ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1B1

A HIGHLY COMPETITIVE NON-STANDARD LATTICE FOR A 4th GENERATION LIGHT SOURCE WITH METROLOGY AND TIMING CAPABILITIES

P. Goslawski*, M. Abo-Bakr, J. Bengtsson, K. Holldack, Z. Hüsges, A. Jankowiak, K. Kiefer, B. Kuske, A. Meseck, R. Müller, M. Sauerborn, O. Schwarzkopf, J. Viefhaus, J. Völker
Helmholtz-Zentrum Berlin, BESSY, Berlin, Germany

Abstract

The PTB, Germany's national institute for standards & metrology, has relied on synchrotron radiation for metrology purposes for over 40 years and the most prominent customers are lithography systems from ASML/ZEISS. HZB is now working on a concept for a BESSY II successor, based on a 4th generation light source with an emittance of 100 pm rad @ 2.5 GeV. It is essential, that this new facility continues to serve the PTB for metrology purposes. This sets clear boundary conditions for the lattice design, in particular, the need for homogeneous bends as metrological radiation sources. Different Higher-Order-Multi-Bend-Achromat lattices have been developed, based on combined function gradient bends and homogeneous bends in a systematic lattice design approach. All lattices are linearly equivalent with the same emittance and maximum field strength. However, they differ significantly in their non-linear behavior. Based on this analysis, the choice of the BESSY III lattice type is motivated. A special focus is set also on TRIBs (Transverse Resonance Island Buckets) to operate with two orbits as a bunch separation scheme in MBAs, for different repetition rates or for the separation of short and long bunches.

HZB's AND BESSY's NEAR FUTURE

HZB is preparing for its future light source with two main projects [1]: the BESSY II+ project and BESSY III. BESSY II+ is a refurbishment and modernization project of BESSY II, to enable state-of-the-art operation for the next decade. The greenfield BESSY III project aims to establish a storage ring-based light source of the 4th generation based on a Multi-Bend-Achromat (MBA) lattice. A first sketch of the facility was recently published in a pre-CDR [2]. The initial operation of a greenfield project is not expected earlier than 2035, so a modernization of BESSY II, which has been running for 25 years, is mandatory and requested with the BESSY II+ project. It will pave the way towards BESSY III. The time schedule for BESSY II+/III is shown in Fig. 1.

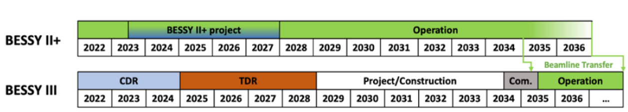

Figure 1: Time schedule for BESSY II+/III project.

VIA BESSY II+ TOWARDS BESSY III

The strategic focus points of the BESSY II+ project are *operando capabilities, modernization, and sustainability*. Overall it is a 100 M€ project, where nearly 25% will be covered by HZB, another 25% by strategic partners or third-party projects and 50% has been requested from the funding bodies. About 50% of the BESSY II+ project scope will be invested in new beamlines and endstations (25%), sample environment (12.5%), and digitalization (12.5%) to strengthen the operando capabilities of BESSY II and HZB. 35% will be used for the modernization of the accelerator complex (30%) and beamline instruments (5%), and 15% is foreseen to improve the sustainability of BESSY II.

The modernization scope for the accelerator complex will not only cover general preservation and modernization measures, but also includes technology development towards BESSY III.

A project already advanced is the development of an active normal conducting 1.5 GHz higher harmonic cavity (HHC) with HOM damper within a European collaboration between ALBA, DESY, and HZB. The prototype, designed and purchased by ALBA and RF tested at HZB, is installed in the BESSY II storage ring. Since autumn 2022, it is tested with beam and conditioned for user operation. Based on this experience, a new HHC system will be developed for BESSY II also including the option for a 1.75 GHz cavity system to generate a beating in the bunch focusing, allowing for simultaneously storing of short and long bunches.

Another important work package is the development of a BESSY II+/III digital twin as a natural interface for the efficient implementation of digitalization measures. This framework and methods are mandatory for the startup, commissioning, and efficient operation of BESSY III and already for the design process, e.g., in order to check for lattice robustness.

The work package *Permanent Magnets for Energy Efficiency* within the BESSY II+ is mainly motivated by BESSY III. In order to improve sustainability and to reduce the power consumption of BESSY III, it is discussed to replace the well-established classical iron yoke electromagnet technology with permanent magnets wherever possible, i.e., at dipoles and quadrupoles. Therefore conceptional designs, prototyping, and testing under real operating conditions are necessary. Within BESSY II+, it is foreseen to replace a very power-hungry bending electromagnet in the transferline between booster and storage ring with a permanent magnet

* paul.goslawski@helmholtz-berlin.de

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1B1

solution to gain experience and know-how. Since the PTB has special requirements on the bending radiation source for metrology purposes, it is also discussed to replace two main bends of one double-bend-achromat section with permanent magnets.

BESSY III PARAMETERS & OVERVIEW

The main objectives and also largest changes compared to BESSY II, as summarized in Table 1, is the increase of energy up to 2.5 GeV and the decrease of emittance down to 100 pm rad, motivated by the science case request for diffraction-limited radiation with adjustable polarisation up to 1 keV photon energy from the 1st undulator harmonics.

Table 1: Main parameters of BESSY II and BESSY III.

Parameter	BESSY II	BESSY III
Energy	1.7 GeV	2.5 GeV
Circumference	240 m	~ 350 m
# of straights	16 with 5.0 m	16 with 5.6 m
Emittance ε_0	5 nm rad	100 pm rad
$\beta_{x,y}$ in straights	(1.2, 1.2) m	~ (3, 3) m

At BESSY II 1 keV photon energy is only accessible with the 3rd or 5th harmonics using APPLE II undulators, as shown in Fig. 2. With the increase of the electron beam energy up to 2.5 GeV, the 1st harmonic with a standard period length of 40 mm will cover this range. It seems that beamline scientists and the user community will prefer the In-Vacuum-Apple type Undulator (IVUE) because the gap can be closed down to ~5 mm instead of ~12 mm for the out-of-vacuum type, enabling a wider photon energy range starting from 100 eV or even below. By the reduction of the emittance by a factor of 50, the spectral brilliance will increase by 2 orders of magnitude in the soft-X-ray regime and by 3 orders of magnitude in the tender-X-ray range.

Not only HZB's scientific infrastructure but also those of its partners as the Max-Planck-Institutes, PTB/BAM, Leibniz institutes (MBI, FBH, IKZ) and the Berlin universities and high-tech companies, make Berlin-Adlershof the one and only place to be for BESSY III. There is still one free site left in Germany's biggest Science and Technology Park, which will limit BESSY III's circumference to ~350 m. With the envisaged emittance of 100 pm rad, BESSY III will rank between current and future upgrades worldwide, staying competitive for the next decades and further scientific challenges to come, see Fig. 3.

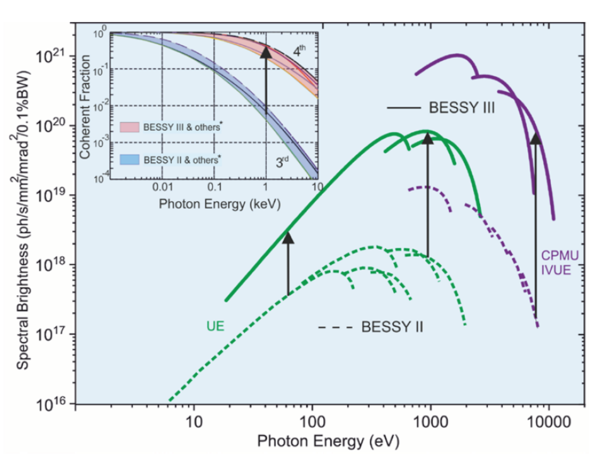

Figure 2: Spectral brightness and coherent flux of BESSY III compared to BESSY II.

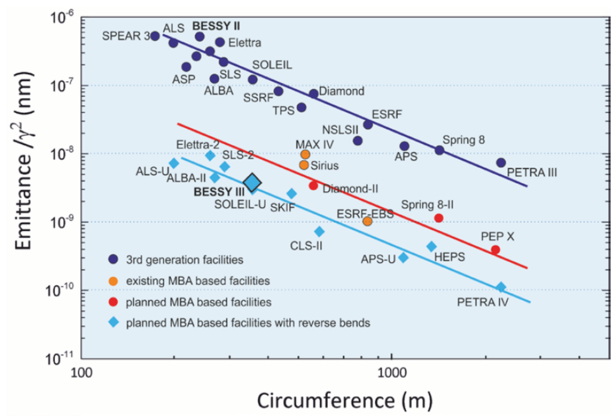

Figure 3: The BESSY facilities on the emittance-circumference landscape.

BESSY III LATTICE DESIGN PROCESS

In addition to the main target parameters, given in Table 1, the momentum compaction factor was chosen not to be too small $\alpha_c > 1.0 \times 10^{-4}$ in order to achieve a reasonable bunch length and manageable collective effects. We aim for a momentum acceptance of 3% or even higher to reach a good Touschek lifetime to keep the option for flexible operation, such as supporting time-resolved experiments. The developments of "TRIBs / Two orbit operation" over the last years motivate us to study this operation scheme for BESSY III and investigate the impact on the achievable parameters compared to a standard user mode with one orbit.

Due to the long-standing partnership with the PTB, an absolutely mandatory demand on the BESSY III facility is to provide a radiation source, usable as a primary radiation standard, i.e., an absolute, predictable, and traceable radiation source for metrology purposes. For that, the deflecting magnetic field around the source point has to be known to high precision and be accessible for an NMR probe measurement. This is best realized with a purely homogeneous dipole magnet. A combined function bend with a magnetic gradient perpendicular to the beam motion, which is often used in MBA unit cells, is therefore not a good choice. The request for the *homogeneous metrology bend* strongly influenced our lattice design process towards a first baseline lattice.

In order to deliver a robust design with good control of non-linear beam dynamics, also with regards to TRIBs operation close to a 3rd order resonance, *we chose the Higher*

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1B1

Order Achromat (HOA) approach, fixing the phase advance between the distributed and repetitive two chromatic sextupole families within the MBA-structure. This cancels all the geometric and quadratic resonance driving terms to 2nd order.

For comparison of a metrology solution using a homogeneous bend with a “classical” combined function bend solution for an MBA lattice, we have chosen a *systematic and deterministic lattice design approach*. That means that all three building blocks of an MBA lattice: the inner MBA unit cell (UC), the dispersion suppression cell (DSC), and finally the matching cell (MC), have been investigated and optimized individually and finally combined like LEGO into a robust sector cell. All lattices designed this way use the same hardware limitations, defined in Table 2 in [3] for a fair comparison.

So far, as shown in Ref. [3] and in Fig. 4, two lattice configurations have been investigated in detail.

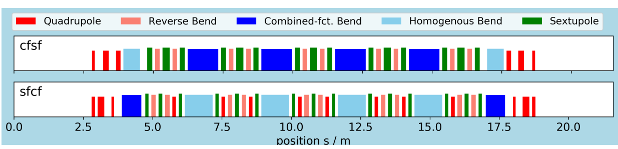

Figure 4: The lattices are named after the type of their bend in the UC and DSC. Top: cfsf (**c**ombined **f**unction, **s**eparate **f**unction) HOA-6MBA lattice. Bottom: sfcf HOA-6MBA.

Due to symmetry reasons, the homogeneous metrology bend was included right from the beginning in the MBA structure to have 16 completely symmetric sectors (or superperiods) as a starting point. In principle, there are then two configurations. In the upper plot the inner UC of the MBA structure is set up with combined function bends (cf), as often used in most MBA lattices. The homogeneous bend - or separated function bend (sf) - is placed at the beginning and end of the MBA structure as matching bend in the DSC. In the bottom plot the configuration is swapped. In the following, we will name the lattices first with the type of the UC bend followed by the type of the DSC bend. So the upper plot shows a cfsf lattice and the lower one an sfcf lattice. The only non-linear elements included so far in the lattice are the two chromatic sextupole families to correct the linear chromaticity to zero.

Since both lattices strongly differ in their non-linear behavior, we decided to study also the more symmetric solutions cfcf and sfsf without switching the type of the bending magnet between UC and DSC. This reduces the perturbation of the optical functions within the MBA structure, especially at the sextupoles in the DSC, and pushes the variation of the optical functions out into the MC. It is clear that the cfcf solution is without a metrology bend, which has to be included later, e.g., in one sector only.

LINEAR LATTICE TUNE FOOTPRINT

Figure 5 shows the optical functions and the magnet arrangement of different lattices for the cf-UC case (cfcf, cfsf) and for the sf-UC case (sfcf, sfsf, sfsf4Q) and Fig. 6 shows the corresponding tune shift with momentum (TSWM). All lattices yield basically the same emittance, momentum compaction factor, working point $(Q_x, Q_y) = (43.72, 12.79)$, maximal field strengths, drift lengths, and straight length of 5.6 m. Therefore, they are linearly equivalent. Only the circumference differs by about 10% because the magnet length has always been adapted to its maximally allowed gradient and in case of the main bend to reach the required emittance. The biggest difference is the construction of the UC, which results in the cf-case in a very strong quadratic behavior of the horizontal TSWM. In the sf-case, the quadratic behavior is reduced and the cubic starts to dominate.

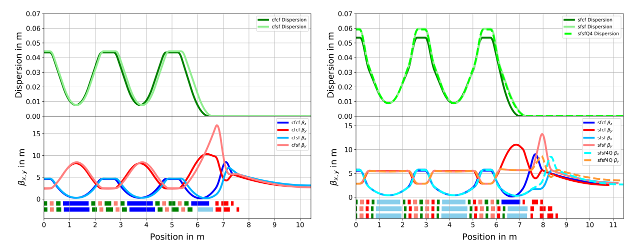

Figure 5: Lattices with optical functions of variants with a cf-UC: cfcf, cfsf (left) and a sf-UC: sfcf, sfsf, sfsf4Q (right).

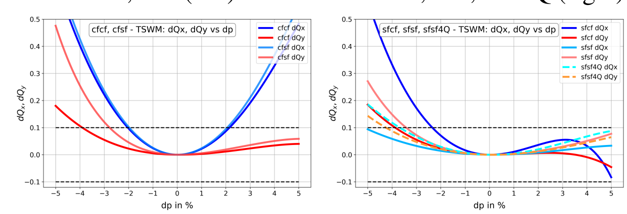

Figure 6: The TSWM for the different lattice variants: cfcf, cfsf (left) and sfcf, sfsf, sfsf4Q (right).

In order to set up a lattice with well-controlled non-linear dynamics one should keep the natural chromaticity and sextupole strength as small as possible to set up an effective chromatic correction $\xi \sim \oint [k_2(s) \cdot D(s) - k_1(s)]\, \beta(s)\, ds$ by placing the sextupoles at the best positions of the optical functions to confine the tune-footprint as good as possible, i.e., to reduce the non-linear behavior and “harmonize” the lattice. Since the chromatic sextupoles introduce the non-linear behavior in order to compensate for the natural chromaticity, we tried to optimize for a solution, where its integrated sextupole strength $\sum (k_2 \cdot L)^2$ is minimized. The most important parameters to judge the non-linear behavior of the different lattice variants are summarised in Tab. 2. To compare the tune footprint of different lattices we define *a tune confinement criterion as a maximal tune shift to be* $dQ_{x,y} = 0.1$ for TSWM and TSWA (tune shift with amplitude).

cf-UC: cfcf, cfsf:

The lattices with cf-UC are limited in the horizontal plane at 2.0 % momentum acceptance if applying the tune confinement criterion. The vertical TSWM is dominated by the cubic order. The change from the cf- to sf-DSC reduces the

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU1B1

Table 2: 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

cubic behavior. It mainly affects the β_y function, shifting its maximum from 10 m up to 16 m, increasing the vertical natural chromaticity from -45 to -60 and reducing the momentum acceptance in the vertical plane from 3.9% to 2.8%.

sf-UC: sfcf, sfsf, sfsf4Q:

The lattices with an sf-UC are not as limited as the cf-UC lattices by the quadratic order. The sfcf lattice shows the strongest cubic behavior and is limited in TSWM in the horizontal plane at 2.3 % (vertically at 3.9 %). The change of the DSC bend from a cf to an sf bend was only possible by introducing an additional vertical focusing quadrupole in the DSC and inverting the quadrupole triplet in the straight. This makes a strong change in the beta-functions at the end of the DSC and in the matching quadrupoles and changes the natural chromaticity from (-94, -39) to (-79, -47). In addition, the length of the main bend had to be increased by 10% to fit the emittance of 100 pm rad. The changes in the optical functions reduced the strong cubic behavior and the TSWM confinement is limited now by the vertical plane and massively relaxed in the horizontal one (5.0%, 3.4%), due to the large value of β_y in the matching quadrupoles and the small values for β_x. Following this argumentation line, it is a logical consequence to change the quadrupole triplet into a quadruplet to improve the control of both beta functions in the matching quadrupole section, which allows a careful adjustment of the non-linear behavior and tune confinement. The quadruplet solution "sfsf4Q" is shown with dashed lines and allows to equalize the TSWM behavior in both planes resulting in a TSWM confinement of (3.8%, 4.3%).

The TSWA is shown in Figs. 7 and 8 for the different lattices in the middle of a straight with $\beta_{x,y} \approx (3\,\text{m}, 3\,\text{m})$. The cfcf-lattice gives the best results with amplitudes of 4 mm to 5 mm. The worst case is the sfcf lattice with amplitudes of 1.5 mm to 2.5 mm, whereas the other three cfsf, sfsf, sfsf4Q range at 2 mm to 3.5 mm.

So far no measures have been introduced to the lattices to optimize the TSWA behavior. The inner beam pipe radius of 9 mm results in an aperture in the straights of 5 mm to 6 mm in the horizontal and 3.5 mm to 5.5 mm in the vertical plane for the different lattice candidates. First tests showed that an improvement could be possible by splitting up the chromatic sextupole families or introducing geometric/harmonic multipoles.

The direct next step is the introduction of a non-linear optimization scheme. For example, chromatic octupoles can

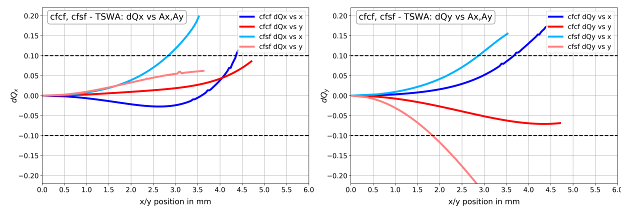

Figure 7: TSWA for lattice variants with a cf-UC: cfcf, cfsf. Left: dQ_x vs. $A_{x,y}$. Right: dQ_y vs. $A_{x,y}$.

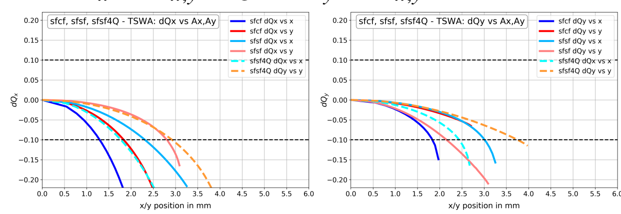

Figure 8: TSWA for lattice variants with a sf-UC: sfcf, sfsf, sfsf4Q. Left: dQ_x vs. $A_{x,y}$. Right: dQ_y vs. $A_{x,y}$.

be introduced to reduce the quadratic order, especially for the cf-UC lattices. Or the two families of sextupoles could be split up to improve the tune footprint. Discussion and work are ongoing to find a robust solution for BESSY III. Further steps are the verification of robustness, the development of an injection concept, the implementation of a simulated commissioning scheme, and a detailed analysis of collective effects.

CONCLUSION

In this paper, we have given an overview of the BESSY III project and shown how a careful setup of the linear lattice influences the non-linear beam dynamics. The choice for a different hardware realization of the UC with cf or sf bends has a big impact on the non-linear tune footprint and sets a starting point for further optimization of the non-linear behavior including higher-order multipoles.

REFERENCES

[1] O. Schwarzkopf *et al.*, "Materials discovery at BESSY", *Eur. Phys. J. Plus*, vol. 138, no. 348, 2023. doi:10.1140/epjp/s13360-023-03957-8

[2] P. Goslawski *et al.*, "BESSY III - The Materials Discovery Facility", PreCDR, 2022. doi:10.5442/r0004

[3] P. Goslawski *et al.*, "BESSY III - Status Report and Lattice Design Process", presented at IPAC'22, Bangkok, Thailand, May 2022, paper TUPOMS010. doi:10.18429/JACoW-IPAC2022-TUPOMS010