PHYSICS DESIGN PROGRESS TOWARDS A DIFFRACTION LIMITED UPGRADE OF THE ALS*

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Abstract

Improvements in brightness and coherent flux of more than two orders of magnitude 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. We will describe the progress in the physics design of this upgrade, including lattice evolution, error tolerance studies, simulations of collective effects, and intra beam scattering.

INTRODUCTION

To achieve diffraction-limited performance throughout the soft x-ray (SXR) range, the ALS-U proposal [2] pushes the limit of accelerator design. Because ALS-U is a smaller and lower energy machine than APS-U or ESRF-II (with a resulting larger effect of intrabeam scattering), it requires design solutions different from those being pursued for these hard x-ray projects. This includes operating with round beams, aggressive use of harmonic cavities to stretch bunches, using high betatron phase advances per cell (which has effects on dynamic aperture, as well as impedances), and the use of swap-out injection. Table 1 summarizes the main parameters of ALS-U and Figure 1 shows the ALS-U nine bend achromat as well as the new accumulator ring inside the existing shielding.

Table 1: Parameter List Comparing ALS with ALS-U

Parameter	Current ALS	ALS-U
Electron energy	1.9 GeV	1.9–2.2 GeV (2.0 GeV base)
Beam current	500 mA	500 mA
Hor. emittance	2000 pm-rad	~50 pm-rad
Vert. emittance	30 pm-rad	~50 pm-rad
Beam size (IDs)	251 / 9 μm	≤10 / ≤10 μm
Beam size (bends)	40 / 7 μm	≤5 / ≤8 μm
Energy spread	9.7×10^{-4}	$\leq 9 \times 10^{-4}$
bunch length (FWHM)	60–70 ps (harm. cavity)	120–200 ps (harm. cavity)
Circumference	196.8 m	~196.5 m
Bend angle	10°	3.33°

The swap-out mechanism will enable a generational leap in performance. Not only does it allow operating with ultralow emittance, it also makes it possible to employ very small, round chambers in the insertion-device straight sections. These small chambers, in turn, enable higher-performance helical or Delta undulators with small apertures to be used, which will generate unprecedented coherent flux.

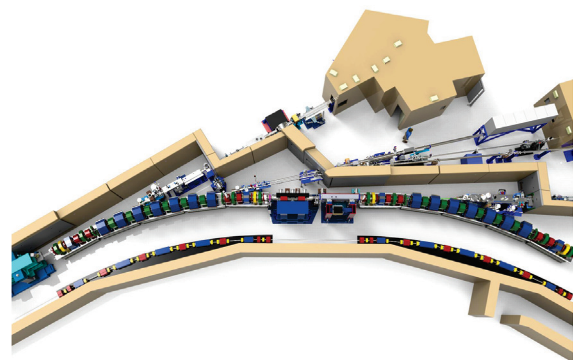

Figure 1: Model of ALS-U showing the existing accelerator tunnel with two sectors of the new storage and accumulator rings.

LATTICE OPTIMIZATION

The lattice design has to balance competing goals like radiation output requirements (e.g., high brightness), technological limitations (e.g., maximum available magnetic gradients), and operational demands (e.g., acceptable lifetime). The most basic tradeoff is between small emittance and sufficient particle-dynamics stability: low-emittance lattices tend to call for strong focusing fields, which come at the cost of large chromatic aberrations, in turn requiring strong sextupoles for correction. As a result, these lattices are highly nonlinear, exhibiting reduced dynamic aperture and momentum acceptance. While dynamic aperture limitations can, to some extent, be circumvented with innovative technical solutions (e.g., “swap-out” versus the more traditional off-axis injection), it is important that particle stability be maximized. Following a now-common trend, we have been employing multi objective genetive algorithms to simultaneously optimize the linear and non-linear lattice, while pursuing an MBA lattice design. We found configurations with nine bends to be particularly promising.

The new ALS-U ring will have the same periodicity (12 cells) and nearly the same circumference as the present one. In each cell, bending is distributed equally among nine transverse-gradient dipoles [3, 4]. In the present magnet design, the seven inner bending magnets are horizontally offset geometric quadrupoles with the remaining two being combined-function geometric dipoles (see Fig. 2). The

* 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.
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natural emittance (uncoupled, no insertion devices) of the current baseline lattice is about 100 pm.

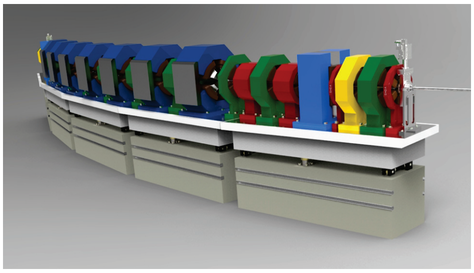

Figure 2: CAD model of one of the nine bend achromats of ALS with conceptual magnet designs and supports.

The nominal tunes are close to the coupling resonance ($\nu_x = 41.380$, $\nu_y = 20.389$) to equipartition the emittance between the two planes. This has two benefits: it provides for optimal (round) bunch cross section at the insertion devices where $\beta_x \sim \beta_y \leq 3$ m and considerably reduces scattering effects (IBS, Touschek). In a fully coupled lattice, and in the absence of radiation effects from the insertion devices, we expect $\varepsilon_x = \varepsilon_y = \varepsilon_0/(1 + \tau_x/\tau_y) \approx 70$ pm.

The dynamic aperture, on the order of 1 mm, is adequate for on-axis injection (see Fig. 3). However, it poses a tight requirement on the emittance of the injected beam, which is fullfilled by the accumulator design. The momentum aperture is good, similar to many third generation light sources at up to 3%. The resulting estimate for the beam lifetime, about 0.7 h, is workable in terms of radiation protection and the existing injection system and the current in the storage ring will be kept almost constant by swap out injection.

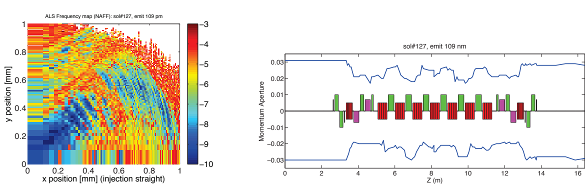

Figure 3: (Left) Frequency map (dynamic aperture) of ALS-U baseline lattice, (Right) dynamic momentum aperture, both with gradient and skew gradient errors.

IMPEDANCE AND INSTABILITIES

Reduced vacuum-chamber apertures are key features of low-emittance machines that enable large focusing gradients and enhance the performance of insertion devices. A significant resulting drawback is a generally larger sensitivity to instabilities driven by collective effects, as the machine impedance tends to scale inversely with vacuum-chamber aperture.

The resistive wall (RW) impedance is expected to be particularly important, primarily as a result of the small gaps in the insertion devices. To mitigate RW effects, we are proposing to use copper for most of the vacuum chambers. Ensuring good vacuum will require the de-ployment of NEG coatings. We are implementing impedance models to estimate the effect of the NEG coating, including its relatively poor conductivity and its high-frequency behavior.

We have carried out preliminary estimates of the RW-driven single-bunch transverse mode-coupling instability (TMCI) threshold. Macro-particle simulations with zero chromaticities (see Fig. 4) in the absence of harmonic cavities and with zero chromaticities show an instability threshold at a bunch current of about $I_b = 4.5$ mA (versus nominal $I_b = 1.8$ mA).

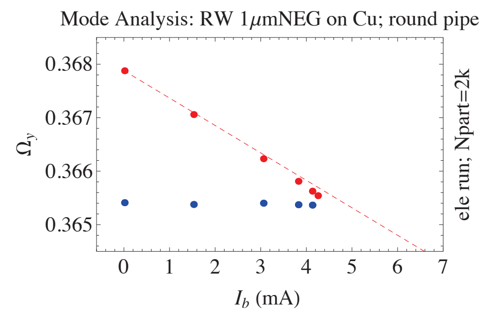

Figure 4: Effect of the RW impedance on the single-bunch transverse motion for vanishing chromaticities: the instability threshold is at a bunch current of $I_b \approx 4.5$ mA.

We anticipate that operations with finite chromaticities and transverse feedback system, similar to the one in the current ALS, should maintain an acceptable safety margin when including all impedances. Longitudinal multibunch instabilities are likely to be driven primarily by the higher-order modes of the RF system, which will be re-used in the upgraded machine. In contrast, we expect transverse multibunch instabilities to be more severe as a result of the enhanced RW effects. We expect that dedicated multibunch feedback systems as in the current ALS will provide sufficient damping.

INTRA BEAM SCATTERING

Particle-scattering effects are more important in low-emittance rings. They have two distinct consequences: growth in the equilibrium emittances (IBS) and particle loss (Touschek lifetime). Both are detrimental to performance and represent the main motivation for harmonic cavities. The third-harmonic cavities in ALS-U are designed to lengthen the bunches by roughly a factor of four, with the exact value expected to vary along a bunch train because of beam-loading transients. Experiments with ALS-U fill patterns in ALS have shown this to be feasible [5]. Additional mitigating strategies consist of operating the machine in full-coupling mode with round beams and maximizing the occupation of the RF buckets. Thanks to these provisions, scattering effects become manageable but are still quite noticeable (see Fig. 5).

ISBN 978-3-95450-147-2

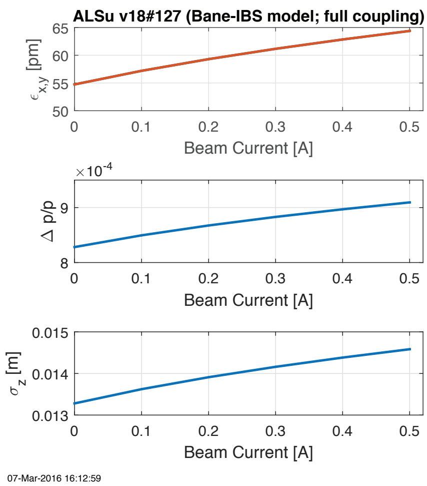

Figure 5: Equilibrium transverse RMS emittances (A), RMS relative energy spread (B), and RMS bunch length (C) as functions of the average circulating beam current. The calculation includes IBS effects, harmonic cavities, and radiation losses of insertion devices.

COHERENT FRACTION AND X-RAY OPTICS DISTORTION

ALS-U with an electron beam energy of 2 GeV will provide the highest coherent fraction throughout the soft x-ray range, reaching the diffraction limit (i.e. electron beam emittance smaller than single photon diffraction emittance) up to about 2 keV. This maximizes the ratio of useful photons compared to the total heat load that can distort photon optics. Raising the electron-beam energy above 2 GeV would not result in higher brightness in the soft x-ray range. Generic scaling studies that we carried out for the 100-eV to 2-keV range showed that rings with beam energies larger than 2 GeV either have substantially larger photon optics heat load for similar brightness, or substantially lower brightness for a similar heat load, assuming equal emittances and undulator technology (see Fig. 6 for an example for a photon energy of 284 eV, i.e. the carbon edge).

ACCUMULATOR RING AND ON-AXIS INJECTION

It is planned to use on-axis injection [2, 6] with bunch train swap-out and an accumulator ring. The new accumulator will be housed in the storage ring tunnel. It 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 ALS-U. Excellent progress has been made with design and test of the fast pulsers [5]. The requirements for the accumulator are relatively relaxed, with an emittance similar to the current ALS and the maximum beam current below 10% of the one in the main storage ring. Important design optimizations include cost, space and reliability. An initial lattice design (see Fig. 7) was finished based on a 5

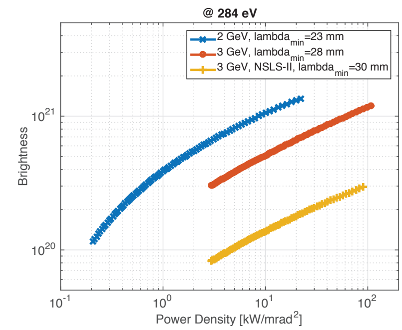

Figure 6: Brightness at 284 eV versus power density for optimized undulator designs. Shown are results for a 2 GeV and a 3 GeV ring, both with equal beta functions, 500 mA beam current, and 50-pm emittances. NSLS-II is also shown for comparison.

bend achromat and studies as to the feasibility of transfer lines were completed.

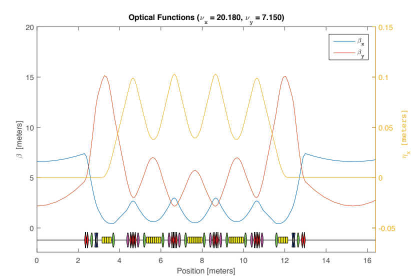

Figure 7: Layout and lattice functions for the five-bend achromat accumulator-ring cell.

SUMMARY

The ALS-U baseline lattice with reduced beta functions provides straight section beamsizes of around 10 microns in both planes, close to the current ALS vertical beamsize of 9 microns. 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 up to three orders of magnitude more coherent flux than the ALS in the few keV range. Dynamic aperture and momentum aperture are workable for swap-out injection and beam lifetime. IBS emittance growth can be mitigated to an acceptable level and single bunch instability thresholds are predicted to be above normal bunch charges in multibunch operations.

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