Energy Recovery Linacs (ERL)

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Preliminary layout view of an ERL upgrade to CHESS in the present CESR tunnel. A new tunnel with a return loop will be added to CESR. Electrons are injected into superconducting cavities at (i) and accelerated to 2.5 GeV in the first half of the main linac, than to 5 GeV in the second half. The green lines show 18 possible beamline locations. Electrons travel around the CESR magnets clockwise and re-enter the linac out of phase. Their energy is extracted and the spent electrons are then sent to the dump (D).

Two superconducting linacs in one tunnel accelerate the electrons to 5 GeV. Person shown for scale.
Outline

- What is an ERL?
- What can it do?
- What is the present status?
Outline

• What is an ERL?
• What can it do?
• What is the present status?
What limits science at storage rings?

1. Transversely coherent flux.
2. Time structure.
3. Source size to optimize nanobeams.

Sources that overcome these limitations will be truly transformative!

Coherent Flux ~ Current / (Emitt$_{x}$ x Emitt$_{y}$)

Emittance dilution is a result of storage
Advantages:

- Injector determines emittances, pulse length, current.
- Flexibility of pulse timing and pulse length.
- Small source size ideal for nanoprobe.
- No fill decay.

Disadvantage: You’d go broke!!

(5 GeV) x (100 mA) = 500 MW!!
Energy Recovery Linac

a radically new SR concept

A superconducting linac is required for high energy recovery efficiency.
ERL will excel in Spectral Brightness, Source Size and Pulse Duration

• ERL hi-brightness for coherence applications.
• Electron source size of a few microns—good for intense, nm diameter, hard x-ray beams.
• Bunch compression allows pulses < 100fs.
• Same beam characteristics in Hor. & Vert.
• Great flexibility in modes of operation.
Transverse Coherence

Avg. Coherent Flux

Coherent Fraction

Photon Energy (eV)
The bunch length can be made much smaller than in a ring.
Bunch charge (e.g., flux) can be traded against brightness.
Rep rate is very flexible.
Outline

• What is an ERL?
• What can it do?
• What is the present status?
ERL X-ray Science Workshops

**Workshop 1 - June 5 & 6, 2006**
"Future Frontiers in High-Pressure Science with ERL X-Ray Beams"

**Organizers:** Neil Ashcroft (Cornell University), Bill Bassett (Cornell University), Raymond Jeanloz (University of California at Berkeley), & Rus Hemley (Carnegie Institution)

**Workshop 2 - June 14 & 15, 2006**
"Scientific Potential of High Repetition-Rate, Ultra-short Pulse ERL X Ray Source"

**Organizers:** Joel Brock (Cornell University), Alex Gaeta (Cornell University), & David Reis (University of Michigan)

**Workshop 3 - June 16 & 17, 2006**
"Almost Impossible Materials Science: Pushing the Frontier with ERL-X-Ray Beams"

**Organizers:** Emir Forteze (Cornell High Energy Synchrotron Source), Peter Abbamonte (University of Illinois at Urbana-Champaign), Darren O'Shaughnessy (Cornell High Energy Synchrotron Source), Qun Shen (Advanced Photon Source, Argonne National Laboratory), & P. James Vicario (Advanced Photon Source, Argonne National Laboratory)

**Workshop 4 - June 19 & 20, 2006**
"Unique Opportunities in Soft Materials and Nanoscience with an ERL"

**Organizers:** Deleif Smilgies (Cornell University), & Ron Pindak (Brookhaven National Laboratory)

**Workshop 5 - June 21 & 22, 2006**
"Workshop on Frontier Applications of X-Ray Science in Biology with an ERL X-Ray Source"

**Organizers:** Richard Gillian (Cornell University), Wah-Kwei Lee (Advanced Photon Source, Argonne National Laboratory), & Lois Pollock (Cornell University)

**Workshop 6 - June 23 & 24, 2006**
"Workshop on New Science Opportunities with Nanometer-Sized ERL X-Ray Beams"

**Organizers:** Don Bilderback (Cornell University), Gene Ise (Oak Ridge National Laboratory), Kenneth Evans-Lutterodt (National Synchrotron Light Source, Brookhaven National Laboratory), Primo van der Veen (Swiss Light Source), & Wenbing Yun (Xradia)

- SRI workshops
- APS workshops
- Coherence 2007
- Gordon Conference
- ...
What Goes on Deep in the Earth & Planets?

- Phys & Chem completely altered. $PV > R_H$
- Many superconductors
- Chemical dynamics drastically modified
- Impacts ore generation, earthquake dynamics, volcanism, weather

Why ERL?

- DAC expts photon starved at existing sources
- ERL nanobeams $10^3 – 10^5$ intensity
- Enables dynamical studies
- High average flux preserves DAC

Sun et al., Science, 312 (2006) 1199
Can We Improve Polycrystalline Materials?

- Most real materials polycrystalline
- Properties far from single crystal ideal
- Wish to probe matter on single grain length scales
- Nanocrystalline matter is new frontier. Revolution in lensless imaging. Requires coherence.

Why ERL?

- 80x80x80 voxels takes 3 hr → few seconds
- 150 s/frame x 50 frame ≈ 2 hr → few seconds
- Can study dynamics: annealing, strain, coarsening, etc.
Can We Determine Macromolecular Structure Without Crystals?

D. Starodub et al. (Spence U Ariz./ALS/LLNL)

Why ERL?

<table>
<thead>
<tr>
<th></th>
<th>d= 0.7 nm</th>
<th>d= 1 nm</th>
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<tbody>
<tr>
<td>ALS</td>
<td>9.5x10^5 s</td>
<td>2.3x10^5 s</td>
</tr>
<tr>
<td>APS</td>
<td>2.1x10^4 s</td>
<td>5.1x10^3 s</td>
</tr>
<tr>
<td>ERL</td>
<td>227 s</td>
<td>54 s</td>
</tr>
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</table>

Calculated exposures (JSR, in print)

**Experimental image of 4micron droplet beam**
(Current 07 droplets are about 1 micron diam)
Can We Probe Dynamics of Macromolecules in Solution?

• Life, polymers, etc. all involve dissolved macromolecules.

• Proteins & RNA fold, multimers associate & disassociate, polymers collapse, etc.

• No good way exists to probe global structural dynamics of large molecules in solution.

• Laminar flow cells access microseconds

Why ERL?

• Existing sources limit expt to msec.

• ERL would reach to microseconds
What is the Nature of the Glass Transition?

- The glass transition is one of the most important outstanding questions in all of science (*Science* magazine, 125th anniv. Issue)


- If we knew where every atom was in a nanoparticle of glass as it melted, we’d have an enormous handle on the glass transition. (Jim Sethna)

Why ERL?

- Lensless coherent imaging offers a way to repetitively determine atomic structure of aperiodic matter as it is warmed.
REASONS TO DEVELOP ERLs

1. **A large user community already exists.** ERLs can do all experiments at the most advanced 3rd gen SR sources, thus meeting growth in demand for SR.

2. **ERLs enable SR experiments not now possible.** Follows from high coherence, short pulses and flexible bunch structure. Leads to transformative science.

3. **ERLs are a promising technology with limits yet to be determined.** ERL retrofits to storage rings and ERL XFELs are good possibilities.
• What is an ERL?
• What can it do?
• What is the present status?
  ➢ Where are we headed?
  ➢ Where are we now?
Next-Generation NSF Light Source Must Meet 3 Criteria:

1. It must be transformational.
2. It must complement DOE sources.
3. It must succeed.
Cornell’s Impact on Synchrotron Science, most with NSF support

World’s first SR beamline, 1952
Tomboulian & Hartman

CHESS today

ERL

1945  LNS (LEPP) started by Bethe returning from Los Alamos
1952  World’s first SR beamline on 300 MeV synchrotron
1965  Tigner proposes ERL idea
1975  Cornell SC synchrotron tests
1979  Cornell Electron Storage ring (CESR) & CHESS start
1982  First storage ring SC tests
1982  Demonstration of curved crystal sagittal focusing
1984  CEBAF cavities developed & tested at CESR
1985  First mammalian virus structure
1985  Image plate developments
1986  Cryogenic monochromator crystal cooling
1987  First hard x-ray circular polarization phase plate
1988  Discovery of resonant x-ray magnetic scattering
1988  First dedicated HP Diamond Anvil Station
1988  Long-period standing waves demonstrated
1989  APS undulator A tested at CESR
1989  Development of cryoloop protein crystal freezing
1991  First CCD detectors for protein crystallography
1992  First Complete Stokes Polarimetry for X-rays
1993  First microsecond time resolved XAFS
1995  First TESLA cavity
1998  K+ Channel structure
1999  First fully SC powered x-ray storage ring
2000  ERL study
2001  First microsecond x-ray Pixel Array Detectors
2001  Envelope phasing of macromolecules
2003  Microfabricated crystal cryomounts
2004  41 attosecond imaging of disturbances in water
2004  Pulsed laser deposition system & layer-by-layer growth studies
2004  Confocal microscope developed and applied to art works
2005  Narrow bandwidth artificial multilayers
2005  High pressure protein crystal cryocooling
2007  ERL injector development
Cornell ERL Project

- ERL Study (w/ Jlab) *(Completed in 2001)*


- **Phase II proposal in 2008**.

- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. *(~5 year construction)*

Operate ERL as **University-based NSF** user facility.
Mission 1: High Research Impact & Productivity

Some CHESS Macromolecular Covers
Mission 2: Train scientists who populate other labs

People are our most important “product”
Schematic ERL Layout View

5 GeV

Key: 1=Main injector; 2=first 2.5 GeV linac; 3=East return loop;
4=second 2.5 GeV linac + cryoplant; 5=South undulator beamlines
6=West return loop (CESR); 7=North undulator beamlines;
8=Beam dump; 9=dump for non-energy recovered fast-pulse undulator beam line.
# ERL Parameters

<table>
<thead>
<tr>
<th>Modes</th>
<th>Hi-Flux</th>
<th>Hi-Coherence</th>
<th>Fast, Hi-Rep Rate</th>
<th>Fast, Lo-Rep Rate</th>
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</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>100</td>
<td>25</td>
<td>TBD</td>
<td>0.1</td>
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<tr>
<td>Bunch charge (pC)</td>
<td>77</td>
<td>19</td>
<td>TBD</td>
<td>1000</td>
</tr>
<tr>
<td>Repetition rate (MHz)</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>0.1</td>
</tr>
<tr>
<td>Geom. emittance (pm)</td>
<td>30</td>
<td>8</td>
<td>TBD</td>
<td>5000</td>
</tr>
<tr>
<td>RMS bunch length (fs)</td>
<td>2000</td>
<td>2000</td>
<td>&lt;100</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Relative energy spread (x10^{-3})</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Energy recovered?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Beamlines will NOT look like typical 3rd generation beamlines. Optimize for experiments that take advantage of unique ERL properties. Emphasis on helical undulators, windowless beamlines with minimal or no optics, multilayers, specimen chambers with multiple simultaneous probes (e.g., EM, optical, magnetic), tailored detectors.
ERLs have many challenges*

- Production of very small emittance beam
- Emittance preservation in beam transport sections and linacs
- Achieve sufficient beam stability for 100 mA beam current
- Beam diagnostic for small emittance, short bunch beams
- Control of beam loss
- High gradient, high Q cavity operation with excellent field stability, HOM loads
- Short period, short gap, but long undulators with phased segments
- X-ray windows that preserve coherence
- X-ray BPMs that work on a submicron scale
- X-ray monochromators that don’t distort under a high-heat load
- X-ray optics to make a nm diameter hard x-ray beams
- X-ray mirrors with extraordinarily small slope error & roughness
- Specialized x-ray detectors optimized for most challenging applications.
- Etc.

The nature of these challenges range from basic science to engineering. Based on R&D to date, there are excellent prospects for success.

But a lot of work needs to be done!

*XFELs have a comparable list
Outline

• What is an ERL?
• What can it do?
• What is the present status?
  ➢ Where are we headed?
  ➢ Where are we now?
Ongoing Cornell R&D Activities

1) DC electron source
   • Gun development
   • HV power supply
   • Photocathode development
   • ERL injector lab
   • Laser system development

2) Superconducting RF
   • RF control
     (tests at CESR/JLAB)
   • HOM absorbers
   • Injector klystron
   • Input coupler (with MEPI)
   • Injector cavity / Cryomodule

3) Beam dynamics
   • Injector optimization with space charge
   • Beam break up instability (BBU)
   • Optics design

4) Accelerator design
   • Optics
   • Beam dynamics
   • Beam stability

5) X-ray beamline design
   • X-ray optics
   • Undulator design
Injector Development: Two stages

- **Now**: Operate gun and diagnostics in gun lab.

- **1st Quarter ’08**: Operate full injector assembly, the heart of the ERL.
Photoemission Gun

Max capabilities:

750 kV
100 mA
GaAs Photocathode

GaAs:Cs is cathode of choice
- good quantum efficiency
- low thermal emittance
- fast time response (@520 nm)
- need extreme UHV for lifetime
- minimum thermal emittance near bandgap (lower QE)
- R&D on other cathodes
Load Lock System

- Load lock chamber w/quick bakeout capability
- Heater chamber
- Cathode preparation and transfer chamber

Can swap a fresh cathode into the gun in ~30 minutes
Beam Line looking toward Gun
Gun and Power Supply in Tank
750 kV, 100 mA Power Supply
Fiber Laser Description

Oscillator

- Pump diode
- Yb fiber

Pre-Amplifier

- Mirror
- Faraday rotator
- Yb fiber
- Collimator
- Birefringent crystals
- Polarizing beam-cube

Amplifier

- Coupled pump power [watts]
- Signal power [watts]
- Coupled pump power [watts] efficiency: 60%
- 15 mW
- 300 pJ
- 60 mW
- 1.2 nJ
- 4 W
- 80 nJ

25 Watts pump laser diode
\[ \lambda = 1040 \text{ nm} \]
pulse duration \( \sim 2.5 \text{ ps} \)
power \( \sim 15 \text{ mW} \)
Laser Shaping

Use ‘optical pulse-stretcher’ to get 20-40 ps flat-top pulses from 2 ps laser (DPA – divided pulse amplifier)

Gauss to flat top using commercial aspheric lens
Initial Beam Tests

- Goal: full understanding of gun beam phase space
- Build gun & diagnostics line
- Full phase space characterization capability after the gun
- Temporal measurements with the deflecting cavity
- Lifetime studies
Cathode Response Time

Deflecting cavity transforms bunch length into transverse spot on view screen.

Gives direct of bunch length measurement
Cathode Response Data

$C = 2.2 \pm 0.1 \text{ ps}$

$\tau = 0.27 \pm 0.04 \text{ ps}$

2 crystals

3 crystals

1 crystal
Full Injector Prototype Progress
Two-cell niobium cavity for ERL injector
Vertical Cold Test

First ERL Injector Cavity: First test 3/30/2006

Eacc [MV/m]

2.0 K

X-rays start
RF Input Coupler

- Cold Bellows
- 5K Intercept
- 80 K Flange
- 80 K Intercepts
- Cold Window
- 300 K Intercept
- Warm Bellows
- Warm Window
- Air Inlets
- 300 K Flange
- Compress Air Inlet for Window Cooling
- Antenna
- 2K Flange
- Compress Air Inlet for Bellows Cooling
- 300 K Intercepts
- 80 K Flange
- 5K Intercept
- Cold Bellows
- Cold Window
- Warm Bellows
- Warm Window
- Air Inlets
- 300 K Flange
- Compress Air Inlet for Window Cooling
- Antenna
- 2K Flange
- Compress Air Inlet for Bellows Cooling
2-cell injector cavity with tuners and power couplers attached
Higher-Order Mode Power

Bunch excites EM cavity eigenmodes (Higher-Order Modes)

\[ f = 1.4 \text{ to } > 100 \text{ GHz} \]

140 W HOM power, (7-cell main LINAC cavity shown)
Cornell ERL HOM Absorber

- Extensive research program to find absorber materials which
  - are effective at 80 K
  - And absorb over required frequency range

- Three materials selected to cover full frequency range

- Simulated damping for 100s of modes ⇒ all modes are sufficiently damped

- The injector cryomodule will be the first high current, short bunch s.c. cavity module.
Cryomodule design

- Cryogenic System
- Input Coupler
- RF Cavity in He Vessel
- Frequency Tuner
- HOM Absorber
Full 5-cavity String Out of Cryostat
ERL injector klystron

- e2v designed high CW power klystron.
- Parameters: 7-cavity tube, max. beam voltage 45 kV, current 5.87 A, full power collector, max. output power 135 kW @ >50% efficiency, gain >45 dB, bandwidth >±2 MHz @ 1 dB and >±3 MHz @ 3 dB.
- First tube delivered and successfully tested in March, 2007.
- Transfer curves were measured for several HV settings.
Injector Assembly 7 Jan 2008
Meanwhile, NYS Supports Proposal Development

Site Test Borings and Hydrogeology


4.4 Tunnels
The original tunnel alignment selected and included in the original pricing was Option 0.

Alternative tunnel alignments have been studied which allow different (and cheaper) tunnelling methods. It is noted that the engineering design for Options 1 and 2 has not been developed to the same level as Option 0 and these cost estimates are to be used to establish the potential magnitude of savings for adopting an alternative tunnel alignment.

4.5 Master schedule (construction/procurement) and early design works

The current construction schedule of 2 years has been considered in isolation to the installation and commissioning of the LINAC, the experimental equipment housed in the laboratory and the cryogenics plant.

Discussions at the workshop indicated that a complex sequencing of activity would be required to install and commission the whole. In addition, procurement of the LINAC and cryogenics plant particularly would be complex and time consuming given the unique nature of the product and the scarcity of manufacturers available globally to be engaged.

B1 Cryoplant information

The workshop, together with a separate cryo plant focused meeting on November 10th, gave rise to a significant amount of information on this element of the project. This brief captures some of that key Information.

B1.1 Design

The cryoplant process comprises a number of components which fit into a 'box' of approx.
55m x 55m x 7m internal height. There is some flexibility on the layout within the 'box' and there may be an ability to 'stack' certain components. Currently, there is no scope definition on which items will be provided by the cryoplant provider and which will be provided by the main project.

- Control rooms
- Storage vessels ('warm' and 'cold', 'liquid' and gaseous – can be external)
- Compressors (heavy and cause significant vibration)
- 1 no. 4K cold box and 1 no. shield (50,000kg each)
- 1 no. 1.8K cold box (30,000kg)
- Delivery times to beam line
- Ancillary equipment

The pipes work connecting each component gets increasingly expensive as the plant reduces the temperature. In some instances having the lowest temperature cold boxes close to the beam line can help mitigate this. However, the boxes need insulations.
Architectural & Environmental Site Studies

Site Layout

Etc.
Cornell ERL Project

- ERL Study (w/ Jlab) *(Completed in 2001)*
- **Phase II** proposal in 2008.
- Build a high energy (5 GeV) ERL x-ray facility at Cornell as an upgrade to CESR. (~5 year construction)

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