Accelerator-Based Gamma Sources
Review and Perspectives

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June 25, 2018
Nuclear Photonics 2018

Work supported by:
- A government (MEXT) subsidy for strengthening nuclear security
- Photon and Quantum Basic Research Coordinated Development Program from the MEXT
- JSPS KAKENHI 17H02818.
• Bremsstrahlung

• Laser Compton scattering

• Other Sources
• Bremsstrahlung
• Laser Compton scattering
• Other Sources
Bremsstrahlung = breaking radiation

Radiation cross section

\[
\frac{d\chi}{d\omega} \approx \frac{16}{3} \frac{Z^2 e^2}{c} \left( \frac{e^2}{mc^2} \right)^2 \ln \left( \frac{\lambda'' EE'}{mc^2 \hbar \omega} \right)
\]

The number of photons decreases as their energy

Bremsstrahlung

S-DALINAC@TU Darmstadt

gamma-ray spectroscopy with BS

\[ ^{11}\text{B}(\gamma,\gamma')^{11}\text{B} \]

\( E_0 = 7.7 \text{ MeV} \)

\[ ^{11}\text{B} \]

\( E_0 = 8.3 \text{ MeV} \)


3-130 MeV, 3 GHz, CW beam for nuclear physics exp.
Outline

- Bremsstrahlung
- Laser Compton scattering
- Other Sources
Laser Compton Scattering (LCS)

Can cover a wide range of photon energies.

With a 1-µm laser,

- 50 MeV electron → 10-keV photon
- 500 MeV electron → 1-MeV photon
- 5 GeV electron → 1-GeV photon

- Pencil like beam \( \sim 1/\gamma \)
- Energy Tunable
- Polarized (linear and circular)
- Correlation of \( E_X \) and \( \theta \)
Brief history of LCS

“Cosmic electrons are eliminated by a sufficient numbers of Compton scattering with starlight in intergalactic space.”

E. Feenberg and H. Primakoff, Phys. Rev. 73, 449 (1948).

Invention of “laser”


Proposal of “laser” Compton scattering for laboratory physics experiments.


5 years after the invention of LASER
Compton or Thomson, that is the question

\[
\begin{align*}
\hat{h}\omega_1 & \quad \gamma mc^2 \\
\text{photon} & \quad \text{electron}
\end{align*}
\]

\[
\begin{align*}
\hat{h}\omega_1' &= \frac{2\gamma \hat{h}\omega_1}{mc^2} \\
mc^2 &= 2\gamma \hat{h}\omega_1
\end{align*}
\]

\[
\begin{align*}
\hat{h}\omega_2 & \quad \gamma_2 mc^2 \\
\text{Labo. frame} & \quad \text{Rest frame}
\end{align*}
\]

For \( \hat{h}\omega_1' \ll mc^2 \) at the rest frame, electron recoil can be neglected

\[
2\gamma \hat{h}\omega_1 \ll mc^2
\]

1-\( \mu \)m laser and 500-MeV electron

\[
2\gamma \hat{h}\omega_1 = 2.3 \text{ keV} \ll mc^2
\]

Cross-section, spectrum can be expressed as Thomson scattering.

The collision is Compton scattering, if the electron recoil cannot be neglected.

“Compton scattering” is often used as a generic term including both elastic and inelastic scatterings.
LCS=Quasi-monoenergetic beam

\[ d\sigma \Bigg/ d\omega = 4\pi r_0 \left( 1 - 2 \frac{\omega}{\omega_{\text{max}}} + 2 \left( \frac{\omega}{\omega_{\text{max}}} \right)^2 \right) \frac{1}{\omega_{\text{max}}} \]

\[ E_X \approx \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L / (mc^2)} \]

\begin{align*}
\gamma_\theta \text{ (scattering angle)} \\
\gamma_\theta = 0.1 & \quad \gamma_\theta = 0.2 & \quad \gamma_\theta = 0.5
\end{align*}

quasi-monoenergetic gamma-ray is obtained with a collimator
LCS=100% Polarization

In the Thomson scattering, polarization is preserved.

Application of polarized gamma-ray

Angular dependence of resonant scattered gamma-ray

Can assign spin and parity of each level

T. Shizuma et al., PRC (2008)
Existing LCS Facilities

HIGS at Duke

1.2 GeV storage ring

http://www.tunl.duke.edu/facilities/

1-100 MeV photon energy is covered

typical performance
1-3 MeV, $10^8$-$10^9$ ph/s (total), $6\times10^7$-$6\times10^8$($\Delta E/E\sim5\%$) ~$100$ ph/eV/s @ 2MeV
13-20 MeV, $10^9$ ph/s (total), $10^8$ ph/s ($\Delta E/E\sim5\%$)
Existing LCS Facilities

NewSUBARU (1.5 GeV storage ring)

1.7-76 MeV gamma ray with different lasers.

Photo flux

17.6 MeV (1 μm laser)

→ 4 x 10^7 (total), 1.5 x 10^6 ph/s (3φ collimator)

LEPS and LEPS-II (8-GeV storage ring)

1.4-2.4 GeV gammas with 355-nm lasers
1.4-2.9 GeV gammas with 266-nm lasers

Photo flux ~ 2 x 10^7 ph/s (355-nm lasers)
~ 2 x 10^6 ph/s (266-nm lasers)

Energy resolution ~ 15 MeV

http://www.lasti.u-hyogo.ac.jp/NS/facility/bl01/


http://www.spring8.or.jp/wkg/BL33LEP/instrument/lang-en/INS-0000000562/instrument_summary_view
Bandwidth is a matter of concern

Nuclear resonance fluorescence from U-238

Each resonance width \( \sim 1 \) eV

Incident gamma ray out of the resonance causes background.

Detectors have a limited count rate and most of countable events is occupied by background.

S.L. Hammond et al., PRC 85, 044302 (2012).
Bandwidth of LCS photons

3D Laser Focus, $k_z$:

$$\Delta \theta_x \approx \Delta \theta_{xL} \approx \left( \frac{\lambda_0}{\pi W_0} \right)^2$$

Laser Bandwidth/Electron Energy Spread:

$$\frac{\Delta \omega}{\omega} \approx \frac{2}{\Delta t_0} \sqrt{\frac{\Delta \omega_0^2}{\omega^2} + \frac{\Delta \gamma^2}{\gamma^2}}$$

Electron Emittance:

$$\Delta \omega \approx \frac{\varepsilon_{nx}^2}{x_f^2}$$

Contribution of Emittance is dominant

D.E. Moncton, FLS-2006 WS.

http://adweb.desy.de/mpy/FLS2006/proceedings/TALKS/PLT05_TALK.PDF
Bandwidth is limited by emittance

**ε_{nx} = 1 mm-mrad**

- Electron beam
  - $E = 350$ MeV
  - $\sigma_x = 30$ µm
  - Collision angle = 10 deg.

**ε_{nx} = 5 mm-mrad**

- Laser beam
  - $\lambda = 1064$ nm
  - $\sigma_x = 30$ µm

\[
\left( \frac{\varepsilon_n}{\sigma_e \cdot x} \right)^2 = 0.1\% \quad \Delta E/E \text{ (emittance)} \quad \left( \frac{\varepsilon_n}{\sigma_e \cdot x} \right)^2 = 3\%
\]

Small emittance is a key to narrow-band LCS beams.
How small should emittance be?

In synchrotron X-ray sources and FELs

```
<table>
<thead>
<tr>
<th>optical beam</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron beam</td>
<td>ε</td>
</tr>
</tbody>
</table>
```

“diffraction limited beam” \( \varepsilon = \frac{\lambda}{4\pi} \) or \( \varepsilon_n = \frac{\lambda}{4\pi\gamma} \)

In LCS \( \Rightarrow \) gamma-ray bandwidth

“bandwidth limited beam”

\[
\frac{dE}{E} = \left( \frac{\varepsilon_n}{\sigma_e} \right)^2,
\frac{dE}{E} = \left( \frac{\lambda}{\pi w_0} \right)^2
\]

electron emittance laser diffraction

\( \varepsilon_n = 0.1 \text{ mm – mrad} \) For 1 \( \mu \text{m} \) laser
Small-emittance electron guns have been developed for light sources such as X-ray FEL and energy-recovery linac.

- Photocathode materials: metal, CsTe, GaAs, CsK$_2$Sb
- Drive laser: transverse and longitudinal shaping
- Injector design: multi-objective optimization technique

$\varepsilon_n \sim 0.4$ mm-mrad at 100 pC is achievable. (thermionic gun $\sim 10$-100 mm-mrad)
Cross section of Compton scattering is so small …

For example, 100 pC bunch, 30 µm spot size → collision probability of laser photon is ~10^{-11}

**Laser Recycling Systems**

- Laser pulse
- e-beam
- Laser enhancement cavity
- Laser recirculation system at ELI-NP
- Multiple collision
New-generation LCS Gamma-ray Sources

MEGA-Ray @ Lawrence Livermore Natl. Lab.
250 MeV Linac, $E_\gamma = 1-2$ MeV

ELI-NP: Complex of PW lasers and LCS

Total cost including facility modifications for 250 MeV system, R&D, controls and additional test stand ~ $30M

8x10^8 ph/0.5%BW

ERL-based LCS gamma-ray @ KEK-JAEA

2-3 MeV gamma
F = 10^{13} ph/s

R. Hajima et al., NIM-A608, S57 (2009)
New-generation LCS Gamma-ray Sources

FEL Compton @ LANL

130-MeV electron beam
248-nm FEL
1.3-MeV gamma
\( F = 1.9 \times 10^{12} \) ph/s


HIGS2

2 \( \mu \)m FP cavity
1-12 MeV gamma
\( F = 10^{11} - 10^{12} \) ph/s
Bandwidth < 0.5%

Y.K. Wu, LDRS-2015
LCS Experiment at the Compact ERL

Superconducting Acc.

Laser enhancement cavity and 45W laser

Electron gun

Beam line

Experimental hut

Laser

Compton scattering

X-ray

Photocathode DC gun

First arc

Beam dump

Main linac

Injector linac

Second arc

Beamline
LCS photons from the Compact ERL

Parameters of electron beams:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>20</td>
</tr>
<tr>
<td>Bunch charge [pC]</td>
<td>0.36</td>
</tr>
<tr>
<td>Bunch length [ps, rms]</td>
<td>2</td>
</tr>
<tr>
<td>Spot size [µm, rms]</td>
<td>30</td>
</tr>
<tr>
<td>Emittance [mm mrad, rms]</td>
<td>0.4</td>
</tr>
<tr>
<td>Repetition Rate [MHz]</td>
<td>162.5</td>
</tr>
<tr>
<td>Beam current [µA]</td>
<td>58</td>
</tr>
</tbody>
</table>

Parameters of laser (enhanced by cavity):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Pulse energy [µJ]</td>
<td>64</td>
</tr>
<tr>
<td>Pulse length [ps, rms]</td>
<td>5.65</td>
</tr>
<tr>
<td>Spot size [µm, rms]</td>
<td>30</td>
</tr>
<tr>
<td>Collision angle [deg]</td>
<td>18</td>
</tr>
<tr>
<td>Repetition rate [MHz]</td>
<td>162.5</td>
</tr>
<tr>
<td>Intracavity power [kW]</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Results:

- Photon energy = 6.95 keV
- Detector count rate = 1370 cps @φ4.66mm (*)
- Energy bandwidth = 30 eV(0.4%)@φ4.66mm (**)  
- Source flux = 2.6 x 10⁷ ph/s (***)

(*) Detector collecting angle is 4.66mm/16.6m = 0.281 mrad  
(**) Detector resolution subtracted  
(***) CAIN/EGS simulations with the detector count rate

T. Akagi et al. PR-AB 19, 114701 (2016)
Photons carrying orbital angular momentum (OAM)


LCS with OAM laser pulse


γ-ray vortex from nonlinear LCS


From Thomson to Compton regime

Photon scattered by 7-GeV electrons

\[ \frac{d\sigma}{dE_2} \text{ (b/MeV)} \]

Thomson

Compton

XFEL Oscillator: 12 keV laser & 7 GeV e-
Outline

• Bremsstrahlung
• Laser Compton scattering
• Other Sources
Gamma-ray FEL

X-ray FEL

LCLS@SLAC

E=14 GeV → 0.1 nm (12 keV) photons

$$\lambda = \lambda_w \frac{1 + a_w^2}{2\gamma^2}$$

Gamma-ray FEL

E=100 GeV → 1.6 MeV photons

Parasite at ILC?

http://wwwal.kuicr.Kyoto-u.ac.jp/~iwashita/ilc/data/05_ILCXFEL_Tanaka.pptx
FEL “was” Bremsstrahlung

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

John M. J. Madey

Physics Department, Stanford University, Stanford, California 94305
(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

In the electron rest frame

Bremsstrahlung

\[ e^- \xrightarrow{v \approx c} Z e \]

nucleus field = virtual photon

LCS

\[ e^- \xrightarrow{v \approx c} 2\gamma h\nu \]

laser = real photon

FEL

\[ e^- \xrightarrow{v \approx c} \vec{B} \]

undulator field = virtual photon
A gamma beam from partially stripped ions


PSI: partially stripped ion

Example

Er-doped laser 1540 nm
$\text{Ar}^{16+}$, $\gamma = 2068$, $n=1 \rightarrow 2$
$E_{\gamma}^{\text{max}} = 13.8$ MeV
$N_{\gamma} \sim 3 \times 10^{17}$ ph/s
Free Positronium Radiation

H. Ikegami,

\[ e^- + e^+ \rightarrow Ps + h\nu \]
\[ h\nu_{max} = \left( \frac{\alpha^2}{2} \right) \gamma mc^2 \]
\[ Ps \rightarrow 2h\nu \]
\[ h\nu_{max} = 2\gamma mc^2 \]

With 500-MeV e- and e+, 6.6 MeV and 1 GeV gamma’s are generated

Both beams must be cooled enough!
Summary

- Accelerator based high-energy photon sources have a long history.
- Since the invention of laser, LCS gamma-ray sources have been developed and utilized as user facilities.
- The performance of LCS gamma-ray source, flux, bandwidth, has been improved in accordance with advancement of laser and accelerator technologies.
- There still remains many challenges in LCS:
  - enlarging flux
  - reducing bandwidth
  - OAM, nonlinear, deep Compton …
- Exotic gamma source: PSI, positronium and more?
Thank you !