Characterisation of a Clover detector

for the development of a Compton Camera

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1- Introduction

The development of High Purity Germanium (HPGe) detectors has reached the stage where they can be used as effective imaging devices. The electrical segmentation of the Germanium crystal coupled with digital signal processing electronics allows the measurement of energy, time, and position following the interaction of a gamma-ray. The position and energy information are extracted following the digitisation of the detector charge signal, analysed using techniques such Pulse Shape Analysis (PSA).

We propose to build a PET-SPECT system composed of two planar segmented HPGe detectors. In our investigation into SPECT, we have built a prototype of Compton camera (figure 1) in order to test our pulse processing techniques and develop a gamma-ray tracking algorithms. The system was composed of a planar detector[1] with 5mm strips in a 24x12 configuration, and a 16 segments coaxial Clover detector. The planar would act as a photon *scatterer* and the Clover a gamma rays stopper or *analyser*.

Before being able to reconstruct the path of the gamma-rays with the camera, it is necessary to **calibrate the response of each detector as a function of the position**.

1) Development of Planar Germanium Detectors for Medical Imaging Applications, J.Norman

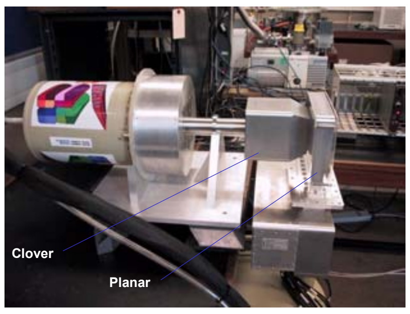

Figure 1. Prototype of Compton camera

2-The Clover detector

The EXOGAM Clover is a High Purity Germanium detector which consists of four coaxial n-type Ge crystals, arranged like a four-leaf clover and housed in the same cryostat (figure 1). Each crystal has a square front face with round edges, obtained by tapering on two adjacent faces with an angle of 7.1 degree. The dimensions of the Clover detector are about 64cm^2 by 9cm in depth.

Each germanium crystal has a central anode biased at ~2.5kV. The outer cathode is grounded and divided into four segments. This results in a total of twenty electronic channels and 16 individual segments. The twenty outputs (four anodes plus sixteen cathodes) are coupled to fast charge pre-amplifiers. A view of the crystals and their segmentation is presented on figure 2.

The clover is originally designed for gamma ray spectroscopy experiments, but its dimensions, and the segmentation of the outer electrodes make it a good **analyser** for our prototype of Compton camera.

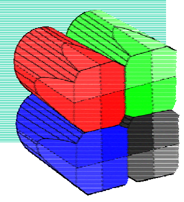

Figure 2. Segmentation of the Clover detector

3-Methods: Pulse Shape Analysis

Following a gamma ray interaction in a crystal, the drift of the electrons and holes under the electric field induce a signal on the electrodes. The growth of the charge pulse depends on the motion of the charges carriers: they have different distances of drift inside the crystal therefore they will be collected at different times. Thus, the shape of the corresponding charge signal is directly dependent on the radius of interaction (figure 3a, 3b).

Figures 3a and 3b show three typical pulses from the Clover, and illustrate the change of pulse shape as a function of the radial position of interaction in a coaxial detector:

- For an interaction close to the centre of the detector (in red), the electrons are collected at the beginning of the pulse rise: a change of slope occur in the leading edge of the pulse. The remaining pulse corresponds to the contribution of the holes.
- For an interaction in the central region (blue), both types of charge carriers have similar drift times.
- For an interaction close to the outer electrode (in green), the holes are collected first; the rise of the pulse is then due to the drift of the electrons towards the anode.

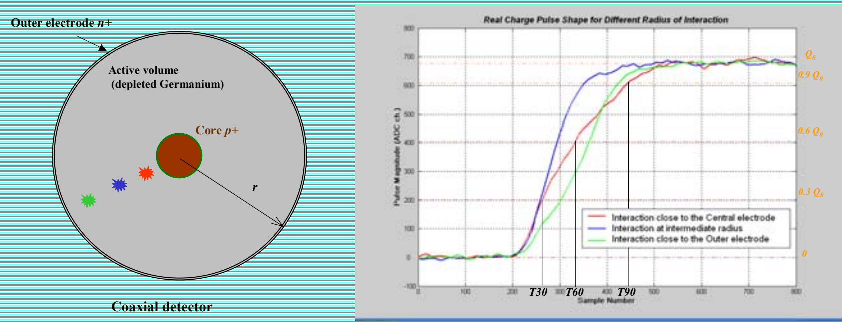

Figure 3. Variation of the detector pulse shape with the position of interaction.

As illustrated on the graph above, ***T30***, ***T60*** and ***T90*** variations (respectively times from 10% to 30%, 60%, and 90% of the total charge magnitude Q_0) can be used to investigate the detector response as a function of the radius of interaction. This Pulse Shape Analysis (PSA) technique is only possible with signals acquired through digital instrumentation.

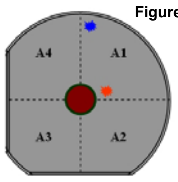

Figure 4. Positions of interactions In crystal A for image charge Analysis

3-Methods: Image Charge Analysis

The motion of the charges collected by a particular electrode induce a signal on adjacent electrodes. The coupling between these moving charges and the electrodes give rise to a transient pulse whose magnitude and polarity depends on the charge created, the nature of the moving charge carriers, and of the position of interaction.

Figure 5 presents two examples of signals observed on the four outer electrodes of the same crystal. The two detected gamma rays were fully absorbed in segment A1, depositing 662keV; the respective positions of interaction are shown in figure 4 above. In both cases, segment A1 displays a resulting net charge (see figure 5). Adjacent electrodes A2 and A4 exhibit some typical image charges.

For the first event (red), the magnitude of the image charge signal seen on segment A2 is large and on A4 is small, due to the respective distance of the interaction from the electrodes.
In the second case (blue), the interaction was located near segment A4; the signal on this electrode has a large amplitude, unlike the image charge on electrode A2.

The variation of the image charge magnitude in adjacent segments can give an indication of the azimuthal position of interaction. One can define the "image charge ***asymmetry***" parameter for a particular segment as:

$$A = \frac{Q_{left} - Q_{right}}{Q_{left} + Q_{right}}$$

Where Q_{left} and Q_{right} are the magnitudes of the signals observed on the adjacent electrodes.
The ***asymmetry*** varies from +1 to -1.

In the previous examples, the values of asymmetry would be:
A ≈ +0.81 for the interaction close to the segment A4;
A ≈ -0.81 for the interaction close to the segment A2.

The variation of the asymmetry with angle of interaction relative to the centre of the crystal will lead to the determination of the azimuthal position of interaction.

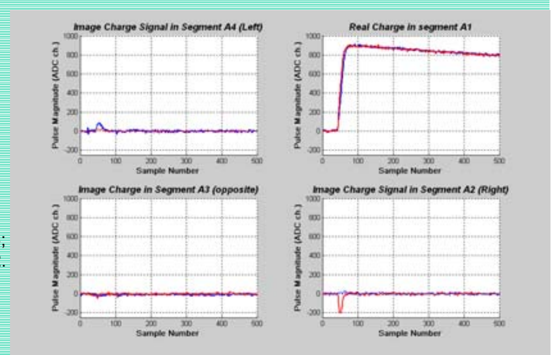

Figure 5. Real charge in segment A1, image charges in A2 and A4.

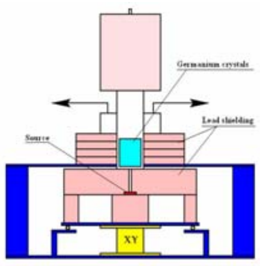

Figure 6. Detector scanning set-up.

4-Characterisation Measurements

Measurements have been carried out in order to ***calibrate the detector response as a function of the position of interaction***. The variation of the pulse shapes rise time (through T30 T60 T90) and asymmetry with radial and azimuthal position of interaction have been characterised. These measurements consisted of a scan of the front face of the Clover detector, the set-up is presented on figure 6.
A collimated ^{137}Cs gamma ray source (662keV) was mounted on the top of an automated X-Y positioning table. The source was moved in front of the detector in two millimetres steps in the X and Y directions. The data were recorded 2 minutes at each position in order to get sufficient counting statistics. The data consisted of 6.3 ms pulse traces and were stored for later ***energy***, ***pulse shape*** and ***image charge analysis***.

Figure 7 represents the intensity response for interactions inside the detector. Each point corresponds to a position of the collimated gamma ray source in the (X,Y) plane. The colour scale expresses the number of 662keV photons detected during the time interval at a particular position. The four germanium crystals are well separated from the background, and the electrical segmentation of the detector is clearly defined.

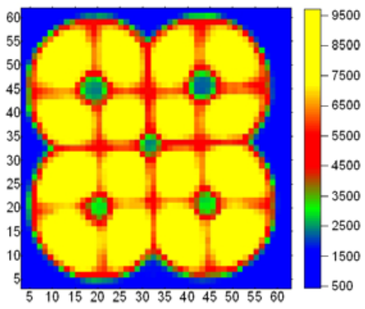

Figure 7. Number of 662keV photons detected by the outer cathodes as function of interaction position. The X and Y axis are given by the positioning system.

5-Digital Acquisition System

The use of PSA techniques is only possible with the use of a digital acquisition system. The acquisition system developed for our project is based on the GRT4 VME acquisition card[2], developed at Daresbury Laboratory for the UK Gamma Ray Tracking Project.

Each card includes 80MHz–14 bits **flash ADCs** which digitizes the detector signals and **FPGAs** for further data processing.

2)The GRT4 VME Pulse Processing Card for Segmented Germanium Detectors, I.H. Lazarus.

6-Radial Position Determination

The figures 8a, 8b and 8c show the average *T30, T60* and *T90* response as a function of position, measured on the anode signals.

1-The variation with radial position. The *T30* value increases from the inner radius towards the outer radius. The *T90* value decreases from the central radius, to reach a minimum when electrons and holes have the same drift time. Then *T90* increases until the outer radius. Similar behaviour is observed for *T60*.

2-The variation with angular position. At constant radius, the values of *T30*, *T60* and *T90* will be minimum at angles equal to *n* * 90 degree (0 °, 90 ° …), and maximum at every *n* * 90 + 45 degree (45 °, 135°…). This observation is related to the anisotropic mobilities of the charge carriers under high electric field.

The radial position of interaction in a single crystal could be determined by quantifying the variation of *T30, T60* and *T90* with radius of interaction in a crystal. The figures 9a, 9b, 9c show such variations for a single crystal (crystal A). In each of the cases, a clear correlation is observed between the rise time and the radius of interaction. Between 15mm and 30mm, the T30 variation shows a sensitivity of about 2ns/mm; the T60 variation shows a sensitivity of about 3.3ns/mm and the T90 variation gives a sensitivity of about 3.5ns/mm.

The spread in the time measurements comes from three factors:
1-The variation of rise time with azimuthal position of interaction;
2-The size of the cone of the gamma ray beam out of the collimator;
3-Gamma rays that Compton scatter in the same segment.

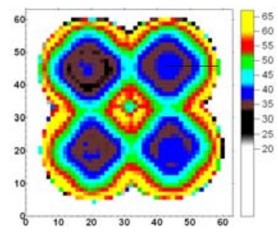

Figure 8a. Average T30 variation per position; measured from the central anodes.

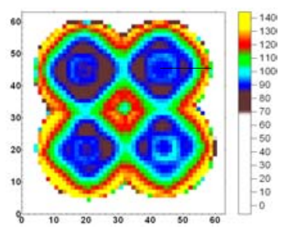

Figure 8b. Average T60 variation per position; measured from the central anodes.

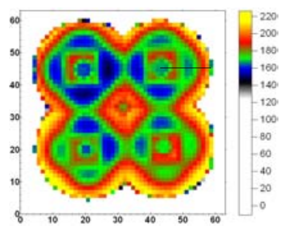

Figure 8c. Average T90 variation per position; measured from the central anodes.

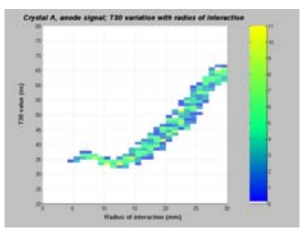

Figure 9a. Average T30 variation per position; measured from the central anode A.

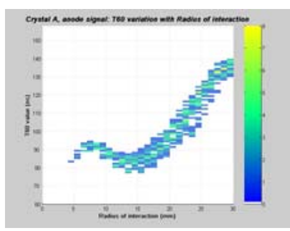

Figure 9b. Average T60 variation per position; measured from the central anode A.

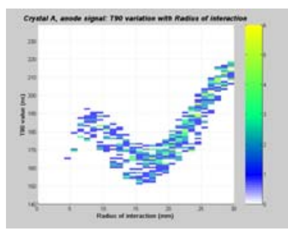

Figure 9c. Average T90 variation per position; measured from the central anode A.

7-About the crystal orientation

When the electric field is sufficiently high, the drift velocity of the electrons and holes varies with the orientation between the electric field and the crystallographic axes. The drift velocities are maximum along the 100 and 010 directions, and minimum along the 110 direction. This effect is the main cause of the spread of the time values measured for the same radius.

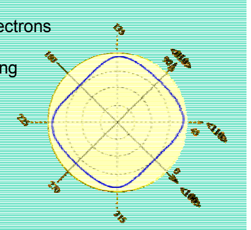

Figure 10. Illustration of the rise time variation with crystal orientation. The blue line shows regions having the same rise time.

Characterising the variation of the T30 T60 and T90 values with the angular position could improve the precision on the rise time measurement.

8-Image charge

Because of the large size of the segments, the coupling between the adjacent electrodes and the moving charges is small. In most of the cases the magnitude of the image charge pulse is as low as the level of the peak to peak value of the electrical noise, which makes its observation very complicated.

The low magnitudes of image charges observed suggests that the temporal analysis of the image charge pulse cannot give satisfactory results regarding the determination of the azimuthal position. The use of a fast Fourier algorithm to extract the image charge signal from the noise may allow a more detailed analysis to be performed.

9-Conclusion and Further Work

The difficulties in the present analysis arise mainly from the complex geometry of the crystals, which combines planes and circular edges in a coaxial design resulting in a complicated electric field configuration. Also, a measure of the depth of interaction, or separate the rise time measured in the front tapered region from values measured in the back coaxial is impossible.

The next step after the characterisation of the Clover and the planar detector will be to combine the characterisation data from both detectors with the test measurements of the Compton Camera prototype (figure 1).

Finally, three planar detectors (figure 11) with an active area of 6x6cm^2 have been ordered for the project, and the first element should be delivered in October 2004.

Figure 11. Future Planar detectors