POTENTIAL AND CHALLENGES OF UPGRADING THE ADVANCED PHOTON SOURCE TO AN ENERGY RECOVERY LINAC

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The Advanced Photon Source (APS) is a third-generation synchrotron radiation source operating at 7 GeV that has been in operation for over 10 years. In that time, the emittance has been improved from 8 nm to the present value of 3.1 nm, which is close to the practical minimum. Recently, APS undertook an intensive exploration of potential upgrades, including options for a replacement storage ring or Energy Recovery Linac (ERL) injector. Our conclusion was that only the ERL would provide a dramatically new capability. This paper discusses the potential performance available from an ERL upgrade to the APS and reviews the challenges of delivering this performance.

I. 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[1,2,3]. 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 light of this, we began investigation of an Energy Recovery Linac (ERL) upgrade.

The ERL was first described as an option for colliding beams by Tigner[4]. Only much later[5] was its potential as a possible x-ray light source explored. The ERL concept, illustrated in Figure 1, assumes an electron gun delivering an essentially continuous stream of bunches. These bunches are delivered at an energy (typically) of 5 to 15 MeV into a linear accelerator, through set of bending magnets called a merger. After acceleration, the bunches are returned to the upstream end of the linac using a transport line system, which, of course, necessarily incorporates bending. This transport system provides the opportunity to create synchrotron radiation through the incorporation of undulator magnets, for example. Upon returning to the upstream end of the linac, the high-energy beam is merged back into the linac. By proper choice of path-length for the transport line, the rf phase of the high-energy beam can be retarded by 180 degrees relative to the accelerating beam. Thus, the high-energy beam is decelerated and returns its energy to the rf fields in the cavities, which accelerate the new beam. Typically, ERLs make use of superconducting (SC) rf systems in order to ensure the greatest efficiency of energy recovery.

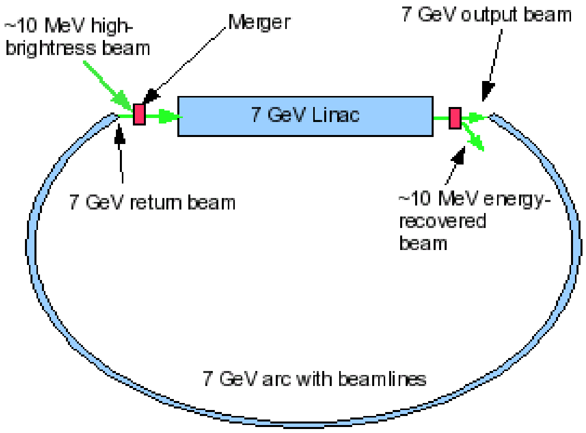

Figure 1: Schematic of an ERL-based light source.

In contrast to a storage ring upgrade, an ERL-based upgrade promises much smaller emittances, while providing beam currents that are comparable to those used today. The small emittances are possible by virtue of the fact that, unlike a storage ring, the beam in an ERL does not reach an equilibrium between quantum excitation and radiation damping. Rather, it has emittances that are much smaller than the equilibrium value, by virtue of only passing through the high-energy transport system once. A typical photocathode injector delivers a normalized emittance of a few microns for a bunch charge of several hundred picocoulombs. In contrast, the normalized equilibrium horizontal emittance of the APS ring is 43 μm, which indicates the promise of a light source where the emittance is dominated by the injector. Hoffstaetter[6] defines a series of possible ERL operating modes, including a high-coherence (HC) mode, the parameters of which are compared to the present-day APS parameters in Table 1. 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. A beam with such small emittance can provide fully spatially coherent radiation at wavelengths above 0.75 Å. In addition, the low energy spread promises high brightness for higher undulator harmonics.

These beam properties have some support in simulations[7,8], but have not been demonstrated experimentally. We will return to this issue in a later section. For now, we assume that such beam properties can be delivered at the exit of the injector at a nominal energy of 10 MeV.

Table 1: Comparison of present APS beam parameters to proposed ERL high-coherence-mode parameters.

Quantity	**APS now**	**High coherence 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
Vertical emittance (pm)	25	6
Rms bunch length (ps)	>20	2
Rms energy spread (%)	0.1	0.02

II. Upgrade Constraints

A requirement for any upgrade is that all user beamlines that now receive beam in the APS must continue to receive beam after the upgrade. We also insist on a minimal impact on operations during the construction and commissioning period, in order to avoid disruption of user programs. In addition, it is highly desirable that we retain the ability to store beam even after completion of the ERL. This allows more flexibility for the facility and also provides an operating mode for supplying beam to users between commissioning periods. Stored beam should be achieved using the existing APS injector, which we must therefore take care not to disrupt.

The APS is a 40-sector ring, with straight sections 1 through 35 devoted to x-ray beamlines. Straights 36 through 40 are used for rf cavities and injection hardware. At present, there are four rf cavities in each of four different straight sections, for a total of 16 cavities. Bringing ERL beam into and out of the ring will require installing significant hardware in straights 36 and 40, which means that eight rf cavities must be removed. Ideally, all of these would be reinstalled in other straight sections. At minimum, we must reinstall six of the eight cavities, in order to allow storing 200 mA in the ring (twice our present operational current). This will require lengthening straight sections 37 and 38, which can be done by removing one quadrupole from each of the triplets that bracket the straight section. This will accommodate six of the eight cavities. Lengthening straight 35 will allow placing perhaps two additional cavities in the downstream end of the straight. We will also need to lengthen straights 36 and 40 to provide sufficient space for ERL magnets. Straight 39 will probably be lengthened in order to keep the system regular and provide space for diagnostics and other displaced items. Because APS has individual power supplies for all quadrupoles, we can and will mock up this configuration well ahead of time by turning off the quadrupoles we are planning to remove.

A less definitive set of constraints is imposed by the APS site. It is imperative to avoid bending the ERL beam more than absolutely necessary, in order to avoid emittance growth, energy loss, and energy spread growth. The region to the north of the APS is thus the most desirable location for the ERL, since sectors 36 through 40 are on the north side of the ring. Unfortunately, this region is also a wetland, so environmental issues will need to be carefully considered.

III. Design Concept

Figure 2 shows a possible design for an ERL upgrade to the APS that satisfies the above constraints. As mentioned above, we assume a 10-MeV injector delivers beam into our system, which starts with a 7-GeV single-pass linac that accelerates beam away from the APS ring and toward a new 7-GeV turn-around arc (TAA). On exiting the TAA, the beam is heading toward the APS and is eventually brought into straight section 40, making nearly one turn around the APS ring before coming out at straight section 36 and returning to the linac for deceleration.

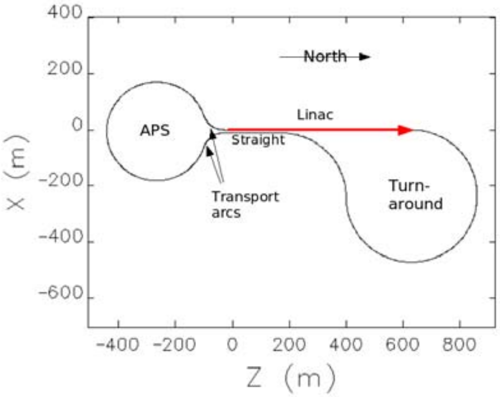

Figure 2: Geometry of a design concept for an APS ERL upgrade.

Because of the cost and capabilities of the superconducting linac, we should not consider this as a single-stage upgrade. Instead, we should plan for a series of upgrades and facility enhancements. This is why we initially accelerate the beam away from the APS, since doing so sets the stage for two additional upgrades. The first of these is use of the linac as a driver for a straight-ahead short-pulse facility, perhaps involving a free-electron laser. This would involve[9] a second injector delivering a kHz-rate ~1nC beam at perhaps 500 MeV to the merger, so that it is accelerated to 7.5 GeV. By virtue of having 500 MeV energy difference, the ERL and ultra-short facility beams could be separated at the end of the linac, thus allowing simultaneous operation.

The second additional upgrade is building a user hall and beamlines around the TAA, which has 48 straight sections and can thus support a very significant expansion of the number of available beamlines. The TAA optics (see below) are designed to accommodate 8-m-long undulators. Sending the ERL beam into the TAA first ensures the highest-quality beams for these new beamlines, without any degrading effects from the APS ring and the incoming and outgoing transport lines. This ensures that the ultimate performance of the ERL upgrade is equal to the ultimate performance of a greenfield ERL.

This concept, with its 7-GeV single-pass linac and large, 7-GeV TAA, is perhaps the most expensive and complex option, but also promises the greatest flexibility and potential. Options for reducing the cost, size, and complexity include multi-pass use of a shorter linac, use of a lower-energy TAA, or some combination thereof. We plan to study such options in detail. For the present, however, we report only on the “ultimate” configuration.

IV. Modeling and Performance Predictions

A model of the system from the 10 MeV injection point to 7 GeV and through deceleration was created using **elegant**[10]. The model includes a full beam optics design and allows tracking with radiation effects to assess emittance and energy spread growth. Before giving detailed results, we discuss the design in more detail.

IV.A. Linac Configuration and Optics

For the linac, we assumed TESLA-style superconducting cavities[11], which is an expedient choice as the wakefields, gradient limits, and other properties are published. In reality, a design with fewer cells per cavity may well be needed to allow extraction of higher-order mode power. We used a gradient of 20 MV/m, which is well within the realm of existing superconducting cavity technology. We assumed that each cryomodule would contain eight such cavities, with two cyromodules forming a superstructure unit (SSU) with space for quadrupoles, diagnostics, and steering magnets every two SSUs at the low-energy ends and every four SSUs in other areas. Quadrupoles are arranged in a doublet configuration. The effective gradient of the linac is 10 MV/m.

Because each point in the linac must support beams with two different energies (e.g., 10 MeV and 7 GeV at the injection and dump ends), the graded-gradient principle[12] was used for the two-beam optics design. This principle states that the focusing elements should be set to give constant focal length for the lowest energy beam present at the location of the element. We started by assuming that all quadrupoles would have the same spacing and focal length and used **sddsoptimize**[13] and **elegant** to optimize these parameters to minimize the maximum beta functions. Following this initial optimization, we used **elegant**'s built-in optimizer to adjust the strength and spacing of all elements, giving another factor of two reduction in the maximum beta functions. The initial beta functions were allowed to vary during these optimizations, but were kept within reasonable bounds. Figure 3 shows the resulting optics for the linac.

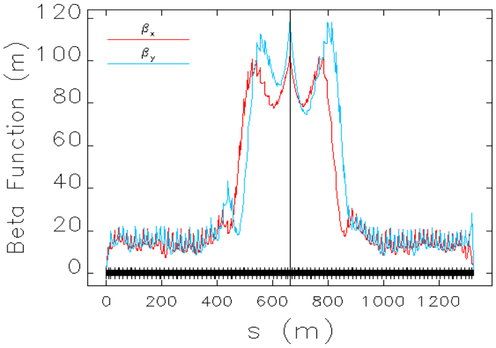

Figure 3: Beta functions for 7-GeV ERL linac. To the left of the linac is the acceleration portion. To the right of the line is the deceleration portion.

IV.B. Bending Arc Design

The TAA design must fulfill several goals. It must, of course, turn the beam around 180 degrees and do so with minimal degradation of beam emittance and energy spread, while fitting on the available site. It must also provide space for many new beamlines accommodating undulators up to 8 m in length.

For a single-pass electron transport line, as distinct from a storage ring, the quantum-excitation rate and hence the emittance and energy spread growth due to ordinary synchrotron radiation both scale inversely with the bending radius[14]. Preservation of emittance and energy spread thus requires a large bending radius. Reduction of emittance growth additionally requires strong focusing, just as in storage rings. In addition, the cell must be achromatic to avoid increasing the effective emittance seen by users[15], as well as to avoid increasing the true emittance via quantum excitation in the undulators. The mean radius of the TAA was chosen as 230 m, which is 30% larger than the APS radius and about as large as will fit within existing site boundaries.

Because the ERL will have short bunches, of the order of 2 ps rms, we must concern ourselves with coherent synchrotron radiation effects as well. For a fixed bending angle, CSR effects depend only weakly on the bending radius[16]. A small vertical beta function in the dipoles is helpful, which is again a typical feature of strong-focusing designs with reduced emittance growth from quantum excitation.

An additional design principle[17,18] for CSR control is to use an isochronous design with judicious choice of horizontal betatron phase advance to obtain cancellation of horizontal CSR kicks. Particles receive effective horizontal kicks from CSR when they are exposed to CSR in a location with non-zero dispersion. The kick depends on the particle's location in the bunch and on the bunch distribution at the time the radiation was emitted. In an isochronous lattice, the bunch distribution and each particle's location in it are essentially fixed, meaning that each particle will receive the same energy kick in each equivalent location in the lattice cell. If the horizontal phase advance per cell is 2πN/M, where N and M are integers, then the horizontal kicks will cancel after M cells. We chose a horizontal phase advance per cell of 5π/4, which provides CSR cancellation every 4 cells. The total number of cells in the TAA is 48. The optics for the cell are shown in Figure 4. A triple-bend achromatic (TBA) design is used as this makes it straightforward to have an isochronous, low-emittance cell.

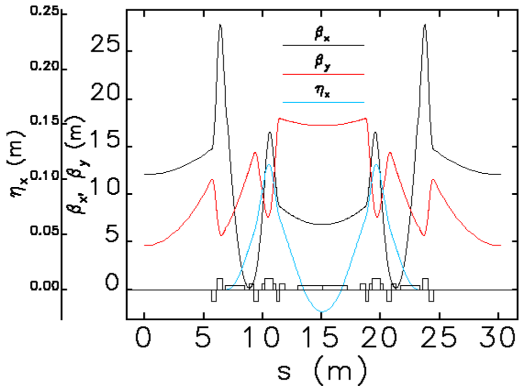

Figure 4: Lattice functions for the TAA cell.

Of course, this design does not cancel the CSR energy kicks. Quite the contrary, it allows them to build up in a consistent pattern. Cancellation of energy kicks could be accomplished in a non-isochronous system, but this would require time-reversal of the longitudinal distribution. As such, it requires full compression of the bunch and would potentially have very serious effects on the emittance. In addition, it requires a chirped bunch, which increases the energy spread and is undesirable for x-ray generation.

Although there is space to make the bending radius of the TAA quite large, this is more difficult for the transport arcs at the entrance and exit of the APS. In the design shown here, we attempted to bring the linac and the long return line into the same tunnel in order to save cost. This requires a mean radius of about 80 m for the incoming and outgoing arcs. This could be relaxed considerably, but only at higher expense. It would also make it more difficult to clear the magnets in the existing ring. Hence, in the present design we've used 80 m. The lattice is once again an isochronous TBA with 5π/4 horizontal phase advance per cell.

The optics for the APS ring itself are less flexible. Because we have a double-bend structure, we cannot have an achromatic cell that is isochronous. Hence, we used a tuning of the cell that minimizes emittance growth subject to the achromatic condition.

In addition to the arcs, we also matched various transitional sections between the linac and arcs in order to create a model from 10 MeV to 7 GeV and back.

V. Tracking Results

We next used **Pelegant**[19], the parallel version of **elegant**, to perform tracking studies of this design. Starting at 10 MeV, we used an initial energy spread of 0.1%, an initial bunch length of 2 ps, and initial normalized transverse emittances of 0.1 μm, which are Cornell's high-coherence mode parameters[6] combined with a reasonable assumption for the initial energy spread based on simulations[7]. Initial distributions were assumed to be Gaussian in all phase space coordinates.

V.A. ISR and CSR Effects

As indicated above, the impact of ISR and CSR is a major concern due to the potential impact on the horizontal emittance and energy spread. Figure 5 shows the evolution of these quantities in the 7 GeV portion of the system. We see that the horizontal emittance grows by about 30% in the TAA and by about 50% in the APS ring. We also see that the effect of CSR for a 19 pC beam is negligible. Indeed, it is similarly negligible for a 77 pC beam corresponding to 100 mA average current, which equals the present average current of the APS ring.

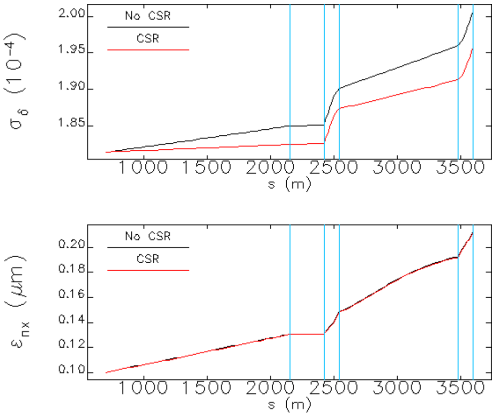

Figure 5: Energy spread and horizontal emittance evolution in the 7-GeV portion of the ERL. The vertical lines show, in order from left to right, the end of the TAA, the start of the injection arc, the start of the APS, end of the APS, and the end of the extraction arc.

One curious feature of the evolution of the energy spread is that it actually decreases due to CSR. This can be understood by realizing that the energy spread at 7 GeV is dominated by the contributions of rf curvature, so that the longitudinal phase space exhibits a cos(ωt) character. For a Gaussian bunch, CSR tends to decelerate the center of the bunch. Since this part of the bunch has higher energy than the bunch average, weak CSR may reduce the energy spread.

Because CSR effects are so negligible, even in the APS ring, it seems likely that the CSR-canceling design of the TAA and transport arcs is unnecessary. We will explore the option of using simpler DBA cells in future work. One consideration is that isochronous cells are advantageous for other reasons than CSR control, for example, reducing the changes in beam arrival phase at the linac due to beam energy changes (which can result from changes in undulator gaps).

V.B. Predicted Performance

Performance of the ERL upgrade must be evaluated by computation of the x-ray properties. Of particular interest are the average spectral brightness and the fraction of the beam that is transversely coherent. We used the programs **sddsanalyzebeam** and **sddsbrightness** for brightness calculations. These programs work directly from phase space distributions dumped by elegant, allowing us to easily perform brightness computations that include any emittance growth, energy spread growth, or mismatch that may occur during transport of the beam.

In order to provide a concrete, straightforward comparison, we used an APS standard U33 (3.3-cm-period) undulator, even recognizing that this is not necessarily the ideal device for any particular application. Figure 6 shows the brightness curves for U33 devices in the APS now compared to various locations in the ERL. We see that, depending on the photon energy, the brightness increases by about two orders of magnitude, with more significant increases at higher photon energy. This is a result of the low energy spread, which enhances the brightness of the 3rd and 5th harmonics. The coherent fraction similarly increases by about two orders of magnitude at 3 keV, with greater increases at higher photon energy.

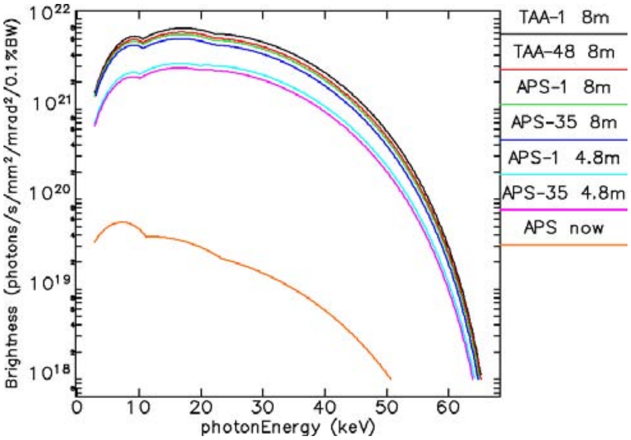

Figure 6: Brightness of APS now (100 mA, 2.4-m U33) compared to ERL high-coherence mode for U33 undulators of various lengths in different locations.

V.C. Impact of Reduced Injector Performance

The spectacular performance improvements predicted for the ERL upgrade depend critically on the performance of the injector. Average current, emittance, and energy spread are all important. Determining the impact of failing to achieve the desired values helps us assess just how critical injector performance is. Of course, reduced average current impacts the brightness and flux in a simple linear fashion. Emittance and energy spread increases must be assessed using simulation. Energy spread is determined by the bunch duration delivered by the injector, rather than by the energy spread from the injector (which is adiabatically damped). We looked individually at the variation in brightness resulting from increases in initial emittance and bunch duration.

Figure 7 shows the impact of increased initial emittance. For an initial normalized emittance of 1.6 μm, the brightness is the same as or slightly better than it is for APS presently. To obtain about an order of magnitude increase in brightness for an identical U33 undulator, we require a normalized emittance of about 0.2 μm.

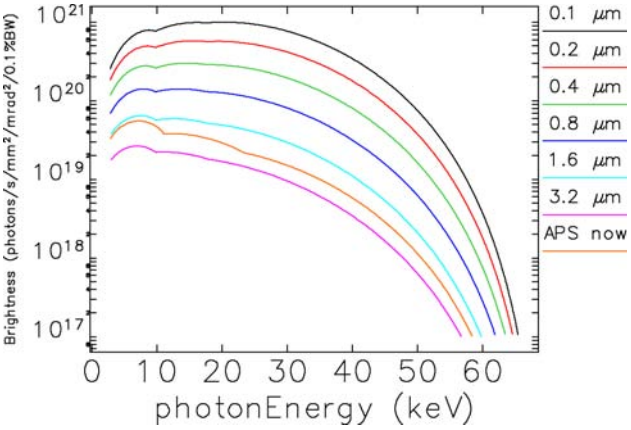

Figure 7: Effect of initial normalized emittance for 2.4-m-long U33 devices in the first in-APS straight section.

In contrast, the impact of increasing the initial bunch duration is much smaller, as Figure 8 shows. For 2.4-m-long undulators, even doubling the initial bunch length results in a less than two-fold decrease in the brightness. This is welcome news because one way to obtain lower emittance is to allow the initial bunch duration to be somewhat longer, as this reduces space charge effects in the injector. However, when 8-m-long undulators are employed in the TAA, the effect of longer bunch duration and the resulting higher energy spread becomes more serious. Since the TAA will not initially be equipped with undulators, this suggests that we may start ERL operation with an injector that delivers ultra-low emittance but relatively long pulses, but that in later stages we need to attempt to reduce the pulse length as well.

VI. Challenges

The predicted performance of this upgrade is revolutionary. However, there are many challenges that must be met in order to deliver this performance, not to mention doing so with reasonable reliability and costs. Research is ongoing at many facilities. Here, we touch on a few of the most challenging requirements and comment on APS-specific issues, without any intention of completeness.

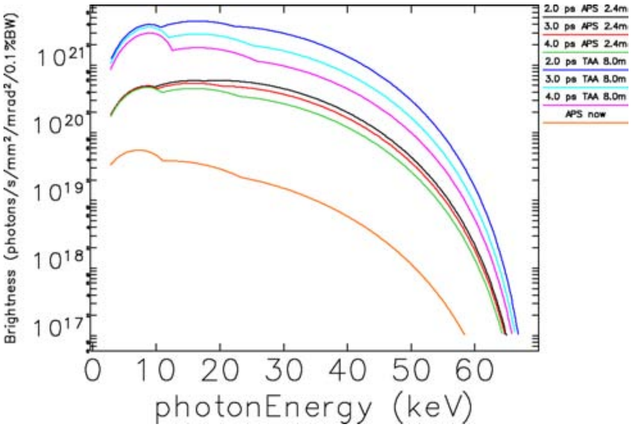

Figure 8: Effect of initial bunch duration on the brightness for the first APS beamline and first TAA beamline, assuming undulators of various lengths.

Perhaps the most challenging aspect of the ERL upgrade is the injector. We saw above that a normalized emittance of 1.6 µm is needed to "break even" with present APS performance, assuming that the gun delivers an average current of 25 mA. The JLab ERL injector[20] presently delivers 9 mA in 122-pC bunches with emittance of under 10 µm. Using a rough linear scaling of the emittance with charge[7], we estimate 1.5 µm for a 19 pC bunch, which is just below the break-even point. Of course, the JLab injector is optimized for much higher bunch charge, which motivates a relatively large laser spot size (2 mm rms) on the cathode. This increases the impact of the thermal divergence. Hence, gun technology may not be as far from the requirements as this simple comparison indicates. Still an improvement of about an order of magnitude is necessary to achieve the performance predicted for the high-coherence mode.

Obtaining high average current is another challenge for the injector. One of the issues here is achieving workable cathode lifetimes. The JLab ERL has a cathode lifetime[20] of 400 C, corresponding to 4 hours of operation at 25 mA. All other things being equal, if the laser spot size is smaller (in order to obtain smaller emittance[7]), the lifetime will decrease since it is just proportional to the active area of the cathode. While a smaller laser spot can be moved around on the cathode to lengthen the effective lifetime, it is unclear if this is compatible with production and preservation of ultra-low emittances. Failure to achieve significantly higher cathode lifetimes would be a serious liability for an ERL-based facility, since it would entail frequent interruption of user operations for cathode replacement. Third-generation light sources like APS typically operate with a mean-time-between-faults of 80 to 100 hours. Given that beamline optical elements typically take an hour to stabilize under the heat load of the x-ray beam, short cathode lifetimes and long replacement times would severely impact the productivity of users. Present-day sources deliver beam about 98% of scheduled time.

A possible, though challenging, scheduling mode for the APS after the upgrade would involve operation as an ERL for a part of the day and operation as a storage ring for the remainder. This will be possible with our concept because we explicitly plan to preserve both the stored-beam capability and the existing injector. Storage ring operation periods would serve high-flux users and would provide scheduled periods for cathode replacement. In addition, liquid helium could be generated and stored for use during ERL operations, thus decreasing the peak electrical power requirement. Such considerations show that there are ways to mitigate the impact of a short cathode lifetime or even turn it to our advantage. Still lifetimes of at least eight hours seem desirable if experimenters are to be productive. In addition, improved rf and x-ray beam position monitors would be necessary to allow quickly and accurately returning the beam to the desired position for each mode.

The linac itself also represents a formidable challenge, owing to its size, complexity, and power requirements. Our concept assumed operation at 20 MV/m, which is conservative compared to what can be achieved in superconducting cavities. Assuming quality factors Q of 10^{10}, the rf power losses at 2K will be about 16 kW. Based on experience at SNS, we assume that static losses will be as much as 50% of the dynamic losses. We must also allow a margin for all other losses and loads. These assumptions lead to the need for approximately 32 kW of cooling power at 2K, which implies 32 MW of helium compressors. This is much larger than any existing cryoplant. The site-installed wall-plug power requirement is on the order of 40 to 45 MW.

While this is not prohibitive, it is clearly desirable to reduce the power requirements. A cryoplant of this size would be very expensive to operate, not simply because of the power requirements, but also because of staffing and maintenance requirements. There are several approaches to mitigating these concerns. First, we could build a multipass ERL injector[21]. This would reduce the cost and power requirements of the linac, but would prevent use of the linac as a driver for short-pulse experiments at 7 GeV. Recent work[22] indicates that with proper attention to cavity design beam-breakup would not be an issue in a two-pass linac. Second, we could build a longer linac, thus allowing the voltage V of each cavity to be reduced. Since the power dissipation in each cavity is proportional to V^2, the total power requirement scales inversely with the length of the linac. Third, we can develop cavity technology that increases the Q. Increasing the Q to 4×10^{10}, for example, would cut the wall plug power for the cryoplant to ~10 MW, which is more manageable. Finally, we can investigate improved cryogenic system designs with an eye to improved efficiency and reduced static losses. A combination of some or all of these approaches seems likely to yield a workable solution.

An issue with existing ERLs, such as the JLab machine, is control of beam loss. This will be important for the proposed machine as well, in particular because the shield wall for the APS itself was built to accommodate an injector that delivers only about 40 nA. Even losses at this level would create an unacceptable radiation hazard outside the shield wall, yet this is less than 10^{-6} of a 100 mA beam, such as might be delivered by an ERL injector. We've estimated that for 100 mA ERL operation, losses in the APS ring itself must be less than ~170 pA, or 1.7 parts per billion (PPB). In normal 24-bunch stored beam mode, losses in one turn around the APS are about 10% of this, so it is not impossible to achieve such a low level of loss. The ERL beam is, of course, different from a storage ring beam, since the latter has a predictably gaussian distribution with very tenuous tails, whereas a linac beam may have a significant halo. Careful understanding and control of beam halo is a challenge that must be met in order to ensure that the ERL can operate safely.

Of course, we are concerned about losses in other parts of the system as well. These are somewhat less of an issue in the new areas of the project, since we can design the shielding to meet somewhat higher loss levels. However, the losses in the linac will need to be on the order of 10 PPB/m, in order to keep cryogenic loading to less than 10% of the rf load. Collimators may be needed in front of the linac cavities to achieve this result.[23]

A final issue that merits mention is the impact of insertion devices on the ERL. Users at third generation light sources routinely change the gaps of their insertion devices as dictated by experimental needs. In high energy rings like the APS, at least, this has relatively little impact on operations. In an ERL, however, this may not be the case. The proposed ERL will, in its final form, contain many more insertion devices that are each significantly longer than the present devices. Thus, there is the potential for significant variation in the energy loss per pass as well as in the growth of emittance and energy spread. These will potentially impact not only downstream users, but also energy recovery itself. Possible mitigating approaches include booster linac cavities at intervals in the 7-GeV transport system, which will be adjusted continuously to restore the average beam energy. This will not, of course, address the energy spread issue. Details of this issue are under study now for the APS design. Lowering the beam energy would reduce the quantum-excitation- and energy-loss-related aspects of this problem, perhaps at the expense of somewhat more impact on the beam optics.

This discussion merely touches the surface of some of the most pressing issues for an ERL upgrade. These and other issues are under study at APS and elsewhere.

VII. Conclusion

APS has considered a number of avenues for a major upgrade of the facility. We determined that replacing the storage ring does not provide a sufficient improvement to justify the necessary interruption of user operations. In contrast, adding an ERL injector promises revolutionary improvements in brightness and transverse coherence. We have developed a high-performance concept for such an upgrade that maintains the ability to operate in stored beam mode with the existing injector. This concept provides additional upgrade paths in the form of a dedicated ultra-short pulse facility and a large number of new insertion device straight sections.

Assuming 25 mA average beam current, 0.1 μm normalized emittances, and 2 ps rms bunch duration, we predict more than two orders of magnitude improvement in brightness and transverse coherence. These parameters are very challenging, requiring up to an order of magnitude improvement compared to existing performance.

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