Echo-seeding options for LCLS-II

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Outline

- Principles of echo FEL
- Design considerations
- Steady-state simulation
- Time-dependent simulation
- Frequency doubler/tripler to extend wavelength range to <1nm
- Two-color x-ray generation with the long wavelength pulse leading the short wavelength pulse
Physical pictures of echo-seeding scheme

- Separated energy bands
- Separated current bands

Key advantage: \( b_n \sim n^{-1/3} \)
Preservation of the fine structures

- Quantum diffusion in bend

\[ \Delta \sigma_E^2 = \frac{55e^2 \hbar c L}{24\sqrt{3} \rho^3 \gamma^7} \]

Strong dependence on energy

- Quantum diffusion in undulator

\[ (\Delta \gamma)^2 = \frac{7}{15} \frac{\hbar}{m_0 c} L_{\text{u}} r_e \gamma^4 \kappa_w^3 K^2 F(K) \]

Strong dependence on energy
Preservation of the fine structures

- Finite laser size & coherent undulator radiation

\[ \Delta \gamma(z) = A \sigma_E \sin(kz) \left[ \frac{1}{1 + \sigma_x^2 / \sigma_r^2} - \frac{1}{(1 + \sigma_x^2 / 2 \sigma_r^2)^2} \right]^{1/2} \]

\[ \sigma_r / \sigma_x = 1 \]

\[ \sigma_r / \sigma_x = 4 \]

- Transverse emittance

\[ z = z_0 + R_{56} \delta_0 + T_{522} x_0 \, '2 + T_{544} y_0 \, '2 + \ldots \]
## Parameters for echo-seeding in LCLS-II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>4.3 GeV</td>
</tr>
<tr>
<td>Peak current</td>
<td>800 A</td>
</tr>
<tr>
<td>Normalized slice emittance</td>
<td>0.6 mm mrad</td>
</tr>
<tr>
<td>Slice energy spread at linac exit</td>
<td>700 keV</td>
</tr>
<tr>
<td>$N_p \times \lambda_u$ for M1</td>
<td>$8 \times 35$ cm</td>
</tr>
<tr>
<td>$N_p \times \lambda_u$ for M2</td>
<td>$8 \times 35$ cm</td>
</tr>
<tr>
<td>Seed laser wavelength</td>
<td>202 nm</td>
</tr>
<tr>
<td>Seed laser peak power for M1 and M2</td>
<td>300 MW</td>
</tr>
<tr>
<td>Seed laser pulse length for M1 and M2</td>
<td>100 fs</td>
</tr>
<tr>
<td>Seed laser energy for M1 and M2</td>
<td>75 uJ</td>
</tr>
<tr>
<td>Energy modulation in M1 and M2</td>
<td>1.40 MeV</td>
</tr>
<tr>
<td>$R_{56}^{(1)}$</td>
<td>3.58 mm</td>
</tr>
<tr>
<td>$R_{56}^{(2)}$</td>
<td>109 $\mu$m</td>
</tr>
<tr>
<td>Slice energy spread at radiator entrance</td>
<td>1.57 MeV</td>
</tr>
<tr>
<td>Gain length for 6 nm radiation</td>
<td>1.6 m</td>
</tr>
</tbody>
</table>
Smearing from quantum diffusion

Separation of energy bands: $\pi \sigma_E / B_1 \approx 120 \text{keV}$

- ISR in bend

$$\Delta \sigma_E (\text{keV}) \approx 6.4 \times \sqrt{\frac{L(\text{m})}{\rho(\text{m})}} \left[ E(\text{GeV}) \right]^{7/2}$$

Chicane: $L_B = 1 \text{m}$, $L_S = 2 \text{m}$, $\theta = 1.48^\circ$

$$\Delta \sigma_E = 8.7 \text{keV}$$

- ISR in undulator

$$\Delta \sigma_E = 5.6 \text{keV}$$

- Laser size is $\sim 5$ times larger than e-beam size
Lattice

Matching quads

ECHO_LCLSII

m1

D1

D2

m2

SXR1

Win32 version 8.51/15

β (m)

0.0  6.5  13.0  19.5  26.0  32.5  39.0  45.5  52.0  58.5  65.0

s (m)

D (m)

25/01/10  12.01.32
Emittance effects: tracking a Delta bunch

\[ z = z_0 + R_{56} \delta_0 + T_{522} x_0^2 + T_{544} y_0^2 + \ldots \]

Path length difference

\[ \sigma_z \] (nm)

\[ z \] (m)

m1  Chicane 1  quad  m2  Chicane 2

SLAC
NATIONAL ACCELERATOR LABORATORY
Steady-state simulation for the 34th harmonic

After the first modulator

After the first chicane

After the second modulator

After the second chicane
Steady-state simulation for the 34th harmonic

- Horizontal beam size
- Vertical beam size
- Bunching factor
- Radiation power
Particle distribution

Phase space

Slice energy spread

Current

Emittance

SLAC National Accelerator Laboratory
Echo VS Sase at 6 nm

Radiation power profile

\[ \frac{\Delta \lambda_{\text{FWHM}}}{\lambda} \approx 1.2 \times 10^{-4} \]

♥ Bandwidth is ~40 times narrower than SASE \( \rho = 0.0022 \)
6 nm @ 16 m statistic properties

- Simulation with different seed for the initial shot noise
- Excellent stability
- Coherent radiation power in the first gain length (~10 MW) is much larger than the effective shot noise power (~400 W)
Echo-seeding for 3 nm

- With maximized bunching factor at $n=34$, one gets bunching at $n=68$ for free
- Adjust the radiator to make it resonant at 3 nm
- Coherent radiation power in the first gain length ($\sim 1 \text{ MW}$) is much larger than the effective shot noise power ($\sim 600 \text{ W}$)
Echo-seeding performance at 3 nm @ z=22 m

Radiation power profile

\[ \frac{\Delta \lambda_{\text{FWHM}}}{\lambda} \approx 6 \times 10^{-5} \]

Bandwidth is \(\sim 60\) times narrower than SASE \((\rho = 0.0017)\)
Frequency doubler/tripler

Power vs z for 3 nm radiation

Energy spread vs z

- $z = 0$
  - $\sigma_E = 1.6\text{MeV}$

- $z = 12\text{ m}$
  - $\sigma_E = 2.4\text{MeV}$

- $z = 20\text{ m}$
  - $\sigma_E = 5.8\text{MeV}$

Extract out beam at 12 m when energy modulation $\sim$ slice energy spread
Frequency doubler/tripler

- 1.5 nm bunching 11%
- 1.0 nm bunching 3.5%

Use 1/3 of the SXR1 to generate energy modulation at 3 nm
Use a chicane to convert energy modulation to density modulation
Use 2/3 of the SXR1 to generate radiation at 1.5 nm or 1 nm
## Tunability of echo-seeding scheme

<table>
<thead>
<tr>
<th>n</th>
<th>λ (nm)</th>
<th>$R_{56}^{(1)}$ (mm)</th>
<th>$R_{56}^{(2)}$ (um)</th>
<th>$b_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10.1</td>
<td>2.158</td>
<td>114.7</td>
<td>10.16%</td>
</tr>
<tr>
<td>24</td>
<td>8.42</td>
<td>2.566</td>
<td>112.6</td>
<td>9.61%</td>
</tr>
<tr>
<td>28</td>
<td>7.21</td>
<td>2.973</td>
<td>111.1</td>
<td>9.16%</td>
</tr>
<tr>
<td>34</td>
<td>5.94</td>
<td>3.582</td>
<td>109.4</td>
<td>8.62%</td>
</tr>
<tr>
<td>38</td>
<td>5.32</td>
<td>3.986</td>
<td>108.5</td>
<td>8.33%</td>
</tr>
<tr>
<td>46</td>
<td>4.39</td>
<td>4.794</td>
<td>107.2</td>
<td>7.84%</td>
</tr>
<tr>
<td>60</td>
<td>3.37</td>
<td>3.114</td>
<td>107.3</td>
<td>3.47%</td>
</tr>
<tr>
<td>68</td>
<td>2.97</td>
<td>3.516</td>
<td>106.5</td>
<td>3.35%</td>
</tr>
<tr>
<td>80</td>
<td>2.53</td>
<td>4.117</td>
<td>105.6</td>
<td>3.19%</td>
</tr>
<tr>
<td>86</td>
<td>2.35</td>
<td>4.418</td>
<td>105.2</td>
<td>3.13%</td>
</tr>
<tr>
<td>92</td>
<td>2.20</td>
<td>4.718</td>
<td>104.9</td>
<td>3.06%</td>
</tr>
<tr>
<td>100</td>
<td>2.02</td>
<td>5.118</td>
<td>104.5</td>
<td>2.99%</td>
</tr>
<tr>
<td>100~200</td>
<td>2.02~1.01</td>
<td>Frequency doubler</td>
<td>~10%</td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>1.49</td>
<td>Frequency doubler</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>200~300</td>
<td>1.01~0.67</td>
<td>Frequency tripler</td>
<td>~3%</td>
<td></td>
</tr>
</tbody>
</table>
Two-color x-ray pulse generation

Radiation generated in SXR1 is leading that generated in SXR2

SASE

- Energy spread for ALL the bunch increased after SXR1
- Radiation in SXR1 -> short wavelength
- Radiation in SXR2 -> long wavelength

Short wavelength radiation leading the long wavelength radiation

More ideal case for pump-probe experiments

Long wavelength radiation leading the short wavelength radiation
Echo for two-color x-ray pulse generation

With a short laser pulse, we can speed up the lasing process for only part of the bunch, so that when this part of the beam has effectively lased, other part of the beam has not started lasing yet.
Echo for two-color x-ray pulse generation

Part of the beam is still “fresh” after SXR1 and it can be used to generate short wavelength radiation in SXR2

Long wavelength radiation leading the short wavelength radiation
Timing jitter issue

\[ \Delta t \sim R_{56} \delta / c \sim 80 \text{fs} \]

- Use a long laser pulse (~1 ps) to mitigate the jitter issue

Radiation power profile

- Slightly broadened spectrum with some satellite spikes

Spectrum
Conclusion

- Echo-seeding works well for LCLS-II
- Single-stage echo-seeding covers 2~10 nm
- Extension to 0.6~2 nm is straightforward with frequency doubler/tripler
- X-ray pulse bandwidth is close to transform limit
- Two-color x-rays: long-wavelength x-ray pulse leading the short wavelength pulse
- More work is needed: sensitivity to timing jitter; noise amplification, etc

Thanks!