Nuclear Instruments and Methods in Physics Research A 652 (2011) 641–645

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Simulation and detector response for the High Efficiency Multimode Imager

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ARTICLE INFO

Available online 1 September 2010

Keywords:
HEMI
Simulation
Gamma-ray detection
CdZnTe
Detector response

ABSTRACT

The High Efficiency Multimode Imager (HEMI) is a gamma-ray detection system consisting of two planes of CdZnTe detector elements to allow for both coded aperture and Compton imaging of radioactive sources. The HEMI detector is being developed to detect, characterize, and locate gamma-ray sources within the energy range of tens of keV to a few MeV. This paper details the methods used to make accurate simulations and performance predictions and provides an overview of the data analysis pipeline for imaging sources. Compton mode reconstruction and detector response results of simulations and measurements are shown for a 24-detector HEMI array.

1. Introduction

The High Efficiency Multimode Imager (HEMI) concept arose from a need for an instrument to detect and characterize radiological and nuclear materials. The HEMI detector utilizes both coded aperture and Compton scatter imaging techniques and therefore is ideally suited for the detection and localization of radioisotopes whose gamma-ray emissions are within the energy range of tens of keV to a few MeV. Fig. 1 shows one possible configuration for a prototype HEMI detection system: a modular array consisting of two 8×8 detector planes. Simultaneous multimode imaging is accomplished by using a partially populated front plane as an active mask combined with a fully populated back plane.

The HEMI coplanar-grid CdZnTe detectors are 1 cm^3 modular elements with good spectral resolution ($<2\%$ at 662 keV). This energy resolution provides the basis for spectroscopic characterization and identification of radioisotopes, thereby making it possible for the HEMI system to discriminate between threat and non-threat radioactive sources. Additionally, the large area and modularity of the detectors allow for scalable and flexible instrument configurations in order to optimize the sensitivity and angular resolution of the system for specific applications. Further details about the HEMI system can be found in Ref. [1].

In order to predict the performance of a large scale HEMI configuration it is necessary to understand the detector response parameters. Comparisons between measurements of energy deposition within a prototype HEMI instrument and accurate simulations of photon interactions within a detector model provide a means to understand and fine-tune these parameters. In this paper we detail the simulation and data analysis techniques and show spectral and imaging results for simulations and measurements from a 24-detector HEMI prototype.

2. Simulation

The first step in the simulation process is the construction of a detailed mass model of the HEMI detector assembly using Geomega, the geometry package included in the data analysis toolkit MEGAlib [2]. This requires an accurate representation of all passive and active materials of the detector system and objects in the nearby environment. Precisely defining the shape, volume, location, and material properties of each component is essential for a reliable reproduction of Compton scattering effects, pair creation, and photo electric absorptions that take place within the actual HEMI system. Fig. 2 shows the HEMI-24 prototype next to the mass model used for the 24-detector HEMI simulations (the table and other surrounding structures are not shown).

Monte Carlo simulations are then performed using Cosima [3], the simulation toolkit contained in MEGAlib. The simulator imports the Geomega geometry and converts it into a Geant4 [4] format. Cosima then uses the Geant4 geometry and radioactive source information in conjunction with a physics list of the relevant electromagnetic processes, including Doppler broadening, in order to generate a data file containing the simulated interaction information. The resulting simulation file includes information regarding the time and type of each interaction and all relevant position and energy information.

3. Detector response

The next step in creating an accurate simulation is to fold the information regarding the detector response into the simulated

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doi:10.1016/j.nima.2010.08.101

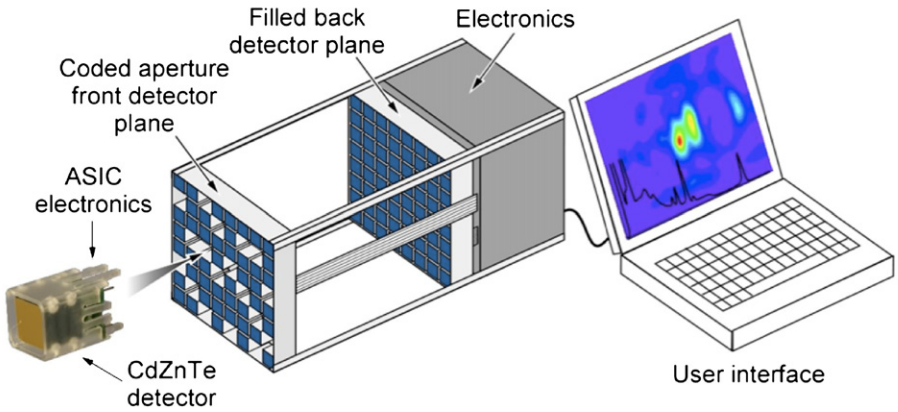

Fig. 1. HEMI two plane detector module.

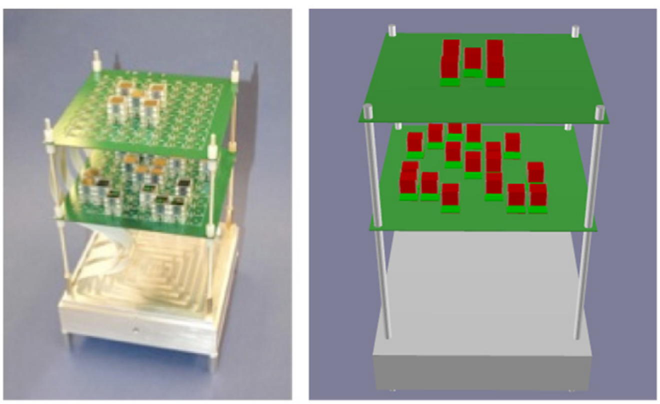

Fig. 2. HEMI-24 prototype, left, and Geomega mass model of HEMI prototype, right.

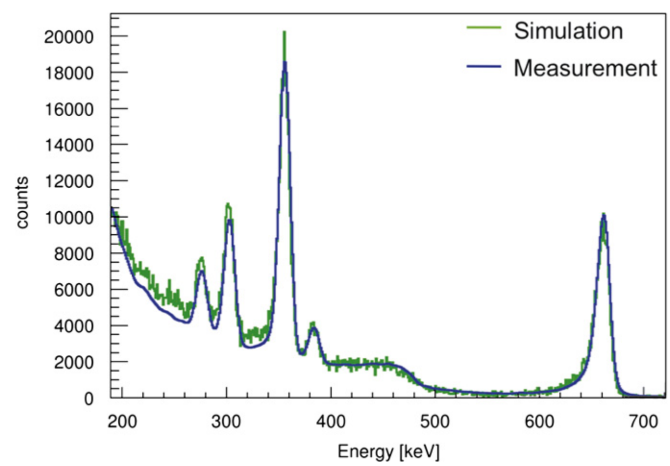

Fig. 3. Refining energy resolution parameters by peak shape matching using gamma rays from ^{133}Ba and ^{137}Cs sources, scaled by time.

data by utilizing the detector effects engine in MEGAlib. This information includes, e.g., time noising, energy resolution, energy calibration information, and a charge collection loss map for the detectors. With the exception of the charge collection loss map, which is calculated using charge transport simulations, the remaining parameters are determined through a direct comparison of spectral features between the measured and simulated datasets. In this method, the parameters found are an average over the whole detector array, although in reality these values will vary slightly from detector to detector. Refinement of these parameters allows for confident predictions of various configurations and scaled versions of HEMI.

Measurements using various radioactive sources at different positions relative to the detector have been performed with a 24-detector HEMI prototype. The measured data consist of pulse height in ADC units, time, and detector identification number for each event. Before a comparison with simulated data can be made, the measured pulse heights are converted from ADC units to their corresponding energies, and the detector numbers are converted into a position.

3.1. Energy resolution

Ideally the charge collection loss map would dictate the dominate contribution to the intrinsic energy resolution of the detectors. However, non-ideal detector effects (such as non-uniform electric fields and non-uniform charge trapping) as well as electronic noise contribute to the peak width and shape in measured spectra. Consequently, the average energy noising of the HEMI prototype array is determined by analyzing the peak shapes in a measured spectrum and adjusting the energy resolution parameters accordingly. The measured peaks are fit using a Gaussian approximation with a Landau component on the low energy tail of the peak. The resulting detector response parameters, e.g., a sigma value for both the Gaussian and Landau components, the ratio between the two components, and the mean of the peak, are then used to convolve the simulated spectrum through the detector effects engine in order to more accurately reflect the noising effects. The energy resolution parameters are further refined by matching the resulting simulated peak shape to the measured peak shape using a χ^2−test. This method is repeated using various gamma-ray energies within the target range of the HEMI detector (tens of keV to a few MeV). Fig. 3 shows peak shape matching between simulation (green) and measurement (blue) using gamma rays from ^{133}Ba and ^{137}Cs sources.

3.2. Time resolution

In addition to spectral energy comparisons, a comparison of the time between events yields information regarding the time noising of the detectors and also provides an estimate on the coincidence window needed for Compton reconstruction. Fig. 4 shows a scaled by time comparison between measurement (blue) and simulation (green) for a far-field ^{137}Cs source on-axis above the HEMI-24 detector. The time resolution parameter is found by

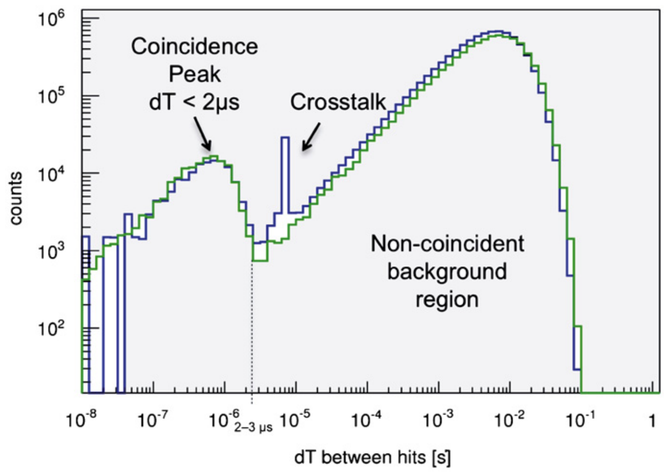

Fig. 4. Time between hits comparison of simulation (green) and measurement (blue), scaled by time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

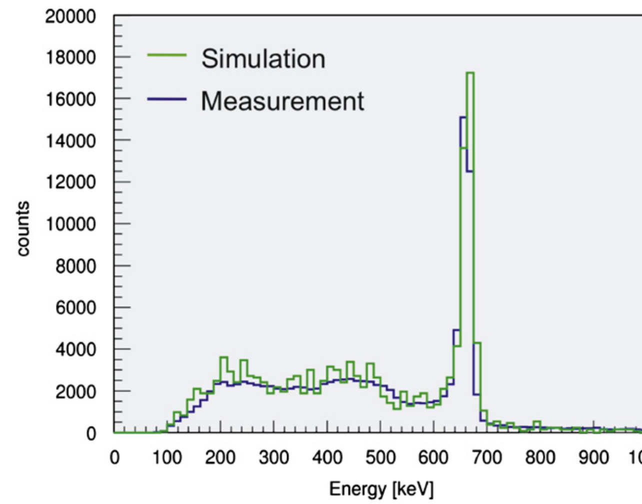

Fig. 5. Reconstructed Compton events comparison, scaled by time.

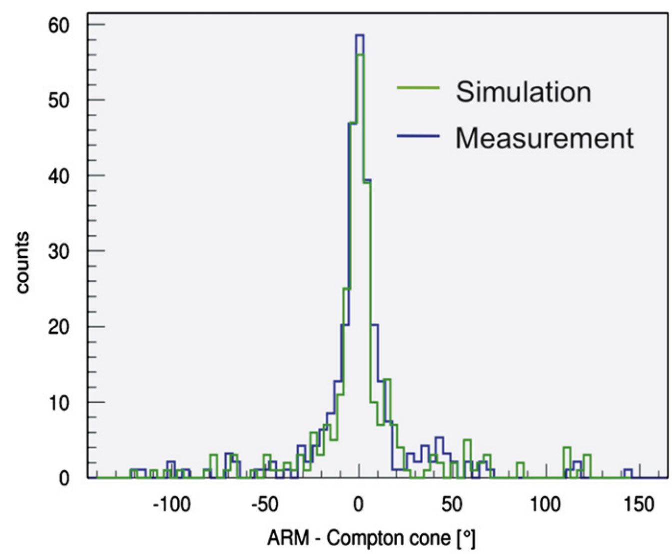

Fig. 6. Comparison of angular resolution measurement, scaled by time.

aligning the abscissa (time between two hits) of the simulated data with the measured data. The best fit yields a time resolution of 0.5 μs (1σ) Gaussian).

The resulting plot shows a clear distinction between the background flux and the coincidence peak, which indicates that an appropriate coincidence window is approximately 2 μs. All hits occurring within this time interval are assumed to be coincident hits and are combined into Compton events with the proper interaction sequence determined during event reconstruction. Also seen is a distinct peak in the measured spectrum at a time interval of approximately 8 μs. This peak is a result of crosstalk between two neighboring detectors. As it is outside of the coincidence window, it does not interfere in the Compton reconstruction and therefore does not need to be reproduced in the simulation.

3.3. Countrate

In addition to finding the energy and time noising parameters, the scaled by time comparisons yield important information regarding the accuracy of the simulated source activity and also provide a means to determine the rate and distribution of the background radiation. The source activity of the simulation is verified by matching the peak heights between measurement and simulation in the energy spectrum and in the coincidence peak of the time resolution spectrum. The shape of the background spectrum in HEMI measurements is best fit by simulating a broken power law distribution. The flux and parameters of the simulated background distribution are determined by comparing the background shape between a measured spectrum and the convolved simulated spectrum. The background flux and energy distribution are constant within the HEMI laboratory environment but require some adjustment as the sensitivity of the detection system improves with the addition of more detectors.

4. Compton mode reconstruction

Once the coincidence window has been determined, the Compton event and image reconstruction toolset, MEGAlib, is used to analyze the Compton interactions and to locate and image the source. For two-site Compton events the sequence with the larger Klein–Nishina times photo-absorption probability is used as the correct interaction sequence. Fig. 5 shows a scaled by time comparison of the Compton reconstructed events between measurement (blue) and simulation (green) for an on-axis detection of a ^{137}Cs source using the HEMI-24 detector array. The energy resolution for reconstructed two-site Compton events for HEMI-24 gives a FWHM of 20 keV, corresponding to an average energy resolution of 3% at 662 keV ($<2\%$ for single hits).

The angular resolution in the form of an Angular Resolution Measurement (ARM) distribution is shown in Fig. 6 for simulation (green) and measurement (blue) of an on-axis ^{137}Cs source. An energy cut from 640 to 680 keV was applied to only include the primary ^{137}Cs gamma peak. Only Compton events that are suitable for localizing the source, i.e., sequential events occurring between the two detector planes, are used for reconstruction. The resulting angular resolution corresponds to approximately 11° FWHM for a 24-detector HEMI array and is only limited by position resolution, i.e., the voxel size of each detector and the distance between the two detector planes.

MEGAlib then allows for the generation of Cartesian and spherical images of the source location by applying a list-mode maximum-likelihood algorithm. Each image shown was reconstructed using five iterations of the LM-ML-EM algorithm, see Ref. [5]. Only Compton events that occur between the two detector planes are included. Fig. 7 shows images reconstructed from near-field measurements of a ^{133}Ba source at 50 cm distance and 60° off-axis, and a ^{137}Cs source at 50 cm distance and 90° off-axis. Figs. 8 and 9 show images of a far-field ^{137}Cs source for both simulation and measurement, respectively.

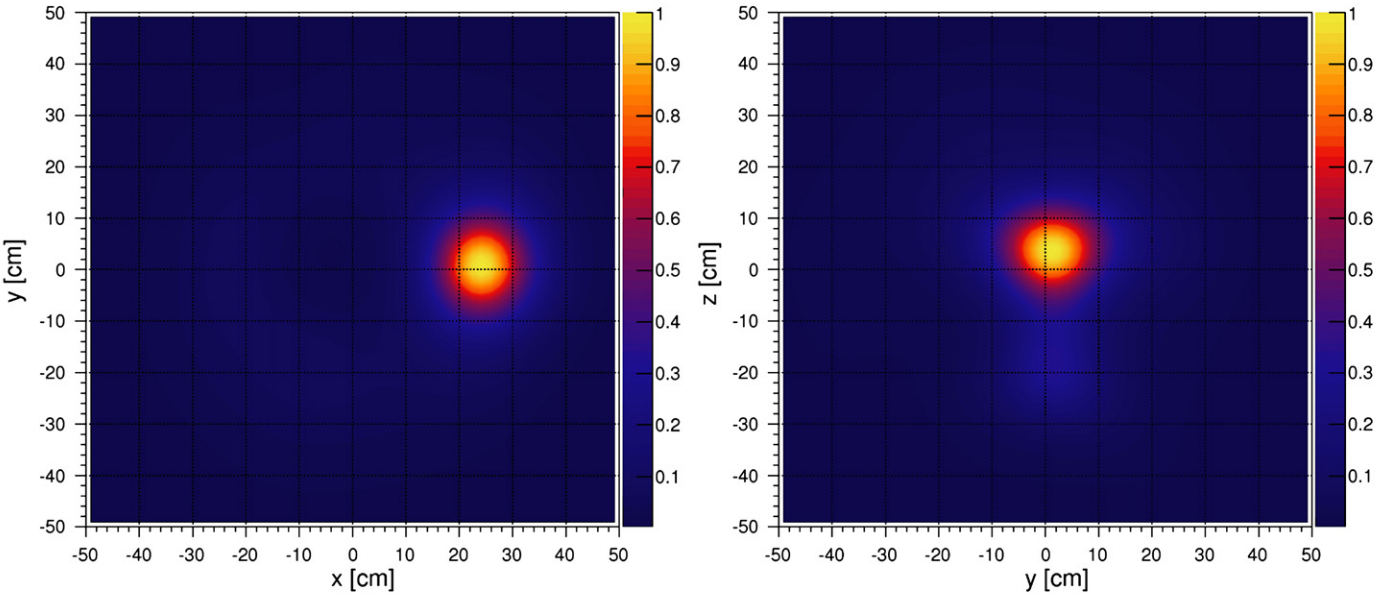

Fig. 7. Image reconstruction from measurement of a near-field ^{133}Ba source (340–370 keV) located at 60° off-axis (x=25 cm, y=0 cm, z=50 cm), left, and a ^{137}Cs source (640–680 keV) located at 90° off-axis (x=50 cm, y=0 cm, z=0 cm), right.

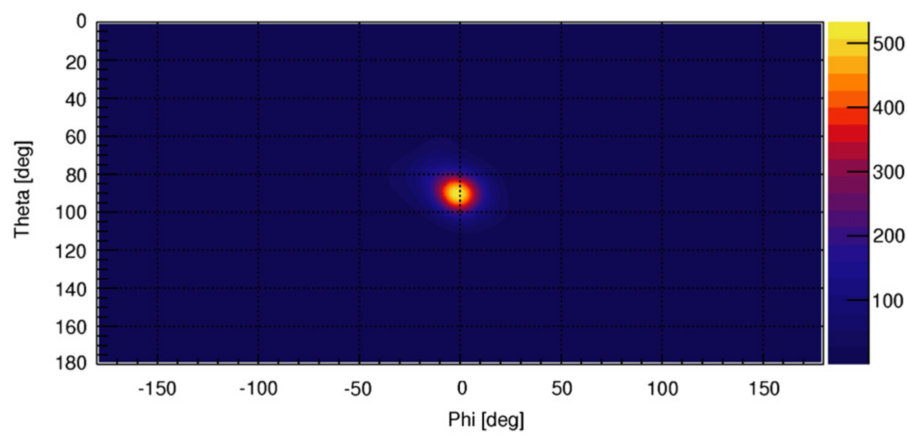

Fig. 8. Image reconstruction from simulation of a far-field ^{137}Cs source, 640–680 keV.

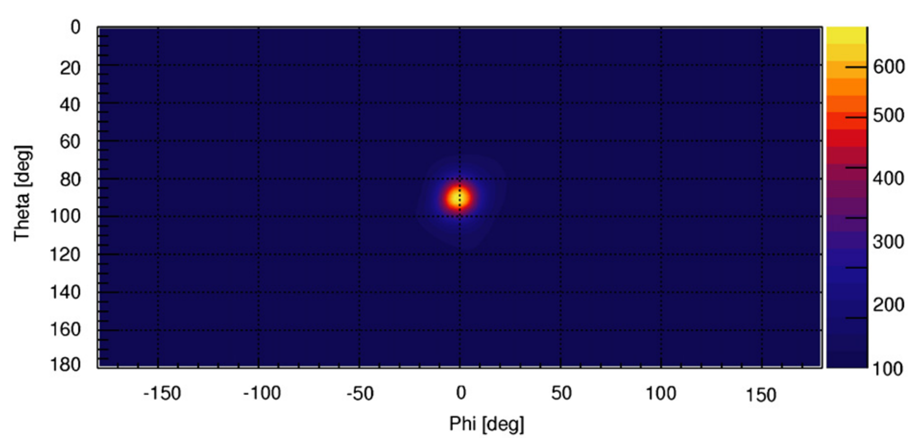

Fig. 9. Image reconstruction from measurement of a far-field ^{137}Cs source, 640–680 keV.

5. Summary and future

Through careful construction of a simulation model, we have shown that the measured response of a 24-detector HEMI can be accurately reproduced in simulations. Future measurements using a HEMI array with more detectors will be used to verify the scaling of the detector response, thereby allowing for confident predictions of large scale HEMI detectors through the use of simulation.

Acknowledgements

This work was supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office, under Interagency Agreement HSHQDC-08-X-00832 and by the U.S. Department of Energy, Office of Science, under Contract DE-AC02-05CH11231.

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