ERL STAGING*

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Abstract

Energy recovery linac (ERL) staging is a novel concept that provides a practical path to upgrading an existing synchrotron light source while minimizing disruption to the users and managing the technical risk. In the very first stage, the accelerator operating parameters are comparable to CEBAF without recirculation. Therefore, initially, energy recovery is not required and the injector is more modest. Consequently, the technical risk is significantly reduced relative to the full ERL. Using the Advanced Photon Source (APS) as an example, the first stage is based on a full-energy, 7-GeV superconducting radiofrequency (srf) linac and a pulsed electron source that is almost off-the-shelf. Given a linac geometric emittance that is much smaller than the storage ring, the x-ray brightness can exceed the APS at a relatively low average current. Furthermore, the spatial coherence fraction can be higher and the x-ray pulse length shorter by about two orders of magnitude compared to the APS. Valuable srf operating experience is attained at an early stage while allowing critical srf and energy recovery issues to be studied. Energy recovery is commissioned in stage 2. The optics design and performance at each stage will be presented.

STAGING CONCEPT

An ERL is a promising upgrade option for the Advanced Photon Source (APS) [1]. The “ultimate” ERL promises an average x-ray beam brightness that is orders of magnitude higher than the present APS [1,2]. However, present-day accelerator technology does not meet the demanding performance requirements of an ERL-based x-ray source. Critical accelerator R&D includes high-average-current ultra-low emittance continuous-wave (cw) electron sources, high-quality-factor srf cavities, and high-power rf input couplers. ERL staging is introduced as a complementary approach to upgrading an existing x-ray source to an ERL. Unlike a stand-alone prototype ERL R&D facility [3], the staging concept allows delivery of a low-emittance linac beam through the APS in stages while critical injector and rf R&D continues in parallel. At each stage, microscopy and coherent imaging users benefit from improvements to the x-ray source performance [4], initially modest and gradually approaching the promise of a high-average-current, diffraction-limited ERL source. In this sense, each stage is a stand-alone upgrade in a series to reach a final goal.

Two criteria for the first stage are that initial operation be non-energy-recovered and the average x-ray brightness equals or exceeds the present APS. Stage 1 is based on a full-energy 7-GeV superconducting radiofrequency (srf) linac and a pulsed electron source that is almost off-the-shelf. The beam is dumped after a single pass, although recirculation is also possible. The accelerator operating parameters are comparable to CEBAF [5]; therefore, energy recovery is not required. This meets the first criterion for staging. As will be shown in the next section, the second criterion can also be met with a relatively modest injector average current. Consequently, the technical risk for stage 1 is significantly reduced relative to a full ERL. On the accelerator side, valuable srf operating experience is attained at an early stage, including testing the cryogenic system dynamic and static heat load. Other critical issues can also be tested [1,2]: beam loss control, path-length tuning, compensation for user changes to undulator gaps, and a beam-based longitudinal alignment system.

Energy recovery is implemented in the second stage with construction of a simple return arc. Testing of critical issues in stage 1 reduces the technical risks. As with the ultimate ERL concept, the existing storage ring injector complex is unchanged and the ability to store beam is thereby unaffected. This minimizes “dark time” and allows energy recovery to be commissioned while interleaved with normal operations [1]. Flux-hungry users continue to use stored-beam operation. Staging is compatible with an ultimate ERL upgrade and its construction is no more disruptive to APS operations.

An exciting new development is a proposal for an x-ray FEL oscillator (XFELO) that takes advantage of recent advances in material properties suitable for x-ray mirrors. The XFELO requires a high-coherence beam and promises average x-ray brightness that exceeds even SASE FEL sources [6]. As an added benefit, the staged ERL provides a means by which an XFELO could be experimentally tested, well before construction of an ultimate ERL or XFELO facility [6,7].

ERL STAGE 1

In the first stage, the 7-GeV srf linac points towards the APS in the same position as for the ultimate ERL, depicted in Fig. 1 (left). Other authors have explored this configuration [8-10] but did not consider it as a staging step for a full ERL. The linac gradient is assumed to be 18 MV/m [11]. The injection and extraction lines into the APS are built per [2] but extended in length. There is a high-energy beam dump in the APS extraction line.

An XFELO is easily accommodated in this stage on a separate straight-ahead beam line (a 100-m insertion including 60 m of undulators), depicted in Fig. 1. This beam line also requires a beam dump (not shown.)

An important criterion for stage 1 is that initial operation be non-energy-recovered. The beam parameters are comparable to CEBAF [5], which is designed to deliver 200 μA at 5 GeV; its beam dump design limits the full beam power to 1 MW. By the same criterion, the average beam current in ERL stage 1 would be ~150 μA at 7 GeV;

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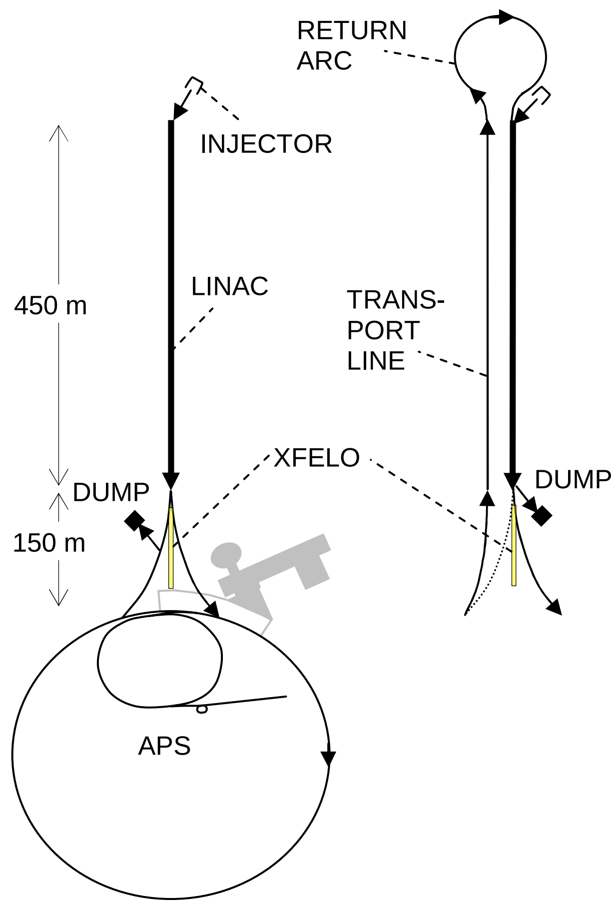

Figure 1: In stage 1 (left), the linac points towards APS and can accommodate an XFELO. The beam power is limited to 1 MW and initial operation is non-energy-recovered. In stage 2 (right), a simple return arc and merger optics are constructed to test energy recovery. High-coherence beam is provided to APS with a pulsed electron source. When a cw source becomes available, energy recovery testing with accumulation can proceed.

this can define a threshold above which energy recovery would be required [11]. The CEBAF beam dump design can be adopted for stage 1; the axial power deposition in the dump for 5 GeV and 10 GeV are comparable at 1 MW [12]. From the machine point of view, the initial focus can be on gaining experience operating a superconducting linac, controlling beam losses, and generating and preserving the ultralow emittance electron beam.

Injector and Relative X-ray Brightness

A critical component for an ERL x-ray facility is an injector with an emittance that is two orders of magnitude smaller than existing sources in operating ERLs [13]. The "high-coherence" mode defined by Cornell [14] specifies a beam with 0.1 mm-mr emittance normalized to the beam energy and at least 20 pC per bunch. Operating ERLs deliver cw beams but with much higher beam emittance. An injector based on the SCSS FEL injector design [15] can potentially be scaled for ERL stage 1, where high average current is not required (~150 µA). A design for a thermionic cathode in a VHF rf cavity for a pulsed low-emittance XFELO injector is being pursued [16].

In order to maximize the relative ERL brightness, given by $I_{ERL}/(V\delta\omega)_{ERL} \times (V\delta\omega)_{APS}/I_{APS}$, the total phase space volume V_{ERL} should be minimized. I is the average beam current, and the spectral line width $\delta\omega$ includes the beam energy spread [10,17]. The optimum condition occurs when the beam and photon phase-space volumes are matched and the beta function $\beta_u = L/2\pi$. For the present L = 2.4 m undulators, the optimum β_u = 0.38 m, to be compared with the present APS (β_x,β_y) = (20,3) m. This beam would be rather poorly matched, and it is advantageous to design a new APS lattice that approaches the optimum condition. The following lattice parameters were studied: (20,3), (15,1.3), (3,3), and (1,1) m. The assumptions for APS are: I = 100 mA, ε_x = 2.5 nm, ε_y = 0.012 ε_x, η_x = 0.17 m, δ = 9.6e-4, L = 2.4 m; for ERL stage 1: I = 150 µA, $\varepsilon_{x,y}$ = 0.1e-6/(7e9/0.511e6) = 7.3 pm, η_x = 0, δ = 2e-4; and for $\delta\omega$: N = 70 (number of undulator poles).

Figure 2 shows a comparison of the relative ERL brightness as a function of photon energy, where different undulator harmonics n = 1,3,5 are shown with different line styles. The benefit of small (β_x, β_y) in increasing the relative ERL brightness is clearly shown. The criterion for ERL stage 1 is virtually satisfied for (1, 1) m; the relative ERL brightness exceeds the APS for photon energies above λ = 1 Å (12.4 keV, at n=3).

A preliminary analysis shows that the (1, 1)-m solution is possible using the present quadrupoles. The emittance growth due to quantum excitation was estimated to be ~8 pm on one turn. Reducing β_x further without increasing the emittance improves the results. The feasibility of this lattice and other lattices, as well as emittance growth, will be analyzed in the near future.

It should be noted that the transverse coherence fraction scales only with total phase-space volume and is therefore over two orders of magnitude higher than APS even in stage 1; experiments sensitive to coherent scattering will benefit greatly. In addition, an x-ray pulse length of 1-2

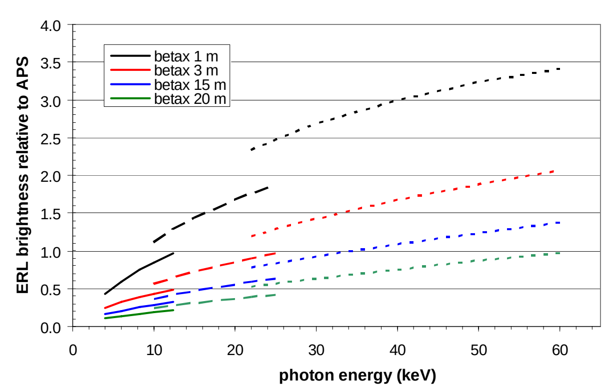

Figure 2: ERL brightness relative to APS in stage 1 as a function of APS lattice parameters (β_x is labeled). The computations are valid for sector 1 with no emittance growth due to quantum excitation. The machine parameter assumptions are given in the text (2.4-m undulators).

ps, if it can be provided, is of potential interest to a specialized set of users.

ERL STAGE 2 AND BEYOND

In stage 2, a new extraction line bypasses the exit of the linac and is extended parallel to the linac. A simple return arc is constructed to transport the beam into the low-energy end of the linac and merger optics are added. A schematic is shown in Fig. 1 (right). The configuration allows testing energy recovery with co-propagating high-energy beams (≤7 GeV) and modest average current (up to 1 MW beam power). The highest-energy demonstration of an ERL was by CEBAF at 1 GeV and ~1 µA (~1 kW); this was done for only a single-pass acceleration and deceleration [18]. It may be noted that the highest-power FEL ERL, at JLab, operates with 1.4-MW beam power at low beam energy [19].

A pulsed electron source can continue to be used while cw injector R&D proceeds and a prototype becomes available. At that point, energy recovery testing with accumulation to higher current can proceed (Stage 3). A low-energy dump can be designed for the full ERL power anticipated. Cornell gives a design for a 1-MW dump in [20]. In the final stage, the linac is turned around after the emittance-preserving turn-around arc is constructed for the ultimate ERL [1,2].

Optics

Lattices for accelerating and recovery linacs as well as for the APS ring are the same as in [2]. The transport line, return arc, and matching sections were modified to accommodate the ERL staging concept (Fig. 3). The brightness of the APS will be slightly better than the reported value in [2] due to direct injection from the 7-GeV linac.

SUMMARY

ERL staging allows APS operation with a high-coherence ERL beam at a lower risk compared with the ultimate ERL. The stage 1 operating parameters are comparable to CEBAF without recirculation. For an ERL linac delivering 150 µA in high-coherence mode, the average x-ray brightness above 1 Å would exceed the present APS and the photon beam would be over two orders of magnitude more coherent transversely with a pulse duration of ~1 ps. Initial operation is non-energy-recovered, providing experience with superconducting linac operation and allowing energy recovery to be tested in stages. Because the APS benefits immediately from non-energy-recovered operation, energy recovery can be tested at full beam energy with relatively low risk. As an added feature, staging allows testing of a prototype XFELO in the first stage. The ERL staging concept is compatible with upgrade to an "ultimate" ERL based on a cw injector and turn-around user arc. The concept is an alternative to and complementary with a low-energy, high-average-current prototype ERL R&D test facility and offers the added benefit of providing APS users with improved source performance at an early stage.

A key component of the staged ERL is a pulsed injector, possibly based on the SCSS thermionic DC FEL injector. The technical challenge for the injector involves demonstration of 0.1 mm-mr normalized emittance and 150-200 µA average current.

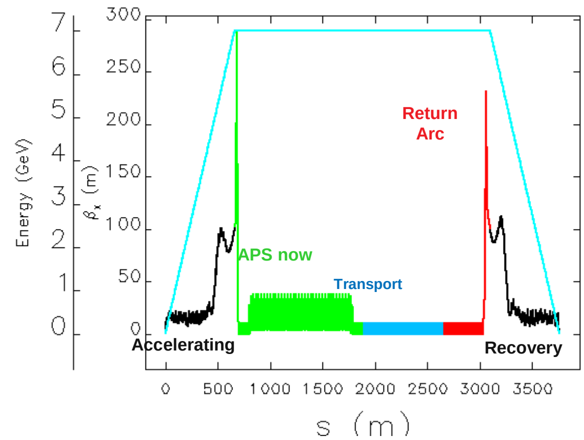

Figure 3: Lattice functions, stage 2.

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