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STUDY OF AN UPGRADED LATTICE FOR TAIWAN PHOTON SOURCE

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Abstract

In pursuit of maximizing the performance of the Taiwan Photon Source (TPS), we conducted a feasibility study aimed at reassessing and optimizing the lattice configuration within the existing tunnel infrastructure. One of our main objective is to minimize displacement of source points for insertion devices (IDs) while augmenting overall beam performance. To achieve this, we propose an upgraded lattice design based on the multi-bend achromatic (MBA) scheme, featuring 5 bending achromat (5BA) in each arc. This report discusses the challenges encountered and presents preliminary results regarding the implementation of this 5BA lattice design.

INTRODUCTION

Globally, there is a concerted effort to explore advanced technologies aimed at driving the development of green energy particle accelerators for sustainable resource utilization. These technological advancements encompass diverse strategies, including the substitution of permanent magnets for electromagnets, the implementation of a compact injectors featuring higher gradient accelerating structures, the reduction of unnecessary power consumption, and the enhancement of electric power transfer efficiency, among others. Of particular significance among these innovations is the development of storage ring lattice configuration capable of generating an electron beam emittance approaching the diffraction limit. This advancement holds the key to energy conservation, with direct implications for users including increased coherent photon numbers and brightness at the experimental end station. These enhancement enable shorter experiment sampling time and contribute to the reduction of waste heat, thereby promoting greater sustainability in particle accelerator applications.

With the successful establishment and operation of prominent facilities such as MAX-IV, SIRIUS, and ESRF-EBS [1–3], the present development trend of storage ring light sources is steering towards the diffraction-limited storage rings (DLSRs). To enhance the performance of the current TPS, recognized as one of the bright third-generation storage rings since 2015 [4], we are undertaking a study to upgrade the machine toward DLSR for a brighter synchrotron radiation light source and a green energy oriented facility. Analytical estimations indicate that relative brightness and coherent fraction, in comparison to the current TPS operation conditions, could improve by a factor of several tens as the electron beam emittance is reduced to one hundred pm-rad from its current level.

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TPS TOWARDS TPS-II

TPS is a 3 GeV, 518.4 m storage ring, with both the booster ring and the storage ring installed within the same tunnel as concentric circles. The storage ring lattice follows a 6-fold configuration where each super cell consists of four DBA cells separated by a triple of short straight sections at 7 m, along with two halves of long straight section (SS) at 6 m each, positioned at the up- and down- streams. To upgrade the lattice configuration , several constraints must be addressed as follows:

- Implementing the upgrade storage ring in the existing tunnel space.
- Minimizing the horizontal offset of ID source points to maintain the same shielding wall.
- Ensuring the length of each SS is at least 5 m to accommodate current IDs and existing RF modules.
- Preserving the functionality of both bending and ID beamlines.

In comparison to other electron storage ring facilities of similar size, the occupation ratio of SS in TPS is notably high. Second, the ring configuration deviates from ideal symmetry, featuring a 6-fold layout with a total of 24 SSs. Moreover, there is a considerable difference in length between the long and short SSs. These inherent conditions not only greatly restrict the available space, but also make it more challenging to control the electron beam performance within the sub-nm emittance range.

In the initial phase, we started from an H7BA lattice [5]. The chromaticity can be corrected without blowing up the Hamiltonian sextupole geometric terms through the art of -I transform. The dynamic aperture (DA) is comfortably acceptable, however, controlling the off-momentum optics poses challenges for achieving a reasonable Touscheck lifetime (TLT). Nevertheless, we have explored a solution based on the MBA configuration. According to the emittance scaling law, $\epsilon_0 \propto \theta^3$, increasing the number of dipole magnets by at least 25 times, from 48 to 120, is necessary to improve beam emittance from 1.6 nm-rad to 100 pm-rad . Moreover, it is also the maximum feasible number of dipoles for a practical mechanical arrangement within the TPS short arc with length of 20.16 m. For the 5BA lattice with ideal symmetric configuration, we can get a satisfied performance without too many troubles. But the problem is that it needs a whole new shielding wall that the cost and estimated dark period is not acceptable. For the higher order achromat (HOA) scheme under the fixed arc length as TPS, it is composed of a couple of 5BA and 4BA in the super-period [6]. The SSs of each arc could be adjusted to be similar in length to improve the symmetric property of the lattice. The on-momentum DA comes to 8 mm and the estimated TLT is sufficiently long to cover the radiation safety issues at nominal beam operation

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with total beam current of 500 mA. Unfortunately, the offset of ID source point is still too large to fit the existing tunnel.

From the analytical estimation of geometrics based on the 5BA configuration, we need to reduce the length of an unit cell more than 41 cm from the previous HOA scheme to minimize the offset of ID source point within 1 mm. Under this extreme tiny space, the length of unit is 2.37 m, and the natural chromaticity comes to an uncontrollable level due to the strong focusing magnets. In addition, the amplification factor of the lattice with machine errors is too large to provide a stable operation. To compromise all the requirements and constraints, we deliver a lattice design with acceptable horizontal offset (≤ 40 mm) at the straight section and it provides the ability to keep both of the existing TPS beamlines for bending magnets and IDs without reconstructing the new shielding wall. Table 1 summarizes the main parameters of TPS and TPS-II.

Table 1: Main Parameters of TPS and TPS-II

Parameters	**TPS**	**TPS-II**
Lattice	DBA	5BA
Energy (GeV)	3	3
Circumference(m)	518.4	518.4
Straight section	7 m × 18	5.22 m× 18
	12 m × 6	5 m × 6
		2.51 m × 12
Natural emittance	1.6 nm–rad	107 pm–rad
Tune	(26.19, 13.25)	(55.296, 19.224)
Energy spread	0.886×10^{-3}	0.965×10^{-3}
Natural chromaticity	(-75, -27)	(-108.3, -63.5)
Momentum compaction	$(2.4 \times 10^{-4}$,	$(0.67 \times 10^{-4}$,
factor (1^{st}, 2^{nd}order)	$2.1 \times 10^{-3})$	$3.55 \times 10^{-4})$
Radiation loss per turn (keV)	852	598
Damping time (ms)	(12.2, 6.1, 6.1)	(9.8, 17.3, 14.0)

PRELIMINARY RESULTS

The linear lattice setup and the optimization of nonlinear dynamics are performed using OPA [7], and the beam performances are verified through ELEGANT 6-D tracking [8]. To meet all the specified constraints, adjustments to the locations, lengths and strengths of each dipole magnet had been carefully made. Moreover, significant efforts are underway to minimize the natural chromaticity of the linear lattice, thereby reducing the required strengths for chromaticity correction. While extending the length dispersion suppression region is beneficial for reducing the natural chromaticity, it introduces sensitivity to the offset of ID source point and results in decreased SS length meanwhile. Geometric analysis indicates that even a smaller increase of 1 cm in the dispersion suppression section, we need to reduce more than half of the unit cell length to maintain the minimal offset at ID source point. This extreme compact unit cell of length less than 1.2 m, makes it impossible to accommodate all the required elements and components.

To overcome these challenges, the ratio of length between the nominal dipole and the outer dipole for dispersion suppression has been carefully adjusted [9]. Additionally, we adopt the linear gradient dipole (LGB) and combined reverse dipole (RB) to ease the sensitivity of horizontal offset at the ID source point. The combined RB at the center of each cell serves both phase matching and dispersion correction roles. It is helpful to mitigate the quantum excitation effects by lowering the dispersion function at the middle of LGBs, where bending strength is strongest. Meanwhile, this configuration enables reduction of the second order chromaticity without introducing excessive dispersive kick associated with a quadupole magnets. The center field of LGB is designed at the same field as TPS one at 1.91 T, ensuring coverage of the same radiation spectrum for bending users without compromising critical photon energy. The above strategies also ensure sufficient space for the allocation of correctors and beam position monitors at each unit cell for global orbit correction requirements. The linear optics function of a single TPS-II supercell is illustrated in Fig. 1. The occupation of SS to the circumference exceeds 29 %, while the length of SSs where β_y reaches its local minimum extends beyond 5 m. This configuration ensures ample space for the existing RF module and IDs to resolve the potential issues of reduced photon flux resulting from a decrease in period numbers.

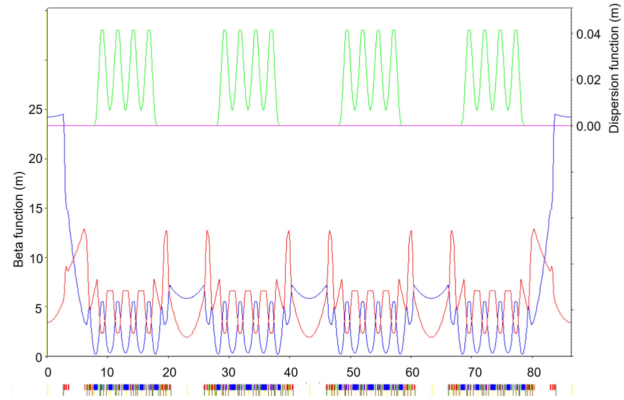

Figure 1: Optics function of TPS-II 5BA scheme. The green line represents the dispersion function, while the blue line and the red line denote the β_x and β_y function respectively.

To simplify the system configurations, the octupole magnets which may introduce unwanted side effects such as the deterioration of DA are not included. Quadrupole magnets at both sides of SS are carefully fine-tuned to ensure phase matching of each arc. It is observed that the identical phase conditions across each arc significantly enhance the beam performance on DA and TLT [10]. A pair of chromatic sextupoles located at each unit cell is used to correct the chromaticities around (1.0, 0.56) in operation. The phase and amplitude of both sextupole and quadrupole magnets are adjusted carefully to minimize the nonlinear Hamiltonian driving terms, the off-momentum resonance terms and the integral of sextupole strengths throughout iteration processes. The on-momentum DA reaches about 8 mm in the negative horizontal direction (the side of injection) and it

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retains over 4 mm for the off-momentum cases at ±5 % as shown in Fig. 2. A single nonlinear magnetic kicker is considered as the injection scheme to mitigate the injection difficulties arising from a relative small dynamic aperture.

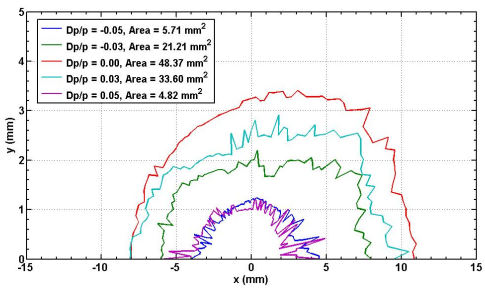

Figure 2: Performance of off-momentum DA for the error-free lattice.

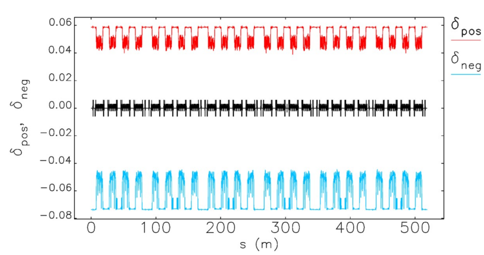

Figure 3: The tracking momentum aperture of the bare lattice.

During the optimization of the linear lattice, the first-order momentum compaction factor α_1 is controlled to be above 0.6×10^{-4}. Additionally, the second order momentum compaction factor α_2 is conducted to maintain the lowest possible ratio of α_2/α_1 to mitigate RF bucket deformation. The momentum tune shifts for ±5 % off-momentum particles in the horizontal direction remain less than 0.2, while those in the vertical direction are less than 0.3 to avoid the half integer resonance. The amplitude dependent tune shift (ADTS) extends to approximately 5 mm and 3 mm within the integer and half integer resonances for the horizontal and vertical direction, respectively. The tracking momentum aperture, assuming an RF voltage of 2 MV, is illustrated as Fig. 3. TLT is estimated at 2.4 h assuming a bunch charge of 1.431 nC (500 mA stored in 604 bunches) and emittance coupling of 1 %. With the nominal rms bunch length at 2.2 mm, plans are underway to include a passive superconducting 3rd harmonic cavity for further bunch lengthening to improve the lifetime [11]. The estimated lifetime could be doubled at least. It is considered that the serious ADTS of current lattice is the bottle neck limiting the TLT performance. Although decreasing $\beta_{x,max}$ along the lattice aids in reducing ADTS, current results indicate that the available length of SS may not satisfy constraints under the phase matching condition. Further exploration for better control of tune shifts to improve the performance of DA and TLT is underway. The uniform filling pattern with a higher occupation ratio of available buckets to reduce bunch charge is also being considered to improve the efficiency of the harmonic cavity.

CONCLUSION

We propose the design of a 5BA lattice for the TPS-II, tailored to fit within the existing TPS tunnel. Comprising 24 SSs, each exceeding 5 m in length, this lattice configuration enables the adoption of current IDs and bending magnet features, while also minimizing the ID source point displacement. Preliminary analysis indicates that this lattice can achieve at least a tenfold improvement in natural beam emittance. The on-going design efforts include the incorporation of a harmonic cavity and a nonlinear kicker, aimed at ensuring a better and more stable beam operation. Additionally, analyses to assess the beam performance with machine errors, the impacts of IDs, and further optimization of nonlinear dynamics to improve DA and TLT are currently in progress.

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