ALS-II, a Potential Soft X-ray, Diffraction Limited Upgrade of the Advanced Light Source*

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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 technology and lattice design appear to open the door for very large further increases in brightness [1], particularly by reducing the horizontal emittance, even within the space constraints of the existing tunnel. Initial studies for possible lattices will be presented that could approach the soft x-ray diffraction limit around 2 keV in both planes within the ALS footprint. 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, and resonant inelastic soft X-ray scattering at high resolution.

1. Introduction

Most designs under consideration for diffraction limited light sources make use of Multi-Bend Achromat (MBA) lattices. The first proposals for such lattices were made in the 90s and recently construction has started on the first implementation of the concept [2]. 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. Figure 1 and 2 show the expected brightness performance of ALS-II and the coherent fraction for envisioned insertion devices.

Fig. 1: Brightness for ALS before upgrade (blue) after recently complete brightness upgrade (green) and for ALS-II lattice (red).

Fig. 2: Coherent fraction for ALS-II lattice for selected insertion devices.

2. ALS-II Scientific Case

The storage ring-based sources with diffraction-limited performance in both the horizontal and vertical plane will benefit many scientific applications of synchrotron X-ray beams e.g. nanometer imaging.

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spectroscopy, diffraction microscopy and soft X-ray scattering and result in an efficient use of the emitted photons [3, 4].
A 100x increase in coherent flux at ALS-II compared to the current ALS is driven mainly by three scientific application;

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

3. ALS-II Candidate Lattice Overview
The proposed lattice for ALS-II is based on MBA, similar to what has been adopted at MAX-IV (under construction) and for upgrade plan at ESRF, PEP-X [5, 6]. The ALS-II lattice retains 12-fold symmetry and has a very compact arc structure facilitated by the fact that the magnet apertures, and hence the machine admittance, are defined by the small gap insertion devices. The small magnet aperture allows for the introduction of a strong defocusing gradient in the bending magnet and also a strong focusing gradient of the quadrupole magnets.
Initial optimization using multi-objective genetic algorithms has been carried out to improve the linear and basic non-linear lattice and yielded a candidate Nine-Bend Achromat lattice, Figure 3, with an emittance of 50 pm.rad at 2 GeV beam energy (fully coupled) and low beta function in the straight sections to optimize brightness and match the electron and photon phase space [7].
The proposed scheme for the chromaticity correction in the ALS-II lattice is based on compactness and flexibility. The small apertures in the sextupole magnets are used to introduce very strong sextupole fields. We avoided the introduction of these fields in the pole shape of the bending and quadrupole magnets where the flexibility of the lattice would have been compromised. The configuration of the matching cell which has relatively higher values of $\beta_x$, $\beta_y$, and $\eta_x$ functions is used to house four sextupole magnets families, two focusing and two defocusing ones, to correct the chromaticity.
The nonlinear effects driven by the strong sextupoles result in reduced dynamic aperture which hampers injection and reduces the Touschek lifetime. To overcome this, the ALS-II lattice will be operated at full coupling, i.e. with a round beam and an on-axis injection scheme. With on-axis injection electrons in already filled buckets in the storage ring are exchanged with newly injected buckets from an accumulator (swap-out injection [8]). The dynamic aperture and momentum aperture of the candidate lattice is sufficient even when introducing errors (> 200 $\sigma_{x,y}$) to allow high efficiency on-axis injection and provide decent beam lifetime (see Fig. 4).

![Fig.3: ALS-II lattice Twiss functions.](image1)

![Fig.4: ALS-II Lattice dynamic aperture with errors.](image2)
4. Intrabeam Scattering and Collective Effects

In electron storage rings, Intrabeam Scattering (IBS) can lead to an increase in the six dimensional emittance when the starting emittance is small, the bunch charge is high and the beam energy is moderate, as in the ALS-II case [9].

Mitigation of the impact of the IBS effect on the equilibrium emittance of the ALS-II lattice will be achieved by operating the lattice with full coupling where the vertical emittance is given entirely by betatron coupling and by bunch lengthening using a 3rd harmonic RF system. This leads to smaller electron density and hence less IBS growth rates in emittance, energy spread and bunch length.

Figure 5 shows an IBS growth rate comparison between a 500 MHz and a 100 MHz RF system with bunch lengthening based on the high energy approximation of the Bjorken-Mtingwa theory derived by K. Bane [9]. Given the small dispersion invariant $H$ for the ALS-II lattice, the IBS growth rates are larger for the 100 MHz case even though the bunches are longer. This stems from the fact that the inverse dependence of the growth rates on the bunch length seems to be weaker than the dependence on the bunch population which is higher for the 100 MHz system with its fewer bunches.

As described above, the lattice uses small gap magnet elements to achieve low emittance. As a consequence, the resistive wall impedance becomes higher. In addition, small gap insertion devices also result in large resistive wall impedances, with apertures of 4 to 6 mm foreseen for the insertion devices. 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.

In the low emittance ring such as ALS-II ring single bunch instability thresholds can be relatively low due to the small momentum compaction factor and small synchrotron tune. Figure 6 shows a comparison of the single bunch current threshold due to the Transverse Mode Coupling Instability (TMCI) for a case with the natural bunch length and one case where the bunch is lengthened. Assumed is an impedance of 1 M$\Omega$ and Q-factor of 1 at 100 GHz resonant frequency. The benefit of bunch lengthening to increase the single bunch threshold is clearly visible [10].

![Fig.5: Steady state emittance dependence on beam current accounting for the effect of IBS.](image1)

![Fig.6: TMCI current threshold with natural as well as long bunch lengths.](image2)

5. Design Concepts for the ALS-II Magnets

The ALS-II lattice will be built around the insertion device, i.e. the ring admittance is defined by the low gap of the insertion devices and this gives the opportunity to use a small aperture within the magnetic elements of the arcs. This allows for the introduction of strong combined bending magnet and quadrupole and sextupole strengths. The compactness allows to achieve ultra low emittance with short circumference fulfilling the design goals and constraints. Another result is the small magnet size, which leads to less material to fabricate the magnets and low power consumption which is advantageous for cost considerations. Figures 7, 8 & 9 show conceptual designs of the ALS-II bending, quadrupole and sextupole magnets and Table 1 summarizes the maximum strength of the different types of the ALS-II magnets. The ALS-II lattice has no dedicated bending magnet instead uses shifted quadrupole magnets due to the high gradient required.
6. Conclusion
The ALS-II candidate lattice has been designed based on the MBA concept 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 magnet elements can be built from low carbon steel without suffering saturation effects that would produce large multipole errors. 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 design of key components.

7. References
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