ENERGY RECOVERY LINAC EXPERIMENTAL CHALLENGES

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Abstract

ERL projects are ongoing at Jlab, Daresbury, KEK and Cornell. Here we describe the typical experimental concerns of using high-coherence and ultra-fast pulses from the Cornell ERL as an example of a new opportunity. The hi-flux mode is one where the ERL runs at 5 GeV and 100 mA. Many experiments are photon-starved, such as inelastic x-ray scattering. The high-coherence mode is obtained at 25 mA and the transverse emittances could be as low as 8 pm. The beam size will be at its smallest under this operating condition and average spectral brightness as high as 10E23 (standard units) are calculated. We expect to produce a 3 micron round emitting source for imaging and coherence experiments on individual biological cells. The ultra-fast mode is one obtained by reducing the repetition rate to 1 MHz and by increasing the bunch charge to 1 nC per pulse and compressing the natural 2 ps bunch length to less than 50 fs. We present below the science opportunities for x-ray experiments on a single atom as well as the challenges in x-ray optics, other experiments, and beam control issues when making a 1 nm focused x-ray beam size.

ENERGY RECOVERY LINACS AS LIGHT SOURCES

Energy Recovery Linac (ERL) light source projects are ongoing at Jlab (IR FEL), Daresbury (4GLS), KEK and Cornell. At Cornell University we are now part way through the very first stage of its design, construction and prototyping cycle. Funding from the National Science Foundation was awarded in February 2005 for a 4 year project to construct a photo-cathode gun and first superconducting accelerating module of an ultimate 5 GeV, 100 mA ERL source of x-rays. Here we describe the typical experimental concerns of using high-coherence and ultra-fast pulses from an ERL class of machine and will use the Cornell ERL as a representative example of a new class of x-ray source. Fig. 1 shows the layout view of an upgrade to the present CESR machine to one that has ERL capability. The existing CESR tunnel will be reused and new tunnel will be added to house the superconducting linac and turn-around arc.

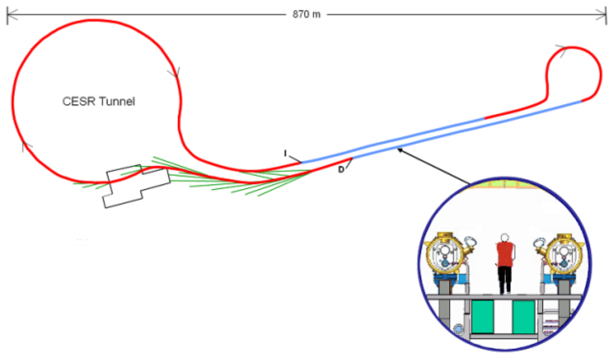

Figure 1: The present CESR machine in a circular tunnel will be expanded to the right with two 2.5 GeV linacs (shown in blue) in new tunnel to be added to the existing accelerator complex. Electrons are injected at (I), are accelerated in the first ½ of the linac to 2.5 GeV, turned around in the short loop and then finally accelerated to 5 GeV. The electrons then travel through as many as 18 insertion devices surrounding the CESR tunnel end before re-entering the linac out of accelerating phase where their energy is recovered and sent to the dump (D).

Possible Operating Modes

What we have learned so far from our studies at Cornell [1, 2] is that three modes of ERL operation are likely, which we call hi-flux, hi-coherence, and ultra-fast modes. The capabilities are listed in Table 1.

Table 1: Summary machine parameters for three modes of operation: hi-flux, hi-coherence and ultra-fast after a short commissioning period. Items in ( ) are numbers that seem very challenging at the moment, but we have ideas on how to achieve each of the parameters after a lengthy development period

Mode	Key parameters at 5 GeV
Hi-flux	100 mA, 31 pm emittance (5 pm), 77 pC, 1300 MHz repetition rate, electron energy spread ~ 2E-4
Hi-coherence	25 mA, 8 pm emittance (100 mA, 5 pm)
Ultra-fast	50 fs, 1 MHz repetition rate, 1 mA, 1 nC/bunch, electron energy spread ~ 3E-4, 511 pm emittance, (20 fs)

Hi-flux for Photon-starved Experiments

The hi-flux mode is one in which the ERL runs at 5 GeV and 100 mA (transverse emittances of 31 pm initially, bunch charge of 77 pC with a 1300 MHz repetition rate). Many x-ray experiments are photon-starved, such as inelastic x-ray scattering. While

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preserving relatively low divergence, we want to increase the number of x-rays/sec onto a sample as much as possible, Fig. 2. This is why we are planning to have several 25-meter long undulators with many periods.

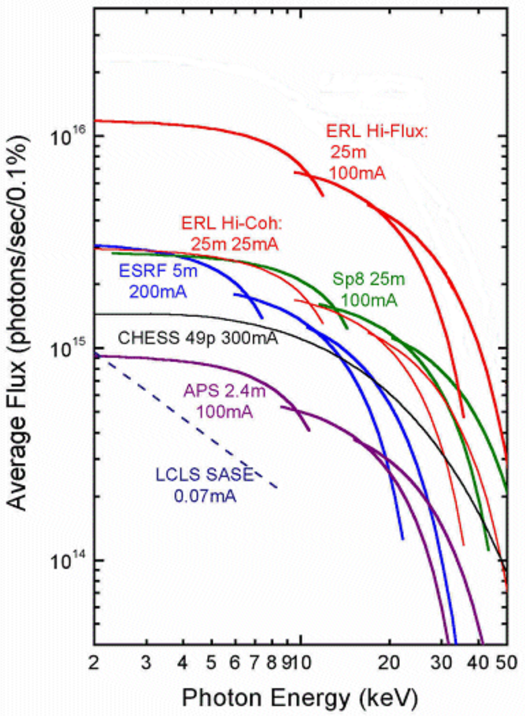


Figure 2: The time-averaged flux vs. photon energy for the ERL with 17 mm period, 25 m long undulators as compared to ESRF, SPRING-8, APS and the LCLS.

Hi-coherence X-ray Experiments

The high-coherence mode is one in which the current is turned down to 25 mA and the corresponding transverse emittances could be as low as 8 pm-rad. The beam size will be at its smallest under this operating condition and average spectral brightness as high as 10E23 (standard units) are expected, Fig. 3

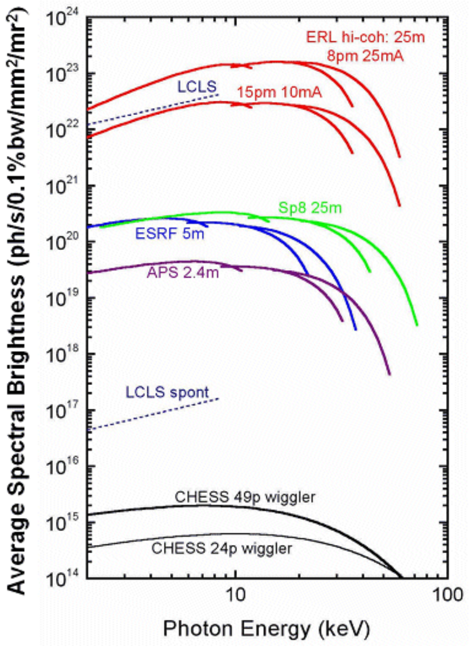


Figure 3: Average spectral brightness vs. photon energy for the ERL, ESRF, APS, LCLS and present CHESS facility.

With a short 2m long ID and a 1 meter beta function, we expect to produce a 3 micron rms round emitting source for exciting imaging and coherence experiments, such as diffraction imaging from non-crystalline materials such as individual biological cells, Fig 4.

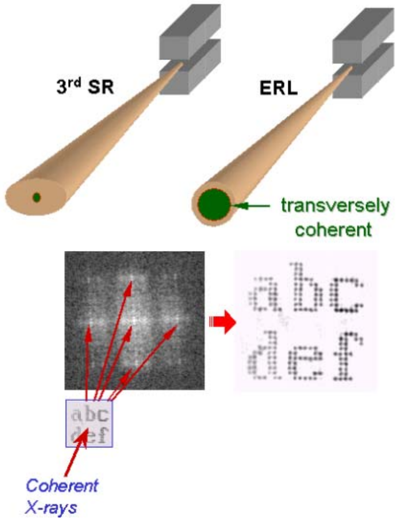
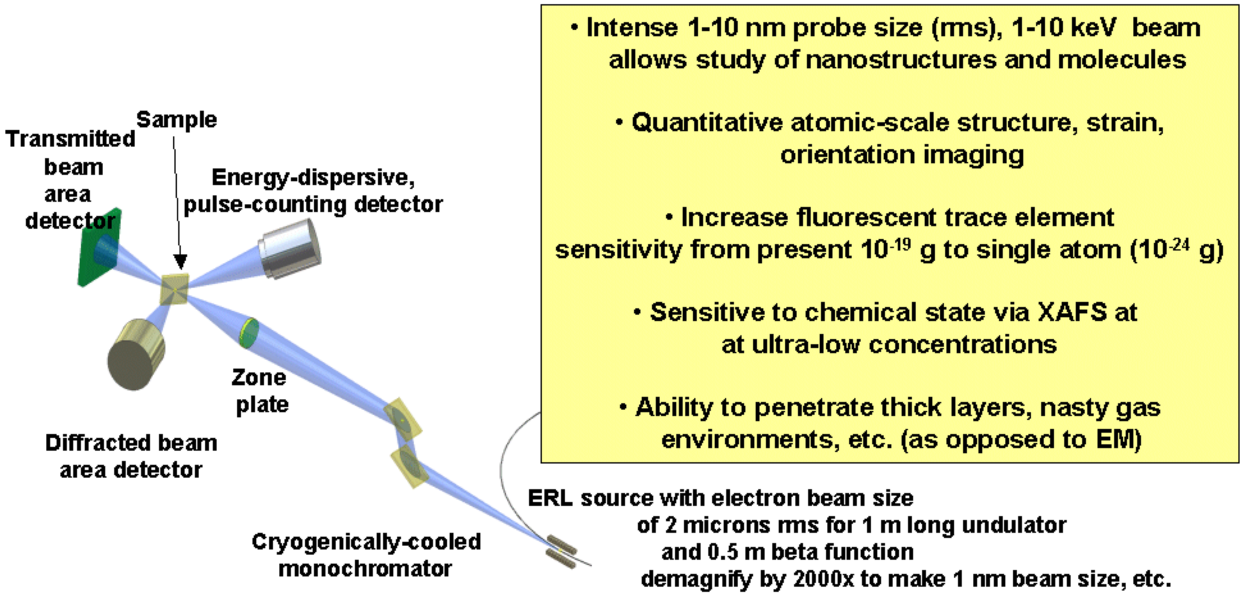


Figure 4: Top cartoon shows that the transversely coherent component from a 3rd generation storage ring is very small compared to the nearly fully coherent x-ray beam from an ERL. The bottom image shows how coherent x-rays from the NSLS may illuminate a non-periodic sample from which the reconstructed image can be mathematically obtained [3].



- Intense 1-10 nm probe size (rms), 1-10 keV beam allows study of nanostructures and molecules
- Quantitative atomic-scale structure, strain, orientation imaging
- Increase fluorescent trace element sensitivity from present 10^{-19} g to single atom (10^{-24} g)
- Sensitive to chemical state via XAFS at at ultra-low concentrations
- Ability to penetrate thick layers, nasty gas environments, etc. (as opposed to EM)

ERL source with electron beam size of 2 microns rms for 1 m long undulator and 0.5 m beta function demagnify by 2000x to make 1 nm beam size, etc.

Figure 5: Nanoprobe instrument for making a 1 to 10 nm diameter x-ray beam. Such an instrument offers the possibility of making x-ray experiments possible, for the first time, on a single atom.

We next turn to the experimental challenges that will require new developments and planning for hi-flux and hi-coherence operation. One aspect of the development process is to ask how close we are to the limit of 3rd generation storage ring technology and how much above this limit the ERL levels of performance could be. Let us explore these issues starting from the insertion device, then covering x-ray windows, x-ray optics, science experiments possible.

Insertion Device Challenges

Insertion devices may be quite similar to the permanent magnet technology at present day SR sources except that an ERL may produce an electron beam of smaller, round diameter. Our group has started to think about in-vacuum magnetic gaps in the 3 to 5 mm regime that would allow us to consider short period planar undulators or even helical superconducting undulators. Since flux goes as the number of periods of an undulator, we are particularly eager to have as many poles as possible in our devices to make them as competitive as possible. We also wish to have many periods in constructive interference so that in some cases (particularly for coherence experiments) we might dispense with the monochromator altogether.

X-ray windows will present some challenges. The angular power density may be higher than for current designed windows (more poles on the undulator, divergences may be less) so that we may run into some problems here. Windows will probably have to be polished to uniform thickness over larger areas than the current technology demands as the ERL will be able to produce nearly 100% coherent x-ray beams over the whole opening cone of the x-ray beam up to 10 keV photon energy in the high coherence mode.

Windows and X-ray Optical Challenges

X-ray optics will have similar heat-loading issues as the windows. Since preservation of spectral brightness is a key item, keeping the lattice planes parallel (i.e. minimizing the thermal bump induced by the photon beam) will be another key issue (slope error and roughness are related issues for x-ray mirrors). Cryogenically cooled silicon and diamond look like a viable route. We soon will be designing against materials limits where even the enhanced thermal conductivity from isotopically pure materials may offer a real technical advantage.

A Nanometer-Diameter X-ray Beam Challenge

Nanometer beam x-ray optics is another area of challenge. Hard x-ray beam sizes down to the 50 nm vertical size range are now being reported by various storage ring groups. One of the ERL goals is to make a round 1 nm beam size with a flux of 10E11 x-rays/sec/nm**2 behind a silicon (111) monochromator that can focus x-rays onto a single atom [4], Fig 5.

For instance, we might be able to focus on a single impurity atom (dopant) in a fine linewidth transistor and tell if it is electrically active or not by observing its near edge absorption structure.

The optics community is still discussing whether 1 nm probe size is possible or not. Possible optic choices are zone plates [5-7], Kirkpatrick-Baez mirrors [8-9], 2-dimensional waveguides [10], refractive lens [11] and Laue lens [12] for making the smallest beam sizes that are near 100-nm in size or below.

On the x-ray mirror front, a focusing mirror (say part of a K-B type mirror assembly) producing a 1 nm focus (if such is possible) would have to have slope errors of order 0.01 microradians or less to keep from steering the beam by an extra nm at the focus located 50 cm away. This is two orders of magnitude lower than current practice. If you then integrate the slope error over a correlation length of 100 microns (arising from polishing), then the tolerable height differences (roughness) needs to be below 0.01 Angstrom. This is again as much as two orders of magnitude smaller than current practice on state-of-the-art silicon mirrors. Dialog with opticians will be needed to see what progress is possible in this field in the next decade of time.

Nanometer Stability at the End of the Beam Line

Additional challenges? No one has yet taken x-rays from such a large-scale accelerator and kept then stably through an optical chain delivering 1 nm stability at the end of the beam line. BPMs, steering systems, etc. will all have to work in concert to make this possible. Because the final optic demagnifies by 1/2000 or so, photon beam stability only needs to be submicron before the final optical element. Radiation damage of samples will be an issue also, but not fundamentally so for robust samples of silicon, for instance.

Ultra-fast X-ray Opportunities

The ultra-fast operation of the ERL will present its own set of opportunities/challenges. The ultra-fast mode is one in which we change the average current to 1 mA by reducing the repetition rate to 1 MHz but increase the bunch charge to 1 nC per pulse. For this type of operation, the natural 2 ps bunch lengths can be compressed to 50 fs (rms) or shorter in a section of the return arc. After some significant development period, we are hopeful of making 20 fs long pulses.

Timing synchronization is an issue, but one that the SPPS, XFEL and optical laser communities are actively working to solve and we will follow their lead. First estimates are that we might be able to achieve 20 fs jitter in pump/probe operation.

Since the ERL features pulses at very high repetition rate, Fig 6, the challenge will be to develop samples and situations that can benefit from repetitive laser pumping followed by delayed x-ray probing that can be accumulated over billions of cycles. [This is quite a different regime than some of the single-shot experiments initially planned on the LCLS XFEL, for instance].

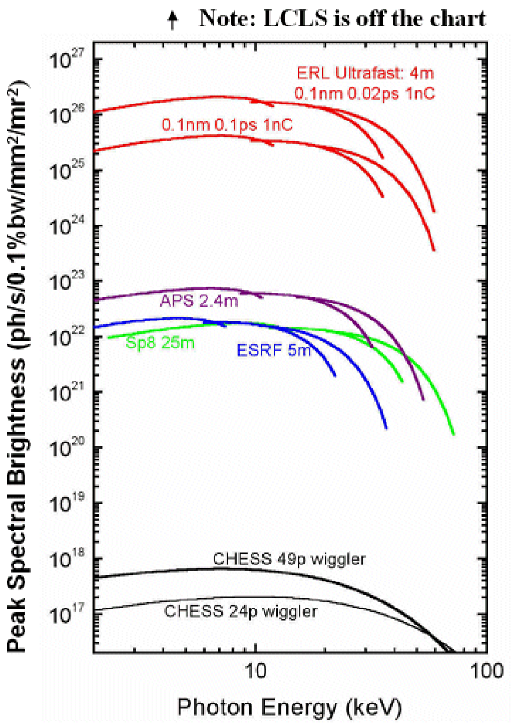
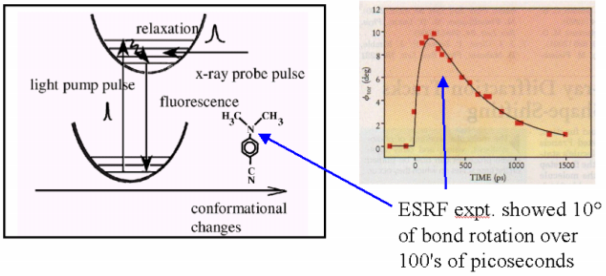

↑ **Note: LCLS is off the chart**

Figure 6: The peak spectral brightness vs. photon energy for the LCLS, ERL, APS, SPRING-8, ESRF, and the present CHESS facility. The LCLS with a SASE amplifier is off the chart.

Stroboscopic powder diffraction experiments pioneered on storage rings, Figure 7, can be pushed to significantly shorter time resolution with ERL technology. In this case a powder sample is repetitively stimulated by a laser into an altered state and the decay to the original state is followed with the full power of 3-d crystallography. In the example here, the two parts of the organic molecule are connected by a single bond that is rotated by as much as 10 degrees. It then relaxes in 100's of picoseconds back to the un-rotated state. A similar situation with the ERL experiment could be followed on the fs rather than the ps time scale.



ESRF expt. showed 10° of bond rotation over 100's of picoseconds

Figure 7: ESRF stroboscopic powder diffraction experiment that is repetitively pumped with a laser and probed with a single bunch of x-rays with delays up to 1500 ps in time [13].

Stroboscopic resonant diffraction from charge density waves in solid-state crystals such as $NbSe_3$ looks like another candidate area for ultra-fast studies, Figure 8. Observing the changes in structure will help physicists to better model and understand the dynamics of charge density waves.

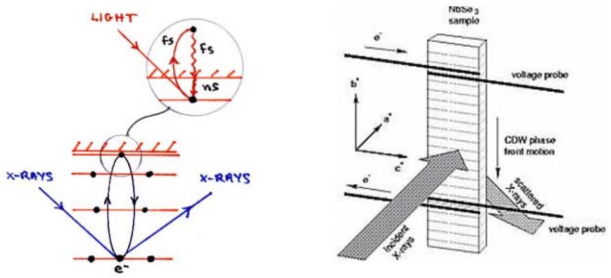


Figure 8: In this resonant diffraction experiment, hard x-rays of just the right energy pump an electron from a lower lying bound state to sample the energy region around the Fermi level. The decay time of the transition is significantly longer than the pump time and diffraction in this time window will reveal the structural change in response in the stimulation [14].

Another challenging problem in science is to understand chemical reactions in solution. The extension of XANES and EXAFS to the fs domain may allow viewing of the transition stages of ultra-fast chemical reactions. Dissociation dynamics are not well understood and it is very desirable to structurally view what is happening during the short reaction period. Stroboscopic XANES and EXAFS are possible on liquid samples such as iodine in solution as shown in Figure 9.

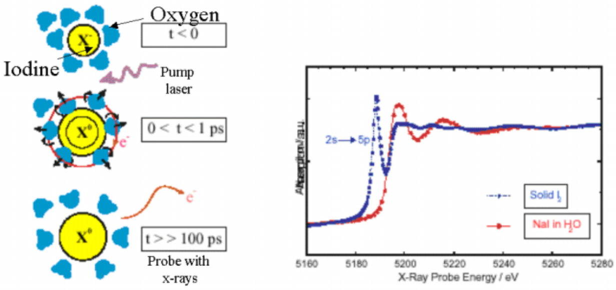


Figure 9: Figure taken from reference [15]. Oxygen ions surrounding an Iodine ion in solution are repetitively driven outward by the pump laser and allowed to relax back to the unexcited state. This is an example of dissociation dynamics that are not well understood. With ERL x-rays, it may be possible to observe what physically happens during the reaction and to observe intermediate states.

Specialized x-ray detectors will be needed to take advantage of this new kind of source. Photon counting detectors will work fine as the source, in the 1.3 GHz mode, will look like a continuous DC source if individual pixels can be read out quickly. On the other hand, there may be multiple events/pixel in the ultra-fast timing mode that would favor integrating detectors. So a combination of new technologies will be needed to take the most advantage of the new source.

CONCLUSIONS

Energy Recovery Linacs are of growing interest because they offer the potential to push x-ray science further than seems possible with just extensions of present day storage ring technology. With enhanced spectral brightness and further development of x-ray optics, ERL technology might make it possible to do x-ray experiments on even a single atom, something that is beyond the reach of today’s technology. With ultra-fast pulse durations in the 20 to 50 fs range, stroboscopic experiments look very feasible. With the improved parameters of an ERL type of source, we anticipate many hours of designing/planning/building new equipment and experiments to work further out on the exciting new frontier of precision photon science.

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