ERL: Energy Recovery Linacs

Chaivat Tengsirivattana
CASA, Jefferson Lab
University of Virginia

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High-Current Energy-Recovering Electron Linacs

1. Introduction
2. Historical Development of Energy-Recovering Linacs
3. The Jefferson Laboratory Infrared Demonstration Free-Electron Laser
4. Overview of Energy-Recovering Linac Projects and Proposals
5. Scaling of Energy-Recovering Linacs to Higher Energies
6. Scaling of Energy-Recovering Linacs to Higher Currents
1.1 Traditional Types of Electron Accelerators

Figure 1 Main accelerator types.
1.2 Beam Recirculation

**Multipasses**

Accelerate - Decelerate

**Linacs**

1. Electron resides briefly.
2. Laser-driven photocathode – Polarization and control
3. Emittance
4. Pulse duration

**Ring**

1. Equilibrium – by radiation damping
2. Naturally bunched
1.3 Beam Energy Recovery

Simplest case: single recirculation

1. Accelerate in 1st pass
2. Recirculate in 2nd pass, plus \( \frac{1}{2} \) Rf wavelengths.

Efficiency: Rf to beam multiplication factor

\[
\kappa = \frac{P_{\text{beam}}}{P_{\text{RF}}} = \frac{I_bE_f}{I_bE_{\text{inj}} + P_{\text{rf,linac}}}
\]

Accelerating gradients 20 MV/m
Quality factor \( 10^{10} \)
Continuous wave
2. Radiofrequency Superconductivity and Recirculating Linacs

Superconducting cavities:
1. CW or high-duty-factor
2. Highly efficient coupling
3. High-average-current
4. Reduction in length of the accelerator


SRF CEBAF
• High-repetition-rate cw electron beam.
• High-brightness DC electron sources
3.1 JLab IR Demo FEL System Design

10 MeV to 35-48 MeV

Figure 2 The Jefferson Laboratory Infrared Demonstration Free-Electron Laser.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy at wiggler</td>
<td>42 MeV</td>
<td>42 MeV</td>
</tr>
<tr>
<td>Average beam current</td>
<td>5 mA</td>
<td>5 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>60 pC</td>
<td>60–135 pC</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>74.85 MHz</td>
<td>18.7–74.85 MHz</td>
</tr>
<tr>
<td>Normalized emittance (rms)</td>
<td>13 mm-mrad</td>
<td>5–10 mm-mrad</td>
</tr>
<tr>
<td>Bunch length at wiggler (rms)</td>
<td>400 fs</td>
<td>400 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>60 A</td>
<td>60 A</td>
</tr>
<tr>
<td>FEL extraction efficiency</td>
<td>&gt;0.5%</td>
<td>&gt; 1%</td>
</tr>
<tr>
<td>$\delta p/p$ before wiggler (rms)</td>
<td>0.5%</td>
<td>&lt;0.25%</td>
</tr>
<tr>
<td>$\delta p/p$ after wiggler (full)</td>
<td>5%</td>
<td>6%–8%</td>
</tr>
<tr>
<td>cw FEL power</td>
<td>1 kW</td>
<td>2.13 kW</td>
</tr>
</tbody>
</table>
Figure 3 Longitudinal matching scenario in the JLab IR Demo FEL, showing phase versus energy diagrams at critical locations.
3.2 Longitudinal Matching

- 2-MeV full energy spread, 20% of 10 MeV.
- Energy recovery proved quite efficient.

Figure 4 Beam viewer image in chicane downstream of FEL (dispersion of 0.4 m). Left: lasing, right: no lasing.
Figure 5 RF system generator power for each linac cavity without beam, without and with energy recovery at various current levels.
### 3.3 System Operation and Performance

**Table 2 Chronology of the JLab IR Demo FEL**

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1997</td>
<td>first electron beam in vault (injector)</td>
</tr>
<tr>
<td>December 1997</td>
<td>first electron beam to straight-ahead dump</td>
</tr>
<tr>
<td>March 1998</td>
<td>high-current single-pass linac operation (1.1 mA cw to straight-ahead dump)</td>
</tr>
<tr>
<td>June 1998</td>
<td>wiggler installed, first light (155 W cw at 5 μm, 1.1 mA straight ahead)</td>
</tr>
<tr>
<td>July 1998</td>
<td>recirculator construction completed, first energy-recovered beam, first (low-power) lasing with energy recovery</td>
</tr>
<tr>
<td>December 1998</td>
<td>high-power lasing with energy recovery (&gt;200 W cw at 5 μm, 1.4 mA)</td>
</tr>
<tr>
<td>March 1999</td>
<td>kW-class 5 μm operation (710 W cw at 3.6 mA, mirror limited)</td>
</tr>
<tr>
<td>July 1999</td>
<td>1.72 kW cw at 3 μm/4.4 mA; kW-class tunable light at 3, 5 and 6 μm 5th harmonic (1 μm) lasing</td>
</tr>
<tr>
<td>September 1999</td>
<td>detection of Thomson scattered x-rays</td>
</tr>
<tr>
<td>August 2001</td>
<td>2 kW IR operation</td>
</tr>
<tr>
<td>November 2001</td>
<td>final beam operations, including production of nearly 20 W THz radiation; decommissioning and start of 10-kW upgrade installation</td>
</tr>
</tbody>
</table>
3.4 10kW IR/1kw UV Upgrade

1. Doubling current, from 5 to 10 mA, bunch charge from 60 to 135 pC.
2. Installing 2 additional cryomodules, E - 160 MeV.
3. Upgrading the recirculators.
4. Adding a pair of optical cavities.

October 30th, 2006:
14.2kW at 9.1 mA and 150 MeV
160 MeV, 9.1 mA, 150 pC, 74.85 MHz, 7 mm-mrad, 150 fs
Figure 6 Schematic of JLab 10-kW IR/1-kW UV FEL upgrade configuration.
Table 3 System parameters of the JLab IR and UV FEL upgrade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IR FEL Upgrade</th>
<th>UV FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy at wiggler</td>
<td>80–210 MeV</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Average beam current</td>
<td>10 mA</td>
<td>5 mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>135 pC</td>
<td>135 pC</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>74.85 MHz</td>
<td>74.85 MHz</td>
</tr>
<tr>
<td>Normalized emittance (rms)</td>
<td>13 mm-mrad</td>
<td>5–10 mm-mrad</td>
</tr>
<tr>
<td>Bunch length at wiggler (rms)</td>
<td>200 fs</td>
<td>200 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>270 A</td>
<td>270 A</td>
</tr>
<tr>
<td>FEL extraction efficiency</td>
<td>1%</td>
<td>0.25%</td>
</tr>
<tr>
<td>$\delta p/p$ before wiggler (rms)</td>
<td>0.5%</td>
<td>0.125%</td>
</tr>
<tr>
<td>$\delta p/p$ after wiggler (full)</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>CW FEL power</td>
<td>$&gt;10$ kW</td>
<td>$&gt;1$ kW</td>
</tr>
</tbody>
</table>
4.1 High-Average-Power FELs

- JAERI FEL, Japan
- Accelerator-Recuperator FEL, Novosibirsk, Russia
- KAERI FEL, Korea
- JLab 10-kW IR FEL Upgrade
4.2 ERL-Based Light Sources

ERLs:

• Average current-carrying capability of storage-ring.
• Smaller beam emittance and energy spread.
• Higher photon brilliance and coherence, round sources, and short-pulse-length radiation. 100-fsec pulse width domain.

• ERL at Cornell, 77pC, 1.3 GHz, 100 mA.
• PERL at Brookhaven.
• 4GLSP at Daresbury, UK.
• LUX at LBNL.
Figure 7 Accelerator-recuperator FEL in Novosibirsk. 1: electron gun; 2: bending magnets; 3: RF resonators; 4,5: injection and extraction magnets; 6: focusing quadrupoles; 7: straight sections with the quadrupole lenses; 8: FEL magnetic system; 9: beam dump.
4.3 Beam Electron Cooling

- Same gamma, act as heat sink – higher luminosity.
  RHIC cooler – 50 MeV, 100 mA ERL.
- High-average-current source, but low frequency = 9 MHz, so high bunch charge = 10 nC.
- Maximize the longitudinal overlap to maximize the cooling rate, beam need to be debunched and rebunched.
4.4 Electron-Ion Colliders

- Advantageous and produce higher luminosity.
- Ring: one damping time – 1,000 revolutions.
- Increase $N_i$
- eRHIC, ELIC

1. Cornell/JLab ERL phase I – 100 MeV, 100 mA.
2. Brookhaven e-cooling prototype.
3. JLab 10-kW FEL Upgrade.
4. CEBAF-ER.

\[
L = \frac{\int N_e N_i}{2\pi \left( \sigma_{x}^2 + \sigma_{ix}^2 \right)^{1/2} \left( \sigma_{y}^2 + \sigma_{iy}^2 \right)^{1/2}}
\]
Figure 8 Energy-recovering linacs in terms of energy versus average current: existing, planned, and proposed ERL-based schemes.
5.1 Injection Energy

- Low $E_i$ vs high $E_i$.

5.2 Number of Passes

- Cost-control measure and optimizing performance.

5.3 General Features of Machine Topology

- Use of spreaders and recombiners

5.4 Phase-Space Matching

- Longitudinal phase-space
- Transverse phase-space
- Graded-gradient focusing
Figure 9 A split-linac topology for ERL-based light source.
Figure 10 Beam envelopes (m) in a 10-MeV to 10-GeV recirculating, energy-recovering accelerator using graded-gradient focusing.
5.5 Phase-Space Preservation

- Transfer matrix element
- One parameter, one knob

5.6 Beam Halo

- Beam loss 0.1 µA out of 5 mA – kilowatts of lost beam power

5.7 CEBAF-ER Experiment

- Chicane – a half-rf-wavelength phase delay.
  1. Allow investigation of beam-quality preservation.
  2. Allow investigation of dynamic range (injected to full energy ratio).
  3. Large-scale demonstration.
- 1 GeV full energy and recovered it, 56 MeV injection Energy, cw and 80 µA.
Figure 11 CEBAF-ER experiment. Accelerated (left) and recovered (right) beams at midpoint of the south linac. This viewer image demonstrates that the decelerating beam remained well-defined and of similar quality to the accelerating beam.
Figure 12 CEBAF-ER experiment. RF system gradient modulator drive signals during pulsed beam operation, with and without energy recovery.
6.1 Generation and Preservation of Low-Emittance, High-Current Beams

- Low emittance – 1 mm-mrad.
- Short bunch-length – 1 psec.
- Preservation in low energy regime – space charge effect.
- Linac and beam lines – wakefield effects.
- Recirculators – Coherent Synchrotron Radiation.
6.2 Multibunch Instabilities

- ERLs more susceptible, support current approaching or exceeding these threshold.
- Beam Breakups, HOMs

\[ I_{th} = \frac{-2p_c}{e(R/Q)_m Q_m k_m M_{ij}} \sin(\omega_m t_r + l\pi/2) e \]

Longitudinal BBU
- \( i, j = 5, 6 \) and \( m \) – longitudinal HOM.

Transverse BBU
- \( i, j = 1, 2 \) or \( 3, 4 \) and \( m \) – transverse HOM.

Beam-loading instabilities
- \( i, j = 5, 6 \) and \( m \) – fundamental accelerating.
Figure 13 Beam breakup stability plot for the JLab IR Demo FEL, By MATBBU codes.
Figure 14 RF cavity response to beam excitation at higher-order mode frequency of 1887 MHz at various beam currents from 0 to 4 mA.
6.3 Superconducting RF Issues and HOM Power Dissipation

- cw beam – high average current.
- Multi GeV.
- Gradient – 20 MV/m
- $Q_0 = 1 \times 10^{10}$

- Extraction of HOMs
- Could be up to 1 kW per cavity, destroy cooper pairs
Figure 15 Measured higher-order mode (HOM) power dissipated in one of two HOM loads per linac cavity versus bunch charge at three bunch repetition rates.
6.4 RF Coupling Optimization and RF Control

- Multiplication factor increases as a function of the loaded quality factor $Q_L$.
- Microphonic vibrations.
- Radiation pressure during turn-on.
- Self-excited loop, Generator-driven system, or Hybrid.
- Piezo to suppress microphonic noise and Lorentz-force-detuning.