Development of Next Generation Compton Gamma-ray Telescope

Hiroyasu Tajima
Stanford Linear Accelerator Center

May 3, 2004
UC Santa Cruz
Collaboration

H. Tajima, T. Kamae, G. Madejski, E. do Couto e Silva
Stanford Linear Accelerator Center

T. Takahashi, K. Nakazawa
Institute of Space and Astronautical Science

Y. Fukazawa
Hiroshima University

M. Nomachi
Osaka University

D. Marlow
Princeton University

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
Outline

• Concept.
• Science.
• Key features (requirements.)
• Instrument description.
  ▪ Low noise front-end VLSI.
• Results.
  ▪ Noise Performance.
  ▪ Energy resolution.
  ▪ Angular resolution, background rejection.
  ▪ Polarization measurements.
Introduction

• **Gamma-ray Astrophysics**
  - Photon is a great probe to study Universe.
    • Universe is transparent to photons.
      - up to TeV scale.
    • No effect from magnetic field.
  - Gamma-ray allows us to study energetic and dynamic process beyond thermal equilibrium.
- Gamma-ray telescopes must be in space.
  - Atmosphere is not transparent for gamma-ray.
• No approved mission to cover 0.1–20 MeV energy band.
  ▪ Sensitivity is mostly limited by BG.

Next Generation Compton Telescope, H. Tajima, UCSC, MAY 3, 2004
Multiple Compton Technique

\[
\begin{align*}
\cos \theta_1 &= 1 + \frac{m_e c^2}{E_1 + E_2 + E_3} \left( \frac{m_e c^2}{E_2 + E_3} \right) \\
\cos \theta_2 &= 1 + \frac{m_e c^2}{E_2 + E_3} \left( \frac{m_e c^2}{E_3} \right)
\end{align*}
\]

Proposed by T. Kamae \textit{et al.} 1987
Science Objectives

• **Wide Field-of-view (FOV)**
  - All sky survey in soft gamma-ray band.
  - Time variability monitor.
    - Supernovae
    - Flares (Blazars, AGNs, Solar corona).
    - Gamma-ray burst
  - New discovery.

• **Narrow FOV**
  - Low background, better sensitivity.
    - Faint objects.

• **Particle acceleration**
  - Supernova remnants.
  - Galaxy clusters.

• **Polarization.**
Supernovae Science

- Nucleosynthesis of supernovae.
  - Nuclear gamma-ray lines.
  - Distinguish type Ia supernovae explosion models.
    - $^{56}\text{Ni}$ distribution vs. light curve and/or line profile.
    - Crucial for measurement of cosmic expansion acceleration.

---

Next Generation Compton Telescope, H. Tajima, UCSC, MAY 3, 2004
Expected Nuclear Lines from SNe Ia

Expected $^{56}\text{Ni}$ and $^{56}\text{Co}$ nuclear lines from SNe Ia

- Delayed-detonation model
- Deflagration model
- Helium-triggered detonation model

$^{56}\text{Ni}$ (0.812 MeV)

$^{56}\text{Co}$ (0.847, 1.238 MeV)

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
Active Galactic Nuclei (AGN)

- **Unified scheme for AGN**
  - Super-massive back holes ($10^6 - 10^{10}$ solar mass)
  - Different phenomenology is due to the orientation of jet with respect to the line of sight.
  - Quasars, seyfert galaxies, radio galaxies and blazars.

HST Image of M87 (1994)
AGN Spectra

- Multi-wave analysis is crucial to understand photon production mechanism in AGNs

SSC model constraints (Synchrotron Self-Compton)

\[ \square_{HE} = \frac{4}{3} n_e \square_{LE} \]

\[ \square_{LE} = 3.7 \times 10^6 B \square_{LE} \frac{\square}{1 + z} \]

\[ L_{HE} = \frac{U_{-sync}}{U_B} \]

\[ L_{LE} = 4 \pi R^2 c \theta^4 U_{sync} \]

Next Generation Compton Telescope, H. Tajima, UCSC, MAY 3, 2004
Gamma-Ray Bursts (GRB)

- Diverse time variability

- Short (0.4s) burst
- Double peaked
- ~100 s
- Multiple episodes

Many short bursts in multiple episodes

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
GRB Properties

- Isotropic spatial distribution: cosmological origin.
- Two categories of GRBs: “long” and “short”.
  - Afterglow of “long” GRBs facilitates extensive studies in optical and radio band.
    - Leading candidate: Hypernova
  - “Short” GRBs remain mystery.

2704 BATSE Gamma-Ray Bursts

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
GRB Science

- Constraints on GRB models.
  - Polarization measurement.
  - Gamma-ray production mechanism via multi-wave analysis.
Particle Accelerator in the Universe

- Strong electromagnetic field.
  - Neutron stars

- Shock acceleration.
  - Supernova remnants.
  - GRBs

- Large volume.
  - Galaxy clusters.
Supernova Remnants

- RX J1713-3946: Candidate for proton acceleration.
  - GLAST can give definitive answer.

Galaxy Clusters

- Marginal evidence of non-thermal emission from Galaxy clusters in hard X-ray band.
  - Connection with the origin of UHECR?
  - AGN contamination

![Graphs showing spectral data for Abel 2252 and a combined spectrum for many clusters.](image)

Abel 2252 spectrum

Combined spectrum for many clusters

Next Generation Compton Telescope, H. Tajima, UCSC, MAY 3, 2004
Polarization in Astrophysics

- Inverse Compton scattering.
  - Polarization depends on scattering angle or polarization of seed photons.
  - Geometrical information

- Synchrotron radiation.
  - Polarization is perpendicular to magnetic field direction.
Key Features (Requirements)

- **High energy resolution**: ~ 1 keV (FWHM).
  - ~ 120 $e^-$ (RMS)
  - High angular resolution: ~ 1° (FWHM).
  - High background rejection.
    - Constraints from Compton kinematics.
    - Low background: $10^{-7}$ counts/cm$^2$/s.

- **Polarimetry**.

- **Low weight**.
  - No heavy calorimeter.

- **Wide energy band**: 0.1–3 MeV.

- **Large Field-of-View**: > 2 sr.
Doppler broadening will limit ultimate angular resolution.
Semiconductor Multiple-Compton Telescope

Doppler broadening is much smaller in Si.

Si Detector

CdTe Detector

Single-Layer Interaction Probability

- photo-absorption
- Compton Scattering
- pair-creation

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
Wide FOV Instrument Concept

- Si+CdTe is essential for wide energy band.
  - Si: smaller Doppler broadening.

40+40 layers of 0.5mm thick Si and CdTe,

4x4 array of identical modules

Takahashi (ISAS)
Narrow FOV Instrument Concept

- SGD (soft gamma-ray detector) on board NeXT mission proposed at ISAS, Japan.
  - Low background.
  - 50 keV – 1 MeV

Y. Suzuki (ISAS)
Expected Performance of SGD

Effective Area vs. Incident Energy

- Abs. mode
- Comp. mode

Effective Area (cm²)

Incident Energy (keV)

Large effective area (3300 cm²)
High background
(5x10⁻⁴ cm⁻² s⁻¹ keV⁻¹)

Expected SGD spectra (100 ks)

Counts/s/cm² keV

Energy (keV)

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
Polarization Measurement with SGD

\[ \frac{\partial}{\partial W} \left( \frac{E_g^2}{E_g} \right) + \frac{E_g}{E_g'} \cdot 2\sin^2 \theta \cdot \cos^2 \theta \]

5σ detection limit:
2.7% @ 100mCrab

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
VA32TA: Low Noise Front-end VLSI

- **Low noise**
  - Front-end MOSFET geometry optimized for small capacitance load in 1.2 µm process.
    \[
    \left(0.37 + 0.16 C\right)/\sqrt{t}\ [\text{keV}] \quad \left(45 + 19 C\right)/\sqrt{t}\ [e^-] \text{ (RMS)}
    \]

- Internal DAC (4-bit trim DAC, bias).
- Fabricated in AMS 0.35 µm process
- SEU (single event upset) tolerant. (>70 MeV/µm²)

Noise Analysis

- **Amplifier noise**: capacitance load.
- **Shot noise**: leakage current.
- **Thermal noise**: detector bias resistance.

![Graph showing noise analysis with peaking time and noise levels](image-url)

DC configuration, 0 °C

- **Amplifier noise**: red line
- **Shot noise**: yellow line
- **Thermal noise**: green line
- **Total noise**: blue line
- **Measured noise**: diamond marker

120 $e^-$ (rms)
$^{241}\text{Am}$ Spectrum (SSD)

25.6mm x 0.3mm x 0.3mm Si strip (0.1mm gap)

Entry [Counts/0.2 keV]

Energy [keV]

$^{241}\text{Am}$

13.9 keV

17.6 keV

21.0 keV

26.3 keV

59.5 keV

1.2 keV (FWHM)

DC configuration, 0 °C

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004
$^{241}\text{Am}$ Spectrum (CdTe)

2mm x 2mm x 0.5mm CdTe, 16 x 16 pixels

$^{241}\text{Am}, \text{CdTe}$

1.6 keV (FWHM)

VA32TA

Tanaka et. al. (ISAS)
Imaging Test

$^{57}$Co source

Double-sided Silicon Strip Detector (DSSD)

Photoelectric Absorption

Compton Scatter

Junction side  Ohmic side
Background rejection

$^{57}$Co Data

Angular resolution

Tail due to Doppler broadening

Next Generation Compton Telescope, H. Tajima, UCSC, MAY 3, 2004
Polarization Measurement @ SPring-8

177 keV polarized photon

Data

Good agreement between data and MC

43 ± 3 %

41 ± 2 %

EGS4.4 MC

Azimuth Scattering Angle (deg)
Conclusions and Future Prospects

- Compton telescope will advance MeV gamma-ray Astrophysics.
- Demonstration of Compton telescope.
  - 1.3 keV for SSD, 1.7 keV for CdTe pixel @0 °C.
    - Noise sources are well understood.
  - Compton imaging.
  - Polarization measurement with a stacked DSSD/CdTe prototype was successful.
- Further improvements for larger full-sized sensors.
  - New ASIC developed to reduce power by a factor of 10.
    - Same noise performance at slight loner peaking time.
    - Optimize frond-end MOSFET in 0.35 μm process.
  - Development of 2-dimensional single-sided SSD.
    - Larger and cheaper sensor using 6-inch wafer.
  - Compact assembly technique.
Compact Assembly Technique

- Compact packing is the key technology for SGD.
  - Double-sided solder bump technologies.
  - Low mass mechanical support.
  - Minimum crosstalk.

Advanced design

Next Generation Compton Telescope,
H. Tajima, UCSC, MAY 3, 2004