October 10, 2005
ICFA Workshop on
The Physics and Applications of High Brightness Beams

“Medical Application of Multi-beams Compton Scattering Monochromatic Tunable Hard X-ray Sources”

Nuclear Professional School
University of Tokyo

Mitsuru Uesaka
# Staged Development of Compact Accelerator at University of Tokyo

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band Linear</td>
<td>User Facility</td>
</tr>
<tr>
<td>Accelerators</td>
<td>Application: Radiation Chemistry/Physics, Beam Physics</td>
</tr>
<tr>
<td>RF</td>
<td>2.856 GHz</td>
</tr>
<tr>
<td>Gradient</td>
<td>10 MV/m</td>
</tr>
<tr>
<td></td>
<td>Size: Building</td>
</tr>
<tr>
<td>X-band Linear</td>
<td>Proto-type Development</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Application: Dual-Energy/Subtraction X-ray CT for Medical Use</td>
</tr>
<tr>
<td>RF</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Gradient</td>
<td>40 V/m</td>
</tr>
<tr>
<td></td>
<td>Size: Room</td>
</tr>
<tr>
<td>Laser Plasma</td>
<td>Beam Physics</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Size: Table-top</td>
</tr>
<tr>
<td>RF</td>
<td>10〜100 THz</td>
</tr>
<tr>
<td>Gradient</td>
<td>~ 100GV/m</td>
</tr>
</tbody>
</table>
Development of Advanced Compact Accelerators

Virtual Laboratory

Japan Atomic Energy Research Institute
Hiroshima University
Kyoto University
High Energy Accelerator Research Organization
National Institute of Radiological Sciences
The University of Tokyo
Osaka University
Advanced Industrial Science and Technology
Japan Nuclear Cycle Development Institute
Monochromatic Tunable Hard X-ray Source by X-band-linac/YAG-laser Compton Scattering

Scale of system: less than 5m x 5m (with the power supply)

Price: ~4 million dollars

X-ray energy (max.): 10~50 keV

X-ray intensity: >10^9 photons/s (total)

Total Cross Section of X-ray attenuation for various elements
Monochromatic Hard X-ray by Compton Scattering

\[ \lambda_r = \frac{\lambda_L}{2\gamma^2} \left(1 + \frac{1}{2} K^2 \right) \]

(K: Wiggling angle of electron)

\[ \lambda_L \approx 1 \mu m \quad \text{(laser wavelength)} \]

\[ \gamma \leq 10^2 \quad (50 MeV) \]

\[ \lambda_{\gamma} \leq 1 \AA \quad \text{(X-ray)} \]

X-ray energy vs Angle
First and Second Generation Inverse Compton Scattering X-ray Sources

First Generation
MXI Sys/Vandervilt, PLEADES, U.Tokyo/KEK/JAERI, Sumitomo etc.
- Single-electron-single-laser Compton scattering
- First demonstration and application
- Intensity up to only $10^6$ photons/s
- Rather large fluctuation due to the time-jitter between electron and laser pulses

Second Generation
U.Tokyo, Lyncean Tech.(R.Ruth), Sumitomo/AIST, etc.
- Multi-scattering of electron- and laser-pulses
- Intensity of more than $10^8$ photons/s
- A variety of applications for medicine, protein structural analysis, security and nuclear engineering
## Performance of Linac/Laser Inverse Compton X-ray Source

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Electron Energy</th>
<th>Charge</th>
<th>Wavelength &amp; Power of Laser</th>
<th>X-ray Energy &amp; Intensity</th>
<th>Uncertainty of X-ray Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHI[1]</td>
<td>14 MeV (S-band)</td>
<td>400 pC Single Bunch</td>
<td>800 nm, 300 mJ, (Ti:Sapphire, 300 ps)</td>
<td>3.5 keV &lt; 1.0E+4 photons/shot</td>
<td>50%</td>
</tr>
<tr>
<td>MXI Systems Inc[2]</td>
<td>25 MeV (S-band)</td>
<td>500 pC Single Bunch</td>
<td>1 μm, 20 J (Nd:Glass)</td>
<td>12~50 keV 1.0E+8 photons/sec</td>
<td>50%</td>
</tr>
<tr>
<td>LLNL[3]</td>
<td>57 MeV (S-band)</td>
<td>250 pC Single Bunch</td>
<td>780 nm, 400 mJ, (Ti:Sapphire, fs)</td>
<td>40~80 keV 1.0E+7 photon/sec</td>
<td>50%</td>
</tr>
<tr>
<td>SLAC</td>
<td>60 MeV (S-band)</td>
<td>500 pC Single Bunch</td>
<td>800 nm, 300 mJ, (Ti:Sapphire, fs)</td>
<td>20~85 keV 1.0E+8 photons/s</td>
<td>80%</td>
</tr>
<tr>
<td>Univ. of Tokyo /NIRS/KEK[4]</td>
<td>35 MeV (X-band)</td>
<td>20 pC×10000 Multi Bunches</td>
<td>1 μm, 2 J, (Nd:YAG, 10 nsec)</td>
<td>33 keV 1.0E+8 photons/s</td>
<td>&lt;10%</td>
</tr>
</tbody>
</table>

# Performance of Typical Monochromatic Tunable Hard X-ray Source

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Source of X-ray</th>
<th>Changing method of X-ray Energy</th>
<th>X-ray Intensity</th>
<th>Changing time</th>
<th>Intensity Fluctuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK, SPring-8, etc</td>
<td>SR</td>
<td>Diffraction grating</td>
<td>$10^{11}$ photons/sec</td>
<td>~ 10 min.</td>
<td>&lt; 10 %</td>
</tr>
<tr>
<td>Univ. of Tokyo/NIRS/KEK</td>
<td>Compton Scattering</td>
<td>Wavelength of Laser</td>
<td>$10^8$ photons/sec</td>
<td>~ 40 msec (@ 25 Hz)</td>
<td>&lt; 10 %</td>
</tr>
</tbody>
</table>

Compton scattering hard X-ray source

Compact hard X-ray source based on Compton Scattering

Properties of the generated X-ray

<table>
<thead>
<tr>
<th>Electron beam energy : 35 MeV, Charge : 20 pC/bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength (nm)</td>
</tr>
<tr>
<td>Pulse energy (J/pulse)</td>
</tr>
<tr>
<td>X-ray yield (photons/pulse)</td>
</tr>
<tr>
<td>Maximum X-ray energy (keV)</td>
</tr>
<tr>
<td>Energy spread (%) rms</td>
</tr>
</tbody>
</table>

Details are in RPAP006 and WPAP019

The X-ray energy can be changed quickly (40ms) by introducing two lasers

10 pps with laser circulation
医療用小型ライナック室

電波発生装置

電子発生装置
System of Beam-Experiment
Laser circulation system

RF pulse length: ζ 10000 bunches
Laser pulse length: 10 ns (FWHM)
ζ collide with 110 bunches

Increase X-ray yield by re-incident the laser light.
21 ns per a revolution ζ 47 revolutions per 1ms

Enhancement:
- 10 times (max.) with 90% transmission per revolution: \(10^9\) photons/s
- 100 times with 5J pulse and laser power compensation by Nd:YAG rod: \(10^{10}\) photons/s

Laser pass length per circulation: 6.4m (21ns)
**Experiment**

We are doing a proof-of-principle experiment for the laser pulse circulation system. Purposes of the experiment are:

- Proving enhancement of the laser intensity in the circulation system.
- Measurement of the revolving laser, the transmission efficiency and the enhancement amount.
- Establishment of a technique to control the laser beam profile at the collision point in order to apply the system into the hard X-ray source.

<table>
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<th>Property of the Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>$\lambda = 532$ nm</td>
</tr>
<tr>
<td>Q-switch Nd:YAG Laser</td>
</tr>
<tr>
<td>(2nd harmonic)</td>
</tr>
<tr>
<td>Pulse Energy</td>
</tr>
<tr>
<td>25 mJ/pulse @532nm</td>
</tr>
<tr>
<td>Pulse Width</td>
</tr>
<tr>
<td>3.5 ns (FWHM)</td>
</tr>
</tbody>
</table>

**Control of the Beam size at the Collision Point**

The beam size at the collision point $\sigma_0$ (rms) is

$$\sigma_0 = M^2 \frac{\lambda}{4\pi} \frac{f}{\sigma_f}$$

where $\sigma_f$: Beam size at the focusing lens, $f$: Focal length of the focusing lens.

The beam size at the collision point is controlled outside of the circuit.

**Control of the Beam Position at the Collision Point**

The beam position at the collision point is

$$r = x\theta + l$$

$\theta$: Angle of the mirror before the collision point (0.02° accuracy).

$\theta$: Rough Control

$l$: Position of the focusing lens (5µm accuracy).

$\theta$: Precise Control

To avoid an error due to circulation, we move the lens and mirror after the collision point equally to the focusing lens and the mirror before the collision point.

**Results**

The laser pulse revolves more than 50 times (650 ns). Attenuation of the laser pulse energy at 400 ns (the 30th revolution) is approximately 80%.

- The transmission efficiency is larger than 90% ($A > 0.9$).
- Using the circulation system, the X-ray yield will become more than 10 times.

Therefore,

**the monochromatic hard X-ray source will generate at least** 10$^9$ photons/sec **with the laser pulse circulation system!**

**Summary**

- We develop the laser pulse circulation system for the compact monochromatic hard X-ray source.
- Using this system, the X-ray yield will become 10 times larger.
- In the experiment, the transmission efficiency was larger than 90% and the laser intensity became more than 10 times.
- We do further experiments for laser profile control at the collision point.

**REFERENCES**

Applications

- Static/dynamic imaging by 100 µm spatial resolution

- Dual energy X-ray CT to get 3D distributions of atomic-number- and electron-densities for light atoms up to $^{43}$Tc

- Subtraction CT across the K-edge to get 3D distribution of specified atoms

- Protein structural analysis
Energy differences in a finger or in a body, such as a mouse

19 keV 29 keV

Energy movie from 15 keV to 33 keV

We have the ability to specifically tune the X-rays to the imaging task at hand.
John Lewin, M.D.- University of Colorado Health Sciences Center:

High Energy - Low Energy = Iodine Image
Stylized diagram of an atom:

Each electron is bound in its orbit by a characteristic energy for that particular atom/orbit. This is called its binding energy. The binding energy is different for each atom in the periodic chart.

Our beam can be tuned to just the right energy to knock the k-shell electron out of its orbit. For the Iodine atom that energy is 33.2 keV.
Ultra Micro-vessel Angiography for Diabetic Femur and Thrombus @ NCVC (National CardioVascular Center)

X-ray tube (50kVp) with high-sensitivity HARP camera

HARP (High-gain Avalanche Rushing amorphous Photoconductor) camera

Micro-vessels visualized by contrast agent

Imaging area:
20cm × 20cm
Space resolution:
25 µm

X-ray phospher

HARP

C-Arm

50 keV X-ray tube

Small blood vessels in femur

Signal electrode
amorphous-Se

Avalanche multiplication

electron

light

hole

Scanning beam
e- gun
## Ultra Micro-vessel Angiography by Compact Monochromatic Hard X-ray Source

### Ultra Micro-vessel angiography by monochromatic hard X-ray

- 30 images/s
- Space resolution: 25 μm

**Required photon intensity**

\[ 4.8 \times 10^{10} \text{ photons/mm}^2/\text{s } @33-35\text{keV} \]
\[ 4.8 \times 10^{9} \text{ photons/mm}^2/\text{s } @51-54\text{keV} \]

### Compact hard X-ray source based on electron-laser collision

- 10 times circulated laser colliding with electron

**Expected photon intensity**

\[ 2 \times 10^{7} \text{ photons/mm}^2/\text{s } @33-35\text{keV} \]
\[ 1 \times 10^{7} \text{ photons/mm}^2/\text{s } @51-54\text{keV} \]

### Angiography by the compact hard X-ray source

- High-sensitivity HARP camera
- 10 images/s
- Pixel size (100 μm × 100μm)

- Photon intensity is reduced
- Angiography can be performed!
  (Space resolution: 100 μm)

### Future plan to perform ultra micro-vessel angiography

High power laser (7J/pulse), 40 times circulated laser, Wide length of electron macro pulse and Small light spot (25 μm diameter) etc…  

> Space resolution: 25 μm
3D Evaluation of Atomic Number Distribution

1. Light Atoms up to $^{43}\text{Tc}$
   - Interpolation of the X-ray attenuation constant between characteristic edges is available.
   - 3D distributions of the atomic number density and electron density can be obtained
   - Their spatial resolution is determined by the X-ray source size.

2. Heavy Atoms
   - The interpolation does not work.
   - Subtraction CT gives 3D distribution of specified atoms.
Linear attenuation coefficient is approximately written as a function of $Z$ and $E$

\[
\mu \approx \rho \frac{N_A}{A} Z \left( 4\sqrt{2} Z^4 \alpha^4 \left( \frac{mc^2}{E} \right) f_{\text{al}} + \sigma_{\text{KN}} + \frac{Z(1-Z^{-1})}{Z^2} \sigma_{\text{SC}}(Z', E') \right)
\]

\[
= \rho \left( Z^4 F(Z, E) + G(Z, E) \right)
\]

Effective atomic number and electron density are derived from linear attenuation coefficients for two energies

\[
\mu(E_1) = \rho_e \left( Z^4 F(Z, E_1) + G(Z, E_1) \right)
\]

\[
\mu(E_2) = \rho_e \left( Z^4 F(Z, E_2) + G(Z, E_2) \right)
\]

**Effective atomic number**

\[
Z^4 = \frac{\mu(E_2)G(Z, E_1) - \mu(E_1)G(Z, E_2)}{\mu(E_1)F(Z, E_2) - \mu(E_2)F(Z, E_1)}
\]

**Electron density**

\[
\rho_e = \frac{\mu(E_2)F(Z, E_2) - \mu(E_1)F(Z, E_1)}{F(Z, E_2)G(Z, E_1) - F(Z, E_1)G(Z, E_2)}
\]

Dual-energy X-ray CT experiment

- monochromatic X-ray ($E_1$)
- monochromatic X-ray ($E_2$)

Torikoshi (NIRS), et al.
Dual-energy X-ray CT by SR light sources

Electron density and atomic number have been measured for biological materials consist of light elements (Z<20) [1,2]

$\rho_e$ measurement

Precise electron density can be measured in agreement with 1% of the theoretical values
(X-ray energy : 40 keV, 70 keV)

Volume rendering of a rat

Volume data of a rat are constructed
(X-ray energy : 40 keV, 70 keV)

Dual-energy CT for atomic number identification in a material

Can we apply the method to medium Z elements?

- The dual-energy analysis cannot be used below K-edge energy of a atom
- When maximum X-ray energies are 21.9 keV and 43.8 keV, elements up to Z = 38 should be identified
- Energy spread $\Delta E/E$ of the monochromatic X-ray
  SR light : $10^{-1} - 10^{-2}$ % (negligible), Compact X-ray source : 1 to 10%

Numerical simulation to examine applicability
Applicability of the dual-energy analysis

Assuming a point light source
Pixel size: 0.1 to 1.0 mm
Electron beam energy: 35MeV
Laser wavelength: 1064nm, 532nm
Maximum X-ray energy: 21.9keV, 43.8keV

Energy spread $\Delta E/E : 1$ to 10%

X-ray energy depends on the position on the detector

Pixel size: 0.5mm
$\Delta \theta$: less than 0.2 mrad
$\Delta E/E$ in a pixel: 0.1%

Effective atomic number simulated by considering the X-ray energy profile

Effective atomic number calculated at each pixel

Average of the effective atomic numbers

$\Delta Z/Z < 3\%$ (rms)
CT simulation for low to medium Z elements

Geometry of the CT system

Sample 1 (low Z elements)
Atomic number distribution
Sample
Reconstructed image

Sample 2 (medium Z elements)
Atomic number distribution
Sample
Reconstructed image

Cylindrical sample contains low to medium Z elements is simulated
Atomic number identification for material inside iron can (EGS4 test geometry) (**Radiography****)

X-ray(114,117,120,123keV)

Fe(2.6mm)
thickness=0.5mm

10cm camera

Air (inside)
X-ray distribution at CCD camera (just a plot. Pixel size is not considered)
Application plans of the compact hard X-ray source

Atomic number identification by dual-energy X-ray CT

- Nondestructive test
- Radiation Treatment Planning
- Neutron radiography with X-ray CT
  - Imaging of water in a plant [3,4]

Element analysis inside a package

Dose calculation by considering elements in a tumor for advanced radiation therapy

Micro vessel angiography

- Image of coronary [5]
- Diameter of micro vessel is less than 100μm
- Micro vessel angiography will be tested with spatial resolution of 100μm

Compact monochromatic hard X-ray source

- Movement of a element in a living plant

Protein structural analysis

- Structure analysis in a small laboratory
Scheme of CCB X-Ray Testing System

Compact Compton Backscattering

Hard X-ray Source (UTNL)

Photon energy:
10 ~ 50 keV

Ex. T = 10 ns
N = 10/sec
P_S = 10^7 photons/shot
P_F = 10^8 photons/s
~ 10^9 photons/s; laser circulation

Periodic Motion of Sample (< 200 Hz)

X-ray source (tunable, pulsed)

Tunable Collimator

N/sec

HARP-based detector (NHK)

CCD type detector

Active area: 21cm x 21cm
Spatial resolution: 90 μm
(~ 0.5 MUSD)
Applications of Hard X-ray and Nano Particles for Cancer Therapy and Diagnosis

Polymeric micelles for drug delivery

- Application for cancer therapy
- Site-specific targeting and accumulation by micelles

Tumor targeting

- Normal cell
- Blood flow
- No way out
- Lymphatic system
- Leaky vessel wall
- Cancerous cell

X-ray application for cancer therapy and diagnosis with micelles

**Diagnosis**

- X-ray imaging of tumors
- Contrast agent including iodine delivered and accumulated by micelles

**Therapy**

- Enhanced radiation damage to cancer cells targeted and stimulated by micelles with specific agents
- X-ray irradiation to micelles for nucleic acid and protein delivery to cancer cells

Ref.

K. Kataoka lab. http://bmw.mm.t.u-tokyo.ac.jp
4D(space and time) control of Chemo-radiology

M.Uesaka(Nuclear Engineering Research Laboratory, Univ.Tokyo)
K.Nakagawa(Department of radiology, Univ.Tokyo Hospital)

1. Advanced compact accelerators available at hospital
   - higher RF(C,X,Ka,Ku,W-bands)
   - Compton scattering hard X-rays
   - compact ion accelerator
   - Table-top TW laser

2. Spatial control
   (i) X-ray and electron
     - IMRT
   (ii) Compton scattering hard X-rays
     - Intravenous angiography
     - Auger electron therapy
   (iii) Precise spatial dosimetry
     - new material and phantom

3. Temporal control
   - simulation and diagnosis for circulatory system(medicine, contrast agent, Au powder)
   - Timing control of irradiation
   - detection and control of oxygen content
   - radiation chemistry of bio-water and control of OH radical content
   - simulation and diagnosis of blood flow in capillary
   - PET analysis

4. Upgrading and optimization by integrated treatment program
Structure of RF Gun

Thermionic Cathode
System of RF Gun Aging

Measurement by Oscilloscope

Gun

α Magnet
Trouble Point

Discharge @ RF Window (12MW)

- Discharge of multi-pactaring

In addition, We could not see discharged signature at Gun side.

Worse vacuum at upstream

Amplified discharge
Discharged Signatures
Cathode
New Beam Line
We can evaluate the characteristics of the gun with 400ns pulse.
Return loss at the gun

![Return Loss Graph]

- Return Loss [dB] vs Frequency [MHz]
  - Y-axis: Return Loss [dB]
  - X-axis: Frequency [MHz]
  - Data points indicate return losses at various frequencies.
Development of an S-band RF Window for Linear Colliders
A.MIURA and H.MATSUMOTO
KEK Preprint 92-215 March 1993 A

Discharged signatures remain like shape of 8.
付録B ガスケット・カソード周辺詳細図および写真
Design of New Compact Stereotactic X-band Therapy Machine

Stable and high-current commercial S-band machine, but large

Compact X-band (9.3GHz) machine, but unstable and low-current

This stability and high-currents

This size
Schematic layout of compact accelerator using multi-beam klystron (Type 1)

Structure of standing wave acc. tube

RF input

RF output

Drift tube

Pole piece

Cathode

10 MeV triode thermionic gun

50 kV power supply

Multi-beam klystron (20)

Electron beam
Schematic layout of compact accelerator using multi-beam klystron (Type 2)
## Hard X-ray Sources by Thomson Scattering

<table>
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<td>3.5keV &lt;1.0E+4 photon/shot</td>
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<td>20pC x 10000 Multi bunch</td>
<td>1μm, 2J (Nd:YAG, 10ns)</td>
<td>33keV &lt;1.0E+8 photon/sec</td>
</tr>
<tr>
<td>Univ.Tokyo/NIRS</td>
<td>~10MeV (Laser Plasma Acc.)</td>
<td>&gt;10pC Single bunch</td>
<td>800nm, 300mJ (Ti: Sapphire, 40fs)</td>
<td>10-20keV &lt;2.0E+7 photon/sec</td>
</tr>
</tbody>
</table>


### Therapy Accelerator

<table>
<thead>
<tr>
<th>Accelerator Type</th>
<th>Average Current</th>
<th>Peak Current</th>
<th>Repetition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Medical Linac Acc.</td>
<td>~30mA</td>
<td>~500 mA (3μs)</td>
<td>300Hz</td>
</tr>
<tr>
<td>Laser Plasma Acc.</td>
<td>~100 pA</td>
<td>~200 A (~50fs)</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
Waveform of Oscilloscope

- 160ns
- Current Transformer
- Output of Klystron RF
- Flash at RF window (PMT)
- Reflection from RF gun
History of RF aging of RF-gun