Medical Applications of Compact Laser-Compton Light Source

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Medical X-ray and γ-ray Sources

- radioisotopes
  - monochromatic, MeV
  - intensity ~ source size
  - hazardous, radioactive waste

- bremsstrahlung sources
  - wide range of energies (keV-MeV)
  - broad spectrum

- synchrotron radiation
  - mostly <100 keV
  - high flux, monochromatic, tunable -> less dose, more contrast, K-edge subtraction imaging
  - small source size -> sharper image, phase contrast imaging
  - facility too large for clinical use

Laser-Compton photon generation

\[ E_{\text{scattered}} \approx \frac{4\gamma^2}{1 + \gamma^2 \theta^2 + 4\gamma k_0 \lambda_c} E_{\text{laser}} \]

\[ \theta = 1/\gamma \]

Electron beam

Electron and X-ray beam

Sun et. al, PRSTAB 14, 044701 (2011)
Laser-Compton X-ray Source at LLNL
LLNL X-band Electron Linear Accelerator

- LLNL/SLAC photoinjector[1]
  - 185 MV/m, ~7 MeV
- 1 T53 accelerating section
  - 45 MV/m, ~30 MeV
- 50 MW klystron, modulator
- up to 16 bunches per pulse (MOPIK111)
- energy upgrade: pulse compressor & 2nd section
  - >85 MeV electrons
  - >270 keV X-rays

**measured e⁻ beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>30 MeV</td>
</tr>
<tr>
<td>charge</td>
<td>10-200 pC</td>
</tr>
<tr>
<td>bunch length</td>
<td>2 ps*</td>
</tr>
<tr>
<td>spot size</td>
<td>14x11 μm</td>
</tr>
<tr>
<td>pos. jitter</td>
<td>5x2 μm</td>
</tr>
<tr>
<td>energy spread</td>
<td>0.03%</td>
</tr>
<tr>
<td>energy jitter</td>
<td>0.06%</td>
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<tr>
<td>emittance</td>
<td>0.3 mm-mrad</td>
</tr>
<tr>
<td>RF frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>rep. rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

*PARMELA simulation value

Laser-Electron Interaction

**laser & X-ray parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser energy</td>
<td>750 mJ</td>
</tr>
<tr>
<td>wavelength</td>
<td>532 nm</td>
</tr>
<tr>
<td>pulse length</td>
<td>6.5 ns</td>
</tr>
<tr>
<td>beam waist</td>
<td>50 μm</td>
</tr>
<tr>
<td>X-ray energy</td>
<td>30 keV</td>
</tr>
<tr>
<td>X-ray flux</td>
<td>$3 \times 10^5$/shot</td>
</tr>
</tbody>
</table>

IPAC’16 TUPOW052 (X-ray characterization)
NAPAC’16 WEPOB35 (source size measurement)
IPAC’17 MOPAB146 (K-edge filter diagnostic)
Laser-Electron Interaction

Laser & X-ray parameters
- Laser energy: 750 mJ
- Wavelength: 532 nm
- Pulse length: 6.5 ns
- Beam waist: 50 μm
- X-ray energy: 30 keV
- X-ray flux: $3 \times 10^5$/shot

IPAC’16 TUPOW052 (X-ray characterization)
NAPAC’16 WEPOB35 (source size measurement)
IPAC’17 MOPAB146 (K-edge filter diagnostic)
K-edge subtraction imaging

- two images above and below contrast agent K-edge
  - I (33.2 keV), Gd (50.7), Au (80.7)
- requires narrowband dual-color X-ray beam
  - change in e- energy, viewing angle

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  - I (33.2 keV), Gd (50.7), Au (80.7)
- requires narrowband dual-color X-ray beam
  - change in e⁻ energy, viewing angle
- applications in angiography, bronchography
- experiment with capillary tubes
  - Ag (25.5 keV) in current setup
Auger therapy

- Auger cascade from external X-rays causes dose enhancement
  - must be close to cancer cells
- Nanoparticle cancer targeting
  - nanoparticles naturally accumulate at tumor - enhanced permeability and retention (EPR) effect
  - cancer-seeking molecules can be attached to nanoparticles
  - AuNPs most widely studied
- Diagnostics + therapy -> ‘theranostics’

Phase contrast imaging

- phase change information to enhance contrast
- in-line PCI
  - simplest geometry
  - requires small source size
- diffraction-enhanced
  - crystal to detect small angle change
  - requires monochromatic beam
- interferometry, diffraction grating
- demonstrated by Lyncean, AIST, etc.

![conventional absorption radiography](image)

![in-line phase contrast imaging](image)


Kitchen et al., Br. J. Radiol., **78** 1018 (2005)
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Bech et al., J. Synchrotron Rad. 16, 43 (2009)
Schleede et al., PNAS 109, 17885 (2012)
Kuroda et al., NIMA 637, S183 (2011)
Summary

• Laser-Compton light sources can produce tunable, narrow bandwidth, small source size X-ray beam for medical use in a much smaller footprint than those of synchrotron facilities

• A compact X-band linac has been built at LLNL and is producing 30 keV X-rays, upgradable to >250 keV

• e⁻ beam and X-ray characterization is nearly complete and matches the modeling very well

• K-edge subtraction imaging and Auger therapy experiments are being planned