# OPTIMIZATION OF LATTICE FOR AN ERL UPGRADE TO THE ADVANCED PHOTON SOURCE*

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## *Abstract*

An Energy Recovery Linac (ERL) is one possibility for an upgrade to the Advanced Photon Source (APS). In addition to the linac itself, our concept involves a large turnaround arc (TAA) at 7 GeV that would eventually accommodate many new beamlines. Previously, we based the TAA design on isochronous triple-bend achromat (TBA) cells, since these are expected to provide some immunity to the effects of coherent synchrotron radiation. In the present work, we compare the previous TBA-based design to a new design based on double-bend achromat (DBA) cells, in terms of emittance growth, energy spread growth, and energy recovery. We also explore the trade-off between optimization of the beta functions in the straight sections and minimization of emittance growth.

## INTRODUCTION

An ERL [1] upgrade to the APS promises a revolutionary improvement in x-ray properties. In previous work [2] we made use of a TBA-based cell design for the TAA for the ERL upgrade. This choice was inspired by the desire to make an isochronous system with cancellation of coherent synchrotron radiation (CSR) effects [3, 4]. However, we found that CSR effects were very small, even as we increased the charge in the beam. Hence, we hypothesized that perhaps a simpler cell design might be acceptable. In this paper, we show results for a DBA-based design and compare these to the previous TBA-based design. (The APS ring portion of the ERL is necessarily DBA, since we don't propose to replace the APS ring. However, for simplicity we'll refer to "TBA" or "DBA" designs based on the optics design used for the non-APS portions.)

We also noted previously that with smaller beta functions at the insertion devices, x-ray brightness might be increased beyond what was predicted in [2]. In the second part of this paper, we explore the potential benefit and issues related to smaller beta functions.

## NEW ARC DESIGN

To develop the new arc design, we started with the APS cell including the Decker distortion[5], since this cell design is close to what we want. We then used `elegant` [6] to evolve this cell as follows: (1) Bending angle per cell of $\pi/24$ (48 cell turn around), just as for the TBA design. (2) $\eta_x = \eta'_x = 0$ in straights. (3) Increase space for insertion devices (IDs) from 4.8 m to 8 m. (4) $\beta_x \approx \beta_y \leq 5\mathrm{m}$ at center of ID straights. (5) Mean arc radius of 230 m, just as for the TBA design. (6) Minimize the $I_2$, $I_3$ and $I_5$ radiation integrals. (7) Similar maximum lattice beta functions as the TBA design, e.g., $\sim 25\mathrm{m}$. As Figure 1 shows, it was possible to make $\beta_x \approx \beta_y \approx 3\mathrm{m}$, which has advantages for brightness compared to the $\beta_x = 12\mathrm{m}$ and $\beta_y = 4.7\mathrm{m}$ values for the TBA. It is likely this could be achieved in the TBA only by moving away from the CSR canceling tunes and perhaps giving up isochronicity.

We attempted to simplify the DBA cell by having doublets on each side of the ID instead of triplets. We did not find a solution that had satisfactory emittance growth and beta functions. Hence, the promise of the DBA to simplify the cell structure didn't bear fruit. We eliminate one dipole magnet, but the dipoles are longer.

We also performed a DBA-based design of the arcs ("transport arcs") that bring the beam into and out of the APS ring. The constraints are very similar to those just listed, except there is no need for long straight sections. The mean radius was 75 m with a total bending angle of 72 degrees in 8 cells, as in the TBA design.

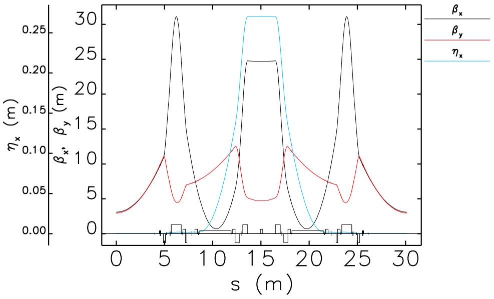

Figure 1: Optics for turn-around arc DBA cell.

## TRACKING COMPARISON

The next step is to compare tracking results for the DBA and TBA designs. We are interested in absolute energy loss, energy droop (deviation from reference), energy spread increase, and emittance increase. Mechanisms involved are classical, incoherent, and coherent synchrotron radiation. All the tracking studies used `Pelegant` [7] and the high-coherence-mode beam parameters [8], i.e., 0.1 $\mu$m initial normalized emittance with a 2-ps rms bunch length. For consistency with previous work, we assumed an initial

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energy spread of 0.1% rms, which is very likely too large but which doesn't impact our results.

We found that neither design has a worrisome energy droop. As Figure 2 shows, the DBA design is superior overall in terms of energy spread growth. This is in spite of larger growth in the TAA and results from very low growth in the transport arcs. Clearly, we might combine the TBA-based TAA with our DBA-based transport arcs if we wished. The emittance grows more rapidly in the DBA version of the TAA, then at about the same rate in the transport arcs and the APS itself. These differences are negligible.

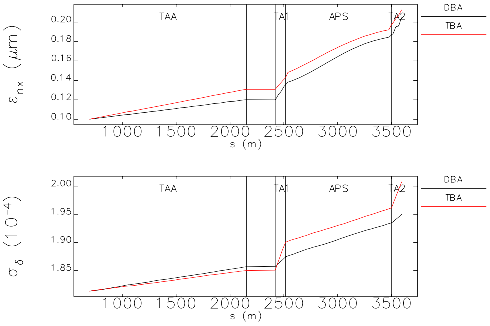

Figure 2: Evolution of normalized rms horizontal emittance and rms fractional momentum spread in 7-GeV portion for the two designs.

For the deceleration phase, increasing fractional energy spread and beam size may lead to beam loss. The final longitudinal distribution, shown in Figure 3, exhibits low- and high-energy tails, resulting from non-isochronous transport. The effects are worse in the all-DBA design, but still present in our "TBA" design because the APS portion is still DBA. This can be mitigated by moving the rf phase in the deceleration stage, at the cost of less efficient energy recovery. This is shown in Figure 3 for a deceleration phase that is 0.5 degree off trough. The average final momentum increases by only 1.5%.

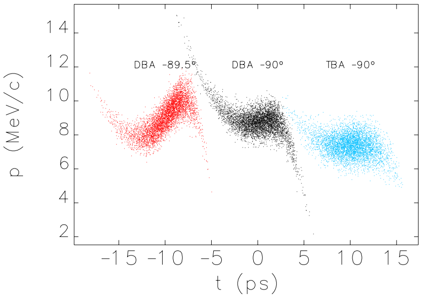

Figure 3: Comparison of final longitudinal phase space for three cases. Data are offset horizontally for clarity.

In passing, we note that one advantage of the TBA design is that the $R_{56}$ is adjustable. Hence, we could perhaps adjust the total $R_{56}$ of the 7-GeV transport lines to be zero, something we can't do with an all-DBA system. This would result in lower post-deceleration energy spread.

Next, we performed tracking with CSR to compare the DBA and TBA lattices. We are most interested in the 25 mA high-coherence mode [8], which has 19 pC per bunch. We also looked at the high-flux mode, which has 77 pC per bunch, leaving the emittance fixed for simplicity in comparisons (in reality the emittance is expected to increase four-fold). As seen from Figure 4, the effects of CSR are quite modest. This is the same result as we saw for the TBA-based design. Of course, these studies are for a very smooth initial distribution. Since the all-DBA lattice has considerable path-length dispersion, we must look carefully at possible microbunching instabilities [9]. This is the subject of another paper in these proceedings.

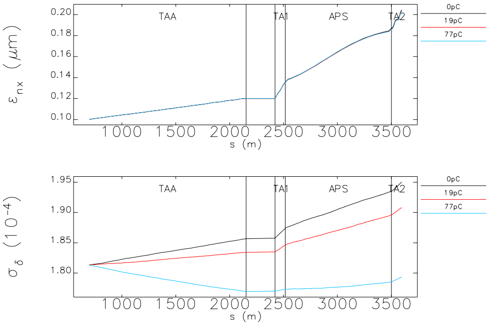

Figure 4: Evolution of normalized rms horizontal emittance (top) and rms fractional momentum spread (bottom) in 7-GeV portion of DBA design for three charge levels.

We next used `sddsanalyzebeam` and `sddsbrightness` [10] to compute the x-ray brightness for U33 undulators of various lengths at various locations, including emittance and energy spread growth. We found that the DBA-based design is about 70% brighter than the TBA-based design in the TAA, and basically indistinguishable in the APS itself. The improvement in the TAA results from the smaller beta functions in the straight sections.

## BRIGHTNESS OPTIMIZATION

The brightness improvement from the DBA cell design is, of course, not inherent in the DBA but results simply from the improved beta functions. Ideally, the beta function of the electron beam would be the same as the beta function of the single-electron undulator radiation. The latter is $\beta_r = \epsilon_r/\sigma_{r'}^2$, where $\epsilon_r = \lambda/(4\pi)$ is the intrinsic radiation emittance, $\sigma_{r'} = \sqrt{\lambda/(2L)}$ is the intrinsic radiation divergence, $\lambda$ is the radiation wavelength, and $L$ is the undulator length [11]. The result, $\beta_r = L/(2\pi)$, is quite small and not easily obtained in a storage ring. With the greater optical freedom of a single-pass system, it might be feasible.

Toward this end, we used `elegant` to rematch the APS DBA cell for a grid of target $\beta_x$ and $\beta_y$ values at the ID. We included the following constraints: (1) $\eta_x = \eta'_x = 0$ at

ID. (2) Maximum beta functions under 70 m in both planes, in order to reduce beam motion, halo generation, and optics sensitivity to the orbit. That 70m is necessary and sufficient is an educated guess at this point. (3) Acceptable emittance growth, implemented by constraining the cell's equilibrium emittance $\epsilon_0$ to less than 10 nm. Although the equilibrium emittance is not of course directly relevant, it provides an intuitive way to constrain $I_5$.

The maximum beta function constraint proved difficult. By introducing small gradients in the dipoles, we reduced this problem and got significantly smaller beta functions in the straight sections. We limited ourselves to $|K_1| \leq 0.05\mathrm{m}^{-2}$, which might require only pole-face windings.

In an attempt to ensure that chromatic effects are manageable, we eliminated all solutions for which our present maximum sextupole strength of $K_2 = 31.5\mathrm{m}^{-3}$ was insufficient to correct the chromaticity to zero. We also removed all solutions for which $\max(\beta_{\{x,y\}} \geq 75$ m and $\epsilon_0 \geq 11$ nm. This eliminated about 17% of the solutions.

Following matching, we chose to compute the x-ray brightness at Sector 35 (the end of the APS portion of the ERL), since it is the most sensitive to emittance increase. To save computation, instead of tracking we estimated the emittance using [12]

$$\Delta\epsilon_x = \frac{55 r_e \hbar}{48\sqrt{3} m_e c}\gamma^5 I_5, \qquad (1)$$

where $I_5$ is the radiation integral for 35 sectors. Similarly, the fractional energy spread growth is [13]

$$\Delta\sigma_\delta^2 = \frac{55 r_e \hbar}{24\sqrt{3} m_e c}\gamma^5 I_3. \qquad (2)$$

We checked these equations against tracking with `elegant` for the nominal design and got good agreement.

The beam parameters at the entrance of the APS portion are $\epsilon_x = 10.9$ pm, $\epsilon_y = 7.1$ pm, and $\sigma_\delta = 0.0186\%$. After computing the beam properties at Sector 35, we used `sddsbrightness` to determine the brightness for the first three harmonics assuming at 4.8-m undulator and 25 mA average beam current. We found the largest improvement in brightness for $\beta_x = 1.0\mathrm{m}$ and $\beta_y = 1.1\mathrm{m}$, the smallest we could get in both planes (see Figure 5). This solution is close to the limits for maximum beta functions, emittance increase, and sextupole strength. As Figure 6 shows, the improvement in brightness relative to the reference case is a factor of 2.5.

## CONCLUSION

Based on an analysis of emittance growth including coherent synchrotron radiation, we found no advantage to a TBA-based design for the turn-around arc and transport arcs in an APS ERL upgrade. Even for 77 pC/bunch, the use of CSR-canceling optics appears to be unnecessary, which relaxes several constraints on the lattice. This would allow, for example, optimization of the beta functions at the insertion devices, giving significantly improved brightness.

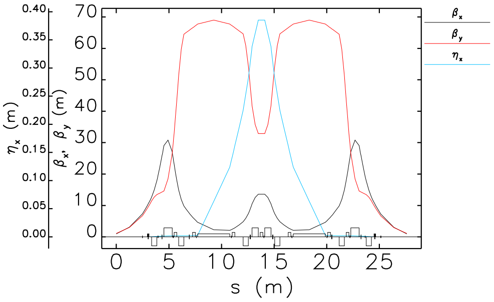

Figure 5: Optics for optimized APS DBA cell.

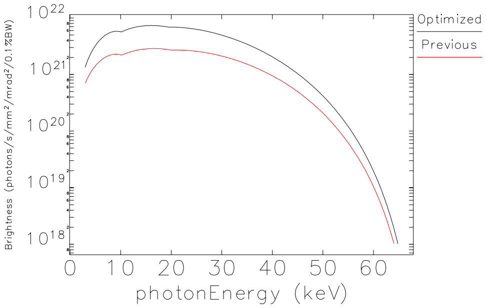

Figure 6: Comparison of brightness for the optimized APS DBA cell and the previous solution.

We showed an example of applying this, albeit to the APS DBA cell only, gaining a factor of 2.5 in the brightness. Strong path-length dispersion in the all-DBA design may increase the growth of microbunching in the beam, which is the subject of another paper in these proceedings.

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