Overview of Energy-Recovery Linacs

Ryoichi Hajima
Japan Atomic Energy Agency
ERL Development Group

Acknowledgement
Georg Hoffstaetter (Cornell)
George Neil (JLAB)
Susan Smith (CCLRC/DL/ASTeC)
Nikolay Vinokurov (BINP)
Energy Recovery Linac

- Energy conversion at FEL ~1% → the spent beam still has ~99% energy.
- Recycling the remaining energy is possible by “deceleration”.
- ERL technique works quite efficiently with a superconducting linac.
- High-average current beams with small RF sources.
- Fresh electrons every turn → high brightness beams
## History of ERL

- **First proposal of ERL concept**
  - M. Tigner (1965)
- **Energy recovery at DC acc. (UCSB FEL, 1985)**
- **Early experiments**
  - Stanford SCA FEL, T. Smith et al. (1987)
  - Los Alamos FEL, D. Feldman et al. (1987)
- **First successful demonstration of ERL**
  - JLAB IR-demo, G. Neil et al. (2000)
- **ERL facilities in operation**
  - JAERI FEL, R. Hajima et al. (2003)
  - BINP FEL, E.A. Antokhin et al. (2004)
  - JLAB IR upgrade, C. Behre et al. (2004)
- **First “ERL session” at PAC-2003**

chronicle by paper publishing date.
History of ERL

History of ERL

• First proposal of ERL concept
  – M. Tigner (1965)

• Energy recovery at DC acc. (UCSB FEL, 1985)

• Early experiments
  – Los Alamos FEL, D. Feldman et al. (1987)

• First successful demonstration of ERL
  – JLAB IR-demo, G. Neil et al. (2000)

• ERL facilities in operation
  – JAERI FEL, R. Hajima et al. (2003)
  – JLAB IR upgrade, C. Behre et al. (2004)

• First “ERL session” at PAC-2003

chronicle by paper publishing date.
History of ERL

D.W. Feldman et al., NIM A259 (1987) 26


reduction of RF input power by recirculation
History of ERL

• First proposal of ERL concept
  – M. Tigner (1965)

• Energy recovery at DC acc. (UCSB FEL, 1985)

• Early experiments
  – Los Alamos FEL, D. Feldman et al. (1987)

• First successful demonstration of ERL
  – JLAB IR-demo, G. Neil et al. (2000)

• ERL facilities in operation
  – JAERI FEL, R. Hajima et al. (2003)
  – JLAB IR upgrade, C. Behre et al. (2004)

• First “ERL session” at PAC-2003

chronicle by paper publishing date.
History of ERL

Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery


Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
(Received 3 September 1999)

Jefferson Laboratory’s kW-level infrared free-electron laser utilizes a superconducting accelerator that recovers about 75% of the electron-beam power. In achieving first lasing, the accelerator operated “straight ahead” to deliver 38-MeV, 1.1-mA cw current for lasing near 5 μm. The waste beam was sent directly to a dump while producing stable operation at up to 311 W. Utilizing the recirculation loop to send the electron beam back to the linac for energy recovery, the machine has now recovered cw average currents up to 5 mA, and has lased cw with up to 1720 W output at 3.1 μm.
### History of ERL

- **First proposal of ERL concept**
  - M. Tigner (1965)
- **Energy recovery at DC acc. (UCSB FEL, 1985)**
- **Early experiments**
  - Stanford SCA FEL, T. Smith et al. (1987)
  - Los Alamos FEL, D. Feldman et al. (1987)
- **First successful demonstration of ERL**
  - JLAB IR-demo, G. Neil et al. (2000)
- **ERL facilities in operation**
  - JAERI FEL, R. Hajima et al. (2003)
  - BINP FEL, E.A. Antokhin et al. (2004)
  - JLAB IR upgrade, C. Behre et al. (2004)
- **First “ERL session” at PAC-2003**

*chronicle by paper publishing date.*
ERL FELs

- JAEA ERL, Japan
- Novosibirsk FEL, BINP, Russia
- FEL upgrade, JLAB, USA
JAEA ERL (formerly JAERI FEL)

17MeV SCA FEL

17MeV ERL-FEL
FEL wavelength ~ 20\(\mu\)m

undulator

17 MeV

gun

injector

2.5 MeV
10mA

main acc.

20m

Beam loading with ERL and without ERL.


Novosibirsk FEL (BINP)

Normal conducting cavities

Four tracks in horizontal plane with two IR FELs (under construction)

4-turn, 40MeV, 150mA

One track in vertical plane with terahertz FEL (exists)

1-turn, 12MeV, 20mA

Common for all FELs accelerating system (exists)

180MHz

Normal conducting cavity
JLAB FEL upgrade

- 100 W broadband 2 to 50 cm\(^{-1}\)
- 10 kW average power, 1–14 microns
- (3 kW average power, .3 to 1 micron – in construction)
- all 400 femtosec FWHM @ 75 MHz
High-Power Record at JLAB-FEL

Short wavelength results to date:

<table>
<thead>
<tr>
<th>wavelength (µm)</th>
<th>1.1</th>
<th>1.6</th>
<th>2.8</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>pulsed (kW)</td>
<td>2.5</td>
<td>14.6*</td>
<td>6.7</td>
<td>10.6 (1s)</td>
</tr>
<tr>
<td>cw (kW)</td>
<td>2.2</td>
<td>14.6*</td>
<td>6.7</td>
<td>8.5</td>
</tr>
</tbody>
</table>

- Short wavelength performance improves as we develop and test low absorption (<100ppm) dielectric coatings for high power optics
Advantages of ERL

- In FELs, only a small part of electron beam power is converted into laser power.

- We can improve the total efficiency by recycling the unused electron beam power = Energy Recovery.

- Energy Recovery is also excellent at high-brightness beams, because ERL is free from bunch thermalization = fresh bunch every turn.

- ERL is applicable to FEL, synchrotron light sources, collider, e-cooler ....
On-going and Future ERL Projects

(evolution towards small emittance, and shorter pulse as well.)
ERL X-ray light sources

Why ERL?

- free from emittance growth and bunch lengthening
  - higher brilliance and shorter pulse than 3rd-gen.
- average current \(~100\text{mA}\)
  - X-ray flux comparable to 3rd-gen.
- many beam lines through the return loop
  - multi-user facility same as 3rd-gen.

Evolution of X-ray science towards the new regime:
science with coherent X-ray and ultrafast X-ray
Proposal of ERL X-ray Light Sources

Proposal of ERL LS at APAC-1998

MARS - A PROJECT OF THE DIFFRACTION LIMITED FOURTH GENERATION X-RAY SOURCE

D.A. Kayran et al.

“diffraction limit”

e-beam divergence < X-ray divergence

\[ \varepsilon < \frac{\lambda}{4\pi} \]

emittance reduction by adiabatic damping during “linear acceleration”

\[ \varepsilon = \frac{\varepsilon_n}{\gamma} \]

\[ \varepsilon_n = 0.1 \text{mm} - \text{mrad} \]

\[ \gamma = 10^4 \text{ (5GeV)} \]

diffraction limit for 1Å X-ray
ERL Light Source - Expected Performance

Example of ERL Light Source

\[ \varepsilon = 8.5 \text{ pm}, \, I = 100 \text{ mA}, \, \sigma_{E/E} = 0.04\% \]

Coherence of 1Å X-rays

0.2% (SPRing-8) → 25% (ERL)

Science with coherent X-rays will be promoted strongly.
Science with ERL light source

ERL opens a door to novel science with coherent X-ray and ultrafast X-ray.

diffraction microscopy by coherent X-ray

coherent X-ray (non-crystal)

bacteria
diffraction
reconstruction

higher coherence
→ shorter irradiation time and/or better resolution

ultrafast X-ray science

photoinduced metallization ~ 1.5ps


dynamics of material = function of material

ERL Light Sources

- 4GLS at Daresbury, UK
- ERL@CESR, Cornell University, USA
- ERL Light Source in Japan
4GLS at Daresbury, UK

- 500 MeV, 100mA ERL for undulator radiation and VUV-FEL
- 700 MeV, XUV-FEL branch
- 25-35 MeV, ERL for IR-FEL

covers wide range of wavelength: IR ~ XUV complementary to DIAMOND
Prototype ERL is under construction to demonstrate ERL technologies including gun, SCA and FEL.

First Beam from the Gun, at 16th Aug. 2006

- 350 kV gun
- 8.35 MeV injector
- 35 MeV loop
- 1.3 GHz SCA
- 80 pC x 81.25 MHz x 100 μs x 20 Hz
✓ 5 GeV, 100 mA ERL
✓ use CESR tunnel
✓ 2 linacs in 1 tunnel
Cornell Univ.

Gun prototype: verify beam production

- 500-750 kV DC gun
- NEA-GaAs photocathode
- 5-15 MeV SC booster (not yet installed)
- R&D towards 100mA, 0.1mm-mrad
The ERL light source in Japan

Two projects merged into a single project (Mar. 2006)

KEK 5-GeV ERL at Tsukuba site

JAEA 6-GeV ERL at Naka site

The ERL light source in Japan (have no name yet).

KEK, JAEA and scientists from ISSP U. Tokyo, UVSOR, SPring-8.

ERL R&D in Japan

superconducting cavity at KEK
9-cell cavity with strong HOM damping
BBU threshold over 600mA

see poster K. Umemori et al.

Photocathode DC Gun at JAEA
a 250kV-50mA gun is under construction

see poster R. Hajima et al.

construction of 5GeV ERL
after demonstration of all the relevant technologies.

ERL test facility (60MeV-200MeV, 100mA)

see poster T. Kasuga et al.
Photocathode for high-average current and small emittance is one of the most critical R&D issues for future ERL light sources.

We propose new type of semiconductors, bulk AlGaAs, and superlattice.
## Summary

- ERL offers a versatile technology to generate high-power and high-brightness electron beams.
- Useful for many applications – FEL, X-ray LS, collider ...
  - contribute to intrinsic progress in science and industry.
- Extensive R&Cs are carried on
  - see Lia Merminga’s talk: Technological challenges of ERLs.
- Collaborative interaction with other projects is expected.
  - Superconducting Acc. (ILC, CEBAF-upgrade, SNS)
  - High-brightness beams (XFELs)
Welcome your participation to the ERL club!

especially from Asian countries.
backup slides
Superconducting Accelerator Technology

- European XFEL
- CEBAF upgrade
- Spallation Neutron Source
- International Linear Collider

Brilliance and coherent fraction spectra from ERL (5GeV, 0.3GeV)

It is possible to cover the energy range from VUV to X-ray by using 5GeV ERL and 0.3GeV ERL.

Coherent fraction expected from ERL. It is possible to achieve the values of 10-20% at the energy range of 10keV.
ERLs for High-Energy and Nuclear Physics

- Electron cooling of hadron beams
  - 54 MeV electrons are required for RHIC
  - ERL is the only solution

- Electron-hadron collider eRHIC

Advantage of ERL colliders

- High-energy, high-current, high-charge
- Free from tune shift limitation at IP
- Highly polarized electron beams
- Very high luminosity

- Electron-light ion collider ELIC

Superlattice Photocathode

improvement of photocathode by optimizing band structure

- superlattice photocathode

<table>
<thead>
<tr>
<th></th>
<th>Q.E.</th>
<th>emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>B</td>
<td>large</td>
<td>large</td>
</tr>
<tr>
<td>C</td>
<td>large</td>
<td>small</td>
</tr>
</tbody>
</table>

bulk GaAs

CB

VB

superlattice GaAs

CB

VB

Excitation photon energy

Superlattice

Energy width

$\Delta E_{SL}$

$\Delta E_{bulk}$

$\frac{m_c v^*}{\hbar^2}$

Joint density of state

A

B

C


35