Development of LCS X-rays and coherent THz sources on the basis of S-band compact linac at AIST

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AIST is one of the largest national research institutions in Japan. About 2,500 Ph. D researchers are working for cutting-edge R&D in wide research fields such as life science, information technology, environment technology, nanotechnology, Geological survey, Measurement Technology …etc.

Accelerator group is very small group about 10 peoples.
**Introduction**

**Storage ring TERAS**
Laser Compton gamma-ray experiment
(NRF, gamma-ray imaging)

**Accelerator Facility at AIST**
*(nearby KEK in Tsukuba)*

400 MeV linac
(since 1978)

**Storage ring NIJI-IV**
FEL

**Focus!**

**New**
Compact S-band linac
Laser Compton X-ray source
Coherent THz radiation source

**Positron Beam line**
• Positron annihilation lifetime spectroscopy

**Accelerator Facility at AIST**
*(nearby KEK in Tsukuba)*

400 MeV linac
(since 1978)

**Focus!**

**New**
Compact S-band linac
Laser Compton X-ray source
Coherent THz radiation source

**Positron Beam line**
• Positron annihilation lifetime spectroscopy
S-band compact linac facility @AIST

Electron beam

Energy: ~42 MeV
Bunch charge: 1 – 3 nC
Bunch length: sub ps - 3ps (1σ)
Bunch number: 1 – 100
(Bunch spacing: 12.6 ns)
Repetition range: 10Hz - 50Hz

All components are installed in one middle size room (10m × 10m)
©Laser Compton scattering X-ray source
Principle of Laser Compton Scattering (LCS)

Interaction between high energy electron beam and high power laser

LCS X-ray source
- Short pulse
- Energy tunability
- Quasi-monochromatic
- Small source size
- Good directivity
- Good polarization
- Compact system … etc

Many benefits!

X-ray wave length
\[ \lambda \approx \frac{\lambda_0 (1 + K^2 / 2 + \gamma^2 \theta^2)}{2 \gamma^2 (1 - \cos \phi)} \]

\[ K = \frac{eA_0}{m_e c^2} \approx 0.85 \times 10^{-9} \lambda_0 \sqrt{I} \]

\[ \lambda = \frac{\lambda_0 \cos \phi}{1 - \beta \cos \theta + \left(1 + \cos(\theta + \phi)\right) \frac{E_0}{\gamma m_0 c^2}} \]

Laser Undulator Radiation

Scattered X-ray energy

High Power Laser
High Energy Electron Beam
Scattered X-ray

Electron beam
Laser
X-ray (\( \lambda (E) \))

\( \lambda_0 [\mu m] \) (\( E_0 [eV] \), I [W/cm²])
Laser Compton Scattering (LCS) hard X-ray Source at AIST

Application Space

- X-ray detector
- Specimen
- Beam dump
- Ti:Sa laser
- Compton chamber
- Collision point
- Q-triplet
- Achromatic arc section

Cs-Te Photocathode rf gun

S-band accelerating tube 8m
Compact UV laser system for rf gun

UV laser status
All solid-state and compact
Pulse energy: 10 µJ \times 100 \text{ pulse/ macro pulse}
Pulse width: 10\text{ps (FWHM)}
Pulse number: 1 – 100 pulses

We can arbitrary generate a single pulse and multi pulses (100 pulses).
Cs-Te photocathode rf gun

(in Collaborating with KEK and Waseda Univ.)

Compact Cs-Te cathode
load-lock system

BNL-type RF-gun

Delivering unit

New rf gun

Cathode plug
(Mo)

Compact evaporation chamber

Electron beam status at rf gun out

Energy: 4 MeV (40MeV at linac out)
Bunch charge: 1 nC
Bunch length: 3 ps (rms)
Bunch number: 1 – 100
(Bunch spacing: 12.6 ns )
Repetition rate: 10Hz (Max 50Hz)
Collision Laser (CPA Ti:Sa laser) for single collision LCS

**Laser Status**
- Wavelength: 800 nm
- Pulse energy: 100-140 mJ
- Pulse width: 100 fs (FWHM)

**Q-ray**
- Pulsed: 10 Hz
- Power: 7W~9W

**Q-ray**
- Pulsed: 10 Hz
- Power: 4W

**Regen**
- 200 ps
- 1200 gr/mm²

**Stretcher**
- 40 mJ
- 200 ps
- 1200 gr/mm²

**Pre. AMP.**
- 60 mJ
- Pulse pick up @10 Hz

**Main AMP.**
- 200 mJ

**Compressor**
- SESAM (PZT)
- OC
- Laser Status
- Wavelength: 800 nm
- Pulse energy: 100-140 mJ
- Pulse width: 100 fs (FWHM)

**OSC.**
- Millennia
- 79.3 MHz
- 200 mW
- 50 fs

**Vacuum pipe**
- 12480 gr/mm²

**Millennia**
- PD 79.3 MHz
- PLL circuit

**OSC.**
- PC
- PBS

**PD 79.3 MHz → PLL circuit**

**OSC.**
- SESAM (PZT)

**Pre. AMP.**
- 300 mJ

**Main AMP.**
- 200 mJ
Timing synchronization system (Low-jitter)

- Two lasers are synchronized to the master with 36th harmonics of their mode-lock frequencies.
- Relative timing jitter between the master and the laser is < 10fs.

(F. Sakai, Proceedings of SPIE, 5194, 149-156 (2003))

This synchronization system has been accomplished in order to generate 150 fs LCS X-ray in FESTA project in collaborating with SHI.
# Present beam status (single pulse collision – single pulse X-ray)

## Electron beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>20 ~ 42 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.2%</td>
</tr>
<tr>
<td>Bunch charge/bunch</td>
<td>1 nC</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>3 ps</td>
</tr>
<tr>
<td>Beam size ($\sigma_x/\sigma_y$)</td>
<td>40/30 $\mu$m</td>
</tr>
</tbody>
</table>

## TW Ti:Sa Laser beam (CPA)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length</td>
<td>800 nm</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>140 mJ</td>
</tr>
<tr>
<td>Pulse width (FWHM)</td>
<td>100 fs</td>
</tr>
<tr>
<td>Beam size ($\sigma_x/\sigma_y$)</td>
<td>30 $\mu$m</td>
</tr>
</tbody>
</table>

## X-ray beam

- Application to biological and medical research
  - In-line phase contrast imaging, K-edge imaging
  - (because of quite small size of X-ray source about 30~40 $\mu$m)

<table>
<thead>
<tr>
<th>Collision angle ($\phi$)</th>
<th>Max photon energy</th>
<th>Pulse width (rms)</th>
<th>Number of Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>~20 keV</td>
<td>150 fs</td>
<td>$\sim10^6$/s (max) @10Hz</td>
</tr>
<tr>
<td>165</td>
<td>10 ~ 40 keV (tunable)</td>
<td>3 ps</td>
<td>$\sim10^7$/s (max) @10Hz</td>
</tr>
</tbody>
</table>
Applications to biological & medical uses

1. Experimental results of in-line phase contrast imaging

2. Experimental results of K-edge imaging
**In-line phase contrast imaging for biological application**

Sample 1: lumbar vertebra of rat  
Sample 2: Hind limbs of Ovariectomized mouse (OVX*) and Normal mouse  

*OVX mouse is female mouse whose ovary is extracted and it forcibly make osteoporosis (bone disease).*

X-ray energy: 30 keV  
Detector: Blue Imaging Plate (IP)  
Exposure Time: 30 min (18000pulse)

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**Experimental Setup**

Laser Compton Scattering

0~750mm 1m 2m

IP Sample Be Window (30mmφ) X-ray Source

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H. Ikeura-Sekiguchi, R. Kuroda et al., APL 92, 131107 (2008)  
K. Yamada, R. Kuroda et al., NIMA (2009) (accepted)

[In Collaborating with Ibaraki Prefectural University of Health Sciences in Japan]
Results of in-line phase contrast imaging

1. Lumbar vertebra of rat

Distance between sample and detector
40mm
750mm

Absorption
Phase Contrast

Contrast enhancement

Comparison

2. Hind limbs of normal and OVX mouses

Normal
OVX

We can observe the bone erosion of OVX mouse which is the initial symptom of osteoporosis!

Micro-focus X-ray tube (80kV)

LCS X-ray source can realize more contrast enhancement than X-ray tube!
K-edge imaging for angiography using laser Compton X-ray source @AIST

In Collaborating with Prof. Mori Group at National Cardiovascular Center in Japan in order to research the new diagnosis for the initial symptom of the blood vessel disease (such as diabetes)

Samples:
Sample1: Resolution chart
Sample2: Rabbit ears with iodinated contrast media (K-edge: 33.17 keV)

Exposure time of 1 frame: 3ps (rms) @ single shot, 30 ps @10 shot

Detector: Real time camera (HARP) with X-ray II


K. Yamada et al., ICFA Workshop "Compton Sources for X/γ Rays: Physics and Applications“, Italy, September 2008
Real time imaging with picosecond (ps) X-ray pulse

Resolution

Single shot: 250 μm
10 shots: 125 μm

Achieved spatial resolution of single shot imaging is 480 μm!
(System optimization is not completed)

Resolution chart

Rabbit ear (iodine)

30 frame/sec
(X-ray is 10Hz)
1 frame: 3ps single shot X-ray

1 frame/sec
1 frame: 30 ps X-ray (10 shot)

1 frame/sec
1 frame: 30 ps X-ray (10 shot)
Multi-Collision Laser Compton Scattering (Multi-LCS)

Cavity length: 7.6 m @79.3MHz
Laser average energy: 100 mJ
Laser pulse number: 100
Stored laser power: 10 J

Not super cavity
Regenerative Amp. type laser cavity!

100 electron bunches × 100 laser pulses → 100 X-ray pulses

Electron beam is ready

Multi-pulse X-ray
Build-up wave form of collision laser
Laser cavity like regenerative amplification

Multi-pulse UV laser
Electron beam is ready
S-band linac
RF gun

Laser system for LCS
synchronized
Calculation of hard X-ray yield using Multi-LCS

### Parameters for calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>40 MeV</td>
</tr>
<tr>
<td>Electron charge</td>
<td>1 nC/bunch</td>
</tr>
<tr>
<td>Bunch number</td>
<td>100</td>
</tr>
<tr>
<td>Electron spot size $(\sigma_x, \sigma_y)$</td>
<td>40 µm</td>
</tr>
<tr>
<td>Electron bunch length</td>
<td>10 ps (FWHM)</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Stored laser power</td>
<td>10 J / 100 pulse</td>
</tr>
<tr>
<td>Average laser energy</td>
<td>100 mJ/pulse</td>
</tr>
<tr>
<td>Laser spot size $(\sigma_x, \sigma_y)$</td>
<td>38 µm</td>
</tr>
<tr>
<td>Laser pulse width</td>
<td>10 ps (FWHM)</td>
</tr>
<tr>
<td>Collision angle</td>
<td>170 deg</td>
</tr>
<tr>
<td>Maximum LCS X-ray energy</td>
<td>38 keV</td>
</tr>
<tr>
<td>LCS photon number</td>
<td>$5 \times 10^6$ /pulse</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Total photon yield</td>
<td>$5 \times 10^9$ /s</td>
</tr>
</tbody>
</table>

The yield of Multi-LCS hard X-ray on this design was estimated to be about $5 \times 10^9$ /s.
©Coherent THz radiation source based on S-band compact electron linac
The high power THz source

Design values

- Electron energy: 40 MeV
- Bunch Charge/bunch: 1 nC ~ 2 nC
- Bunch length: 300 fs ~ 3 ps (1σ)
- Bunch number: 1 ~ 100
- Rep. rate: 10 Hz ~ 50 Hz
- Average current: 10 μA (2 nC, 100, 50 Hz)

THz freq.: 0.1 ~ 2 THz
- Pulse energy: >10 nJ
- Peak power: >1 kW

THz-Time Domain Spectroscopy
THz imaging

- Cs₂Te photocathode RF gun
- S-band linac
- THz CSR pulse
- Ti:Sa fs-laser
- fs electron bunch

Achromatic arc.

(Bunch compressor)
Ultra short electron bunch generation

S-band compact electron linac

Laser photocathode rf gun

Achromatic arc section

S-band linac

8m

Energy distribution

Achromatic arc section

©Bunch compression using achromatic arc
Generation of THz coherent synchrotron radiation (CSR)

**Thz CSR**

- 90° Bending
- THz CSR
- 45° Bending

**Achromatic arc section**

- Q-Triplet
- Bunch length monitor
- Q1, Q2, Q3, Q4

**Generation of ultra-short electron bunch & THz CSR**

**W-band detector (WiseWave FAS-10SF-01)**

- Frequency range: around 0.1THz
- 0.075~0.11THz (2.7~4.0mm)
- Aperture: 1mm(H) X 2mm(V)
- Sensitivity: 500mV / 1mW

**W-band RF detector**

- Wave guide (WR-10)
- E-bend
- Quarts Window
- Parabolic antenna
- ATT
Coherent THz pulse

WR-10 wave guide

Parabolic antenna

Sample position

Sample

XY stage

THz detector (0.1, 0.3 THz)

Japanese Train card

Detector

Wave guide

@0.1THz

@0.3THz
**Liquid bond**

⇒ bonded by removing water ⇒ high polymer

\[
\begin{array}{c}
\text{H} \\
\text{C} \equiv \text{C} \\
\text{H}
\end{array}
\text{OCOCH}_3
\quad \rightarrow
\quad
\begin{array}{c}
\text{H} \\
\text{C} \equiv \text{C} \\
\text{H}
\end{array}
\text{OCOCH}_3
\]

Optical image

THz image

after 1 week

Polypropylene plate
Other Imaging results

○ Sample 1 Vegetable

○ Sample 2 Biological imaging (pork)

○ Sample 3 Inside of Envelope

○ Sample 4 Credit Card

- Sample 1 Vegetable
  - Vegetable
  - 5 cm
  - 0 hour

- Sample 2 Biological imaging (pork)
  - Pork
  - 3 cm
  - Fat
  - Protein
  - Envelope
  - 10 hours later
  - 9 cm
  - 14 hours later

- Sample 3 Inside of Envelope
  - Envelope
  - 9 cm

- Sample 4 Credit Card
  - Credit card with IC chip
  - @0.3THz
**THz-TDS system design**

Under development!

**Off-axis parabolic mirror**

**Sample**

**EO crystal (ZnTe)**

**1/4 \( \lambda \) plate**

**Polarizer**

**PD**

**Quartz window (z-cut single crystal)**

**Ti:Sa laser**

800nm, 50fs

**THz-pulse**

0.1~2 THz, 700fs

**Optical delay stage**

**Polarizer**

**PD**

**Fourier transform**

**Time domain**

(THz temporal distribution)

**Freq. domain**

(Spectrum distribution)

**Reference spectrum**

**Transmission spectrum**

Under development!
Summary

Laser Compton scattering X-ray source based on S-band linac

X-ray energy: 12 - 40keV (electron beam energy: 42MeV)
Photon number: >10^7 photos/s @ 10Hz

In near future, we will generate more than 10^9 /s via Multi-LCS for biological and medical applications.

Coherent THz radiation source based on S-band linac

The coherent THz radiation has been observed on S-band compact electron linac at AIST. THz scanning transmission imaging has been successfully demonstrated for many samples.

In near future, we will finish set up of the high power THz-TDS system and start the investigation of the un-researched materials in the frequency range of 0.1 - 2 THz.

Thank you for your attention!