OPTIMIZATION 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 approach that we applied to design and optimize a multi-bend achromat based storage ring lattice for the proposed ALS upgrade.

INTRODUCTION

Storage ring based third generation synchrotron radiation light sources have been operating for more than two decades in many accelerator facilities around the world. They have provided valuable tools for probing the structure of matter in a wide range of fields from material science, chemistry, medicine to industrial applications. However, continuing support of scientific breakthroughs requires levels of coherent photon flux that are beyond the capabilities of the existing facilities. Recent developments in multi-bend achromat (MBA) technology [1] hold the promise of a dramatic increase in coherent flux, reaching the diffraction limit over a wide range of the radiation spectrum. 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 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 [2]. The present triple bend achromat (TBA) lattice will be replaced by an MBA based lattice within the current ALS footprint. The design study of this ALS-U lattice has a goal of achieving a natural emittance of about 100 pm-rad at beam energy around 2 GeV. When fully coupled, the ALS-U lattice will produce round beams of approximately 50 pm-rad emittance in both the horizontal and vertical planes.

The ALS-U storage ring lattice design and optimization is one of the challenging aspects for this proposed upgrade.

Figure 1: Magnet layout of one arc of ALS-U MBA lattice.

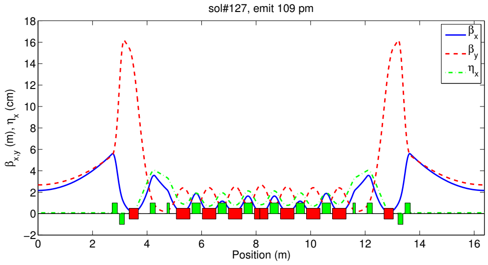

Figure 2: Optics functions for one of the twelve 9-Bend Achromat superperiods.

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 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) [3] is applied to optimized this problem. In this paper, we will present the approach and strategy that we applied to design and optimize an MBA based storage ring lattice for the proposed ALS-U upgrade.

LATTICE CONFIGURATIONS AND DESIGN GOAL

A nine-bend achromat lattice is proposed to replace the present triple-bend achromat (TBA) lattice [4]. The magnet layout of this lattice is shown in Fig. 1. This new storage ring lattice has the same periodicity (12 cells) and nearly the same circumference (196.5 m) as the present machine. In each cell, the bending is distributed equally among the 9 bending elements which consist of 2 combined-function dipoles at the entrance and exit of the arc and 7 offset defocusing quadrupoles in the center of arc. There are 14 quadrupoles, 7 families and 2 in each family, located between the bending magnets in each cell. There are 4 chromatic sextupoles (2 families) located in the high dispersion section and 4 harmonic sextupoles (2 families) located in the straight. The proposed lattice should meet the natural emittance design goal of 100 pm-rad, achieved with maximum 50 T/m field gradient and 0.8 T bending field in the bending quadrupoles. The maximum gradient in the other quadrupoles is about 106 T/m. The ring should has a close horizontal and vertical tune to equipartition the emittance

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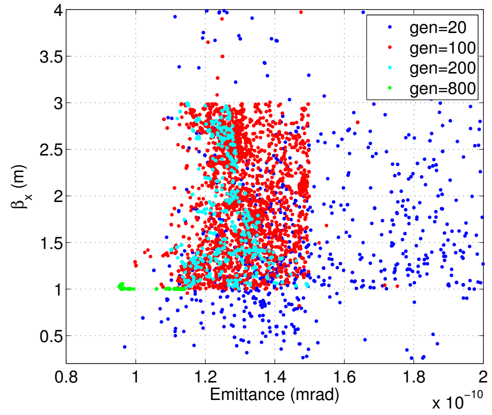

Figure 3: Linear lattice solutions at different generations.

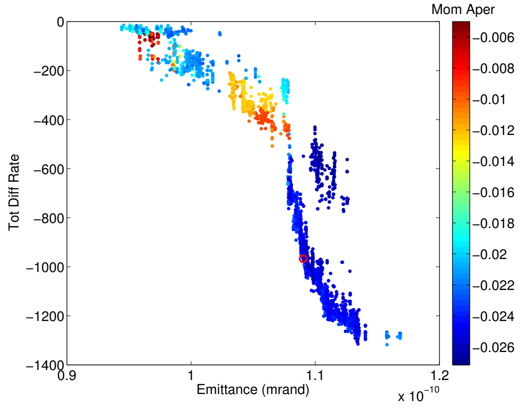

Figure 4: Linear and nonlinear lattice solutions.

between the two planes through linear coupling. See Table 1 for other relevant parameters.

The ALS-U lattice design 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. Therefore, the lattice design is a highly non-trivial multi-objective optimization problem that requires use of the most advanced numerical and analytical resources available to the community. To this end, MOGA methods have been extensively applied to optimize and design the ALS-U lattice.

Table 1: Parameters of 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}

OPTIMIZATION STRATEGY

In the past, MOGA methods have been successfully employed to optimize the existing ALS Triple-Bend Achromat lattice [5]. However, due to a large parameter space, the optimization of the ALS-U MBA lattice is much more difficult than that of the ALS TBA lattice. Here, we have a total of 11 independent magnet strengths that need to be tuned: 7 quadrupole gradients, 2 bending magnet gradients (the gradients of the 1st and 9th, as well as those of 2nd through 8th bending magnets are set to be the same) and 2 harmonic sextupole strengths. Two additional chromatic sextupoles are used for chromaticity fitting in the optimization.

Our initial approach was first to optimize the linear lattice by varying the magnet strengths, lengths and spacings based on trials and experiences, and then to optimize the nonlinear properties of the lattice by minimizing resonance driving terms. However, this approach didn't generate satisfactory results, especially for the dynamic and momentum apertures.

Since the design goals of the lattice properties (linear and nonlinear) are often in conflict with each other, we resolved to optimize this problem using MOGA [5]. For this optimization, the magnet lengths and spacings are fixed to the values found in our initial approach and 11 independent magnet strengths are used as the optimization variables. In our first attempt, we ran the MOGA optimizer with a large (5000) population of lattices, searching the whole 11-dimension variable space without any boundary constraints on the variables. During the run, the linear (emittance) and nonlinear (total diffusion rate and momentum aperture) properties of each lattice are evaluated. Unfortunately, the evaluation of the nonlinear properties are timing consuming; the converging speed of the solution is very slow and also greatly affected by the choice of the genetic algorithm parameters (mutation and crossover indices and probabilities) [3]. This makes it difficult to obtain a stable converged solution in a reasonable time

To overcome this difficulty, we carry out the MOGA optimization in several steps. First, a fast linear lattice optimization without evaluating dynamic and moment apertures is carried out. Through this optimization, we hope to explore the 9 parameter space of quadrupole gradients and narrow down their search range for later optimizations.

Fig. 3 shows linear lattice solutions at different generations. The initial solutions are randomly generated and the optimization is carried out in the search of full range of parameter space. Solutions start to converge at the 20th generation and fully converge after the 800th generation. In this optimization, the natural emittance is minimized ($\epsilon \rightarrow 0$) and the beta functions are optimized to 1 meter ($|\beta_{x,y} - 1| \rightarrow 0$). To speed up the optimization, constrains are imposed on the natural emittance and beta functions, i.e., the emittance is less than 150 pm ($\epsilon < 150$ pm) and beta functions are less than 3 m ($\beta_{x,y} < 3$ m). Horizontal and vertical tunes are forced to be close to each other in order to have lattices at coupling resonance. With this optimization, we are able to explore the quadrupole parameter spaces, and narrow down the search ranges for 9 quadrupole gradients. These ranges are used for the next step optimization. Instead of using fully converged solutions after the 800th generation, we are using the solutions at the 100th generation for the following optimizations.

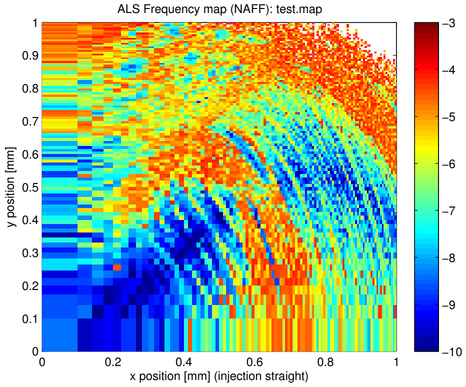

Figure 5: Frequency map analysis at the center of straight

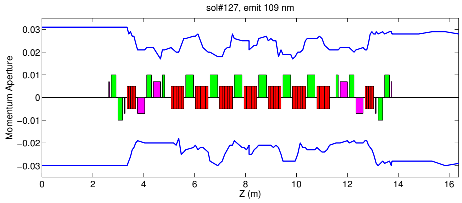

Figure 6: Momentum acceptance along a superperiod

Finally, the linear and nonlinear lattice are optimized simultaneously. 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. 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 stable converged solution front for ALS-U lattice in a reasonable time. Fig. 4 shows Pareto front at the final optimization step. We can pick up a candidate lattice from this solution front and carry out further lattice characterizations. Fig. 2 shows the optics function of a candidate lattice marked in the Fig. 4. 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 5 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. 6. The Touschek beam lifetime is about 0.8 hours.

CONCLUSION

The present candidate lattice represents a workable solution but can 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 [6]. 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. A thorough analysis of this lattice is underway.

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