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FLASH CHAMBERS AS 'ACTIVE' DETECTORSANDA SPECIAL PROCESSOR FOR FAST DECISION MAKING

M. Conversi* and C. Verkerk

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ABSTRACT

The potential of the flash chamber technique is considerably enlarged by exploiting the electric signals derivable from the discharged cells, so as to achieve logical decisions through suitable electronic systems operating in real time. The chambers then become 'active devices' by which other electrically pulsed chambers can be sensitized, whenever required, provided that the trigger logic signal is available within the chamber sensitive time ($\sim 1\mu\text{s}$). This case is discussed in detail, in the context of an experimental investigation of charmed particles produced in nuclear emulsions by high energy neutrinos. A design of a special processor is described, into which the signals from the flash chamber cells are fed and which can achieve in less than $\sim 1.5\mu\text{s}$ the recognition of two tracks, converging inside a small fiducial volume around the neutrino-interaction vertex in the emulsion.

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* Present Address: Istituto di Fisica dell'Università di Roma, Rome, Italy

1. Introduction

All electrically pulsed (ep-) chambers developed over the past 23 years (flash chambers, spark chambers, streamer chambers¹⁾...) are in general employed in a 'passive' way, i.e. merely to detect particle tracks, after a logical decision selecting the events has been taken electronically, starting from the signals of d.c. operated 'active' detectors (scintillators, Cerenkov counters, etc.). However, the light emitted in the electric discharges (flashes, sparks, streamers ...) can in all instances be recorded by video-optical systems²⁾ by which 'second-stage' logical decisions can be taken in real time. Such systems, employing usually vidicon or plumbicon arrays, are characterized by a remarkable level of flexibility but are comparatively slow, a typical value of the electron-gun scanning time being about 60 μ s.

More direct and faster methods of achieving second-stage logical decisions, which confer the role of an 'active device' to the ep-chamber, are possible in the case of a flash chamber. In fact, in such a chamber not only are the light signals emitted individually by the sensitive elements (one signal per each discharged flash tube or plastic cell), but electrical signals can also be obtained directly via simple electric probes³⁾⁴⁾. The probes are small metallic electrodes applied externally, in the case of the glass neon-filled flash tubes³⁾, or inside the flash cells of the recently-developed chambers of plastic material⁴⁾. In the latter case pulses that need no amplification and have only a small jitter (some 10ns) are easily obtained on a 50 Ω grounded resistor⁵⁾. These pulses are therefore amenable to elaboration by fast electronics, by which second-stage logical decisions can be taken in times of the order of 1 μ s. Hence a second ep-chamber can be triggered by this method, if required, since the sensitive time of any ep-chamber can easily be made as large as a few μ s.

The development of flash chambers made of low-cost honeycomb extruded plates of polypropylene has opened new possibilities to the application of the technique. In this context we recall that applications to high⁶⁾, medium and low energy⁷⁾ neutrino experiments, to directional search of solar neutrinos⁷⁾ and to the investigation of charmed particles⁸⁾, have been suggested, and a large-scale neutrino detector has been proposed, which, in the words of the authors⁹⁾, would allow 'exploration of a new range of physics inaccessible to present bubble chambers and electronic detectors'.

In the applications mentioned above, the flash chambers are considered as triggered devices, capable of operating at repetition rates of a few triggers per second, with no 'active part' in taking logical decisions. Clearly the range of applicability of the technique would be greatly enlarged by:

- (i) releasing the trigger requirement;
- (ii) decreasing the chamber recovery time which limits the maximum attainable repetition rate;
- (iii) utilizing the chambers as active devices.

Concerning the first point, flash chambers have been operated successfully in a 'non-triggered mode'¹⁰⁻¹²⁾ by applying to them HV pulses synchronized with the beam spill of an accelerator, for spill-out times of up to a few ms. This work was prompted by the wish to utilize the sensitive cells of a lexan flash chamber, installed inside a large hydrogen bubble chamber, as time detectors of the outgoing particles¹⁰⁾. Operation at low temperatures was also achieved successfully¹¹⁾ and further study of this 'non-triggered' or 'synchronized mode'⁴⁾ of operation is now in progress¹²⁾.

Reduction of the plastic flash chamber recovery time (point (ii) above) should be possible by analogy to the case of the glass neon-filled flash tubes, for which repetition rates of the order of 1 KHz have been reported¹³⁾.

Utilization of the flash chambers as active devices (point (iii) above), even when operated under the usual 'triggered mode', will be the subject of the present note.

In the next section we illustrate, on qualitative grounds, the enlarged potentiality of the technique resulting from utilization of the chamber cells as active detectors. Secondary triggers based on energy threshold, ionization level, and pattern recognition will be considered as examples.

In the subsequent sections we will discuss in detail the specific case of a second-stage trigger based on fast logical decisions, bearing in mind the application to a particular experiment. This will be of the type being prepared at Fermilab⁸⁾ to investigate charmed particle production by high energy neutrinos interacting in nuclear emulsions, by a hybrid technique. A special purpose processor, fast enough to reach the second-stage logical decisions in times sufficiently short to sensitize efficiently another ep-chamber, will also be described in detail. Needless to say, this high-speed special-purpose processor could be applied to take fast logical decisions on the basis

of input data coming from fast track detectors of any other type (scintillator hodoscopes, multiwire proportional chambers, drift chambers, etc.).

2. Flash Chambers as Triggering Devices

The possibility of achieving second-stage logical decisions on the basis of the luminous discharges occurring in the flash-tubes traversed by ionizing particles, was pointed out several years ago¹⁴⁾. At that time it was suggested to transform the optical into electrical signals by means of photomultipliers, and to utilize these latter signals in a 'logic' by which the decision to open a fast camera shutter was taken on condition that a certain pattern of flashes appeared at the application of the sensitizing HV pulse. Since flash tubes have recovery times of several ms, the tubes discharged by this HV pulse could be set alight again by a second HV pulse applied a few ms later, so as to allow the flashes to be recorded by the camera. In this example the flash chamber is indeed utilized as a triggering device allowing one to record photographically only the events characterized by the chosen pattern of flashes.

Other examples of similar second-stage logical decisions can be found in the literature¹⁵⁾, applied to large-scale flash-tube installations developed for cosmic ray research.

A flash chamber can be clearly regarded again as an active device when it is sensitized by an HV pulse synchronous with the beam spill-out of a particle accelerator (the 'non-triggered mode' mentioned above in Section 1). In this case, in fact, its sensitive cells behave like any particle counter: they are prepared to flash at the instant of any particle traversal, and this instant can be recorded by means of light sensors, or directly by the probes attached to the cells. Many applications based on this mode of operation can be conceived. As an example (in which, however, the time information just mentioned above is not exploited) the application to a search for neutrino oscillations has recently been discussed¹⁶⁾. We shall not insist any further on this mode of operation, however, for the present article is essentially dedicated to the utilization of the chambers as active devices when they are operated under the normal triggered mode.

We shall now illustrate briefly a few examples of triggers derivable from the signals of the cells of a flash chamber of plastic material⁴⁾.

Energy Trigger

In a calorimeter sandwich of plastic flash-chambers alternated with thin lead plates⁹⁾¹⁶⁾, the total number of flashes, N_f , produced by a primary electron of energy E_e , is an experimentally-known function of E_e (the dependence is nearly linear up to energies as large as $\sim 10\text{GeV}$). Since the total amount of light emitted is proportional to N_f , an 'energy trigger' can promptly be obtained by any light sensor operating under linear conditions over the range of N_f -values of interest. Thus, one can easily select, for instance, only electromagnetic showers of total energy exceeding a given threshold value.

This type of trigger can also be applied, of course, to hadron showers.

Ionization Trigger

In a many-layer flash chamber of thin-walled plastic materials, such as 'moplen'⁴⁾, the average number of flashes accompanying a single particle traversal depends in principle on the specific ionization, j , of the particle, because the probability p of flashing a cell is a function of j . For a large number N of layers the binomial distribution

$$P(n,N) = \binom{N}{n} p^n (1-p)^{N-n}$$

of the number n of flashes can be replaced by a normal distribution of standard deviation $\sqrt{Np(1-p)}$, the average number of flashes being $m=Np$. For another particle with $j=j'$ and $p=p'$, the average number $m'=Np'$ differs from m by $\Delta m=N\Delta p$, where $\Delta p=p'-p$.

The quantity Δm , representing the distance between the peaks of the two distributions, has to be compared with the sum $\sqrt{Np(1-p)} + \sqrt{Np'(1-p')}$ of the two standard deviations in order to obtain an estimate of the sensitivity by which particles of different specific ionization can be distinguished by this method. The sensitivity increases as $\sqrt{N}$ by increasing the number of layers.

The method can be applied, for example, to search for fractionally charged particles, and a search for relativistic $e/3$ quarks in extensive cosmic ray air showers was actually carried out a few years ago¹⁷⁾, using about 12,000 glass neon-filled flash tubes disposed in nearly 200 layers. Considerable improvement in sensitivity should be achieved by using plastic flash chambers where a much larger number of thin wall layers can easily be employed.

For the applicability of this method to accurate ionization measurements, however, care should, of course, be taken to ensure that the flashing probability p is the same all over the many cells of the flash chamber system.

For a given ionization the probability p can be varied by different methods (for instance by acting on the nature of the gas mixture), so as to obtain the maximum separation between the peaks of two given particles.

Pattern Recognition Trigger

We have already mentioned an example of trigger which was suggested¹⁴⁾ to select photos of events fulfilling a given pattern of flashes. In that example the second-stage logical decision could be taken in a time comparatively long, in the multi-millisecond region, i.e. in the range of the flash-tube recovery time.

With reference to a concrete example we shall now discuss a type of trigger which requires a given pattern to be recognized in a time short enough to trigger a second ep-chamber, i.e. in the microsecond range.

As we shall see, such a goal can be achieved by means of a special purpose processor¹⁸⁾ receiving as input signals those provided by the cells of a plastic flash chamber.

3. Fast Vertex Reconstruction as an Example of Pattern Recognition Trigger

The concrete example we wish to refer to is based on an experiment now being prepared at Fermilab⁸⁾ to study short-lived states (charmed particles or heavy leptons) produced by high energy neutrinos in a stack of nuclear emulsions by a hybrid technique. The crucial point in experiments of this type¹⁹⁾ is to locate the neutrino interaction points in the emulsion within a small fiducial volume, so as to reduce to a reasonable level the emulsion scanning time which otherwise would be prohibitively long.

Plastic flash chambers are widely employed, in this new Fermilab experiment, in the usual 'passive way'. In particular, they are utilized in the first stage of an original and accurate three-stage vertex reconstruction method, by which the neutrino interaction point is located within a 'search volume' claimed to be less than 0.1 mm^3 . Such an accurate vertex localization is achieved by working back from a system of plastic flash chambers ($\sim 0.5 \text{ cm}$ spatial resolution) via evaporated-gold self-marking minispark chambers⁸⁾ ($\sim 0.5 \text{ mm}$) and a glass plate coated with emulsion on both sides ($\sim 1 \mu\text{m}$ resolution). Sparks occurring between the two evaporated-gold glass plates of the minispark chamber will make small holes ($\sim 500 \mu\text{m}$ diameter) in the gold coating of the plates. These

holes will help to find the areas on the emulsion coated glass plates which must be searched under the microscope in order to determine tracks pointing to the ν -interaction point inside the emulsion stack.

All ep-detectors in this experiment are pulsed for each trigger produced by a veto-coincidence counter system which detects the ν -interactions occurring in the emulsion stack. Under the beam conditions of the present Fermilab neutrino facility only a few tracks per trigger are expected, spread over the whole apparatus; so that the background of holes from other triggers should not be serious in an exposure of adequate duration. This would no longer be true, however, after a long exposure under beam conditions (such as those of the present CERN wide-band neutrino beam facility) where a rate of several tracks per trigger would be found on the same area. Hence the same technique could not be applied under these circumstances, unless the trigger rate of the minispark chambers is drastically reduced. Experience gained at Fermilab¹⁹⁾ and at CERN²⁰⁾ shows that such a drastic reduction can hardly be obtained merely by improving the vetoing of the counter system, without appreciable loss of 'good events'.

Instead, a simple method of achieving this goal would be to trigger the minispark chambers only on the requirement that the tracks observed in the flash chambers converge within a small volume of the emulsion stack. This can actually be done using the flash chamber cells as 'active' sensitive elements whose signals, as shown in Fig. 1, are fed to a special purpose processor capable of testing the 'convergence requirement' in a time shorter than the minispark chamber sensitive time.

4. Special Processor for Fast Vertex Reconstruction

We outline a possible solution for extrapolating straight tracks and checking in a time as short as required if a possible vertex exists within the emulsion stack. It is based on a hardware processor which executes a simple and straightforward algorithm on encoded (binary) values of the coordinates of the lighted flash cells. The method checks different combinations of co-ordinates and requires the repeated use of relatively slow arithmetic elements. In spite of this the required decision can be taken in a few microseconds. This time is long compared to the time attainable with combinational logic (coincidence matrices)²¹⁾ but for a reasonable precision the number of cells involved rules out the latter solution in most cases.

We will give an outline of the algorithm and of a possible implementation, assuming that all the coordinates are available inside the processor, in the form of numbers stored in scratch pad memories. The algorithm aims at finding the vertex as quickly as possible, by extrapolating two tracks in each projection. Instead of searching for all tracks, a search is made for straight lines at the edges only of the cone of outgoing particles. This affects the search strategy in the presence of inefficiencies and spurious firings of flash cells. Three detector planes at least are required to check if fired cells lie on a straight line, but for the case of inefficient detectors it is advisable to add redundant planes.

The implementation of the algorithm aims at increasing execution speed by performing as many operations in parallel as possible. The processor can be implemented for any number of detector planes, but to fix ideas we will assume that there are four planes ($Z=\text{constant}$) of active flash tubes, each perpendicular to the forward direction and providing for each plane the X-coordinates of the particles contained in the forward cone (see fig.2). Similarly, we will assume the presence of four parallel planes giving the Y-coordinates of the same particles at their crossing of four Z-planes.

In order to meet the time constraint (decision time $\approx 2\mu\text{s}$) there will be very stringent requirements on the read-out system which has the task of transforming the flash chamber signals into the encoded coordinate values needed by the processor.

4.1 Algorithm

From the two intersection points X_i^I and X_j^J of a straight track with two different planes I and J (see figure 2, where $I=1, J=4$), we predict the intersection point in any other plane K by:

$$X_{\text{pred}}^K = (X_j^J - X_i^I) * \beta_{IJK} + X_i^I \quad (1)$$

where β_{IJK} is the ratio d_{IK}/d_{IJ} of the distances between planes. Therefore, to check if in a third plane K there exists a point (corresponding to a lighted flash cell) which lies on the line through the two points chosen in the master planes I and J, a search is to be performed over all values of X_k^K , $k=1, \dots, n_K$ each time comparing X_k^K with X_{pred}^K . The search will be successful if for a given, small value of δ a point satisfying

$$|X_{\text{pred}}^K - X_k^K| \leq \delta \quad (2)$$

exists. Assuming that the points X_k^K are ordered, the search can be stopped

when $X_{\text{pred}}^K - X_k^K$ has changed sign and $|X_{\text{pred}}^K - X_k^K| > \delta$.

When all coordinates have been stored in increasing order, the straight line found will be the projection of a track on - or close to - one of the edges of the cone of outgoing tracks. Performing the same search on sets of coordinates in decreasing order, the projection of a track at the opposite edge of the cone can be found. These two lines make in general a comparatively large angle and are, therefore, well suited to check if they intersect inside the target region.

The relation (1) can also be used to predict the intersection of a straight track with any plane of the target emulsion stack (for instance the median plane). Together with the two projected tracks, two predictions for the vertex will be found: $X_{\text{pred,incr}}^{\text{vertex}}$ and $X_{\text{pred,decr}}^{\text{vertex}}$. It is probable that there is a real vertex inside the emulsion stack if these two predictions are close:

$$|X_{\text{pred,incr}}^{\text{vertex}} - X_{\text{pred,decr}}^{\text{vertex}}| < \Delta \quad (3)$$

where Δ is a previously defined and sufficiently small distance.

The same procedure can be applied to the Y coordinates and the confidence in the test increased when (3) is satisfied for the Y projection as well.

For the ideal case of 'clean' events, without background tracks or scattered particles, or inefficient flash cells, the first choice of X_i^I ; or X_j^J ; (which is in fact X_1^I and X_1^J) would lead to finding a straight line intersecting inside the target the line at the other side of the cone (through X_{nI}^I and X_{nJ}^J). One has to take imperfections into account however and new combinations of X_i^I ; and X_j^J must be tried if the first fails. The failure to find a track will always show up by the impossibility to find points in the intermediate planes K satisfying (2). Figure 3 shows a few examples of the situations that may arise. From figure 3 and considerations on the relative frequencies with which the different situations arise, one can easily derive a search strategy, leading in the shortest time to the desired result. Thus, when the choice $i=1, j=1$ fails, the next one to try is $i=1, j=2$, followed by $i=2, j=1$, and $i=2, j=2$. It is assumed here that the plane I is closest to the target. Similarly, when $i=n_I, j=n_J$ fails, one continues with $i=n_I, j=n_J-1$, etc.

A more complicated situation arises when two projected tracks have been found, but do not intersect inside the target. Strategies for continuing the search can be formulated to cope with this case also, but the process risks to take too much time. A more drastic decision - reject or accept the event - seems more appropriate at this stage.

4.2 Implementation

A block diagram of a possible implementation of the straight line search is shown in figure 4. Using the coordinates stored in the scratch pad memories shown in the upper part of the figure, relation (1) is evaluated directly with the help of arithmetic elements (adders and multipliers) stringed together. The part to the right of the dashed line evaluates (1) and checks (2) for the points in a single intermediate plane. It can be replicated as many times as there are intermediate planes. The searches through the points in the intermediate planes are thus performed simultaneously and in the shortest possible time. On the left of the dashed line, the same equipment is used to calculate the predicted vertex position.

The entire circuitry of figure 4 can be replicated four times, to perform simultaneous searches for projected tracks at the edges of the cones, two in the X- and two in the Y- projection. This is indicated in figure 5 which also shows the additional comparators needed for checking the validity of (3). It should be noted that this check can be made while the search through the points in the intermediate planes is still in progress.

A certain amount of logic is required to control the entire process and to decide how to proceed at the completion of each step. The status signals to base this decision on are essentially the outputs of the different comparators (a total of $2+8m$ where m is the number of intermediate X-planes). A next step through the algorithm is initiated by incrementing one or more of the address registers of the scratch pad memories. These increment signals can be easily generated from the status signals with the help of a Programmable Logic Array (PLA). The use of PLAs to generate the desired sequences of control signals is described in more detail by one of the authors¹⁸⁾ and in manufacturer's literature²²⁾. One large PLA could control the entire processor, but to limit the size of the PLA (as well in number of input/output signals as in number of product terms), it is best to keep the control of the four

replicas of figure 4 separate from each other and from the overall control (figure 5).

The crucial element in this implementation is the multiplier, which must be replicated $4(m+1)$ times. A fast array-type multiplier²³⁾ is needed to obtain the required speed (~ 200 ns for Schottky TTL and 16×16 bits). Such multipliers are expensive (~ 2000 \$/piece) and consume relatively large amounts of power (~ 35 W). In many cases the multiplier can be replaced by cheaper elements. This is so when the multiplication by β_{IJK} can be replaced by a single 'shift' or by a single 'shift and add' operation. The case of five equidistant planes, where the values of β are $\beta_{152} = \frac{1}{4}, \beta_{153} = \frac{1}{2}, \beta_{154} = \frac{3}{4}, \beta_{155} = 1$, may serve as an example. An important simplification is obtained when a look-up table can be substituted for the multiplier and additional arithmetic elements. For instance, if we are dealing with 256 or less cells per plane, we can divide these in a maximum of 16 groups of 16 cells/group. Writing $X_i = \bar{X}_{i,1} + x_i$ where $\bar{X}_{i,1}$ is the integer part of $X_i/16$ and $x_i = X_i \bmod 16$, relation (1) can be rewritten as:

$$X_{pred}^K = [(\bar{X}_{j,m} - \bar{X}_{i,1})\beta_{IJK} + \bar{X}_{i,1}] + \{(x_j - x_i)\beta_{IJK} + x_i\} \quad (4)$$

For a given value of β_{IJK} , the term within square brackets can at most assume $16 \times 16 = 256$ distinct values. The same holds for the term within accolades. Both terms can, therefore, be easily and rapidly evaluated with the help of two look-up tables, of 256 entries each. This is shown in figure 6, where the part within dotted lines evaluates the same expression (4) as the parts within dotted lines in figure 4. This implementation with look-up tables is faster (~ 70 ns), cheaper and less power-consuming than the one using a multiplier. It can be adapted to straight line finding in all those cases where the number of elements or cells per detector plane remains below a practical limit of 1-2K or so. Extensions beyond this limit are possible, but they require additional stages of adders, so that the gain in speed may be lost rather soon.

The time it takes to reach a decision can only be estimated if one takes account of realistic situations presented by inefficient cells and by spurious firings²⁴⁾. It is reasonable to assume that two trials are needed before a point on the line is found for an intermediate plane. The basic time to find the four projected tracks and check their intersections can then be evaluated - adding individual access and processing times - at 700-750 ns. This assumes the use of TTL or Schottky TTL throughout and the use of an array multiplier. Assuming further that the probability to find a knock-on or scattered track

outside the cone is ρ and that each plane has a detection efficiency of $1-\epsilon$, the probability that the process is finished in this time is $1-4(\rho+2\epsilon)$ in first approximation and for ρ and ϵ small. The probability that this time is doubled is approximately $4(\epsilon+\rho)$, and tripled: 4ϵ . The probability that the time will exceed $2.1\mu\text{s}$ is small; in a first approximation this probability is $4(\rho^2+\epsilon^2+\epsilon^m)$, where m is again the number of intermediate planes.

Using the table look-up method will further reduce these times: the basic evaluation time will become 500ns or less. The total processing time will then rarely exceed $1.5\mu\text{s}$.

To avoid adding large amounts of time to this processing of $1.5\mu\text{s}$ duration, very stringent requirements are imposed on the read-out system.

Fast read-out systems, capable of delivering coordinates at a rate of approximately one every 100ns exist²⁵⁾. It is clear, nevertheless, that in order to keep read-out times in line with the $1.5\mu\text{s}$ processing time, each plane must have its own read-out so that all planes may be read out in parallel and simultaneously. Since we need the coordinates in increasing and in decreasing order, two read-out systems per plane are in fact required. The complexity, and therefore cost, is increased by more than a factor 2 over a conventional system, reading plane after plane.

When the scratch-pad memories used are of the register file type, allowing simultaneous reading and writing, the processing could start as soon as the first coordinate from each plane has been stored. Writing into the register file of the following coordinates can proceed during the processing of the first pair of pivot points.

5. Conclusion

We have shown on a number of illustrative examples that plastic flash chambers can be utilized as active detectors capable of providing various types of 'secondary triggers'. If the secondary trigger has to be utilized to sensitize ep-chambers with sensitive times in the microsecond region, a fast processor is required which has to be capable of reaching the logical decision in a time of the order of a microsecond.

It has been shown that such a processor can be built and applied to check for a possible interaction point inside the target in a time normally less than $1.5\mu\text{s}$. The cost would, however, be considerable (in the 100-200 Kfrs range for a processor for 8 planes of 256 cells each). The cost and complexity

increase linearly with the number of planes, but only slightly with the number of cells per plane. The technique is, therefore, well suited also for use with detectors having a high resolution (MWPC).

The secondary trigger derived from the processor can in this and other cases also be used for other purposes than triggering ep-detectors. It can, for instance, be used to reject events and to initiate the lengthy read-out of large set-ups of detectors only for those events which stand a better chance of final acceptance. This is particularly useful at high trigger rates, as often encountered in experiments on hadron physics. In these cases the requirements on execution time of a processor are mainly dictated by the read-out time, which is much longer than the sensitive time of an ep-detector, although much shorter than the attainable processing time on a minicomputer. A simplified, and therefore cheaper, processor, where sequential processing is substituted for parallel operations, can be attractive for experiments on hadron physics.

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FIGURE CAPTIONS

- Figure 1 Schematic layout of an experiment using flash chambers and a fast processor to derive a secondary trigger to pulse the gold-plated self-marking spark-chambers ('holey' chamber).
- Figure 2 Principle of the checking for straight tracks and extrapolation to the median plane of the target emulsion stack.
- Figure 3 Cases which can present themselves in the line finding process.
Case 1: a knock-on particle. The pivot point in plane 4 must be replaced by the next point.
Cases 2 and 3: an inefficient cell in one of the pivot planes. The next point in the other pivot plane must be chosen.
Case 4: inefficiencies in both intermediate planes. New points in both pivot planes must be chosen.
- Figure 4 Block diagram of the line-finding and line-extrapolation part for one edge of the cone of outgoing particles and for a single intermediate plane. The right hand part can be replicated at will.
- Figure 5 Overall block diagram of the processor. The part shown in figure 4 is replicated four times and overall control added in the form of a Programmed Logic Array (PLA).
- Figure 6 Two look-up tables and their associated addressing can replace the subtractor-multiplier-adder chain shown in Figure 4. The part inside the dotted lines can be substituted for the equivalent parts (also inside dotted lines) in Figure 4.

FIGURE 1

FIGURE 2

Case 1

Case 2

Case 3

Case 4

X fired cell

○ cell which has not fired

— actual track

- - - track assumed in first trial

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6