レーザー逆コンプトンX線光源を用いたフェムト秒時間分解X線研究の可能性

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• Motivation
• Feasibility
• Case study
**Time Domain Science with SR**

**Phonon-polariton wave in LiTaO₃ (ALS)**


**Ni(II) porphyrin (APS)**

**Bond softening in Bismuth (SPPS)**

**C₂H₄I₂ in methanol (ESRF)**

**Magnetic excitations in permalloy squares (SLS)**

**Mutant myoglobin (ESRF)**
Femtosecond X-ray Pulses at 0.4 Å
Generated by 90° Thomson Scattering: A Tool for Probing the Structural Dynamics of Materials
Schoenlein et al. (1996) Science 274, 236.

**Electron:** 50 MeV, 1.3nC, 20 ps (FWHM)
**Laser:** 60mJ, 100fs, 10Hz, 800 nm
**X-ray:** 30 keV, ~300fs, $2 \times 10^5$ photons/pulse/15%

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**Fig. 1.** Schematic of the femtosecond Thomson scattering geometry.

**Fig. 2.** False-color CCD image of the spatial profile of a 30-keV (0.4 Å), ~300-fs x-ray pulse striking a phosphor screen at a distance of 80 cm from the scattering point. Vertical and horizontal lineouts indicate a beam size of ~12 mm by ~8 mm (FWHM).

**Fig. 3.** Spectral measurements of the femtosecond x-rays at observation angles of $\theta_0 = 0$ mrad, 5 mrad, and 10 mrad ($\theta_0 = \pi/2$). The detector lies in the $yz$ plane. Also shown (solid lines) are theoretically predicted spectra corrected for detector sensitivity and window transmission as described in the text.
“Rapid advances in diode-pumped, solid state lasers and superconducting linac structures may provide substantially higher x-ray brightness in future Thomson sources by operating at very high repetition rates.”

1996
Electron: 50 MeV, 1.3nC, 20 ps (FWHM)
Laser: 60mJ, 100fs, 10Hz, 800 nm
X-ray: 30 keV, ~300fs, 2 x 10^5 photons/sec/15% b.w.

2007
Electron: 60 MeV, 1nC, 1 ps
Laser: 1 mJ, 150 fs, 10000 Hz, 800 nm
X-ray: 42 keV, 1 x 10^{10} photons/sec/10% b.w. !!
Laser-Compton X-ray source at ERL test facility (60-150MeV)

\[ E_{\text{Xray}} = 2\gamma^2 E_{\text{Laser}} (1-\cos\theta_L)/(1+\gamma^2 \theta^2) \]

\[ \text{Flux} = (N_L N_e/wh)(L_{\text{eff}}/L_b)\sigma_c \]

\( E_{\text{Laser}} = 1.55\text{eV}, \quad E_{\text{electron}} = 60\text{ MeV} (\gamma=117), \quad \theta_L = 90\text{ degree} \) のとき、

軸上(\( \theta=0 \))で\( E_{\text{Xray}} = 42.4\text{ keV} \)

レーザーパルス(1.55eV, 1mJ)のフォトン数: \( N_L = 4 \times 10^{15} \) photons

電子バンチ中の電子数(60MeV, 1nC): \( N_e = 6 \times 10^9 \) electrons

電子バンチの水平幅: \( w = 50 \times 10^{-6} \) m

電子バンチの高さ: \( h = 50 \times 10^{-6} \) m

コンプトン散乱断面積: \( 1 \times 10^{-28} \)

1パルスあたり、

\[ \text{Flux} = 1 \times 10^6 \text{ phs/pulse}/10\%\text{b.w.} \]

10kHzのとき、

\[ \text{Flux} = 1 \times 10^{10} \text{ phs/sec}/10\%\text{b.w.} \]
<table>
<thead>
<tr>
<th>Source</th>
<th>Pulse length (fs)</th>
<th>Repetition rate (Hz)</th>
<th>Photon flux</th>
<th>Energy range</th>
</tr>
</thead>
</table>
| Compact ERL/Laser-Compton Source (1nC, 10kHz)    | ~150              | 10000                | $1 \times 10^{10}$ phs/sec/10% b.w.  
$1 \times 10^6$ phs/sec/0.1% b.w.  
$1 \times 10^6$ phs/pulse/10% b.w. | 10-100 keV       |
| PF-AR NW14 (80nC, 794kHz, 60mA)                  | $100 \times 10^3$ | $794 \times 10^3$    | $1 \times 10^{15}$ phs/sec/10% b.w.  
$1 \times 10^{12}$ phs/sec/0.1% b.w.  
$1 \times 10^9$ phs/pulse/10% b.w.  
$1 \times 10^6$ phs/pulse/0.1% b.w. | 5-30 keV         |
| KEK-ERL Low-rep. mode (1nC, 10kHz, 0.01mA)       | 100 – 1000        | 10000                | $1 \times 10^{11}$ phs/sec/10% b.w.  
$1 \times 10^7$ phs/sec/0.1% b.w.  
$1 \times 10^7$ phs/pulse/10% b.w. | 5-30 keV         |
| Laser Bunch Slicing (ALS upgrade)                | 200               | 40000                | $5 \times 10^7$ phs/sec/0.1% b.w. | 0.2-10 keV   |
| Laser-produced plasma X-ray                      | ~100              | 10                   | $6 \times 10^{10}$ phs/pulse/4\pi sr         | 8 keV (Cu-K$\alpha$) |
| Laser / high harmonic generation                 | 100 - 0.1         | 10 - 10000           | $\sim 10^8$ phs/sec/0.1% b.w. | 10 eV-1 keV  |
| Sub-Picosecond Pulse Source (SLAC)               | 80                | 10                   | $2 \times 10^7$ phs/pulse/1.5% b.w. | 8-10 keV     |
| KEK PF-BT line                                   | 500               | 20                   | $\sim 10^7$ phs/pulse/10% b.w. | 0.2-10 keV   |
| Linac Coherent Light Source (SLAC)               | 230               | 120                  | $2 \times 10^{12}$ phs/pulse/0.2% b.w. | 1-10 keV     |
X-ray beam characteristics from superconducting-linac-based Laser-Compton X-ray sources

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>High repetition frequency</td>
<td>(&lt; 1 GHz)</td>
</tr>
<tr>
<td>Hard X-ray available</td>
<td>(~ 10-100 keV)</td>
</tr>
<tr>
<td>Short pulse duration</td>
<td>(~ 100 fs)</td>
</tr>
<tr>
<td>Large beam divergence</td>
<td>(~ 10 mrad)</td>
</tr>
<tr>
<td>Relatively high average photon flux</td>
<td>(~ $10^{10}$ photons/sec/~10%b.w. @ 10 kHz)</td>
</tr>
</tbody>
</table>
X-ray beam focusing with multilayer K-B mirrors

Collision point
50 μmφ

1 m

10 mmφ

multilayer K-B mirrors

Ru/C N80
Size: 300mm(L)
d-spacing: ~20 Å
X-ray energy: 30 keV (0.4 Å)
Bragg angle: 0.59 degree (10.3 mrad)
Reflectivity: > 80%
deltaE/E: 6-7%

Beam acceptance: 0.3 x 10.3 = 3.1 mm
Other issues to be addressed …

- Timing jitter
- Timing and beam position monitor
- Laser-electron collision
- Bunch compression
- Shot-by-shot fluctuation
- etc…
Motivations for femtosecond X-ray reaction dynamics in solution @ NW14

Collaboration with Hyotcherl Ihee Group (KAIST, Korea)
Solution scattering profiles

\[ \lambda = 0.827 \, \text{Å} \]
\[ \text{det} x = 51.8 \, \text{mm} \quad q < 7 \, \text{Å}^{-1} \]

- Before Calibration: \( \text{det} x = 55 \)
- After Calibration: new \( \text{det} x = 51.8 \)
Photoreaction of $I_3^-$ in methanol

$I_3^- + h\nu \rightleftharpoons I_2^- + I^-$

Difference liquid scattering profile

- 50 sec exposure for 1 image
- 10 repetitions for each time delay
- 15 mM $I_3^-$ solution
- Laser: 400 nm, 60 $\mu$J/pulse

Reaction time course
UV spectroscopy revealed dumped oscillations in femtosecond time domain

Caging and Geminate Recombination Following Photolysis of Triiodide in Solution


Figure 1. Transient transmission scans of triiodide in ethanol solution with both UV pump and probe pulses. The inset depicts the first 8 ps of probe delays, exhibiting a rapid decay of the initial bleach superimposed by impulsive Raman-induced spectral modulations. See text for details.
Other applications at NW14 which might be suitable for femtosecond X-ray studies

<table>
<thead>
<tr>
<th>Type of experiments</th>
<th>sample</th>
<th>Typical repetition rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-crystal diffraction</td>
<td>Charge transfer complex crystal</td>
<td>1kHz</td>
</tr>
<tr>
<td></td>
<td>Transition metal oxides</td>
<td>1kHz</td>
</tr>
<tr>
<td></td>
<td>Protein crystal</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Liquid scattering</td>
<td>Organic &amp; inorganic solution</td>
<td>1kHz</td>
</tr>
<tr>
<td></td>
<td>Protein solution</td>
<td>1kHz</td>
</tr>
<tr>
<td>XAFS</td>
<td>Transition metal complex solution</td>
<td>1kHz</td>
</tr>
</tbody>
</table>
No!

\[ \lambda = 1 \, \text{Å}, \Delta x = 50 \, \mu\text{m} \] のとき、

\[ \Delta x \cdot \Delta \theta = \frac{\lambda}{4\pi} \approx 10^{-11} \, \text{mrad} \]

\[ \Delta \theta \approx 10^{-11} / 50 \times 10^{-6} = 2 \times 10^{-7} \, \text{rad} = 0.2 \, \mu\text{rad} \]
Short pulse + X-ray imaging?

X-ray Imaging of Shock Waves Generated by High-Pressure Fuel Sprays

see video!
Medical imaging?

- Hard X-ray available (~ 10-100 keV)
- Large beam divergence (~ 10 mrad)
- Relatively high average photon flux (~ $10^{10}$ photons/sec/$\sim$10\%b.w. @ 10 kHz)
- Relatively compact setup