Recent Results on X-ray Generation at LUCX

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1. LUCX (Laser Undulator Compact X-ray)

Laser Compton Scattering (LCS)

Inverse Compton Scattering
- Laser
- Several 10 MeV electron beam
  (Small accelerator)

Several 10 keV X-ray
  (like as large SR accelerators)

Property of LCS X-ray
- small source point
- monochromatic by collimation
- Tunable Energy
- short pulse (ps, fs)

\[ E_x = \frac{2\gamma^2 \cdot hc}{\lambda_L / (\cos\phi + 1/\beta)} \]

(Exam.) Laser 800 nm
0° scattering

Head-on collision
90° collision
Electron Accelerators in KEK used for LCS R&D

**Electron beam:** 1.3 GeV  
**Intensity:** $\sim 2 \times 10^{10}$ e/bunch,  
$1 \sim 20$ bunches/train, 3.12 Hz  
$\varepsilon_{x/y} \sim 1.5$ nm/4 pm

**ATF**

- Superconducting RF
- Pulsed beam: 1.3 GHz, 1 ms
- Higher energy: 60 MeV $\rightarrow$ 300 MeV
- Under upgrading

**STF**

- Normal conducting RF
- Pulsed beam: 357 MHz - 1000 bunches/pulse
- 1000 kW pulse laser stacking in optical cavity
- 24 MeV

**LUCX**

- Superconducting RF
- CW beam 100 uA $\rightarrow$ 10 mA
- 20 MeV

**cERL**

- Superconducting RF
- Pulsed beam: 1.3 GeV
- Intensity: $\sim 2 \times 10^{10}$ e/bunch,  
$1 \sim 20$ bunches/train, 3.12 Hz  
$\varepsilon_{x/y} \sim 1.5$ nm/4 pm
Since we consider the generation of short bunched electron beam, high RF gradient acceleration and short pulse laser to generate photo-electron bunch in the cavity are necessary for the generation of high quality electron beam. This is a photo-cathode RF gun.

**Old RF-gun cavity & cathode block**

Cathode block with Cs$_2$Te coating

End plate with cathode block
S-band 1.6 cell RF Gun, 100MV/m more Operation 120MV/m, achieved highest accelerating gradient 140MV/m, ~ 6 MeV

S-band 2.6 cell RF Gun ~ 8MeV

S-band 3.6 cell RF Gun ~ 10MeV
3.6 cell RF Gun

Installation

In 2010

9.6MeV beam in a week RF aging with ~20.3MW RF input power

PARMELA SIMULATION

3.6 cell RF-Gun

Start of beam acceleration test from 1/11,2012.

11MeV beam at 120MV/m, from 100 bunches/pulse to 1000 bunches/pulse beam generation was expected.
LUCX and ATF electron source: 3.6-cell RF gun

- Frequency (π-mode): 2856 MHz
- Q-value: 15000
- Coupling β: 0.99
- R/Q: 395Ω
- Mode separation (π-2π/3): 2.8 MHz
LUCX accelerator

Optical Cavity: LCS X-ray source

12-cell Booster

electron source
Photocathode RF gun

Optical Cavity
My colleagues got the X-ray Flux of $10^7$ at 12.5Hz.

Still we have problem on cavity rigidity. We need the improvement of table and installation of high reflectivity mirrors.

**Energy** 30MeV  
**Intensity** 0.4nC/bunch  
**Number of bunch** 1000  
**Beam size at the collision point** $33\mu m \times 33\mu m$  
**Bunch length** 10ps  
**Bunch spacing** 2.8ns

<table>
<thead>
<tr>
<th>Energy</th>
<th>$1.17eV(1064nm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>8mJ/pulse</td>
</tr>
<tr>
<td>Waist size(1σ)</td>
<td>$55\mu m \times 25\mu m$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>7ps</td>
</tr>
</tbody>
</table>

**Brightness** $10^{12}$  
Photon/sec/mm²/mrad² in 0.1%bw.

**Photon flux more than $10^8$ per second**

Several seconds is enough to get X-ray imaging.
2. Laser Pulse Accumulation with Burst Amplification

*LUCX Optical cavity and Laser system*
Burst mode optical enhancement cavity


Use PDH method

Main laser (CW)
CCW circulate

Scanning
Piezo
ccw trans.
cw trans.

Split
2

Amp. By QCW
amp. More
than 1000 Main path
With amp.

FB path
w/o amp.

1000 times higher peak power can be achieved on electron beam timing, which stabilized by reverse path in the optical cavity.

Main and rev. path resonate on same cavity length

K. Sakaue (Waseda univ.)
We installed the Pockels cell in order to collect the amplification power at the electron beam timing.
Burst Storage with PC

Histogram of peak power stored in the optical cavity

Power jitter is also small, about 5% in rms

1MW peak power storage was successfully achieved, but the cavity mirror was broken.
Laser power stability in the optical cavity

Stability of stored pulse intensity: 15% rms
About 0.2nm accuracy of cavity length adjustment was not achieved two years ago.

Stability of stored pulse intensity: 3.5% rms
About 0.2nm accuracy of cavity length adjustment is achieved now.

Optical cavity is not stable due to the vibration and laser injection optics drift.

2.8mJ/pulse
3. Results at LUCX
Four mirror 2D optical cavity to generate X-ray. LUCX Project

• To downsize the accelerator, we have installed a 3.6cell rf-gun and a 12cell booster.
  • 3.6cell rf-gun
    • Beam test has been started from Jan 2012.
  • 12cell booster
    • This booster was installed in last June.
Development of multi-bunch e\(^{-}\) beam at LUCX

**LUCX beam target:**
- 30 MeV, 357 MHz
- bunch spacing 2.8 ns
- more than 1000 bunches/pulse,
- beam size less than 100\(\mu\)m

**2012:** 150 bunches, 90 nC
**2013:** 300 bunches, 380 nC

**2014:** **1000** bunches, **600 nC**, **24 MeV**

Energy compensation by RF amplitude modulation
### Summary of Laser-Electron Beam Parameters at the photon-electron collision point

**Laser**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1064nm</td>
</tr>
<tr>
<td>Repetition</td>
<td>357MHz</td>
</tr>
<tr>
<td>Power</td>
<td>1MW</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>2.8mJ</td>
</tr>
<tr>
<td>Size (H)</td>
<td>60μm</td>
</tr>
<tr>
<td>Size (V)</td>
<td>25μm</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>7ps</td>
</tr>
<tr>
<td>Col. angle</td>
<td>7.5°</td>
</tr>
</tbody>
</table>

**Electron**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>22MeV</td>
</tr>
<tr>
<td>Repetition</td>
<td>357MHz</td>
</tr>
<tr>
<td>Charge</td>
<td>0.6nC</td>
</tr>
<tr>
<td>N. bunch</td>
<td>1000</td>
</tr>
<tr>
<td>Size (H)</td>
<td>40μm</td>
</tr>
<tr>
<td>Size (V)</td>
<td>70μm</td>
</tr>
<tr>
<td>Bunch length</td>
<td>15ps</td>
</tr>
<tr>
<td>Emi (H)</td>
<td>5πmmrad</td>
</tr>
<tr>
<td>Emi (V)</td>
<td>6πmmrad</td>
</tr>
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**9keV LCS X-ray Energy**
We found the present multi-pixel detector was saturated. This problem will be solved using SOI detector because of the pixel size of 17μm soon.

**Measured X-ray intensity distribution and the comparison with CAIN simulation**

**CAIN Simulation assumed following measured values.**
- Number of X-ray: 3.6x10⁷ Photons/sec
- X-ray Energy: 9keV
- Source size: 60μm x 25μm

![Graph showing X-ray flux at the HyPix-3000](image)

- X-ray energy distribution at the HyPix-3000
- Energy band width (FWHM): ~4%
- X-ray flux at the HyPix-3000: 11.83 photons/sec/pixel
  - This pixel size is 100μm x 100μm.

![Graph showing X-ray flux distribution](image)

Calculated by CAIN
LCS X-ray imaging at LUCX

X-ray detector
HyPix-3000

X-ray detector (movable)
MCP+I.I.+CCD
SOI: INTPIX4

Sample 1 for SOI, for Hypix (doubly scaled image)
Sample 2 for HyPix-3000

LCS X-ray source point
10 keV
10^7 photon/sec

Dimensions:
- 2200 mm
- 2300 mm
**X-ray detector for the X-ray imaging at LUCX/cERL**

**HyPix-3000 (Rigaku)**

High-resolution/high-speed 2D photon counting X-ray detector

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Semiconductor pixel sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>2984 mm² (77.5 × 38.5 mm)</td>
</tr>
<tr>
<td>Pixel size</td>
<td>100 × 100 µm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>775 × 385 = 298375 pixels</td>
</tr>
</tbody>
</table>

**Figure 1. Schematic view of hybrid pixel array detector**

- Hit/zero dead time
  - (>1 × 10⁶ cps/pixel)
  - (Normal: 16-bit/pixel)
- Zero dead time mode
  - at Cu Kα
  - × 180(D) mm
  - kg
**LCS X-ray imaging at LUCX**

- small source dimensions
- clear expansion of image
- edge contrast enhancement by refraction
Evaluation of present LCS performance

SR X-ray (PF-AR)
30 msec exposure for angiography

Assume the angiography by LCS X-ray, need 100 improvement

- intense electron beam
- intense laser pulse
- smaller beam size
- increase repetition rate
- ...
- small crossing angle
- higher e-beam energy
- ...

integrate challenges!

LCS X-ray (LUCX)
10 sec exposure at $10^7$ photons/sec

...still improving...

LCS X-ray (cERL)
100 sec exposure at $10^7$ photons/sec

$10^9$ photons/sec will be expected at the end of this March.
4. Summary

• We have been developing a X-ray source by a Laser Compton Scattering.

• It is a fundamental technology development to realize a compact X-ray source, which energy is several tens of keV, where a wide variety of application are expected.

• Compact LCS X-ray source can be small to fit in universities, industrial labs and hospitals, then will contribute to improve our life.
To get clear X-ray imaging every second, we have to increase the X-ray flux by factor \(\sim 10\).

**High brightness X-ray facility based on LCS**

Normal conducting accelerator system for compact high brightness X-ray under design

Thank you for your attention!

Downsizing to 6m x 8m by new technologies