DESIGN OF THE ALS-U STORAGE RING LATTICE*

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Abstract

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is proposing the upgrade of its synchrotron light source to reach soft x-ray diffraction limits within the present ALS footprint. The storage ring lattice design and optimization of this light source is one of the challenging aspects for this proposed upgrade. The candidate upgrade lattice needs not only to fulfill the physics design requirements such as brightness, injection efficiency and beam lifetime, but also to meet engineering constraints such as space limitations, maximum magnet strength as well as beamline port locations. In this paper, we will present the lattice design goals and choices and discuss the optimization approaches for the proposed ALS upgrade.

INTRODUCTION

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is investigating the upgrade plan (ALS-U) of the existing accelerator facility to approach the soft x-ray diffraction limit in both horizontal and vertical planes [1]. The present ALS Triple Bend Achromat (TBA) lattice will be replaced by a Multi-Bend Achromat (MBA) lattice within the current ALS footprint. The MBA based storage ring lattices have more magnets with smaller aperture and stronger focusing field gradients than conventional storage ring lattices. The stronger focusing magnets enable to focus the electron beam to a smaller spot, resulting in light with much higher brightness and coherent flux. The design study of this ALS-U lattice has a goal of producing round beams of approximately 70 pm-rad emittance in both the horizontal and vertical planes with full coupling at 2 GeV.

The ALS-U storage ring lattice design and optimization is one of the challenging aspects for this proposed upgrade. The candidate upgraded lattice needs not only to fulfill the physics design requirements such as brightness, injection efficiency and lifetime, but also to meet engineering constraints such as space limitation, maximum magnet strength as well as beamline port locations. These requirements are often in conflict with each other. Multi-Objective Genetic Algorithm (MOGA) [2] is applied to optimized this problem. In this paper, we will first present the ALS-U lattice design goal and choices, and then discuss the optimization approach and strategy for an MBA based storage ring lattice.

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LATTICE DESIGN GOALS AND CHOICES

A Multi-Bend Achromat (MBA) lattice is proposed to replace the present Triple-Bend Achromat (TBA) lattice [3] for the ALS upgrade. This upgrade storage ring lattice will have the same periodicity (12 cells) and nearly the same circumference (about 196.5 m) as the present machine. The bending elements used in this machine are all combined function magnets with quadrupole field components. The proposed lattice should meet the natural emittance design goal of about 110 pm-rad (uncoupled lattice), achieved with maximum 50 T/m field gradient and 0.8 T bending field in the bending elements. The maximum gradient in the quadrupoles should be less than 105 T/m. The ring should have close horizontal and vertical tunes to equipartition the emittance between the two planes through linear coupling. See Table 1 for other relevant parameters.

Table 1: Parameters of a Candidate ALS-U Lattice

Parameter	Value
Beam Energy (GeV)	2.0
Circumference (m)	196.5
Natural Emittance (pm.rad)	109
Tune ν_x/ν_y	41.385 /20.385
Natural Chromaticity ξ_x/ξ_y	-65/-68
Damping Time H/V/E (msec)	7.7/14.4/12.7
Energy Spread	8×10^{-4}
Momentum Compaction Factor α_c	2×10^{-4}

One of the most basic design choices is the determination of the number of bending magnets per sector. To study this we considered a model MBA lattice consisting of strictly periodic FODO-like cells in the arc center, with these arc cells sandwiched between two dispersion matching sections which include the two outer bending magnets, and two Twiss matching sections. We can ignore the settings of the quadrupoles in the Twiss matching sections, which affect the beta functions in the straight section but not the emittance. Control of the dispersion is carried out by two families of quadrupoles in the dispersion matching section. As a result, one is left with three field-gradient variables: the gradient of focusing quadrupoles QF in the arc cell, the quad gradient of bending elements B in the arc cell and the quad gradient of the outer bending elements BE in the dispersion matching sections.

The emittance is most sensitive to the strength of QF and has very limited dependence on the outer bend gradient. The main result of the study is summarized in Fig. 1 where the natural emittance for a 12-fold lattice is shown for

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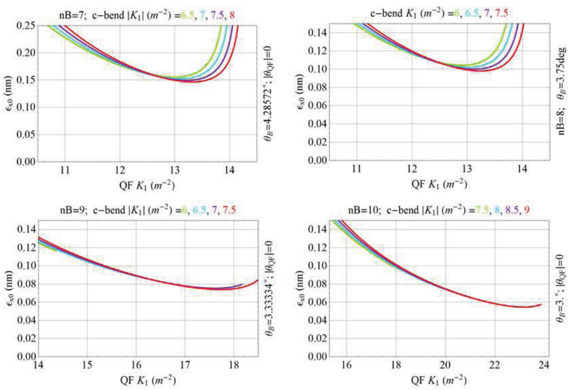

Figure 1: Natural emittance as a function of the arc-cell focusing quadrupole gradient for MBA lattices with $M = 7, 8, 9$ and 10 bending magnets per sector.

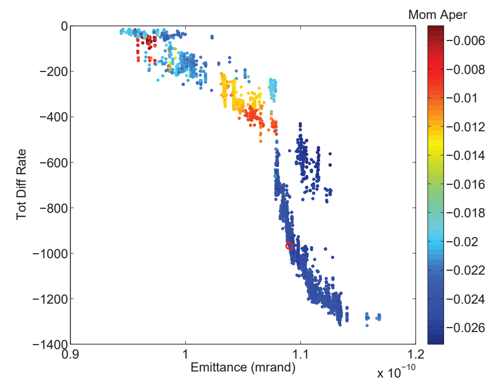

Figure 2: Linear and nonlinear lattice solutions for nine bend achromat.

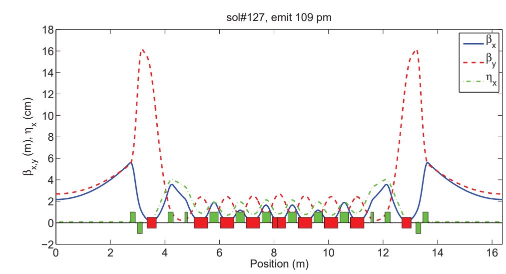

Figure 3: Optics functions for one of the twelve 9-Bend Achromat superperiods.

$M = 7, 8, 9$ and 10 as function of QF gradient K_1. The four different colored curves correspond to various choices of B's gradient K_1. Inspection of the figures immediately rules out a 7BA as a suitable candidate to reach the target emittance. As expected a $M = 10$ MBA lattice has the potential to reach the smallest emittance however at the expense of large gradients. In fact, the target 110 pm emittance can only be achieved with larger field gradient than required in a 9BA, mainly as a result of the quadrupoles having to be shorter in order to accommodate the larger number of magnets in the available arc space. This analysis leaves MBAs with $M = 8, 9$ as the only suitable candidates to reach the target emittance. In the following sections, we will discuss the optimization of this 8BA and 9BA lattices.

OPTIMIZATION APPROACH

The optimization of MBA based ALS-U lattices has to balance competing goals such as high brightness, large dynamic aperture and acceptable lifetime, while satisfying a number of constraints imposed by technological limitations such as maximum available magnetic field strengths, same beamline port locations and space limitation within the current ALS footprint. The most basic trade-off is the one between the goals of attaining small emittance and sufficient dynamic and momentum apertures. Low emittance lattices tend to call for strong focusing fields, which come at the unavoidable cost of aggravating chromatic aberrations, in turn requiring strong sextupoles for correction. As a result, these lattices are inherently highly nonlinear, exhibiting reduced dynamic aperture and momentum aperture compared to those of third generation light sources. Furthermore, the MBA based lattice also have more parameters to be optmized compared to the lattices used in third generation light sources. Therefore, the MBA lattice design is a highly nontrivial multi-objective optimization problem that requires use of the most advanced numerical and analytical resources available to the community.

Our initial approach was to design and optimize the linear and nonlinear lattice by varying the magnet strengths, lengths and spacing using resonance driving terms technique based on trial and error. However, this approach didn't generate satisfactory results, especially for the dynamic and momentum apertures. To this end, Multi-Objective Genetic Algorithm (MOGA) [2] methods are extensively applied to further optimize the ALS-U lattices. For this optimization, the magnet lengths and spacing are fixed to the values found in our initial approach and independent magnet strengths are used as the optimization variables. We carry out the MOGA optimization in several steps to speed up the converging. First, a fast linear lattice optimization without evaluating dynamic and moment apertures is carried out. Through this optimization, we hope to explore the parameter space of quadrupole gradients and narrow down their search range for later optimization.

Then, the linear and nonlinear lattices are optimized simultaneously [4]. Three optimization objectives, emittance, total diffusion rate (dynamic aperture) and momentum aperture are evaluated. The same linear constraints as before are imposed in the optimization. The search ranges for these quad gradients are chosen slightly lager than those found in the previous optimization. Since the genetic algorithm parameters greatly affects the converging speed and behavior, we carried out this optimization in several runs with different tuning of the algorithm parameters in each run. The initial solution for each run is from the previous run and the search ranges of the problem variables are slightly adjusted according to the ones found in the previous run.

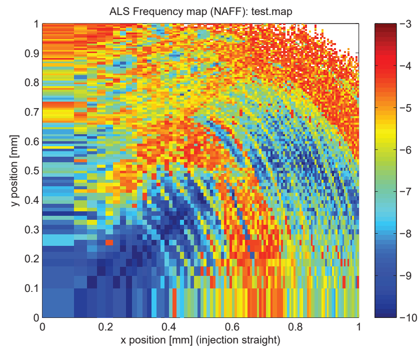

Figure 4: Frequency map analysis at the center of straight. The skew quad amplitude error 5×10^{-4} and normal quad gradient error 2×10^{-4} are included in the lattice.

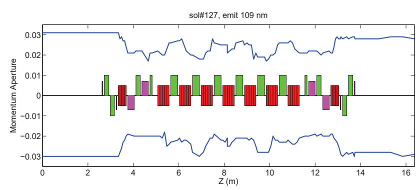

Figure 5: Momentum acceptance along a superperiod.

If the solutions hit the boundary of the search range, the range will be slightly increased in the following run or vice versa. The optimization is carried out for 200 generations at each run. The genetic parameters are varied as following: at the early runs, large mutation and crossover probabilities, small mutation and crossover indices are used in order to fully explore the search range; at the later runs, a slightly smaller probabilities and large indices are used to a get fast converging speed.

With the above optimization strategy, we are able to obtain a converged Pareto front for ALS-U lattice in a reasonable time. Figure 2 shows the Pareto front for 9BA lattices optimization. We can pick up a candidate lattice from this solution front and carry out further lattice characterizations. Figure 3 shows the optics function of the candidate lattice marked in the Fig. 2. It has natural emittance about 109 pm, and the horizontal and vertical tunes about 41.38/20.38 at coupling resonance. When fully coupled, the horizontal and vertical emittance is about 70 pm-rad. Figure 4 shows the frequency map of this lattice. The dynamic aperture on the injection point is about 1 mm which is adequate for on-axis swap-out injection. The momentum aperture is about between 2-3% as shown in Fig. 5. The Touschek beam lifetime is about 0.7 hours.

8BA VS 9BA

An 8BA lattice presents some attractive features in comparison to a 9BA lattice. The reduced number of bending magnets frees up additional room that could be used for lengthening the strong focusing quadrupoles and thus possibly easing their design, and for the insertion of an additional family of chromatic sextupoles. In addition, 8 magnets/sector provides a better fit to the existing ALS bending-magnet beamlines, which then would have to undergo only a modest adjustment to accommodate the new machine.

Following the optimization approach described in the above Section, we have devoted considerable effort to optimize the linear and nonlinear dynamics of 8BA lattices. Early results were very promising and we were able to identify solutions with emittance better than our target and on-momentum dynamic apertures larger than those seen in our best solutions for the 9BA lattices. Further investigations showed that 8BA lattices with the best DA properties are strongly correlated to an odd-integer multiple $\Delta\varphi_x = 5\pi$ of the phase advance difference between the pair of focusing chromatic sextupoles.

Unfortunately we were not able to identify solutions with momentum aperture at least as good as those found in 9BA lattices. Large nonlinear chromaticities are the obvious culprit. The favorable phase advance differences between sextupoles are apparently sufficiently perturbed to compromise the dynamic aperture. The possibility of control the nonlinear chromaticities by introducing additional sextupole families by breaking the 12-fold lattice symmetry is being investigate.

CONCLUSIONS

The present candidate 9BA lattice represents a workable solution for ALS upgrade. Our preliminary studies show that the 8BA lattices have better dynamic aperture than the 9BA lattice but worse momentum aperture. However, both 9BA and 8BA lattices could be further improved. For one thing it is possible that not all the corners of the very large parameter space have been fully explored by the optimization algorithm. To this end, an effort is undergoing to expand the menu of search algorithms available to our optimizer. Further reduction of the natural emittance can be achieved with the introduction of reversed bends, as a way to better match dispersion and beta functions [5]. Our preliminary studies have shown a potential for further reduction of the transverse natural emittance by about 20% or more, while increasing the natural energy spread only minimally. However, part or all of this emittance advantage will be needed to offset the emittance degradation due to IBS effects.

REFERENCES

[1] C. Steier, *et al.*, " Status of the Conceptual Design of ALS-U", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper WEPAB104, this conference.

[2] K. Deb, *IEEE Trans. Evolutionary Comput.*, vol. 6, p.182, 2002.

[3] H. Tarawneh , C. Steier, D. Robin, H. Nishimura, C. Sun, W. Wan, in *Proc. of NA-PAC'13*, Pasadena, CA, Sep. 2013, p. 288-230.

[4] C. Sun, D. S. Robin, H. Nishimura, C. Steier, and W. Wan, Phys. *Rev. ST Accel. Beams*, vol 15, p.054001, 2011.

[5] A.Streun, *Nucl. Instr. Meth. Phys.*, vol. A737, pp.148-154, 2014.

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