Nuclear Instruments and Methods in Physics Research A 787 (2015) 207–211

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A portable Si/CdTe Compton camera and its applications to the visualization of radioactive substances

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ARTICLE INFO

Available online 19 December 2014

Keywords:
Gamma-ray imaging
Semiconductor Compton camera
Silicon
CdTe
Hot spot monitoring

ABSTRACT

Gamma-ray imagers with the potential for visualizing the distribution of radioactive materials are required in the fields of astrophysics, medicine, nuclear applications, and homeland security. Based on the technology of the Si/CdTe Compton camera, we have manufactured the first commercial Compton camera for practical use. Through field tests in Fukushima, we demonstrated that the camera is capable of hot spot detection and the evaluation of radioactive decontamination.

1. Introduction

A gamma-ray imaging system that can visualize the distribution of radioisotopes is extremely useful in many fields such as scientific research, non-destructive inspection and homeland security. For example, in the case of Fukushima, the visualization of the radioactive contamination by the gamma-ray imager is expected to accelerate the prioritization and verification processes of the decontamination. Based on recent development of high-quality room temperature semiconductor devices and readout analog ASICs, gamma-ray imagers have been improved [1–4] to realize sufficient angular resolution to locate the sources as well as sufficient energy resolution to reject background.

A Compton camera is regarded as powerful technology since it can directly locate sources without collimators, i.e. it can obtain a wider field of view (FoV) than coded aperture gamma cameras. The wider FoV is advantageous in real-world situations since radioactive substances can be distributed over large patches of ground. It is difficult to precisely track the scattering gamma-rays with traditional scintillation detectors. Therefore, a semiconductor Compton camera is desirable to meet requirements in practical use. Since the early 2000s, we have been developing a new Compton camera which consists of Si and CdTe semiconductor detectors [5,6]. Original technologies of low-noise silicon devices, high resolution Schottky CdTe diodes and dedicated low-noise analog ASICs allow the tracking of low energy gamma-rays, yielding a wide energy band from 100 keV to a few MeV. In the Si/CdTe Compton camera, the events involving the incident gamma-ray being scattered in the Si detector and then fully absorbed in the CdTe detectors are used for Compton imaging. Since the effect of Doppler broadening is smaller in the Si devices than in other semiconductor devices, the camera allows the difference between the measured and actual scattering angles to be constrained, meaning that higher angular resolution is expected. CdTe works very nicely as an absorber thanks to its large atomic numbers (48, 52) and high density (5.8 g/cm^3).

ASTROCAM 7000HS (see Fig. 1) is the first commercial Compton camera based on the Soft Gamma-ray Detector (SGD) [7] onboard the ASTRO-H satellite [8] planned for launch in 2015. The camera unit is 445 mm in depth, 340 mm in width and 235 mm in height, and the weight is approximately 10 kg. All measurements can be controlled on the user interface screen of a PC via a control box that houses a camera control circuit, a temperature control circuit, a high voltage control circuit, a power supply circuit, etc. In addition to its portability, ASTROCAM features scalability, that is, the efficiency can be optimized by customizing the number of detectors according to requirements of each application.

2. Design of ASTROCAM 7000HS

In early 2012, we developed a prototype Si/CdTe Compton camera and tested its feasibility in the evacuation zone [9], situated around 20 km from Fukushima Daiichi Nuclear Power Plant. The

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http://dx.doi.org/10.1016/j.nima.2014.11.119
0168-9002/

prototype consists of 2 layers of Si double-sided strip detectors (Si-DSDs) and 3 layers of CdTe double-sided strip detectors (CdTe-DSDs), which have a detector area of 3.2 × 3.2 cm and a strip pitch of 250 μm. Its imaging capabilities such as a good angular resolution of 3.8° (FWHM) at 662 keV, an excellent energy resolution of 2.2% (FWHM) at 662 keV, and a wide FoV corresponding to 2π steradian (180° × 180°) have been reported [10]. Hot spots above the environmental radiation level of a few μSv/h were clearly visible in exposure times of around 60 min.

The efficiency obtained by the prototype was 0.035 cps/MBq at 1 m (^{137}Cs, 662 keV). This refers to the count rate in the full energy peak at 662 keV for a ^{137}Cs point source (1 MBq) located 1 m from the camera. Because this prototype required 60–120 min for visualization on a few μSv/h background, improvement of the efficiency was highly desirable in order to shorten the exposure time to around 10 min.

Fig. 1. Photo of the ASTROCAM 7000HS.

To improve the efficiency in ASTROCAM, the detector size was increased to 5 × 5 cm wide and the camera has the capability to have lager numbers of layers. This type of detector is used in the SGD onboard ASTRO-H, and the details of each detector and their modularization are reported in Watanabe et al. [7]. The standard model of the camera consists of 8 layers of Si detectors and 4 layers of CdTe detectors. An efficiency of 0.16 cps/MBq at 1 m (^{137}Cs, 662 keV), about 5 times higher than that of the initial prototype, is measured, which agrees well with design value.

It is possible to integrate more detectors, up to 32 layers of Si and 8 layers of CdTe detectors. In addition, all four horizontal directions of the accumulated detectors are covered by 2 layers of CdTe modules. In this enhanced model, the efficiency is improved to 2.8 cps/MBq at 1 m (^{137}Cs, 662 keV), which is about 16 times higher than that of the standard model.

The energy resolution of the camera is measured to be 2.2% (FWHM) for 662 keV gamma-rays. A moderate angular resolution of 5.4° (FWHM) in ARM (Angular Resolution Measure) is obtained, meaning that it has about 1 m spatial resolution at 10 m from the camera. The basic specifications of ASTROCAM are summarized in the technical review [11].

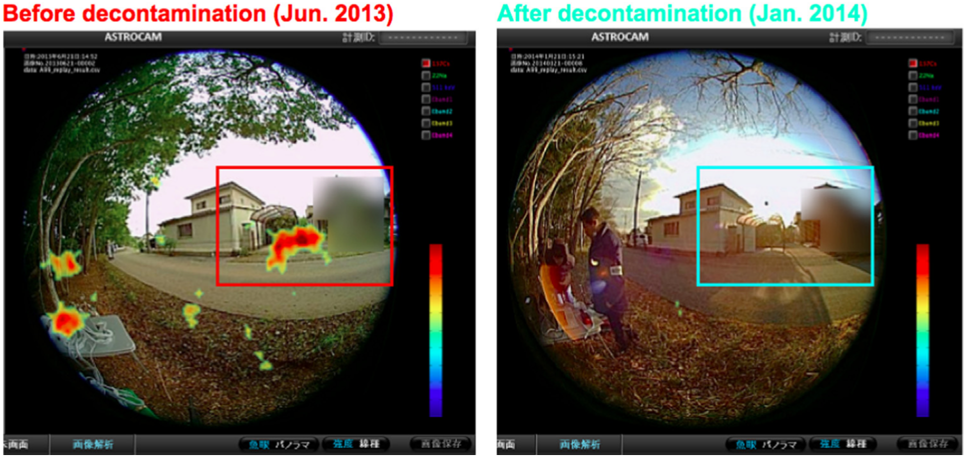
3. Demonstrations in Fukushima

Tests of ASTROCAM have been performed several times in the 20 km zone. Here, we show two examples that clearly demonstrate the power of gamma-ray imaging. Data were taken with the standard model using an exposure of 30 min.

In order to suppress image noise, only the parts which have a certain significance are shown in the camera image. As described in the previous work [9], this is realized by quantifying the statistical uncertainty of the signal and an offset component due to backgrounds appeared in the sky region of the back-projection image.

One potential use of gamma-ray imagers is to visualize the effect of decontamination efforts. An example for “before and after” clean-up is shown in Fig. 2. The environmental radiation levels in this area were around 0.5–1.0 μSv/h. The camera was located at the same position, both (left) before and (right) after clean-up. As clearly seen, extended hot spots were detected before clean-up, while one cannot recognize any accumulation of radioactive substances in the image after clean-up. This result means that ASTROCAM is capable of not only hot spot detection but also being utilized for the verification of decontamination .

Another desired capability is to be able to visualize the distribution of radioactive substances spread on a wide area, because a


Before decontamination (Jun. 2013)

After decontamination (Jan. 2014)

Fig. 2. One example demonstration in the 20 km zone of the nuclear plant. ASTROCAM was located at the same position, both (left) before radioactive clean-up in June 2013, and (right) after radioactive clean-up in January 2014.