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FIRST THOUGHTS ON LATTICES FOR A POSSIBLE METROLOGY LIGHT SOURCE 2

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Abstract

The Physikalisch-Technische Bundesanstalt (PTB), in cooperation with the Helmholtz-Zentrum Berlin (HZB), operates the Metrology Light Source (MLS), which is a low-energy electron storage ring. The MLS can be operated in a low-alpha mode to produce coherent synchroton ration in the far-IR and THz spectral range. In the scope of the Conceptual Design process for a BESSY II successor, the PTB also requested for an MLS successor to cover their increasing demands on synchrotron radiation. A combination of two different machines, one optimized for low emittance (BESSY III) and one for flexible timing capabilities (MLS II), would provide best radiation capabilities for our user community. In this paper, we discuss the demands on the MLS II and propose first lattice candidates which may meet the needs of the PTB and HZB. Currently, we focus on linear lattices for standard user mode with first steps towards nonlinear optimization.

INTRODUCTION

As stated in [1] HZB started in 2020 the discussion process on a BESSY II successor. The PTB, one of HZB's main partners and users, proposed to include right from the beginning the successor of the MLS [2] into this process. This would allow to set up a complementary two source concept, one optimized for soft and tender X-rays (core range from 0.1 keV to 8 keV) the other one for THz, IR up to VUV, EUV radiation, reaching towards soft X-rays, in analogy to the MAX IV laboratory. The science case and user demands on a BESSY III mainly ask for a 4th generation lightsource with highest brilliance, coherence and smallest spot size, aiming to be diffraction limited at 1 keV. This could be best realized with a low emittance multi-bend-achromat ring.

Timing modes [3] have been always of importance in operation and development of BESSY II and MLS: (i) short pulse generation (low-α [4], femtoslicing [5] and the recent first demonstration of Steady-State-MicroBunching [6]) and (ii) different repetition rates (as Pulse-Picking-Resonant-Excitation [7] or Transverse-Resonance-Island-Buckets (TRIBs) operation [8]). Its implementation is quite a challenge in a low emittance ring, due to the small beam pipe apertures and low lifetimes (see [9]). With TRIBs operation different repetition rates,i.e., single bunch operation, can be offered simultaneously. However, the generation and extraction of coherent THz and IR radiation is at this point of the discussion not foreseen in BESSY III. With the MLS II, we aim to preserve these experimental techniques.

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In contrast to the current MLS situation with PTB as only user, the PTB offered a shared machine concept for the MLS II. The PTB demand on beamlines is listed in Table 1.

Table 1: Beamline Request of PTB for MLS II

Beamline	Source	spectral range
EUV/GI	UE short per.	31 eV to 620 eV
VUV/BI+GI	UE long per.	3.1 eV to 124 eV
Primary	Bend. Mag.	1.2 eV to 1 240 eV
EUVR	Bend. Mag.	25 eV to 620 eV
VUVR	Bend. Mag.	3.1 eV to 31 eV
IR	Bend. Mag.	0.012 eV to 2.5 eV
THZ	Bend. Mag.	0.12 meV to 12.4 meV

As starting point PTB proposed a storage ring lightsource with 6 straights and a beam energy of 0.8 GeV. Two straights would be covered by PTB beamlines, and two straights by the long periodic undulator communities from BESSY II, the U125 ranging from 6 eV to 40 eV and the UE112 with a spectral range from 8 eV to 690 eV. Since two further straights would be allocated to injection and rf cavities, there will be no free straight capacity.

The out-of-vacuum undulator with shortest period length without dark gaps in the spectrum could reach within the 5th harmonic up to 450 eV photon energy at a 0.8 GeV storage ring. Because timing experiments at BESSY II request energies up to 1 keV, an increase of the ring energy would be desired, strengthen by the argument that the MLS operation and stability is limited by ion effects. Therefore we proposed to start lattice designs for a storage ring with 8 straights and 1.2 GeV beam energy. The advancing science case discussion on the complementary concept of BESSY III and MLS II and the metrology needs of PTB will finally define the MLS II parameters.

The MLS is a double-bend achromat (DBA) lattice and Table 2 summarizes its lattice parameters and the desired goals for its upgrade, the MLS II. A very important demand on the MLS II as for BESSY III is to use the ring as absolutely calculable primary radiation source for metrology applications. Therefore it is needed to determine the required storage ring parameters with highest precision over a wide range: beam energy and current and the magnetic field at the source point. To generate the requested bending magnet radiation at 5 eV critical photon energy the ring energy and the magnetic field have to be ramped down by a factor of 6.3 ($E = 1.2\,\text{GeV} \rightarrow 190\,\text{MeV}$ and $B = 1.3 \rightarrow 0.21\,\text{T}$, $\rho = 3.1\,\text{m}$). Beside this special modes like the low-α operation are requested features of high interest.

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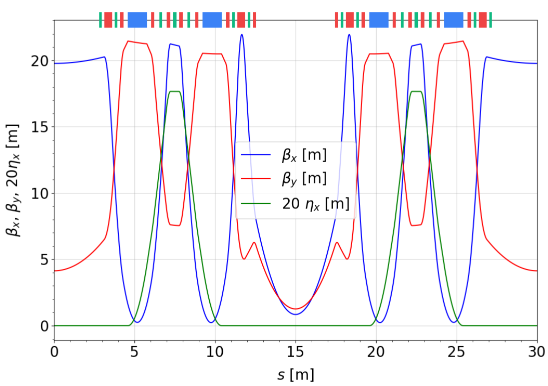
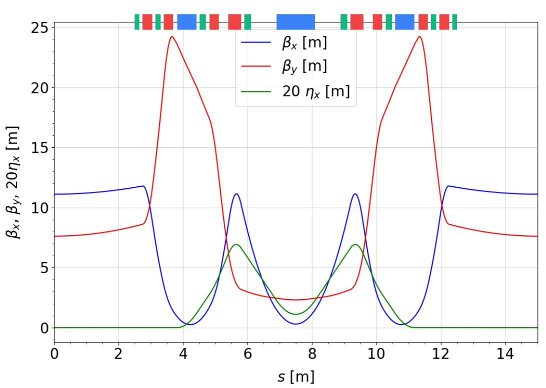
Table 2: MLS Parameters for Standard Operation Mode [10] and the Desired Upgrades

	MLS	**MLS II**
Energy	629 MeV	0.8 – 1.2 GeV
Circumference	48 m	~ 100 m
Natural emittance ε_0	120 nm rad	< 20 nm rad
# of straights	4 (2.5 m, 6 m)	6-8 (5 m)
Tune (Q_x, Q_y)	(3.18, 2.23)	-
Mom. comp. factor α	0.03	-
Chromaticity (ξ_x, ξ_y)	(-3.4, -5.6)	-



(a) DBA unit cell



(b) TBA unit cell

Figure 1: Blue rectangle: dipoles, red rectangle: quadrupoles, green rectangle: sextupole.

LATTICE CANDIDATES

Unlike other storage rings, the ultimate objective of the MLS II is not to reach ultra-low emittances but to be optimized for metrology purposes, i.e., for stability in all parameters and reliability. However, a lower emittance than that of the MLS is desired but it should not be at the expense of stability, reliability and flexibility. Lattice candidates with homogeneous dipoles are favored, again for flexibility and metrology purposes. The lattice design should take into consideration the upper boundaries on the quadrupole strength $|k_1|$ and sextupole strength $|k_2|$ which are $5\,\mathrm{m}^{-2}$ and $150\,\mathrm{m}^{-3}$

Table 3: Specifications of the Proposed Lattices

	DBA BII	**TBA**
Energy	1.2 GeV	1.2 GeV
Circumference	120 m	120 m
Natural emittance ε_0	15.2 nm rad	4.9 nm rad
Tune (Q_x, Q_y)	(9.205, 3.245)	(11.195, 3.245)
Mom. comp. factor α	4.0×10^{-3}	2.5×10^{-3}
nat. chromat. (ξ_x, ξ_y)	(-32.9, -11.6)	(-28.8, -17.7)

respectively. These are limited by large (3rd generation) beam pipe apertures of ~ 40 mm in the vertical plane due to collective effects, the impedance budget and an optimized extraction of THZ power. The minimum length of a drift is limited to 10 cm and the maximum field strength for the dipole magnets is 1.3 T. At this stage, we focus on lattices for standard user mode based on the preliminary upgrade requirements. OPA [11] was used to design the lattices while analysis and optimization were carried out in Elegant [12] together with Python.

A lattice which has already proven its low-α capabilities is the BESSY II ring, a DBA structure at 1.7 GeV and 240 m circumference. It consists of 32 dipoles and by scaling it down, we would expect an emittance around 20 nm rad for a DBA with 16 dipoles and an energy of 1.2 GeV. The scaling statement is obtained from the formula for minimum emittance of a DBA with homogeneous dipoles [13, Eq. (7.128)] which can be written as $\varepsilon_0 \sim E^2/N_d^3$, where E is the energy and N_d is the number of dipoles in the ring. The angle of each dipole is $\theta = 360°/N_d = 22.5°$ and that of a superperiod is 90°. The length L of each dipole is obtained from the formula for beam rigidity $E\,[\mathrm{GeV}] = 0.3BL/\theta$ where B is the magnetic field strength. By assuming $B = 1.3$ T and $E = 1.2$ GeV, the length of each dipole in the DBA is set to approximately 1.2 m. The optics i.e. beta functions (β_x, β_y) and dispersion η_x of the scaled DBA lattice (from BESSY II) are shown in Fig. 1(a) and its global parameters are listed in Table 3. The unit cell consists of a doublet section with high β_x and low β_y and a doublet-triplet section where β_x and β_y are both low.

As a second solution, we propose a simple triple-bend achromat (TBA) lattice which is a natural extension of the DBA to achieve a much lower emittance as it contains a larger number of bending magnets, namely 24 in our case. Using the same formula for the beam rigidity as for the DBA, we obtain an average bending angle of 15° and an average length of 0.8 m per dipole. All the dipoles have the same bending radius. It has been shown before [14] that choosing the bending angle/length of the inner dipole to be the same as the outer ones reduces the emittance only by 23%. A more effective option is to choose the inner dipole to be twice as long as the outer ones which is not a strict TBA with theoretical minimum emittance (TME) condition, but rather a modified version of it. Using arguments from [14] we expect $\varepsilon_0(\mathrm{TBA}) = 11/48\,\varepsilon_0(\mathrm{DBA}) \approx 3.5$ nm rad. The optics for

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the TBA are shown in Fig. 1(b) and its corresponding lattice parameters are found in Table 3.

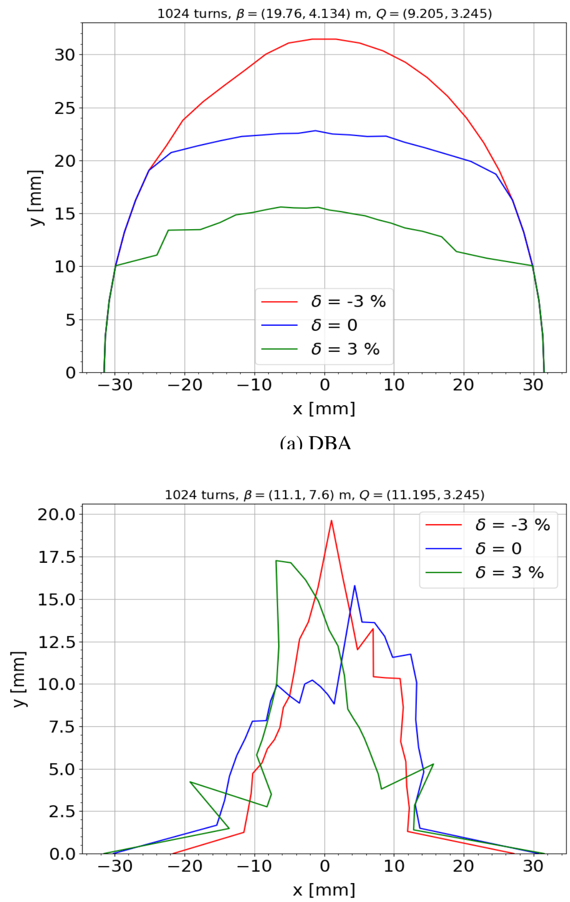
The working points of both lattices are chosen to be far from low order resonance lines namely integer, half-integer and third-order resonances assuming that the strengths of the resonances decrease with increasing order. This justification is based only on lowest order perturbation theory but it is a well-known fact that sextupoles potentially drive resonances to all orders and there is no a priori reason to assign different weights to each of them. The fractional tunes of the two lattices are set to have slightly different values so that the systematic fifth-order horizontal resonance $Q_x = 1/5$ is not reached due to the amplitude-dependent tune shift (ADTS). It should be noted that both lattices were designed without exceeding current standard limits on sextupole and quadrupole strengths, mentioned above. Hence the circumference could not be brought below 100 m for the TBA lattice which was made as compact as possible while keeping the optics reasonable ($\beta_{x,y} < 30$ m).

FIRST NONLINEAR CONSIDERATIONS

In terms of low emittance, the TBA is a more appropriate solution but complicates the chromaticity correction since the required sextupoles cannot be placed exactly at maximum positions of $\beta_x \eta_x$ and $\beta_y \eta_x$ c.f. the chromaticity formula e.g. in [13]. Therefore, strong sextupoles are needed to correct the chromatic and geometric aberrations, potentially reducing the stability. This is less the case for the scaled DBA and it is expected that the TBA will have a weaker performance in terms of nonlinear dynamics but a smaller emittance usually comes with a price.

As a first step, we consider only first-order (in sextupole strength) nonlinear corrections. To prevent the tune from reaching quickly integer and half-integer values for off-momentum particles, we need to correct the natural chromaticity which in general is a large negative value as can be seen from Table 3. This is achieved by placing focusing sextupoles ($k_2 > 0$) where $\beta_x > \beta_y$ and defocusing sextupoles ($k_2 < 0$) where $\beta_y > \beta_x$ inside the achromat (dispersive region). In both lattices, two families of chromatic sextupoles were optimized to correct the first-order chromaticity to $(\xi_x, \xi_y) = (1, 1)$. This value is chosen to avoid the head-tail instability [13].

After correcting the chromaticity, the (chromatic) sextupoles unfortunately introduce geometric aberrations which lead to the loss of on-momentum particles. These geometric effects are at an analytical level encoded in the resonance driving terms (RDTs) h_{ijklm} with $m = 0$ as given in [15]. At this stage we are considering first-order effects and therefore we aim to minimize only the first-order geometric terms which are related to the distortion of phase space ellipses. This is achieved by placing (harmonic) sextupoles in the non-dispersive region. Again, two sextupole families are used for both lattices. Then, the RDTs are minimized using Elegant's internal optimizer, using equal weights for the five geometric terms in [15]. After minimizing the first-order RDTs, the second-order amplitude-dependent tune shifts are automatically optimized because they are directly related [15]. Consequently, the dynamic aperture (DA) is optimized to first-order. Figure 2 shows the short-term (1024 turns) DA tracking results for both bare (error-free) lattices.



(a) DBA

(b) TBA

Figure 2: Dynamic aperture for the bare lattices. $\delta = \Delta p/p_0$ is the momentum offset.

It is expected that the DBA lattice will be more robust against practical errors (misalignments, field errors, ...) because, in general, the DA is reduced in their presence.

SUMMARY AND OUTLOOK

We proposed two lattice candidates, a DBA and a TBA for the MLS II based on the preliminary upgrade requirements and compared their linear and first-order nonlinear performances. At this stage, it is too early to decide which lattice is more appropriate because the design goals are still being discussed. It may turn out that other variants of these lattices will be more adequate. Further optimization and robustness studies should be performed and at a later stage, special operation modes (e.g. low-α) will have to be implemented in a robust manner. For example, an octupole scheme will have to be developed to control the nonlinear momentum compaction factor [10] which will be a non-negotiable attribute of MLS II.

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