A Concept for z-Dependent Microbunching Measurements of Electron Beams with CXTR

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OUTLINE

• Introduction

• Experimental Background
  - Optical Transition Radiation (OTR)
  - Coherent effects (COTR)
  - X-ray Transition Radiation (XTR)
  - Coherent microbunching effects (CXTR) in LCLS

• Experimental results in the UV-Visible regime

• Proposed applications of XTR and CXTR in LCLS

• Summary
Introduction

• Characterization of particle-beam properties in accelerators and transport lines is often important to the experiment’s success. This is particularly true of SASE FELs where intraundulator measurements are critical.

• A number of SASE experiments have been done in the UV-visible regime using z-dependent measurements of SASE and the electron beam microbunching via COTR at APS.

• However, the Jan.04 LCLS workshop identified a number of challenges in performing z-dependent, intra-undulator evaluations of SASE in the presence of spontaneous radiation and x-ray power absorption issues.

• We discuss the first use of COTR interferometric (COTRI) measurements and the preliminary extension of the model to the x-ray regime and the potential use for LCLS.
Strategy

• Convert the electron beam information to OTR or XTR. Thin Carbon foils should survive the x-ray power at 1.5 Angstroms.

• Coherence factors are involved for wavelengths longer than the bunch length or for micro-bunched beams (such as in a SASE FEL) at the fundamental. The COTR or CXTR provides a sensitive link to the basic SASE FEL process.

• In LCLS would need to use x-ray diagnostics techniques.
Optical Transition Radiation Patterns

a.) NORMAL INCIDENCE

b.) OBLIQUE INCIDENCE ($\phi = 45^\circ$)

CHERENKOV RADIATION PATTERN ($\theta \sim 46^\circ$)

$\beta n \sim 1.5$

$\theta \sim 46^\circ$

$\beta \sim 0.99$
Coherent Optical Transition Radiation Interferometry Calculations

Coherent Spectral-Angular Distribution from a Macropulse,

- Number of Photons per Unit Frequency and Solid Angle

\[
\frac{d^2 N}{d\omega d\Omega} = \left| r_{\perp,\parallel} \right|^2 \frac{d^2 N_1}{d\omega d\Omega} I(k) \bar{\Omega}(k)
\]

Single Particle OTR Spectral-Angular Distribution

\[
\frac{d^2 N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \left( \theta_x^2 + \theta_y^2 \right) \left( \gamma^{-2} + \theta_x^2 + \theta_y^2 \right)^2
\]

From D. Rule and A. Lumpkin, PAC’01

\[ E = 220 \text{ MeV} \quad \sigma_{x', y'} = 0.2 \text{ mrad} \]
Wartski Interferometer Phase Term

\[ I(k) = 4 \sin^2 \left( \frac{kL}{4} \left( \gamma^{-2} + \theta_x^2 + \theta_y^2 \right) \right) \]

\[ L = \text{foil separation distance} \]

\[ k_x = k \sin \theta \cos \phi = k \sin \theta_x \approx k \theta_x \]
\[ k_y = k \sin \theta \sin \phi = k \sin \theta_y \approx k \theta_y \]
\[ k_z = k \cos \theta \approx k = \omega / c \]

\[ \theta^2 = \theta_x^2 + \theta_y^2 \ll 1 \]

E = 220 MeV, \( \sigma_x, y = 0.2 \text{ mrad} \)
L = 6.3 cm, \( \lambda = 537 \text{ nm} \)

From D. Rule and A. Lumpkin, PAC’01
COTRI Calculations (cont.)

Coherence Function

$$\mathcal{Z}(k) = N + N_B \left( N_B - 1 \right) |H(k)|^2$$

Fourier Transform of Charge Form Factors

$$H(k) = \frac{\rho(k)}{Q} = g_x(k_x)g_y(k_y)F_z(k_z)$$

Q = total charge of macropulse

Bunching fraction = $$f_B = \frac{N_B}{N}$$

Note: The coherence function reduces to just the number of particles, N, when the number of microbunched particles, $$N_B$$, is zero.

From D. Rule and A. Lumpkin, PAC’01
COTRI Calculations, (cont.)

Transverse Form Factors

\[ g_i(k_i) = \frac{1}{\sqrt{2\pi}} e^{-\sigma_i^2 k_i^2 / 2} \quad i=x,y \]

Longitudinal Form Factor for Train of \( M+1 \) Micropulses

\[ \widetilde{F}(k_z) = f(k_z) \sum_{m=0}^{M} e^{-ik_z m \ell} = f(k_z) \frac{\sin(Mk_z \ell / 2)}{\sin(k_z \ell / 2)} \]

Longitudinal Form Factor for Individual Microbunch

\[ f(k_z) = \frac{1}{\sqrt{2\pi}} e^{-\sigma_z^2 k_z^2 / 2} \]

From D. Rule and A. Lumpkin, PAC’01
COTRI Fringe patterns show clear beam size sensitivity

\[ E = 220 \, \text{MeV} \]
\[ \sigma_{x',y'} = 0.2 \, \text{mrad} \]
Comparison of Images with OTR and COTR Shows Effective Core
SASE Saturation Regime Attained First in Visible Light Regime

Figure 2

Radiated Energy (a.u.)

Distance Traversed in Undulator (m)
Extensive COTRI Vertical Fringe Pattern Seen in Saturation Regime
COTRI Analytical Model Directly Compared to Data for the First Time

Y Profile, Image #12425 03/10/01
cotri57.spw, y-rms=20 and 25 micron, B.F.=1%

Experiment
Calculation
COTRI Image symmetry Guides Electron-beam Steering at Undulator 8 for Improved Gain (09-01-02)
## Comparisons of Images

Table 1. Comparison of integrated image intensities obtained before and after the COTRI-guided steering for VLD-8.

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Before (DS#3) Intensity Units $10^5$</th>
<th>After (DS#4) Intensity Units $10^5$</th>
<th>Ratio After/Before</th>
</tr>
</thead>
<tbody>
<tr>
<td>SASE</td>
<td>$2.61 \times 10^5$</td>
<td>$9.56 \times 10^5$</td>
<td>3.7</td>
</tr>
<tr>
<td>COTR</td>
<td>$2.41 \times 10^2$</td>
<td>$6.78 \times 10^2$</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The 50th-percentile integrated intensities are used.
LCLS Undulator Hall Schematic

Distances, rounded to the nearest meter, are given as from downstream side of the concrete wall on the west end of the research yard. This differs from Jacobs reference (upstream side of wall) by about 1 m. Zero is 287.052 m from Station 100 in LCLS coordinate system.

Changes from 3/16/04 version:

Treaty flange locations are shown. Toroid moved to other side of treaty flange.
Dump line and Muon shielding moved 8 m upstream.
DRAFT LONG BREAK
ASSEMBLY SCHEMATIC
(NOT TO SCALE)
Schematic of Sources in LCLS Undulator Line

14-GeV e beam
SASE (1.5 Å)
SER (1.5 Å)

Thin Foil or Foil Stack

XTR (1.5 Å)\textsubscript{1,2}

\[ \theta = \frac{1}{\gamma} = 35 \text{ µrad} \]

L = 24 m

YAG: Ce Converter
(x-rays to visible light)

Detector

Lens

Annular Crystal

850 µm
XTR at 8 keV would be generated by 14-GeV electrons

- From J.D. Jackson’s Classical Electrodynamics, 2nd edition, p.692:

![Diagram of Classical Electrodynamics](image-url)
GINGER Simulations for LCLS predict z-dependent gain and microbunching
Microbunching Spectral Bandwidth Narrows by $z=18.5$ m
GINGER predicts SASE Radiation bandwidth and intensity profile at z=42.8 m
Preliminary CXTR modeling shows Bunching Fraction effects at angles within the XTR cone

- Assuming there are ~500 microbunches in a coherence length, the XTR would be multiplied by 500 and the CXTR by 500².
Possible XTR experiment at SPPS

- **IP** Interaction Point
  - Focusing element
  - Defocusing element
- **SPPS Source**
  - \( E \text{ (keV)} = 9.1 \) with 28 GeV electrons
  - Intensity = \( 10^7 \) photons/pulse with \( Q = 3\text{nC} \)
Proposed XTR experiments at SPPS to establish signal strengths

• Initial experiments with 28-GeV e beam would use the existing infrastructure of OTR stations, monochromator, and x-ray transport as feasible.
• SPPS x-rays would be used as reference in detectors.
• Propose convert x-ray energy to visible light with YAG:Ce converter and use MCP/PMT or ICCD detection.
• Evaluate use of existing SPPS x-ray detectors.
• Would need to open the wiggler gap to turn off SPPS x rays at some point, test signal with Ti foil in and out.
• Scan e-beam angle while tracking XTR intensity.
• Future experiments with prototype intra-undulator diagnostic chamber would be suggested if tests are successful.
• Test of a foil stack is warranted.
Summary

Electron-beam diagnostic techniques based on COTR/CXTR provide a unique, direct link to the SASE FEL process of microbunching that some conventional techniques lack.

- The overlap of the electron and photon beams is a key aspect of achieving gain.
- For UV-visible SASE FELs, we have now demonstrated a novel, on-line technique for fine-tuning the angular alignment of the two beams using the COTRI patterns.
- For x-ray SASE FELs, we are just beginning the feasibility studies for applying XTR and CXTR techniques. Separation of the sources using angular and spectral effects will be the keys.
- A systematic application of the techniques should lead to gain optimization.
- An analytical model has been directly compared to COTRI data for the first time, and a preliminary extension to the x-ray regime done. Further modeling and experimental efforts are needed.
Beam Intraundulator Alignment Options

- Physical survey of the quadrupole magnets and undulator mechanical centerline. Magnetic field centerlines can be different.

- Use reference fiducials at each diagnostic chamber, e.g., holey mirror for survey.

- Alignment laser beam injected into chamber bore and centered on fiducials at each end.

- RF BPM mechanical positions and offsets determined. This can be e-beam based, but no direct tie to SASE photon beam.

- Tune on SASE gain intensity, station by station. Fluctuations and saturation are complications. Reference beam positions in cameras.

- Tune on COTR or CXTR which are coupled to the SASE FEL process. Improve overlap of the electron and photon beams.
Schematic of Sources within Undulator Vacuum Chamber

- Thin Foil or Foil Stack
- XTR (1.5 Å)₁,₂
- Annular Crystal
- Detector
- Lens
- YAG: Ce Converter (x-rays to visible light)
- 14-GeV e beam
- SASE (1.5 Å)
- SER (1.5 Å)
- θ = 1/γ = 35 μrad
- 850 μm
- L = 24 m
Coherent OTRI Inner Lobes Have Sensitivities to Beam Size

\[ E = 220 \text{ MeV} \]
\[ \sigma_x' = 0.2 \text{ mrad} \]
Optical Ray Diagram for OTR Imaging
COTRI Analytical Model Matched to VUV Data Including Gaussian Shape Assumption

X Profile, VUV6, 157nm, Image #332, 03/07/03
Profile thru center
9/23/03

exp. data
50 µm - 50 µm
50 µm - 25 µm
40 µm - 25 µm
45 µm - 25 µm
43 µm - 25 µm

θx (mrad)

Intensity (arb. units)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

-3 -2 -1 0 1 2 3
Symmetric Gaussian Beam Form Factor

![Graph showing the Symmetric Gaussian Beam Form Factor with curves for 25 µm, 50 µm, and 100 µm. The y-axis represents the Coherence Factor / Ne, and the x-axis represents the Angle (radians).]
Strategy

Convert particle-beam information to optical radiation and take advantage of imaging technology, video digitizers, and image processing programs. Some reasons for using OTR are listed below:

• The charged-particle beam will transit thin metal foils to minimize beam scattering and Bremsstrahlung production.

• These techniques provide information on
  - Transverse position
  - Transverse profile
  - Divergence and beam trajectory angle
Coherent OTRI Fringe Intensities are Sensitive to Beam Size

E = 220 MeV
\( \sigma_{x'} = 0.2 \text{ mrad} \)
Schematic Layout for APS Accelerators

Layout of Nonintercepting Beam Diagnostics in the APS

- Storage Ring (7 GeV, 1104 m circumference)
  - 360 BPMs
  - 1 DOCT, 1 PCM
  - 1 BM/(OSR + XSR) Port
  - 1 Undulator Radiation (UR)
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- Injector Synchrotron (0.32–7 GeV, 368 m circumference)
  - 80 BPMs
  - 1 PCM
  - 3 Optical Synchrotron Radiation (OSR) ports
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- Accumulator Ring (325 MeV)
  - 16 BPMs
  - 2 PCMs
  - 2 OSR Ports
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- Low Energy Undulator Test Line (LEUTL)
  - 8 BPMs
  - 1 PCM
  - 1 Loss Monitor

- Low Energy Transport 2
  - 8 BPMs
  - 1 PCM
  - 1 Loss Monitor

- Low Energy Transport 1
  - 8 BPMs
  - 1 PCM
  - 1 Loss Monitor

- Beam Dump
- High Energy Transport
  - 12 BPMs
  - 1 PCM
  - 1 Loss Monitor
  - 1 ODR Monitor (proposed)

- Linear Accelerator
  - 1-4 OSR ports

- rf Gun
Schematic of APS SASE FEL Experiment
Intraundulator Diagnostics Stations Used to Track Evolution of Microbunching and SASE.
Schematic of the VUV-visible Intraundulator Station

- Near and Far Field Focus Mirrors
- Stationary Mirror
- Nd Band Pass Filters
- Diagnostic Chamber
- VUV CCD Imager
- Undulator
- Retractable Mirror
- YAG Crystal/OTR Foil/Finhole
- Button BPMs
- Quad X-Y Corrector