CONFIGURATION, OPTICS, AND PERFORMANCE OF A 7-GEV ENERGY RECOVERY LINAC UPGRADE FOR THE ADVANCED PHOTON SOURCE*

M. Borland†, G. Decker, A. Nassiri, M. White, Argonne National Laboratory, Argonne, IL, USA

Abstract

The Advanced Photon Source (APS) is a 7-GeV storage ring light source that has been in operation for over a decade. In order to make revolutionary improvements in the performance of the existing APS ring, we are exploring the addition of a 7-GeV energy recovery linac (ERL) [1] to the APS complex. In this paper, we show the possible configuration of such a system, taking into account details of the APS site and the requirement that stored beam capability be preserved. We exhibit a possible configuration for the single-pass, 7-GeV linac. We discuss optical solutions for transport from 10 MeV to 7 GeV and back, including a large turn-around arc that would support 48 additional user beamlines. Tracking results are shown that include incoherent and coherent synchrotron radiation, resulting in predictions of the beamline performance. We also demonstrate the desirability of operation at high beam energy.

INTRODUCTION

The present-day emittance of the 7-GeV APS storage ring is 3.1 nm in the horizontal and 0.025 nm in the vertical. This represents the practical minimum that is achievable with the existing hardware. We have explored various methods of reducing the emittance by replacing the storage ring [2]-[4]. Practical replacement storage rings promise no more than a factor of three improvement in emittance, which does not seem to be sufficient to justify the disruption of APS operations needed to install the new ring.

In contrast, an ERL-based light source promises much smaller emittances and comparable beam currents to those used today. Hoffstaetter [5] defines a series of possible ERL operating modes, several of which are listed in Table 1. Of particular interest are the "high flux" (HF) and "high coherence" (HC) modes. The HC mode has a horizontal emittance that is 500 times smaller and a vertical emittance that is 4 times smaller than presently delivered at APS, and is potentially fully spatially coherent at 1 Å. These beam properties, if delivered to x-ray users, promise a revolution in x-ray science.

Figure 1 shows a possible configuration for a 7-GeV ERL. The long, single-pass linac is envisioned to point away from the APS ring, which offers two advantages. First, we can contemplate delivering a straight-ahead beam to a new facility that could provide ultra-short pulses using a separate injector [6]. This facility might be based on spontaneous radiation or an FEL. Second, we deliver the highest quality beam to the new turn-around arc (TAA), which features 48 straight sections that could eventually be used for new beamlines. This configuration represents the ultimate upgrade and would also be the most complex and costly. Other configurations involving multi-pass linacs and/or a lower-energy TAA are also possible but have not been modeled in detail.

Table 1: Potential beam parameters of a 7-GeV APS ERL based on scaling of Cornell numbers [5].

	APS today	HF	HC
Average current (mA)	100	100	25
Repetition rate (MHz)	0.3-352	1300	1300
Bunch charge (nC)	0.3-60	0.077	0.019
Rms geom. emit. (H) (nm)	3.1	0.022	0.006
Rms geom. emit. (V) (nm)	0.025	0.022	0.006
Rms bunch length (ps)	20-70	2	2
Rms momentum spread (%)	0.1	0.02	0.02

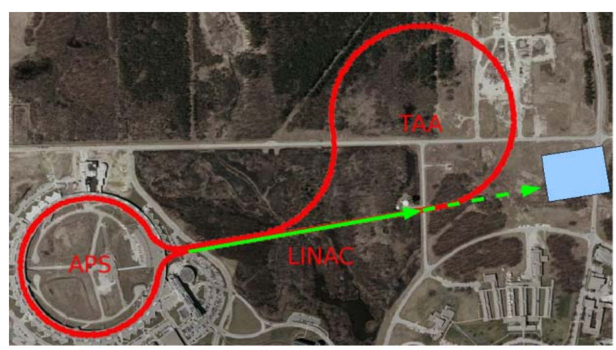

Figure 1: Diagram of the ERL concept, showing the APS itself, the linac, and the turn-around arc (TAA). The ERL path is from `elegant`'s floor coordinate output.

LINAC CONFIGURATION AND OPTICS

For concreteness, we elected to use the 1-m-long TESLA nine-cell cavity as part of our preliminary design model. In reality, one would almost certainly use a cavity with fewer cells, and indeed perhaps with a different rf frequency. A possible cryomodule layout is shown in Figure 2. We assumed two cryomodules would form a superstructure unit (SSU) with space for quadrupoles, diagnostics, and steer-

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† borland@aps.anl.gov

ing magnets every four SSUs. The cavity gradient is 20 MV/m and the effective gradient is 10 MV/m.

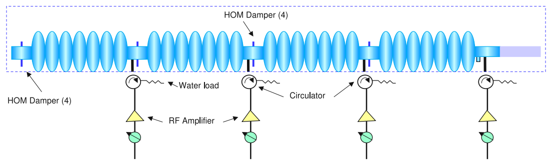

Figure 2: Cryomodule concept using nine-cell cavities.

We assumed that beam would be injected at 10 MeV, giving a maximum energy ratio of 700. We designed the optics using the graded gradient principle [7], which states that all quadrupoles should have constant focal length for the lowest energy beam at their location. We used `elegant`[8] and `sddsoptimize`[9] to create a minimum-beta-function lattice with constant spacing between the quadrupoles in the doublets and strict graded gradient for the strengths. We then used `elegant`'s internal optimizer to adjust the strengths and spacing of all quadrupoles independently, resulting in another factor of two reduction in the maximum beta function, which should help raise the beam break-up threshold. The result is shown in Figure 3.

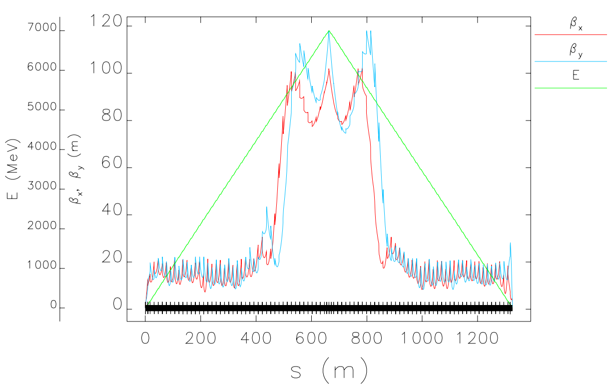

Figure 3: Doublet optics for the 10 MeV to 7 GeV linac, showing lattice functions for acceleration and deceleration.

Cryogenic power is a serious issue with this concept. For operation at 20 MV/m with $Q \sim 10^{10}$, the rf power losses at 2 K will be about 16 kW. Allowing for static losses and efficiency, we estimate the helium plant power consumption at 45 MW. One solution is a multipass linac [10]; however, this may have a lower instability threshold and would prevent delivery of 7-GeV ultrashort pulses. Alternatives include optimizing cavities for higher Q rather than high gradient, since a gradient of 20 MV/m is well below the state-of-art for such cavities; decreasing the gradient to 10 MV/m and doubling the linac length, which halves the power; and developing a more efficient cryoplant design.

OPTICS AND EMITTANCE PRESERVATION

The next task is design of the 7-GeV transport systems. Our primary concern is to minimize emittance growth due to incoherent and coherent synchrotron radiation (ISR and CSR). To best control CSR, the TAA and input/output transport lines to the APS were designed using isochronous, achromatic triple-bend cells [11, 12]. We chose a horizontal phase advance per cell of $5\pi/4$ in order to obtain cancellation of CSR kicks every four cells. In addition, having such high phase advance naturally controls quantum excitation (ISR), just as it would in a high-energy storage ring. `elegant` was used to design both the TAA and the input/output arcs, which have mean radii of 230 and 80 m, respectively. The large size of the TAA improves emittance preservation and provides more straight sections for eventual user beamlines with 8-m-long undulators. The tight radius of the input/output arcs results from the desire to avoid existing buildings.

The APS storage ring will nominally be unchanged (see below) and has a double-bend structure. It is not possible to make this both isochronous and to control ISR, so we opted for the latter. The lattice must also have zero dispersion in the straight sections [13] so that CSR and ISR effects have less impact on the effective emittance.

Using `elegant`, we tracked beam for the high-coherence parameters starting at 10 MeV and including energy recovery. Figure 4 shows horizontal emittance evolution for the 7-GeV transport, showing approximately two-fold growth by the end of the APS ring. Due to the low charge, the impact of CSR is minor, hinting that we may be able to relax the TAA design.

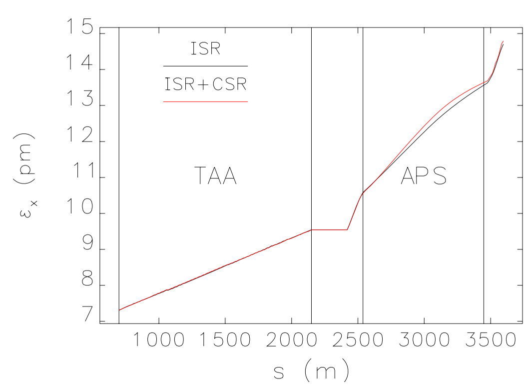

Figure 4: Emittance evolution at 7 GeV from tracking.

Using `sddsanalyzebeam` and `sddsbrightness` [14], we can readily compute brightness curves from phase-space data at any point in the system. Curves for a standard APS undulator with 3.3-cm period are shown in Figure 5. We see that for the in-APS beamlines using 4.8-m undulators, we get two more more orders of magnitude improvement. Using 8-m undulators, which is possible with local ring modifications, we get another factor of two to three, bringing us very close to the brightness of beamlines in the TAA. This demonstrates convincingly that we do not give up any of the ERL's potential by building it as an upgrade to the APS.

One issue with respect to the ERL upgrade is whether to lower the beam energy. At first blush, this offers several

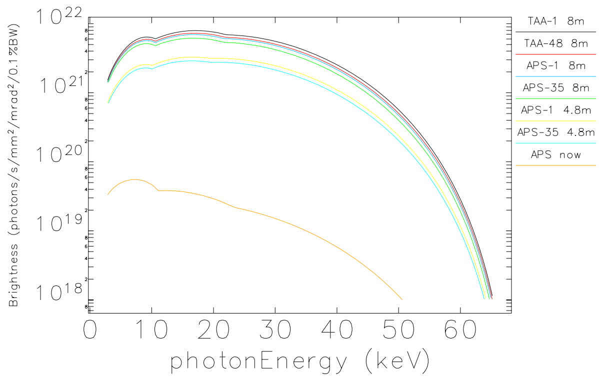

Figure 5: Comparison to present brightness using U33 undulators of various lengths in various positions in the ERL.

advantages: the linac is shorter, cheaper, and less power-hungry; the emittance growth due to ISR is reduced; and the TAA is smaller and cheaper. However, at lower energy the initial geometric emittance is larger. More importantly, the photons are softer and less numerous (both like E^2), so that shorter-period, smaller-gap undulators must be used. We analyzed this question by assuming hybrid-permanent-magnet undulators, which follow [15]

$$B_y[T] = 3.33 e^{-\frac{g}{\lambda_u}\left(5.47-1.8\frac{g}{\lambda_u}\right)}, \tag{1}$$

where B_y is the peak field, λ_u is the undulator period, and $g = 8.5$ mm is the full magnet gap. We ran `elegant` for a series of beam energies between 5 and 8 GeV to create a table of beam properties in that range. (8 GeV was chosen for its proximity to the design energy limit of APS, 7.7 GeV.) We then used `sddsoptimize`, `sddsurgent`, and `sddsbrightness` to adjust the beam energy and undulator period to maximize the brightness for a series of target photon energies starting at 3 keV, with proper consideration of power and power density limits [16]. The results, shown in Figure 6, demonstrate that there is a strong advantage to operation at energies above 7 GeV. Only for soft photons is there an advantage to lower-energy operation.

STORAGE RING MODIFICATIONS

To reduce the impact of ERL construction and commissioning on the user program, it is essential that the ability to store beam in the APS ring not be impaired. This also provides the option of gradually transitioning from stored beam operation to ERL operation. In the long run, stored beam at currents up to 200 mA may be provided as a special operating mode for users requiring high flux.

The APS has 40 sectors, with beamlines in sectors 1 through 35. Sectors 36, 37, 38, and 40 are used for rf cavities, while sector 39 is used for injection. The input transport line will thus use sector 40, while the output transport line will use sector 36. Hence, cavities must be relocated from sectors 36 and 40 to sectors 37 and 38, which requires lengthening the straight sections. In addition, the straight sections in sectors 36 and 40 will need to be lengthened to accommodate the magnets for the new transport lines.

Previous studies have demonstrated that we can create straight sections with an additional 3 m of free space by removing one quadrupole and one sextupole from each side of a straight section. This will have to be done in sectors 36 through 40. Given that APS has independent power supplies for all multipole magnets, we can mock this up in studies to ensure that there are no unforeseen problems. Lengthening the straight sections will permit retaining 14 of the 16 cavities, which should be adequate for 200-mA operation, albeit not with the same reliability as we presently have with 16 cavities.

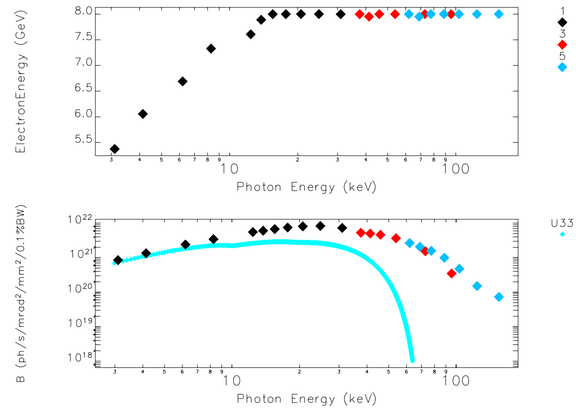

Figure 6: Results of optimization of beam energy and undulator period to maximize the brightness at various target photon energies for various undulator harmonics (1,3,5). Results for U33 at 7 GeV are shown for comparison.

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