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Lattice and emittance optimization techniques and the ALS brightness upgrade

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ABSTRACT

An upgrade project is under way to further improve the brightness of the Advanced Light Source at Berkeley Lab by reducing its horizontal emittance from 6.3 to 2.2 nm (effective emittance in the straights from 6.4 to 2.5 nm). This will result in a brightness increase by a factor of three for bend magnet beamlines and at least a factor of two for insertion device beamlines and will keep the ALS competitive with newer sources. This paper presents an overview of the upgrade project with emphasis on the nonlinear beam dynamics simulations. It also discusses in a more general way the techniques used at LBNL for finding optimum lattices (e.g. the ones with maximum brightness) and optimizing the particle dynamics, thereby increasing beam lifetime and stability.

1. Introduction

For synchrotron light sources, the main performance defining parameter is the photon brightness available at its beamlines. This paper will use the example of the Advanced Light Source to highlight modern techniques for optimizing linear lattice designs as well as the nonlinear dynamics behavior of lattices.

Over the years, the brightness of the ALS has been steadily improved, keeping track with newer light sources and keeping the ALS the brightest third generation light source in the energy range below 1 keV. The upgrades included improvements in beam parameters, addition of new radiation producing devices, as well as stability improvements going hand-in-hand with the brightness improvements. The last upgrade was the migration to top-off operation completed in 2009, which required a complete rework of the injector systems as well as many new radiation safety systems and resulted in a doubling of the average flux and an improvement in average brightness by up to one order of magnitude. To remain competitive in the future, it was recognized a few years ago that further upgrades will be necessary.

The low emittance upgrade as described in this paper will increase the brightness at the ALS by another factor of three in the bending magnet beamlines, and by about a factor two in the existing insertion device beamlines. The upgrade also opens the door to a potential further increase of the brightness in a future "ultimate" upgrade allowing lattices with small horizontal beta functions in the insertion device straights and much higher brightness because of the better match of the electron phase space to the photon diffraction ellipse. This ultimate upgrade is under study and some of the optimization techniques to optimize those lattices are described later in this paper. It potentially requires a new injection scheme and further strength increases of the original sextupole magnets. The brightness for ALS insertion devices is shown in Fig. 1 for present parameters, for the baseline of the low emittance upgrade, as well as for the ultimate upgrade future brightness scenarios. The brightness computations assume current insertion device technology, i.e. room temperature in-vacuum undulators.

2. Upgrade lattice choice and options

The ALS lattice is a triple bend achromat structure, with 12 arcs and a fixed, large defocusing gradient in the bending magnets. There are three quadrupole families in the normal arc sectors and four in the Superbend sectors. Most quadrupoles are individually powered. Originally, there were only two families of sextupoles, with four sextupoles in each arc. To understand the potential of the ALS magnet arrangement, multiple techniques were employed. At first, lattices close to the nominal lattice were studied [1]. Since the Superbend upgrade the ALS operates with distributed dispersion ($\eta_x = 6$ cm in the straights), a method previously used at other light sources [2], which helped to mitigate the emittance increase due to the Superbends. In the newer studies, in addition to increasing the dispersion in the straights further, we also looked at raising the phase advance per cell, for simplicity we considered

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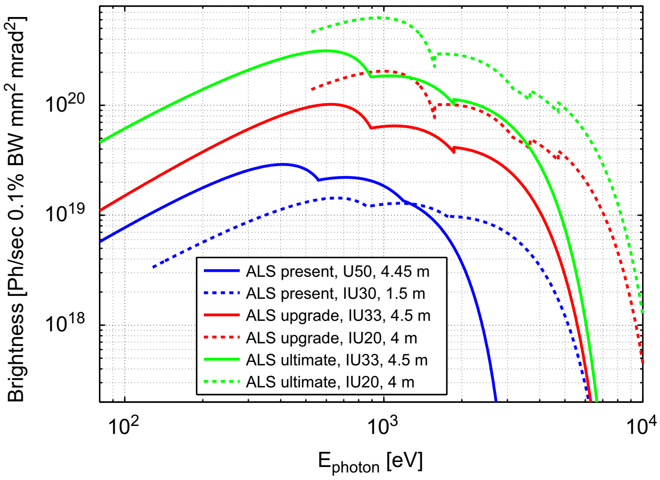

Fig. 1. Comparison of the current ALS brightness around 1 keV (i.e. after top-off upgrade) with future brightness after the low emittance upgrade (as well as a more speculative case, if low horizontal beta function lattices are workable).

equal fractional tune but integer tunes larger by one, two and three units. An attractive set of possible lattices was found with a straight section dispersion of $\eta_x = 12-15$ cm and an integer tune two units higher than the current lattice ($\nu_x = 16.25$ instead of 14.25). Those lattices have natural emittances of just above 2 nm (compared to the more than 6 nm of the current lattice) and despite the fairly sizeable dispersion in the straights, the effective emittance is small as well (2.5 nm).

2.1. Systematic lattice optimization techniques

Historically, lattice design depended strongly on the experience of the person developing the design as well as choosing from a menu of known lattice choices. Many choices in this approach are subjective and usually the optimization of the nonlinear dynamics properties is carried out separately from the linear lattice design. Given the success of 3rd generation light sources, this approach has worked well in the past, but with advances in computation power and algorithms as well as better understanding of the nonlinear dynamics of low emittance lattices, more systematic approaches have become possible.

Some of those systematic techniques were used to further improve candidate lattices for the ALS brightness upgrade. The first one was employed to find the globally optimal (but still symmetric, linear) lattices in terms of emittance or brightness: GLASS [3] used a global grid scan of the parameters of a simplified standard cell with three parameters. It then analyzed the properties of all lattices that were stable. This allowed to search for potential lattices with certain properties.

Specifically for the case of the ALS upgrade, we learned that the simple lattice solution we had found before was already very close to the global minimum for the natural as well as effective emittance. However, GLASS showed that there also existed two other interesting classes of lattices, which have similarly small emittance, but combine them with other interesting qualities. In one case the lattices have simultaneously small beta functions in both planes in the insertion device straights, This allows a better match to the photon diffraction ellipse and therefore would result in again significantly higher brightness. However, those lattices present challenges for injection, which will be briefly discussed later. The other interesting class allows for small momentum compaction factor at the same time as small natural emittance, and might be interesting for short bunch and coherent THz radiation operation modes.

The next technique we used were multi-objective, genetic algorithms. Those algorithms are already fairly old, but applications to accelerators are still fairly new. The first major one was Ref. [4] and optimized a high brightness DC photoinjector. Another early application was Ref. [5], where parametric studies were carried out to find optimum damping ring designs using genetic algorithms.

The use of multi-objective algorithms at the ALS [6] was to our knowledge the first application of those algorithms for detailed linear lattice design. In this case, the algorithms allowed the study of lattices with more parameters than what was possible in GLASS, as well as a direct optimization of the lattices (including effects of the diffraction ellipse) for insertion device and bend magnet brightness. Using these techniques, we also studied hybrid lattices, with high horizontal beta functions in some straight sections and low ones in other ones. Those lattices make the optimization for injection easier and might provide the ultimate brightness performance shown in Fig. 1 for a subset of the straight sections.

The newest application of multi-objective algorithms is for the multi-parameter optimization of the nonlinear dynamics of complex or low-periodicity lattices, which also allows for the simultaneous optimization of linear and nonlinear lattices [7]. The results of this approach at the ALS are still developing. They include the demonstration that splitting the new harmonic sextupoles into multiple families allows better dynamic (momentum) aperture, in particular for the low beta function lattices. The multi-objective nature of the algorithms also provides quantitative information on how much one has to detune the emittance from its minimum value, in order to find a solution with sufficiently large dynamic aperture for injection or sufficiently small sextupole strength to keep the existing sextupole magnets unchanged.

2.2. Merit function for nonlinear lattice optimization

A relatively new merit function [8] has been used at the ALS and elsewhere to optimize the nonlinear dynamics. We use frequency map analysis, particularly using the sum of all diffusion rates over a predefined area of interest (in x–y or x–$\Delta p/p$ configuration space) as the merit function to optimize.

2.2.1. Frequency map analysis

Frequency map analysis [9] has been in use for particle accelerators for well over 10 years now. It started as a tool to understand the global dynamics of the system, usually mapping $x-y$ configuration space into ν_x,ν_y tune space. Later it was expanded to be used on measured data [10], as well as to study off energy dynamics [11]. Fig. 2 shows an example of a simulated frequency map for the ALS in tune space (top) as well as configuration space (bottom). The simulation was carried out including (small) lattice errors, where the quadrupole and skew quadrupole gradient distributions were derived from measured orbit response matrix analysis. The color code indicates the tune diffusion rate, defined by

$$d = \sqrt{(\nu_{x,1}-\nu_{x,2})^2+(\nu_{y,1}-\nu_{y,2})^2}/N \quad (1)$$

on a logarithmic scale, where $\nu_{x,1}$ denotes the horizontal tune calculated for the first N turns of tracking data, $\nu_{x,2}$ the one for the following N turns.

Further simulation studies as well as detailed experiments over the years provided the experience to identify, which resonance structures in frequency maps tend to be dangerous, when adding for example additional machine errors, or insertion devices, and which ones are not. One very simple rule of thumb turned out to be,