Ultrafast Compton Scattering X-Ray Source Development at LLNL


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- Introduction, Motivation & Background
- Experimental Setup: Laser & E-Beam
- Experimental Results
- Dynamic Diffraction
- Nonlinear Regime
Currently, No Bright Sources > 50 keV, < 50 ps

- 3\textsuperscript{rd}-Generation: < 50 keV, > 50 ps
- LCLS: max. energy 24 keV
- K-\(\alpha\): energy limit \(\sim\) 100 keV, \(4\pi\)

- PLEIADES: has already established record brightness at 140 keV
Compton Scattering X-Ray Source

High-Brightness RF Gun

TW-Class CPA Laser

High-Gradient Linac

\[ \omega_x \cong \frac{\omega_0}{\left(1 + \frac{A_0^2}{1 + \frac{\gamma - u \cos \theta}{\gamma - u \cos \phi}} \right)^2} \]

Diagram showing scattering angles and polarization vectors.

Frame Parameters:
- x: +/- 100 μm
- y: +/- 100 μm
- z: +/- 1.2 mm +/- 4 ps

Animation/Simulation by Fred V. Hartemann & Winthrop J. Brown
PLEIADES Modeling Capabilities

Step 1: PARMELA-SUPERFISH Design

Step 2: Phase Space

Step 3: 3D X-Ray Simulations
FALCON Laser Overview

Pulse Duration

GRENOMILL Traces

| Measured | Retrieved |

\[ \Delta t = 54 \text{ fs} \]

Ti:Al\textsubscript{2}O\textsubscript{3} OPCPA Hybrid
800 nm
500 mJ (compressed)
50 fs FTL
20 \( \mu \)m FWHM (M\textsuperscript{2} \sim 1.4)
10 Hz
PLEIADES Electron Bunch Measurements

\[ \langle q \rangle = 266 \text{ pC} \]

\[ \epsilon_x = 5 \text{ mm mrad} \]

\[ \epsilon_y = 13 \text{ mm mrad} \]
PLEIADES Electron Bunch Measurements

Energy Spectrometer

- \( E = 59.2 \text{ MeV} \)
- \( \sigma_E = 0.2 \% \)

Beam Spot At Interaction

- \( \sigma_x = 14 \mu\text{m} \)
- \( \sigma_y = 20 \mu\text{m} \)
- 2 mm (1.0 %)

- 14 x 20 \( \mu\text{m}^2 \)
Note that x-rays propagate through BK7 folding mirror.
First Light: 200 ms X-Ray CCD Capture
• BK7 flat (800 nm fold mirror) attenuates x-rays according to their energies (higher att. at low energy)
• Angular correlation between scattering angle & energy results in narrowing of the angular distribution

X-Ray energy distribution is given by:

\[ L(\theta) \sim \frac{1}{1 + (\gamma \theta)^2}^3 \]
• However, emittance and 3D focusing broaden angular distribution:

\[ \frac{1}{\gamma} \sqrt{1 + \left( \frac{\varepsilon_n}{\sigma} \right)^2} \]

• All these effects must be accounted for to match data
X-Ray Dose per Shot: > 2 \times 10^7
Red: experimentally measured data

Blue: theoretical Lorentzian profile for Gaussian pulses, using the measured laser parameters

The asymmetry reflects the fact that the electron beam current is higher at the tail than at the front: for positive delays, the bunch tail is closer to the focus where the highest photon density is reached.
On-Axis Spectral Brightness

$n$ foils

X-Ray CCD

Integrated Transmission

Number of Al Foils

Photon Energy (keV)

CCD Spectral Density (a.u.)

$>10^{16}$ ph./s/mm$^2$/mrad$^2$/0.1%bw
Radiography and Tunability

0.005” Tantalum foil; K-edge @ 67.46 keV
U K-Edge 115.6 keV

73.5 MeV, 15 mil

800 x 800 pixels

71.5 MeV, 15 mil

800 x 800 pixels

73.5 MeV, 33 mil

800 x 800 pixels

71.5 MeV, 33 mil

800 x 800 pixels
Dynamic Diffraction Experimental Setup

Gated X-Ray MCP/ICCD

Sample

Pump Laser Delay Line

X-Ray Probe
HOPG Static Diffraction

Main Beam  Diffracted Beam

$2 \times \theta_{\text{Bragg}}$

Rocking Curve ($\circ$) at Cu $K_{\alpha}$

Diffraction Efficiency

Diffraction Angle $\text{asin}(\lambda/2d)$ ($\circ$)

Static Diffraction from HOPG
High-Contrast Dynamic Diffraction

Au(111)

XCCD

IR Pump Beam

Sn Filter

Diffraction Angle +/- 2.5 mrad

Background-Free Region

Ultrafast (Non-Thermal) Melting: Fluence 5-20 mJ/cm²

Gaussian Shape is Due to Pump Laser Illumination on Crystal

Edge Shift is a Direct Measurement of 2d-Spacing

Au from Room Temperature to Melting: 1.5% Increase of 2d
K-Edge Tagging: 250 µm Sn

By using K-edge tagging, one can considerably improved the data collection technique used by LBNL on InSn
Darwin Curve Au (111)
\[
\theta > \theta_{\text{Bragg}}, \lambda > \lambda_{\text{Sn}}
\]

\[
hc / e\lambda_{\text{Sn}} = 29.2001 \text{ keV}
\]

\[
2d_{\text{Au}(111)} = 4.7092 \text{ Å}
\]

\[
2d \sin \theta = \lambda
\]
Au (111) High-Contrast Dynamic Diffraction

Au from Room Temperature to Melting: 1.5% Increase of 2d-Spacing

Ultrafast (Non-Thermal) Melting: Fluence 5-20 mJ/cm²

Gaussian Shape is Due to Pump Laser Illumination on Crystal

Edge Shift is a Direct Measurement of 2d-Spacing
Pushing Toward $\mu$m, fs/as Beams

$> 500$ T/m

$14 \times 20\ \mu m^2$

Compressed Beam Pulse Length Measurement

$\sigma < 0.3$ psec

700 attoseconds (after 1' wiggler!)

Attosecond X-ray strobe light
Linear & Nonlinear Compton Scattering

\[ A_0 = \frac{eE}{\omega m_0 c} \iff K = \frac{eB_w}{m_0 k_w c} \quad < 10^{17} \text{ W/cm}^2 \]

Analogy: Strong Wiggler Field
X-Ray Harmonic Production

\[ E \propto A_0 \rightarrow v_\perp \approx c \]

\[ B \propto A_0 \rightarrow F_\perp \propto v_\perp \times B \propto A_0^2 \]

X-Ray Spectrum (a.u.)

Normalized Doppler-Shifted Frequency

Normalized Doppler-Shifted Frequency
Linear & Nonlinear Compton Scattering
3D NL Code: Linear Polarization

\[ \theta_x = \theta_y = 0 \quad \text{w}_0 = 30 \ \mu\text{m} \]
\[ \Delta t = 10 \ \text{fs} \quad \text{30 MeV} \]
\[ A_0 = 0 - 2 \quad \frac{\omega_x}{4\gamma_0^2} = 0 - 2 \]
NL Compton Scattering: Off-Axis Spectrum

\[ A_0 = 1 \]
\[ w_0 = 30 \text{ \(\mu\)m} \]
\[ \Delta t = 10 \text{ fs} \]
\[ 30 \text{ MeV} \]
\[ \theta_x = 0 - 20 \text{ mrad, // polarization (right)} \]
\[ \theta_y = 0 - 20 \text{ mrad, \ perpendicular polarization (left)} \]
\[ \frac{\hbar \omega_x}{4 \gamma_0^2 \hbar \omega_0} = 0 - 2 \]
3D NL Code: Circular Polarization
Spectral Control: Laser pulse Shaping

Approach:

1) Circular Polarization, to Eliminate High Harmonics

2) Temporal Pulse Shaping, to Eliminate “Transient” Lines (Dazzler)

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*Sinc* Phase & Amplitude Mask

Laser Phase

Short-pulse oscillator

Initial short pulse

2,000 picoseconds

Power amplifiers

Long, low-power pulse for amplification

2,000 picoseconds

High-energy pulse after amplification
High Brightness NL Compton Scattering

\[ \lambda_x = \frac{\lambda_w (1 + A_0^2)}{4\gamma^2} \] 
- Increase Laser Intensity
- Increase E-Beam Energy

\[ \frac{\varepsilon_n}{\gamma} \] 
Decreases: Much Smaller Spot Size

Circular Polarization, Gaussian
Circular Polarization, Square
Circular Polarization, Square
X-Ray Energy Fixed
Picosecond Positron Pulse Production at PLEIADES

Linac Beam at 150 MeV
FALCON at 3 \( \omega \), 10%
Pb Target

- \( 10^7 \) Above State-of-the-Art
- Time-Resolved Positron Annihilation Spectroscopy