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Employing thin HPGe detectors for gamma-ray imaging[†]

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Abstract

We have evaluated a collimator-less gamma-ray imaging system, which is based on thin layers of double-sided strip HPGe detectors. The position of individual gamma-ray interactions will be deduced by the strip addresses and the Ge layers which fired. Therefore, high bandwidth pulse processing is not required as in thick Ge detectors. While the drawback of such a device is the increased number of electronics channels to be read out and processed, there are several advantages, which are particularly important for remote applications: the operational voltage can be greatly reduced to fully deplete the detector and no high bandwidth signal processing electronics is required to determine positions. Only a charge sensitive preamplifier, a slow pulse shaping amplifier, and a fast discriminator are required on a per channel basis in order to determine photon energy and interaction position in three dimensions. Therefore, the power consumption and circuit board real estate can be minimized. More importantly, since the high bandwidth signal shapes are not used to determine the depth position, lower energy signals can be processed. The processing of these lower energy signals increases the efficiency for the recovery of small angle scattering.

Currently, we are studying systems consisting of up to ten 2mm thick Ge layers with 2mm pitch size. The required electronics of the few hundred channels can be integrated to reduce space and power.

We envision applications in nuclear non-proliferation and gamma-ray astronomy where ease of operation and low power consumption, and reliability, are crucial.

Introduction

The ability to image and characterize known as well as unknown gamma-ray sources finds a variety of applications in national security, such as nuclear nonproliferation and stockpile stewardship programs, in nuclear waste control and monitoring, in nuclear medicine for cancer diagnosis and therapy as well as in astrophysics. Besides these applications, which are based on the natural gamma-ray emission of radioactive material of interest, gamma-ray imaging can be employed in alternate modes, such as particle induced gamma-ray emission, scattering or transmission modes.

Recent advances in the manufacture of two-dimensional segmented semi-conductor detectors enable to determine energies and three-dimensional positions of individual gamma-ray interactions in the detector. Using tracking algorithms, which are based in the underlying interaction processes such as the Compton scattering and the photo-electrical effect, it is possible to determine the time sequence of the interactions. Knowing the energies and positions of the first interactions allows to determine the incident angle of the incoming gamma ray without the use of a collimator which will significantly increase the efficiency a gamma-ray imaging system. However, to realize the full potential of gamma-ray tracking and Compton-tracking based gamma-ray imaging the excellent position and energy resolution of a semi-conductor detector is needed.

In this study we are focusing on the use of thin high-purity Ge (HPGe) detectors in planar geometry, which are equipped with orthogonal strips on each side (so called double-sided strip detector (DSSD)).

Coaxial vs. planar HPGe detector:

Detector size and segmentation:

Generally, two-dimensionally segmented HPGe detectors can be built in two different geometries: planar and coaxial.

Coaxial detectors can be built up to diameters of 8cm and lengths of 14cm. The Boron contact at the outside can be segmented longitudinally and azimuthally as shown on the left side of figure 1. The advantage of coaxial detectors is their compactness and therefore their high efficiency in detecting gamma radiation and the large field-of-view (FOV).

Planar detectors can be built up to 20mm thick and with an area of up to 90x90mm². They can be segmented two-dimensionally either in pixels on one side or in orthogonal strips on each side. Recent advances in detector processing enable to use reliable contacts on both sides of the crystal. To increase efficiency in particular for higher gamma-ray energies several of these planar DSSD detectors can be arranged in a stack, as shown in figure 1.

However, for imaging applications the high efficiency of large volume detectors is not the primary goal but the sensitivity to measure a weak signal out of background radiation. Only the capability to provide a spatial resolution as with an imaging device can effectively increase the signal-to-background ratio by distributing the background throughout the solid angle while maintaining the gamma-ray flux of interest locally in one point. Only increasing the efficiency will increase both, the signal and the background.

Ultimately, only an imaging capability is able to provide geometric dimensions and extensions of materials of interest.

Pulse-shape processing:

To obtain energy and three-dimensional position information of individual interactions as a prerequisite for gamma-ray tracking in a two-dimensionally segmented coaxial detector, in **coaxial HPGe detectors** the pulse shapes of charge collecting as well as

adjacent segments have to be analyzed which requires **complex processing of the signals**. However, in this way not only the radius can be determined but also the longitudinal and azimuthal positions can be determined to much higher accuracy than the segment size.

The **planar geometry** is much simpler and allows to obtain positions and energies with higher accuracy than the segmentation size and the crystal thickness with **much reduced signal processing**. It is even possible to build a stack array of thin planar DSSD detectors which **don't require any complex processing** to obtain energy and position of individual interactions. If the detector is thin enough and the pitch size of the strips is sufficiently small to minimize multiple scattering processes in one of these "voxels" and to provide sufficient position resolution just by the dimensions of these "voxels", then just the strip and crystal IDs and their measured energies can be used for tracking.

Features and advantages of thin DSSD HPGe detectors:

In thin planar DSSD HPGe detectors no complex and high-bandwidth related pulse processing is required since only the energy has to be determined. The thickness of the planar crystals and the strip sizes on each side define a three-dimensional "voxel" which is dimensioned to provide sufficient position resolution and to reduce the number of multiple interactions in one "voxel". As indicated above, if an energy is measured in one "voxel" then the position of the interaction is known to the accuracy of this voxel just by its ID number.

We envision crystal thicknesses of 2mm and pitch sizes of 2mm and therefore "voxel" sizes of 2mm³

Electronics:

In a low count-rate environment in which neither timing nor position determination requires a bandwidth in the order of 10MHz the bandwidth can be lowered to about 100kHz to provide the necessary shaping to optimize the energy resolution for each "voxel". The **costs for the processing electronics** can be reduced due the reduced number of parts required and the lower costs of the parts. In addition, the electronics can be built **more compact** which is very important for eventually integrating the hundreds of channels.

Since thin HPGe detectors can be depleted with a few hundreds instead of a few thousands volts the high voltage support can be simplified. In particular, the dimensions of the high-voltage filter can be reduced as well as the Z of the material can be lowered to reduce scattering sources for gamma rays outside the detector.

Since no high-power demanding high-bandwidth analog or digital electronics is required the **electronics power consumption can be minimized**.

FET's and all parts of the electronics can be moved outside the cryostat and can be thermally decoupled from it to minimize necessary cooling of the Ge detector.

Detector:

By using thin HPGe detectors the requirements for **material quality**, for example in terms of the concentration and distribution of impurities, can be reduced. Otherwise disturbing effects caused by **charge trapping** or by **material and field inhomogeneities are minimized**.

Lowering the requirements for the crystal quality significantly lowers the **costs in manufacturing** these detectors since Ge material can be used which otherwise would have to be reprocessed to achieve sufficient quality for other detectors.

Since the requirements to obtain a three-dimensional position of interactions is reduced to filtering a signal out of the noise background which can be done very effectively with slow shaping amplifiers much smaller signals can be accepted for the position determination. Since small signals are associated with small energies which themselves are related with small scattering angles, smaller scattering angles can be accepted.

Since the distances between the HPGe wafers can be changed, systems can be optimized for efficiency (small distances) or spatial resolution (large distances).

Drawbacks of thin DSSD HPGe detectors:

Number of electronics channels:

One drawback in using thin DSSD HPGe detectors to obtain energies and positions of individual gamma-ray interactions is the number of required electronics channels. Instead of using in the order of 40 as in a coaxial system or 100 in a mixed planar DSSD system, here we need to equip potentially more than 1000 channels with shaping amplifiers and digitizers. However, since the requirements for processing are low, integrated electronics including amplifiers and digitizers can be built and employed to minimize space requirements. In addition amplifier and digitizer systems can be envisioned in which each channel only requires 20-30mW per channel resulting in about 30W for a system of 100 channels.

Loss in efficiency due to escaping Compton and photo electrons:

Using thin detectors increases the probability that electrons, which are scattered out of the atom from the interacting gamma ray are escaping the Ge detector or at least the sensitive part of the detector without leaving the full energy. These events reduce the efficiency in detecting the full energy of the incident gamma ray and cause an increased background in the gamma-ray spectrum.

Figure 2 shows calculated losses in efficiencies for different thicknesses and numbers of planar HPGe detectors for three different gamma-ray energies: 186keV (^{235}U), 375keV (^{239}Pu) and 646 (^{239}Pu). For example, in our proposed design of 10 layers of 2mm thick HPGe detectors we expect to loose about 15% of full-energy events at a gamma-ray energy of 646keV.

Cooling of HPGe detector:

The advantage of the excellent energy resolution of Ge is associated with the requirement to cool the Ge crystal close to liquid nitrogen temperatures to reduce the thermal noise. However, recent developments in cooling technologies allow now to cool Ge detectors by

electromechanical means and avoiding the many problems of liquid nitrogen, particularly for remote detection applications. The cryostat, wiring and feedthroughs have to be designed to minimize the thermal power consumption. We envision that a system can be designed and built with a heat load which requires less than 30W electrical power.

Conclusions:

We have studied an array of thin DSSD HPGe detectors to be used as gamma-ray imager. Three-dimensional positions of gamma-ray interactions are measured by the strip and crystal ID. Therefore, no complex signal processing is required to obtain positions. Only low bandwidth analog electronics is necessary to obtain energy for each "voxel" fired. Positions and energies from such an array can be used to track the interactions of the gamma ray through the detector and to determine the incident angle of the incoming gamma ray which enables collimator-less gamma-ray imaging.

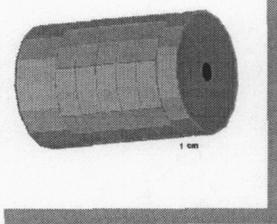
Low bandwidth electronics as well as thin planar HPGe detectors can be manufactured with very low cost and can be operated very reliably due to the reduced sensitivity to detector and electronics quality. Since only a signal which is above the noise is required to determine the position of the scattering process, events with smaller scattering angles can be accepted.

In summary, the proposed array of thin two-dimensionally segmented HPGe detectors represents an appealing approach for remote gamma-ray imaging applications which realizes the full potential of gamma-ray tracking by minimizing costs, power and signal processing complexity.

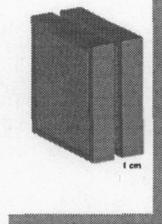
Figure 1:

Different possible geometries of two-dimensionally segmented HPGe detectors

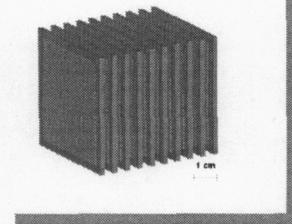
Closed-ended coaxial HPGe detector



Two-crystal stack of "thick" planar DSSD HPGe detectors



Many-crystal stacks of "thin" planar DSSD HPGe detectors



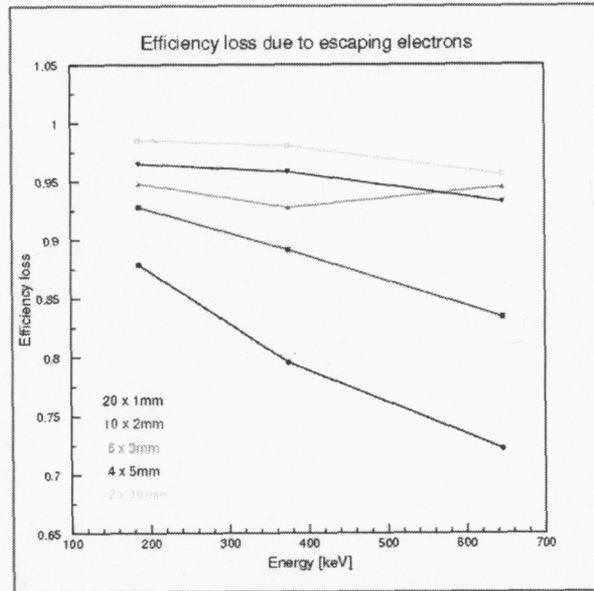
Signal processing complexity	Very complex, has to be done in digital electronics	Medium, depth and potentially x and y can be done in analog electronics	Very low, only analog electronics required for energy determination
Bandwidth of processing electronics	High	High	Low
Number of electronics channels	Low	Medium	High
Power	High	Low	Low
Costs	High	High	Low

Figure 2:

Calculated efficiency losses due to electrons which leave the sensitive volume of the HPGe detector. Shown are 5 different stacked planar DSSD HPGe systems with wafer thicknesses varying in between 1mm and 10mm and numbers of layers in between 20 and 2, respectively.

Efficiencies are plotted for three gamma-ray energies: 186keV, 375keV and 646keV.

While in the two-layer system the maximum loss is about 4% at 646keV, in a 20 layer system about 28% of the full-energy efficiency will be lost.



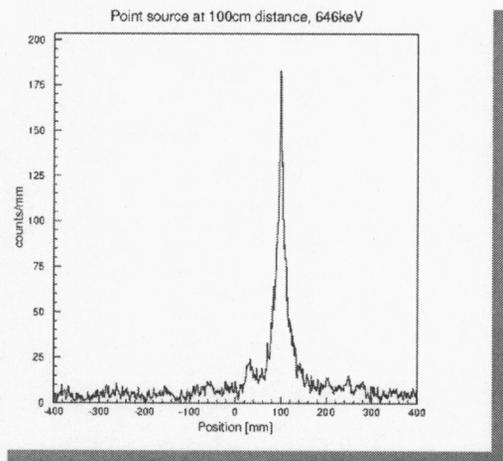
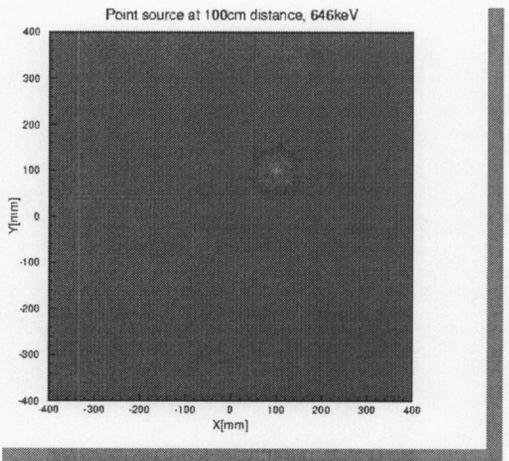
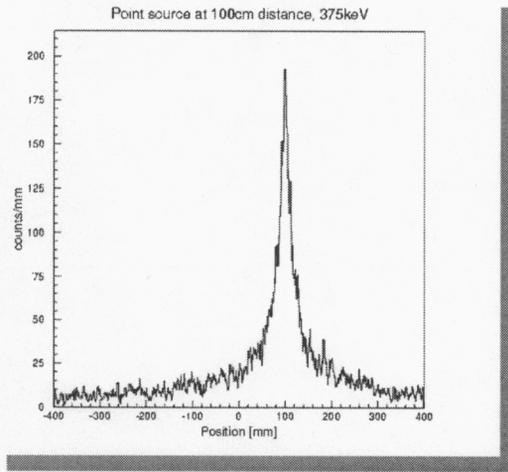
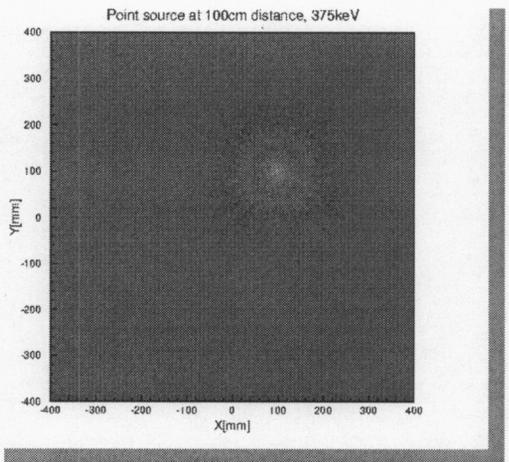
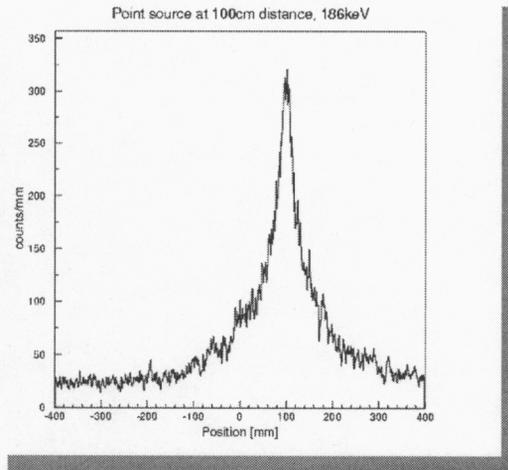
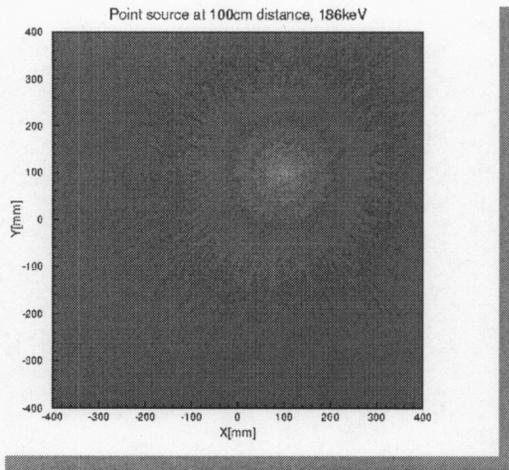


Figure 3:
 Simulated images for point sources of different energies at 100cm distance from a thin DSSD stack array of HPGe detectors.