Soft X-ray HGHG FEL
Team 6

R. Kinjo, T. Lang, L.L. Lazzarino,
C. Lechner, S. Liu, N. Lockmann, J. Pforr
Cascaded HGHG-Seeded FEL

Stages: 3 (two fresh bunches per stage)
Harmonic per stage: <=9
Seed wavelength: 200 nm
Bunch charge: 1 nC
Continuous tuning from 1 nm to 10 nm

Major question to be answered:
• FEL design
  • undulator parameters
  • electron beam parameters
• Current and FEL power at 1 nm
• Temporal jitter and noise in upconversion process

L. Giannessi

Fresh Bunch Technique
Laser Tuning Range

- Assignment calls for continuous tuning of seeded FEL wavelength
- Scanning of atomic transitions, other AMO applications
- Largest gap between 20\textsuperscript{th} and 24\textsuperscript{th} harmonic
- To close gap, we need:

\[
\frac{200 \text{ nm} - u}{20} = \frac{200 \text{ nm} + u}{24}
\]

- Result \( u = 18.2 \text{ nm} \)

**Going for seed wavelengths**

180nm..220nm

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Possible Upconversion Configurations

Total harmonic factors:
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20, 24, 27, 28, 30, 32, 36, 40, 42, 45, 48, 50, 54, 56, 60, 63, 64, 70, 72, 75, 80, 81, 84, 90, 96, 98, 100, 105, 108, 112, 120, 125, 126, 128, 135, 140, 144, 147, 150, 160, 162, 168, 175, 180, 189, 192, 196, 200

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Undulator Parameters

• Three-stage HGHG setup requires 6 undulators with 4 different parameters sets
  – planar, variable-gap undulators (hysteresis-free, tunable)
  – lengths determined by FEL considerations

<table>
<thead>
<tr>
<th></th>
<th>period [mm]</th>
<th>Krms min</th>
<th>Krms max</th>
<th>radiation wavelength [nm] min</th>
<th>radiation wavelength [nm] max</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod 1</td>
<td>128</td>
<td>8.45</td>
<td>12.68</td>
<td>180</td>
<td>220</td>
<td>?</td>
</tr>
<tr>
<td>Rad 1, Mod 2</td>
<td>80.4</td>
<td>3.45</td>
<td>7.96</td>
<td>20</td>
<td>55</td>
<td>?</td>
</tr>
<tr>
<td>Rad 2, Mod 3</td>
<td>59</td>
<td>1.71</td>
<td>5.84</td>
<td>4.5</td>
<td>22</td>
<td>?</td>
</tr>
<tr>
<td>Rad 3</td>
<td>37</td>
<td>1.22</td>
<td>3.66</td>
<td>1.0</td>
<td>10</td>
<td>?</td>
</tr>
</tbody>
</table>
Electron Beam Parameters

- Beam current has strong impact on FEL performance
  \[ P_{\text{sat}} \propto I^{4/3} \]
- Energy spread is proportional to beam current
  - suppose, laser heater does 10keV slice energy spread at 60A injector current [similar to FERMI@Elettra parameters, see S. Spampinati, et al., PRSTAB 17, 120705 (2014)]
  - for 1kA current after compression, 170keV slice energy spread

Final radiator performance with 1kA beam
Estimation of Seed Power

- Obtained by integrating FEL pendulum equation

- Transverse intensity profile of seed has to be reasonably uniform over electron beam

\[ \Delta E = h \cdot \sigma_E \]

\[ \Delta \gamma = \sqrt{\frac{P}{P_0} \frac{2K_m L_m JJ}{\gamma_0 w_0}} \]

\[ JJ = J_0(\xi) - J_1(\xi) \]

\[ \xi = K_m^2 / (4 + 2K_m^2) \]

\[ P_0 = 8.7 \text{ GW} \]

See e.g. E. Hemsing, et al., Rev. Mod. Phys. 86, 897 (2014)

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Diffraction Effect between Radiator and Modulator

\[ P(z) = P_{\text{th}} \left[ \frac{\frac{1}{3} \left( \frac{z}{L_g} \right)^2}{1 + \frac{1}{3} \left( \frac{z}{L_g} \right)^2} + \frac{\frac{1}{2} \exp \left( \frac{z}{L_g} - \sqrt{3} \right)}{1 + \frac{P_{\text{th}}}{2(P_F - P_{\text{th}})} \exp \left( \frac{z}{L_g} - \sqrt{3} \right)} \right] \]
## Active Lengths of Undulators

Assume conservative initial bunching $b_0=0.1$

<table>
<thead>
<tr>
<th>Mod/Modes</th>
<th>Length [m]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod 1</td>
<td>3m</td>
<td>200MW seed power gives $\Delta E=2.6\text{MeV}$</td>
</tr>
<tr>
<td>Rad 1</td>
<td>10m</td>
<td>1GW</td>
</tr>
<tr>
<td>Mod 2</td>
<td>3m</td>
<td>1GW seed power gives $\Delta E=2.3\text{MeV}$</td>
</tr>
<tr>
<td>Rad 2</td>
<td>16m</td>
<td>1GW</td>
</tr>
<tr>
<td>Mod 3</td>
<td>4m</td>
<td>1GW seed power gives $\Delta E=1.7\text{MeV}$</td>
</tr>
<tr>
<td>Rad 3</td>
<td>53m</td>
<td>1GW @1nm</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>89m</strong></td>
<td>active length of undulators</td>
</tr>
</tbody>
</table>
Temporal Jitter

• We need some budget for temporal jitter (and drifts)
• Assume relative laser-electron jitter of 70 fs rms
• Supported by measurements:
Electron Bunch Allocation
for 70fs rms jitter

750fs * 1kA = 0.75nC

150fs for jitter
150fs spacer
150fs spacer
150fs for jitter

3x50fs lasing regions

R1
R2
R3

current I [kA]

750fs

1kA

t [s]

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Noise in HGHG Seeding

\[ \left( \frac{P_s}{P_n} \right)_{\text{out}} = \frac{1}{\hbar^2_{\text{tot}}} \left( \frac{P_s}{P_n} \right)_{\text{in}} \]  


• Signal-to-noise ratio degrades in upconversion process (signal: seed laser, noise: shot noise)

• Parameters:
  – Seed power at 200nm: \( P_s=200\text{MW} \times 1/9 \)
  – \( P_n=50\text{W} \)
    – factor 1/9: seed power within electron beam diameter

• Final SNR only 11 with \( h_{\text{tot}}=200 \)
Summary

• Designed 3-stage HGHG setup
  – Calculated undulator parameters
  – Defined electron bunch parameters (1kA, 2.5GeV / 3.5GeV for short wavelengths)
  – 200MW @200nm seed FEL with 1GW @1nm

• Shotnoise upconversion obliterates quality of seeded pulses (poor signal-to-noise ratio)

• LCLS soft x-ray self seeding: 500eV—1000eV (2.5nm – 1.25nm)

• (identification of next steps)
thank you for your attention
The Next Steps ...

• Stability analysis to determine
  – distribution of harmonics for given total upconversion
  – electron beam parameters
  – time-dependent simulations

• Consider different (longer) laser wavelengths centered, for instance
  – THG from OPA: 235nm—300nm
  – Or 260nm—310nm, around 100uJ pulse energy
  – Significantly higher laser pulse energies, BUT higher harmonics in FEL upconversions
BACKUP SLIDES
HGHG Seeding Principle

see lecture by L. Giannessi...
Bunching Formula

\[ b_h = J_h \left( \frac{\Delta E}{E_0} \right) \exp \left( -\frac{1}{2} \left( \frac{h k R_{56}}{E_0} \frac{\sigma_E}{E_0} \right)^2 \right) \]

- In all radiator stages, assume conservative \( b = 0.1 \)
- For harmonic \( h \), energy modulation amplitude:
  \[ \Delta E = h \cdot \sigma_E \]
Radiator 1

calculated with 900keV slice energy spread
Radiator 2

calculated with 900keV slice energy spread
Radiator 3

At short wavelengths:
Different performance
With different energies

black dashed = 2.5GeV, black solid = 3.5GeV, red solid = 5.0GeV
1kA, sigmaE=900keV (including modulation for h=9), emit_n=1.5e-6
Needed Harmonics in First Stage

... defines the resonance condition for R1
Total Up-Conversion in Radiator of Second Stage (h1*h2)
Lowest Factor First: $h_1$
Lowest Factor First: $h_1 \cdot h_2$

Tune 2nd radiator over $h=10...28$
Slice Energy Spread can be a Deal Breaker

FEL saturation power of radiator

needed seed power in modulator of next stage

\[ \Delta E = h \cdot \sigma_E \]

Power P [W]

rms slice energy spread

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Infos Regarding Beam in Modulator


- FERMI CDR, p. 96 says:
  - 200MW of FEL emission from first stage radiator at FEL-2
  - “Provisionally the fresh bunch delay section is presumed to have a 1.8 m length (necessary in the numerical simulations to include proper diffraction effects).”

- Beam size at E=2.5GeV, emit=1.5mm*mrad, \(<\beta>=10m \Rightarrow \sigma_x=55\mu m\)
Modulator Noise

Diffraction Effect between Radiator and Modulator

Evolution of FEL power in radiator computed with formula from presentation by L. Giannessi

\[ P(z) = \frac{P_{th}}{P_{th}^{6/9/2016}} \left[ \frac{1}{3} \left( \frac{z}{L_g} \right)^2 + \frac{1}{2} \exp \left( \frac{z}{L_g} \sqrt{3} \right) \right] \]

\[ \Delta \gamma = \ldots \]