Measuring the performance of the iThemba LABS segmented clover detector

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Abstract. The iThemba LABS segmented clover detector, capable of performing gamma-ray tracking, was characterised. The measured energy resolutions (FWHM) of this detector at 121 keV and 1332 keV are < 1.4 keV and < 2.2 keV respectively for the inner-core contacts. The photo-peak efficiency in direct and add-back modes were measured at four different distances. The detector preamplifiers are fast enough to enable time variations larger than 40 ns to be distinguished, which is sufficient for measuring variations in the signal rise time of ~200 ns for the iThemba LABS segmented clover detector.

1. Introduction

Large volume high-purity germanium (HPGe) detectors are commonly used in applications (such as gamma-ray spectroscopy) that require good energy resolution and high detection efficiency. iThemba LABS recently bought a new state of the art segmented clover detector. The new detector contains four cylindrical HPGe crystals (see figure 1) housed in a common vacuum cryostat and held at temperature of around 75 K by a metal cooling structure that extends back into a dewar of liquid nitrogen. This detector has 32 outer contacts. These are in addition to the four inner-core contacts, and so the total number of electrical signals from the detector is thirty-six. The principal reason for this segmentation is to provide information about the three-dimensional localization of gamma-ray interactions within the detector. Charge sensitive preamplifiers allow all thirty-six electrical signals to be read out, providing precise energy information from the core contact and signals for position localization from the outer contacts. Due to its segmentation, the detector can be used not just as a standard clover detector, but also in a gamma-ray tracking mode. Therefore measurement for the performance of this detector is very important prior to developing γ-ray tracking. In this work results obtained from tests which include measuring the energy resolutions (FWHM) for each crystal and for the outside electrodes at different rates, measuring rise and decay times and efficiency at different source-to-detector distance are presented. Measurements were carried out mainly by means of Pixie-4 digital electronics.
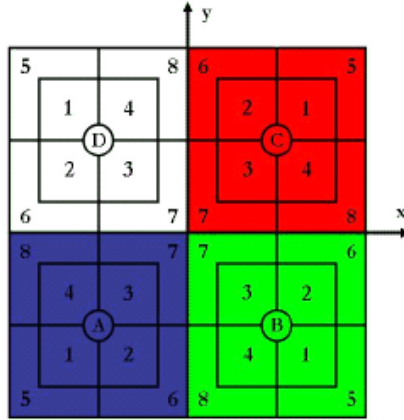
Figure 1. Schematic drawing of the iThemba LABS segmented detector layout. The colours of the crystals, corresponding to labels A through D, are Blue, Green, Red, and White.

2. Experimental measurements and results

2.1. Preamplifier response measurements
The preamplifier represents an interface between the detector and the signal processing electronics. Its basic function is to amplify and shape the small signal from the detector and to transfer it to the electronic chain with the least degradation. Typically, charge sensitive preamplifiers are used for Ge detectors. In a charge sensitive preamplifier, the charge carried by the incoming pulse is first integrated on a capacitor and then removed by a slow discharge through a resistive feedback network. This produces a pulse with a fast leading edge (rise time), corresponding to the charge collection time in the detector, and a slow exponential decay (fall time). In order to preserve as well as possible the information carried in the signal leading edge, a very fast, low noise, low power consumption and stable preamplifier is required. To obtain a fast response, i.e. a signal with short rise time, a large bandwidth (BW) preamplifier is required.

The preamplifier response of the detector was measured by injecting a 5 ns rise time square wave into the test input of each crystal, and measuring the rise time and decay constant τ of the subsequent core signal. The rise time was measured as the time the pulse takes to grow from 10% to 90% of its final amplitude using a Tektronix DPO3054 digital oscilloscope (500 MHz, 2.5 GS/s). The shapes of the injected and preamplifier output signals are shown in figures 2(a)-(d) and figures 3(a)-(d).

Several different decay time constants τ are being used:

(i) The decay time constant τ: is equal to the time at 37% (1/e) of the pulse amplitude.

(ii) 50% time constant $t_{1/2}$: is equal to the time at 50% of the pulse amplitude. It is related to τ by
$$\tau = t_{1/2}/\ln 2.$$

(iii) 90% - 10% time constant $t_{90\% - 10\%}$: is equal to the time taken by the pulse to fall from 90% to 10% of its amplitude. It is related to τ by $\tau = t_{90\%-10\%}/\ln 9$.

All core contacts exhibit good rise times and decay constants, falling well below 44 ns and 52.5 μs respectively (see table 1). It can then be concluded that the detector preamplifiers are fast enough to enable time variations larger than 40 ns to be distinguished. This time resolution is sufficient for measuring variations in the signal rise time, which for the iThemba LABS segmented clover detector is of the order of 200 ns. Note that the shape of the signal observed from crystal C shows some oscillations (see figure 2(c)). When the signal oscillates, the settling time is an issue in addition to the

amounts of over/under shoots. Thus the performance of the preamplifier of crystal C raises a concern, and is under further investigations[1].

Table 1. Rise times and decay time constants τ for the iThemba LABS segmented clover detector. The value marked with * is measured when ignoring the oscillation of the signal.

	Injected 5 ns square pulse	
Crystal	Rise time (ns)	Decay constant τ (µs)
A	42.6	49.9
B	42.2	49.9
C	33.0*	50.5
D	43.8	51.7

(a) Crystal A
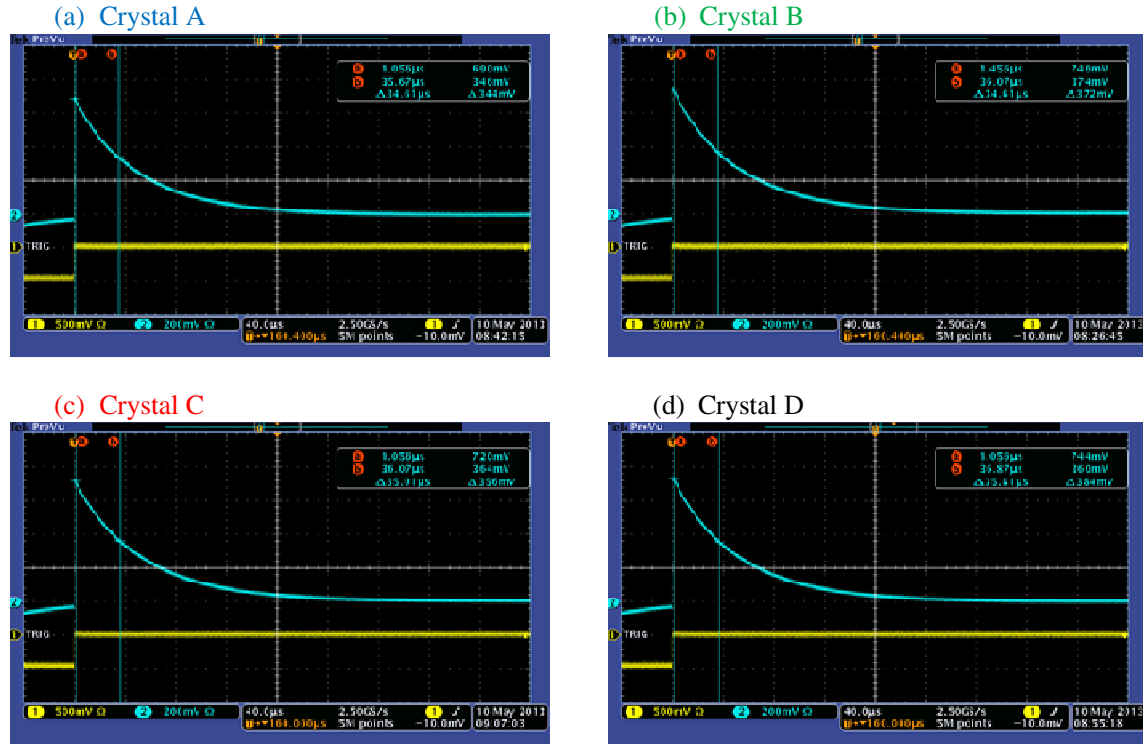
(b) Crystal B

(c) Crystal C

(d) Crystal D
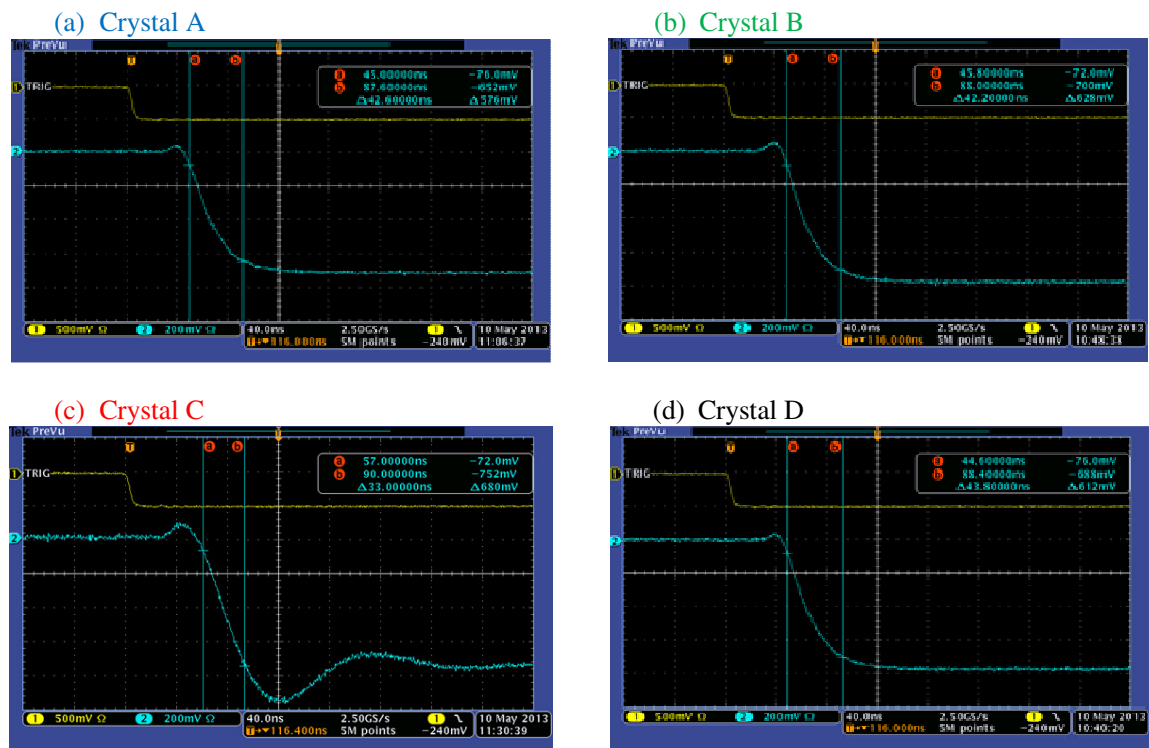
Figure 2(a)-(d). Rise times of each full volume signal from iThemba LABS segmented clover detector, resulting from an injected 5 ns rise time square pulse.

2.2. Energy resolution and efficiency measurement

Detector energy resolution is a quantity that reflects the capability of a detector to distinguish between two close-lying energy peaks in a spectrum. According to the Institute of Electrical and Electronics Engineers (IEEE) standard [1], the energy resolution for a Ge detector is defined by the full width at half maximum (FWHM) of the photo-peak at 1332 keV from a ^{60}Co source.

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[1] While the article was in the process of reviewing the issue was resolved by increasing the bandwidth of the preamplifier of the test input on crystal C.

The detector efficiency reflects the probability that a photon (or a particle) emitted from a source will be detected in a radiation detector. Furthermore, the detector efficiency depends not only on the type of the radiation but also on the energy of the incident radiation and the geometry of the detector. It is convenient to divide the detector efficiency into three types.

(a) Crystal A

(b) Crystal B

(c) Crystal C

(d) Crystal D

Figure 3(a)-(d). Decay time constant τ of each full volume signal from iThemba LABS segmented clover detector, resulting from an injected 5 ns rise time square pulse.

(i) The absolute efficiency ϵ_{abs} is defined as the number of registered particles divided by the total number of particles emitted by the source in all directions, and it is therefore influenced by the detector and source geometry.

(ii) The intrinsic efficiency ϵ_{int} is defined as the number of registered particles divided by the number of particles incident on the detector. It depends on the detector material, the type of radiation, the energy as well as the geometry of the detector. The absolute efficiency is related to the intrinsic efficiency via the geometrical factor, η. This coefficient reflects the geometrical configuration of the detector and the source and their mutual positions.

(iii) The relative efficiency ϵ_{rel} is the efficiency of a germanium detector relative to a NaI(Tl) crystal, 76 mm in diameter and 76 mm in length, measured at 25 cm from the source. This is the absolute efficiency ϵ_{abs} divided by 1.244×10^{-3}.

In this work the absolute efficiency was measured.

Our measurements were performed while the detector was in direct and add-back modes. In direct mode each of the four n-type coaxial HPGe crystals (A, B, C and D) comprising the segmented clover detector was considered as an independent detector. In this mode each individual crystal measures separately the γ-ray energy absorbed.

In add-back mode, the four separate n-type coaxial HPGe crystals (A, B, C and D) comprising the segmented clover detector are considered as a composite detector. In the add-back mode, the crystals work together and sum up all the detected energies in each crystal on an event-by-event basis. This technique is very important for increasing the photo-peak efficiency, because if a γ-ray is detected in one crystal and Compton scatters to another crystal where it also gets detected, the energy deposited in the first crystal should be added to the energy deposited in the second crystal to recover the total energy.

Five different radioactive standard sources, ^{152}Eu, ^{133}Ba, ^{60}Co, ^{137}Cs and ^{241}Am emitting γ-rays of different energies were used. Sources were placed at distances of 11 cm, 14.5 cm, 19.6 cm and 22.5 cm in front of the Ge crystals. Source activities were approximately 10 μCi for ^{152}Eu, ^{60}Co and ^{137}Cs; 10.72 μCi for ^{133}Ba, and 12.36 μCi for ^{241}Am. The data were collected for 15 minutes per measurement and recorded with Pixie-4 digital electronics.

2.2.1. *Energy resolution.* The energy resolutions (FWHM) of the iThemba LABS segmented clover detector in direct mode are shown in figure 4. The specification is FWHM ≤ 1.35 keV and FWHM ≤ 2.35 keV at 121 keV and 1332 keV respectively for the cores; and FWHM ≤ 3.00 keV and FWHM ≤ 3.50 keV at 121 keV and 1332 keV respectively for the segments [2]. We found that in add-back mode the width of the peaks are slightly larger than in direct mode. In direct mode some of the measured FWHM for the core and segments at 121 keV and 1332 keV γ-ray are slightly larger than the guaranteed values given by the manufacture, see figure 4. We also found that changing the position between the detector and the source has little impact on the FWHM of the detector.

2.2.2. *Efficiency.* Figure 5 shows the measured absolute photo-peak efficiencies for the detector in direct (left) and in add-back (right) modes. In direct mode all the crystals have a similar absolute efficiency. At low γ-ray energies the photo-peak efficiency in the direct mode is higher than the efficiency in add-back mode due to coincidence summing. It needs to be underlined that apparently the coincidence summing has significant effect also for such low gamma-multiplicity sources as ^{152}Eu and ^{133}Ba. The photo-peak efficiency at higher γ-ray energies shows an enhancement in add-back mode over the sum of the photo-peak efficiencies of all four crystals in direct mode. The photo-peak efficiency in add-back mode increases with γ-ray energy due to the increased contribution of Compton scattering. The add-back factor is a measure of the enhancement in the add-back photo-peak energy efficiency of a γ-ray, and is defined as the ratio of the photo-peak detection efficiency in the add-back mode divided by that in the direct mode. Short source-to-detector distance results in an increase of the photo-peak efficiency, but is strongly affected by the coincidence summing effects and increase in the dead time. One can note that the measured efficiency (dashed) at d = 11 cm is much lower than the one (dash-dotted curve) obtained from the efficiency at d = 22.5 cm after normalization with a geometrical factor for d = 11 cm. This shows that considerable efficiency is lost due to these effects. The evaluation of the impact of these two effects is in progress.
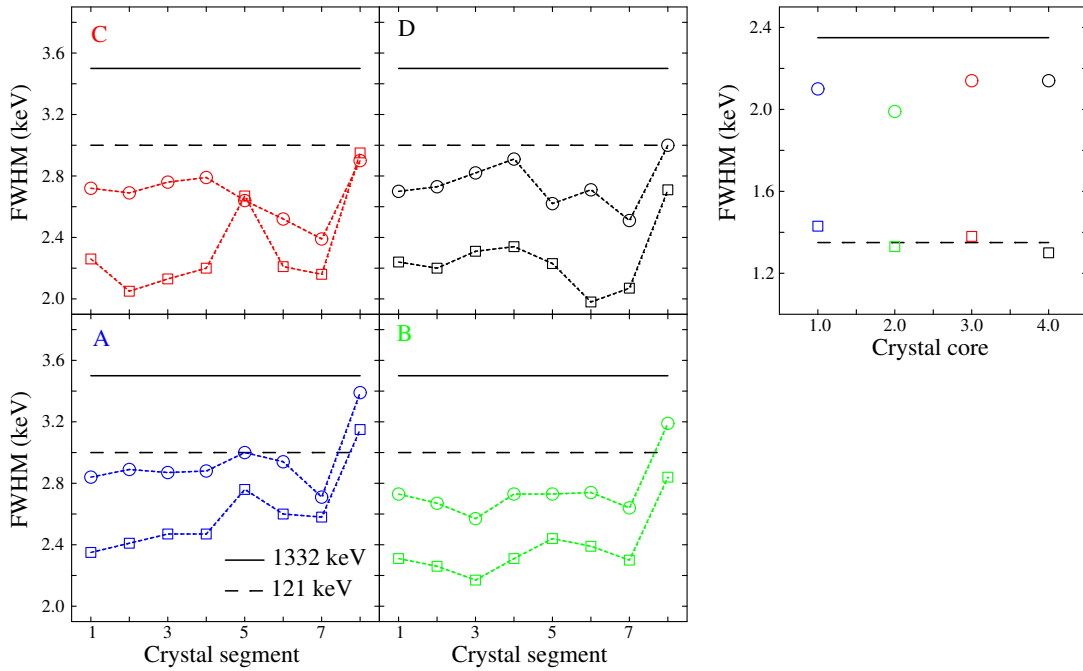
Figure 4. Measured energy resolutions (FWHM) of iThemba LABS segmented clover detector for a 121 keV (squares) and 1332 keV (circles) photo-peaks from ^{152}Eu and ^{60}Co respectively. Solid and dashed lines correspond to the manufacturer guaranteed values of FWHM for 1332 keV and 121 keV respectively.
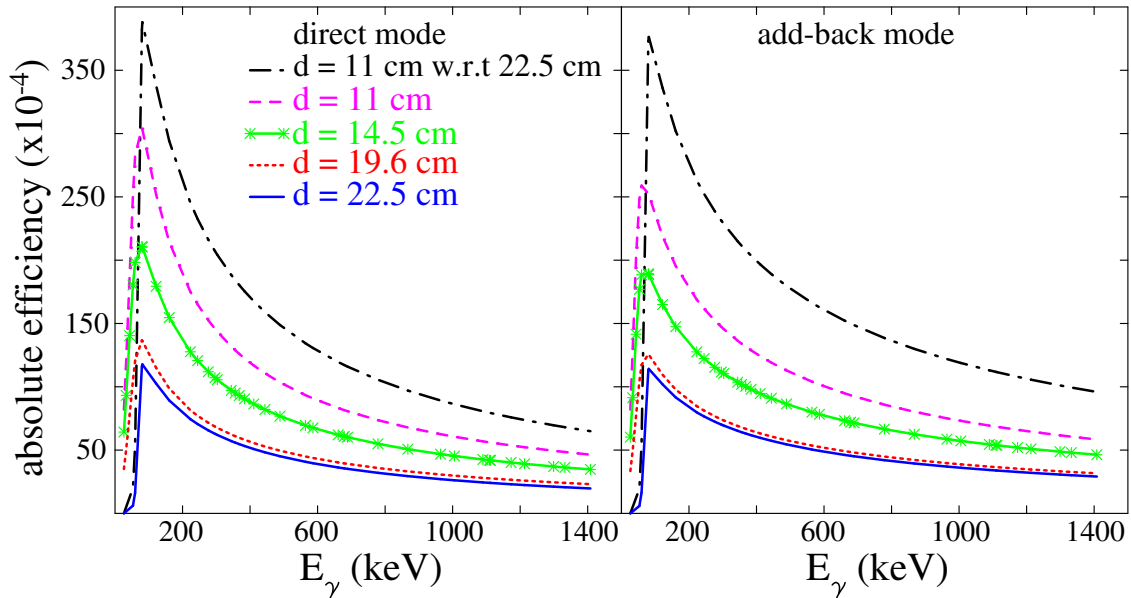
Figure 5. Measured absolute efficiencies in direct (left) and add-back (right) modes for the iThemba LABS segmented clover detector. The absolute efficiency for the dash-dotted curve was obtained from the absolute efficiency at d = 22.5 cm after normalization with a geometrical factor for a distance of d = 11 cm.

3. Summary

The iThemba LABS segmented clover detector characteristics such as energy resolution and absolute efficiencies in direct and add-back modes were measured. The measured FWHM values are consistent with the values given by the manufacturer. At low γ-ray energies the photo-peak efficiency in the direct mode is higher than the one in add-back mode. For higher γ-ray energies the values for the photo-peak efficiency show an enhancement in add-back mode over the efficiencies in the direct mode. Short source-to-detector positions exhibit effects of the coincidence summing. We also found that the detector preamplifiers are fast enough to enable time variations larger than 40 ns to be distinguished. This time resolution is sufficient for measuring variations in the signal rise time, which for the iThemba LABS segmented clover detector is of order of 200 ns.

References
[1]   325-1996-IEEE standard test procedures for germanium gamma-ray getectors 1997
[2]   Canberra iThemba clover 4x60x90 seg32 user's manual s/n: 21 2010