The Energy Recovery Linac (ERL) as a Driver for X-ray Producing Insertion Devices


* †

CHESS / LNS

Supported by NSF Coop. Agrmts
PHY 9809799, DMR-9713424

Jefferson Lab

Supported by US DOE No. DE-AC05-4ER40150

†
Critical electron beam parameters

6D Phase Space Area:

- Horizontal Emittance \{x, x'\}
- Vertical Emittance \{y, y'\}
- Energy Spread & Bunch length \{\pm E, t\}

Number of Electrons / Bunch,

Bunch Rep Rate: \(I_{\text{peak}}, I_{\text{average}}\)
What exactly is emittance?

\[ \varepsilon_x = \sqrt{\langle x^2 \rangle \langle \theta_x^2 \rangle - \langle x \theta_x \rangle^2} \]

emittance [mm mrad] \( \sim \) source size \cdot divergence

\[ \theta_x = \frac{dx}{dz} \]

Liouville’s Theorem: phase space volume is “incompressible fluid”
Adiabatic Damping
(Linear Accelerator Case)

\[ \varepsilon_2 = \varepsilon_1 \frac{p_{1,z}}{p_{2,z}} \]

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

\( \varepsilon_n \) is invariant since \( \{x; p_x = mc^2\beta \gamma \cdot \theta_x\} \) form canonically conjugate variables.
Why electron emittance matters?

In undulator

\[ e \text{_{elec}} \]

\[ e \text{_{x-rays}} \sim e^2 \text{_{elec}} + e^2 \text{_{ph}} \]

\( e_{ph} = \frac{?}{4p} \) Diffraction Limit (Heisenberg uncertainty principle)
Storage Ring Case

Equilibrium

Quantum Excitation \textbf{vs.} Radiative Damping

\[ \rho = \frac{p}{eB} \]

Emittance (hor.), Energy Spread, Bunch Length
Touschek Effect

Beam Lifetime vs. Space Charge Density
ERL X-ray SR Source Topology

**Single linac scenario**
- Pros: only one loop
- Cons: energy ratio of $\sim 10^2 - 10^3$

**Split linac scenario**
- Pros: energy ratio of $\sim 10 - 10^2$; more flexibility for longitudinal phase space manipulations
- Cons: two loops

**Multipass scenario**
- Pros: srf structure is only half (or $1/N$) the size
- Cons: higher current ($\times N$) in the linac; unstable @ $\sim 10\text{s mA}$
## ERL Sample Parameter List

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>5-7</td>
<td>GeV</td>
</tr>
<tr>
<td>Average Current</td>
<td>100 / 10</td>
<td>mA</td>
</tr>
<tr>
<td>Fundamental frequency</td>
<td>1.3</td>
<td>GHz</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>77 / 8</td>
<td>pC</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>10</td>
<td>MeV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>2 / 0.2*</td>
<td>μm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.02-0.3*</td>
<td>%</td>
</tr>
<tr>
<td>Bunch length in IDs</td>
<td>0.1-2*</td>
<td>ps</td>
</tr>
<tr>
<td>Total radiated power</td>
<td>400</td>
<td>kW</td>
</tr>
</tbody>
</table>

* rms values
Quick Run Through the Main ERL Components …

• Electron Source
• Superconducting Linac
• Transport Loop
• Undulators
• Used Beam Dump
Electron Source

DC Gun

SRF Booster
Space Charge Emittance Compensation in the Injector

electron bunch

Goal: To approach thermal emittance of the Gun
Superconducting Linac

\( Q_0 \sim 10^{10} \text{ @ } 20 \text{ MV/m} \)

TTF 9-cell 1.3 GHz niobium cavity

Superconducting RF cavities

+ Cryogenic system

+ Klystrons

+ RF Control
Beam Transport Loop & IDs

Transport loop is similar to that of a storage ring flexibility to perform longitudinal gymnastics ...

... and very loooong undulators
ERL Peak Brilliance and Ultra-Short Pulses

- **Photon Energy (keV)**
  - **Peak Brilliance @ 8 keV (ph/s/0.1%/mm²/m²)**
  - **X-ray Pulse Duration \( \tau \) (ps)**

- **Sources and Parameters**
  - **CHESS 49-pole G/A-wiggler**
    - \( \tau = 153 \text{ps} \), \( f = 17.6 \text{MHz} \) (9x5)
  - **CHESS 24-pole F-wiggler**
  - **Sp8 25m**
  - **Sp8 5m**
  - **ESRF U35**
  - **APS 2.4m**
  - **ERL 25m**
    - \( 0.015 \text{nm} \)
    - \( 10 \text{mA} \)
    - \( 0.3 \text{ps} \)
  - **ALS sect.6**
    - **undulator**
  - **3rd SR**
    - **APS upg**
  - **2nd SR**
    - **CHESS 49p**
    - **24p**
  - **ALS fs BLs**
    - **ALS sect.6 undulator**
    - **ALS 5.3.1**

**Peak Brilliance (ph/s/0.1%/mm²/m²)**

- **Photon Energy (keV)**: 1000, 100, 10, 1, 0.1
- **Peak Brilliance**: \( 10^{27} \), \( 10^{26} \), \( 10^{25} \), \( 10^{24} \), \( 10^{23} \), \( 10^{22} \), \( 10^{21} \), \( 10^{20} \), \( 10^{19} \), \( 10^{18} \), \( 10^{17} \), \( 10^{16} \), \( 10^{15} \)
- **X-ray Pulse Duration \( \tau \) (ps)**: 1000, 100, 10, 1, 0.1
Sub-ps bunches: how to make those in ERL?

off-crest running

Magnetic Compressor

linac

Gun 17 ps Main Linac ? 2 ps Undulators ? 0.1 ps
Reasons to be excited about ERL

**ESRF 6 GeV @ 200 mA**
- $\varepsilon_x = 4 \text{ nm mrad}$
- $\varepsilon_y = 0.01 \text{ nm mrad}$
- $B = 5 \times 10^{20} \text{ ph/s/mm}^2/\text{mrad}^2/0.1\%\text{BW}$
- $L_{ID} = 5 \text{ m}$

**ERL 5 GeV @ 100 / 10 mA**
- $\varepsilon_x = \varepsilon_y = 0.2 / 0.02 \text{ nm mrad}$
- $B = 10^{22} \text{ ph/s/mm}^2/\text{mrad}^2/0.1\%\text{BW}$
- $B = 3 \times 10^{22} \text{ ph/s/mm}^2/\text{mrad}^2/0.1\%\text{BW}$
- $L_{ID} = 25 \text{ m}$
Challenges to be resolved

- Low emittance production & preservation
  - Achieving thermal emittance from gun (emittance compensation)
  - CSR, wakes (77 pC, not 1 nC!)
- Photocathode longevity at high average current (vacuum)
- Longitudinal phase space preservation in bunching (curvature correction)
- BBU in the main linac (HOMs damping)
- Beam loss ~ μA (halo)
- Highest $Q_L$ possible (microphonics)
- Diagnostics …
Cornell involvement in ERL work

- **1965** – Original ERL concept for HEP purposes proposed by Maury Tigner
- **1999** – LNS director-to-be (Tigner) and CHESS director (Gruner) discuss ERL X-ray Source. Presented to CHESS Advisory Board in early 2000.
- **August, 2000** – ERL Machine Workshop at Cornell with JLAB contribution
- **December, 2000** – ERL Science Workshop at Cornell
- **July, 2001** – Proposal submitted to the NSF for a prototype ERL, based on studies by Cornell and JLAB scientists
Goals of Cornell ERL Project

• Initial R&D of ERLs
• Build and Test a Phase I machine (100 mA, 100 MeV) to resolve machine issues
• Design and Build a high energy ERL (5-7 GeV) X-ray facility
• Perform R&D on utilization of ERLs and their X-ray and electron beams
We hope to begin work in the fall!
3.5 year construction, 1.5 year measurements

**ERL Phase I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>5-8 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>77 pC</td>
</tr>
<tr>
<td>Emittance, norm.</td>
<td>2* µm</td>
</tr>
<tr>
<td>Shortest bunch length</td>
<td>100* fs</td>
</tr>
</tbody>
</table>

* rms values