Some Application of Laser-Compton Scattering from Intermediate Energy Electron Beams

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Laser-Compton Scattering (LCS)

- Interaction of high-energy electron with photon
  $\Rightarrow$ electron scatters low energy photon to higher energy at the expense of the electron kinetic energy.
- Similar to channeling/Undulatorator radiation
- Emission of highly directed (direction of e- beam), mono-energetic, and tunable X-ray beams with divergence on the order of $1/\gamma$. 
Relativistic electron bunch $\gamma = E_{\text{cm}}/mc^2 = 10 - 60$

Scattered photons are upshifted in energy $h\nu_{\text{scat}} = 4\gamma^2 h\nu_{\text{laser}}$ and emitted in a forward cone with angle $\sim \frac{1}{\gamma}$

Compton scattering of laser photons by relativistic electrons

Incident laser pulse
• Compton x-ray energy (from energy momentum conservation):

\[ E_\gamma \approx \frac{E_L (1 + \beta \cos \alpha)}{1 - \beta \cos \theta}. \]

• \( E_\gamma \) = x-ray energy, \( E_L \) = Laser photon energy, \( E_B \) = Electron beam total energy.

• For collision geometries were \( \alpha \approx 0 \) and for emission angles close to the electron beam direction:

\[ E_\gamma \approx E_M / (1 + \gamma^2 \theta^2). \]

• Where \( E_M = 4 \gamma^2 E_L \) is the maximum energy generated in the forward direction for a head-on collision (Highest gain in energy, twice Doppler shifted).
LCS Spectrum

Laser photon energy in e- frame \(< mc^2 \implies\) motion of e- is non-relativistic (Thomson scattering).

Energy of incoming photon = energy of scattered photon in rest frame

Rest frame differential cross section (for an incident linearly polarized plane wave):

\[
\frac{d\sigma}{d\Omega} = r_0^2 \sum \left| \mathcal{E}'_l \cdot \mathcal{E}'_\gamma \right|^2 = r_0^2 (\cos^2 \theta' \cos^2 \phi' + \sin^2 \phi')
\]

After transformation to laboratory frame (laser polarization along x axis)

\[
\frac{d\sigma}{d\Omega} = r_0^2 \frac{1 - \beta^2}{(1 - \beta \cos \theta)^2} \left( \cos^2 \varphi \frac{(\cos \theta - \beta)^2}{(1 - \beta \cos \theta)^2} + \sin^2 \varphi \right)
\]
\[ \frac{d N_\gamma}{d E_\gamma} = \int \frac{d N_\gamma}{d \Omega_d} d \Omega_d, \]

\[ \frac{d N_\gamma}{d \theta_{x,d} d \theta_{y,d} d E_\gamma} = L \frac{d \sigma}{d \theta_{x,d} d \theta_{y,d} d E_\gamma} \]

\[ = \frac{L 2r_0^2}{(2\pi)^{3/2}} \frac{\int \int d \gamma}{\int \int d \gamma} \frac{\int \int (1+\beta)(\cos 2\varphi + 1) \frac{E_\gamma^2}{E_M} \left( \frac{E_\gamma}{E_M} - 1 \right) + 1/2}{\int \int d \gamma} \]

\[ x \exp\left( -\frac{(\gamma' - \gamma)^2}{2 \sigma_e^2} \right) \exp\left( -\frac{(\theta_{x,d} - \theta_x)^2}{2 \sigma_x^2} \right) \exp\left( -\frac{(\theta_{y,d} - \theta_y)^2}{2 \sigma_y^2} \right) d\varphi d\gamma'. \]

\[ d\Omega_d = d\theta_{x,d} d\theta_{y,d}, \quad \theta_{x,d} \approx \theta_d \cos \varphi_d, \quad \theta_{y,d} \approx \theta_d \sin \varphi_d, \]

\[ \theta_x \approx \theta \cos \varphi, \quad \theta_y \approx \theta \sin \varphi, \quad E_M = 4\gamma'^2 E_L \quad \text{and} \quad \theta \approx \sqrt{(E_M / E_\gamma - 1) / \gamma'}. \]

\( L \): single collision luminosity.

Assume transverse and longitudinal spatial distributions are Gaussians:
If laser pulse length much shorter than Rayleigh range and e-beam envelope function greater than e-pulse length, transverse rms widths considered independent of longitudinal coordinate and \( \sin \alpha \approx \alpha \) (laser propagates in the \( y-z \) plane):

\[
L = \frac{N_e N_L (1 + \beta)}{2 \pi \alpha c \sigma \sqrt{x^2 + \sigma_w^2}} \exp\left(-\frac{\tau^2}{2\sigma^2}\right),
\]

\[
\sigma = \left((1 + \beta)/\alpha c\right) \sqrt{(\alpha/(1 + \beta))^2 (\sigma^2 + \sigma_L^2) + (\sigma^2 + \sigma_w^2)}.
\]

\( \tau \): delay between laser and electron beam

For \( \alpha = 0 \)

\[
L = N_e N_L \sqrt{x^2 + \sigma_w^2} \sqrt{y^2 + \sigma_w^2}
\]

Number of LCS X-rays/burst:

\[
N_{LCS} = L \sigma_\Omega(\sigma_x, \sigma_y), \quad \sigma_\Omega = \text{Cross section within cone of solid angle } \Omega.
\]
LCS x-ray energy and energy spread (FWHM) depend on

- Laser frequency bandwidth.
- Electron beam energy and energy deviation.
- e- beam angular spread.
- Electron beam direction.
- Finite detector collimation.
- Finite interaction length.
Potential applications of LCS

- LCS x-ray pulse durations:
  - 180° geometry: $\tau_x \approx \tau_e$
  - 90° geometry: $\tau_x = \text{transit time}$

- 90° LCS geometry: scanning laser across e-beam spot size (nm range).

- Electron beam emittance, energy, energy spread and direction.
Spectral bandwidth vs collimator radius

\[ E = 22 \text{ MeV} \]
\[ \Delta E_e = 220 \text{ keV} \]
\[ \lambda = 532 \text{ nm} \]
\[ \sigma_x = 2 \text{ mrad} \]
\[ \sigma_y = 3 \text{ mrad} \]
\[ \theta_d = 0 \text{ mrad} \]

Yield

X-ray energy (keV)
LCS energy and FWHM dependence on beam divergence $\sigma_x$ and $\sigma_y$ for scans along x-direction (laser electric field)
IAC L-band LINAC Layout

IAC 5-44 MeV, 50 ps LINAC

Qs = Quadrupole singlet
Qt = Quadrupole triplet
Qd = Quadrupole doublet
VS = View screen
Electron beam and laser parameters (LCS-Experiment) B-Line

<table>
<thead>
<tr>
<th>Electron beam:</th>
<th>YAG-Laser:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy:</strong></td>
<td>Fundamental</td>
</tr>
<tr>
<td>5-44 MeV</td>
<td>$\lambda_1 = 1064$ nm +second, third and fourth harmonic</td>
</tr>
<tr>
<td><strong>Pulse length:</strong></td>
<td><strong>Pulse length:</strong></td>
</tr>
<tr>
<td>50 ps</td>
<td>250 ps</td>
</tr>
<tr>
<td><strong>Charge/bunch</strong></td>
<td><strong>$E_1 = 1$ J/pulse</strong></td>
</tr>
<tr>
<td>up to 10 nC.</td>
<td><strong>$E_2 = 500$ mJ/pulse</strong></td>
</tr>
<tr>
<td><strong>Typical bunch charge:</strong></td>
<td><strong>$E_4 = 33$ mJ/pulse</strong></td>
</tr>
<tr>
<td>0.35 nC</td>
<td><strong>Rep. Rate = 60 HZ</strong></td>
</tr>
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<td><strong>Rep. Rate = 60 HZ</strong></td>
</tr>
</tbody>
</table>
- Laser-beam line angle: $\alpha \approx 2.2 \text{ mrad}$.
- Solid angle: $d\Omega_\gamma \approx 0.2 \mu\text{sr}$.
- 1064 nm-Pol: $\pi$, 532 nm-Pol: $\sigma$, 266 nm-Pol: $\pi$
- Seed laser phase locked to Linac 108 MhZ clock. Jitter e-beam and laser $\approx 1\text{ps}$
Laser Room (4 GW, 60 Hz, 250 ps Nd:YAG)
Optics room:
Prior to injecting laser to interaction area
Inside LINAC room
e-beam-laser pulses temporal overlap:
a- Discreet jumps \textit{i.e.} 9.26 ns
b- Seed laser phase \textit{i.e.} 4.6 ns
c- Translator \textit{i.e.} 9.26 ns
(2x1.7 m)
Delay between laser and e-beam pulses
Rms spot size at interaction
e\textsuperscript{-} beam (depends on bunch charge):
x_\sigma = 1.95 \pm 0.02 \text{ mm}
y_\sigma = 0.625 \pm 0.004 \text{ mm}

Laser (depends on optics and wavelength)
x_\sigma = 82.6 \pm 0.1 \mu\text{m}
y_\sigma = 154.3 \pm 0.4 \mu\text{m}
\( \tau_e = 50 \text{ ps} \), \( \tau_L = 250 \text{ ps} \), \( Q = 0.35 \text{ nC} \), laser, \( E_L = 50 \text{ mJ} \), 
\( \alpha = 2.5 \text{ mr} \), \( d\Omega = 0.25 \mu\text{Sr} \), \( N_{LCS} = 2.76 \pm 0.02 \)

\( E_b = 36.4 \text{ MeV} \)
\( E_\gamma = 48.27 \pm 0.01 \text{ keV} \)
\( \Delta E_\gamma = 1.6 \pm 0.03 \text{ keV} \)
\( \lambda = 532 \text{ nm} \)
\[ g(E_\gamma) = \int f(E'_\gamma) f(E_\gamma - E'_\gamma) \, dE'_\gamma \]

\[ h(E_\gamma) = \iiint f(E''_\gamma) f(E'_\gamma - E''_\gamma) f(E_\gamma - E'_\gamma) \, dE''_\gamma \, dE'_\gamma \]

**Pileup energy distribution**
\[ \tau_e = 5 \text{ ns}, \quad \tau_L = 7 \text{ ns}, \quad Q_{\text{macropulse}} = 0.2 \text{ nC}, \quad \text{laser}, \quad E_L = 200 \text{ mJ}, \quad \text{Slit width} = 3.4 \text{ mm} \]
LCS as a non-invasive beam diagnostics technique: Angular measurements

• Scan across x-ray cone along horizontal and vertical directions.

Minimization method:

• Common fit to spectra to determine common e-beam parameters from several responses *i.e.* spectra.

• Minimization of \( \text{det} \{ V_{i,j} \} \)

\[
\{ V_{i,j} \} = \sum_k \frac{(y_{i,k} - f_{i,k})}{\sigma_{i,k}} \frac{(y_{j,k} - f_{j,k})}{\sigma_{j,k}}
\]
# Measured beam parameters with minimization method

With 15 spectra:

- \( E = 22.27 \pm 0.04 \text{ MeV} \)
- \( \Delta E = 0.21 \pm 0.07 \text{ MeV} \)
- \( \sigma_x = 2.08 \pm 0.13 \text{ mrad} \)
- \( \sigma_y = 3.05 \pm 0.5 \text{ mrad} \)
- \( \theta_b = -2.12 \pm 0.32 \text{ mrad} \)

With energy and FWHM (\( E \) and \( \Delta E \) fixed):

- \( \sigma_x = 2.23 \pm 0.11 \text{ mrad} \)
- \( \sigma_y = 2.81 \pm 0.5 \text{ mrad} \)
- \( \theta_b = -2.15 \pm 0.5 \text{ mrad} \)

LCS Energy, FWHM VS Observation angle
LCS for non-proliferation ➔ Hybrid K-edge densitometry (HKED) ➔ Identifications and quantification (concentration/concentration ratio) of actinide elements in liquid samples.

KED utilizes abrupt change in x-ray transmission at the k absorption edge of a certain heavy element in order to determine its concentration. XRF determines various ratios of concentrations (U/Pu). Measured ratios allow determination of each minor element relative to major elements and therefore after appropriate calibration allow determination of absolute concentration of a minor element.

Need to reach 42.3 MeV ➔

$E_γ = 129.5 \text{ keV} > k$-edges of 238U, 237Np, 239Pu, 241Am and 244Cm (128.2 keV).
Ottmar et al. Hybrid K-edge densitometry with bremsstrahlung beams:
* 150 kV/15 mA X-ray tube.
* 2 high purity Germanium detectors.
* XRF detector at 150° with respect to primary direction of X-ray beam. Lots of useless photons and poor signal to noise ratio.
3 M Nitric acid solution (reference solution), Path length = 2 cm, Volume = 7ml, 1.08g/cm³
E beam energy = 42.5 MeV, Laser energy = 3 mJ

Samples provided by Sandia National Laboratory
$E = 42.5\ \text{MeV}$
$\lambda = 266\ \text{nm}$
U sample labeled = 300 g/l
$N_{\text{LCS}}^{\text{Brunt}} = 0.523 \pm 0.02$

U K-edge = 115.6 keV

$E = 42.5\ \text{MeV}$
$\lambda = 266\ \text{nm}$
U sample labeled = 300 g/l

U-Kα1 = 98.4 keV
U-Kα2 = 94.6 keV
U-Kβ1 = 111.3 keV

Reference solution HNO₃

Counts/0.011886 keV

Counts/0.011886 keV

U 200 g/L
U 300 g/L

X-ray energy (keV)

X-ray energy (keV)
Concentration measurements

E = 42.5 MeV
λ = 266 nm
E_γ = 122.6 ± 0.03 keV
3M Nitric Acid

Counts/0.011886 keV

Defective pulses
Pile-up of main peak with defective pulses

X-ray energy (keV)

Counts/0.011886 keV

E = 42.5 MeV
λ = 266 nm
3M Nitric Acid
U-sample label= 300 g/L
U concentration measured = 148.8 ± 3 g/L

X-ray energy (keV)

Counts/0.011886 keV

E = 42.5 MeV
λ = 266 nm
3M Nitric Acid
U-sample label= 200 g/L
U concentration measured = 91.8 ± 5 g/L

Energy region not included in fit

X-ray energy (keV)

Yield

U 150 g/L
U 300 g/L

X-ray energy (keV)
Main goal:
1- Determination of detection limit of actinide elements concentration that can be reached with LCS x-rays and comparison with x-ray tubes (1mg/l up to about 300 g/l).
2- U/Pu sample 200g/l-1g/l
3- TRU product
Bio-Medical Imaging
Production of high-quality images of soft tissue while reducing dose.
Typical x-ray yield = $10^7$ photons/cm$^2$ and $\Delta E \leq 5\%$.
X-ray yield as a function of laser energy for optimum delay. Solid angle $d\Omega = 9.3 \times 10^{-2} \mu\text{Sr}$, $Q = 0.4 \text{ nC}$
Gendex dental plates
1064 nm laser wavelength.
X-ray energy = 20 keV.
Fish-X-ray flux: $\approx 10^4$ Ph/mm$^2$
Mouse- X-ray flux: $\approx 10^5$ Ph/mm$^2$
LCS X-ray beam image
Off axis emission ➔ Factor of >4 loss in X-ray yield
Phase imaging
Laser (1064 nm) spot size $\sigma \approx 180 \, \mu m$
X-ray image of memory stick at X-ray energy $\approx 47$ keV (532 nm). Dimensions = 1.5x3.5cm
Total flux $\approx 1.2 \times 10^5$ Ph/mm$^2$
Spatial resolution $\approx 12$ Lp/mm
Polarized x-rays: Material science i.e. magnetic Compton scattering, x-ray magnetic dichroism (XMCD), x-ray diff optics.

Fixed detector position at 90° with respect to scatterer.

\[ E_b = 36.9 \text{ MeV} \]
\[ \lambda = 532 \text{ nm} \]
\[ \frac{(P_\perp - P_{||})}{(P_\perp + P_{||})} = 84 \pm 3.5\% \]
Conclusion

LCS can be a versatile x-ray source provided that one has the necessary yield!

LCS has a wide range of applications in accelerator physics, bio-medical field, material sciences and non-proliferation.

Current LCS projects at the Idaho Accelerator Center include:

* Proof of principle of single shot electron beam diagnostics, transverse phase space mapping and comparison of LCS to other developed diagnostic techniques.
* HKED with U/Pu, Dissolver solution (U/Pu/Np/Am/Cm) and TRU (Pu/Np/Am/Cm) (April 2010).
* Image contrast/ X-ray dose VS LCS X-ray bandwidth (May 2010).
* Low Z material embedded in soft tissue.