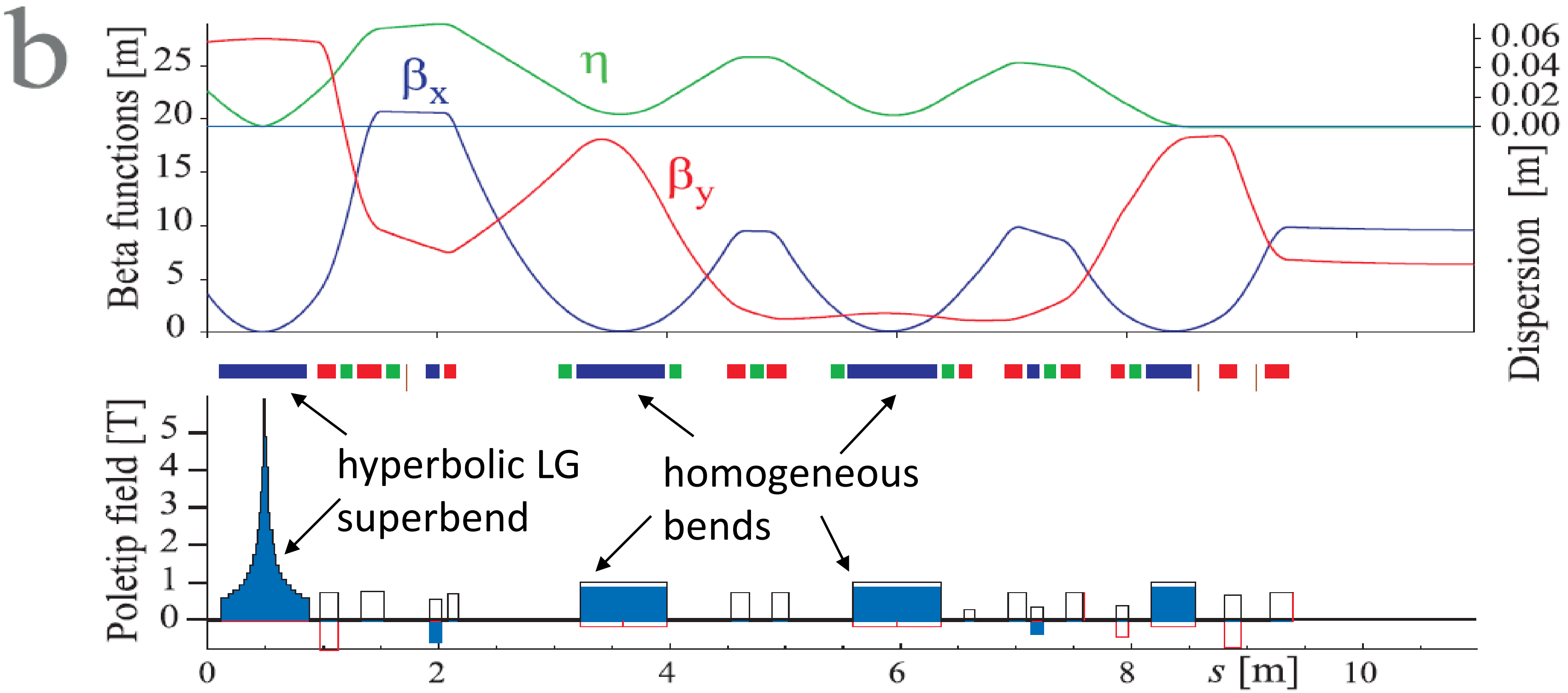


+z is head of bunch

Bucket size limited by non-linear roll-off in momentum compaction

- Lattice is below transition
- Higher orders of momentum compaction calculated using TPSA.
- Goal: ±5% bucket.
- Possible solution: use multipoles to manipulate nonlinear momentum compaction to widen bucket.

b) back down lattice



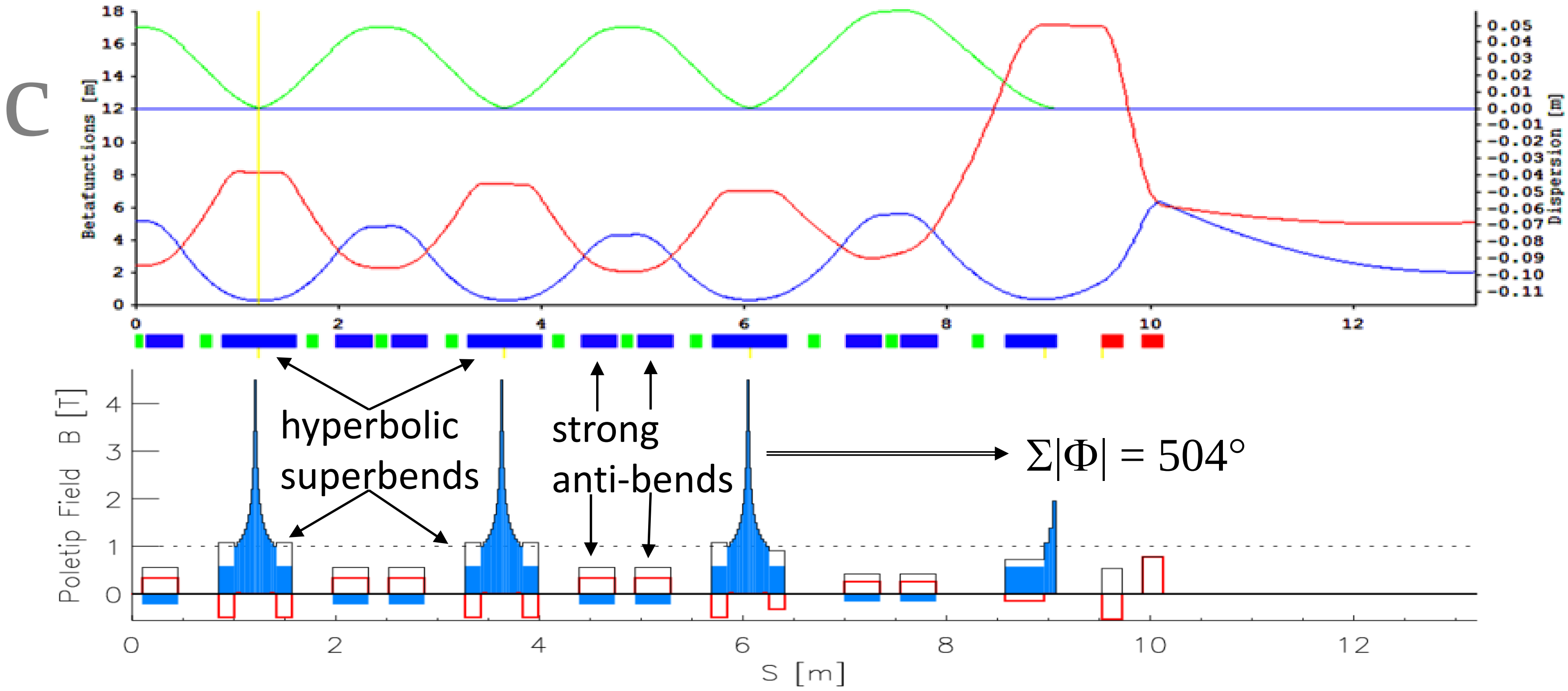
☑ acceptable emittance: $\varepsilon = 183$ pm

☑ ≈ feasible magnets, ≈ sufficient dynamic aperture

☑ large MCF ($\alpha = +1.3 \cdot 10^{-4}$) → bunch length & E-acceptance ✓

☒ large normalized chromaticities $-\xi/Q = 4.1 / 6.5$

c) symmetric lattice *„below transition“*



hyperbolic superbends

strong anti-bends

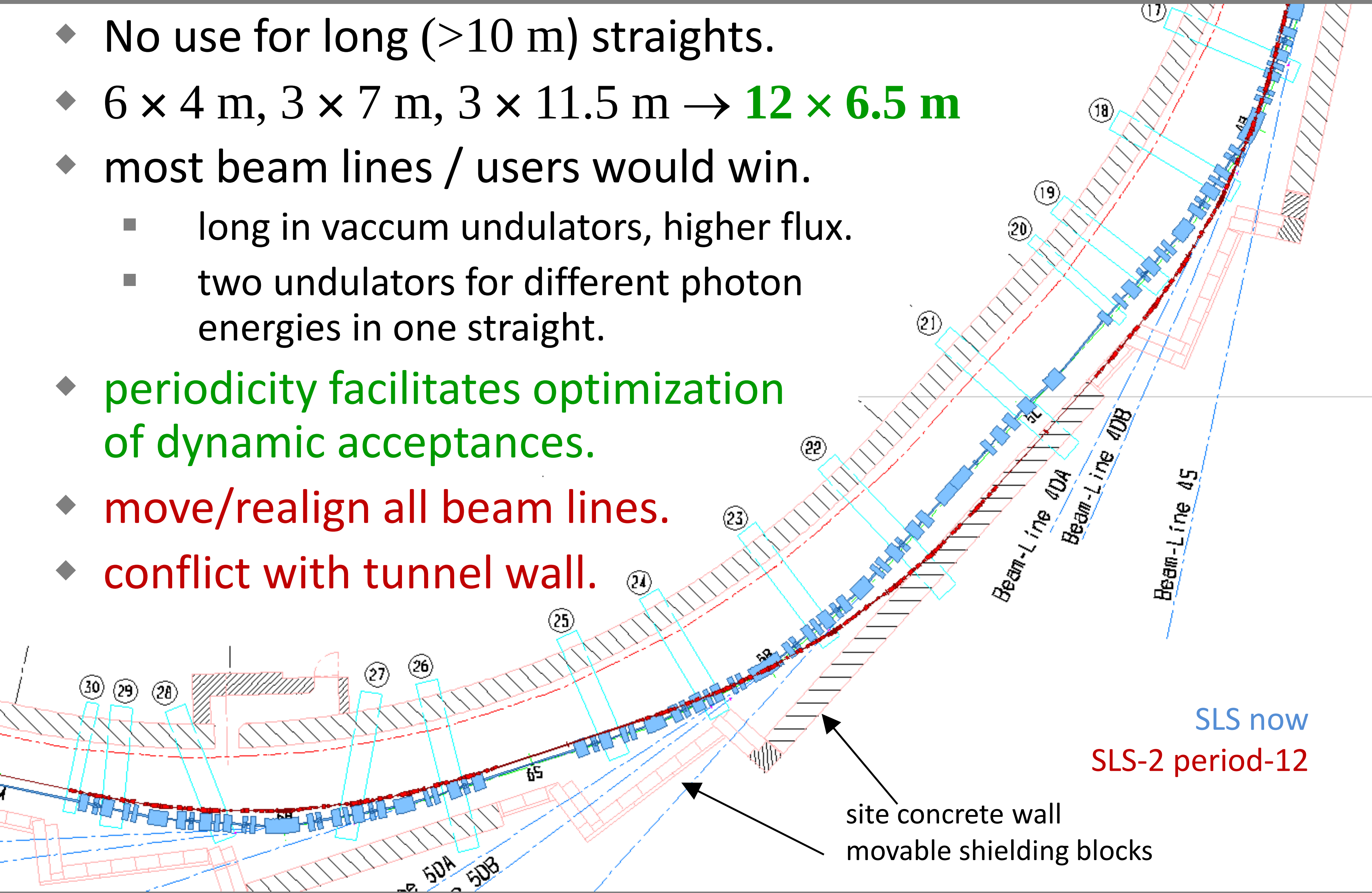
$\Sigma|\Phi| = 504°$

Period-12 lattice: 12× 6.5 m straights, identical cells (tunes 0.4/0.1)

- ☑ good emittance: ε **= 126 pm**
- ☑ large *negative* MCF ($\alpha = -10^{-4}$) → *„below transition“*
- ☑ very low horizontal normalized chromaticity $-\xi_x/Q_x = 1.6$
- ☑ first-order cancellations of sextupole resonances, good acceptance

Period-12 lattice

- No use for long (>10 m) straights.
- 6 × 4 m, 3 × 7 m, 3 × 11.5 m → **12 × 6.5 m**
- most beam lines / users would win.
  - long in vaccum undulators, higher flux.
  - two undulators for different photon energies in one straight.
- periodicity facilitates optimization of dynamic acceptances.
- move/realign all beam lines.
- conflict with tunnel wall.



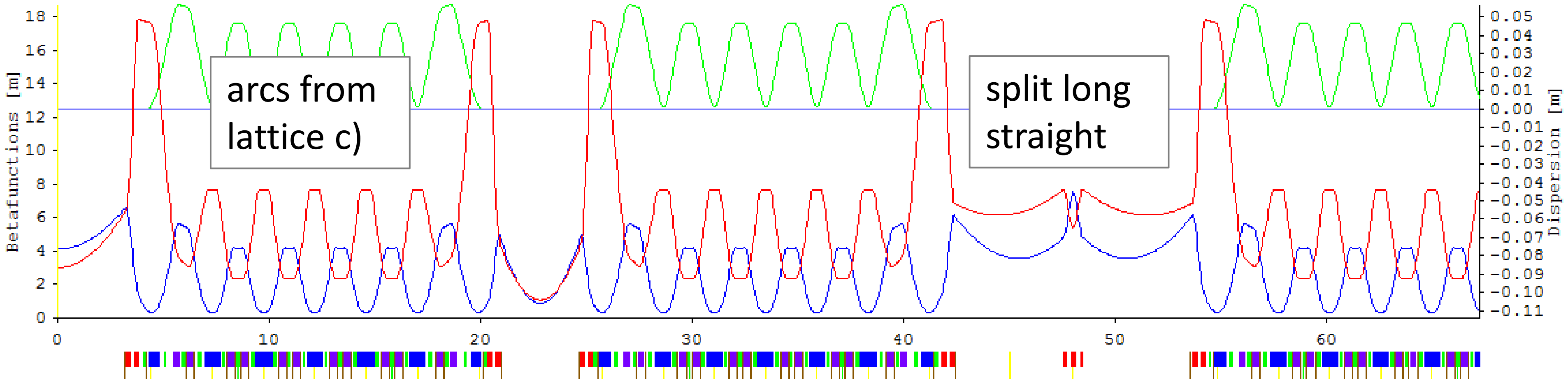
SLS now

SLS-2 period-12

site concrete wall

movable shielding blocks

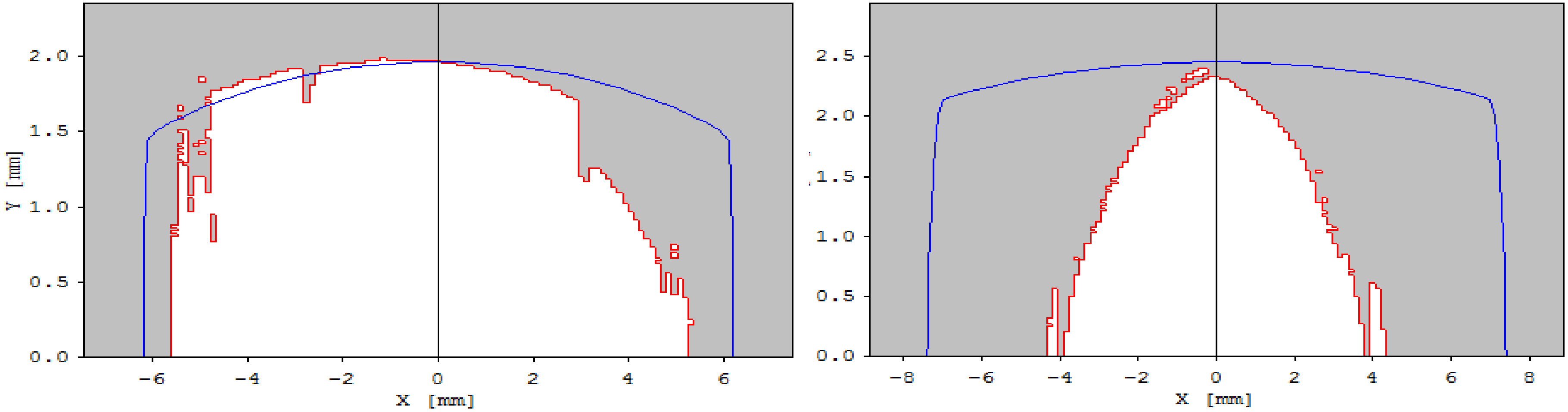
d) Period-3 split long straight lattice



arcs from lattice c)

split long straight

3 × 6.2 m , 6 × 3.6 m and 3 × (5 + 5) m straights



Dynamic aperture for ⇖period-12 (c) and period-3 (d) ⇧ lattice

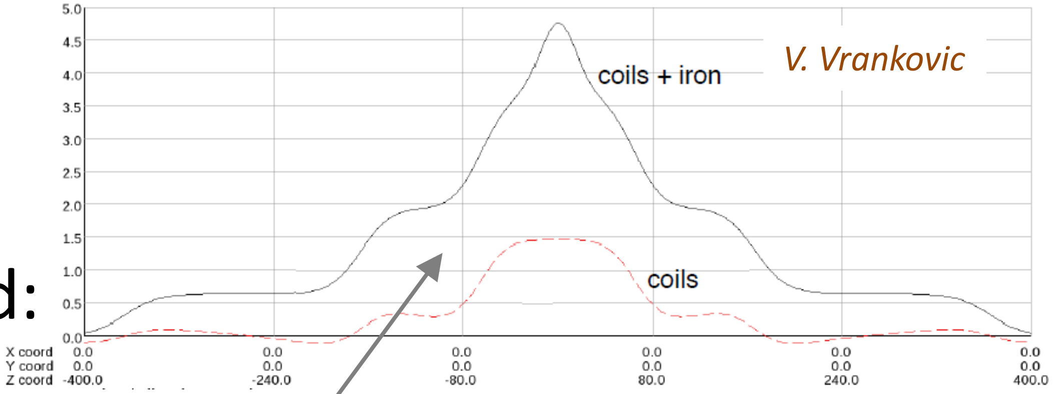
Comparison of SLS-2 draft designs

	SLS	MAX IV	a) `ad05f`	b) `ah04n`	c) `ca05q`	d) `ca06b`
Circumference [m]	288	528	288	288	288	288
Periodicity	1 (3)	20	3	3	**12**	3
Σ |bend angle|	375°	360°	460°	391°	504°	504°
Tunes	20.43/8.74	42.20/16.28	39.42/10.76	39.39/10.76	37.28/9.12	37.68/10.78
-Chroma/Tune	3.3/2.4	1.2/3.1	3.9/4.3	4.1/6.5	1.6/5.0	1.6/4.5
Mom. comp. [10^{-4}]	6.1	3.1	**-0.5**	1.3	-1.0	-1.0
Damping part. J_x	1.00	1.85	1.36	1.13	1.41	1.41
Hor. Acc.*[mm mrad]	27	18	**2.2**	3.3	10	6.4
Δp/p. Acc.* [%]	3.0	6.8	**2.2**	3.9	4.5	3.4
Energy [GeV]	2.4	3.0	2.4	2.4	2.4	2.4
Emittance [pm]	5558	328	**73**	**183**	**126**	**126**
Energy loss [keV]	548	**363**	610	466	730	736
ΔE/E spread [10^{-3}]	0.86	**0.77**	1.13	1.04	1.21	1.24

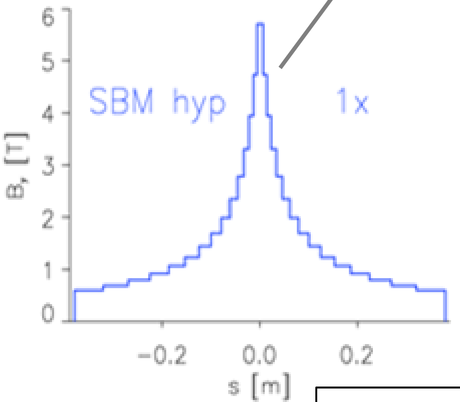
* max. horizontal betatron amplitude and momentum deviation of stable particles in ideal lattice

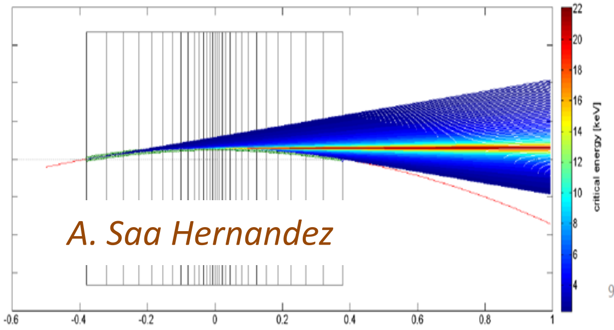
Longitudinal gradient superbend

- Hyperbolic field shape
  - rough approximation is sufficient.
- Narrow peak of high field:
  - emittance minimization.
  - limitation of heat load and radiated power.
- Benefits of high field:
  - Hard X-rays available at a 2.4 GeV ring.
  - Photon BPMs for orbit correction.
  - X-ray pinholes for beam size measurements.



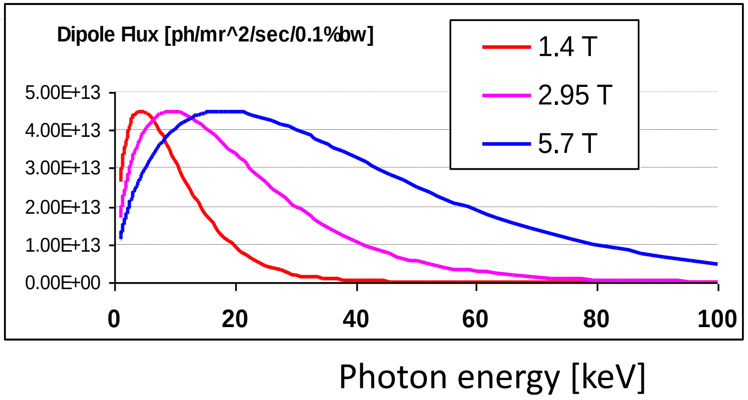
V. Vrankovic





A. Saa Hernandez

SLS normal bend
SLS superbend
SLS-2 LG superbend

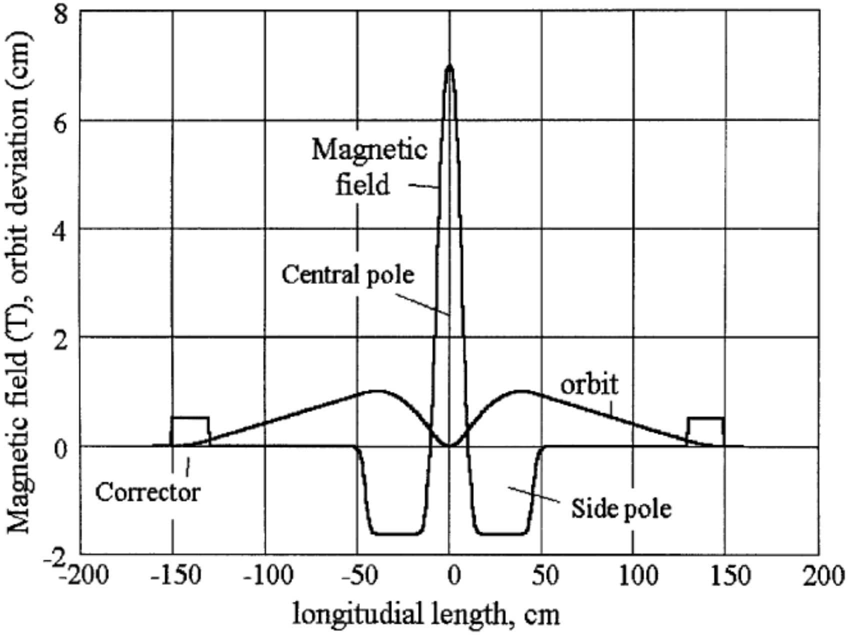


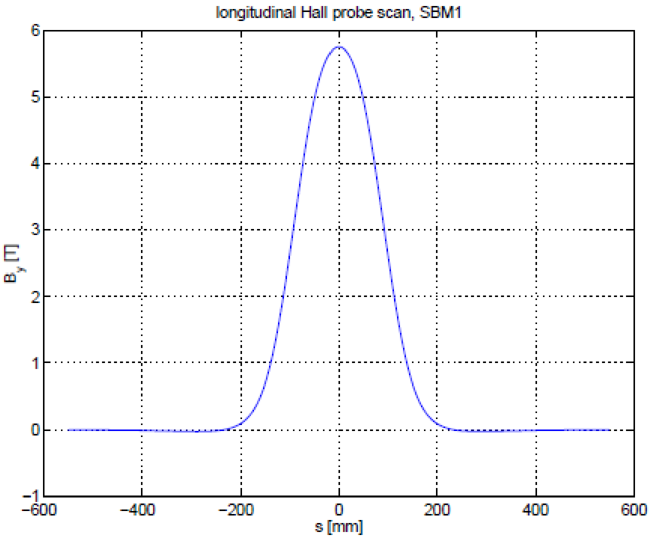
LGSB predecessors

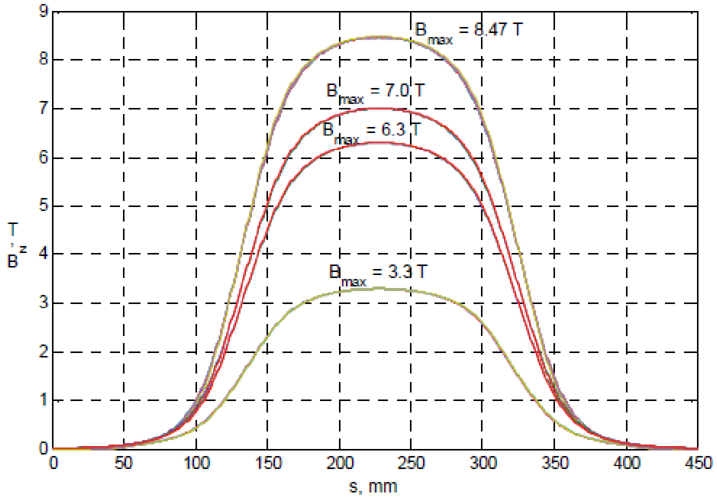
V. Shkaruba et al., *Superconducting high field three pole wigglers at Budker INP,* NIM A448 (2000) 51–58 ⇨

K. Zolotarev et al., *9 Tesla superbend for Bessy II,* APAC-2004 ⬂

D. Robin et al., *Superbend project at the Advanced Light Source,* PAC-2001 ⬃ ⇩

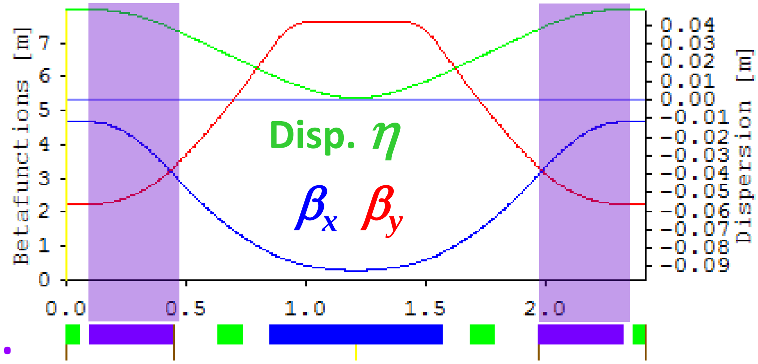


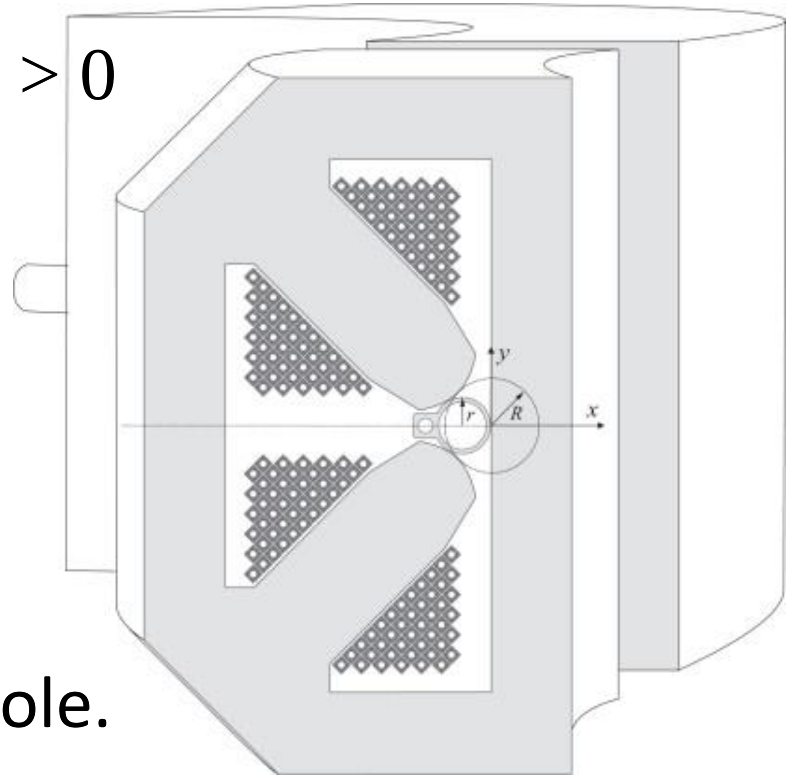




Anti-bend

- Anti-Bend: inverse field, $B < 0$
- Low field, long magnet
  - emittance contribution $\propto |B|^3 \mathcal{H}$ L
  - $\mathcal{H}$ is large and ≈constant at anti-bend.
- Strong horizontal focusing, $dB/dx > 0$
  - needed for optics at location out of phase with main bend.
  - manipulation of damping partition to get lower emittance:
    - vertical focusing in normal bend.
    - horizontal focusing in anti-bend.
- anti-bend = off-centered quadrupole.
- most convenient magnet design = half quadrupole.





SLS-2 design tasks and challenges

- Optimize dynamic lattice acceptances to provide sufficient injection efficiency and beam lifetime.
- Prevent and suppress instabilities due to interaction of electron beam with narrow beam pipe.
- Minimize blow-up of emittance due to intra-beam scattering.
- Set tolerances for magnets and girders.
- Establish methods for beam based alignment in commissioning.
- Develop orbit feed-back based on photon BPMs.

- Explore limits of vacuum chamber and magnet miniaturization.
- Explore round beam schemes.
- Explore on-axis injection schemes

Conclusion

- SLS-2 design is handicapped by comparatively small ring circumference.
- But the new LGB/AB cell provides a solution for compact low emittance rings.
- An emittance of 100-200 pm seems possible with contemporary magnet technology.
- But feasibility has not yet been proven.
- A conceptual design report is planned for 2016.