Overview of ERL R&D Towards Coherent X-ray Source

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ERL x-ray light source concept
Acknowledgements

- Matthias Liepe for SRF slides; Georg Hoffstaetter for slides from his ERL’11 talk – and by proxy to the entire international ERL community

- Cornell team:

- NSF DMR-0807731 for ERL R&D support at Cornell
Outline

- Introduction & motivation
- Main technological challenges
- Alternative ideas
- Outlook
**ERL development timeline**

1960


1970

1980


1990

1990: S-DALINAC (Darmstadt)

1998: BINP FEL

1999: JLAB DEMO-FEL

2000

2000: ERL-P

2004: BNL R&D ERL

2005: Cornell gets $

2004: ERL-P

KEK, BESSY, China

2004: JLAB FEL Upgrade

2010
Synchrotron Radiation Sources for the Future

Sol Gruner\textsuperscript{1,2,3}, Don Bilderback\textsuperscript{1,4}, Maury Tigner\textsuperscript{2,5}
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\textsuperscript{2} Department of Physics
\textsuperscript{3} Laboratory of Atomic and Solid State Physics (LASSP)
\textsuperscript{4} School of Applied and Engineering Physics
\textsuperscript{5} Laboratory of Nuclear Studies (LNS)
Cornell University, Ithaca, NY 14853

discusses $10^{23}$ brightness (s.u.) out of an ERL

- Geoff Krafft and Dave Douglas talk about ERL-based X-ray light source around that time (slightly earlier); MARS proposal by Gennady Kulipanov et al. (1998)
Progress in ERLs for Light Sources

XDL’11 workshops – exciting science enabled by X-ray ERLs

CDI

Transparent electrode

Metal electrode

ANIMAL CELL

Nucleus

Ribosomes

Nucleolus

Mitochondrion

Cytoskele

Centrioles

Smooth endoplasmic reticulum

Peroxisome

Plasma membrane

Tickle-Probe

SAXS/WAXS @ sub-ps

IXS

Earthquake

Vertical fabric

Horizontal fabric

SoS

Hypothalamic velocity zone

Meso-layer

Iron-heme displacement: $\Delta d \approx 0.33A$

His64

His93

A-helix

G-helix

H-helix

F-helix

0.02 Å rmsd
Progress in ERLs for Light Sources

Operations at JLAB
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury,
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Designs at Cornell
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS

3GeV ERL First Stage
7GeV Double Acc.

XFEL-O Second Phase
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK
Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK, HZB
Progress in ERLs for Light Sources

Operations at JLAB, Daresbury, BINP
Designs at Cornell, KEK/JAEA, BAPS
Test loops at KEK, HZB, IHEP

I.V. Bazarov, Overview of ERL R&D Towards Coherent X-ray Source, March 6, 2012
Energy Recovery Installations:
Successful tests for ERL beam dynamics, controls, and technology

- ALICE, 21MeV, 20pC

- Demonstrated 9 mA CW at 150 MeV, 14kW (Jlab FEL)

- VUV loop: Lasing at 10eV, achieved 2010

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)
New test installations
Double Loop Compact ERL (KEK)

- **Why did we choose a double loop circulator?**

  It is for saving construction area, number of accelerator cavities, running cost of the refrigerators.

### Main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>5-10 MeV</td>
</tr>
<tr>
<td>Full energy</td>
<td>245 MeV</td>
</tr>
<tr>
<td>Electron charge</td>
<td>77 pC</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>&lt; 1 mm-mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1-3 ps</td>
</tr>
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**Layout of double loop Compact ERL**
New test installations
BNL, KEK, BESSY, and IHEP

IHEP Compact TF-- 35 MeV-10 mA

BNL ERL test for coherent e-cooling of RHIC

BERLinPro: ERL demonstration facility
Cryogenic plant
BESSY II
ERL X-ray source R&D

• **Essentials**
  - SRF (high $Q_0$, $Q_L$ for low operation cost; HOM damping for > 100mA; cost-efficient cryomodule design & fabrication)
  - Photoinjector (demonstrate high current, longevity, brightness)
  - Generic facility strawman (undulators, magnets, power budget, cryoplant)

• **And beyond**
  - Multi-turn designs (depends on how cheap/efficient SRF can be made)
  - Marry XFEL solutions (simultaneous low rep rate beam operation with high current – e.g. KEK design)
Significant photoinjector developments

- First beam from new SRF electron sources (HZB/JLAB for ERLs; Niowave/NPS; more coming up)
- More new guns (DC, NCRF, and SRF) with ~100mA in mind either being commissioned or under construction
- Cornell photoinjector highlights (over the last year):
  - Maximum average current of 50 mA from a photoinjector demonstrated (Feb 2012)
  - Demonstrated feasibility of high current operation (~ kiloCoulomb extracted with no noticeable QE at the laser spot)
  - Original emittance spec achieved: now getting x1.8 the thermal emittance values, close to simulations (Sept 2011)
  - Beam brightness @5GeV same as 100 mA 0.5x0.005nm-rad SR
Boeing/LANL RF gun tribute

The Boeing 433 MHz RF Photocathode Gun

- New current record is 52 mA at Cornell
  - beats Dave Dowell’s 32 mA record of 20 years!
- More in my photoinjector overview talk
Main Linac Cavity Development and high $Q_0$

Specs: Support ERL operation with $>100$ mA; must minimize cryogenic wall losses ($Q \sim 2 \cdot 10^{10}$ at 1.8 K)

Completed:
- RF design
- Mechanical design
- Cavity fabrication
- Vertical cavity RF test
- Horizontal cavity test in cryomodule
- Meets ERL specs: 16 MV/m, $Q_0 \sim 2 \cdot 10^{10}$
RF Optimization for >100 mA ERL Operation (I)

Cell shape optimization:
- ~20 free parameters
- Full Higher-Order Mode characterization (1000’s of eigenmodes)
- Verification of robustness of cavity design

- Dipole mode damping calculated up to 10 GHz with realistic RF absorbers
- Worst mode limits beam current!

$I_{BBU} \sim 1/(\text{worst BBU-parameter})$
RF Optimization for >100 mA ERL Operation (II)

- Optimize Cavity W.R.T. BBU parameter
- Introduce realistic shape variations (400 cavities)
- Compute dipole HOMs to 10 GHz (1692 modes /cavity)
- Generate realistic ERL (x100)
- Compute BBU current

Key: simulate realistic linac

Optimized cavity shape robust up to ±0.25 mm shape imperfections!

*Courtesy M. Liepe
Optimized cavity with ±0.25 mm shape imperfections supports ERL beam currents well above 100 mA!

Some of this work is summarized in N. Valles & M. Liepe, PAC’11, TUP064, p. 937
Mechanical Design for efficient Cavity Operation

- Small bandwidth cavity vulnerable to cavity microphonics (frequency modulation), especially by helium pressure fluctuations.
- Diameter of cavity stiffening rings used as free parameter to reduce $df/dp$.
- ANSYS simulations: large diameter rings and no rings at all have smallest $df/dp$.
- Build two prototype cavities (with and without rings) to explore both options.

![Model of Cornell ERL Main Linac Cavity](image)

**Stiffening rings can vary from ID at iris to OD at equator.**

![Graph showing df/dp vs. ID of stiffening rings](image)

Cavity optimized!

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S. Posen & M. Liepe, PRST-AB 15 (2012) 022002
Prototype Cavity Fabrication

Electron Beam Welding

Quality control: CMM and frequency check

Finished main linac cavity with very tight (±0.25 mm) shape precision ⇒ important for supporting high currents (avoid risk of trapped HOMs!)
Vertical Performance Test of Prototype Cavity

- Cavity surface was prepared for high $Q_0$ while keeping it as simple as possible: bulk BCP, 650°C outgassing, final BCP, 120°C bake

The achievement of high Q is relevant not only to Cornell's ERL but also to Project-X at Fermilab, to the Next Generation Light Source, to Electron-Ion colliders, spallation-neutron sources, and accelerator-driven nuclear reactors.
One-Cavity ERL Main Linac Test Cryomodule

- Assembled and currently under testing at Cornell:
  - First full main linac system test
  - Focus on cavity performance and cryogenic performance
Preliminary Test Results of First ERL Main Linac Cavity in Test Cryomodule

Cryomodule cavity test results at 1.8K

Administrative limit. Cavity can go to higher fields

Cavity exceeds ERL gradient and $Q_0$ specifications in its first cryomodule test!
Alternative & developing ideas

- **MARS**
  - Trade off current for higher undulator $N \sim 10^4$, use many passes
  - Much reduced injector requirements, can use lower gradient linac
  - Becomes less appealing as injector & SRF performance/efficiency improves

- **Moderate number, e.g. two-pass, approaches**
  - Several labs pursuing, capital and operational cost savings
  - Full energy CW linac is a nice investment if can afford

- **Extend ERL’s to x-ray free electron laser techniques**
  - Not appealing for GHz rep. rates; instead use simultaneous operation with a lower rep rate beam
When to use energy recovery

- Simultaneous operation with high current at e.g. XFELO specs
- Keep additional (unrecovered) RF load ~1-2kW per SRF cavity

<table>
<thead>
<tr>
<th>Rep. rate</th>
<th>Beam power @ 5GeV</th>
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<tbody>
<tr>
<td>100pC @ 100MHz</td>
<td>50MW</td>
</tr>
<tr>
<td>100pC @ 10MHz</td>
<td>5MW</td>
</tr>
<tr>
<td>100pC @ 1MHz</td>
<td>0.5MW</td>
</tr>
<tr>
<td>100pC @ 0.1MHz</td>
<td>0.05MW</td>
</tr>
</tbody>
</table>

Absolutely

Maybe

No
Simultaneous short pulses for XFEL and generic ERL running

• Initial analysis to meet XFELo specs shows it’s doable using non-energy recovered beamline

from Cornell ERL Science Workshops, June 2006
KEK plans for ERL with XFEL-O

Others to follow?

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

all of the above

3 GeV ERL with XFEL-O at KEK
Summary & Outlook

• Based on demonstrated source performance: if a hard X-ray ERL were to be built today, it would already be the brightest quasi-CW source of x-rays

• There is a long list of technical issues still requiring attention, but also great progress over the last 2 years

• Further light source evolution calls for free-electron laser techniques married to ERLs (or rather its CW linac at a reduced bunch rep rate) to enhance brightness and better control coherence
END
Advantages of ERL beams for light sources

ERLs have advanced, science enabling capabilities:

a) Large currents for Linac quality beams
b) Continuous beams with flexible bunch structure
c) Small emittances for round beams
[Similar transverse properties have recently been proposed for 3km long rings]
d) Openness to future improvements
[today’s rings can also be improved, improvements beyond ring performances mentioned under c) may be harder to imagine]
e) Small energy spread (2.e-4 rather than conventional 1.e-3)
f) Variable Optics
g) Short bunches, synchronized and simultaneous with small emittances

Thus: many advantages beyond increased spectral brightness!

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, and extensions can be envisioned, e.g. XFEL-O.
Advantages of ERL beams: 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.