APS-U LATTICE DESIGN FOR OFF-AXIS ACCUMULATION*

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Abstract

A 67-pm hybrid-seven-bend achromat (H7BA) lattice is being proposed for a future Advanced Photon Source (APS) multi-bend-achromat (MBA) upgrade project. This lattice design pushes for smaller emittance and requires use of a swap-out (on-axis) injection scheme due to limited dynamic acceptance. Alternate lattice design work has also been performed for the APS upgrade to achieve better beam dynamics performance than the nominal APS MBA lattice, in order to allow off-axis accumulation. Two such alternate H7BA lattice designs, which target a still-low emittance of 90 pm, are discussed in detail in this paper. Although the single-particle-dynamics performance is good, simulations of collective effects indicate that surprising difficulty would be expected accumulating high single-bunch charge in this lattice. The brightness of the 90-pm lattice is also a factor of two lower than the 67-pm H7BA lattice.

OVERVIEW ON ALTERNATE LATTICE DEVELOPMENT

The equilibrium emittance is aggressively pushed to a low value in the nominal lattice design [1] of the Advanced Photon Source (APS) Multi-Bend Achromat (MBA) upgrade. To achieve low emittance, seven bending magnets with either transverse or longitudinal gradients, plus strong quadrupole focusing are employed in each of the 40 arc cells [2]. The strong nonlinearities introduced by the chromaticity correction sextupoles make the dynamic acceptance (DA) insufficient for beam accumulation, given the large injected beam size from the booster and the assumed 2-mm septum thickness. The on-axis swap-out injection scheme [3, 4] is the only option for this lattice.

Alternate lattices have also been studied with relaxed goals for the equilibrium emittance, which aim to achieve better beam dynamics performance than the nominal lattice, and allow possibility for traditional off-axis accumulation injection scheme. There are some advantages and requirements of adopting off-axis accumulation

- Requires minimal changes to the existing systems (injectors, control system, timing system, etc.).
- Does not require new capabilityes as for the on-axis injection scheme (very fast stripline kickers, high-charge-booster, a new beam dump system, etc.).
- Requires better magnet quality, alignment precision, power supply stability, and beam trajectory plus orbit control.
- May require some additional octupole magnets and the power supplies for these magnets, in order to achieve larger dynamic acceptance.
- Needs special optics design (smaller β_x) at some insertion devices (ID) to accomodate small horizontal gap IDs (helical undulator etc.).

Three types of lattice design, from five-bend achromat (5BA) to 8BA, were investigated and compared in terms of the requirements on the techinical systems (magnets, power supply, vacuum) and the nonlinear beam dynamics performance, as listed below. The MAX-IV style: uniform TME cells with many families of sextupoles [5]; the ESRF-II style: high dispersion bump with -I phase separation [2]; the SIRIUS-inspired style [6]: a combination of MAX-IV and ESRF-II styles. Reverse bending fields in some focusing quadrupole magnets [7,8] are also studied and employed in the lattice design. In the following sections, two 90-pm Hybrid-7BA lattice design are presented in some detail. The general APS-U lattice design considerations plus hard constraints are employed [1].

LINEAR AND NONLINEAR OPTICS

To achieve a high dispersion bump and a smaller emittance, two longitudinal gradient dipoles (LGD) with three uniform-length segments each are adopted at both sides of the dispersion bump. The maximum bending field is 0.44 T in the LGDs, while it is 0.72 T in the central transverse gradient bending magnet. There are 16 quadrupole magnets per sector, with a maximum gradient of 81 T/m. All the quadrupole magnets are matched [9, 10] to be within engineering design limits with at least 10% margin, while all the sextupole magnets are within 20% margin of engineering design limits. The maximum pole-tip fields for the magnets are: 1 T for quadrupoles; 0.6 T for sextupoles; 0.3 T for octupoles.

Compared to the nominal APS-U lattice, the alternate 90pm lattice has several potential advantages:

- Uniform-section-length LGD dipole magnets may be easier to produce and operate than the five-section, variable-section-length dipoles for the nominal lattice.
- There are 2.5 meters free space next to the two LGDs inside the dispersion bump available in each sector for other components (e.g., traditional injection kickers, skew quadrupoles magnets, steering magnets, etc.).
- There are four additional 0.32 m spaces available for octupoles inside the dispersion bump in each sector.
- The ID straight length is increased from 5.8 m to 6.1 m, which can accomodate two additional harmonic sextupoles for nonlinear optics tuning.

The Twiss parameters for one sector of 90pm alternate lattice are shown in Fig. 1. Four injection kickers and one injection septum are employed in one unmodified 90pm lat-

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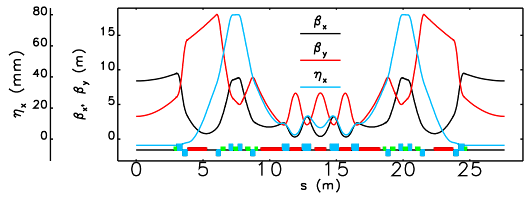

Figure 1: Twiss parameters in one sector of alternate 90pm lattice. Blue blocks represent quadrupoles, red blocks represent dipoles, and green blocks represent sextupoles. The free space (each of 0.8 m) at s=5.5m and s=22m can be used to accomodate injection kickers.

tice arc sector, using the free spaces mentioned above. The kicker K1 is located in the 0.8 m free space next to the first LGD, while the kicker K2 is next to the first quadrupole magnet. Kicker K3 and K4 are accomodated with a mirror symmetry. The injection septum is located at the center of the long straight section. The horizontal phase advance is close to 90° between kicker K1 (or K4) and the injection septum. The required minimum horizontal dynamic acceptance (measured in full width) is from 5.4 mm to 4.1 mm (with different emittance of injected beam), which will accommodate 6 sigma of injected beam, 10 sigma of stored beam, plus septum thickness of 2 mm, and some margin.

A direct-tracking-based multi-objective genetic algorithm (MOGA) [11–14], was employed to vary the linear and nonlinear optics for better beam dynamics performance. The optimization objectives include: DA; local momentum acceptance (LMA); and the desired positive chromaticity for high bunch charge mode. The algorithm is allowed to vary the linear optics, using either a direct variation of the quadrupole gradients or a variation of linear optics targets (e.g., emittance, betatron tunes, beta functions at ID, phase separation between sextupole pairs). Additionally 10 families of sextupole plus 4 families of octupole magnets (with two types of sectors) are varied to optimize dynamic acceptance and local momentum acceptance.

By introducing reverse bending fields [7, 8] in 6 of the focusing quadrupole magnets of each sector, it is possible to further reduce the emittance and/or increase the height of dispersion bump. The maximum dispersion in the 90-pm alternate lattice was increased from 80mm to 110mm with the help of reverse bends, which will greatly reduce the sextupole magnets strength needed, and improve the nonlinear beam dynamics performance. Table 1 shows a one-to-one comparison of the currently operating double-bend lattice (APS), the nominal H7BA lattice (67pm), and the two 90-pm alternate H7BA lattices with and without reverse bends (90pm and 90pm-RB).

EVALUATION

Simulated commissioning was performed on the nominal H7BA lattice and the 90-pm alternate H7BA lattice without reverse bends [15]. The following errors are included: magnet strength, tilt, and misalignment errors; BPM errors; and corrector errors. The 100 corrected lattice ensembles are used in tracking simulations to get the DA and LMA, plus lattice functions and the emittance ratio. The tracking simulations included nominal multipole errors. Besides the nominal physical apertures (half aperture of 10 mm by 3 mm at all IDs), narrow ID apertures of 4 mm by 3 mm (half) are also included in selected IDs. After including the bunch-lengthening effect of an optimized 4^{th} harmonic cavity, intrabeam scattering (IBS) was modeled using `ibsEmittance` [16]. IBS-inflated beam parameters were then used together with the LMA to compute the Touschek lifetime using the program `touschekLifetime` [17]. As seen in Fig. 2, the 90-pm lattice enjoys a nearly two-fold increase in Touschek lifetime.

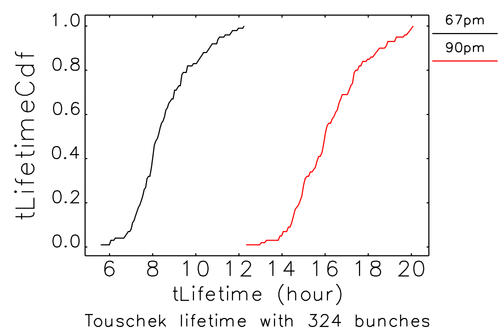

Figure 2: Cumulative distribution of Touschek lifetime out of 100 corrected error ensembles. 200 mA in 324 bunches.

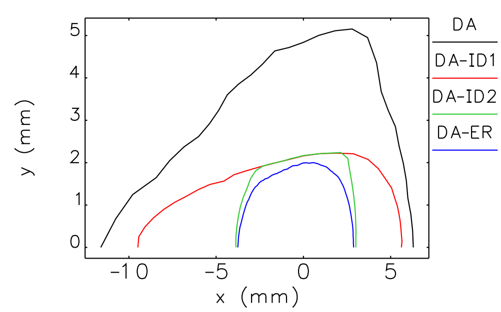

Figure 3: Comparison of dynamic aperture and dynamic acceptances. DA: dynamic aperture; DA-ID1: with physical aperture (half) of 10 mm round in arc, 10 mm (x) by 3 mm (y) in all IDs; DA-ID2: on top of DA-ID1, with several narrow IDs 4 mm (half) in x; DA-ER: physical aperture of DA-ID2, 50th percentile of ensemble evaluations.

As shown in Fig. 3, without narrow IDs and with small errors, the DA of 90-pm lattice may meet the accumulation requirements. With narrow IDs and standard errors, the DA is not large enough, without sharing oscillations between the injected and stored bunch. Although the oscillations-sharing scheme is currently used in the APS operations, simulations show that for APS-U there may be stored beam loss due to collective effects for high bunch charge mode.

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Table 1: Parameter Comparison of the APS DBA and APSU Nominal (Alternate) H7BA Lattices

Parameter	APS	67pm	90pm	90pm-RB	Unit
Tune, ν_x	36.21	95.12	94.13	95.13	
Tune, ν_y	19.28	36.12	34.11	36.13	
Chrom., $\epsilon_{x,nat}$	-89.1	-138.6	-131.3	-141.8	
Chrom., $\epsilon_{y,nat}$	-42.7	-108.5	-103.4	-122.2	
Maximum β_x	31.34	12.91	9.50	14.62	m
Maximum β_y	29.12	18.94	18.02	20.72	m
Maximum η_x	0.28	0.074	0.080	0.11	m
Average β_x	13.06	4.25	4.30	4.14	m
Average β_y	15.89	7.82	7.45	8.59	m
Beam energy E_0	7.0	6.0	6.0	6.0	GeV
Natural emittance ϵ_0	2637.7	66.9	90.6	90.0	pm
Energy spread σ_e	9.6×10^{-4}	9.6×10^{-4}	9.6×10^{-4}	1.0×10^{-3}	
Energy loss per turn U_0	5.35	2.27	2.69	2.48	MeV
Momentum compaction α	2.8×10^{-4}	5.7×10^{-5}	4.0×10^{-5}	2.9×10^{-5}	
Damping time τ_x	9.6×10^{-3}	0.012	0.012	9.9×10^{-3}	s
Damping time τ_δ	4.8×10^{-3}	0.014	0.010	0.015	s
Damping partition J_x	1.00	1.61	1.40	1.80	
Damping partition J_δ	2.00	1.39	1.60	1.20	
Insertion device, $\beta_{x,ID}$	19.49	6.97	8.40	5.03	m
Insertion device, $\beta_{y,ID}$	2.89	2.45	3.28	1.85	m
Insertion device, $\eta_{x,ID}$	0.17	1.1×10^{-3}	-0.00	-0.00	m

That is a combined effect of high impedance in APS-U and smaller physical apertures, where the high-charge stored bunch drives oscillations in the injected bunch that leads to particle loss on the narrow gap ID chambers.

COLLIMATION IN BTS LINE

To fix this requires leaving the stored bunch on the closed orbit, so that only the injected bunch sees injection-induced betatron oscillations. Paths to achieving this include reducing the septum thickness, which depends on technical advances; reducing the booster emittance, which requires modification of the booster lattice; and using collimators in the booster-to-storage-ring (BTS) transport line to reduce the effective emittance.

Possible locations of horizontal collimators are at high β_x. These are also high dispersion regions so electrons with large energy offset may also get collimated. To separate the collimation from horizontal and longitudinal plane, the collimator needs to be placed at a dispersion-free region. A similar arrangement can be employed for vertical collimators. Assuming $\beta_x = 32m$, $D_x = 0$ at the horizontal collimator and standard injected beam, collimation at $\pm2\sigma$ and $\pm1\sigma$ requires a collimator diameter of 4.8mm and 2.4mm respectively (5% and 32% bunch charge collimated). The horizontal beta function at the horizontal collimator may be increased if needed. Past experience at APS with transport line collimation gave problems with radiation outside the shield wall. Hence, several collimators in different stages (primary, secondary,...) may be needed [18].

CONCLUSIONS

A 90-pm H7BA lattice design was developed for the APS MBA upgrade. It has free space for the traditional injection kickers (septum), as well as free space for octupoles and harmonic sextupoles. Off-axis accumulation is possible, assuming sufficiently high-quality magnets, alignment, and other technical systems. With reverse bending fields, it is possible to further improve the nonlinear beam dynamics performance. Collimation in the BTS line may help to improve the injection efficiency and allow high-charge accumulation, as a high charge injected bunch is not required by accumulation scheme.

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