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

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Abstract

The ALS Upgrade to a diffraction-limited soft x-ray storage ring calls for ultralow emittance in a very limited circumference. In this paper we report on progress with a lattice based on a 7BA with distributed chromatic correction. This lattice relies heavily on longitudinal gradient bends and reverse bending in order to suppress the emittance, so that, despite having only seven bends, ultralow emittance can be achieved in addition to large dynamic aperture and momentum acceptance. An initial alternate 7BA lattice has been revised to relax magnet requirements as well as further increase off-energy performance and resilience to machine imperfections. We now demonstrate ±2.5 mm dynamic aperture including errors and calculate the effect of IBS to show that this lattice achieves 6 hours Touschek lifetime (at 500 mA, including errors) and a brightness of roughly 3×10^{21} ph/s/mm^2/mrad^2/0.1%BW at 1 keV.

INTRODUCTION

A previous lattice study [1] had demonstrated that the performance requirements of the ALS-U storage ring [2] can be achieved while supplying large lifetime and dynamic aperture (DA) by using a 7BA lattice that provides space for distributed chromatic correction. By limiting the number of arc bends to seven, space can be provided for seven families of chromatic sextupoles throughout the arc thereby allowing the arc to be designed as a higher-order achromat free from lower-order aberrations. This not only significantly reduces resonance driving terms (RDTs) rendering larger DA, it also allows for a reduction in chromatic footprint thereby providing large momentum aperture (MA). This nonlinear optics has proven to be rather robust in the presence of imperfections unavoidable in a real storage ring.

The reduced number of arc bends obviously comes with an emittance penalty. This, however, can be alleviated by making use of reverse bending in the focusing quadrupoles and longitudinal gradients in the bends. The zero-current bare lattice emittance in this 7BA lattice is $\varepsilon_0 = 78$ pm rad. Because the horizontal damping partition in this 7BA lattice remains moderate, the resulting emittances in both transverse planes, when tuned for round beam operation, become sufficiently low for diffraction-limited soft x-ray production in both planes ($\varepsilon_x = \varepsilon_y = 49$ pm rad at zero current). Finally, by enforcing strict achromaticity of the arc and by tuning the beta functions through the insertion device (ID) straights (cf. Fig. 1) to better match the ideal optics (electron beam optics matched to diffraction-limited photon beams from undulators [3]), the resulting brightness can be further increased.

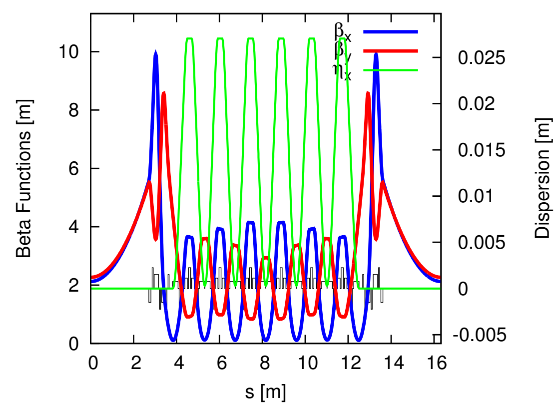

Figure 1: Optics in one of twelve 7BAs.

LATTICE & OPTICS TUNING

This 7BA lattice offers tuning flexibility in that emittance can be traded off for momentum compaction and vice versa through the amount of reverse bending chosen [1]. In fact, the revised 7BA lattice described here has been detuned from minimum emittance condition to increase the magnitude of momentum compaction in order to ensure better stability. Compared to [1], the 7BA lattice has been modified to 1.16° reverse bending angle in each unit cell which renders for the entire lattice $\alpha_c = -1.0 \times 10^{-4}$ and $\varepsilon_0 = 78$ pm rad (at zero current). This choice delivers a momentum compaction large enough to guarantee stable longitudinal motion (as verified with 6D tracking in Tracy-3 [4]) while also delivering ultralow emittance. If smaller values of momentum compaction could be tolerated, the minimum achievable emittance of the achromat can be reduced to 60 pm rad. In addition to lower emittance, an advantage of such a more aggressive tuning lies in the reduction of reverse bending which reduces the radiated power (and thereby the heat load on the vac chamber) and renders slightly better DA.

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Smaller values of beta functions through the ID straights have also been investigated. While they can improve the brightness due to improved matching to the photon beam, they tend to drive large peak beta functions in the matching cell thereby raising the natural chromaticity to levels that no longer allow for a stable and robust nonlinear optics. The solution presented here represents a compromise designed to achieve highest brightness both through lattice emittance suppression and ID optics matching while limiting chromaticities to values that can be corrected through many small but strong sextupoles leaving ample margins for imperfections found in any real machine.

For 500 mA operation in 11 trains of 25/26 bunches (Q_b = 1.15 nC accounts for gaps in fill pattern) the effect of IBS has been calculated assuming that this lattice, like the 9BA baseline, is operated in round beam mode, i.e. close to the linear coupling resonance with equal emittances in both planes, and that bunches are stretched by 3rd-harmonic cavities (3HCs) to roughly 4 times their natural length. For the 7BA lattice this results in transverse emittances of $\varepsilon_{x,y} = 49$ pm rad at zero current which then increase to $\varepsilon_{x,y} = 54$ pm rad at 500 mA.

Nonlinear Tuning

An additional improvement was made compared to [1] regarding the nonlinear lattice: the three octupole families in the matching cell have been removed. Instead, one harmonic sextupole family has been added to the two that were already provided. Since betatron amplitudes in this 7BA are very small, octupoles tend to require very large strength to contribute in a beneficial manner thereby driving undesired higher-order contributions. The harmonic sextupoles, on the other hand, present desired knobs to complete the higher-order achromat: when individual unit cells are joined with dispersion suppressors and matching cells, and the working point and ID beta functions are chosen, this usually results in a perturbation of the ideal phase advance between unit cell sextupoles. The three families of harmonic sextupoles in the matching cell allow recovering the higher-order achromat thereby again minimizing RDTs across the entire arc. The 10 families of chromatic and harmonic sextupoles are tuned using SVD (with manually set weights for various contributions to RDTs, amplitude detuning, and higher-order chromatic terms) with the boundary constraint that linear chromaticities are corrected to −1 [5]. Once this had been finalized, a MOGA study was carried out to ensure that no good sextupole solutions had been missed in the manual tuning process. In this study MOGA was allowed to adjust all sextupoles throughout their full range while keeping linear chromaticity corrected to −1. The target was to maximize DA on energy and for $\delta = \pm 4\%$. No radically different or better solutions were found. However, MOGA did render one solution that allowed for a slightly more even distribution of sextupole strengths among the various chromatic families while at the same time rendering a more symmetric and slightly larger DA. Table 1 summarizes the most important storage ring parameters.

Table 1: Storage Ring Parameters for the 7BA Lattice

Energy	2.0 GeV
Circumference	195.942 m
$\varepsilon_0 \rightarrow \varepsilon_x = \varepsilon_y$ (round beam)	78 → 49 pm rad
$\varepsilon_x = \varepsilon_y$ (w/ IBS, 500 mA)	54 pm rad
ν_x, ν_y	40.38, 14.36
J_x	1.72
U_0 (bare lattice)	442.6 keV/turn
α_c (linear)	-1.0×10^{-4}
σ_δ (natural)	1.06×10^{-3}
$\xi_{x,y}$ (natural → corrected)	−106.4, −40.1 → −1.0
$\sigma_{x,y}$ in ID (w/ IBS, 500 mA)	11 μm

PERFORMANCE

The DA in the presence of errors has been determined through tracking revealing about ±2.5 mm at the injection point (cf. Fig. 2). This offers more than ample reserves for the foreseen on-axis swap-out injection from the ALS-U accumulator ring. For the imperfection models, both alignment

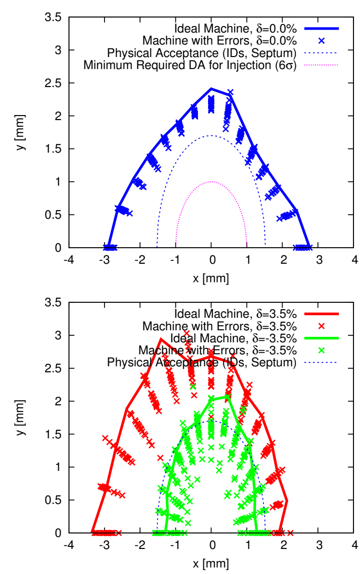

Figure 2: On-momentum (top) and off-momentum (bottom) DA from 6D tracking in Tracy-3 including errors (20 seeds).

and field/multipole errors have been included. Alignment errors are applied to girders and individual magnets, and orbit correction is then simulated to determine resulting closed orbit deviations. Similar to the approach chosen for the 9BA baseline lattice, rather than apply expected field errors and simulate local and global optics corrections, field errors and rolls of the quadrupoles have been scaled up until resulting in beta beats of 1–2% and coupling on the order of 1%. In this way we mimic the situation after optics symmetrization without actually simulating an entire LOCO-like procedure[1].

[1] For the 9BA baseline lattice efforts are under way to simulate the entire optics correction chain starting from a realistic set of expected field and multipole errors in order to verify resulting performance. An example for this effort based on the ALS-U accumulator ring can be found in [6].

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Using the same error and correction model as detailed above, the local MA has also been determined through tracking with Tracy-3. The overall MA of this lattice is almost entirely dominated by the RF acceptance set at 4% (cf. Fig. 3). For even the worst of the error seeds, an overall MA of

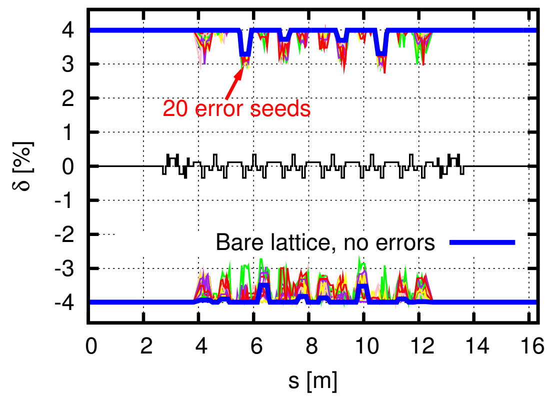

Figure 3: Overall MA (shown for one achromat) from 6D tracking including alignment, field, and multipole errors (20 seeds), and assuming RF acceptance set at 4%.

$\geq 3.5\%$ in almost all sections of the arc is recorded. Assuming bunch length stretched by a factor 4 by 3HCs, as done for the baseline lattice, and using emittances including the effect of IBS at 500 mA, this results in a Touschek lifetime with errors of 6.0 ± 0.8 hours at 500 mA.

Finally, the peak brightness of a flagship ALS-U ID was calculated for this lattice. The ID is a 4-m long 28-mm period Delta-type undulator assumed to be operated at the first harmonic to generate 1 keV photons [2]. The brightness and coherent fraction have been calculated assuming stored current of 500 mA (again including gaps in the fill pattern), including the effect of IBS as well as broadening of the undulator peak due to the beam energy spread. A peak brightness at 1 keV for this ID in linear polarization of 2.85×10^{21} ph/s/m^2/mrad^2/0.1%BW has been calculated. The coherent fraction at 1 keV is 24%, indicative of the excellent matching of the electron beam optics to the photon beam produced by this ID.

TECHNICAL CONSIDERATIONS

The price to pay for all these improvements is a dense lattice[2] employing high-gradient quadrupoles and dipoles with significant longitudinal gradients. The peak gradient required from the arc quadrupoles in this 7BA lattice is $b_2 = 16.1\,\mathrm{m}^{-2}$, the quadrupole families in the matching cell are weaker at $b_2 = 6.6 - 15.4\,\mathrm{m}^{-2}$ depending on family. The sextupole gradients in this 7BA lattice require $b_3 < 1637\,\mathrm{m}^{-3}$ depending on family. Magnet lengths and gradient maxima during optimization were chosen to result in manageable pole-tip fields assuming 18 mm magnet bores, which is expected to provide a uniform ±7.5 mm of aperture to beam throughout the arc[3]. From the point of view of DA and MA, this could be reduced if it facilitates magnet engineering as long as the impedance contribution remains manageable.

The longitudinal gradient bends as described in [1] assume a peak dipole field of 2 T (pure dipole, no transverse gradient) which tapers off to ≈ 1 T toward the ends of the magnet. In the lower-field end sections of the bend a transverse gradient provides vertical focusing. An alternative to facilitate the bend design consists of using a strong pure dipole at the center, flanked by two weaker transverse gradient dipoles. This is not ideal in terms of longitudinal field profile to minimize emittance [8, 9], but a roughly 10% emittance penalty could be outweighed by a more simple and robust magnet design. This emittance penalty could also be recuperated by tuning for slightly lower momentum compaction if deemed necessary.

Superbends

In the meantime, the ALS-U baseline lattice has been redefined to include six superbends in three arcs. In the 9BA lattice this is provided by replacing a regular 3° arc bend with a QD-Superbend-QD segment. In this 7BA lattice such a segment can also be included. As for the 9BA baseline, this process requires a local retuning of the linear optics. The 7BA lattice provides a large number of sextupole families, which should allow for much flexibility to tailor the nonlinear optics to the insertion of superbends if required.

Vacuum System

The technical risk associated with this 7BA lattice lies primarily in the LGB magnets and a vacuum system capable of handling high local heat loads. Presently, similar LGBs are already being prototyped by CERN and PSI for CLIC damping rings [10] and SLS-2 [11], respectively. Regarding vacuum system, so far nothing indicates a MAX IV approach for an entirely NEG-coated Cu vacuum system with distributed cooled inline absorbers should not work for this 7BA. However, this lattice does present the challenge of a shorter distance between source points and chamber wall (smaller chamber cross section and smaller bending radii) thereby resulting in higher local heat densities. An interesting study would be to see if a MAX IV style vacuum system could be augmented by including slotted antechambers that would provide for more distance to the cooled outer chamber acting as the inline absorber. Such an approach would present the additional advantage that secondary emission surfaces would be located farther from the beam with reduced vacuum conductance in between.

[2] Spacing between magnets in this lattice has actually been chosen more generously than in MAX IV. The minimum separation is 48 mm (2.7× magnet bore diameter), but for most magnets a separation of 100 mm has been chosen. Space has also been set aside for 120 BPMs. Corrector magnets are assumed to be realized as auxiliary windings on quadrupoles/sextupoles as done at MAX IV [7] and in the 9BA baseline lattice [2].

[3] Note that in terms of acceptance, this is still quite large compared to the assumed 2 mm septum clearance, the 2.4 mm required aperture in the arc to ensure 4.5% MA, and the vertical acceptance set by typical in-vacuum undulators at ±2 mm or narrow-gap EPU chambers at ±4 mm.

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