Optimized Laser-Compton Light Sources for Nuclear Photonics

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Laser-Compton scattering off of high energy electrons can produce high energy photons.

Energy-momentum conservation yields $\sim 4\gamma^2$ upshift.

Thomson cross section is very small $\sim 6 \times 10^{-25}$ cm$^2$.

A photon flux of $1.7 \times 10^{24}$ ph/cm$^2$ @ 532 nm in a 100 micron spot = 44 J!
High-flux, Compton systems aim to produce high photon & electron densities at a common focus

At 250 MeV, scattered radiation is upshifted by \(~1,000,000\)x and is forwardly-directed, polarized, narrowband (0.1%) and laser-like (<mrad divergence)

US patent #8,068,522 Barty - Hyper-dispersion Chirped Pulse Amplification and Compression
Recirculation can give > 50x increase in Compton photon production for “free” and has ~10,000x less stringent requirements than resonant ‘cavity’ schemes.

Overall Compton scattering is broadband, but it is highly angle correlated and is ‘narrowband’ on axis.

\[ \Delta \Omega \approx \pi \left( \frac{1}{\gamma} \right)^2 \]

few mrad
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![Graph showing intensity versus normalized gamma-ray energy](image)
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\[ \Delta \Omega = \pi \left( \frac{1}{\gamma} \right)^2 \]

Few mrad

\[ \Delta \Omega = \pi \left( \frac{\varepsilon_n}{\gamma \Omega} \right)^2 \]

Few \( \mu \)rad

“Mono-Energetic Gamma-rays” - MEGa-rays
Many factors contribute to the minimum possible bandwidth*

\[ q = k \frac{\gamma - u \cos(\varepsilon + \varphi)}{\gamma - u \cos \varepsilon + (1 - \cos \varphi) \left\{ \frac{A^2}{\left[ \gamma - u \cos(\varepsilon + \varphi) \right]^2 + \kappa^2} \right\} } \]

- Laser Bandwidth
  \( \sim 10 \text{ ps} \)
  \[ \frac{\Delta q}{q} = \frac{\Delta k}{k} \quad \text{O}(10^{-4}) \]

- Laser Focal Spot
  \( \sim 10 \text{ microns} \)
  \[ \frac{\Delta q}{q} \approx \frac{1}{4} \Delta \varphi^2 \quad \text{O}(10^{-4}) \]

- Nonlinear Radiation Pressure
  \[ \frac{\Delta q}{q} \approx \frac{\Delta A^2}{1 + A^2} < 10^{-4} \]

- Electron Energy Spread
  \[ \frac{\Delta q}{q} \approx 2 \frac{\Delta \gamma}{\gamma} < 10^{-3} \]

- Electron Beam Emittance
  \[ \frac{\Delta q}{q} \approx -\gamma^2 \Delta \varepsilon^2 < 10^{-3} \]

* order-of-magnitude estimated contributions based on 2013 LLNL technology and optimized laser-Compton interaction geometry
Overall Compton scattering is broadband, but it is highly angle correlated and is ‘narrowband’ on axis.

\[ \Delta \Omega = \pi \left( \frac{1}{\gamma} \right)^2 \]

few mrad

\[ \Delta \Omega = \pi \left( \frac{\xi_n}{\gamma \Omega} \right)^2 \]

few \( \mu \)rad

Optimized laser-Compton sources can have fractional bandwidths of < \( 10^{-3} \) FWHM.
The characteristics of optimized laser-Compton gamma-ray sources enable “nuclear photonics”

- **Peak Brilliance** vs. **Photon Energy**
  - Log-log scale
  - **1-J Laser-Compton Source**
  - **APS** (Advanced Photon Source)
  - **>15 Orders of Magnitude**

- **Energy Levels**:
  - 10 keV to 10 MeV
  - 10^10 to 10^25 photons/sec/mm^2/mrad^2/0.1%BW

- **Labels**:
  - “atomic”
  - “nuclear”

- **Document**:
  - T-REX: Thomson-Radiated Extreme X-rays Moving X-Ray Science into the “Nuclear” Applications Space with Thompson Scattered Photons
  - C. P.J. Barty, F. V. Hartmann
  - September 27, 2004
The characteristics of optimized laser-Compton gamma-ray sources enable “nuclear photonics”
Gamma-ray absorption & radiation by the nucleus is an “isotope-specific” signature of the material.

Nuclear Resonance Fluorescence (NRF) is analogous to atomic resonance fluorescence but depends upon the number of protons AND the number of neutrons in the nucleus.
NRF transitions are common and many have cross sections larger than the atomic background.

Gammas in the 1 MeV to 3 MeV range are both highly penetrating and non-activating.
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Gammas in the 1 MeV to 3 MeV range are both highly penetrating and non-activating.
Potential NRF-enabled applications are numerous

- **HEU Grand Challenge**
  - detection of shielded material

- **Nuclear Fuel Assay**
  - 100 parts per million per isotope

- **Waste Imaging & Assay**
  - non-invasive content certification

- **Industrial NDE**
  - micron-scale & isotope specific

- **Medical Imaging**
  - low density & isotope specific

- **Dense Plasma Science**
  - isotope mass, position & velocity

US patent #7,564,241 C. P. J. Barty, F. V. Hartemann, D. McNabb & J. Pruet - detection, assay and imaging with laser-Compton gamma-rays
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US patent #7,564,241 C. P. J. Barty, F. V. Hartemann, D. McNabb & J. Pruet - detection, assay and imaging with laser-Compton gamma-rays
Laser-Compton gamma-rays could transform our ability to assay nuclear fuels and monitor nuclear waste
The primary research challenge and opportunity in characterization is nondestructive assay of plutonium and other isotopes in the high-radiation environment that is typical of most spent fuels...
Precision assay & imaging of nuclear fuel systems is possible with laser-Compton gamma-ray sources

Monte Carlo Simulations

**UO₂ fuel rod model**

- **Zircaloy-2 cladding**
  - (1.0 mm wall, $\rho = 6.84 \text{ gm/cc}$)

- **Nominal UO₂ fuel mix**
  - (3% U235, $\rho = 10.96 \text{ gm/cc}$)
Precision assay & imaging of nuclear fuel systems is possible with laser-Compton gamma-ray sources

Monte Carlo Simulations

Material Voids

- 0.125 mm crown erosion (void)
- 0.50 mm Ø gas bubble (void)
- 1.00 mm Ø gas bubble (void)
- 0.50 mm Ø gas bubble (void)
- Zircaloy-2 cladding (1.0 mm wall, ρ = 6.84 gm/cc)
- Nominal UO₂ fuel mix (3% U235, ρ = 10.96 gm/cc)

Precision assay & imaging of nuclear fuel systems is possible with laser-Compton gamma-ray sources

Monte Carlo Simulations

Density Defects

0.50 mm Ø density defect (80% nom ρ)

0.50 mm Ø density defect (40% nom ρ)

0.50 mm Ø density defect (60% nom ρ)

1.00 mm Ø density defect (20% nom ρ)

Zircaloy-2 cladding (1.0 mm wall, ρ = 6.84 gm/cc)

Nominal UO₂ fuel mix (3% U235, ρ = 10.96 gm/cc)

irregular density defect (10% nom ρ)
Precision assay & imaging of nuclear fuel systems is possible with laser-Compton gamma-ray sources

Monte Carlo Simulations

Isotopic Defects

- 0.50 mm $\Theta$ isotope defect (25% U235)
- Irregular isotope defect (0.2% U235)
- Irregular isotope defect (7.5% U235)
- 2.00 mm $\Theta$ isotope defect (5% U235)
- Zircaloy-2 cladding (1.0 mm wall, $\rho = 6.84$ gm/cc)
- Nominal UO$_2$ fuel mix (3% U235, $\rho = 10.96$ gm/cc)
- 1.00 mm $\Theta$ isotope defect (10% U235)

Conventional 2 MeV CT imaging reveals presence of void structures & density defects (as expected)

Monte Carlo Simulations

2 MeV Bremsstrahlung Image

- 0.50 mm Ø density defect (80% nom ρ)
- 0.50 mm Ø gas bubble (void)
- 1.00 mm Ø gas bubble (void)
- 0.125 mm crown erosion (void)
- 0.50 mm Ø density defect (40% nom ρ)
- 0.50 mm Ø density defect (60% nom ρ)
- 0.50 mm Ø gas bubble (voids)
- 1.00 mm Ø density defect (20% nom ρ)
- Zircaloy-2 cladding (1.0 mm wall, ρ = 6.84 gm/cc)
- Nominal UO₂ fuel mix (3% U235, ρ = 10.96 gm/cc)
- Irregular density defect (10% nom ρ)

Conventional 2 MeV CT imaging reveals nothing regarding isotopic inhomogeneities

Monte Carlo Simulations

2 MeV Bremsstrahlung Image

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- Nominal UO₂ fuel mix (3% U235, ρ = 10.96 gm/cc)
- 1.00 mm Ø isotope defect (10% U235)
Laser-Compton CT imaging via $^{235}$U resonance clearly reveals density AND isotopic defects

**Monte Carlo Simulations**

1.733 MeV NRF CT image reconstruction (on resonance)

- 0.50 mm $\varnothing$ isotope defect (25% U235)
- Irregular isotope defect (0.2% U235)
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Zircaloy-2 cladding
(1.0 mm wall, $\rho = 6.84$ gm/cc)

Using novel detection schemes, 80-ppm accuracy of the relative enrichment level is achievable with 95% confidence

The T-REX (Thomson-Radiated Extreme X-rays) project created LLNL’s 1st laser-Compton gamma-ray source.
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Ultra-low Emittance Photo-gun

Fully Symmetrized - 120 MV/m

The T-REX (Thomson-Radiated Extreme X-rays) project created LLNL’s 1st laser-Compton gamma-ray source.

Hyper-dispersion Pulse Compressor

Compresses 1-ns pulses in 1 m to 10 ps

The T-REX (Thomson-Radiated Extreme X-rays) project created LLNL’s 1st laser-Compton gamma-ray source.

- **Collimated & Polarized**
  - Beam profile: $6 \times 10 \text{ mrad}^2$

- **Tunable**
  - Tuned with e-beam energy

**Measured & predicted spectra**
- Narrow band peaked at 478 keV

**2008 World’s highest peak “Brilliance” at 0.5 MeV**

The T-REX (Thomson-Radiated Extreme X-rays) project created LLNL’s 1st laser-Compton gamma-ray source

Isotope-specific detection of low-density materials with laser-based monoenergetic gamma-rays


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478 keV excitation of $^7$Li

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Repetition rate < 10 Hz
Source Spectral Density ~13

“Detection” in 6 hours

478 keV excitation of $^7$Li
Source spectral density (SSD) determines the viability of many NRF-based applications

“Mono-energetic”
Gamma-ray Source

ΔE/E = 10^{-3}

keV-wide Laser-Compton spectrum

Object

Detector
Source spectral density (SSD) determines the viability of many NRF-based applications.
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“Mono-energetic” Gamma-ray Source

ΔE/E = 10^{-3}

keV-wide Laser-Compton spectrum

ΔE/E = 10^{-6}

Object

Detector

Signal
Source spectral density (SSD) determines the viability of many NRF-based applications.

“Mono-energetic” Gamma-ray Source → Object (Signal: $\Delta E/E = 10^{-3}$, Noise: $\Delta E/E = 10^{-6}$) → Detector

- keV-wide Laser-Compton spectrum

- Signal
- Noise
Source spectral density (SSD) determines the viability of many NRF-based applications

SNR $\propto$ (Flux on Resonance) / (Flux off Resonance)
Source spectral density (SSD) determines the viability of many NRF-based applications.

\[ \Delta E/E = 10^{-3} \]

\[ \Delta E/E = 10^{-6} \]

"Mono-energetic" Gamma-ray Source

Object

Detector

keV-wide Laser-Compton spectrum

\[ \text{SNR } \propto \frac{\text{(Photons/sec/eV)}}{(\text{Fractional Source Bandwidth})} \]
Source spectral density (SSD) determines the viability of many NRF-based applications. 

\[ \Delta \frac{E}{E} = 10^{-3} \]

"Mono-energetic" Gamma-ray Source

Object

Detector

keV-wide Laser-Compton spectrum

\[ \Delta \frac{E}{E} = 10^{-6} \]

Signal

Noise

SNR \( \propto \frac{(\text{Photons/ sec/ eV})}{(\text{Fractional Source Bandwidth})} \) = SSD
Simulations have determined the magnitude of SSD required for 3% assay sensitivity within ~ 5 minutes.

Monte Carlo simulations using COG

U235 Assay Sensitivity (% FSD) vs. Total Dwell Time
(conventional UO2 fuel rods (3.00% enrichment); 9.60E+09 photons/sec; ΔE/E = 0.0016)

3,462,200 = SSD
New applications become viable with increasing SSD

Isotope-Specific Assay
New applications become viable with increasing SSD

Specific Spectral Density (photons/sec/keV/FSB)

Inverse Fractional Source Bandwidth

- Line-width-resolved, nuclear spectroscopy
- Isotope-Specific Medical Radiography
- Isotope-Specific Tomography
- Isotope-Specific Assay
- Isotope Detection
- Gamma optics R&D
- PoP Detection
Many applications require one to take the source to the object and not vice versa.

\[ ^{235}\text{U} \text{ and } ^{239}\text{Pu} \text{ management requires 2-MeV-scale photons, SSD > 100,000 and 250 MeV accelerator technology that is truck size or smaller} \]
S-band technology can be scaled to produce 250 MeV electrons but is NOT compact.

LLNL’s T-REX laser-Compton source used 3-GHz, S-band accelerator sections operated at an average acceleration gradient of approximately 10 MeV/m.
High gradient x-band technology developed at DOE’s SLAC National Accelerator Lab enables compactness.

Reliable acceleration gradients of greater than 120 MeV/m have been demonstrated from x-band (~12 GHz) technology at SLAC.
A path to extreme capability has been defined at LLNL

A relocatable device could be built from x-band technology
A path to extreme capability has been defined at LLNL

Line-width-resolved, nuclear spectroscopy
Isotope-Specific Medical Radiography
Isotope-Specific Tomography
Isotope-Specific Assay
Isotope Detection
Gamma optics R&D
PoP Detection
T-REX
HIGS

VELOCIRAPTOR

Very Energetic Light for the Observation and Characterization of Isotopic Resonances and the Assay and Precision Tomography of Objects with Radiation
The first step is to validate Compton architectures based on x-band tech at LLNL.
LLNL’s Advanced Concepts, Laser Compton Test Station enables validation of new, high-flux, laser-Compton concepts and related technologies.
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- State-of-the-art, solid-state, x-band RF power
- Custom, high-brightness, x-band photo-gun
- High-gradient, x-band RF accelerator sections
- Complete suite of laser, e-beam & Compton diagnostics
LLNL’s Advanced Concepts, Laser Compton Test Station enables validation of new, high-flux, laser-Compton concepts and related technologies.
LLNL’s high-collimation, multi-bunch, laser-Compton architecture minimizes bandwidth.

Highly collimated, minimizes bandwidth, reduces complexity of the interaction laser and system timing - requires high energy laser & high repetition seed.

Seed source patent pending

Concept patent granted

< 5 micro rad

Proof-of-principle experiments have validated the multi-bunch, extended pulse interaction geometry.

4, 100 pC electron bunches
1J, 5 ns, 532 nm laser pulse

87.5 ps Interaction Point
Proof-of-principle experiments have validated the multi-bunch, extended pulse interaction geometry.
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Narrow band operation has been verified via simple k-edge radiography of a silver foil

Simulation parameters:
- E-beam energy: 26.4 MeV
- E-beam emittance: 0.4 mm mrad
- E-beam rms size: 30 μm
- E-beam charge: 50 pC
- E-beam pulse length: 2 ps
- Interaction laser wavelength: 532 nm
- Interaction laser energy: 750 mJ
- Interaction laser waist size: 50 μm
- Interaction laser pulse length: 6 ns
- Total flux: 182,000 photons

Graphs showing:
- Spectrum of Compton-scattered X-rays within various aperture angle
- Transmission spectrum through 50 μm silver foil
Narrow band operation has been verified via simple k-edge x-ray radiography of a silver foil

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**Silver Transmission**

- **Ag foil attenuation**
  - **Theory**
  - **Ag foil attenuation**

**Graph**

- **Spectrum of Compton-scattered X-rays within various aperture angle**
  - 16 mrad
  - 12 mrad
  - 8 mrad
  - 4 mrad
  - 2 mrad

**Above k-edge**

- **Below k-edge**
LLNL’s “Picket Fence” multi-GHz, laser-Compton source architecture dramatically increases output

This configuration enables near UNITY efficiency, operates with high beam current, maximizes flux & is intrinsically synchronized to an RF clock.


>100 kHz effective repetition rate

4000x higher average beam current, 400x higher photon density at the interaction and 100x narrower bandwidth than T-REX circa 2008

SSD ~100,000,000
individual 300 shot exposures
300 Hz equiv. 3000 Hz equiv. 30,000 Hz equiv. theory

with picket fence greater than $10^{13}$ photons/sec are possible
European Synchrotron Radiation Facility (ESRF) was used to validate the potential of future high SSD machines.

Beam Line - ID15A has a Specific Spectral Density of ~3,000,000 at 500 keV BUT SSD is only ~10 at 800 keV.
New applications become viable with increasing SSD

Specific Spectral Density (photons/sec/eV/FSB)

Inverse Fractional Source Bandwidth

- Line-width-resolved, nuclear spectroscopy
- Isotope-Specific Medical Radiography
- Isotope-Specific Tomography
- Isotope-Specific Assay
- Isotope Detection
- Gamma optics R&D
- PoP Detection
- Duke U HIGS
- LLNL T-REX

ESRF ID15A@ 0.5 MeV
New applications become viable with increasing SSD

1E+11
1E+10
1E+09
1E+08
1E+07
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00

Specific Spectral Density (photons/sec/eV/FSB)

- Line-width-resolved, nuclear spectroscopy
- Isotope-Specific Medical Radiography
- Isotope-Specific Tomography
- Isotope-Specific Assay
- Isotope Detection
- Gamma optics R&D
- PoP Detection
- Duke U HIGS
- LLNL T-REX
- ESRF ID15A@ 0.5 MeV
- ESRF ID15A@ 0.8 MeV

Inverse Fractional Source Bandwidth
Collaboration between LLNL, Institute Laue-Langevin, ESRF and TU-Darmstadt

LLNL’s DINO detector + ESRF’s ID15A photons enabled isotope specific imaging

ESRF 10^{-3} Bandwidth Gamma Beam

*US Patent #8,369,480 C. P. J. Barty - Dual isotope notch observer for material identification, assay and imaging
Collaboration between LLNL, Institute Laue-Langevin, ESRF and TU-Darmstadt

LLNL's DINO detector + ESRF's ID15A photons enabled isotope specific imaging

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LLNL’s DINO detector + ESRF’s ID15A photons enabled isotope specific imaging

Test Objects

18650 Li battery
7LiF powder
7LiF powder
6LiF powder
W block
W block

478 keV beam (on resonance)

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Test Objects

- 18650 Li battery
- W block
- $^7$LiF powder
- $^7$LiF powder
- $^6$LiF powder
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Test Objects

18650 Li battery
W block
LiF powder
LiF powder
LiF powder
W block

1.00
0.75
0.50
0.25
0.00

No 7Li

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Test Objects:
- 18650 Li battery
- W block
- $^7$LiF powder
- $^7$LiF powder
- $^6$LiF powder
- W block

Graph showing isotope specific imaging with peak at $^7$Li for 1x and 2x doping.
Collaboration between LLNL, Institute Laue-Langevin, ESRF and TU-Darmstadt

LLNL’s DINO detector + ESRF’s ID15A photons enabled isotope specific imaging

US Patent #8,369,480 C. P. J. Barty - Dual isotope notch observer for material identification, assay and imaging
Next generation machines and technology are also being pursued in Europe and Japan.
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Next generation machines and technology are also being pursued in Europe and Japan.
These next generation gamma-ray machines will do for the “isotope” what the laser did for the “atom”

- Enable linear spectroscopy with bright, tunable, monochromatic & polarized light

- Enable important, isotope-specific material detection, assay & imaging applications

- Allow novel nuclear science and engineering opportunities to become practical
LLNL’s Dual Isotope Notch Observation (DINO) was invented to enable Compton-based material assay.
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DINO’s first calorimeter collects both resonantly and non-resonantly scattered probe beam photons

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US patent #8,369,480 C.P.J. Barty - Dual isotope notch observer for material identification, assay and imaging
DINO’s first calorimeter collects both resonantly and non-resonantly scattered probe beam photons.
DINO’s second calorimeter collects only non-resonantly scattered probe beam photons.

**Diagram Description:**
- **MEGa-ray source**:
  - Emitting rays towards the **Shielded container**.
  - **235U** is inside the container.
- **Calorimeter**:
  - Located next to the container.
  - **238U** is inside the calorimeter.
- **Beam monitor**:
  - Positioned on the right side of the diagram.
- **Only Non-resonant Scatter**:
  - Arrows indicating the path of the scattered photons.
- **ΔE/E = 10^{-3}** and **ΔE/E = 10^{-6}**
  - Represent the energy loss ratios for different scattering events.

**References:**
US patent #8,369,480 C.P.J. Barty - Dual isotope notch observer for material identification, assay and imaging.
DINO’s second calorimeter collects only non-resonantly scattered probe beam photons.
The difference between the DINO witness signals is a measure of the isotopic material seen by the beam.

DINO is ideally suited to high-peak flux, laser-Compton sources.
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Differential Calorimetry:
- NRF + Compton + Delbrück + Rayleigh + Thomson
- Compton + Delbrück + Rayleigh + Thomson

MEGa-ray source

Shielded container

$^{235}\text{U}$

$\Delta E/E = 10^{-3}$

Calorimeter

$235\text{U}$

Beam monitor

$238\text{U}$

$\Delta E/E = 10^{-6}$

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