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MULTI-BEND ACHROMAT LATTICE DESIGN FOR THE FUTURE OF TPS UPGRADE

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Abstract

We present a TPS upgrade option with the hybrid 7BA (H7BA) lattice. We also derive a simple formula on optimal dipole angle distribution among H7BA dipoles. The agreement is satisfactory. We also report preliminary results on the dynamic aperture (DA) optimization. Possible improvement on H7BA lattice is outlined.

INTRODUCTION

The Taiwan Photon Source (TPS) is a low-emittance 3 -GeV light source at National Synchrotron Radiation Research Center (NSRRC). It had succeeded to deliver to user operation since Sep. 22, 2016 [1]. The circumference of the storage ring is 518.4 m. The TPS consists of 24 DB(A) cells with a natural emittance of 1.6 nm. The booster ring and storage ring are concentric structure, located in the same tunnel. Off-axis top-up injection (AC septum + 4 kicker magnets) is adapted to inject beam from booster ring to storage ring through BTS (Booster to Storage ring) transfer line.

To meet the demand of low emittance and high coherence synchrotron light from scientific community to explore frontier in science applications, a number of new or storage ring upgrade projects from the existing 3rd generation storage rings based on the multi-bend achromat (MBA) lattice [2], e.g. ESRF-EBS [3-4], APS-U [5], ALS-U [6], SLS-2 [7], Diamond-II [8], SOLEIL-II [9], Spring-8 II [10], MAX IV, and HEPS [11], etc.

We study the prospective for the future TPS upgrade. The future upgrade of TPS storage ring is constrained by the existing tunnel, circumference of 518.4 m, 500 MHz SRF system and injector system (LINAC and Booster). We wish to maintain the injection scheme with off-axis top-up injection. We carry out several different types of lattices, e.g. QBA [12], 5BA, 6BA, and 7BA. Among of them, those who match the criteria will be chosen as candidates for the future of TPS upgrade. The selection criteria include the beam emittance, Touschek lifetime, momentum acceptance (MA), dynamic aperture (DA), user requirements and the upgrade costs.

Our MBA lattice design plans are described below. First step is to scale MBA lattices specific to the TPS storage ring using the matching module of MAD8 [13]. In order not to disturb the photon beam lines, the cell number kept at 24. This determines the bending angles of the dipoles and the cell length. It also needs to consider enough space for diagnostic and vacuum components. Once a stable solution is obtained, we use this solution as a seed to generate many stable linear lattices with different tunes. For each stable lattice, nonlinear optimization algorithms, e.g. multi-objective genetic algorithm (MOGA), and/or multi-objective particle swarm optimization (MOPSO) [14], are used to optimize the dynamic aperture (DA) and momentum acceptance (MA). The optimization procedure includes multipole errors with a dozen of random seeds during the computation of DA and MA to find out a most robust lattice. The iteration between linear and non-liner lattice optimization or combined linear and non-liner lattice optimization are integrated into our design code. We report the H7BA upgrade option in this report. The paper is organized as follows. Section 2 discusses the H7BA option. Section 3 derives analytic formula and finds the optimal dipole angles of the DBA and FODO sections. Our design agrees well with the theoretical result. The conclusion is discussed in Section 4.

H7BA CELL DESIGN

The hybrid 7BA (H7BA) cell design is started by scaling the ESRF-EBS lattice cell to the TPS storage ring. The H7BA cell structure can be treated as three FODO cells and sandwiched in between two DBA cells. The DBA cells mentioned here are not complete symmetric, lacking of quadrupoles in one side. A pair of quadrupole doublets is located at both sides of the H7BA cell to match the beta function and dispersion. The dipoles in the FODO cells are combined-function magnets with transverse gradient. The dipoles in the DBA cells have longitudinal gradient. Three chromatic sextupoles (one focusing and 2 defocusing) and one octupole are located in between two longitudinal gradient dipoles to correct chromaticities and optimize dynamic aperture, respectively. The dispersion bump is created in between two longitudinal dipoles to reduce the sextupole strength for chromaticity correction. The difference of phase advances between two focusing sextupoles, located in two DBA cells, respectively are $3\pi/\pi$ for horizontal and vertical planes, respectively to cancel resonance driving terms of geometric aberration. It is called -I transformation. This type of lattice is also adopted by APS-U [5] and HEPS [11]. APS-U and HEPS employ some quadrupoles of H7BA cell in horizontal plane to form reverse bends for a better dispersion function matching control.

In this design, we set a standard straight section of 5.5 m for 24 cells in the TPS-2. The cell length is 21.6 m and the bending angle per cell is 15 degrees. Figure 1 shows the layout of the H7BA cell and lattice functions, matched by MAD8 [13], without reverse bend. Lattice properties comparison between TPS and TPS-2 are listed in Table 1. Lattice magnets are still under optimization, not yet final.

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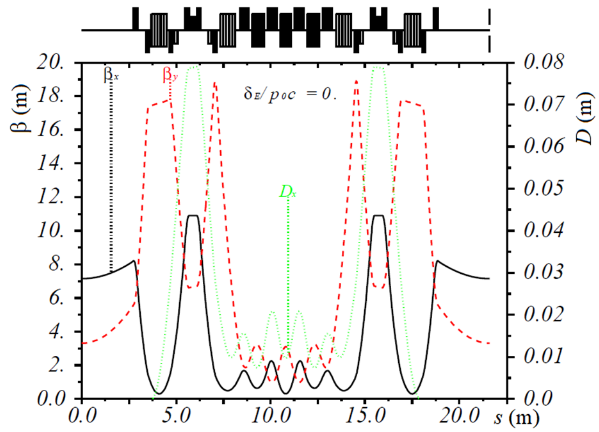

Figure 1: Lattice function of H7BA cell for TPS upgrade.

Table 1: Lattice Parameters

Parameters	TPS	TPS-2
ν_x/ν_y	26.16/14.24	59.237/19.397
Natural emittance	1.6 nm	115 pm
Natural $\xi_{x,y}$	-75.3/-28.95	-103/-85
Energy spread	8.864×10^{-4}	6.590×10^{-4}
Damping time (x/y/z) (ms)	12.2/12.1/6.1	20.1/27.3/16.6
Energy loss per turn (MeV)	0.852	0.380
Compaction factor	2.39×10^{-4}	1.10×10^{-4}
Lattice-Type	DB(A)	H7BA

Dynamic Aperture

We use the OPA [15] code to optimize the dynamic aperture of 24 identical H7BA cells without considering multipole errors and misalignment errors. Figure 2 shows the dynamic aperture tracking of on- and off-energy = +/- 2%) particle at the middle of the straight section. Although the dynamic aperture is still under optimization, our preliminary result shows that off-axis accumulation injection can be adapted by the MBA lattice of TPS-2.

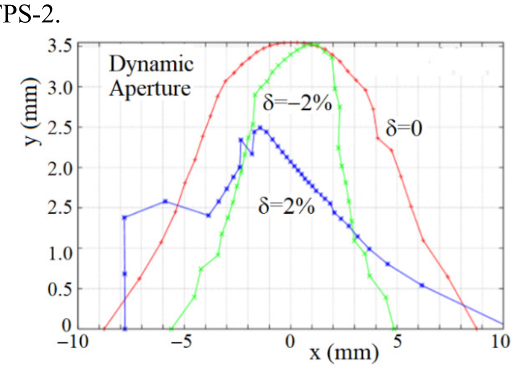

Figure 2: Dynamic aperture at the middle of straight section without multipole errors and misalignment errors.

Frequency Map Analysis (FMA) and Diffusion Index

The dynamic aperture is dominated by nonlinear resonances. The FMA is an important tool to see the effect of resonance lines on particle. The diffusion index will become large when particles are locked on resonance lines. Figure 3 shows the diffusion index of TPS-2 as a function of the fractional momentum deviation. Note that coupling resonance lines appears in the phase space. In the future, we will analyse the characteristics of these resonances and possible method to make them stable.

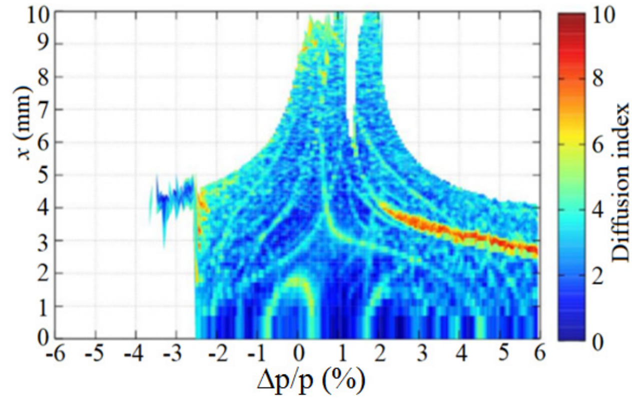

Figure 3: Diffusion index obtained from the frequency map analysis of H7BA TPS-2 upgrade lattice.

Tune Shift with Energy and Momentum Acceptance

The tune shift with energy may cross integer resonance line at δ = -2.5%. Figure 4 shows betatron tunes vs momentum deviation and the momentum acceptance of TPS-2, calculated by TRACY-2 [16] 6-D tracking, without considering multipole errors and misalignment errors of the ring magnets.

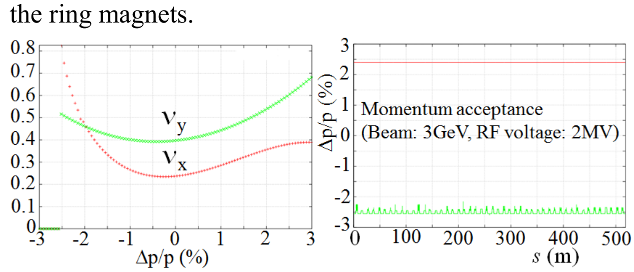

Figure 4: Fractional betatron tunes vs the momentum deviation and the corresponding momentum acceptance of TPS-2 ring.

ANALYSIS OF H7BA LATTICES

The current design of H7BA lattice is a combination of 2 DBA cells matched onto 3 combined function FODO cells. The emittance of such a lattice can be expressed as

$$\epsilon_x = C_q \gamma^2 I_5 / I_2 \mathcal{J}_x \tag{1}$$

, where $C_q = 3.83 \times 10^{-13}$ m, I_2 and I_5 are radiation integrals, $\mathcal{J}_x$ is the damping partition number, and γ is the relativistic energy factor. The radiation integrals of the H7BA can be decomposed into:

$$I_5 = I_{5,DBA} + I_{5,FODO} \cong 4\frac{\mathcal{F}_{DBA}}{4\sqrt{15}}\frac{\theta_{DBA}{}^4}{\rho_{DBA}} + 3\frac{\mathcal{F}_{FODO}}{4\sqrt{15}}\frac{\theta_{FODO}{}^4}{\rho_{FODO}},$$

$$I_2 = I_{2,DBA} + I_{2,FODO} \cong 4\frac{\theta_{DBA}}{\rho_{DBA}} + 3\frac{\theta_{FODO}}{\rho_{FODO}},$$

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where the factors 4 and 3 in these radiation integrals signify the number of dipoles in 2 DBA cells and 3 FODO cells, θ_{DBA} and θ_{FODO} are the bending angles of the DBA cell dipole and FODO cell dipole respectively, and ρ_{DBA} and ρ_{FODO} are respectively the bending radii of the DBA and FODO cell dipoles. Typical achievable design factors are $\mathcal{F}_{DBA} \approx 2$ and $\mathcal{F}_{FODO} \approx 3$ for the DBA and FODO lattices [17]. The constraint on the dipole angles is $4\theta_{DBA} + 3\theta_{DBA} = \theta$, the bending angle of one H7BA cell. The resulting emittance is

$$\epsilon_x = \frac{C_q\gamma^2}{4\sqrt{15}\mathcal{J}_x}\frac{4\mathcal{F}_{DBA}\frac{\theta_{DBA}{}^4}{\rho_{DBA}}+3\mathcal{F}_{FODO}\frac{\theta_{FODO}{}^4}{\rho_{FODO}}}{4\frac{\theta_{DBA}}{\rho_{DBA}}+3\frac{\theta_{FODO}}{\rho_{FODO}}}. \qquad (2)$$

For simplicity, we consider an isomagnetic ring, where ρ_{DBA}=ρ_{FODO}. The emittance becomes

$$\epsilon_x = \frac{C_q\gamma^2}{4\sqrt{15}\mathcal{J}_x}\frac{4\mathcal{F}_{DBA}\theta_{DBA}{}^4+3\mathcal{F}_{FODO}\theta_{FODO}{}^4}{4\theta_{DBA}+3\theta_{DBA}}$$

$$\approx \frac{C_q\gamma^3}{4\sqrt{15}\mathcal{J}_x}\frac{1}{\theta}\left[8\theta_{DBA}{}^4 + \frac{1}{9^3}(\theta - 4\theta_{DBA})^4\right] \qquad (3)$$

, where we use $\mathcal{F}_{DBA} \approx 2$ and $\mathcal{F}_{FODO} \approx 3$ [17]. Minimization of the emittance gives $\theta_{DBA} \cong 0.15\theta$, and $\theta_{FODO} \cong 0.133\theta$. i.e. equal bending for the DBA and FODO sections. The resulting emittance is

$$\epsilon_x \approx \frac{C_q\gamma^2\theta^3}{4\sqrt{15}\mathcal{J}_x} \times 0.0069. \qquad (4)$$

Equation (4) is based on isomagnetic lattice design, i.e. ρ_{DBA}=ρ_{FODO}. If there is a need for different magnet field in these dipoles, one can also obtain an optimal dipole angle ratio. In reality, The H7BA of TPS-2 has $\theta_{DBA} \cong 0.167\theta$ and $\theta_{FODO} \cong 0.111\theta$. From Eq. (3), the emittance is $\epsilon_x \approx \frac{C_q\gamma^2\theta^3}{4\sqrt{15}\mathcal{J}_x} \times 0.0074 = 116$ pm. This agrees nicely with the numerical simulations shown in Table I.

SUMMARY

This paper studies the H7BA option for the TPS upgrade. The resulting emittance agrees well with that derived simple analytic formula. The choices of parameters are not far away from the optimized values. It appears that the result can accommodate the current top-up injection. We will be working with the magnet group for the TPS-2 upgrade.

We shall optimize dynamic aperture and momentum acceptance with MOGA and MOPSO codes in the near future. We will study the DA and MA optimization including the multipole errors and misalignment errors.

We have also begun our study of the QBA option for the TPS-2 upgrade. Our preliminary result indicates that an emittance of 260 pm is achievable. Nonlinear optimization of the QBA option will be reported in the near future.

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