POSSIBLE UPGRADE OF THE ADVANCED PHOTON SOURCE WITH AN ENERGY RECOVERY LINAC *

M. Borland †, G. Decker, X. Dong, L. Emery, A. Nassiri, ANL, Argonne, IL 60439, USA

Abstract

The Advanced Photon Source (APS) is a third-generation storage-ring-based x-ray source that has been operating for over 13 years and is enjoying a long period of stable, reliable operation. While APS is presently providing state-of-the-art performance to its large user community, we must clearly plan for improvements and upgrades to stay at the forefront scientifically. Significant improvements should be possible through upgrades of beamline optics, detectors, and end-station equipment, along with evolutionary changes to the storage ring itself. However, major accelerator upgrades are also being investigated. One very promising option that has been the subject of considerable research is the use of an energy recovery linac (ERL). In this option, APS would transition from a source based on a stored electron beam to one based on a continuously generated high-brightness electron beam from a linac. Such a source promises dramatically improved brightness and transverse coherence compared to third-generation storage rings, as well as distinctly different temporal properties.

INTRODUCTION

The 7-GeV APS storage ring was originally designed to operate with an emittance of 8 nm and 10% coupling. Over time, this has evolved to an effective emittance of 3.1 nm with emittance coupling of typically 1.5%. This is close to the practical optimum that can be achieved with the existing hardware and existing top-up rates. One possibility for continuing to improve the brightness is an in-tunnel replacement of the storage ring. We have explored several possible designs [1, 2, 3], but in the final analysis found that the likely improvements to brightness (perhaps 40-fold) and transverse coherence (perhaps 3-fold) did not justify the required extended downtime for installation of a new ring. In light of this, we have explored the possibility of an upgrade based on an energy recovery linac (ERL).

The ERL concept was first described by Tigner [4] as an option for colliding beams, and only much later proposed [5, 6] as a possible x-ray light source. The ERL concept involves an electron gun delivering an essentially continuous stream of bunches. These are accelerated to ∼10 MeV and injected into a linear accelerator through a set of bending magnets known as a "merger." After acceleration, the bunches are returned to the upstream end of the linac via a transport system that must, of course, incorporate bending, which provides the opportunity to insert many synchrotron radiation beamlines with undulator sources. Upon returning to the upstream end of the linac, the high-energy beam is merged back into the linac where it co-propagates with the low-energy beam. However, by correct choice of path length, the high-energy beam can be made to give up its energy to the linac cavities. This recovered energy is then available to accelerate fresh electron bunches.

In contrast to an in-tunnel ring replacement, an ERL-based upgrade promises much smaller emittance, while providing beam currents that are comparable to those used today. Unlike a storage ring, the ERL emittance is determined mainly by the emittance of the injector, rather than by an equilibrium between quantum excitation and radiation damping. For example, a photocathode injector may deliver normalized emittances of $\sim 1\ \mu$m for a $\sim$ 1-nC bunch. At 7 GeV, this corresponds to a geometric emittance of 73 pm, far less than the 3.1-nm effective horizontal emittance of the APS (but somewhat larger than the vertical emittance). Hoffstaetter [7] defines several possible ERL operating modes, including a high-coherence (HC) mode, the parameters of which are shown in Table 1 in comparison with the APS. We will discuss below the extent to which the ERL beam parameters are realistic.

Table 1: Comparision of Present APS Parameters to Proposed ERL High-coherence-mode Parameters at 7 GeV

Quantity	APS now	HC mode
Average current (mA)	100	25
Repetition rate (MHz)	6.5 to 352	1300
Bunch charge (nC)	< 59	0.019
Horiz. emittance (nm)	3.1	0.006
Vert. emittance (pm)	$25 \sim 50$	6
Rms bunch length (ps)	> 20	2
Rms energy spread (%)	0.1	0.02

CONCEPTS AND OPTIONS

Several ERL upgrade concepts have been investigated, including single- and multi-pass linacs either in the infield of the APS or outside the APS altogether. One attractive idea is to put a multi-pass linac in the infield of the APS [8, 9], which has the advantage of reduced environmental impact compared to an "outfield" ERL. The major downside is that it prevents or complicates expansion of the facility or use of the linac for other purposes. For this reason, we've concentrated most of our study on outfield concepts.

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† borland@aps.anl.gov

For outfield designs, we can initially accelerate beam toward or away from the APS. The former is more natural, and allows a relatively small turn-around arc (TAA) since concerns about emittance increase are reduced [10]. However, accelerating the beam away from the APS allows supplying the highest brightness beam to the TAA, which we envision as a large system with space for many additional beamlines. Further, one can imagine a straight-line extension of the linac to support applications requiring shorter, more intense beam pulses, driven by a low-duty-factor injector and operating together with the ERL [11].

For these reasons, our favored concepts feature a linac accelerating away from the APS ring into a large, emittance-preserving TAA supporting additional beamlines. Previously, we designed the TAA to support 48 new beamlines with 8-m-long insertion devices (IDs). In the present work, we targeted a relatively small number of new beamlines with very long IDs.

Another design choice is the beam energy. Previously [12], we reported that we obtained the highest brightness for x-ray energies over 8 keV for an electron beam energy of 7 GeV or higher. In addition, higher electron energy also permits greater total undulator length. Our argument starts by noting that a significant issue for ERLs is the energy spread of the beam, since larger energy spread makes it harder to obtain high transport efficiency when the beam is nearing the end of its deceleration. The energy variance increase [13] in a bending system is $\Delta\sigma_E^2 \propto \gamma^7 I_3$, where $I_3 = \int \frac{ds}{|\rho|^3}$ and $\rho \propto \gamma/B$ is the instantaneous value of the bending radius in a magnetic field B for a beam with relativistic factor γ. For the contribution I_{3u} of the undulators, we have $B = B_o \sin\frac{2\pi s}{\lambda_u} \propto \frac{K}{\lambda_u}\sin\frac{2\pi s}{\lambda_u}$, where λ_u is the undulator period and K is the undulator strength parameter. Hence $I_{3u} \propto K^3 L_u/(\gamma^3\lambda_u^3)$, where L_u is the total length of the undulators. To maximize the first harmonic brightness, we need $K \sim 1$. However, the undulator period must vary with γ to keep the photon wavelength λ_γ fixed. In particular, $\lambda_u \propto \gamma^2\lambda_\gamma$ so that $I_{3u} \propto L_u/\gamma^9$ and thus $\Delta\sigma_{E,u}^2 \propto L_u/\gamma^2$.

ERLs that decelerate to the same final energy have the same tolerance for $\Delta\sigma_E^2$. Ideally, we should design the ERL such that $\Delta\sigma_E^2$ is dominated by the undulators. Hence, it is plausible that the acceptable length of undulators increases roughly quadratically with beam energy. A 7-GeV ERL can thus accommodate roughly twice as much total undulator length as a 5-GeV ERL. Based on these arguments, we've assumed that an APS ERL would operate at our present energy of 7 GeV.

INJECTOR

A new injector design has been developed [14] that satisfies the requirements of high-coherence mode. This builds on previous work [15], but now includes the merger.

The injector design has much in common with the Cornell concept [16], including a high-voltage DC photocathode gun, an rf buncher, and a booster cavity. We simplified the configuration by using a single 9-cell booster cavity (this would not work in practice due to coupler power limits). As in [15], we used an ellipsoidal beam with a fixed 10 ps rms duration, but with variable transverse dimensions. We added a zigzag-type merger [17], with 10 (20) degree bend angles for the outer (inner) dipoles, and a transverse dipole displacement of about 7 cm. There's no indiciation of emittance growth in the merger, so it is likely that the bend angles could be increased.

For the target intensity of 19 pC/bunch, transverse normalized emittances of 0.09 μm were obtained in both planes after the merger at an energy of 12.4 MeV. The bunch length was 590 μm with less than 7 keV energy spread. This required a 0.29 mm rms laser spot size, a DC gun voltage of 721 kV, a buncher cavity gradient of 2.7 MV/m, and a booster cavity gradient of 22 MV/m. Of these, the high DC gun voltage is certainly very challenging. In these simulations, an intrinsic "thermal" energy of 27 meV was assumed, corresponding to an intrinsic normalized emittance of 0.067 μm. Raising the intrinsic energy to 50 meV results in a final emittance of 0.11 μm, only 10% above the goal.

LINAC

In our previous work [12, 18], we used a single-pass linac (i.e., one pass for acceleration, one for deceleration). However, for cost reasons one may clearly wish to consider a multi-pass linac. Using `elegant`[19], we have developed a two-pass design that preserves the beam quality.

Beam enters the linac at 10 MeV and is accelerated to 3.5 GeV in the first pass. We again used doublet focusing and the graded-gradient principle [20] with optimization [18] to design the optics. We also constrained the Twiss parameters at 3.5 GeV in such a way that both the accelerating and decelerating beams are matched to the same values when at the same location with the same energy.

The linac consists of 12 cells, each of which has a sequence `Doublet1-N*SSU-Doublet2-N*SSU`, where `Doublet1` and `Doublet2` are quadrupole doublets and an `SSU` is a unit containing two nine-cell 1.3-GHz superconducting cavities. Each 20-MV cavity is about 1 m long. For the first and last cell, we used `N=2`, whereas for other cells we used `N=4`. Figure 1 shows the results. We succeeded in keeping the maximum beta function under 100 m. The initial and final part of the linac, where the beam energy is lowest, have fairly small and regular beta functions.

The 3.5-GeV recirculation arcs have a 50-m average radius. Each 180-degree arc contains 16 isochronous, triple-bend achromat (TBA) cells with a horizontal phase advance per cell of $5\pi/4$ [21, 22]. Tracking studies with parallel `elegant` [23] show no significant emittance or energy spread growth in the linac or 3.5-GeV recirculation arcs, even with coherent synchrotron radiation (CSR) effects up to 77 pC/bunch. We did not include the separator or combiner design in this work, but these small systems have only a few bending magnets, so no signficant impact is expected on energy spread or emittance.

HIGH-ENERGY TRANSPORT

Previously [12], we used 48 TBA cells for our TAA designs in order to preserve emittance, give isochronous transport, and support many new beamlines. We subsequently determined [24, 25] that these features were not necessary even for 77 pC/bunch and that a non-isochronous double-bend achromat (DBA) design was just as good.

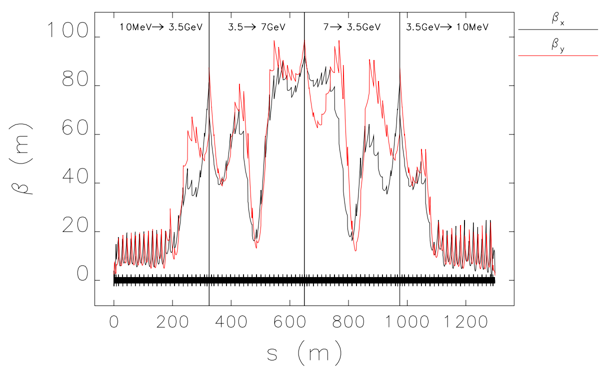

Figure 1: Optics for the two-pass linac, showing acceleration and deceleration stages.

In the present work, we consider a design optimized for fewer, very long undulators. We targeted 48-m undulators (50-m drift spaces) and adopted an arc design based on theoretical minimum emittance (TME) cells with dispersion suppressors. Each octant of the TAA consists of 15 TME cells plus dispersion suppressors and quadrupoles for matching into the drift spaces (Figure 2). The beta functions at the center of the straight sections are matched to the ideal values of $L_u/(2\pi)$, where L_u is the undulator length. The matching section has a 5-m drift space that could accommodate one or more rf cavities for restoring lost beam energy (see below). Figure 3 shows the layout of the entire system, including the two-pass linac. This design could accommodate nine 48-m-long undulators in the TAA.

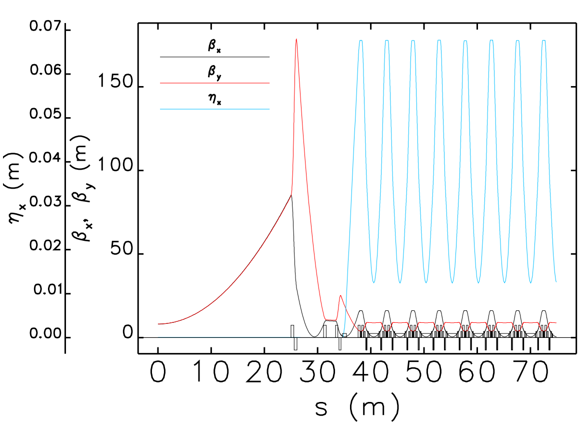

Figure 2: Optics for one half of a TAA octant.

We are concerned about effects of changing the gap on one long device on the downstream beamlines and on energy recovery. After the last ID, the energy centroid variation could amount to several MeV, which is not negligible when the beam is to be decelerated to ~10 MeV. The energy variation at the last ID due to upstream gap motion could easily exceed the energy spread of the beam (1.4 MeV rms), causing significant variations in brightness. To deal with these problems, we envision an rf cavity downstream of each long ID. These cavities are adjusted continuously to compensate for the variation in energy loss in the ID as the gap is changed by the user. To assess this, we populated the model with nine various APS undulator designs at their maximum design K values, as shown in Table 2. The rf voltage and power requirements for the booster cavities do not seem difficult.

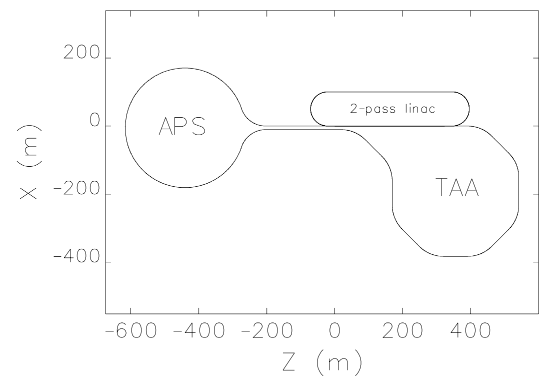

Figure 3: Geometry for the upgrade with very long straights in the TAA.

We must still concern ourselves with emittance and energy spread growth due to these long devices. We used `elegant` to perform matching of each straight section to compensate for the focusing effects of each undulator, then tracked with parallel `elegant` to determine the energy spread and emittance growth. The undulators were modeled with the `CWIGGLER` element, which uses a wiggler approximation. After deceleration to 12.2 MeV/c, the rms energy spread increases from 810 keV (no undulators) to 950 keV (all long undulators closed). (Integration over the photon spectrum gives 900 keV with all undulators closed. The wiggler approximation overestimates the contribution of the large K devices while underestimating the contribution of the small K devices.) No appreciable effect is seen on the emittance, which is not surprising since the undulators are in zero-dispersion locations. Hence, given booster cavities to compensate for the average energy loss, such long devices are feasible.

In the APS ring portion of the ERL, we lack the space near each ID to have a booster cavity. However, since the IDs are necessarily shorter (less than 8 m long), this is presumably not necessary. Instead, we could have booster cavities located periodically in the ring at selected straight sections, where they would displace the IDs.

The decelerating beam in the 3.5-GeV recirculation arcs

Table 2: Booster Cavity Requirements for 48-m-long Undulators, Assuming a 25-mA Beam

Undulator		Booster cavity		Number
Period mm	K max.	Voltage MV	Power kW	
18	0.45	0.11	2.7	1
23	1.20	0.46	11.6	1
27	1.78	0.74	18.5	2
30	2.20	0.92	22.9	1
33	2.74	1.18	29.4	2
35	3.08	1.32	33.0	1
55	4.97	1.39	34.8	1

of the linac has an energy offset of -0.5% (about 18 MeV) due to the energy loss in the dipoles of the high-energy transport system. In principle, this could be avoided with a booster cavity downstream of the APS, but that cavity would have beam power requirements (450 kW) in excess of those required for the injector. The offset does not appear to cause any problem with beam transport.

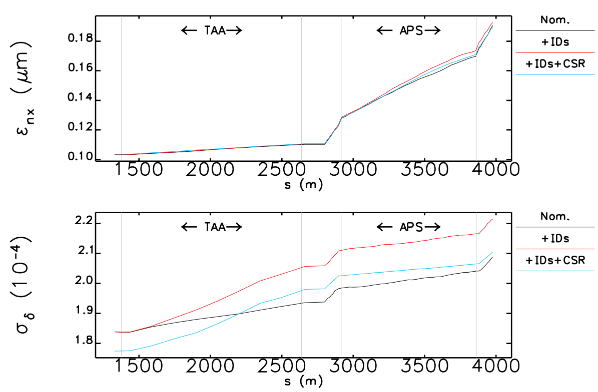

Figure 4: Evolution of horizontal normalized emittance and energy spread in the 7-GeV portion of the system.

As seen in Figure 4, tracking shows that effects of CSR at 20 pC/bunch are modest, particularly for the x-ray users. (The decrease in the initial energy spread results from the shape of the CSR "wake" compared to the shape of the longitudinal phase space that results from rf curvature [18].) The most significant effect may be on the energy-recovered beam. Figure 5 shows the final longitudinal phase space with and without unshielded CSR in the dipoles and drifts. Sensitivity of this result to shielding effects needs to be explored, but could be significant [26].

X-RAY PERFORMANCE

We computed the expected brightness and flux for these IDs using beam parameters generated from analysis of tracking results. Compared to the present-day APS performance with a typical 3.3-cm-period, 2.4-m-long undulator at 100 mA with 1.5% coupling, we gain up to 3.5 orders of magnitude in brightness in the TAA (Figure 6), with similar improvements in the coherence (Figure 7). For the beamlines in the APS ring, the brightness increase will be less, but we can lengthen the APS straight sections ring to accommodate 8-m-long IDs without significantly impacting emittance preservation. In that case, we gain 2 orders of magnitude in the APS ring portion, assuming lengthened straight sections that accommodate 8-m-long undulators.

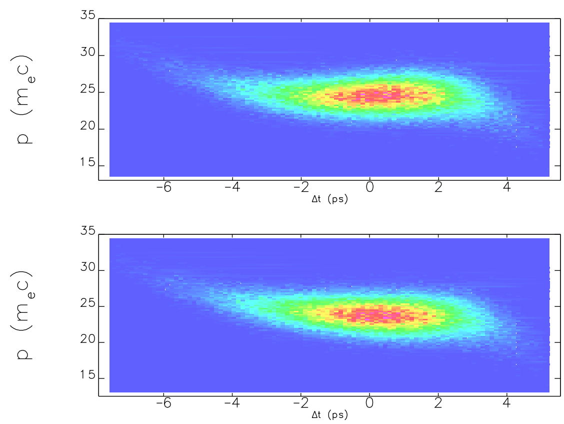

Figure 5: Tracking results at 20 pC/bunch, comparing final longitudinal phase space with (bottom) and without (top) unshielded CSR in dipoles and drifts.

One concern is reduced flux from the reduced average current (25 mA compared to 100 mA). However, because of the long undulators, the flux increases by a factor of ∼5 for the TAA beamlines, and is essentially unchanged for the APS beamlines (Figure 8). The total power and on-axis power density for the TAA beamlines increase by the same factor, which results in power density and power that are 40 and 65% higher, respectively, than the existing high heat-load front-end designs [27] can handle. A modest (20%) increase in the distance between the IDs and the front ends should alleviate such concerns.

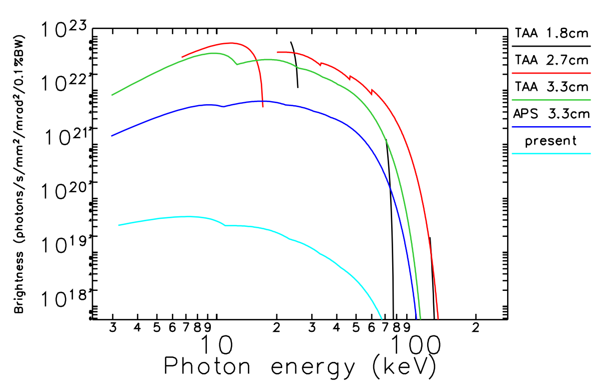

Figure 6: Brightness curves for various 48-m-long undulators in the TAA and an 8-m-long device in the APS, along with the present typical APS performance.

CONCLUSION

We've presented a concept for an ERL-based upgrade of the APS complex that features nine new beamlines with 48-m-long undulators. These beamlines show a dramatic increase in brightness and a significant increase in flux compared to present APS performance. In addition, the existing beamlines in the APS could be upgraded to 8-m-long undulators and would show a very significant increase in brightness with no change in flux. The concept outlined above is perhaps the ultimate APS ERL upgrade. Simpler, less costly possibilities include directing the beam into the APS first and using a small TAA without user beamlines [10]. A few long-undulator beamlines might be accommodated in the transport system before or after the APS.

An ERL integrated into the APS complex is not the only option for an enhanced source of hard x-rays at Argonne. Another option is a separate "greenfield" ERL facility, which would have comparable performance and cost but would disrupt APS operations less. On the downside, existing beamlines would not benefit from the higher brightness and coherence.

Two other options worth mentioning are an Ultimate Storage Ring (USR) [28, 29, 30] and an x-ray free-electron laser (XFEL) such as the oscillator-based XFEL-O concept [31]. The USR promises performance that is comparable to the ERL in terms of brightness and flux [30] and the technology to build it appears to exist today. The XFEL-O concept promises much higher average brightness and full coherence. It shares many of the challenges of an ERL in terms of beam quality requirements, but eases requirements for high average current and beam loss control.

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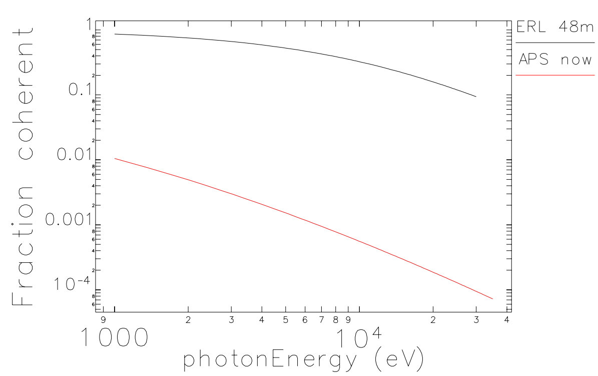

Figure 7: Fraction of radiation that is coherent, for APS today and 48-m-long undulators in the ERL.

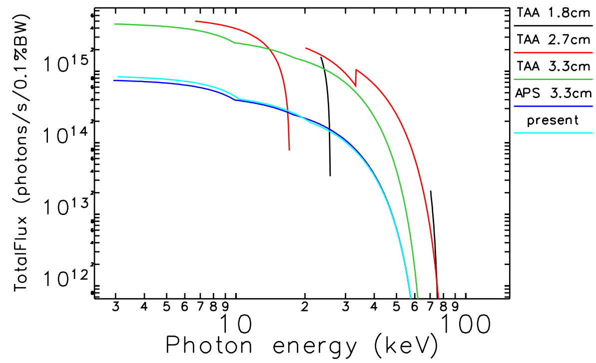

Figure 8: Flux tuning curves for various 48-m-long undulators in the TAA and an 8-m-long device in the APS, along with the present typical APS performance.

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