Research Highlight

New Energy Recovery Linac Source of Hard X-rays Planned

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Introduction: Synchrotron radiation x-ray beams from third generation light sources are rapidly approaching fundamental limitations inherent to storage ring technology. These limitations result from the equilibrium electron beam emittance and bunch length that are obtained after the beam has circulated for some thousands of turns. Electron accelerator technology beyond storage rings will be necessary to produce x-ray beams with significantly greater brightness and shorter pulse durations. We propose to build such a machine at Cornell University.

An Energy Recovery Linac Source of X-rays: A high brightness electron source coupled to a linac can readily generate electron bunches with beam sizes and bunch lengths considerably smaller than the equilibrium values possible in electron storage rings. These can then be passed though insertion devices to generate x-ray beams superior to any presently available. However, to produce x-ray fluxes comparable to those from storage rings requires an electron beam with very high average power. Simply dumping such a beam after passage through a series of insertion devices would require prohibitively large amounts of electric power (and an impossible beam dump).

The solution to this problem is to recover the electron beam energy before dumping the beam (see figure 1). By passing the electron beam through the linear accelerator a second time, 180 degrees out of RF phase from the accelerated beam, the beam kinetic energy is returned to electromagnetic field energy in the accelerating structure. Superconducting linacs are required to achieve the necessary energy recovery efficiency. Although the idea of such an Energy Recovery Linac (ERL) was recognized many years ago [1], it has only recently become practical with advances in superconducting linac and electron source technology. By way of development history, the idea of an ERL as a new x-ray source was first presented by Maury Tigner to the CHESS Policy Board in February 2000.

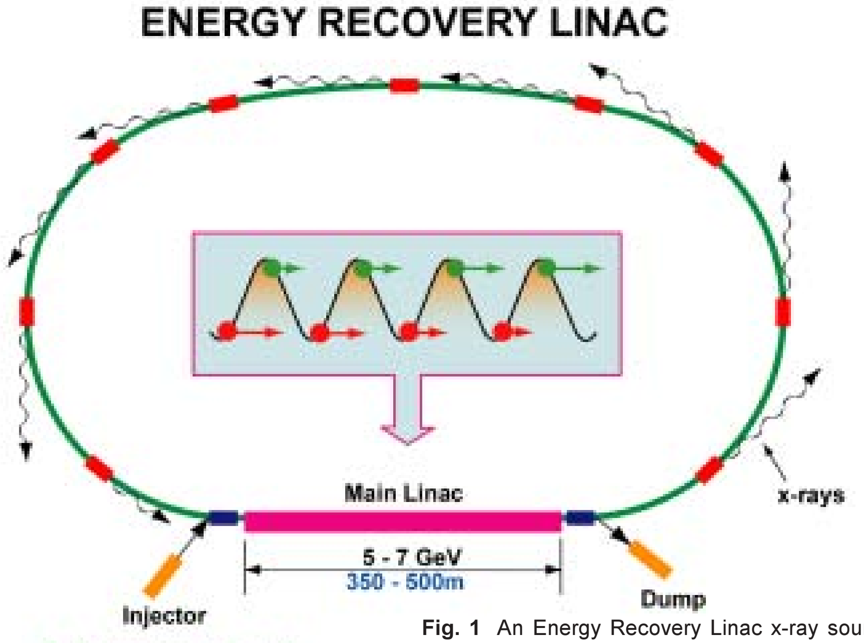

Fig. 1 An Energy Recovery Linac x-ray source consists of a brilliant source of electrons, a long linac to boost the electrons to high energy, a return loop in which to generate the x-rays from undulators, and a dump to remove spent electrons after a one-pass trip around the machine. The insert illustrates how accelerating and decelerating particle beams can be interleaved in the same superconducting RF cavity. (Drawing is schematic only and not to any scale.)

Several years ago, a superconducting linear accelerator developed as part of an infrared free electron laser at Jefferson Lab became the first machine with a circulating electron beam power larger than the total installed RF power [2]. This accelerator maintained a 4.8 mA continuous electron beam at 48 MeV, and is presently being upgraded to double the beam current and increase the beam energy to about 160 MeV. Although this machine proved that ERLs are feasible, the specifications required for the IR FEL application are considerably less demanding than those of a high brilliance x-ray source.

Expected X-ray ERL Performance: Our goal is to make an x-ray machine that greatly exceeds the performance capabilities of current 3rd generation machines, including brilliance higher by factors of 100 – 1000, bunches shorter by factors of 10 – 100 (down to 100 fs rms), programmable pulse trains with periods as short as 770 ps, round microbeam source sizes on the 3 micron scale, and continuous injection for CW operation. Since the properties of the electron bunches are predominantly determined in the injector, future injector upgrades may yield shorter bunches and lower emittance operation - inviting whole new realms of experiments even after the machine has initially become operational. Figure 2a shows the average brilliance and Figure 2b the coherent flux in comparison to other related machines. Table 1 gives a parameter list for our proposed ERL x-ray source.

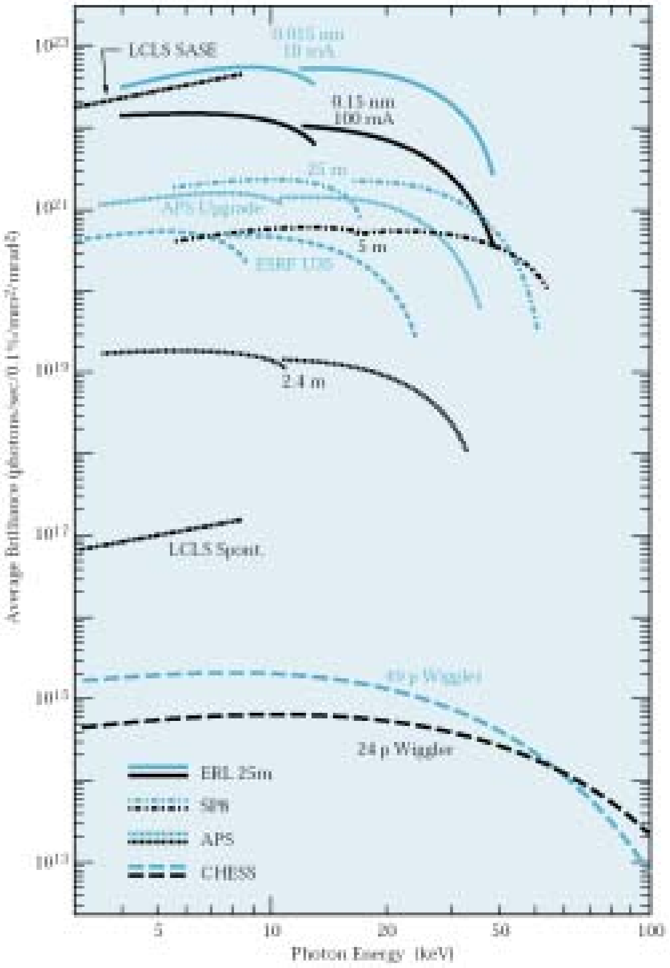

Fig. 2a Expected ERL average brilliance vs. x-ray energy in the high-flux (100 mA) mode as compared with the CHESS, ESRF, APS, and Spring-8 storage ring sources and the LCLS in SASE mode.

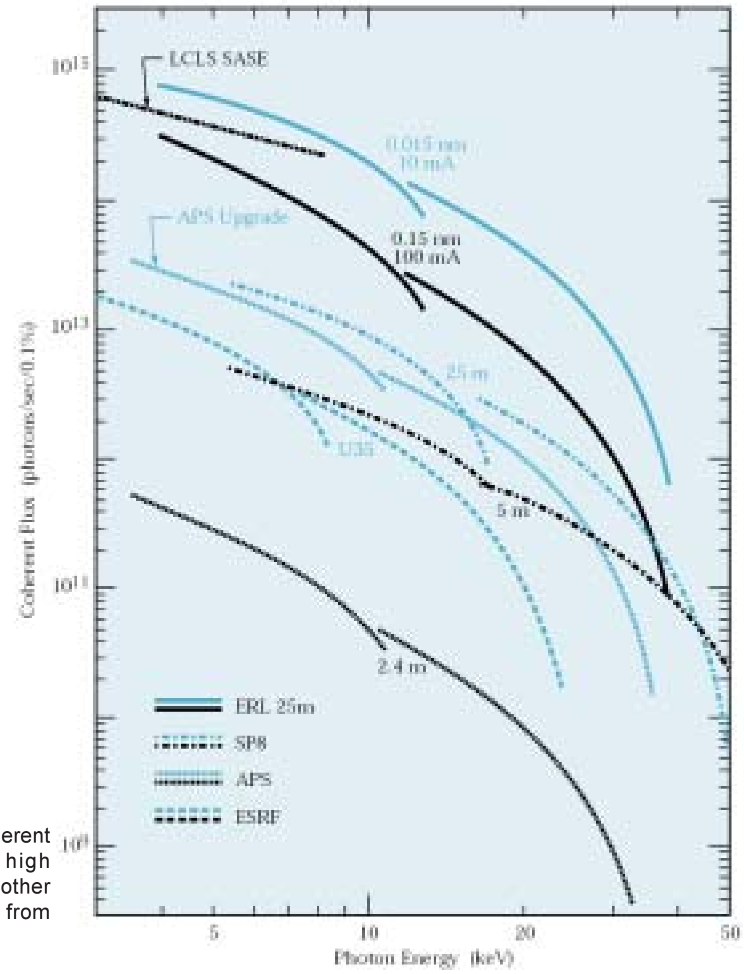

Fig. 2b Comparison of the coherent flux from the ERL in the high coherence (10 mA) mode to other machines. Figures reprinted from reference [3].

Table 1: Parameter list for an Energy Recovery Linac source of x-rays with a 5.3 GeV beam energy. Two modes are given: one for "high-flux" production with a 100 mA beam current and the second for "high-coherence" production with a very low emittance, 10 mA beam. By illuminating a smaller area on the injector photocathode, a smaller transverse diameter beam can be generated at the expense of beam current. Not shown on this table is a 2 m long low beta insertion device that can produce a 3 micron rms round beam with a calculated brilliance of 5 x 10^{21} x-rays/sec/mrad^2/mm^2/0.1%bw in the 2-30 keV range for microdiffraction applications.

		ERL high-flux	ERL high-coherence
Machine design	Energy E_G (GeV)	5.3	5.3
	Current I (mA)	100	10
	Charge q (nC/bunch)	0.077	0.008
	ε_x (nm-rad)	0.15	0.015
	ε_y (nm-rad)	0.15	0.015
	Bunch fwhm τ(ps)	0.3 – 5	0.3 – 5
	# of bunches f (Hz)	$1.3 \cdot 10^9$	$1.3 \cdot 10^9$
Insertion device	Undulator L (m)	25	25
	Period λ_u (cm)	1.7	1.7
	# of period N_u	1470	1470
	Horizontal β_x (m)	12.5	4.0
	Vertical β_y (m)	12.5	4.0
	Undulator K @ E_1	1.38	1.38
	1st harmonic E_1 (keV)	8.0	8.0

ERL Science Potential: The science potential of an x-ray ERL source is enormous. It extends the very strong case for the most powerful 3rd generation sources even further into these identified areas:

- Microbeam diffraction and fluorescence
- High pressure diffraction and spectroscopy
- Femtosecond x-ray studies of solids, molecules and proteins
- Coherent imaging and microscopy
- Photon correlation spectroscopy
- Nuclear resonant scattering
- Inelastic x-ray scattering
- Normal diffraction, x-ray metrology, and x-ray interferometry
- Polarized x-ray beam studies, resonant scattering and circular magnetic dichroism studies

The x-ray beams for such applications will be more "ideal" - with higher brilliance, smaller source size, more flux, higher coherence, shorter bunch lengths, etc. - all the properties that existing 3rd generation applications wish to improve upon. We believe that having more powerful x-ray beams in the laboratory will bring increased performance [4] for applications in such scientific disciplines as physics, chemistry, biology and medicine and into such industrial areas as polymers and plastic materials, pharmaceuticals, metallurgy and microelectronics.

Other Linac-Based X-ray Sources: Our colleagues at other laboratories are also very busy designing alternate x-ray sources based on linear accelerators [5]. Some of the devices are based on Energy Recovery Linac technology while others use the SASE (Self-Amplified Spontaneous Emission) FEL (Free Electron Laser) principle. While FEL sources will explore new regimes, they also will require the development of new ways of performing practically every experiment. By contrast, ERLs will be capable of both serving present 3rd generation applications and extending capabilities into new areas not presently accessible by 3rd generation storage rings. Thus, ERLs are a good choice to meet the growth in demand from the existing synchrotron radiation community and to extend synchrotron technology into new areas. In the United States, ERL design/construction efforts are underway at the Jefferson National Laboratory (JLab, IR FEL upgrade), Cornell/JLab (ERL Prototype proposal submitted), LBNL (design, fast fs timing experiments), and BNL (design, PERL project for new x-ray light source). At the same time, SLAC is proceeding on the construction of the Linac Coherent Light Source (LCLS), an x-ray FEL.

Need for an ERL Prototype: Numerous accelerator physics and technology challenges must be overcome before a high brilliance x-ray ERL can be realized [6]. These include the generation of high average current, very bright electron beams; the preservation of beam brightness during acceleration and transport; the removal of the power deposited by electromagnetic wake fields in the cryogenic environment of the superconducting accelerator; and the development of non-intercepting beam diagnostics to allow setup, control and stabilization of the beam. Fortunately, these issues can be studied and resolved with a relatively small accelerator. Such a small machine would include an electron injector producing an average current and beam brightness suitable for a full scale x-ray source.

Cornell University (CHESS and the Laboratory of Elementary Particle Physics) and Jefferson Lab have proposed a collaborative project to build such a prototype ERL at Cornell. The proposal to the NSF requests about $39M over 5 years to develop and operate the machine. The proposal has now been through both written and site-visit reviews, with a strong recommendation from the review panel for full funding of the project. At present (October 2002) we are awaiting a funding decision from the NSF.

The prototype ERL is designed to resolve all the critical issues that need to be addressed before a full-scale x-ray ERL can be built. It would be a 100 MeV, 100 mA average current machine, and thus would not generate x-rays. The injector, based on photoemission from a GaAs cathode, would demonstrate high beam brightness at full average current, and would be capable of delivering a much brighter beam at reduced average current. The superconducting linear accelerator would operate with an average accelerating gradient of 20 MV/m and would require 200 to 300 watts of refrigeration at 2K. The machine would be capable of producing electron bunches shorter than 100 fsec rms. State-of-the-art beam diagnostics would allow a complete characterization of the exceptionally bright beam and beam stabilization at the level required for an x-ray source utilizing the full beam brightness.

The prototype ERL would take about 3.5 years for construction, followed by about 1.5 years of tests and measurements with the full electron beam. To keep costs down, a 2 K refrigerator that would be able to support full operation only about 30% of the time is specified. While this extends the calendar time required for the measurement program, it also allows a smaller staff to conduct the measurements, and gives time to analyze results. The injector would be completed before the end of the construction period, allowing measurements on this key element to begin earlier.

While serious construction work on the prototype cannot begin until NSF funding is in place, a number of tasks that can be accomplished with modest university funding are underway or completed. For example, Ivan Bazarov has developed a complete design for the electron beam optics of the prototype machine. A small ultrahigh vacuum system to allow photocathode preparation and evaluation has been assembled by Yulin Li, and cathode tests are soon to begin. Matthias Liepe has completed a detailed study of the required tolerances of the complex RF system. Both summer undergraduate students and current graduate students have worked or are actively working on ERL problems, such as the development of low temperature, very high frequency microwave power absorbers; the design of the photoemission electron gun; optimally shaping the profile of the laser beam which illuminates the photoemission cathode; and development of non-evaporable getter coatings for critical vacuum systems. Full specifications for some of the long lead-time procurements, such as the klystrons and the 2 K refrigerator, are being developed. Finally, detailed planning of beam diagnostic devices is underway. All these activities keep the laboratory staff thinking about the ERL, and place us in a position to move quickly to realize the prototype once we have funding.

Conclusion: We have a very exciting opportunity to build the next high-performance synchrotron x-ray source at Cornell University. Given adequate funding, beam studies with the prototype machine could begin within 4 years and a full-scale x-ray ERL could be operational well within 10 years.

Acknowlegments

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[3] S.M. Gruner & D.H. Bilderback, Energy Recovery Linacs as Synchrotron Light Sources in SLAC Beamline, Vol. 32, No. 1, 22-31 (Summer 2002). The whole issue is available online at http://www.slac.stanford.edu/pubs/beamline/pdf/02i.pdf
[4] See the link http://erl.chess.cornell.edu/papers/X-rayScienceWorkshopDec2000.htm where the viewgraphs of the speakers at the December 2000 Science Workshop are posted.
[5] References to other linac based sources of synchrotron radiation can be found at http://erl.chess.cornell.edu/WorldwideReferences.htm
[6] The ERL white paper and many other related references to the Cornell/Jlab ERL design can be found at website http://erl.chess.cornell.edu/.

ERL Staff Highlights

Many individuals are making important contributions to the ERL project. Here are two of them.

Ivan Bazarov joined us from Vladivostok, Russia. He earned his PhD in 2000 doing Laser Plasma Spectroscopy research in the Far Eastern State University of Russia. At the moment Ivan is a Postdoctoral Research Associate with the ERL program at CHESS. His main task has been designing magnetic optics for electron beam transport in the ERL Phase I machine, as well as computer simulations of various beam dynamics phenomena potentially detrimental for high brightness of an ERL beam and lattice calculation on CESR. Obtaining experimental data and better theoretical understanding of these unfavorable phenomena with the Phase I ERL will clear the way for designing a full-scale ERL x-ray source with optimized performance.

Charlie Sinclair is no stranger to Cornell, having attended graduate school in Physics here during the 1960's. After grad school, he worked briefly at Tufts University before becoming a staff scientist in the Research Division at SLAC. It was during his time at SLAC that he began working on the development of photoemission electron sources, of the sort planned for the ERL. In 1987, he left SLAC for the new CEBAF laboratory (now the Thomas Jefferson National Accelerator Facility, or Jefferson Lab), where he had the good fortune to participate in the design, construction, and commissioning of a large superconducting electron accelerator at a "green site" facility. After a long-planned retirement from Jefferson Lab last year, he joined the new ERL program at Cornell in January, and is eager to begin "cutting metal".