ISSN: 1791-4469 Copyright © 2012 Hellenic Naval Academy

A Gamma Spectroscopic Radiation Detector for Security Purposes

K. Karafasoulis[a,b], K. Zachariadou[c,b], S. Seferlis[b], I. Kaissas[b], I. Papadakis[d], D. Loukas[d], C. Lambropoulos[e] , C. Potiriadis[b],

a. Hellenic Army Academy, 16673 Vari, Greece
b. Greek Atomic Energy Commission, Patriarxou Grigoriou & Neapoleos, 15310 Athens, Greece
c. Technological Educational Institute of Piraeus, Department of Physics, Chemistry & Material Technology, P. Ralli & Thivon 250, 12244, Greece
d. National Centre for Scientific Research "Demokritos" , Institute of Nuclear Physics, 15310 Athens, Greece
e. Technological Educational Institute of Chalkida, Psachna Evias 34400, Greece

Abstract. We present the development of a stacked gamma radiation detecting system, consisting of three layers of pixelated Cadmium Telluride detectors (PID350). A high speed (120 frames/s) data acquisition system has been developed in order the system being able to compete with high flux of gamma rays. The PID350 detector's photo-peak energy resolution ranges from 1.73 keV to 2.15 keV (FWHM) at 59.5 KeV. Spectroscopic measurements performed have shown that the stacked detecting system is able to accurately evaluate the position of a 140.5 keV radioactive source located at distances in the range from 30 cm to 1 m.

Keywords: Semiconductor detectors, Gamma-ray spectroscopy, CdTe diode detector
PACS: 29.40.Wk, 29.30.Kv

INTRODUCTION

The last decades, the world's growing interest in homeland security has given new impetus to the efforts of the scientific community to improve gamma radiation detection technologies. Within this research field, the current work aims to explore the ability of a radiation detecting system under development to identify both the energy and the source-to-detector distance of gamma radioactive sources. The system consists of three planar pixelated Cadmium Telluride (CdTe) semiconductor detectors (PID350) stacked together.

Pixelated detectors have the advantage of providing accurate information on both the energy deposition and the position of each interaction of gamma radiation with the detecting materials. Moreover, by choosing the geometry of a stacked detector (in which thin layers are stacked together), the efficiency of detecting the gamma rays is increased and more information about the original gamma radiation can be extracted (since successive interactions with the detecting layers are recorded).

Described in the following sections is the general structure of a PID350 radiation detector, its calibration procedure as well as the high speed readout system developed so that the detector being able to compete with high flux of gamma rays. A prototype stacked system consisting of three PID350 detectors is presented as well as results on its ability of estimating the position of point-like gamma sources.

THE PID350 DETECTOR

For the development of the gamma radiation stacked system, PID350 detectors provided by AJAT [1] have been used. PID350 is a pixelated detector based on CdTe-CMOS technology, suitable for gamma and X-ray detection (Figure 1). Its active area is 4.5 cm x 4.5 cm and consists of eight CdTe-CMOS hybrid elements. Each hybrid element has 2048 radiation sensing pixels of 350μm size, thus a PID350 detector consists of 16384 pixels. Each pixel is capable of recording the energy deposited of every detected interaction. The maximum energy deposited in each detector pixel during two successive readout cycles is stored into a specific address in a local memory.

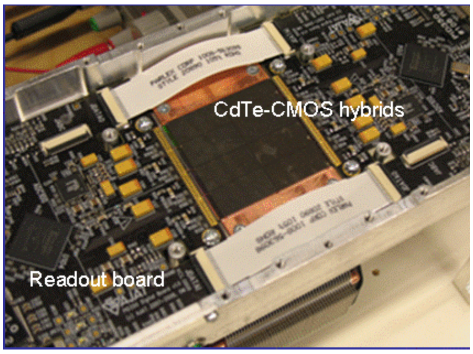

FIGURE 7. The PID350 pixelated detector.

The eight CdTe-CMOS hybrid elements of a PID350 detector are grouped into two modules each one connected to a digital control board having individual power supply and data readout (Figure 2). During one readout cycle, the contents of all the 8192 pixels of one PID350 module are read and stored in the computer forming a frame. The data are transferred from the control board of each module directly to a PC station through a Serial Peripheral Interface (SPI) bus.

In the present work three PID350 detectors have been used for spectroscopic measurements and their performance has been evaluated in order to be used in a stacked prototype system under development. The detectors are labeled as PID350#1, PID350#2 and PID350#3. The two modules of each detector are labeled with a subscript (e.g. the PID350#1 detector consists of the PID350#1_1 and PID350#1_2 modules).

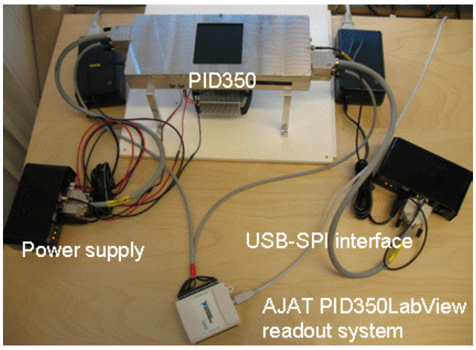

FIGURE 2. The PID350 system.

CALIBRATION

The hardware calibration procedure of a PID350 detector concerns the adjustment of both the offset and the gain parameters of each pixel. The calibration has been performed by using the PID350 standard data acquisition system provided by AJAT, having a maximum data rate transfer of 2 frames/s and a graphical user interface based on LabView.

For the offset adjustment, noise data have been collected in order to locate the noise peak of each pixel. Several iterations are needed in order to reduce the width of the noise peak to no more than two channels.

For the gain adjustment, data have been collected for each PID350 detector using a ^{241}Am radioactive source. The gain adjustment procedure searches for the gamma peak location and corrects the gain parameters in order to align the gamma peaks of all pixels. Several iterations have been performed in order to squeeze the distribution width of the gamma peak positions (centroids) of each pixel to no more than two channels.

Since the offset and gain adjustments are not completely independent, they have been repeated iteratively several times, in order to reduce the FWHM of the cumulative gamma ray spectrum.

The cumulative spectrum of ^{241}Am radioactive source calibration is shown in Figure 3 before and after the hardware calibration, for the case of the detector PID350#3. Similar spectra have been obtained for PID350#1 and PID350#2 detectors.

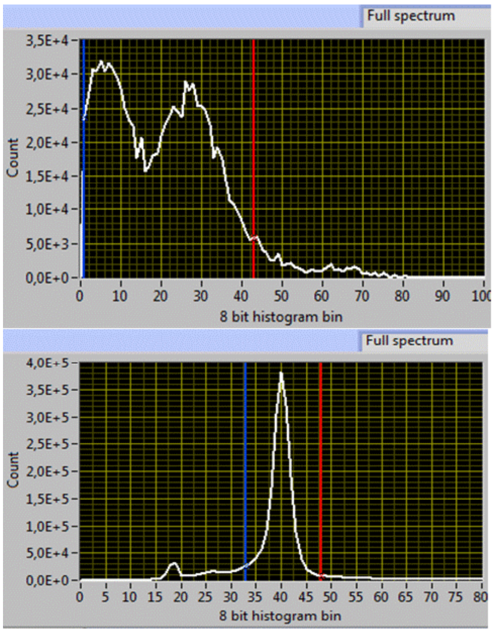

FIGURE 3. Cumulative spectrum of a ^{241}Am radioactive source recorded by the PID350#3 detector, before (up) and after (down) the adjustment of the offset and gain parameters of all its pixels.

.

A HIGH SPEED READOUT SYSTEM

The read out of the PID350 detector, provided by AJAT is slow compared to the internal memory writing speed resulting to data loss during the collection of data. In order to reduce the data loss we have developed a new high speed readout system (Figure 4) consisting of an

FPGA SPI, a High Speed USB and a user interface software written in VHDL and C languages. This system manages to increase the data transfer speed to the PC from 2 frames/s, which was the data transfer speed of the standard PID350 readout system to 120 frames/s.

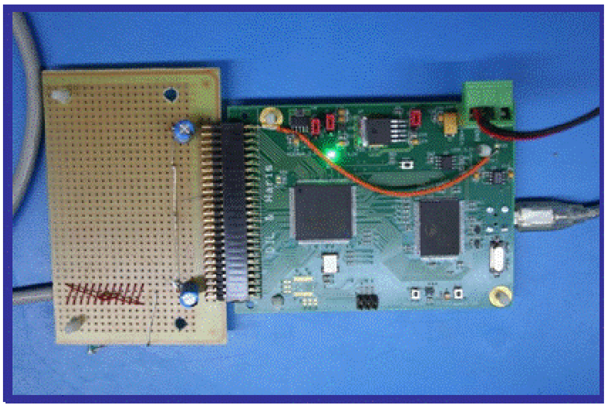

Figure 4. The high speed PID350 readout system.

The user interface software of the high speed readout system checks the PID350 status, uploads the offset and gain parameters derived by the hardware calibration procedure described in the previous section and starts the data gathering.

The raw data recorded are stored in binary data files in a stream of bytes which are grouped in 8-byte packets. Each packet stores the content of a single pixel from every PID350 module. This leads to a high data rate of 112.5 Mbytes/min. In order to manipulate the raw data with greater flexibility a software package has been developed under the ROOT framework [2]. The software transforms the raw data packets into usable frames and stores them in ROOT format. A frame holds an identification number for the frame (ID), the signal amplitude collected by each pixel, the spatial coordinates of each pixel and a sequence number which carries an estimation of the time when the interaction occurs. Furthermore, the software checks the energy resolution, the number of bad pixels and the upper channel limit of the noise peak.

ENERGY RESOLUTION

Although the width of the distribution of the photo-peak centroids has been adjusted to be no more than two bins during the hardware calibration of the PID350 by using a ^{241}Am source (as described previously), it becomes much wider when the detector is irradiated by a different mono-energetic gamma source. This is evident in Figures 5a and 5b illustrating the photo-peak centroid distributions of all pixels of the PID350#3 detector, when irradiated by an ^{241}Am and ^{109}Cd radioactive source respectively (the bad pixels are excluded). The broad distribution of the photo-peak centroids results to a broad energy peak in the energy spectrum, since the energy peak is the convolution of the width of each pixel's photo-peak with the distribution of the photo-peak centroids.

In order to improve the energy resolution of the cumulative spectra, the PID350 detectors have been irradiated by two known energy sources and a software energy calibration procedure has been developed. According to this procedure, a total of 8192 histograms (one per each pixel) are created dynamically and are filled with the content of the corresponding pixel, creating in this way the spectrum of each pixel. Then, the peaks of every single pixel spectrum above the dc level are searched and two calibration constants are determined for each pixel based on the position of the two peaks.

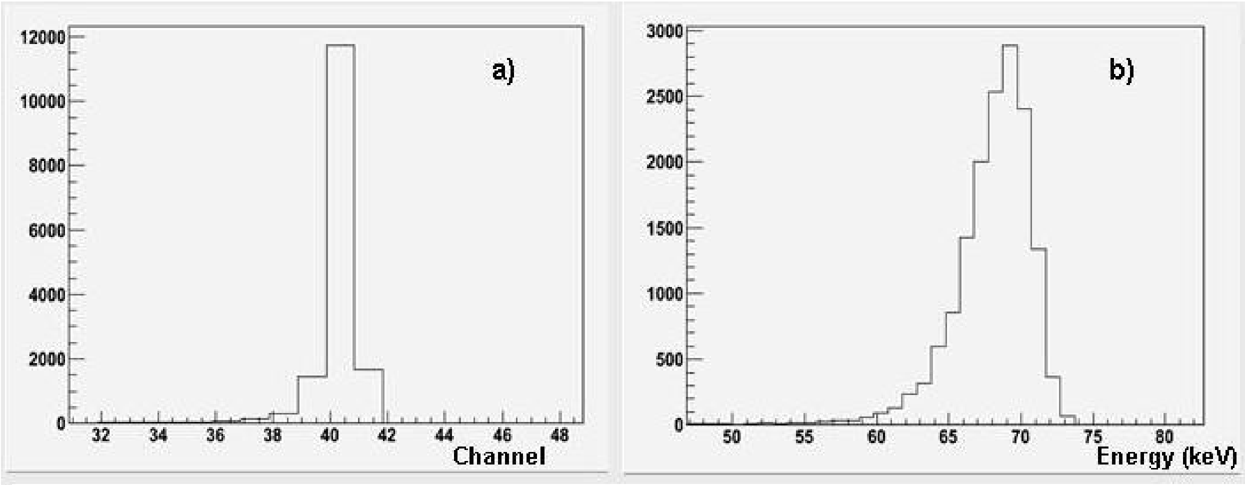

FIGURE 5.. The PID350#3 centroid channel distribution for (a) ^{241}Am and (b) ^{109}Cd sources.

To improve further the energy resolution, the software does not use in the energy calculation process the "bad" pixels. The bad pixels are defined as those pixels for which the energy calibration procedure either fails (the calibration algorithm can't find two peaks in order to calibrate the pixel), or the pixel is noisy (it has noisy channels above the upper edge of the dc level).

The energy calibration has been performed for each PID350 detector, using two low energy gamma ray standard isotopes: ^{241}Am (59.5keV) and ^{109}Cd (88keV). Figure 6 illustrates the spectrum of the PID350#3 detector before and after the software energy calibration.

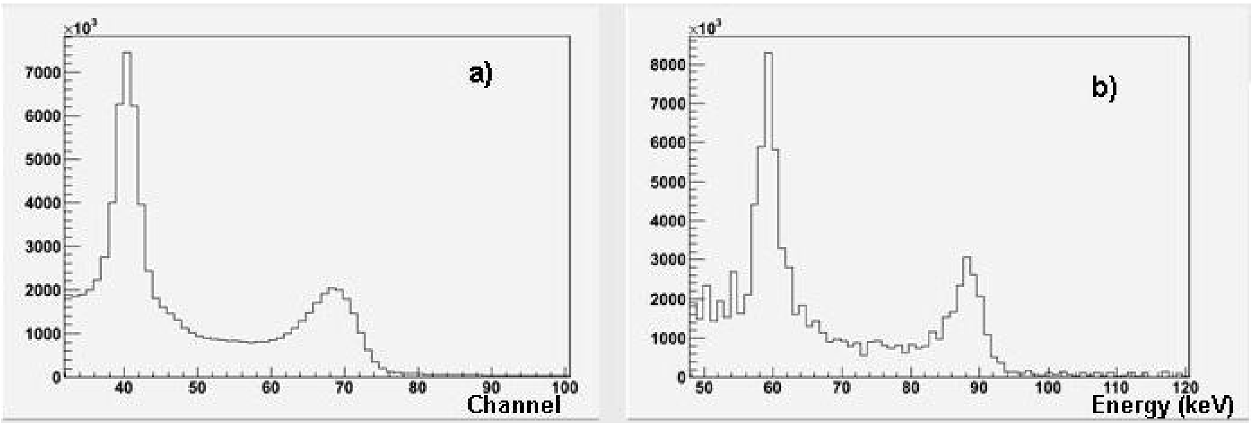

FIGURE 6. a) The un-calibrated spectrum of the PID350#3 detector (b) The calibrated spectrum after a pixel by pixel adjustment.

Moreover, the calibrated ^{241}Am photo-peak of each PID350 detector after the software calibration is shown in Figure 7. The archived energy resolution at 59.5 KeV ranges 1.73 keV to 2.15 keV (FWHM)

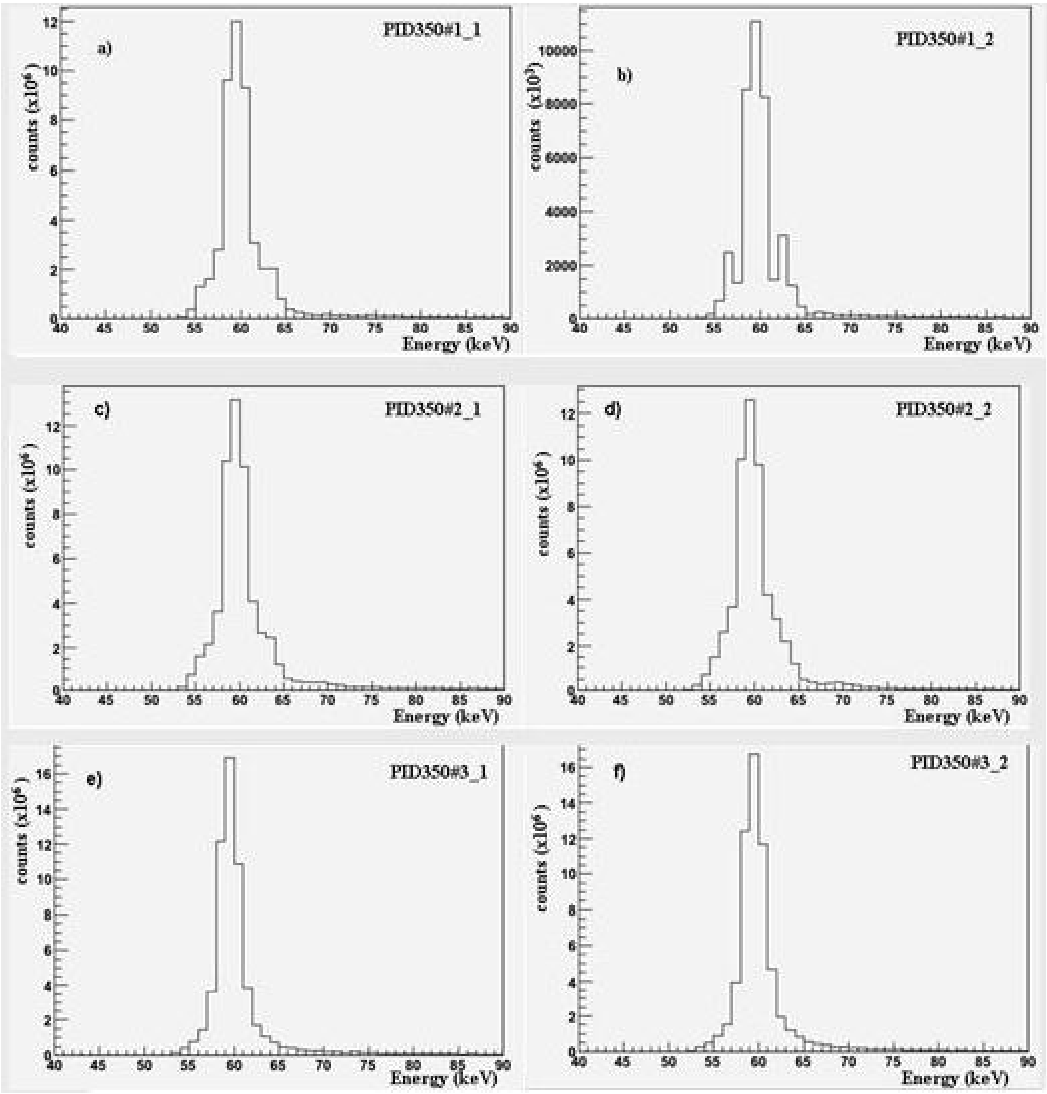

FIGURE 7. Calibrated photo-peaks of ^{241}Am radioactive source acquired with a) PID350#1_1, b) PID350#1_2, c) PID350#2_1, d) PID350#2_2 e) PID350#3_1 and f) PID350#3_2 detector modules.

THE STACKED PROTOTYPE SYSTEM

The Structure of the System

We have assembled a prototype system as a stack of three PID350 detectors. The ordering of the PID350 layers in the stacked system reflects the performance of each layer, i.e. the PID350s are stacked from the top to bottom with decreasing quality. The quality is defined by three parameters: the energy resolution, the number of bad pixels and the upper channel limit of the noise peak. The experimental setup used to test the performance of the prototype system is shown in Figure 8. For the data acquisition the system described in the previous section has been used.

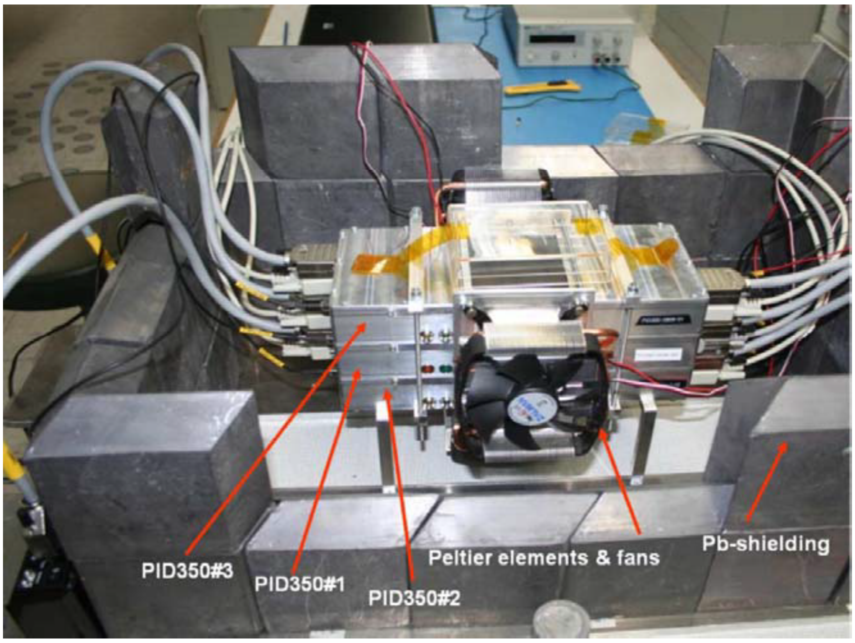

FIGURE 8. Experimental setup with the PID350 stacked prototype.

Simulation Studies

The response of both the PID350 detector and of the stacked system has been modeled using an open-source object oriented software library (MEGAlib [3]) providing interface to the GEant4 [4] toolkit that simulates the passage of particles through matter.

A large number of gamma rays (~10^9) emitted from point-like isotropic sources placed on the detector's axis of symmetry and at different distances interact with the PID350 detector model and the deposited energy is smeared using a Gaussian distribution of 7keV FWHM [1]. Shown in Figure 9 is the case of a simulated event of a 10keV gamma ray that interacts with the model of the stacked system creating two energy depositions (hits).

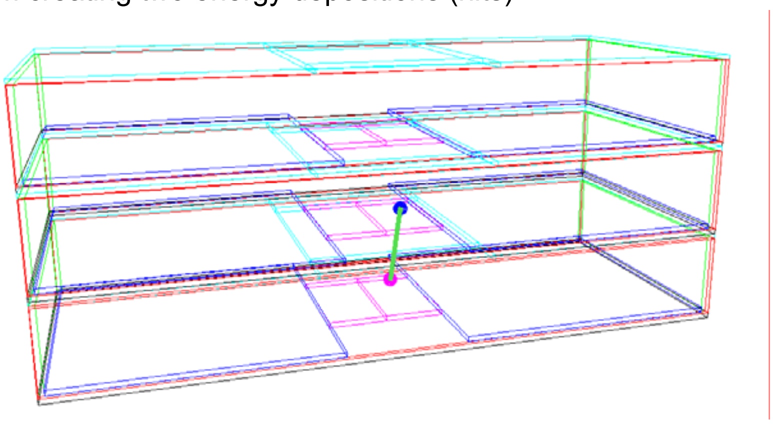

FIGURE 9. An 140 keV gamma ray interacts with the stacked system creating two hits (energy depositions).

Shown in Figure 10 is the simulated energy deposition of all hits for the case of 60 keV incident gamma rays. The peak (59.5 keV) due to interactions of the gamma rays with the detecting materials via the photoelectric effect process, the Ka x-ray from Cadmium (23 keV) and the escape peak (26.5 keV), broadened due to the smearing, are visible.

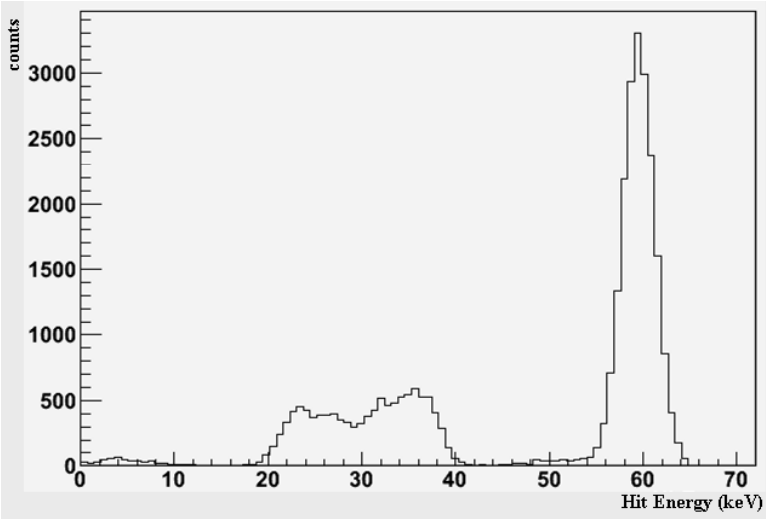

FIGURE 10. Simulated spectrum of the energy deposited in each PID350 detector pixel, for 60 keV incident gamma rays

Source-to-detector distance Estimation

The ability of the stacked detector to estimate the distance of a radioactive source has been tested by using a ^{99m}Tc (140.5 keV) source placed at various distances from the system's upper detecting layer. The estimation of the source-to-detector distance is based on the distribution of the fully absorbed photons (via a photoelectric effect) in each detecting layer [5].

The distance (d) of a radioactive source from the first detecting layer of the stacked system is evaluated by fitting the following function on the distribution of the photo-peak counts (N_i) of each PID350 detector layer (i):

$$N_i \propto \exp\left(-(i-1)\left(\sum_j \mu_j t_j\right)+a\right)\cdot\frac{\sin^{-1}\left(\dfrac{k^2}{[d+(i-1)g]^2+k^2}\right)}{\sin^{-1}\left(\dfrac{k^2}{d^2+k^2}\right)} \quad (58)$$

where t_j is the thickness of a material of each detecting PID350 layer with corresponding total absorption coefficient μ_j, g is the distance between the layers, k is half the length of the rectangular layer side and α is a parameter evaluated experimentally. The sum runs over all materials of the ith layer.

The first term of the above equation reflects the absorption by the front layers of the detector. The second term is the ratio of the solid angle subtended by the ith rectangular detecting layer over the solid angle subtended by the first one. Experimental results for the determination of the distance (d) by using a ^{99m}Tc radioactive source are presented in Figure 11. It can be noticed that the 3-layer PID350 stacked prototype system is capable of evaluating the distance of a gamma ray source with good accuracy in the distance range from 30 cm up to 100 cm.

Additionally, the complete geometry of the stacked PID350 detecting system has been simulated using the GEANT4 package and the estimated distance using the simulated data is depicted in Figure 11 for the case of a 140.4KeV radioactive point-like source (^{99m}Tc). The solid line represents the case of the ideal source-to-detector distance estimation.

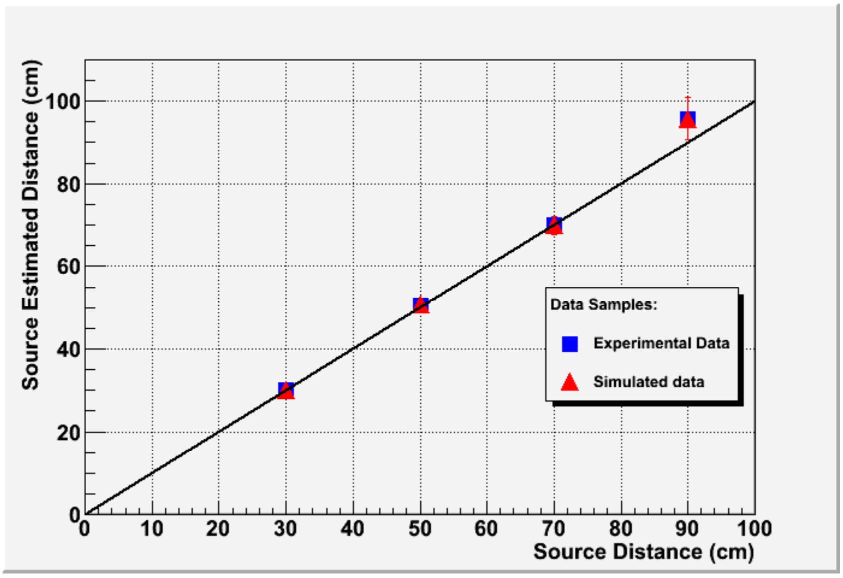

Figure 11. Estimated distance vs. real distance of a ^{99m}Tc radioactive source using both real and simulated data.

SUMMARY

We have developed a prototype stacked system consisting of three PID350 pixelated detectors.

In order to reduce the data loss in case of a high flux of photons, we have developed a data acquisition system with data transfer speed of 120 frames/s.

Furthermore, we have developed a data analysis framework that transforms the raw data collected by the PID350 detectors into useable frames and performs a software energy calibration for each pixel of the detector independently. The achieved energy resolution ranges from 1.73 keV to 2.15 keV (FWHM) at 59.5keV.

Spectroscopic measurements show that the stacked system is able to accurately evaluate the distance of a ^{99m}Tc radioactive source from its first detecting layer, in a broad range of source-to-detector distances from 30cm to 1m.

REFERENCES

[1] AJAT, http://www.ajat.fi/index.php?option=com_content&view=article&id=37

[2] ROOT Data Analysis Framework, http://root.cern.ch

[3] Zoglauer, R. Andritschke, F. Schopper: “MEGAlib-The Medium Energy Gamma-ray Astronomy Library”, New *Astronomy Reviews*, Volume 50, Issues 7-8, Pages 629-632, October 2006

[4] GEANT4-A toolkit for the simulation of the passage of particles through matter, http://geant4.web.cern.ch/geant4/

[5] Shin Watanabe et al. “Stacked CdTe gamma-ray detector and its application to a range finder”. Nuclear Instruments & Methods in Physics Research A 505(2003)118-121