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Progress of SLS-2 Project

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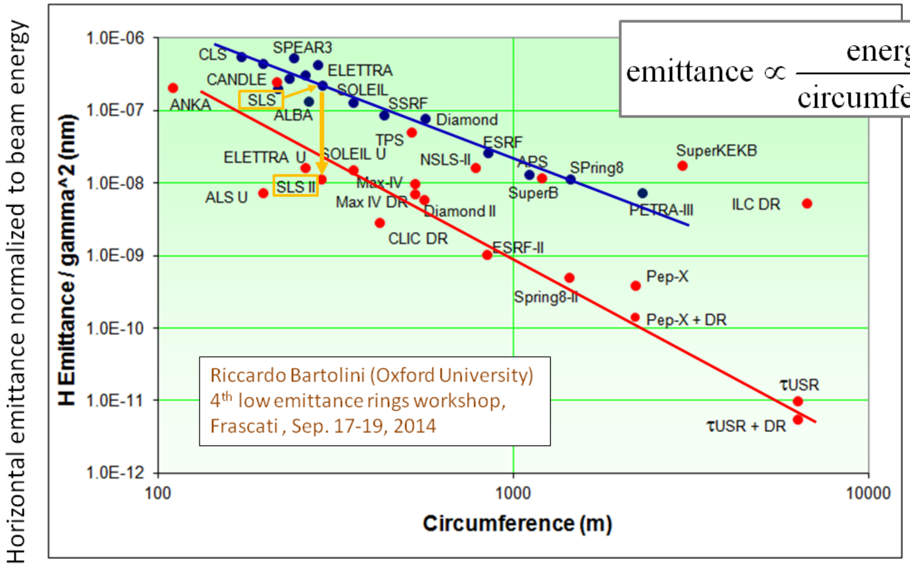
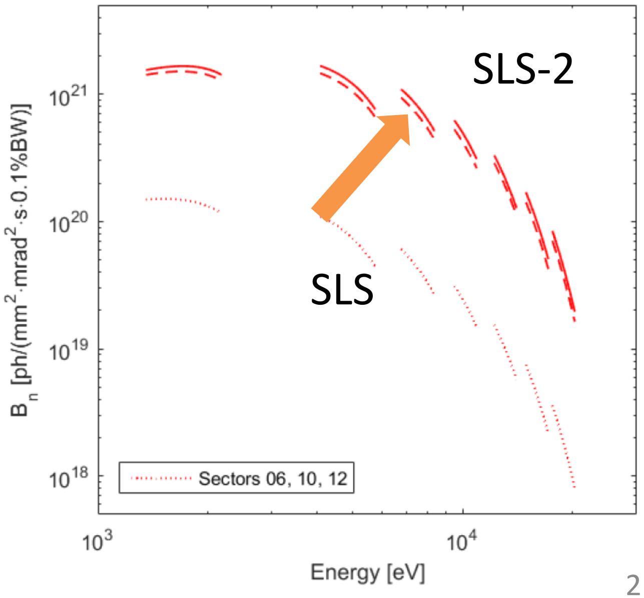
LER2016 workshop at Soleil

SLS-2 project – Goals and Constraints

- Goals
  - Factor 20~50 lower emittance (5 nm → 100~250 pm)
  - Operation parameters as in the present SLS:
    Energy = 2.4 GeV, Current = 400 mA (top-up), Stability = 1 μm, etc.
- Constraints
  - Reuse the building → Storage ring circum. = 288 m ☹ (3BA→7BA is not enough)
  - Reuse the injector chain (Gun, Linac and Booster) → ε @ 2.4 GeV < 10 nm ☺



$$\text{emittance} \propto \frac{\text{energy}^2}{\text{circumference}^3}$$



AB+LGB lattice (1)

Longitudinal Gradient Bend

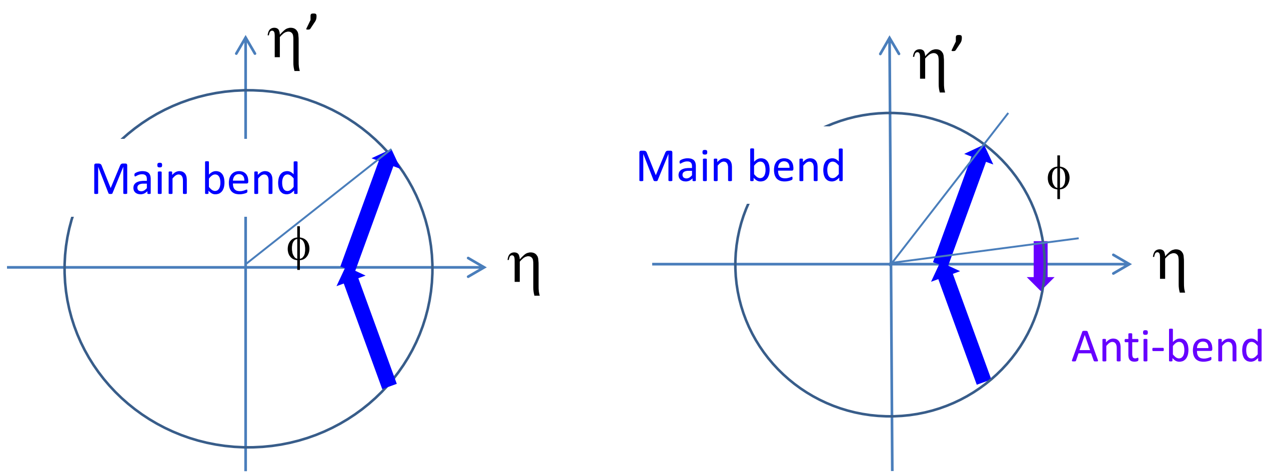
$$\varepsilon \propto I_5 = \int_L |h(s)|^3 \mathcal{H}(s) ds$$

$$\mathcal{H} = \frac{\eta^2 + (\alpha\eta + \beta\eta')^2}{\beta}$$

- Dispersion's betatron amplitude
- Orbit curvature $h(s) = B(s)/(p/e)$
- Longitudinal field variation $h(s)$ to compensate $\mathcal{H}(s)$ variation

Anti-Bend

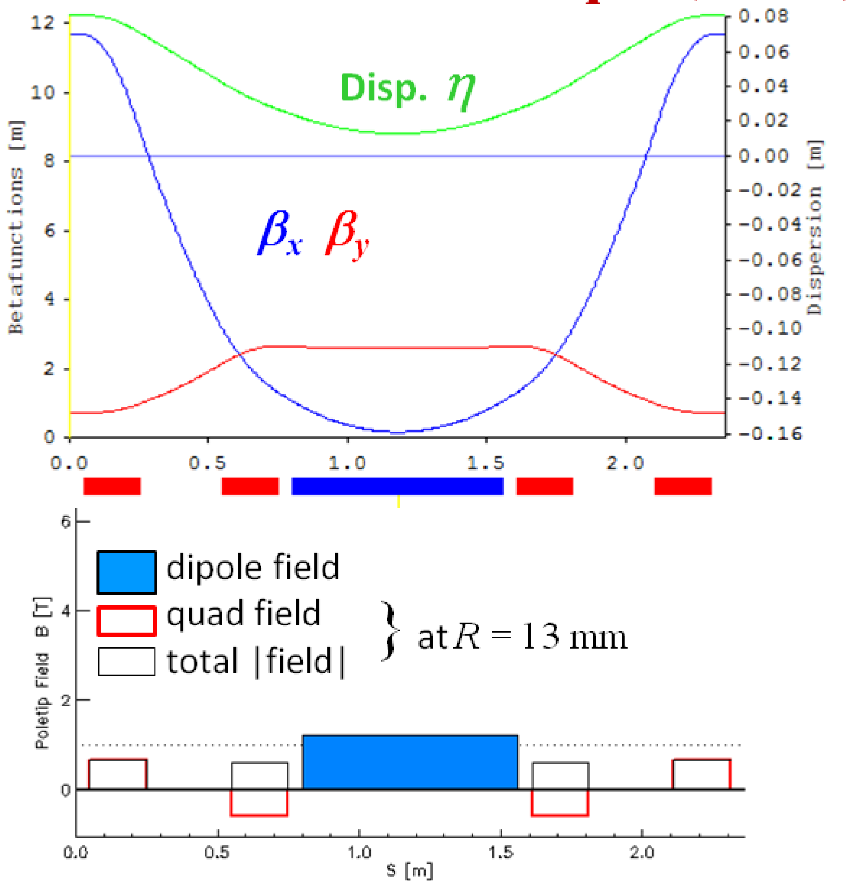
Anti-bend gains "dispersion phase advance"
→ Smaller dispersion in Main bending magnet



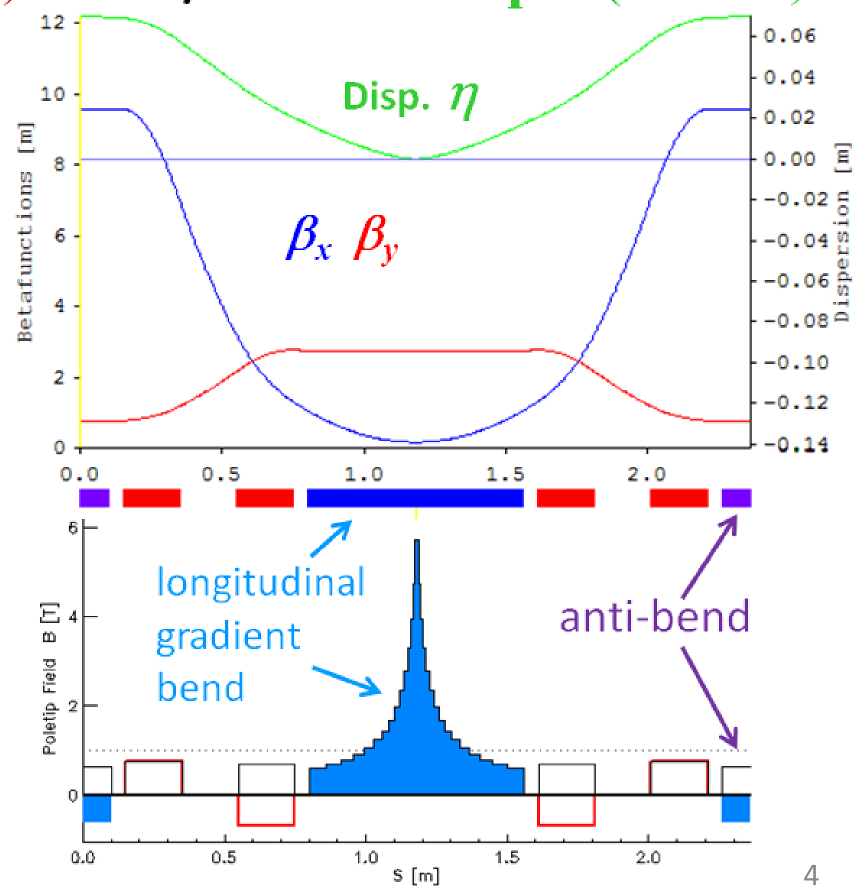
AB+LGB lattice (2)

- 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: $\varepsilon = 990$ pm $(F = 3.4)$



LGB/AB: $\varepsilon = 200$ pm $(F = 0.69)$



LGB modeling (1)

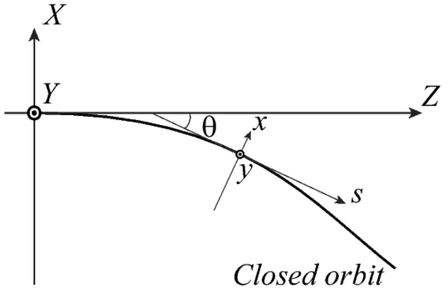
- Field description:

Horizontal gradient Longitudinal gradient

$$B_1 = \left.\frac{\partial B_Y}{\partial X}\right|_{X_0,Z_0} \cos\theta_0 + \left.\frac{\partial B_Y}{\partial Z}\right|_{X_0,Z_0} \sin\theta_0,$$

$$B_2 = \left.\frac{\partial^2 B_Y}{\partial X^2}\right|_{X_0,Z_0} \cos^2\theta_0 + \left.\frac{\partial^2 B_Y}{\partial Z^2}\right|_{X_0,Z_0} \sin^2\theta_0,$$

$$B_3 = \left.\frac{\partial^3 B_Y}{\partial X^3}\right|_{X_0,Z_0} \cos^3\theta_0 + \left.\frac{\partial^3 B_Y}{\partial Z^3}\right|_{X_0,Z_0} \sin^3\theta_0,$$

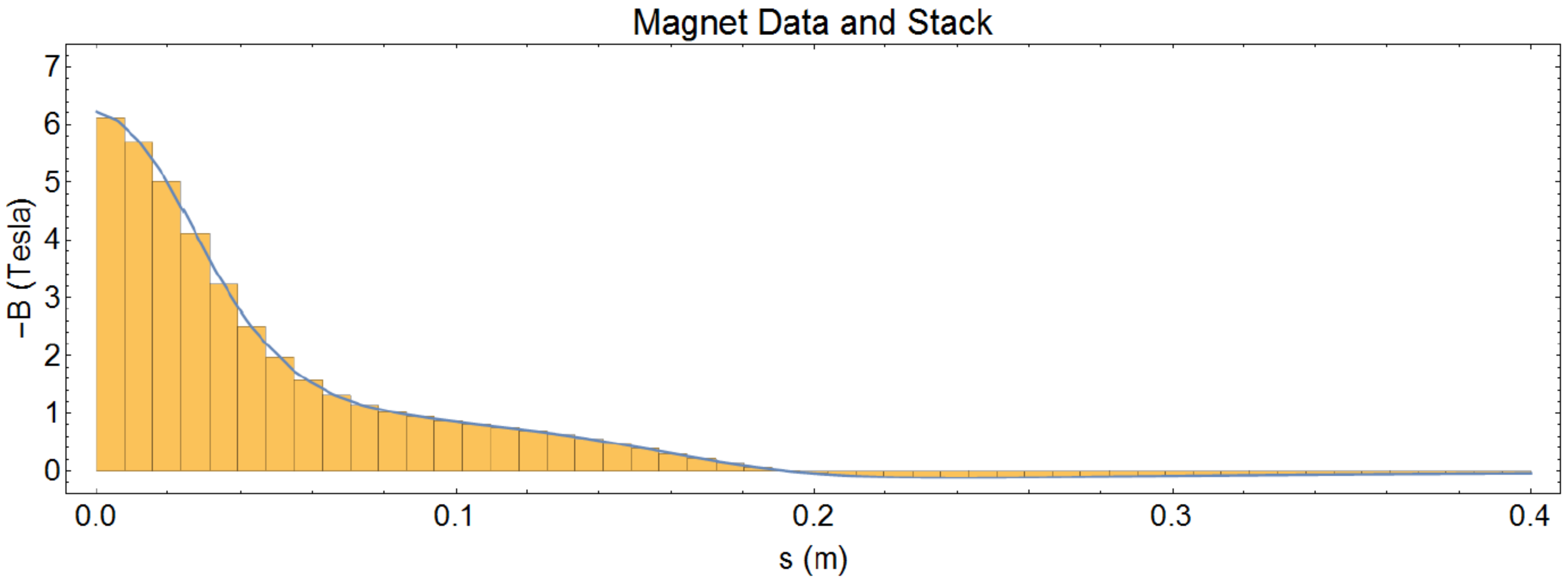


  - Longitudinal gradient is included as a projection to the horizontal plane
  - Higher order terms are strongly attenuated by $\sin^n\theta$ term

LGB modeling (2)

- Two methods:
  1) Rbend: Face angles adjusted such that all faces are parallel in the lab frame.
     - No K_{quad} or higher values.

     (X-Y-Z)
  2) Sbend: Faces are perpendicular to closed orbit, except for ends, which are parallel.
     - K_{quad} calculated from bend field data.
     - Simple extension to higher order focusing terms.



Both models agree with a tracking using the field map within 10^{-4} level

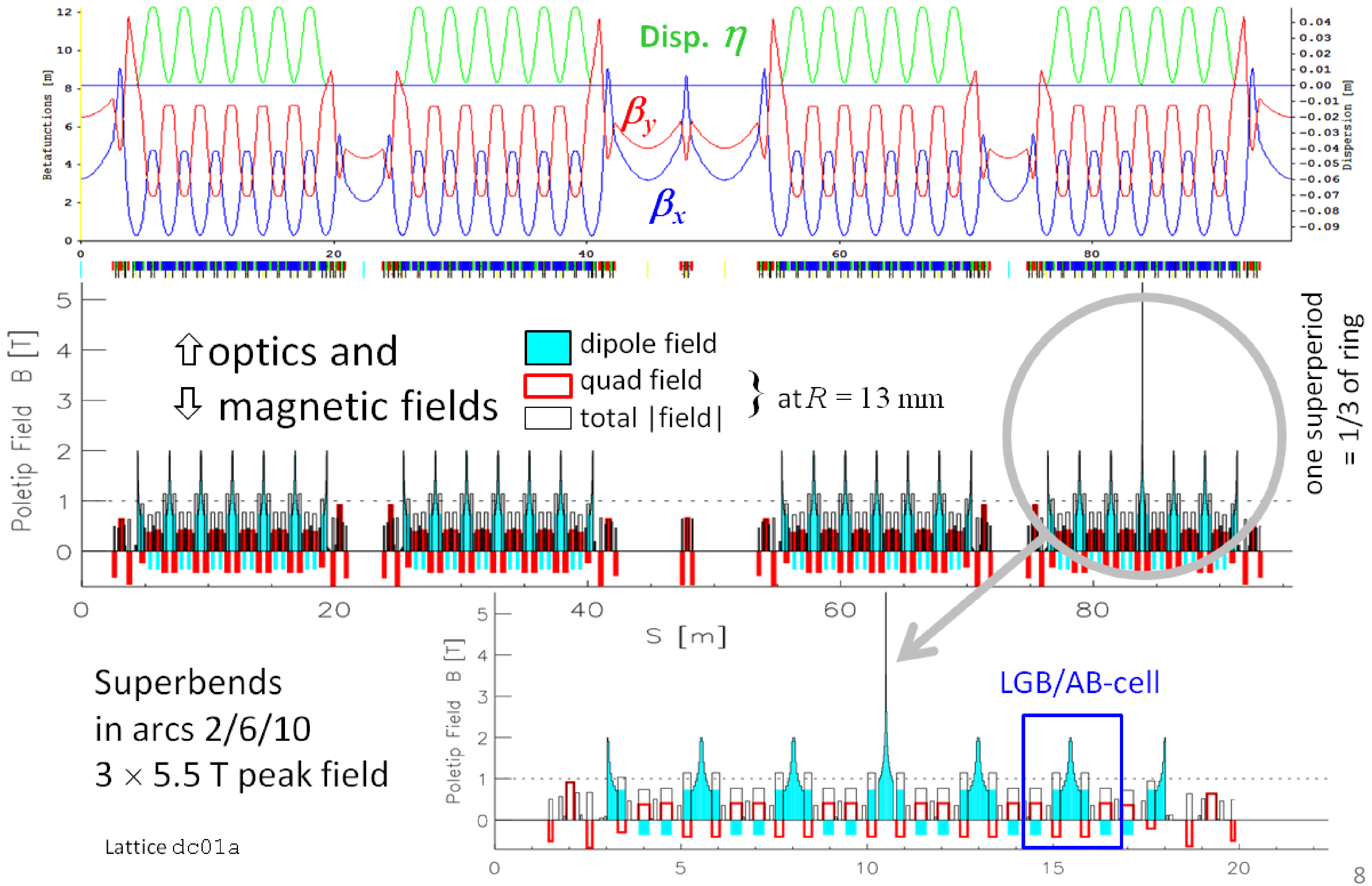
Lattice parameters (1)

Name	SLS*)	dc01a	fa01f
status	*operating*	*baseline*	*fallback*
Emittance at 2.4 GeV [pm]	5022	137 → 150♦)	262
Lattice type	TBA	7BA	5BA
Total absolute bending angle	360°	585°	488°
Working point $Q_{x/y}$	20.42 / 8.74	37.38 / 10.28	28.29 / 10.17
Natural chromaticities $C_{x/y}$	–67.0 / –19.8	–64.9 / –34.5	–64.1 / –39.9
Optics strain[1)]	7.9	5.8	8.9
Momentum compaction factor [10^{-4}]	6.56	–1.41	–1.86
Radiated Power [kW] [2)]	205	232	271
rms energy spread [10^{-3}]	0.86	1.03 → 1.08♦)	1.15
rms bunch length [mm]	3.73	2.72 → 8.59♦)	3.15
damping times x/y/E [ms]	9.0 / 9.0 / 4.5	4.5 / 7.9 / 6.4	5.0 / 6.8 / 4.1

1) product of horiz. and vert. normalized chromaticities C/Q
2) assuming 400 mA stored current, bare lattice without IDs
*) SLS lattice `d2r55`, before FEMTO installation (<2005)

♦) including intra-beam scattering for 1 mA bunch current (400 mA in 400 of 479 buckets; 500 MHz), 10 pm vertical emittance, 3rd harmonic cavity for 3× bunch length.

Lattice parameters (2)



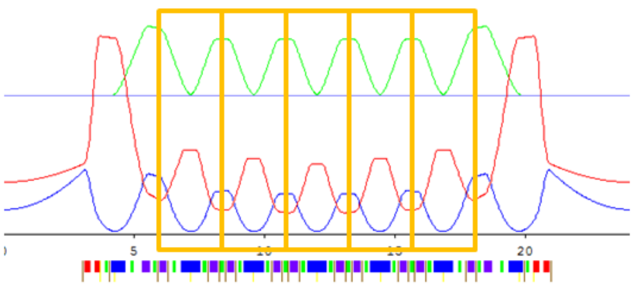
Superbends
in arcs 2/6/10
3 × 5.5 T peak field

Lattice dc01a

Nonlinear optimization (1)

- Cancellation by cell tune

N full cells: $(N+2)$ bend achromat



Sextupole and octupole Hamiltonian modes

SLS-2

$$\sum_{\text{modes}} \left| \sum_{n=0}^{N\text{-}1} e^{in\left((j-k)Q_x+(l-m)Q_y\right)} \right|$$

```
j = 2,3,1,1,1,2,0, 4,2,2,3,0
k = 1,0,0,0,0,0,0, 0,0,0,1,0
l = 0,0,1,0,2,0,2, 0,2,0,0,3
m = 0,0,1,2,0,0,0, 0,0,2,0,1
```

Light source cell
Q_x high (≈ 0.4)
Q_y low (≈ 0.1)

$N = 5,\ Q_x = 2/5 = 0.40,\ Q_y = 1/10 = 0.10$
$N = 7,\ Q_x = 3/7 = 0.43,\ Q_y = 1/7 = 0.14$
$N = 8,\ Q_x = 3/8 = 0.38,\ Q_y = 1/16 = 0.06$
$N = 9,\ Q_x = 4/9 = 0.44,\ Q_y = 1/9 = 0.11$

- Harmonic sextupoles situated outside achromat arc to suppress driving terms as much as possible

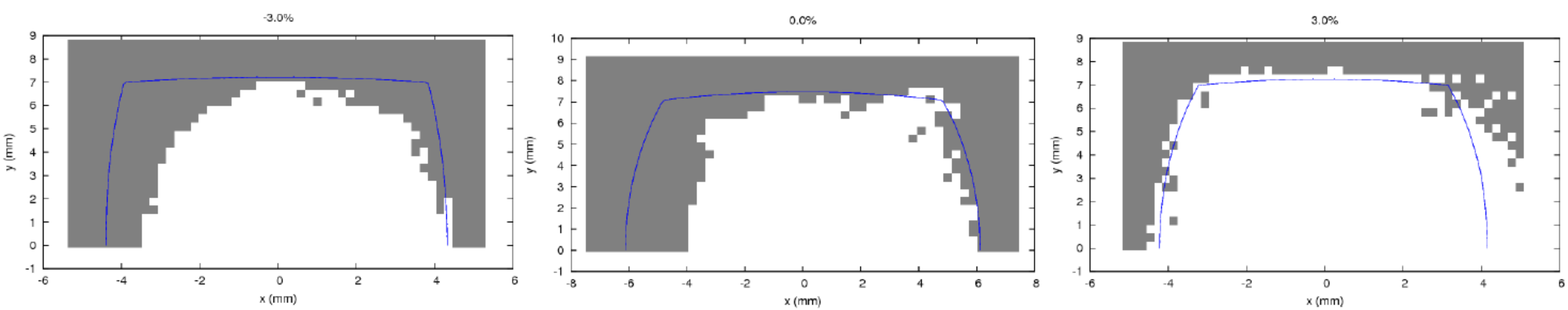
Nonlinear optimization (2)

- MOGA optimization
  - Baseline lattice has almost enough aperture at least with zero chromaticity

Variables for optimization
- 4 chromatic sextupole families
- 9 harmonic sextupole families
- 10 octupole families
- constraint on chromaticity: -2 variables

→21 variables

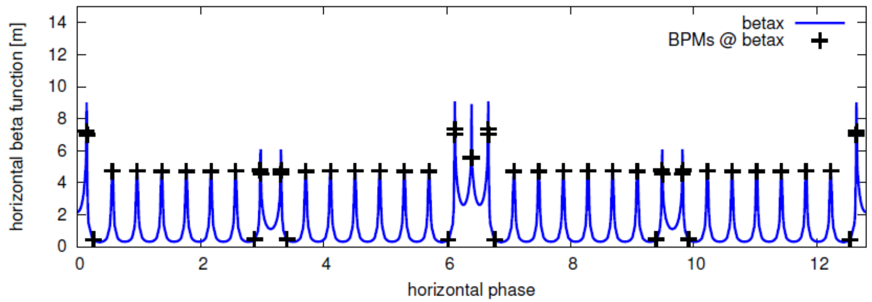
Baseline at chrom (0,0)

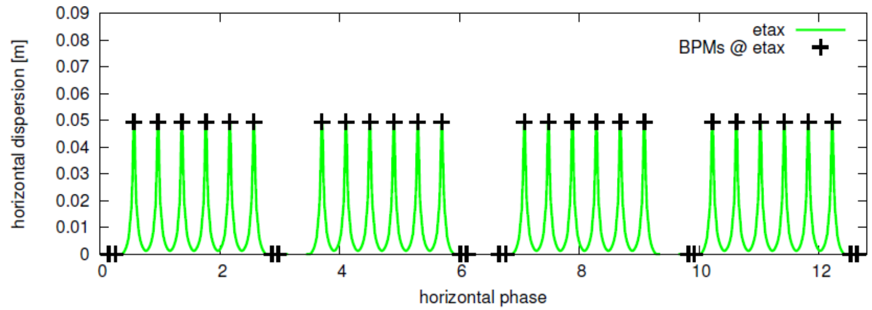


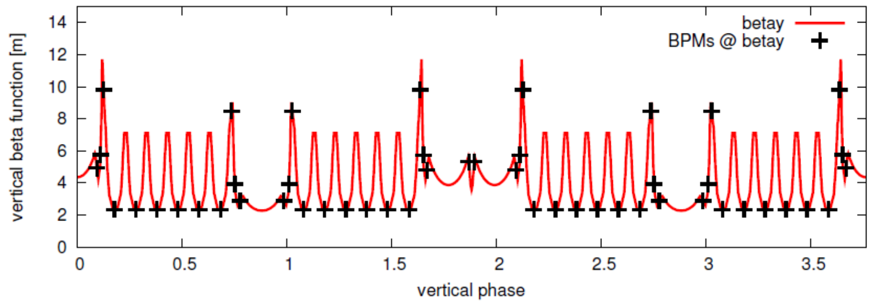
Higher superperiodicity, i.e. 12, is considered
→Talk by Michael Ehrlichman this afternoon

BPM layout

- BPM layout is determined taking into account:
  - Available space
  - Proper optics sampling
  - Pairing with correctors to lower required corrector kick

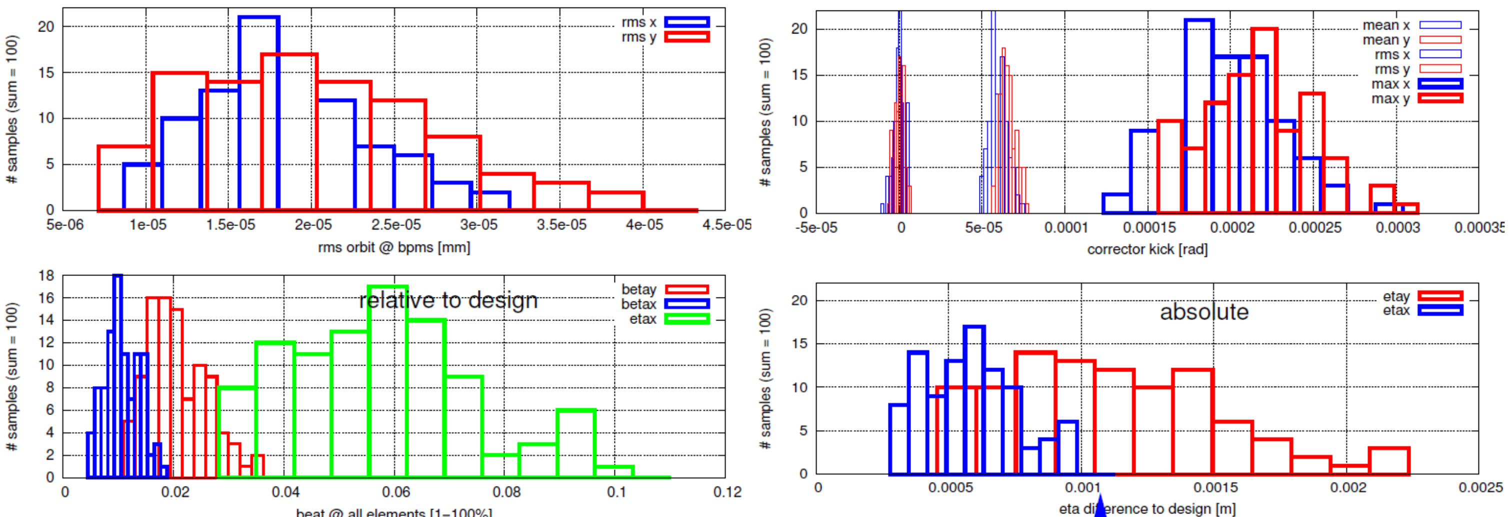






Imperfection study (1)

- Misalignment → BBA

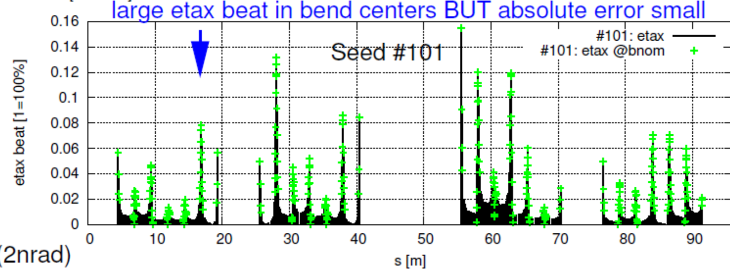


large etax beat in bend centers BUT absolute error small

histograms for 100 seeds

alignment errors: 50.20.20.0
20 um element–to–element
20 um girder joints
50 um girder absolute
Gaussian (2 sigma cut)

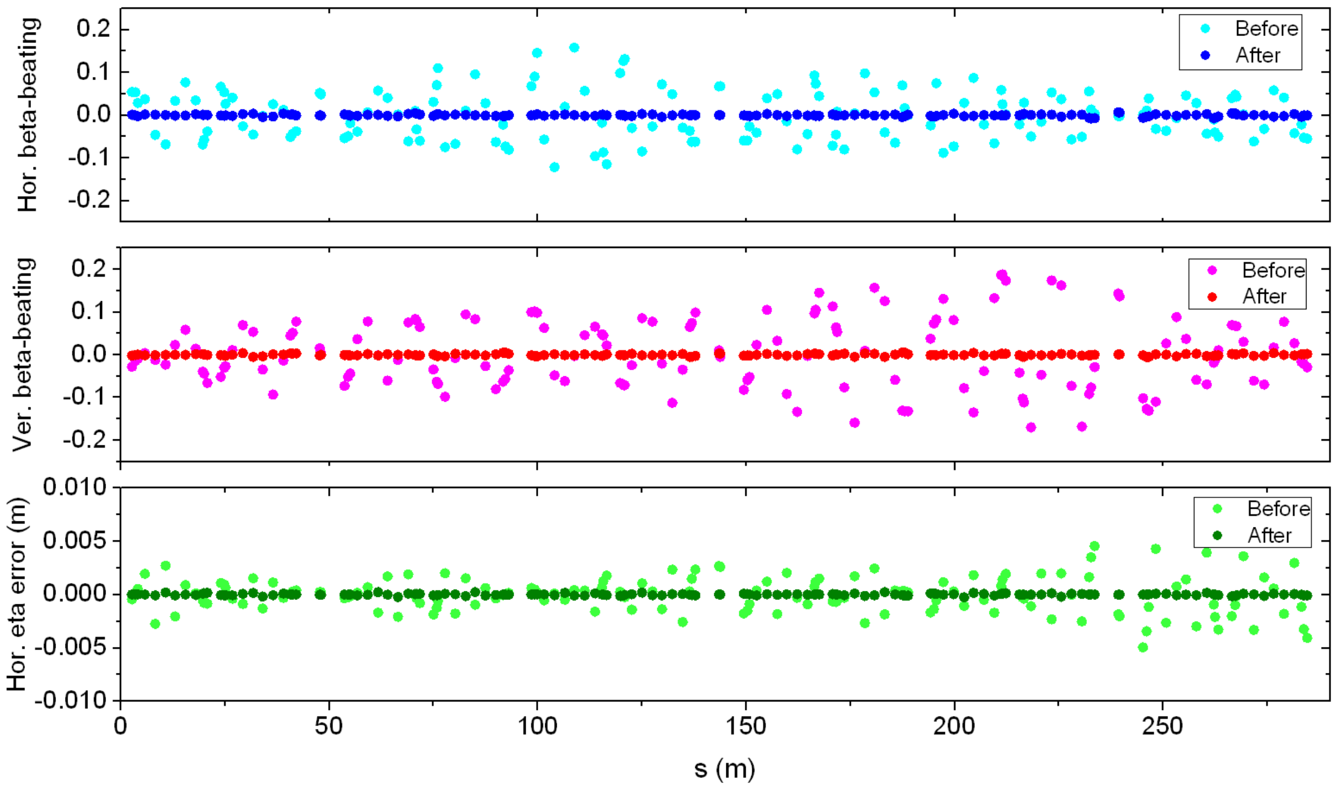
BBA resolution 10 um
Corrector resolution 20bit/2mrad (2nrad)



Optics distortion due to misalignments is tolerable after beam-based alignment

Imperfection study (2)

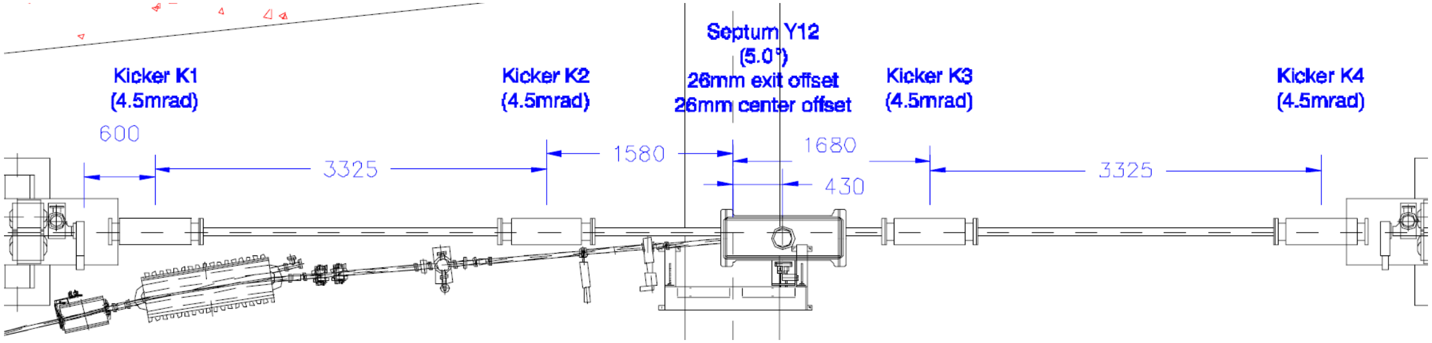
- K1 errors → Optics correction



Optics distortion can be suppressed through LOCO style optics correction

Injection (1)

- Injection - Present SLS



  – Booster beam emittance <10 nm ☺

- Challenge

	SLS	SLS-2
Straight section	~10 m	~5 m (Period 12)
Dynamic aperture	~10 mm	~5 mm
Septum thickness	3 mm	1.5 mm?

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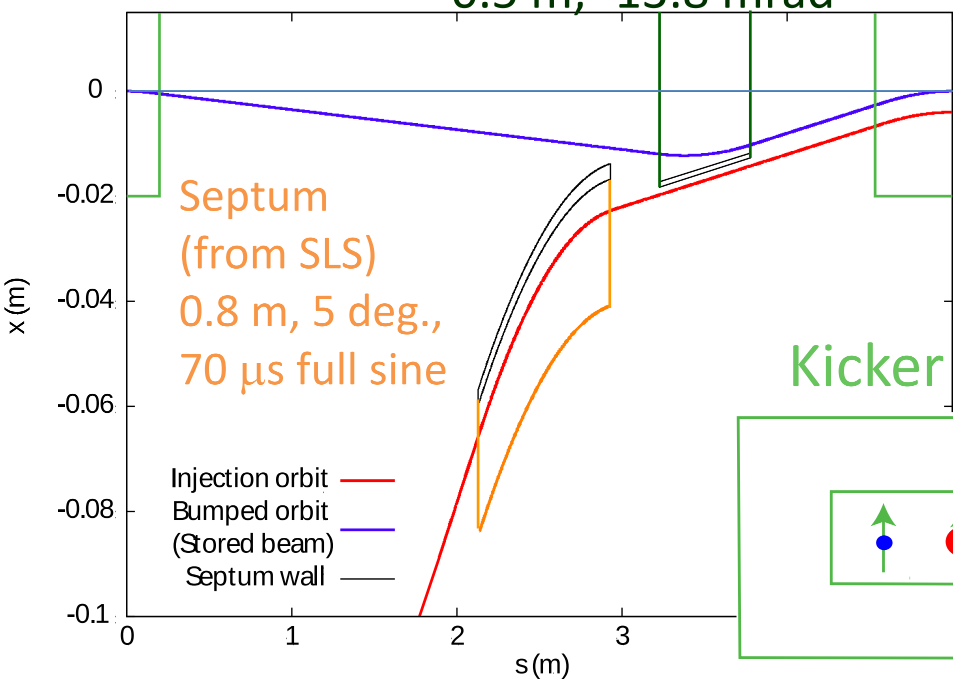
Injection (2)

- Compact injection straight with “anti-septum”

Kicker-1
0.15 m, 3.8 mrad

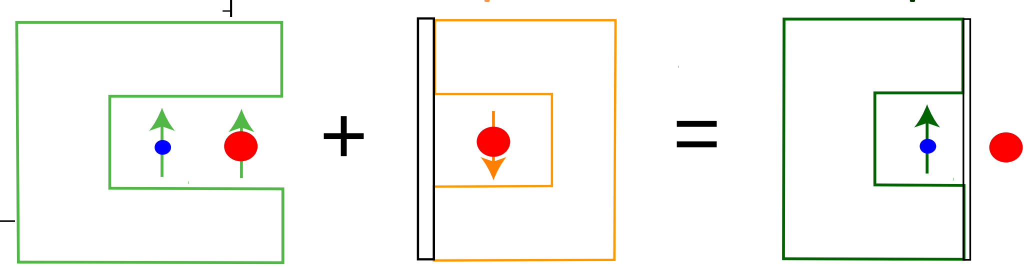
Kicker-2
(Anti-septum)
0.5 m, -13.8 mrad

Kicker-3
0.4m, 10 mrad



Bump height = -12 mm
Anti-septum wall = 1 mm
Injection point -15~-16mm
(separation = 3~4 mm)
Dynamic aperture ~ 5 mm

Kicker + Septum = Anti-septum

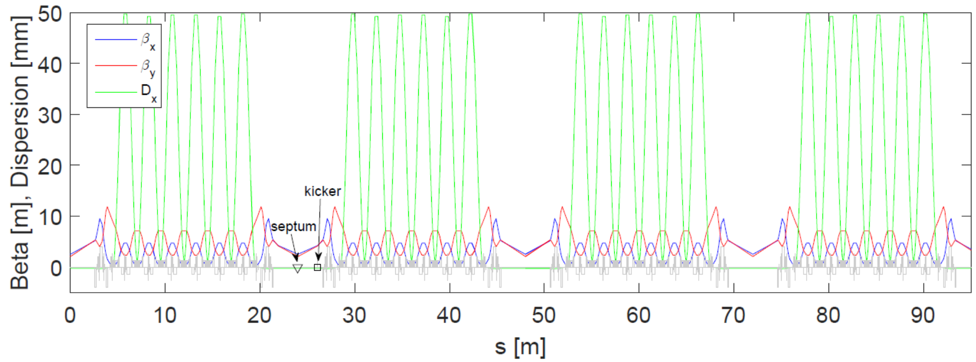


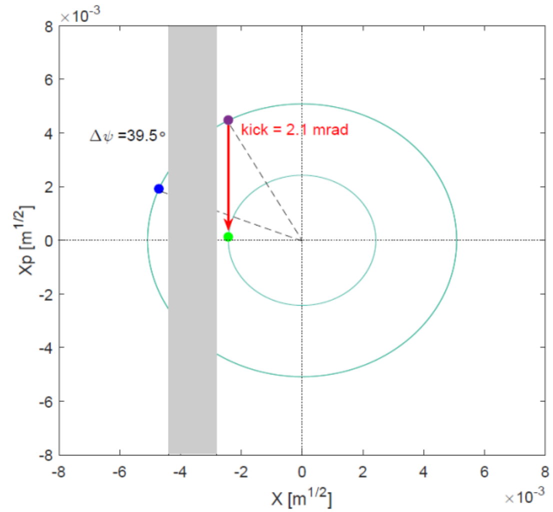
Preliminary design found in backup slide

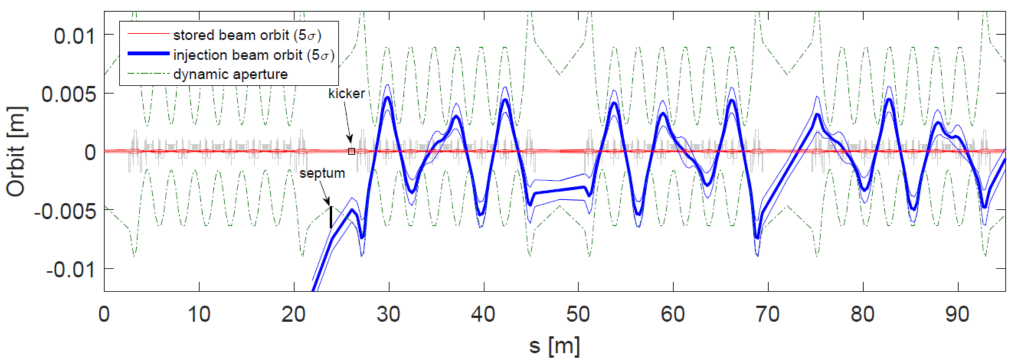
Anti-septum wall thickness can be 1 mm:
- Short pulse (6 μs, half sine)
- Stray field comes after the injection bunch passes!

Injection (3)

- Multipole-kicker injection





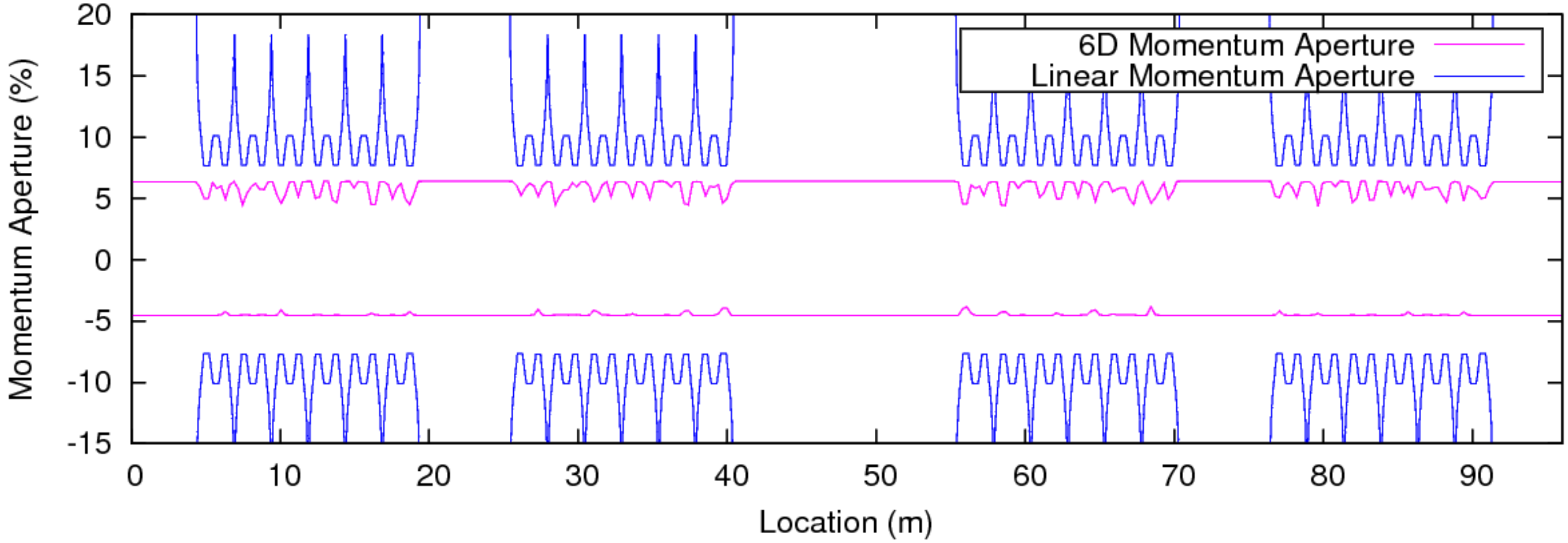


Parameters assumed

- Septum thickness = 2.5 mm
- Kicker kick angle = 2.1 mrad
  → 0.5m, 35 mT @ x ~ -5 mm
- Injection beam emitt. = 8 nm

Multipole/Nonlinear-kicker injection is also considered

Touschek lifetime



- Lifetime ~4.6 hours
  - Estimated from momentum aperture(6D track)
  - With 5% bucket
  - Without third harmonic cavity

Intra Beam Scattering – update (1)

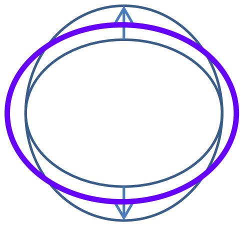
- “Standard” simulation procedure
  - Compute IBS growth rate for one turn
    - IBS (diffusion) increases **the momentum spread ($\langle px^2 \rangle$, $\langle py^2 \rangle$, $\langle \delta^2 \rangle$)**
  - Add synchrotron radiation damping at the end of turn
    - For the transverse planes:

      $$\varepsilon=\varepsilon_0+d\varepsilon_{IBS}+d\varepsilon_{SR}$$

      $d\varepsilon_{SR}$ is computed for “given” equilibrium emittance and damping time
    - For the longitudinal plane:

      $$\delta=\delta_0+d\delta_{IBS}+d\delta_{SR}$$

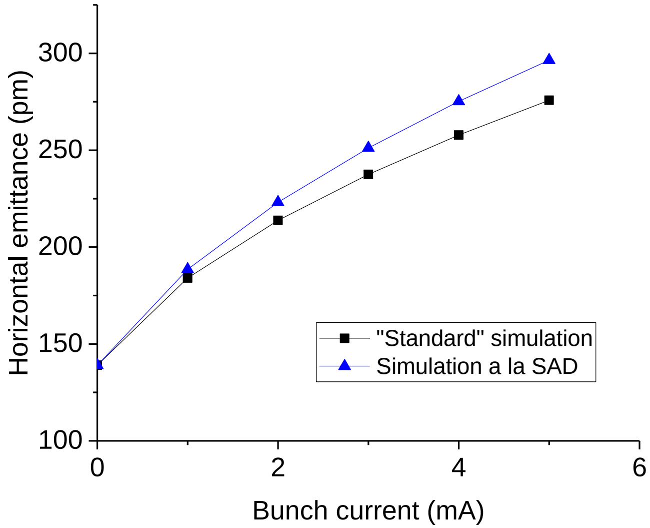
      and **the bunch is “forcibly” fit to the RF bucket**



  - Continue the tracking until $d\varepsilon_{IBS}+d\varepsilon_{SR}\sim 0$ and $d\delta_{IBS}+d\delta_{SR}\sim 0$
  - Faster simulation: $\varepsilon=\varepsilon_0+N(d\varepsilon_{IBS}+d\varepsilon_{SR})$ (N~10-1000)

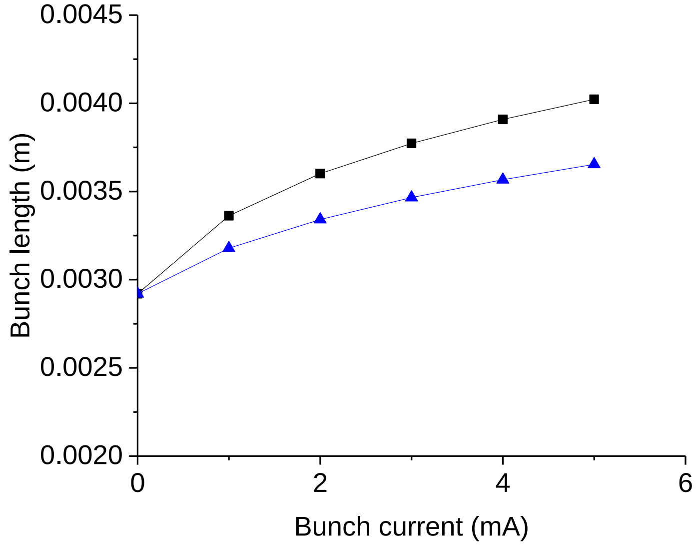
→Turn-by-turn envelope tracking with SR damping and IBS (a la SAD code)

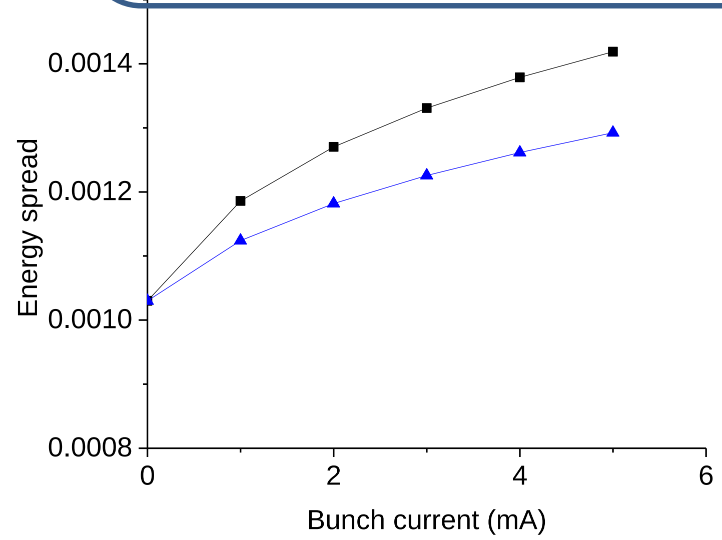
Intra Beam Scattering – update (2)



- Result for:
  - Zero current bunch length ~ 3mm
  - Zero current vertical emittance = 5 pm
  - Operation bunch current ~ 1 mA

Standard →Simulation a la SAD:
Horizontal emittance ↑
Vertical emittance →
Longitudinal emittance ↓



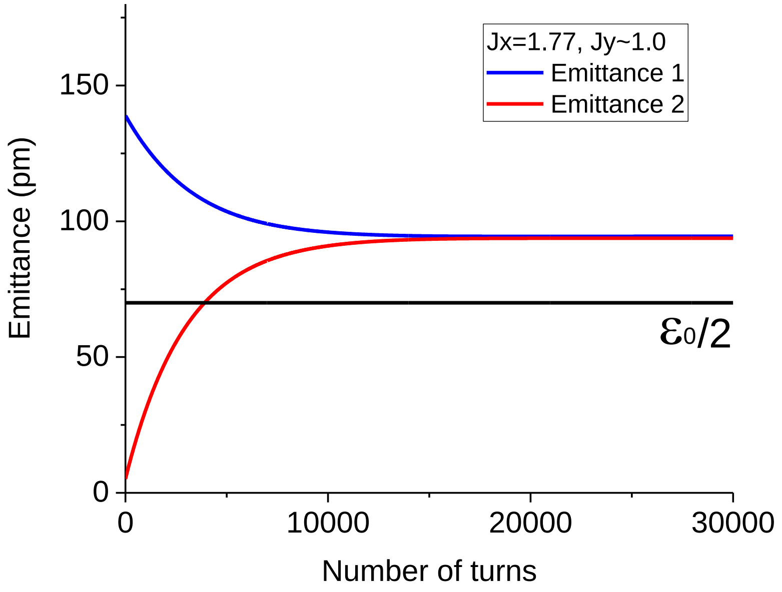


Instability study

→Talk by Haisheng Xu tomorrow

Round beam operation

- A few beamlines are interested in Round beam
- Emittances in Mobius ring computed with envelope tracking (a la SAD):



Round beam operation is not so attractive for "high Jx" ☹

References

- LGB: A. Streun and A. Wrulich, “Compact Low Emittance Light Sources Based on Longitudinal Gradient Bending Magnets”, NIM-A, 770 98-112 (2015)
- Anti-bend: J. P. Delahaye and J. P. Potier, “Reverse Bending Magnets in a Combined-function Lattice for the CLIC Damping Ring”, PAC’89 / A. Streun, “The Anti-bend Cell for Ultralow Emittance Storage Ring”, NIM-A, 737 148-154 (2014)
- MOGA for SLS-2: M. Ehrlichman, “Genetic Algorithm for Chromaticity Correction in Diffraction Limited Storage Rings”, PRAB, 19 044001 (2016)
- Multipole kicker injection / Nonlinear kicker: H. Takaki et al., “Beam Injection with a Pulsed Sextupole Magnet in an Electron Storage Ring”,PR-STAB, 13, 020705 (2010) / T. Atkinson et al., “Development of a Non-linear Kicker System to Facilitate a New Injection Scheme for the BESSY II Storage Ring”, IPAC’11
- Envelope tracking: K. Ohmi, K. Hirata and K. Oide, “From the Beam-Envelope to Synchrotron-Radiation Integrals”, Phys. Rev. E, 49 1 (1994)
- IBS: J.D. Bjorken, S.K. Mtingwa, “Intrabeam Scattering”, Part. Acc. Vol. 13, pp. 115-143 (1983) / K. Kubo, K. Oide, “Intrabeam Scattering in Electron Storage Rings”, PRST-AB 4, 124401 (2001)
- Mobius ring: R. Talman, “A Proposed Möbius Accelerator”, PRL, 74 1590 (1995)

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Summary

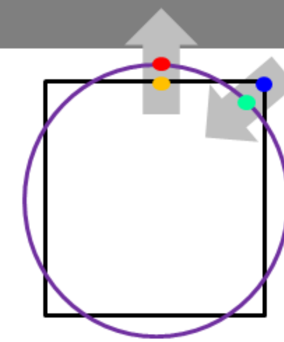
- SLS-2 design study is on a good track:
  - Target emittance is achievable with the given circumference
  - Baseline lattice is evaluated from the viewpoints of
    - Nonlinear optics
    - Top-up injection
    - Imperfections
    - Collective effects
  - Increasing (or restoring) superperiod to 12 is considered

Back up slides

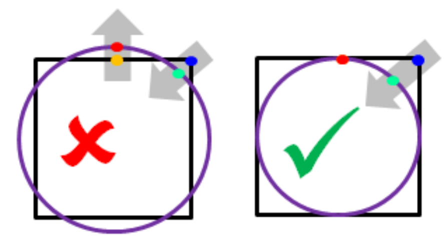
Beam line source points

- Lateral shift of source points (when keeping circumference)
  - undulators ≈ 120 mm out
  - bends ≈ 100 mm in

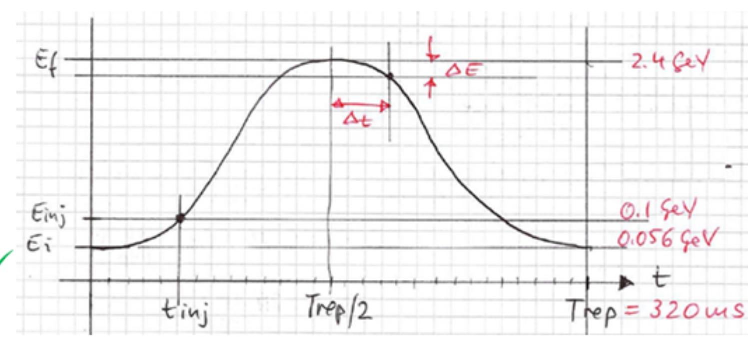
SLS undu. bend
SLS-2 undu. bend



- Maintain at least undulator positions
  - circumference 288.00 → 287.25 m
  - undulator source point shifts < 1 mm
  - Harmonic number (500 MHz): 480 → 478¾ → 479
  - Frequency shift -261 kHz → inelastic cavity deformation ✓



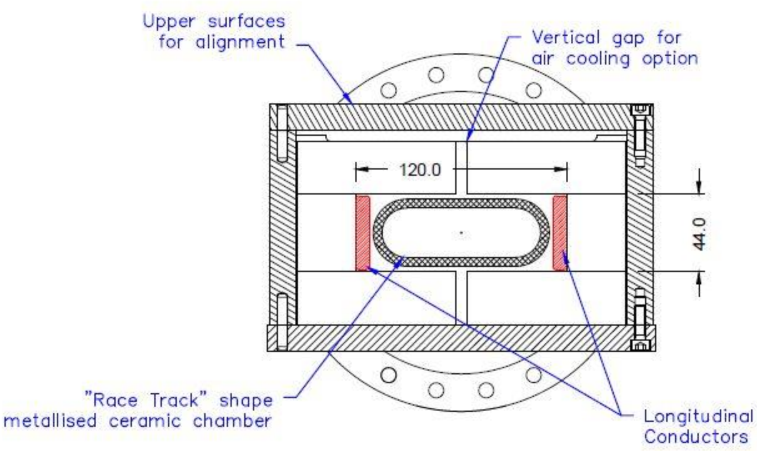
- Injection timing
  - booster: no frequency shift
  - wait for correct bucket *and* phase
  - delay max. ±1 ms ⇨ $\Delta p/p < 10^{-4}$ ✓



Anti-septum

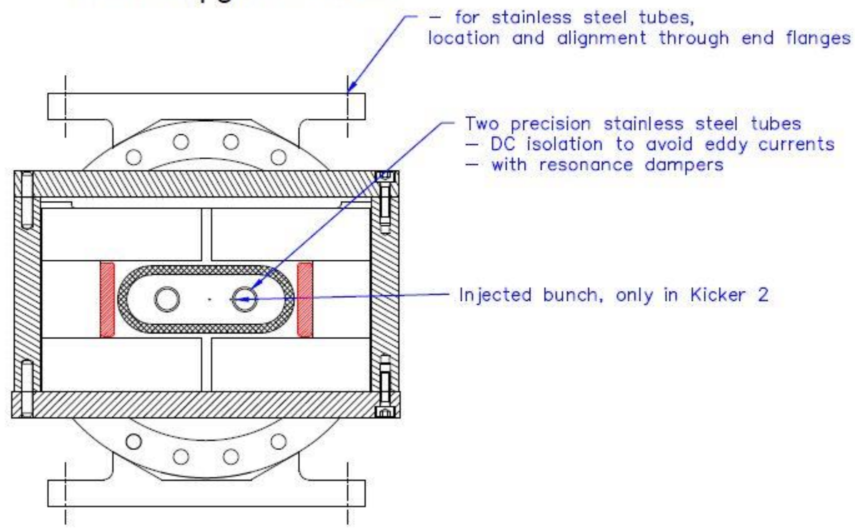
- Preliminary design

Existing Kicker



- locating pins for precise re-assembly
- all kickers with time waveforms matched to <1ppt at all times

Idea for upgraded kicker



- kickers 1-3 all fitted with stainless steel tubes so time waveform in remains matched
- only kicker 2 has injected bunch passing through shielded region in tube
- injected bunch-to-stored bunch separation 3-4mm

SR and IBS a la SAD

- SR and IBS effects are computed at each element

1) At all elements

IBS: $\sigma_{beam} \rightarrow \sigma_{beam} + \Delta_{IBS}$

$$\Delta_{IBS} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta_{x'} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta_{y'} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta_{\delta} \end{bmatrix}$$

$\Delta_{x'}, \Delta_{y'}, \Delta_{\delta}$ are computed with IBS theory for given sigma matrix elements

2-a) If the element is dipoles

Damping: $\sigma_{beam} \rightarrow (I - lD)\sigma_{beam}(I - lD)^T$

Transport & Diffusion:

$$\sigma_{beam} \rightarrow M\sigma_{beam}M^T + \int MBM^T ds$$

Damping matrix (on-energy beam)

$$D = \frac{P}{E_0}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ G_x & 0 & G_y & 0 & 0 & 2 \end{bmatrix}$$

$G_{x,y}$ include gradient and edge of bending

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & B_{66} \end{bmatrix}$$

$$B_{66} = \frac{55}{24\sqrt{3}} \frac{r_e \hbar}{mc} \frac{\gamma^5}{|\rho|^3}$$

2-b) If the element is not dipoles

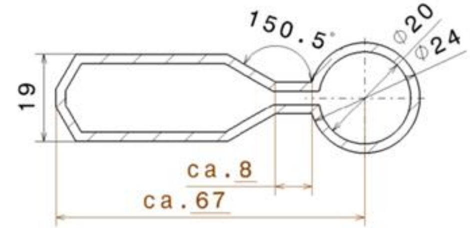
Transport: $\sigma_{beam} \rightarrow M\sigma_{beam}M^T$

3) Continue tracking until an equilibrium is reached

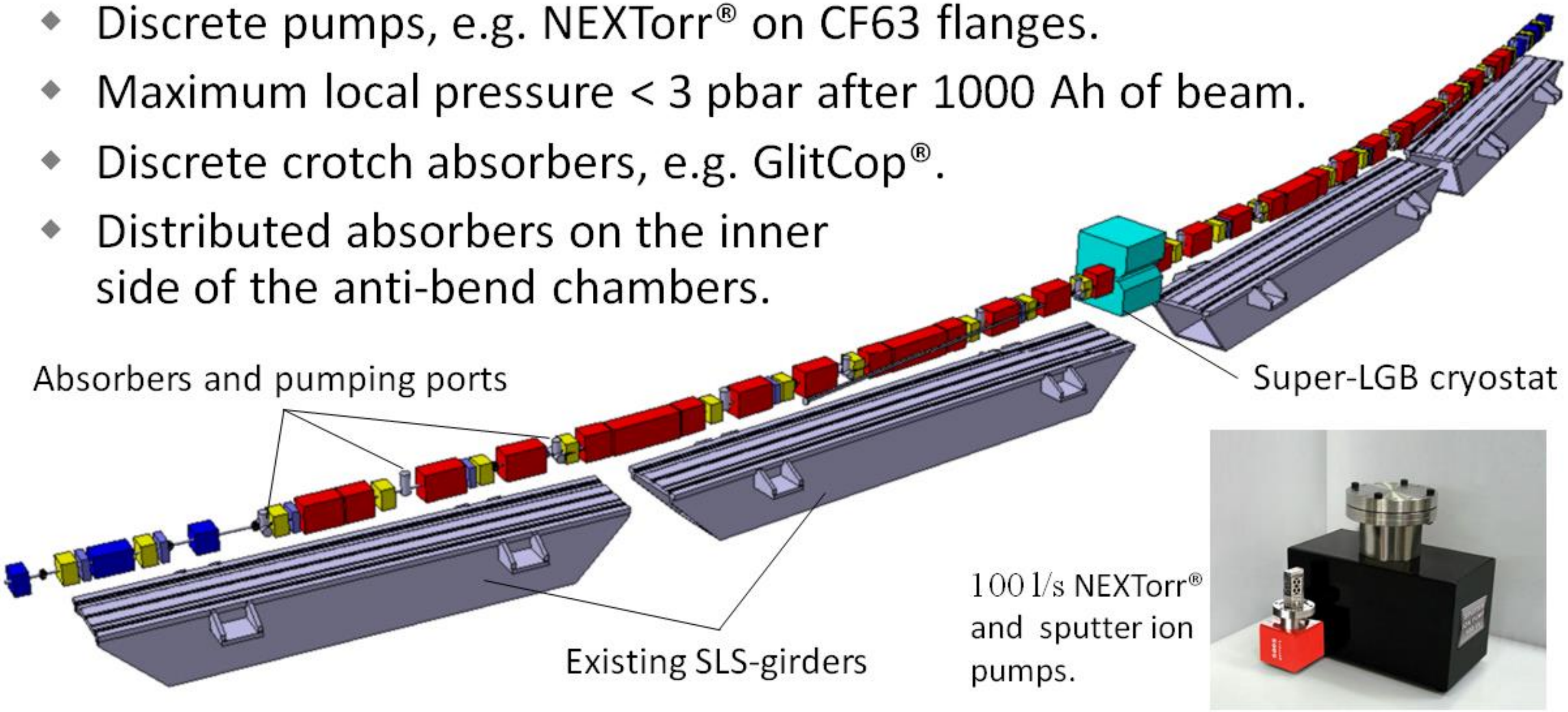
Vacuum system

PSI Vacuum group

- High field bends (2 T n.c., 5.5 T s.c.) ⇨ antechambers.
- No NEG coating.



- Full copper or copper-coated stainless steel (at correctors).
- Discrete pumps, e.g. NEXTorr® on CF63 flanges.
- Maximum local pressure < 3 pbar after 1000 Ah of beam.
- Discrete crotch absorbers, e.g. GlitCop®.
- Distributed absorbers on the inner side of the anti-bend chambers.

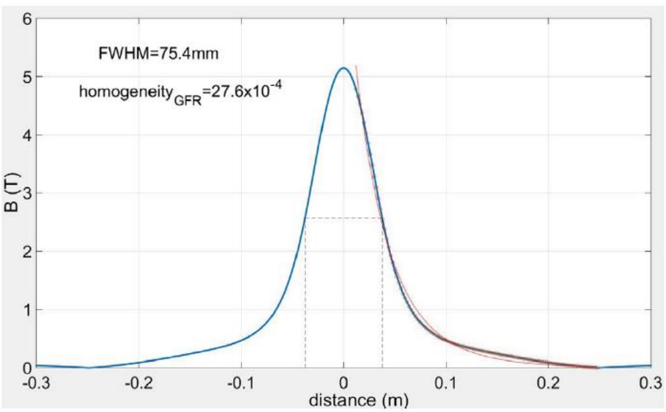


100 l/s NEXTorr® and sputter ion pumps.

LGB design study

PSI magnet group

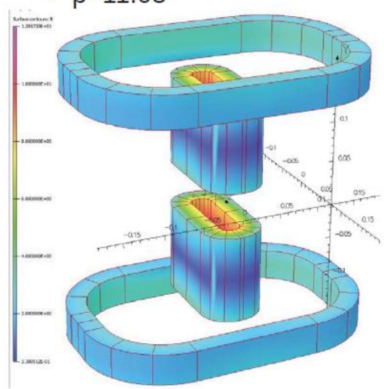
B-field profile



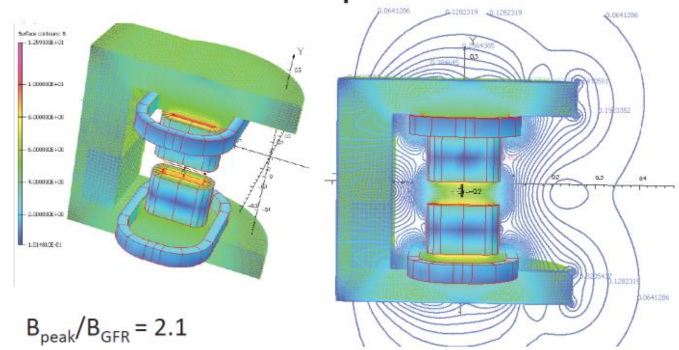
$B_{peak}/B_{GFR} = 2.3$
(vertical aperture:57 mm)

$$\frac{b_0}{(1+h(s/L))^p}$$

Fitting parameters:
- b0: 7.49
- h: 0.22
- p=11.08



B-field profile



$B_{peak}/B_{GFR} = 2.1$
(vertical aperture:57 mm)

Overall structure