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UPDATE ON THE LATTICE DESIGN PROCESS OF BESSY III: TOWARDS A BASELINE LATTICE

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Abstract

The lattice design process for BESSY III is based on a systematic & deterministic approach where sub-structures of the magnetic lattice are analyzed and optimized before the lattice is composed. During this process, 5 standardized Higher-Order-Multi-Bend-Achromat (HO-6MBA) lattices were developed utilizing different combinations of homogeneous and gradient bends in the unit and the dispersion suppression cell. All lattices yield basically the same emittance, momentum compaction factor, working point, maximal field strengths, and drift lengths. Therefore, they are equivalent to the linear optics. This enables us to attribute any differences in their nonlinear behavior to the specific lattice structure. A detailed description and analysis of the trade-offs of these standardized lattice structures are given. Based on this analysis, the choice of the BESSY III baseline lattice is motivated.

INTRODUCTION & CONSTRAINTS

HZB is preparing for its light source future with two main projects: the BESSY II+ project and BESSY III. The status and overview of BESSY III and how the BESSY II+ will act as a bridge towards it, is described in [1, 2]. A first sketch of BESSY III, a 2.5 GeV, 100 pm rad greenfield facility, was recently published in a pre-CDR [3]. Its main parameters compared to BESSY II as well as the technical limits for magnets are given in Tables 1 & 2 of Ref. [4]. The circumference is limited to ~350 m by the envisaged site in Berlin-Adlershof and the momentum compaction factor was chosen not to be too small $\alpha_c > 1.0 \times 10^{-4}$ in order to achieve 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 [5].

Due to the long-standing partnership with the PTB, Germany's national institute for standards & metrology, 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 multi-bend-achromat (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.

BESSY III LATTICE DESIGN PROCESS

In order to deliver a robust design with good control of non-linear beam dynamics [6], also with regards to TRIBs operation close to a 3^{rd} order resonance, *we chose the Higher 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 & quadratic resonance driving terms to 2^{nd} 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 & deterministic lattice design approach* [4, 7–9]. 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 [4] for a fair comparison.

So far, as shown in Ref. [4] and in Fig. 1, two lattice configurations have been investigated in detail. Due to symmetry

Figure 1: The lattices are named after the type of their bend in the UC and DSC. Top: a cfsf (**c**ombined **f**unction, **s**eparate **f**unction) HOA-6MBA lattice. Bottom: an sfcf HOA-6MBA lattice.

reasons, the homogeneous metrology bend was included right from the beginning in the MBA structure to have 16 completely symmetric sectors (or super-periods) 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

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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 & 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 2 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. 3 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 for quadrupoles and sextupoles has always been adapted to its maximally allowed gradient and the length 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. For the different variants, the optical functions are very similar within the MBA-UC and differ mainly at the end of the DSC and in the adjacent quadrupole configuration.

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 Table 1. 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).

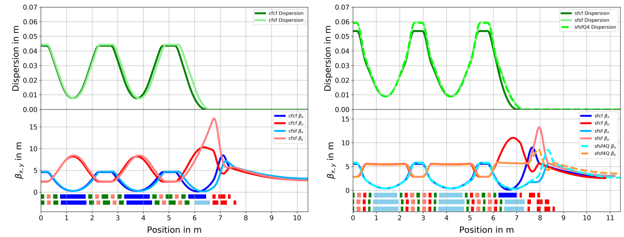

Figure 2: Lattices with optical functions of variants with a cf-UC: cfcf, cfsf (left) and a sf-UC: sfcf, sfsf, sfsf4Q (right).

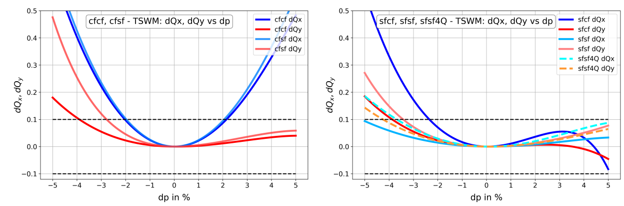

Figure 3: The TSWM for the different lattice variants: cfcf, cfsf (left) and sfcf, sfsf, sfsf4Q (right).

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 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 Quadrupol-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 quadrupole 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%).

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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

The TSWA is shown in Figs. 4 and 5 for the different lattices in the middle of a straight with $\beta_{x,y} \approx (3\,\mathrm{m}, 3\,\mathrm{m})$. 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

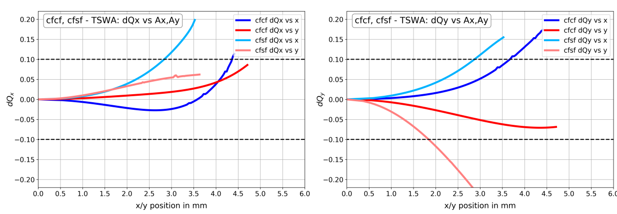

Figure 4: TSWA for lattice variants with a cf-UC: cfcf, cfsf. Left: dQ_x vs. $A_{x,y}$. Right: dQ_y vs. $A_{x,y}$.

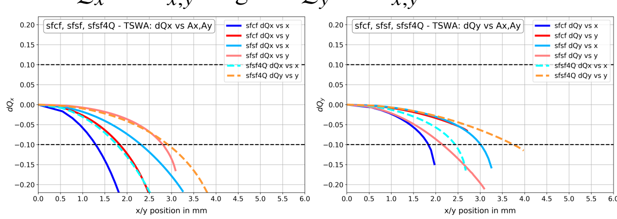

Figure 5: TSWA for lattice variants with a sf-UC: sfcf, sfsf, sfsf4Q. Left: dQ_x vs. $A_{x,y}$. Right: dQ_y vs. $A_{x,y}$.

introduced to the lattices to optimize the TSWA behavior. The aperture, given by the beam pipe diameter, is at 9 mm, and so the aperture in the straight with $\beta_{x,y} \approx 3$ m is 5 mm to 6 mm in the horizontal plane and 3.5 mm to 5.5 mm in the vertical plane. First tests [4, 9] showed that an improvement is possible by splitting up the chromatic sextupole families or introducing geometric/harmonic sextupoles or octupoles and we are aiming to improve the TSWA to match the geometric acceptance.

The direct next step is the introduction of a non-linear optimization scheme [10]. For example, chromatic octupoles can be introduced to reduce the quadratic order, especially for the cf-UC lattices. Will they have any impact on the sf-UC lattices, which show a strongly suppressed quadratic order? 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 [11], the development of an injection concept, the implementation of a simulated commissioning scheme, and a detailed analysis of collective effects.

FIRST IBS ESTIMATES

Using the ibsEmittance script in Elegant, a first estimate is given in Fig. 6 of the expected emittance blow-up from IBS depending on beam current and coupling for the sfsf4Q lattice, assuming a 500 MHz main rf system only, operated at 1 MV. A homogeneous multi-bunch fill of 610 bunches has been assumed. The ibsEmittance script uses the optical

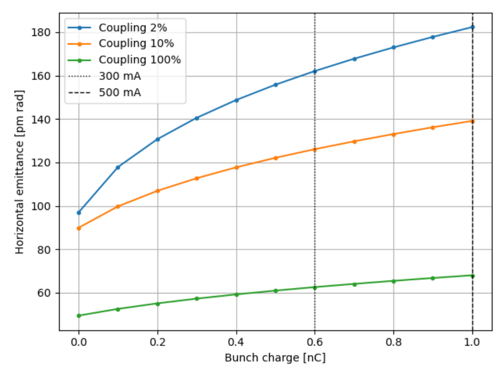

Figure 6: IBS estimate for BESSY III.

functions for an uncoupled lattice to calculate the IBS growth rates for a given coupling. The results, therefore, do not take into account the impact of the different partition numbers in J_x, J_y, so the IBS effect is slightly overestimated. Tracking of IBS for a coupled lattice that takes this into account will be done at a later stage. In addition, bunch lengthening from longitudinal impedance has not yet been included which will also mitigate the blowup from IBS. However, at 300 mA and 10% coupling, we expect a blow-up of 25% in the emittance to 125 pmrad. This can be mitigated by the introduction of higher harmonic cavities, which will be studied in the near future.

CONCLUSION

In this paper, we show how a careful setup of the linear lattice influences the non-linear beam dynamics. The choice for 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.

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