STATUS OF THE LOW EMITTANCE UPGRADE OF THE ADVANCED LIGHT SOURCE*

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Abstract

The Advanced Light Source is one of the earliest 3rd generation light sources. With an active upgrade program it has remained competitive over the years. The latest in a series of upgrades is a lattice upgrade project that was started in 2009. When it will be completed, the ALS will operate with a horizontal emittance of 2.2 nm and an effective emittance of 2.6 nm. Combined with the high current of 500 mA and the small vertical emittance the ALS already operates at, this upgrade will keep it competitive for years to come. This paper summarizes the status of the upgrade, including beam dynamics studies and lattice optimizations as well as the magnet design.

INTRODUCTION

For light sources, the main performance defining parameter is the photon brightness available at its beamlines. At the ALS two main beamline categories exist: the ones with sources in the bending magnets (some of them on the superconducting Superbend magnets) and those with sources in the insertion devices (undulators and wigglers) situated in the accelerator straight sections. 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 (current and emittance), addition of new radiation producing devices (Superbends and advanced insertion 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 current, significant improvements in thermal stability and allowed to reduce the vertical emittance by a factor of 3. To remain competitive into 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 about a factor 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 even further increase of the ALS 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 would require a new injection scheme and potentially further strength increases of the original sextupole magnets. The new magnets described later in this paper have been designed to be compatible with all lattices.

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.

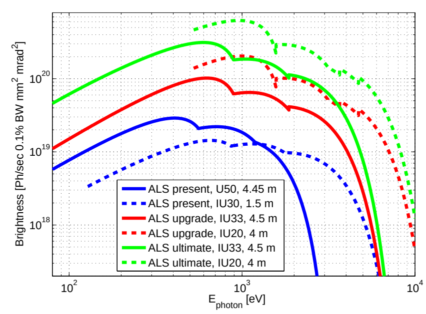

Figure 1: Comparison of the current ALS brightness around 1 keV (i.e. after top-off upgrade) with future brightness after the low emittance upgrade (as well as a more speculative case, if low horizontal beta function lattices are workable).

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 3 quadrupole families in the normal arc sectors and 4 in the Superbend sectors. Most quadrupoles are individually powered. Originally, there were only 2 families of sextupoles, with 4 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), 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 equal fractional tune but integer tunes larger by one, two and three units. An attractive set of possible lattices was

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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 lattice 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 (2.6 nm).

Later on, more systematic techniques were used to find the global optimal lattices in terms of emittance or brightness: GLASS [2] 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. MOGA [3]), the use of multi objective, genetic algorithms allowed to study lattices with more parameters as well as a direct optimization of the lattices (including effects of the diffraction ellipse) for insertion device and bend magnet brightness. These studies in general confirmed the lattices found earlier were already optimal in terms of emittance, but there is an additional family of low emittance lattices with very small horizontal beta function (order of 0.5 m) in the straights at much higher phase advance (tunes in the range of $21-22$). In conclusion, we decided to use the lattices with higher straight section beta function as the baseline of the upgrade, and the low beta lattices as a further upgrade goal, while working on solving the additional difficulties those present (namely that they require a different injection scheme and potentially further strength increases of the arc sector sextupoles).

These high-beta baseline lattices are within the range of the existing quadrupoles and quadrupole power supplies, however, the sextupoles would not be strong enough and the dynamic aperture would be very poor. However, it was realized very quickly that the addition of moderately strong sextupoles in the straight sections would allow very good dynamic (momentum) apertures and also reduce the required strength for the chromatic sextupoles to achievable values. There is one other side effect of these lattices, namely an increase in horizontal beta function in the straight sections from about 14 to a little over 20 m, which leads to a worse match to the photon diffraction ellipse and therefore means that undulator beamlines do not realize the full factor of 3 brightness increase expected from the emittance reduction.

As a final step, frequency map scans were used to fine tune the betatron tunes and find optimal sextupole configurations for dynamic purposes.

SCOPE OF UPGRADE

- Replace exisiting corrector magnets with combined sextupole/corrector/skew quadrupole multimagnets
- Implement new low emittance lattices enabled by the addition of the harmonic sextupoles
- New power supplies, controls for the new magnets
- Magnetic measurements, fiducialization, EPS systems, installation
- Top-off qualification of all new lattices
- Transition with minimum negative impact (orbit feedbacks, commissioning time, teething period)

New Hardware

In total 48 new magnets will be installed. Because the ALS is already a fairly congested ring with many (more than 40) user beamlines, this is not an easy undertaking. The new magnets replace 46 existing dipole corrector magnets, which are used in slow and fast orbit feedback, as well as insertion device feed-forward, so the new magnets will have to take over this functions. There are also space restrictions in the injection straight, which is why there were two corrector magnets missing there. However, we found in our nonlinear dynamics optimizations that we needed sextupole magnets in all straights, so a shorter, special design was devised for the injection straight. Finally, user beamlines pass by the location of about half of the magnets, requiring C-shaped magnets with larger aperture to be installed at those locations. Therefore, we ended up with three different magnet designs (with 22, 2, and 24 magnets). Models of the conceptual magnet designs can be seen in Fig. 2.

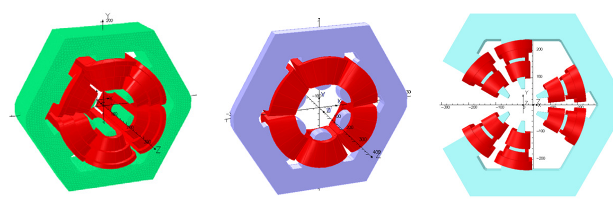

Figure 2: Models of the conceptual designs for the 3 different types of magnet designs. Left: Straight section magnet; Middle: Special injection straight magnet; Right: Arc magnet.

One of the families is optimized for small effects due to saturation (by using a smaller aperture and lower fields), small hysteresis and fast time response and has a closed yoke. It will be used as primary correctors in orbit feedback. Fig. 3 shows the 3D magnetic simulation of this magnet. In general, because of the still relatively large pole tip radius (required bu the existing vacuum chambers) and the relatively weak sextupole strength (the new magnets are a factor of almost 5 weaker than the original chromatic sextupoles of the ALS), the multipole found in the magnetic simulations (including machining errors, stauration, 3D effects) presented no problems for the beam dynamics.

BEAM DYNAMICS

A relatively new technique [4] has been used to optimize the nonlinear dynamics in the upgrade lattices. We use frequency map analysis, particularly using the sum of all diffusion rates over a predefined area of interest (in x-y or x-dp/p configuration space) as the merit function to optimize. We then typically conduct scans of two parameters simultaneously and iterate between harmonic sextupoles,

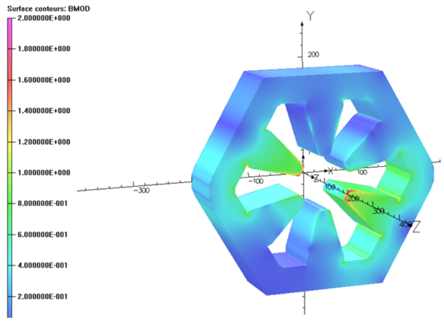

Figure 3: Field simulation of the straight section magnet type using 3D finite element analysis.

tunes, etc. In the case of the upgrade lattices, this converged quickly and resulted in lattices that are robust also for insertion device effects. Fig. 4 shows an on-energy frequency map for the baseline lattice of the upgrade, including lattice errors and physical apertures. The dynamic aperture is more than sufficient for injection and in fact larger than for the present ALS lattice.

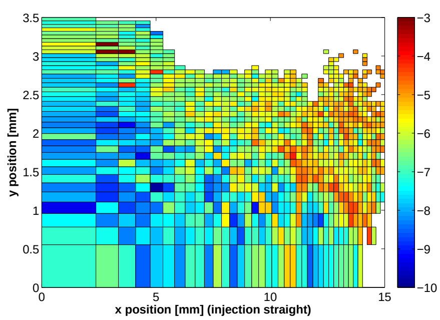

Figure 4: Example of an optimized frequency map for the baseline lattice (including magnet errors and physical apertures)

We also studied effects of all existing insertion devices, using RADIA kick-maps including all effects of dynamic multipoles. Because of the larger horizontal beta functions, these could in principle have larger impact, however, we found that the impact both on and off-energy is acceptable. Finally we calculated expected Touschek lifetimes. Fig. 5 shows the calculated dynamic momentum aperture of the upgrade lattice, including all lattice errors and physical apertures. The momentum aperture is larger than for the current lattice, mostly because of the smaller H-function in the arcs.

With those dynamic momentum apertures and the fact that the RF-bucket acceptance will increase, because of the smaller momentum compaction factor, the expected Touschek lifetime of the upgrade lattice is actually larger than for our current lattice, despite the smaller horizontal emittance.

Other Challenges

In addition to the lattice and magnet design and nonlinear dynamics challenges mentioned above, there are several

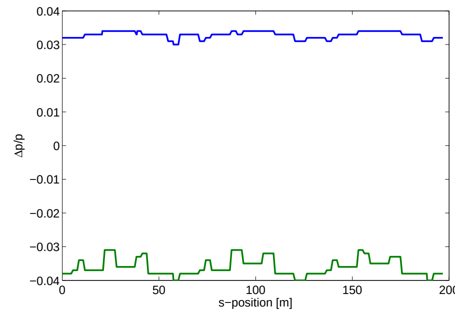

Figure 5: Calculated dynamic momentum aperture around the ring (including magnet errors and physical apertures).

other challenges to the project. As already mentioned, one family of the new sextupole multimagnets will also be used in the fast orbit feedback, requiring high bandwidth and low hysteresis. Extensive measurements and simulations were carried out to minimize this risk. Other challenges include the smaller instability thresholds and shorter bunchlengths due to the smaller momentum compaction factor. Finally, the new lattices need to be qualified for top-off operations [5] requiring rerun of some simulations. Overall, the results on all of those issues are positive so far and the project successfully passed a comprehensive review in December.

Beyond the baseline of the project, which is aimed at delivering higher brightness, work is also going on to study low alpha modes of operation as well as injection into the more speculative low beta lattices [6].

SUMMARY

An upgrade project is under way to further improve the brightness of the ALS by reducing the horizontal emittance from 6.3 to 2.2 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. Preliminary magnet designs are finished and beam dynamics calculations show sufficient dynamic and momentum aperture. Magnet construction will start in the next few months and installation is planned for 2011/12.

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