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METHODS OF 2D- READOUT FOR MWPCS AND THEIR APPLICATION TO POSITRON EMISSION TOMOGRAPHY

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Abstract

A recently developed detection principle for gamma rays offers the prospect of improving the performance of positron emission tomograph scanners. This detection principle is based on the use of BaF_2 Scintillator and photosensitive multi wire proportional chambers (MWPCs). Here we present the various methods used in 2D – readout with particular attention to the requirements of a MWPC- based PET (Positron Emission Tomography) medical imaging system.

Keywords: BaF_2 , Multi wire Proportional Chambers, Positron Emission Tomograph, Solid Scintillator Proportional Counter.

Introduction

Since its original development by Charpak (1970), the Multi-wire Proportional Chamber (MWPC) has found application in materials science (Bareman *et al.*, 1983), X-ray astronomy (Anerson, 1981), and Particle Physics Ford (*et al.*, 1984). The proportional chamber in its simplest from consists of a tubular cathode surrounded by a longitudinal anode and filled with a gas operating in the proportional region. The MWFPC developed from this comprises of anode wires and two or more sets of cathode wires usually in planar form. It is from these anode and/or cathode planes that two dimensional information may be obtained. Previous studies, (Sanli 1972) have explained the physics of chamber operation. The origin of the resulting signals are summarised in the preceeding section. Here we consider the various methods used in 2D – read out with particular attention to the requirements of a MWPC-based PET (Positron Emission Tomography) medical imaging system.

MWPC Operation

A MWPC can generate two types of signals a fast small negative amplitude anode pulse and an integrated larger amplitude positive signal from the cathode. These signals originate from the ionization of the proportional gas as described below.

In particle physics experiments the passage of a charged particle through the chamber causes ionization of the gas. However in other systems such as those where X- rays or annihilation radiation is to be detected, a conversion stage needs to be incorporated. Several different designs have successfully been used; e.g. a thick lead lattice convertor used in the Jeavons PET system (Stephenson, 1984) (Fig.1); multiple lead convertor cathode planes in the R.A.L. PET system (Jeavans), (Fig. 2). A similar high density drift space has also been used in the Lawrence Berkeley PET camera (Guerra *et al.*, 1982) which has a hexagonal geometry. The disadvantage is that the detection efficiency is never better than 10%. Recently BaF_2 scintillator coupled to the front of a

MWPC filled with Tetrakis (dimethylamino) ethylene (TMAE) has been considered a potential candidate because of the fast scintillation light component (180 / 210nm) detected by the gas which is ideal for high counting rates (Mine *et al.*, 1986).

Once the gas has been ionized the primary electrons formed drift towards the anode wire under the influence of an applied electric field typically at velocities ~5cm μs^{-1}. On reaching the area of greatest field intensity, a few wire diameters from the anode, secondary ionization takes place and thus an avalanche from the anode, secondary ionization takes place and thus an avalanche is formed. As this progresses a tear-drop effect develops around the anode wire (Figs. 3,4). The signal is mainly due to the ions moving away from the avalanche area.

The ions created during this avalanche drift towards the cathode under the influence of a uniform electric field. The movement of charge generates a complimentary signal on the cathode. Normally this is integrated giving a slow rising pulse with better signal to noise ratio than the anode signal, which is usually amplified using current to voltage amplification.

By forming two planes of orthogonal cathode wires, above and below the anode plane, the x and y co-ordinates of the avalanche may be obtained. For most chambers this involves many wire channels so often groups of cathode wires (typically between 2–5) are connected together to form cathode strips or pads. Although this reduces the number of channels the spatial resolution attainable can be considerably better than the inter-strip distance by evaluating the centre of the induced charge centroid. Alternatively the anode signal may be used and analogue methods employed to obtain the second co-ordinate in the direction along the wire. This has previously been a popular method because only one set of anode-cathode planes is required, simplifying chamber construction.

Anode read-out

Typical amplification in a proportional chamber is 10^5-10^6. But even with this gain the anode wires will still require individual amplification to obtain a reasonable (~ 1V) signal level. (When cathode read-out techniques are used the anode wires may be linked together and connected to a single RC differentiator to form a fast trigger).

Analogue methods of read-out have been well established and have the advantage of not requiring two sets of cathode planes. The three commonest techniques are:

1. Charge division
2. Rise-time
3. Direct timing

Charge division (Radeka *et al.*, 1979; Alberie *et al.*, 1976) determines the position of an avalanche along the wire by calculating the ratio of the charges that are induced at each end (see Fig. 5). If an avalanche occurs at a distance x from the centre of the wire (L/2) the charges induced on the ends of the wire will be inversely proportional to the impedance of the lengths (L/2-x) and L/2+x), and the impedance of the

preamplifiers at both ends. This is only true if:

$t >> \rho\ LC_w$

where t = Integration time

ρ = Resistivity

L= Length of anode

C_w = Distributed capacitance.

If this condition is maintained it can be shown that the ratio of the collected charges is given by:

$Q_a = (L/2+x)\ \rho + Z_b$

$Q_b = (L/2-x)\ \rho + Z_a$

Where $Z_{a,b}$ = Input impedances of the preamplifiers

Several analogue methods Alberie *et al.* 1976), have been used to obtain the above charge division ratio or similar expressions for other forms of charge division.

The preamplifier input impedances Z_a and Z_b should be small compared to the resistance of the wire. The determined position, x, from the above expression may need to be corrected for any fluctuations in amplifier gain, pedastol correction. Using this method spatial resolutions of 400μm along the wire have been achieved.

A slightly slower technique is the rise-time (diffusion) method (De Graaf,1982) (Fig. 6) where read-out time is around 8μs. By digitizing a reference time signal the position of an avalanche along a wire may be determined from the difference in times of zero-crossing (after differentiation) of the two discharges at the ends of the line. The following approximation (Caraf *et al.*, 1982) may be used for position determination (to an accuracy of 1%).

$\Delta t = k.\ (RC\ \tau_c)^{1/2}.(L / 2-x)$

Where R = Resistance per unit length

C = Capacitance per unit length

X=Distance from end of wire

τ_c = Time constant of filter

k = 1.338

The spatial resolution available from this technique has been estimated to be 0.5mm (FWHM), but will degrade if the timer is too slow. Accurate read-out requires high uniformity and stability of the electrode resistance and capacitance because the position depends linearly on the RC product (in contrast to the ratio dependence of charge division). Therefore any non-uniformities such as local temperature variations have to be carefully avoided. The main advantage of the above technique is that only a time digitizer is required and so complicated read-out circuitry or chamber design are avoided.

Direct timing of the difference on output signals at the two ends of the wire has also been used to obtain second co-ordinate information (Bioc *et al.*, 1981) and also requires only simple read-out circuitry (Fig.7). The technique basically uses the signals at the two ends of the electrode to trigger fast discriminators and measures the difference in the time of arrival. However the authors acknowledge the poor resolution but suggest that the

technique may be advantageous in large detectors (>1m^2). It has been shown that this method will be superior to charge division when:

$L > 250w$

Where L=Length of the electrode

w= Cathode – cathode distance.

Delay lines have also been used to obtain second coordinate information (Battistoni et al., 1978). A delay line is placed either adjacent or helically wound round the anode wire. The difference in arrival times of the two pulses is used to determine the position of the avalanche along the wire.

Cathode read-out

Cathode read-out can be broadly divided into two categories; methods which employ delay lines and methods which use charge-to-digital (QDC) conversion of the cathode strips. A further technique of convolution filtering which uses both analogue and digital circuitry has also been included below.

Obtaining position information using cathode strips with delay lines has been used not only on MWPCs, but also in drift chambers (Sanli, 1977), parallel plate avalanche chambers (Comberi *et al.*, 1986) and PC-based calorimetry (Fujja *et al.*, 1984).

A simple MWPC has been read-out (Fischer *et al.*, 1978) using the induced pulses on an external helical delay line placed adjacent to one active cathode (Fig.8). The signal on the active cathode induces a complimentary signal on the external delay line. Read-out strips have also been placed outside the device, orthogonal to the chamber cathodes, to extract the position of the avalanche (Boic *et al.*, 1981).

Close tolerance delay line i.c.s (4.9ns per tap) have also been used to obtain azimuthal information in a tubular MWPC (Ambota *et al.*, 1980). The delay lines were connected between each cathode strips. The difference in the start signal and the time of arrival of the pulse gives a measure of which strip has been hit.

More commonly the various strips are connected to periodic taps on a helically wound resistive delay line (e.g. Bellazzini *et al.*, 1984), (Fig. 9). By measuring the difference in the arrival times of the pulses at each end, the hit strip may be determinded. When delay lines are used time-to-amplitude (TAC) or time-to-digital (TDC) conversion units may be employed. The delay time is thus converted to an analogue or digital signal proportional to the position of the strip hit.

The direct disadvantage of this technique is to limited resolution available (for the RAL system this is ~ 5mm, however better resolutions have been reported (Bellazini *et al.*, 1984).

Improved resolution is available by evaluating the centre of the induced charge centroid. When a chamber is operated with sufficient sensitivity the avalanche will cause an approximately gaussian distribution of charge across a number of strips. By considering the output from several strips the position of the avalanche may be interpolated between the discrete strip co-ordinates obtained by other methods. Two

methods are included here along with the simple centre of cluster method used in the Jeavons PET system.

The Charpak and Sauli group have proposed two methods of calculating the induced charge centre of gravity. The first of these involves performing current division on two strips (Charpak *et al.*, 1973) the second involves taking the weighted average from several strips (Endo *et al.*, 1981).

The ratio method has the same range of accuracies as those using rise-time and external delay lines, and has the advantage of requiring only simple read-out electronics. The chamber must be operated such that charge is induced on only two adjacent strips. (This is highly dependant on the anode-cathode distance, strip width and spacing used). Current division is performed on the two output, A and B, and from this the avalanche position may be interpolated between the strips. The best resolution obtained is 350μm (FWHM), but this becomes worse when the avalanche is located near the centre of a strip. This method offers the possibility of using a two stage vernier method to localize the position (Fig.10). The cathode strips are positioned orthogonally to the anode wires and connected alternately to the outputs A and B. Simple current or charge division is performed on the anode to give the gross co-ordinate with the current division of A/B providing the fine measure. A refinement of this method is to digitize all the strips and use the highest ADC output as a coarse measurement. The ratio between this channel and the next highest adjacent channel may then be used as a fine measurement of the position. Obviously this refinement will be slow and not lend itself well to fast on line calculation. The simpler analogue current division method is a potentially fast method and has the added advantage of using low resistance wires and common high impedance amplifiers.

Using QDC outputs from all of the strips has also previously been investigated by Charpak (1973). By using a suitable bias level to minimise pick-put and electronic noise, the charge centre of gravity may be evaluated from:

$$X = \frac{\Sigma (q_i - b).\ S_i}{\Sigma (q - b)}$$

Where b = bias level
q_i = charge on strip i
S_i = strip number i

The bias level is determined from:

$$b = k.\ \Sigma (q_i)$$

Where k has been evaluated empirically as ~0.025 for minimum ionizing particles. When correctly determined this given rise to an average of five strips containing valid data, yielding resolutions better than 200μm (FWHM) along the anode wires. The resolution is limited by the systematic quantization error introduced by this method, but may be improved by optimising the strip width to anode/cathode distance and using the linear correction proposed by Endo *et al.*, (1981).

The chamber is read-out by amplifying each strip and passing the signal along a delay whilst a decision is made to check for an event of interest. The pulses are selected by strobing through a linear gate (Fig.11). The digital information is passed to a computer for calculation of

the centroid. This is well suited to High Energy Physics applications where the extra computing required is negligible compared to the computing for selecting events of interest.

The S:N ratio is set by optimising the delay times and the gating window. It can be expected that with too short gating times or too long delay times the amount of charge integrated will be less, resulting in a broadening of the centroid distribution. However at normal incidence it has been found that gating times play little effect in the spreading of the distribution except in circumstances where very short gate widths (~ 15 ns) are employed. Furthermore, if too long a gate time is used, remote electrons will also be integrated. This is to be avoided as it is this component which contributes to the inaccuracies of ungated methods such as current division and delay line techniques. The main disadvantage with this technique (for PET applications) is the expense incurrent by using one ADC on each channel and the further time required to select the correct channels for valid events and compute the charge centroid. However, some of these problems may be solved by incorporating some of the features of the centre of cluster technique.

The centre of cluster technique employed by Jeavns (1978), simplifies the above procedure by dispensing with the ADCs. Instead only discriminators are used on each channel to register strips containing charge above a certain threshold. As the only event of interest is the avalanche produced by a single coincident gamma absorption then all the valid strip combinations may be encoded into a ROM memory.

When a coincident event is registered the cluster of hit strips generate a group signal and an individual strip signal (Fig. 12). These two signals pass to two ROM chips; one being the group decode, the other the individual strip decode. The group decode registers a coarse localisation of the event which is then fine tuned by the individual signals. Thus all the valid combinations can be efficiently stored in ROM. If a valid combination is present then a valid address is outputted corresponding to the centre of the cluster of the strips hit. This co-ordinate is calculated from:

$$\chi = S_L + (S_u - S_L)/2$$

Where S_L = lower strip number
S_u = upper strip number

Therefore a co-ordinate is produced, x being the distance from the edge of the chamber. If an invalid combination is registered such as a multihit situation, then a ' data invalid' or veto signal is returned. Clearly this method cannot obtain the high resolution of the centre of gravity method, the best resolution available begin limited to half the strip width. But it has the advantage of requiring only relatively simple, cheap read-out circuitry which both checks for valid events and produced avalanche co-ordinates in a very short period (typically ~ 100 ns).

Two further methods are now also included; sequential switching and convolution filtering.

The first of these collects the charge induced on each strip by means of individual strip capacitors (Radika *et al.*, 1980). When an ionizing event is registered a cluster of adjacent capacitors will integrate the induced

charge from the avalanche (Fig. 13). Each capacitor is then sequentially switched to a read-out bus for discharging using a shift register. (For reference 25 each channel requires 10 μs for switching and discharge). These values may then be processed in analogue or digital form by one of the methods described above. The system is too slow for PET because of the considerable time wasted switching all channels for read-out and then requiring further processing time to determine the charge centroid.

Convolution filtering (Hoffman *et al.*, 1986) also requires sequential switching of the charged capacitors but the method does not require further processing to obtain the required position information. The technique proposed by Radeka and Boie involves the switching of charge through a frequency weighting filter (Fig. 14). Each cathode strip is connected to a pulse shaping circuit followed by a sample and hold section. Alternatively in cases where the number of channels is prohibitively large a resistor ladder may connect the strips. The charge collecting channels are then connected at regular intervals, e.g. every four or five strips.

The time taken for sampling is independent of the switching stage. Therefore switching and sampling times can be optimised separately. The read-out time is mainly limited by the speed of the time digitizer. For a clock speed of 200 MHz and 10^3 channels, the read-out time will be approximately 5 μs (with a resolution of 100 μm (FWHM)).

Alternatively the induced charge signals may be passed along a delay line and then applied to the filter. The difficulty here is ensuring uniform delays in between the delay line taps. A more elaborate scheme is to complete a fast search to find the cluster. Then the sampled charges are sequentially applied to the centroid filter. Read-out time will then be reduced to approximately $5T_s$ (T_s being the time to switch and discharge one position element). The result generated once the zero-crossing point as halted the timer is a measure of the centre of the induced charge centroid. This is given by the expression:

$$t_f = T_m/2 + t_c$$

Where t_f = time of zero crossing

T_m = filter impulse response

$$t_c = \frac{\int tf(t)\,dt}{\int f(t)\,dt}$$

f(t) = sequentially switched charge samples

The advantage of this technique is that the quantization error introduced in ADC techniques is avoided but as with other techniques employing analogue circuitry, the resolution is sensitive to temperature variation.

Requirement of a pet system

MWPC based PET systems can potentially offer a high spatial resolution and a high data rate imaging capability. This is a major advantage over other systems such as ECAT (Blaine *et al.* 1982) and DONNER (Charpak *et al.* 1988), which are based on large arrays of photo-multimpliers coupled to scintillators such as BGO or CsF. Such systems (Charpak *et al.* 1988) have been

able to incorporate time-of-flight (TOF) information to improve their signal to noise ratio. At present this is beyond the scope of PET using MWPCs. However recent advances made using BaF_2 coupled to MWPCs using TMAE has led to direct comparison with coventional PM-based systems because of the fast scintillation component detected by these cameras permitting high data rates.

The disadvantages of such a system are:

1. Sensitivity to Compton scatters.

2. Sensitivity of TMAE to air.

The first of the above is due to the size of the crystal used (5mm x 5mm x 5cm) and the lower density of BaF_2 (compared to BGO) which means that proportionally less of the 511 keV gammas give a full energy deposition in the crystal. The second means that the gas must be handled in an oxygen free environment. (If this is not observed the TMAE loses its detection properties and will become luminescent). However current research at CERN (Charpak *et al.*, 1988) and Brunel Moghal 1988), seeks to replace the TMAE with a new proportional gas or with a large de-mountable photo-cathode respectively.

PET examinations take place shortly after the administration of the positron emitting isotope. Typical activities present at the time of examination are 3.7 0.037 MBq (Batman *et al.*, 1982) but patient movement can limit the amount of valid data taken (e.g. movement of 1mm for scan times of 1 minute in favourable cases (Deremzo, 1984)). Assuming 90% of this activity is due to positron emission then data capture needs to operate at rates of around ≤ 1 MHz (allowing for losses due to lack of full 4π coverage). Data taking may also be limited by the speed at which data can be written for storage, such as disk or magnetic tape. In order to match the data rates of the various parts of the system it would be logical to incorporate FIFO memories (as used in the DONNER camera) in particular if parallel processing is used for evaluation of the x/y co-ordinates and / or the co-ordinate pairs from each detector. (The modularity of this proposal would also simplify read-out development work).

The system must also be able to reject multi-hit situations because if other hits are present when the two co-linear gammas are detected then the original annihilation vector cannot be correctly reconstructed.

Furthermore, since only one form of interaction is to be detected (511 keV photoelectric absorption) it would seem logical to incorporate some form of discrimination in the read-out to reject events depositing more (e.g. a photoelectric absorption and a random single photon) or less (e.g. photon previously scattered in the patient) than the expected amount of energy. All events of interest should yield a similar spread of pulses across the anode and cathode wires within the limits the limits set by statistical fluctuations, conversion point in the chamber etc. However this will only be workable if chamber energy resolution is improved. (The Belgian prototype is presently having separate conversion and amplification gaps installed).

The spatial resolution of any MWPC using arreys of BaF_2 crystals will be limited by the size of the crystal used. Once a photoelectric absorption has taken place the original angle of incidence information is lost and the resulting avalanche can only be resolved to the accuracy of one crystal cross sectional area. For this reason inter-strip interpolation (as used in Centre – of– Gravity read-out) will be of little value in this context.

However ADCs switched to a limited number of strips may be useful for events with scattering in adjacent crystals. A coincident event is registered in two opposing detectors, but may not yield a full energy deposition in both (one or both interactions resulting in scattering in several crystals). When ADCs are switched to the original interaction point. Event selection/ rejection might be determined by the ROM decode used in centre of cluster read-out. As mentioned previously this type of refinement can only be potentially useful when chamber energy resolution is improved.

At present the EEC collaboration has built one small planar detector and is presently constructing a second similar chamber. This will enable simple tests with phantoms to be undertaken. Once these investigations are complete it is planned to extend the design to a ring camera geometry. It has been shown that this will reduce in the simple twin detector arrangement needs to be upgradeable to the ring geometry. This can be achieved by dividing the ring into six sectors. When an event is registered in one sector, the opposing three sectors are checked for a corresponding coincidence (Fig. 15).

The cathode wires may be configured such that each strip defines one column or row of crystals. The resolution in this case is only limited by the local spread of the avalanche and the refracted angle of the emitted scintillation photons. These parameters can be optimised by appropriate chamber geometry.

TOF capability may not be a worthwhile option for the proposed camera because time of flight can only localise events to approximately 10cm. The proposed camera will be intended for head scans where the aperture will be ~ 30 or 40cm in diameter. The added complexity and cost of such an option outways the marginal improvement in S:N ratio available under such conditions.

Many of the above criteria may be satisfied or adapted from the system used for MWPC X-ray detection by the Orsay group. Their VME-based read-out system uses centre-of-gravity read-out with custom ADCs on all channels. The VME standard offers fast data transfer although the added expense of the ADCs is not necessary for the BaF_2 - MWPC detector under consideration.

However, none of the methods described previously is entirely suitable for a ring MWPC PET camera. For this problem we need to consider first, how far conventional techniques (as described above), and second, the methods used in conventional PM systems (such as forming coincidences by sectors) can be used in a BaF_2- MWPC ring PET camera. This would then make the wire chamber camera superior in terms of dose required and cost to conventional PM PET systems and produce comparable, if not better tomographic images.

Conclusion

PET system in the past have relied on scintillator/PM arranged in a ring geometry to minimise the intrinsic error. Read-out of a conventional pair of rectangular MWPCs has been previously demonstrated, but the quality of final image dose not compare well with PM system. However a MWPC camera arranged in a ring geometry should offer the high data rates and good spatial resolution of wire chambers and also incorporate the lower error associate with ring camera geometry. The read-out technique will probably not be dissimilar from a number of previous methods.

It has been shown that there exist numerous techniques to obtain bi-dimensional information from a MWPC. However, for medical imaging applications, namely PET, then only those candidates which exhibit high stability and resolution and short resolving times can be considered as a basis for read-out. High stability and short resolving times eliminate most of the analogue methods particularly where wire uniformity is critical or where switching is required. However previous works have shown that delay lines can give spatial resolutions comparable to digital techniques.

The disadvantage with the centre of gravity technique is the slowness of operation and the unnecessary expense of using one ADC per channel. For a ring camera this makes the time and cost of processing parallel to the ring axis prohibitively expensive.

A development of the centre of cluster technique would seem the most promising way forward at present. This is because no other method can offer efficient event selection/rejection with valid co-ordinate read-out in such a short time. Methods with greater spatial resolution are not necessary when the intrinsic resolution is limited to the scintillation crystal width. Some limited ADC processing may be useful if Compton scatters in the BaF_2 scintillator can be utilised.

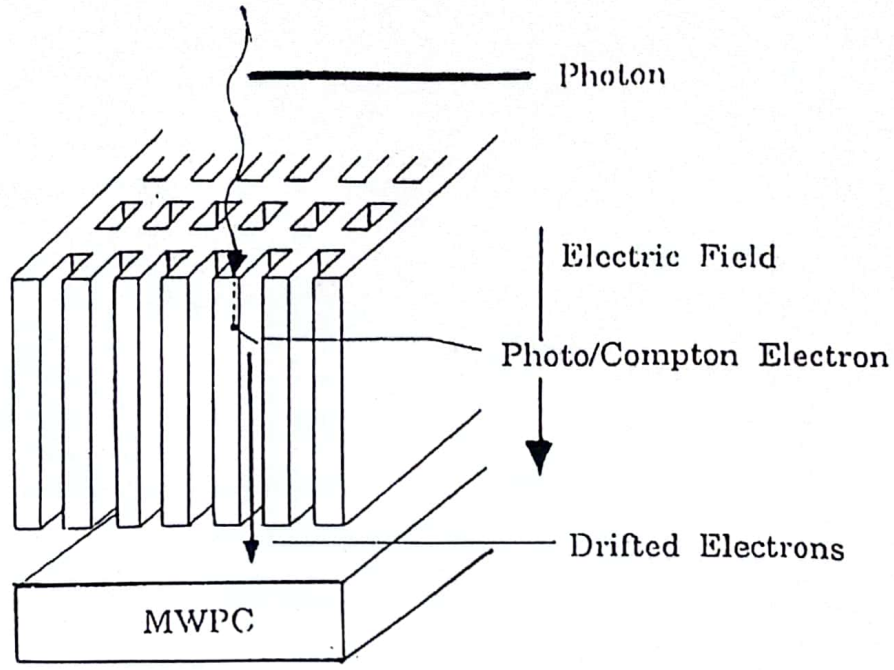


Fig. 1 High Density Drift Space used on Jeavons' PET Camera

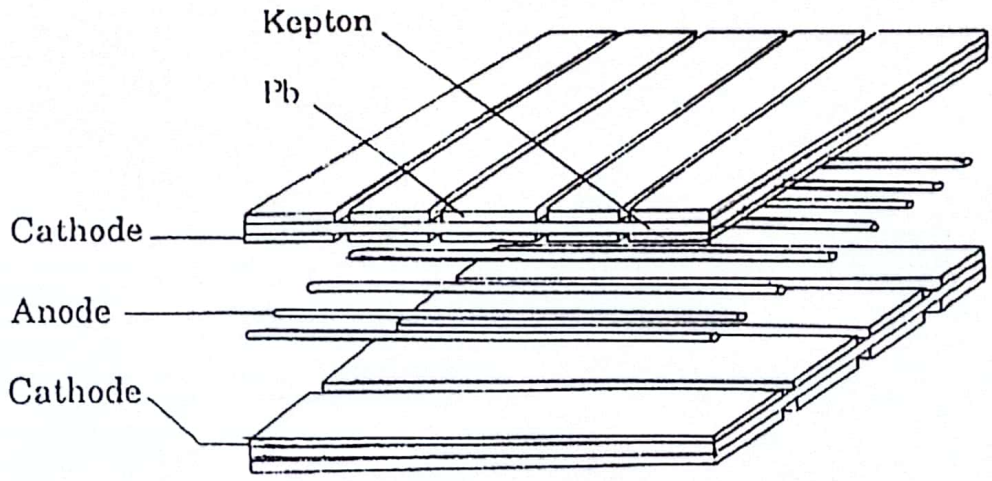
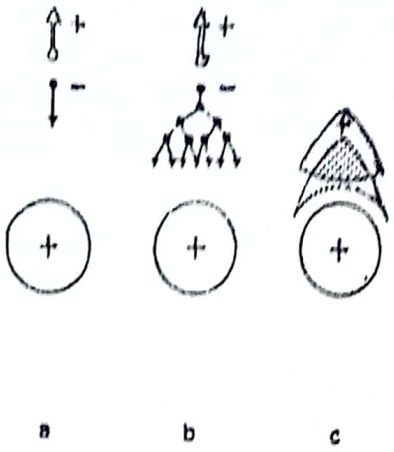


Fig. 2 Multiple Lead Photocathodes used on RAL PET Camera

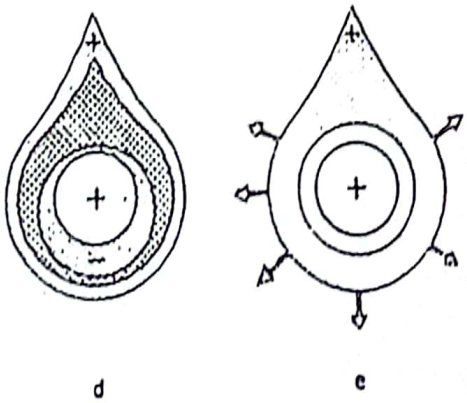


a A single primary electron proceeds towards the anode

b Multiplication starts

c Electron cloud starts to surround the wire, ions drift away

Fig. 3 Preliminary Stages of Avalanche Formation in a Proportional Chamber



d A drop like avalanche surrounds the wire

e Electrons are collected in about 1 ns, positive ions slowly migrate to the cathode

Fig. 4 Final Stages of Avalanche Formation in a Proportional Chamber

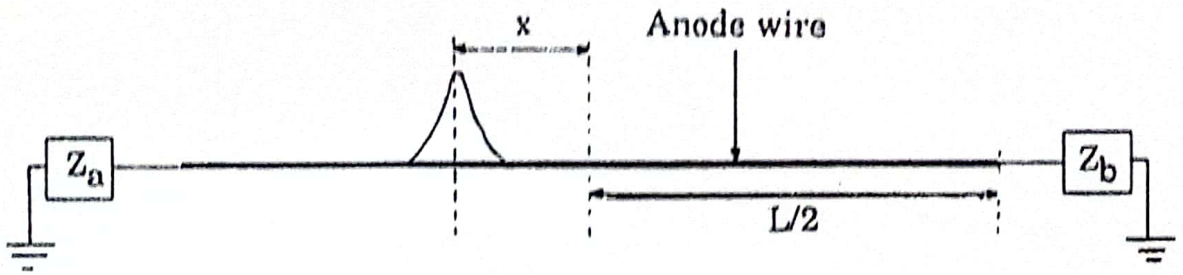


Fig. 5 Principle of Charge Division

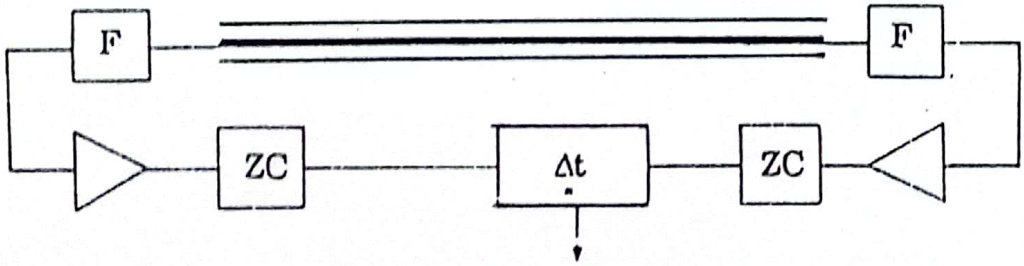
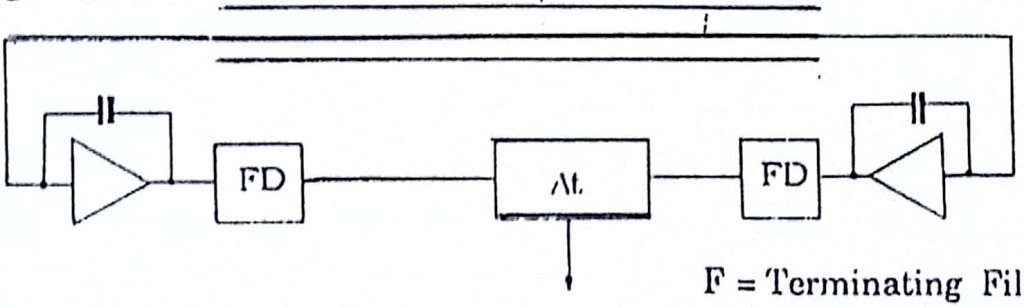


Fig. 6 Schematic Diagram of the Rise-time Method

Fig. 7 Direct timing of the Induced Signal Schematic Diagram



F = Terminating Filter
ZC = Zero-crossing Detection
FD = Fast Discriminator

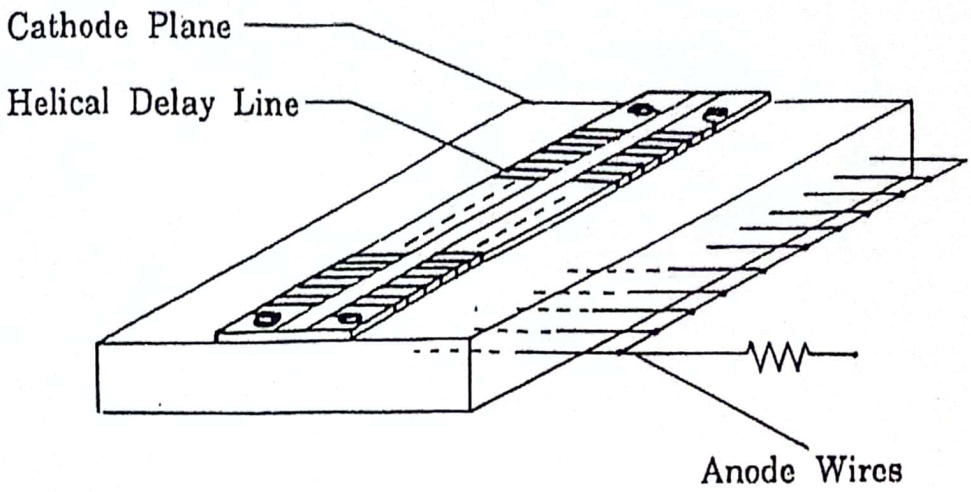


Fig. 8 Schematic Diagram of Induced Delay Line Read-out

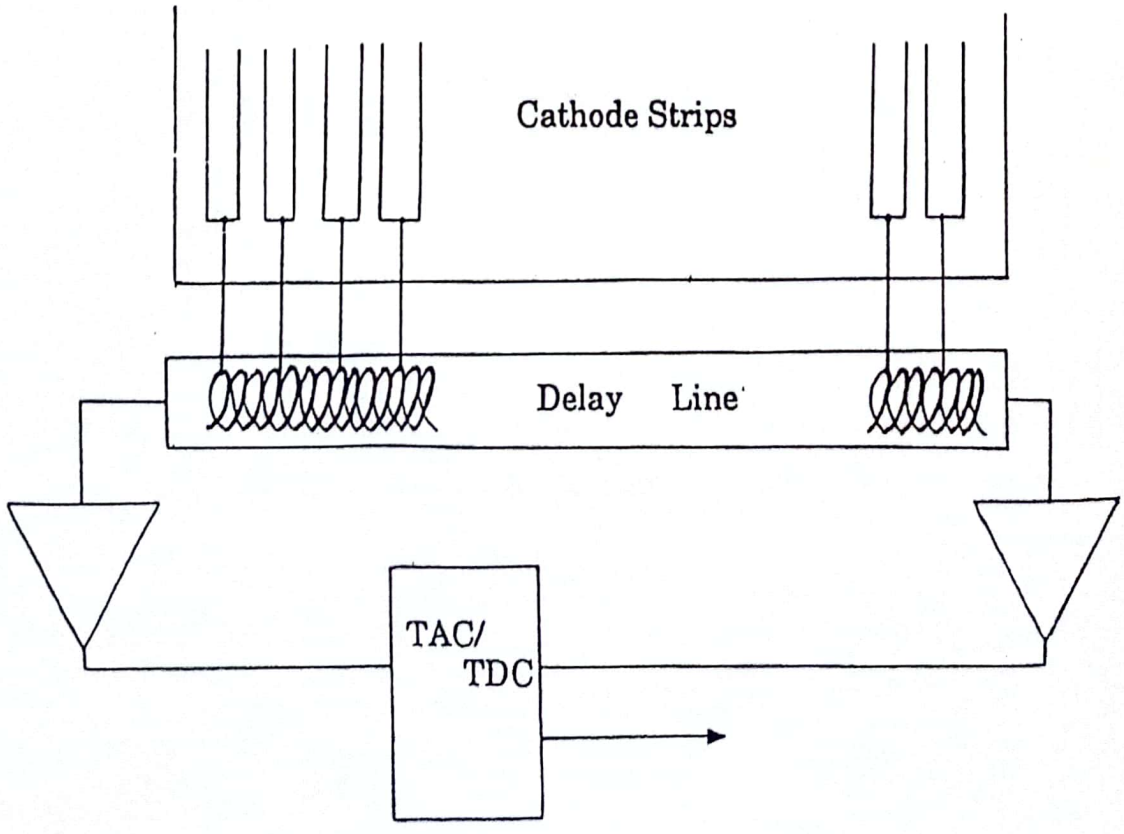


Fig. 9 Cathode Read-out using a Delay Line

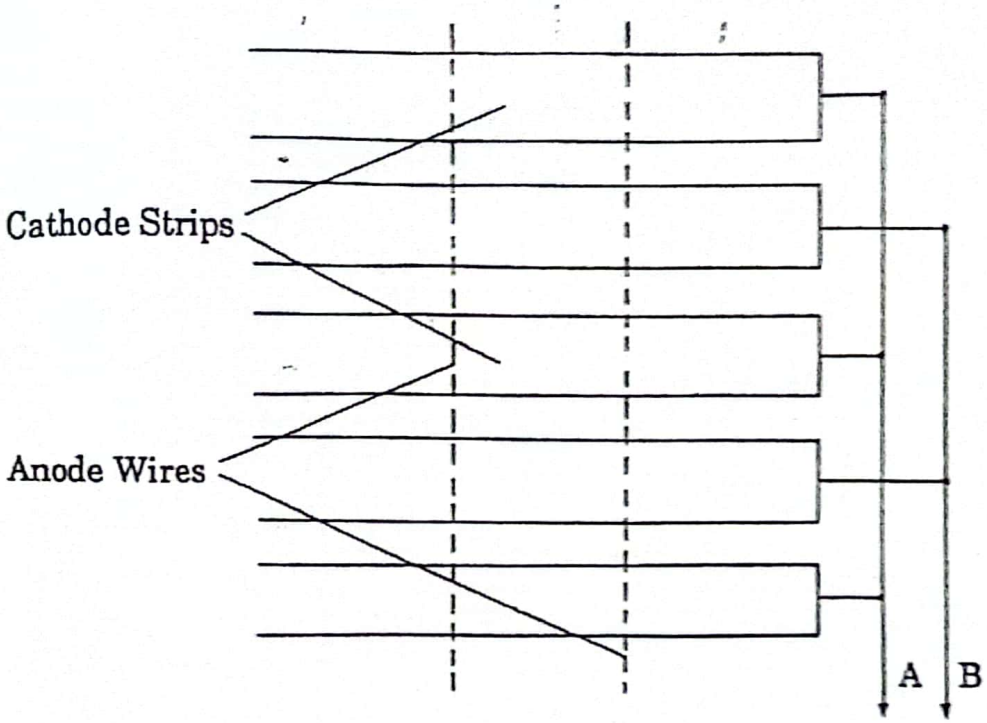


Fig. 10 Principle of a Vernier Method used by Charpak et al

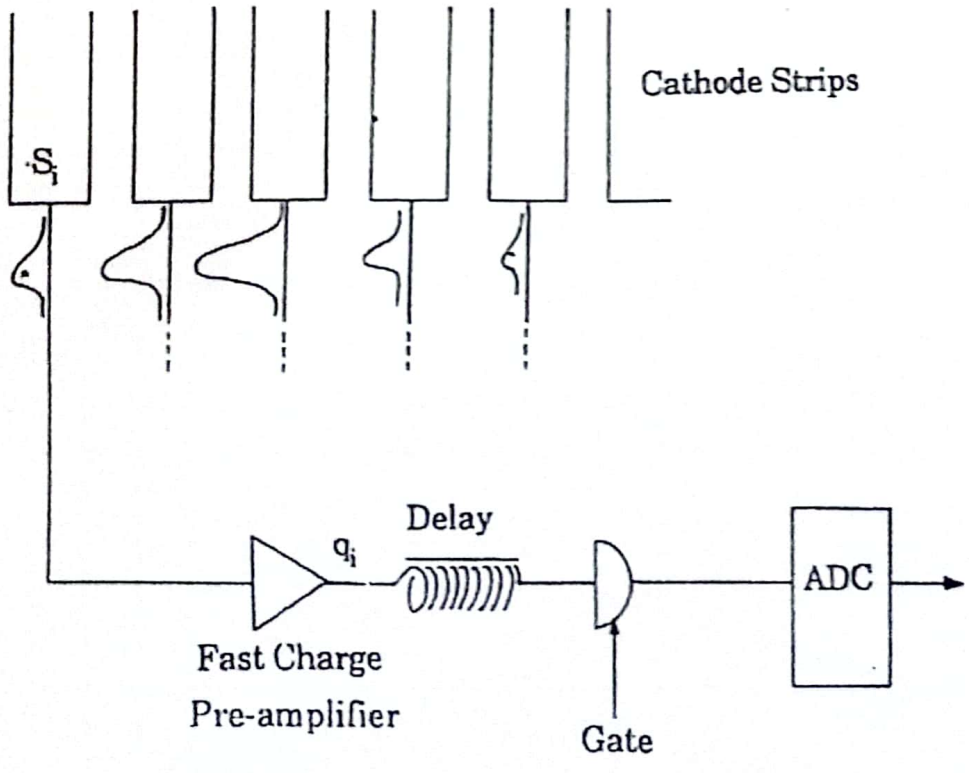


Fig. 11 Diagram of Centre of Gravity Read-out

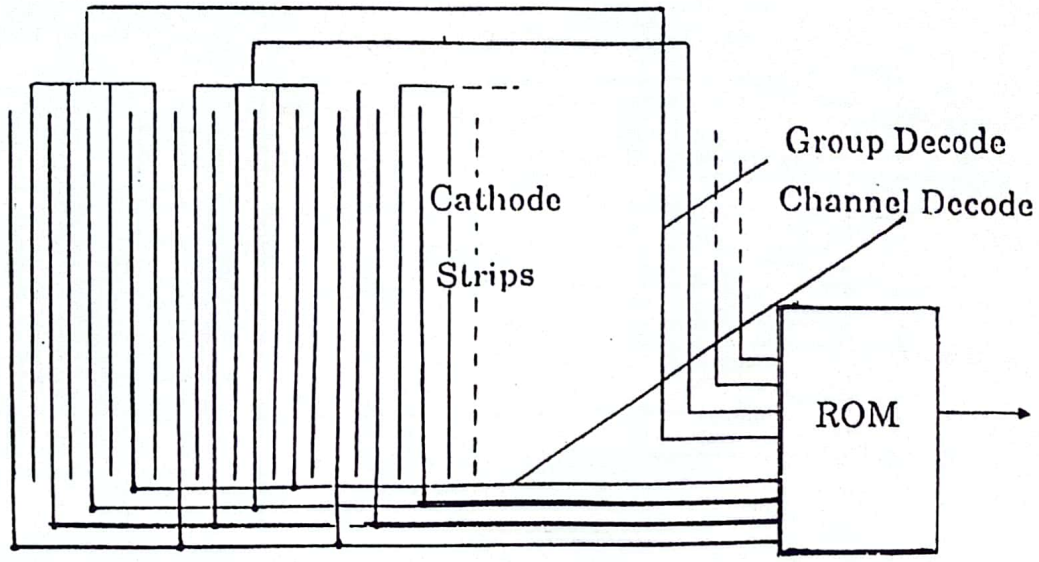


Fig. 12 Schematic Diagram of Centre of Cluster Read-out

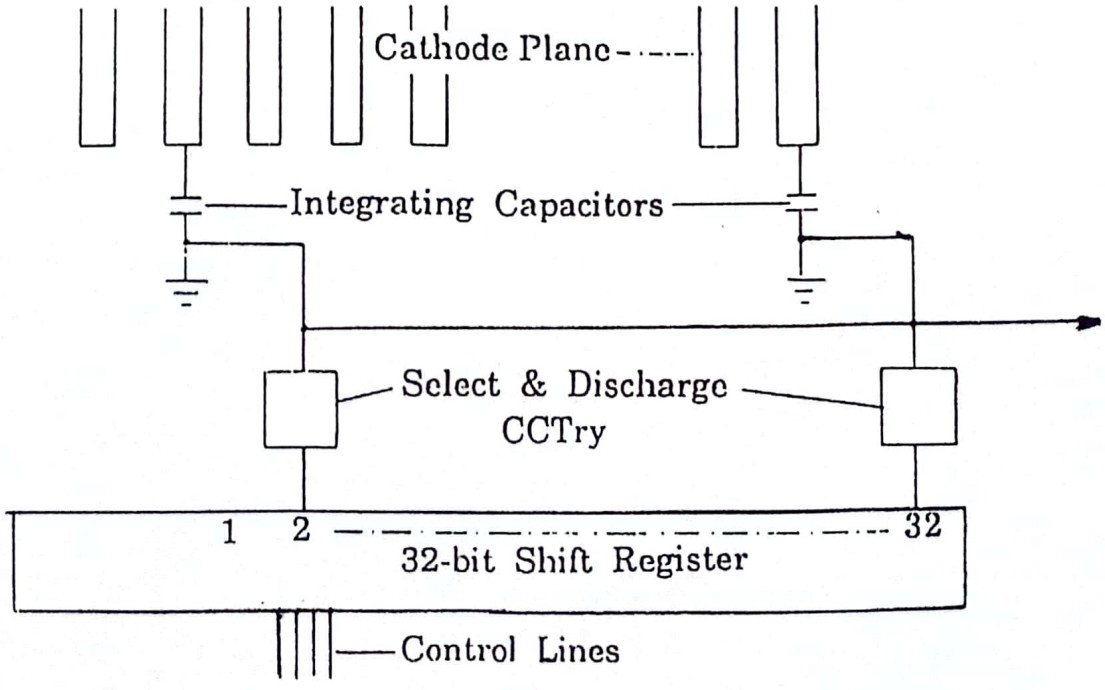


Fig. 13 Diagram of Sequential Switching Method of Read-out

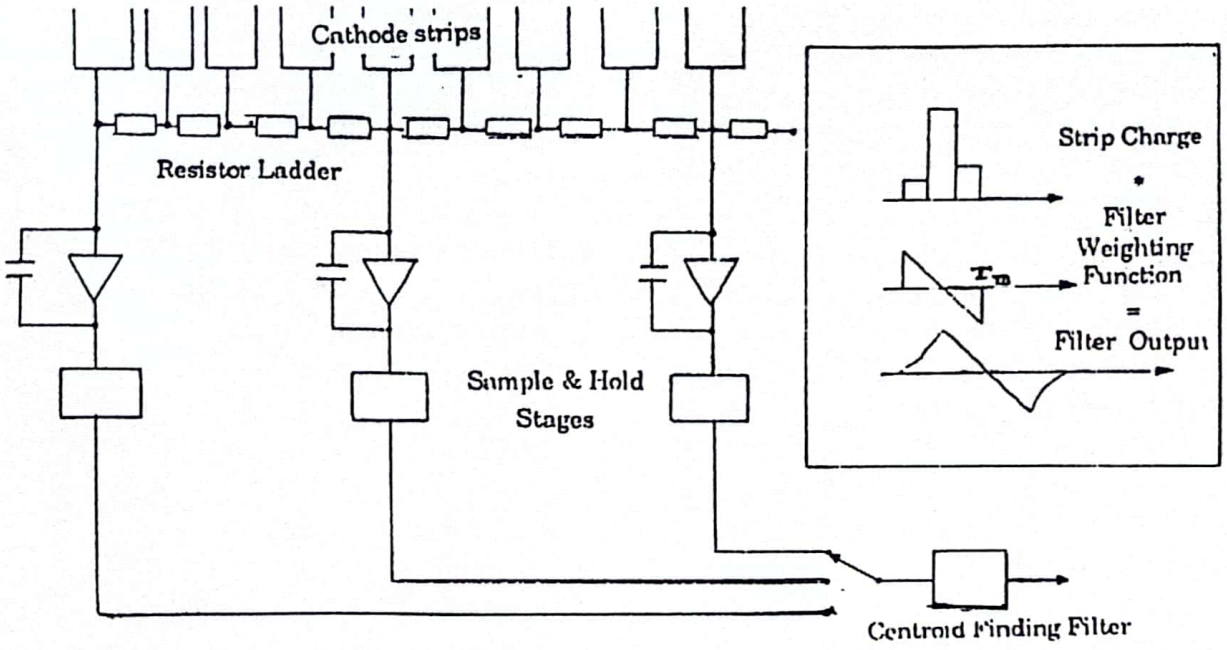


Fig. 14 Diagram of Convolution Filtering Method of Read-out

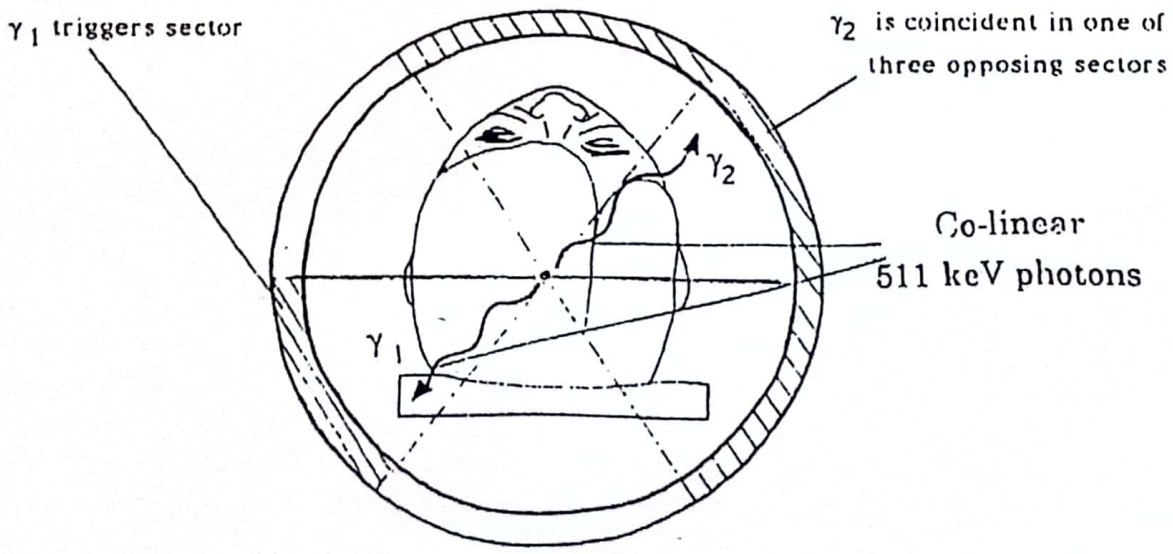


Fig. 15 Sector Division of a PET Ring Camera

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