Energy recovery linacs as synchrotron radiation sources (invited)

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Practically all synchrotron x-ray sources to data are based on the use of storage rings to produce the high current electron (or positron) beams needed for synchrotron radiation (SR). The ultimate limitations on the quality of the electron beam, which are directly reflected in many of the most important characteristics of the SR beams, arise from the physics of equilibrium processes fundamental to the operation of storage rings. It is possible to produce electron beams with superior characteristics for SR via photoinjected electron sources and high-energy linacs; however, the energy consumption of such machines is prohibitive. This limitation can be overcome by the use of an energy recovery linac (ERL), which involves configuring the electron-beam path to use the same superconducting linac as a decelerator of the electron beam after SR production, thereby recovering the beam energy for acceleration of new electrons. ERLs have the potential to produce SR beams with brilliance, coherence, time structure, and source size and shape which are superior to even the best third-generation storage ring sources, while maintaining flexible machine operation and competitive costs. Here, we describe a project to produce a hard x-ray ERL SR source at Cornell University, with emphasis on the characteristics, promise, and challenges of such an ERL machine.
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I. INTRODUCTION

Synchrotron radiation (SR) sources have proven to be immensely important research tools throughout the biological, physical, and engineering sciences. World wide, about 70 SR sources are in various stages of operation, construction, or planning, representing a cumulative investment of many billions of dollars and serving a rapidly growing community on the order of 10 000 scientists.

New SR sources will certainly be needed to meet the growing demand. Presently, all x-ray SR facilities are based on storage rings. Given the cost and lead time in designing a new SR source, it is important to ask:

- Are storage rings the optimal SR technology for the future?
- Are there alternatives to storage rings which enable new science?

The energy recovery linac (ERL), which is based on superconducting linacs, is being intensively investigated as a future SR source which both meets the growing needs of existing storage ring applications and also opens new paths

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for future x-ray science. To avoid confusion, it is important to understand that ERLs are distinct from x-ray free-electron lasers (XFELs), which are also linac based, and are also under development.[1,2] As explained below, ERLs and XFELs are both exciting developments and fill very different research needs.

The characteristics of synchrotron radiation beams are ultimately limited by the properties of the electron (or positron) beams used to produce the SR. These limits are well understood for storage rings and the ultimate characteristics obtainable with storage rings are within sight of those now obtained with the best third-generation machines.[3] The principle limitations are on the bunch length, cross-sectional distribution, and the vertical and horizontal emittances. Most typically, the bunches are several tens of ps long, and have horizontal emittances and sizes which are considerably larger than in the vertical direction. The emittances ultimately limit the brilliance of the SR, which, in turn constrains the transverse coherence; the source size and shape constrains the micro-x-ray beams possible; and the bunch length limits the ability to produce intense sub-ps x-ray pulses. The combination of transverse and longitudinal emittances also constrains the degeneracy factor, i.e., the number of photons in a given quantum mode. Many applications have been suggested which would benefit from higher brilliance, smaller source size, and shorter pulses than are feasible with storage rings.

In storage rings, the emittance and bunch length are established by a dynamic radiation equilibrium, the minimum value of which is controlled, for a given focusing lattice, by the beam energy: the higher the energy, the larger the emittance. The emittance of the best lattices known are now close to theoretical limits and significant improvements are unlikely. By contrast, the beam emittance and bunch length in a well-designed linac are controlled entirely by the particle *source* preceding the linac. Today's electron sources have inherent six-dimensional emittances less than those achievable in SR-controlled storage rings, making higher brilliance possible with linac drivers. This is why the proposed XFELs, which require very low emittance, are all based on linacs.

Since properly designed linacs do not degrade emittance, why not use a linac to accelerate a very low-emittance particle beam, which is then passed through an undulator to produce a brilliant SR beam? The drawback is that it takes a lot of power to accelerate the high-current electron beam needed to produce high x-ray flux: A 100 mA beam at 7 GeV (typical of the APS) carries 700 MW of power, which is the output of a large electrical generating station. A continuously operating high-current linac is simply prohibitively expensive to operate if the electron-beam energy is discarded. In a storage ring, using the same electrons over and over again circumvents this continual power need, so the kinetic energy of the initial acceleration is not wasted.

A solution to this dilemma is to use energy recovery in the linac.[4] Linacs operate by maintaining a resonant electromagnetic field so as to exert a unidirectional force on a charged particle. Whether a linac accelerates or decelerates electrons depends on the position of the electrons relative to the phase of the electromagnetic field. When a linac is used as a decelerator, the particle kinetic energy is transferred into

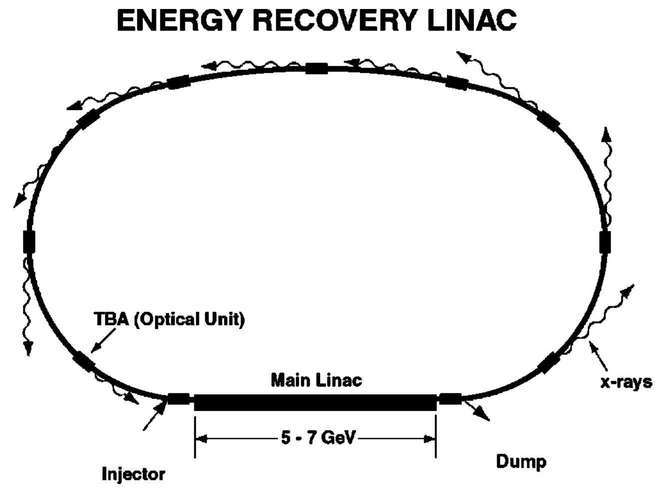

FIG. 1. Schematic layout of an ERL. The electrons are injected into a superconducting linac and then routed by electron optics (e.g., TBA=triple bend achromats, etc.) through undulators to produce SR. The bunches then decelerate in the linac and are bent aside by a weak dipole into a beam dump. Bunch compressors and decompressors (not shown) in the loop are used to produce very short bunches.

the resonant electromagnetic field, which can then be used to accelerate other electrons. Very efficient (>99.98%) energy recovery has been demonstrated at the Thomas Jefferson National Accelerator Facility (JLAB), which recently commissioned an ERL-based IR FEL.[5,6] In the simplest ERL layout, the bunches which emerge from the linac are routed through undulators using standard electron optics and then looped back into the low-energy end of the linac 180° out of the accelerating phase (Fig. 1). The bunches decelerate through the linac and emerge with low energy and are then dumped. The characteristic damping times are sufficiently long that desirable bunch characteristics can be maintained around the ERL loop (equilibrium in a storage ring is established only after many thousands of revolutions around the ring). Thus, the primary distinction between a storage ring and an ERL is that the ERL is designed to recycle the electron energy rather than the electrons themselves.

Superconducting linacs, with Q_s of $\sim 10^{10}$ are necessary to minimize wall losses and obtain high efficiency. Cornell University has been a pioneer in the use of superconducting niobium linacs to drive accelerators. CESR, the storage ring used by CHESS, is entirely powered by superconducting rf cavities. Cornell superconducting linac technology was the basis for the CEBAF accelerator facility in Newport News, VA, a 5.5 GeV electron accelerator.[5] The TESLA XFEL being designed in Germany will also use similar technology, as will the Spallation Neutron Source at Oak Ridge National Laboratory. Cornell has proposed a two-phase project to develop ERL x-ray SR sources: The phase I ERL would be a low-energy machine (100 MeV) to resolve machine issues and to optimize the ERL design of a full-scale phase II x-ray ERL source.[7–9] The possibilities of ERLs have excited the x-ray community. ERL SR projects are also being pursued at BNL (Ref. 10) and LBNL.[11] A related "recuperator" SR source has been proposed by Kulipanov, Skrinsky, and Vinokurov.[12]

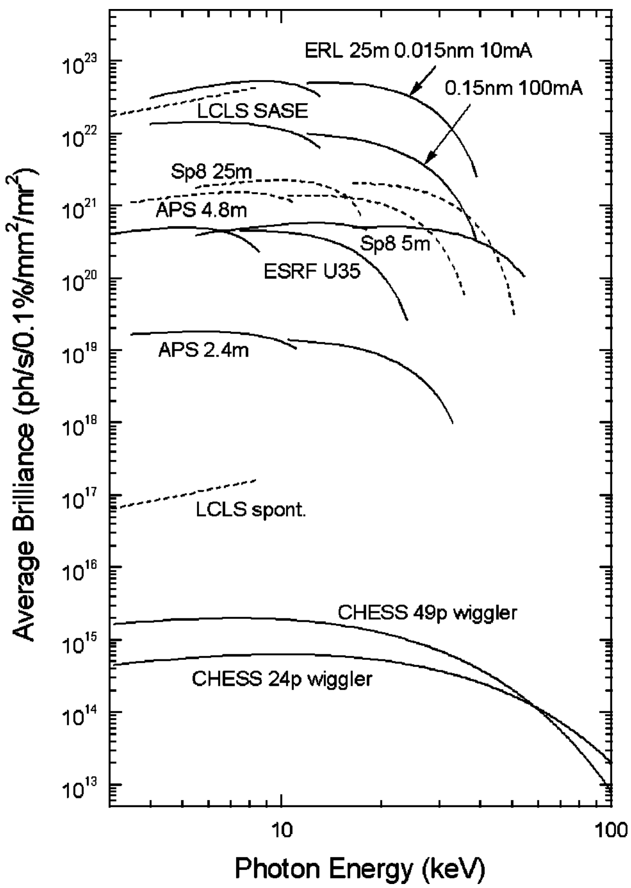

FIG. 2. Comparison of calculated average spectral brilliance of the various sources. The parameters used for undulator sources are listed in Table I. The CHESS wiggler sources assume 5.3 GeV 300 mA operation and a FWHM source size of $d_x = 5.5$ mm and $d_y = 0.9$ mm for the 24-pole wiggler at the F line and $d_x = 3.3$ mm and $d_y = 0.85$ mm for the 49-pole wiggler at the A/G line.

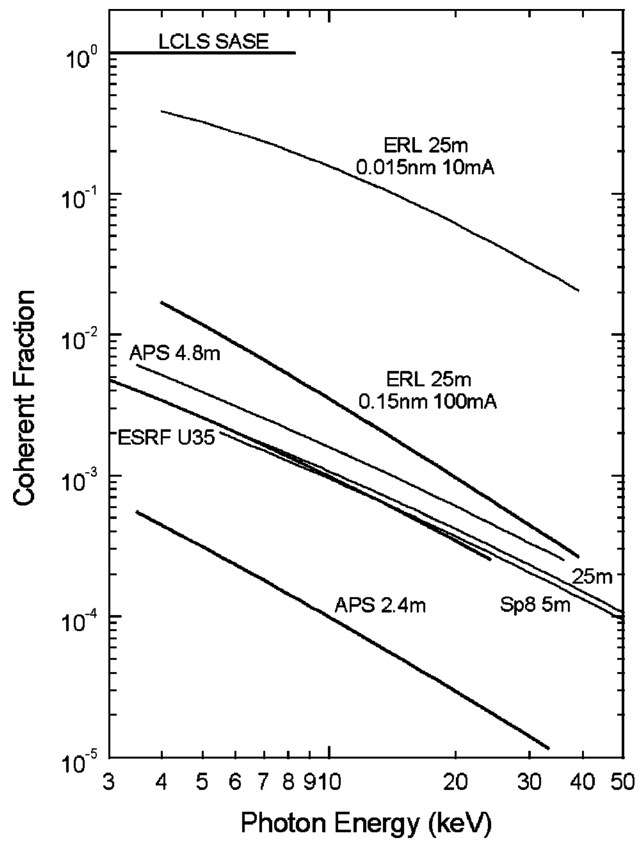

FIG. 3. Comparison of calculated coherent fractions of the various sources with photon energy.

II. POTENTIAL OF AN ERL SR SOURCE

The projected performance of a phase II ERL is shown in Figs. 2 and 3 and Table I. See Refs. 8 and 13–15 for details. Figures 2 and 3 and Table I assume ERL parameters which are believed to be achievable by extension of existing technology.[16]

In this design, every 1.3 GHz rf oscillation in the linac may be filled with both an accelerating and a decelerating bunch; thus, on time scales longer than about 10^{-9} s, the ERL is a quasicontinuous SR source. As opposed to storage rings, where the characteristic equilibrium time is many thousands of periods around the ring, the injector limits the bunch properties. This is a major advantage of the ERL, since the ultimate performance can be upgraded by improving the injector, which is a relatively small, if vital, part of the machine. Figures 2 and 3 show the projected performance in two modes of operation: In a high-flux mode (flux$=1.5\times10^{16}$ photons/s/0.1% BW at 8 keV) the injector is assumed to operate at an average current of 100 mA with 0.15 nm rad geometrical emittance in both the horizontal and vertical directions. We believe this level of photoinjector performance is achievable with existing technology. In a high-brilliance mode, the injector average current (and, hence, flux) and emittances are all assumed to be ten times smaller. Achievement of this lower level of emittance will be challenging. A primary purpose of the phase I ERL is to develop a very low-emittance injector, which is capable of continuous operation at the requisite average currents.

There is much more flexibility to manipulate bunches in any recirculated linac than in a storage ring because there is no need to meet the stiff constraints of long-term bunch storage.[17] For example, bunch lengths as short as 85 fs rms have been achieved at high energy at CEBAF at Jefferson Laboratory,[18] and standard operation at 200 fs rms is routinely obtained.[19] For the ERL, bunches 2 ps rms in length are readily achievable with laser-driven photoinjectors. Standard bunch compression techniques can be used to shorten the bunches further in part of the return loop to ~100 fs rms (~0.3 ps full width at half maximum) to produce very short x-ray pulses, leading to very high peak brilliances. The short pulses and low emittances yield high coherent fractions (Fig. 3). Degeneracy factors, which specify the number of photons in a given quantum mode, will be in the range of several hundred in the 8 keV region. By contrast, degeneracy factors of the best existing third-generation sources are on the order of unity. A major distinction between the ERL and the XFELs (which will be essentially fully coherent) is that the ERL operates at 1.3 GHz, which will allow use as a quasi-continuous source with an instantaneous flux on the sample that is sufficiently low that samples will survive for relatively long periods of time.

Short-pulse (10–1000 fs rms) x-ray science is an emerging frontier which has largely been inaccessible with storage

TABLE I. Proposed operation parameters for ERL compared with existing Spring8 and ESRF storage rings and to the proposed linac coherent light source (LCLS) of Stanford University.

Operation/ undulator length		25 m ERL undulator 5.3 GeV 100 mA	25 m ERL undulator 5.3 GeV 10 mA	SPring8 8 GeV 25 m	ESRF 6 GeV 5 m	LCLS XFEL 15 GeV 100 m
Source size (μm rms)	Horizontal	103	24.5	890	879	78
	Vertical	103	24.5	22.8	13.9	78
Source div. (μrad rms)	Horizontal	9.1	6.2	37.4	26.8	1
	Vertical	9.1	6.2	4.3	10.4	1
Beam size (μm rms) at 50 m	Horizontal	467	311	2071	1603	93
	Vertical	467	311	216	520	93
Average brilliance (p/s/0.1% bw/mm^2/mrad^2)		1.3×10^{22}	5.2×10^{22}	2.2×10^{21}	3.1×10^{20}	4.2×10^{22}
% beam coherence		0.52	20	0.14	0.14	100

ring SR sources, and will, no doubt, be major areas of research with both ERLs and XFELs. This is the relevant time scale for atomic state rearrangements, and phonon–electron, and even electron–electron, scattering. The combination of optical laser pumping with x-ray structural probing opens many possibilities to explore transition state chemistry, transient, nonequilibrium excitations in solids and liquids, hydration dynamics, etc.—see, for example, Ref. 20. Short ERL bunches will need to be decompressed prior to energy recovery to avoid wake field effects in the linac. Another major concern, to be explored with the phase I machine, is the level and control of the coherent synchrotron radiation associated with short bunches.[21–25]

Microbeam science, one of the great successes of the third-generation sources, can be significantly extended by ERL source characteristics (Table I). Whereas the storage ring electron-beam cross section and divergences differ in the horizontal and vertical directions, the round ERL beams facilitate the use of demagnifying optics. The smaller focused and more-intense x-ray beams possible from an ERL will extend the examination of the submicron grain structure of matter. Full utilization of ERL beams will, no doubt, challenge the perfection of manufacture of x-ray optics. Inelastic scattering studies would also benefit from the brilliance and source characteristics of an ERL. Although high-energy-resolution x-ray beams can be selected with very high-order multibounce reflections from silicon crystals, the flux falls rapidly with the source size and divergence. The meV resolution of useful third-generation beams can likely be extended into the several hundred μeV regime with an ERL. This will allow unprecedented explorations of the phonon spectrum of materials.

III. FUTURE SR SOURCES

As noted at the beginning of this article, SR utilization is still growing rapidly and new sources will be needed. The community is entering an exciting period of development of novel SR sources, including ERLs, FELs, and, plausibly, ERL-driven free-electron lasers. The diversity of source characteristics will offer the user community many more options in the performance of x-ray experiments. ERL sources promise to meet the existing requirements of practically all existing storage ring applications, and, at the same time, allowing extension into new science areas. Thus, a successful ERL source would already have an enormous constituency of users. Other major advantages of ERLs are flexibility of operation and facilitation of the upgrade path via improvements in the injectors. At the same time, successful development of XFELs will provide x-rays beams of astounding peak power and brilliance, and are likely to allow exploration of regimes, which have hitherto been totally inaccessible by x-ray structural probes. However, the high instantaneous intensity, as well as the pulsed, relatively low-repetition-rate nature of the beams may not be so readily adapted to the many of the standard applications which comprise the bulk of use at storage rings. Thus, if XFELs are fourth-generation sources, then ERLs might appropriately be called 3.5th-generation sources.

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