The BESSY III Lattice

A highly competitive non-standard lattice for a 4th gen. Light Source
with Metrology and Timing Capabilities

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(K. Holldack, Z. Hüsges, K. Kiefer, A. Meseck, R. Müller, M. Sauerborn, O. Schwarzkopf, J. Viefhaus et al.,)

Combined function
or
Homogenous bend

Overview - The Menu

- What is currently going on…
  - HZB with BESSY II & MLS (PTB)
  - BESSY II+ with focus on operando capabilities, modernization & sustainability

- BESSY III
  - Overview, Goals, Planning, Parameters
  - **Towards a BESSY III design lattice**
    A Metrology Solution,
    an unconventional, but competitive approach

Two partners & two synchrotron radiation sources

Fernsehturm am Alexanderplatz

HZB Helmholtz Zentrum Berlin

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

BESSY II

1.7 GeV, DBA,
5 nm rad, 300 mA
240 m, 16 Straights, 5 m
since 1998

Soft and tender X-rays
Spectro-Microscopy
Timing: low α, femto-slicing
SB, VSR, TRIBs/2-Orbits

MLS Metrology Light Source

630 MeV, DBA
100 nm rad, 200 mA
48 m, 4 Straights
since 2007

THz / IR to VUV, EUV
Optimised for low α,
SSMB studies

Solar Energy	Chemical Energy	Quantum & Functional Materials
Photon Science	Accelerators	Scientific Instrumentation & Support


Lithography Optics Division

CARL ZEISS SMT

Acknowledgment

Thanks to a huge team effort at…

- FOM-Rijnhuizen
- TNO TPD
- PTB-BESSY
- IWS Dresden
- Philips
- Heidenhain
- The teams at ASML and Zeiss
- …and many others

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ZEISS ASML HZB BESSY II Light Source

BESSY III - The triad for a world leading facility for material discovery

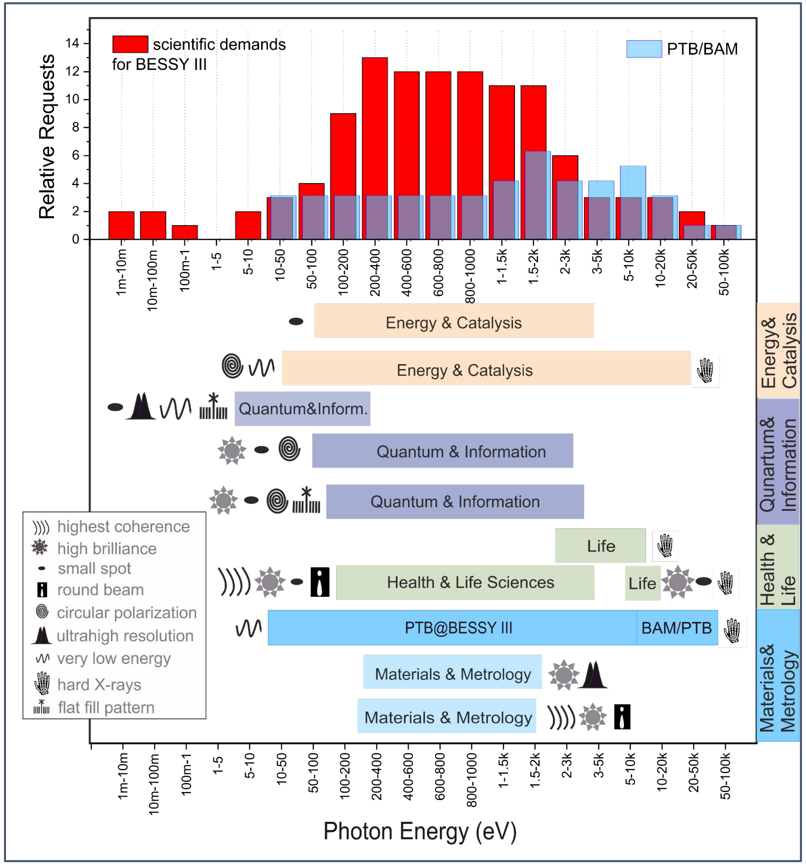
① a globally competitive 4th generation synchrotron radiation source

② embedded in the integrated research campus Berlin-Adlershof

③ dedicated to metrology and metrological materials science

Combined function or Homogenous bend

BESSY III Requirements & Objectives



Facility parameters

1. 1^{st} undulator harmonics polarized up to 1 keV from conventional APPLE-II
2. Diffraction limited till 1 keV
3. Stay in Berlin-Adlershof
4. Nanometer spatial res. & phase space matching
5. PTB/BAM metrology applications

Already at BESSY II, a 3rd generation **without** combined function bends

Ring parameters

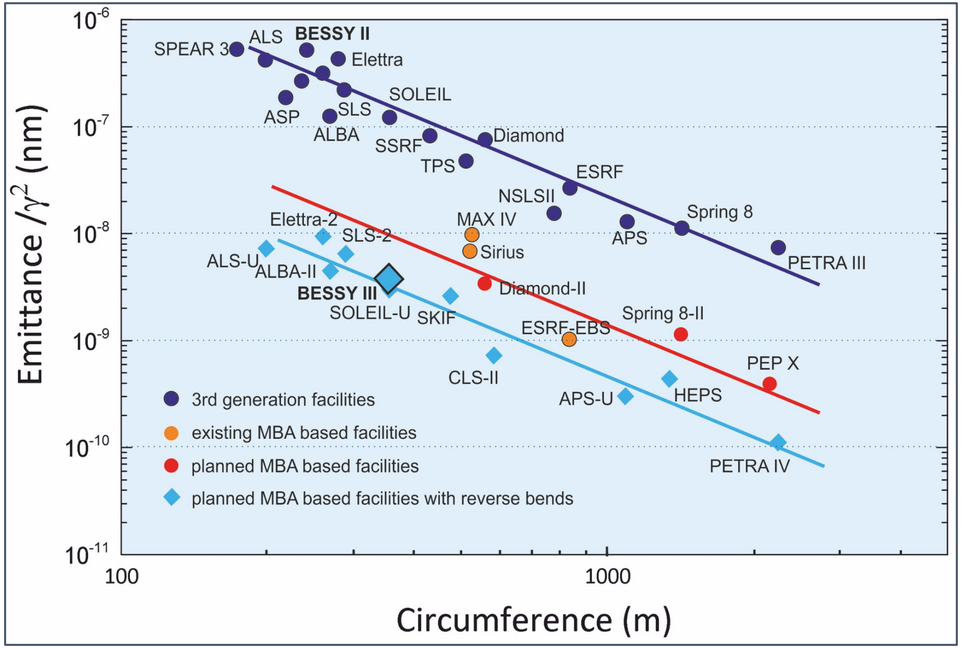
1. Ring Energy **2.5 GeV** (1.7 GeV)
2. Emittance **100 pm rad** (5 nm rad)
3. Circumference **350 m**
   16 straights @ 5.6 m
   (240 m @ 4.5 m)
4. Low beta straights & maybe round beams
5. **Metrology source Homogenous bends**
   Measuring the field at the source point with a NMR probe in a volume of 10x10x10 mm

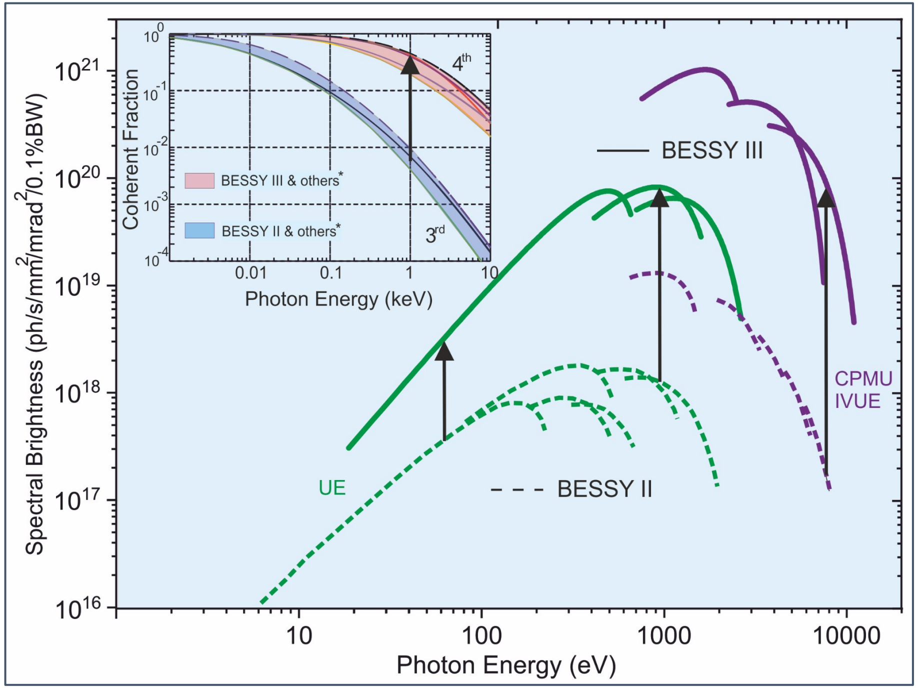
1-2 bends per arc

6. Momentum compaction factor **> 1.0e-4**

BESSY III

100x times more brightness than BESSY II &
1000x times smaller focus at sample (10µm down to 10nm)





In situ & operando, sample environment, material labs → **Integrated Research Campus**

Overview - BESSY II+ / III

Towards BESSY III by using BESSY II, BESSY II+

BESSY II+ paves the way to BESSY III

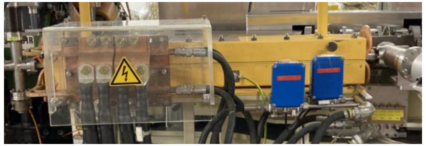
BESSY II+ application/project: operando capabilities, modernization, and sustainability.

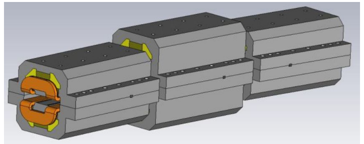
100 M€ (25 % HZB, 25% strategic partners or third-party projects, 50 % request funding bodies) split up in

- 50 % for 8 new beamlines, endstations & sample environment, → Future BESSY III Science Case
- 15 % for improving the sustainability of BESSY II, → BESSY III Hardware / Tech.
- 35 % modernization of the accelerator complex

Active Higher-Harmonic Cavities together with ALBA & DESY – first beam test in BESSY II now !

Hybrid-Permanent Magnets
– replace power hungry (30 kW) bending electromagnet in BESSY II transferline
– metrology suitable PM dipole





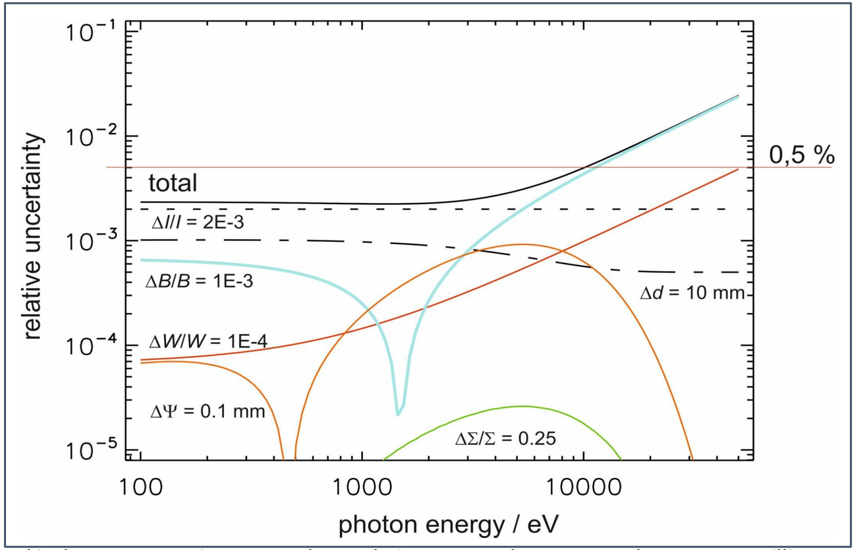
PTB (Physikalisch Technische Bundesanstalt) - Metrology Sources, Homogenous Bends

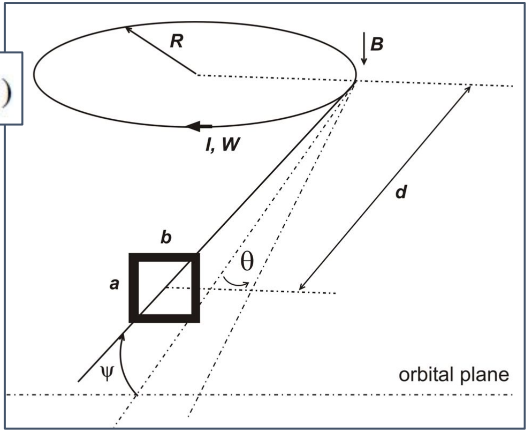
An absolute measurement of the radiation power with highest accuracy

- Schwinger equation with its parameters
  - Electron Energy W with rel. unc. < 5e-4
  - Electron Current I with rel. unc. < 2e-4
  - Magnetic Field B with rel. unc. < 1e-4
  - Source size & div. with rel. unc. < 20 %
  - Distance to apert. with rel. unc. ~ 2 mm

R. Klein et al., Phys. Rev. STAB 11 (2008) 110701

$$\Phi_\lambda = \Phi_\lambda(\lambda; W, B, I, \Sigma_y; y_0, d, r)$$





BESSY III Lattice Design

A Metrology Solution,
an unconventional, but competitive approach

4th Generation Lightsource Lattices

The Higher Order Achromat, HOA-MBA

- MAX IV, SLS 2.0 … up to 3 GeV
  - A. Streun, J. Bengtsson, S. Leeman, et al.

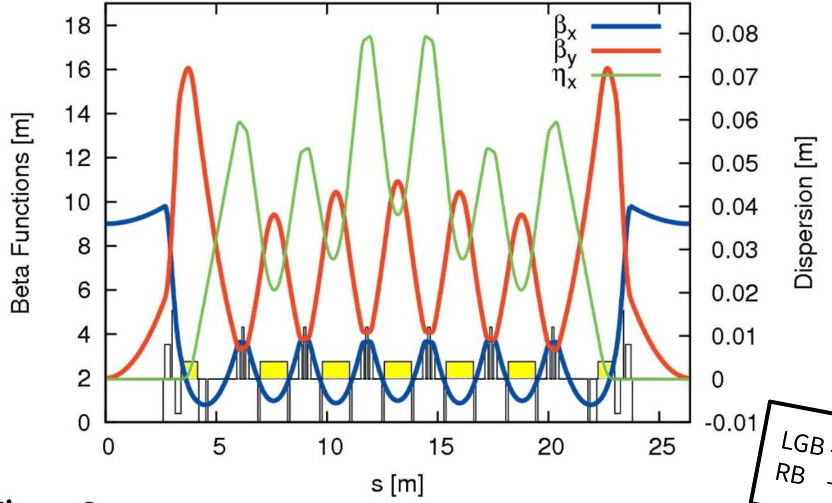
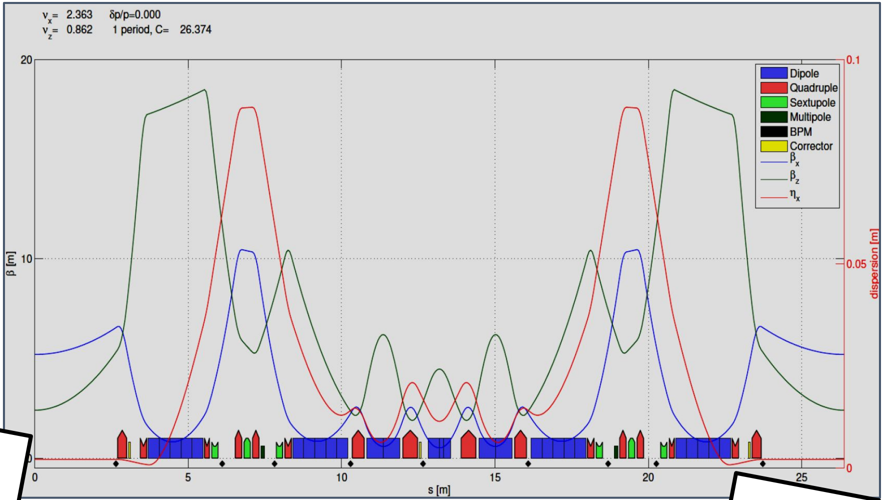


Figure 3
β functions and dispersion for one achromat of the MAX IV 3 GeV storage ring. Magnet positions are indicated at the bottom.

LGB - no
RB - no

The Hybrid, HMBA

- ESRF-EBS, PETRA IV … above 3 GeV
  - P. Raimondi



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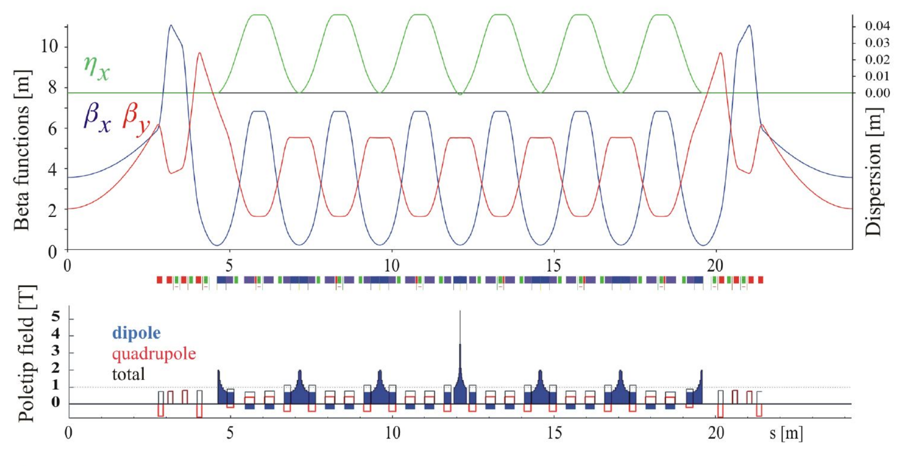
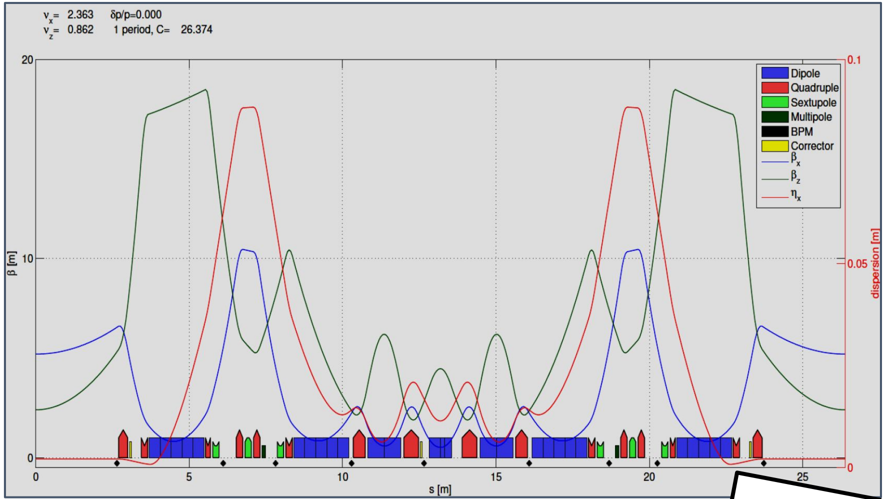


Figure 2.3: Optical functions and field components for one 7BA-arc where the center LGB has been interchanged by a super-LGB of 5.5 T peak field. Bending magnets are in dark blue, quadrupoles red and sextupoles green.

LGB - yes
RB - yes

The Hybrid, HMBA

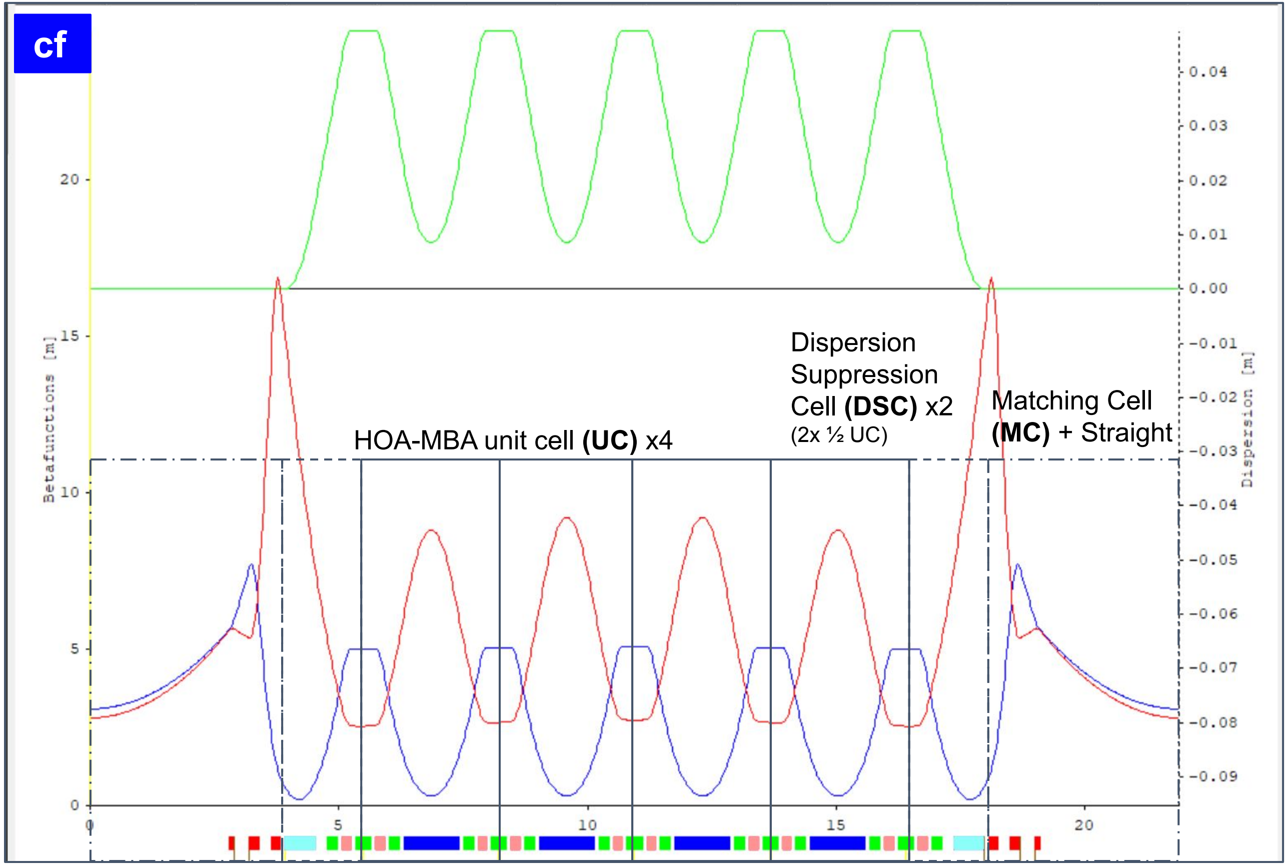
- ESRF-EBS, PETRA IV … above 3 GeV
  - P. Raimondi



LGB - yes
RB - no

HZB BESSY II Light Source

LEGO Approach - Basic building blocks of one sector



UC - Unit Cell
DSC - Dispersion Suppress..
MC - Matching Cell

A 6-MBA has 5-MBA-UC
4 pure UC and
1 (2 x ½) broken UC → DSC

16 straights & sectors:

360° / 16 = 22.5° per sector
4*4.5° main UC bend &
2*2.25° DSC bend

The process towards a BESSY III lattice - metrology challenge

A deterministic lattice approach

- Stepwise: Power and Function of each Component &"Knob" → **LEGO approach**
- After first "wild" lattices we concluded on:
- **Limiting the hardware** (conservative ansatz)
  - Bore diameter of 25 mm
    Diameter inner/outer vac. pipe of 18/21 mm
  - Bends up to 1.4 T
  - Combined fct. Bend 0.8 T & 15 T/m or 30 T/m
  - Quads up to 60 - 80 T/m (depends on RB)
  - Sextupoles up to 4000 T/m^2
  - Spacing between magnets 100 mm
- **H**igher**O**rder**A**chromat Approach:
  - 6MBA + **homogenous metrology bend**
  - With Reverse Bends, so far no LGBs

A homogenous metrology bend

- Include it right from the beginning
  → Symmetric sector cell ansatz
- Two lattice candidates:
  - **cf**-lattice: combined function bend
    In center of 6MBA (community standard)
    sf - **cf - cf - cf - cf** - sf
    cf - **cf - cf - cf - cf** - cf
  - **sf**-lattice: separated (homogenous)
    Bend in the center of 6MBA (metrology):
    cf - **sf - sf - sf - sf** - cf
    sf - **sf - sf - sf - sf** - sf

The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach of building a lattice
Setting up and investigation the individual components

- **MBA-unit cell (UC)**, Dispersion suppression cell (DSC), Matching Cell (MC) Quadrupol-Triplett + straight
  - **MBA-UC:** Main bend; 2x focusing in x,y plane; 2x sextupoles for chromaticity correction
- Pure 6-MBA **HOA** - fixed phase advances between sextupoles, defines the MBA-UC !!
  - Integer tunes UC: (0.4, 0.1) * 5 = (2.0, 0.5), Section (2.75, 0.8125), Ring (44, 13)
  - 2 families of chromatic sextupoles **only**. SX & SY to fit chromaticity to zero
- **Findings, Results:**
  -

$$\xi = \frac{\Delta Q}{\Delta p/p} \sim \oint -k_1(s)\beta(s)ds$$

$$\xi_{tot} \sim \oint [k_2(s)\ D(s) - k_1(s)]\ \beta(s)\ ds$$

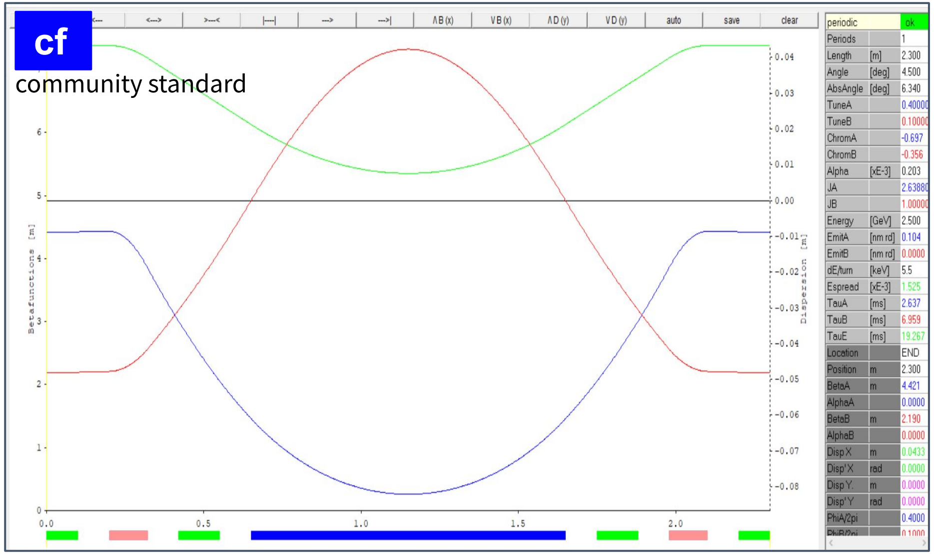
The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach - the “one and only” (deterministic) MBA-Unit Cell (UC) for

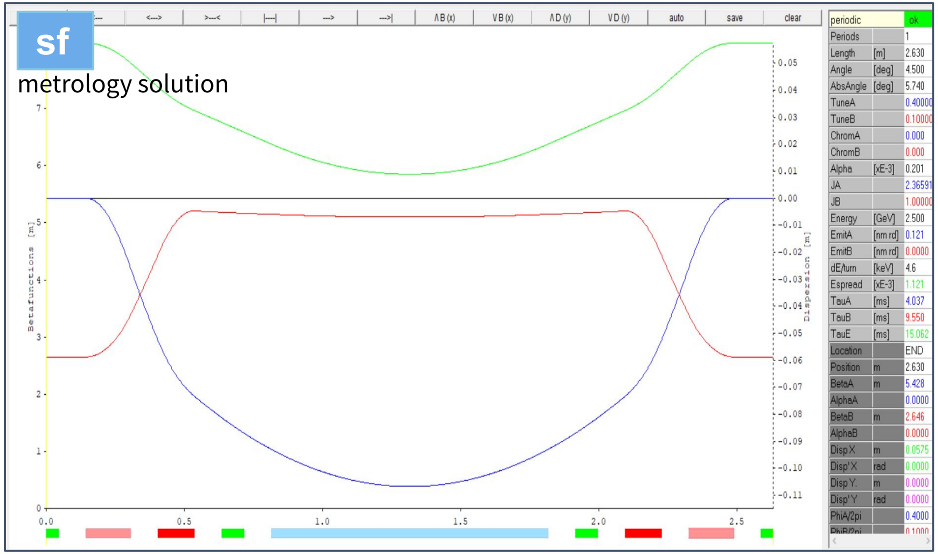
- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)

and for the hardware specifications of our project

Impact of reverse bend on alpha & emittance
Magnet arrangement



SX, RB, SY, B, …



SX, RB, QD, SY, B, …

The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach - Unit Cell - Impact of Reverse Bend

- The two different MBA-UCs: **cf & sf**
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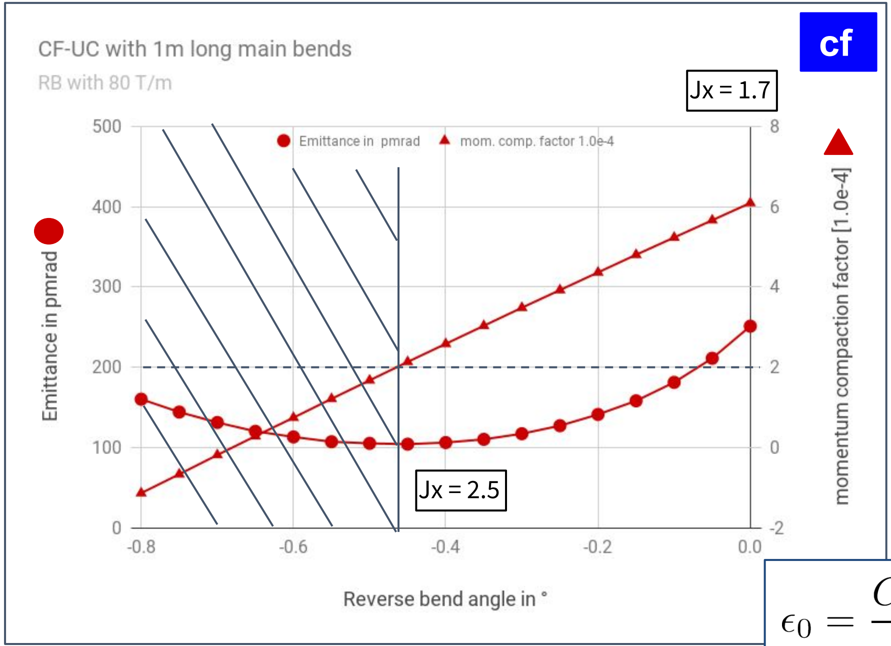
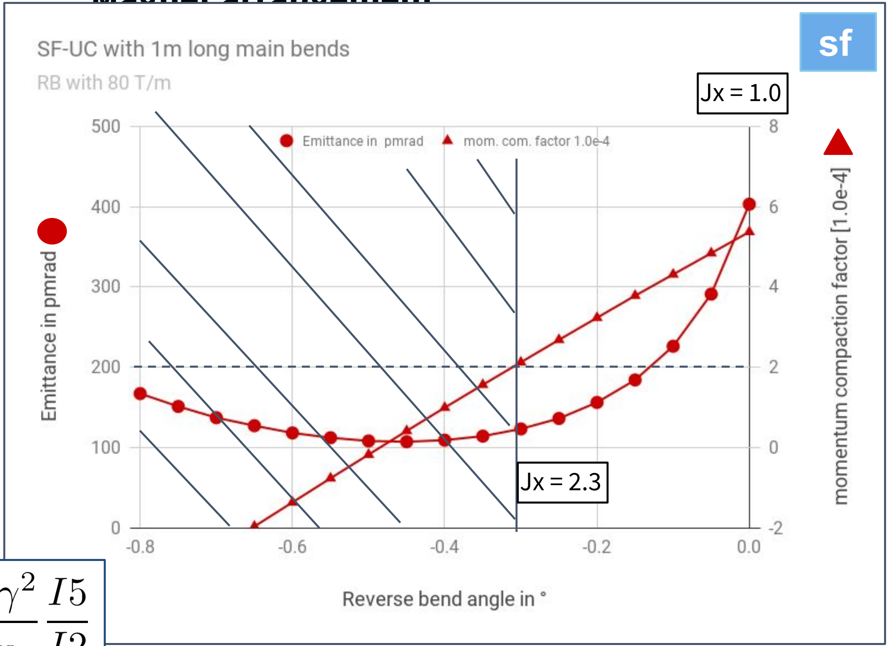


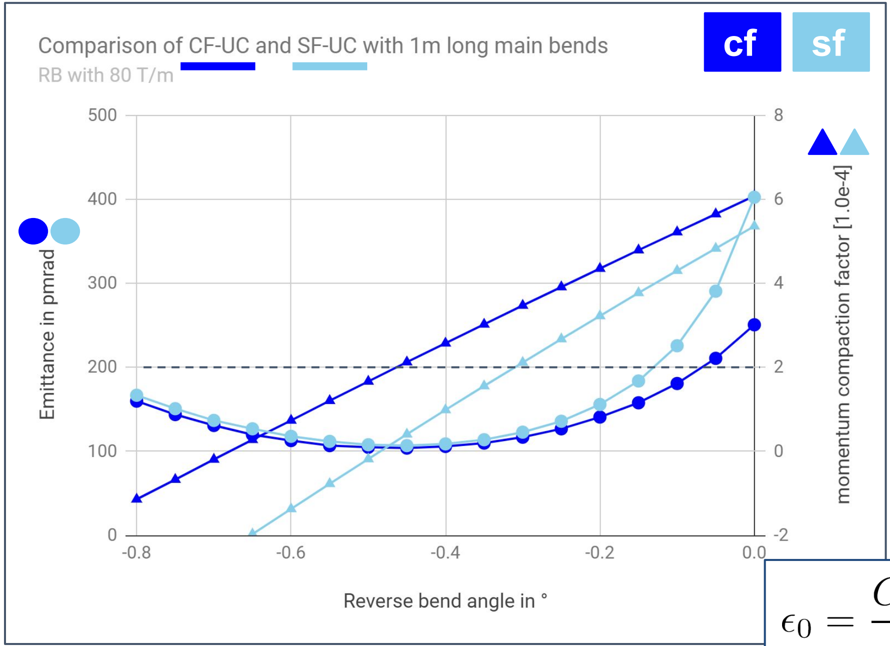


$$\epsilon_0 = \frac{C_q \gamma^2}{j_X} \frac{I5}{I2}$$

The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach - Unit Cell - Impact of Reverse Bend

- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)



$$\epsilon_0 = \frac{C_q \gamma^2}{j_X} \frac{I5}{I2}$$

and for the hardware specifications of our project

Impact of reverse bend on alpha & emittance ✔

Magnet arrangement

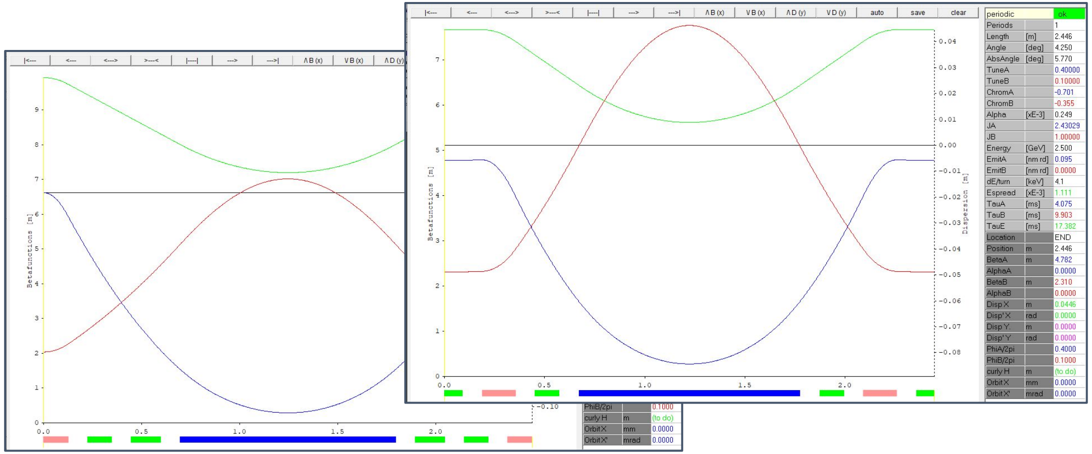
The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach - Unit Cell - Magnet arrangement

- How to set up the MBA-UC ?
- Magnet positioning/arrangement in that way, to reduce the sextupole strength for the chromatic correction → as less as possible non-linear power

$$\xi_{tot} \sim \oint [k_2(s)\ D(s) - k_1(s)]\ \beta(s)\ ds$$

- **The cf MBA-UC:**

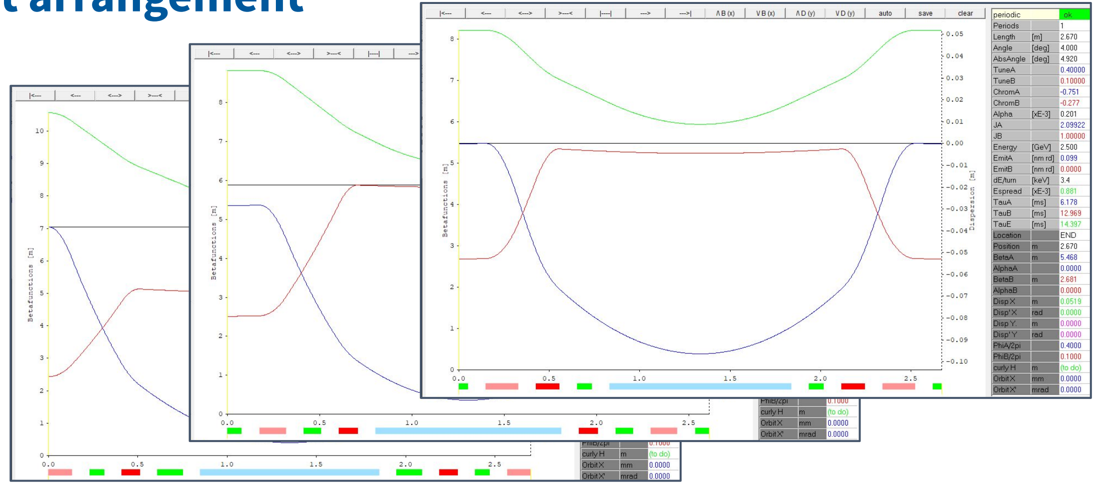


SetUp	Length	alpha	Emittance	RB angle	Nat Chrom	SUM(b3 * L)² for Chrom = 0 SF, SD [1/m²]
SX, RB, SY, B	2.446 m	2.5e-4	95 pm rad	-0.38 ° (k = 6.7) L = 0.163*2	-0.701, -0.355	**2324.77** 21.02, -26.84
RB, SX, SY, B	2.490 m	2.7e-4	95 pm rad	-0.26° (k = 6.8) L = 0.125 *2	-0.802, -0.278	**3905.21** 27.96, -34.22

The process towards a BESSY III lattice - Linear Beam Dynamics

LEGO approach - Unit Cell - Magnet arrangement

- How to set up the MBA-UC ?
- Magnet positioning/arrangement in that way, to reduce the sextupole strength for the chromatic correction → as less as possible non-linear power



$$\xi_{tot} \sim \oint [k_2(s)\ D(s) - k_1(s)]\ \beta(s)\ ds$$

- **The sf MBA-UC:**

SetUp	Length	alpha	Emittance	RB angle	Nat Chrom	SUM(b3 * L)² for Chrom = 0 SF, SD [1/m²]
SX, RB, QD, SY, B	2.670 m	2.0e-4	100 pm rad	-0.23 ° (k = 8.6) L = 0.175*2	-0.751, -0.277	**901.43** 10.56, -18.42
SX, RB, SY, QD, B	2.610 m	2.1e-4	98 pm rad	-0.23° (k = 8.5) L = 0.14 * 2	-0.740, -0.295	**1500.19** 17.60, -20.98
RB, SX, QD, SY, B	2.700 m	2.0e-4	98 pm rad	-0.19° (k = 8.4) L = 0.13 * 2	-0.835, -0.232	**2781.58** 19.39, -31.86

The process towards a BESSY III lattice - Linear Beam Dynamics

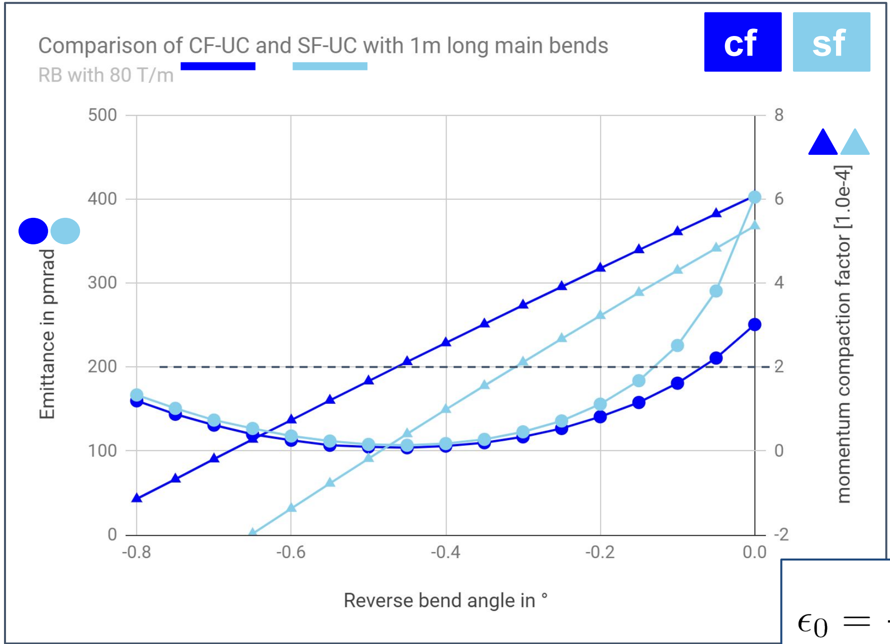
LEGO approach - Unit Cell - Impact of Reverse Bend

- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)

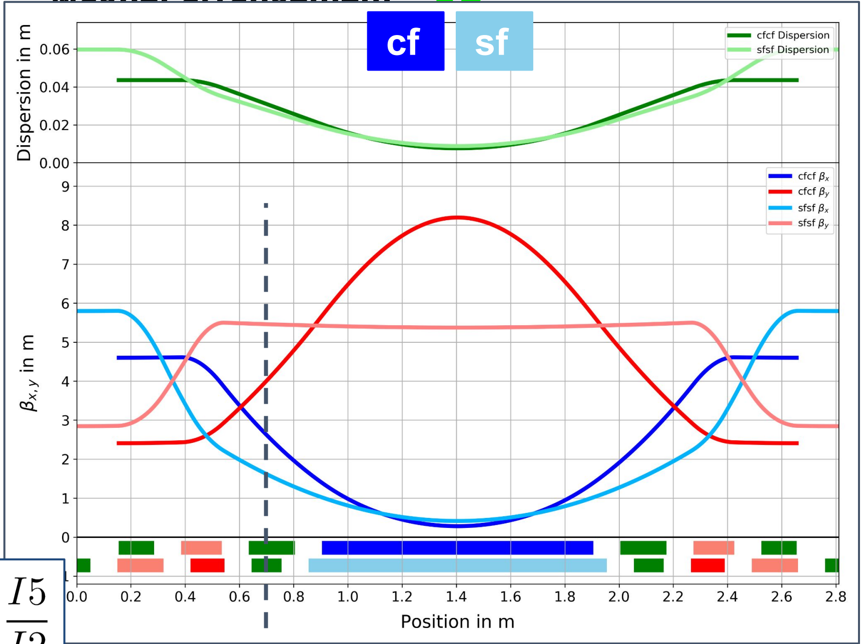
and for the hardware specifications of our project

Impact of reverse bend on alpha & emittance

Magnet arrangement

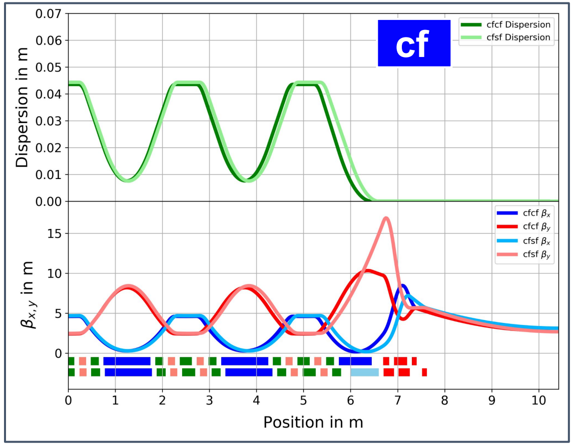


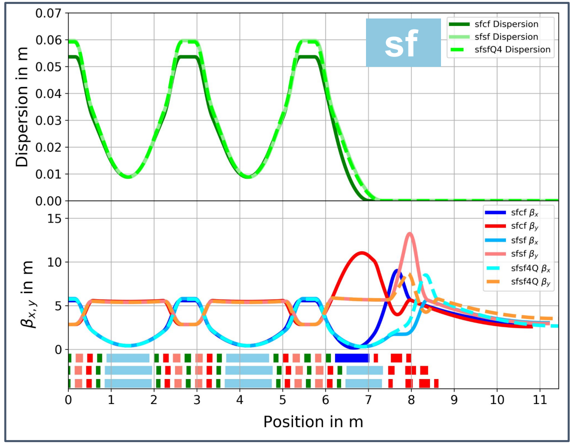
$$\epsilon_0 = \frac{C_q \gamma^2}{j_X} \frac{I5}{I2}$$



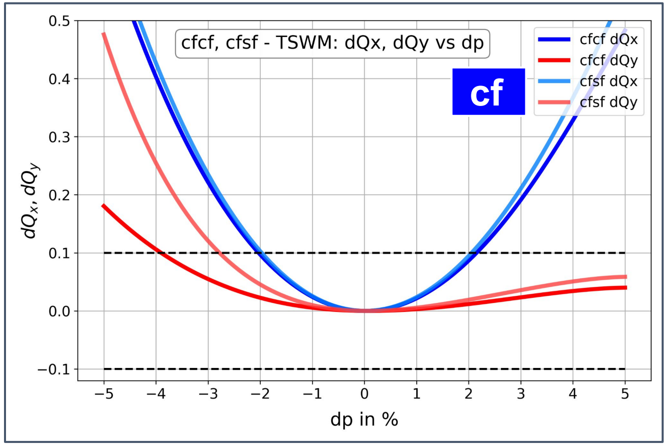
The process towards a BESSY III lattice - Non-Linear Beam Dynamics

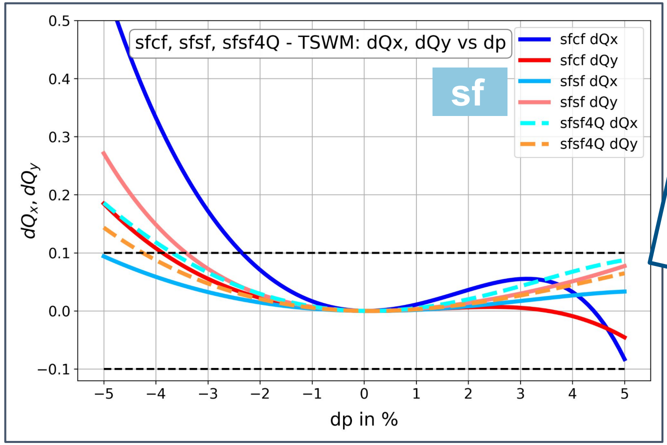
TSWM
Chromatic Tune Shift





With two sextupole families only: Sx, Sy

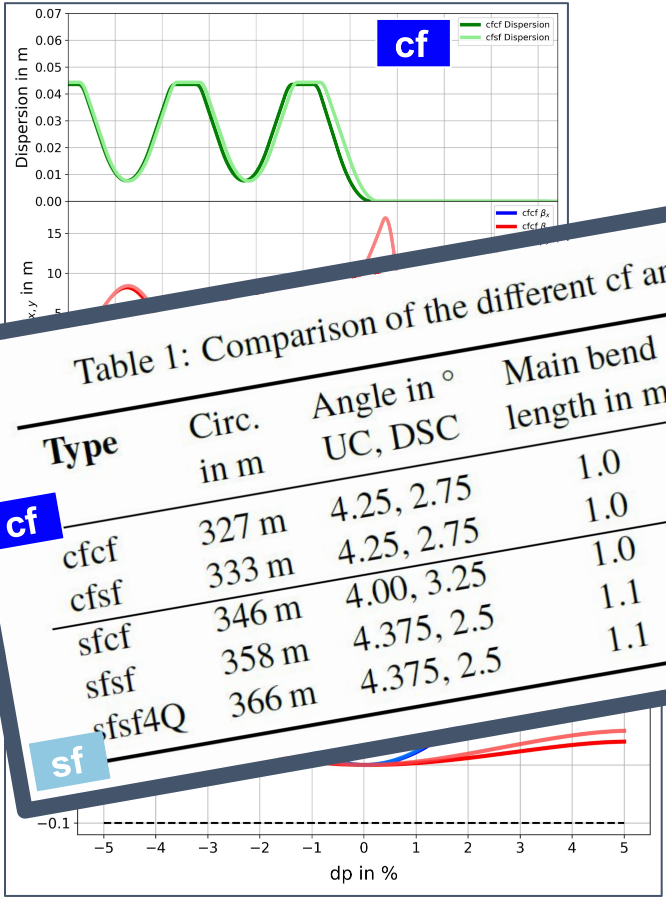




The flatter the curve the better
→ Robustness, Lifetime

The process towards a BESSY III lattice - Non-Linear Beam Dynamics

TSWM
Chromati ... hift



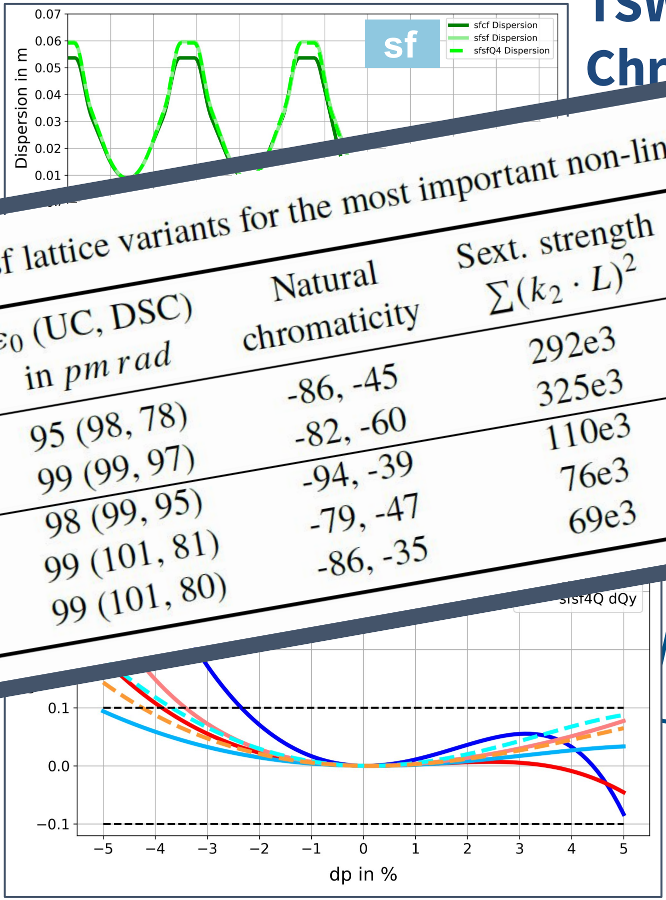


Table 1: Comparison of the different cf and sf lattice variants for the most important non-linear parameters.

Type	Circ. in m	Angle in ° UC, DSC	Main bend length in m	ε_0 (UC, DSC) in $pm\,rad$	Natural chromaticity	Sext. strength $\sum(k_2 \cdot L)^2$	TSWM, dp in % for $dQ_{x,y} = 0.1$
cfcf	327 m	4.25, 2.75	1.0	95 (98, 78)	-86, -45	292e3	2.0, 3.9
cfsf	333 m	4.25, 2.75	1.0	99 (99, 97)	-82, -60	325e3	2.1, 2.8
sfcf	346 m	4.00, 3.25	1.0	98 (99, 95)	-94, -39	110e3	2.3, 3.9
sfsf	358 m	4.375, 2.5	1.1	99 (101, 81)	-79, -47	76e3	5.0, 3.4
sfsf4Q	366 m	4.375, 2.5	1.1	99 (101, 80)	-86, -35	69e3	3.8, 4.3

cf

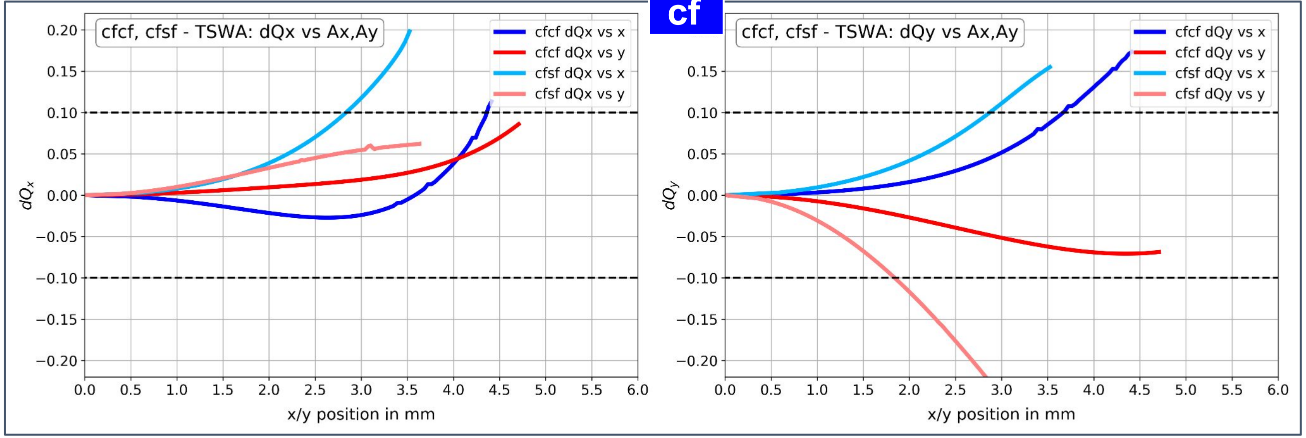
sf

The flatter the curve the better
→ Robustness, Lifetime

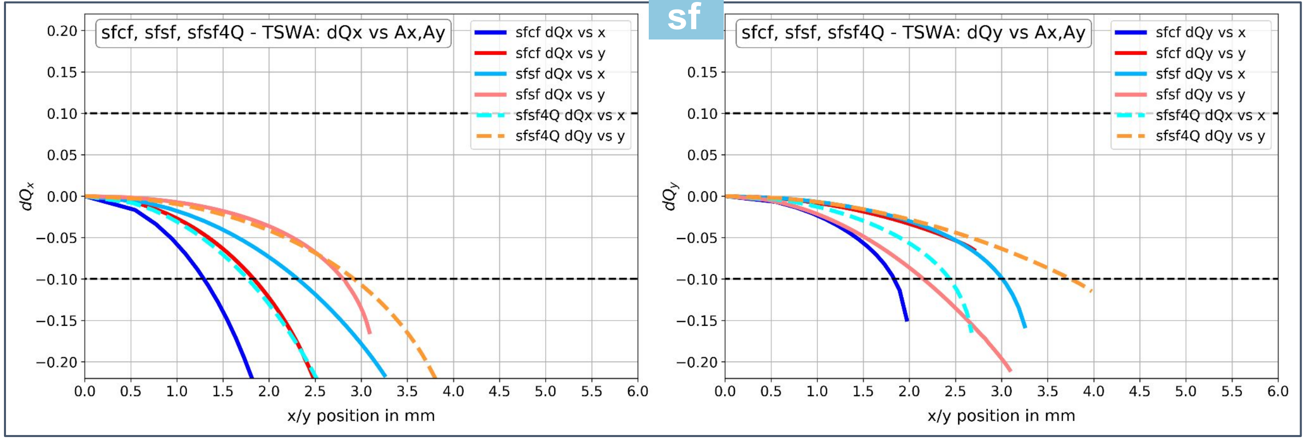
The process towards a BESSY III lattice - Non-Linear Beam Dynamics

TSWA
Amplitude Dependent Tune Shift

cf



sf

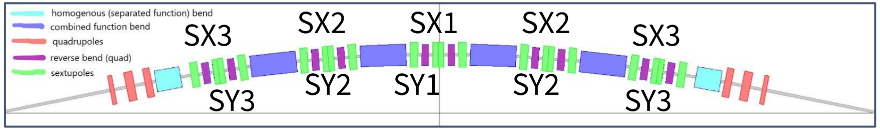


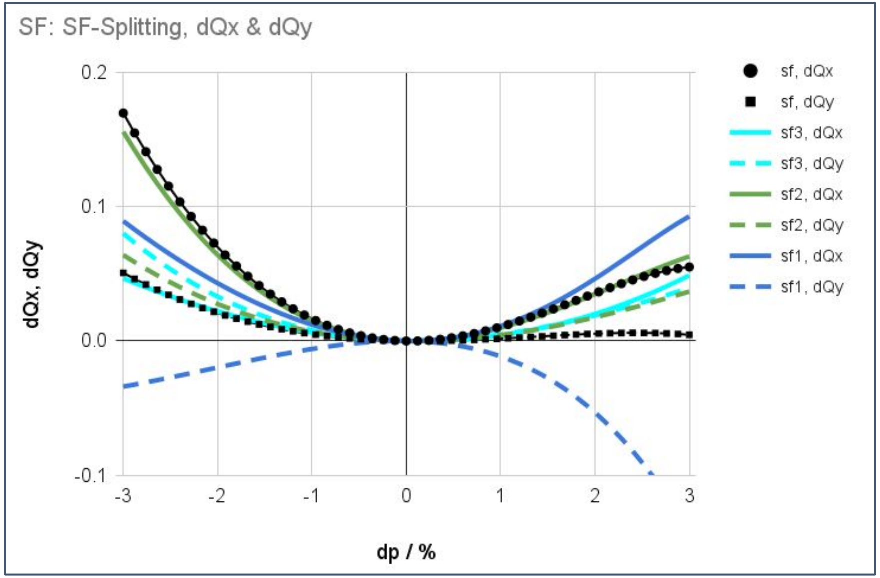
The process towards a BESSY III lattice - Non-Linear Beam Dynamics

In progress

Non-linear optimization

- Defining target parameters for non-linear optimization and “knobs”
- **Target parameters:** (benchmark MAX IV, SLS2):
  - Tune Shift With Momentum **TSWM:**
    ΔQx, ΔQy ~ 0.1 at Δp = +-3% (+-5%)
  - Tune Shift with Amplitude **TSWA:**
    ΔQx, ΔQy ~ 0.1 limits acceptance ~3mm
- **Knobs:**
  - Chromatic Octupoles for 2nd order chromaticity
  - Split up of chromatic sextupoles (TSWM + TSWA)
- **Findings, Results:**
  - The two lattice candidates show an opposite behavior in order to reduce TSWM
    - SF3 with biggest impact at sf lattice
    - SF1 with biggest impact at cf lattice

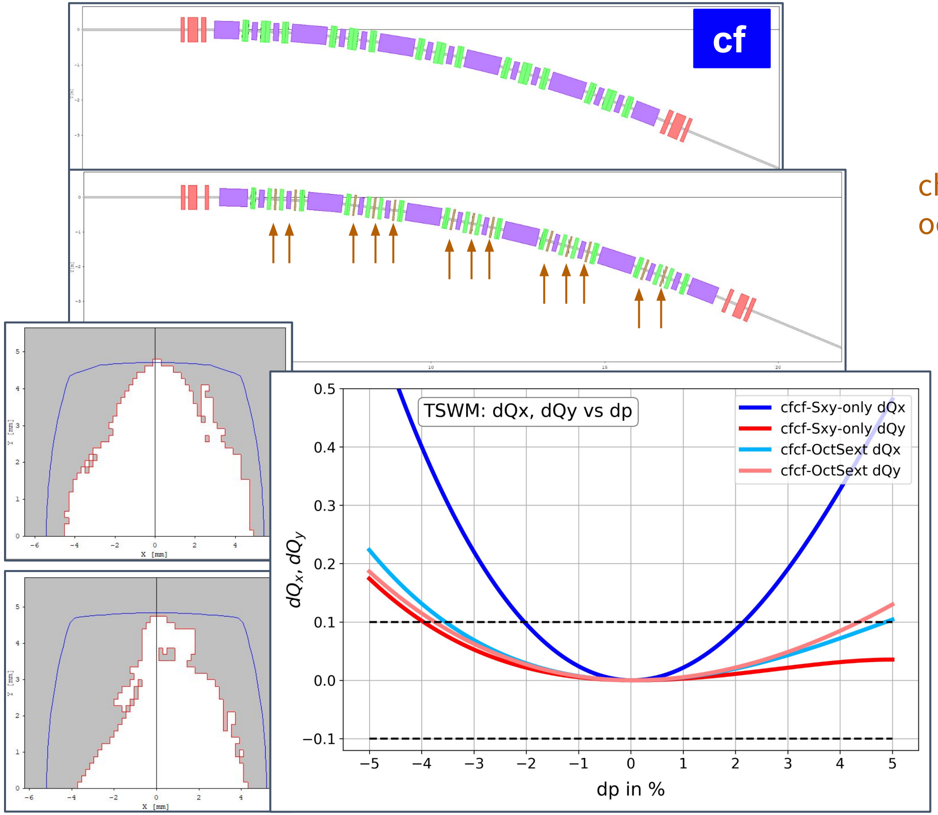




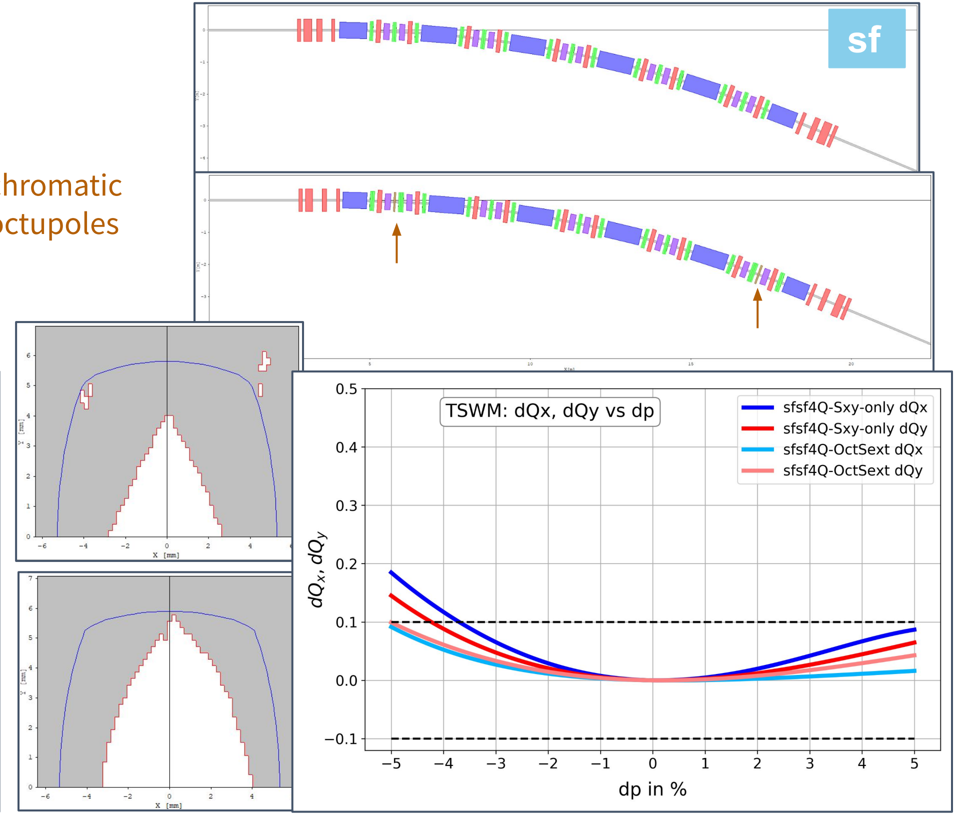
The process towards a BESSY III lattice - Non-Linear Beam Dynamics

In progress

Non-linear optimization



chromatic octupoles



4th Generation Lightsource Lattices

In progress

The Higher Order Achromat, HOA-MBA

- MAX IV, SLS 2.0 … up to 3 GeV
  - A. Streun, J. Bengtsson, S. Leeman, et al.

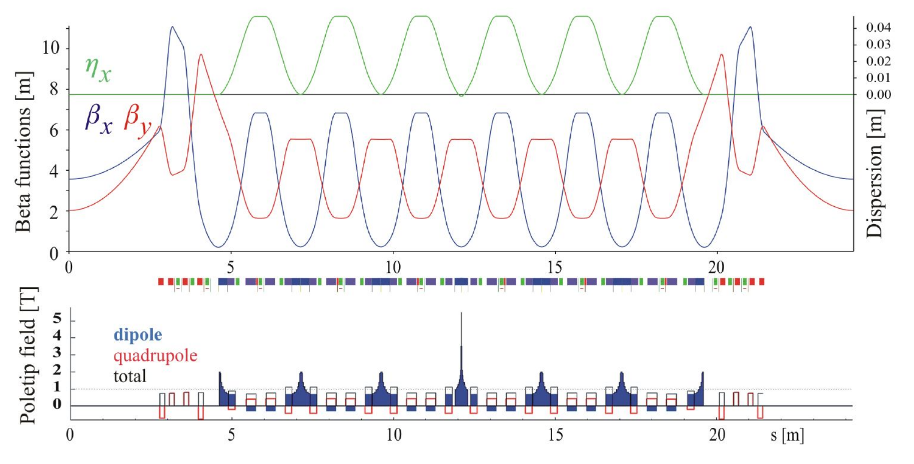
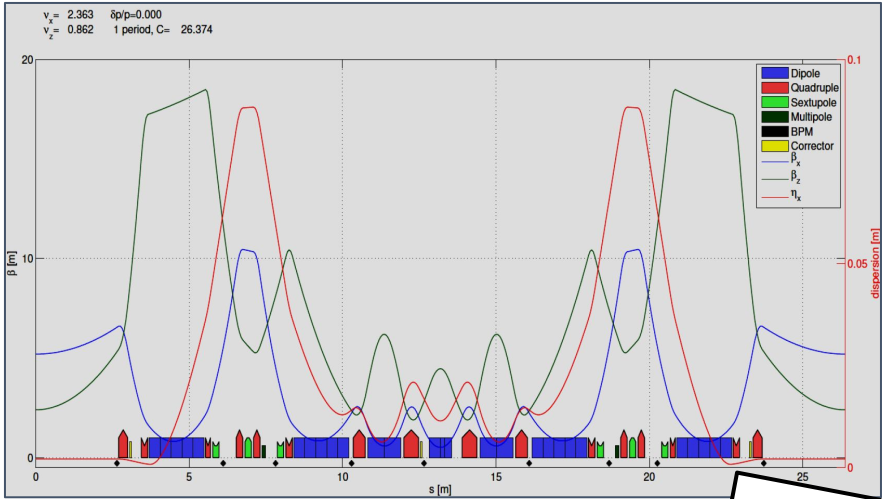


Figure 2.3: Optical functions and field components for one 7BA-arc where the center LGB has been interchanged by a super-LGB of 5.5 T peak field. Bending magnets are in dark blue, quadrupoles red and sextupoles green.

LGB - yes
RB - yes

The Hybrid, HMBA

- ESRF-EBS, PETRA IV … above 3 GeV
  - P. Raimondi



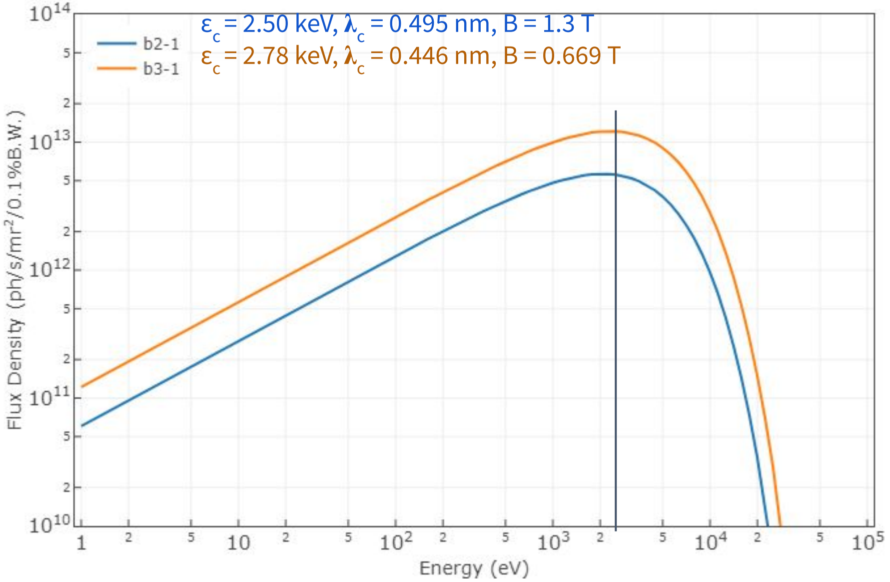
LGB - yes
RB - no

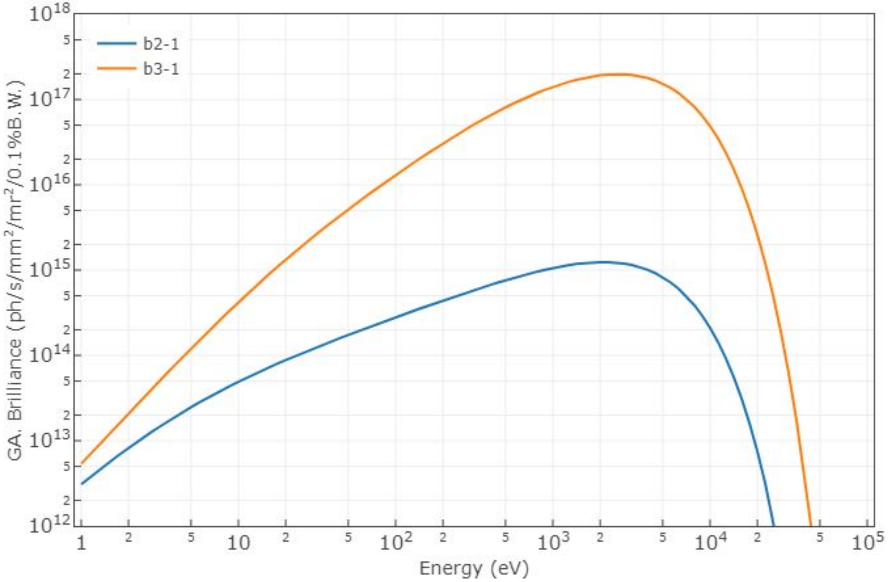
BESSY III and Bending Radiation Sources

Homogenous bends and/or Longitudinal Gradient Bends

Currently ongoing

- Two/Three applications:
  - PTB, Metrology, similar to BESSY II (primary radiation standard): **2.5 keV**
  - Tender X-rays bends: **> 3, 5, 10 keV**
  - Hardest X-rays bends, 20 keV and beyond: ?





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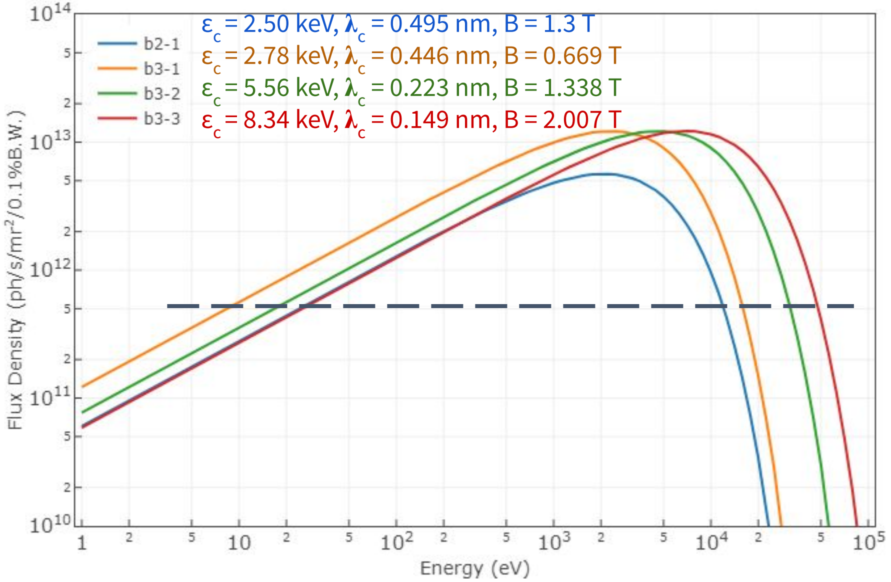
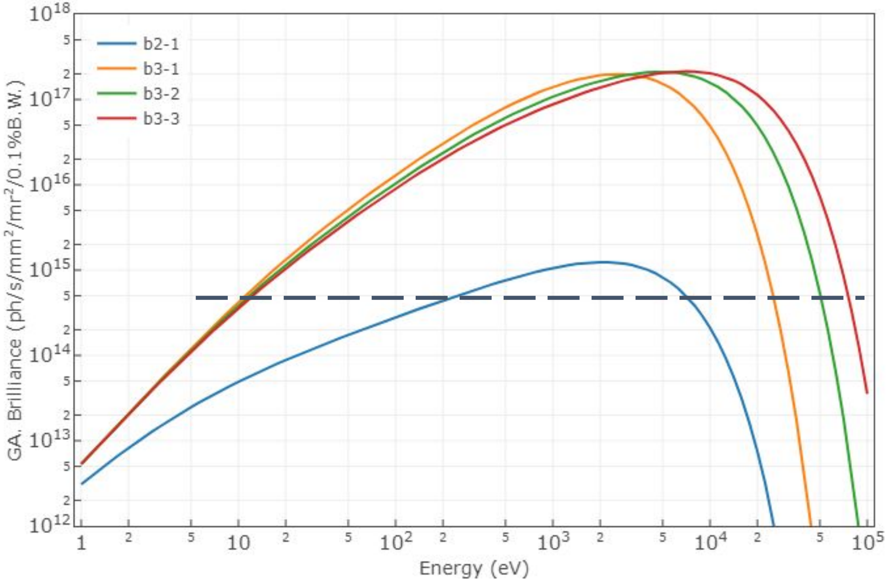




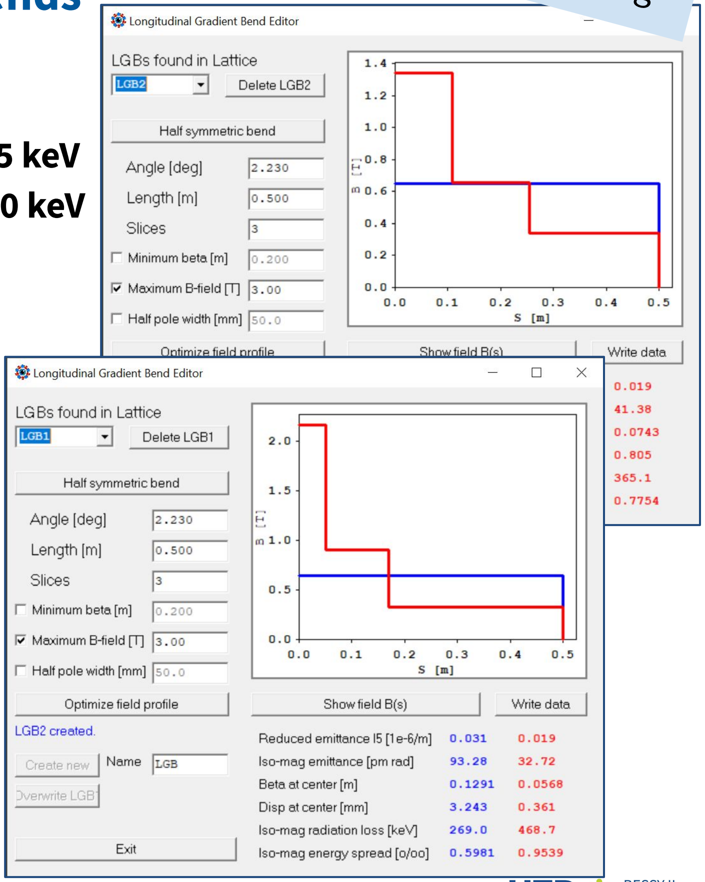
BESSY III and Bending Radiation Sources

Homogenous bends and/or Longitudinal Gradient Bends

Currently ongoing

- Two/Three applications:
  - PTB, Metrology, similar to BESSY II (primary rad. std): **2.5 keV**
  - Tender X-rays: > **3, 5, 10 keV**
  - Hardest X-rays, 20 keV and beyond: ?

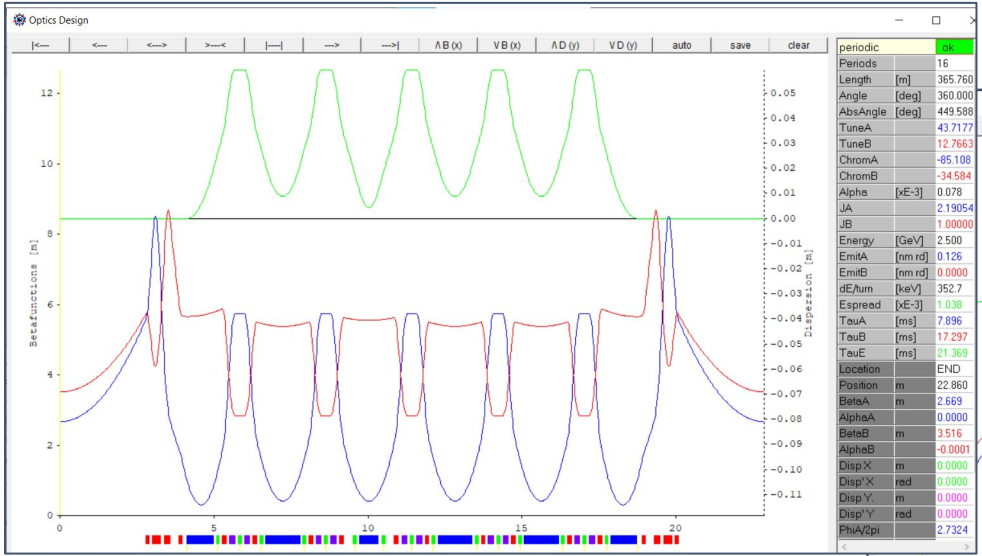
- An approach: Longitudinal Gradient Bends (LGBs):
  - Homogenous Bend:
    L = 1.0 m, 4.46°, rho = 12.85 m, B = 0.65 T, **Ec = 2.7 keV**
  - LGB 1.3 T
    L = 0.22 m, 2.0°, rho = 6.3 m, B = 1.3 T, **Ec = 5.5 keV**
  - LGB 2.2T
    L = 0.1 m, 1.45°, rho = 3.85 m, B= 2.2 T, **Ec = 9.0 keV**
  - Hardest X-rays: SC Bend with > 5 T gives Ec = 20 keV



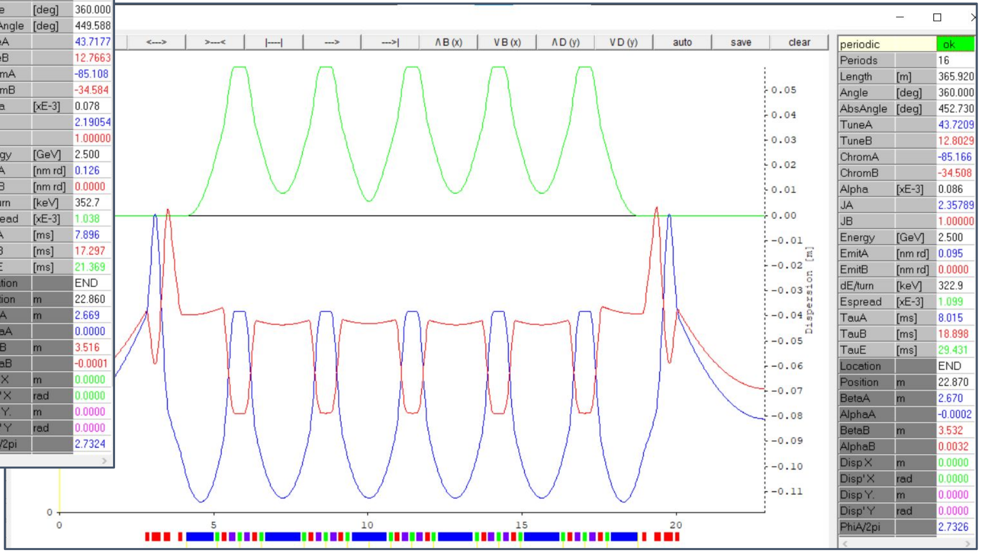
BESSY III and Bending Radiation Sources

Homogenous bends and/or Longitudinal Gradient Bends

Currently ongoing



Shorter bend with 1.3 T



LGB with 1.3 or 2.0 T

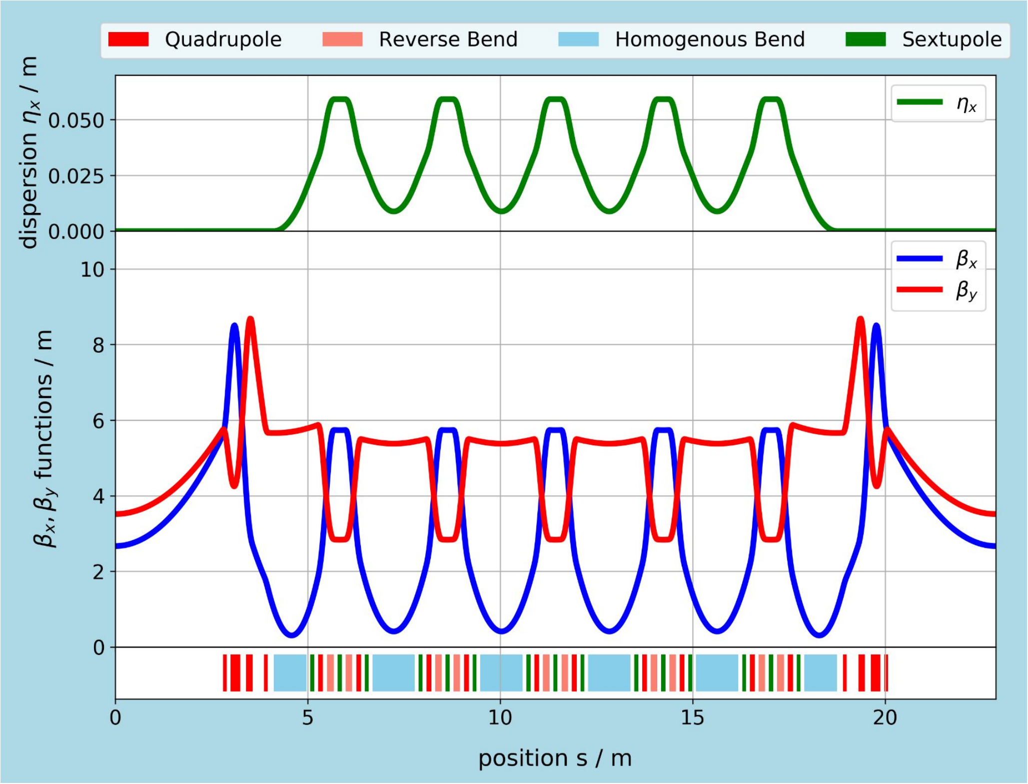
The process towards a BESSY III lattice - Summary

Table 3: Chromatic Sextupole Strength

	ε pm	E GeV	ε/E^2 pm/GeV²	$\Sigma(b_3 * L)$ 1/m²
MAX 4	336	3.0	37.3	5180
SLS 2	123	2.4	21.4	8148
BESSY III	99	2.5	15.8	5742
Soleil	81	2.75	10.7	20278

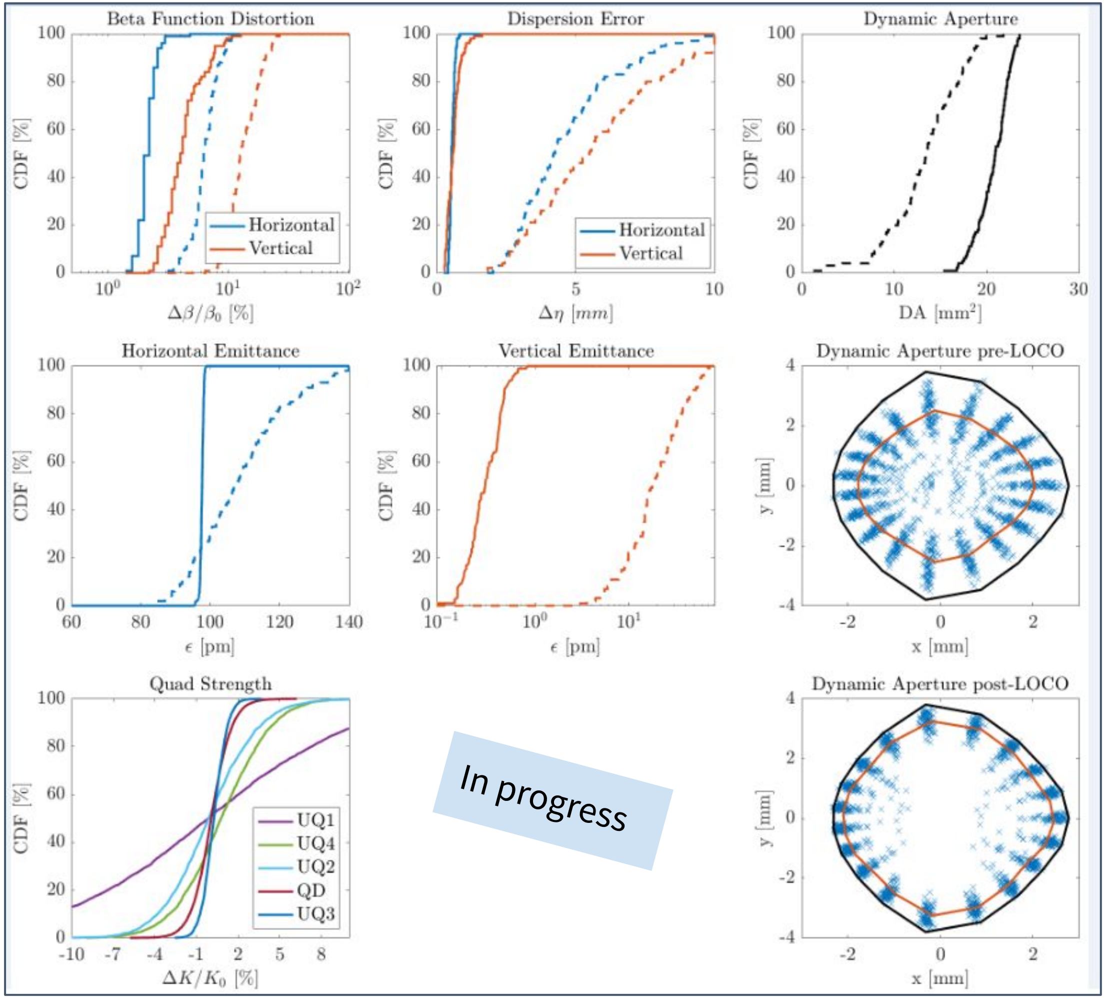
Homogenous bend lattice

- With advantages:
  - Strongly reduced sextupole strength for chromaticity correction
  - Better momentum acceptance due to reduced higher order chromaticity contributions
- Next steps:
  - Non-linear optimisation scheme
  - Robustness & Tolerance analysis
  - Injection scheme & Collective effects
  - **Intensify discussions with construction & engineering department**



The process towards a BESSY III lattice

Simulated Commissioning Robustness Analysis



Thank you for your attention !

Entering the CDR Phase with **New Positions:**

Magnet Development	– >	J. Völker
Beam Dynamics	– >	P. Goslawski
Overall	– >	A. Jankowiak

See HZB homepage: **www.helmholtz-berlin.de**
(if available again after CyberAttack)