Vertex Detection in a Stack of Si-Drift Detectors for High Resolution Gamma-Ray Imaging

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***Abstract*—Usually the position resolution in imaging applications with gamma rays is limited due to the range of secondary reaction products to a few mm. Here a new approach will be presented using the vertex of the gamma interaction as the quantity for position measurement. Because the dominant interaction is the Compton effect the vertex detection method as used in particle physics needs a number of essential modifications. Therefore a detector system is investigated consisting of a stack of Si-drift detectors for the vertex detection of the first Compton interaction and a secondary absorption detector where the position of the scattered photon is detected. A number of effects and possible solutions will be discussed including depth of interaction measurement and track reconstruction of the Compton electron which yields useful information. Another very promising approach of measuring the track projection as in a TPC (Time Projection Chamber) will be presented including first successful measurements in a gas detector. Because the expected rate in the first and second detector is of the order of 1 MHz and 10 MHz respectively the concept of read out electronics and data processing based on VLSI custom chips for signal shaping and first buffering and digital pipe-line processors based on FPGAs is presented. Finally a full system for small animal imaging based on the principle of a Compton Camera will be discussed in terms of achievable resolution and sensitivity.**

***Index Terms*—Compton camera, gamma camera, Si-drift detector, vertex detection.**

FOR imaging applications with gamma rays a position resolution at the order of $100 \ldots 200\ \mu\mathrm{m}$ will be highly desirable for applications in safety inspection, material science, portal imaging, astrophysics and - of course - nuclear tracer methods in bio-medicine and nuclear medicine. The latter has received recently a large attention for small animal imaging.

Because of the inherent range of the secondary reaction products from absorbed gamma rays in the order of a few mm this represents the physical limit for position resolution in the actual imaging devices.

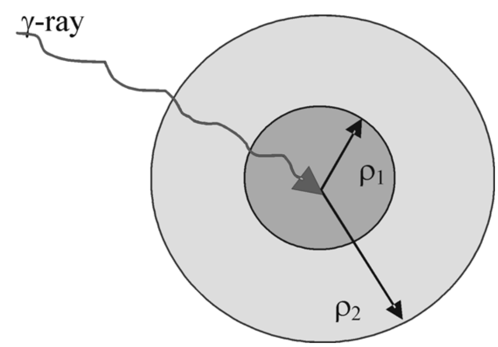

Fig. 1. Limits of position resolution for gamma rays. The range of secondary radiation is indicated. The smaller ρ_1 could be due to the range of photo- or Compton-electrons, the larger ρ_2 due to fluorescence or scattered radiation.

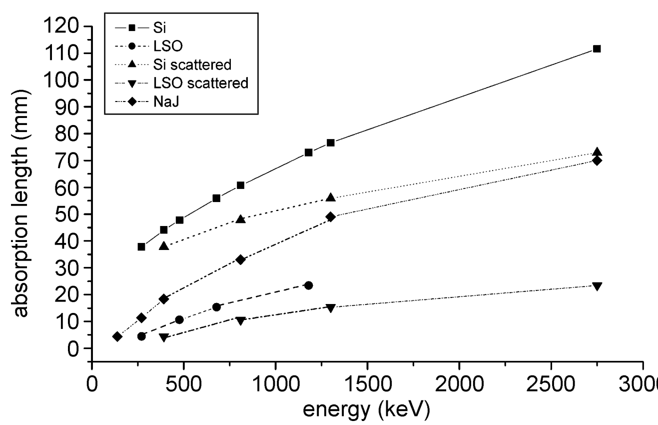

Fig. 2. Absorption length of primary and scattered radiation in detector material.

In Fig. 1 the principle is visualized where it is assumed for simplicity that the emission of the secondary radiation is isotropic. A sphere for the range of the ejected electrons and a mostly larger sphere for the emitted photons are indicated. In Fig. 2 the range (absorption length) for the scattered radiation is compared to the absorption length of the primary radiation. For higher energies (about 1 MeV) the detector—even for heavy scintillators as LSO—has to be fairly thick (>20 mm) and the range of the scattered radiation is not much smaller (about 10 mm) limiting the intrinsic resolution correspondingly.

In the proposed work a new approach will be investigated by using the vertex of the gamma interaction as the quantity for position measurement. This principle has been used successfully in high energy physics for elementary particles and a resolution

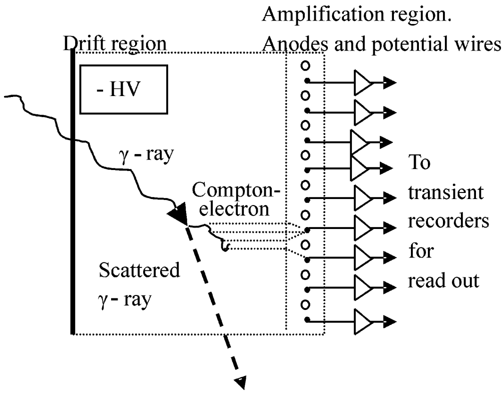

Fig. 3. Drift chamber (TEC) for measurement of Compton electron direction.

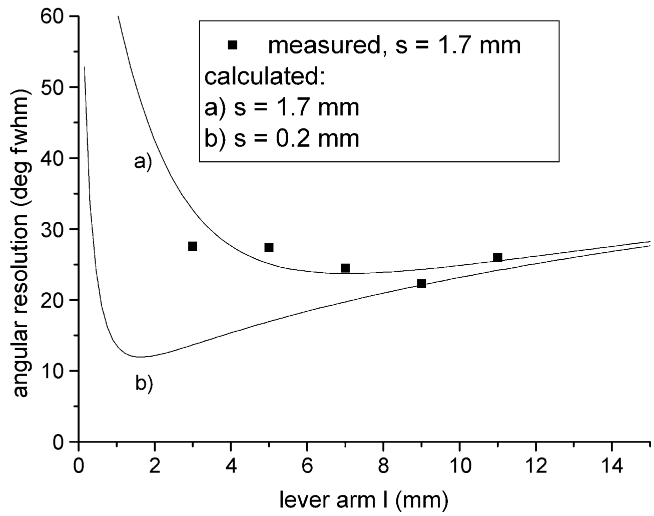

Fig. 4. Angular resolution in the direction of the mean ionization track with Kr-filling, 1.4 bar, $s = 1.7$ mm. a) and b) calculated according to (1) for $s = 1.7$ mm and 0.2 mm, respectively [2].

of far less than 100 μm could be achieved using modern silicon detector based detection systems.

As long as the energy of an electron varies from 1 MeV to few hundred MeV, the methods used in particle physics can be utilized by designing a stack of detectors [1]. However, in nuclear medicine, where the energy of the electron is generally at most an MeV, new improvements have to be done to achieve the tracking of an electron.

I. Vertex Reconstruction of the Compton Scattering Process

Although a large part of the development work (and investment) done in particle- and astro-physics can be used, the application of this principle for gamma ray imaging needs a number of essential modifications. This is due to the fact that the dominant interaction is the Compton scattering leaving only a single charged track in the outgoing channel and a second gamma ray. This necessitates a very good low energy spectroscopy and the incorporation of a second gamma ray absorbing detector. Drift chambers offer the possibility to develop and test such a system since they measure the projection of the spatial charge distribution as generated by the electron track. Fig. 3 shows an arrangement which consists of a gas filled Time Expansion Chamber with a read out in a separated region for gas amplification in the proportional mode.

It turns out that the arrival time sequence reproduces fairly well the projection of the charge density onto the drift path when appropriate gas mixtures and operational conditions are chosen. This type of read out became possible when transient recorder based on flash-ADCs became available.

Fig. 4 shows as results the measured angular precision in the direction of the electron track in TEC after reconstruction as function of the sampling intervals (in two projections, one given by the wire spacing, the other by the time sampling) for the position measurement. The solid line represents a simple model incorporating multiple scattering and a fixed precision of position measurement ultimately limited by diffusion and the range of delta-electrons. The model can be parameterized as

$$\Delta\theta = 57.3 \cdot \arctan \frac{\sqrt{s^2 + 0.0183 \cdot l^3}}{l} \tag{1}$$

where s is the sampling interval of a position measurement (equal wire spacing in a drift chamber) and l is the track length used as a lever arm for angular measurement and subsequent angular calculation. The coefficient 0.0183 is calculated for multiple scattering in the gas used in Fig. 4. Clearly these effects have opposite effects such that a minimum of angular precision is obtained. It is seen that an angular resolution of about 25 deg can be obtained for Compton electrons of 100 keV (662 keV primary rays) with a wire sampling interval of 1.7 mm. An extrapolation for the possibly achievable spacing of read out structures of 0.2 mm using gas micro-strip detector techniques would result in an angular precision of close to 10°.

A recent development of the Si-drift chambers may allow in the same way a directional information although the denser material would require even smaller sampling intervals. Technically this may be possible but the inherent diffusion of the drift process would limit the resolution. In any case the projection principle will allow the measurement of the interaction vertex with a precision given by the inherent detector resolution and not by the range of the secondary radiation. The sampling interval is also the limit for the vertex measurement if only one track is available for reconstruction. In gas detectors $s \approx 200$ μm is possible (μ-strip detectors), in Si-detectors the same value is used but 10 μm may be possible. In comparison, the precision of a centroid measurement ($\sigma_{\mathrm{centroid}}$) for the projected electron track which is in good approximation given by $\sigma_{\mathrm{centroid}} = 0.45\rho_1$ with ρ_1 being the extrapolated range of the electron. Depending on the energy this value may exceed by large the sampling interval (100 keV in Kr, 1 bar, 36 mm!) [3], [4]. In order to investigate the limits the time response of the signals has to be drastically sharpened. The small stray capacity of the technology placing the first transistor on the detector is required. First measurements are described below.

II. Compton Camera for Small Animal Imaging With Nuclear Tracers

Besides a very high position resolution in a projective geometry the Compton Camera principle provides angular information of the direction of the incoming gamma ray. It could be shown that this information is sufficient for a reconstruction of the intensity distribution of the emitting resources [5], [6]. Since

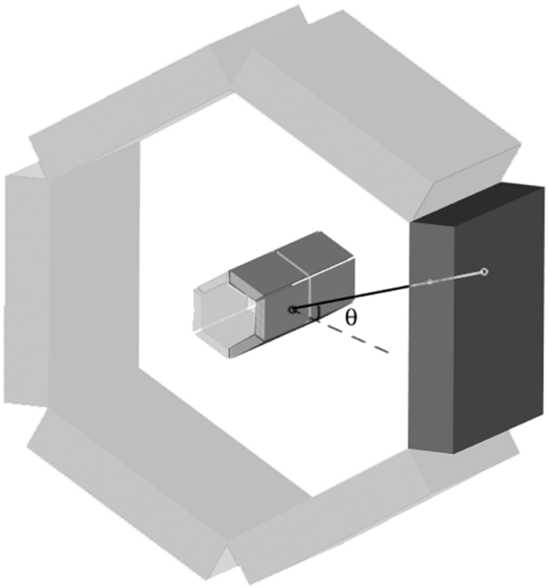

Fig. 5. Setup of Compton coincidence imaging system consisting of a smaller inner ring of a Si-stack and an outer one as absorption detector.

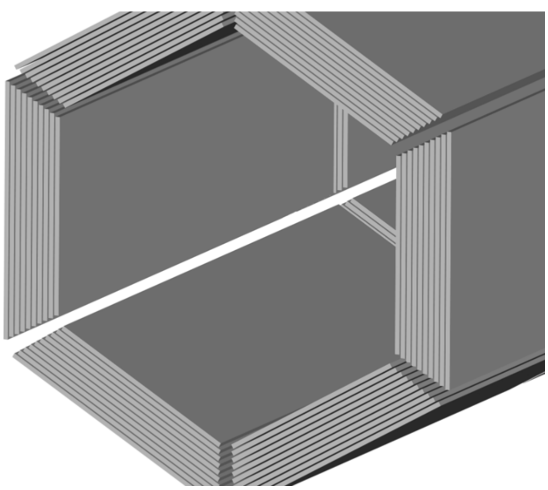

Fig. 6. Close-up of Si-stack. The individual Si drift detectors can be arranged in about 10 layers to have the ends free for connections of amplifiers and read-out.

the Compton Camera principle acts like a gamma ray optics and consequently avoids the high losses occurring in conventional collimators for SPECT applications a many-fold sensitivity for radio tracers can be obtained. The combination of high sensitivity and high spatial resolution make this device well suited for applications with small animals.

A detector system (Fig. 5) is investigated consisting of a stack of Si-drift detectors (Fig. 6) for the vertex detection of the first Compton interaction and a secondary absorption detector where the position of the scattered photon is detected. The ultimate position resolution is determined by the achievable vertex resolution in the first detector convoluted with the projected angular resolution (0.5…1 deg. for $\mathrm{E}_\gamma = 511\ \mathrm{keV}$) into a plane in the object which is limited by the achievable energy resolution for the Compton electron and the Doppler broadening [7]. For small animal imaging the lever arm may be rather small (10…20 mm from the source to the first detector, resulting in a contribution to the resolution of $100\dots300\ \mu\mathrm{m}$) such that the vertex detection will be crucial. This argument is in particular important if one considers the use of lower energy tracers ($\mathrm{E}_\gamma = 511\ \mathrm{keV}$) which would degrade the angular resolution, but a smaller lever arm could partially compensate for it.

TABLE I

Data for Si Detector Stack

Component	number	Performance
Stacks of Si detectors, 2 modules 2 x 12 x 40 mm^2	6	
Si- detector layers, 300 μm each	10	Efficiency 6% @ 810 keV
Energy resolution		300 eV (fwhm) @ 6 keV
Shaping time		50 …100 ns
Time resolution		5 ns
Read out time		1 … 2 μs
Spatial resolution		150 μm x 150 μm
Read out channels	30,720	
Read out chips	240	

Although the Compton electron has a rather low energy (100…500 keV) the range is not negligible (0.075…1.2 mm, compared to a wafer thickness of 0.1…0.3 mm) hits in two consecutive detectors are rather likely and additional useful information can be extracted by the method of pattern recognition of track segments. In addition the track information for the electrons can also be used to improve the reconstruction process since only a segment of the backprojected cone—corresponding to the achievable electron direction measurement—is considered [2], [8]. This would greatly improve the signal-to-noise ratio after reconstruction. It also plays a role for the determination of the polarization [8].

A particular advantage of drift detectors is the fact that only at the ends read out connections have to be implemented which makes it possible to arrange a rather thick stack without sacrificing useful detection area to insensitive read out structures as necessary in pixel detectors. Nevertheless the high spatial resolution still requires the total of 30 720 read out channels with a pitch of 150 $\mu\mathrm{m}$ on one side. Fortunately these type of preamplifier with fast buffer and multiplexing data transfer has been developed in particle physics as custom chips with 128 channels for application with vertex detectors. The main features are summarized in Table I.

On the other hand drift detectors need a start timing in order to allow the coordinate measurement in drift direction. The precision depends on the desired position resolution at a given drift velocity. For typical values of $\mathrm{V}_{\mathrm{dr}} = 5\dots10\ \mu\mathrm{m/ns}$, a timing precision of 10 ns would be sufficient. This could be obtained from a fast scintillator based absorption detector. Another solution consists in the implementation of a Controlled Drift Detector (CDD) as shown in Fig. 7. The drift channels, each about 150 $\mu\mathrm{m}$ wide, are transformed via perpendicular structures in a number of small charge pockets where a potential barrier is created just big enough to keep the charges from the ionization in this location. When a trigger from another detector is received the potential barriers are removed by electrical means such that all charges start to drift at the same time. This signal then serves

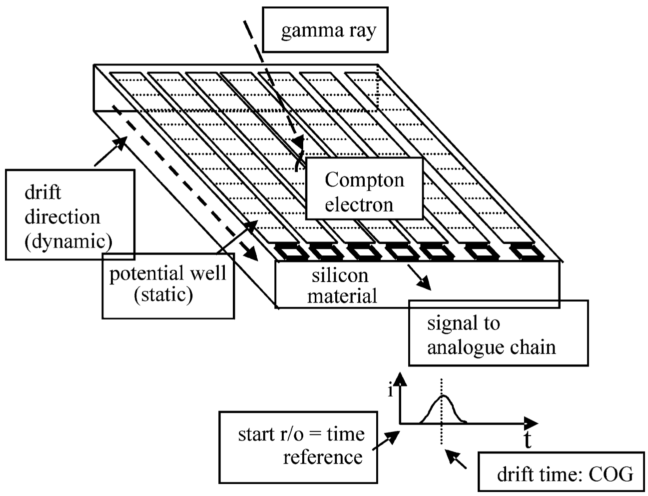

Fig. 7. Controlled Drift Detector (CDD, [9]), a Si-drift detector which generates its own start signal.

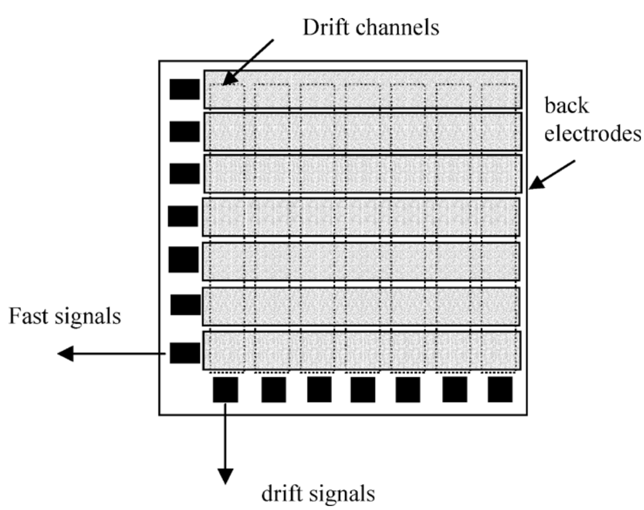

Fig. 8. Back-side read-out of Si drift detector.

as start signal and the measured drift time gives the coordinate as in the other case.

Another way of generating a fast start signal is shown in Fig. 8 where structured back-electrodes are used to pick-up fast signals generated immediately after ionization when the charge separation takes place. The limitation of the speed depends on one side on the induction process and the signal to noise ratio. First estimates allow a precision of about 5 ns (fwhm) being confirmed by first measurements using laser ionization.

Also the information of the scattered photon in the second detectors will contribute useful information to the event reconstruction (beyond the angular information). There exist an ambiguity in deciding which detector is hit first, depending on gamma-ray energy, scattering angle and detector energy resolution. Fig. 9 shows the importance of energy resolution for discriminating forward events (where the Si-detector is hit first and the scattered photon is seen in the second detector) from backscattered events (where the second detector is hit first).

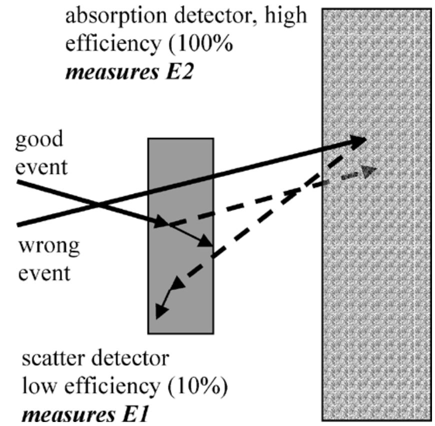

Fig. 9. Problem of misinterpretation of events using detectors in forward scattering geometry. Wrong events pass the first detector and are backscattered from the second detector.

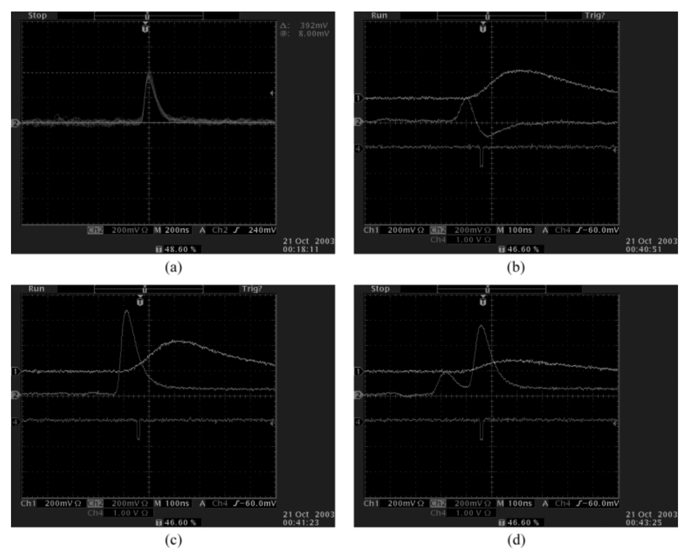

Fig. 10. Response to different ionization in the Si-drift chamber (middle trace). The corresponding signal of the Anger camera (upper trace) is shown in coincidence. The third trace is the coincidence gate. (a) Point-like ionization (^{55}Fe). (b) Compton electron. (c) Compton electron. (d) Compton electron (double).

III. Test Setup Using Si-Drift Detectors

The concept of vertex detection is tested with a 19-cell setup of a Si-drift detector (Fig. 10). A collimated γ-ray (Cs 137, ca. 1 Ci activity) is directed on the Si-detector allowing the positioning within a detector cell at different distance from the read out electrode. An old Anger Camera serves as detector for the scattered radiation defining by the impact position uniquely the energy of the Compton electron in the Si-detector.

Fig. 10(a) shows the shaper output when the silicon detector is irradiated with ^{55}Fe. The signal has a normal form such that it has no tails, multiple peaks etc. Fig. 10(b), (c), and (d) demonstrate different signal forms obtained in coincidence with Anger camera when 662 keV photons interacted in the silicon [10]. The bipolar signal shown in Fig. 10(b) is due to the diffused electron cloud. Such signals are observed more frequently when the interaction occurs near the edge of the detector where the electric field is weaker. As electrons reach the anode region, some electrons escape to the transistor channel which is at more positive potential than the anode. In this case, since they move away from the anode, the negative tail of the signal is observed. The signal form shown in Fig. 10(c) occurs when the energy deposited in the Si-drift chamber is high. The signal with a double peak shown in Fig. 10(d) is produced by double Compton events. More detailed analysis of these signal forms require the investigation of the complicated 3D dependence which is under study. The horizontal trace depends on the drift time and the time difference between the two peaks in Fig. 10(d) provides information on one component of the distance between the two Compton events. This preliminary study indicates that it may be beneficial to investigate these effects further.

IV. Conclusion

Although the Compton event has only a low energy electron as ionizing track in the outgoing channel modern drift detectors (gas and Si) allow the full reconstruction. This may lead to high resolution γ-detectors in particular for a Compton Coincidence Imaging for application in nuclear medicine.

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