USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

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Jefferson Lab and Cornell University

Cornell ERL Project
1. Introduction to ERLs (Review)
2. Vision of a Full Scale X-ray Producing ERL Facility at Cornell (Phase II)
3. Need for the ERL Prototype (Phase I)
4. Zooming-In on ERL Prototype
   1. Injector
   2. Transport Lines
   3. RF system
5. Experimental Program for ERL Prototype
6. Home Assignments
7. Further Reading on Cornell ERL
Let’s review why ERL is such a great idea for a light source

We already know that for X-ray production the critical electron beam parameters are:

6D Phase Space Area:
- Horizontal Emittance \{x, x’\}
- Vertical Emittance \{y, y’\}
- Energy Spread & Bunch length \{\Delta E, t\}

Number of Electrons / Bunch,
Bunch Rep Rate: \(I_{\text{peak}}, I_{\text{average}}\)
Introduction (contd.): what exactly is emittance?

R.M.S. definition:

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

Liouville’s Theorem: phase space volume is “incompressible fluid”
Introduction (contd.): adiabatic damping

Electron bunch $\varepsilon_1$

$p_1, z$

$\theta_{1,x}$

$p_1, x$

$p_{1,z}$

Linac

$p_2, z$

$\theta_{2,x}$

$p_2, x$

$p_{2,z}$

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

Geometric

$\{x, \theta_x\}$

$\varepsilon = \frac{\varepsilon_n}{\beta \gamma}$

Normalized

$\{x, \frac{p_x}{mc^2}\}$

$\varepsilon_n$ is invariant since

$\{x; p_x = mc^2 \beta \gamma \cdot \theta_x\}$ form canonically conjugate variables
Introduction (contd.): x-ray phase space mimics e⁻.

\[ \varepsilon_{\text{elec}} \]

in undulator

\[ \varepsilon_{\text{x-rays}} \approx \varepsilon_{\text{elec}}^2 + \varepsilon_{\text{ph}}^2 \]

\[ \varepsilon_{\text{ph}} = \frac{\lambda}{4\pi} \text{ Diffraction Limit (Heisenberg uncertainty principle)} \]

electron phase space

x-rays phase space
Equilibrium

Quantum Excitation vs. Radiative Damping

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

Emittance (hor.), Energy Spread, Bunch Length

\[ \frac{d\sigma_E^2}{dt} \sim \dot{N}_{ph} E_{ph}^2 \]
Introduction (contd.): what about storage rings (II)?

Touschek Effect

Beam Lifetime vs. Space Charge Density
Introduction (contd.): why ERL?

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

**ESRF 6 GeV @ 200 mA**
- $\varepsilon_x = 4$ nm mrad
- $\varepsilon_y = 0.02$ nm mrad
- $B \sim 10^{20}$ ph/s/mm$^2$/mrad$^2$/0.1%BW
- $L_{ID} = 5$ m
Vision of ERL Facility at Cornell (Phase II)

Schematic layout only!!
Exact layout depends on Phase I results.

<table>
<thead>
<tr>
<th>Machine design</th>
<th>Energy $E_G$ (GeV)</th>
<th>5.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current $I$ (mA)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Charge $q$ (nC/bunch)</td>
<td>0.077</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm-rad)</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_y$ (nm-rad)</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Bunch fwhm $\tau$ (ps)</td>
<td>$0.3 - 5$</td>
<td></td>
</tr>
<tr>
<td># of bunches $f$ (Hz)</td>
<td>$1.3 \cdot 10^9$</td>
<td></td>
</tr>
</tbody>
</table>

Average Brilliance (ph/s/0.1%/mm$^2$/mrad$^2$)

Photon Energy (keV)

ERL 25m 0.015nm 10mA
LCLS SASE 0.15nm 100mA
Sp8 25m
APS 4.8m
Sp8 5m
ESRF U35
APS 2.4m

LCLS spont.

CHESS 49p wiggler
CHESS 24p wiggler

Schematic layout only!!
Exact layout depends on Phase I results.


Table 1: Comparison of the Cornell ERL source with other existing and proposed synchrotron light sources.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>ERL hi-flux</th>
<th>ERL hi-coh.</th>
<th>APS und. A</th>
<th>APS upgrade</th>
<th>ESRF U35 87.5m</th>
<th>Spring8 5m</th>
<th>Spring8 25m</th>
<th>LCLS spont.</th>
<th>LCLS SASE</th>
<th>TESLA spont.</th>
<th>TESLA SASE</th>
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<tbody>
<tr>
<td>Energy $E_G$ (GeV)</td>
<td>5.3</td>
<td>5.3</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>15 (15)</td>
<td>0.063</td>
<td>0.063</td>
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<tr>
<td>Current $I$ (mA)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>72.10^{-6}</td>
<td>72.10^{-6}</td>
<td>0.063</td>
<td>0.063</td>
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</tr>
<tr>
<td>Charge $q$ (nC/bunch)</td>
<td>0.077</td>
<td>0.008</td>
<td>14</td>
<td>14</td>
<td>0.85</td>
<td>0.29</td>
<td>0.29</td>
<td>1 (1)</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>$\varepsilon_x$ (mm-rad)</td>
<td>0.15</td>
<td>0.015</td>
<td>8</td>
<td>3.5</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>0.05 (0.05)</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>$\varepsilon_y$ (mm-rad)</td>
<td>0.15</td>
<td>0.015</td>
<td>0.08</td>
<td>0.0035</td>
<td>0.01</td>
<td>0.003</td>
<td>0.003</td>
<td>0.05 (0.05)</td>
<td>0.02</td>
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<tr>
<td>Bunch fwhm $\tau$ (ps)</td>
<td>0.3</td>
<td>0.3</td>
<td>73</td>
<td>73</td>
<td>35</td>
<td>36</td>
<td>36</td>
<td>0.23 (0.23)</td>
<td>0.188</td>
<td>0.090</td>
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</tr>
<tr>
<td># of bunches $f$ (Hz)</td>
<td>1.3.10^9</td>
<td>1.3.10^9</td>
<td>7.3.10^6</td>
<td>22.10^6</td>
<td>2.3.10^8</td>
<td>3.4.10^8</td>
<td>3.4.10^8</td>
<td>120 (120)</td>
<td>56575</td>
<td>56575</td>
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Machine design

<table>
<thead>
<tr>
<th>Insertion device</th>
<th>ERL hi-flux</th>
<th>ERL hi-coh.</th>
<th>APS und. A</th>
<th>APS upgrade</th>
<th>ESRF U35 87.5m</th>
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<th>Spring8 25m</th>
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<th>LCLS SASE</th>
<th>TESLA spont.</th>
<th>TESLA SASE</th>
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<tbody>
<tr>
<td>Undulator $L$ (m)</td>
<td>25</td>
<td>25</td>
<td>2.4</td>
<td>4.8</td>
<td>5</td>
<td>4.5</td>
<td>25</td>
<td>100 (100)</td>
<td>30</td>
<td>87</td>
<td></td>
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<tr>
<td>Period $\lambda_u$ (cm)</td>
<td>1.7</td>
<td>1.7</td>
<td>3.3</td>
<td>3.3</td>
<td>3.5</td>
<td>2.4</td>
<td>3.2</td>
<td>3 (3)</td>
<td>3.81</td>
<td>5</td>
<td></td>
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<tr>
<td># of periods $N_u$</td>
<td>1470</td>
<td>1470</td>
<td>72</td>
<td>145</td>
<td>142</td>
<td>187</td>
<td>781</td>
<td>3300 (3300)</td>
<td>787</td>
<td>1740</td>
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<td>Horizontal $\beta_x$ (m)</td>
<td>12.5</td>
<td>4.0</td>
<td>15.9</td>
<td>4.0</td>
<td>35</td>
<td>24</td>
<td>24</td>
<td>18 (18)</td>
<td>14.7</td>
<td>33.3</td>
<td></td>
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<tr>
<td>Vertical $\beta_y$ (m)</td>
<td>12.5</td>
<td>4.0</td>
<td>5.3</td>
<td>4.0</td>
<td>2.5</td>
<td>3.9</td>
<td>15</td>
<td>18 (18)</td>
<td>14.7</td>
<td>33.3</td>
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<tr>
<td>Und. $K$ (@ $E_i$)</td>
<td>1.38</td>
<td>1.38</td>
<td>1.24</td>
<td>1.24</td>
<td>0.67</td>
<td>2.08</td>
<td>1.66</td>
<td>3.9 (3.9)</td>
<td>2.28</td>
<td>4.14</td>
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<tr>
<td>1st harmonic $E_1$ (keV)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.26</td>
<td>8.26 (10)</td>
<td>12.4</td>
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</table>

Beamline & optics

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<thead>
<tr>
<th>Beamline &amp; optics</th>
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<th>TESLA SASE</th>
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<tbody>
<tr>
<td>H. div. fwhm (µrad)</td>
<td>9.1</td>
<td>6.2</td>
<td>54.3</td>
<td>70.2</td>
<td>26.8</td>
<td>38.4</td>
<td>37.4</td>
<td>4.9 (1)</td>
<td>6.7</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>V. div. fwhm (µrad)</td>
<td>9.1</td>
<td>6.2</td>
<td>16.2</td>
<td>9.7</td>
<td>10.4</td>
<td>10.0</td>
<td>4.3 (4.9)</td>
<td>1.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. source fwhm (µm)</td>
<td>103</td>
<td>24.5</td>
<td>839</td>
<td>277</td>
<td>879</td>
<td>892</td>
<td>82</td>
<td>78 (60)</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>V. source fwhm (µm)</td>
<td>103</td>
<td>24.5</td>
<td>48.6</td>
<td>11.4</td>
<td>13.9</td>
<td>10.6</td>
<td>22.8</td>
<td>82 (78)</td>
<td>60</td>
<td>60</td>
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<tr>
<td>Power $P_0$ (kW)</td>
<td>33.9</td>
<td>3.4</td>
<td>1.2</td>
<td>7.2</td>
<td>1</td>
<td>15.7</td>
<td>31.2</td>
<td>0.0027 (0.003)</td>
<td>0.070</td>
<td>1.6</td>
<td></td>
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<tr>
<td>Beamline &amp; optics</td>
<td>H. div. fwhm (µrad)</td>
<td>3.1</td>
<td>6.2</td>
<td>9.7</td>
<td>9.7</td>
<td>10.0</td>
<td>4.3</td>
<td>4.9</td>
<td>1</td>
<td>6.7</td>
<td>1.76</td>
</tr>
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<td>16.2</td>
<td>9.7</td>
<td>10.4</td>
<td>10.0</td>
<td>4.3</td>
<td>4.9</td>
<td>1</td>
<td>6.7</td>
</tr>
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<td>60</td>
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<td>Power $P_0$ (kW)</td>
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<td>1.2</td>
<td>7.2</td>
<td>1</td>
<td>15.7</td>
<td>31.2</td>
<td>0.0027</td>
<td>0.003</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>$dP/dA \ @ 20m$ (W/mm²)</td>
<td>2600</td>
<td>260</td>
<td>180</td>
<td>1080</td>
<td>194</td>
<td>1830</td>
<td>4568</td>
<td>0.45</td>
<td>63</td>
<td>336</td>
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<tr>
<td>DC experiments</td>
<td>Ave. flux $F_0$ (p/s/0.1%)</td>
<td>1.5·10^{16}</td>
<td>1.5·10^{15}</td>
<td>7.0·10^{14}</td>
<td>4.2·10^{15}</td>
<td>1.3·10^{15}</td>
<td>2.4·10^{15}</td>
<td>9.0·10^{15}</td>
<td>3.3·10^{16}</td>
<td>2.4·10^{14}</td>
<td>6.4·10^{12}</td>
</tr>
<tr>
<td></td>
<td>Ave. brilliance $B$ (p/s/0.1%/mm²/mr²)</td>
<td>1.3·10^{22}</td>
<td>5.2·10^{22}</td>
<td>1.5·10^{19}</td>
<td>1.5·10^{21}</td>
<td>3.1·10^{20}</td>
<td>5.0·10^{20}</td>
<td>2.2·10^{21}</td>
<td>1.6·10^{17}</td>
<td>4.2·10^{22}</td>
<td>3.6·10^{19}</td>
</tr>
<tr>
<td></td>
<td>Coh flux $F_c$ (p/s/0.1%)</td>
<td>8.1·10^{13}</td>
<td>3.1·10^{14}</td>
<td>9.0·10^{11}</td>
<td>9.0·10^{12}</td>
<td>1.8·10^{12}</td>
<td>3.0·10^{12}</td>
<td>1.3·10^{13}</td>
<td>9.0·10^{8}</td>
<td>2.4·10^{14}</td>
<td>1.4·10^{11}</td>
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<td>Coh. fraction $p_c$ (%)</td>
<td>0.52</td>
<td>20</td>
<td>0.013</td>
<td>0.22</td>
<td>0.14</td>
<td>0.13</td>
<td>0.14</td>
<td>2.7</td>
<td>100</td>
<td>2.1</td>
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<tr>
<td>Pulsed exps.</td>
<td>Photons / bunch</td>
<td>1.2·10^{7}</td>
<td>1.2·10^{6}</td>
<td>9.6·10^{6}</td>
<td>1.9·10^{8}</td>
<td>5.7·10^{6}</td>
<td>7.1·10^{6}</td>
<td>2.7·10^{7}</td>
<td>2.8·10^{8}</td>
<td>2.10^{12}</td>
<td>1.1·10^{8}</td>
</tr>
<tr>
<td></td>
<td>Peak brilliance (p/s/0.1%/mm²/mr²)</td>
<td>3.0·10^{25}</td>
<td>1.2·10^{26}</td>
<td>2.5·10^{22}</td>
<td>8.3·10^{23}</td>
<td>3.3·10^{22}</td>
<td>3.6·10^{22}</td>
<td>1.6·10^{23}</td>
<td>4.8·10^{27}</td>
<td>1.2·10^{33}</td>
<td>3.4·10^{27}</td>
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<td></td>
<td>Peak flux (p/s/0.1%)</td>
<td>3.9·10^{19}</td>
<td>3.9·10^{18}</td>
<td>1.3·10^{18}</td>
<td>2.6·10^{18}</td>
<td>1.6·10^{17}</td>
<td>1.9·10^{17}</td>
<td>7.4·10^{17}</td>
<td>1.2·10^{21}</td>
<td>7.2·10^{24}</td>
<td>6.0·10^{20}</td>
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<tr>
<td></td>
<td>Pk coh. flux (p/s/0.1%)</td>
<td>2.1·10^{17}</td>
<td>7.9·10^{17}</td>
<td>1.7·10^{14}</td>
<td>5.6·10^{15}</td>
<td>2.2·10^{14}</td>
<td>2.5·10^{14}</td>
<td>1.1·10^{15}</td>
<td>2.7·10^{19}</td>
<td>7.2·10^{24}</td>
<td>1.4·10^{19}</td>
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<td>Peak degen. par. $\delta_0$</td>
<td>95</td>
<td>368</td>
<td>0.078</td>
<td>2.6</td>
<td>0.103</td>
<td>0.113</td>
<td>0.49</td>
<td>1.3·10^{3}</td>
<td>3.3·10^{9}</td>
<td>4.7·10^{3}</td>
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<tr>
<td>Nonlinear exps.</td>
<td>Ave. coh. power (W)</td>
<td>0.10</td>
<td>0.40</td>
<td>1.2·10^{-4}</td>
<td>0.011</td>
<td>0.0023</td>
<td>0.0038</td>
<td>0.017</td>
<td>1.2·10^{-5}</td>
<td>0.32</td>
<td>2.2·10^{-4}</td>
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<tr>
<td></td>
<td>Peak coh. power (W)</td>
<td>269</td>
<td>1011</td>
<td>0.22</td>
<td>7.2</td>
<td>0.28</td>
<td>0.32</td>
<td>1.4</td>
<td>3.8·10^{4}</td>
<td>9·10^{9}</td>
<td>2.2·10^{4}</td>
</tr>
<tr>
<td></td>
<td>A coh dP/dA (W/mm²)</td>
<td>12.0</td>
<td>848</td>
<td>0.0029</td>
<td>3.5</td>
<td>0.19</td>
<td>0.40</td>
<td>0.84</td>
<td>2.3·10^{4}</td>
<td>0.0077</td>
<td>0.078</td>
</tr>
<tr>
<td></td>
<td>P coh dP/dA (W/mm²)</td>
<td>3.2·10^{3}</td>
<td>2.2·10^{6}</td>
<td>5.4</td>
<td>2280</td>
<td>22.9</td>
<td>33.8</td>
<td>69.0</td>
<td>7.2·10^{6}</td>
<td>1.9·10^{12}</td>
<td>7.8·10^{6}</td>
</tr>
<tr>
<td></td>
<td>Ave. $E$-field (V/m)</td>
<td>1.0·10^{5}</td>
<td>8.0·10^{5}</td>
<td>1479</td>
<td>5.1·10^{4}</td>
<td>1.2·10^{4}</td>
<td>1.7·10^{4}</td>
<td>2.5·10^{4}</td>
<td>416</td>
<td>2410</td>
<td>7670</td>
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<tr>
<td></td>
<td>Peak $E$-field (V/m)</td>
<td>4.9·10^{6}</td>
<td>4.1·10^{7}</td>
<td>6.4·10^{6}</td>
<td>1.3·10^{6}</td>
<td>1.3·10^{5}</td>
<td>1.6·10^{5}</td>
<td>2.3·10^{5}</td>
<td>7.4·10^{6}</td>
<td>3.8·10^{10}</td>
<td>7.7·10^{7}</td>
</tr>
</tbody>
</table>
Need for the ERL prototype

Issues include:

- **CW injector:** produce \( i_{\text{avg}} \geq 100 \text{ mA} \), \( q_{\text{bunch}} \sim 80 \text{ pC} @ 1300 \text{ MHz} \), \( \varepsilon_n \sim 1 \text{ mm mr} \), low halo with very good photo-cathode longevity.

- Maintain high Q and \( E_{\text{acc}} \) in high current beam conditions.

- Extract HOM’s with very high efficiency (\( P_{\text{HOM}} \sim 10x \) previous).

- Control BBU by improved HOM damping, parameterize \( i_{\text{thr}} \).

- How to operate with hi Q\( L \) (control microphonics & Lorentz detuning).

- Produce + meas. \( \sigma_t \sim 100 \text{ fs} \) with \( q_{\text{bunch}} \sim 0.3-0.4 \text{ nC} \) (\( i_{\text{avg}} < 100 \text{ mA} \)), understand / control CSR, understand limits on simultaneous brilliance and short pulses.

- Check, improve beam codes. Investigate multipass schemes.

**Our conclusion:** An ERL Prototype is needed to resolve outstanding technology and accelerator physics issues before a large ERL is built.
Energy 100 MeV
Max Avg. Current 100 mA
Charge / bunch 1 – 400 pC
Emittance (norm.) \( \leq 2 \text{ mm mr@77 pC} \)

Injection Energy 5 – 15 MeV
\( E_{\text{acc}} @ Q_0 \) 20 MeV/m @ \( 10^{10} \)
Bunch Length 2 – 0.1 ps
Injector Parameters:

Beam Energy Range: 5 – 15 MeV
Max Average Beam Current: 100 mA
Max Bunch Rep. Rate @ 77 pC: 1.3 GHz
Transverse Emittance, rms (norm.): ≤ 1.5 µm
Bunch Length, rms: 2.1 ps
Energy Spread, rms: 0.2 %

^a at reduced average current
^b corresponds to 77 pC/bunch
Emittance growth in the Injector

\[ \varepsilon_{th} = \frac{r_{cath}}{2} \sqrt{\frac{E_{GaAs}}{mc^2}} \leq 0.2 \, \mu m \]
Emittance “Compensation”

\[ \Delta E - \phi \]

“Invariant Envelope” Flow:

\[ \sigma_r = \frac{2}{\gamma'} \sqrt{\frac{I_{\text{peak}}}{3I_{\text{Alfen}}}} \]
Example of Simulations for 5.5 MeV Injector

- Emittance* $x,y$ : 1.0 µm
- Bunch length* : 0.63 mm
- Energy spread* : 0.1 %

*rms value
Optics requirements for prototype

- Low Chromatic and Geometric Aberrations
- Adjustable Momentum Compaction \( R_{56} \)
- Second-Order Momentum Compaction \( T_{566} \)
- Betatron Phase Advance Flexibility to study BBU and CSR Emittance Compensation
JLAB Demo IR-FEL arcs work as flexible chicanes

Adjustable $R_{56}$

$$R_{56} = \int_{1}^{2} \frac{\eta_x}{\rho} ds$$

trim quads

Q1

Q2
Sextupole “Linearizer”

RF waveform
CSR wakes
higher order optics effects

“Curvature” can be fixed with Sextupoles

changing sextupoles strength in the Arc…
Coherent Synchrotron Radiation

\[ \lambda_{SR} \propto \frac{\rho}{\gamma^3} \]
\[ P_{SR} \propto N \frac{\gamma^4}{\rho^2} \]
\[ \lambda_{CSR} \geq l \]
\[ P_{CSR} \propto N^2 \frac{1}{\rho^{2/3} l^{4/3}} \]

Longitudinal Effect

Transverse Effect

Dispersion \neq 0

emittance growth
Longitudinal phase space manipulations

I. Low Emittance Regime

II. Sub-ps Regime

\[ R_{56, \text{Arc}} = -\frac{1}{\partial \delta / \partial l} \]

Rule of Thumb: Match

\[ \frac{\partial \delta}{\partial l} \xrightarrow{\text{d)}} \frac{\partial \delta}{\partial l} \quad (R_{56}), \quad \frac{\partial^2 \delta}{\partial l^2} \xrightarrow{\text{d)}} \frac{\partial^2 \delta}{\partial l^2} \quad (T_{566}) \]
Monopole Higher-Order-Mode Single Bunch Power Excitation per 9-Cell Cavity

σ_{bunch} = 0.6 mm \quad q_{bunch} = 77 \text{ pC}

P_{total} = 160 \text{ W}

P(f<3.5 \text{ GHz}) = 30 \text{ W}
P(f>3.5 \text{ GHz}) = 130 \text{ W}
P(f>5 \text{ GHz}) = 115 \text{ W}
P(f>10 \text{ GHz}) = 83 \text{ W}
P(f>20 \text{ GHz}) = 51 \text{ W}
P(f>40 \text{ GHz}) = 23 \text{ W}
P(f>80 \text{ GHz}) = 5 \text{ W}
Trapped and Propagating Modes: Power Extraction

- Trapped and quasi trapped modes
- Propagating modes

4*HOM couplers to room temperature load
- 30 W per cavity

HOM beam-pipe absorber
- 70 K
- Absorber between cavities at temperature level with good cryogenic-efficiency
- 130 W per cavity
TESLA 9-Cell Cavity with HOM-Absorber

Fundamental mode: \( f = 1.300 \text{ GHz} \)

- Low field at absorber \( \Rightarrow \) no significant damping of fundamental mode,

But:

- Propagating modes have higher fields at the absorber \( \Rightarrow \) damping and power extraction!

Example: dipole mode: \( f = 3.874 \text{ GHz} \)

\[ Q \approx 3170 \]
Conclusion: HOM Damping for the ERL

- HOM damping scheme for the ERL:

- This damping scheme fulfills the requirements on:
  - HOM power extraction
  - Monopole HOM damping
  - Transverse HOM damping
Transverse Beam-Break Up

BBU threshold for a single loop, single HOM:

\[ I_{th} = -\frac{2E_r}{eR_{12} (R/Q)_m Q_m k_m \sin(\omega_m t_r)} \]

1. Favors higher injection energy

2. Periodic matrix element \( R_{12} = \beta \sin \mu \), i.e. recirculating phase advance ought to be \( n\pi \).

3. Adequate HOM damping required (frequency spread of the same HOMs is analogous to better damping)

4. Some optimal recirculating path length exists
Linac Optics for BBU suppression

**BBU threshold ~ 20 mA**

\[ R_{12} = \gamma_i \sqrt{\frac{\beta_i \beta_f}{\gamma_i \gamma_f}} \sin \Delta \psi \]

**BBU threshold ~ 200 mA**
Prototype will help benchmark the code

BBU threshold vs. betatron phase advance of the arc. Squares – no frequency randomization; circles, diamonds, triangles – HOM frequencies are random in the range \([f_{\text{HOM}}, f_{\text{HOM}} + 1]\) MHz.
Other BBU related issues

1. Instability buildup time is relatively slow, i.e. suppression with active feedback appears to be possible

2. Such active feedback approach will be tested with the prototype

3. If systems with much higher instability threshold are developed, multi-turn ERL becomes attractive as a more economical option
List of experiments with ERL prototype

• Low emittance mode in back leg checked
• Highly compressed bunches in back leg checked
• Measured injector beam properties, checked performance of emittance compensation and checked merger CSR
• BBU stability studies completed
• CSR parameter studies utilizing bends
• Beam Loss studies completed
• HOM cooling studies completed
• Surface roughness and resistive wakes measured in experiments on the back leg
• Completed cavity HOM measurements with beam
Home Problems

1) Chicanes can be used in ERLs to achieve two different goals: bunch compression and path length adjustment. Let $\rho$ be radius of trajectory in the dipoles, $L$ dipole length, $\alpha$ bending angle in dipoles, $\lambda$ spacing between the first and the second, the third and the fourth dipoles, $d$ distance between the second and the third magnets. Chicane is an achromat due to its symmetry. Find expressions for a) dispersion function in the middle of chicane and b) momentum compaction ($R_{56} = \partial l/\partial \delta$, here $l$ and $\delta$ are the path length difference between a trajectory and the reference particle trajectory and the relative momentum difference respectively. c) Design a chicane for path length adjustment corresponding to $+/−$ 10º RF phase (frequency 1.3 GHz) at 5 GeV beam energy. What is the corresponding range of magnetic field and $R_{56}$ for such chicane.

2) Longitudinal phase space $(\delta, l)$ can often be represented as $\delta(l) = \delta_0 + \frac{\partial \delta}{\partial l} l + \frac{\partial^2 \delta}{\partial l^2} l^2$ where $\delta_0$ is uncorrelated energy spread, the first partial derivative represents $\delta - l$ linear correlation coefficient, while the second derivative represents quadratic correlation or “curvature”. Retaining only these two most significant terms, calculate energy spread and longitudinal emittance after 100 MeV linac for on-crest, 10º and 20º RF phase, assuming that initially bunch had no $\delta - l$ correlation, 10 MeV beam energy, 20 keV uncorrelated energy spread, and the bunch length of 1º RF (both rms values). What is the shortest bunch length achievable after compression for 10º and 20º RF phase? What is the corresponding $R_{56}$ required in each case?
Home Problems

3) RF guns have demonstrated good performance over the years for low duty factor operation. ERL needs a high current CW source. For normal conducting (copper) RF structures CW operation poses a challenge of removing excessive heat due to wall losses. Estimate the highest accelerating gradient for a half-cell RF gun at 1.3 GHz assuming heat removal capacity of 0.5 kW/cm² and heat removal area of 400 cm². A typical value of geometric shunt impedance $R/Q = 200 \, \Omega / \text{cell}$, and copper structure at that frequency has intrinsic $Q_0 = 2 \times 10^4$. If one uses superconducting half-cell instead (e.g. $Q_0 \sim 10^9$), what would be the required refrigeration power to run at the gradient of 20 MV/m? (Tip: to remove 1 W of wall losses in cryogenic environment @ 4 °K requires ~ 400 W of refrigeration power).

4) Design a beam dump for ERL (hint: follow the Cornell ERL prototype sketch). Use the parameters of the ERL prototype. Distance from quadrupole to collector is 8 m. Assume collecting angle is tilted 6°. What is quadrupole field strength and the beam spot size near the collector? What is the required water flow to cool the collector (use water temperature difference of 20 °C)?

5) Consider ERL prototype with injection kinetic energy of 5 MeV. At this energy the bunch moves with the speed $\beta = 0.9957$. SRF structure in the linac is optimized for $\beta = 1$. a) Calculate phase mismatch in 100 MeV linac for injected and energy recovered beams assuming 5 m long linac. b) If linac consists of 5 cavities (1 m each) with independent phasing, what is the phase mismatch in the first / last cavities?
Further Reading on Cornell ERL

Two web-sites are available

1) Information about Cornell ERL, X-ray science applications, other related projects worldwide
   http://erl.chess.cornell.edu/

2) ERL technical memorandum series
   http://www.lepp.cornell.edu/public/ERL/
USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

G. A. Krafft and I.V. Bazarov
Jefferson Lab and Cornell University

ERL Examples
ERL examples

Other Proposals and Pre-proposals (not in any particular order)

- BNL Project
- Daresbury Laboratory, 4GLS Light Source (IR, VUV, XUV)
- BINP MARS
- University of Erlangen, Synchrotron-ERL
- JAERI ERL IR-FEL
Potential Performance of a PERL Light Source at the NSLS

- Energy ~ 3-7 GeV
- Average current ~ 200 ma
- Sub-picosecond pulses ~100 fs
- Brightness ~ $10^{21-22}$ ph/sec/mm$^2$/mrad$^2$/0.1% BW
- Diffraction limited source:
  - $\lambda$~10 Å in BOTH planes, $\varepsilon_x\varepsilon_y$ ~ ($1\text{Å}$)$^2$ at 3-GeV.
  - $\lambda$~ 5Å in BOTH planes, $\varepsilon_x\varepsilon_y$ ~ ($0.5\text{Å}$)$^2$ at 6-GeV.
- Round beams and variable $\varepsilon_x/\varepsilon_y$ emittance ratio,
  (at a constant product $\varepsilon_x\varepsilon_y$)
- Virtual ‘top-off’ yielding a constant heat load on chambers, optics - high long-term stability
- Electro-optical control of the pulse-format

Presented by J. Murphy at SRI 2001 ERL workshop
A reduction of $\varepsilon$ by at least $10^2$ is desirable!
Average Brightness

\[ B \propto \frac{IL_u}{\varepsilon_x \varepsilon_y} \]

\[ \text{PERL: } \varepsilon_x \varepsilon_y = \varepsilon_0^2 \]

\[ \text{Ring: } \varepsilon_x \varepsilon_y = \frac{r\varepsilon_0}{(1+\chi)(1+\chi)} \frac{r\varepsilon_0\chi}{(1+\chi)(1+\chi)} \]

Flat Beam: \( \chi \ll 1 \), \( r = 10^2 \)

Round Beam: \( \chi = 1 \), \( r = 10^2 \)

\[ B_{\text{PERL}} \approx B_{\text{RING}} \times \begin{cases} 10, & \chi = 10^{-3} \\ 10^2, & \chi = 10^{-2} \end{cases} \]

\[ B_{\text{PERL}} \approx 2500 \times B_{\text{RING}} \]

**PERL can provide a brightness increase of 10-10^3!**

Presented by J. Murphy at SRI 2001 ERL workshop
# Electron Bunch Length & Peak Current

<table>
<thead>
<tr>
<th>Machine</th>
<th>E [GeV]</th>
<th>$\sigma_L$ [ps]</th>
<th>$I_{pk}$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
<td>1.5</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>SLS</td>
<td>2.4</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>SOLEIL</td>
<td>2.5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>NSLS XRAY</td>
<td>2.8</td>
<td>158</td>
<td>90</td>
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<tr>
<td>DIAMOND</td>
<td>3</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>ESRF</td>
<td>6</td>
<td>21-61</td>
<td>295</td>
</tr>
<tr>
<td>APS</td>
<td>7</td>
<td>17-54</td>
<td></td>
</tr>
<tr>
<td>PERL</td>
<td>3-7</td>
<td>0.1-0.4</td>
<td>600</td>
</tr>
</tbody>
</table>

A reduction of $\sigma_L$ by at least $10^2$ is desirable!
L-Band Gun + 25 MeV Pre-Accelerator

\[ E = 2 \text{ MeV} \]
\[ \gamma \varepsilon \sim 0.5-1 \text{ \(\mu\)m} \]
\[ K_2\text{CsSb} \]
3 ps RMS length
heat is a concern
Strawman Layout for a 3 GeV PERL

2 x 12 TBA cells with 6m IDs; tunable R_{56} for compression

Presented by J. Murphy at SRI 2001 ERL workshop
NSLS Upgrade: Ultra-bright X-ray Source

Ring: 24 Cell, Triple Bend Achromat
- Ultra-Low Emittance (1 nm)
- 21 Insertion Devices
- 24 Bending Magnets

LINAC: 3 GeV Superconducting
- Top-off Injection
- Future Upgrade Opportunities
  - PERL
  - HGHG FEL@ 6 GeV

Option: FEL

3 GeV SC Linac for Top-off & Short Pulse X-Rays

Presented by P. Paul at 2002 ICFA mtg at CERN
Daresbury Project 4GLS FEL (IR, VUV, XUV)

http://www.4gls.ac.uk/
Phase I. 3.5 GeV storage ring
Phase II. ERL using same beamlines (shown)

http://www.erlsyn.uni-erlangen.de/
Fig. 1: Scheme of MARS.

Table 6: Accelerator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
</tr>
<tr>
<td>Electron current</td>
<td>mA</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>nm-rad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>nm-rad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: MARS source parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x$</td>
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<td>75</td>
</tr>
<tr>
<td>$\beta_z$</td>
<td>m</td>
<td>75</td>
</tr>
<tr>
<td>$\eta$</td>
<td>m</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>$\mu$m</td>
<td>18</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>$\mu$m</td>
<td>11</td>
</tr>
<tr>
<td>$\sigma_x'$</td>
<td>$\mu$rad</td>
<td>0.9</td>
</tr>
<tr>
<td>$\sigma_z'$</td>
<td>$\mu$rad</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Schematic Drawing of the FEL Driven by an Accelerator-Recuperator

IR-FEL being built at BINP, Novosibirsk
JAERI Energy-Recovery Linac for 10kW FEL

- Natural extension of the original configuration.
- 8 times larger e-beam power.
- Fitting to the concrete boundary.

Energy = 17MeV
FEL: \( \lambda = \sim 22\mu m \)
Bunch charge = 500pC
Bunch length = \sim 15ps (FWHM)
Bunch rep. = 10.4MHz – 83.3MHz
Average current = 5.2mA – 40mA after injector-upgrade

in a macropulse
Analysis of HOM instability

Using measured HOM parameters, designed optics, and a numerical code similar to TDBBU.

$I_{AV}=40\text{mA}$ is far below the instability threshold.

HOM instability is not a critical phenomenon for JAERI-ERL.
Beam energy compression at the return path

Energy compression for $\Delta E/E=8\%$ beam

$\Delta E=1.33\text{MeV}@\text{undulator, 17MeV}$

$\Delta E=0.46\text{MeV}@\text{dump, 2.8MeV}$

$R56=-0.49\text{m}$

11deg. off-trough deceleration

dump

dump

PARMELA simulation

arc exit
dump
undulator