ERL Project Update

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The goal of the Energy Recovery Linac (ERL) project is to research and develop a next generation synchrotron x-ray source. An ERL, for readers unfamiliar with the term, is neither a storage ring nor an x-ray free electron laser. Recall that synchrotron radiation (SR) is produced when ultrarelativistic charged particles, such as electrons, are deflected perpendicular to their forward velocity. In a storage ring, electrons are kept in circulation for long periods of time, typically many hours. As the electrons circulate, they suffer stochastic changes in energy and momentum due to emission of synchrotron photons, as well as due to absorption of energy from the RF cavities that drive the ring. The consequence of these changes is that within a few thousandths of a second the electrons assume an ensemble of orbits characteristic of the ring. It is the spatial and angular distribution of the electron orbits, quantified by a ring parameter called the emittance, that limits the brilliance of the emitted SR. For this reason, the most important goal in designing an SR source is to maximize brilliance by minimizing the vertical and horizontal particle beam emittances. A half century of R&D on storage rings have brought us to the point of diminishing returns for today’s state-of-the-art, third generation storage rings.

The SR community is now hard at work developing future generation hard x-ray sources. Two next generation technologies, both based on linacs, are being hotly pursued. The first is the x-ray free electron laser (XFEL), as represented, for example, by the Linac Coherent Light Source project at SLAC and the TESLA project at DESY. XFELs are designed to produce fully coherent x-ray pulses of extreme peak power, but at far lower repetition rates than storage rings. XFELs are likely to drive SR research in new directions. But the pulsed nature and high peak power of an XFEL will require the development of new ways of performing most x-ray experiments. For this reason, a principal goal of SR research over the last half-century has been to maximize brilliance by minimizing the vertical and horizontal particle-beam emittances in storage rings. Unfortunately this effort has begun to reach fundamental limits of SR sources.

ERLs, represented by the project at Cornell University, are a distinctly different route to a next generation source. ERLs combine the very small emittance electron beams of modern laser-driven photoinjectors with the exceptional acceleration and deacceleration properties of superconducting linacs. In a nutshell, the photoinjector produces low emittance electron bunches that are accelerated to ultrarelativistic energies in the linac. The electron beams are then used to produce SR in a single pass round a ring. A key feature of an ERL is that the electrons are used to produce SR before the emittances are degraded. The electron energy is then efficiently extracted by a second pass through the linac and the resultant energy-depleted electrons are dumped. Thus, storage rings recycle electrons, whereas ERLs only recycle the electron energy. Readers interested in more details are referred to a wealth of material on the ERL website (http://erl.chess.cornell.edu/).

ERL Properties

ERLs will be capable of producing extraordinary SR beams. As opposed to XFELs, ERLs produce beams sufficiently similar to storage ring beams that they can directly serve almost all existing storage ring applications. At the same time, the beam properties are sufficiently superior so as to enable numerous experiments that cannot be done with storage rings. Specifically:

1. ERL beams will be several orders of magnitude more brilliant (Figure 1). This has the very important consequence that the x-ray beams will be nearly fully transversely coherent, even in the hard x-ray region (Figure 2). By contrast, 3rd generation storage ring beams are less than 1% coherent. An ERL can also be operated as a very high flux source (Figure 3).

2. ERL bunches can be compressed to be very short, thereby yielding short x-ray pulses. Storage ring pulses are typically longer than 30 ps. ERL pulses can be shorter than 100 fs, and possibly down to 20 fs.

3. The ERL source size is small and round, as opposed to the flat, extended shape of storage ring sources. This feature greatly expands the ability to produce x-ray microbeams.

The types, intervals and lengths of ERL electron bunches can be changed on very rapid (<< 1 sec) time scales. By contrast, the bunch structure of a storage ring is set for the entire multi-hour fill time.
Fig 1: Average brilliance versus x-ray energy for the 25m ERL undulator under two proposed current and emittance modes of operation. These are compared to the existing CHESS 24 pole and 49 pole wigglers and the 2.4, 5, and 25 meter undulators at the APS, ESRF and Spring-8, resp. Also shown are the spontaneous and SASE average brilliances expected from SLAC’s proposed LCLS x-ray free electron laser. The ERL undulator length, emittance, and currents are also given.

Fig 2: Transversely coherent fraction versus x-ray energy. See Figure 1 caption for an explanation of the curves.

Fig 3: Average flux versus x-ray energy for the ERL under several operating modes. See Figure 1 caption for an explanation of the other curves.
Project Update

The ERL project at Cornell is a collaboration between CHESS, the Laboratory of Elementary Particle Physics (LEPP, which built and operates the Cornell storage ring), and the Thomas Jefferson National Accelerator Facility in Newport News, VA. Recent work on the ERL project has been focused on four key areas: (1) Design and computer modeling of the photoinjector; (2) Design of the superconducting linac; (3) Design studies of the layout of an ERL facility at CHESS; and (4) Workshops to explore applications enabled by ERL beams. Each of these is now discussed in turn.

Photoinjector & Superconducting Linac

The ERL photoinjector is a small but critical part of the entire machine, since the brilliance of an ERL is ultimately limited by the photoinjector. There has been much progress on the ERL injector design (Figure 4).

This consists of the electron gun, a bunching cavity, and a superconducting accelerating module consisting of five two-cell niobium RF cavities operating at 1.3 GHz. The cavities have integrated liquid helium vessels and tuners, input couplers that deliver 100 kW of RF power to the beam, and ferrite lined beam pipe segments to intercept and damp higher order modes excited by the beam so that these modes cannot disrupt the beam quality. The injector will be used for the ERL prototype as well as for the final ERL light source. The design of all components for the superconducting cryomodule is fast approaching completion. Construction of a test stand is underway to qualify cavities for the injector as well as for the main linac in the future.

A key advantage of an ERL is that the machine can be upgraded by improving the photoinjector (as opposed to storage rings where dramatic upgrades generally require rebuilding the entire ring). CW photoemission electron injector optimization – a technical area in its infancy – requires numerical simulation of highly nonlinear space charge effects. Computational optimization of the injector, incorporating the many variables involved (i.e. field strengths and physical locations of the elements; and the size, shape, and duration of the laser pulse illuminating the photocathode) has been facilitated by the use of the Feynman parallel processing MacCHESS computer. The enormous processing power of this machine has allowed thousands of individual simulation runs through the entire injector in a relatively short period of time. Each run tracks 50,000 “macroparticles” through the full injector (and each macroparticle represents about 10,000 electrons). To date, we have obtained simulated emittances considerably smaller (by a factor >15) than proposed two years ago for full bunch charge. We have also obtained simulated emittances smaller than the original design specification by a factor of two for bunch charges ten times larger than the original design.

These improvements in the simulated injector performance, as reflected in Figures 1-3, vindicate the assertion that ERL performance improvements start where storage ring improvements top out. Of particular note is that with the improved brilliance of the injector, the ERL would be diffraction limited up to 12.6 keV. In other words, such an ERL would essentially be a source of nearly fully transversely coherent x-rays.
Current effort is focused both on prototyping critical ERL components (e.g., the photoinjector and linac), and on design exercises for a full-scale x-ray ERL at Cornell. Much thought has gone into devising ways of building an x-ray ERL with as little disruption as possible to the existing programs operating at CESR. Two seemingly conflicting requirements have to be considered: to make the design cost efficient, much of CESR’s infrastructure should be reused, since it will no longer be needed for high energy physics experiments after the CESR-c/CLEO-c project is phased down in about 4 years. However, the operation of CHESS should be disrupted as little as possible while building and commissioning the ERL. Figure 5 shows the CESR tunnel and the layout of a possible ERL extension. Electrons from a 10 MeV injector (1) would be accelerated to the East in a 2.5 GeV linac (2). A return loop (3) would send them into a second linac which is located in the same straight tunnel (4) and accelerates to 5 GeV. A half-circular arc (5) injects the electrons into the CESR ring (6) where they travel clockwise until a second half circle (7) injects them back into the first linac, where they are decelerated to 2.5 GeV. The return loop leads the electrons to the second linac section where deceleration back to 10 MeV occurs, and then to the beam dump (8). The South half of the CESR tunnel would contain undulators and would reuse the current facilities of CHESS. New user areas could be created in the North section of CESR and in straight sections of the linac tunnel.

While it was originally thought that reusing CESR imposed too many constraints, surprisingly it has been found that the flexibility of CESR’s magnet arrangement holds several advantages for an ERL design. First and second order electron optics can be found for bunch compression down to <100 fs, and nearly all required magnet strength could be supported by today’s magnets. This ERL upgrade of the 2nd generation light source of CHESS suggests how other existing storage rings can be extended to ERL light sources with much improved beam qualities. The ultimate reason that first-generation lattice components from CESR are compatible with an ultrabrilliant machine is that the brilliance degradation characteristic of storage rings only occurs after many of circuits around the ring.

The half-circular transition from the linac to CESR and the similar ejection from CESR to the linac has been chosen so that the ERL could be built and commissioned independently from CESR. Electrons could be accelerated and returned to the linac through the two half circles without passing through CESR. CHESS operation could continue during this period. Other advantages of this upgrade plan are that all of the CESR tunnel is reused, which creates space for a large number of insertion devices. The location of the linac at the edge of the Cornell campus is chosen in such a way that no building foundations are of concern and that further extensions to the linac would be possible. The straight tunnel houses two linacs, which reduces tunnel cost as well as the required length of cryogenic lines and cables. The tunnel is laid out longer than required for the two linacs, so that an extension of the facility by extra undulators or an FEL would be possible.
ERL Science Workshops

Workshops to explore science enabled by ERLs are an important part of ERL R&D. In August 2003, we organized an International Workshop on X-ray Science with Coherent Radiation, in collaboration with LBNL, Arizona State University, and SSRL as a satellite meeting to the 2003 International Conference on Synchrotron Radiation Instrumentation. The workshop attracted more than 120 attendees from many countries (For a more detailed recap of the workshop, see the companion article on Page 37. The workshop addressed two closely related questions: (a) What new types of experiments may be done with coherent x-ray sources? (b) What new techniques and instrumentation are needed for these new types of experiments? Through the two-day workshop, many participants showcased a number of scientific application areas in coherent x-ray imaging and scattering, as well as the state-of-the-art coherent x-ray optics and analytical methods. The general consensus at the workshop is that the enhanced coherence and coherent flux by two to three orders of magnitude from future x-ray sources would greatly benefit these applications and enable potentially new areas of research in x-ray structural science.

In April 2004, the ERL group participated in Ultrafast X-rays 2004, a workshop series organized by LBNL with a focus on production and applications of <100 femtosecond x-ray pulses. Although several new source proposals aim for <100fs pulses (Figure 6), the relatively high repetition rate of an ERL source would be ideal for studying ultrafast electronic transition states and collective mode excitations in condensed matter, as well as chemical structural changes that can be induced by high rep-rate optical lasers. Many experiments being done at existing storage rings with high rep-rates can be directly transferred to an ERL source, with ~1000 times reduction in x-ray pulse length and more flexibility in pulse timing. Examples of applications may include pump-probe imaging of magnetic nanostructures, x-ray spectroscopy studies of near-edge and extended structures, resonant scattering on laser-pumped charge-density-wave systems, and wide-angle scattering on laser induced molecular transition states.

We plan to organize more workshops in the near future on ERL related science and technologies. In addition to coherence and ultrafast pulses, the topics will also include nano-probes, x-ray optics, insertion devices, etc. Please contact us directly if you have ideas on these topics, and visit our website often to check on the latest news.

Summary

ERL work at Cornell is progressing. After several years of critical examination, the ERL concept looks even better than originally thought. We are anxious to start constructing prototype hardware. Towards this end we are awaiting a funding decision by the NSF.