PROGRESS OF THE R&D TOWARDS A DIFFRACTION LIMITED UPGRADE OF THE ADVANCED LIGHT SOURCE*

C. Steier†, A. Anders, D. Arbelaez, J. Byrd, K. Chow, R. Duarte, J. Jung, T. Luo, A. Madur, H. Nishimura, J. Osborn, C. Pappas, L. Reginato, D. Robin, F. Sannibale, S. De Santis, R. Schlueter, C. Sun, C. Swenson, W. Waldron, E. Wallen, W. Wan, LBNL, Berkeley, CA 94720, USA

Abstract

Improvements in brightness and coherent flux of about two orders of magnitude over operational storage ring based light sources are possible using multi bend achromat lattice designs [1]. These improvements can be implemented as upgrades of existing facilities, like the proposed upgrade of the Advanced Light Source, making use of the existing infrastructure, thereby reducing cost and time needed to reach full scientific productivity on a large number of beamlines. An R&D program funded by internal laboratory funds was started at LBNL to further develop the technologies necessary for diffraction-limited storage rings (DLSR). It initially involves five areas, and focuses on the specific needs of soft x-ray facilities: vacuum system/NEG coating of small chambers, injection/pulsed magnets, RF systems/bunch lengthening, magnets/radiation production with advanced radiation devices, and beam physics design optimization. Some hardware prototypes have been built. The work will expand in the future to demonstrate necessary key technologies at the subsystem level or in beam tests and include new areas like photon beamline optics.

INTRODUCTION

To achieve diffraction-limited performance throughout the soft x-ray (SXR) range, the ALS-U proposal pushes the limit of accelerator design beyond the level of the first examples of multi bend achromat (MBA) light sources currently under construction. Because ALS-U is a smaller and lower energy machine than all other proposed MBA machines or upgrades, with a resulting larger effect of intrabeam scattering (IBS), it requires design solutions different from those being pursued for the higher energy projects [2]. Therefore an R&D program funded by laboratory directed research and development funds (LDRD) was started in early FY14 at LBNL with the goal of reducing the technical risks of a soft x-ray diffraction limited storage ring and to optimize the possible performance of an eventual upgrade proposal.

Similar to the approach elsewhere, we have chosen a multi-bend achromat lattice, in our case with nine bends (9BA), and retained twelve arcs as in the existing ALS [3] (see Figure 1). No damping wigglers are foreseen and round beams will be used. Lattice optimization is ongoing, including optimization of the nonlinear dynamics wih genetic algorithms, similar to past work for the ALS brightness upgrade [4].

* This work was supported by the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under U.S. Department of Energy Contract No. DE-AC02-05CH11231.

† CSteier@lbl.gov

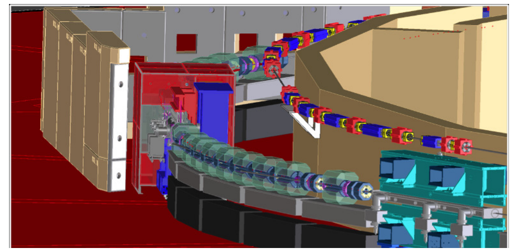

Figure 1: Model of ALS-U storage ring, accumulator and existing undulators in the ALS tunnel.

Including the effects of IBS, harmonic cavities, as well as insertion devices, the baseline lattice provides equal emittances of about 50 pm at 500 mA in both planes, yielding straight section beamsizes of around 10 μm. The electron beam ellipse is matched well to the diffraction ellipse leading to excellent brightness performance for soft x-rays (see Figure 2).

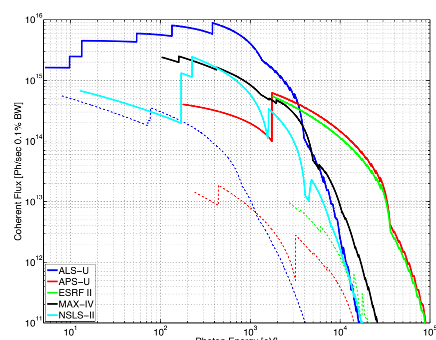

Figure 2: Coherent flux envelopes for ALS-U (blue) and several other facilities and upgrades. Dashed lines indicate pre-upgrade performance of facilities in operations now.

R&D PROGRAM

The R&D program at LBNL towards soft x-ray diffraction limited light sources initially involved five areas: Vacuum system/NEG coating of small chambers, Injection/pulsed magnets, RF systems/bunch lengthening, magnets/radiation production with advanced radiation devices, and Beam Physics optimization of the overall upgrade proposal. Several hardware protoypes have been built and the work includes demonstration of necessary key technologies at the subsystem level or in beam test. The program was recently expanded to include new areas, like photon beamline optics. It concentrates on the areas with the highest technical risk, with the selection of R&D topics well aligned with the community consensus of remaining challenges of MBA lattices, as well as the special needs of a soft x-ray DLSR.

Achieving the small equilibrium emittance drives the need for compact, small aperture magnets, which also results in a very small vacuum chamber diameter and leads to the need for NEG coated chambers. It also means that the dynamic aperture will be small enough that swap-out injection is required. Because a ring optimized for soft x-rays will have a low beam energy, IBS is potentially severe, requiring aggressive bunch lengthening as well as filling as many buckets as possible, which leads to the need for pulsers/injection magnets with very small rise and fall times. Photon beams with the highest possible brightness generate the need for optics that preserve coherent wavefronts. Finally, having the opportunity of small apertures (in both planes) opens new opportunities for radiation production devices.

Magnets and Radiation Production

The current ALS experimental program makes extensive use of bending magnet and Superbend source points in addition to undulator sources. Therefore, ALS-U will have to maintain the ability for a large number of (Super-)bend beamlines, in addition to the insertion device straights. This provides challenges for the small aperture magnets and vacuum chambers, and requires several tailored magnet designs. Currently, multiple design options are being pursued for radiation producing devices. These include permanent magnet or superconducting dipoles (including longitudinal gradients) replacing a small number of normal dipoles, very short straights for 3 pole wigglers or short other radiators, and round vacuum chambers for polarization control undulators. Optimization is also going on for the lattice magnets to achieve excellent field quality in a space effective lattice, including magnet designs with longitudinally curved quadrupole poles and nosecones (see Fig. 3).

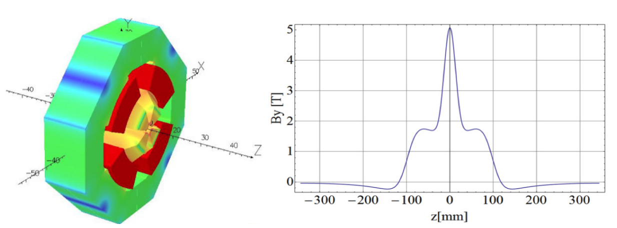

Figure 3: Left: Example of a compact, small aperture quadrupole design with nosecones to optimize space efficiency. Right: Longitudinal gradient Superbend.

On-axis Swap-out Injection

It is planned to use on-axis injection [5] with bunch train swap-out and an accumulator ring. The new accumulator ring will be built and housed either in the ALS storage ring tunnel or the booster tunnel. The accumulator ring will act as a damping ring where its lattice will allow for off-axis injection from the current ALS booster and the extracted low emittance beam is injected on-axis into the small dynamic aperture of the ALS-U ring.

On-axis swap-out injection requires special fast pulsers [6] and state-of-the-art stripline kicker magnets [7]. Prototype high-voltage pulsers, based on inductive and transmission line adder technology, are being developed and tested to meet the requirements of ALS-U or APS-U (see Fig. 4).

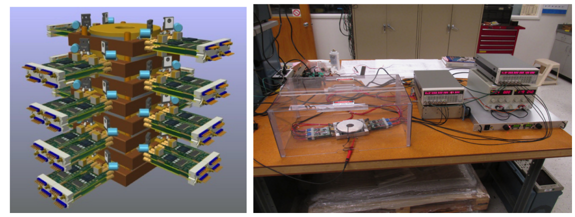

Figure 4: Left: CAD model of inductive adder for fast injection magnets. Right: Single stage of inductive adder during testing.

We have demonstrated pulses with the necessary very short rise and fall-times, as well as flat-top length and flatness for individual stages of an inductive adder (see Fig. 5). We are also working with industry to explore commercially available options.

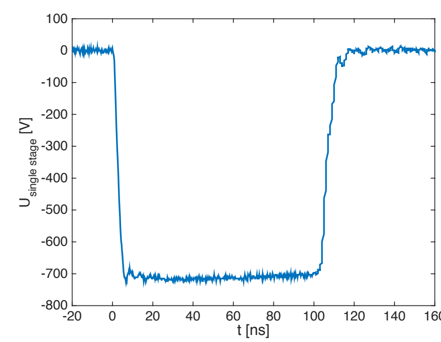

Figure 5: Pulse shape of a single stage of the inductive adder, demonstrating 0-100% rise time of about 5 ns and the necessary flat-top length and flatness.

NEG Coating of very Small Chambers

The most promising technology to achieve good vacuum pressures with the small apertures necessary for DLSRs are Non Evaporable Getter (NEG) coated vacuum chambers. Substantial progress has been made, both in industry, and within this R&D program, bringing NEG coated chambers with less than 6 mm diameter within reach. Figure 6 shows the test stand at LBNL used for pulsed magnetron sputtering deposition as well as the smallest chamber coated today, a 6 mm inner diameter copper chamber that was coated with Ti-Zr-V. We also use multiple characterization tools, including rutherford backscattering, electron microsopy and XPS. Several challenges remain, particularly in terms of how to best activate these vacuum chambers, as well as with photon extraction chambers for user beamlines.

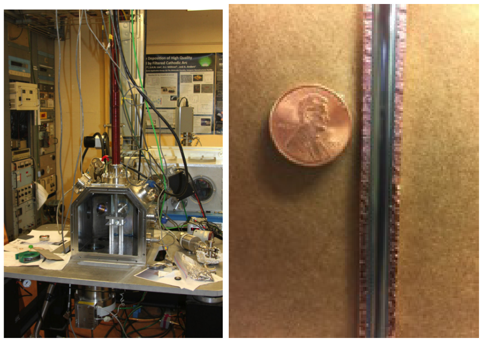

Figure 6: Left: Coating test setup for small NEG chambers. Right: Picture of 6 mm inner diameter NEG (Ti-Zr-V) coated Cu round test-chamber.

Intrabeam Scattering and Harmonic Cavities

IBS can lead to an increase in the six-dimensional emittance of the particle bunch. This is especially true when the emittance is very small, the beam energy is moderate and the bunch intensity is fairly high, all of which is true in the ALS-U case. The mitigation of the impact of the IBS effect on the equilibrium emittance will be achieved by three means:

1. Operate ring with full coupling.
2. Bunch lengthening factor of 3-4 with higher harmonic cavities.
3. Operate with multibunch fill with most buckets filled.

With these mitigation measures, the predicted emittance at 500 mA is about 50 pm, consistent with the goal of reaching the diffraction limit up to about 2 keV. However, bunch lengthening factors at this level have not been routinely achieved so far. The main reason are transient effects (both in amplitude and phase) due to inhomogenities in the fill pattern. Those inhomogenities can have different reasons, like gaps for timing experiments, ion clearing gaps, gaps due to the injection system, or bunch intensity variations. For ALS-U, swap-out injection requires short gaps in the fill pattern (500 MHz RF system). The demonstrated performance of the inductive adder allows gaps as small as 10 ns, i.e. four unfilled buckets. The baseline plan is to use 11 bunch trains with 25 bunches, each, separated by gaps of 4 empty buckets. This minimizes the number of swap-put cycles, bunch-to-bunch intensity variations, and the overall number of empty buckets. We have replicated this fill pattern in the ALS and have demonstrated lengthening factors >4, using three normal conducting, passive 3rd harmonic cavities (see Figure 7).

Coherence Preserving Optics

Having to transport beams with unparalleled brightness and coherence presents new challenges for the photon beamline optics. While optics exist that preserve diffraction limited emittances in one dimension, preserving similar emittances in both dimensions requires development work. The main challenge is the thermal distortion of the first mirror in the beamline. The most promising option is to cool the first

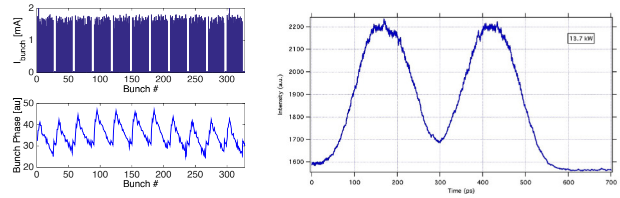

Figure 7: Left: ALS-U like fill pattern with 11 bunch trains with short gaps tested in ALS. Right: Bunch lengthening by factor of four with this pattern.

optics to liquid nitrogen temperatures, where thermal expansion is much reduced and therefore distortions get minimized. However, contamination issues present new challenges in this regime. A detailed research and development program was started recently, with the first emphasis being simulations, namely finite element analysis of cryo-cooled optics and studies of effects of the optics on coherent wavefronts.

Future work will include the continued modeling of thermal errors and effects of mirror fabrication errors as well as R&D on liquid nitrogen cooled optics, including deformation measurements of existing Si optics when cooled to liquid nitrogen temperatures. As part of this, we plan to develop methods for measurement of nano-radian level errors at liquid nitrogen temperatures.

SUMMARY

The ALS-U upgrade proposal promises soft x-ray brightness performance exceeding all ring based sources in existence or under construction, approaching the diffraction limit up to 2 keV. An R&D program funded by the LBNL laboratory directed research and development program is under way since FY14. Its primary goal is to retire technical risks. Substatial progress has been made in all R&D areas pursued, most notably by successfully building an inuctive adder for swap-out injection, NEG coating of 6 mm inner diameter copper chambers with Ti-Zr-V, and demonstrating that the necessary bunch lengthening factors of more than four to combat IBS can be achieved with existing 3rd harmonic cavities. Work is currently expanding to demonstrate more critical technologies at the subsystem level or in beam tests and to include coherence preserving photon optics.

REFERENCES

[1] M. Bai et al., Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.01.045.

[2] C. Steier, Synchrotron Radiation News, 27, 6, 2014, doi:10.1080/08940886.2014.970934.

[3] H Tarawneh et al 2014 J. Phys.: Conf. Ser. 493 012020 doi:10.1088/1742-6596/493/1/012020

[4] C. Sun, et al., Phys. Rev. STAB 15, 054001 (2012).

[5] M. Borland, AIP Conf Proc 1234, 2009.

[6] G.C. Pappas, et al., Proc. of IPAC 2014, 564.

[7] S. De Santis, et al., Proc. IPAC 2014, 1977.