A NOVEL 7BA LATTICE FOR A 196-m CIRCUMFERENCE DIFFRACTION-LIMITED SOFT X-RAY STORAGE RING*

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Abstract

The current baseline for the ALS Upgrade to a diffraction-limited soft x-ray storage ring is a 9BA lattice with two dispersion bumps for localized chromatic corrections. Although this lattice meets the very aggressive emittance goal, it offers limited margins in terms of dynamic aperture and momentum acceptance. In this paper we explore a different approach based on a 7BA lattice with distributed chromatic correction. This lattice relies heavily on longitudinal gradient bends and reverse bending in order to suppress the emittance so that despite fewer bends an emittance comparable to the baseline lattice can be reached albeit with larger dynamic aperture and momentum acceptance. We present linear optics design, trade-offs between achievable emittance and longitudinal stability, as well as the employed nonlinear tuning approach and the resulting performance of this alternate lattice.

INTRODUCTION

The ALS Upgrade (ALS-U) Project aims to transform the 3rd-generation ALS into a diffraction-limited source of ultra-bright and highly coherent soft x-rays that fits within the existing ALS tunnel. The key deliverable for the ALS-U is an increase in brightness and coherent flux at 1 keV of at least a factor 100 compared to the present-day ALS. In terms of accelerator physics and machine design, this translates—assuming an energy of 2 GeV and stored current of 500 mA—to a round beam with approximately 75 pm rad or less in either plane and beta functions at the center of the insertion devices (IDs) at or below 2.5 m [1]. The present ALS-U baseline lattice foresees a 9BA with two discrete dispersion bumps for chromatic correction, and relies on reverse bending provided through offset focusing quadrupoles in the arc to achieve a zero-current emittance of 92 pm rad (flat beam, bare lattice, i.e. no superbends or insertion devices) which renders 62 pm rad in each transverse plane (full coupling, round beam).

One key issue with this approach is the very limited Touschek lifetime of less than 20 min at natural bunch length despite full coupling (at full current, without effects of insertion devices or intrabeam scattering). Higher harmonic cavities (HHCs) are expected to stretch bunches by roughly a factor 4 thus raising overall lifetime to beyond one hour which should be compatible with swap-out injection shots occurring once every 30 s from the new ALS-U accumulator ring. The on-axis injection process allows for lattices with very small dynamic aperture (DA); however, the limited lifetime remains a concern in terms of stability (injection frequency, top-off deadband) and radiation safety.

The source of limited Touschek lifetime lies in the limited momentum aperture (MA) of the 9BA baseline lattice. Despite extensive optimization efforts including MOGA, the local momentum aperture (LMA) is 2–3%, while the ALS RF system is capable of supplying beyond 3.5% RF acceptance. The limited LMA is the result of significant chromatic beating which stems from the localized chromatic correction in the two discrete dispersion bumps. Since Touschek lifetime scales with roughly the third power of the overall MA, a minor increase in LMA could significantly improve the Touschek lifetime of the ALS-U lattice.

We therefore investigate a new approach for an ALS-U lattice where distributed chromatic correction is employed in an effort to correct chromaticity at its source and limit chromatic beta beating, thereby increasing the off-momentum DA which in turn should provide larger LMA and higher Touschek lifetime.

LATTICE DESIGN

The initial challenge for an alternate ALS-U lattice is incorporating many sextupoles for distributed chromatic correction in an already very dense lattice. Assuming we retain the 196-m circumference, 12-fold periodicity, and ≈5.3-m long straight sections for insertion devices (IDs), this leaves no more than 11 m available for magnets in each arc. Since each unit cell will consist of a bending magnet (with transverse gradient for vertical focusing) and a horizontally focusing quadrupole, it has to provide space for two sextupole magnets to perform the local chromatic correction (similar to e.g. MAX IV [2,3]). A rough estimate shows that under these space constraints a maximum of seven bends can be housed in one arc. The resulting alternate lattice will therefore have to rely on a 7BA.

Because the bending angle per dipole is larger in the 7BA compared to the 9BA baseline, an emittance increase has to be expected. Since this is unacceptable in light of the brightness requirements for ALS-U, this lattice has to leverage additional improvements. One important addition is the use of longitudinal gradients in the bending magnets [4] which allows tuning of the optics in the dipoles to suppress emittance. Furthermore, the focusing quadrupoles can be offset radially in order to provide aggressive reverse bending [5] which

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allows tuning the dispersion independently from the beta functions and thereby optimizes the unit cell for ultra-low emittance and appropriate phase advance while simultaneously preventing the lattice from becoming isochronous.

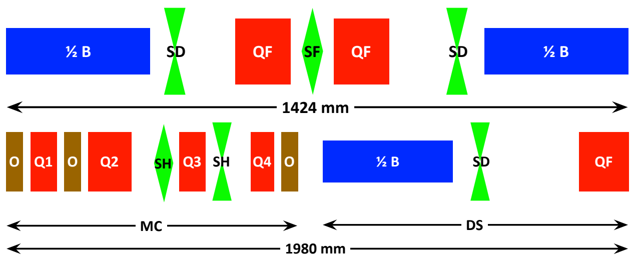

Figure 1: Schematics of the cell types in the 7BA: unit cell (top), matching cell and dispersion suppressor (bottom).

The proposed 7BA consists of five unit cells and two matching/dispersion suppressor cells (cf. Fig. 1). Each unit cell (UC) consists of a reverse bend (RB) which also serves as the focusing quadrupole (QF) and a longitudinal gradient bend (LGB) which, in addition to bending, performs the vertical focusing. The RB is split at its center and the two halves moved apart in order to provide space for a focusing sextupole (SF). A defocusing sextupole (SD) is inserted at either end of the LGB. The dispersion suppressor (DS) is derived from one half of a UC. Finally, between DS and straight section (SS) a matching cell (MC) is inserted which provides four quadrupoles in order to match arc optics to the IDs. The matching cell also has to provide space for two harmonic sextupoles and three octupoles.

OPTICS TUNING

The unit cell linear optics are essentially controlled by three parameters: the horizontally focusing gradient in the RB, the vertically focusing gradient in the LGB, and the reverse bending angle. The 5° main bending angle of the UC has to be provided by the LGB, plus a slight addition to compensate for the reverse bending. Early parameter scans, assuming the above detailed space constraints, indicated that lowest emittance is achieved for focusing gradients $k_{\mathrm{RB}} > 12\,\mathrm{m}^{-2}$ and defocusing gradients $k_{\mathrm{LGB}} < -5\,\mathrm{m}^{-2}$. Furthermore, achievable magnet gradients and the "chromaticity wall" limit k_{RB} from above. In order to achieve a higher-order achromat [6–9] across the seven cells, appropriate tunes for the UC are then $(3/7, 1/7)\times 2\pi$.

Assuming a minimum β_x^* and η_x^* at the center of the LGB and allowing for a 2-T peak dipole field at the LGB center, we derive a longitudinal profile for the LGB that minimizes the emittance contribution from the dipole. Presently we derive this profile assuming 12 slices. Substantially increasing this partitioning has no significant impact on the resulting emittance or optics. We assume that the vertical focusing performed by this LGB is provided by a transverse gradient which cannot be implemented in the high-field central area of the LGB. Instead, the transverse gradient is designed into the outer slices where the bend field has tapered off (cf. Fig. 2).

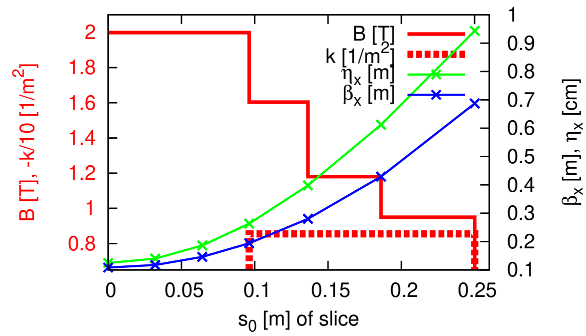

Figure 2: Field profile in one half of the LGB modeled as six slices: bend field (solid red), vertical focusing (dashed red). Resulting optics are also indicated (blue, green).

Finally, this then leaves the RB angle as the last free parameter. A study was undertaken to determine minimum achievable emittance in the UC when varying the RB angle: the RB angle was adjusted, the LGB and RB focusing gradients re-adjusted for cell tunes $(3/7, 1/7)\times 2\pi$, and the resulting emittance was recorded. Minimum emittance is observed at 0.95° of RB angle (cf. Fig. 3). Note, however,

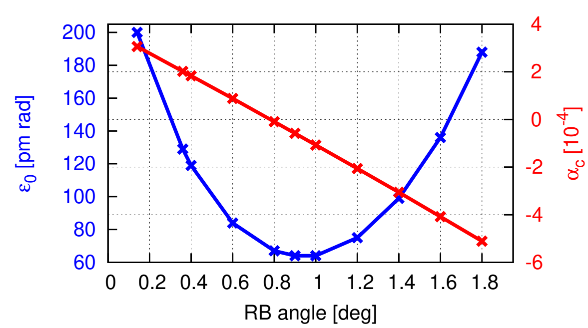

Figure 3: Emittance and momentum compaction of the UC as a result of RB angle tuning.

that choosing a RB angle for minimum emittance renders a quasi-isochronous lattice. Fortunately, the resulting lattice emittance of this UC is so low (64 pm rad minimum emittance vs. the baseline 9BA's 92 pm rad) that we may chose to detune from minimum-emittance conditions in order to reach a sizable amount of (negative) momentum compaction. For the present 7BA lattice we have detuned to 1.27° rendering $\alpha_c = -1.25\times 10^{-4}$ and $\varepsilon_0 = 89$ pm rad (for the entire storage ring). This choice delivers a momentum compaction large enough to guarantee stable longitudinal motion (as verified with 6D tracking in Tracy-3 [10]) while also delivering an emittance just below that of the 9BA baseline lattice.

The DS RB retains the angle of the UC RB, while its gradient as well as the transverse focusing gradient of the DS dipole are adjusted to achieve zero dispersion at the end of the cell. Finally, the MC provides four quadrupoles which are tuned for $\beta^*_{x,y} \approx 2.5\,\mathrm{m}$ at the ID source points and to provide a storage ring tune near the linear coupling resonance thereby facilitating round beam operation.

Nonlinear optics tuning is performed in three steps. A first step involves tuning the SD and SF in the UCs such that they correct the linear chromaticity to -1 and perfectly cancel any residual 1st-order resonance driving terms (RDTs). Since the DS lacks a dedicated SF, two additional harmonic sextupoles (SH) installed in the MC can be used to ensure that all 1st-order RDTs cancel perfectly. In a second step, all sextupole families are further tuned to minimize 2nd-order RDTs while the 2nd- and 3rd-order chromaticities are set to appropriate small values determined iteratively with 6D tracking in Tracy-3 taking into account tune shifts across $\pm 5\%$ in momentum. In a final step, the three octupole families in the MC are tuned to achieve 1st-order amplitude-dependent tune shift (ADTS) that, according to 6D tracking, minimizes tune excursions throughout the physical acceptance of the machine. The iterations between setting target values for various detuning terms (employing SVD and including weights as provided by OPA [11] using formulae derived in [12]) and observing tune shifts in 6D tracking are carried out in a manner similar to the nonlinear optics tuning performed for the MAX IV 3 GeV storage ring [13].

Realistic magnet lengths have been chosen for all magnets. The maximum required quadrupole gradient is below $18\,\mathrm{m}^{-2}$ which we believe is compatible with an 18-mm magnet gap. The maximum required sextupole gradient is just below $1750\,\mathrm{m}^{-3}$ (using the convention $b_3 = B''/(2B\rho)$) while the octupoles are comparably weak at about $19{,}000\,\mathrm{m}^{-4}$. Minimum magnet separation has been set to no less than two magnet gaps in order to limit cross-talk (similar to MAX IV). Drift space for 120 BPMs and vacuum equipment has been provided, while no drift space has so far been set aside for dedicated corrector magnets. As in the 9BA baseline lattice, it is presently assumed that they can be implemented as additional winding on quadrupoles and/or octupoles.

RESULTING PERFORMANCE

The most important lattice parameters for the proposed 7BA lattice are summarized in Table 1 while Fig. 4 shows the optics in one arc.

Table 1: Storage ring parameters for the 7BA lattice.

$\varepsilon_0 \rightarrow \varepsilon_x = \varepsilon_y$ (round beam)	$89 \rightarrow 57$ pm rad
ν_x, ν_y	39.36, 14.38
J_x	1.739
U_0 (bare lattice)	457.7 keV/turn
α_c (linear)	-1.25×10^{-4}
σ_δ (natural)	1.066×10^{-3}
$\xi_{x,y}$ (natural $\rightarrow$ corrected)	$-106.0, -35.9 \rightarrow -1.0$

The DA that results from the above mention nonlinear tuning is substantially larger than that of the baseline 9BA. In fact, even when errors and correction are included in 6D tracking, DA well in access of ± 1 mm (slightly less is

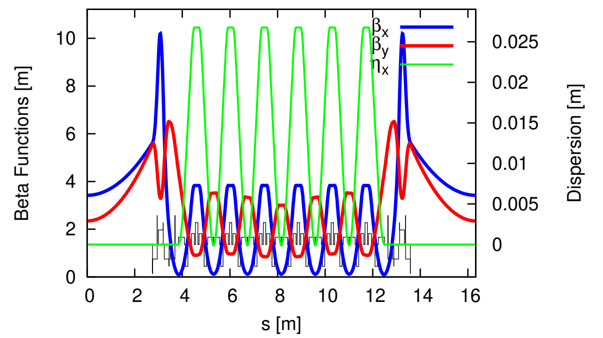

Figure 4: Optics in one 7BA.

expected to be required for 100% efficiency with on-axis injection) is recorded. An example for DA under the influence of errors (misalignments and field errors) is displayed in Fig. 5. Tracking with errors also shows off-momentum DA remains sizable for δ beyond $\pm 3.5\%$ which results in LMA significantly above that of the baseline 9BA lattice, in most parts of the lattice in fact limited by the RF acceptance. Using the same parameters as in the baseline 9BA studies (500 mA, standard ALS-U fill pattern, 4-fold stretching from HHCs, 3.5% RF acceptance), the Touschek lifetime in the presence of errors (calculated with 6D tracking, 20 error seeds) is 4.0 ± 0.5 hours. This is more than twice as much as provided by the baseline 9BA.

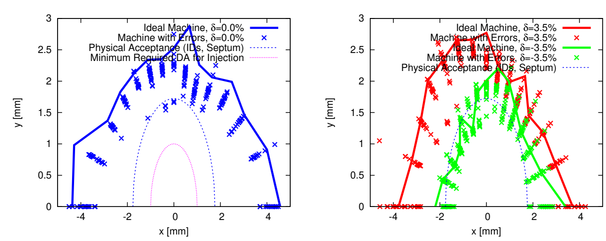

Figure 5: On-momentum (left) and off-momentum (right) DA from 6D tracking in Tracy-3 including errors (20 seeds).

CONCLUSIONS & OUTLOOK

A study has been carried out to derive an alternate ALS-U lattice based on a 7BA with distributed chromatic correction. This 7BA relies heavily on LGBs and reverse bending. Although the required normal-conducting LGB is a demanding magnet, other projects are already studying similar magnets and construction of a prototype is also underway [14, 15]. We believe we have been able to show a realistic optics capable of matching the aggressive brightness of the 9BA baseline lattice, while providing more than twice the DA and Touschek lifetime.

The next steps include iterations with magnet and vacuum engineering in order to refine the lattice for technical feasibility, collective effects studies aimed primarily at confirming stability at negative momentum compaction and chromaticity, as well as further optics improvements. For the latter, we would like to investigate reduced reverse bending (for lower emittance) and lower $\beta^*_{x,y}$ in the IDs in order to achieve substantially higher brightness than the baseline 9BA as well as extensive linear/nonlinear optimizations (including MOGA) to determine maximum achievable DA and lifetime for such a ultra-high brightness lattice.

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