OPTICS DESIGN AND BEAM DYNAMICS OPTIMIZATION OF A FIVE-BEND ACHROMAT LATTICE FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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

Abstract

For the proposed future Advanced Photon Source (APS) upgrade, a multi-bend achromat design with very low emittance has been studied. Such a ring promises to enhance the photon brightness and transverse coherence by two orders of magnitude. In this paper, one possible lattice design is presented, which is composed of five-bend achromat arc cells. The linear optics design is done for an emittance of 150 pm at a beam energy of 6 GeV. The nonlinear optics are optimized using the Multi-objective Genetic Algorithm (MOGA) technique for good injection efficiency and beam lifetime. Beam dynamics performance is also preliminarily evaluated.

OVERVIEW

Storage rings based on alternate strong focusing have been widely used for many years in the design of colliders and synchrotron radiation light sources. Several focusing configurations have been invented and some of them applied in real ring construction and operation, including the separated-function FODO cell, combined function FD-cell, double-bend achromat (DBA), triple-bend achromat (TBA), and theoretical minimum emittance lattice (TME) [1].

In simplified form, the natural emittance in a storage ring scales as [2]

$$\epsilon_0 \sim \frac{F \cdot E^2}{(N_d N_s)^3 \cdot J_x}, \qquad (1)$$

where ϵ_0 is the equilibrium emittance in a storage ring, F is a dimensionless factor depending on the arc cell focusing, E is the electron energy, N_s is the number of sectors, N_d is the number of dipoles per sector, and J_x is the horizontal damping partition number.

To improve the photon brightness and coherence in a storage-ring-based light source, a low-emittance electron beam (matched to the photon beam) is needed. In general, the requirement to achieve very low emittance means employment of many weaker dipoles (smaller dispersion) and stronger quadrupoles (focusing). Stronger (or better) focusing approaches the ideal TME condition, while more dipole magnets direct us toward a multi-bend achromat (MBA) lattice where $M \geq 4$.

Such a lattice was first studied and proposed in the 1990s [3]. Similar ideas were also discussed for a future APS upgrade with MBA lattices [4] [5] [6], providing a lower natural emittance below 200 pm. The MAX-IV storage ring is the first MBA lattice being built and will be commissioned in 2015 [7]. It employs 20 seven-bend achromat (7BA) cells in a 528-m circumference, which provides an emittance of 330 pm at a beam energy of 3 GeV. ESRF is also proposing an upgrade using a hybrid multi-bend achromat lattice where larger dispersion is adopted to decrease sextupole strength [8].

Recently the APS has begun to explore replacing the current DBA lattice with a new MBA lattice as part of its ongoing upgrade project. A MAX-IV-like 7BA lattice [9], and an ESRF-like hybrid-7BA are being studied [5]. In this paper, another MBA design for the APS upgrade is presented, namely, a five-bend achromat lattice that provides an emittance of 150 pm at 6 GeV.

LINEAR OPTICS DESIGN

It is proposed to enhance the photon brightness and coherence by two orders of magnitude in the new APS MBA lattice. To achieve this goal, and to reuse as much existing hardware as possible, there are several optics design constraints:

- A natural emittance below 150 pm
- Match the existing ID beamline locations
- Maintain the bending-magnet beamlines
- 40 identical cells, each 27.6 m long
- Straight section length longer than 5 m
- Electron beam energy of 6 GeV
- Reuse the existing rf and injector system

Another important design constraint is from the available magnet technology. It is foreseen to use normal-conducting magnets with a bore radius around 12 mm. The drift length between magnets is limited to a minimum of 10 cm. The assumed maximum dipole, quadrupole, and sextupole strength are listed below.

- Combined dipole: dipole field $< 1\ T$; quadrupole gradient $< 50\ T/m$
- Quadrupole gradient $< 100\ T/m$
- Sextupole gradient $< 10000\ T/m^2$

Based on the above contraints, the linear optics matching is performed using ELEGANT [10]. The minimum magnet length is set to be 15 cm, with the magnet strength as low as possible. The linear optics in one sector is shown in Figure 1, where the starting and ending points are the insertion device (ID) center. One observes that the use of a triplet on either side of the ID straight has allowed tuning the beta

* Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.

† yisun@aps.anl.gov

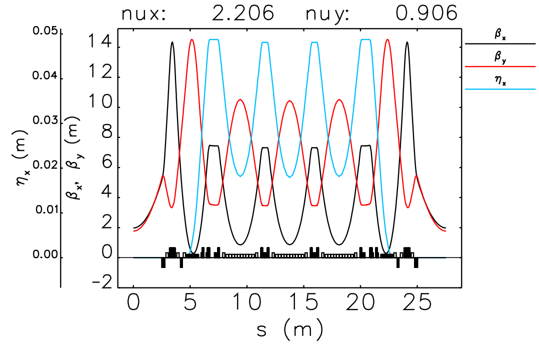

Figure 1: Twiss parameters in a sector with a length of 27.6 m. Natural emittance is 150 pm at a beam energy of 6 GeV. Black curve denotes horizontal beta function; red curve, vertical beta function; blue curve, horizontal dispersion function.

functions (β_x = 2 m, β_y = 1.9 m) at the ID to near the ideal value of L_u/π from the photon beam. In the central three TME-like cells, there are long dipoles combined with a quadrupole gradient. There are two quadrupoles in each dispersion-matching cell at the two ends. The maximum dipole field is 0.6 T, and the maximum quadrupole gradient is 65 T/m. The betatron phase advance is matched to be (2.206, 0.906), which generates a quasi-third-order achromat [11] in a storage ring consisting of 40 such identical 5BA cells.

There is limited space available for dedicated orbit/optics correction magnets and beam instrumentation. That means the correction magnets may need to be integrated into the main magnets. Alternatively, the main magnets could be made stronger and shorter, which would provide more free space. At a beam energy of 6 GeV, the main parameters of the storage ring are listed in Table 1.

Table 1: Parameters of the 5BA Storage Ring

Parameter	unit	value
Circumference	m	1104
Phase advance x/y per cell	2π	2.206/0.906
Tune x/y/s	2π	88.2/36.1/0.06
Natural chromaticity x/y		-166/-80
Rf voltage	MV	3.8
Rf frequency	MHz	352.8
Rf bucket height	%	3
Harmonic number		1296
Momentum compaction	10^{-5}	9
Natural emittance	$pm \cdot rad$	150
Damping time x/y/s	ms	12/20/14
Energy loss per turn	MeV	2.2
Energy spread	10^{-4}	9
RMS bunch length	mm	15

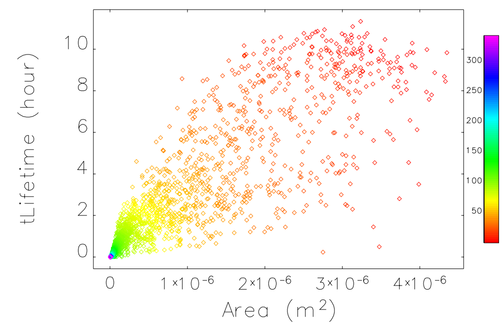

Figure 2: MOGA optimization plot. Horizontal axis is the dynamic acceptance area (β_x = 2 m, β_y = 1.9 m) and vertical axis is the Touschek lifetime.

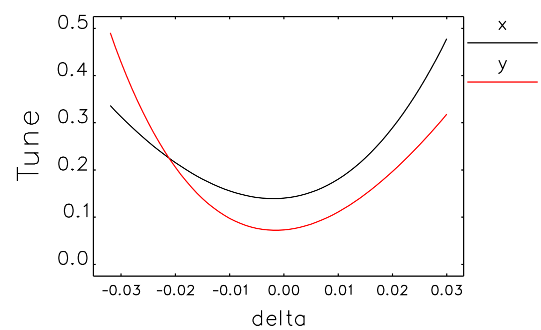

Figure 3: Horizontal (black curve) and vertical (red curve) betatron tune as a function of momentum offset $\Delta E/E$, dominated by second-order chromaticity.

NONLINEAR OPTICS OPTIMIZATION AND PERFORMANCE

In each 5BA cell, there are four families of focusing chromaticity sextupoles (SF) and another four families of defocusing chromaticity sextupoles (SD). The horizontal dispersion is zero in the straight section where there are six harmonic sextupoles. As with the linear optics, mirror symmetry is employed for the sextupole arrangement.

MOGA [12] is adopted to directly optimize both dynamic acceptance (DA) and Touschek ifetime from tracking simulations. The fractional tune is allowed to change in a range of (0.05, 0.45) while the linear optics is still matched. Six families of chromaticity sextupoles and three families of harmonic sextupoles are used as variables that may evolve “naturally” via the genetic algorithm. The two remaining chromaticity sextupoles (SF1 and SD1) are used to correct the first-order chromaticity to 1. A set of solutions with higher DA and lifetime are used as the parents for the next generation. The linear chromaticity penalty function also needs to be small. The MOGA optimization process is shown in Figure 2. It is observed that the DA area is increased from 2×10^{-7} mm^2 to 4×10^{-6} mm^2, and the Touschek lifetime is increased from 0.05 hours to

ISBN 978-3-95450-138-0

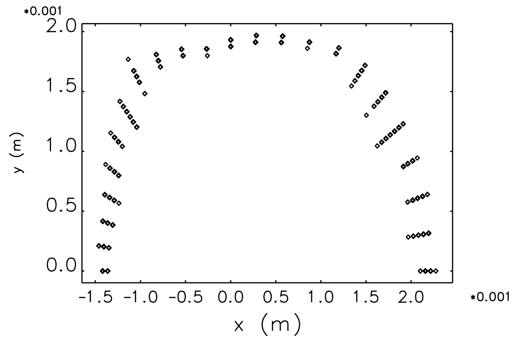

Figure 4: Dynamic acceptance with 50 ensembles of errors (random, systematic magnetic errors, and tilt errors on all the quadrupoles and sextupoles). Tracking is performed at the center of the ID where β_x = 2 m, β_y = 1.9 m.

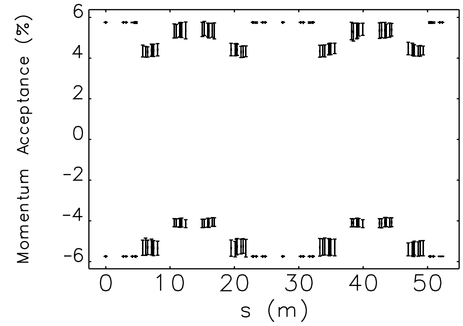

Figure 5: Local momentum acceptance with 50 ensembles of errors (random, systematic magnetic errors and tilt errors on quadrupoles and sextupoles). Tracking is performed at locations next to each magnet in two sectors (a total length of 55 m).

above 10 hours.

One of the best MOGA solutions was picked to be analyzed for its beam dynamics performance. The nominal dynamic acceptance area is 4.2×10^{-6} mm^2 and the Touschek lifetime is 10 hours. The sextupole gradient is less than 6000 T/m^2 with a sextupole length of 0.25 m. There is room to adopt longer sextupoles with lower strength. As mentioned above, the nonlinear optics aberrations are optimized using MOGA. The linear chromaticity is corrected to be 1, which counters the head-tail instability. Examining the solution found by MOGA, we find that the higher-order chromaticities are optimized such that the off-momentum tune spread is minimized. Given the fractional tune close to integer, the second order chromaticities are also optimized to be positive (less than 500), as shown in Figure 3. The global momentum acceptance is limited by the rf bucket, which is 3%.

Dynamic acceptance is the maximum stable transverse amplitude, which is determined by a single-particle numerical tracking simulation. It should ensure efficient acceptance of the injected beam with large emittance and energy spread. It may also impact on the circulating beam lifetime. As shown in Figure 4, the dynamic acceptance is 2 mm $\times$ 1.5 mm at the center of the ID where β_x = 2 m, β_y = 1.9 m. Fifty ensembles of magnetic errors and tilt errors are applied on the quadrupole and sextupole magnets. Note that errors are added to give optics beating of around 1%. No explicit misalignment errors are included, but the effect of such errors is nominally included by the choice of uncorrected optics beating. It is concluded that the DA is enough for on-axis swap-out injection. It is possible to increase the beta function in the injection area and reoptimize the DA for off-axis accumulation, which needs further investigation.

Scattering effects in the electron bunch change both transverse and longitudinal momentum of an electron. Local momentum acceptance is defined to be the maximum acceptable momentum change in a specified location. The mechanisms causing electrons to lose momentum may be physical aperture, DA, or rf bucket limitations. The LMA is determined by tracking and is shown in Figure 5. It is close to 4%, which ensures a good lifetime. (In this simulation we increased the rf voltage to reveal the limitation due solely to beam dynamics.) Collective effects are not studied yet, but expected to be on a smiliar level with the 7BA design [9].

CONCLUSION

A five-bend achromat lattice was developed for a possible future APS MBA upgrade. The linear and nonlinear optics are both optimized to improve the beam dynamic performance.

ACKNOWLEDGMENT

The authors would like to thank C. Wang, Z. Gu, V. Sajaev and L. Emery for helpful discussions.

REFERENCES

[1] L. Teng, Fermilab Report No. TM-1269 (1984).

[2] J. Murphy, Synchrotron Light Source Data Book, BNL 42333 (1989).

[3] D. Einfeld et al., NIM A 335 (1993) 402.

[4] L. Emery, M. Borland, Proc. PAC03, TOPA014, 256 (2003).

[5] M. Borland, private communication.

[6] M. Borland, NIM A 557 (2006) 230.

[7] S. C. Leemann et al., PRST-AB 12 (2009) 120701.

[8] L. Farvacque et al., Proc. IPAC13, MOPEA008, 79 (2013).

[9] M. Borland et al., MOPHO07, proceedings of NA-PAC13 (2013).

[10] M. Borland, Advanced Photon Source ANL/APS/LS-287 (2000).

[11] Y.-P. Sun and M. Borland, MOPHO13, proceedings of NA-PAC13 (2013).

[12] M. Borland et al., ANL/APS/LS-319 (2010).