Observation of Coherent OTR at LCLS

Unexpected Physics in Standard Beam Diagnostics
Outline

- Introduction into LCLS Injector
- Coherent OTR Observations
- Analysis and Interpretations
- Plans
LCLS Injector Layout

6 MeV

RF Gun
Gun Solenoid
Gun Spectrometer
Emittance Screens/Wires
RF Deflector

135 MeV

σ_z ≈ 1 mm

250 MeV

σ_z ≈ 0.2 mm

OTR screens (7)
YAG screens (7)
Wire scanners (7)
Dipole magnets (8)
Beam stoppers (2)
S-band RF acc. sections (5)

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OTR Diagnostics

- **OTR screen**
  - Aluminum foil
  - Thickness 100um
  - Angle at 45 degrees to beam

- **Imaging optics package**
  - Telecentric lens, F2.8
  - 100 line pairs/mm
  - Typical magnification up to 1:2.5
  - Two neutral density filters with OD0.5 and OD1
  - Beam splitter and reticle for in situ calibration

- **CCD camera**
  - Megapixel CCD
  - Digital with 12bit depth
  - Pixel size 4.65µm
  - Linear response within digitizing range
  - Sensitive between 350nm and 1um
COTR Observations I: Fluctuating Shapes

OTR12, downstream of BC1

Shot to shot samples, 300pC, max compression w/ L1S & L1X
COTR Observations II: Bunch Compression

BLEN Monitors

300 GHz

100 GHz

OTR

L1S Phase

350pC, max compression

Wire Profile

σ = 300μm

OTR Profiles

400μm
COTR Observations III: Charge Dependency

nom. compression w/ L1S & L1X

OTR

Incoherent OTR

OTR saturates

Incoherent OTR

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Theory Group Meeting
COTR Observations IV: Micro-Bunching

Incoherent Level

Intensity peaks

1 nC, no compression, BC1 off, scan quad in DL1

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Theory Group Meeting
COTR Observations Summary

- OTR light increases by orders of magnitude when bunch is compressed
- At high compression, transverse shape appears to fluctuate significantly
- At highest compression, ring shaped light distribution occurs
- OTR light has quadratic dependency on charge at lower charge
- Quadratic dependency saturates at high charge
- Uncompressed beam shows coherence and apparent size change after DL1 depending on $R_{56}$
- OTR is not a reliable diagnostic under certain conditions. Is expected to be worse for even shorter bunches after BC2
Optical Transition Radiation

Transition radiation is scattering of virtual photons off boundary to generate real photons.

Source of radiation is Coulomb field
- Temporal and spatial frequency components
  \[ E(\vec{k}) \propto \frac{\vec{k}_\perp}{k^2 / \gamma^2 + k^2_{\perp}} \]

Diffraction and imaging with optical system
- Angular acceptance of system \( \theta_0 \)
  \[ E(\vec{r}_\perp) \propto \int_{0}^{k \sin \theta_0} k_{\perp} dk_{\perp} J_1(k_{\perp} r_{\perp}) \frac{k_{\perp}}{k^2 / \gamma^2 + k^2_{\perp}} \]

Effective source distribution
\[ E(\vec{r}_\perp) \propto \frac{\vec{e}_{\perp}}{r_{\perp}} [1 - J_0(r_{\perp} k \sin \theta_0)] \frac{r_{\perp} k}{\gamma} K_1\left(\frac{r_{\perp} k}{\gamma}\right) \]

Camera Image Calculation
- Lens images field distribution from target to CCD
- CCD measures field intensity

Incoherent light
- Convolute source intensity with beam distribution

Coherent light
- Convolute source field with beam distribution
Diffraction Limited Source Distribution

\[ r \left( \mu m \right) \]

\[ \theta_0 = \pi / 2 \]
\[ \theta_0 = 0.1 \]

\[ \gamma = 500 \]
\[ \lambda = 1 \mu m \]
COTR from Electron Bunch

- Source field spectral distribution

\[ \tilde{E}(\vec{\kappa}) = \frac{iq}{2\pi^2\nu} \frac{\vec{\kappa}}{(k/\gamma)^2 + \kappa^2} \]

- Field on screen is convolution of source field with lens diffraction pattern

\[ \tilde{E}_s(\vec{r}) = \int_0^{kd/z_L} d^2\kappa e^{i\vec{\kappa}\cdot\vec{r}} \tilde{E}(\vec{\kappa}) \]

- Field of N radiating particles

\[ \tilde{E}_N(\vec{\kappa}) = \sum_j e^{ikz_j + i\vec{\kappa}\cdot\vec{r}_j} \tilde{E}(\vec{\kappa}) \]

- Radiation intensity for frequency k

\[
S(\vec{r}) \propto |E_N(\vec{r})|^2 = N \int d^2r'dz \rho(\vec{r}' - \vec{r}, z) |E(\vec{r}')|^2 \\
+ N(N-1) \int d^2r'dez' e^{ikz} \rho(\vec{r}' - \vec{r}, z) |E(\vec{r}')|^2
\]
Coherent OTR Imaging

- Intensity of coherent part for fully coherent beam
  \[ \tilde{E}_N(\vec{r}) = \int_0^{kd/\gamma} d^2 \kappa e^{i\vec{\kappa}\cdot\vec{r}} \rho(\vec{\kappa}) \frac{iq}{2\pi^2 v} \frac{\kappa}{(k/\gamma)^2 + \kappa^2} \]
- Assume Gaussian charge distribution
  \[ \rho(\vec{\kappa}) = e^{-\kappa^2 \sigma^2 / 2} \]
- If \( \sigma > \gamma/k \), beam larger than source size
  \[ \tilde{E}_N(\vec{r}) = \int_0^{kd/\gamma} d^2 \kappa e^{i\vec{\kappa}\cdot\vec{r}} \rho(\vec{\kappa}) \frac{q \gamma^2}{2\pi^2 v k^2 i\vec{\kappa}} \]
- This gives the field as the gradient of the charge distribution
  \[ \tilde{E}_N(\vec{r}) = \frac{q \gamma^2}{2\pi^2 v k^2} \nabla \rho(\vec{r}) \]

- Beam size « \( \gamma \lambda \)
  - Image is OTR source distribution
- Beam size » \( \gamma \lambda \)
  - Image is gradient of beam distribution
Horizontal Polarization Component of Source

\( y = 500 \)
\( \lambda = 1 \mu m \)
\( \theta = 0.1 \text{ rad} \)
Convolution of Source with Beam

- Radial Polarization of TR Source
- Horizontal Polarization of TR Source
- Transverse Distribution of Electron Beam
- COTR Distribution of Electron Beam

\[ \gamma = 500 \quad \lambda = 1 \mu m \]
\[ \sigma = 200 \mu m \]
Image on OTR12

- Measured image
- Light intensity 30x above incoherent level

Simulation
- Source acts like gradient operator
- Creates doughnut shape

COTR Distribution of Electron Beam

σ = 200μm
Max. Compressed Bunch Form Factor

Initial 6keV, 0.8mm

Energy spread (MeV)

-10  -5  0  5  10
-20  -10  0  10

Form factor

Counts

-10  -5  0  5  10
0  5  10

10⁵ Particles

Initial 3keV, 0.8mm

Energy spread (MeV)

-10  -5  0  5  10
-20  -10  0  10

Form factor

Counts

-10  -5  0  5  10
0  5  10

10⁶ Particles

6 10⁹ Particles
Observed Intensity Estimation

- Observed factor 30 enhancement
- Fully coherent 2 \(10^9\) enhancement
- Beam size effect 2 \(10^3\) suppression
- Long. form factor \(10^4 - 10^7\) suppression

\[10^4 \cdot 10^3 \cdot 10^2 = 10^9\]
COTR Charge Dependency

COTR saturates
COTR \sim N^2
Incoherent OTR \sim N

Quadratic dependency for small charge
Micro-Bunching Simulation

- Start w/ energy modulation in injector
- R56 of DL1 generates temporal modulation
- Simulation
  - Modulate beam at 1μm
  - x-z tilt on OTR12
  - Calculate reduction in modulation when QB changes
  - Neglect energy spread
  - Use full beam and transverse core of beam

Phase space x-z

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Bunching Factor vs. QB

Modulation 1um

10% Core Beam

100% Beam

Measured
Issues

- In most cases, coherent effect only visible in increase in light output
- No significant change in beam shape noticeable
- COTR from fully transverse coherent beam should give ring structure
- COTR from small coherent transverse fraction of beam should give spike
- Needs many coherent small parts of beam radiating at different wavelengths to explain still Gaussian beam shapes
Future Plans

- Measure spectrum of coherence light
  - Grating for spectrally resolved OTR profiles at visible wavelengths
  - UV and IR diode with filters for range beyond visible
  - Color CCD?

- Measure polarization of COTR
  - Polarization dependence of transverse distribution can indicate transverse coherence
  - Add radial to linear polarization transformer?
Transmission Grating Spectrometer

- Modifications of present setup
  - Add grating in one of the filter slots
  - Use transmitted light through beam splitter
- Grating diffraction in first order
  - \( x_S = x_0 - L_G \frac{\lambda}{d} \)
- Transmission grating in front of lens
  - Distance foil – grating: \( L_G = 130 \text{mm} \)
  - Grating frequency: \( g = \frac{1}{d} = 100/\text{mm} \)
  - Max wavelength: \( \lambda = 800 \text{nm} \)
- Spectral resolution
  - \( \Delta \lambda = \frac{d \lambda}{dx_S} 3\sigma = 3\sigma gL_G \)
  - \( \Delta \lambda = 100 \text{nm} (\sigma = 300 \text{um}) \)
  - \( \Delta \lambda = 20 \text{nm} (\sigma = 60 \text{um}) \)
LCLS Commissioning Team

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