SLS-2

1. Concept for a compact low emittance cell
2. Plans for an upgrade of the Swiss Light Source

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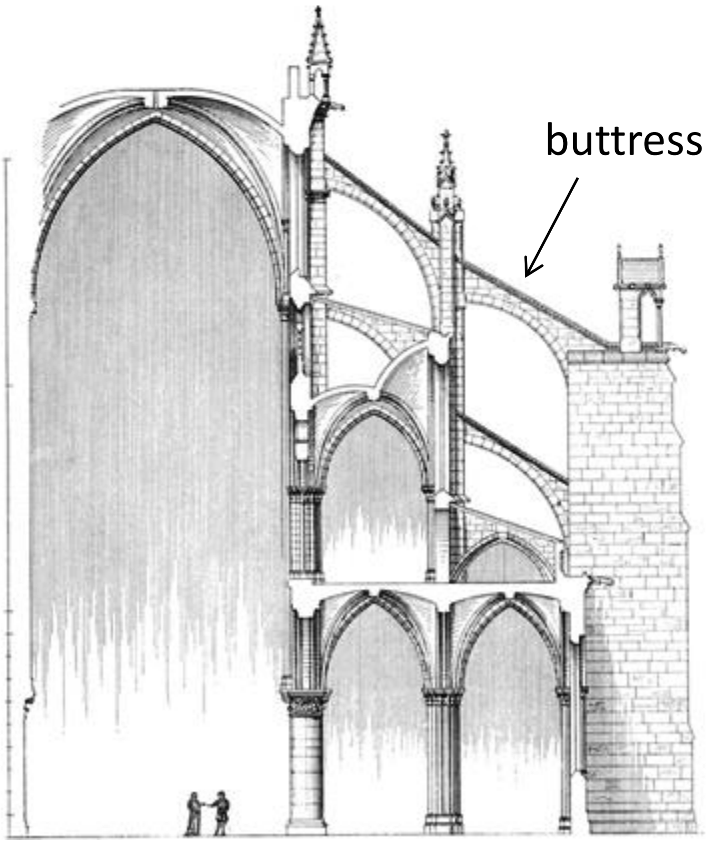
1st Workshop on Low Emittance Lattice Design
Barcelona, April 23-24, 2015

Antoni Gaudí (1852-1926):

“buttresses are the crutches of the Gothic”

⇨ follow nature (i.e. the directions of force):

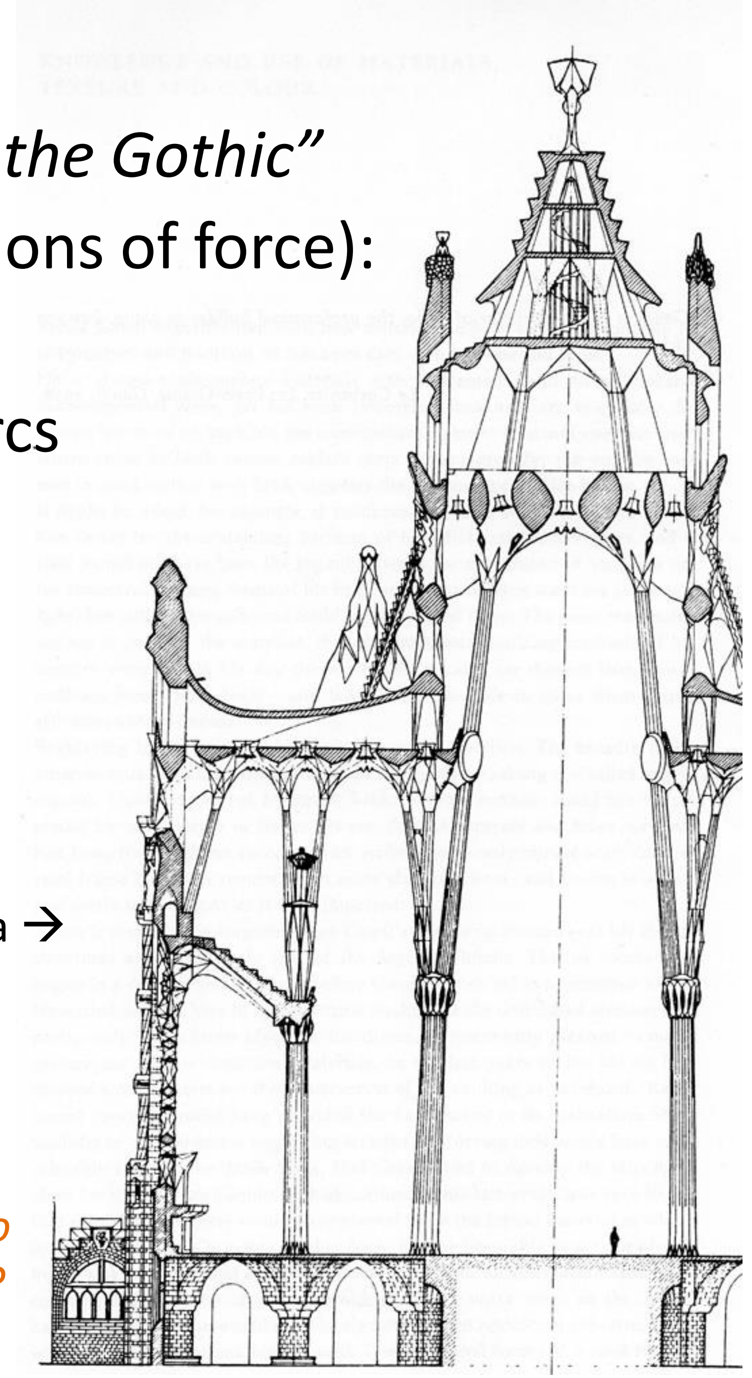
- inclined columns and walls
- cosh-shaped (“parabolic”) arcs



buttress

← Notre Dame Paris

Sagrada Familia → Barcelona



which constraints may be released to get new solutions?

The theoretical minium emittance (TME) cell

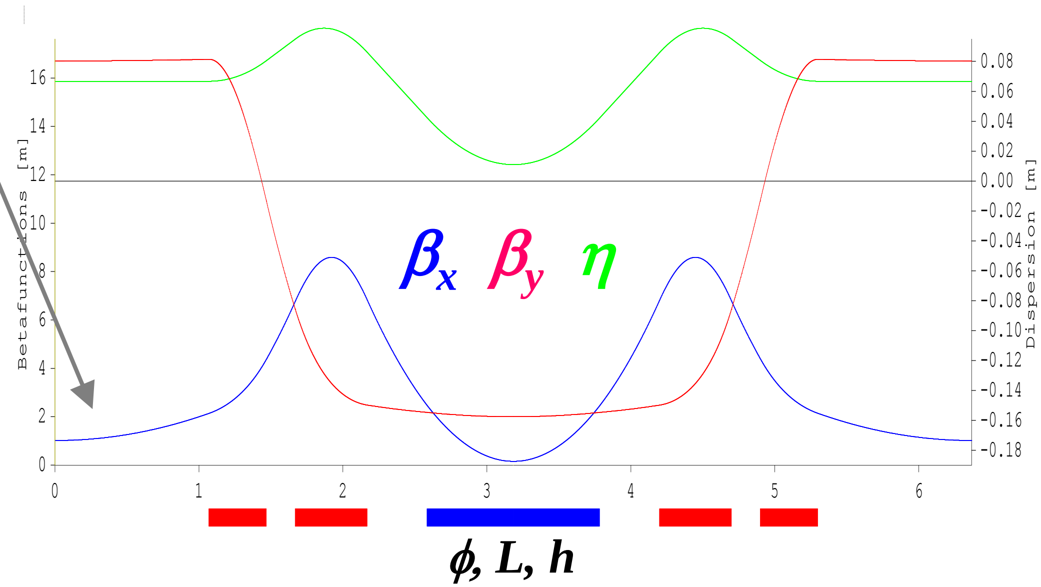
- Conditions for minimum emittance

$$\beta_o^{\min} = \frac{L}{2\sqrt{15}} \qquad \eta_o^{\min} = \frac{hL^2}{24} \quad \Rightarrow \quad \varepsilon_{xo}^{\min}[\mathrm{pm\cdot rad}] = \frac{7.8}{12\sqrt{15}} (E[\mathrm{GeV}])^2 \frac{(\phi[^\circ])^3}{J_x}$$

- periodic/symmetric cell: $\alpha = \eta' = 0$ at ends

⇨ over-focusing of β_x ⇨ phase advance $\mu^{\min} = 284.5^\circ$

- ✘ 2nd focus, useless
- ✘ overstrained optics, huge chromaticity...
- ✘ long cell
- ⇨ better have two relaxed cells of $\phi/2$
- ⇨ MBA concept...



Relaxed TME cells

- Deviations from TME conditions

$$F = \frac{\varepsilon_{xo}}{\varepsilon_{xo}^{\min}} \quad b = \frac{\beta_o}{\beta_o^{\min}} \quad d = \frac{\eta_o}{\eta_o^{\min}}$$

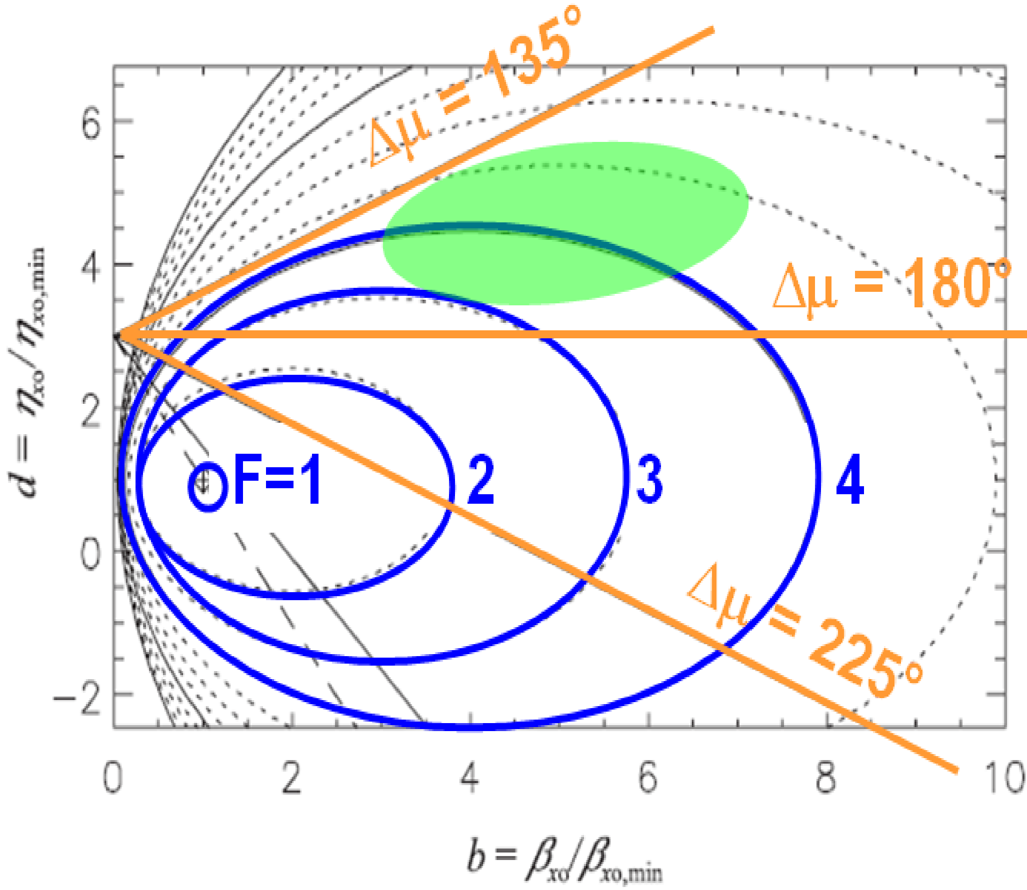
- Ellipse equations for emittance

$$\tfrac{5}{4}(d-1)^2 + (b-F)^2 = F^2 - 1$$

- Cell phase advance

$$\tan\frac{\mu}{2} = \frac{6}{\sqrt{15}}\frac{b}{(d-3)}$$

⇨ Real cells: $\mu < 180°$ ⇨ $F \sim 3...6$



is this what we really wanted ?

what would Gaudí do ?

1. disentangle dispersion η and beta function β_x
   - ⇨ *release constraint: focusing is done with quads.*
   - ⇨ use "anti-bend" (AB) out of phase with main bend
   - ▪ suppress dispersion ($\eta_o \approx 0$) in main bend center.
   - ▪ allow modest β_{xo} for low cell phase advance.
2. optimize bending field for minimum emittance
   - ⇨ *release constraint: bend field is homogeneous.*
   - ⇨ use "longitudinal gradient bend" (LGB)
   - ▪ highest field at bend center ($h_o = (e/p)\, B_o$)
   - ▪ reduce field $h(s)$ as dispersion $\eta(s)$ grows

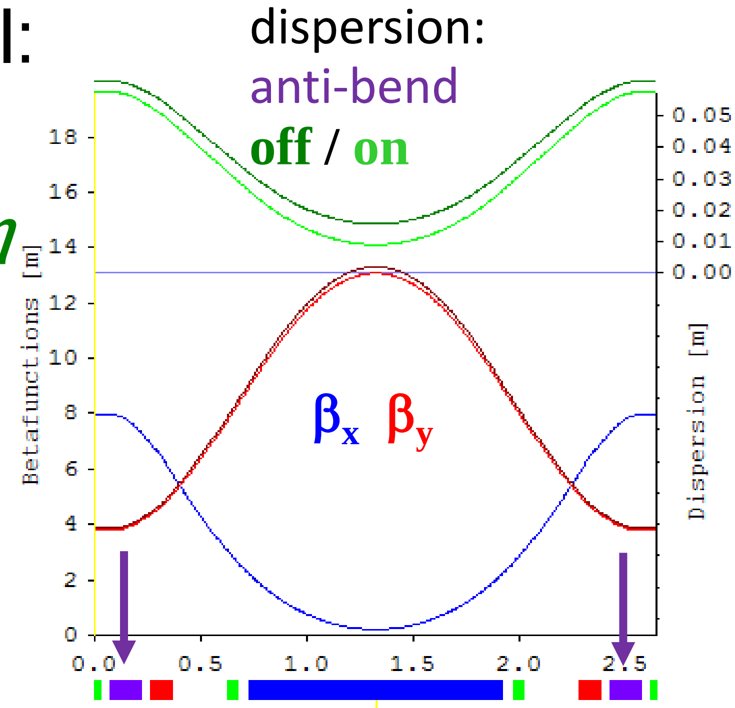
⇨ sub-TME cell ($F < 1$) at moderate phase advance

step 1: the anti-bend (AB)

- General problem of dispersion matching:
  - dispersion is a horizontal trajectory
  - dispersion production in dipoles → "defocusing": $\eta'' > 0$
- Quadrupoles in conventional cell:
  - over-focusing of 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

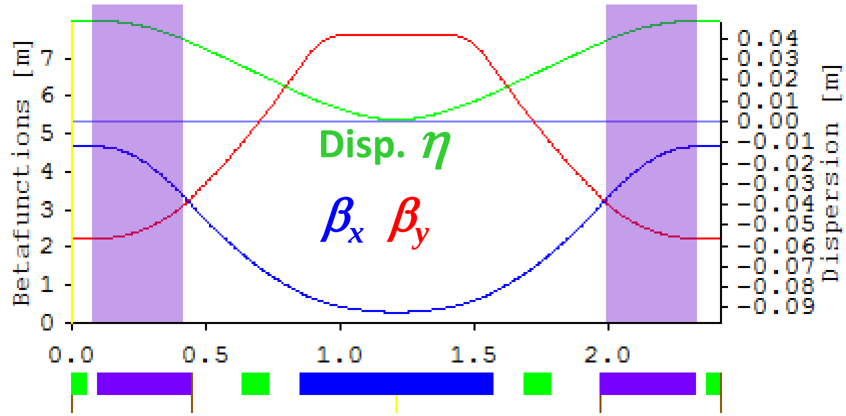


relaxed TME cell, 5°, 2.4 GeV, $J_x \approx 2$
Emittance: **500 pm** / **200 pm**

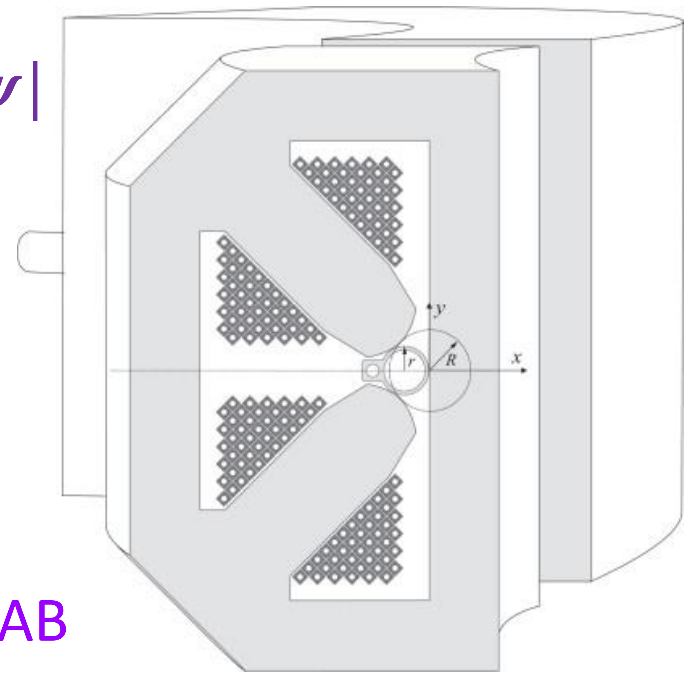
AB emittance effects

- AB emittance contribution

$$\varepsilon \propto I_5 = \int_L |h|^3 \mathcal{H}\, ds \xrightarrow{AB} \approx |h|^3 \frac{\eta^2}{\beta} L$$



  - η is large and ≈constant at AB
  - ⇨ low field, long magnet
- Cell emittance (2×AB +main bend)
  - main bend angle to be increased by $2|\psi|$
  - ⇨ in total, still lower emittance
- AB as combined function magnet
  - Increase of damping partition J_x
    - vertical focusing in normal bend
    - horizontal focusing in anti-bend.
  - horizontal focusing required anyway at AB
  - ⇨ AB = off-centered quadrupole ⇨ half quadrupole ⬀



AB impact on chromaticity

- Anti-bend ⇨ negative momentum compaction α

$$\alpha = \frac{1}{C}\left(\int_{\mathrm{LGB}} \underbrace{\eta}_{\text{small}} h\, ds + \int_{\mathrm{AB}} \underbrace{\eta}_{\text{large}} \underbrace{h}_{\text{negative}}\, ds \right) < 0$$

⇨ Head-tail stability for negative chromaticity!

- First simulations on transverse instabilities (Eirini Koukovini-Platia @CERN)
  - SLS candidate lattice : $\alpha = -10^{-4}$; 100 MHz, 5 mA/bunch
  - resistive wall: 10 mm radius Cu-pipe, 1 μm NEG
  - broad band resonanter: 8 GHz, $Q = 1$, $R = 500$ kΩ/m
  - transverse instability from HEADTAIL code

  ⇨ unstable for $\xi = 0$, stability for $\xi < -4$

step 2: the longitudinal gradient bend (LGB)

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

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

- Longitudinal field variation $h(s)$ to compensate $\mathcal{H}(s)$ variation
- Beam dynamics in bending magnet
  - Curvature is source of dispersion: $\eta''(s) = h(s) \rightarrow \eta'(s) \rightarrow \eta(s)$
  - 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 $h(s)$, simple (few parameters):
variational problem → minimization problem

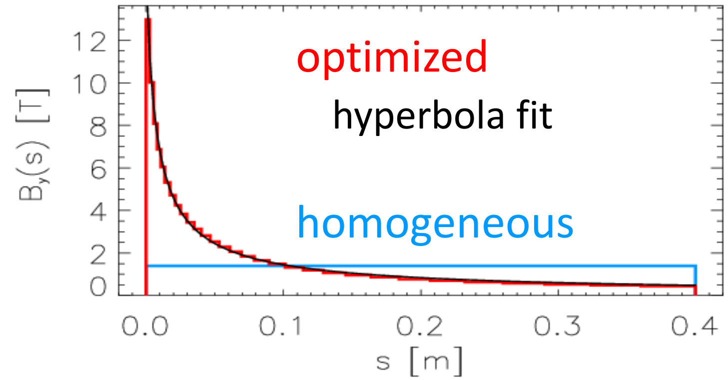
→ numerical optimization

LGB numerical optimization

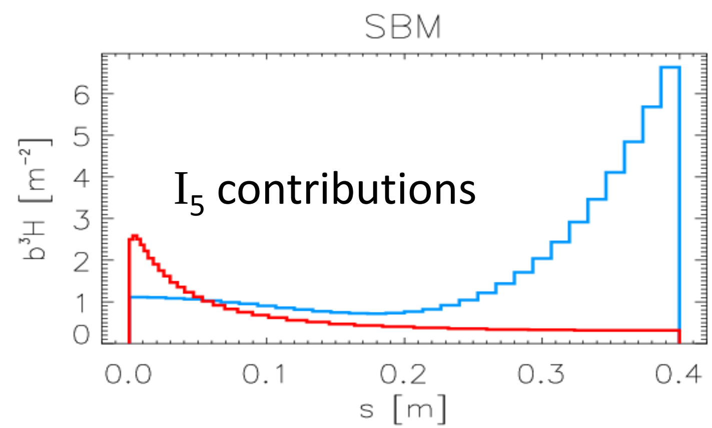
- Half bend in N slices: curvature h_i , length Δs_i
- Knobs for minimizer: $\{h_i\}$, β_0, η_0
- Objective: I_5
- Constraints:
  - length: $\Sigma\Delta s_i = L/2$
  - angle: $\Sigma h_i \Delta s_i = \Phi/2$
  - [field: $h_i < h_{max}$]
  - [optics: β_0 , η_0]
- Results:
  - hyperbolic field variation
    (for symmetric bend, dispersion suppressor bend is different)
  - Trend: $h_0 \to \infty$, $\beta_0 \to 0$, $\eta_0 \to 0$

Results for half symmetric bend

(L = 0.8 m, Φ = 8°, 2.4 GeV)

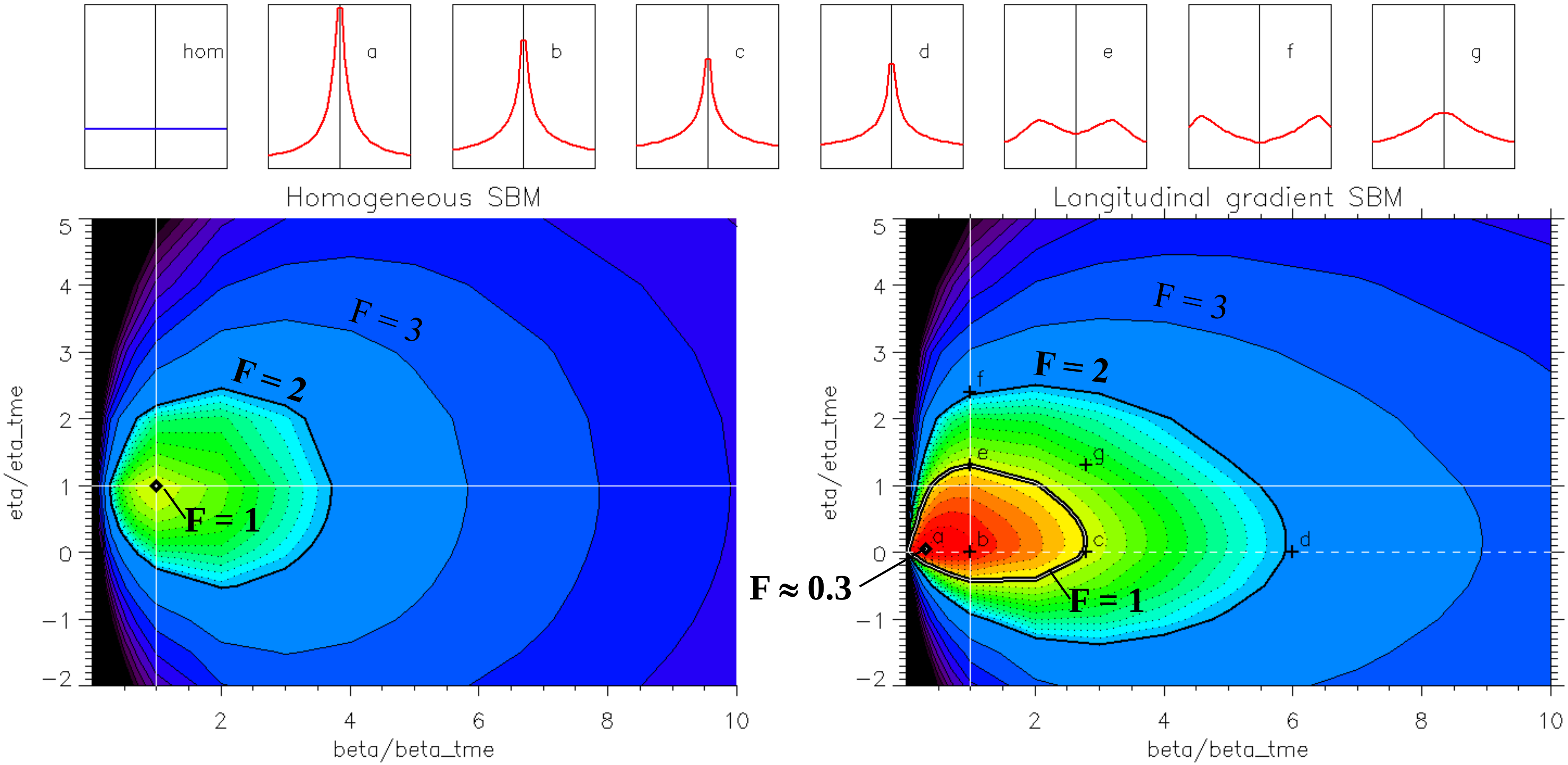


I



LGB 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

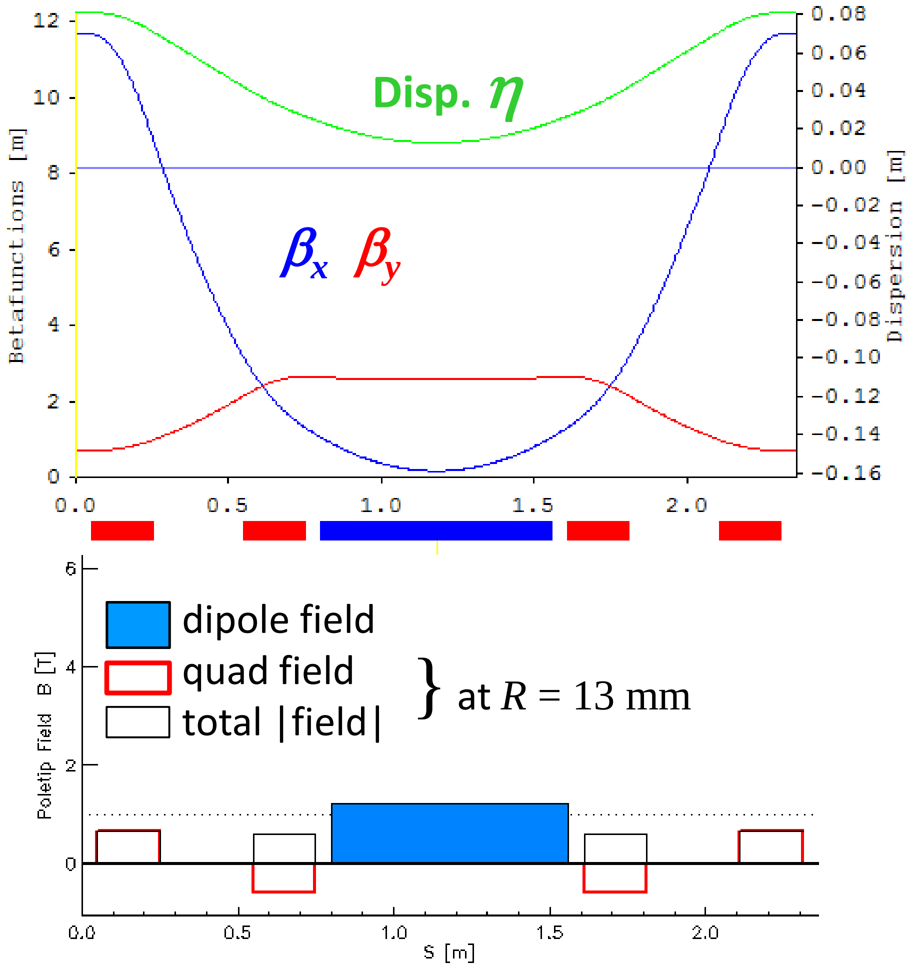


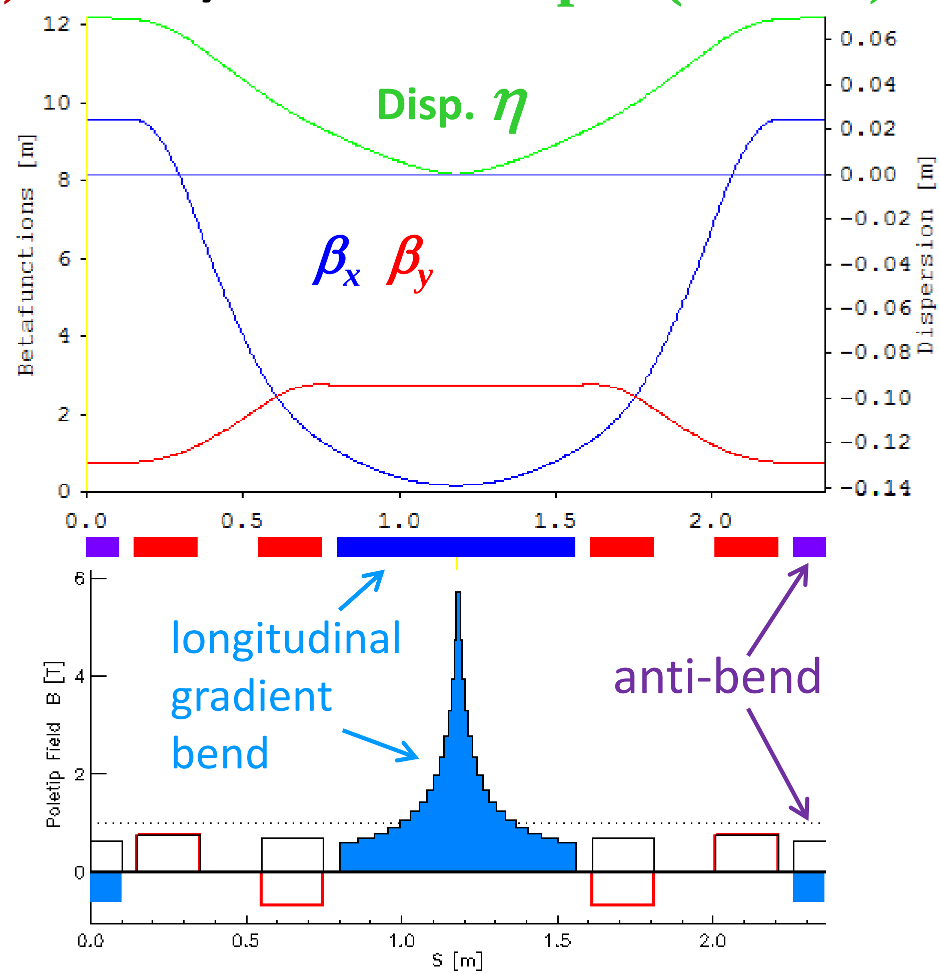
small (~0) dispersion at centre required, but tolerant to large beta function

The LGB/AB cell („Gaudí cell“)

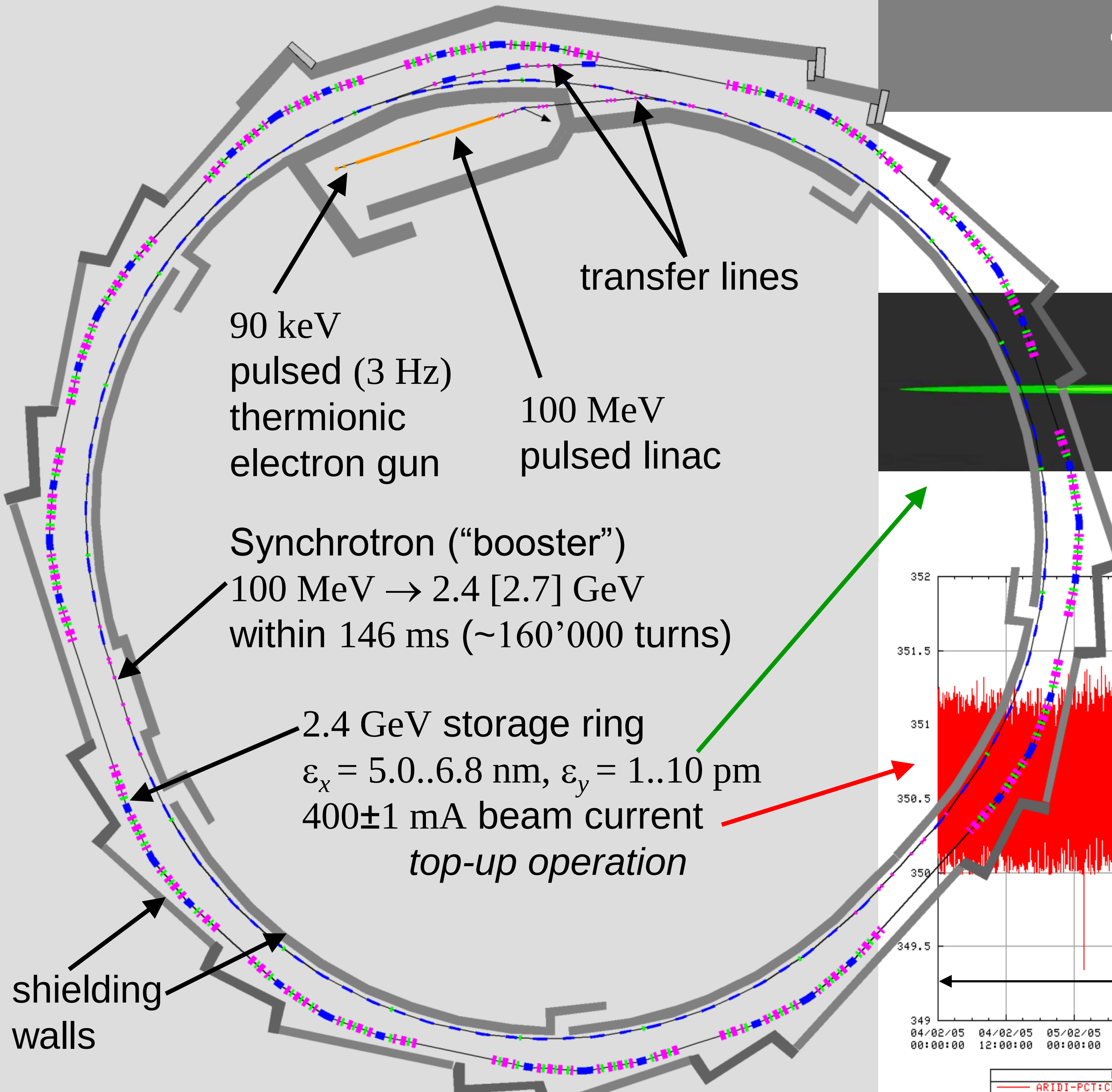
- Conventional cell vs. longitudinal-gradient bend/anti-bend cell
  - both: angle 6.7°, E = 2.4 GeV, L = 2.36 m, $\Delta\mu_x$ = 160°, $\Delta\mu_y$ = 90°, $J_x \approx 1$

conventional: ε = 990 pm (F = 3.4) **LGB/AB:** ε = 200 pm (F = 0.69)

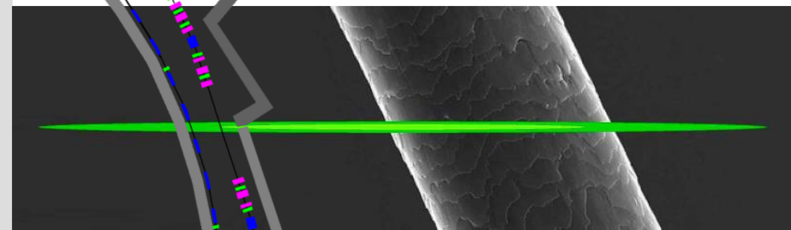




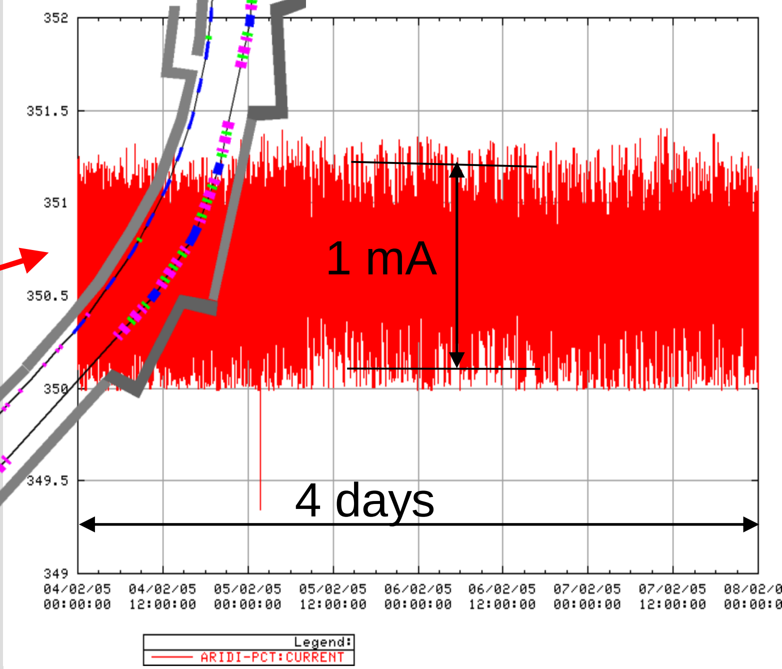
The SLS



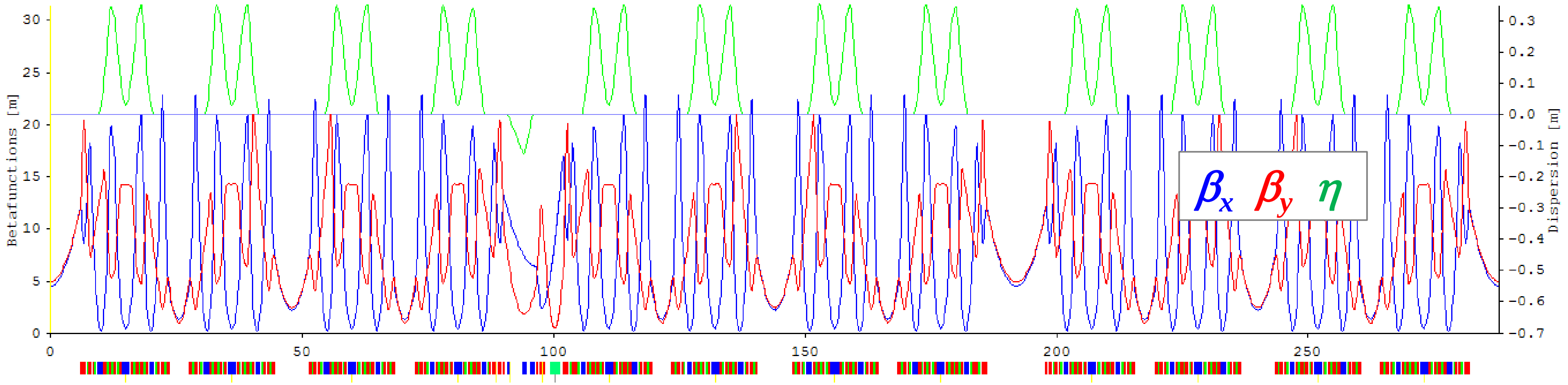
Electron beam cross section in comparison to human hair



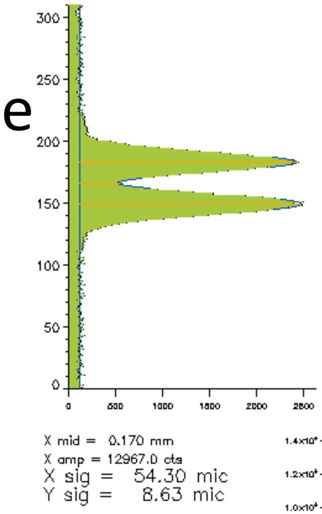
Current vs. time

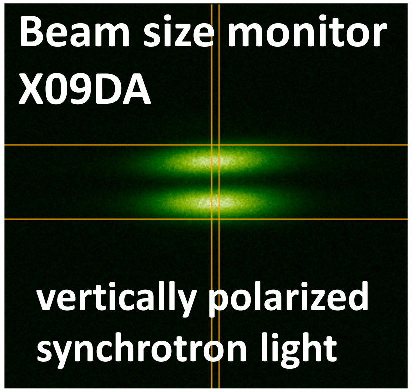


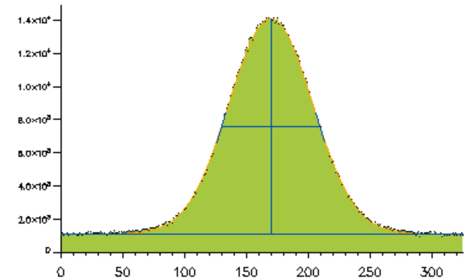
SLS lattice and history



- 288 m circumference
- 12 × TBA (triple bend achromat) lattice
- straight: 6 × 4 m, 3 × 7 m, 3 × 11.5 m
- FEMTO chicane for laser beam slicing
- 3 normalconducting 3T superbends
- Horizontal emittance 5.5 nm
- Vertical emittance 1...5 pm
- User operation since June 2001
- 18 beam lines in operation







SLS upgrade constraints and challenges

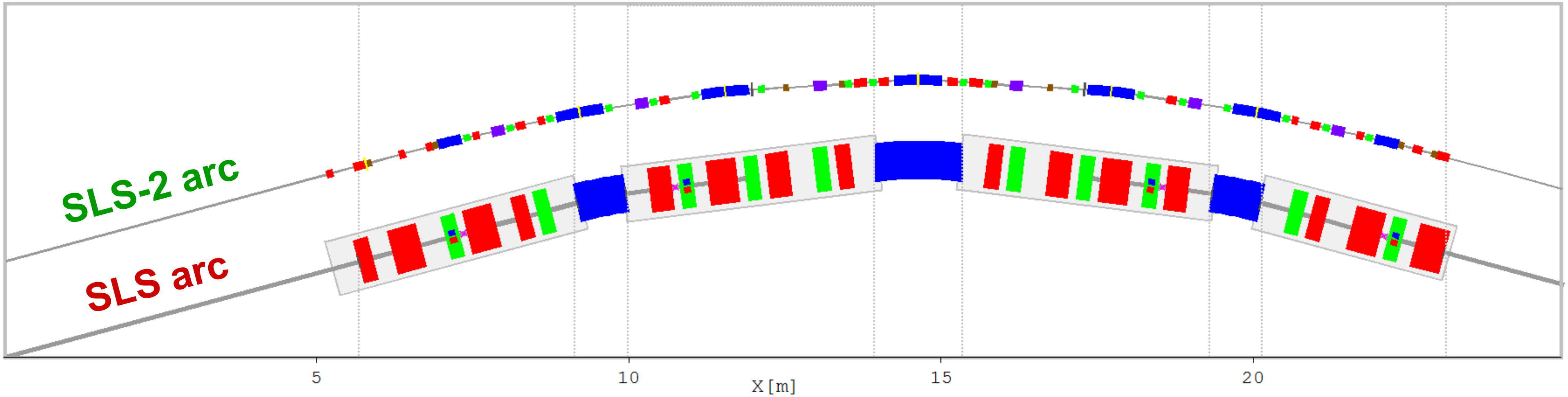
- Constraints
  - get factor 20...50 lower emittance (100...250 pm)
  - keep circumference & footprint: hall & tunnel.
  - re-use injector: booster & linac.
  - keep beam lines: avoid shift of source points.
  - "dark period" for upgrade 6...9 months
- Main challenge: *small circumference* (288 m)
  - Multi bend achromat: $\varepsilon \propto (\text{number of bends})^{-3}$
  - Damping wigglers (DW): $\varepsilon \propto \frac{\text{ring}}{\text{ring} + \text{DW}}$ radiated power

⇨ Low emittance from MBA and/or DW requires space !

⇨ Scaling MAX IV to SLS size and energy gives $\varepsilon \approx 1$ nm ✘

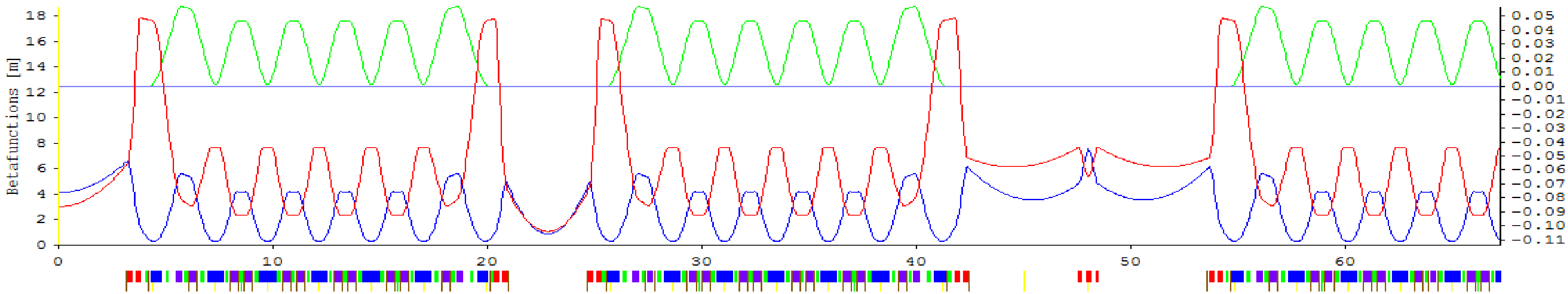
⇨ **LGB/AB-cell based MBA** ⇨ $\varepsilon \approx 100...200$ pm ✓

SLS-2 lattice design



- Various concept lattice designs for 100-200 pm (factor 25...50 compared to SLS-1)
  - based on a 7-bend achromat arc.
  - longitudinal gradient bends and anti-bends.
  - period-3 lattice: 12 arcs and 3 different straight types.
  - beam pipe / magnet bore ∅ 20 / 26 mm.

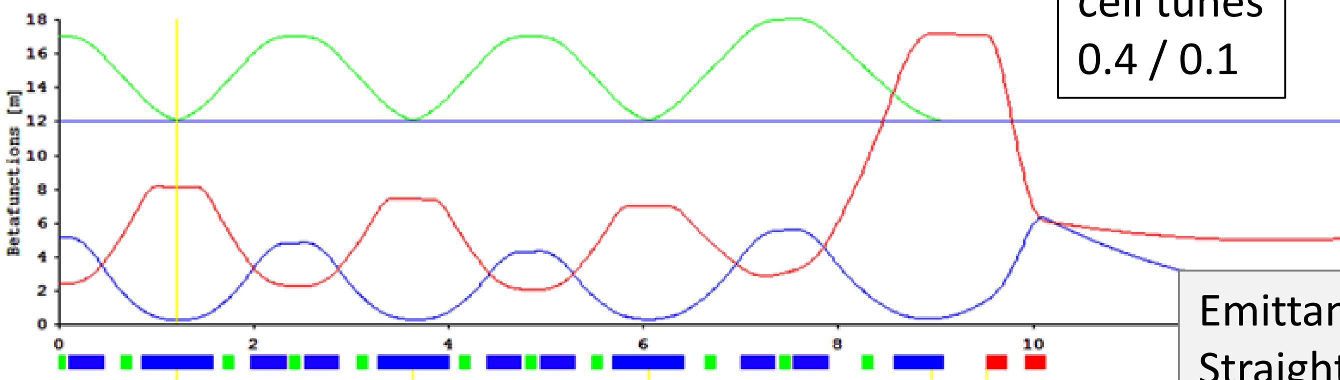
60 s.c. superbend LGB/AB lattice

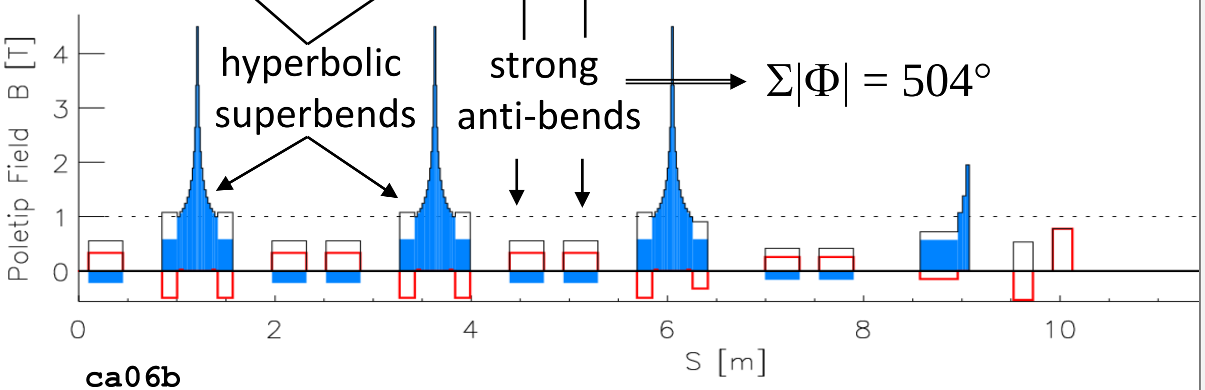


2½ of 12 arcs ⇧ ½ arc ⇩

cell tunes
0.4 / 0.1

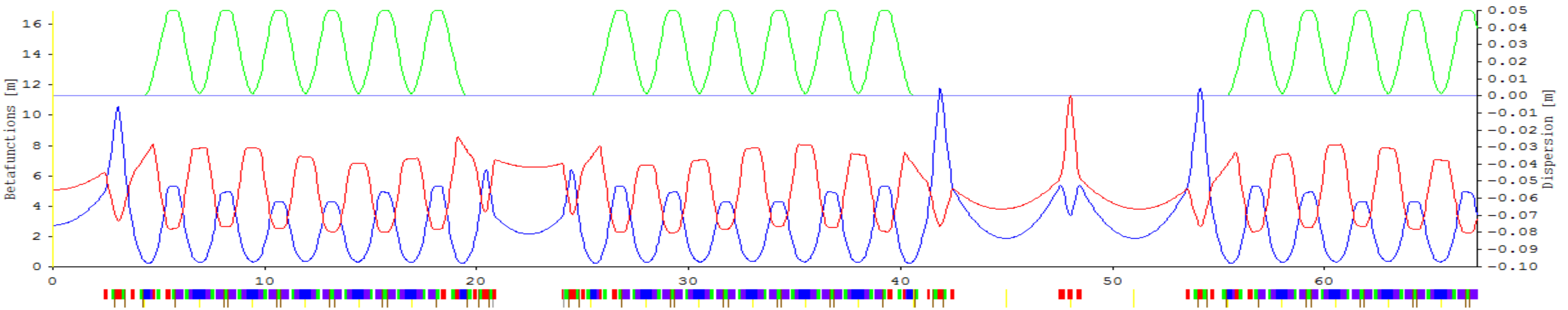
β_x β_y η



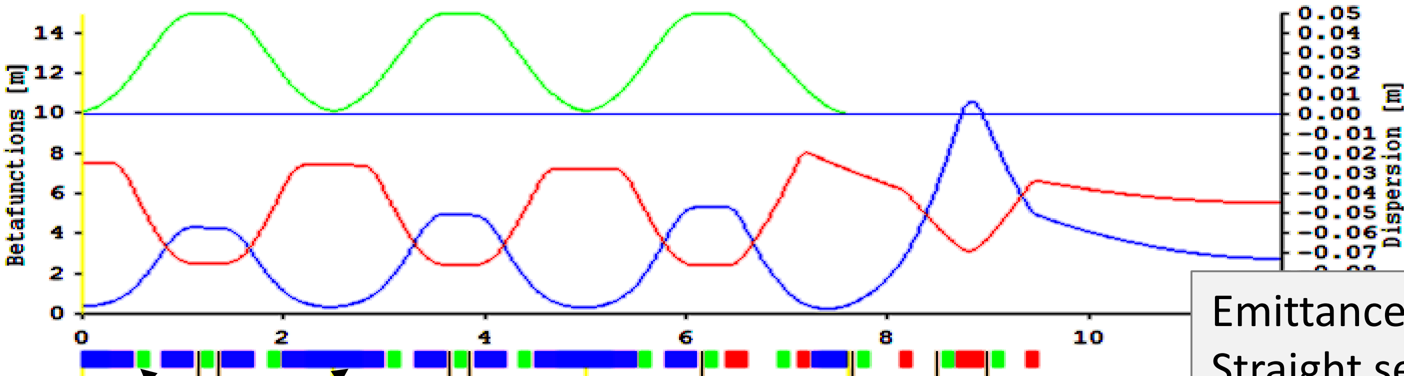


Emittance	126 pm
Straight sections	6 × 3.6 m
	3 × 6.2 m
split long straights →	3 × (5 + 5) m
Radiation loss	735 keV
Energy spread	$1.24 \cdot 10^{-3}$
Working point	37.7 / 10.8
Chromaticities	–61 / –49
MCF α	$-1.00 \cdot 10^{-4}$

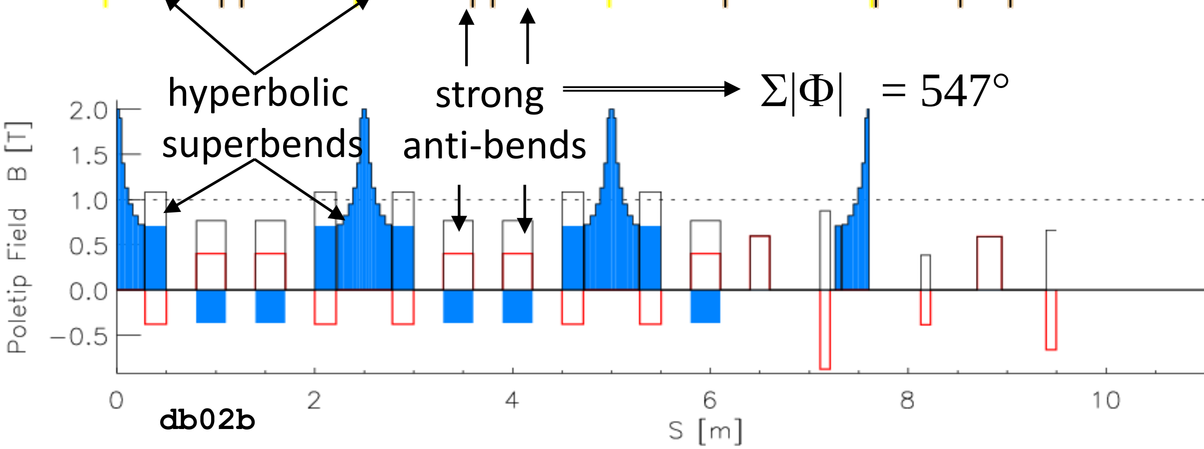
n.c. bend LGB/AB lattice



2½ of 12 arcs ⇧ ½ arc ⇩

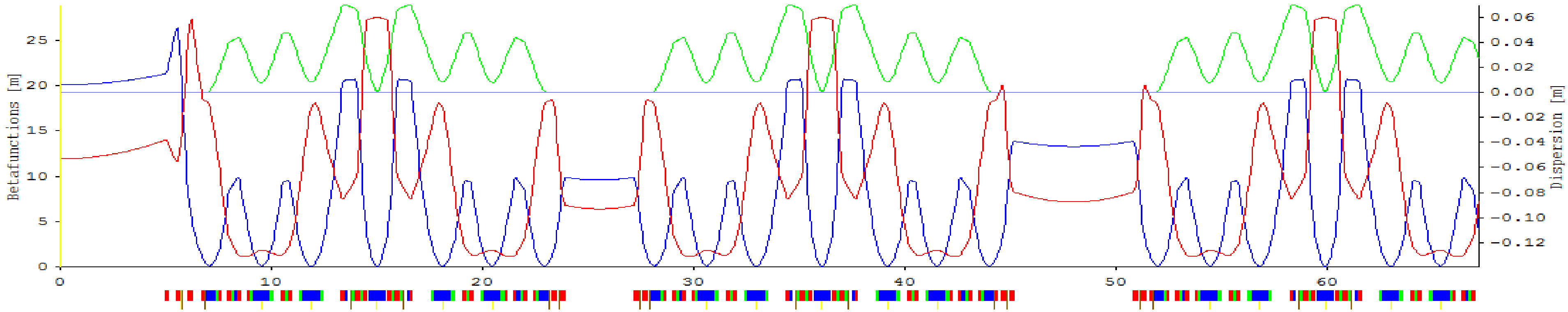


β_x β_y η



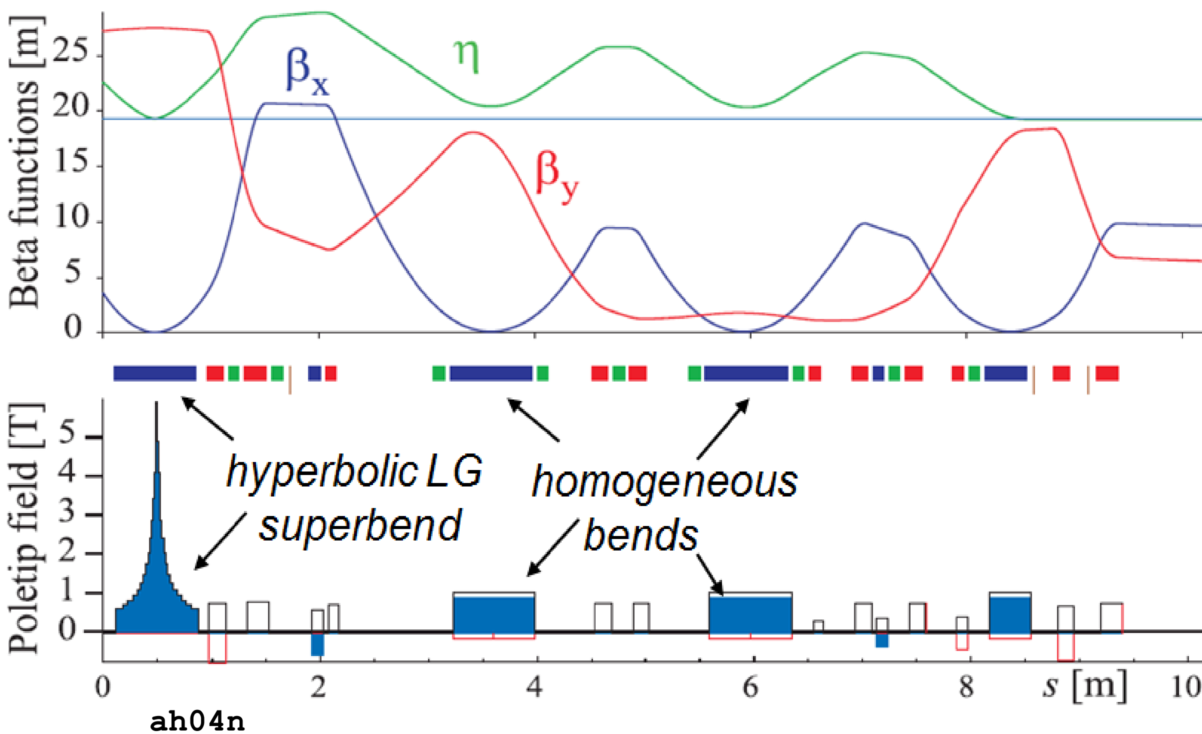
Emittance	**132 pm**
Straight sections	6 × 3.1 m
	3 × 4.9 m
split long straights →	3 × (5 + 5) m
Radiation loss	**544 keV**
Energy spread	**$1.00 \cdot 10^{-3}$**
Working point	38.2 / 10.3
Chromaticities	**–70 / –34**
MCF α	$-1.01 \cdot 10^{-4}$

s.c./n.c. hybrid MBA lattice



2½ of 12 arcs ⇧ ½ arc ⇩

β_x β_y η



Emittance	**183 pm**
Straight sections	6 × 3.2 m
	3 × 5.7 m
	3 × 10 m
Radiation loss	**466 keV**
Energy spread	**$1.04 \cdot 10^{-3}$**
Working point	39.4 / 10.8
Chromaticities	–163 / –70
MCF α	$+1.29 \cdot 10^{-4}$

SLS-2 design priorities

- Dynamic aperture optimization
  - Non-linear optics optimization to provide sufficient lifetime and injection efficiency.
  - ⇨ Mike Ehrlichman's talk
- Injection scheme
  - off-axis and on-axis schemes using existing SLS injector.
  - ⇨ Angela Saa Hernandez' talk
- Impedances and instabilities
  - Interaction of beam with narrow, NEG coated beam pipe.
- Alignment and orbit correction
  - Magnet/girder integration, dynamic alignment, photon BPMs.
  - Rely on beam based alignment methods.

Time schedule

- Jan. 2014 Letter of Intent submitted to SERI
  (SERI = State secretariat for Education, Research and Innovation)
  - schedule and budget
    - 2017-20 studies & prototypes 2 MCHF
    - 2021-24 new storage ring 63 MCHF
      beamline upgrades 20 MCHF
  - Oct. 2014 positive evaluation by SERI:
    SLS-2 is on the "roadmap".
- Concept decisions fall 2015.
- Conceptual design report end 2016.

Conclusion

- Anti bends (AB) disentangle horizontal beta and dispersion functions.
- Longitudinal gradient bends (LGB) provide minimum emittance by adjusting the field to the dispersion.
- The new LGB/AB cell provides
  low emittance at modest cell phase advance.
- Upgrade of the Swiss Light Source SLS has to cope with a rather compact lattice footprint.
- Draft designs for an SLS upgrade are based
  on LGB/AB-MBAs and on hybrid MBAs,
  and promise an emittance in the 100..200 pm range.
- A conceptual design report is scheduled for end 2016.