To uncover hotspots of radiation with a Si/CdTe Compton Camera

-- Recovering from the tragedy --

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1. Effects caused by the nuclear accident at Fukushima

2012/June 22-28

Radiation Level

Cs134/137 Bq/m³

Quick removal of dust with radioactive materials (decontamination) is essential

http://radioactivity.nsr.go.jp
### 3. Our Challenges, since the first e-mail in April/2011

<table>
<thead>
<tr>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Quake March 11</td>
<td>A-H SGD Type (2011)</td>
<td>Commercial ASTROCAM-7000HS</td>
</tr>
<tr>
<td>Proto Type (2011)</td>
<td>A-H SGD Type (2011)</td>
<td></td>
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<tr>
<td></td>
<td>Demonstration Type (2012)</td>
<td></td>
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<tr>
<td>Earthquake in April 2011</td>
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</tbody>
</table>

HSTD9, 2013
4. Requirements for “Gamma-Camera” in Fukushima

1. Spectral Resolution (need to identify $^{134}$Cs, $^{137}$Cs : ~3%)
2. Image (Larger FOV is better)
3. Angular Resolution (a few degrees)
4. Efficiency (Shorter exposure is better)
5. Portability

6. Availability
   (People in Fukushima really need this kind of device, now.)

Spectrum taken in Fukushima

![Spectrum graph showing peaks at 605 keV, 662 keV, and 796-802 keV corresponding to $^{134}$Cs and $^{137}$Cs.]

HSTD9, 2013
5. Our technology - Si/CdTe Compton Camera -

\[
\cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)
\]

Si and CdTe are the best match to realize semiconductor based Compton Camera (Si/CdTe Compton Camera)

Si : Good scatterer ← High $\sigma_{\text{Compton}} / \sigma_{\text{PhotoAbs}}$ Ratio

CdTe : Good absorber ← High stopping power.

5. Our technology - Si/CdTe Compton Camera -

\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \]

Si and CdTe are the best match to realize semiconductor based Compton Camera (Si/CdTe Compton Camera)

Si: Good scatterer ← Low Doppler Effect (Low Z)

Angular Resolution (ARM)

\( \theta_G \)

\( \theta_K \)

\( \Delta \theta (\text{ARM}) \)

5. Our technology - Si/CdTe Compton Camera -

Large FOV (180x180 deg)
10 times larger than existing gamma cameras

Good Energy resolution
(2.2 % @ 662 keV)
5. Our technology - Si/CdTe Compton Camera -

Key Technology - High Resolution CdTe Imager -

1. Thin device (0.5 – 2.0 mm)
2. Schottky diode
3. Guard ring

- Extremely low leakage current
- High bias voltage

Best spectra we presented 10 years ago.

- (3x3 mm, 1 mm\text{t})
- (2x2 mm, 0.5 mm\text{t})

Low work function metal (In or Al)

Takahashi et al. 1998
with ACRORAD

Full charge collection
(NO TAIL)
5. Our technology - Si/CdTe Compton Camera -

- High energy/position resolution & high uniformity are quite important.

-20deg

 Applied bias: 250 V
 \( \Delta E: 1.7-1.9 \text{ keV at } 60 \text{ keV} \) (FWHM)
 Low threshold: 5 keV

250 micron pitch strips for both side

Watanabe et al., 2011
Doppler effect in Si limits the angular resolution.

- **Si**: $\Delta E = 1.6$ keV
- **CdTe**: $\Delta E/E = 1\%$

Si: 400 $\mu$m DSSD
CdTe: 1.4 x 1.4 mm pixel

**Angular Resolution of a Si/CdTe Compton Camera**

Energy Resolution + Doppler broadening

Position resolution

$1 \text{ deg}$

Takeda et al. 2008
7. Performance of the first prototype

- $^{133}\text{Ba}$
- $^{137}\text{Cs}$
- $^{22}\text{Na}$
7. Performance of the first prototype

Compton camera

137-Cs (662 keV)

Field of view

Only 20 % down @ 80 deg

Large FOV of ~2π str., Angular resolution 3.8 deg

Takeda et al. (2012)
Si/CdTe Compton Camera went to Fukushima.

Optical image taken with a fish-eye lens

Select lines, directly emitted from Cs, to avoid scattered component
An image shot by the Ultra-Wide-Angle Compton Camera showing the intensity (flux) distribution of gamma rays of 605, 662, 796, and 802 keV directly emitted from Cesium-134 and 137. Red is high intensity while blue is low.
8. Demonstration in Fukushima - Part 1 -

Point Spread Function for a point source

Takeda et al. (2013)
8. Demonstration in Fukushima - Part 1-

An image shot by the Ultra-Wide-Angle Compton Camera showing the intensity (flux) distribution of gamma rays of 605, 662, 796, and 802 keV directly emitted from Cesium-134 and 137. Red is high intensity while blue is low.

Contour on the Back projection Image

Intensity

Significance

180 deg

(back ground \( \sim 3 \mu Sv/h \))
An image shot by the Ultra-Wide-Angle Compton Camera showing the intensity (flux) distribution of gamma rays of 605, 662, 796, and 802 keV directly emitted from Cesium-134 and 137. Red is high intensity while blue is low.

30 µSv/h
9. Further Improvements

- **Higher sensitivity (Shorter Exposure)**
- **Portability**

  - 0.6 mm thick Si Pixel + 0.75 mm thick CdTe Pixel
  - 3.2 by 3.2 mm pixel size for Si and CdTe

First Demonstration Type (2011)

Use the design of the ASTRO-H SGD Compton Camera

see Watanabe’s talk in this session

ASTRO-Hに搭載される軟ガンマ線検出器

30 times higher sensitivity

10 times higher sensitivity (reasonable price)

Supported by the JST Program
"development of systems and technology for advanced measurement and analysis" (2012-)
9. Further Improvements  
(Same design as the ASTRO-H SGD Compton Camera)

- 32 layers of Si  
  (~2 cm in total)  
- 8 layers of CdTe  
- 2 layers of side CdTe

see Watanabe’s talk in this session

### Si Pixel (Pad) detector

<table>
<thead>
<tr>
<th>45%</th>
<th>19</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>FWHM 1.7 keV @122 keV</th>
</tr>
</thead>
</table>

### CdTe Pixel (Pad) detector

<table>
<thead>
<tr>
<th>57Co</th>
<th>FWHM 1.1 keV @59.5 keV</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>241Am</th>
<th>FWHM 1.1 keV @59.5 keV</th>
</tr>
</thead>
</table>

HSTD9, 2013
10. Vast Improvements

(10 cm)

Still very comact

137-Cs, 2.7 MBq @ 1 m

Efficiency 0.03 cps/MBq @ 137-Cs, 1m

→ 1.1 cps/MBq @ 137-Cs, 1m

※First Prototype (2012) took 5 min.

10 sec!
We can learn a lot from the real detector

Ex. Scattering Sequences

Multi Hit Analysis

Field of view

Multi Hit Analysis Included

Si (1hit) + CdTe (1hit) event only

Ichinohe et al. (2013)
### Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>445L x 340W x 235H (mm)</td>
</tr>
</tbody>
</table>
| View Angle             | 180 degrees (ultra-wide)  
< detection efficiency depending on angular positions > |
| Weight                 | Approximately 8 ~ 13kg (Camera Unit Only)  
< depending on specifications > |
| Power Source           | AC100V~240V and Battery |
| Operating Temperature  | 0 to 40 degrees Celsius |
| Storage Temperature    | 0 to 50 degrees Celsius |
| Operating Humidity     | 35 to 80% (Non-condensing) |
| Auxiliaries            | Camera Controller Box, Laptop PC, Visualization Software |

*All specifications may be changed without notice*

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ISAS/JAXA* and Mitsubishi Heavy Industries have developed a camera using cutting-edge, high-resolution radioactive sensor technology developed for the ASTRO-H* satellite. A visible light image is overlapped with a radioactive image into one display.

**Visualization of radiation distribution**

**High direction resolution**

**Capability of measuring radioactive energy bands**

**Identification of radioactive materials**

The system is capable of measuring the energy bands of Sodium22, Cobalt60, Iodine131, Barium133, Cesium134, Cesium137 and others.
12. ASTROCAM-7000HS (Our technology goes to the market)

Status
Operation
Nucleid

137-Cs
133-Ba
22-Na

Spectrum
Light Curve

HSTD9, 2013
12. ASTROCAM-7000HS (Our technology goes to the market)

Performance

137-Cs

662 keV
$\Delta E/E = 2.2 \% \text{ (FWHM)}$

Angular Resolution (ARM)

5.4 ° (FWHM)

Pixel size (~3 mm) is optimized to get required angular resolution
14. Summary

1) Space science missions require cutting edge technology due to its high scientific requirements (e.g. X-ray Satellite ASTRO-H)

2) We are now able to access all the technologies which are necessary to make the next-generation CdTe-based gamma-ray imager (ASTRO-H Hard X-ray Imager & Soft Gamma-ray Compton Camera)

3) Si/CdTe Compton camera has been demonstrated in Fukushima as a “Gamma Camera” with high angular resolution (a few degrees at ~600 keV). The camera meets the requirements. 3D Imaging is possible by multiple pointing.

4) Our technology has been transferred to the industry. “Ultra-wide angle Compton Camera” is now commercially AVAILABLE.
A. Appendix

1) Space science mission requires cutting edge technology due to its high Scientific Requirements

2) We are now able to access all the technologies which are necessary to make the next-generation CdTe-based gamma-ray imager (ASTRO-H HXI&SGD)

3) Our Si/CdTe Compton Camera can be applied to various fields. One example is...

4) Still need further efforts to reach the final goal.

See presentation by Takeda, today (MIC 5-7)

Takeda et al. 2011
3D Imaging

Stereoscopic Observation of Mouse (ISAS/JAXA, Gunma U., JAEA)

Yamaguchi et al (2009)

CdTe/CdZnTe seem to be the only candidate at least, at this moment

- High Z semiconductor ($Z_{Cd} = 48$, $Z_{Te} = 52$), $\rho = 5.9 \text{ g/cm}^3$
- Room Temperature Operation or Cool Environment

<table>
<thead>
<tr>
<th>Material</th>
<th>Ge (77K)</th>
<th>Hgl$_2$</th>
<th>CdTe</th>
<th>CdZnTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>32</td>
<td>80, 53</td>
<td>48, 52</td>
<td>48, 30, 52</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>0.74</td>
<td>2.13</td>
<td>1.50</td>
<td>1.57</td>
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<tr>
<td>Energy per e-h pair (eV)</td>
<td>2.97</td>
<td>4.2</td>
<td>4.4</td>
<td>4.6</td>
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<tr>
<td>Fano factor</td>
<td>0.08</td>
<td>0.19</td>
<td>0.11</td>
<td>0.09</td>
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<tr>
<td>$\mu_e$ (cm$^2$/Vs)</td>
<td>40,000</td>
<td>100</td>
<td>1100</td>
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<td>$\mu_h$ (cm$^2$/Vs)</td>
<td>40,000</td>
<td>4</td>
<td>100</td>
<td>10</td>
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<tr>
<td>$\tau_e$ (s)</td>
<td>$10^3$</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$\tau_h$ (s)</td>
<td>$10^3$</td>
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<td>$10^6$</td>
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Takahashi and Watanabe (2000)