LATTICE STUDIES FOR A POTENTIAL SOFT X-RAY DIFFRACTION LIMITED UPGRADE OF THE ALS*

C. Steier†, J. Byrd, R. Falcone, S. Kevan, D. Robin,
C. Sun H. Tarawneh, W. Wan, LBNL, Berkeley, CA 94720, USA

Abstract

The Advanced Light Source (ALS) at Berkeley Lab has seen many upgrades over the years, keeping it one of the brightest sources for soft x-rays worldwide. Recent developments in magnet and vacuum technology, as well as lattice design (multi bend achromat lattices) appear to open the door for very large further increases in brightness [1]. This could be achieved by reducing the horizontal emittance, with the new ring remaining within the space constraints of the existing tunnel. Initial studies yielded candidate lattices which approach the soft x-ray diffraction limit in both planes within the ALS footprint (diffraction limit around 2 keV, compare projected brightness in Fig. 1).

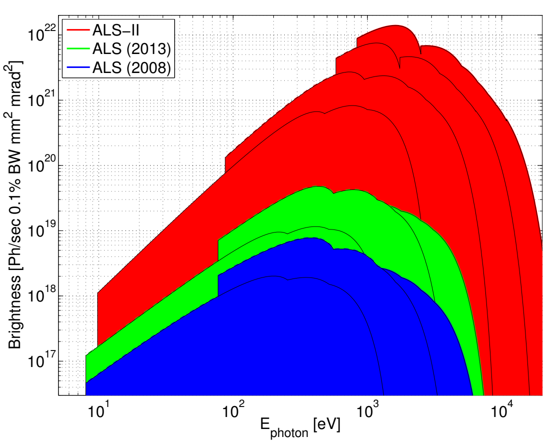

Figure 1: Comparison of the ALS brightness before the recent upgrades (blue) with the one after the recently completed brightness upgrade (green) as well as the projected brightness of a soft x-ray diffraction limited ring based on a multi bend achromat lattice in the existing ALS tunnel (ALS-II, red).

INTRODUCTION

Most designs under consideration for diffraction limited light sources make use of multibend achromat lattices [2, 3, 4]. The first proposals for such lattices were made in the 90s and recently construction has started on the first implementation of the concept. The required magnet strengths to realize small equilibrium emittances with those lattices are enabled by smaller vacuum chamber apertures and smaller magnet bores. This is possible because of recent advances in vacuum technology (NEG coating) magnet technology (wire EDM machining of poles) as well as advances in the understanding of nonlinear dynamics, beam based calibration of lattices and the understanding of collective effects. The chosen candidate lattice for ALS-II is a nine bend achromat with a fully coupled beam and no damping wigglers.

SCIENCE CASE

Emerging scientific applications and experimental methods that would greatly benefit from ring-based sources having much higher brightness and transverse coherence than present or near-future storage ring facilities include nanometer imaging applications, X-ray correlation spectroscopy, diffraction microscopy, holography, ptychography (see example in Fig. 2), and resonant inelastic soft x-ray scattering at high resolution [5, 6].

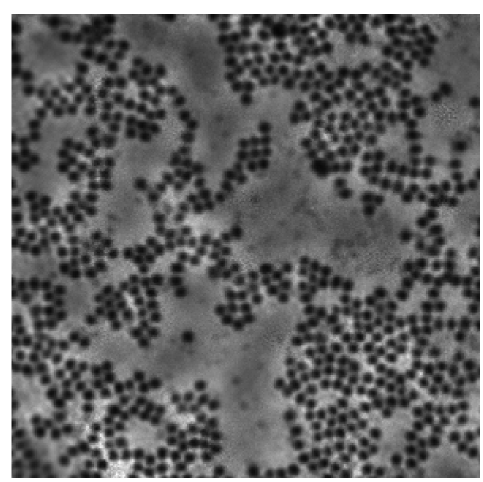

Figure 2: 2d ptychography image of Au nanoparticles taken with the ALS nanosurveyor (beamline 9.0.1). Currently the achieved 2d resolution is on the order of 10 nm. A 100x increase in coherent flux at ALS-II compared to the current ALS would enable much higher resolution and allow 3d imaging at extremely high resolutions.

Specifically for soft x-rays and ALS-II, the strongest science applications are seen in three areas:

- Three dimensional imaging down to few nm resolution with chemical specificity, using techniques like ptychography.

* The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
† CSteier@lbl.gov

- Q-resolved resonant inelastic x-ray scattering (q-RIXS) combined with dispersive spectroscopy making use of the full bandwidth of the undulator peaks and of the high spectroscopic resolution afforded by small source emittance in both planes.
- Correlation spectroscopy over various length (nm to μm) and time scales (ps to s).

CANDIDATE LATTICE

Similar to the approach at Max-IV, ESRF-2 and other places, we have chosen a multi bend achromat lattice (9 bends) while keeping the 12 arcs of the existing ALS. Magnet apertures will be reduced by roughly a factor of 3 down to a pole radius of 12 mm. Initial optimization using multi objective genetic algorithms have been carried out to improve the linear and basic non-linear lattice. Fig. 3 shows the result of one optimization run and the trade-off between three of the objective functions used in this run. Two of them are directly related with brightness, namely the natural emittance and the beta function in the straights, which determines the match of the photon and electron phase space. The third objective was natural chromaticity, which is used as a proxy for how difficult the optimization of the nonlinear properties of any lattice will be.

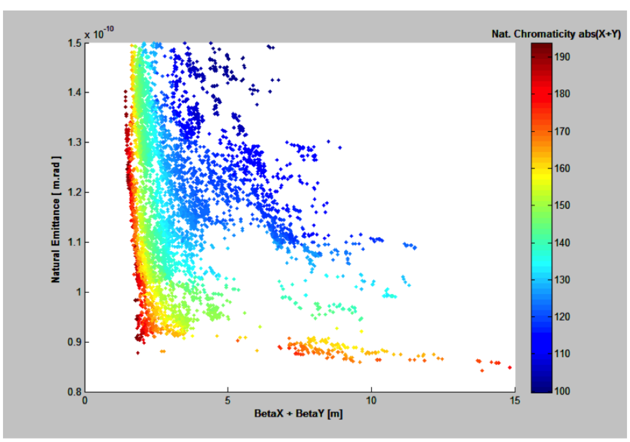

Figure 3: Result of a multi objective algorithm used to find lattice candidates. The three objective functions plotted in this case are natural emittance, natural chromaticity and sum of the straight section beta functions.

These studies yielded a candidate nine bend achromat (9BA) lattice with the desired emittance (50 pm fully coupled) and reasonable beta functions and dynamic aperture. The lattice functions as well as the magnet arrangement is shown in Fig. 4. Further optimization is planned to reduce straight section beta functions. At a later point we also plan to fully integrate the optimization of the nonlinear dynamics into the genetic algorithm, similar to what has been used in the past to optimize lattices for the just completed ALS upgrade [7].

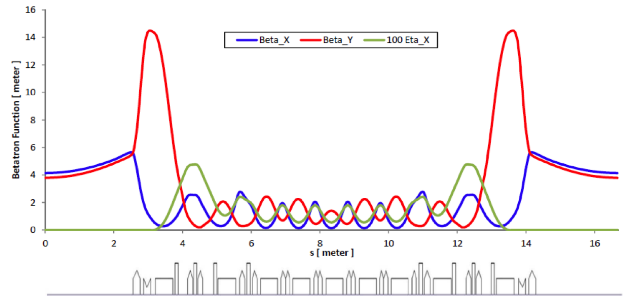

Figure 4: Candidate lattice for ALS-II using a nine bend achromat.

EVALUATION OF LATTICE

Nonlinear Dynamics

The very strong focusing required for low emittance introduces large chromatic aberrations in the lattice that must be corrected using strong sextupoles. The sextupole field non-linearities introduce resonance driving terms that reduce dynamic and momentum acceptance, potentially leading to low lifetime and even the inability to inject beam into the machine. While it is desirable to preserve the capability for off-axis injection if possible, beam can be injected into a small dynamic acceptance on-axis if necessary. With on-axis injection electrons in the bucket are kicked out and replaced with the newly injected electron (swap-out injection [8]). The dynamic aperture (compare Fig. 5) and momentum aperture of the candidate lattice is sufficient ($> 100\,\sigma_{x,y}$) to allow high efficiency on-axis injection and provide decent beam lifetime.

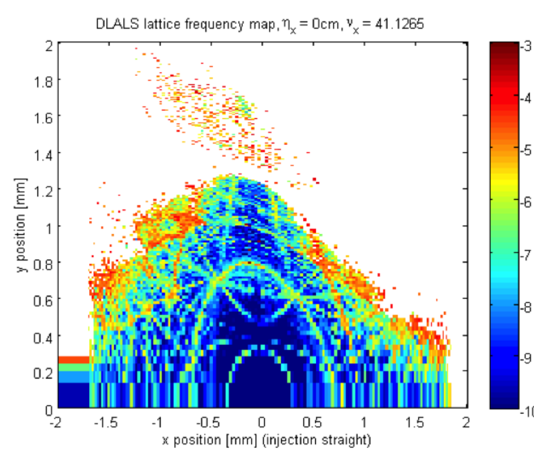

Figure 5: On-energy frequency map of candidate lattice with normal and skew gradient errors.

Intrabeam Scattering and Collective Effects

Even in electron storage rings, Intrabeam Scattering (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

ISBN 978-3-95450-122-9

and the bunch intensity is fairly high, all of which is true in the ALS-II case. The IBS calculation for the ALS-II lattice is based on the high energy approximation of the Bjorken-Mtingwa theory derived by K. Bane [9]. The mitigation of the impact of the IBS effect on the equilibrium emittance of the ALS-II lattice will be achieved by two means:

1. Lattice will be operated with full coupling.
2. Bunch lengthening with a 3rd harmonic RF system.

Figure 6 shows the predicted steady state emittance for two different RF systems: a 100 MHz system like it is proposed for MAX-IV and a 500 MHz system. For both RF systems, a lengthening factor of 4 is assumed with the use of harmonic cavities. Such lengthening factors would require a s/c 3rd harmonic cavity for the 500 MHz case, as well as a fairly uniform fill pattern with small gaps. Surprisingly the IBS growth rates are larger for the 100 MHz with longer bunches when compared to the 500 MHz system. This stems from the fact that the higher growth rates for the shorter bunches are more than compensated by effect of the lower bunch charge for the 500 MHz system. Overall IBS appears manageable with realistic bunch lengthening factors and the reduction in brightness is small for soft x-rays.

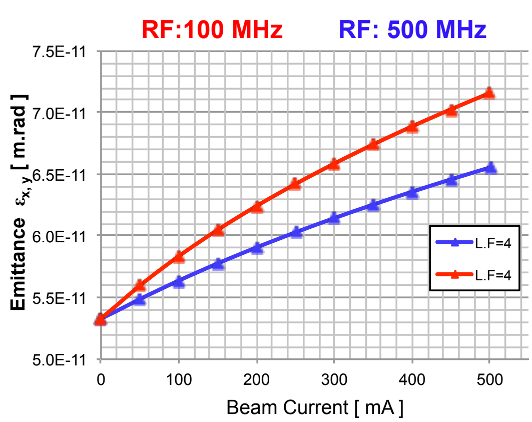

Figure 6: Predicted increase in emittance due to intra beam scattering for two different RF frequencies (100 and 500 MHz), assuming a bunch lengthening factor of four by using a third harmonic cavity system.

The low emittance is achieved by small gap magnet elements. As a consequence, the resistive wall impedance becomes higher. In addition, small gap insertion devices result in large resistive wall impedances, since apertures of 4 to 6 mm are foreseen for the insertion devices gaps. The bunch lengthening cavities, together with the choice of the fractional betatron tunes below the half-integer and the low momentum compaction factor, play an important role in mitigating this effect. Early calculations show acceptable growth rate for resistive wall driven instabilities.

Similarly, the harmonic RF system also helps to increase the threshold for the single bunch, transverse mode coupling instability. We predict that the TMCI threshold with harmonic cavities will be above the bunch currents necessary for 500 mA multibunch operations.

Predicted Brightness Performance

The candidate lattice provides straight section beamsizes of below 15 microns in both planes, close to the ALS vertical beamsize of 9 microns. Further improvements in beta functions are envisioned. The predicted brightness performance exceeds all ring based sources in existence or under construction and approaches the diffraction limit up to 2 keV (compare Fig. 1). The coherent fraction will exceed 50% at 1 keV.

SUMMARY

Pursuing multibend achromat concepts similar to MAX-IV and the concepts under discussion at ESRF, Spring-8, and other places, a candidate lattice has been designed that provides diffraction limited performance up to about 2 keV for a 2 GeV ring with slightly less than 200 m circumference, that fits in the existing ALS tunnel. The lattice has the same 12-fold symmetry as the existing ALS and retains the geometry of the existing straights. The dynamic aperture appears sufficient for decent Touschek lifetime and to support on-axis injection. Intra beam scattering appears manageable with 3rd harmonic cavities and bunch lengthening ratios similar to what is planned at MAX-IV. The predicted brightness of such a facility could exceed 10^{22} just above 1 keV photon energy and it would outperform any ring based facility already in operation or currently under construction. Further design work is planned to solidify the concept and start detailed engineering designs of key components.

ACKNOWLEDGEMENTS

The authors want to thank Bob Hettel, Michael Borland, Karl Bane, and Andrea Franchi for helpful discussions. Furthermore we would like to thank ALS management, as well as the ALS user community for strong support of continuous ALS accelerator development.

REFERENCES

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

[2] A. Ropert et al., Proc. European Particle Accelerator Conference 2000, Vienna, 2000.

[3] K. Tsumaki, N. Kumagai, Nucl. Instr. Meth. A 565 (2006) 394.

[4] R. Hettel et al., Proc. Particle Accelerator Conference 2009, Vancouver, 2009.

[5] ANL, BNL, LBNL, SLACNAL, Science and Technology of Future Light Sources - A White Paper, SLAC R-917, 2008.

[6] Workshop on Science at the Hard X-ray Diffraction Limit, XDL 2011, Cornell, June 2011.

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

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

[9] K. Bane, SLAC-PUB-14892, 2012.