Final Report on DOE Project (Number: DE-FG07-98ID13645)

Development of Gamma-Ray Compton Imager Using Room-Temperature 3-D Position Sensitive Semiconductor Detectors

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Report Period: July 1, 1998 - December 30, 2001

Introduction

During the three years of this project, two 3-dimensional position sensitive CdZnTe spectrometers were upgraded in collaboration with Johns Hopkins University Applied Physics Laboratory. A prototype Compton-scattering gamma-ray imager was assembled using the two upgraded CdZnTe detectors. The performance of both gamma-ray spectrometers were individually tested. The angular resolution and detection sensitivity of the imaging system were measured using both a point and a line-shaped ^{137}Cs radiation source. The measurement results are consistent with that obtained from Monte-Carlo simulations performed during the early phase of the project.

Phase 1: July 1, 1998 - June 30, 1999.

The project was began by evaluating system performance using Monte-Carlo simulations. A computer program was written to simulate gamma-ray interactions with the detector systems using EGS-4, and a second computer program was set up to perform image reconstruction using the list-mode maximum likelihood method. The simulation results showed that we should be able to achieve about 3.5° FWHM angular resolution at 511 keV incident gamma-ray energy and better at higher energies.

The effects of Doppler-broadening was investigated in detail during the first year. In classical Compton scattering, the incident photon scatters with a free electron at rest. In reality, all electrons are bound to the nucleus and have a distribution of linear momentum. Therefore, instead of the energy of scattered gamma-ray being uniquely determined by the scattering angle, the energy of the scattered photon has an intrinsic uncertainty for each scattering angle. This effect, called Doppler broadening, limits the minimum angular resolution achievable by a system. Improvements in detector technology, particularly energy and position resolution, have now made Doppler broadening a limiting factor in imaging. Detailed simulations of the effects of Doppler broadening was carried out. It was discovered that the wide band-gap semiconductor detectors, such as CdZnTe, are well suited for constructing Compton imagers because their energy resolution is at the same level of the intrinsic uncertainty of scattered gamma-ray energy due to Doppler broadening.

Other factors which could affect the imaging performance of the system, such as mechanical misalignment of detectors, were also studied in simulations. Methods for correcting the distorted image have been investigated. Our study shows that it is possible to identify systematic errors caused by mechanical misalignment by imaging three point

sources of known activity and location. This developed calibration procedure would eliminate any imaging distortions caused by mechanical misalignment.

In addition to studying system performance using Monte-Carlo simulations, efforts began on developing a new data acquisition system with a joint effort with IDE AS, a Norwegian company. The new electronic circuitry can provide not only good spectroscopic information, but also the electron drift times for each energy deposition.

In parallel to the development of the new electronic data acquisition system, new 3-dimensional position sensitive CdZnTe semiconductor detectors were also developed. One key change is the use of the plate-through-via technique to significantly increase the reliability and ruggedness of detectors.

Phase 2: July 1, 1999 - June 30, 2000.

During the second year period of this NEER project, two 3-dimensional position sensitive CdTe detectors using the plate-through-via technique were constructed in collaboration with Acrorad in Japan. However, due to high leakage current and unstable (polarization) performance at room temperatures, the effort was not successful.

In parallel, construction of two 3-dimensional position sensitive CdZnTe detectors began in collaboration with eV Products using the plate-through-via technique.

Considering the risk on constructing 3-dimensional CdZnTe detectors with new configurations, the two first-generation 3-dimensional position sensitive CdZnTe detectors built in 1998 were upgraded in collaboration with Johns Hopkins University Applied Physics Laboratory (as a backup plan). A 128-channel resistor-capacitor array were added between each detector and the input of the front end electronics (VA1 chip). This change from DC coupling to AC coupling stopped the leakage current going to the preamplifiers, thus reduced the low energy threshold of both detectors from about 120 keV to about 35 keV. This upgrade increased the detection efficiency of the Compton scattering system significantly by extending the useful region of the energy spectrum. Since the input pads of the VA1 chip have a very fine pitch, the wire-bonding modification requires specialized tools and skills. The task was performed at Johns Hopkins University Applied Physics Laboratory.

The first generation VAS-TAT data acquisition system designed in 1998 for 3-D pixel detectors was delivered in the summer of 1999. The system was tested extensively until the end of 1999. Although some functions worked as planned, significant modifications were required. This included the dynamical range of the TAT chip, the uniformity of the independent channels and the trigger mode of the special channel (#1) on each chip. The specifications for the second-generation system were proposed to IDE AS in January 2000. The new system should upgrade the hybrid-repeater boards (which interface, handle data communication and provide power to the VAS-TAT chip pairs), and the VAS-TAT chips.

A special data acquisition circuit was built and successfully tested. This circuit synchronizes the operation of two independent 3-dimensional position sensitive CdZnTe detectors to form a Compton scattering imaging device. When both detectors record a coincident event, specialized control circuitry initiates the full readout of both detectors. A computer program written in C++ can read signals from all 244 channels on both detectors and perform data processing. This includes obtaining energy depositions and

Figure 1: Electronic Noise

decoding the positions of each gamma-ray interaction for image reconstruction. If only one detector registers an event, the control circuitry resets both charge sensing amplifier chips so that the detector system is ready for the next event. A group of computer programs were written to perform a number of specialized tasks in software, such as to change energy thresholds on each detector, adjust the time delay between triggers of the two detectors for optimum coincidence measurement, and to synchronize the readout of two VA1 chips in parallel mode.

Phase 3: July 1, 2000 - July 31, 2001.

The upgrade of the two first-generation 3-dimensional position sensitive CdZnTe gamma-ray spectrometers was successfully completed. Electronic noise of both detector systems were measured and the results from detector #1 are shown in figure 1. Since there are only 121 anode pixels on each detector, the first 5 and last 2 channels on the VA1 chip were left open. It can be seen from figure 1 that the electronic noise of those open channels, which is the intrinsic electronic noise of the VA1 chip, are only about 1.5 keV. For the connected 121 channels, the electronic noise is increased to about 3 keV due to the capacitance of each bonding wire and of the pixel anode, as well as the contribution from the leakage current.

The spectroscopic performance of each detector has been improved significantly due to the upgrade modification. The electronic noise of each detector was reduced from 6-7 keV FWHM to about 3 keV FWHM at 662 keV gamma-ray energy. The energy resolutions of both CdZnTe detectors were measured and they are about 5.3 keV, 6 keV and 9.3 keV

Figure 2: Cs-137 spectrum for the first detector from central pixels

FWHM at gamma-ray energies of 59.5 keV, 122 keV and 662 keV respectively. Figure 2 shows the total ^{137}Cs spectrum of the first detector from the central 9×9 pixel anodes. The low energy threshold was reduced from about 120 keV to about 35 keV. This improvement on low energy threshold increases the efficiency of the system significantly. The imaging capability of this prototype Compton-scattering gamma-ray imager was tested using both a point ^{137}Cs source, and a line-shaped ^{137}Cs source representing a spatial extended object. Figure 3 is the reconstructed image of a point ^{137}Cs source located 8.4 cm from the center of the first detector. A list mode maximum-likelihood algorithm was used for the imaging reconstruction process. The measured angular resolution for the point source is about 5° FWHM, which is slightly worse than our estimated angular resolution of 3.5° at 662 keV based on Monte-Carlo simulations. It is believed that two factors contributed most to the degradation of the angular resolution. First, the point source is weak ($10 \mu\text{Ci}$) and the coincident count rate was low. Therefore, it took a long time (about a week) to collect enough events for a smooth image. Any systematic shifting, such as the gain variation of the ASIC electronics, introduces measurement error and degrades the image. The second factor is from the difference between simulations and the actual measurements. In simulations, only those gamma-ray events which deposited part of its energy in the first detector and then is scattered into the second detector was considered. In reality, the recorded coincident events include those gamma rays that first scattered in the second detector and then the scattered photon is detected by the first detector. These events contribute erroneous angular information in the reconstructed image. By considering these effects, the measured angular resolution is consistent with the prediction based on Monte-Carlo simulations. The measured sensitivity of the imaging

system is also consistent with simulations.

Figure 4 is the reconstructed image of a line ^{137}Cs source. The length of the source is 5 cm and its center was located 8.5 cm from the center of the first 1 cm cube CdZnTe detector. The angular resolution for the line source is similar to that of the point source. Good agreement between theoretical analysis and experimental results was achieved.

Figure 3: Reconstructed image for a ^{137}Cs point source. The units of both axes are in cm.

Conclusion: We have built the world's first prototype Compton scattering gamma-ray imager using 3-dimensional position-sensitive CdZnTe semiconductor spectrometers. It is of significant interest in the design and construction of future compact room-temperature gamma-ray imaging spectrometers. This work could be of special interest to national security applications considering the threat of possible nuclear terrorism and nuclear proliferation.

Collection of publications of this project:

Ph.D thesis:

“Development of a Prototype Compton-scattering Camera using 3-D Position Sensitive CdZnTe Spectrometers,” Y.F. Du successfully passed his thesis defense on July 26, 2001.

Peer Reviewed:

1. Y.F. Du, Z. He, G.F. Knoll, D.K. Wehe, “Effects of Mechanical Alignment Errors on Compton Scatter Imaging,” IEEE Transactions on Nuclear Science, Vol.47(3)(2000)885-889.

Figure 4: Reconstructed image for a line Cs-137 source. The units of both axes are in cm.

2. Y.F. Du, Z. He, G.F. Knoll, D.K. Wehe, W. Li "Evaluation of a Compton Scattering Camera using 3-D Position Sensitive CdZnTe Detectors," , A457(2001)203-211.
3. Z. He, Y.F. Du, D.K. Wehe "The first prototype Compton-scattering gamma-ray imager using two 3-dimensional position-sensitive CdZnTe spectrometers," presented at IEEE Nuclear Science Symposium, San Diego, California, Nov. 3-10, 2001, and will be submitted for publication in Nuclear Instruments and Methods.

Conference presentations:

1. Y.F. Du, Z. He, G.F. Knoll, D.K. Wehe, W. Li "Evaluation of a Compton Scattering Camera using 3-D Position Sensitive CdZnTe Detectors," SPIE Symposium on Hard X-ray, Gamma-ray, and Neutron detector physics, Colorado, Denver, July 19-23, 1999.
2. Y.F. Du, Z. He, G.F. Knoll, D.K. Wehe, W. Li, J. Berry "Development of the readout electronics for CdZnTe Compton Imaging System," IEEE Nuclear Science Symposium, Lyon, France, October 15-20, 2000.
3. (Invited) Z. He, Y.F. Du, D.K. Wehe "Gamma-Ray Imager using 3-D Position Sensitive CdZnTe Spectrometers," ANS summer meeting, Milwaukee, Wisconsin, June 17-21, 2001.