AN ENERGY RECOVERY LINAC UPGRADE FOR THE ADVANCED PHOTON SOURCE LOCATED IN THE STORAGE RING INFIELD*

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Abstract

Recently physicists at the Advanced Photon Source (APS) have begun to explore a revolutionary upgrade based on emerging energy recovery linac (ERL) technology. In an ERL, the energy of the 7-GeV, 100-mA beam is recovered after the beam passes through user beamlines by decelerating the beam back through the same superconducting linac cavities that accelerated it. The main constraint on this upgrade is that the existing APS beamlines must not be disturbed. This requires that the APS storage ring be used as a single-pass transport line in the overall ERL beamline layout. A natural place to locate the ERL is inside the existing APS storage ring "infield" area, which has unoccupied space south of the existing APS injector complex. Other important constraints include minimal disturbance of existing buildings and injector beamlines. The existing injector complex should be preserved so that stored beam operation can be continued throughout and beyond ERL construction and commissioning. In this paper we describe a layout that satisfies these constraints. We also estimate the amount of emittance increase the beam will experience before it is delivered to user beamlines.

INTRODUCTION

A factor of 100 or more increase in brightness should be possible in the existing APS ring by making use of ERL technology [1]. In addition, a possible ultrafast ($\leq$ 1 ps FWHM) mode will appeal to user groups performing timing experiments. An obvious place to put the ERL linac is in the APS infield [2]. Placing a new recirculating 7-GeV superconducting linear accelerator inside the APS storage ring (SR) offers some advantages relative to the external ERL option proposed by Borland *et al.* [1]. Both options preserve the existing APS user beamline infrastructure as a bottom line requirement. As with the external ERL option, the existing APS injector complex is preserved and stored beam operation will be available to users as the ERL is commissioned. The infield ERL option has the advantage that the APS infield is already heavily developed with utilities and roads so that locating an ERL here would have minimal environmental impact. In contrast, the external ERL must be built over wetland areas. Various utilities in the infield would most likely have to be relocated. New access paths to the ring superdoors would also probably need to be created, depending on the exact ERL configuration. Utility relocation and preserving access to the ring superdoors are expected to be of minimal to modest cost compared to the scale of the ERL upgrade.

The main disadvantage to locating an ERL in the APS infield is limited real estate. Lack of space, together with foreseeable maximum cavity gradients and Q values will require at least some amount of recirculation to obtain 7 GeV for an infield ERL. The recirculation arcs add cost and complexity as well as increase the emittance due to incoherent and coherent synchrotron radiation (ISR, CSR). The multipass Beam Breakup (BBU) instability will also require careful evaluation due to the high cw current anticipated in the machine (100 mA) [3]. Even though space is limited in the APS infield, room for long undulators can be found, albeit with some difficulty, so some expansion of user facilities may be possible. However, the expansion would clearly be much less than available from an external ERL [1]. The infield ERL configuration has the flexibility to allow commissioning of energy recovery without disturbing the users. This is a distinct advantage over the external ERL option, which requires use of the APS ring to commission the energy recovery process.

INFIELD ERL INJECTION, EXTRACTION AND RF CONSIDERATIONS

To minimize injection and extraction transport line complexity, the infield ERL injects and extracts the 7-GeV beam into the APS via a common dipole and set of matching doublets in storage ring (SR) sector 37, as shown in Figure 1. Following Decker's suggestions for the external ERL option, all four rf cavities as well as the Q1 quadrupoles are removed from sector 37 to make room for the new dipole and matching doublets [1]. Decker has shown that the four removed rf cavities can easily be relocated to the other existing rf cavity sectors, thereby preserving the present storage ring accelerating voltage. Additionally, it is likely possible to condition the existing storage ring cavities 15% higher in gradient. Higher cavity gradients would require only 14 cavities to maintain the existing ring accelerating voltage, thereby requiring relocation of only two of the removed rf cavites.

In Figure 1 the injection/extraction dipole bends at approximately 2.3 degrees (half the storage ring dipole bend angle) at 7 GeV so that the injection and extraction beam pipes have enough clearance at the Q2 quads. This dipole can be shorter than 1.5 meters to save space (storage ring dipoles are 3 m long). The dipole field can be increased above that of the existing storage ring dipoles because the

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ring dipoles operate at a relatively low field of 0.6 T at 7 GeV. If more space is needed in this section, one could shorten the storage ring dipoles upstream and downstream of sector 37 to make more space for the injection and extraction beam pipes.

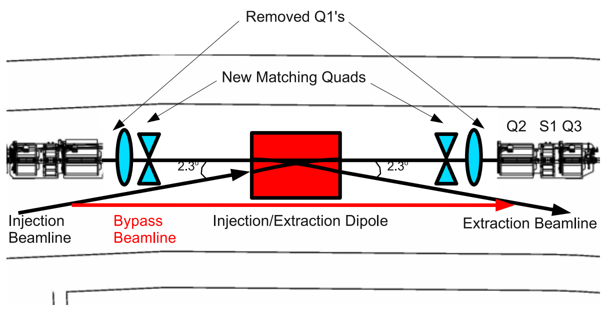

Figure 1: Storage ring sector 37 ERL injection and extraction configuration.

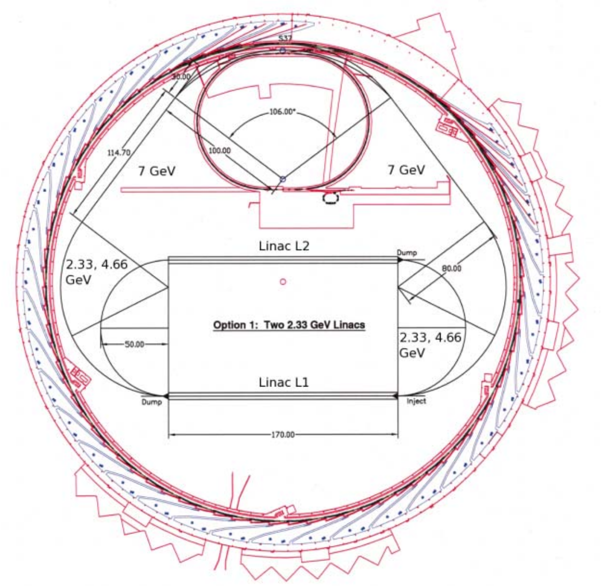

Figure 2: Layout of the three pass recirculating linac in the APS infield. Shown at each end of the linacs is a single arc which actually contains two beams of energy 2.33 and 4.66 GeV respectively.

INFIELD ERL LAYOUT

Figure 2 shows the infield ERL configuration consisting of two 2.33-GeV linacs arranged in a racetrack configuration. The linacs have an effective gradient of 13.7 MV/m that corresponds to a cavity gradient of 22.8 MV/m assuming a packing fraction of 60%. This means that 60% of the physical linac length is rf cavities. Gradients at this level are presently achieved in TESLA cavities when operating in pulsed mode [4]. Each linac will therefore have 102 rf cavities for a total of 204 rf cavities (each roughly 1 m long) for both linacs. Each linac is, relatively speaking, short at only 170 m. This is only about 30% of the length of the full 7-GeV linac assumed for the external ERL option [1]. Using a graded gradient optics design for the (relatively short) linacs [5] will minimize the severity of the linac beam optics compared to the external ERL option.

In Figure 2 the beam is injected at 10 MeV into linac L1 and accelerated to 2.33 GeV where it is transported to linac L2. L2 brings the beam to 4.66 GeV where it is transported back to L1 at the injection point. The beam is brought to 7 GeV after being accelerated a second time in L1. The 7-GeV beam is transported to the ring and is injected at sector 37 via the injection scheme shown in Figure 1. Here all 7-GeV transport arcs are maintained at approximately 80-100 m minimum bend radius to minimize incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) [1]. After one turn in the ring, the beam is extracted at sector 37 and transported to the L1 injection point. The beam is then decelerated twice through L1 and once through L2, and dumped at low energy at the downstream end of L1. A single arc is shown connecting the two linacs for clarity though it actually consists of two separate low-energy arcs at 2.33 and 4.66 GeV, respectively. The racetrack shape allows the helium refrigerator to be easily located close to each linac, roughly in the center of the racetrack. The additional straight sections of transport line at 7 GeV may be possible locations for long undulators. If higher gradients prove achievable, it may be possible to construct a 3.5-GeV single-pass linac in the infield. Such a linac would achieve 7 GeV beam energy after only a single recirculation arc.

One advantage of the infield ERL configuration is that it allows energy recovery commissioning at the full 7-GeV beam energy before beam is ever introduced into the storage ring. Figure 1 shows schematically a bypass line that allows the 7-GeV beam to bypass injection into the SR. There is a big advantage to have the ability to commission full 7-GeV energy recovery without disturbing the APS users for the relatively small cost of an extra transport line in the booster tunnel. One can also imagine a staged approach to commissioning energy recovery. In stage 1, the beam is accelerated to 4.66 GeV, then decelerated back to the injection energy and dumped at a special beam dump after linac L2. In stage 2, full 7-GeV energy recovery commissioning is completed using the bypass transport line shown in Figure 1. The final stage would be to demonstrate energy recovery using the SR to transport the beam.

INFIELD ERL EMITTANCE AND ENERGY SPREAD CALCULATIONS

Initial calculations of emittance and energy spread were performed for a simplified model of the infield ERL. ISR and CSR effects are expected to be most important at 7 GeV, so the initial calculations were performed for only the 7-GeV arcs as shown in Figure 3. The figure shows parts of the ERL that were modelled. The low energy arcs of the ERL were not modeled, but emittance and energy spread blowup is expected to be much less than that at 7 GeV. At injection into and extraction from the ring, detailed optics matching was not performed, but an ideal match was imposed in the simulations.

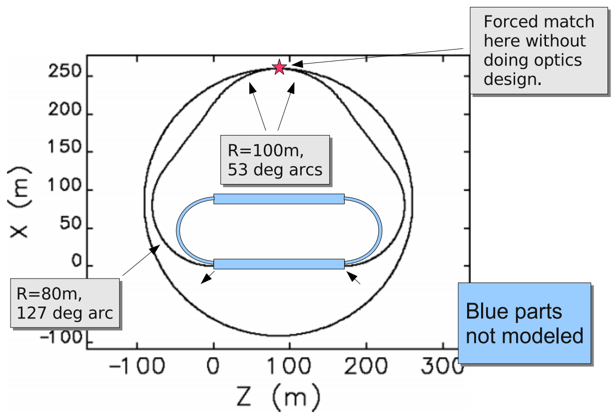

Figure 3: Layout of the infield ERL indicating parts modeled by elegant. At injection into the ring, detailed optics matching was not performed, but an ideal match was assumed for the emittance and energy spread calculations.

Figure 4 shows the emittance and energy spread increase from the exit of the ERL linac at 7 GeV through the APS and back to the entrance of the ERL linac, assuming Cornell's high-coherence mode parameters [6] ($\epsilon_n = 0.1$ μm, $\sigma_\delta = 0.02\%$, and $\sigma_t = 2$ ps) as starting values. One sees about a factor of two emittance increase and about 16% energy spread increase. The small low-energy recirculation arcs in the ERL were not modeled but are expected to contribute much less emittance and energy spread increase due to the strong energy dependence of these effects. Nevertheless, effects of the low-energy arcs would have to be included in a detailed analysis of the infield ERL. The effect of emittance and energy spread increase for the infield ERL option is only slightly worse than that for the outfield ERL option [1].

CONCLUSION

A concept for a racetrack ERL located in the APS infield was described. The maximum achievable gradient ultimately determines the number of linacs as well as the recirculation arc scheme used. In general, minimizing recirculation arcs and linac length are desirable. This desire pushes the effective and cavity gradients to higher values, which are more difficult to achieve reliably. Initial simulations of emittance and energy spread increase due to ISR and CSR show modest increases in these quantities. Multipass beam breakup also needs to be simulated to make sure that at 100 mA the use of a multi-pass system does not cause instability. Path length adjustment is also required, to ensure complete energy recovery. A bypass transport line that allows the 7-GeV beam to be brought back to the recirculating linac is a nice feature of this design. The bypass line will allow energy recovery to be commissioned

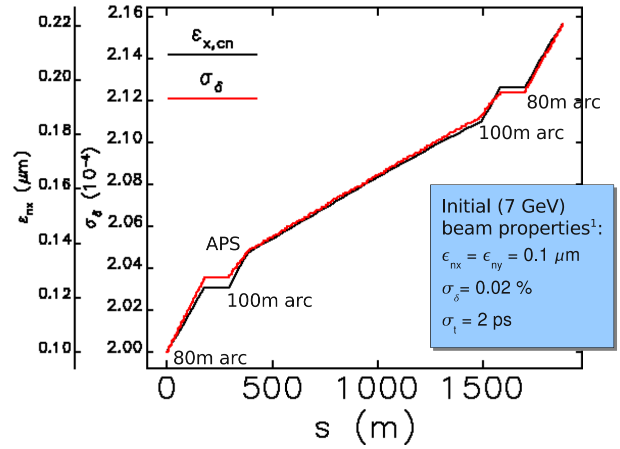

Figure 4: Emittance and energy spread increase calculated from the exit of the ERL linac at 7 GeV through the APS and back to the entrance of the ERL. The 80- and 100- m values refer to the mean radii of the bending arcs.

in the ERL without having to use the SR for recirculation. One can envision a staged approach to commissioning energy recovery where energy recovery is first demonstrated at low energy using only the ERL racetrack. Energy recovery at the full 7-GeV energy is then demonstrated without using the SR and finally the full system is commissioned.

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