HZB BESSY II Light Source

BESSY III Progress

A successor for BESSY II

P. Goslawski for the CDR & lattice design team
(M. Abo-Bakr, B. Kuske, J. Bengtsson, J. Völker et al.,)

Combined function or Homogenous bend

Two partners & two synchrotron radiation sources

Fernsehturm am Alexanderplatz

HZB Helmholtz Zentrum Berlin

BESSY II

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

Soft and tender X-rays
Spectro-Microscopy
Timing: low α, femto-slicing
TRIBs/Two orbit mode

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

MLS Metrology Light Source

630 MeV
48 m
4 Straights (2x2.5m, 2x6m)
DBA
100 nm rad (std mode)
200 mA

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

Part of this work was supported by:
Bundesministerum für Bildung und Forschung Projekt „Grundlagen der EUV-Lithographie“ 13N8088 and 13N8837, MEDEA Projects „EXTATIC“ and EAGLE“ and European Commission Project 507754 „More Moore“

Gefördert vom Bundesministerium für Bildung und Forschung

2006 EUVL Symposium — Enabling the Nano-Age World® — Page 18

ZEISS ASML HZB BESSY II Light Source

Outline of talk

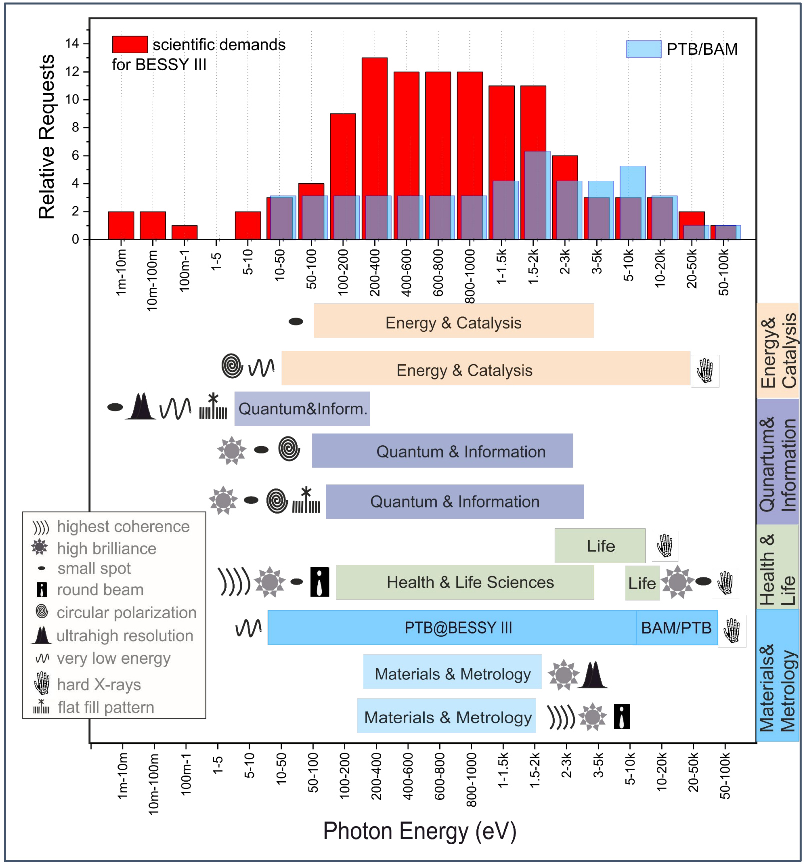
A BESSY III "project" timeline

- 2020
  - "CDR - Team", 15 Science Expert Groups Workshops
  - **Synchrotron Rad. / Ring parameters**, Greenfield Design
- 2021
  - Solutions within the tunnel BESSY III in BESSY II building
  - And back to Greenfield solutions
- 2022
  - **PreCDR** for Helmholtz & Berlin & BMBF
  - **First baseline lattice**
- 2023 Conceptual Design Report
- 2024 - 2027 Technical Design Phase
- 2028 - 203X Project & Construction
- 203X Operation

A BESSY III lattice timeline

- 2020
  - **Define ring parameters**
  - First "wild" lattices
  - **Technical limitations**
- 2021
  - **1st milestone lattice**, Most simple HOA-MBA, Linear beam dynamics
- 2022
  - **2nd milestone lattice,** First nonlinear optimization

BESSY III Requirements & Objectives



Facility parameters

1. 1st 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

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 m)
4. Low beta straights & round beams
5. **Metrology - Homogenous bends**
   Measuring he field at the source point with a NMR probe in a volume of 10x10x10 mm
   (and one bending beamline per sector)
6. Momentum compaction factor **> 1.0e-4**

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

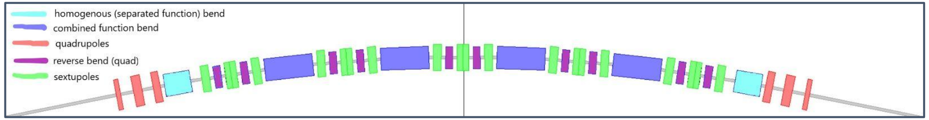
The process towards a BESSY III lattice - metrology challenge

A deterministic lattice approach

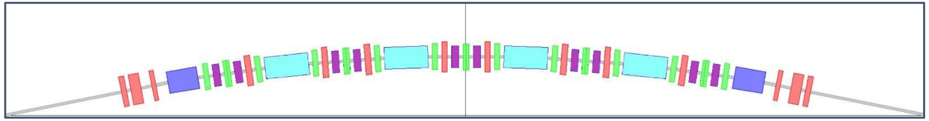
- Stepwise: Power and Function of each Component &“Knob” → **LEGO approach**
- After first “wild” lattices we concluded on:
- **Limiting the hardware** (conservative ansatz)
  - Bore radius of 12.5 mm
    Radius of inner/outer vac. pipe of 9/11mm
  - Bends up to 1.4 T
  - Quads up to 60 - 80 T/m (depends 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

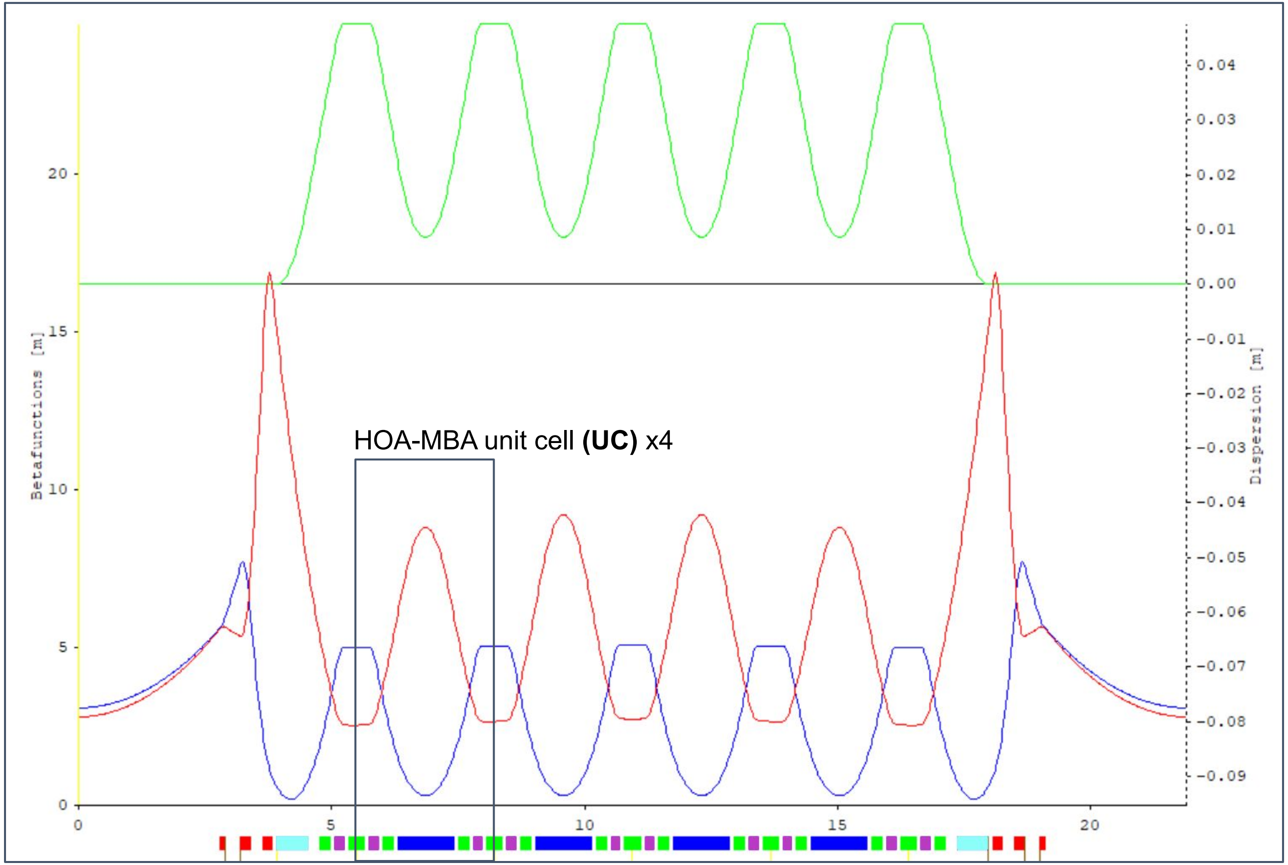
- Include it right from the beginning
  → Symmetric sector cell ansatz
- Two lattice candidates:
  - **cf**-lattice: combined function bend
    In center of 6MBA (community standard)
    sf - **cf - cf - cf - cf** - sf



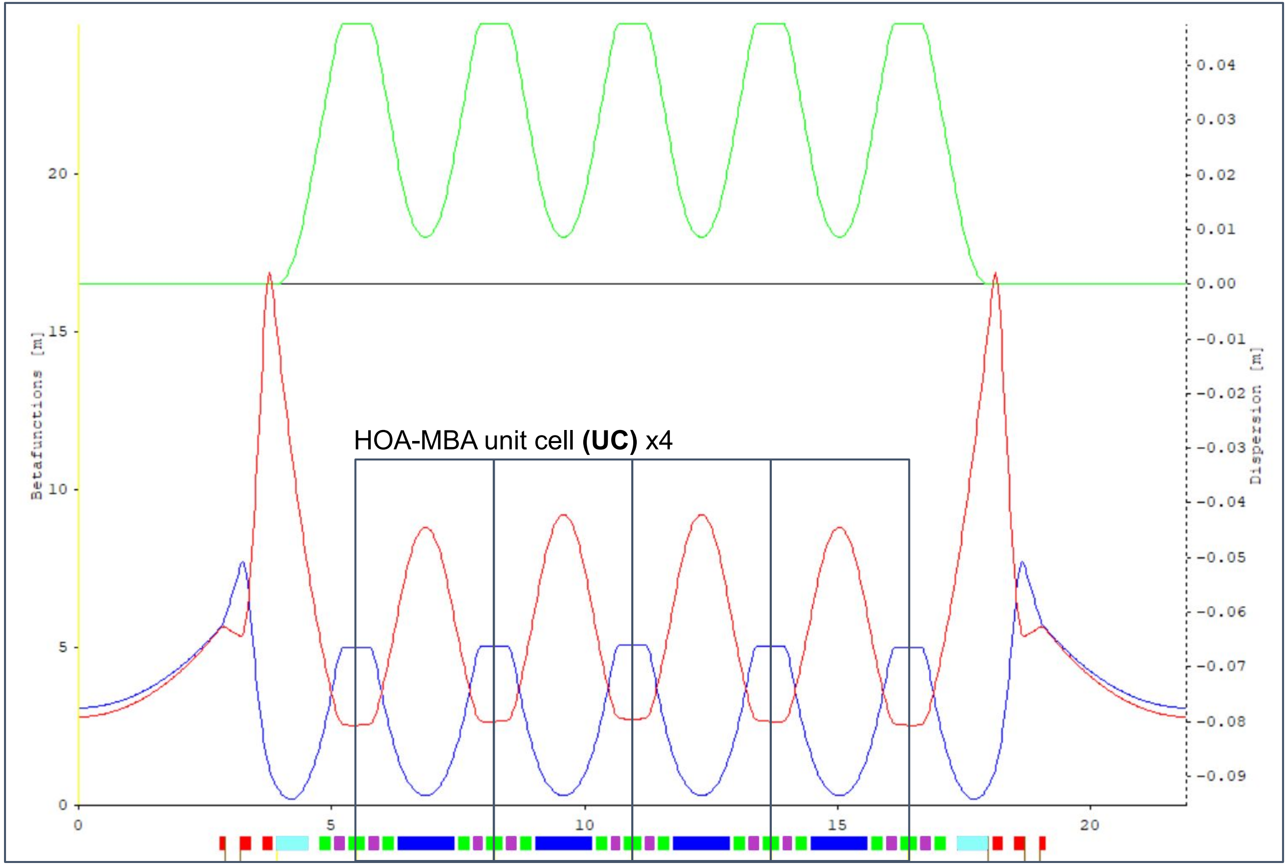
  - **sf**-lattice: separated (homogenous)
    Bend in the center of 6MBA (metrology):
    cf - **sf - sf - sf - sf** - cf



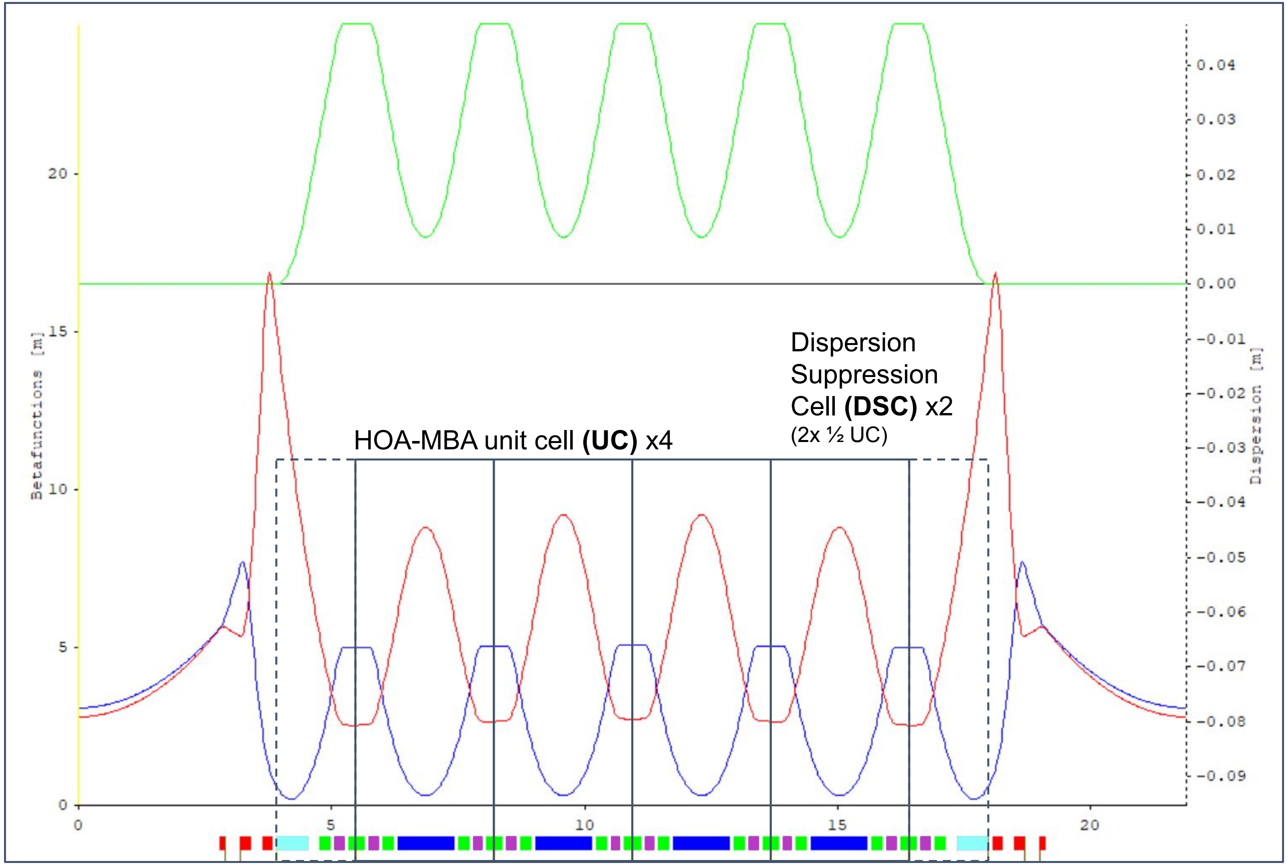
LEGO Approach - Basic building blocks of one sector



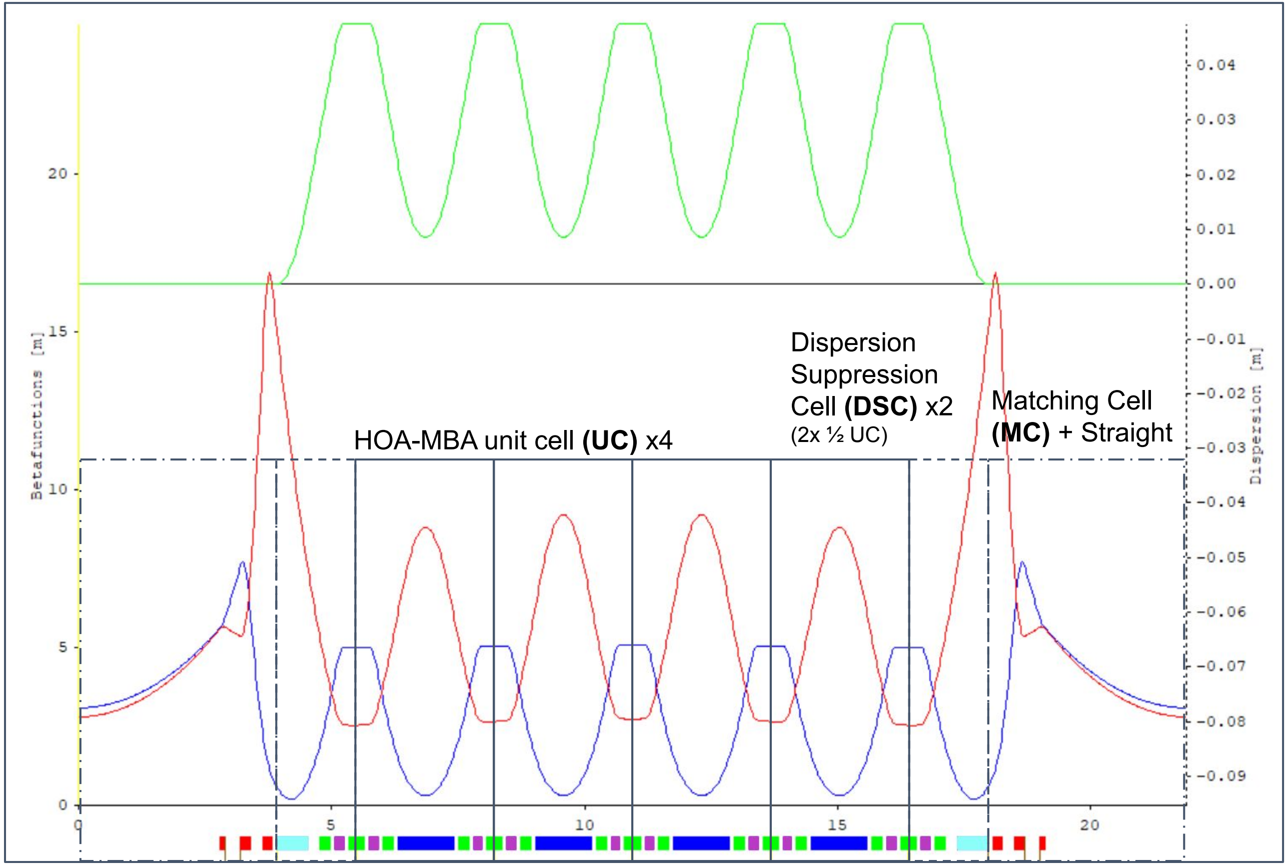
LEGO Approach - Basic building blocks of one sector



LEGO Approach - Basic building blocks of one sector



LEGO Approach - Basic building blocks of one sector



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

1st Milestone Lattice: HOA - Linear Beam Dynamics

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

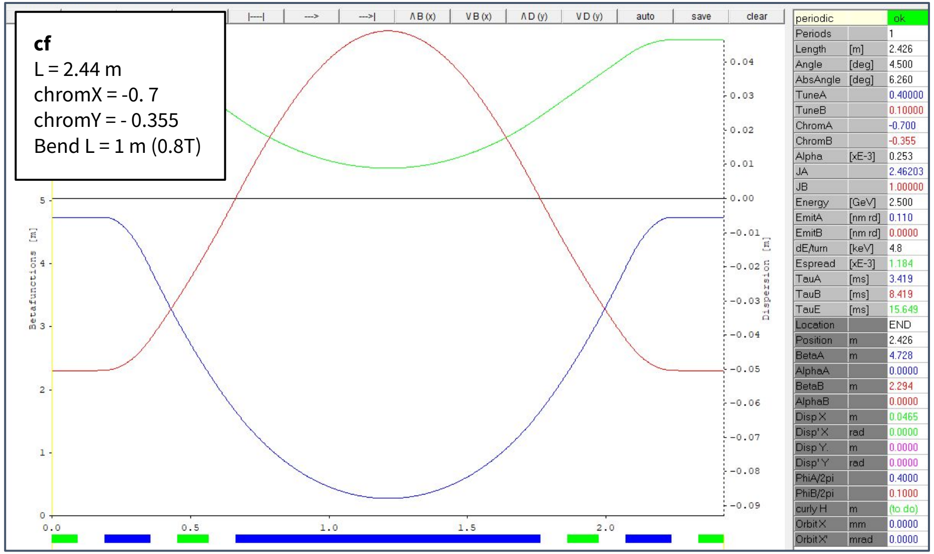
- **MBA-unit cell (UC)**, Dispersion suppression cell (DSC), Matching Cell (MC) Quadrupol/Triplett + straight
- Pure 6-MBA **HOA** - fixed phase advances between sextupoles, defines the MBA-UC !!
  - Integer tunes UC: (0.4, 0.1) * 5 = (2.0, 0.5), Section (2.75, 0.8125), Ring (44, 13)
  - 2 families of chromatic sextupoles **only**. SF & SD to fit chromaticity to zero
- **Findings, Results:**
  -

1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach - the "one and only" (deterministic) MBA-Unit Cell (UC) for and for the hardware specifications of our project

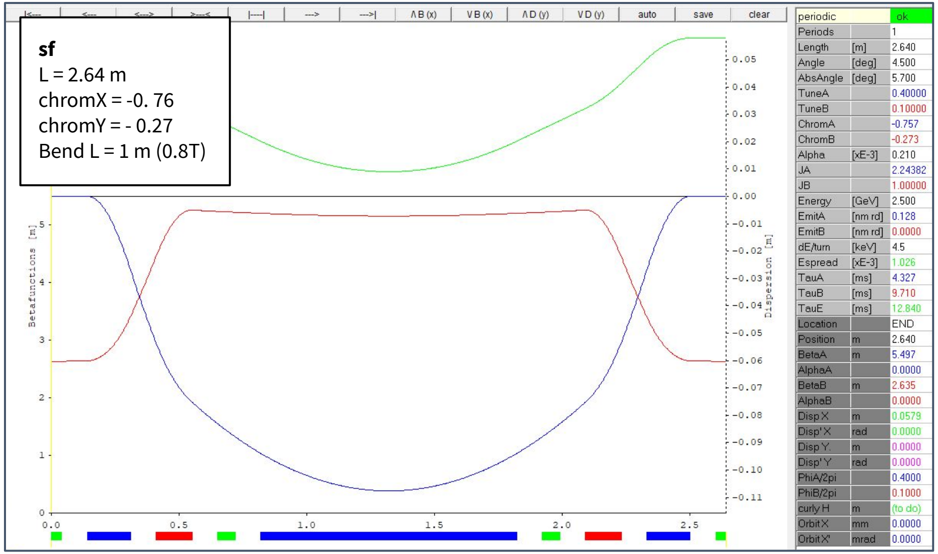
- The two different MBA-UCs: **cf & sf**
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0)

Impact of reverse bend on alpha & emittance



periodic		ok
Periods		1
Length	[m]	2.426
Angle	[deg]	4.500
AbsAngle	[deg]	6.260
TuneA		0.40000
TuneB		0.10000
ChromA		-0.700
ChromB		-0.355
Alpha	[xE-3]	0.253
JA		2.46203
JB		1.00000
Energy	[GeV]	2.500
EmitA	[nm rd]	0.110
EmitB	[nm rd]	0.0000
dE/turn	[keV]	4.8
Espread	[xE-3]	1.184
TauA	[ms]	3.419
TauB	[ms]	8.419
TauE	[ms]	15.649
Location		END
Position	m	2.426
BetaA	m	4.728
AlphaA		0.0000
BetaB	m	2.294
AlphaB		0.0000
Disp X	m	0.0465
Disp' X	rad	0.0000
Disp Y.	m	0.0000
Disp' Y	rad	0.0000
PhiA/2pi		0.4000
PhiB/2pi		0.1000
curly H	m	(to do)
Orbit X	mm	0.0000
Orbit X'	mrad	0.0000

SF, RB, SD, B, …



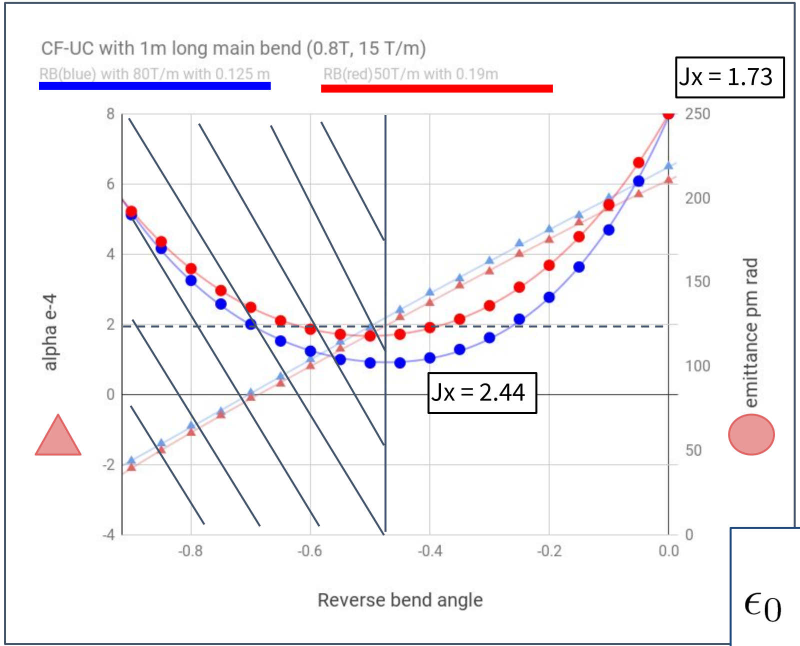
periodic		ok
Periods		1
Length	[m]	2.640
Angle	[deg]	4.500
AbsAngle	[deg]	5.700
TuneA		0.40000
TuneB		0.10000
ChromA		-0.757
ChromB		-0.273
Alpha	[xE-3]	0.210
JA		2.24382
JB		1.00000
Energy	[GeV]	2.500
EmitA	[nm rd]	0.128
EmitB	[nm rd]	0.0000
dE/turn	[keV]	4.5
Espread	[xE-3]	1.026
TauA	[ms]	4.327
TauB	[ms]	9.710
TauE	[ms]	12.840
Location		END
Position	m	2.640
BetaA	m	5.497
AlphaA		0.0000
BetaB	m	2.635
AlphaB		0.0000
Disp X	m	0.0579
Disp' X	rad	0.0000
Disp Y.	m	0.0000
Disp' Y	rad	0.0000
PhiA/2pi		0.4000
PhiB/2pi		0.1000
curly H	m	(to do)
Orbit X	mm	0.0000
Orbit X'	mrad	0.0000

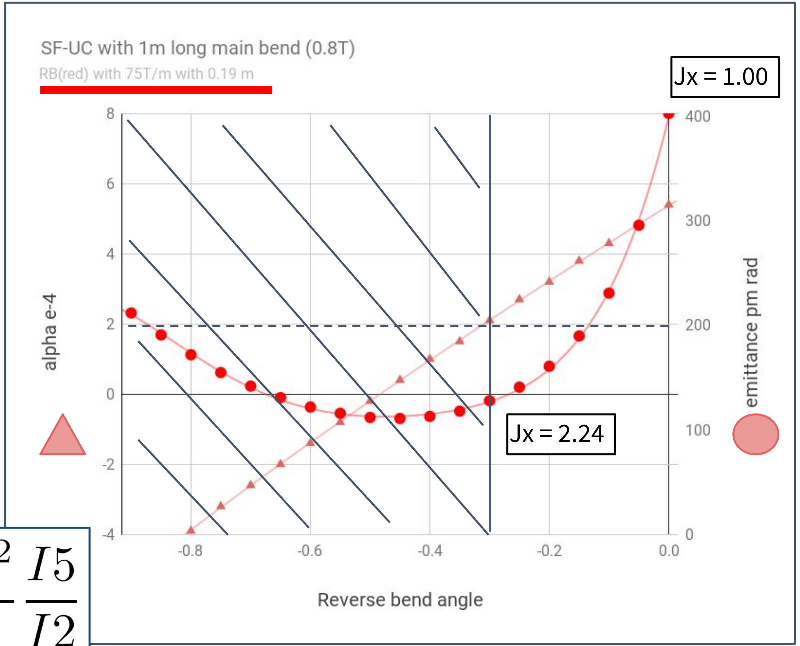
SF, RB, QD, SD, B, …

1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach - UC - Impact of Reverse Bend

- The two different MBA-UCs: **cf & sf** and for the hardware specifications of our project
- UC (4.5°): Q_xy = (0.4, 0.1), Chrom_xy = (0.0, 0.0) **Impact of reverse bend on alpha & emittance**





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

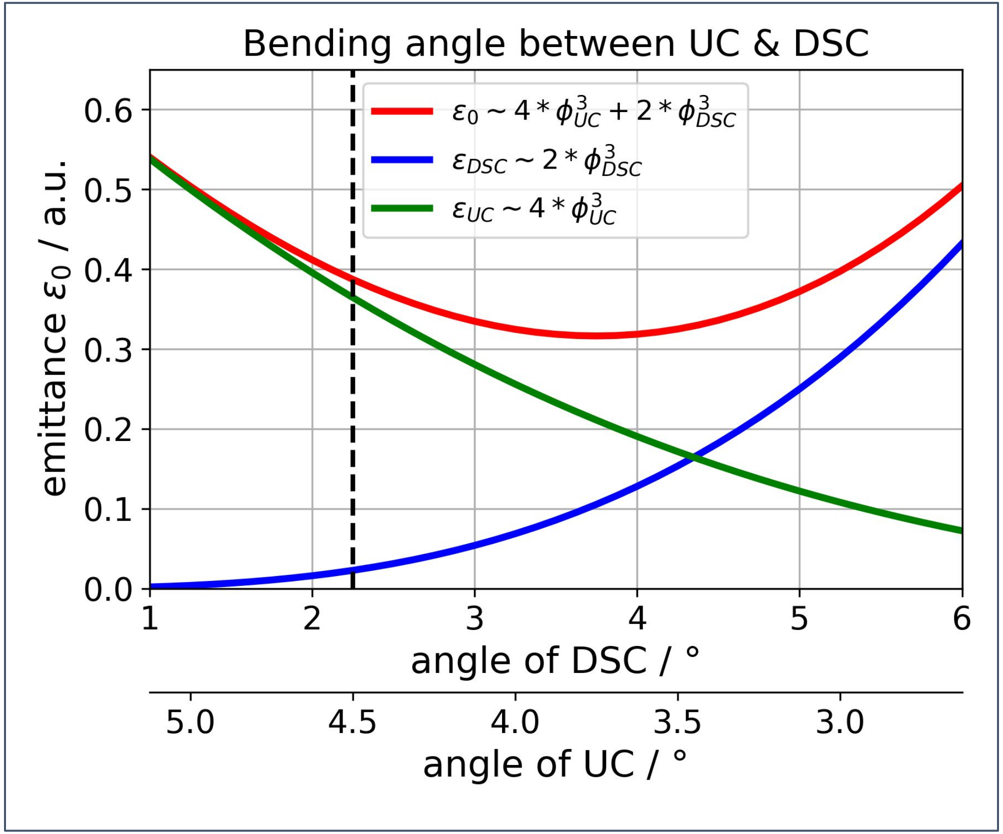
1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach - UC - Angle distribution between UC & DSC

Distribution of bending angles

$$\epsilon_0 \sim \phi^3$$

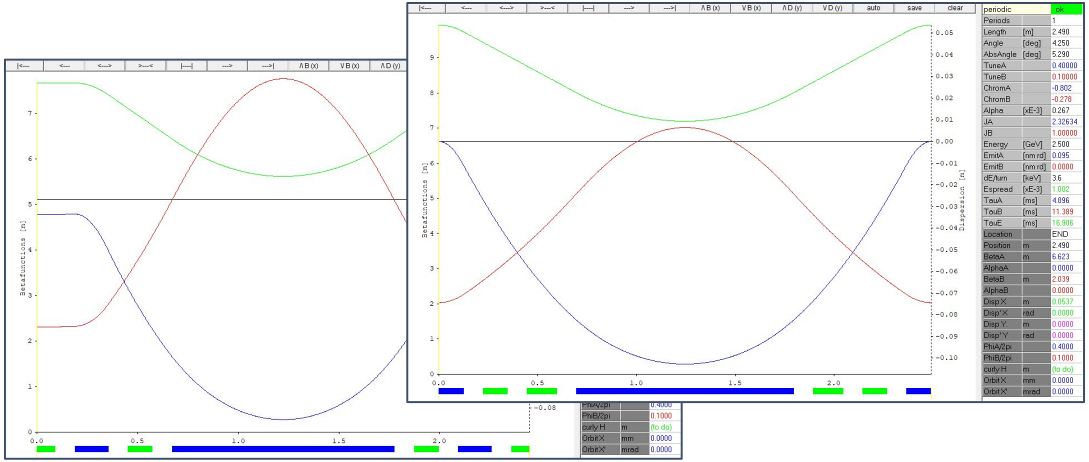
- 16 sectors → 360/16 = 22.5°
- With a 6-MBA: ½ + 4 + ½
  - 2.25° + 4.5° + 4.5° + 4.5° + 4.5° + 2.25°
- For our 6-MBA with 16 straights it is a 20-30% reduction
  - at UC ~ 4.0° and DSC ~ 3.25°



1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach - UC - 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]
SF, RB, SD, 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, SF, SD, 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

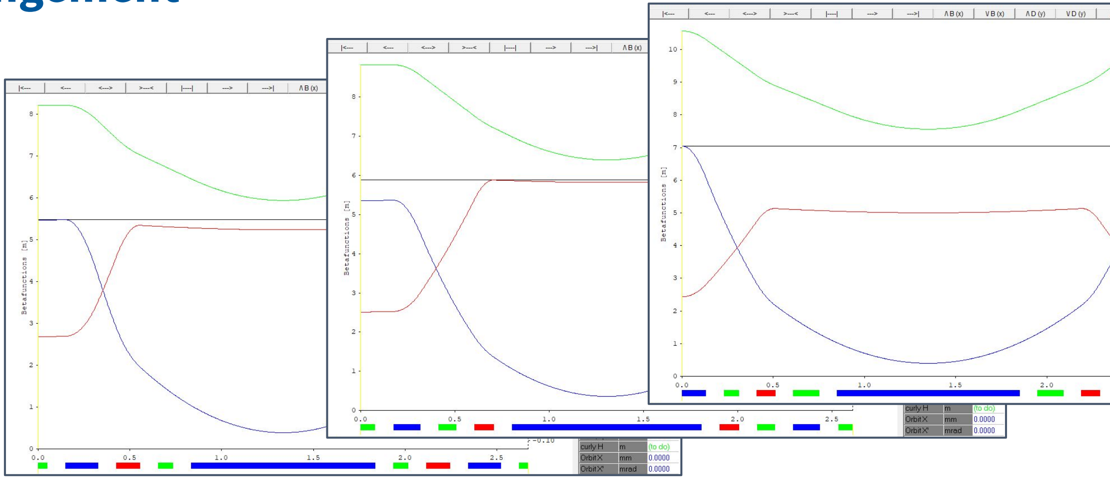
1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach - UC - 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 SF, SD [1/m²] for Chrom = 0
SF, RB, QD, SD, 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
SF, RB, SD, 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, SF, QD, SD, 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

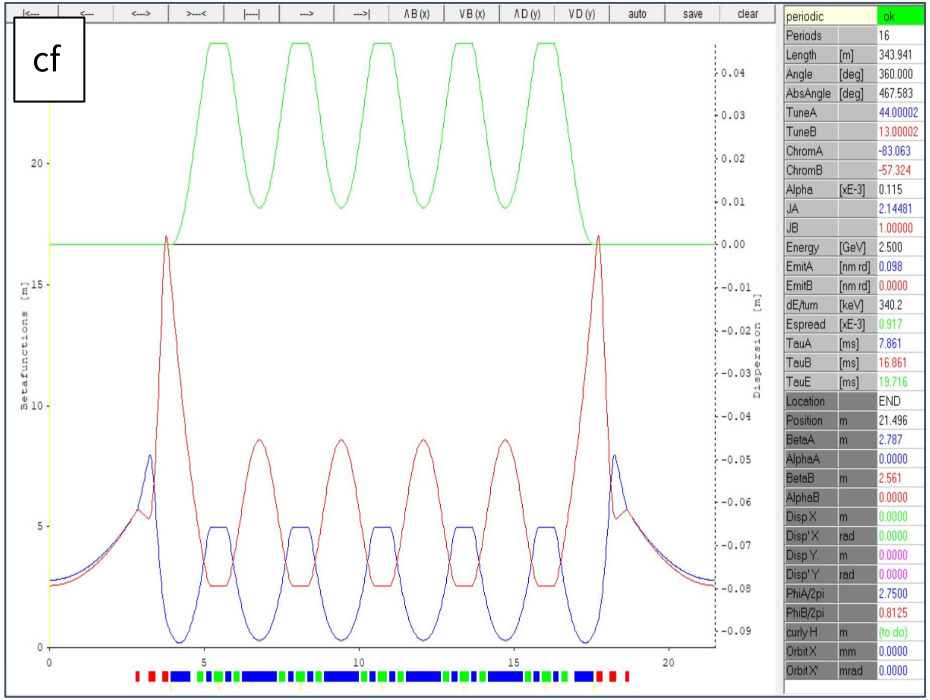
1st Milestone Lattice: HOA - Linear Beam Dynamics

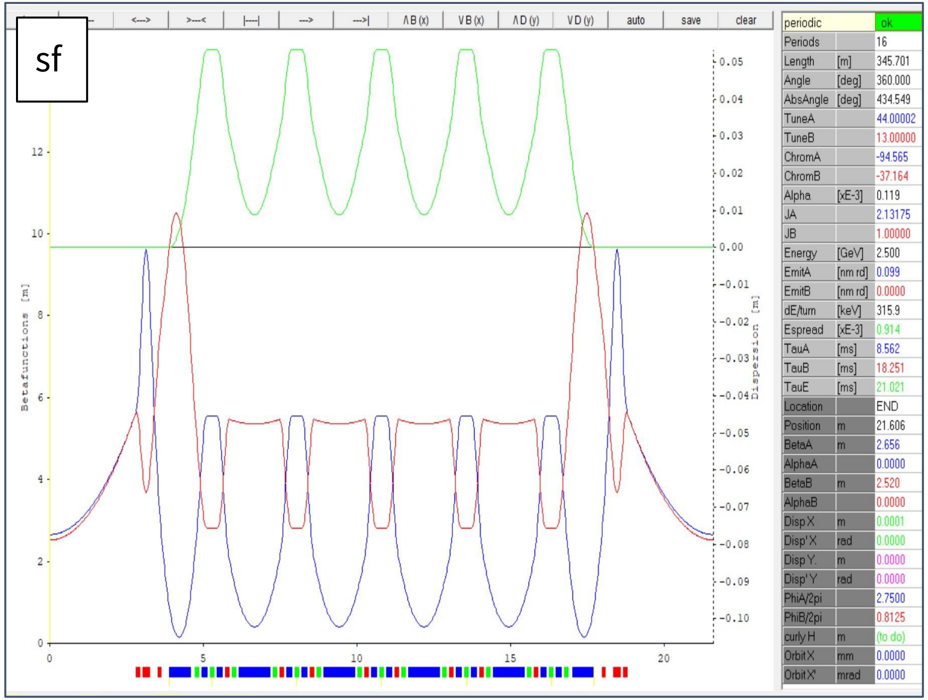
LEGO approach of building a lattice
Setting up and investigation the individual components

- **MBA-unit cell (UC)**, Dispersion suppression cell (DSC), Matching Cell (MC) Quadrupol/Triplett + straight
- 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**. SF & SD to fit chromaticity to zero
- **Findings, Results:**
  - Difference in bending angle between UC & DSC necessary to reach emittance goal
    - cf: 4*4.25° + 2*2.75 ° = 22.5°
    - sf: 4*4.00° + 2*3.25° = 22.5°
  - Positioning of magnets in UC in order to reduce the sextupole strength for chromatic correction !
→ the “one and only” (deterministic) magnet arrangement for MBA-HOA unit cell

1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach of building a lattice - the two lattice candidates





Surprising: - No big difference in circumference between cf and sf lattice ~ 350 m

- cf lattice needs 50% more sextupole strength to correct chromaticity

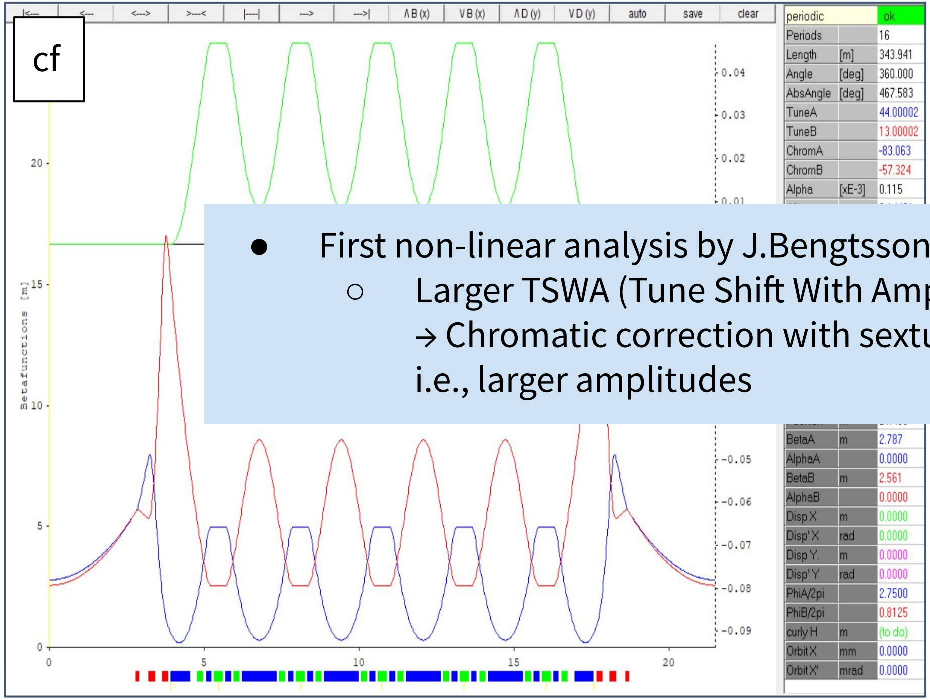
1st Milestone Lattice: HOA - Linear Beam Dynamics

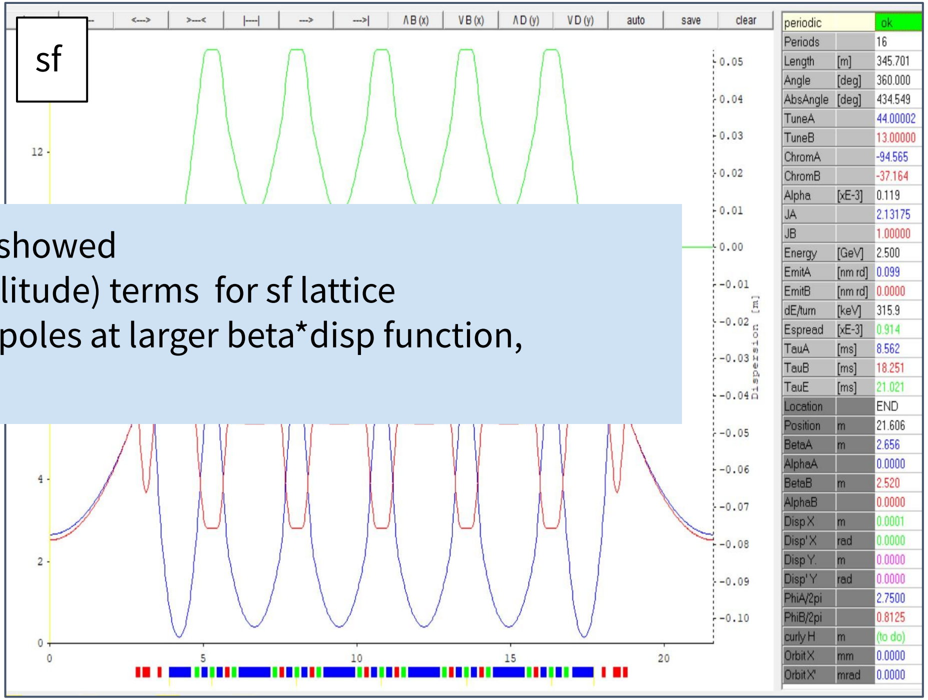
LEGO approach of building a lattice - the two lattice candidates

Lattice	Length	Emittance	Alpha	Tunes	NatChrom	k2*L (ChromXY=0)	Bend source (hom)
CF (4.25, -0.38, -0.16)	344 m	98 pmrad	1.15e-4	44.0, 13.0	-83, -57	397e5 (29.2, -40.3)	
UC	2.646 m	97 pmrad	2.09e-4	0.4, 0.1	-0.686, -0.367	4960	1.1m,5.01°,0.66T, 2.75 keV
DSC	1.533 m	105 pmrad	0.85e-4	0.383, 0.051	-0.396, 0.225		**0.6m,2.91°,0.7T, 2.9 keV**
T+S	3.923 m	0.0	L-alpha	0.193, 0.163	-0.879, -1.315		
Sec	21.496 m			2.75, 0.8125	-5.2, -3.6		467.583° abs angle
SF (4.0, -0.23, -0.245)	346 m	99 pmrad	1.19e-4	44.0, 13.0	-94, -37	175e5 (17.3, -28.2)	
UC	2.760 m	95 pmrad	1.90e-4	0.4, 0.1	-0.747, -0.277	2189	**1.0m,4.46°,0.65T, 2.7 keV**
DSC	1.390 m	109 pmrad	1.67e-4	0.396, 0.041	-0.482, -0.557		0.7m,3.5°, 0.73T, 3.0 keV
T+S	3.893 m	0.0	L-alpha	0.179, 0.165	-0.978, -0.050		
Sec	21.606 m			2.75, 0.8125	-5.9, -2.3		434.549° abs angle

1st Milestone Lattice: HOA - Linear Beam Dynamics

LEGO approach of building a lattice - the two lattice candidates





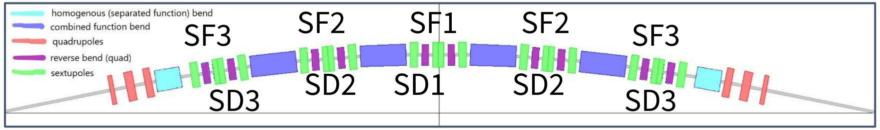
- First non-linear analysis by J.Bengtsson showed
  - Larger TSWA (Tune Shift With Amplitude) terms for sf lattice
    → Chromatic correction with sextupoles at larger beta*disp function,
    i.e., larger amplitudes

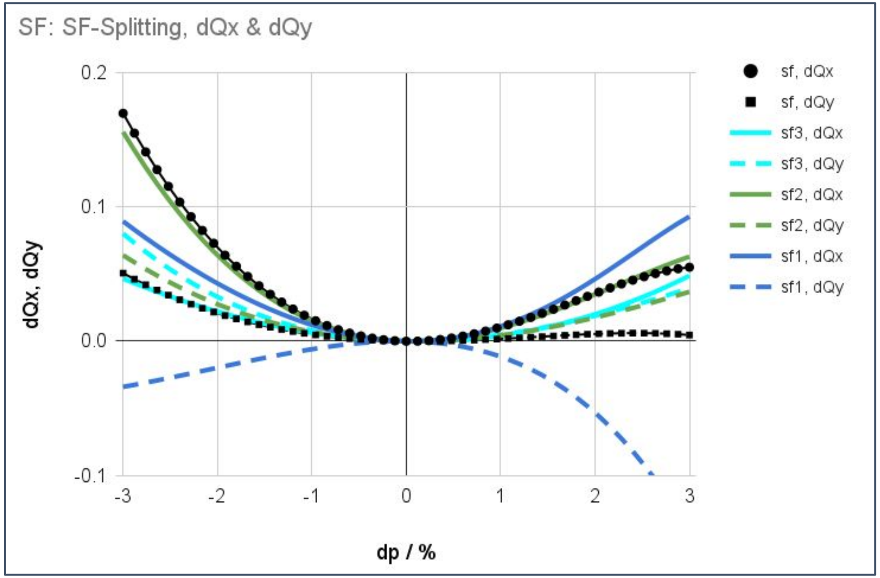
Surprising: - No big difference in circumference between cf and sf lattice ~ 350 m
- cf lattice needs 50% more sextupole strength to correct chromaticity

2nd Milestone Lattice: HOA - First nonlinear optimization

Defining target parameters for non-linear optimization and “knobs”

- 2nd Milestone lattice: chose non-integer working point, investigate existing nonlinear elements before introducing new ones, RDT
- 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



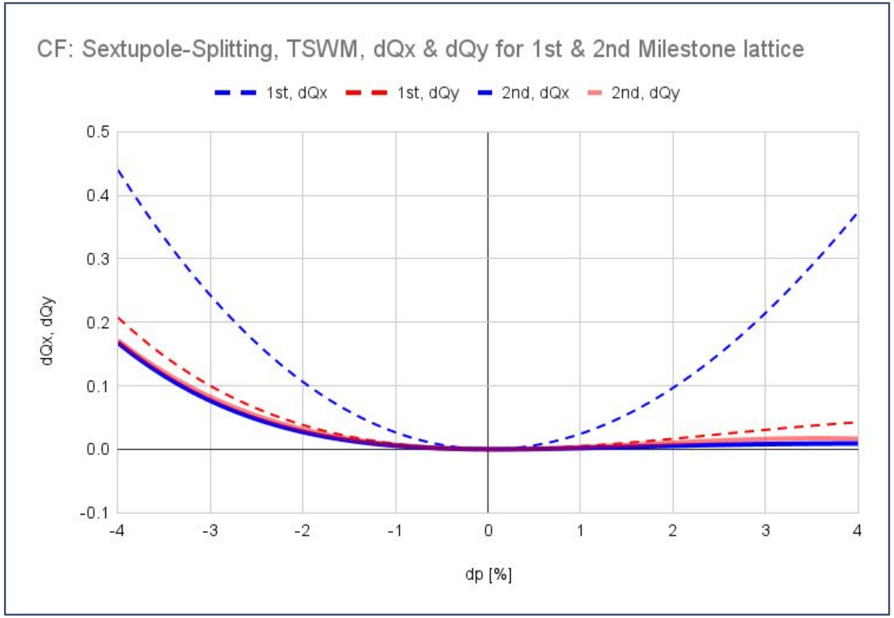


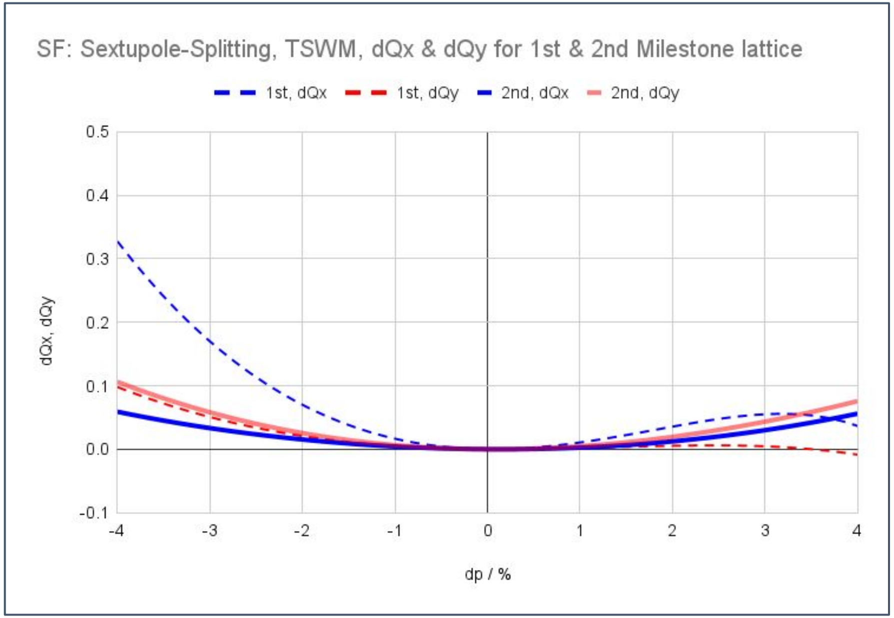
- **Findings, Results:**
  - The two lattice candidates show an Opposite behavior in order to reduce TSWM
    - SF3 with biggest impact at sf lattice
    - SF1 with biggest impact at cf lattice

2nd Milestone Lattice: HOA - First nonlinear optimization

Individual powered chromatic sextupoles for TSWM & TSWA fine tuning (with 3 harmonic octupoles)

- TSWM at Δp = +- 4% could be reduced for
  - cf-lattice: from ΔQxy = (0.44, 0.21) down to (0.17, 0.17)
  - sf-lattice: from ΔQxy = (0.32, 0.10) down to (0.06, 0.10)





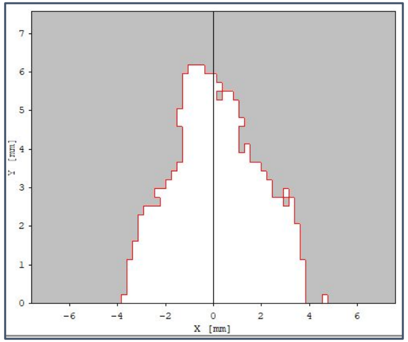
2nd Milestone Lattice: HOA - First nonlinear optimization

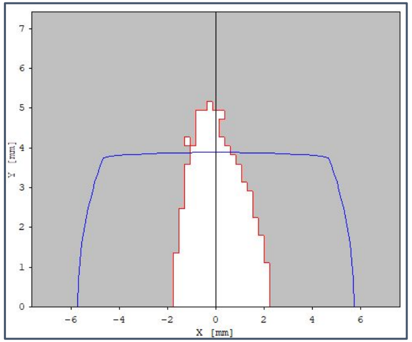
Individual powered chromatic sextupoles for TSWM & TSWA fine tuning

1st Milestone Lattice
Two sextupole families only: SF, SD

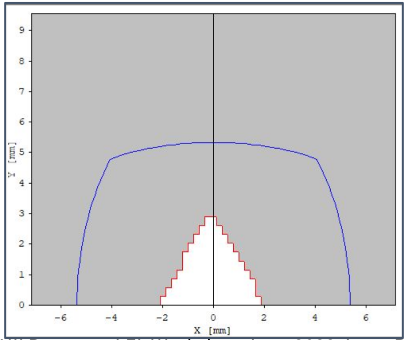
2nd Milestone Lattice
SF & SD splitted in 3 families: SF3, SF2, SF1, SD3, ..

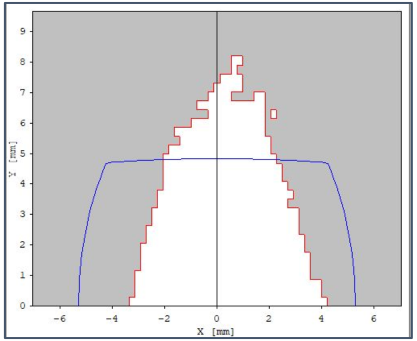
CF



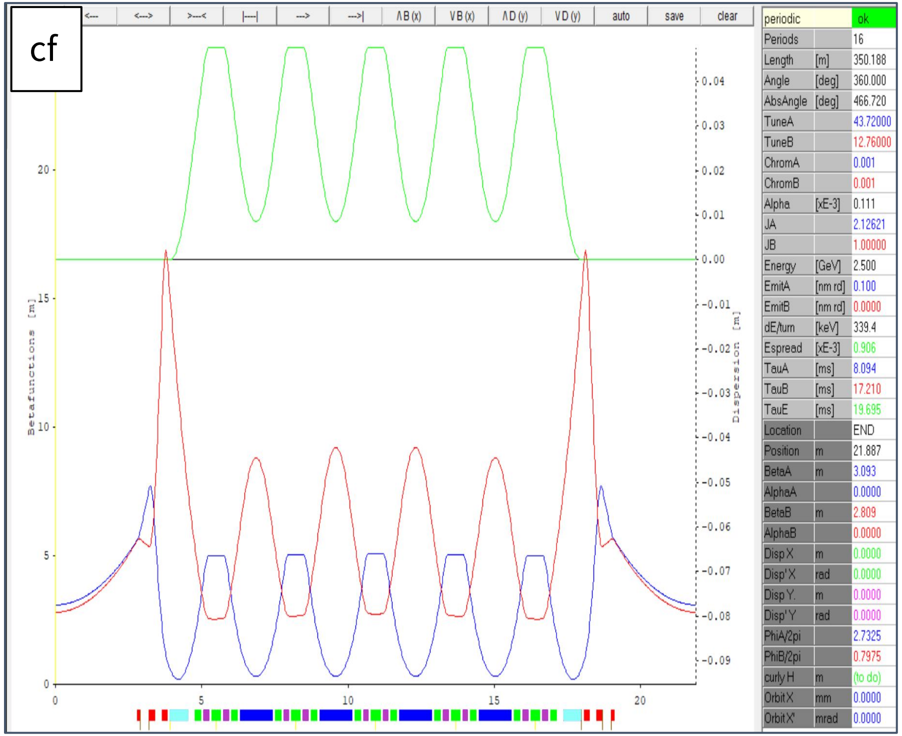


SF

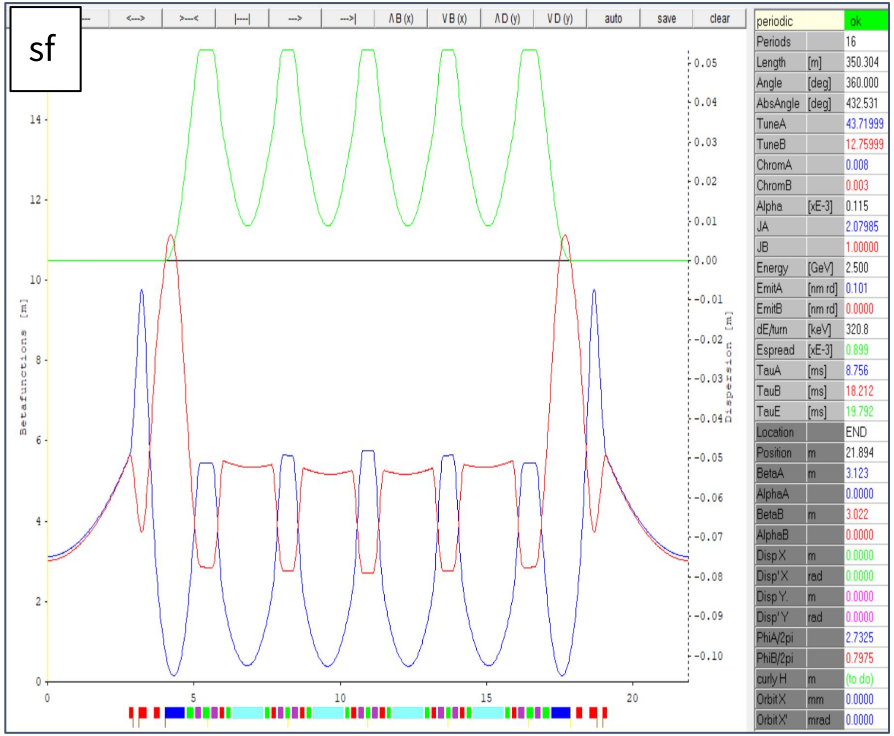




2nd Milestone Lattice: HOA - First nonlinear optimization



SF3 = 253.20, SF2 = 163,39, SF1 = 79.81
SD3b = -246,39, SD3a = -237,65, SD2 = -166.80, SD1 = -126.70



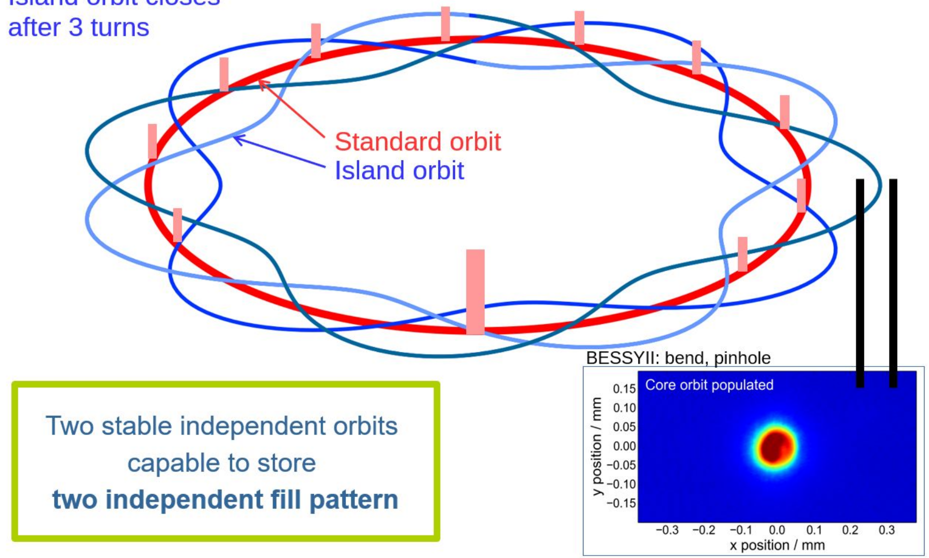
SF3 = 254.84, SF2 = 197.47, SF1 = 181.73
SD3b = -200,29, SD3a = -235,67, SD2 = -188.85, SD1 = -181.73

Bending: 2.75 + 4.25 + 4.25 + 4.25 + 4.25 + 2.75
2.75 + 4*4.25 = 22.5° … *16 = 360

Bending: 3.25 + 4.00 + 4.00 + 4.00 + 4.00 + 3.25
3.25 + 4*4.00 = 22.5° … *16 = 360

BESSY III and TRIBs operation

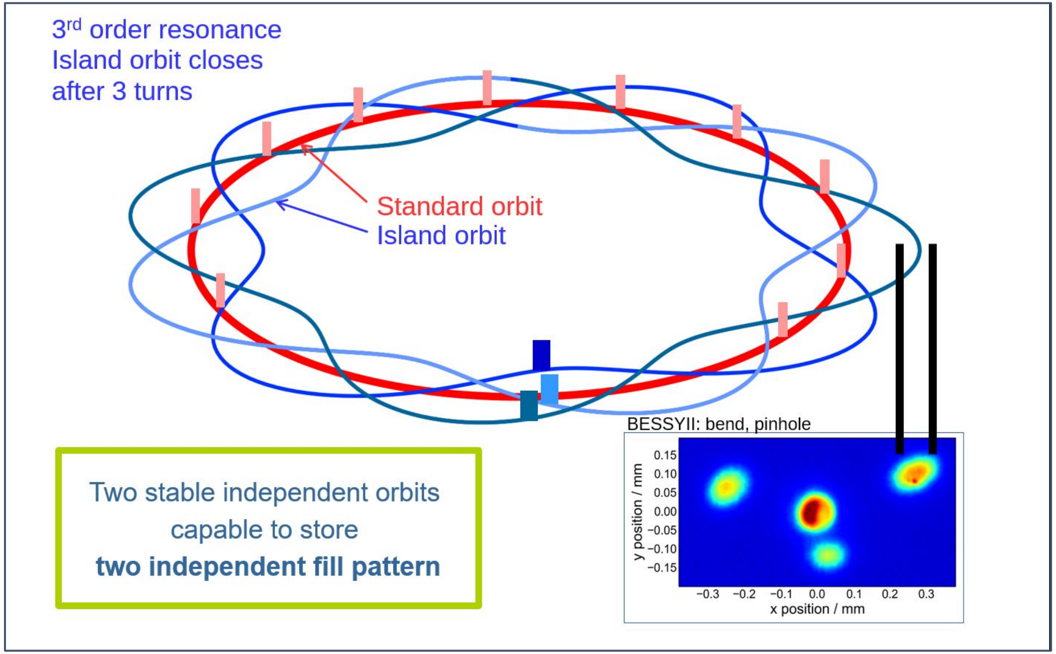
Transverse Resonance Island Buckets generate a 2nd Orbit



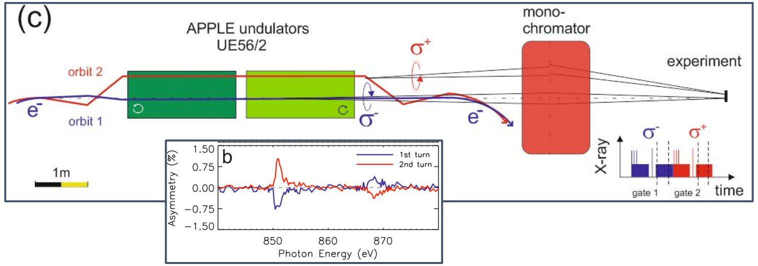
Two stable independent orbits
capable to store
two independent fill pattern

BESSY III and TRIBs operation

Transverse Resonance Island Buckets generate a 2nd Orbit



1.) MHz helicity flipping from an undualtor



2.) Turn-by-Turn Two color experiments (under publications)

3.) Turn-by-Turn Reference beam

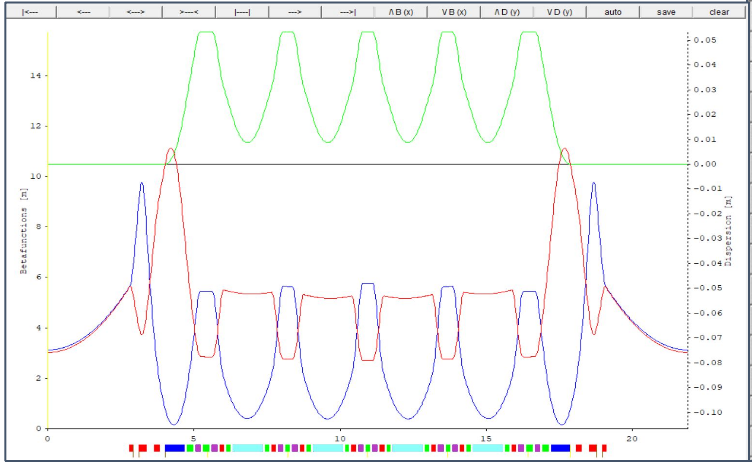
Summary & Outlook

Combined function or Separated function (homogenous bend) Unit Cell

- BESSY III lattice development is ongoing. (so far mainly OPA (great tool), but now elegant, tracy, madx)
  Special request: **homogenous bend for metrology applications**
- **LEGO approach:** Study individual components UC, DSC, MC
- sf lattice (at least) as good as cf lattice ! → Less chromatic sextupole strength needed.
  Is there a benefit of combined function bends, when using reverse bends

- Non-linear optimization on the way, control of TSWM, TSWA to improve DA, MOGA, …
- Injection
- Bending sources per sector, LGB ?

periodic		ok
Periods		16
Length	[m]	350.304
Angle	[deg]	360.000
AbsAngle	[deg]	432.531
TuneA		43.71999
TuneB		12.75999
ChromA		0.008
ChromB		0.003
Alpha	[xE-3]	0.115
JA		2.07985
JB		1.00000
Energy	[GeV]	2.500
EmitA	[nm rd]	0.101
EmitB	[nm rd]	0.0000
dE/turn	[keV]	320.8
Espread	[xE-3]	0.899
TauA	[ms]	8.756
TauB	[ms]	18.212
TauE	[ms]	19.792
Location		END
Position	m	21.894
BetaA	m	3.123
AlphaA		0.0000
BetaB	m	3.022
AlphaB		0.0000
Disp X	m	0.0000
Disp'X	rad	0.0000
Disp Y.	m	0.0000
Disp'Y	rad	0.0000
PhiA/2pi		2.7325
PhiB/2pi		0.7975



Questions for Discussion

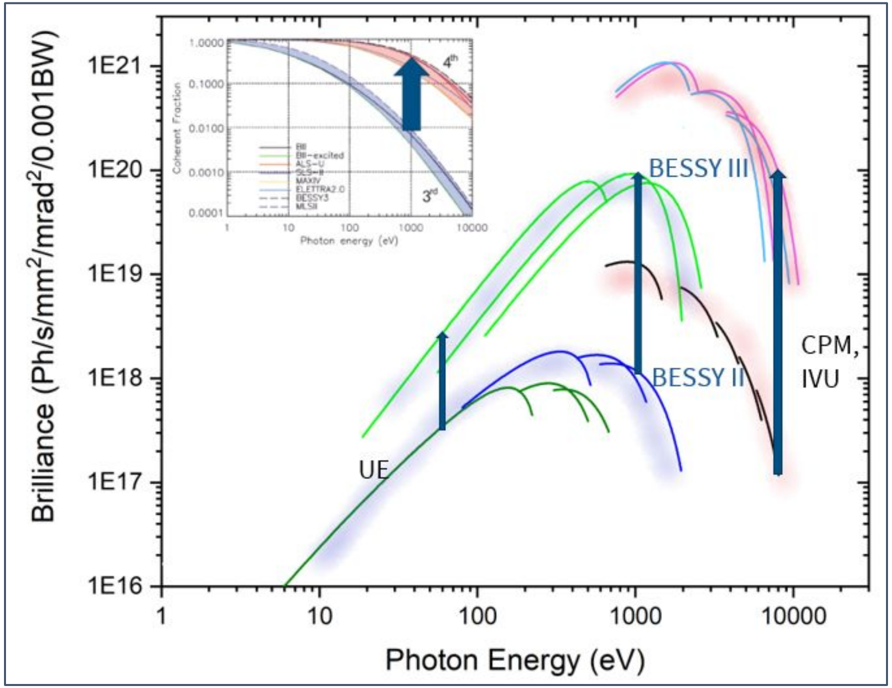
Open points

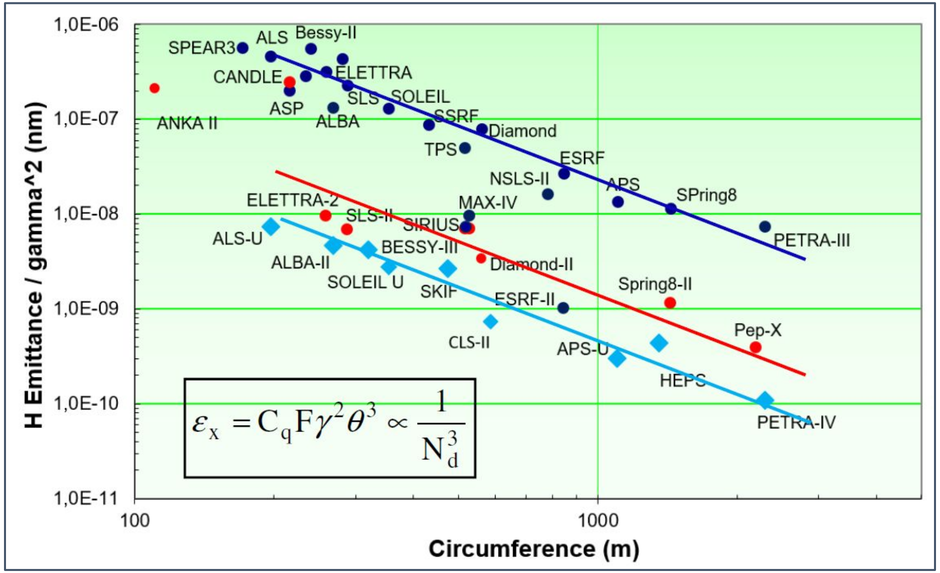
- **How do you realize the Reverse Bend?**
  - Shifted quadrupole or Extra windings or Steered off orbit in quads?

- **What limits the spacing between magnets?** Technical limits or beam dynamics (cross-talk)
  - Rule of thumb: Spacing at least 2x bore diameter
    - 3rd generation lightsources: bore diameter 70 - 80 mm → ~ 150 mm spacing
    - 4th generation lightsources: bore diameter 25 mm → ~ 50 mm spacing

BESSY III

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

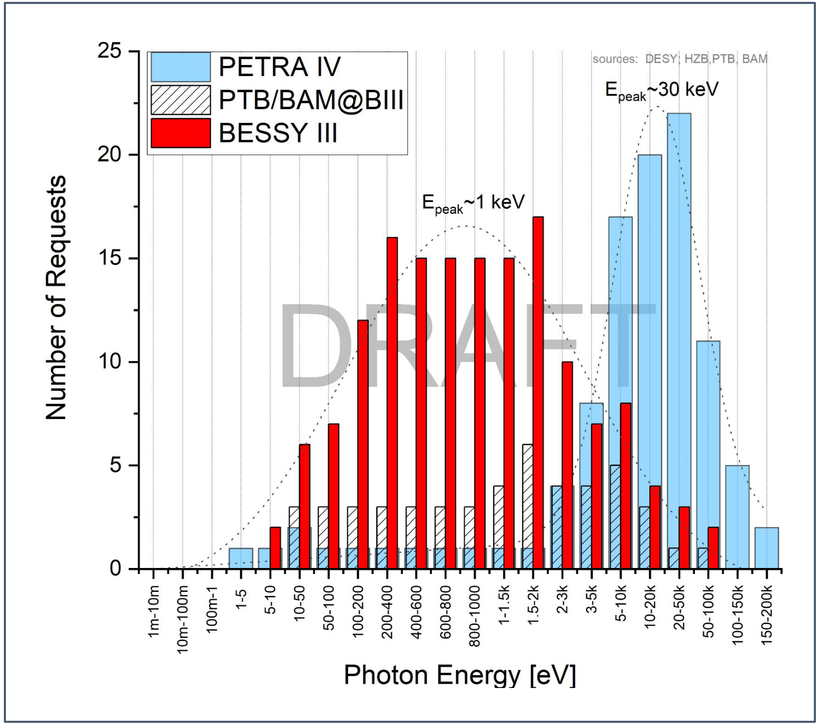




In situ - in operando, sample environment, Labs → Integrated Research Facility

BESSY III

Beamline Requests & Portfolio



#	Name	Photon Energy	Main Methods	Main Applications
1	VUV to Hard	5 eV - 20 keV	XPS, HAXPES, NEXAFS, STXM	Catalysis, Energy (Storage, Batteries, Solar Fuels)
			XPS, HAXPES, NEXAFS, STXM	
		DIP 20 -1.500 eV	UPS/XPS, NEXAFS, EXAFS, XPS, UPS, ARPES	Energy, Catalysis
2	Soft and Tender	100 - 4.000 eV	PES, HAXPES	Energy (Batteries), Quantum
			Resonant Scattering, CDI	Energy, Quantum
		DIP 2 - 14 keV	Diffraction/ EXAFS/XRF, NEXAFS,	Energy, Quantum, Catalysis
3	XUV to Soft	60 - 1.500 eV	BElChem, XPS	Catalysis, Chemistry
			BElChem, XPS	Catalysis, Chemistry
		DIP-2 - 14 keV	XRD/ EXAFS, WAXS, SAXS, HAXPES	Energy, Catalysis
4	Magnetic Imaging	150 - 2.000 eV	Lensless Imaging, X-ray holography, XPCS	Quantum, Energy
			STXM, Resonant Scattering, 3D mag. tomogr.	Quantum, Energy
		DIP 100 eV 1.5 keV	XMCD, XAS with magnetic vector fields	Quantum, Energy
5	VUV Spectroscopy	4 - 200 eV	ARPES	Quantum , Energy, Catalysis
			nano-ARPES	Quantum, Energy Catalysis
		DIP 80 eV - 1.500 eV	NEXAFS, XPS	Catalysis, Energy, Quantum
6	Soft and Tender Imaging	180 eV - 8 keV	TXM, FIB-TXM	Life Sciences, Energy
			Tender TXM,Tomography	Life Sciences, Energy
		DIP	Soft & Tender	Catalysis, Energy, Quantum
7	Inelastic Scattering	180 - 3.000 eV	RIXS	Quantum, Energy Catalysis
			meV@1keV RIXS	Quantum, Energy, Catalysis
8	Spectro Microscopy	< 100 -1.800 eV	(S)PEEM, PEEM, Ptychography	Quantum, Energy, Catalysis
			nano-ARPES	Quantum, Energy, Catalysis
		DIP	Broad band soft X-ray spectroscopy	open port
9	Macromolecular Crystallography	5 - 20 keV	X-ray Diffraction	Life Sciences
			X-ray Diffraction	Life Sciences
		DIP	Broad band X-ray spectroscopy	open port
10	Multimodal Spectroscopy	20 eV- 8 keV	Multimodal Spectroscopy	open port
			Time-resolved spectroscopy	open port
		DIP	Declined beamline, Multimodal spectroscopy	Catalysis
11	PTB: PGM/EUV	60 eV - 1.85 keV	Reflectometry / Scatterometry	Metrology for Industry
			Reflectometry / Scatterometry	Metrology for Industry
	PTB: FCM	DIP 1.7 keV - 11 keV	X-ray radiometry / X-ray reflectometry	Metrology
12	PTB: PGM/RFA	80 eV - 2 keV	X-ray spectometry	Materials Metrology
			X-ray spectometry	Materials Metrology
	PTB: white light	DIP 40 eV - 20 keV	Primary source standard BESSY III	Metrology
13	PTB: Tender X-ray	1 keV - 10 keV	µ-XRF/ (GI)SAXS / Ptychography	Materials Metrology, Energy
			µ-XRF/ (GI)SAXS / Ptychography	Materials Metrology, Energy
	PTB: XPBF/ESA	DIP 1 keV - 3 keV	X-ray optics for astrophysics	in-line Metrology for Manufacturing
14	BAMline	5 keV - 120 keV	Diffraction, XRF, µCT	Materials Metrology
			Diffraction, XRF, µCT	Materials Metrology

Backup Slides

BESSY III Requirement: Diffraction limited at 1 keV

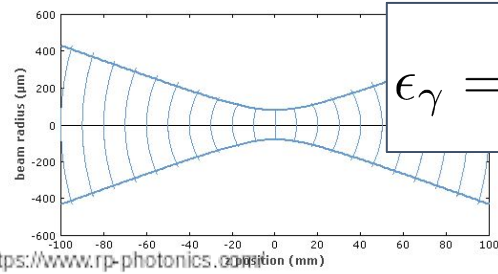
The Diffraction Limit

- Brilliance of radiation source: $$B(\lambda) = \frac{F(\lambda)}{4\pi^2\, \epsilon_x\, \epsilon_y}$$
- Emittance: $$\epsilon_x = \epsilon_{x,e^-} \otimes \epsilon_\gamma$$

  electron beam : $\epsilon_{x,e^-} \sim E^2/N_d^3$

  photon beam : $\epsilon_\gamma = \sigma_\gamma \sigma'_\gamma$
- Photon diffraction limited emittance:

$$\epsilon_\gamma = \sigma_\gamma\, \sigma'_\gamma = \frac{\lambda}{4\pi}$$



https://www.rp-photonics.com/gaussian_beams.html

Storage ring based (transverse) diffraction limited radiation source

$$\epsilon_{x,y,e^-} \ll \epsilon_\gamma = \frac{\lambda}{4\pi}$$

- Diffraction Limited for

0.1 keV	~ 12.4 nm	→	1000 pm rad
1.0 keV	**~ 1.24 nm**	**→**	**100 pm rad**
10.0 keV	~ 0.124 nm	→	10 pm rad

- **1 keV diffraction limited radiation → 100 pm rad e^- beam emittance**

BESSY III Requirement: 1st harmonic up to 1 keV

Energy Range and Period Length of (planar) Undulator Sources

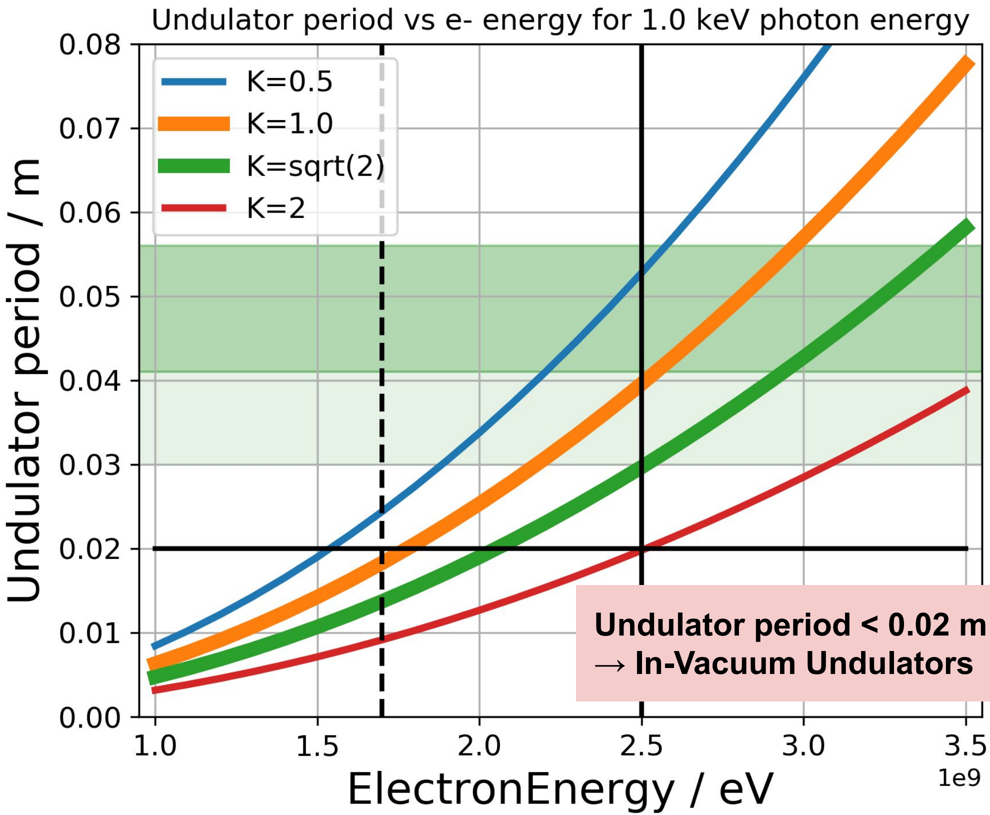
$$\lambda_n(\theta) = \frac{\lambda_u}{n\,2\,\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{e}{2\pi m_e c} B_0 \lambda_0 = 93.36\; B_0[T]\;\lambda_0[m]$$

With

- **The first harmonic n = 1**
- **On axis radiation: $\theta = 0$**
- **K-range 0.8 - 4**
- **λ_1 = 1.24 nm ~ 1 keV**

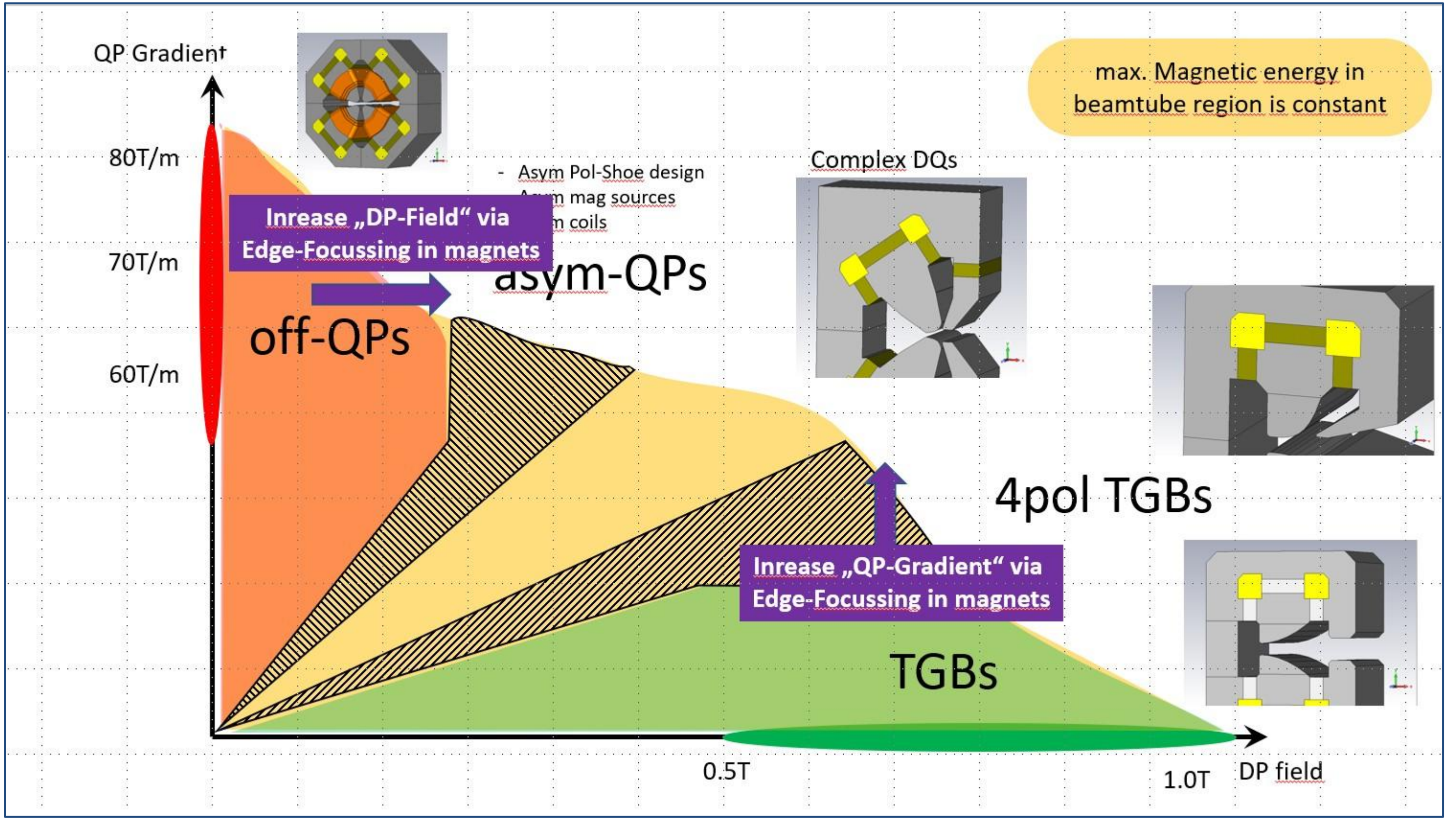
1st harmonic up to 1 keV
→ 2.5 GeV beam energy



Undulator period < 0.02 m
→ In-Vacuum Undulators

1st Milestone Lattice: HOA - Linear Beam Dynamics

Technical limitations: Magnetic specifications Gradients, Bore radius,



1st Milestone Lattice: HOA - Linear Beam Dynamics

Realisation of Reverse Bend ?

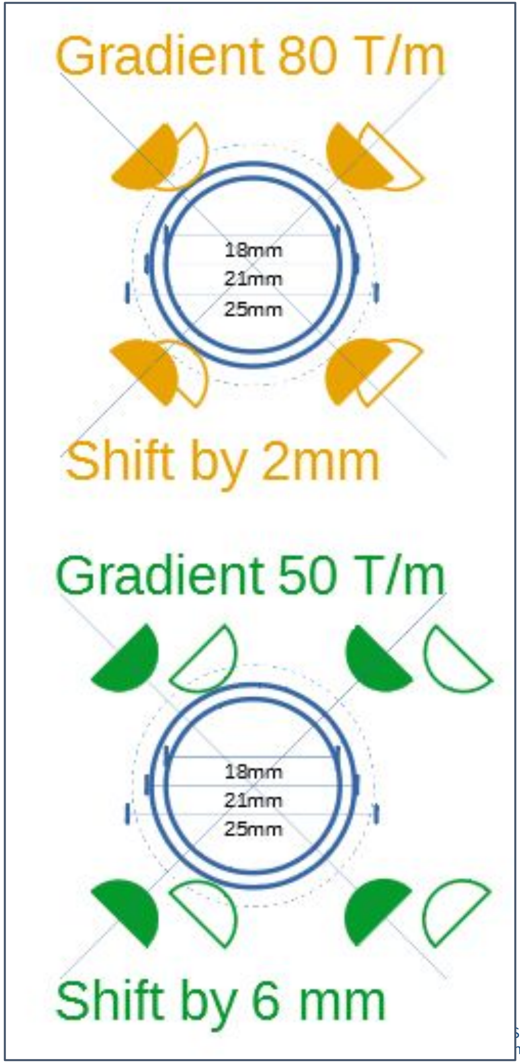
Shifted Quadrupole or Extra Windings or Orbit Shift (Steerers)

Compact combined function unit cell:

- 4.5° / bend (*5 = 22.5)
- HOA-condition Qx, Qy = 0.4, 0.1
- Main bend B < 0.8 T, 15 T/m, 1.0m
  Reverse bend B < 80 T/m

- Reverse bend realised as shifted Quadrupole,
  → Gradient and offset (shifts) possible

80 - 70 T/m	-	0 - 2 mm
70 - 60 T/m	-	2 - 4 mm
60 - 50 T/m	-	4 - 6 mm
< 50 T/m	-	> 6 mm



1st Milestone Lattice: HOA - Linear Beam Dynamics

Realisation of Reverse Bend ?

Shifted Quadrupole or Extra Windings or Orbit Shift (Steerers)

max. B field in the yoke: $B_{max} = 1.0$ T

yoke radius: PSR → $f_{yoke} = PSR^2/2 / x$

Quad Gradient: $g = Bmax / PSR$

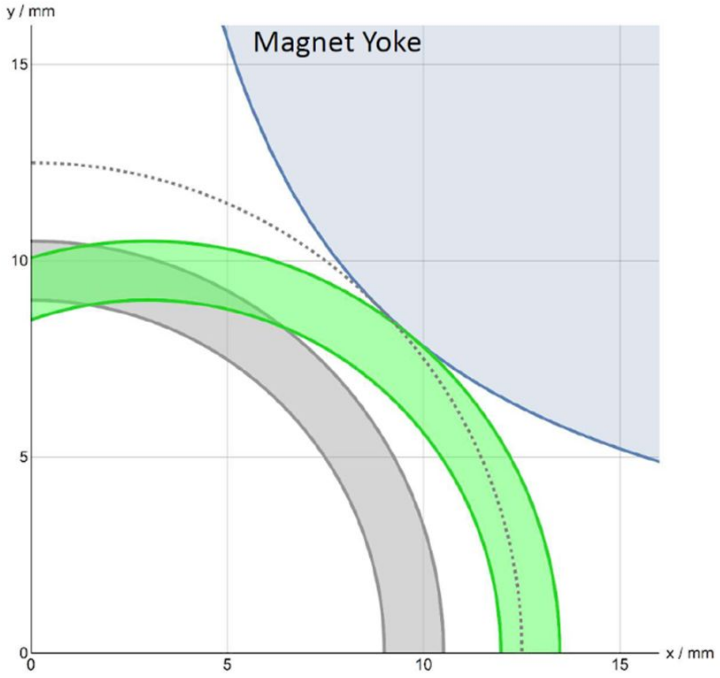
Field in center of shifted vacuum chamber:

$B(Xoffset) = g * Xoffset = Bmax / PSR * Xoffset$

What is the maximum possible offset?

→ analytical: yoke == vacuum chamber (y & dy/dx)

eating up safety margin (heating space)

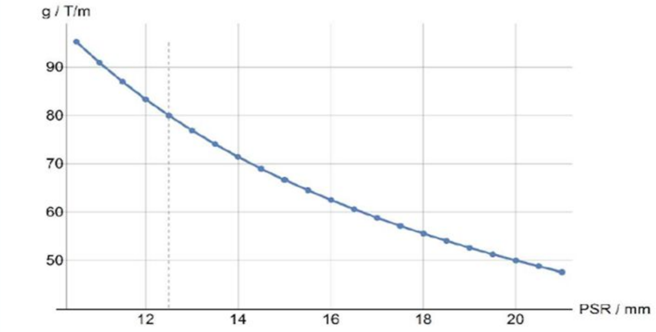


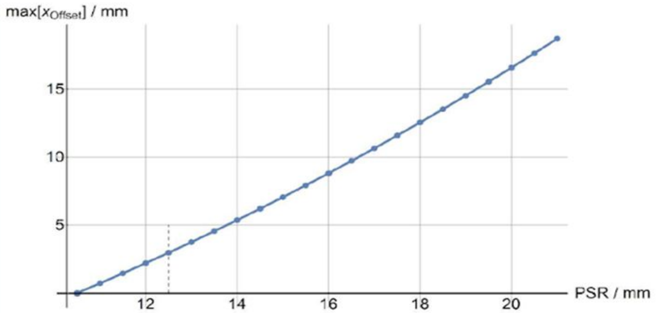
HZB BESSY II Light Source

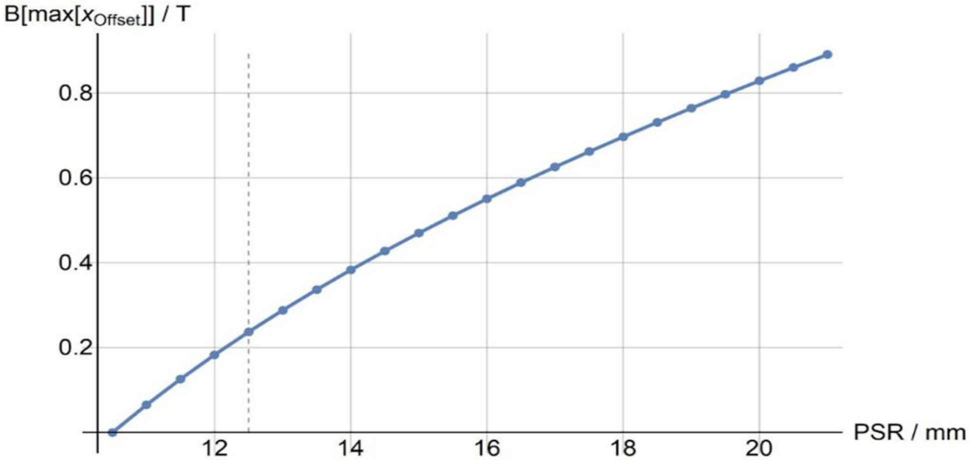
1st Milestone Lattice: HOA - Linear Beam Dynamics

Realisation of Reverse Bend ?

Shifted Quadrupole or Extra Windings or Orbit Shift (Steerers)







vacuum chamber: outer radius = 10.5 mm (kept const)

safety space = 2.0 mm

magnet: B_{yoke} = 1.0 T