PERFORMANCE COMPARISON OF VARIABLE BENDING MAGNETS AND SANDWICH MAGNETS FOR THE SOUTHERN ADVANCED PHOTON SOURCE*

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Abstract

The Southern Advanced Photon Source (SAPS) is a planned 3.5 GeV ultra-low emittance storage ring based on a modified hybrid 7-bend achromat (H-7BA) lattice, located in Dongguan, China. To achieve an extremely low natural emittance, the lattice incorporates a novel unit cell consisting of a 'Sandwich' bending magnet combined with reverse bends. This design has resulted in a remarkable natural emittance of 26.3 pm·rad. Although variable bending magnets with a trapezoidal bending radius and gradient are also recognized for their effectiveness in emittance reduction, their performance relative to the compact thin-center 'Sandwich' design remains unclear. This paper presents a comprehensive comparison of these two magnets, along with the performance differences of the SAPS lattice employing each of them, detailing the nonlinear optimization process and evaluating their respective performance.

INTRODUCTION

The storage ring emittance of the fourth-generation synchrotron light source approaches or even reaches the diffraction limit of X-rays. Compared with third-generation sources, the brightness is increased by one to two orders of magnitude. In addition, it intersects with cutting-edge fields such as quantum information, coherent imaging, and in-situ characterization, becoming a key facility driving multidisciplinary breakthroughs [1]. As the main part of the storage ring lattice, the unit cell is central to achieving ultra-low emittance in the storage ring. Over the past decades, researchers have devoted considerable efforts to exploring different unit cells, aiming to minimize the beam emittance under reasonable nonlinearities and cell lengths. Concretely, to reach the theoretical minimum emittance within a practical cell length, the positions of the two quadrupoles in the standard TME cell [2] were swapped [3]. Subsequently, the modified TME cell, which integrates the horizontally defocusing quadrupoles on both sides of the bending magnet into the dipole itself, was developed and widely used in multi-bend achromat lattices, further reducing the cell length [4].

However, although the modified TME cell compresses emittance over a short cell length, its emittance compression capability is inferior to that of the standard TME cell. Under reasonable nonlinearities, the lowest achievable emittance is about twice the TME limit. To further lower the emittance, a cell composed of a longitudinal gradient bend (LGB) and two reverse bends (RBs) has been proposed. This cell requires a longer length than the modified TME cell, but it can attain an emittance close to or even below the TME limit under reasonable nonlinearities [5, 6]. The LGB/RB cell was first proposed and applied in the storage ring design of SLS-2.0 [7], and has since been widely adopted in fourth-generation light source storage rings [8, 9]. Nevertheless, using too many LGB/RB cells drastically reduces the momentum compaction factor, potentially making it negative, which leads to short bunch lengths and a low instability threshold.

To address this issue, a "sandwich" magnet, termed the transverse-longitudinal gradient combined dipole (TLGB) in this paper, is proposed to replace the LGB magnet in the LGB/RB cell. This combination preserves the emittance compression capability while minimizing the reduction of the momentum compaction factor. Previous work [10] has shown that a thin-center TLGB/RB cell can achieve an emittance comparable to that of an LGB/RB cell with a shorter cell length and reasonable nonlinearities. The Southern Advanced Photon Source (SAPS) [11], a medium-energy (3.5 GeV) diffraction-limited storage ring light source planned for construction in Guangdong Province, China, adopts this thin-center TLGB/RB cell in its storage ring design and reaches an ultra-low emittance of approximately 26.3 pm·rad.

Recently, it has been noted that when the bending radius of the dipole field in a combined-function dipole follows a trapezoidal distribution, the beam emittance can also be effectively reduced. Such variable bending magnets (VB) were demonstrated in the CLIC DR [12, 13] and applied to the design of ELETTRA 2.0 [14]. However, the performance difference between the thin-center TLGB/RB cell and this VB/RB cell under the same bending angle remains unclear. Hence, in this paper we compare the performance of the two types of unit cells, as shown in Fig.1, and replace the thin-center TLGB/RB cell in the SAPS baseline lattice with a VB/RB cell to evaluate the performance differences.

UNIT CELL COMPARISON

To ensure a fair comparison between the two different unit cells, the optimization of their linear performance is carried out using a multi-objective particle swarm algorithm. The optimization objectives are the natural emittance and the sum

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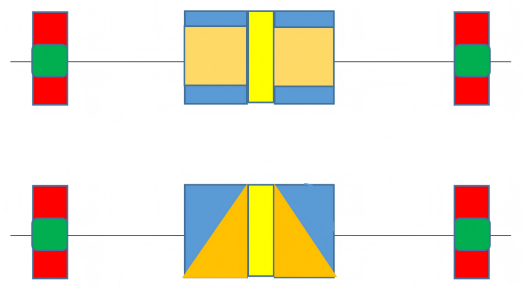

Figure 1: Layout of TLGB/RB and VB/RB unit cells (from top to bottom). A red box combined with a green box represents the RBs, and a yellow box represents a dipole. A blue box combined with an orange box and an orange triangle represents a dipole combined with a horizontally defocusing gradient and a variable bend with a trapezoidal radius and a horizontally defocusing gradient, respectively.

of the absolute values of the horizontal and vertical natural chromaticities. All adjustable parameters of the elements are treated as optimization variables. In addition, the following constraints are imposed during the optimization process:

1. Only drifts, dipoles, and antibends are contained in the unit cell.
2. The total bending angle is considered under two different cases: 2.263° and 1.3522°. This difference in angle mainly results from the maximum dipole field strengths of the TLGB and VB, which are 2 T and 0.9 T, respectively. These values are based on the maximum dipole field strength of the central TLGB in the SAPS baseline design.
3. The length of the unit cell is kept constant at 1.9057 m, a value also derived from the length of the most central unit cell in the SAPS baseline design.
4. The minimum distance between adjacent magnets is set to 0.1 m.
5. The maximum magnet pole face field is 1 T. For a pure quadrupole with a radius of 13 mm, the corresponding maximum gradient is 77 T/m, which is equivalent to $K = 6.58\ \mathrm{m}^{-2}$ for an energy of 3.5 GeV.

Based on the above constraints, the optimization was performed with the same population of 500, and was continued until convergence, which occurred at approximately 100 generations. Fig.2 presents the optimization results comparing the performance of the two unit cells. As can be seen from the figure, when the bending angle is larger, particularly when the maximum dipole field is high, the VB/RB unit cell achieves a further reduction in emittance of about 4 to 10 pm·rad compared to the TLGB/RB unit cell under the same chromaticity conditions. However, when the bending angle is smaller, especially when the maximum dipole field is below 1 T, the emittance reduction capabilities of the VB/RB and TLGB/RB unit cells become similar.

To further analyze the specific differences between the two types of unit cells, a comparison was made between TLGB/RB and VB/RB unit cells under identical chromaticity conditions, with a maximum dipole field gradient of 2 T. Fig.3 shows the optical parameters of the two unit cells. It can be observed that the dispersion functions and beta functions of the VB/RB unit cell, which achieves lower emittance, are generally smaller. Table 1 lists the linear performance parameters of the two unit cells. Under the same chromaticity, the horizontal tunes of the two unit cells are essentially the same. The VB/RB unit cell, which has a higher vertical tune, exhibits lower beam emittance. However, it is worth noting that its momentum compaction factor does not decrease significantly.

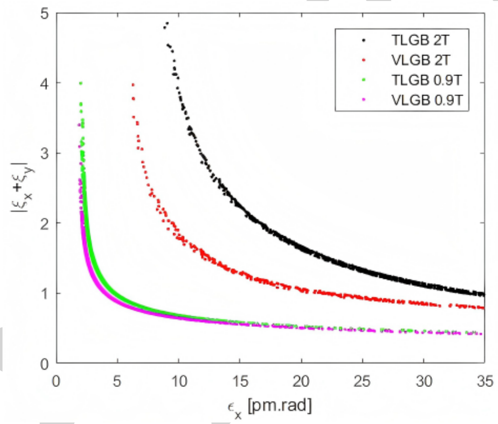

Figure 2: Optimization results for the performance comparison of the two unit cells

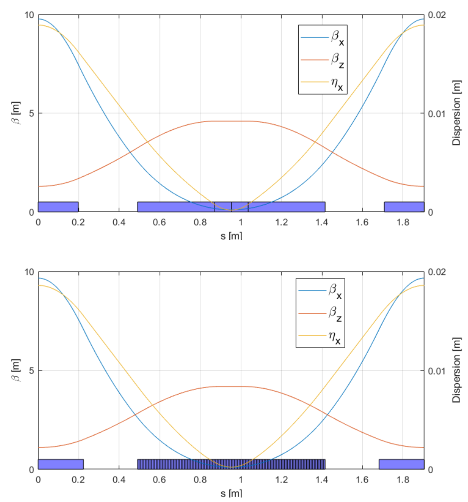

Figure 3: The optics functions of the two unit cells (TLGB/RB unit cell for the up figure, and VB/RB unit cell for the bottom figure) with a maximum dipole field of 2 T are presented. It should be noted that for the VB magnet in the VB/RB unit cell, its trapezoidal radius is implemented by dividing it into 120 slices.

Table 1: Main Parameters Comparison Between Two Types of Unit Cells

Parameters	TLGB/RB unit cell	VB/RB unit cell	Unit
Natural emittance	16.6	9.46	pm·rad
Length of unit cell	1.9057	1.9057	m
Absolute value of the cell angle	2.263	2.263	°
Tune	0.4526/0.12	0.4522/0.1391	
Momentum compaction factor	-1.98×10^{-5}	-2.08×10^{-5}	
Natural chromaticity	$-1.71/-0.29$	$-1.71/-0.29$	

LATTICE PARAMETERS COMPARISON

Next, the three TLGB/RB unit cells in the SAPS baseline design are replaced with VB/RB unit cells. It is known that in the SAPS baseline scheme, there are two groups of TLGB magnets, with maximum dipole fields of 2 T and 0.9 T, respectively. Based on the earlier performance comparison of the TLGB/RB and VB/RB unit cells, it can be anticipated that replacing the TLGB/RB unit cell with a maximum dipole field of 0.9 T by a VB/RB unit cell will not significantly change the emittance. In contrast, replacing the central TLGB/RB unit cell with a maximum dipole field of 2 T by a VB/RB unit cell may lead to a further reduction in emittance. For a fair comparison, all three TLGBs are replaced with VBs while keeping the total bending angle unchanged. Taking the central TLGB as an example, Fig.4 shows the variation curves of the field strength and bending radius along half of the magnet for both the TLGB and the VB.

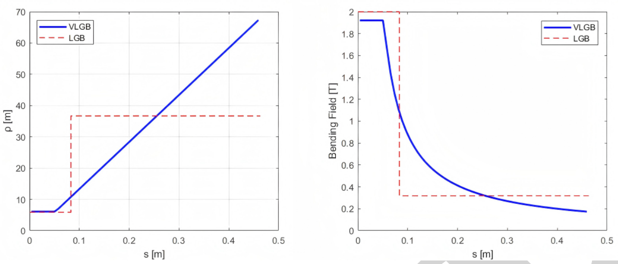

Figure 4: The changes in bending radius and dipole field along the longitudinal half of TLGB and VB.

After replacing the unit cells, the lattice was readjusted and reoptimized, ultimately reducing the emittance to 22.5 pm·rad. Table2 presents a comparison of the parameters for the two SAPS lattices. As observed in the table, while keeping the integer parts of the tunes unchanged, the VB/RB unit cell exhibits a modest but noticeable advantage. Specifically, the beam emittance is reduced to 85% of its original value, and the momentum compaction factor increases to 1.06 times its original value. Meanwhile, the damping time experiences a slight increase, which remains within a reasonable range. Fig.5 shows the optical parameters over one period of the lattice.

Now the nonlinear performance differences between the two lattices are compared. Since the SAPS baseline employs on-axis injection, the baseline design primarily considers a large momentum acceptance (MA) of 4%, and the on-energy and off-energy dynamic apertures (DA) meet the requirements for on-axis injection. After replacing the central unit cells with the VB/RBs, Fig. 6 presents the frequency map analysis results after 4D tracking for 1024 turns at the midpoint of the long straight section. It can be observed from the figure that the on-energy DA remains comparable to that of the baseline design, approaching 5 mm. Fig.7 shows the local momentum acceptance (LMA) and the variation of the tune with energy deviation for the new design. Compared with the baseline design, the MA is somewhat reduced but remains above 3%, imposing stricter requirements on the parameters for longitudinal injection while still satisfying the needs for swap-out injection.

Table 2: Main Parameters of the SAPS Storage Ring (Bare Lattice)

Parameters	Baseline Design	Lattice with VB	Unit
Beam energy	3.5	3.5	GeV
Natural emittance	26.3	22.5	pm·rad
Circumference	810	810	m
Natural energy spread	1.1×10^{-3}	1.1×10^{-3}	
Length of LSS	6	6	m
RF frequency	166.6	166.6	MHz
RF voltage	2	2	MV
Corrected chromaticity (H/V)	$+5/+5$	$+5/+5$	
Momentum compaction factor	3.61×10^{-5}	3.84×10^{-5}	
Harmonic number	450	450	
Natural bunch length	5.8	6.5	mm
Betatron tune (H/V)	78.21/44.16	78.16/44.12	
Radiation energy loss per turn	0.768	0.715	MeV/turn
Damping partition $[x/y/z]$	1.63/1/1.37	1.67/1/1.33	
Damping time $[x/y/z]$	15.1/24.6/17.9	15.8/26.5/19.9	ms
β function at LSS	5.11/2.74	5.44/2.73	m

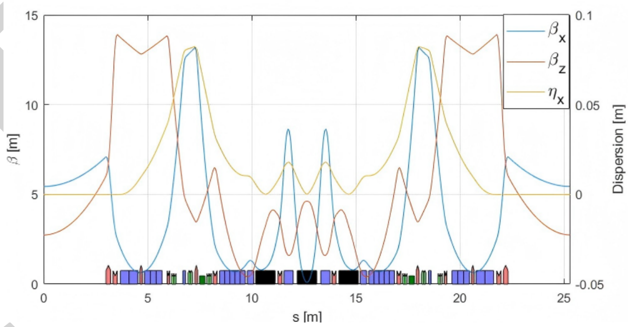

Figure 5: The optics functions of one period of SAPS design with VB/RB unit cells

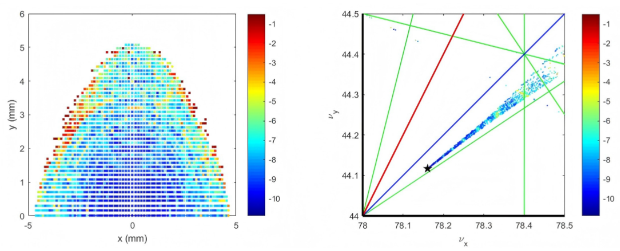

Figure 6: Dynamic aperture and frequency map analysis obtained after tracking over 1024 turns for SAPS design with VB/RB unit cells (color bar represents stability of particles; blue and red imply more regular and chaotic motions, respectively).

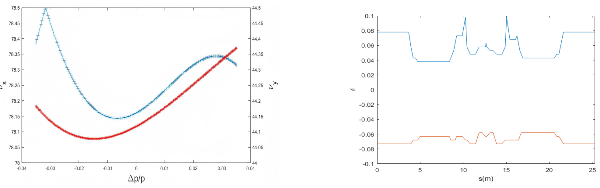

Figure 7: Tune-shifts with momentum deviation and local MA along one period for SAPS design with VB/RB unit cells, tracked over 1024 turns with 6D tracking.

CONCLUSION

To achieve ultra low emittance in fourth generation light sources, it is essential to use advanced unit cells that offer excellent emittance reduction capabilities. This study compares two types of unit cells, the TLGB/RB and the VB/RB, under identical bending angles and cell lengths. The results show that when the maximum dipole field is high (2 T), the VB/RB cell achieves a significantly lower natural emittance than the TLGB/RB cell. In contrast, when the maximum dipole field is low (0.9 T), both cells perform similarly. Replacing the three TLGB/RB cells in the SAPS baseline lattice with VB/RB cells reduces the natural emittance from 26.3 pm·rad to 22.5 pm·rad. This improvement comes with only a slight increase in the momentum compaction factor and with damping times remaining within acceptable limits. The nonlinear performance, including dynamic aperture and momentum acceptance, remains adequate for on axis injection. These findings indicate that the VB/RB cell is a promising alternative for future ultra low emittance storage ring designs, offering better linear performance without compromising beam dynamics.

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