

A non-standard, but competitive, lattice solution for a 4th generation light source with capabilities for metrology applications & timing

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Abstract. HZB is working on a concept for a BESSY II successor, based on a 4th generation light source with an emittance of 100 pmrad@2.5 GeV. The PTB, Germany's national metrology institute, has relied on synchrotron radiation for metrology purposes for over 40 years and the most prominent customers are lithography systems from ASML/ZEISS. It is essential, that this new facility continues to serve the PTB for metrology purposes. This sets clear boundary conditions for the lattice design, particularly the need for a homogeneous bend as a metrological radiation source. 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.

1 HZB's and BESSY's near future

HZB is preparing for its large-scale facility future 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 is running for 25 years, is mandatory and requested with the BESSY II+ project [3, 4]. It will pave the way towards BESSY III.

2 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 MEUR project, where nearly 25% will be covered by HZB, other 25% by strategic partners or third-party projects and 50% are requested from the funding bodies. About 50% of the BESSY II+ project scope will be invested in new beamlines & 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 existing beamline instruments (5%), and 15% is foreseen to improve the sustainability of BESSY II.



The modernization scope for the accelerator complex will cover general preservation (e.g., a new uninterruptible power supply) and modernization measures (e.g. turn-by-turn BPM system) and include 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 realized for BESSY II+, including a 1.75 GHz cavity system to generate a beating in the bunch focusing, allowing for simultaneously storing of short and long bunches [5].

Another important work package within the BESSY II+ is the development of *Permanent Magnets for Energy Efficiency*, which 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 resistive iron yoke electromagnet technology with hybrid permanent magnets wherever possible, i.e., at dipoles and quadrupoles [7]. Therefore conceptual 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 the booster and storage ring with a permanent magnet solution to gain experience and know-how in real operation.

3 BESSY III Parameters & Overview

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

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

3rd or 5th harmonics using APPLE II undulators, as shown in Fig. 1 (left). 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. In-Vacuum-Apple Undulators (IVUE) [8] are currently under development at HZB 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, which better serves the future needs of our user community. 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 - Max Born Institute, FBH - Ferdinand Braun Institute, IKZ - Leibniz Institut für Kristallzüchtung), and the Berlin universities and high-tech companies, make Berlin-Adlershof the 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 pmrad, BESSY III is well placed between current and future upgrades worldwide, staying competitive for the next decades and further scientific challenges to come, see Fig. 1 (right).

4 BESSY III lattice design process

Besides the parameter goals presented in Tab. 1, the main objective for the lattice design process was to design a **flexible** and **robust/stable** lattice.

The **flexibility** is important due to the diverse user community of BESSY II and its demands for timing modes. Additionally to the well-established timing modes [9], a TRIBs/two-orbit operation mode was developed in the last years, which can be used as bunch separation scheme [10] or enables so far non-accessible radiation parameters at lightsources, as MHz helicity flipping or MHz two-color spectroscopy [11, 12]. Unfortunately, not all beamlines at BESSY II are equipped with the necessary apertures

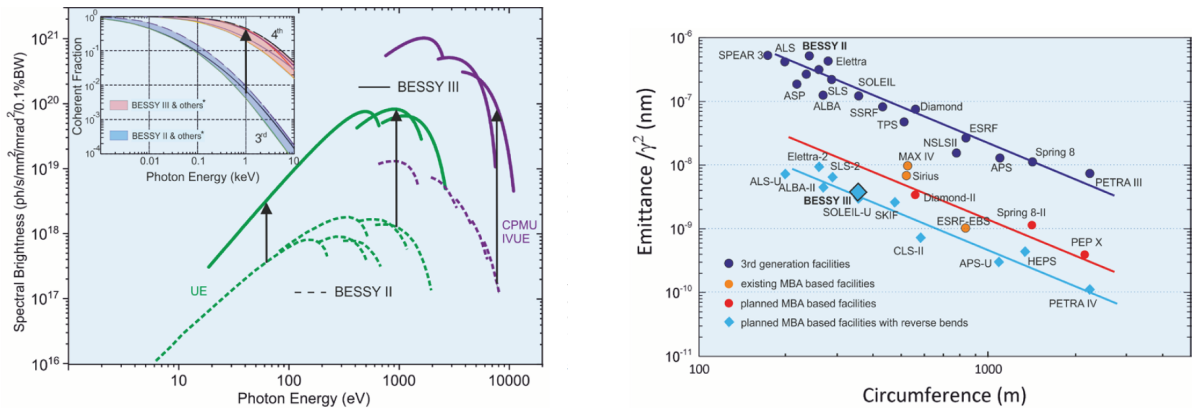


Figure 1: Spectral brightness and coherent fraction of BESSY III compared to BESSY II (left) and the BESSY facilities on the emittance-circumference landscape (right).

to select only one of the source spots, so they accept all of them, which decreases the beamline performance, e.g., worsens the energy resolution. So the decision was taken not to offer TRIBs at BESSY II as user mode. However, the promising achievements with TRIBs/two orbit operation 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 [13].

The other important quantity is **stability & robustness**, particularly concerning the metrology needs of PTB. 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 [14]. 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**. Therefore, a combined function bend with a magnetic gradient perpendicular to the beam motion, often used in multi-bend-achromat (MBA) unit cells, is not a good choice.

To deliver a flexible and robust/stable lattice we focused during the design process of the BESSY III lattice on reducing deteriorating non-linear beam dynamics contributions. The main goal is to achieve a confined tune foot print, i.e., a small chromatic and amplitude-dependent tune shift (or tune shift with momentum or amplitude (TSWM, TSWA)) allowing for a large momentum acceptance δ_{acc} and dynamic aperture. The overall non-linear beam dynamics is defined by the natural chromaticity and the non-linear power needed to correct it, i.e., integrated sextupole strength, which we tried to reduce. A main effort was set to achieve a good chromatic tune shift, giving a good momentum acceptance, which impacts the Touschek-lifetime cubically, see Eq. 1

$$\frac{1}{\tau_T} = \frac{N r_e^2 c}{8\pi} \frac{1}{\sigma_x \sigma_y \sigma_0} \frac{1}{\gamma^2 \delta_{acc}^3} D(\zeta). \quad (1)$$

Only with a sufficient lifetime, timing modes will become accessible at 4th generation lightsources, and the 10 ps time range may be preserved. As seen at most 4th generation lightsources, the non-linear beam dynamics limits the lattice performance resulting in a very small Touschek-lifetime, which is then often improved by increased transverse coupling (10% to 100%) or longitudinally lengthening of the bunches with HHCs to hundreds of picoseconds¹.

4.1 The BESSY III baseline lattice

All MBA lattices are mainly based on two different types: the ESRF-type hybrid lattice [15] with dispersion bumps at the beginning and end of a sector for chromatic correction with sextupoles and the Higher Order Achromat (HOA) [16], with distributed and repetitive two chromatic sextupole families within the MBA-structure. We chose to investigate the HOA solution because most low energy facilities ($E < 3$ GeV) with small circumference ($C < 400$ m) are based on this approach. The 6-MB-HOA with

¹Often MBA lattices are operated only with homogenous fill pattern, without special bunches or gaps for timing experiments, to improve the HHC lengthening.

5 sextupole cells and a phase advance of $(\mu_x, \mu_y) = (0.4, 0.1)$ between the sextupole cells to cancel all the geometric & quadratic resonance driving terms to 2nd order [16] is the best choice concerning the envisaged emittance, allowed circumference, and required number of straights².

Due to the necessarily low dispersion and the strong focusing of MBA lattices, their strong sextupoles lead to a demanding non-linear behavior. Since the non-linearities in the transverse plane limit the performance of many³ MBA lattices, we focused right from the beginning on relaxing the transverse non-linear beam dynamics, despite providing the required emittance of 100 pm rad. Therefore we followed a systematic and deterministic lattice design approach [17]. That means the various possibilities to set up the different basic building blocks of an MBA lattice, which are the inner MBA-unit-cell (UC), the dispersion suppression cell (DSC), and the dispersion-free matching cell (MC) have been studied with the objective to reduce the sextupole power needed for the correction of the transverse natural chromaticity and provide the necessary phase matching for cancellation of the lower order resonance driving terms. The best solutions for UC, DCS & MC concerning non-linear behavior have been then combined like "LEGO bricks" into a robust sector cell. The BESSY III baseline lattice which will be further developed in the TDR phase is shown in Fig. 2. It mainly differs from other MBA-HOA lattices by using only

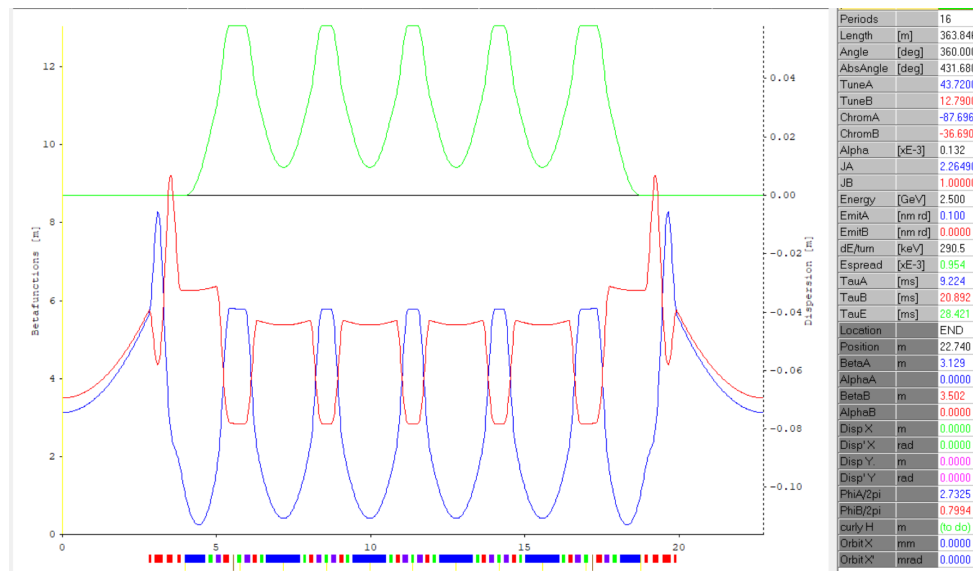


Figure 2: The BESSY III baseline lattice with homogenous bends (blue), pure quadrupole (red), off-axis quadrupole with a small bending contribution (purple) and two chromatic sextupoles (green).

homogenous / separated function bends and an additional vertical focusing quadrupole, instead of a main combined function bend with integrated vertical focusing.

For the MBA-UC, which consists of the main bend, two focusing, and two chromaticity correcting components in the x-plane and y-plane respectively, we could show that utilizing a setup build-up on a separated function (**sf**) bend reduces the sextupole power by factor 2, resulting in a factor ~ 2 smaller TSWM compared to a combined function (**cf**) bend solution. Fig. 3 shows on the left different cf-UC lattices, which differ mainly by the bend in the dispersion suppression cell, once realized with a sf-bend and once with a cf-bend, named as cfcf or cfsf. On the right three different sf-UC lattices are shown (sfcf, sfsf, sfsf4Q) with different DSC and MC solutions resulting in different natural chromaticities with different residual non-linear chromatic tune shifts (TSWM) as shown in Fig. 4. The sfcf lattice with a cf-bend in the DSC has a strong cubic term, which is reduced by choosing a sf-bend: sfsf. With 4 quadrupoles (sfsf4Q) in the MC it is possible to adjust the beta functions in both planes to some extent individually and match the TSWM in both planes. 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

²So far we have solely considered HOA-lattices with non-linear sextupoles placed in dispersive regions between the bending magnets. Setups with geometric/harmonic sextupoles in the adjacent bending free straights have not yet been studied in detail.

³"maybe all"

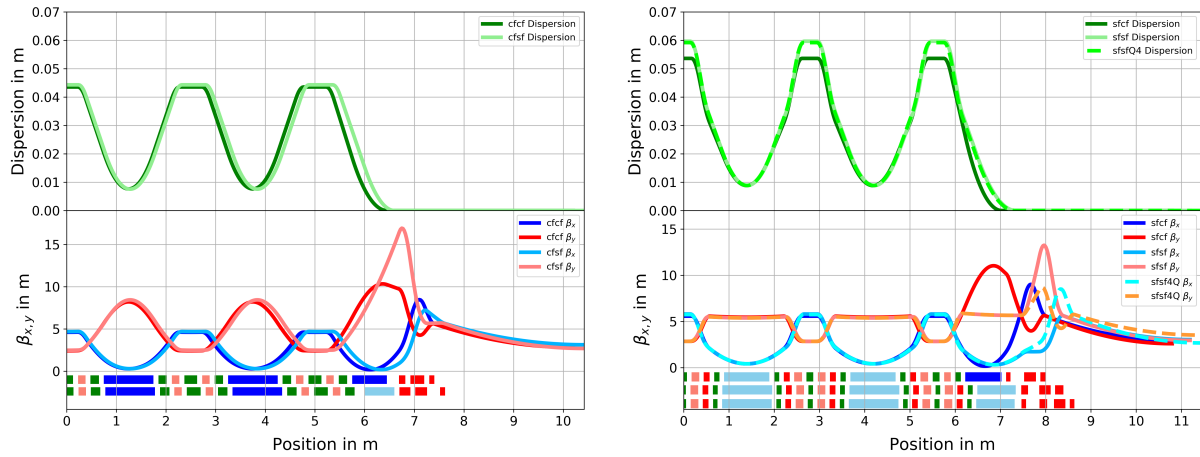


Figure 3: Lattices with optical functions of variants with a cf-UC: cfcf, cfsf (left) and a sf-UC: sfcf, sfsf, sfsf4Q (right).

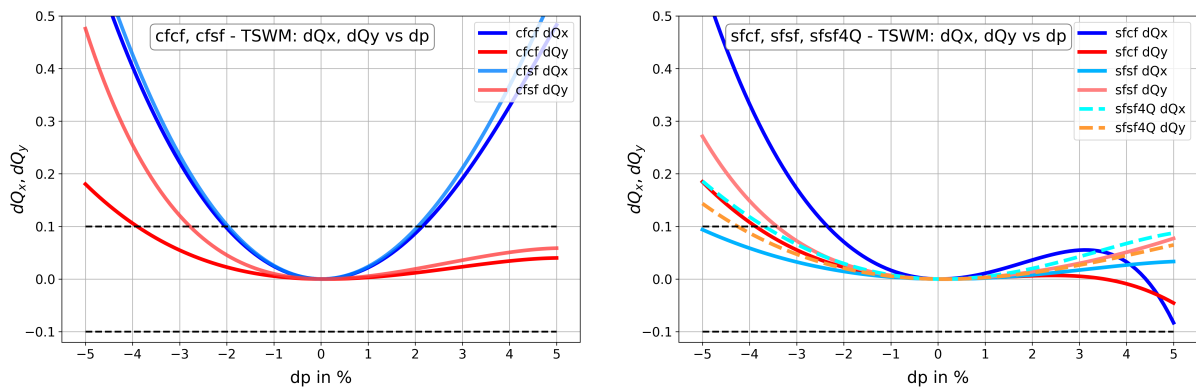


Figure 4: The TSWM for the different lattice variants: cfcf, cfsf (left) and sfcf, sfsf, sfsf4Q (right).

and TSWA. When comparing these lattices with only two sextupole families for correcting the horizontal and vertical natural chromaticity, the TSWM is dominated by the quadratic term and limited to 2% for the cf lattices and extends to 4% for the best sf lattice. By splitting up the sextupoles families and introducing chromatic octupoles, it can be improved to $\sim 3\%$ for cf- and $\sim 5\%$ for sf-lattice⁴.

Further adjustment of the sfsf4Q lattice was necessary to preserve the transverse momentum acceptance of $dp \approx 5\%$. Unfortunately, the rf momentum acceptance was limited by the non-linear beam dynamics to 3.5%, but could be improved to 5-6%, fitting very well the transverse one, by small adaption of the UC and DSC, described in detail in [18]. Currently, we are working to develop a well-defined recipe to optimize the non-linear knobs and beam dynamics. Further steps are implementing an orbit correction scheme, verifying the robustness, designing an injection concept, implementing a simulated commissioning scheme, and a detailed analysis of collective effects.

4.2 Bending magnets as radiation sources

The flux density and the brilliance of the bending sources at BESSY II and the intended bending sources at BESSY III are shown in Figure 5. BESSY II currently provides two different types of bending sources: Homogeneous bends based on iron yoke electromagnets at 1.3 T@1.7 GeV, which provide a critical photon energy of 2.5 keV (blue) and superconducting wavelength shifters with 7 T@1.7 GeV, providing a critical photon energy of 13 keV (orange).

⁴In this stage of the design process the numbers belong to bare lattices without errors.

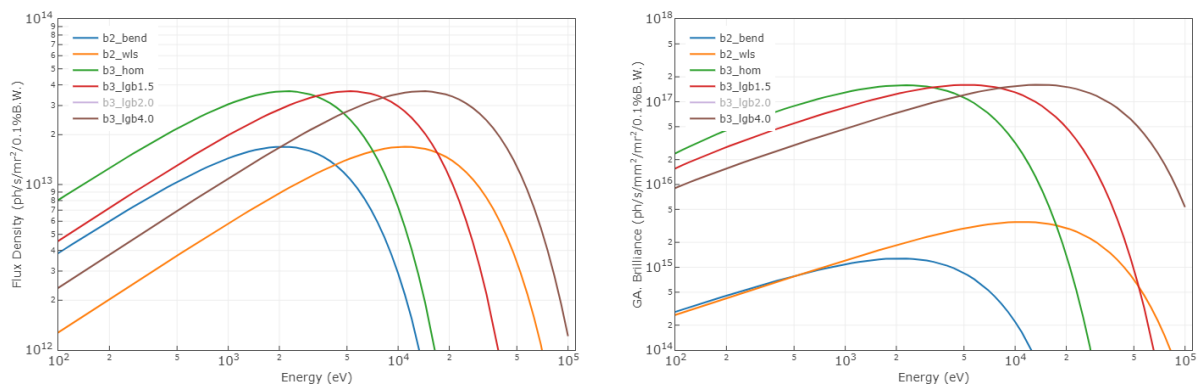


Figure 5: Flux and brilliance of different bending sources at BESSY II (blue and orange) and of bending sources discussed for BESSY III (green, red, and brown).

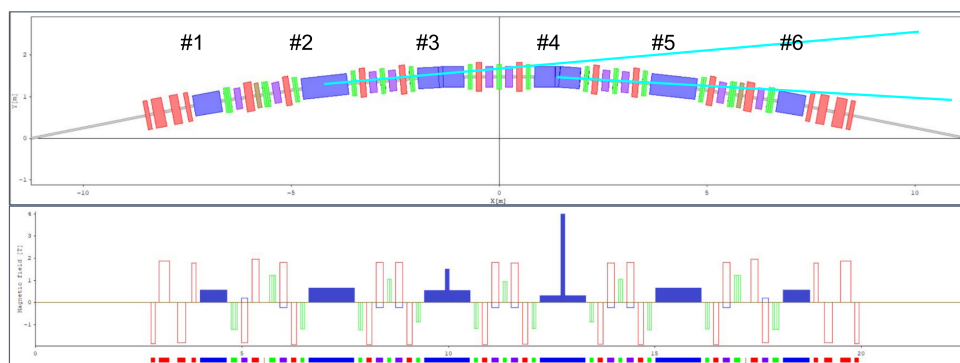


Figure 6: (top) The magnetic arrangement of a BESSY III sector (bends - blue, quadrupoles - red, reverse bends (shifted quadrupoles) - purple, sextupoles - green). (bottom) The magnetic peak field for the different magnets.

For BESSY III users request also bending beamlines with different spectral ranges, from EUV to soft X-rays (0.01 keV to 2 keV), from soft to tender X-rays (2 keV to 10 keV) and hard X-rays (≥ 10 keV).

For geometric reasons, radiation can be best extracted from three inner dipole magnets (#2, #3, #4) of the arc of the BESSY III 6-MBA sector, shown in Figure 6 (top). It is foreseen to provide at least one bending beamline per arc, two might also be possible.

The standard homogeneous bend at BESSY III based on permanent magnets technology with 0.64 T at 2.5 GeV does nicely match PTB's needs for metrology applications, providing a critical photon energy of 2.6 keV (green) and delivers nearly the same spectral range as the bending magnet at BESSY II, but increases the flux density by a factor 2 and the brilliance by 100, as shown in Figure 5. It is under discussion if the request for higher photon energies can be covered by longitudinal gradient bends (LGB). As a first guess, the homogeneous bend was separated into three areas supplying a higher field at the center and reduced fields at the beginning and end, see Figure 6 (bottom). Initial studies showed no severe impact on the beam dynamics when modifying the main bend as long as the phase advances over the MBA-UC and the matching conditions for the optical functions are maintained. Without changing the vacuum pipe diameter a field of up to 1.5 T could be possible using permanent magnet solutions, which would provide a critical photon energy of 6.2 keV (red). A superconducting solution with 4 T would push the critical energy up to 16.3 keV, but this solution needs more technical R&D and would increase the project risks. So far, our investigations show no notable emittance-reducing impact of the LGB. As the phase advance is kept constant and the optical functions are not adapted to the higher field, no emittance-reducing effect is expected. Further studies should investigate the impact of adjusted optical functions on the overall performance with LGBs. So far, it is foreseen to use the LGBs as adapted bending sources.

5 Conclusion & Outlook

In a careful process, focusing on suppressing non-linear beam dynamics contributions, a BESSY III baseline lattice was developed based on a 6-MBA HOA with separate function dipoles. Limitations of the transverse & longitudinal non-linear beam dynamics behavior were analyzed and could be minimized and adapted in both plans to above 4% TSWM, without corrupting other design criteria. Plans for supplying different wavelengths from the bending magnets were introduced. For moderate field increase and/or a limited number of higher field bending magnets, no relevant deterioration of the dynamic was observed. As the next steps, we will further develop the BESSY III lattice toward the TDR phase, i.e., technical adaptation, orbit correction & injection scheme, robustness against errors, and collective effects.

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