Helmholtz Zentrum Berlin

DETERMINISTIC DESIGN OF MULTIBEND HOA LATTICES

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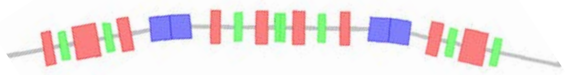
LAL 2022, Barcelona, June 28th, 2022

Stop fishing in the dark

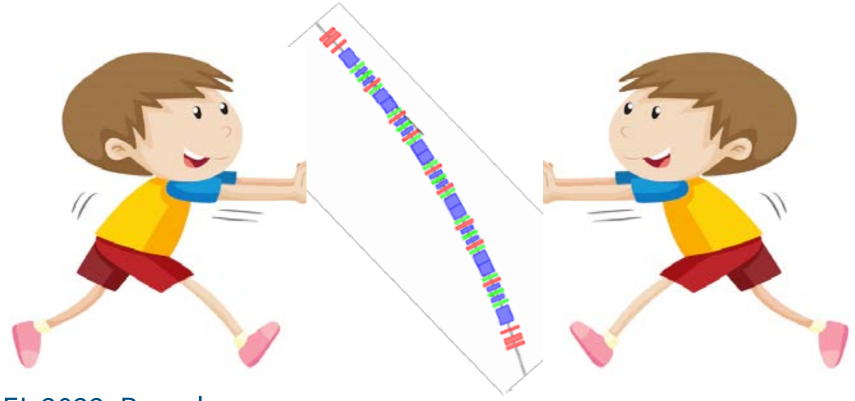
3rd generation light sources
Bessy II



2 dipoles
9 quadrupoles
7 sextupoles
19 drifts
Consider symmetry
=> 20+ parameters to optimize

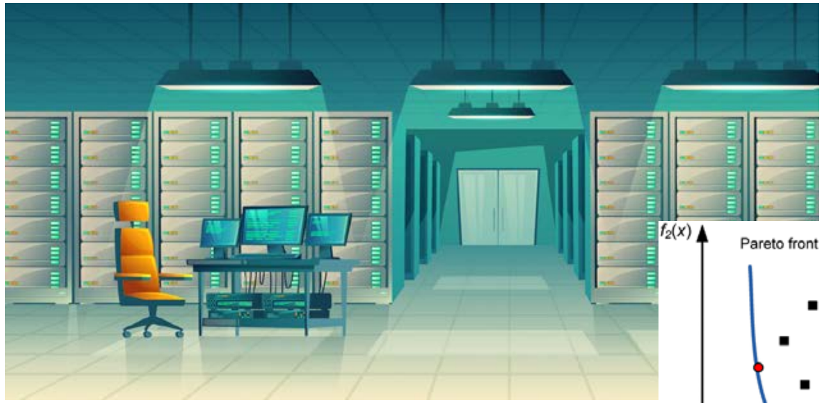
4th generation light sources
Bessy III

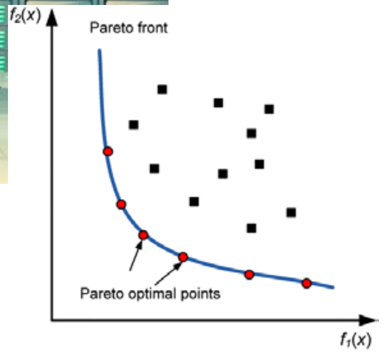
6 dipoles
10 reverse bends
24 quadrupoles
19 sextupoles, octuples?
~ 50 drifts
=> too many parameters to handle



OPTION A: Take existing lattice and push towards own needs and demands

OPTION B: Use Multi-Objective Genetic Algorithms





Both methods show good results, but:

You don’t know how close you are to the optimum.
There always *might* be an even better solution.

HZB approach: Deterministic Lattice Design

- ‘LEGO’-approach: Optimize smaller, generic subsections of the lattice individually
  Cuts down on the number of parameters
- Understand basic functionalities of elements in subsections
  Why a reverse bend? Combined function or separate function magnets? How to order the magnets?
- Deviation from strict ‘LEGO’ approach, asymmetries, injection straights, super bends …
  – all regarded as perturbations from the generic baseline lattice that do not alter the basic design choices

The layout of the talk

- Premises, goals, and limitations
- Optimization of the unit cell
- Optimization of the dispersion suppression cell
- Focusing towards the straight section
- First look at non-linearities
- Summary

Premises:

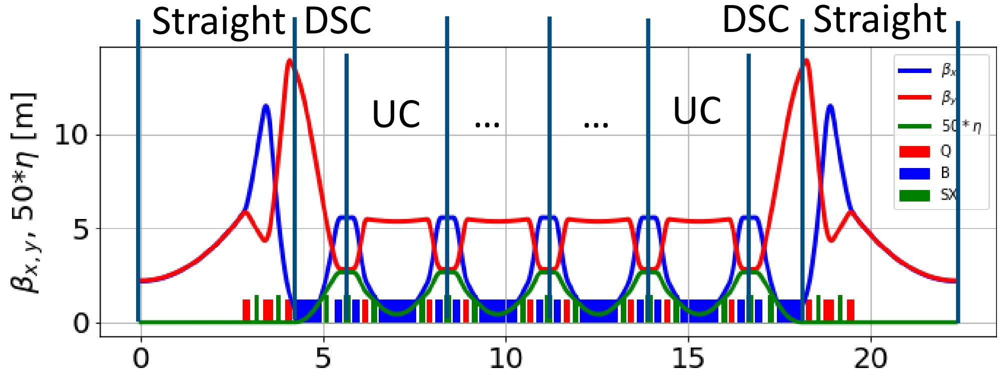
- **Multi-bend achromatic structure**
  repetitive unit cell,
  dispersion suppression cell,
  straight section
- **RB - Reverse bend**
  reduces emittance
  decouples dispersion from betas
  reduces length
- **HOA – higher-order achromat**
  Obey certain phase advance rules to cancel out 2nd and 3rd order driving terms

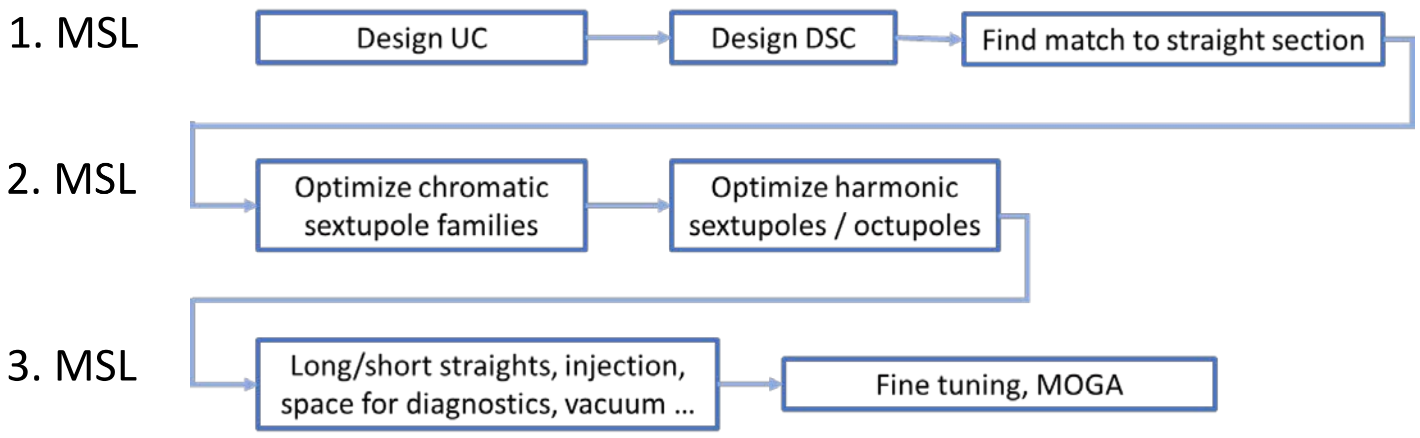
Goals:

- 2.5 GeV
- Diff. limited at 1keV
- Low emittance 100pm
- Moderate, positive α ~1e-4
- At least 16 straights
- 5.6m long straight sections
- Equal betas in straight, <3m

Limitations:

- Short circumference ~350m
- ‘Off-the-shelf’ technology
  (included from the beginning):
  Bends: 1.3T
  Gradient: 80T/m
  Sextupoles: 4000T/m²
  Drifts: 0.10m
- Homogeneous bend radiation for PTB (few bends for main stack holder)





The uniqueness of Unit Cell:

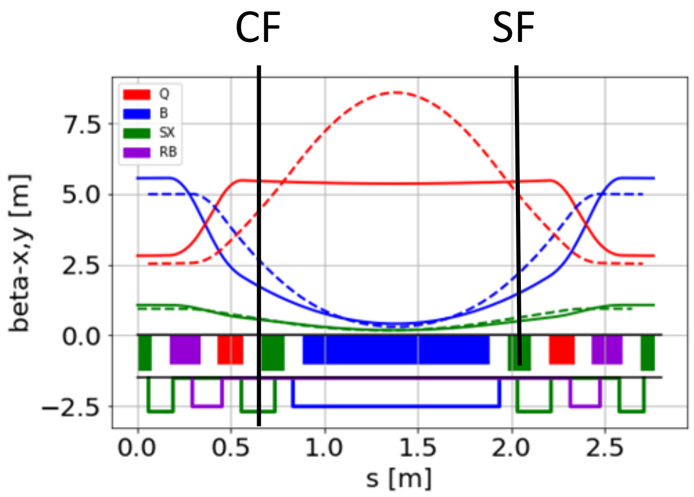
- Fix β_x, η at center, $\alpha_{x,y} = 0$ – 2 gradients => **unique solution**
- 2 phase advances (HOA) – 2 gradients => **unique solution**
- Freedom in dispersion by RB

Magnetic set up of the Unit Cell:

6 magnet permutations

a) include QD into the main bend or not (CF/SF)
b) place the RB or SF at the outside
c) (SF-UC) place QD or SD next to the central dipole

	Bend	UC type	ϵ	ξ_x	ξ_y	SF [1/m²]	SD [1/m²]
1	CF	SF last	96	-0.69	-0.37	-25.1	19.6
2	CF	RB last	96	-0.81	-0.27	-25.5	20.0
3	SF	SF last SD central	94	-0.75	-0.28	-17.8	10.2
4	SF	RB last SD central	94	-0.85	-0.22	-27.5	16.4
5	SF	SF last QD central	96	-0.75	-0.29	-18.6	15.4
6	SF	RB last QD central	97	-0.82	-0.25	-26.0	22.3



Explanation:
Better separation of beta-functions

For similar emittance and horizontal chromaticity, the SX-strength to compensate chromaticity can vary by a factor of >2! SF-UC has 40-50% lower SX-strength than CF-UC.

Higher-Order Achromat condition for Unit Cell:

- Condition on phase advance in UC:
  $\varphi_{x,y} / \mathrm{n} = \mathrm{N}$ n: number of UC, N: lower integer
- Prerequisite for large mom. acceptance and large aperture

- Natural phase advance φ_x ~ 0.4, φ_x ~ 0.1
- φ_x ~ 0.5 not achievable
- φ_x ~ 0.33 longer cell/higher emittance
  $\Rightarrow$ Need to build 6-bend
- 18, 20 super periods exceed circumference
  $\Rightarrow$ Need to build 16 SP

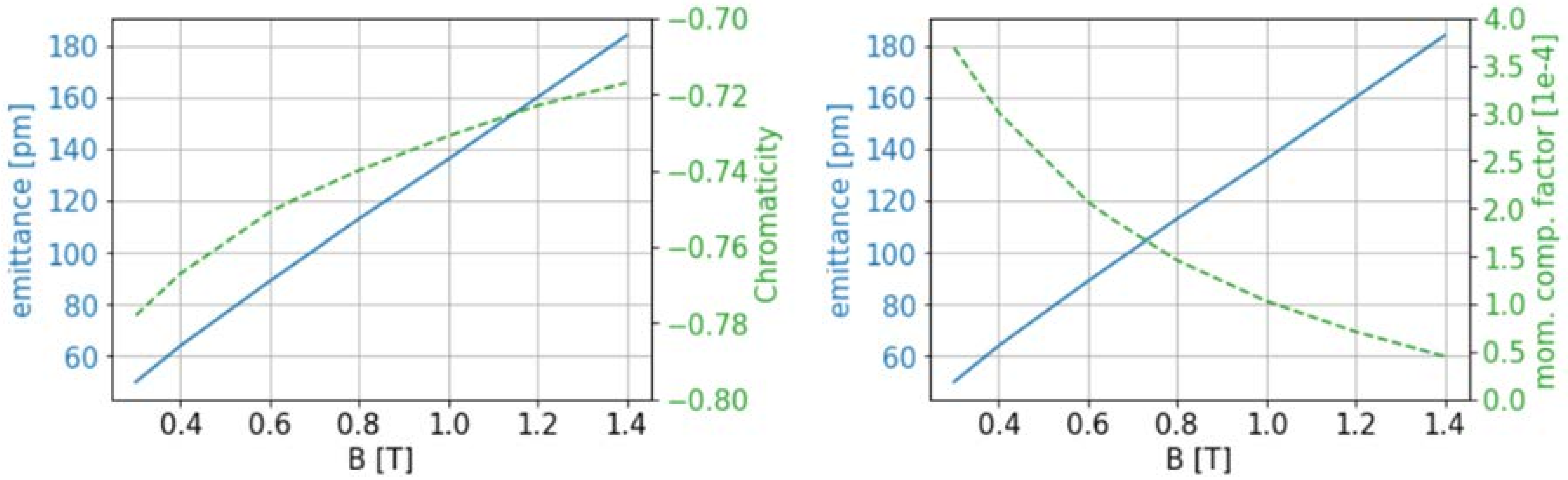
But: How to reach 100pm? Need to optimize dipoles!

Table 2: Summary of Lattice Options.

SP	bends per SP	θ [°]	$\phi_x/2\pi$ HOA	β_0 [m]	ε[pm] @$\eta = 0.004$
	7	3.75	0.33	0.66	271
16	6	4.5	0.40	0.40	246
	5	5.625	0.50	-	-
	7	3.67	0.33	0.64	215
18	6	4.0	0.40	0.39	196
	5	5.0	0.50	-	-
	7	3.0	0.33	0.63	176
20	6	3.6	0.40	0.39	162
	5	4.5	0.50	-	-

The conditions on the phase advance per unit cell is the strongest restriction in the design of the UC. Only a 16-period 6-MBA is feasible for BESSY III. (more bends show higher emittance due to necessarily larger β, η in dipole)

Field strength of main dipole: Change field/length of the dipole, fit HOA-condition (QD, QF), plot ε, ξ, α

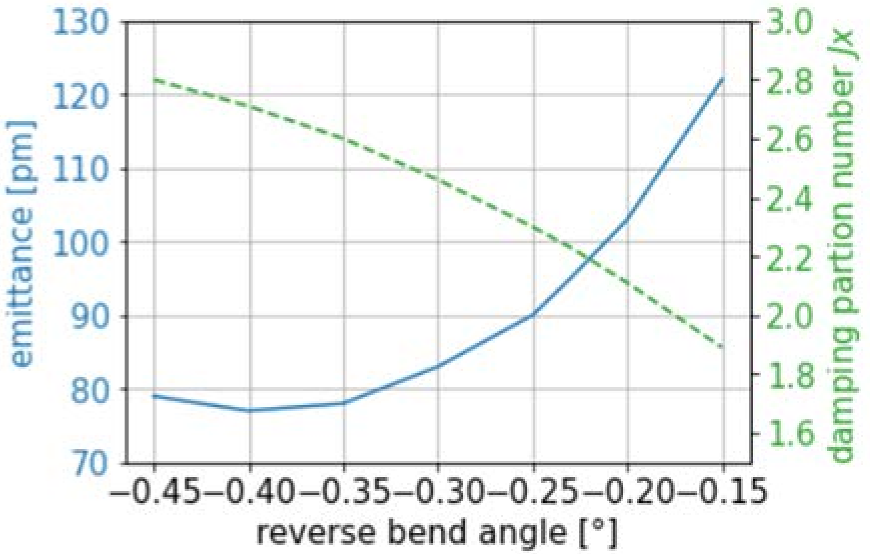


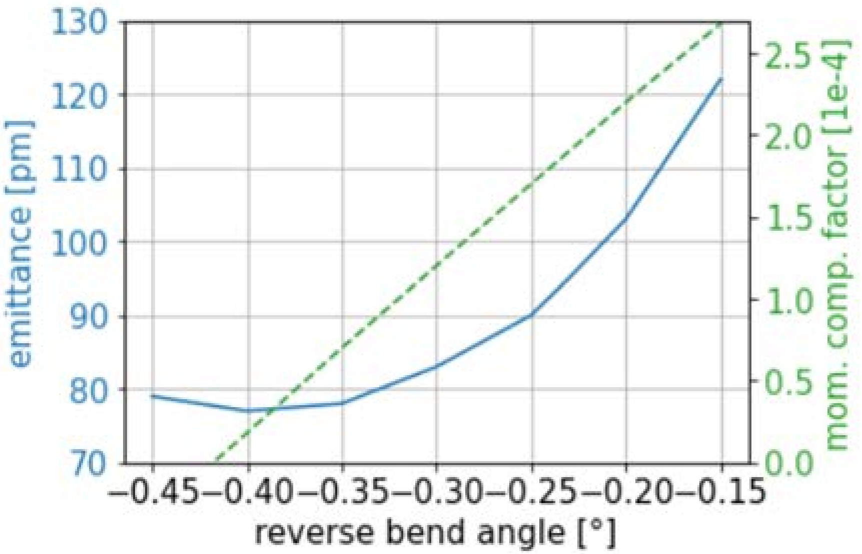
The emittance decreases by >70% for Δξ ~ 8%!   α: 0.5 10^{-4} –> 3.7 10^{-4}

Need α in UC ~2e-4   =>   B ~ 0.6T, L = 1.0m

Plus: Long dipoles relax the focusing - TME conditions: $\beta_{TME} = \frac{L}{\sqrt{15}}$ $\eta_{TME} = \theta \frac{L}{6}$ $\varepsilon_{TME} \propto \theta^3 \frac{2}{3\sqrt{15}}$

Field strength of reverse bend: Change displacement of RB/QF, fit HOA-condition (QD, QF), plot ε, α, J_x





The emittance decreases by >60%, but: $\alpha : 2.7\ 10^{-4} \ -> \ 0.4\ 10^{-4}$
Jx increases because Jx(main bend) decreases
Keeping α *~ 2e-4 limits the RB displacement (as well as technical limits) => RB ~ 0.225T*

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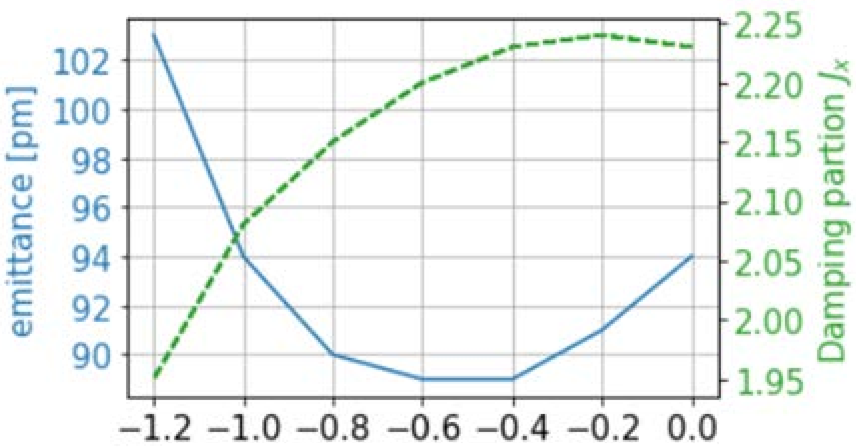
Combined function magnet - revisited: Increase gradient in main bend, fit HOA-condition (QD, QF), plot J_x ε



Damping partition number:

$$J_x = 1 - \int_0^C \frac{\eta}{\rho} + 2k\eta\rho \, ds$$

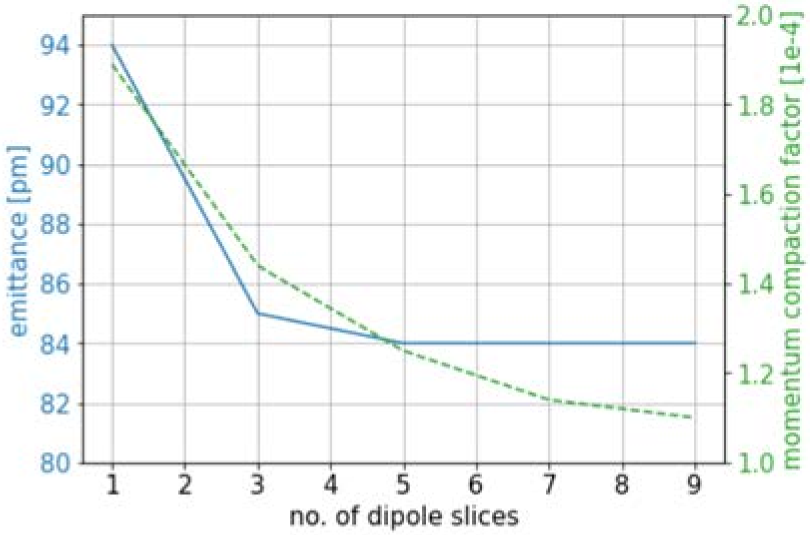
The damping partition number of the UC decreases (!) with raising gradient in the main bend.

Why? The contribution to J_x of the gradient is small compared to that of RB. (~0.3 per dipole, ~160 per RB)
The smaller field of QD leads to a smaller η and k of RB.

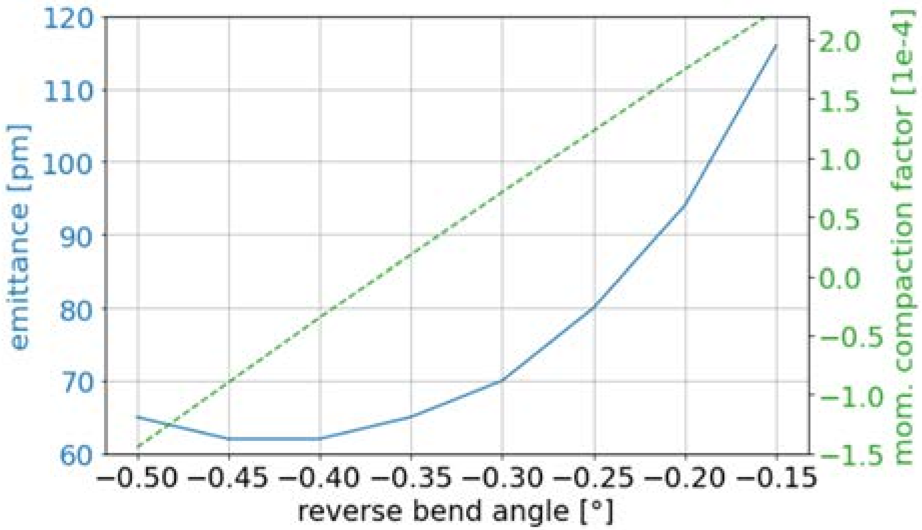
The benefit of a gradient dipole is therefore disputable when an RB is used.

Longitudinal gradient bend:

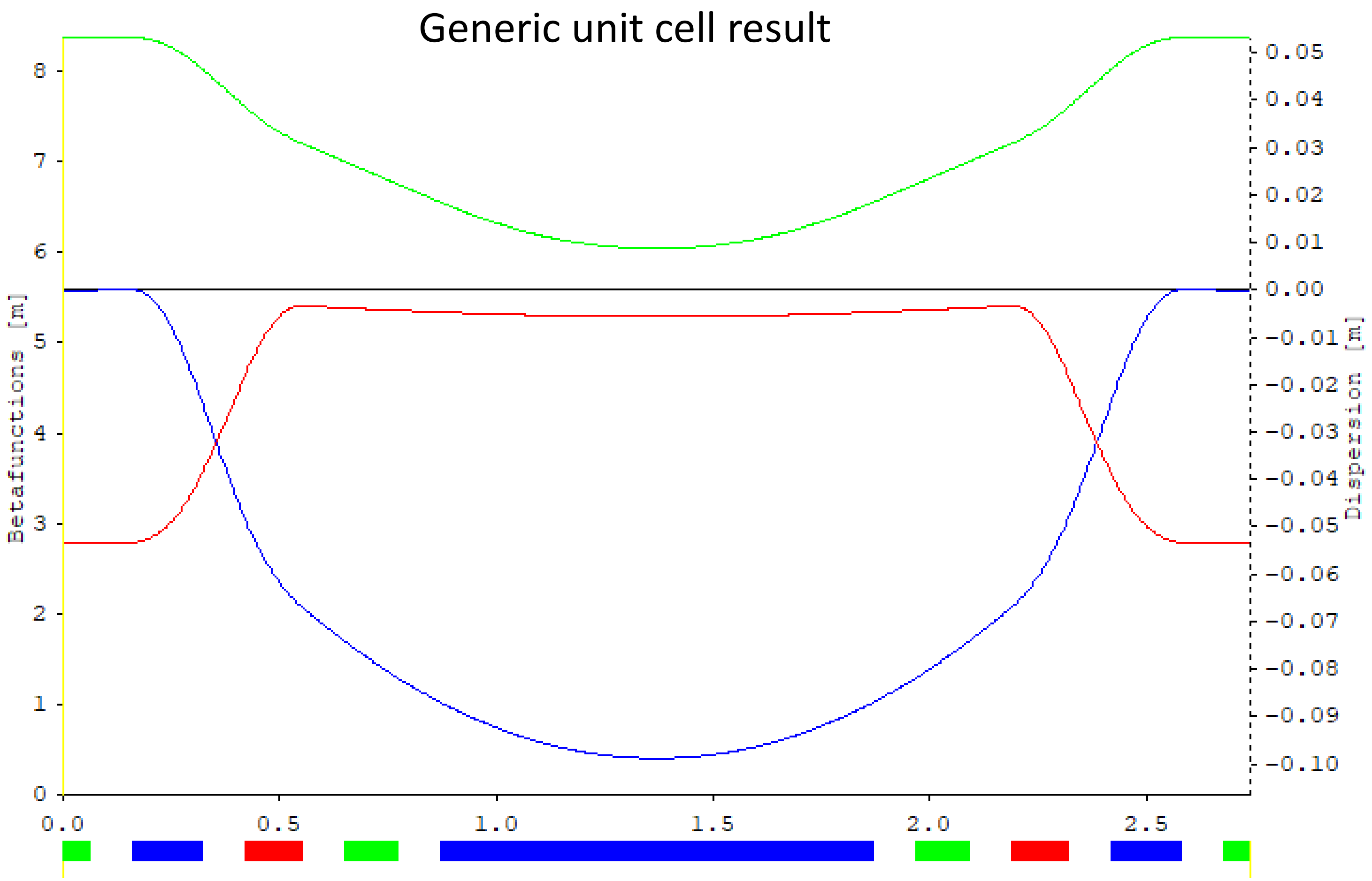
Split main bend into slices, optimize field distribution with OPA, fit HOA-condition (QD, QF), plot ε, α. For 3 slices, vary RB field.



β_0 is fixed by the phase advance
η_0 is fixed by the RB
More slices for fixed RB field don't help



50% emittance gain for increased RB field.
Limited by decreasing α.



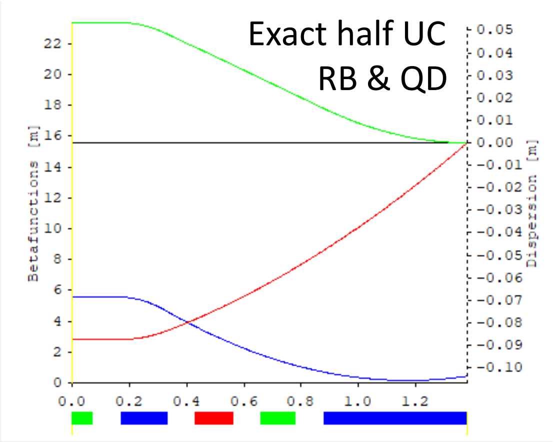
L [m]	2.76
θ [°]	4.0
θ_{abs} [°]	4.92
ε [pm]	95
ε_{TME} [pm] (main bend only)	93
α	1.90e-4
ξ_x, ξ_y	-0.75, -0.28
J_x, J_y	2.23, 1.0
β_{x0}, β_{y0}	0.4, 5.4
η_0	0.0088

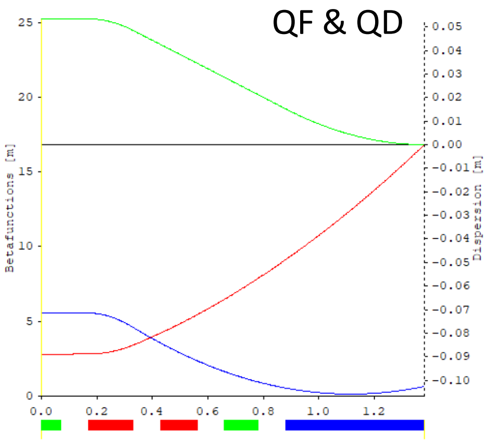
Dispersion Suppression Cell:

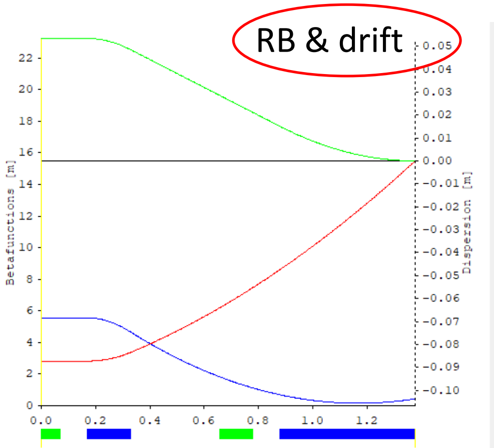
- Guideline: As close as possible to half unit cell – to keep phase between SX
- Boundary conditions unit cell & η, $\eta' = 0$ => 2 parameters for fitting => unique solution

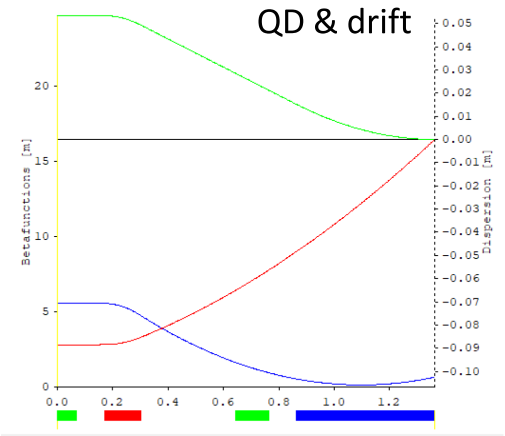
	emittance [pm]	α [10^{-4}]	RB/QF [1/m²]	QD [1/m²]	drift [m]
RB and QD	172	0.72	6.77	0.13	0.1
QF and QD	272	2.23	7.26	0.14	0.1
RB and drift	172	0.72	6.85	-	0.33
QF and drift	273	2.26	8.98	-	0.34

β-functions are similar, emittance lower with RB, QD has a negligible (positive!) gradient









Effect of a gradient in DSC-dipole:

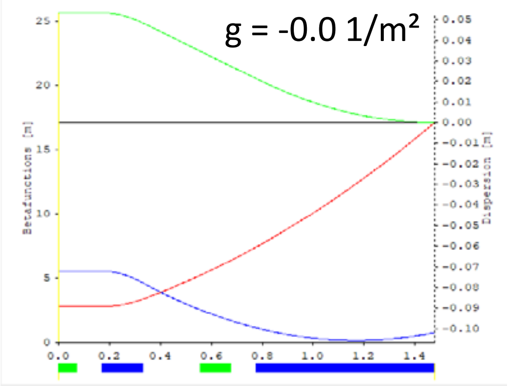
- Homogeneous bend for PTB in UC
- Increase length to 70cm (technical feasibility)

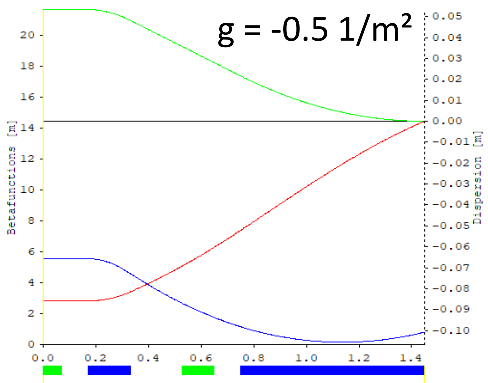
gradient [1/m²]	emittance [pm]	α [10^{-4}]	RB [1/m²]	ML1B/UL1 [m]	ξ_x	ξ_y
0.0	127	0.41	6.86	0.23/0.00	-1.41	-1.08
-0.5	121	0.42	7.17	0.20/0.04	-1.45	-0.88
-1.0	116	0.43	7.49	0.18/0.11	-1.51	-0.72
-1.5	111	0.43	7.82	0.15/0.23	-1.55	-0.61

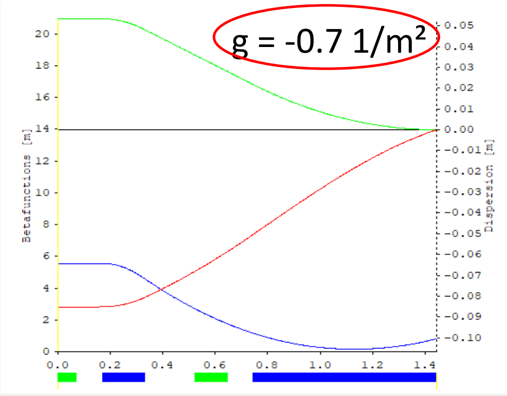
The gradient lowers the emittance (no conditions on phase advance) and β_y, α_y towards straight => lower chromaticity

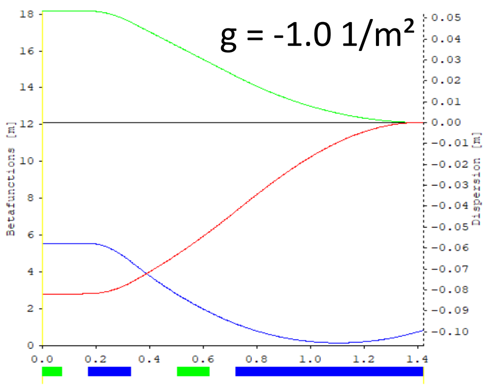
(For the calculation of α and ξ, the contribution of a generic triplet is taken into account.)

L_B = 0.7m







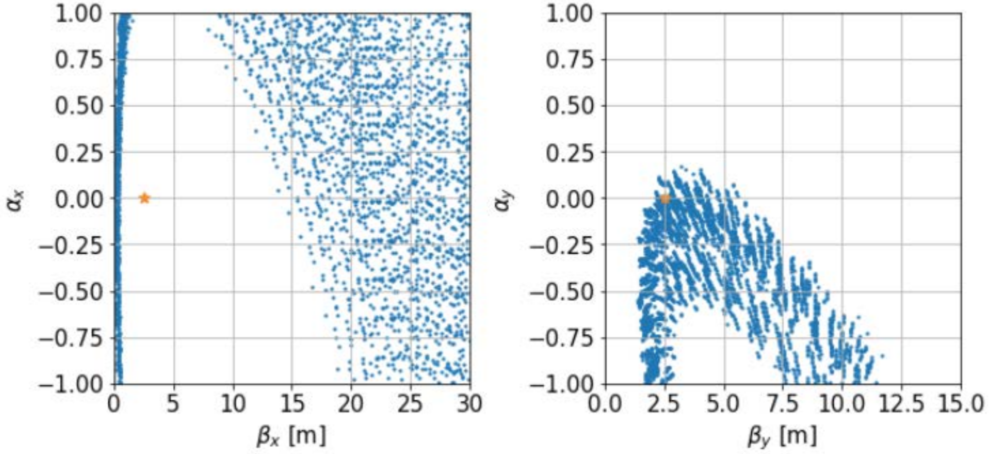


Use numerical scan:

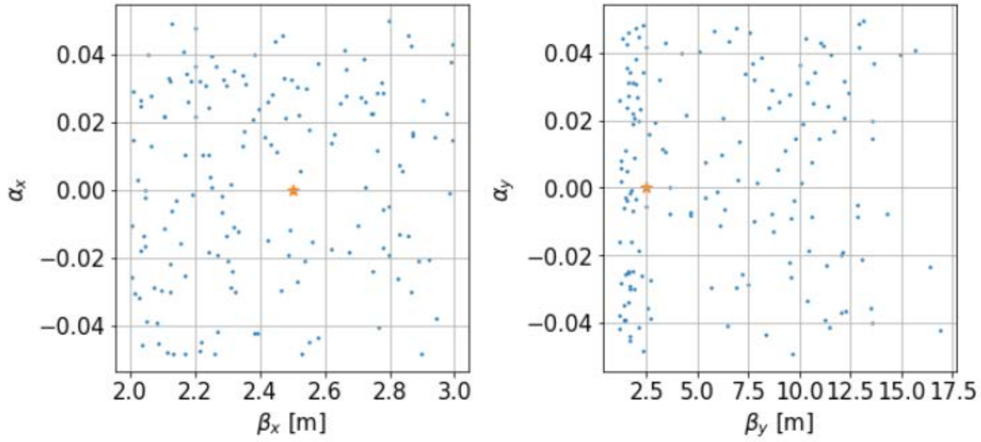
- Boundary condition of DSC, and straight section

- Scan over drift lengths and gradients
- Analyze results graphically
- Select solutions close to $\beta_{x,y} = 2.5\text{m}$, $\alpha_{x,y} = 0$
- Some re-fitting with optics program

- Try doublet: 2 gradients, 2 drifts
- Try triplet: 3 gradients, 3 drifts

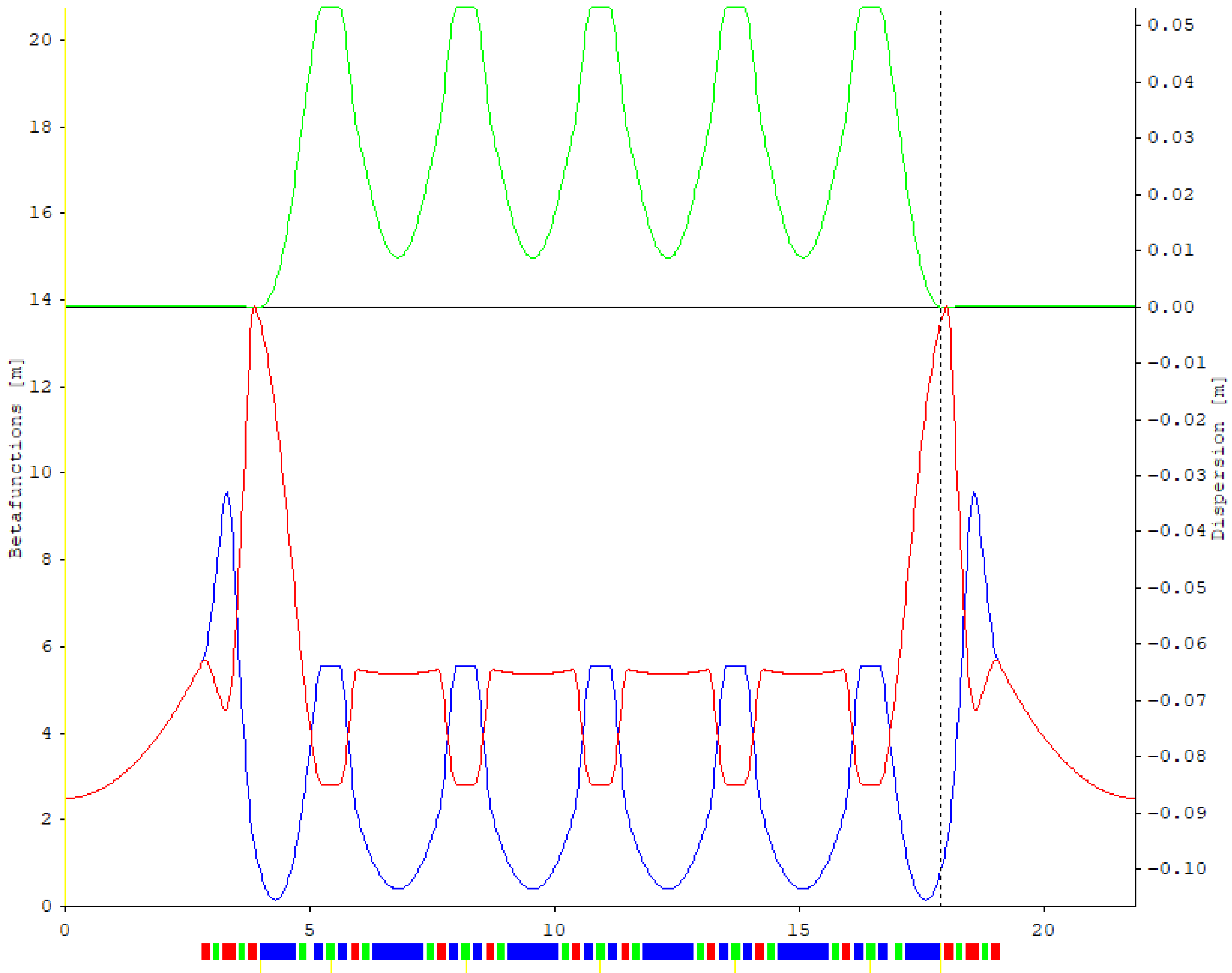


Doublet: No solution for β_x



Triplet: Chose the appropriate solution, f.e lowest chromaticity

The composition of LEGO Blocks now yields a baseline lattice, that fulfills all demands
=> First milestone lattice



L [m]	350.06
Q_x / Q_y	44/13
ε [pm]	101
α	1.17e-4
ξ_x / ξ_y	-95, -44
J_x / J_y	2.06, 1.0

Chromaticity compensation – 2 chromatic sextupole families:

- No harmonic sextupoles, no octupoles

CrX lin		0.00	-0.03
CrY lin		0.00	0.01
Qx	H21000		5.45
3Qx	H30000		2.00
Qx	H10110		4.84
Qx-2Qy	H10020		14.86
Qx+2Qy	H10200		3.37
2Qx	H20001		2.48
2Qy	H00201		0.64
Qx	H10002		0.03
CrX sqr		0.00	191.40
CrY sqr		0.00	46.13
dQxx		0	-147508.
dQxy,yx		0	-62118.4
dQyy		0	-33487.2

Driving term by OPA

SD = -29.9 1/m²
SF = 17.0 1/m²

Chromaticity compensation – 4 sextupole families:

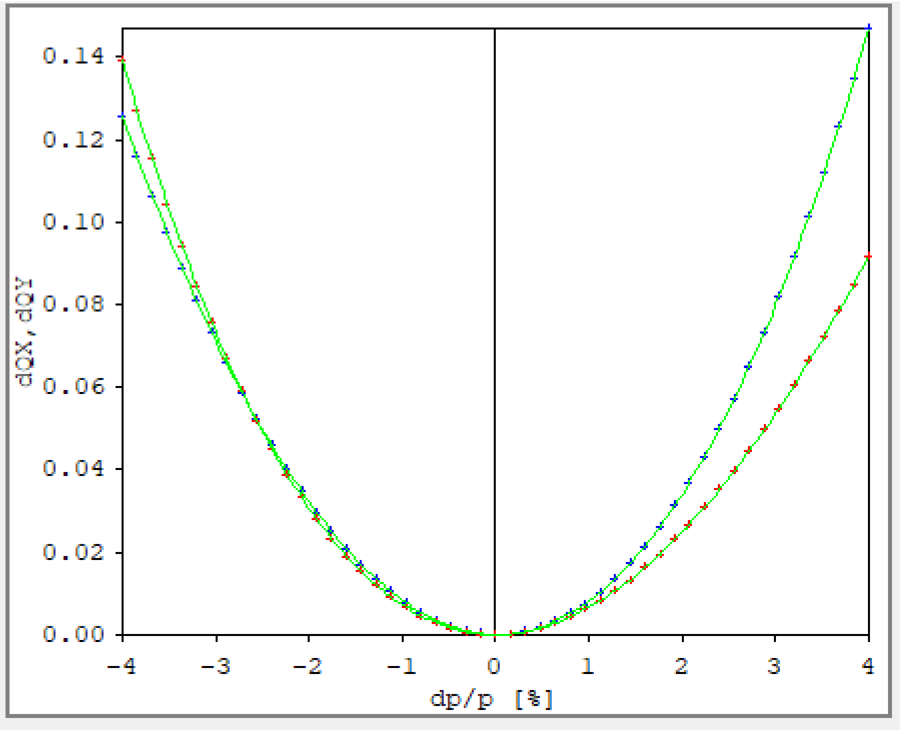
- No harmonic sextupoles, no octupoles

CrX lin		0.00	-0.03
CrY lin		0.00	0.01
Qx	H21000		21.18
3Qx	H30000		7.42
Qx	H10110		6.02
Qx-2Qy	H10020		11.19
Qx+2Qy	H10200		9.46
2Qx	H20001		0.84
2Qy	H00201		0.77
Qx	H10002		0.03
CrX sqr		0.00	64.69
CrY sqr		0.00	76.98
dQxx		0.00	3085.77
dQxy,yx		0.00	8272.42
dQyy		0.00	-33651.98

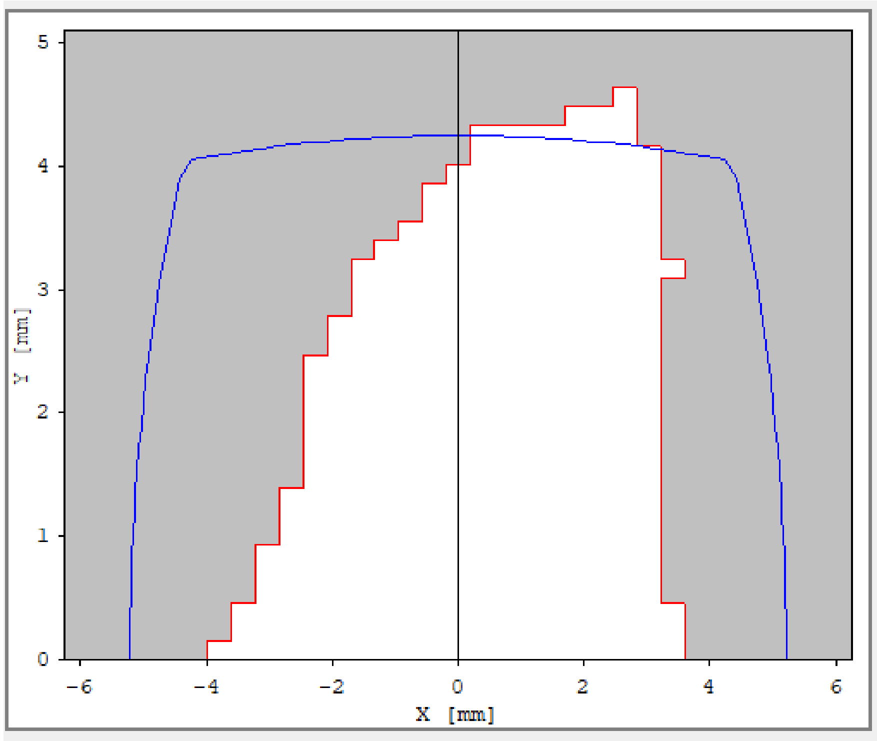
4 SX-families suppress the TS with momentum as well as the TS with amplitude

SD1 = -26.7 1/m²
SF1 = 12.6 1/m²
SD2 = -39.8 1/m²
SF2 = 23.9 1/m²

- No harmonic sextupoles, no octupoles



Momentum acceptance 3-4%



Initial dynamic aperture ($\beta_{x,y}$ = 2.5m)

Summary and conclusion

- Careful analysis of the substructures of MBA lattices leads to a better understanding of design options
- Promising baseline lattices can be deterministically constructed
- Technical feasibility should be included from the start
- Reducing the sextupole strength in the linear optimization yields promising non-linear properties
- Splitting of chromatic sextupole families is mandatory (≧4)

We are not finished:

- Octupoles and/or harmonic sextupoles
- Tune scan
- All drifts are 0.1m – can we improve by variation?
- Need for injection straight? Super-bend? …..
- …
- MOGA for fine tuning

I’m really sorry that I couldn’t join this workshop and I hope that you are having a good time, fruitful discussions, and a great dinner!
I’m looking forward to Paul’s report!
Bettina