PRELIMINARY LATTICE DESIGN TO THE 1 PM-LEVEL EMITTANCE FOR THE SOUTHERN ADVANCED PHOTON SOURCE*

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Abstract

The pursuit of diffraction-limited storage rings has driven emittance targets into the picometer regime. This paper presents a novel Single Hybrid Multi-Bend Achromat (SH-MBA) lattice design for the Southern Advanced Photon Source (SAPS), targeting an emittance at the 1 pm level. The compact SH-16BA design, operating at 3.5 GeV with 36 periods and a 945 m circumference, employs high-gradient quadrupoles, reverse bends, and longitudinal gradient bends. While collective effects such as intra-beam scattering allow the equilibrium emittance to reach the diffraction limit for hard X-rays, the most critical challenge lies in nonlinear dynamics optimization. The required sextupole strengths are extremely high, generating nonlinear driving terms three orders of magnitude larger than in typical 4th-generation sources and restricting the dynamic aperture to about 1 mm. This work demonstrates that achieving a reliable 1 pm-level design will require novel methods to suppress these severe nonlinearities.

INTRODUCTION

The pursuit of higher brightness and improved transverse coherence has long driven the evolution of synchrotron radiation sources. Fourth-generation storage rings, built on multi-bend achromat (MBA) lattices, have reduced natural emittance by two to three orders of magnitude and enhanced brightness by one to two orders of magnitude compared with third-generation facilities [1]. This advance has accelerated the global development of fourth-generation light sources. Among these, sources such as APS-U [2], HEPS [3], and NSLS-II-U [4] have achieved natural emittances in the range of several tens of pm·rad, effectively reaching the diffraction limit for soft X-rays. For hard X-rays at a wavelength of 0.1 nm, however, the diffraction-limited emittance of approximately 8 pm·rad remains unattained. Reducing the emittance to the 1 pm level would yield substantial brightness gains, with transverse coherence approaching unity for soft X-rays and improving significantly for hard X-rays, thereby enabling new classes of coherent scattering and imaging experiments.

Achieving such ultra-low emittance typically requires increasing the number of bending magnets and employing high-gradient quadrupoles for stronger focusing. Scaling studies based on existing designs, such as HEPS, indicate that pushing the emittance down to 3-5 pm·rad would necessitate a ring circumference exceeding 2500 m. Consequently, the central challenge in pm·rad-level lattice design is to realize 1 pm·rad emittance within a compact, practically feasible circumference.

This work builds on the conceptual design of the Southern Advanced Photon Source (SAPS) [5], a 3.5 GeV facility planned for Guangdong, China, adjacent to the China Spallation Neutron Source. Guided by the SAPS baseline parameters, we propose a novel lattice to allow more bends within a reasonable circumference. Finally, we developed a 16BA lattice with a natural emittance of 5.5 pm·rad and conducted a preliminary analysis of its nonlinear dynamics. This paper details the linear optics design, outlines the principal challenges encountered during nonlinear optimization, and discusses the limitations of current nonlinear correction methods in pm-level lattice design.

LINEAR LATTICE DESIGN

To achieve lower beam emittance within a limited storage ring circumference, increasing the number of dipoles or incorporating additional ultra-low emittance unit cells is essential. The hybrid multi-bend achromat(H-MBA) lattice widely adopted in modern light source design typically comprises two modified DBA cells and $M - 4$ modified TME cells [6]. In this configuration, the modified TME cells are primarily responsible for emittance suppression, while the modified DBA cells generate a pair of high-dispersion bumps that reduce the required strength of sextupoles housed within them for chromaticity correction. However, taking the H-7BA lattice as an example, the modified DBA cells occupy approximately 60% of the longitudinal space in the arcs, yet their contribution to emittance reduction is significantly smaller than that of the modified TME cells. For a fixed arc length, minimizing the fraction of modified DBA cells and increasing the proportion of ultra-low emittance cells can effectively shorten the circumference required to reach pm-level emittance. To address this, we propose a novel lattice, as shown in Fig. 1. Using the H-7BA as a reference, removing one modified DBA cell allows three additional modified TME cells to be accommodated within the same period. Since this conceptual design features only a single dispersion bump per period, in contrast to the double dispersion bump arrangement of the conventional hybrid MBA, we term it the single dispersion bump hybrid MBA (SH-MBA). As a proof of concept, applying this configuration to the HEPS lattice reduces the emittance from 34 pm·rad to 15 pm·rad.

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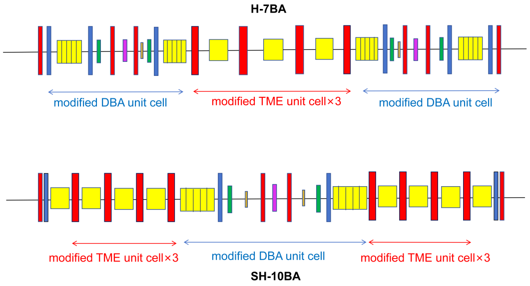

Figure 1: Comparison of layout changes between the H-7BA and the SH-10BA lattice.

We subsequently applied this concept to a pm-level emittance lattice design. Based on the baseline parameters of SAPS and estimates derived from the theoretical minimum emittance formula [7], employing 576 dipoles is projected to reduce the natural emittance to approximately 3–5 pm. Our proposed solution utilizes an SH-16BA cell repeated over 36 periods, yielding a compact circumference of 945 m. Following the SH-MBA layout illustrated in Fig. 1, each period comprises a central modified DBA cell flanked by six modified TME cells on each side, along with a dedicated matching section. To further suppress emittance, we employ high-gradient quadrupoles with a gradient of 150 T/m and integrate six reverse-bend dipoles per cell. The phase advances between the sextupoles adjacent to the two dispersion bumps are explicitly matched to the fixed values of 9π and 5π to satisfy the $-I$ transformation condition. Additionally, all longitudinal gradient bends in the lattice are also combined with horizontally defocusing gradient [8].

However, the strict symmetry of this lattice layout makes it unfeasible for the phase shift between sextupoles to equal that of one period. To resolve this, we merge two standard periods into one superperiod, as depicted in Fig. 2. This superperiod accommodates two long straight sections of unequal lengths (6 m and 4 m), providing the necessary flexibility for precise optics control. Furthermore, both LSSs are designed with achromatic optics. Finally, the ring parameters are listed in Table1. The bare lattice yields an ultra-low natural emittance, which inherently results in a prolonged radiation damping time. To achieve the 1 pm-level emittance target and accelerate the damping process, damping wigglers would be integrated into the lattice design. Additionally, the low momentum compaction factor renders the beam more prone to collective instabilities. Under realistic operating conditions with a 100 mA beam current and an optimally stretched bunch length, tracking simulations predict that the emittance increases to approximately 6.5 pm·rad. At 200 mA, this value rises further to 8 pm·rad.

NONLINEAR DYNAMICS PERFORMANCE

At the current stage of nonlinear optics optimization, the nonlinear driving terms in the lattice are approximately three orders of magnitude larger than those in conventional fourth-generation light sources. To address such strongly enhanced nonlinearities, two complementary approaches are employed: the theoretical cancellation using the conventional $-I$ transformation between sextupole pairs, and multi-objective optimization algorithms [9] to further mitigate the remaining nonlinear effects. In one superperiod, the lattice comprises six sextupole families and four octupole families. Two of the sextupole families are dedicated to chromaticity correction, while the strengths of the remaining multipoles serve as free variables in the optimization process. During optimization, it is observed that the sextupole field strengths required to achieve pm-level emittance remain extremely high, even with the implementation of dispersion bumps to reduce their strength. To keep the strengths of the sextupoles and octupoles within reasonable ranges, their lengths are correspondingly increased, with some reaching up to 0.4 m.

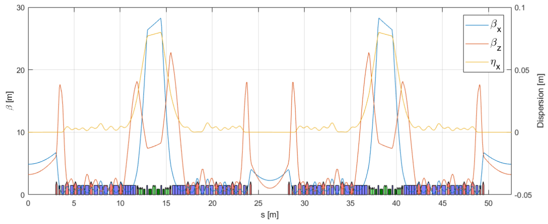

Figure 2: Optics function of one superperiod of pm-level lattice design, which one superperiod is composed by two SH-16BA.

Table 1: Main Parameters of pm-level Lattice Design

Parameters	Value	Unit
Energy	3.5	GeV
Circumference	945	m
Natural emittance	5.568	pm·rad
Damping partitions	2.52/1/0.48	
Ring tunes	165.383/94.365	
Natural chromatities	–279.51/–343.1	
Momentum compaction factor	1.53×10^{-5}	
Energy spread	1.1×10^{-3}	
Energy loss per turn	0.4	MeV
Damping time (x/y/z)	21.8/55/115.4	ms
LSS length	6/4	m
β_x and β_y at LSS center	4.88/3.23 2.28/1	m

Figure 3 shows the tune shifts with momentum deviation for the design, indicating a momentum acceptance of approximately 1%. The on-momentum dynamic aperture at the center of the 6-meter-long straight section is shown in Fig. 4, obtained through particle tracking over 1024 turns. The horizontal and vertical dynamic apertures are approximately 1 mm. While the dynamic aperture may be further improved through high-beta lattice designs, the limited momentum acceptance poses a significant constraint on beam lifetime.

DISCUSSION AND CONCLUSION

We have developed a novel lattice design capable of achieving pm-level emittance in a compact storage ring, meeting the hard X-ray diffraction limit even when intra-beam scattering effects are considered. However, the strong

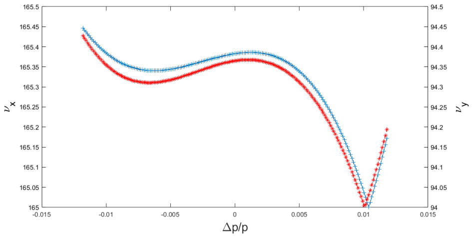

Figure 3: Tune-shifts with momentum deviation of pm-level lattice design.

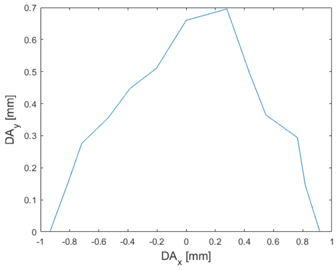

Figure 4: Dynamic aperture obtained after tracking over 1024 turns of pm-level lattice design.

nonlinearity associated with achieving pm-level emittance renders state-of-the-art cancellation techniques insufficient. In our lattice, the -I cancellation scheme, while effectively suppressing geometric resonances, leaves significant residual chromatic terms that severely limit momentum acceptance. For comparison, we also tested a multi-bend achromat design incorporating higher-order achromat correction; although this approach mitigates chromatic aberrations at pm-level emittance, it fails to adequately control geometric resonances, resulting in a dynamic aperture that approaches zero in practice. Neither method proves fully adequate under the extreme nonlinear conditions of the present design. Consequently, overcoming this nonlinearity barrier requires the exploration of entirely new suppression strategies and lattice configurations. Further optimization and investigation are actively underway as part of our ongoing research efforts. Nonetheless, the SH-MBA lattice proposed herein, although challenged by the strong nonlinearities inherent to pm-level emittance designs, remains highly effective at appropriate emittance levels. A systematic demonstration of the SH-MBA performance under such suitable conditions will be presented in a future publication.

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