Review of Lattice Options for High-Brightness Light Sources

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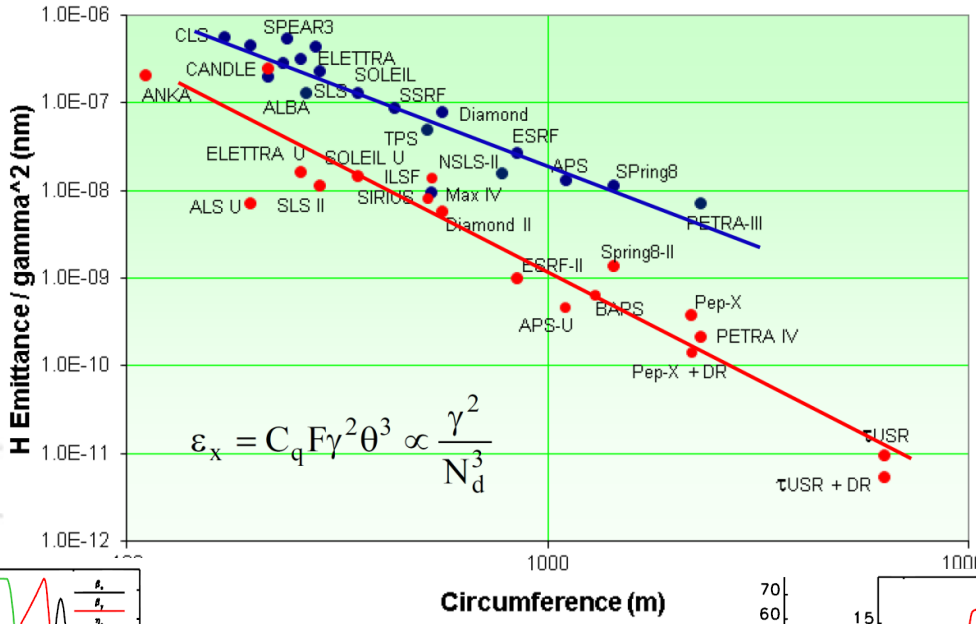
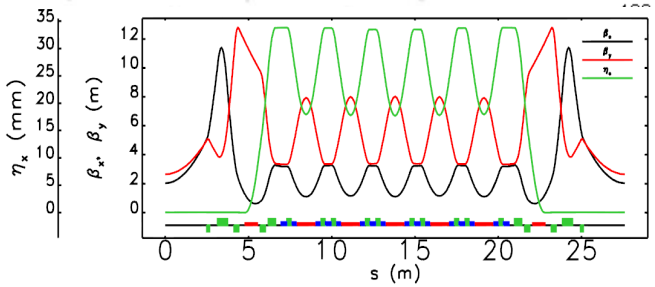
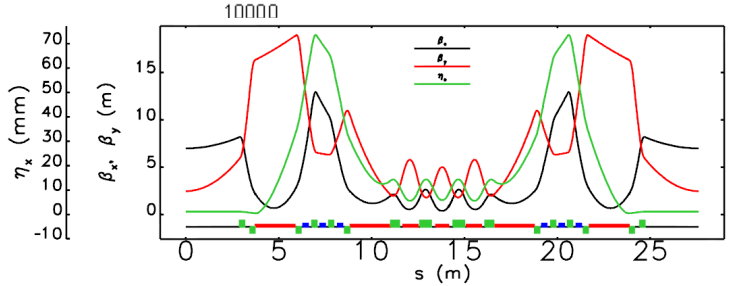


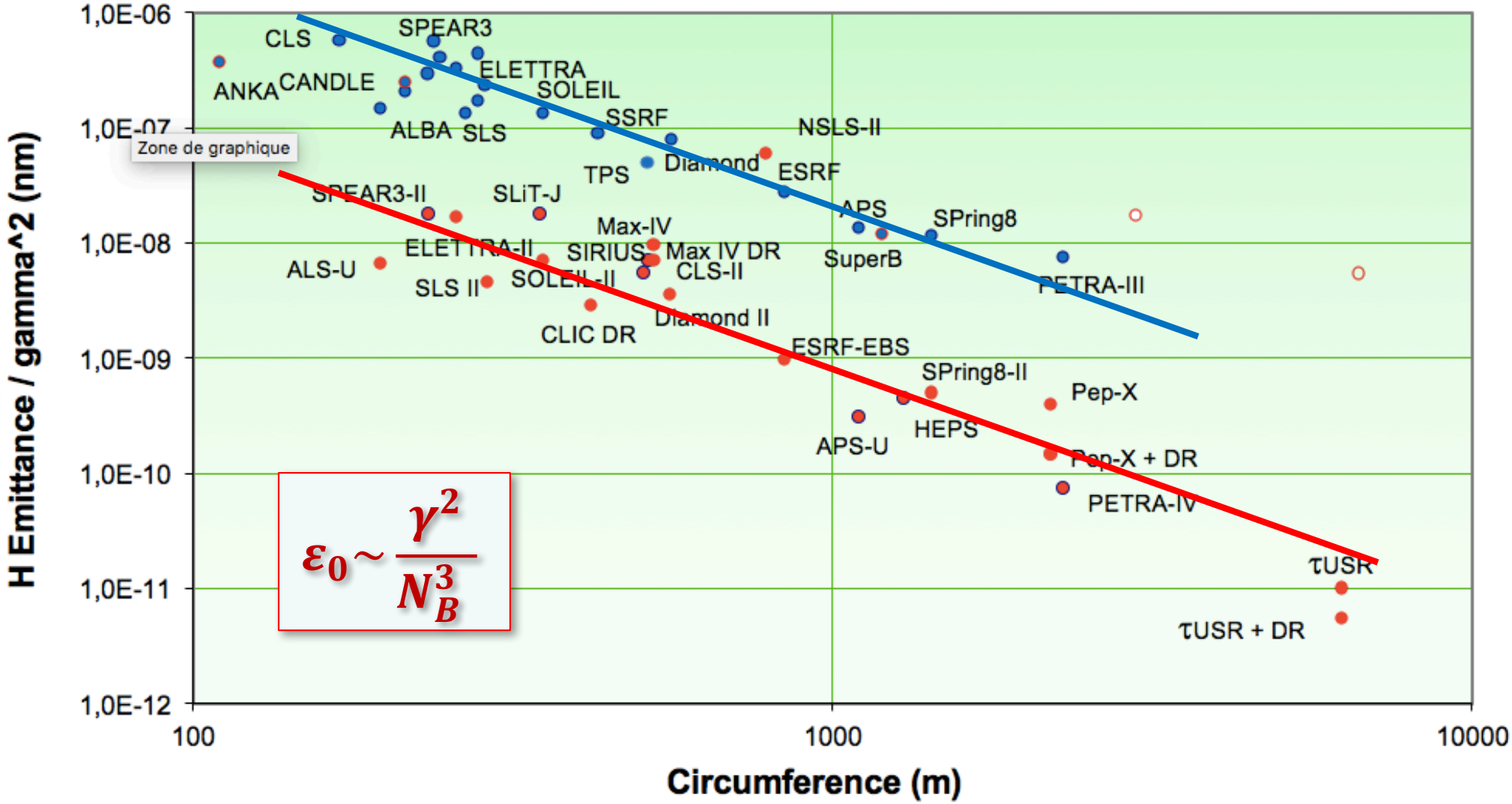




Contents

- High brilliance/low H-emittance
- Lattice design criteria
- Lattice review
- Summary and Conclusion

Roadmap to diffraction Limited Light sources (DLSR)
High Brilliance Light sources (HBLS)

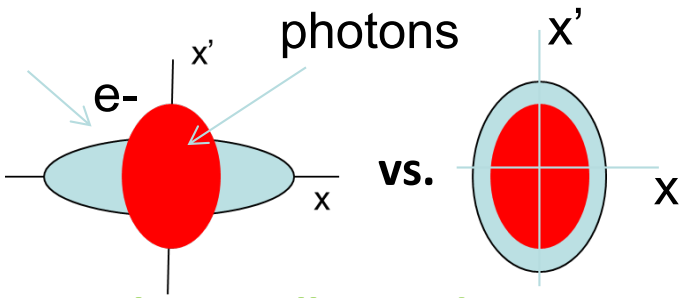


Adapted from R. Bartolini's plot

High brilliance achieved through MBA lattice

$$B_n(\lambda) = \frac{F_n(\lambda)}{4\pi^2(\varepsilon_x \oplus \lambda_n / 4\pi)(\varepsilon_z \oplus \lambda_n / 4\pi)}$$

$F_n(\lambda)$: Photon flux [photons/s/0.1% b.w.]
ε_x, ε_z: Transverse electron emittance
λ : Photon wavelength
($\lambda/4\pi$: diffraction limited photon emittance)



electron-photon ellipse adaptation

$$\varepsilon_0[\mathrm{nm\,rad}] = 1470\, E[\mathrm{GeV}]^2 \frac{I_5}{J_x I_2}, \quad J_x = 1 - \frac{I_4}{I_2}$$

$$= \frac{0.0078}{J_x} E[\mathrm{GeV}]^2\, \Phi[^\circ]^3 \frac{F(\beta_x, \eta)_\rho}{12\sqrt{15}}, \quad \Phi[^\circ]^3 \propto \frac{1}{N_b^3}$$

TME MBA Gradient Dipoles

$$I_2 = \oint \frac{ds}{\rho^2} \qquad I_4 = \oint \frac{\eta}{\rho}\left(\frac{1}{\rho^2} + 2b_2\right) ds \qquad I_5 = \oint \frac{\mathcal{H}}{|\rho^3|} ds \qquad \mathcal{H} = \gamma_x \eta^2 + 2\alpha_x \eta\eta' + \beta_x \eta^2$$

TME: brute-force approach $I_5/I_2 \to 0$ easily leads to overstrained optics, chromaticity wall
MBA: many weak dipoles, distributed chromaticity correction → allows relaxing optics
Gradient dipoles: reduce emittance, allow for more compact optics → improves MBA

TME Theoretical Minimum Emittance

Exploring the emittance formula

$$\varepsilon_0 \sim \frac{\gamma^2}{N_B^3}$$

b = 1/ρ = B/(p/e)

Optic optimization leads to MBA

horizontal focus in each dipole
many small dipoles

Longitudinal Gradient Bend
LGB

$$H = (\eta_x^2 + (\alpha\eta_x + \beta\eta_x')^2)/\beta$$

$$I_5 = \int |b|^3 H \, ds$$

$$\varepsilon_{xo}[\mathrm{m}\cdot\mathrm{rad}] = \tilde{C}_q \gamma^2 \frac{I_5}{I_2 - I_4}$$

gradient bends

$$I_4 = \int b\eta(b^2 + 2k) \, ds$$

for vertical focusing ($bk < 0$)

TGB: transverse Gradient Bend

Radiated power

$$I_2 = \int b^2 \, ds$$

$$\Delta E[\mathrm{keV}] = \tilde{C}_\gamma \gamma^4 I_2$$

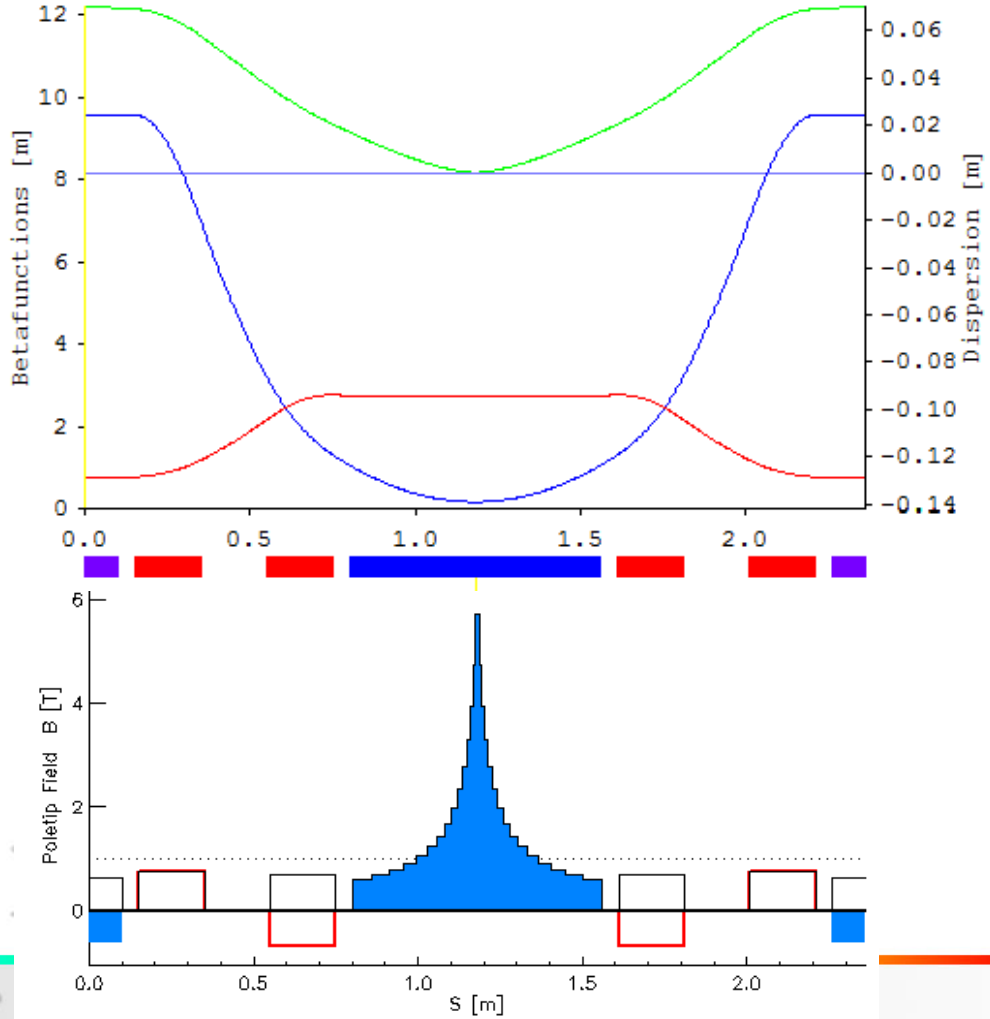
Damping wiggler

$$\tilde{C}_q = 3.83\cdot10^{-13}\mathrm{m} \quad \tilde{C}_\gamma = 9.60\cdot10^{-13}\mathrm{keV}$$

Ingredient: Longitudinal gradient bends

$$I_5 = \int |b|^3 H \, ds \qquad b(s) = B(s)/(p/e)$$

- Longitudinal field variation $b(s)$ to compensate $\mathcal{H}(s)$ variation
- Beam dynamics in bending magnet
  - Curvature is source of dispersion
  - Horizontal optics ~ like drift space
  - Assumptions: no transverse gradient ($k = 0$); rectangular geometry



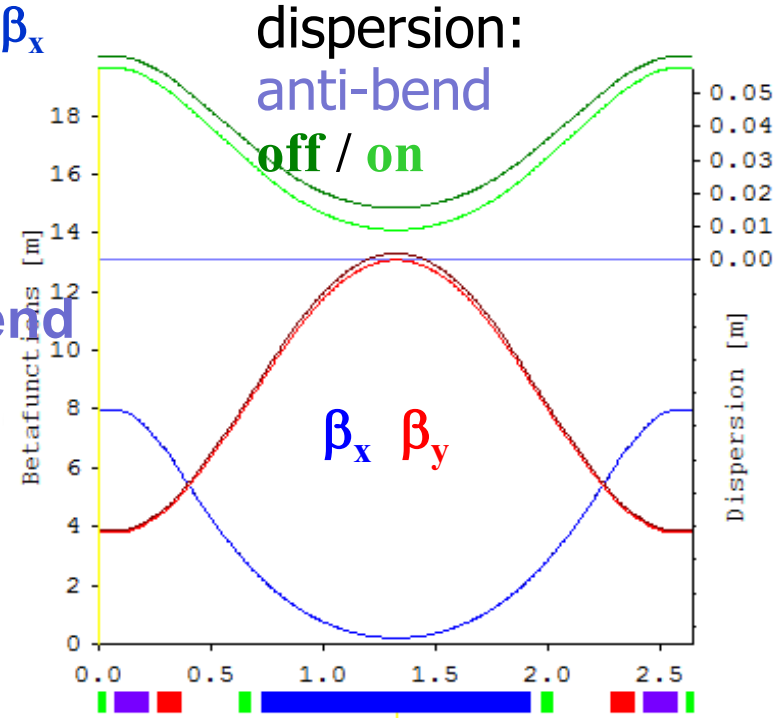
Ingredient to lower the emittance: anti-bend

Courtesy of A.Streun

- **General problem of dispersion matching**:
  - dispersion production in dipoles → "defocusing": $\eta'' > 0$
- **Quadrupoles in conventional cell**:
  - dispersion is horizontal trajectory: quads treat η and β_x in same way.
  - → **over-focusing of horizontal** beta function β_x
  - → insufficient focusing of dispersion η
  - striking example: the TME cell

→ disentangle η and β_x!

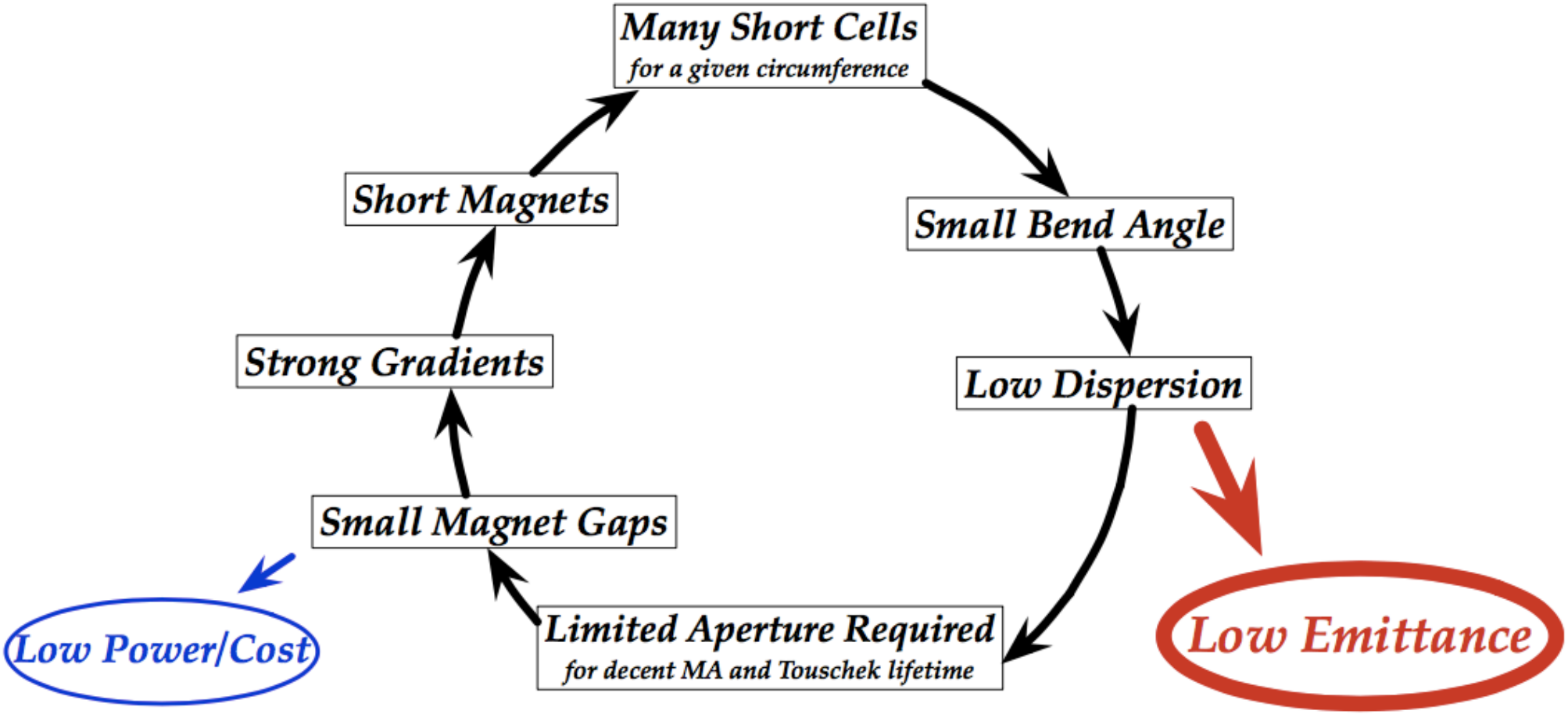
- use negative dipole: **anti-bend/reverse bend**
  - kick $\Delta\eta' = \psi$, angle $\psi < 0$
  - out of phase with main dipole
  - negligible effect on β_x , β_y
- **Side effects on emittance**:
  - main dipole angle increase by $2|\psi|$
  - anti-bend located at large $\mathcal{H}$
  - → in total, still lower emittance



TME: $F = 3.4$, $\varepsilon = 990$ pm
LGAB: $F = 0.69$, $\varepsilon = 200$ pm

The Multibend Achromat Cycle

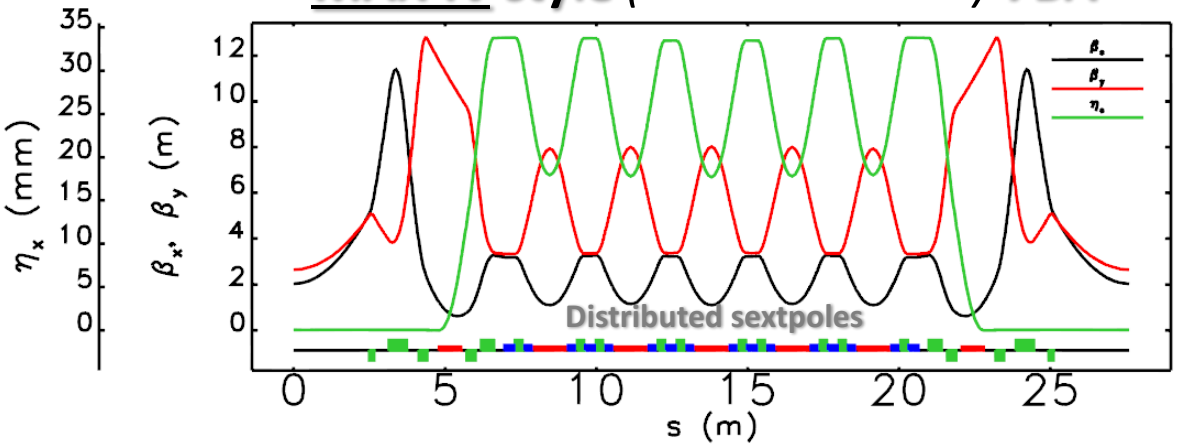
(courtesy A. Streun, PSI)



Deciding on the "M" part of the MBA.

$$\varepsilon_0 \sim \frac{\gamma^2}{N_B^3}$$

MAX-IV style *(or 'traditional')* **7BA***



SIRIUS MAX-IV

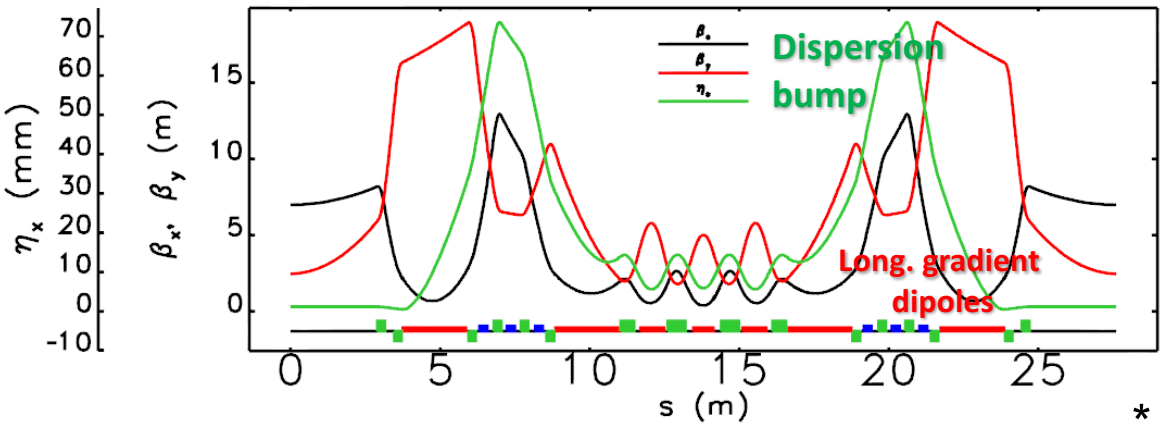
ELETTRA-II* SLS-II**

ALS-U***

CLS-II

SLiT-J

ESRF/APSu style *(or 'hybrid')* **7BA***



ESRF-EBS HEPS

PEPX APS-U*

SPRing8-II

PETRA-IV

DIAMOND-II***

SOLEIL-II***

* variation

Constraints to design a lattice
Compromise-trade-off (1)

~~Budget~~

- Type of Machine: Green field lattice/Upgrade lattice
- Top-up (stability, reliability, lifetime/losses, MTBF, etc.),
- Requirement for Dipole-based beam lines
- Size of the ring/cell (compact/very large, ID lengths)
  - Large ring / hybrid lattice
- Number/Addition of straight sections/beamlines
- Compact lattice (tapers, flanges, bellows, RF-cavities, BPMs, etc.)
- Exotic magnets (LGB, Quad-dipole, combined magnets, all integrated magnets, Permanent magnet, Anti (reverse) bend)

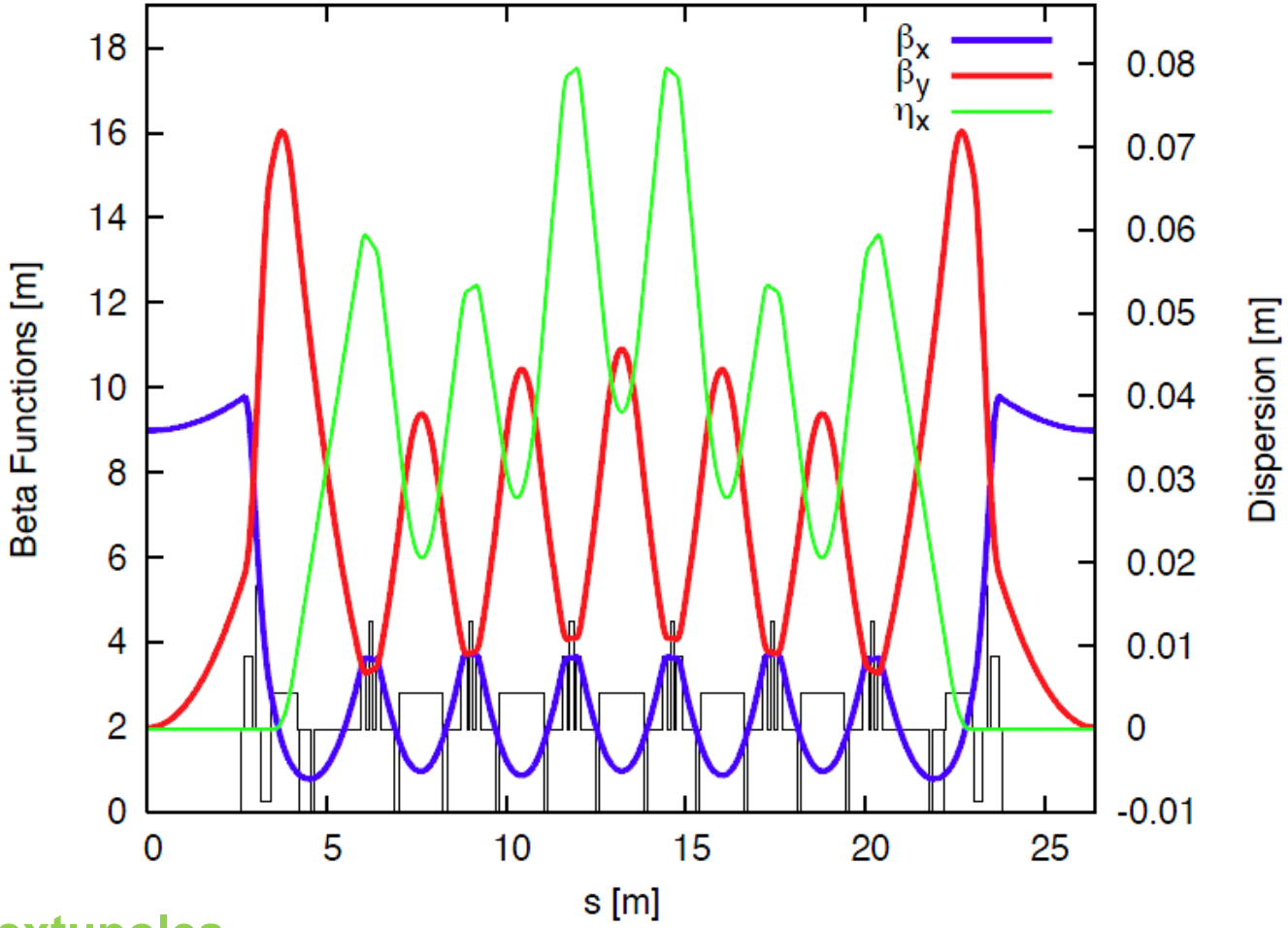
Constraints to select a lattice
Compromise-trade-off (2)

- Injection scheme (off-axis/on axis/swap out, etc.)
- Technology limitations (quad/sextupole strength, space, etc.)
- Collective effect (IBS, Lifetime Time, …)
- Lattice flexibility/tuneability
- Easy of operation (sensitivity to errors, IDs, etc.) /maintainability (MTTR)
- Maximum current / working chromaticities / filling-pattern

LATTICE REVIEW

MAX-IV: 7BA, 3 GeV, 330 pm.rad, N=20, 528 m, 500 mA

First DLSR MBA-based machine in operation



TME-cell + matching cells

Integrated solution

Compact design

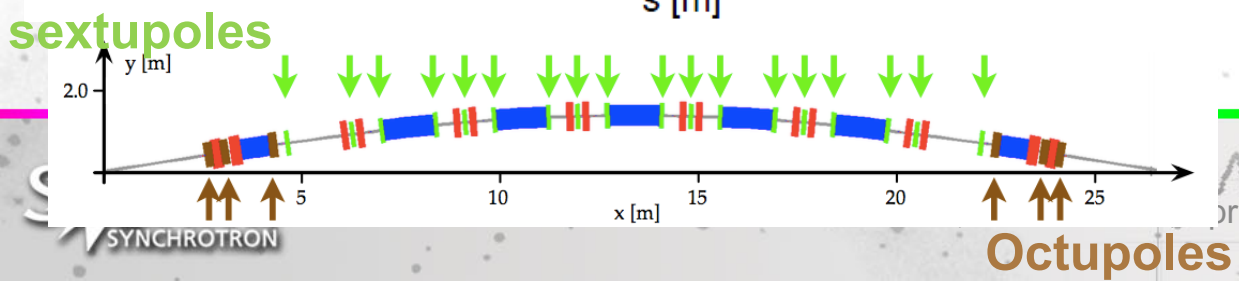
Short straight sections

Off-axis injection, PMK*

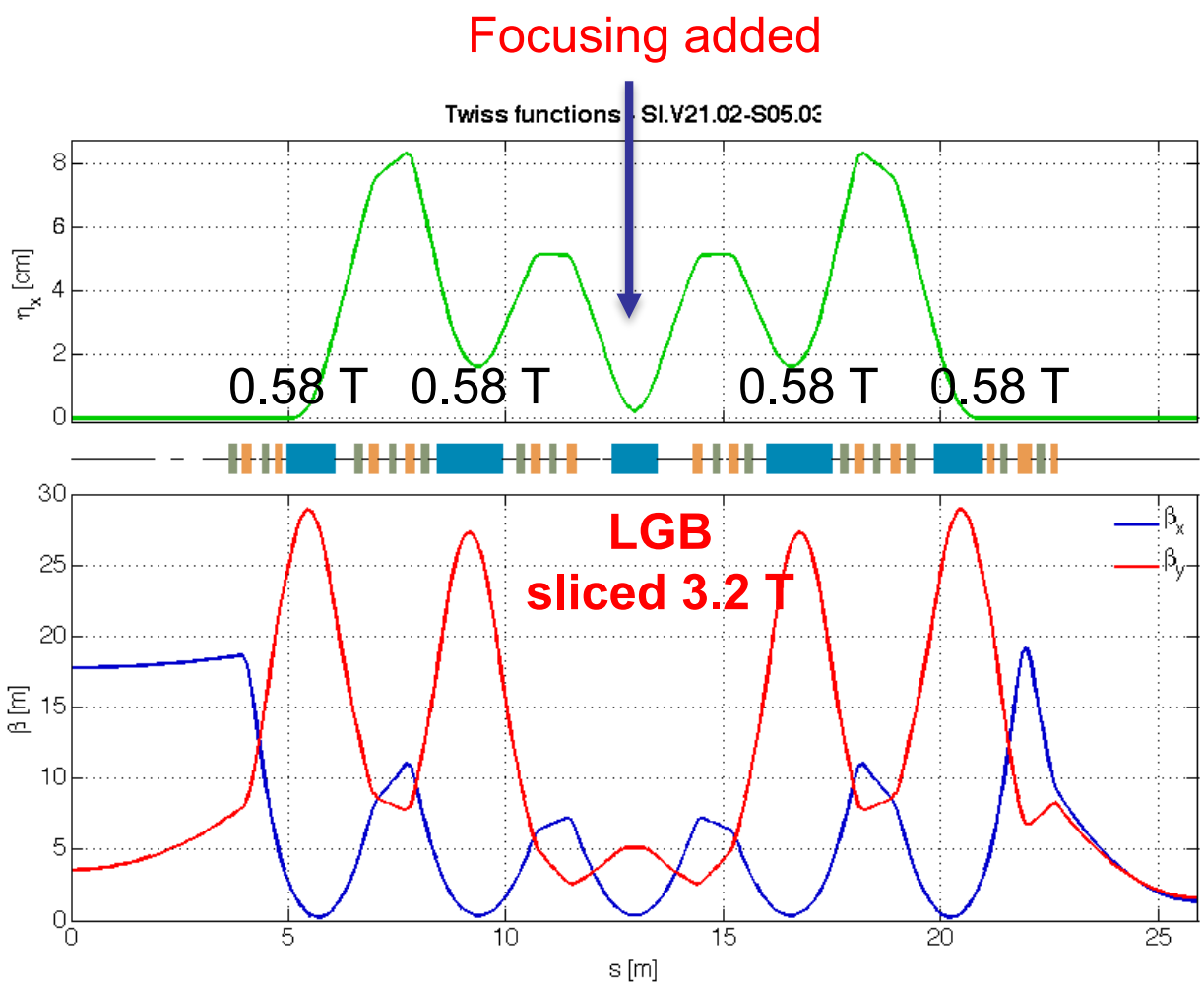
No dipole source (low field gradient dipole)

~Zero dispersion in SS

*PMK Pulsed Multipole Magnet

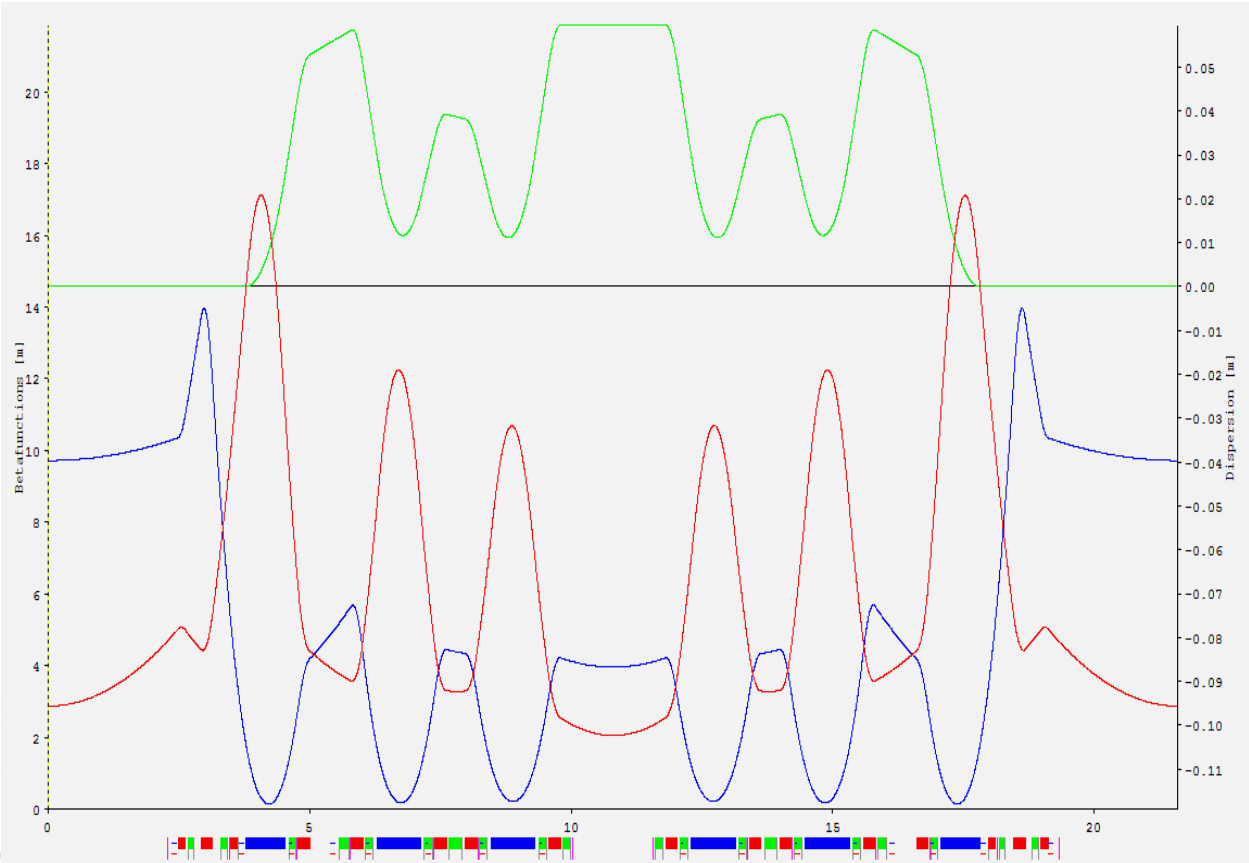


SIRIUS: 5BA, 3 GeV, 240 (150) pm.rad, N=20, 518 m, 500 mA



- 5-fold symmetric optics with **15 low and 5 high β sections.**
- Achromatic cells.
- At low β sections
  - $\beta_x \approx \beta_y \approx 1.5$ m
  - Optimized electron and photon beam phase-space matching for undulators.
- At superbend (PM)
  - Strong focusing of dispersion and β_x functions
  - Beam size: 9.5 x 3.5 μm^2
- **Off-Axis injection**
- pulsed multipole magnet

ELETTRA-II: Special* S6BA, 2 GeV, 250 pm.rad, N=12, 259.2 m



0.58T 0.58T 0.58T 0.58T 0.58T 0.58T

Dipole source

Easy to use

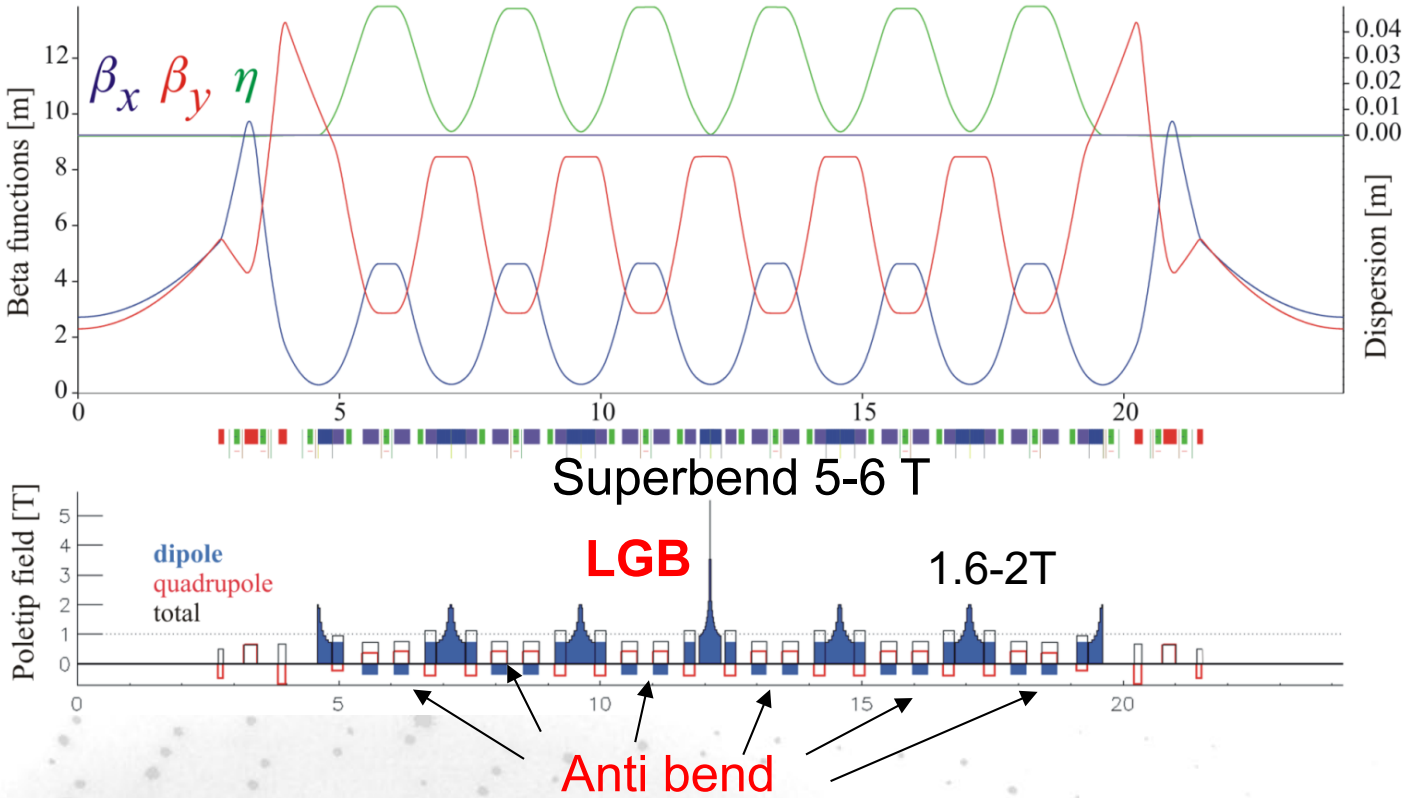
Future:
Introduction of 4 SB of 3.5 T

0.8 T (+ 1.4 T)

*12 achromats each made of 6 “cells” invariant to shift between them

SLS-II: LGAB-7BA, 2.4 GeV, 103 pm.rad, N=12, 290 m

Investigation revealed that, due to low periodicity, SLS upgrade could not operate at high chromaticity (-5,-5).
Half integer resonance



Symmetry is a MUST

Antibend fully exploited (585° total absolute angle)

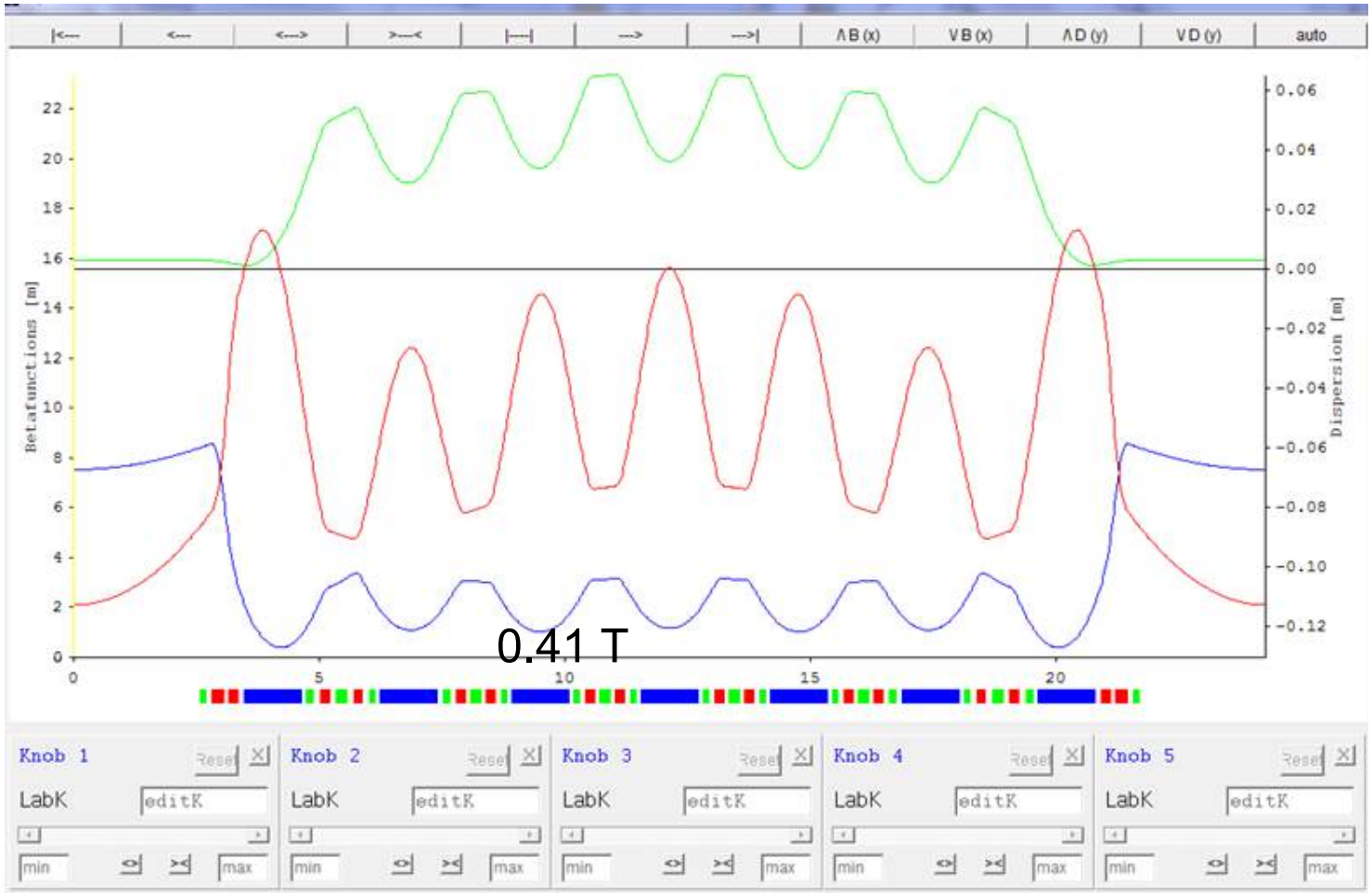
Off-axis injection
Long-axis

⇦ Optical functions

⇦ Magnetic fields
poletip fields for $r = 13$ mm

Low momentum compaction factor

CLS-II: 7BA, 3 GeV, 186 pm.rad, N=21, 510 m

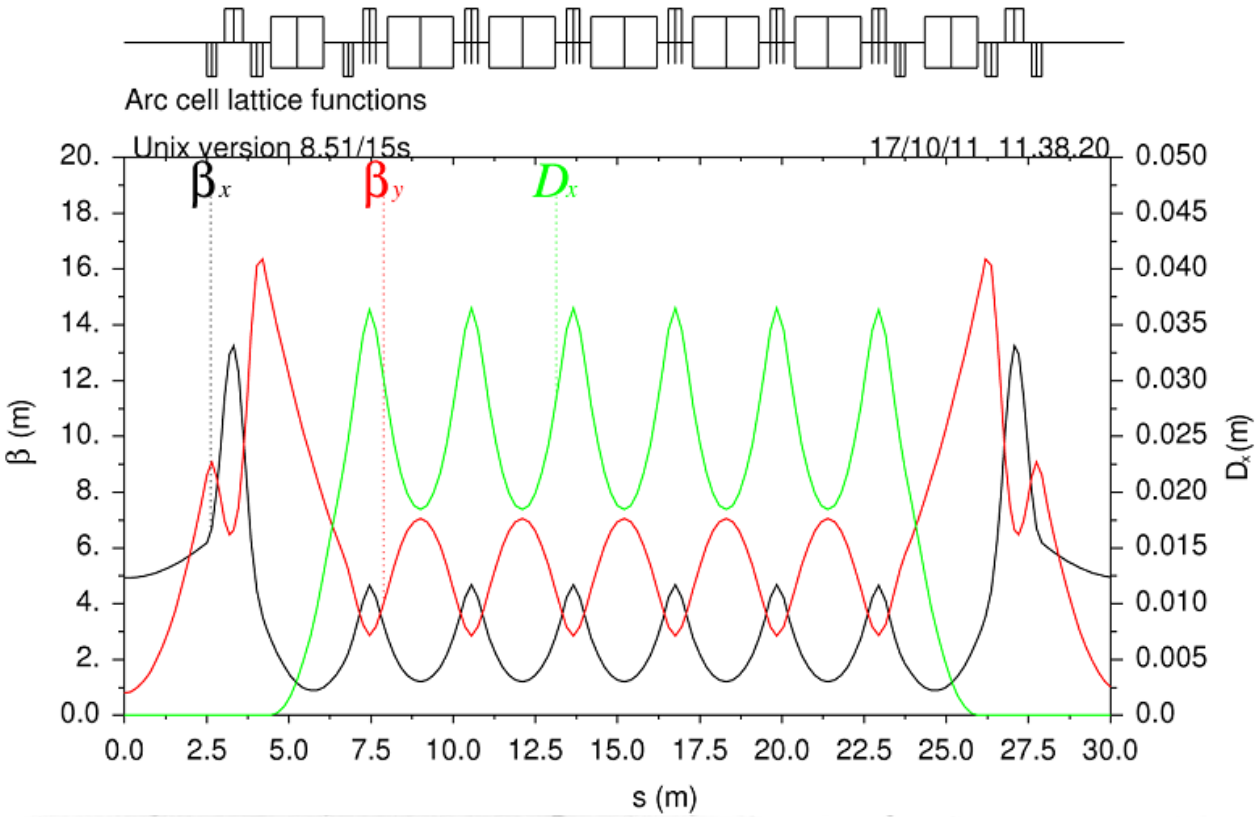


Very preliminary Results

Off-axis injection

PEPX: 7BA, 4.5 GeV, 11pm, 2199m, 1.5 A

Third and fourth order achromat



$$\mu_x = 4\pi + \pi/4 \quad and \quad \mu_y = 2\pi + \pi/4$$

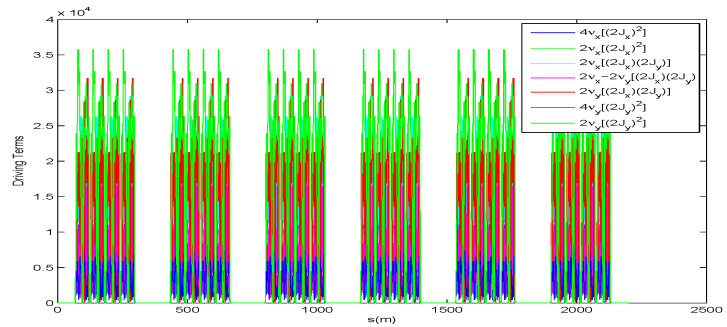
Compact

TME QD replaced with K-dipole

Special phase advance

Sextupole integrated in dipole or quadrupoles

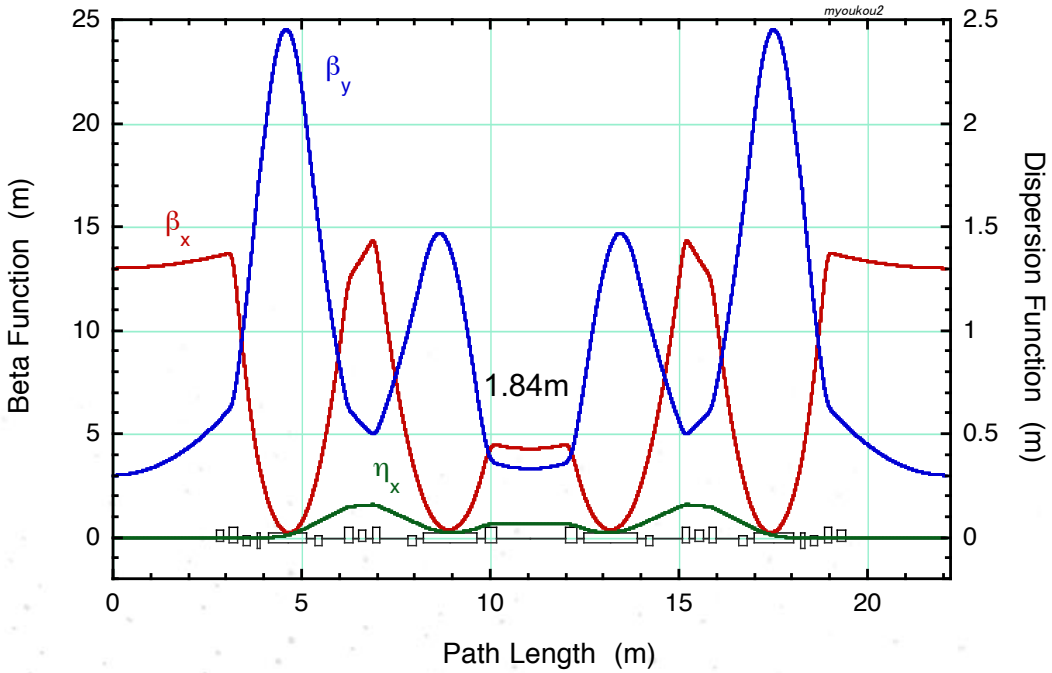
Matching Cell at the end

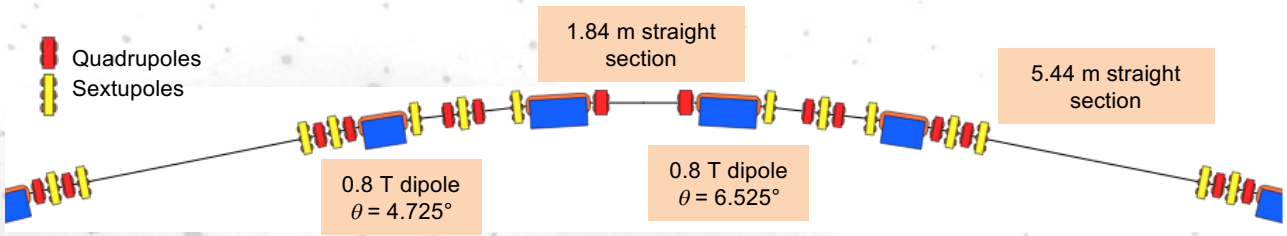


RDTs

SLiT-J: DDBA, 3 GeV, 920 (720) pm.rad, N=16, 350 m

Synchrotron Light in Tohoku, Japan



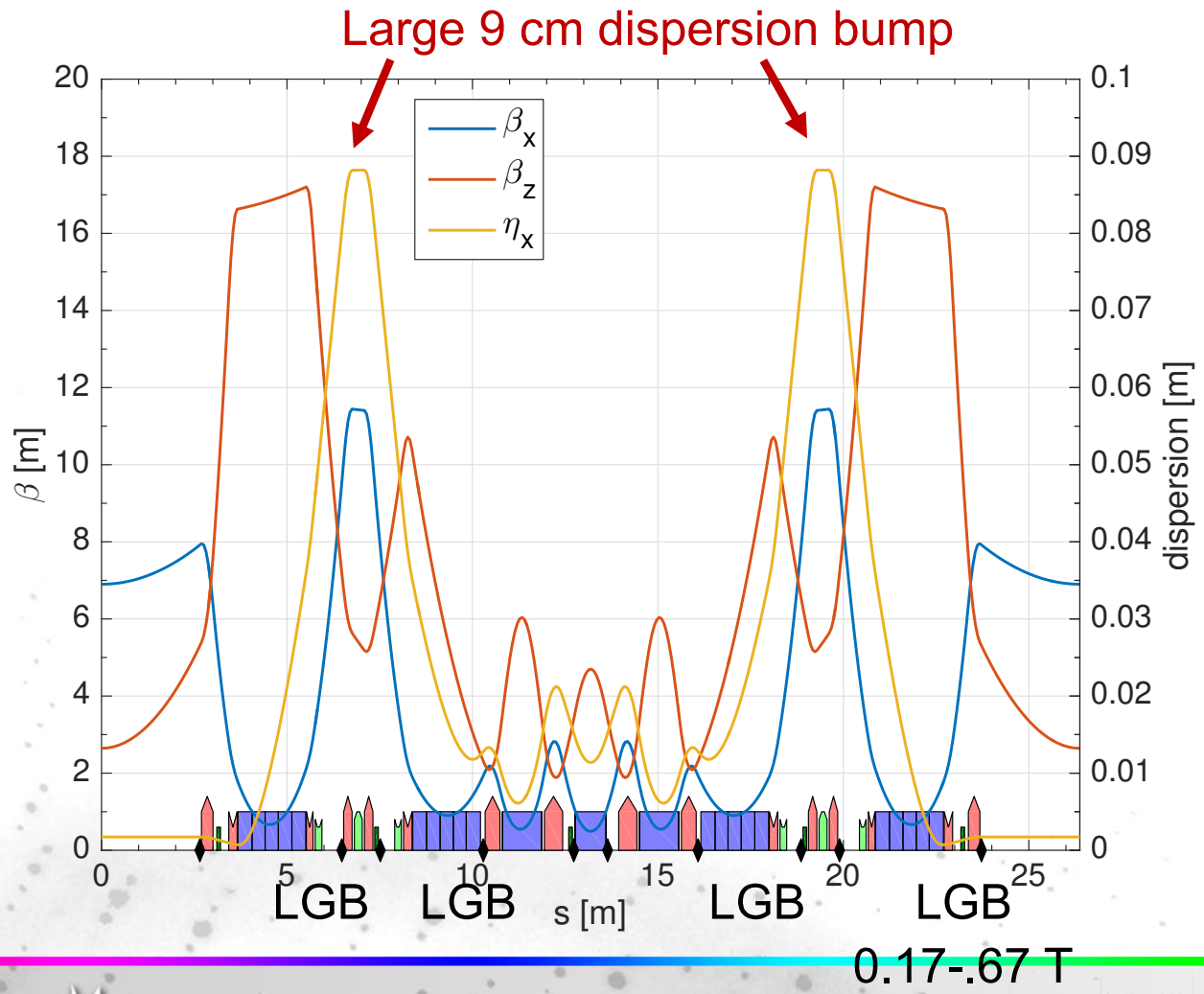


Design a sub-nm emittance storage ring with certain boundary condition (C ~ 350 m).

- Start the project as soon as possible (will be approved soon, hopefully).
- Facility size should be compact because of limited available budget.
- Soft X-ray will be **100 times** brighter than that at SPring-8.
- Complete management of saving-energy for high cost-performance facility.
- Secure expansibility and sustainability for the facility.

ESRF-EBS: H7BA, 6 GeV, 135 (110) pm.rad, N=32, 844 m, 200 mA (4b: 40mA, 16b: 80mA)

Collider optics



Dispersion bump
→ reduce sext. Strengths
→ large DA

No Harmonic sextupole

Low dispersion value
large LMA

Locked Sextupole phase advance

LGB PM magnets
Octupole magnets

Off-axis injection

Cell optimization scan

Empirical finding (*) that some observed parameters (knobs) have **effective impact** on physically relevant quantities:

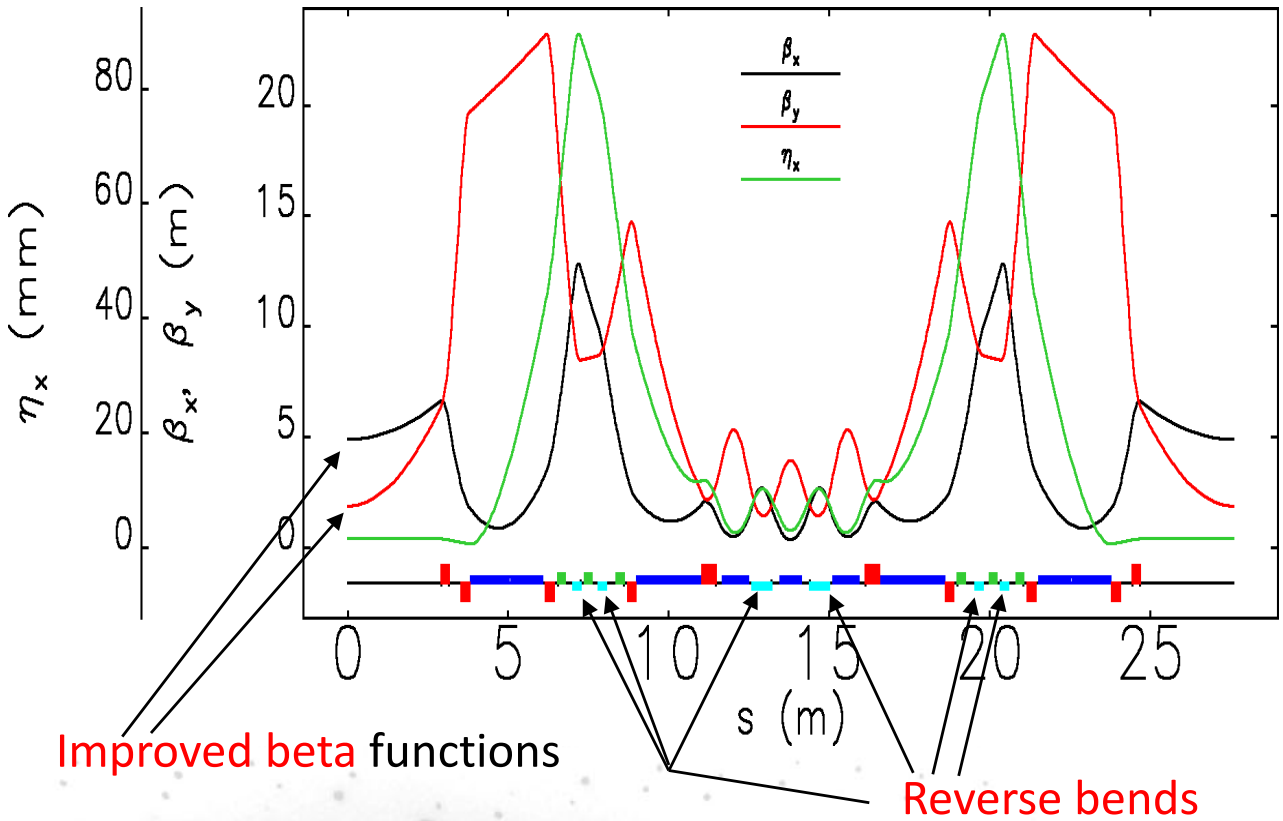
(*) P. Raimondi, ESRF

- β_x @ IDs → ε_x
- β_y @ sext → ε_x, ξ_x
- α_y @ sext → dQ_y/dAy
- K4 @ oct → dQ_x/dAx
- φ_y advance between sextupoles → dQ_x/dAy

Each parameter **<u>scanned individually</u>** while keeping others fixed

courtesy of A. Alekou

APS-U: H7BA, 6 GeV, 41 pm.rad, N=40, 1104 m, 200 mA (324b) + time resolved (48b)



Start with ESRF-EBS-like H7BA[2,3] giving 67-pm emittance

Convert 6 quads/sector to reverse-bends with gradients

- No additional magnets
- Increases energy loss per turn
- Somewhat decouples beta functions and dispersion
- Increases dispersion at the sextupoles

Reduction of sextupole Strength by a factor 3-4

3-pole wiggler (1T)

500 fs FWHM max

Injection: Swap-out

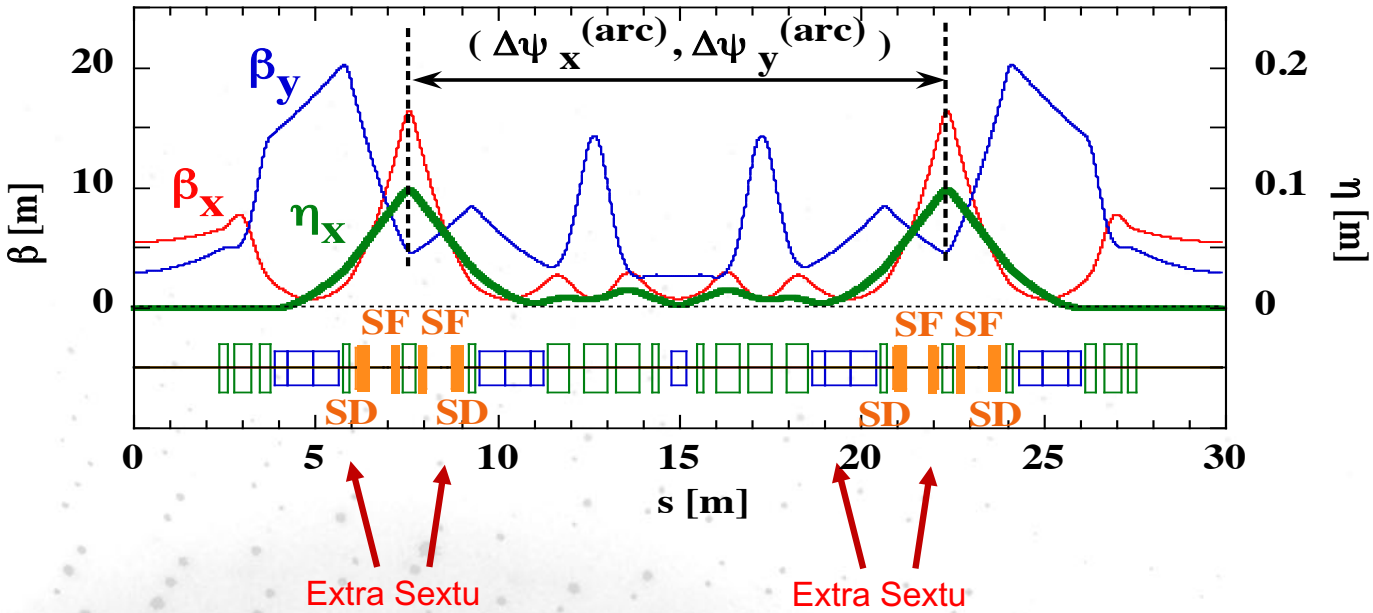
1: M. Borland et al., NAPAC16, WEPOB01.
2: L. Farvacque et al., IPAC13, 79.
3: M. Borland et al., IPAC15, 1776.
4: J.P.Delahaye et al., PAC89, 1611.
5: A. Streun, NIM A 737, 148 (2014).

SPRing8-II: H5BA, 6 GeV, 157 (100) pm.rad, N=40, 1435 m, 100 mA

Practical SR source to allow users to fully use photon performance

1. Chromaticities are compensated by sextupoles at dispersion bumps.
2. Phase advance between bumps is set to Nπ to cancel nonlinear kicks.

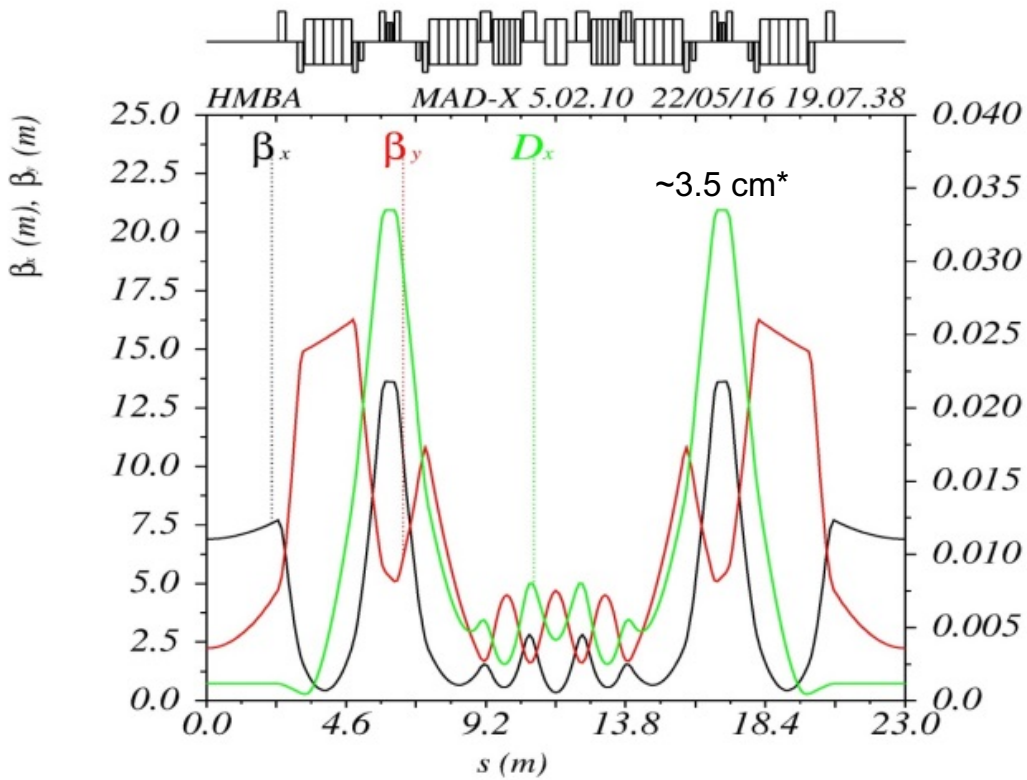
Privilege SACLA for short bunch



Longitudinal Gradient Bend (LGB)

- **Tuning knobs are limited**:
- - A series of sextupoles are closely distributed with each other inside bumps.
- - Phase advance between bumps **should be fixed.**
- - Betatron functions at straight sections should be kept small.
- - Tune at each cell cannot be changed a lot.
- Injection off (on)-axis

PETRA-IV: H7BA, 6 GeV, 12 pm.rad, N=72, 2304 m, 200 mA



Lattice based on HMBA Cells

- Arcs: 9 HMBAs cells to build a 45° arc
- 8 identical arcs
- Straight sections: FODO cells

Cell not yet optimized,
(small dynamic aperture) ✗

Dispersion peak: 9 mm → 3.5 mm
Quadrupoles (120 T/m) & sextupoles stronger
→ DA, MA smaller

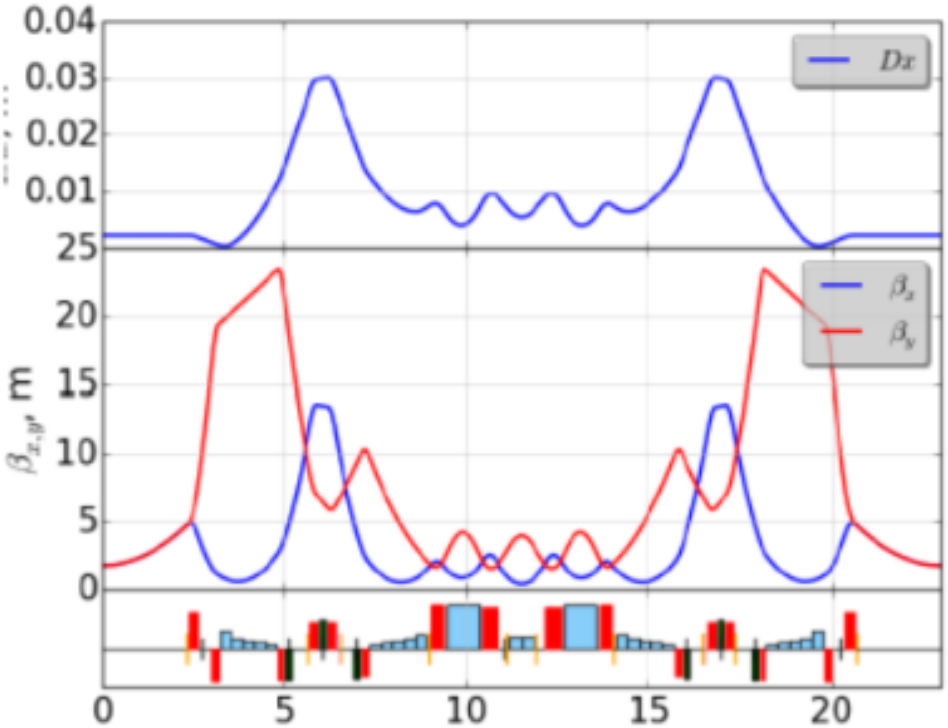
Try a more relaxed H6BA (or H5BA) cell and include
(vertical) damping wigglers to reduce emittance

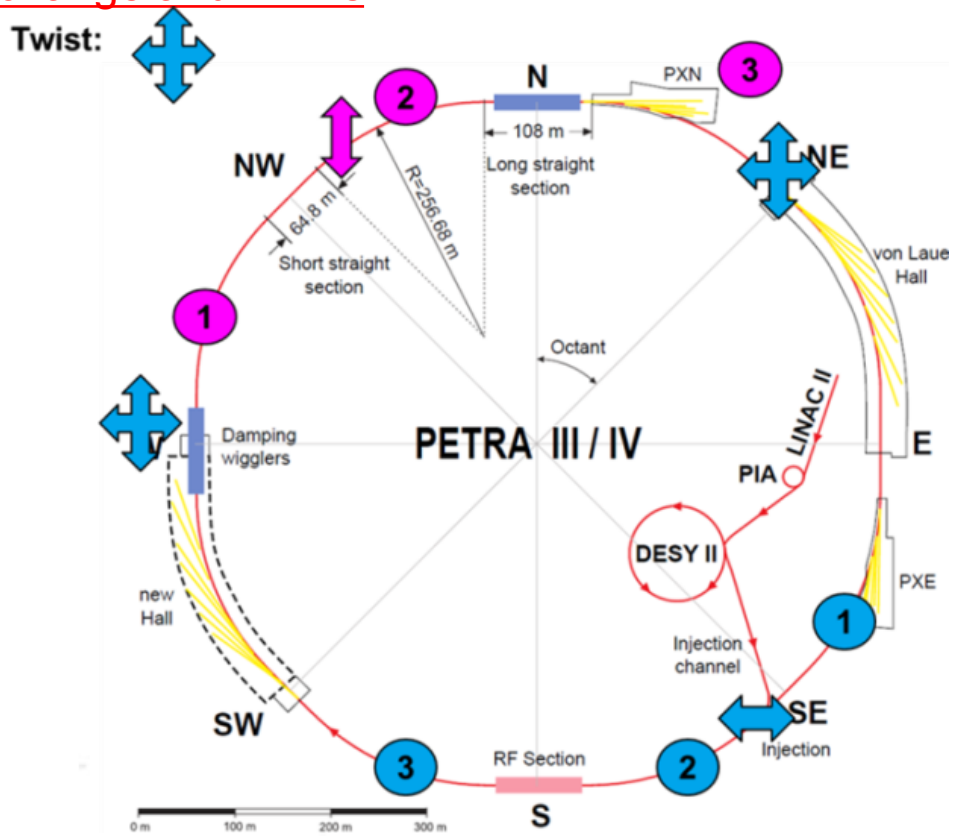
* 9cm for ESRF

FODO cells to connect arcs with matching triplets at both ends
Altogether 4 long (108 m) and 4 short (64.8 m) straight sections

PETRA-IV: H7BA, 5 GeV, 10-30 pm.rad (w/o DW), N=72, 2304 m, 100 mA

4D-phase space exchange and MBAs

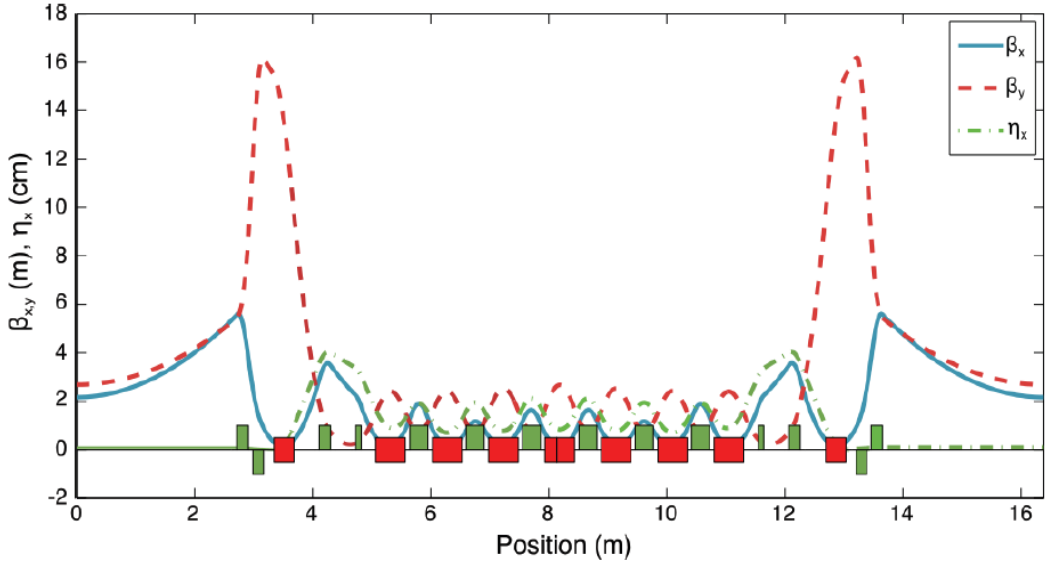




A lattice based on MBAs with non-interleaved sextupole pairs

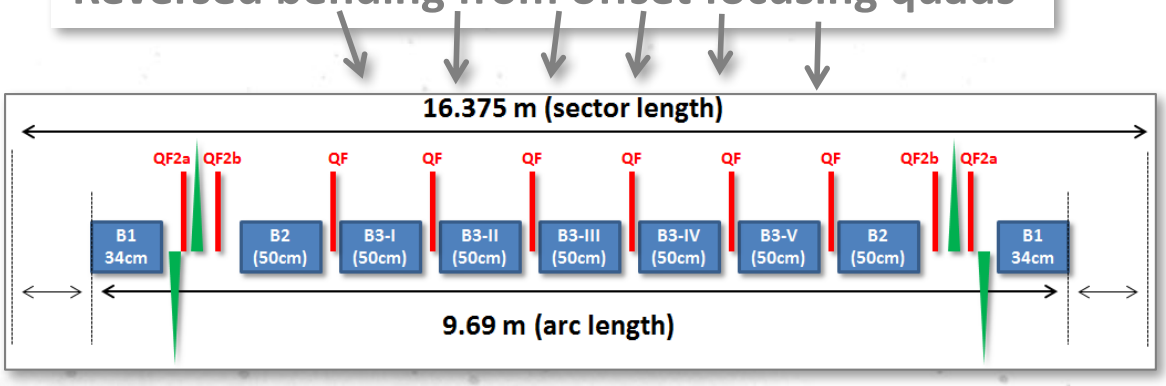
Emittance ~ 20/20 pm ✓
(5 GeV, wigglers not yet included)
Undulator cell not yet optimized ✗

ALS-U: H9BA, 2 GeV, 109 pm.rad, N=12 (4), 196 m, 500 mA



- Symmetric, bare lattice (no IDs, no SuperBends) emittance: $\varepsilon_{x0} = 109pm$
- w/ **full coupling**: $\varepsilon_x = \varepsilon_y = 71\ pm$
- … including additional damping from **ID's**: $\varepsilon_x = \varepsilon_y \sim 55\ pm$
- … including **IBS** (with Harmonic Cavities): $\varepsilon_x = \varepsilon_y \sim 65\ pm$
- Lifetime ~1hr

Reversed bending from offset focusing quads



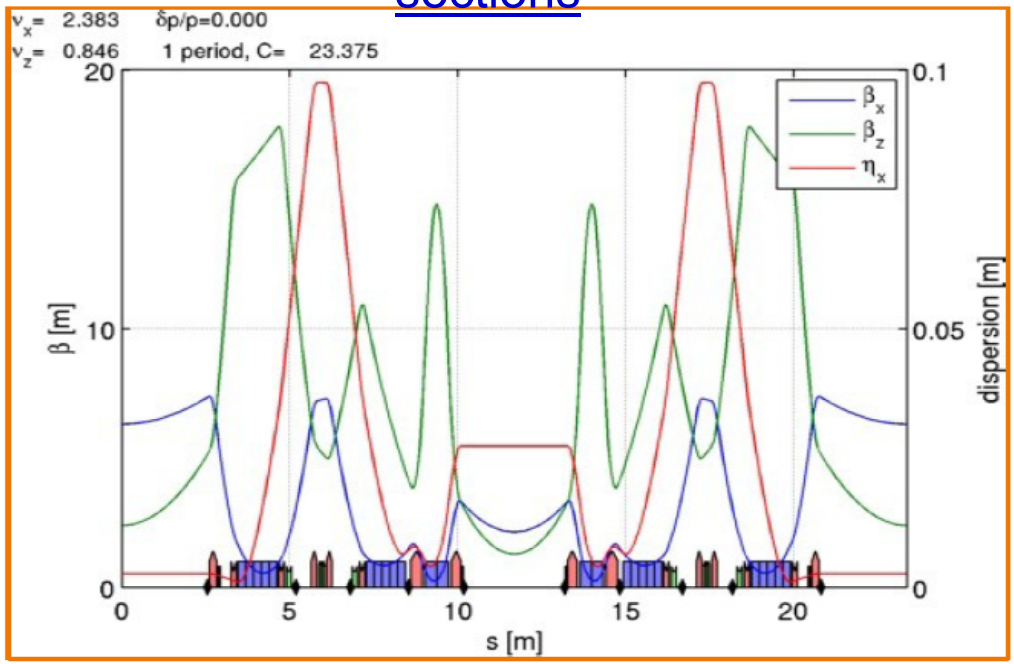
Super-bend
Injection: Swap-out

Longer magnet ➔ lower field-gradients
QF $K_1 \leq 13.2\ m^{-2}$ (88 T/m)
Central bend $|K_1| \leq 6.3\ m^{-2}$ (42 T/m)
Similar magnet designs as for the 9BA lattice

DIAMOND-II: DTBA/M6BA, 3 GeV, 100-140 pm.rad, N=24, 561 m

Diamond II design is striving to combine

low emittance and doubling the straight sections



Collaborative work DIAMOND/ESRF

Use the ESRF cell concept (7BA with longitudinal gradient dipoles) – **removing the mid dipole to make it a 6BA with a straight at the centre**

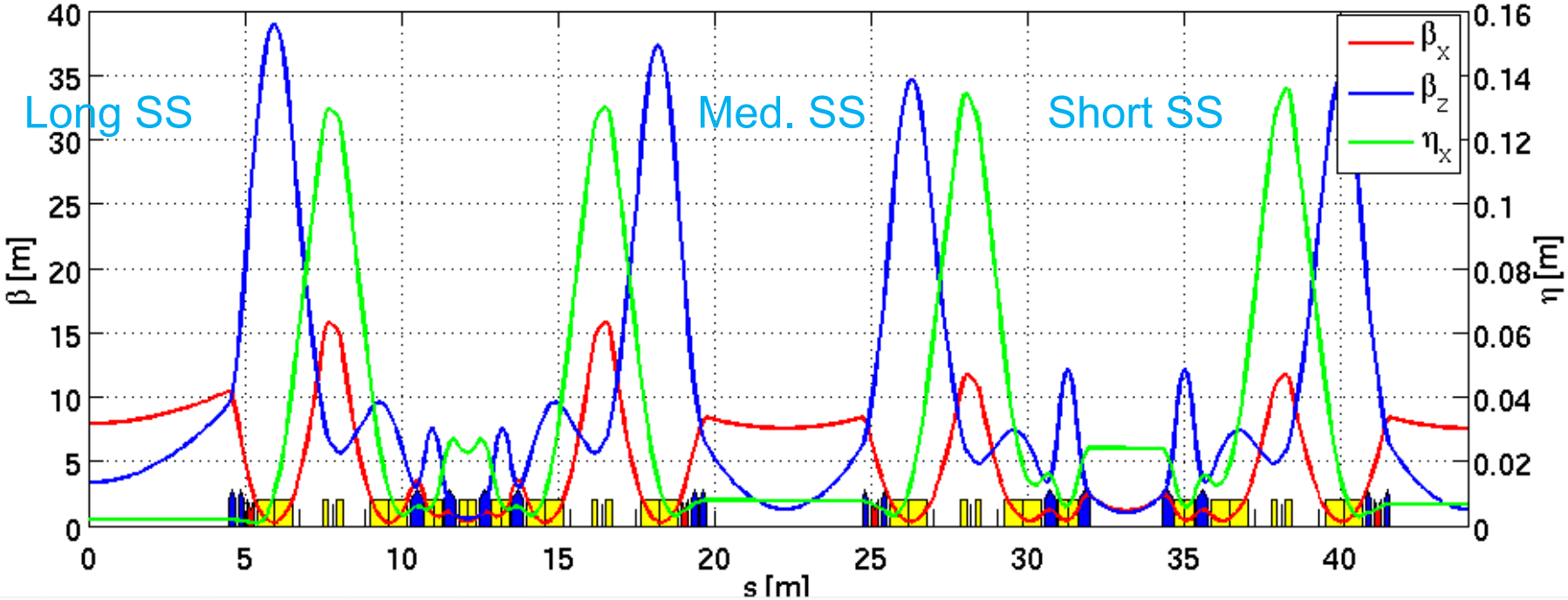
Longitudinal gradient dipoles + strong gradient dipole (up to 1.4 T 40 T/m)

~3 m mid-straight section

Off-axis injection

SS 8.0/5.2/3.0

SOLEIL-II: H6BA-H7BA, 2.75 GeV, 190-230 pm.rad, N=4 (16), 354.1 m



Very Compact lattice → Standard lattice do not apply: 24 straight sections

Off-axis injection

Straight Section length : 9 m, 5 m and 2.8 m Straight / Circumference ~ 32 % (45% today)

Main magnets : Bend : 0.6 T and 30 T/m No LGB, **Use of reverse-bend in dispersion bump**
Quad : 70 T/m max, Low Sext value : 700T/m^2

Conclusions

	Energy	circumference	emittance	emit/gamma^2	Lattice	Qx	Qy	Q'x	Q'y	Optics strain**	Cell length	Cell #
PETRA-IV	6	2304	10	7,3E-08	H7BA							NA
Pep-X	4,5	2200	30	3,9E-07	7BA	113,23	65,4	-162	-130	2,8	30	NA
Spring8-II	6	1436	67	4,9E-07	H5BA	108,1	45,6	-143	-147	4,3	30	40
APS-U	6	1104	41	3,0E-07	H7BA	95,1	36,1	-131	-122	4,7	27,6	40
ESRF-EBS	6	844,4	133	9,6E-07	H7BA	76,21	27,34	-109	-82	4,3	26,4	32
DIAMOND-II	3	561	120	3,5E-06	DTBA	58,18	21,31	-77	-118	7,3	22,6*	24
MAX-IV	3	528	328	9,5E-06	7BA	42,2	16,28	-50	-50	3,6	26	20
SIRIUS	3	518	240	7,0E-06	5BA	49,11	14,17	-119	-81	13,9	25,9	20
CLS-II	3	510	186	5,4E-06	7BA	37,22	10,32	-66,7	-40,4	7,0	24,3	21
SOLEIL-II	2,75	354,1	200	6,9E-06	H6BA-H7BA	39,12	14,24	-75	-85	11,4	22*	16
SLiT-J	3	350	600	1,7E-05	DDBA	29,21	9,28	-69,3	-41	10,5	21,9	16
SLS-II	2,4	290	100	4,5E-06	7BA	37,22	10,32	-66,6	-40,4	7,0	24,1	12
Elettra-II	2	259,2	250	1,6E-05	S6BA	33,2	9,3	-63	-50	10,2	12,6	12
ALS-U	2	196,8	109	7,1E-06	9BA	41,38	20,39	-64	-67	5,1	16,35	12

****Optics strain** = Qx'/Qx*Qy'/Qy

Compact & **Rigid** lattice **Exotic** magnets

TGB / LGB **Combined function** - magnets

Hybrid MBA more adapted for large storage ring (sextupole strength relaxed)

Relevant cell length is the one limited to magnetic structure

Anti-bend relaxes fairly nicely the constraints on the emittance and increases tunability

High periodicity is privileged for ultra-low emittance lattices

3-4 % LMA
Low MCF

Thank You for Your Attention

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