The Status of the Energy Recovery Linac Source of Coherent Hard X-rays at Cornell University

DONALD H. BILDERBACK, CHARLES SINCLAIR, AND SOL M. GRUNER
Cornell University, Ithaca, NY, USA

Synchrotron radiation research as a field is still in a growing phase because newer and more capable X-ray sources are presently under development. Advances in storage ring technology, as explained in the introductory article to this special New Source issue by Kwang-Je Kim, is rapidly approaching the point of diminishing returns. It is expected that within a few years storage ring technology will have matured to the point where it will be become exceptionally difficult and expensive to make further significant improvements to the X-ray beam quality. In contrast, linac-based sources such as energy recovery linacs (ERLs) and X-ray free electron lasers (XFELs) are at an early stage of development, and provide a clear path for dramatically improving X-ray beam qualities that is likely to continue for many years. ERLs promise to generate bright electron beams, and thus X-rays, with dramatically smaller emittances and pulse durations than those available from storage rings, the present workhorse technology for all existing hard X-ray synchrotron radiation sources. As described in the companion X-ray Free Electron Laser (XFEL) article, new opportunities also exist in a complimentary direction, namely, that of making a lower duty factor X-ray laser that will also generate exciting new science. Though both ERL[1] and the XFEL[2] technologies have considerable promise as future X-ray sources, much development work and learning in both accelerator and X-ray technology will be required to realize their potential.

Cornell University is designing a coherent hard X-ray light source based on an ERL upgrade to the CESR storage ring. Here, we review the principle of an ERL, the status of various other ERL synchrotron light projects, the scientific applications of high brightness, coherent, and short pulse X-rays, and some specifics of the Cornell project.

The transverse emittance of the electron bunches used to generate X-rays determines the spectral brilliance and transverse coherence of the X-ray beams. Ideally, the emittance should be small enough to produce full transverse coherence of the X-rays—i.e. to produce a diffraction-limited X-ray beam. Very low emittance electron beams can be generated from a laser-driven photocathode, and accelerated to high (GeV) energies without substantial emittance growth in linear accelerators. High brightness, highly coherent X-ray beams can then be generated from these electrons. Since the electron beam carries several hundred MW of beam power, this is feasible only if the electron beam energy is recovered after the X-rays are generated. Using a superconducting (SC) linac, essentially all the electron energy may be recovered by passing the beam through the linac a second time, 180° out of phase with the accelerated beam, as shown in Figure 1; hence, the name Energy Recovery Linac. The ERL idea was suggested many years ago by Maury Tigner[3], but only became practical for X-ray generation in the mid-1990s, following advances in superconducting linacs and photoemission electron sources[4].

Energy recovery (ER) was first demonstrated with a low average current pulsed electron beam at the superconducting linac at Stanford[5]. It was subsequently demonstrated with higher average current CW beam during injector development for the CEBAF accelerator. ER has also been demonstrated with room temperature linacs[6], but this is

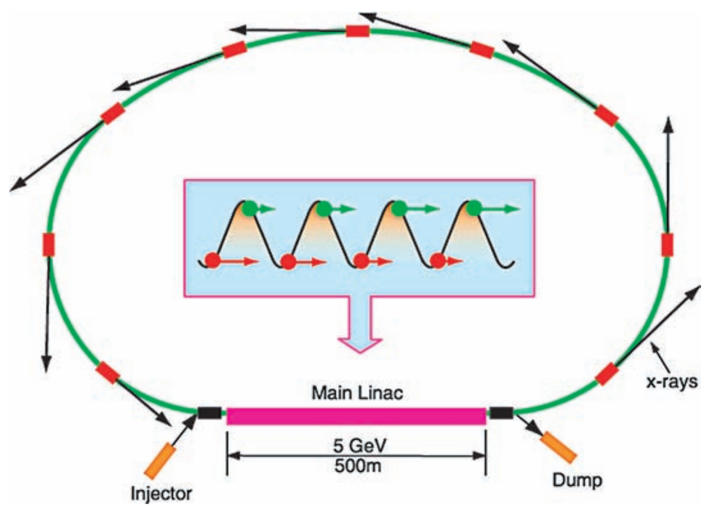

Figure 1: Schematic of an ERL light source. Low emittance electron bunches are produced in a photoemission electron injector and accelerated to about 10 MeV before injection into the superconducting main linac. The oscillating electric field in the cavities accelerates the bunches (green dots riding near the crest of the RF wave in the illustration above) to 5 GeV. The electron bunches produce X-rays in undulator magnets in the beam transport line. The path length of this transport line is such that the electron bunches arrive at the linac 180 degrees from their accelerating phase and are decelerated (red dots) to the injector energy (less the synchrotron radiation losses) and deflected to the beam dump. Each electron makes just one circuit around the machine in this layout. The electrons are accelerated (and decelerated) slightly off the maximum accelerating field to generate a time-dependent energy spread across the bunch, allowing it to be temporally compressed to very short duration in the beam transport line.

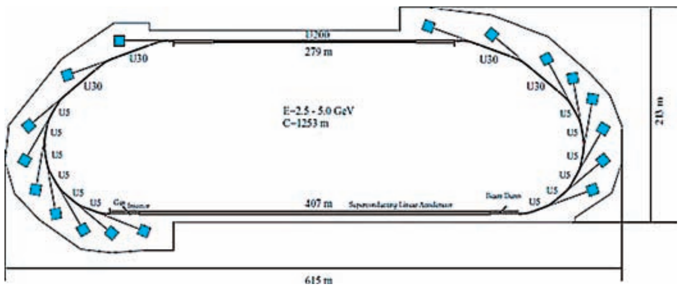

Figure 2: The 2.5 to 5 GeV, 100 mA Energy Recovery Linac under consideration at KEK is designed to provide next generation capability for users of the Photon Factory. Seventeen X-ray beamlines from 5- and 30-meter-long undulators are shown in this schematic layout.

impractical for high current, high energy ERLs for X-ray production, due to the large RF power losses in room temperature accelerators.

Beam breakup (BBU) is a key issue for the application of ER at high average beam current. BBU occurs when the electron optics that transports the beam around the closed loop of the ERL is such that an angular deflection of the beam at a particular accelerator cavity returns the beam to that cavity with a transverse displacement. This allows the beam to act in a feedback loop with the higher order electromagnetic modes (HOMs) in that accelerator cavity. When the beam is deflected by the magnetic field of a HOM and returns with a transverse offset, it may deliver energy to the HOM, resulting in larger deflections and displacements of subsequent beam. When this condition occurs, the beam displacement quickly grows to the point where it strikes the accelerator walls. Computations indicate that with adequate damping of the cavity HOMs, and well designed electron optics around the ERL, the threshold for BBU can be pushed to very high average currents. This understanding has led to widespread interest in ERLs as a way to generate very high average current electron beams for many applications, without the need to provide impractically high power to the beam.

The largest ERL constructed to date operates as the drive accelerator for a very high average power infrared Free Electron Laser (FEL) at Jefferson Laboratory (JLab). This machine uses a 350 kV DC photoemission electron gun followed by two SC cavities as an injector, and a total of 24 SC cavities, in three 8 cavity cryostats, as the main accelerator, to give a total energy of about 140 MeV. They have energy recovered at maximum current of 9.1 mA, and the FEL has delivered a 10 kW average power infrared beam in 1 sec duration bursts. Interestingly, the laser power was limited not by the electron beam, but by optical absorption in the mirrors.

The HOM damping in some cavities of the JLab ERL was known to be inadequate for high average current operation. They observed BBU at the expected threshold of about 3 mA. Accelerator physicists have turned this into an advantage, exploring ways to increase the BBU threshold by changing the electron optics, for example. In addition, measurements of the BBU threshold with various electron optics have been used to benchmark the codes that calculate the threshold, lending confidence in similar calculations made for other, higher current ERLs.

Much higher average current ERLs are presently being studied or developed at a number of laboratories worldwide. For example, at Brookhaven National Lab, they are developing an ERL test facility to demonstrate the technical feasibility of two ERL applications – a 47 mA, 54 MeV machine for electron cooling the heavy ion beam in the RHIC storage ring[7], and a 500 mA, 80 MeV machine for a very high power FEL amplifier.

ERLs may provide a natural path to upgrade existing storage ring facilities or as the basis for total new sources. Plans have been developing at Cornell for several years to upgrade CHESS/CESR[8] with an ERL. The Advanced Photon Source at Argonne Laboratory is beginning to look into an ERL upgrade option for its future as well. Finally, ERLs are proposed for new, lower energy light sources with both FELs and undulators, such as the 4GLS project at Daresbury[9] and a similar machine at BESSY that will need energy recovery when upgraded later to run at very high repetition rates[10].

The only totally new green field ERL hard X-ray source in the planning stage is the one to eventually replace the Photon Factory at KEK with a 5 GeV ERL machine. Figure 2 shows the current layout of the ERL machine under discussion[11]. The official organization of the

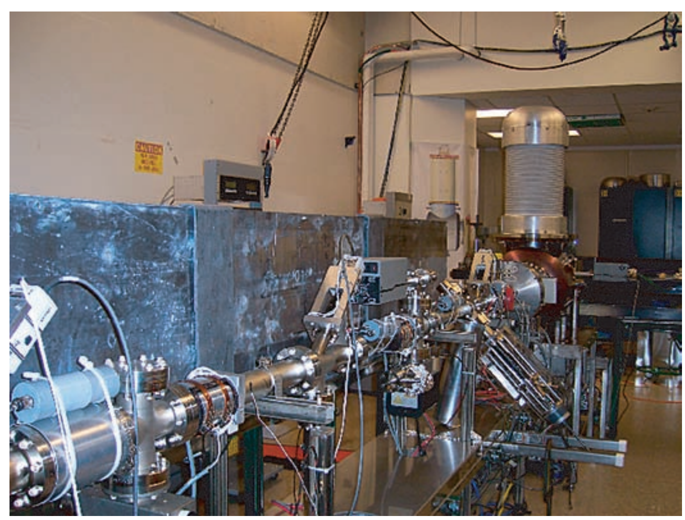

Figure 3: The 750 kV photoemission electron gun and its diagnostic beam line, as presently assembled in a laboratory in Wilson Lab. In operation, the electron gun ceramic insulator and the 750 kV, 100 mA power supply are contained in a pressurized tank containing SF_6 gas as insulation. The high power beam dump is immediately behind the photographer. The first electron beam was achieved on September 7, 2006, when a low power (mW level) green laser illuminated a GaAs photocathode. The gun presently operates at 300 kV max voltage as limited by the available power supply. The operation with the design value for high voltage and beam current is scheduled for late fall of 2006. The beam line above will allow studies of the thermal emittance from the photocathode, and cathode lifetime studies at high average beam current. With the addition of a different laser and a reconfiguration of the beam line, studies of emittance compensation and the emittance of space charge dominated short duration pulses will begin.

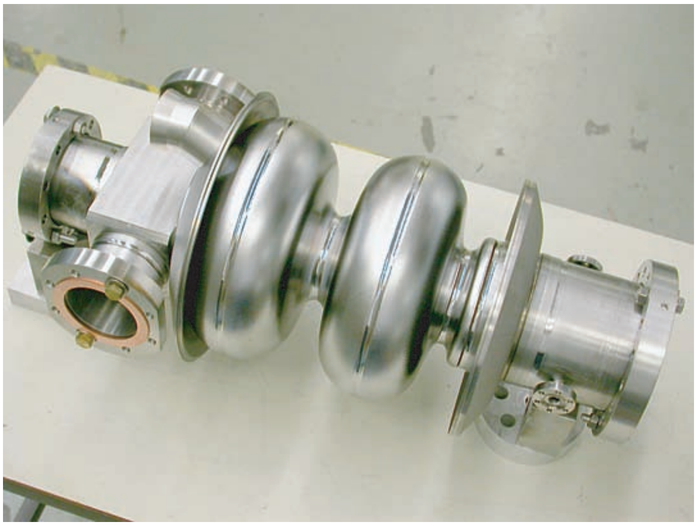

Figure 4: The first two-cell niobium cavity for the injector. Beam will pass along the long axis. The RF power couplers will be mounted in the two large transverse ports on the left side, while the two small ports on the beam tube at the right end of the cavity are used for antennas to sense the cavity field. The larger diameter beam tube on the right-hand side allows the lowest frequency HOMs to propagate to an external load.

ERL project office started as of April 1, 2006, under the leadership of Hiroshi Kawata. An R&D team for a 200 MeV prototype ERL is soon to be organized in collaboration with accelerator scientists from other facilities such as ISSP, UVSOR and SPring-8.

Cornell ERL development

In 1999, Maury Tigner, who had just returned to Cornell as the Director of the Laboratory of Elementary Particle Physics, suggested that the technology that had been developed at Cornell, DESY, and the Infrared FEL at JLab was reaching the point where a hard X-ray ERL light source would be possible. Cornell partnered with accelerator physicists at JLab to quickly outline the scope of the opportunity. A first X-ray science workshop, held at Cornell University in December of 2000, immediately identified a great many attractive science opportunities. Designs for a prototype injector and a superconducting accelerator cavity began to emerge as areas requiring development. Since many of the accelerator parameters needed for a coherent hard X-ray ERL light source were far more challenging than those of the state-of-the-art at the time, it was decided to stage the project in two phases: Phase I would develop and experimentally demonstrate the critical accelerator components, followed by the Phase II construction of a full scale 5 GeV X-ray facility. A 4-year Phase I project started in February 2005 with $18M of support from the National Science Foundation, with the goal of demonstrating the required injector performance. This award has been recently supplemented with $12M from New York State to help prepare the full-scale machine proposal[12]. The Cornell design for a Phase II ERL light source is based on a 5 GeV SC linac operating at up to 100 mA. The resultant X-ray beams would be 100- to 1000-fold better, in terms of brightness, pulse duration, and beam size, than can be delivered from the best present-day 3rd generation storage rings. In this brief part of the report we review the progress of the design work on the 5 GeV machine, describe recent milestones achieved in demonstrating the properties of a 10-15 MeV, 100 mA injector made from a photo-cathode and followed by a two-cell SC cavity.

Planning for the full-scale Phase II machine is proceeding in parallel with the injector development, and has enough design maturity that a realistic physical layout of the full machine is nearing completion. The current design for an ERL machine upgrade to the present CESR ring is shown in Figure 7. The present day CESR ring will be reused as part of the ERL return arc. There is room for three 25-m-long undulators for high flux production. The undulators on the back of the CESR return arc (nearest the injector I) will be located in a segment of the machine where bunch compressors will be located to shorten the bunches down to the range of approximately 50 fs. In the first 15 beamlines, 2ps bunches will be available. The optics for the different working modes of Table 1 have been designed[13], and several emittance-growth effects have been investigated, i.e. coherent and incoherent synchrotron radiation, coupler kicks and space charge. The higher order modes in cavities will be damped sufficiently to avoid transverse beam oscillations[14]. Effects due to ions in the vacuum chamber and their suppression are under investigation[15], and beam stabilization is being studied.

The current parameter set for the ERL X-ray source is given in Table 1. Unlike a storage ring, a linac-based light source is a more flexible source of X-rays. One of the opportunities in investigating this technology is to learn how to run in the various modes and to optimize the X-ray production for X-ray users who want small beams that are

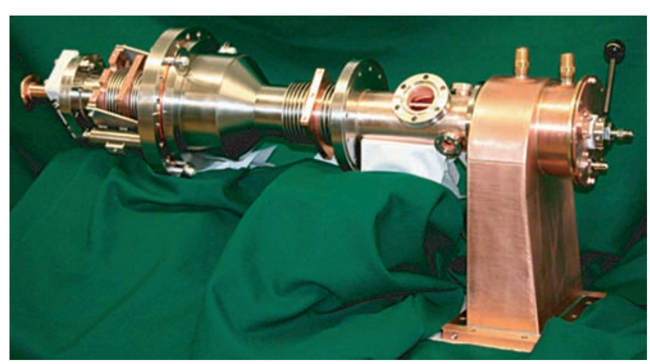

Figure 5: The prototype RF power coupler. 1.3 GHz microwave power enters the waveguide to coaxial coupler transition at the right-hand side, and is fed to the RF cavity at the end of the coaxial line on the far left-hand side. Of the three flanges along the coaxial section, the left-hand one is at 2 K, the central (largest) one is at 80 K, and the right-hand one is at room temperature. Thin copper plating inside the several bellows, and thermal intercepts serve to limit the power deposited at cryogenic temperatures.

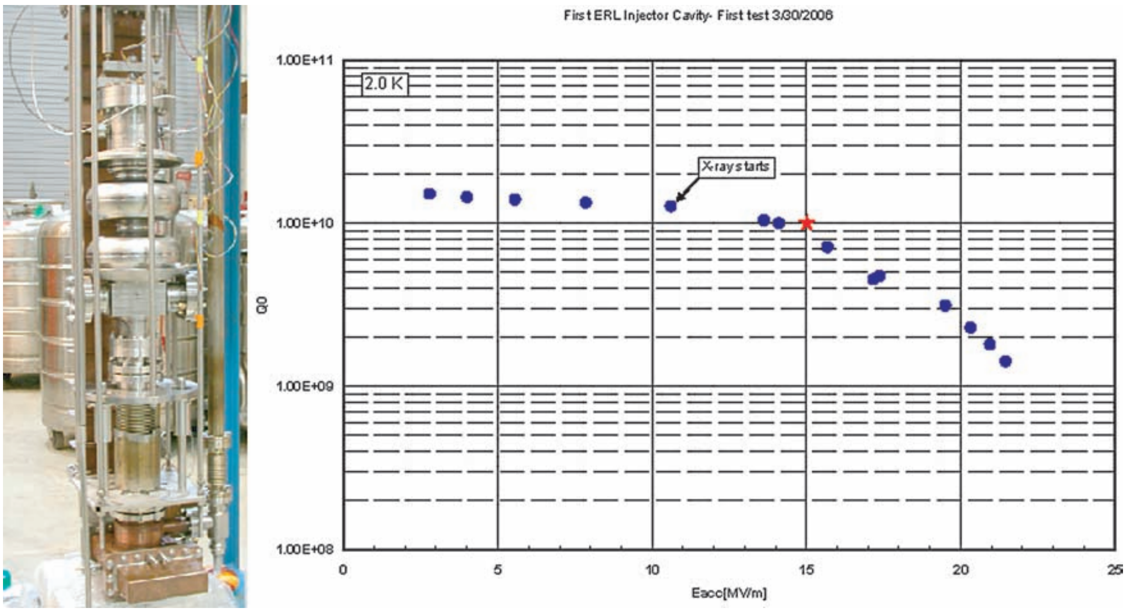

Figure 6: (Left) The two-cell niobium cavity mounted in its dewar insert for cryogenic testing. (Right) The results of the first two-cell cavity test at 2 K. Q_o measures the cavity RF losses, and E_{acc} is the effective cavity electric accelerating field. The red star shows the design goal.

coherent, that have a large flux, or come in short bunches for ultra-fast experiments. The 6 pm emittance (horizontal and vertical) is a nearly diffraction limited value for 12 keV (1 Angstrom) operation.

There are, of course, many spectral curves that show the power of the ERL technology relative to that of current sources. Figure 8 shows the average spectral brightness vs. photon energy for the ERL compared to other existing sources. The ultra-high spectral brightness is useful when performing coherent beam experiments. One of the grand challenges in condensed matter physics is to determine the three-dimensional structure of a glass or amorphous silicon (α-silicon) at the atomic level. A suitable coherent beam of small size might be ideal for this undertaking.

Another advantage of the ERL technology relative to that of storage rings is that the X-ray pulses can be of much shorter duration (Figure 9). We envision expanding the ultra-fast X-ray science into the femtosecond regime, the time scale of chemical reactions. The ERL will be particularly good at repetitive pump-probe experiments where you repeatedly flash with a pump laser and probe at some time later with an

Table 1: ERL parameter sets for short-term commissioning goals (columns A-C) and for longer-term goals (D-E). The longer-term goals are based upon simulations, and show the promise that may be achievable after considerable R&D activity beyond turn on. Please note that each column gives the respective parameters for a mode of operation. In the longer-term goals columns, the high-flux (A) and high-coherence (B) modes are merged into one common ultra-high coherence mode (D) that also will have very high flux.

	Short-Term Goals			Long-Term Goals		
Modes:	(A) Flux	(B) High-Coherence	(C) Short-Pulse	(D) Ultra High-Coherence	(E) Ultra Short-Pulse	Unit
Energy	5	5	5	5	5	GeV
Macropulse current	100	25	1	100	1	mA
Bunch charge	77	19	1000	77	10000	pC
Repetition rate	1300	1300	1	1300	0.1	MHz
Transverse emittance (norm. rms)	0.3	0.08	5.0	0.06	5.0	mm.mrad
Transverse emittance (geometric at 5GeV)	31	8.2	511	6.1	511	pm
Bunch length (rms)	2000	2000	50	2000	20	fsec
intrabunch Energy spread (fractional;rms)	2E-4	2E-4	3E-3	2E-4	3E-3	

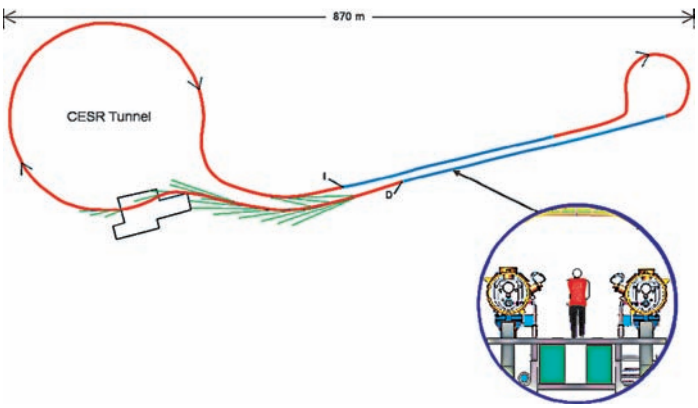

Figure 7: A preliminary layout view of an ERL upgrade to CESR. A new tunnel with a turnaround loop will be added to CESR. Electrons are injected into the superconducting cavities at (I) and accelerated to 2.5 GeV in the first half of the main linac, then to 5 GeV in the second half. The green lines show 18 possible X-ray beamline locations. Electrons travel around the CESR magnets clockwise and re-enter the linac 180 degrees out of phase. Their energy is then extracted and the spent electrons are sent on to the dump (D). The SC linacs will be located on either side of a new bored tunnel that will extend underground from the present CESR ring. A person is shown in the tunnel to give a sense of scale. The X-ray beamlines will be located in a new, partially underground building that is now at the conceptual design stage.

ERL X-ray beam, over and over again. [This is in contrast to the single-pulse flash X-ray experiments planned for XFELs.] We estimate that probe intensities might be of order 10^9 X-rays/pulse, so stroboscopic experiments are favored. An example of the new ultra-fast frontier with an ERL would be to study chemically excited states that give insight into photosynthesis. Such information, for instance, might be useful for developing efficient and cheap use of solar energy.

An ERL X-ray source will be idea for producing X-ray nanoprobe beams. A round source size (instead of a pancake-shaped storage ring source) will be more efficiently used to make the smallest possible diameter X-ray beams (Figure 10).

We estimate that the X-ray from of the nanoprobe will be of real advantage (as compared to electrons) in certain situations where the X-ray beam is not spread in size by scattering for thick practical circuits of some 100s of nm total thickness or where micron-sized objects such as single whole biological cells cannot be easily sectioned into hundreds of slices with a microtome for study in an EM microscope.

Another advantage of the ERL technology is that, in many cases, we can take state-of-the-art 3rd generation beamline designs (and experimental know-how) and just get started with them at an ERL facility. In this sense, ERL beams will be an evolutionary technology where existing (and new novel experiments) will be pushed forward by having X-ray beam qualities 100- to 1000-fold better than can be found at today's state-of-the-art facilities. Once the ERL technology has been proven, it should be possible to upgrade an existing storage ring to far better performance than by pushing the ring technology alone.

In summary, an exciting X-ray science frontier awaits us using Energy Recovery Linacs to further push the frontiers of spectral brightness and short pulses by several to many orders of magnitude under high-repetition-rate "storage ring" like conditions. From femto-second resolved chemistry, coherent scattering from nanoparticles, single biological cells and thin membranes to making the tiniest possible X-ray beams into an EM-like instrument, ERL sources or storage rings with upgraded ERL injectors promise to greatly increase the synchrotron radiation research capability of existing X-ray sources both here at Cornell University and world-wide. ■

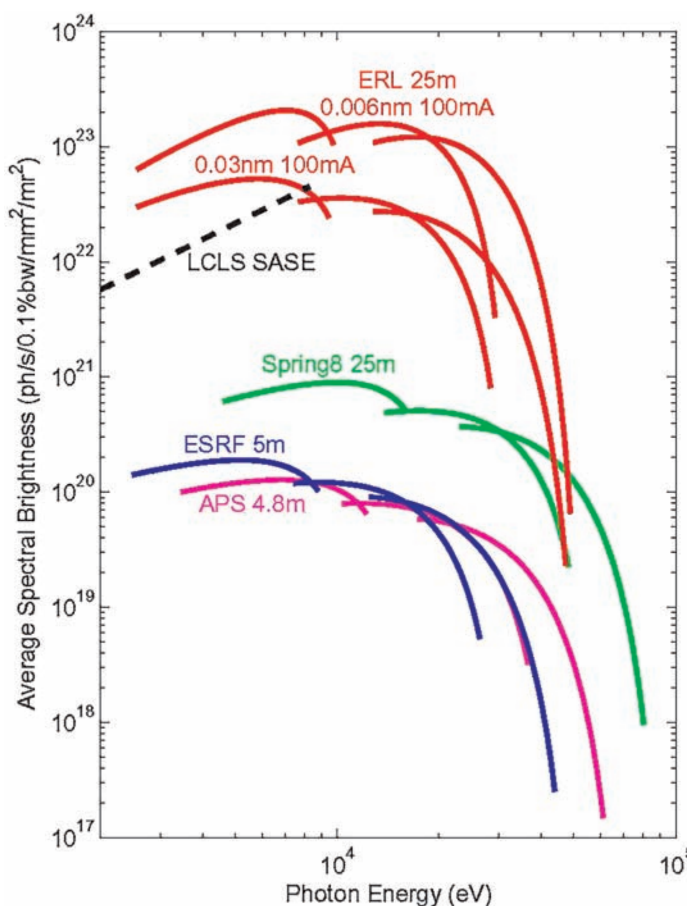

Figure 8: Shows the average spectral brightness vs. photon energy for a 25-m-long ERL undulator[16]. As can be seen in the top curves belonging to the ERL (red), the average spectral brightness will be several orders of magnitude higher than existing storage ring sources and even higher than the average (but not peak) brightness of the LCLS.

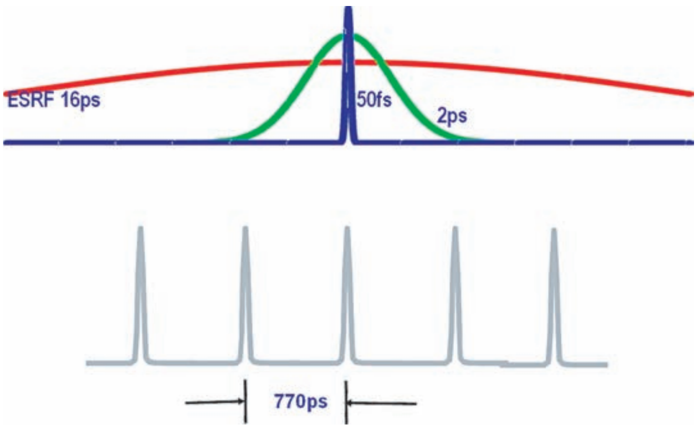

Figure 9: A schematic of the pulse shape in time for (top) the ESRF in single-bunch mode with 16 ps rms bunch length, the ERL natural (uncompressed) pulse length of 2 ps, and bunch-compressed value of 50 fs for ultra-fast operation at 1 nC/bunch. The pulses can occur as often as every 770 ps at 77 pC/pulse, the situation where every RF bucket is filled for a 1.3 GHz operation of the cavities, although lower repetition rates may be chosen as more desirable to match pump-probe opportunities. The injector is planned to have a programmable injector where we could program the laser creating the electrons to fire on every second pulse, etc., to lengthen the inter-pulse period.

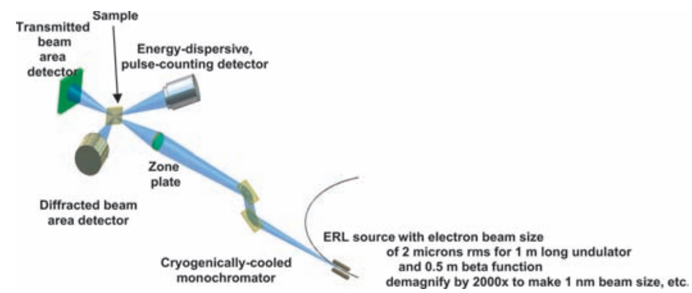

Figure 10: How a small round source size can be demagnified 2000-fold to make a 1 nm beam size at 10 keV. There will be a lot of uses for such a nano-probe that looks in many ways like an electron microscope, but works with X-rays instead of electrons. The zone plate shown[17] is a place holder for the optics that are needed, which could also be an adiabatic refractive lens[18] or a Laue lens[19], depending on which component gives the best performance by the time the instrument is built. The scientific use of this instrument could range from focusing the beam onto a single impurity atom in a transistor of a few atom line width buried inside a practical electronic circuit or of performing fluorescent elemental identification in biological specimens at nm resolution. A spectroscopy experiment on a single impurity atom in a doped silicon wafer could probably reveal whether that atom was electrically active or not. Such information might be of great diagnostic value when learning how to make the smallest possible transistors work 10 years from now.

References

1. S. M. Gruner and D. H. Bilderback, Energy Recovery Linacs as Synchrotron Light Sources, *Nuclear Instrum. & Meth.* **A 500** 25 (2003); G. H. Hoffstaetter, I.V. Bazarov, D. Bilderback, M. Billing, S. Gruner, M. Liepe, D. Sagan, C. Sinclair, R. Talman, M. Tigner, ERL Upgrade of an Existing X-ray Facility: CHESS at CESR, *Proceedings of EPAC 2004*, Lucerne, Switzerland, 497 (2004); Cornell ERL website: http://erl.chess.cornell.edu/
2. See LCLS website at http://www-ssrl.slac.stanford.edu/lcls/; and European x-ray laser website at http://xfel.desy.de/
3. M. Tigner, *Nuovo Cimento* **37**, 1228 (1965).
4. B. Aune et al., *Phys. Rev. ST-AB* **3**, 092001 (2000); G. R. Neil et al., *Phys. Rev. Lett.* **84**, 662 (2000); C. K. Sinclair, *Proceedings of the 2003 Particle Accelerator Conference*, p. 76.
5. T. I. Smith, *Nuclear Instrum. & Meth.* **A 259**, 1 (1987).
6. A 14 MeV prototype version of MARS (a Multi-pass Accelerator-Recuperator) has been built. MARS is a proposed coherent hard X-ray source with energy recovery at low beam current. See G. Kulipanov, A. Skrinsky, N. Vinokurov, "Synchrotron light sources and recent development of accelerator technology," *J. Synchrotron Radiation* **5**, 176 (1998).
7. www.bnl.gov/henp/docs/NSAC_RHICII-eRHIC_2-15-03.pdf
8. The Laboratory of Elementary Particle Physics (LEPP) and the Cornell High Energy Synchrotron Source (CHESS) have joined to become the Cornell Laboratory for Accelerator-based Sciences and Education. See http://news.chess.cornell.edu/articles/2006/Classe.html
9. First beam from photocathode was achieved on August 16, 2006. The prototype ERL will produce mid-IR radiation from a 35 MeV electron beam. See http://www.4gls.ac.uk/ERLP.htm
10. http://www.bessy.de/publicRelations/publications/files/sc.pdf
11. Poster: "Future light source at the Photon Factory," Hiroshi Kawata, personal communication.
12. George Pataki, Governor of the State of New York announces $12M in funding at Cornell Univ. on August 19, 2006, http://news.chess.cornell.edu/articles/2006/Pataki.html
13. G.H. Hoffstaetter, V. Litvinenko, H. Owen, Optics and Beam Transport in Energy Recovery Linacs, *Nuclear Instruments and Methods in Physics Research* A **557**, 345–353 (2006).
14. G.H. Hoffstaetter, I.V. Bazarov, C. Song, Recirculating BBU thresholds for polarized HOMs with optical coupling, ArXiv: physics/0508089 (2005).
15. G.H. Hoffstaetter, M.U. Liepe, Ion clearing in an ERL, *Nuclear Instruments and Methods in Physics Research A* **557**, 205–212 (2006).
16. taken from http://erl.chess.cornell.edu/papers/2006/ERL%20status%20SRI-2006.pdf
17. W. Yun personal communication, see also http://xradia.com/.
18. C. G. Schroer and B. Lengeler, Focusing hard X-rays to nanometer dimensions by adiabatically focusing lenses, *Phys. Rev. Lett.* **94**, 054802 (2005).
19. H. C. Kang, J. Maser, G. B. Stephenson, C. Liu, R. Conley, A. T. Macrander, and S. Vogt, Nanometer linear focusing of hard X-rays by a multilayer Laue lens," *Phys. Rev. Lett.* **96** 127401 (2006).