PRELIMINARY DESIGN OF HIGHER-ORDER ACHROMAT LATTICE FOR THE UPGRADE OF TAIWAN PHOTON SOURCE

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Abstract

We study the upgrade of Taiwan Photon Source (TPS) with energy saving as the prime objective. The upgrade design is dubbed TPS-II. To accommodate the constraints imposed by the existing TPS tunnel, we choose the higher-order achromat (HOA) lattice configuration which is composed of the 5BA and 4BA cells. This HOA lattice produces a natural beam emittance about 131 pm·rad for a 3 GeV, 518.4 m storage ring. The on-momentum dynamic aperture is about 8 mm and the estimated Touschek life time reaches around 5.7 hours at total beam current of 500 mA. As a result of the ultralow beam emittance, the brightness and coherence fraction (CF) of the photon beam are improved with a factor of several tens especially in the photon wavelength around 0.1 nm. The challenges and preliminary results of this HOA lattice design will be presented.

INTRODUCTION

The present trend of development for storage ring light sources is steering towards the design of diffraction-limited storage rings (DLSRs), a trend that has been substantiated by the successful establishment and operation of prominent facilities such as MAX-IV, SIRIUS, and ESRF-EBS [1-3]. In the continuum of this evolution, TPS as one of the bright third-generation storage rings since 2015 [4], we plan to upgrade the machine toward DLSR for a brighter synchrotron radiation light source and a green energy-oriented facility.

Globally, several advanced technologies are undergoing examination to propel the development of green energy particle accelerator. These innovations encompass diverse strategies, including the substitution of permanent magnets for electromagnets, the design of a compact accelerator with higher gradient accelerating structures, the reduction of unnecessary power consumption, the enhancement of electric power transfer efficiency and so on. Among these, a storage ring lattice configuration capable of producing an electron beam emittance toward the diffraction limit is one of the keys for energy saving. Directly impact to the users is the increase of coherent photon numbers and brightness which enable the shorter experiment sampling time and reduction of waste heat.

According to the analytical estimation, the relative brightness and CF with respect to the present TPS operation conditions improves by a factor of few tens as the electron beam emittance is reduced to one hundred pm·rad from the current TPS lattice (Fig. 1). There are several possible schemes under study such as H7BA, H6BA, 5BA and HOA for TPS upgrade [5]. In this report, we delve into the initial design stages of a HOA lattice configuration bounded by the constraints and challenges we are facing.

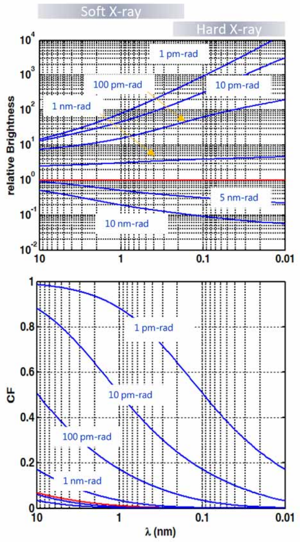

Figure 1: The estimated improvements from TPS to TPS-II on the relative brightness and CF. The red line represents the present operation conditions of TPS (ε_0 =1.6 nm·rad, 500 mA). This calculation employs undulator with the same magnet length and period numbers, optics function of (β_x, β_y) =(5.353, 1.73) m, and $\eta_x = 0$ m.

TPS TOWARD TPS-II

TPS is a 3 GeV, 518.4 m storage ring with the 4-DBA lattice configuration per super-period. There are totally 24 straight sections available for insertion devices (IDs). To use the existing infrastructure of accelerating tunnel, the upgrade design must keep all the source points of ID beamlines fixed. The current long straight section (LSS) to short straight section (SSS) length ratio is large, at 12:7, making it challenging to keep identical unit cells in a super cell while preserving the same source points for the insertion devises and sufficient SSS lengths. Therefore, we have adopted the HOA configuration that is based on the combination of 5-4-4-5 Multi-Bend-Achromat lattice. It is a similar strategy that proposed by SOLEIL-U to overcome the existing constraints in the tunnel [6].

The linear optics function of one TPS-II supercell is shown in Fig. 2. The number of dipole magnets in the ring is increased from 48 to 108. As predicted by the scaling law, $\varepsilon_0 \propto \theta^3$, the beam emittance of the basic HOA scheme is estimated about 430 pm·rad due to the reduction in bending angle. Additionally, the inclusion of combined dipole

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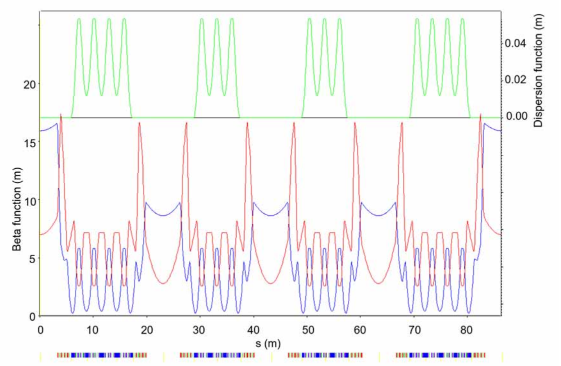

Figure 2: Optics function of TPS-II HOA scheme. The green line represents the dispersion function, while the blue line and the red line denote the β_x and β_y function respectively.

magnets and reverse dipole magnets further improves the horizontal damping and reduces the beam emittance [7]. After the careful adjustment of the length between the central dipole and the matching dipole magnet [8], the natural emittance is reduced to 131 pm·rad that is more than 12 times smaller than the current TPS beam emittance.

The inclusion of reverse dipole magnet primarily enhances the flexibility of dispersion control. The equilibrium HOA beam emittance (which is ~ 1.5 times emittance reduction compared to a lattice scheme without reverse dipoles) and the transverse damping time can be improved further due to the increasing of radiation loss. In our case, the reduction in the horizontal damping time due to reverse dipole magnets is ~ 1.4 times while the vertical damping time is reduced ~ 1.1 times. Nevertheless, the alignment issues of reverse dipole magnets need to be examined carefully.

The main parameters of TPS and TPS-II are summarized in Table 1. The ratio between straight section and circumference for TPS-II is 29 % and the length of each straight section is longer than 6 m. It is adequate to provide sufficient space for the insertion devices, the required vacuum and diagnostic components.

PRELIMINARY RESULTS

The lattice setup and the nonlinear dynamics optimization are performed by OPA [9]. To simplify the system configurations, the octupole magnets which may bring unwanted side effects such as the deterioration of dynamic aperture are not included. A pair of chromatic sextupoles is used to correct the chromaticities around 1.0 in operation. The phase and amplitude of both sextupole and quadrupole magnets are adjusted carefully to minimize the nonlinear Hamiltonian driving terms and the integral of sextupole strengths. Meanwhile, the off-momentum resonances terms are monitored during the iteration processes.

As shown in Fig. 3, the on-momentum dynamic aperture reaches about 8 mm in the horizontal direction and it retains more than 5 mm for the off-momentum case at ± 5 %. A single nonlinear magnetic kicker is considered for the injection scheme to mitigate the injection difficulties due to a small dynamic aperture.

Table 1: Main parameters of TPS and TPS-II

Parameters	TPS	TPS-II
Circumference	518.4 m	518.4 m
Energy	3 GeV	3 GeV
Lattice	4 DBA	HOA
LSS	12 m × 6	6.43 m × 6
SSS	7 m × 18	6.31 m × 18
η_x @ SS center	0.088 m	0 m
Natural emittance	1.6 nm·rad	131 pm·rad
Energy spread	0.886 × 10^{-3}	1.043 × 10^{-3}
Tune (ν_x, ν_y)	(26.19, 13.25)	(49.23, 16.32)
Natural chromaticity (ξ_x, ξ_y)	(-75, -27)	(-92, -59)
Momentum compaction factor (α_1, α_2)	(2.4×10^{-4}, 2.1×10^{-3})	(1.2×10^{-4}, 4.0×10^{-4})
Radiation damping time	(12.2, 12.2, 6.1) ms	(9.2, 20.3, 25.6) ms

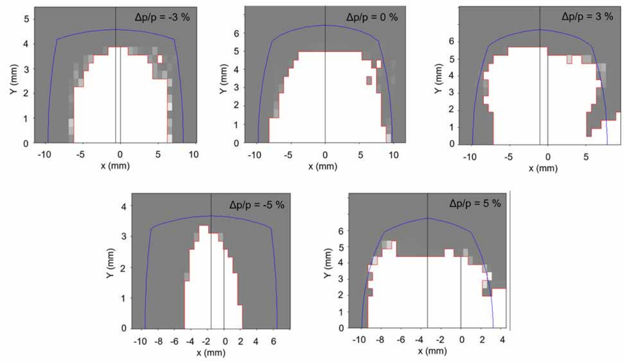

Figure 3: Performance of dynamic aperture for the error-free lattice, $(\xi_{x,ope}, \xi_{y,ope})$ = (0.94, 0.93).

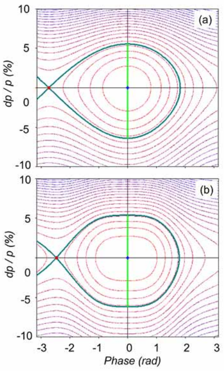

Figure 4: Contour of RF bucket of TPS-II. (a) The considered RF accelerating voltage is assumed to be 2.5 MV, and RF frequency is 499.654 MHz that the harmonic number is 864. (b) With inclusion of a 3rd harmonic cavity.

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In the DLSR lattice, generally, the low momentum compaction factor will lead to a short bunch length. This operation will lead to excessive heat load on vacuum chambers and strong intrabeam scattering (IBS) effects. Hence the first order momentum compaction factor α_1 is controlled to be around 10^{-4} during the optimization of the linear lattice. The second order momentum compaction factor α_2 is also carefully examined to keep the lower possible ratio of α_2/α_1 to mitigate the deformation of RF bucket. Figure 4 (a) is the calculated RF bucket that includes the high order momentum compaction factors. The momentum acceptance ranges from -6.4 % to +5.5 %.

The nominal rms bunch length is 2.8 mm assuming an RF voltage of 2.5 MV, which could cause serious heat load in the in-vacuum IDs operating at the minimum gap [10]. It is planned to install a passive superconducting 3rd harmonic cavity for bunch lengthening. As shown in Fig. 4 (b), the phase diagram of RF bucket potential is flattened with a 3rd harmonic cavity and the estimated bunch length could be increased by about a factor of 2.

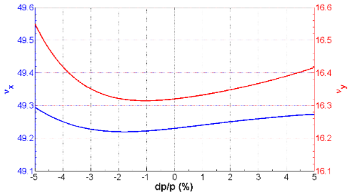

Figure 5: The tracking off-momentum tune-shift.

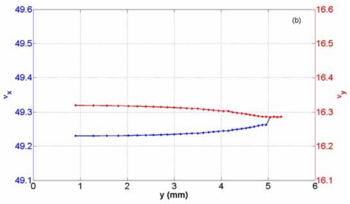

Figure 6: The simulated ADTS. (a) horizontal excitation (b) vertical excitation.

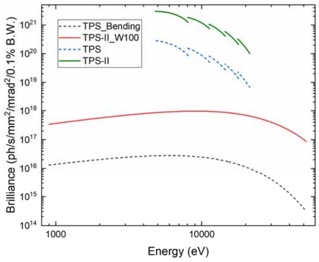

Figure 7: The improvement of spectral brilliance from TPS to TPS-II. Bending: B~ 1.2 T, W100: λ_u =100 mm, N_u=4, B_{max} ~1.8 T, IU22: λ_u =22 mm, N_u=140, B_{max} ~0.76 T.

The off-momentum tune shifts in both the horizontal and vertical directions remain less than 0.1 for ± 4 % off momentum particles (Fig. 5). The amplitude dependent tune shift (ADTS) is shown in Fig. 6. With 70 % of the RF buckets filled, the Touschek life time reaches 5.7 hours at 500 mA when the coupling strength is 1% and the total RF cavity voltage is 2.5 MV. With the 3rd harmonic cavity, the estimated Touschek life time is expected to exceed 10 hours.

To accommodate the existing bending magnet users who need the wider spectrum for experiments, we plan to install wigglers in a three-bump chicane in the straight section. The spectral brilliance achieved with the existing ID IU22, and wiggler magnet W100, is depicted in Fig. 7 [11]. The wiggler radiation is able to provide the brilliance that is more than 40 times of the current bending radiation. The increase of brilliance for IDs is more than one order of magnitude for the hard X-ray spectrum in TPS-II.

CONCLUSION

We propose the design of an HOA lattice for the TPS-II upgrade, tailored to fit the existing TPS tunnel and ID source points. This lattice configuration is composed of 24 straight sections with a length of about 6.3 m. The current TPS insertion devices could be adopted without hardware modification. The preliminary analysis indicates that this lattice design can achieve at least tenfold improvement in natural beam emittance, resulting in enhanced radiation brightness, spectral coherent flux and CF. The on-going design efforts encompass the implementation of a passive harmonic cavity and a nonlinear kicker to ensure a better and stabler beam operation. The analysis for the effects of IDs, multipole error, alignment error, further optimization of nonlinear dynamics, and IBS effect are underway.

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