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ALTERNATE LATTICE DESIGN FOR ADVANCED PHOTON SOURCE MULTI-BEND ACHROMAT UPGRADE*

Yipeng Sun†, Michael Borland, ANL, Argonne, IL 60439, USA

Abstract

A 67-pm hybrid-seven-bend achromat (H7BA) lattice is proposed for a future Advanced Photon Source (APS) multi-bend-achromat (MBA) upgrade. This lattice requires use of a swap-out (on-axis) injection scheme. Alternate lattice design work has also been performed to achieve better beam dynamics performance than the nominal APS MBA lattice, in order to allow beam accumulation. One of such alternate H7BA lattice designs, which still targets a very low emittance of 76 pm, is discussed in this paper. With these lattices, existing APS injector complex can be employed without the requirement of a very high charge operation. Studies show that an emittance below 76 pm can be achieved with the employment of reverse bends in an alternate lattice. We discuss the predicted performance and requirements for these lattices and compare them to the nominal lattice.

OVERVIEW ON ALTERNATIVE LATTICE DEVELOPMENT

In the nominal lattice design [1] for the APS Multi-Bend Achromat (MBA) upgrade, the equilibrium emittance is pushed to the lowest achievable value employing reasonable magnet technology. To this end, seven dipole magnets with transverse or longitudinal gradients, plus strong quadrupole focusing are adopted in each arc cell. The associated strong nonlinearities make the dynamic acceptance not large enough for beam accumulation given the large injected beam size and allowing for a reasonable septum thickness. On-axis swap-out injection seems to be the only workable method for this lattice.

Lattice alternatives have been explored with relaxed goals for the emittance, which may achieve better beam dynamics performance than the nominal lattice, plus possibility for off-axis accumulation. Off-axis accumulation has several advantages. It requires minimal changes from existing systems (injectors, control, timing, etc.). It does not require new techniques as for the on-axis injection scheme (very fast kickers, high-charge-booster, beam dump, etc.). However, it may require better magnet quality, alignment precision, power supply stability, and beam trajectory/orbit control. It may also require additional octupoles and power supplies for these magnets, in order to achieve larger acceptance. Finally, using accumulation restricts the use of small horizontal gaps in IDs (insertion device).

Three different types of lattice structure, from five-bend achromat (5BA) to eight-bend achromat (8BA), were investigated and compared in terms of their requirements on the techinical systems and their beam dynamics performance:

- MAX-IV style: uniform TME cells [2]
- ESRF-II hybrid-lattice style: dispersion bump with -I separation [3]
- SIRIUS-inspired [4]: combination of MAX-IV and ESRF-II

Reverse dipole fields in focusing quadrupole magnets [5] are also considered and adopted in the lattice design. Of all these lattices investigated, a Hybrid-7BA lattice design appears to be the most promising in terms of allowing for the possibility of off-axis accumulation. This design is presented in some detail below. The general lattice design considerations and constraints are discussed in [1].

ALTERNATE H7BA LATTICE DESIGN

Magnets

To generate the dispersion bump more efficiently than uniform dipole magnets and achieve a smaller equilibrium emittance, two 6-section longitudinal gradient dipoles (LGD) are employed at both sides of the dispersion bump. A uniform dipole section length of 0.27 m is adopted. The maximum dipole field is 0.45 T in the LGDs, whereas it is 0.73 T in the central dipoles with transverse gradient. The maximum quadrupole gradient is 82 T/m. All the quadrupole magnets are within engineering design limits with more than a 10% margin, while all the sextupole magnets are within engineering design limits with more than a 20% margin. The maximum pole-tip fields are: 1 T for quadrupoles; 0.6 T for sextupoles; 0.3 T for octupoles. Similar to the nominal lattice design, a 3-pole-wiggler is placed in the center of each cell, to be used for bending magnet beamlines. In each cell, six focusing quadrupole magnets are integrated with reverse dipole fields—a feature not yet included in the nominal lattice—to further optimize the emittance and dispersion. The total number of magnets (dipoles, quadrupoles and sextupoles) is the same as used in the nominal lattice design.

Comparison with Nominal Lattice

Compared to the nominal lattice, the alternate H7BA lattice design has three potential advantages:

- Uniform-section-length dipole magnets are easier to produce and operate.
- Each cell has 2.5 meters of free space available for other accelerator components (e.g., injection kickers, skew quadrupoles, steering magnets, etc.).
- Four additional 0.32 m spaces are available to install ocutpoles near the dispersion peak in each cell.
- The ID straight length increased from 5.8 m to 6.1 m.

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† yisun@aps.anl.gov

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Table 1: Parameters of the APS DBA and APSU Nominal (Alternate) H7BA lattices

Parameter	Unit	APS	APSU Nominal	APSU Alternate
Circumference	m	1104	1104	1104
Energy	GeV	7	6	6
Tune x/y/s	2π	36.20/19.27/0.009	95.11/36.10/0.0025	94.09/34.11/0.0017
Natural chromaticity x/y		-90/-43	-138/-109	-120/-104
Rf voltage	MV	10.7	4.0	4.6
Rf frequency	MHz	351.9	351.9	351.9
Rf bucket height	%	3	4	4
Harmonic number		1296	1296	1296
Momentum compaction	10^{-4}	2.8	0.57	0.27
Eff. emittance	pm·rad	3140	67	76
Damping time x/y/s	ms	10/10/5	12/19/14	7/13/10
Energy loss per turn	MeV	5.3	2.3	3.5
Rms energy spread	10^{-4}	9.5	9.6	11.5
Natural bunch length	mm	5.4	3.8	3.2

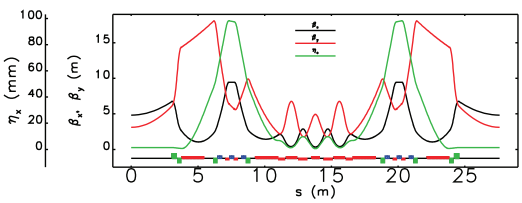

Figure 1: Twiss parameters in one sector of an alternate H7BA lattice design. Green blocks represent quadrupoles, red blocks represent dipoles, and blue blocks represent sextupoles.

Table 1 shows a one-to-one comparison of the currently operating double-bend lattice (APS), the nominal H7BA lattice (APSU Nominal) and the alternate H7BA lattice (APSU Alternate). The Twiss parameters in one H7BA alternate lattice arc cell are shown in Figure 1. Both the emittance and the energy spread are slightly larger than for the nominal H7BA lattice. The brightness should be very similar.

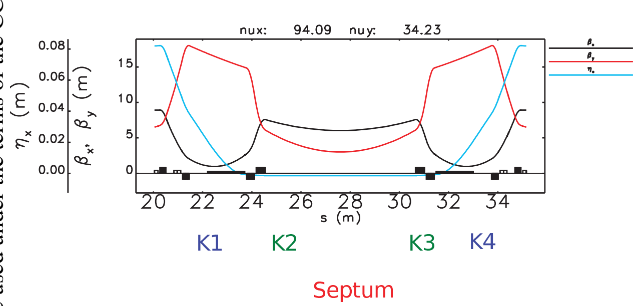

Figure 2: Layout of injection scheme with four injection kickers and a septum magnet.

Injection Section

Four injection kickers and one septum are accommodated in one unmodified alternate H7BA arc cell, as shown in Figure 2, with no sextupoles inside the bump. Close to 90 degree phase advance is achieved in the horizontal plane between K1 (and K4) and the septum. Kicker K1 kicks stored beam by 2 mrad to generate a 7.2 mm bump, while K2 kicks the beam by 0.2 mrad to null out the slope at the septum. The required minimum horizontal dynamic acceptance (in full width) is from 5.4 mm to 4.1 mm (with emittance exchange on injected beam), which accommodates six sigma of injected beam, septum thickness of 2 mm, plus some margin.

NONLINEAR BEAM DYNAMICS

Optimization

The nonlinear optics optimization and evaluation [6] procedures are listed below.

- Linear optics optimization considering amplitude and momentum dependent detuning.
- Integer tune scan and optimization.
- Direct Multi-objective Genetic Algorithm (MOGA) [7] optimization on dynamic acceptance and lifetime: tuning of linear optics; phase separation between sextupoles; 12 families of sextupoles.

It is observed from lattice optimizations that lifetime and dynamic acceptance can be improved by more than 15% with the addition of 4 octupoles per arc cell. The maximum pole-tip fields were 0.3 T for octupoles.

Performance

Numerical simulations were performed with `elegant` to evaluate the performance of the alternate H7BA lattice, including the dynamic acceptance, which is directly relevant for the off-axis injection scheme. Some general simulation conditions include:

- Elliptical physical half-apertures of 10 mm horizontal and 3 mm vertical at the ends of all ID straights.
- Thin rf cavity and synchrotron radiation elements. No quantum excitation was included.
- 2-4% beta beat and emittance ratio from magnet fractional strength and tilt errors; random and systematic

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multipoles (0.001 at 10 mm) in dipoles, quadrupoles, and sextupoles; 36 error seeds.

As illustrated in Figure 3, the off-momentum betatron oscillation tunes cross the integer resonance at approximately -5% and 5%. It is observed that the off-momentum tunes are dominated by second-order chromaticities.

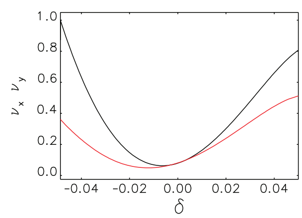

Figure 3: Horizontal (black curve) and vertical (red curve) betatron tune as a function of momentum offset $\Delta E/E$, dominated by second-order chromaticity.

As shown in Figure 4, for the 50^{th} percentile and better cases, the dynamic acceptance (DA) with errors is larger than the required minimum of 5.4 mm in full width. For alternate lattice with octupoles, the DA full width is 13 mm. It should allow accumulation for an injected beam rms size of 0.55 mm (horizontal) and 0.18 mm (vertical). In reaching this conclusion, it is assumed that a non-closed four-kicker bump is employed for those stored electron bunches that see the injection kicker fields. The residual orbit disturbance is shared between these bunches and the injected bunch, which will merge into this specific stored bunch. For other stored bunches which see a fraction of the injection kickers' field, their closed orbit is less disturbed.

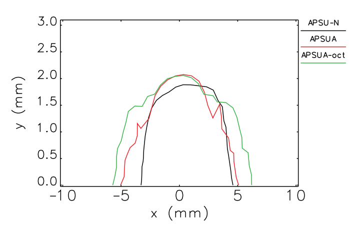

Figure 4: Dynamic acceptance (50^{th} percentile) with physical apertures and errors, nominal lattice (black), alternate lattice with (green) and without octupoles (red).

Scattering effects in the electron bunch may change both the transverse and longitudinal momentum of an electron inside the bunch. The local momentum acceptance (LMA) is defined to be the maximum acceptable momentum change at a specified location of the storage ring. The LMA was evaluated at the exit of specific elements by numerical tracking simulations (1000 turns), with an rf bucket of ±4%. As shown in Figure 5 and Figure 6, good local momentum acceptance and Touschek lifetime are achieved with bunch patterns of 324 bunches and 48 bunches, for a total electron beam current of 200 mA. The lifetime is lower than that achieved in previous alternate lattices, which needs further optimization. One observes asymmetry of local momentum aperture in the positive and negative side, and the LMA exceeds the rf bucket height of 4% at some locations. This is a distortion of rf bucket shape from nonlinear momentum compaction.

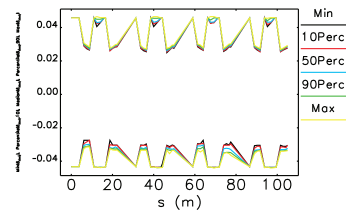

Figure 5: Local momentum acceptance with physical aperture and magnets errors, showing different percentiles.

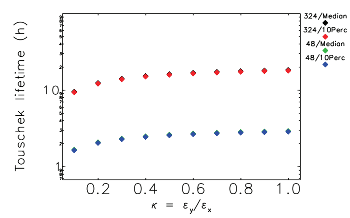

Figure 6: Touschek lifetime, 50 (10) percentile worst cases.

CONCLUSION

A 76 pm H7BA lattice design was developed for the APS MBA upgrade. It has larger dynamic acceptance, as well as longer IDs and more free space. Off-axis accumulation with shared disturbance of the stored and injected beam is possible, assuming sufficiently high-quality magnets, alignment, and other technical systems. This lattice is still being optimized with integration of technical systems, and evaluations of acceptable error levels. We also plan to further develop the nominal lattice to include reverse bends.

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