

TOWARD A ROBUST TPS-II 6BA LATTICE

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Abstract

The Taiwan Photon Source upgrade (TPS-II) study aims to realize an ultralow emittance lattice compatible with the existing TPS tunnel. This work presents an updated 6BA lattice design with a natural emittance of 67 pm-rad at 3 GeV, followed by a preliminary evaluation of its robustness study under machine errors. A key innovation in this design is the strategic integration of sextupole components within the dipole magnets. This approach effectively flattens the amplitude-dependent tune shift (ADTS) and expands the dynamic aperture (DA) while preserving the momentum acceptance (MA). The results establish a feasible and robust path toward the next phase of TPS-II lattice development and engineering integration.

INTRODUCTION

As the TPS approaches its first decade of operation since 2016, a feasibility study for a 4th generation diffraction limited storage ring upgrade, TPS-II, is underway. TPS is a 3 GeV, 518.4 m storage ring housed in a common shielding tunnel with its booster. While the primary objective of the upgrade is to enhance scientific capabilities, energy sustainability is also a key motivation. The new lattice aims to reduce beam emittance at least tenfold from TPS of which the beam emittance is 1.6 nm-rad, resulting to an order-of-magnitude increase in brightness and coherence fraction. Following the successful experiences of 3rd- to 4th-generation storage ring light source upgrades, such as ESRF-EBS [1], APS-U [2], and SLS 2.0 [3], the team evaluated various lattice configurations, balancing the competing demands against scientific, engineering, and facility constraints [4]. To upgrade the TPS, the tangential angle of all beamlines must remain unchanged to preserve the utility of existing experimental hutches. The straight sections must remain longer than 5 m to accommodate current insertion devices and RF modules. While minimizing beamline realignment is desirable, maintaining the storage ring circumference is critical to avoid the consequential RF synchronization risks. Additionally, ensuring feasible magnet strengths is essential for not only the realistic manufacturing but also the reliable operation.

To ensure long term competitiveness and machine robustness while preserving the identical circumference in the constructed tunnel, a 6BA lattice with relaxed constraints on source-point offset has been selected as the primary candidate. A significant advantage of the 6BA lattice is its ability to cancel the nonlinear geometric driving terms between

chromatic sextupoles at specified phase conditions without the need for additional harmonic sextupoles. This promising feature not only simplifies the nonlinear optimization but also relaxes the constraints on the quadrupoles adjacent to the straight sections, which are primarily dedicated to tune and phase matching. The potential of 6BA lattice is well recognized, as evidenced by ongoing upgrade studies for BESSY-III and AS-II [5, 6].

LATTICE ARRANGEMENT AND BASIC PERFORMANCE

The TPS-II 6BA lattice plans to adopt permanent combined dipoles in the arcs, which creates essential space for vacuum and diagnostic components and reduces the power consumption correspondingly. To maintain operational flexibility, the quadrupoles adjacent to the straight sections and the multi-function magnets within the arc will remain electromagnets. A multi-function magnet, refers to the SLS 2.0 design philosophy [7], incorporates quadrupole, skew-quadrupole and octupole in a single unit allowing for optics correction and coupling control within the arc. Additionally, to ensure the performance of bending beamlines, longitudinal gradient bends featuring a center field at 1.233 T are incorporated at specified survey angles.

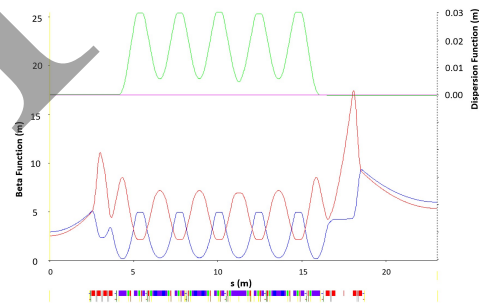


Figure 1: Optics function of the TPS-II 6BA lattice. The arrangement of elements is depicted using different colors: blue for dipoles, purple for combined dipoles, red for quadrupoles, and green for sextupoles.

The linear lattice setup and the analysis of nonlinear dynamics are performed using OPA [8], and the beam performances are verified through ELEGANT tracking [9]. Figure 1 presents the optics functions of the arc connecting the short and long straight sections. The main parameters are summarized in Table 1. The lattice achieves a natural emittance of 67 pm-rad at 3 GeV. With Intra-Beam Scattering (IBS), the horizontal emittance remains around 82 pm-rad at a bunch charge of 1.04 nC and a coupling of 12%, achieving roughly a 20 fold reduction in emittance compared to the

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current TPS. A passive harmonic cavity that stretches the natural bunch length by a factor of three is assumed in the IBS analysis. While the straight sections readily accommodate current insertion devices, the utilization of the remaining space in the long straight sections remains an open topic for exploration. An off-axis injection scheme employing a dual configuration of an orbit bump and a nonlinear kicker is under study; the final injection straight layout will be tailored to this finalized system.

Table 1: Main Parameters of TPS-II 6BA Lattice

Parameter	TPS-II 6BA
Emittance (pm-rad)	$\epsilon_0 = 67 \rightarrow \epsilon_x = 82^\dagger$
(ν_x, ν_y, ν_s)	(66.802, 19.741, 0.00232)
(ξ_x, ξ_y)	(-120.3, -74.8)
(α_1, α_2)	$(0.61, 2.41) \times 10^{-4}$
$\tau_{x,y,l}$ (ms)	(12.25, 19.63, 14.04)
Energy Spread	$(0.85 \rightarrow 1.01^\dagger) \times 10^{-3}$
Bunch Length (mm)	1.84 \rightarrow 6.58 [†] rms
Short Straight Section	5 m
Long Straight Section	8.96 m, 1.037 m \times 2
Injection Straight Section	1.07 m, 3.78 m \times 2

[†]with inclusion of IBS and a harmonic cavity, $\kappa = 12\%$

NONLINEAR DYNAMICS AND ADTS CONTROL

A critical challenge in designing low emittance MBA lattices is that the strong chromatic sextupoles necessary for chromaticity correction often induce substantial ADTS. This severely limits the DA and reduces injection efficiency in the presence of machine errors. Although incorporating octupoles is a general technique for managing ADTS, their usage requires precise optimization; otherwise, they risk amplifying high-order resonance driving terms, leading to the degradation of both DA and MA. Moreover, the introduction of harmonic multipoles adjacent to the straight sections requires additional quadrupoles to maintain the pseudo-symmetric condition in the non-ideal symmetric configurations such as the TPS. This inevitably increases the natural chromaticity and adds unwanted complexity to quadrupole tuning for phase matching. To mitigate this, we propose a strategy of distributing weak sextupole components directly into the centers of dipole magnets. Positioning these components in the dispersion valley, where there is also a significant separation between the horizontal and vertical beta functions, allows for effective control of geometric nonlinearities.

As shown in Fig. 2, the transition from Case 1 to Case 2 demonstrates that embedding these sextupole terms significantly flattens the ADTS. The subsequent inclusion of octupoles in Case 3, while preserving comparable ADTS performance, further expands the MA to a range of -4.29% to 4.71% compared to -3.83% to 4.19% in Case 1. Frequency Map Analysis (FMA) tracking, shown in Fig. 3, confirms that this distributed multipole approach yields substantial

improvements in both the DA and diffusion rates. Overall, this method demonstrates a successful balancing of the nonlinear driving terms without relying on harmonic multipoles. The mechanical feasibility of manufacturing these combined dipoles with embedded sextupole components is under investigation.

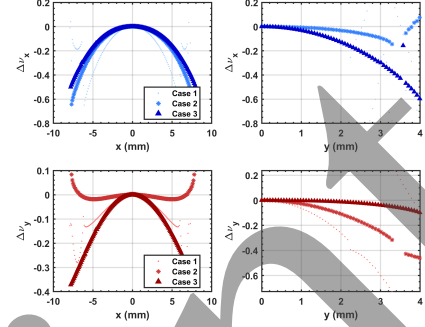


Figure 2: ADTS for three cases. Case 1: chromatic sextupole pair only, Case 2: inclusion of distributed sextupole in the dipoles, Case 3: further addition of chromatic octupole pair.

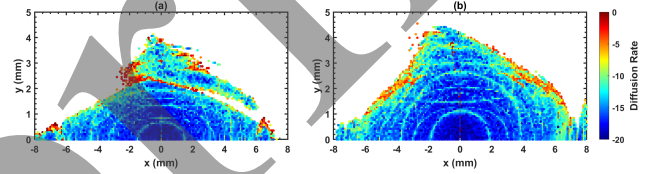


Figure 3: FMA tracking results for (a) Case 1 and (b) Case 3.

PRELIMINARY ERROR ANALYSIS

To examine the lattice robustness and analyze the requirements for hardware development and installation tolerances, a preliminary error analysis was performed using the Simulated Commissioning (SC) package based on Accelerator Toolbox [10, 11]. The SC flow, adopting the error magnitudes summarized in Table 2, consists of the following stages: (1) First-turn beam threading and second-turn beam stitching; (2) Trajectory-based Beam-Based Alignment (BBA) [12]; (3) Ramping of nonlinear multipoles; (4) RF system activation and frequency correction; (5) Linear optics correction by Linear Optics from Closed Orbit (LOCO) [13].

The arrangement of BPMs and correctors along the short arc is illustrated in Fig. 4. Elements within a single arc are grouped onto three girders. A total of 218 BPM and corrector sets are distributed along the entire ring, with 2 to 4 sets located within each girder. The correctors are assumed to be standalone AC magnets capable of providing both slow and fast orbit corrections. Each BPM and corrector set is positioned downstream of the second reverse dipole, whereas the space downstream of the first dipole in each unit cell is reserved for a pumping port and a photon absorber.

A constraint in this error analysis study is that the sextupole terms embedded within the combined-function

Table 2: Assigned Errors for Robustness Study

Parameter	Value
Girder offset	50 μm
Girder roll error	100 μrad
Magnet transverse offset	20 μm
Magnet roll error	100 μrad
Magnet field error	0.1 %
BPM electronic noise	50 μm (TBT mode) 50 nm (CLO mode)
BPM offset	300 μm
(after BBA)	10 μm

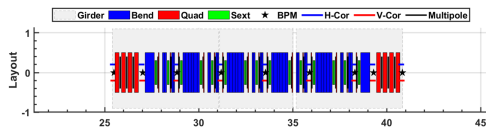


Figure 4: Layout of the magnets, BPMs, and correctors along a single arc segment. The gray region indicates the spans of the girders.

dipoles, assumed to be permanent magnets, are always active from the start of the commissioning process. Trajectory flattening or orbit correction are performed at each operational stage using appropriate Tikhonov regularization. Following Stage 4, the rms orbit errors is approximately 41 μm horizontally and 48 μm vertically, with beta-beating reaching 10.7 % and 13.4 % in the respective planes. Prior to LOCO optimization, the residual dispersion error is around 3 mm and the emittance coupling is roughly 15 %. After six iterations of the LOCO loops, the resulting beta-beating is successfully reduced to below 2 % in both the horizontal and vertical planes. The residual dispersion error is minimized to less than 0.5 mm, and the corrected coupling reaches 0.06 %, while the residual orbit error remains below 50 μm .

DA tracking across 32 random error seeds confirms a survival amplitude of approximately 5 mm, while the MA spans from approximately -4.5% to 5% , as illustrated in Figs. 5 and 6. For the worst seed, the estimated Touschek lifetime reaches 12.6 h when operating at chromaticities of (1, 3) with a passive harmonic cavity, a bunch charge of 1.04 nC, and 10 % coupling. These preliminary results indicate the lattice is robust with beta beating below 2 % and ensuring a lifetime meets the radiation safety criteria for 500 mA top-up operation as well. While these preliminary results are positive, the current analysis does not yet account for high-order multipole errors, or the roll and calibration errors of BPMs and correctors. Additionally, the residual offset achieved by trajectory-based BBA in current model is relatively optimistic. Studies incorporating more rigorous error tolerances while including stored-beam BBA procedure together with orbit correction and optics correction are underway to provide a more comprehensive assessment [12].

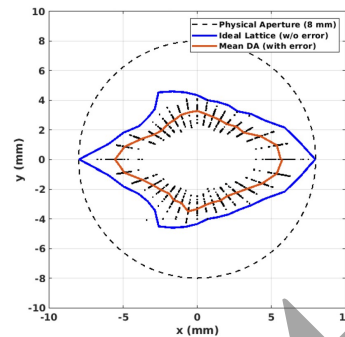


Figure 5: DA tracking evaluated across 32 random machine error seeds. The plot compares the ideal lattice DA (blue) against the mean DA with errors (red).

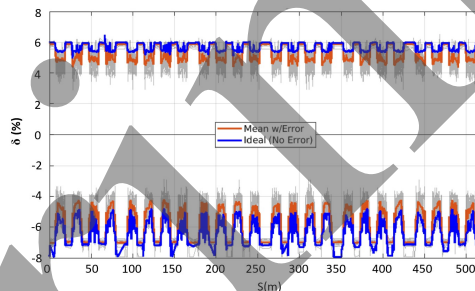


Figure 6: Local MA tracked along the ring for 32 error seeds, comparing the ideal lattice performance (blue) with the mean MA under machine errors (red).

CONCLUSION

The proposed 6BA lattice for the TPS upgrade successfully delivers a sub-100 pm-rad emittance while respecting the existing spatial and engineering constraints. By strategically embedding sextupole components within the dipoles, the design effectively flattens the ADTS, securing a desirable DA and MA without relying on complex harmonic multipoles. Preliminary simulated commissioning results confirm that the lattice maintains sufficient DA and a Touschek lifetime at beta beating below 2 %. These results potentially make the current TPS-II lattice candidate a highly reliable and competitive architecture in more detailed studies. Ongoing work will prioritize comprehensive commissioning simulations, the integration of realistic insertion device models, and the system design of the off-axis injection, ultimately converging on a mature and robust technical design.

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