PROCEEDINGS OF SCIENCE

PoS(ICRC2023)899

Development of miniSGD, a proof-of-concept balloon experiment for a narrow field of view Si/CdTe semiconductor Compton telescope

Keigo Okuma,[a,*] **Kazuhiro Nakazawa,**[a] **Shin'ichiro Takeda,**[b,f] **Mii Ando,**[a] **Yuki Omiya,**[a] **Manari Oguchi,**[a] **Atsuya Tanaka,**[a] **Yuna Tsuji,**[a] **Shin Watanabe,**[c] **Tadayuki Takahashi,**[b] **Masahiko Kobayashi,**[a] **Naoki Ishida,**[d] **Takahiro Minami,**[e] **Mitsunobu Onishi**[f] **and Toshihiko Arai**[f]

[a] *Department of Science, Nagoya University, Furocho, Nagoya, Japan*

[b] *Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Japan*

[c] *Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Japan*

[d] *Technical Center, Nagoya University, Furocho, Nagoya, Japan*

[e] *Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Japan*

[f] *iMAGINE-X Inc., 1-12-8 Shibuya, Shibuya, Japan*

E-mail: okuma_k@u.phys.nagoya-u.ac.jp

[*] Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

The MeV gamma-ray band is very important for understanding high-energy cosmic phenomena such as particle acceleration and elemental synthesis, but its sensitivity is several orders of magnitude less than that of the X-ray, GeV, and TeV bands and is called the "sensitivity gap. The soft gamma-ray detector SGD onboard the ASTRO-H is a narrow-field Compton telescope combining a Si/CdTe semiconductor Compton camera and a BGO active shield, and has demonstrated high performance in orbit. We have proposed a balloon experiment based on this concept and are developing miniSGD as a proof-of-concept. The miniSGD consists of a semiconductor Compton camera with two 0.5 mm thick Si double-sided strip detectors (DSSD) and four 2 mm thick CdTe double-sided strip detectors (CdTe-DSD), and nine 20-30 mm thick BGO scintillators surrounding them. Although the effective area is extremely small because it is a proof-of-concept machine, it incorporates all the necessary technical items to achieve higher positional resolution than SGD. The miniSGD was originally scheduled for balloon testing in April 2023, so the miniSGD was completed by November 2022, but unfortunately, this flight was subsequently canceled and the team is now looking for the next opportunity. Currently, performance evaluation and optimization continues, and we have developed a simplified Depth Of Interaction sensing logic and its calibration method for the 2 mm thick CdTe-DSD. The implementation of this logic has improved the angular resolution of the ARM by a factor of 2. Further improvements are currently underway.

PoS(ICRC2023)899

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

1. Introduction

The MeV band is the boundary between the world dominated by thermal particles and the world dominated by non-thermal particles, and is a very important energy band for understanding high-energy phenomena in the universe. Specifically, non-thermal bremsstrahlung from particles accelerated to relativistic energies, nuclear gamma rays from nuclei produced in elemental synthesis, and jets from black holes at the centers of active galactic nuclei can be observed.

To detect MeV gamma rays, it is necessary to detect both scattered photons and recoil electrons generated by Compton scattering, which is the dominant interaction between photons and detectors. In a Compton camera, the energy and direction of arrival of incident photons can be obtained by using two detectors: a scatterer that scatters the incident photons and detects the recoil electrons, and an absorber that photoelectrically absorbs the scattered photons. In this case, the incident photon energy $E_{\rm in}$ and the scattering angle θ, which indicates the direction of arrival, are obtained using equations 1 and 2.

$$E_{\rm in} = E_{\rm scat} + E_{\rm abs} \tag{1}$$

$$\cos\theta = 1 - \frac{m_e c^2}{E_{\rm abs}} + \frac{m_e c^2}{E_{\rm scat} + E_{\rm abs}} \tag{2}$$

where $E_{\rm scat}$ is the energy detected by the scatterer, $E_{\rm abs}$ is the energy detected by the absorber, and $m_e c^2$ is the electron rest energy of 511 keV. Based on the position where the signal is detected by each detector and the scattering angle, we can obtain a cone, called Compton cone. And the direction where all the observed Compton cones intersect is the direction of arrival of the incident photon.

2. A narrow field of view Compton Telescope

2.1 Hitomi/SGD

One of the next generation MeV observation technologies is the Si/CdTe-Semiconductor Comoton Telescope (Si/CdTe-SCT)[2–4], which uses Si and CdTe semiconductors as scatterer and absorber, respectively. Compton scattering is dominant for Si above 60 keV, and photo absorption of CdTe is dominant below 300 keV, and the two detectors can be operated with the same read-out systems. The Soft Gamma-ray Detector (SGD) onboard the Hitomi satellite, launched in 2016, was a "narrow-field Si/CdTe semiconductor Compton telescope" that aims to eliminate background by combining this Si/CdTe semiconductor Compton telescope with thick active shield covering large angular area, [5–7], and was the only SCT that has been demonstrated to work in orbit. Hitomi/SGD also succeeded in polarimetric observations of the Crab Nebula with an observation time as short as 5000 s[7]. However, the Hitomi satellite was unable to make any further observations because it was lost about a month and a half after launch.

2.2 miniSGD, a proof-of-concept balloon experiment

miniSGD is a proof-of-concept mini semiconductor Compton camera for balloon experiments using the same narrow-field Si/CdTe semiconductor Compton telescope technology as the Hitomi/SGD for the early realization of more sensitive MeV gamma-ray observations. miniSGD

PoS(ICRC2023)899

consists of a Compton camera section, an active shield section, data acquisition electronics for both systems, a power supply section, and a pressure vessel to contain them. The pressure vessel is cylindrical with an inner diameter of 314 mm and a height of 331 mm, and the Compton camera, active shield, and power supply are designed to fit within this volume. The Compton camera section consists of a CdTe-DSD layer, DSSD layer, SPMU FPGA board, daisy-chain board layer, and ASIC DC board layer. The active shield section consists of a BGO unit, a GROWTH-DAQ system, and a Raspberry Pi. See Nakazawa et al. SPIE 2022 for details of the design[15].

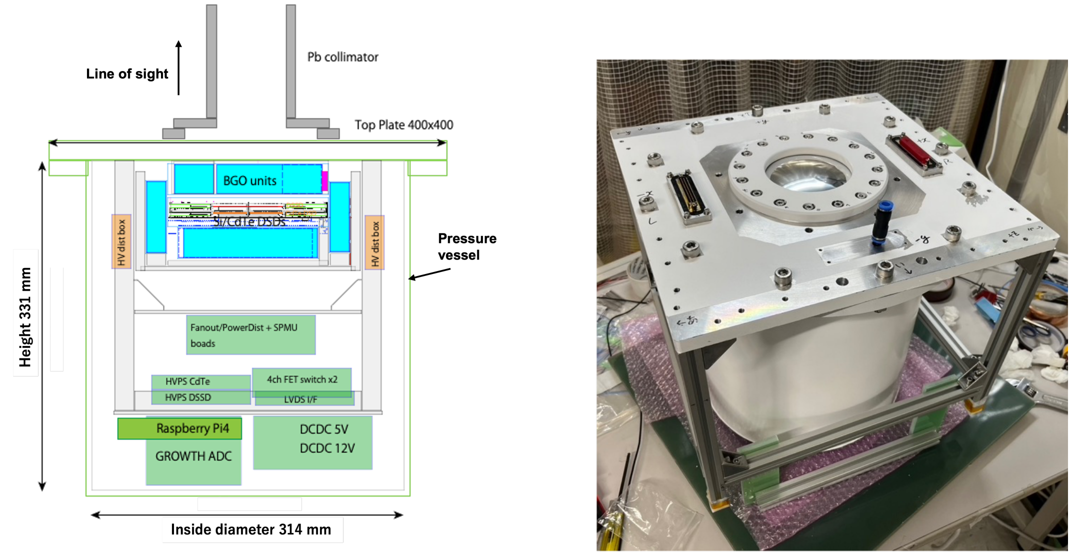

Figure 1: Overview of miniSGD

3. The miniSGD system

3.1 DSSDs and CdTe-DSDs layers

The DSSDs layer of miniSGD consists of two DSSDs as shown in Fig.3 (black part is a vacant place reserved for future addition of two more DSSDs). The DSSD tray consists of a substrate called a front-end card (FEC) on which the DSSD and four analog-ASICs are mounted, and a ceramic and plastic support plate that holds them. The CdTe-DSDs layer of miniSGD consists of four CdTe-DSD trays. The CdTe-DSD tray is the same design as the DSSD tray. The DSSD is 0.5 mm thick, which is the same to those used in the Hard X-ray Imager (HXI) onboard Hitomi. The CDTe-DSD is a new 2 mm thick version, almost three times thicker than those of the Hitomi/HXI. The sensitive area of one tray is 32 mm square.

3.2 BGO active shields

The active shield of miniSGD consists of nine BGO scintillator units. There are four BGOs of size $106 \times 30 \times 40$ mm^2 called Top BGO, two BGOs of size $180 \times 70 \times 20$ mm^2 and two BGOs of size $180 \times 72 \times 20$ mm^2 called Side BGO, and one BGO of size $140 \times 130 \times 30$ mm^2 called Bottom BGO. The BGO is wrapped with two types of reflective material, ESR and 250 μm thick

PoS(ICRC2023)899

Figure 2: DSSDs layer. 2 DSSD trays and 2 black spacers.

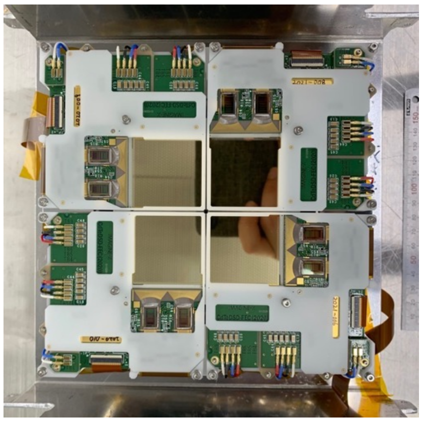

Figure 3: CdTe-DSDs layer.

GoreTex, and attached with 1-4 MPPCs as optical sensors. The active shield section is read out by the GROWTH-DAQ (FY2020FPGA) system[16].

3.3 Systems integration for balloon experiment

We have developed and integrated a system around the detector, including a DCDC converter and a command telemetry system. Figure 4 shows the block diagram of the miniSGD. We passed the connection test with the JAXA balloon team's communication system, completed the development for the balloon experiment, and miniSGD was ready for flight. Unfortunately, the 2023 Spring flight planned at Australia was canceled, and we are aiming for the next chance.

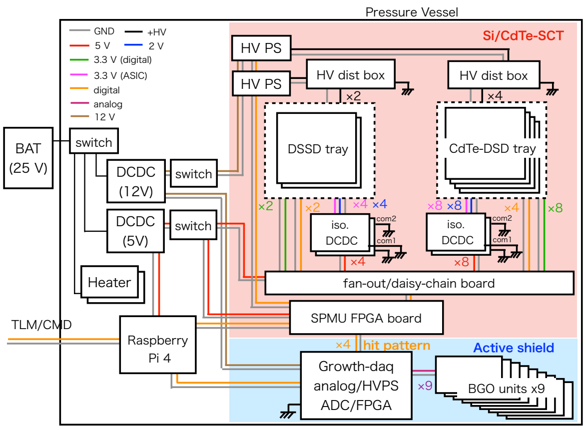

Figure 4: Block diagram of miniSGD.[15]

4. Calibration status of the miniSGD

We performed low-temperature calibration experiments of miniSGD to obtain angular resolution to the gamma rays of the radiation source. At this time, we estimated the Depth Of Interaction

PoS(ICRC2023)899

(DOI) in a 2 mm thick CdTe-DSD by performing DOI sensing. See in coming paper (Okuma et al. 2023 in prep.) for details.

We evaluated the angular resolution by performing Compton reconstruction using the obtained DOI. Figure 5 shows the Compton image and the distribution of the difference ARM between the scattering angle θ calculated from Equation 2 and the scattering angle θ_G calculated from the geometry. The angular resolution of miniSGD at 356 keV is 3.0 deg (FWHM). This is 2.0 times better than the Compton reconstruction without DOI sensing.

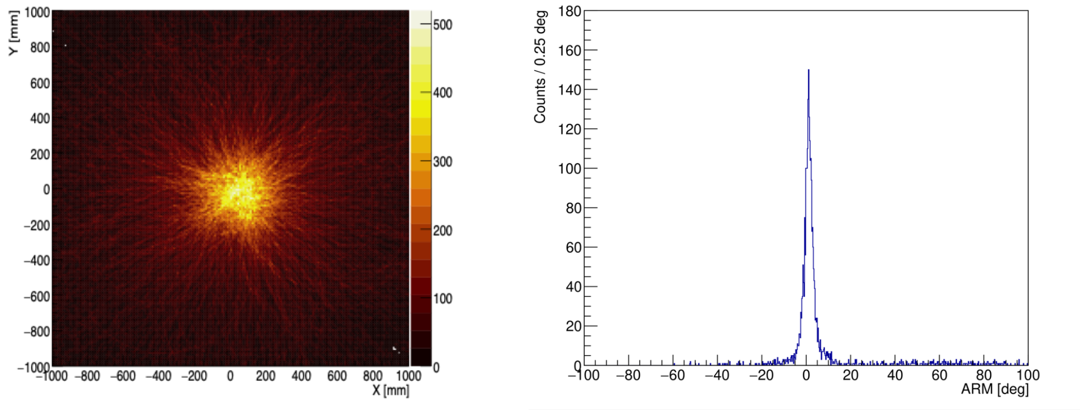

Figure 5: Compton image (left) and ARM distribution (right) for 356 keV of ^{133}Ba.

5. Summary

We have developed miniSGD, a demonstrator for ballooning experiments with narrow-field Si/CdTe semiconductor Compton telescopes to improve sensitivity in the MeV band. The miniSGD is installed with two 0.5 mm-thick DSSDs, four 2 mm-thick CdTe-DSDs, and nine BGO active shield units, and combined with a DCDC converters and a command and telemetry system, it was ready for flight. In the Compton reconstruction, the DOI sensing of the 2 mm thick CdTe provided the angular resolution of 3.0 deg for 356 keV of ^{133}Ba. The angular resolution was improved by a factor of 2.0 compared to the angular resolution without DOI sensing.

Acknowledgments

This work is supported by JSPS KAKENHI Grant Number 20H00157, and partly by 19K21899 and 18H01236. We also appreciate the support work of JAXA ISAS ballooning team, especially Dr. Tamura M. We also owe the electronics design of the active shield part to associate professor Enoto T., Dr. Yuasa T., assistant professor Wada Y. and the GROWTH thunder-cloud gamma-ray observation team.

References

[1] T. Takahashi, Y. Uchiyama, and Ł. Stawarz, “Multiwavelength Astronomy and CTA: X-rays”, Astroparticle Physics, 43, 142, 2012

PoS(ICRC2023)899

[2] S. Watanabe et al., "A Si/CdTe Semiconductor Compton Camera", ISEE TNS, Vol.52(5), 2045–2051, 2005

[3] S. Takeda et al., "Experimental Results of the Gamma-Ray Imaging Capability With a Si/CdTe Semiconductor Compton Camera", ISEE TNS, Vol.56(3), 783–790, 2009

[4] H. Odaka et al., "Development of an integrated response generator for Si/CdTe semiconductor Compton cameras", Nuclear Instruments and Methods in Physics Research A, 624, 303–309, 2010

[5] J. Katsuta et al., "Study of the polarimetric performance of a Si/CdTe semiconductor Compton camera for the Hitomi satellite", Nuclear Instruments and Methods in Physics Research A, 840, 51–58, 2016

[6] H. Tajima et al., "Design and performance of Soft Gamma-ray Detector onboard the Hitomi (ASTRO-H) satellite", JATIS, Vol.4(2), 021411(1–14), 2018

[7] Hitomi Collaboration et al., "Detection of polarized gamma-ray emission from the Crab nebula with the Hitomi Soft Gamma-ray Detector", PASJ, Vol.70(6), 113(1–19), 2018

[8] Z. He, "Review of the Shockley-Ramo theorem and its application in semiconductor gamma-ray detectors", Nucl. Instr. and Meth.J, Vol.A463, 250–267), 2001

[9] K. Hecht, "Zum Mechanismus des lichtelektrischen Primärstromes in isolierenden Kristallen", Zeits. Phys., Vol.77, 235, 1932

[10] W. Bencivellin et al., "Evaluation of elemental and compound semiconductors for X-ray digital radiography", Nucl. Instr. and Meth., A310, 210–214, 1991

[11] C.W.E. van Eijk, "Inorganic scintillators in medical imaging", Physics in Medicine and Biology, 47, R85, 2002

[12] A. Zoglauer and G. Kanback, "Doppler Broadening as a Lower Limit to the Angular Resolution of Next Generation Comptop Telescope", Proc. SPIE, Vol.4851, 1302-1309, 2003

[13] S. Takeda, "Experimental Study of a Si/CdTe Semiconductor Compton Camera for the Next Generation of Gamma-ray Astronomy", PhD thesis, The University of Tokyo, 2009

[14] G. Yabu, "A Study of the next generation semiconductor Compton camera for gamma-ray measurements in physics experiments", PhD thesis, The University of Tokyo, 2022

[15] Nakazawa et al., "Balloon-borne narrow field of view semiconductor Compton telescope concept: miniSGD", Proc. SPIE, Volume 12181, id. 1218172 14 pp. (2022)., 2022

[16] Yuasa et al., "Thundercloud Project: Exploring high-energy phenomena in thundercloud and lightning", Progress of Theoretical and Experimental Physics, Volume 2020, Issue 10, October 2020, 103H01

PoS(ICRC2023)899