PROPOSAL FOR A SOFT X-RAY DIFFRACTION LIMITED UPGRADE OF THE ALS*

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Abstract

The Advanced Light Source (ALS) at Berkeley Lab has been updated many times and remains as one of the brightest sources for soft x-rays worldwide. However, recent developments in technology, accelerator physics and simulation techniques open the door to much larger future brightness improvements. Similar to proposals at several other 3rd generation sources, this could be achieved by reducing the horizontal emittance with a new ring based on a multi-bend achromat lattice, reusing the existing tunnel, as well as much of the infrastructure and beamlines. After studying candidate lattice designs, development efforts in the last year have concentrated on technology and physics challenges in four main areas: Injection, Vacuum Systems, Magnets and Insertion Devices, as well as main and harmonic RF systems.

INTRODUCTION

Most designs under consideration for diffraction limited light sources make use of multi-bend achromat lattices [1]. The first proposals for such lattices were made in the 90s and recently construction has started on the first implementation of the concept at MAX-IV. The required magnet strengths to realize small equilibrium emittances with those lattices are enabled by smaller vacuum chamber apertures and smaller magnet bores.

Science Case

There are many scientific applications and experimental methods that would greatly benefit from much higher brightness and transverse coherence than present or near-future storage ring facilities can provide. Those include nanometer imaging applications, x-ray correlation spectroscopy, diffraction microscopy, holography, ptychography, and resonant inelastic soft x-ray scattering at high resolution [2, 3, 4]. Specifically for soft x-rays, the strongest science applications are seen in three areas:

- Three dimensional imaging down to few nm resolution with chemical, electronic or magnetic contrast.
- Q-resolved resonant inelastic x-ray scattering (q-RIXS) combined with dispersive spectroscopy.
- Correlation spectroscopy over various length (nm to μm) and time scales (ps to s).

CANDIDATE LATTICE

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 [5]. No damping wigglers are foreseen and to optimize the soft x-ray coherent flux, round beams will be used. Magnet apertures will be reduced by roughly a factor of three down to a pole radius of 12 mm. Lattice optimization using driving term analysis and multi-objective genetic algorithms has been carried out to improve the linear and nonlinear lattice, yielding a candidate 9BA lattice with the desired emittance (50 pm fully coupled at 500 mA, including the effects of intra beam scattering and insertion devices) with small beta functions and reasonable dynamic and momentum aperture. The inclusion of three octupole families helped to reduce the straight section beta functions compared to earlier candidate lattices while improving the dynamic momentum acceptance. The lattice functions as well as the magnet arrangement is shown in Fig. 1. 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 [6].

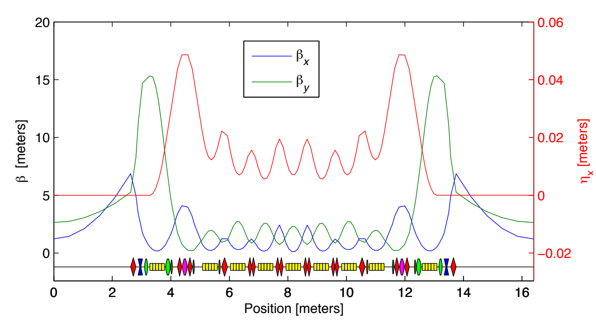

Figure 1: Candidate lattice for ALS-U using a nine bend achromat.

LATTICE PERFORMANCE

Nonlinear Dynamics

The very strong focusing required for low emittance introduces large chromatic aberrations in the lattice that must

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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 [7]). It is planned to use on-axis injection 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. The dynamic aperture and momentum aperture (compare Fig. 2) of the candidate lattice is sufficient ($> 100\,\sigma_{x,y}$) to allow high efficiency on-axis injection and provide decent beam lifetime of several hours.

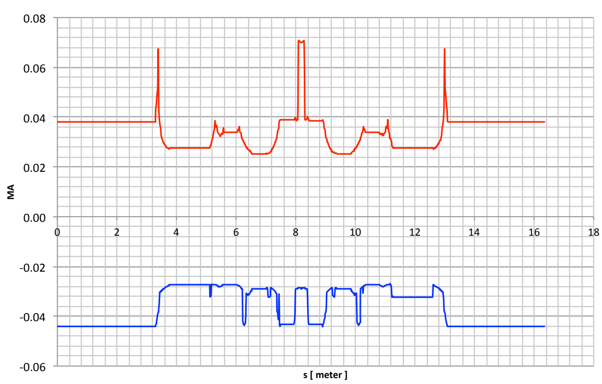

Figure 2: Dynamic momentum aperture for one sector of ALS-U.

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 and the bunch intensity is fairly high, all of which is true in the ALS-U case. The IBS calculation for the ALS-U lattice is based on the high energy approximation of the Bjorken-Mtingwa theory derived by K. Bane [8]. The mitigation of the impact of the IBS effect on the equilibrium emittance of the ALS-U lattice will be achieved by two means:

1. The ring will be operated with full coupling.
2. Bunches will be stretched by a factor of 3-4 with a 3rd harmonic RF system.

Figure 3 shows the predicted steady state emittance including the effects of insertion devices, the harmonic cavities and intra beam scattering. The additional damping due to insertion devices reduces the equilibrium emittance at small current to 38 pm, well below the 52 pm of the bare lattice. At 500 mA the emittance is about 51 pm, consistent with the goal of reaching the diffraction limit up to about 2 keV. Overall IBS appears manageable with realistic bunch lengthening factors and the reduction in brightness due to IBS for soft x-rays is small.

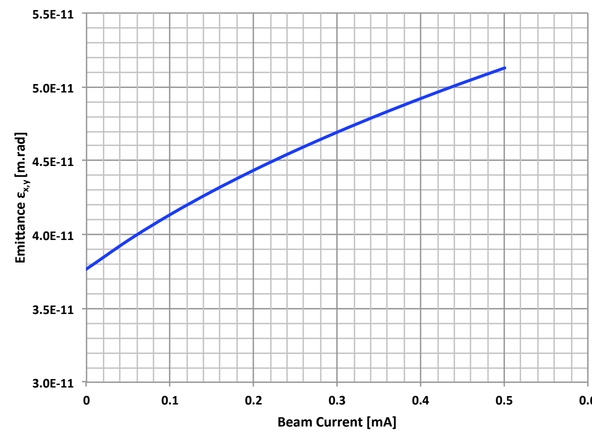

Figure 3: Predicted increase in emittance due to intra beam scattering including the effects of a typical full set of insertion devices, assuming a bunch lengthening factor of four by using a third harmonic cavity system.

The low emittance lattice requires strong magnets and therefore small vacuum apertures. As a consequence, the resistive wall impedance as well as geometric impedances of some transitions 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.

Coherent Flux

Including the effects of intra beam scattering, harmonic cavities, as well as insertion devices, the lattice with the reduced beta functions provides straight section beamsizes of around 10 μm in both planes, close to the current ALS vertical beamsize of 9 μm and the electron beam ellipse is matched well to the diffraction ellipse leading to excellent brightness performance for soft x-rays. Figure 4 shows the coherent flux expected for ALS-U compared to other facilities and planned upgrades.

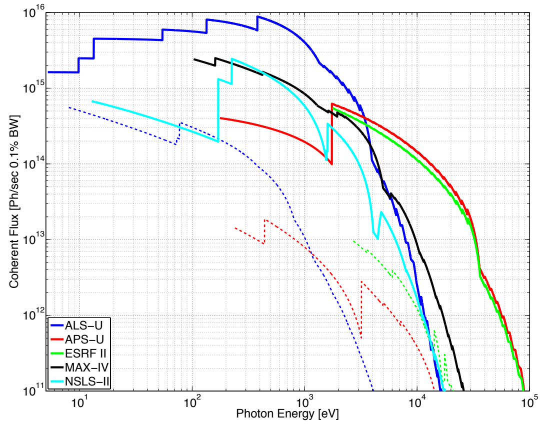

Figure 4: Coherent flux envelopes for ALS-U (blue) and several other facilities and upgrades that are either in planning, under construction or in commissioning. Dashed lines indicate pre-upgrade performance of facilities in user operations now.

PRE-CONCEPTUAL HARDWARE DESIGN

The ALS experimental program makes extensive use of bending magnet and Superbend source points in addition to undulator sources. Of the currently more than 40 independent beamlines, 12 are using insertion devices and 8 are using Superbends. Therefore, ALS-U will have to maintain the ability for a large number of (Super-)bend beamlines, in addition to keeping 12 insertion device straights of equal length and in the same location as in the current ALS. 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 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. All magnet designs needed for the baseline lattice are feasible and layout work of the vacuum system is progressing well (see Fig. 5).

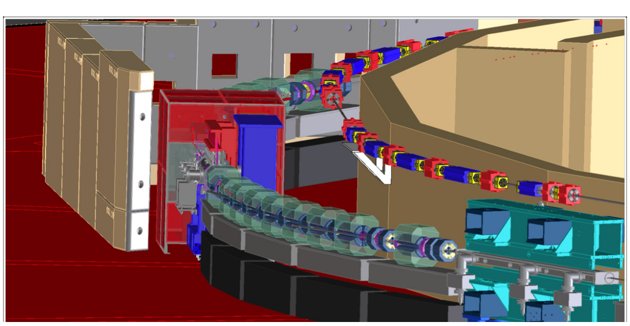

Figure 5: Model of ALS-U storage ring, accumulator and existing undulators in the ALS tunnel.

R+D PROGRAM

To optimize the performance, as well as to reduce risks and costs of the ALS-U proposal, an R+D program funded by laboratory directed research and development funds (LDRD) was started in FY14. It 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 proposal. Some hardware protoypes have already been built (see Fig. 6) and the work will expand in the future to demonstrate necessary key technologies at the component and/or subsystem level and include new areas like photon beamline optics. We will also evaluate various possible strategies for installation and commissioning, including staging.

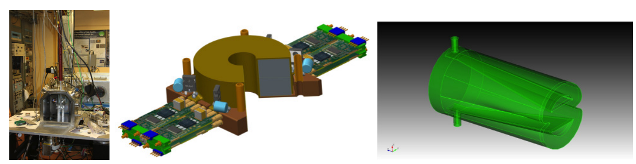

Figure 6: Left: Coating test setup for small NEG chambers. Middle: Single stage of inductive adder for fast injection magnets. Right: Tapered end of small aperture stripline kicker.

SUMMARY

The ALS-U candidate lattice with reduced beta functions provides straight section beamsizes of around 10 μm in both planes, close to the current ALS vertical beamsize of 9 μm. The predicted soft x-ray brightness performance exceeds all ring based sources in existence or under construction and approaches the diffraction limit up to 2 keV, providing more than two orders of magnitude more coherent flux than the ALS in the few keV range. An LDRD funded R+D program is under way to refine the proposal, retire risks and help to reduce the proposal cost.

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