The Cornell Energy Recovery Linac: update on a future source of coherent hard x-rays*

Don Bilderback[1,2], Bruce Dunham[3], Georg Hoffstaetter[3], Alexander Temnykh[3], and Sol Gruner[1,4]
[1]*Cornell High Energy Synchrotron Source, Cornell University*
[2]*School of Applied Physics, Cornell University*
[3]*Laboratory of Elementary-Particle Physics, Cornell University*
[4]*Physics Department, Cornell University*
**For the Cornell ERL Team, Cornell University*

Synchrotron radiation research is still growing, with newer and more capable x-ray sources being constructed. Petra III in Hamburg, Germany and the NSLS II in Upton, NY are examples of storage rings under construction that are nearing the expected limits of storage ring performance. In contrast, linac-based sources such as energy recovery linacs (ERLs) and x-ray free electron lasers (XFELs) are still at an early stage of development, and have great potential for steady improvements in performance for many years to come.

The ERL upgrade to the CESR ring described below promises to generate ultra-bright electron beams, and thus ultra-bright x-ray beams with dramatically smaller emittances and shorter pulse durations than those available from storage rings[1]. The high coherence and temporal properties of the ERL will have **transformative, broad impact** across the sciences and engineering by enabling numerous experiments that are now not feasible at even the most modern 3rd generation storage ring sources; nor would many of these experiments be suitable for x-ray free electron lasers. Enabled science includes many types of imaging of materials and biological structures, macromolecular structure determination without crystals, effective nanoprobes for matter at higher static pressures than are presently feasible, and detailed studies of the structure of glasses, disordered materials, and polycrystalline materials. The ERL would be especially useful in cases where structure needs to be determined on objects for which structural details vary from one specimen to another, which is the case for most nanoparticles and biological cells and organelles. It would also allow the recording of extremely rapid events, so researchers can "visualize" rapid physical, catalytic and biological processes taking place on times scales down to 50 femtoseconds. Societal impacts will come in numerous areas such as life-saving medicines and drugs, new materials for better batteries, more efficient catalysts for fuel cells, better composite materials, smarter electronics, etc.

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. The underlying basis of an ERL is that, in principle, 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 as they pass through undulators. Since the electron beam carries several hundred megawatts of beam power, this is feasible only if the electron beam energy is recovered after the x-rays are generated. Using a superconducting (SC) RF 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, hence, the name Energy Recovery Linac. Although the basis of the ERL idea was suggested many years ago by Maury Tigner[2], it only became practical for x-ray generation in the mid-1990's, due to advances in superconducting linac technology and photoemission electron sources[3].

Phase 1a & 1b: *Testing the first stages of the ERL accelerator*

The ERL group at CLASSE is in the midst of prototyping the technology that will be needed for a 5 GeV ERL facility. The most difficult and critical component in need of R&D is the injector; a full-scale prototype injector has now been assembled in the L0 area of Wilson Laboratory (Figure 1). The injector generates a beam of high average current, low-emittance electrons using a laser-driven photo-cathode and then accelerates them to relativistic energies up to 15 MeV.

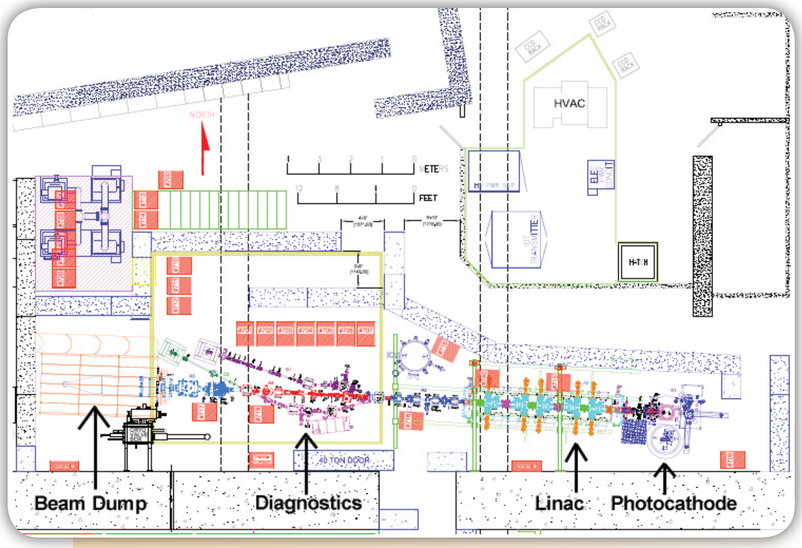

Fig. 1: Floor layout of the ERL test area in L0 of Wilson Laboratory, just south of CHESS East. From right to left: DC photocathode, superconducting linac, branch lines for diagnostics, and finally, a high power beam dump.

A consequence of special relativity is that the mutual charge repulsion that tends to blow apart a bunch of electrons at low energy is counteracted at relativistic speeds. Thus, the difficult task of the injector is not only to generate a low emittance electron beam, but to preserve the emittance until relativistic energies are achieved. Figure 1 shows the layout of the test accelerator designed to generate ultra-low emittance bunches of electrons at a 1.3 GHz rate with up to 100 mA average current. This injector is now in the commissioning stage.

The electrons are produced in a special cathode material using the photoelectric effect. A precisely shaped laser pulse is directed at the cathode, giving the electrons enough energy to escape. The ejected electrons are then accelerated across a small gap using a high voltage power supply. The cathode material is gallium arsenide (GaAs), which is commonly used for high speed electronics, in photomultiplier tubes, and in night vision goggles. To obtain efficient electron emission, the surface of the GaAs wafer must be as clean as possible and maintained at a vacuum level below 10^{-11} torr. After cleaning, it is coated with very thin layers of cesium and fluorine, which act to reduce the work function, making it easier for the electrons to escape (Figure 2 shows the cathode preparation system). The properties of GaAs have been extensively measured[4,5], demonstrating that it is currently the best cathode choice for obtaining low beam emittance and high average current.

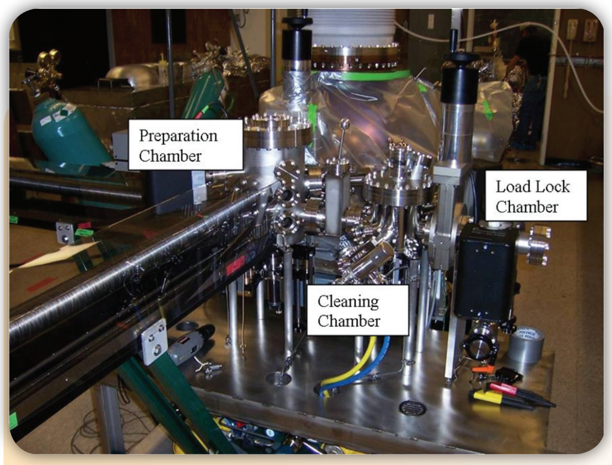

Fig. 2: Photocathode gun area. A vacuum of better than 10^{-11} Torr has to be maintained around the photocathode to avoid ion back bombardment of the photocathode, which would spoil the lifetime of the photocathode by ruining the monolayer of Cs on the surface. A load-lock chamber facilitates quick change of the cathodes for testing and for renewing the Cs monolayer needed for the cathode to work well.

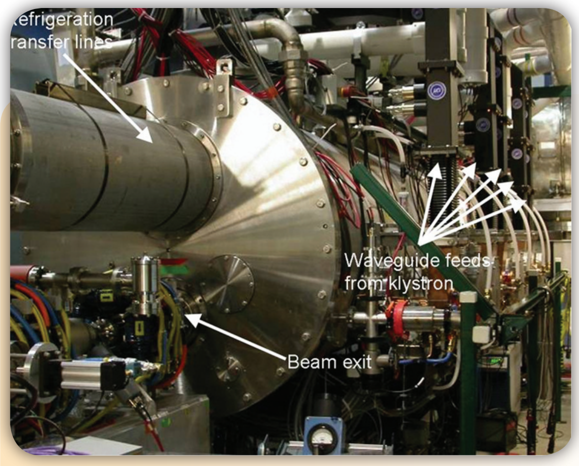

Fig. 3: The superconducting (SC) linac consists of 5 SC cells in series. Each cell uses a waveguide to conduct 1.3 GHz microwave power from associated klystron transmitters on the mezzanine floor above. The cavities are cooled by liquid helium at 1.8 K from a closed-cycle refrigeration system. The linac is now functional.

A very sophisticated laser system is required to produce bunches of electrons with the correct shape, power and time structure. It turns out that the shape of the outgoing electron pulse closely matches the shape of the incoming laser pulse, and the electron beam emittance can be reduced by choosing the correct shape. The spacing (frequency) of the pulses must also match the frequency of the RF accelerating cavities, which operate at 1.3 GHz. There are no commercial laser systems available to meet all of the needs for an ERL injector, thus we have built a custom laser using ytterbium (Yb) doped optical fibers.

After the electron bunches are produced at the cathode and given an initial acceleration by the electron gun, they are boosted to high energy using a series of 5 superconducting RF cavities (Figure 3). Each cavity can transfer up to 100 kW of microwave energy to the electron beam, for a total of 500 kW (1/2 of a million watts!). Superconducting cavities are used to overcome the heating problems that would occur with such large power. Figure 4 shows the five high-power microwave tubes that provide the energy to the accelerating cavities.

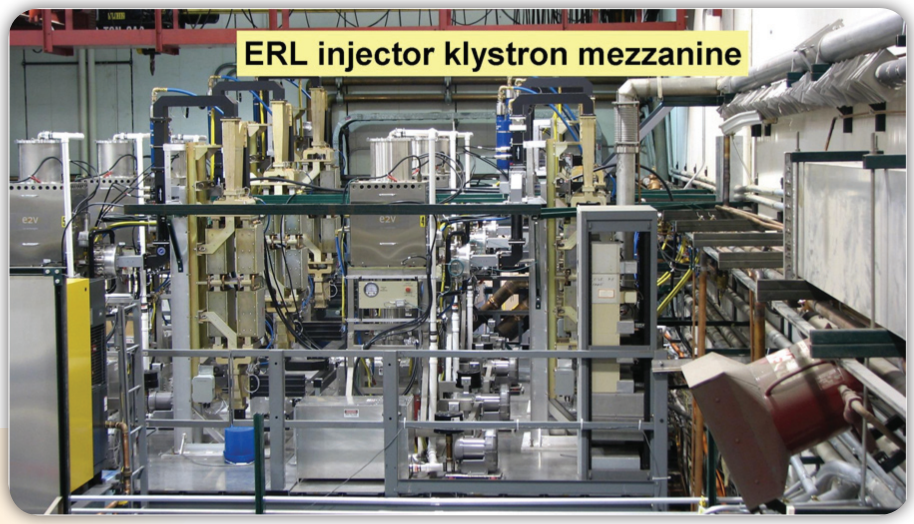

Fig. 4: Microwave generators produce the power needed to drive the superconducting linac.

The final parts of the test set-up are diagnostic tools to measure the emittance of the electron bunches and its pulse duration before the beam is sent to a 0.5 MW beam dump.

We are now starting the second phase of the ERL R&D program. The proposed research program addresses five critically important technology areas:

1. *Superconducting linac development.* The ERL requires linacs capable of continuous duty (CW) operation at high current with short bunch lengths while preserving emittance and dealing effectively with higher order modes. A full linac cryomodule (somewhat similar to the injector linac, but with longer cavities and with much weaker power couplers because in the ERL it is the decelerated beam that fills the cavity with energy, not the power coupler) will be designed and fabricated at Cornell. Cryomodule component testing will be done collaboratively with several other institutions. The program includes development of requisite cavities, higher-order-mode absorbers, beam position monitors, in-vacuum cryomagnets, RF amplifiers and power couplers, and cool-down procedures.
2. *High brightness photoinjector development*. Continued development will be performed on laser driven photoinjectors capable of delivering requisite current at high brightness and long photocathode lifetime. This includes R&D on new photocathodes, high voltage electron sources, drive lasers, and advanced beam simulation tools. Further R&D on the HV insulator is needed to reach the required 500 to 750 kV energy level from the electron gun.
3. *High-brightness electron beam physics and diagnostics.* The program will address challenges of emittance preservation from the electron source, through the injector, merger, and transport loop sections via experiments and simulations on the Cornell injector. Beam diagnostics to monitor bunch timing and position will be advanced, both for beam stability at the x-ray source points, and for simultaneously accelerating and decelerating bunches in the linacs.
4. *Beam dynamic effects* will be investigated, such as ion trapping, short bunch behavior and other possible sources of instability. Beam loss mechanisms, impedance issues, failure modes and beam abort strategies will all be studied through overall system modeling. In each case, methods of mitigation and control will be studied.
5. *X-ray beamline* components necessary to exploit ERL capabilities will be developed. These include novel undulators to exploit the identical horizontal and vertical emittances of an ERL, x-ray optics for high specific heat loads, coherence monitors, and detectors to effectively utilize the temporal possibilities of a coherent ERL source.

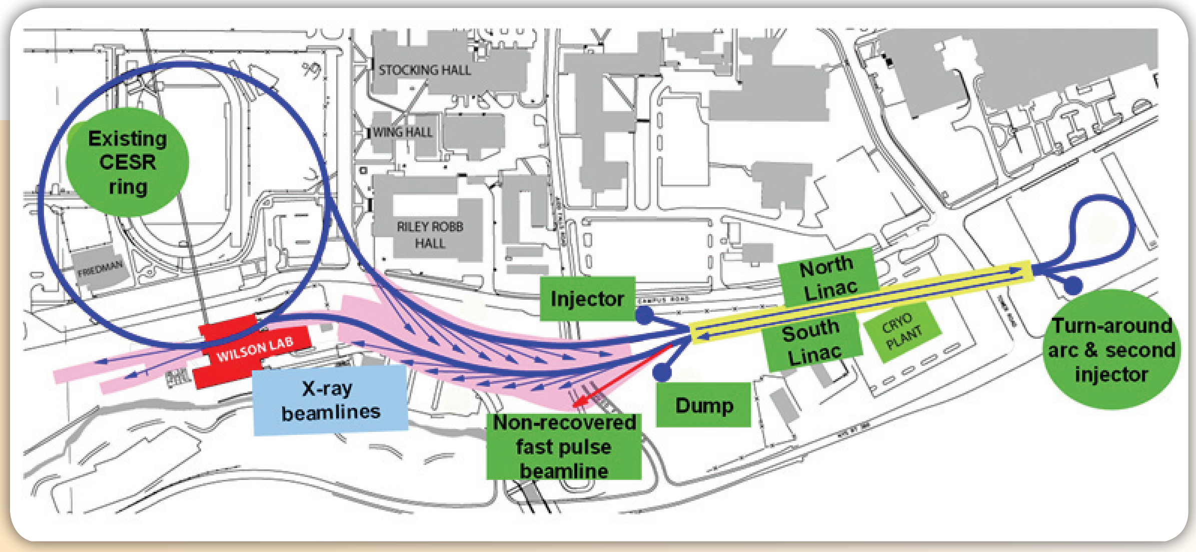

Fig 5: Low-energy electrons are produced and accelerated to 5-10 MeV at the injector. They are raised to 2.5 GeV in the North Linac by traveling "on-crest" through the RF fields produced by the SRF cavities, turned around and raised to 5 GeV after passing through the South Linac. X-rays will be produced in undulators in the position of the blue arrows, mostly in a new building to be added to the east of Wilson laboratory. Electrons returning to the North Linac are shifted 180 degrees out of accelerating phase (by adjusting the path length) so that the electrons are now "off-crest" and their energy is recovered in both linacs before the spent electron beam is sent to the dump. There is room in the layout for a non-energy-recovered, fast-pulse beamline as shown by the red arrow.

Phase II: *the full-energy, 5 GeV machine*

The work of the Phase I development (described above) is designed to provide confidence and costing for a 5 GeV ERL that we would hope to build at Wilson Laboratory.

The CESR tunnel and Wilson laboratory infrastructure will be reused for the ERL facility. Much of the ERL would consist of new construction to the East (above, in Figure 5) of the present CESR and Wilson Lab complex. A new partially-underground laboratory will be added to increase the number of x-ray beamlines and new tunnels will be bored to house the new linacs required. We already have a first round of plans and costing from ARUP, an internationally-based architectural and engineering company that has been contracted to develop plans for the civil engineering (buildings and tunnels) of the project. The present plans are for conceptual design purposes. We are presently optimizing the layout of tunnels, buildings and the machine to fit campus, performance, and cost constraints. For example, we are evaluating layouts with twin linacs in the same tunnel as well as versions in separate tunnels. When this work is completed, we plan to submit a conceptual design proposal to the NSF for a full-scale 5 GeV ERL facility, including x-ray beamlines.

The ERL design group is working on a Conceptual Design Report containing the following parameters table which shows various ERL operating modes. An ERL is more flexible than a storage ring, which opens new opportunities and a plethora of operating modes.

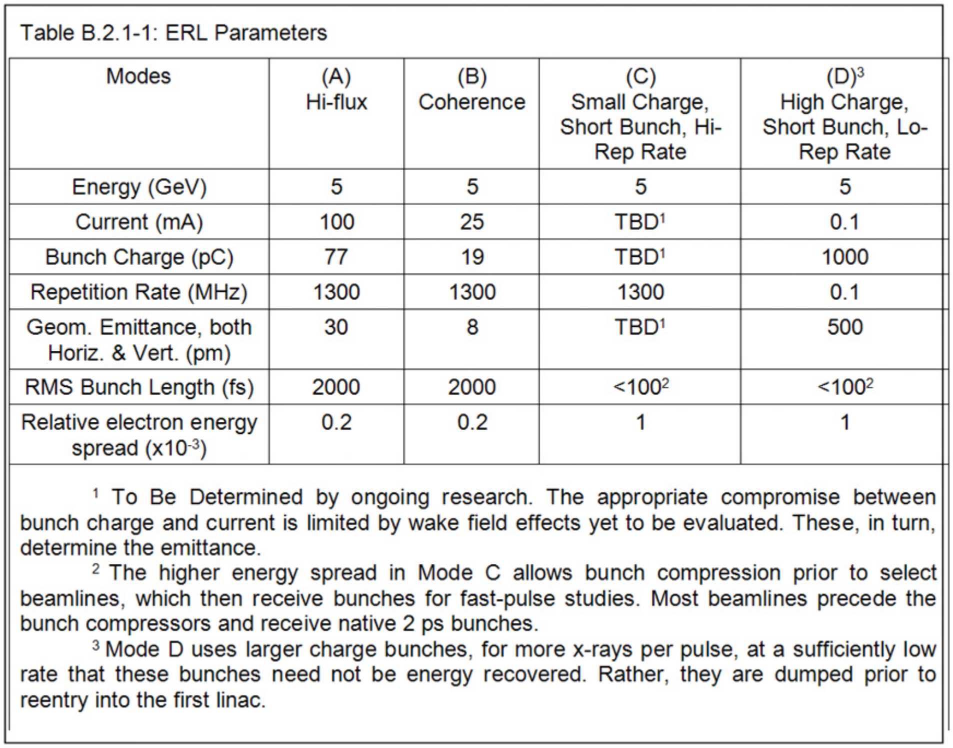

Table B.2.1-1: ERL Parameters

Modes	(A) Hi-flux	(B) Coherence	(C) Small Charge, Short Bunch, Hi-Rep Rate	(D)[3] High Charge, Short Bunch, Lo-Rep Rate
Energy (GeV)	5	5	5	5
Current (mA)	100	25	TBD[1]	0.1
Bunch Charge (pC)	77	19	TBD[1]	1000
Repetition Rate (MHz)	1300	1300	1300	0.1
Geom. Emittance, both Horiz. & Vert. (pm)	30	8	TBD[1]	500
RMS Bunch Length (fs)	2000	2000	<100[2]	<100[2]
Relative electron energy spread $(\times10^{-3})$	0.2	0.2	1	1

[1] To Be Determined by ongoing research. The appropriate compromise between bunch charge and current is limited by wake field effects yet to be evaluated. These, in turn, determine the emittance.

[2] The higher energy spread in Mode C allows bunch compression prior to select beamlines, which then receive bunches for fast-pulse studies. Most beamlines precede the bunch compressors and receive native 2 ps bunches.

[3] Mode D uses larger charge bunches, for more x-rays per pulse, at a sufficiently low rate that these bunches need not be energy recovered. Rather, they are dumped prior to reentry into the first linac.

There is a long list of items that are being worked on in parallel with work on the injector and the 5 GeV facility layout, including electron beam machine design, shielding wall design, collimators ahead of undulators, exit crotch design, etc.

The x-ray group has begun planning for 5 to 25 m long undulators and beamlines that extend outward to 70 m from the source. We have established preliminary working groups to conceive of beamlines in the following areas:

1. Diffraction-limited x-ray scattering beamline suitable for soft-matter using SAXS, USAXS, WAXS and GISAXS techniques;
2. Short-pulse repetitive pump-probe timing beamline for 100 femtosecond pulse work at a repetition rate of 100 kHz and a 2 picosecond pulse length at a 1.3 GHz repetition rate. This will be useful for ultrafast time-resolved experiments;
3. A beamline for coherent diffractive imaging and dynamic studies of bulk materials, interfaces and biological samples including techniques of intensity fluctuation spectroscopy, ptychography. Examples of application areas are dynamics of magnetic materials and the glass transition;
4. Inelastic x-ray scattering (IXS) with meV resolution will be used to study the dynamical properties of materials at atomic to mesoscopic length scales. An ERL IXS facility has the potential to outperform all existing facilities, their proposed upgrades, and sources under construction by one order of magnitude more flux;
5. A nanoprobe for making a 1 nm diameter x-ray beam at 10 keV with as much flux per square nm as most 3rd generation light sources put into a square micron. This will make possible x-ray experiments on even a single atom, which might be useful for studying the *in-situ* doping properties (atom clusters that are electrically inactive) of the smallest line-width transistors or performing x-ray experiments in the smallest possible volumes.

New undulator designs are underway:

ERLs offer opportunities to use insertion devices that take advantage of long, small, round bores (5 mm). This is very different than in a storage ring, where a much wider horizontal bore is needed to provide orbital room for electron injection. The small sized bore feasible with an ERL allows design of very compact magnetic structures that can generate larger magnetic fields than the planar undulators used in 3rd generation storage rings.

Figure 6 shows a novel "Delta" undulator that was designed to utilize the unique properties of ERL electron beams[6]. As opposed to conventional undulators, it provides full control of x-ray polarization and a stronger magnetic field that

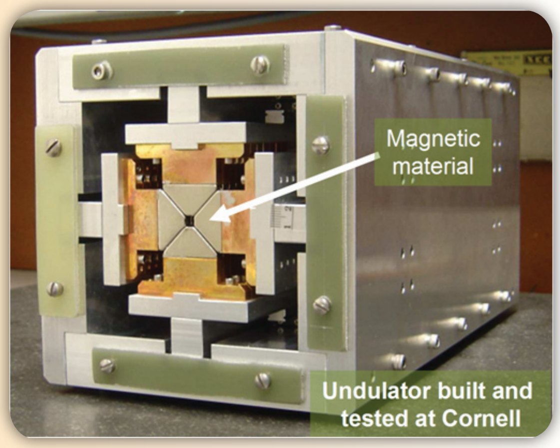

Fig. 6: Prototype of the Delta undulator made from small triangular blocks of NdFeB material with a remnant field of 1.26 Tesla. The central hole for the electron beam is only 5 mm in diameter.

translates to high x-ray flux. In addition, it is much more compact and cost-efficient. To demonstrate the new design principles, a 30 cm long model has been built and recently tested with a Hall probe, Figure 7.

Testing of the very first Delta-type undulator prototype revealed a 1.25T peak field in planar mode and 0.85T in helical (Figure 8) that is approximately 90% of the design value.

The field profile analysis indicates that the field errors cause less than a 3% loss of the x-ray photon flux in the helical mode and 20% loss in the planar mode. These very favorable test results have confirmed the basic principles of the Delta-style design.

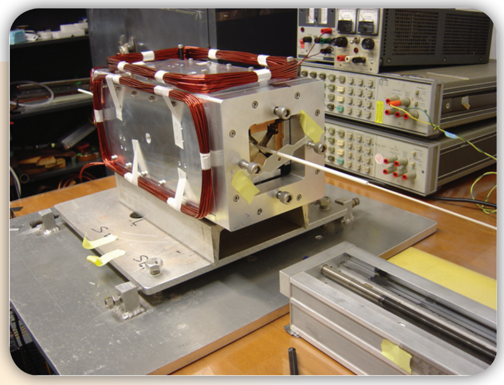

Fig. 7: Delta undulator model on magnetic field measurement bench, complete with coils for compensating for background magnetic fields. The center ceramic tube guides the Hall probe down the bore of the undulator during the magnetic profile measurement.

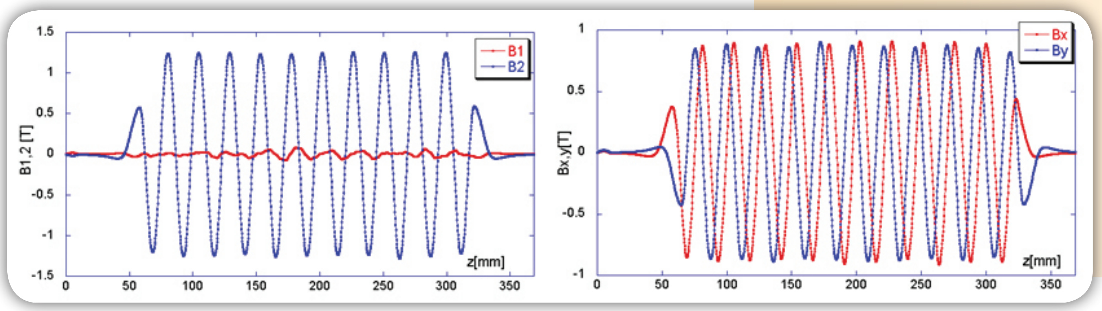

Fig. 8: The measured magnetic field components in planar and in helical mode of operation corresponding to linear and circular x-ray polarization. Plots are from reference [7].

Presently we are working on the next, fully-functioning model. It will have an improved mechanical design which should increase peak field up to the full design value and reduce magnetic field errors still further. The next model will be UHV compatible and will be tested with a small diameter electron beam at a linac test facility.

Conclusion:

A 5 GeV ERL facility would be a great advance to synchrotron radiation science and would have numerous benefits to society. R&D on necessary ERL components is well underway. Plans for a full-scale, 5 GeV hard x-ray ERL are in an advanced stage of planning. We intend to deliver a conceptual design for the full-energy ERL within the next year.

References:

1. C. Sinclair, and S. Gruner; *"ERL Developments"*, CHESS News Magazine, pg 9 (2005)
2. M. Tigner; Nuovo Cimento **37**, 1228 (1965)
3. 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
4. I. Bazarov et al.; *"Thermal Emittance and Response Time Measurements of NEA Photocathodes"*, J. Appl. Phys. **103**, 05490 (2008)
5. I. Bazarov, B. Dunham, and C. Sinclair; "Maximum Achievable Brightness from Photoinjectors:, Phys. Rev. Lett. **102**, 104801 (2009)
6. A. Temnykh; *"Delta Undulator for Cornell Energy Recovery Linac"*, Phys. Rev. ST Accel. Beams **11**, 120702 (2008) URL: http://link.aps.org/doi/10.1103/PhysRevSTAB.11.120702
7. A. Temnykh; *"Evaluation of Magnetic and Mechanical Properties of Delta Undulator Model"*, Reprint CBN 09-1,Cornell (2009) URL: http://www.lns.cornell.edu/public/CBN/2009/