R&D toward an ERL

Georg Hoffstaetter
Cornell Physics Dept. / CLASSE
Cornell’s ERL team

- Undulator R&D
- DC-gun R&D
- CW linac R&D
- SRF injector R&D
- SRF gun R&D
Cornell history: The ERL principle

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.
Can X-ray beams be improved?

- Narrower and less divergent beams
- More coherent beams
- Shorter pulses
Principle of an X-ray ERL

Narrow beams in rings widen up after many hundreds of turns.

Challenges:
- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF

5GV*100mA = 0.5GW (good size power plant)
Principle of an X-ray ERL

Challenges:
• Low emittance, high current creation
• Emittance preservation
• Beam stability at insertion devices
• Accelerator design
• Component properties, e.g. SRF

X-ray analysis with highest resolution in space and time:

5GV*100mA = 0.5GW
(good size power plant)
Narrow beams in rings widen up after many hundreds of turns.

Widening is limited during one turn

Challenges:
- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF

Principle of an X-ray ERL
Can X-ray beams be improved?

- Narrower and less divergent e-beams
- More mono-energetic e-beams
- Shorter pulses

\{ all of the above \}
ERL on Cornell’s campus as extension of CESR

ERL@CESR, Cornell
# Beam goals for ERLs

<table>
<thead>
<tr>
<th>Modes:</th>
<th>(A) Flux</th>
<th>(B) Coherence</th>
<th>(C) Short-Pulse</th>
<th>(D) High charge</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>GeV</td>
</tr>
<tr>
<td>Current</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>0.1</td>
<td>mA</td>
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<tr>
<td>Bunch charge</td>
<td>77</td>
<td>19</td>
<td>77</td>
<td>1000</td>
<td>pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>0.1</td>
<td>MHz</td>
</tr>
<tr>
<td>Norm. emittance</td>
<td>0.3</td>
<td>0.08</td>
<td>1</td>
<td>5.0</td>
<td>mm mrad</td>
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<tr>
<td>Geom. emittance</td>
<td>31</td>
<td>8.2</td>
<td>103</td>
<td>1022</td>
<td>pm</td>
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<tr>
<td>Rms bunch length</td>
<td>2000</td>
<td>2000</td>
<td>100</td>
<td>50</td>
<td>fs</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>3</td>
<td>10⁻³</td>
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<tr>
<td>Beam power</td>
<td>500</td>
<td>125</td>
<td>500</td>
<td>0.5</td>
<td>MW</td>
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</table>
Average spectral brightness for hard x-rays

Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.
Advantages of ERL beams

(a) Large currents of Linac quality beams

The beam power in one-path linacs is limited, but the beam quality is the highest achieved to date.

In an ERL, much larger average currents can be accelerated with linac quality beam.

An ERL is an accelerator type, and can be used for many types of light sources

1) and other accelerators, e.g. the e-RHIC nuclear physics collider

2) ERL driven FELs for IR, UV, soft and hard x-rays
   (up to 14kW IR continuous beam achieved, UV in commissioning at JLAB, ERL-xFEL in Physical Review ST-AB (2005))

3) ERL driven Compton backscattering sources for hard x-ray beams (funded KEK)

4) ERLs for spontaneous undulator radiation (Lead by US, Cornell University)

Most linac-based light sources can be operated by an ERL, but with significantly more current and output power.

A hard x-ray ERL development at Cornell has spinoffs for many accelerator projects, e.g. XFELOs with 10000 X brightness (Phys Rev Letters (2008))
Advantages of ERL beams

(b) Continuous beams with flexible bunch structure

1) High rep rate (up to 1.3GHz with 100mA), large current with small bunch charge
   a) Reduces charging for electron emitting methods, e.g. PEEM, PES
   b) Reduce sample damage for small samples, as compared to huge FEL pulses
   c) Advantages for coincidence measurements, avoiding false positives

2) Variable time structure for timing experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ERL Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with energy recovery</td>
</tr>
<tr>
<td>Bunch length</td>
<td>10 fsec – 10 psec</td>
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<tr>
<td>Repetition Rate</td>
<td>1 MHz – 1.3 GHz</td>
</tr>
<tr>
<td></td>
<td>without energy recovery</td>
</tr>
<tr>
<td>Macropulse Duration</td>
<td>1 microsecond - continuously</td>
</tr>
<tr>
<td>Macropulse Frequency</td>
<td>1 Hz-10 kHz</td>
</tr>
</tbody>
</table>
In pulsed linacs, transients produce changing conditions that are avoided in continuous ERL beams, which can thus be much more stable.
Advantages of ERL beams

(c) Small emittances for round beams

1) Small electron emittances
   a) High spectral brightness, diffraction limited beams
   b) Significantly reduced current and x-ray load for the same spectral brightness
   c) Narrow x-ray beams and small focuses (nanobeams)
   d) Narrow electron beams at all times (no injection orbits)

2) Round beams (small emittances not only in the vertical)
   a) Undulators can have small round chambers
   b) Polarization changes become independent of beam dimensions
   c) Experiments can be oriented in any direction, e.g. horizontal spectrometers
      (problems of nm accuracy for m-large vertical instruments: Jens Als-Nielsen)
Advantages of ERL beams

(c) Small emittances for round beams

1.4T peak field in planar mode

Peak Field [T] vs Gap / Period

- PPM planar vertical field
- Apple-II horizontal field
- Apple-II helical field
- Apple-III vertical field
- Apple-III helical field
- Delta planar field
- Delta helical field
Advantages of ERL beams
(c) Small emittances for round beams

30cm long prototype of Delta undulator installed in beam line #2 at ATF (BNL)

Electron beam image on flag downstream of the undulator

Delta undulator in **planar mode**.
5300nm radiation flux as a function of electron beam energy for ~60mm DIA slit. Dec 18, 2009

**Edge location suggests ~1.28T undulator peak field**

**Calculated flux [photons/0.1%BM]**

- **Measurement**
- **Model**

Electron beam energy [MeV]

**Fundamental harmonics in planar mode**

Delta undulator in **helical mode**.
3600nm radiation flux as a function of electron beam energy through ~10mm DIA slit. Dec 18, 2009

**Peak location corresponds to ~0.93T undulator peak field**

**Reflection from beam pipe wall**

**Calculated Flux [photons/0.1%BM]**

**Electron beam energy [MeV]**

**Fundamental harmonics in helical mode**
Small emittances produce large spectral brightness

Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.
Small emittances produce large spectral brightness

Electron beams from ERLs can have much higher brightness, especially in the core of the beam.

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Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.
1) For rings, the photon energy spread is at least $10^{-3}$ no matter how many undulator poles (N)
Advantages of ERL beams
(e) Small energy spread (order $10^{-4}$)

1) For rings, the photon energy spread is at least $10^{-3}$
no matter how many undulator poles (N)

2) For an ERL, smaller than $10^{-4}$ for large N

3) ERL have a larger fraction of
usable photons, i.e. larger coherent fraction
Advantages of ERL beams

(f) Variable electron optics

1) Beam size vs. divergence can be optimized on each undulator straight section, without limitations by dynamic apertures.
   
   APS: one set of beta functions
   
   ESRF: two sets of beta functions (hi, low)
   
   ERL: all choices are possible, not “one size fits all”

2) Move position of minimum electron beam waist along straight section by changing quadrupole settings, without moving components, e.g. move apparent x-ray source point to compensate for changes in focal length on refractive lenses and zone plates, or move x-ray focus to the sample.

3) There may be other New Features (e.g. optimizing flux through a collimator, monochromator because of extra free knobs) that can be developed because x-ray ERLs are at the start of development.
Advantages of ERL beams: (g) Short pulses, synchronized and simultaneous with small emittances

- Standard bunch lengths in ERLs: 50fs to 2ps for high currents 1.3GHz (ERL mode)
- ERL driven FELs are possible, because beams can be sufficiently short
- Because ERLs have linacs, the shorter bunch lengths that other linacs propose could also be created in the linac of an ERL.

Test of simultaneous linac and ERL operation:
- 77pC, 1.3GHz ERL
- 1nC, 100kHz SASE, not ERL
- 200fs, 200pC, 100kHz HGHG not ERL
- XFELO, 30pC, 1MHz, 10000 X brightness
Summary of Advantages for Hard X-Ray ERLs

X-ray ERLs have unique capabilities and many advantages over rings:

a) Large currents for Linac quality beams
b) Continuous beams with flexible bunch structure
c) Small emittances for round beams
d) Openness to future improvements
e) Small energy spread
f) Variable Optics
g) Short bunches, synchronized and simultaneous with small emittances

The breadth of science and technology enabled is consequently very large and the ERL will be a resource for a very broad scientific community.

X-ray ERLs are at the beginning of a development sequence, whereas decades have brought x-ray rings to the end of their development.
Energy Recovery Installations

• ALICE, 21MeV, 20pC

Other achieved Energy Recovery
• Demonstrated 9 mA CW two-pass at 30 MeV (BINP)
• Demonstrated 70 µA CW at 1 GeV (JLab CEBAF)
• Demonstrated 2.3kW FEL, 17MeV (JAEA)

• Demonstrated 9 mA CW at 150 MeV, 14kW (Jlab FEL)
Energy Recovery Projects: (A) low energy

- ALICE as THz source, IR-FEL, and Compton scattering source

Other Energy Recovery concepts
- Extension in energy of BINP FEL/ERL
- BerlinPro test ERL
- BNL test ERL & coherent electron colling
- Medium Energy Electron Ion Collider
- ERL for eRHIC Electron Ion Collider
- ERL for LHeC

- JLAMP: unparalleled average brightness for 10-100eV photons. 600MeV by 2 pass ERL, pulses of 50fs, 200pC/1µm for HHG-FEL
The Compact ERL for Demonstrating ERL Technologies at KEK

Before constructing large-scale ERL facility, we need to demonstrate the generation of ultra-low emittance beams using developed key devices.

### Parameters of the Compact ERL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Parameters</th>
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</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>35 - 245 MeV</td>
</tr>
<tr>
<td>Average current</td>
<td>10 - 100 mA</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>0.1 - 1 mm·mrad</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>1 - 3 ps (usual)</td>
</tr>
<tr>
<td></td>
<td>~ 100 fs (with B.C.)</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
</tr>
</tbody>
</table>

### Status:
- Clearing 10,000 tons of concrete shields in the East Counter Hall has almost been finished.
- Refurbishments of the building, cooling-water plant, and electric substation have almost been finished.
- Installation of liquid-Helium refrigerator (cooling capacity: 600 W) has almost been finished.
- Installations of rf source (single station) and clean room for SCC development have almost been finished.
Cornell / KEK / JAEA ERLs

KEK

5GeV-ERL

JAEA Naka (East)

JAEA Naka (West)

240m

650m

6GeV-ERL
Cornell / KEK / JAEA / APS ERLs

KEK

5GeV-ERL

JAEA Naka (East)

JAEA Naka (West)

6GeV-ERL

240m

650m
Technical challenges of CW linacs: International CW cryomodule collaboration

- Stanford has provided a 2-cavity cryomodule (incl. some internals).
- Cornell provides two modified and vertically tested 7-cell cavities (original superstructure cavities were supplied by DESY); design of HOM absorbers and input couplers; overall expertise.
- DL provides the HOM absorbers and couplers; modification of the CM; other new components (thermal and magnetic shields, tuners, end caps, ...); facilities for CM assembly and tests.
- FZD have provided the 3D cryomodule drawings.
- LBNL have provided electromagnetic cavity design expertise.
- Engineering and design effort split across institutes (mostly DL and Cornell).
BNL test ERL 5-cell cavity assembly

- 5 cell SRF cavity, 17 cm iris, 24 cm beampipe
- 703.75 MHz, 20 MV/m @ $Q_0 = 1 \times 10^{10}$
- Ferrite Dampers for HOMs at room temp.
- No trapped HOMs
Space charge emittance compensation
Final emittance $< 2 \times$ photocathode emittance

$\varepsilon_{n\perp, \text{final}} \approx 1.4 \times \varepsilon_{n\perp, \text{cath}}$

80pC

$\varepsilon_{x} = 0.077 \text{ mm-mrad}$
$\varepsilon_{z} = 0.000 \text{ mm-keV}$

$\Delta \rho_x (\text{keV/c})$
$\Delta \rho_z (\text{keV/c})$

$\Delta x (\text{mm})$
$\Delta z (\text{mm})$
Field distribution of the 500-kV gun

500 kV for 8 hours without any discharge

8.3 MV/m on the support rod

6.8 MV/m on the guard rings

14.3 MV/m on the nose of support rod

(radius (mm)

(height (mm)

R. Nagai et al., to be published in Rev. Sci. Instr.

current through resistors

radiation level is within the background. no clear evidence for dark current.

Talk by N. Nishimori for more details.
Cornell Injector prototype: Verification of beam production

- dump
- diagnostics
- SC injector
- gun

- HOM absorb.
- CW coupler
- Dressed cavity
- gun
### ERL SRF injector production at Cornell

<table>
<thead>
<tr>
<th>Process</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressed Nb cups for cavities</td>
<td><img src="image1" alt="Pressed Nb cups for cavities" /></td>
</tr>
<tr>
<td>E-beam welding of cavities</td>
<td><img src="image2" alt="E-beam welding of cavities" /></td>
</tr>
<tr>
<td>Tuning of cavities</td>
<td><img src="image3" alt="Tuning of cavities" /></td>
</tr>
<tr>
<td>BCP cavity etch</td>
<td><img src="image4" alt="BCP cavity etch" /></td>
</tr>
<tr>
<td>Cavity with and w/o He vessel</td>
<td><img src="image5" alt="Cavity with and w/o He vessel" /></td>
</tr>
<tr>
<td>Final matching of He vessel</td>
<td><img src="image6" alt="Final matching of He vessel" /></td>
</tr>
</tbody>
</table>

All done at CLASSE – No company could do this today!
ERL SRF injector production at Cornell

Transport from Newman Lab to Wilson Lab
Understanding of emittances

Beam properties at the cathode

- Fixed slits phase space measurements
  - Corrector coils for beam scanning
  - 10 micron precision slits
  - 1 kW beam power handling

Good agreement with theory gives confidence that the very small simulated emittances can be achieved.

Understanding of emittances

Asymmetric phase space distribution leads to reduced brightness

This Brightness reduction has been traced back to asymmetric photon distributions on the cathode.

Are transported through the accelerator, measured in a fixed slit phase space measuring system, and compared with simulations.

Gun milestones:
- Highest current: 25mA
- Highest voltage: 430kV
- Highest bunch charge: 80pC
- Emittance at 250keV: 1.5 µm

Come to the ERL working group
For challenges, prototyping, projects, planning …

ERL@CESR, Cornell

Wilson Lab

X-ray user area

Cooling and cryogenics

Accelerator company

Architects

Cryogenic companies

Tunneling consultants