Radiation Properties of Tapered X-Ray Free Electron Lasers

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Presentation Outline

Motivation

Why tapering for hard X-ray FELs?

What are the requirements on the radiation from high power X-FELs?

Why do we need to study the radiation properties of tapered hard X-ray FELs?

Tapered X-FELs: Physical Examples and Radiation Properties

Conclusion & Future Work
Angstrom scale X-ray diffraction experiments have been performed successfully at LCLS.

Resolution improves with higher photon energy & shorter pulse duration reduces radiation damage.

Achieving ~ 20 fs pulses with $2 \times 10^{13}$ photons/pulse allows single molecule imaging.

Single Molecule Imaging Goal
20 fs - 20 mJ - 2020

Trypanosoma brucei cysteine protease cathepsine B
Why tapering as a path to TW?

LCLS

\[ \frac{\Delta K}{K} \sim 0.8\% \]

\[ \frac{P_{\text{out}}}{P_{\text{sat}}} \sim 2 - 3 \]

LCLS-II

\[ \frac{\Delta K}{K} \sim 10 - 20\% \]

\[ \frac{P_{\text{out}}}{P_{\text{sat}}} \sim 20 - 100 \]

TABLE I: GENESIS Simulation Parameters

<table>
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<tr>
<th>Parameter Name</th>
<th>NCU Value</th>
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<tbody>
<tr>
<td>Beam Energy ( E_0 )</td>
<td>13.4 GeV</td>
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<tr>
<td>Beam Peak Current ( I_{pk} )</td>
<td>4000 A</td>
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<tr>
<td>Bunch Length ( t_b )</td>
<td>16.4 fs</td>
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<tr>
<td>Normalized Emittances ( \epsilon_{x,n}/\epsilon_{y,n} )</td>
<td>0.3/0.3 ( \mu ) m</td>
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<td>Undulator Period ( \lambda_w )</td>
<td>32 mm</td>
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<td>Undulator Parameter ( K )</td>
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<tr>
<td>Radiation Wavelength ( \lambda_r )</td>
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<tr>
<td>Peak radiation power input ( P_{in} )</td>
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</tr>
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<td>FEL parameter ( \rho )</td>
<td>( 7.361 \times 10^{-4} )</td>
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Can we get to TW power and achieve the right coherence/spectral properties for imaging?

Incoherent Scattering gives statistical average of electron density in sample

Coherent Scattering gives exact measurement (after phase retrieval) of electron density


Goal:
Characterize the radiation from tapered hard X-ray FELs and determine its applicability in future coherent X-ray diffraction imaging experiments
Presentation Outline

Motivation

Radiation Properties

What is the physical system we studied? How are the optimal taper profiles obtained?

How does the radiation profile evolve in the tapered X-FELs?

What are the coherence properties and mode structure of the radiation?

Conclusion & Future Work
Self-Seeding + Tapering = TW + Longitudinal Coherence

Gaussian Seed

\[ P_{rad,0} = 5 MW \]

Taper profile

\[ a_w(z) = a_w(z_0)(1 - c \times (z - z_0)^d) \]

Optimization performed over \( z_0, c, d \) using GENESIS for maximum output power

Typical values:

- \( z_0 < L_{sat} \)
- \( d \sim 2 \)
- Taper strength \( \sim 10\text{-}20\% \)

\[ P_{rad} > 1 \text{TW} \]

\[ \eta > 2\% \]

\[ P_{beam} = 50 \text{TW} \]

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Optimized Tapering Simulations: Transverse Effects

Detrapping -> Reduced Guiding -> Increased Diffraction

\[ n = 1 + \frac{\omega_{p,0}^2 r_{b,0}^2 a_w}{\omega_s^2 r_b^2} \frac{2|a_s|}{|J|} \langle e^{-i\Psi} \rangle \]

Longitudinal Effects
Spectral Profile and Sideband instability

Electron detrapping & sideband growth causes saturation in output power of tapered TW X-FEL
Transverse Coherence of tapered X-FELs

\[ \Gamma_{12}(\tau) = \left\langle \vec{E}(\vec{r}_1, t + \tau) \vec{E}^*(\vec{r}_2, t) \right\rangle \]

\[ J_{12} \equiv \Gamma_{12}(0) \]

\[ \mu_{12} = \frac{J_{12}}{\sqrt{J_{11}J_{22}}} \]

Modulus of complex coherence factor at undulator exit (z=200m) for NCU LCLS-II parameters

Gaussian

Parabolic

Uniform
Coherence area >> Radiation spot size

\[ A_{coh} = \int \mu_1 dA > \pi \sigma_r^2 \]

Transverse electron distribution

- Gaussian
- Parabolic
- Uniform
What is the mode structure of tapered X-FELs?

Electric Field expansion in complete set of Laguerre-Gaussian Modes

Higher order mode structure in radiation field

\[ E(r) = \sum_{n=0}^{\infty} a_n e^{-\xi r^2/2} L_n (R(\xi)r^2) \]

\[ a_n = \int_0^{\infty} E(r) L_n(\Re[\xi]r^2)e^{-\xi^* r^2/2} d(L_n(\Re[\xi]r^2)) \]
Structures washed out by diffraction and FEL interaction post-saturation
More than 90% of power in fundamental mode indicates very good transverse coherence.
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<tr>
<td>Undulator Period $\lambda_w$</td>
<td>19 mm</td>
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<tr>
<td>Normalised Undulator Parameter $a_w$</td>
<td>2.44</td>
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<tr>
<td>Radiation Wavelength $\lambda_r$</td>
<td>3.24 Å</td>
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\[ A_{coh} = \int \mu_{12} dA >> \pi \sigma_r^2 \]
Presentation Outline

Motivation

Radiation Properties

Conclusion & Future Work

What have we learned from this study?
Conclusions & Future Work

- X-ray FELs in the TW power region are required to push the frontiers of bio-imaging
- Tapering + Self-seeding is a promising strategy for achieving TW power levels with good longitudinal coherence
- The radiation properties and transverse coherence of tapered X-FELs has been analysed and we determined it sufficient for coherent X-ray diffraction applications
- Start to end simulations of optimised tapered X-FELs at TW power levels
- Analytical studies of particle detrapping and its relation to taper strength in TW tapered X-FELs
Acknowledgments

The authors would like to thank Dr. S. Reiche for useful advice and reference to past work on the subject of transverse coherence in an X-FEL.
References

2. J. Wu, Workshop on advanced X-ray FEL development, DESY May 2014
8. S. Reiche and B. Pedrini, Coherence Properties of Swissfel, PSI
Longitudinal Effects
Spectral Profile and Sideband instability

\[ \frac{P_{\text{sideband}, \text{max}}}{P_{\text{peak}}} \sim 0.3\% - 1\% \]

Sideband Intensity reduced for flatter transverse electron distribution

\[ \int_{\text{sidebands}} P(\lambda) d\lambda = \begin{cases} 
1 & \text{Gaussian} \\
0.4 & \text{Parabolic} \\
0.3 & \text{Uniform}
\end{cases} \]
Mode Decomposition Calculations

**Output E field from GENESIS and compute coefficients for different $\zeta$**

Choose $\zeta$ such that fundamental mode dominates FEL interaction i.e. minimises $\kappa$

$$\kappa = \sum_{n=1}^{\infty} \frac{|a_n|}{|a_0|}$$

$$a_n = \sum_{m_1} \sum_{m_2} \tilde{E}(\Delta x m_1, \Delta y m_2) \exp \left( \frac{-\zeta}{2} r^2 \right)$$

$$L_n (R(\zeta)r^2) R(\zeta) \Delta x \Delta y,$$

**Fig. 2. $\kappa$ varies with $R(\zeta)$**