A BRANCH OFF THE PEPR TREE*

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1. INTRODUCTION

A new automatic measuring device for bubble chamber film has been developed which incorporates features of the PEPR[1,2] and POLLY[3] systems. This device, called RIPPLE, is built around a precision cathode ray tube (CRT) and uses a portion of the standard PEPR package developed at MIT and manufactured by Astrodata, Inc. The line element generation portion of the package has been eliminated from this system, however, and the RIPPLE uses a flying spot as its digitizing element. The digital controller for this device has been newly developed and combines some of the best features of the previous devices. A block diagram of the system is shown in Figure 1.

Before beginning a description of the RIPPLE system, it might be useful to define the functions that an "ideal" controller might perform. It is important in this respect to recognize the practical limitations of existing computers, in particular their calculation times (5 to 10 μs per arithmetic operation). An "ideal" controller would obviously remove as much routine computational burden as possible from the computer. The flying line element of the PEPR is such a feature; it recognizes line elements without the computer having to handle each individual bubble many times in different combinations. However, the line element is not an "ideal" precision encoding element. It is basically a summing device for bubbles along its length; and as such it can be confused in regions of crossing tracks, nearby tracks, etc., since the sum can then contain a few incorrect bubbles. Therefore, the "ideal" device would first detect a particularly outstanding sum composed of

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* Work supported by the National Science Foundation, the U. S. Atomic Energy Commission, and Duke University.

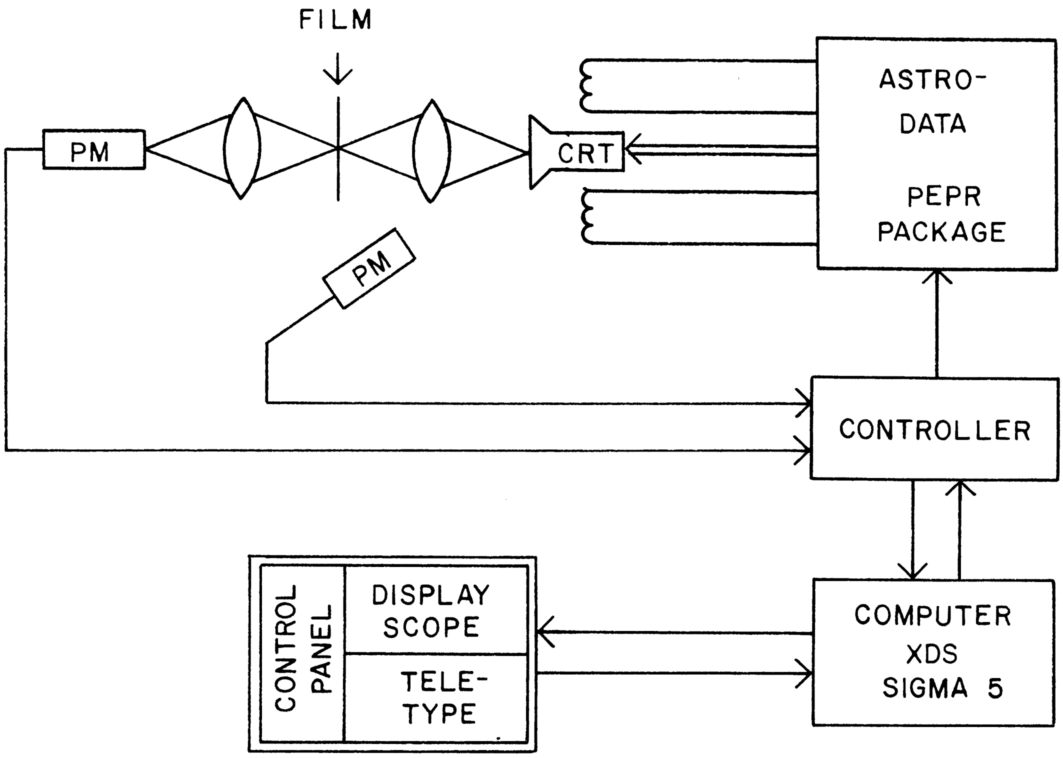

Fig. 1

Block Diagram of the RIPPLE system

many bubbles at some position and angle but would then transfer to the computer the coordinates of each bubble used to obtain the sum. The computer could then use more elaborate methods to eliminate the few offending bubbles and base its resulting master point calculations only on the best information. If such a device were built around a flying spot sweep it would certainly require significantly more controller logic than is currently used.

The RIPPLE was developed with this ideal in mind, and represents a small step in that direction.

2. SWEEP

The primary task of any automatic bubble chamber film measuring device is track following. Currently most methods of scanning for events also involve following beam tracks until a vertex is found. In many ways, the ideal coordinate system for this task is a polar coordinate system centered on the track being followed. In the RIPPLE this polar system is generated by sweeping the CRT spot in a series of small concentric circles of decreasing radii. The circles have a maximum diameter of about 3 mm and can be centered anywhere on a 32000 x 32000 point grid on the CRT face. The coordinate system formed by the sweep is of particular importance in the hardware line element detection system discussed in Section 3.

A comparison of this polar sweep and the raster sweep of the POLLY is shown in Figure 2. If the polar sweep is centered at the intersection point it will "see" each crossing track as a group of bubbles near a particular angle. The corresponding property of the raster sweep is the

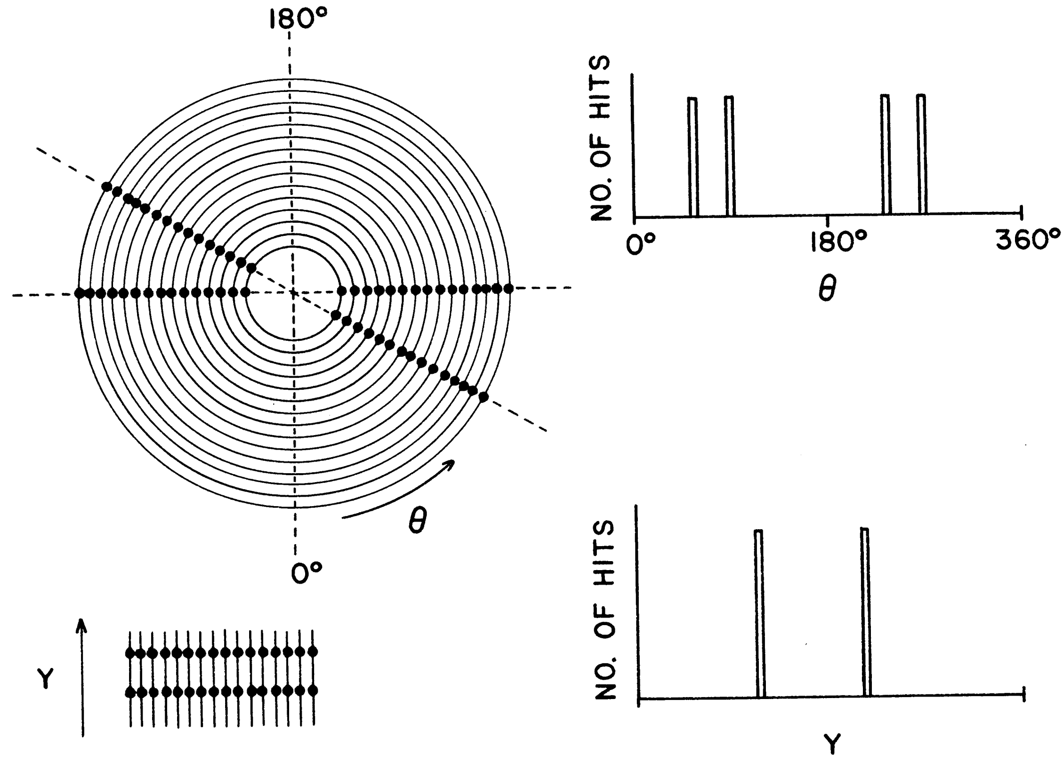

Fig. 2

Comparison of circular sweep of RIPPLE versus the raster sweep of POLLY. With the circles centered on a vertex or interaction, all hits on a track occur near a particular angle, θ, and can therefore be histogrammed on the θ axis to find tracks. The raster sweep has similar properties for parallel tracks.

ability to see parallel tracks when oriented with its sweep lines perpendicular to the tracks.

From this it is clear that the coordinate system formed by the raster sweep is optimal for displaying and finding beam tracks, where the angle of the track is known, but the lateral position is not. The polar scan, on the other hand, is optimal at a vertex where the position is known but the angles of the outgoing tracks are not. Although less distinct, the polar scan is better for detecting narrow angle crossing tracks or two superimposed tracks which split apart. If the polar scan is centered on a track, its sweep line will cross the track at approximately 90^{o}. This is an important point with regard to the hit width which will be discussed in Section 4; a crossing angle of 60^{o}, for example produces hits up to 15 percent wider, depending on the bubble distribution along the track.

Figure 3 shows the details of the sweep pattern generated by the RIPPLE controller. The computer obtains the particular pattern de-

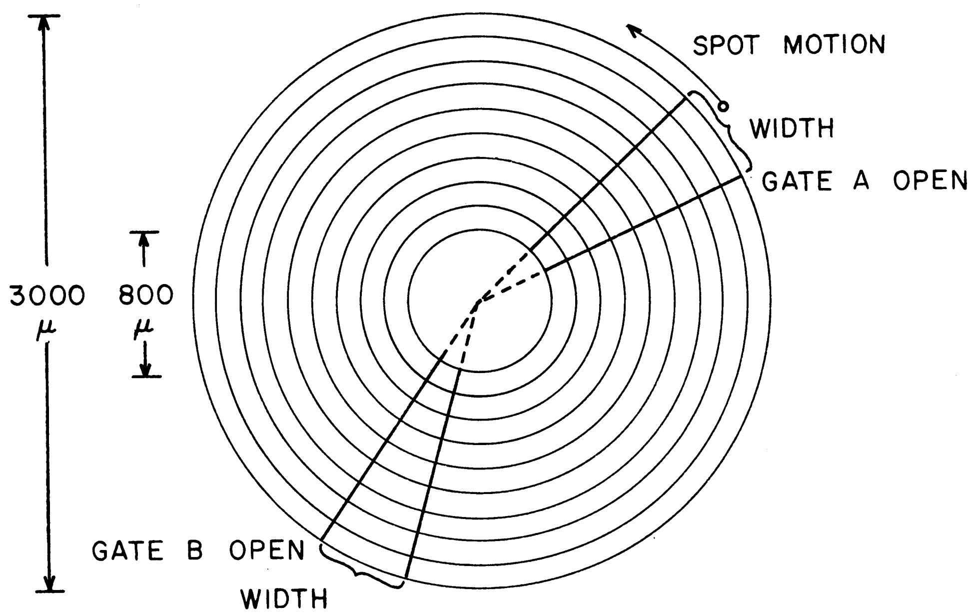

Fig. 3

Sweep pattern of spot around a main deflection point. Dimensions shown are on film after a 3:2 lens reduction. The r, θ position of a hit is transferred to the computer only if the hit occurs within one of the separately adjustable gates shown.

sired by presetting: the maximum radius, the minimum radius, the step size between radii; the gate A and gate B opening angles, the common gate width, and the X, Y center of the pattern. The gates, which may be opened to cover a full 360°, only determine which hits will be transferred to the computer. The hit detection logic continues to function over the full 360° enabling the controller to "see" the film over the full sweep pattern. During track following narrow gates would normally be used, and, under these conditions, only hits on or near the track being followed are available to the computer. This, of course, reduces considerably the number of computer operations necessary to process the sweep.

The schematic diagram of the sweep generation electronics shown in Figure 4 indicates another pleasant feature of the polar sweep. It may be generated very simply by filtering square waves to obtain only

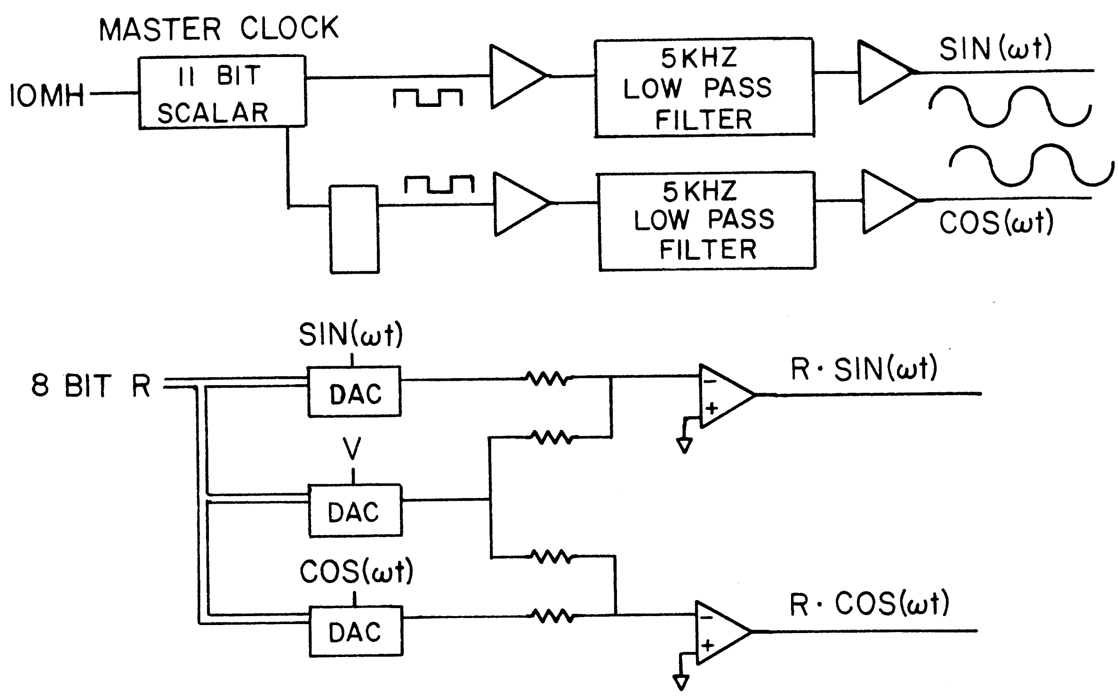

Fig. 4

Schematic diagram of electronics for circular sweep generation. The low pass filters transmit only the fundamental component of the square wave signals. The digital to analog converters multiply the SIN and COS functions by a digital circle radius, R.

their fundamental frequency. The digital square wave signals are automatically phase locked to the master clock which forms the time base for the hit digitizing system. The sweep signal thus formed is stable and relatively insensitive to fast noise signals.

Using a 10 MHz oscillator to drive the master clock, the angular least count of the sweep is 100 ns corresponding to 0.176°. A circle radius on the CRT of $2000\,\mu$ thus requires a spot velocity of $60\,\mu\,/\,\mu$s. We have no difficulty digitizing the film at this velocity, nor do we have difficulty with the four times slower spot velocity needed for the smallest radius. This angular least count of 0.176° corresponds to a $6\,\mu$ least count at $2000\,\mu$ radius, $3\,\mu$ at $1000\,\mu$ radius, etc.

3. HISTOGRAM FEATURE

In an effort to regain some of the track element recognition features given up when the PEPR flying line was eliminated, an automatic histogramming feature has been incorporated into the controller logic. The feature lacks the versatility of the flying line but appears to have very useful properties. The digital logic involved is capable of accumulating hits in 64 angle bins as shown in the top part of Figure 2. The 64 bins normally span the full 360° as shown and operate independently of the hit gates. The controller accumulates hits over a full sweep pattern, normally composed of several concentric circles. At the end of the sweep pattern the controller scans the histogram bins sequentially and obtains the sum of each pair of adjacent bins. If one of these sums exceeds a value preset by the computer the bin number and bin count of both components of the sum are transferred to the computer. The logic is thus able to count all the hits of a given track, even if the hits are distributed into two adjacent bins. With this feature the computer need handle only a few numbers in order to roughly scan the full 360° pattern.

The digital logic used to accomplish this operation is sketched in Figure 5. The central item is an integrated circuit scratch pad memory unit available with address logic on a standard T-series XDS logic module. The read and write times for the memory are 110 ns and 165 ns

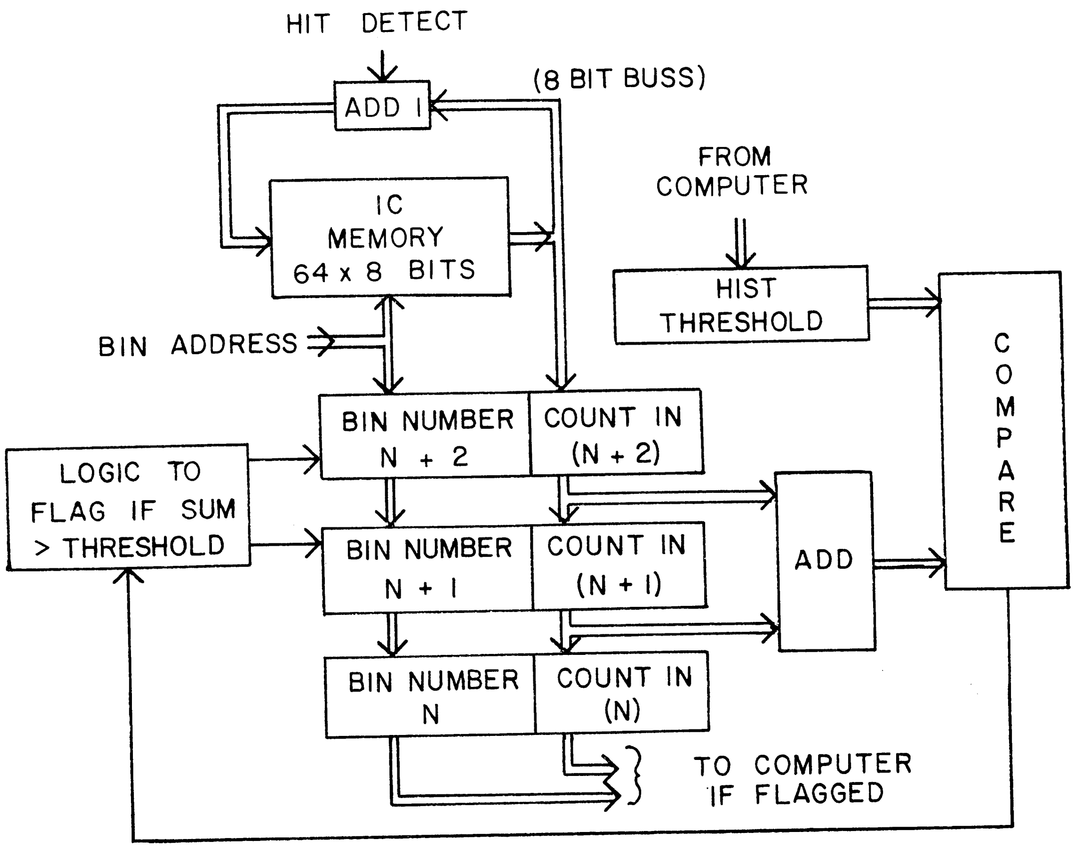

Fig. 5

Block diagram of electronic logic used to count, store, and retrieve the angle histogram information. The memory is automatically scanned following the sweep; whenever the contents of two adjacent bins combine to exceed a computer preset threshold, the bin numbers and contents of both bins are transferred to the computer.

respectively. The counting of hits is accomplished by reading the appropriate byte, adding one and restoring the byte. The memory unit is cleared preceding the sweep pattern and read, compared, and transferred to the computer following the sweep pattern.

Examples of the operation of this feature are shown in Figure 6. This six prong event is in a frame of 82" bubble chamber film. Each part of the figure is a single sweep composed of 46 concentric circles with radii varying from 1500μ to 400μ in 24μ steps on the film. The single dot near the center of each sweep is the center of the circles. Each sweep has been positioned manually by observation of the display shown here. Below each sweep is the complete angle histogram generated by that sweep pattern. The histogram scale runs from 0^{o} to 360^{o} in 64 steps with 0^{o} being toward the bottom of the picture.

Figure 6a shows the beam track for this six prong event. Track elements are clearly seen at angles near 90^{o} (backward direction) and 270^{o} (forward direction). In Figure 6b the histogram indicates several hits at approximately 270^{o} which are caused by the six prong vertex. When positioned near the vertex in Figure 6c the histogram clearly indicates at least four separate tracks. Observation of the actual hits shows five tracks, the sixth is superposed on the second track counter clockwise from the top.

In Figure 6d the sweep has been positioned as though the doubled track were being measured. It can be seen that this track appears to be heavily ionizing due to it being a double track. At this point the software would have no reason to suspect a double track, however. In Figure 6e the histogram information might indicate a problem in the forward direction for this track. And in Figure 6f, with the sweep positioned just beyond the place where the tracks split apart, the histogram clearly shows a new track just below the one being followed and all six prongs of the event have been found. The parallel track just below the one being followed confuses the histogram display considerably, but the separation of the doubled track still stands out clearly in Figure 6f. It should be noted that when following such a track the gates would be quite narrow such that the computer would not have individual hit data available for all the hits plotted on this display.

Figure 7c shows the histogram pattern for a sweep centered on the middle track between a parallel track and a track which crosses somewhat to the right of the sweep. It can be seen that the histogram contains useful information about the nearby tracks even though the polar coordinate system is not optimal. Figure 7d shows a large delta ray making many crossings of the track being followed. Note that the

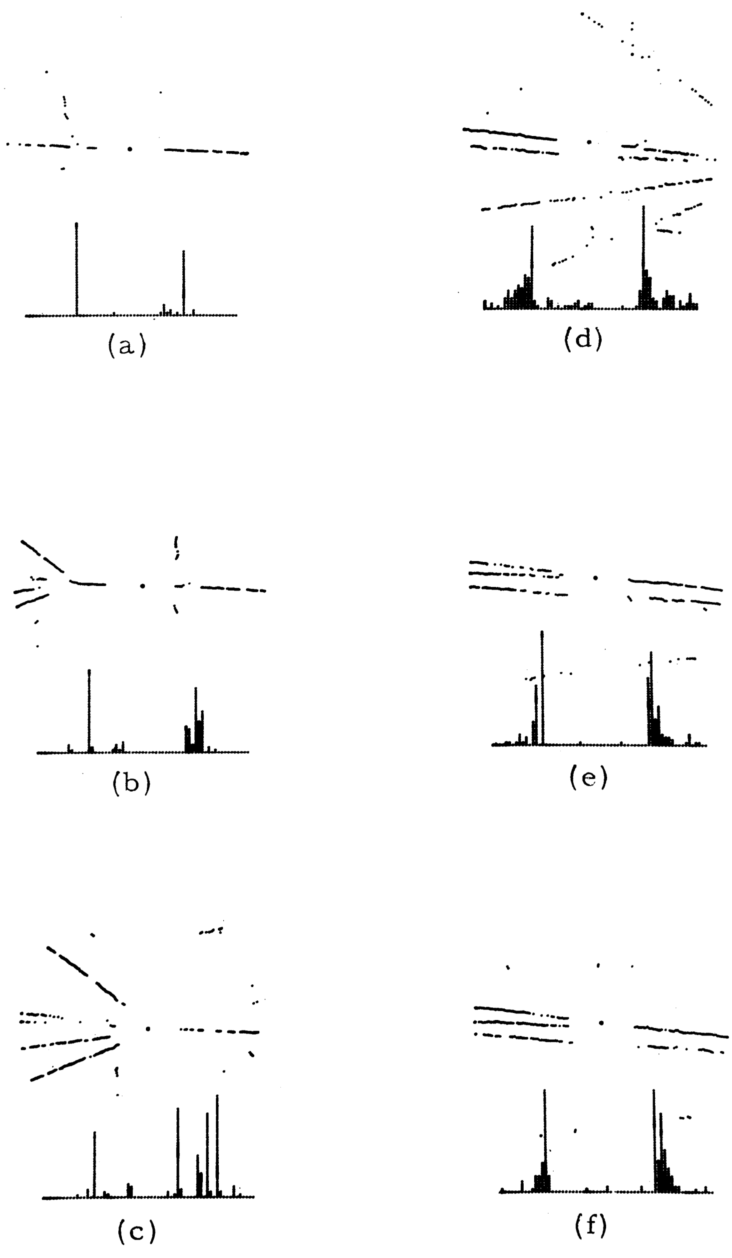

Fig. 6

Sample sweeps on high energy $\pi^+ p$ film from the 82" bubble chamber. The pictures show a sequence of sweeps on the beam track of a six prong event and on an outgoing doubled track which splits apart some distance from the production vertex. Each sweep pattern is centered at the isolated dot near the middle of each picture. The histograms below each sweep show the number of hits as a function of angle, θ, measured counter clockwise from a 6 o'clock position. The scale of each sweep is approximately 3 mm on the film.

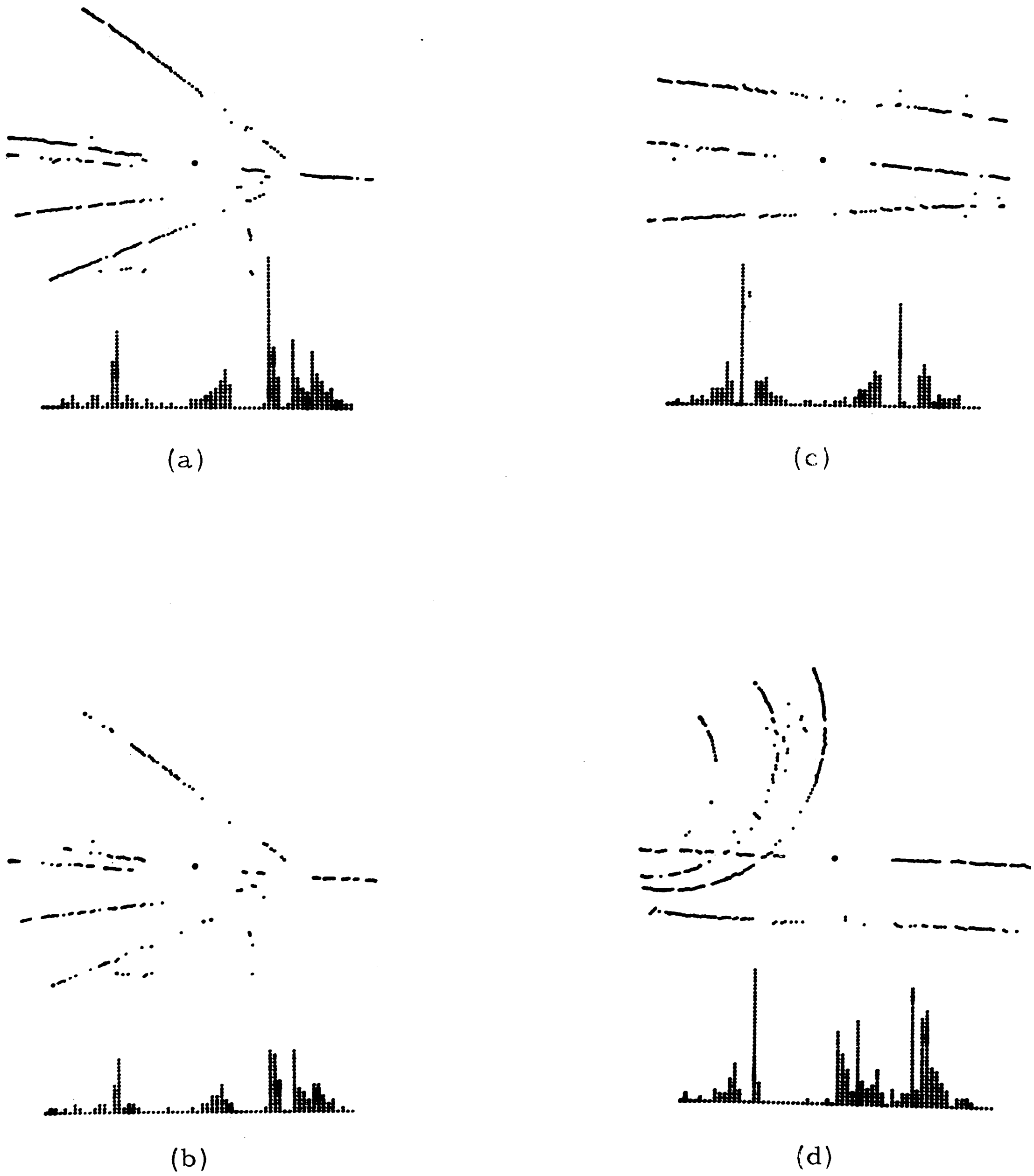

Fig. 7

More sample sweeps of the same frame. Sweeps (a) and (b) show hits on the doubled outgoing track (second from the top counter clockwise) with a wide and narrow hit width restriction. Sweeps (c) and (d) show the complex histogram pattern obtained in regions with many nearby tracks.

sweep does not digitize the delta ray well when the sweep and delta ray track are nearly parallel.

4. HIT DETECTION

The hit detection part of the RIPPLE system includes features found in PEPR, POLLY, and FSD and includes one idea from the SATR system at Wisconsin. The signal obtained from the photomultiplier (PM) viewing the film is normalized by the signal from three monitor PM's in a PEPR-like automatic gain control circuit. The output of this circuit has a base line and hit pulse height which are essentially independent of the CRT light level. After filtering (the time constant is a function of the circle radius), the leading and trailing edges of hits are detected by a threshold comparator circuit. The threshold is formed by a product of a computer preset hit threshold and an averaged base line signal level held in an up/down counter. This latter signal corresponds to the pedestal signal of PEPR and POLLY but is simpler to obtain here since the sweep pattern is continuous.

When the leading edge of a hit is detected the contents of the master clock are transferred to another scalar, called the slow clock. The slow clock is then counted at half speed until the trailing edge of the hit is detected. When this occurs, the slow clock is stopped and used to form the hit data for the computer and/or the histogram counter.

A hit width feature has also been included (as in POLLY) which has several desirable properties. At the time the leading edge of a hit is detected an analog ramp generator is allowed to start charging; the rate of charge is proportional to the instantaneous circle radius. In order for the trailing edge of the hit to generate a digital hit signal it must occur between two computer preset ramp voltages. Thus a PM pulse which is too narrow or too wide does not generate a digital hit signal. This technique differs from POLLY in that the decision to pass the hit is made in the controller rather than in the computer.

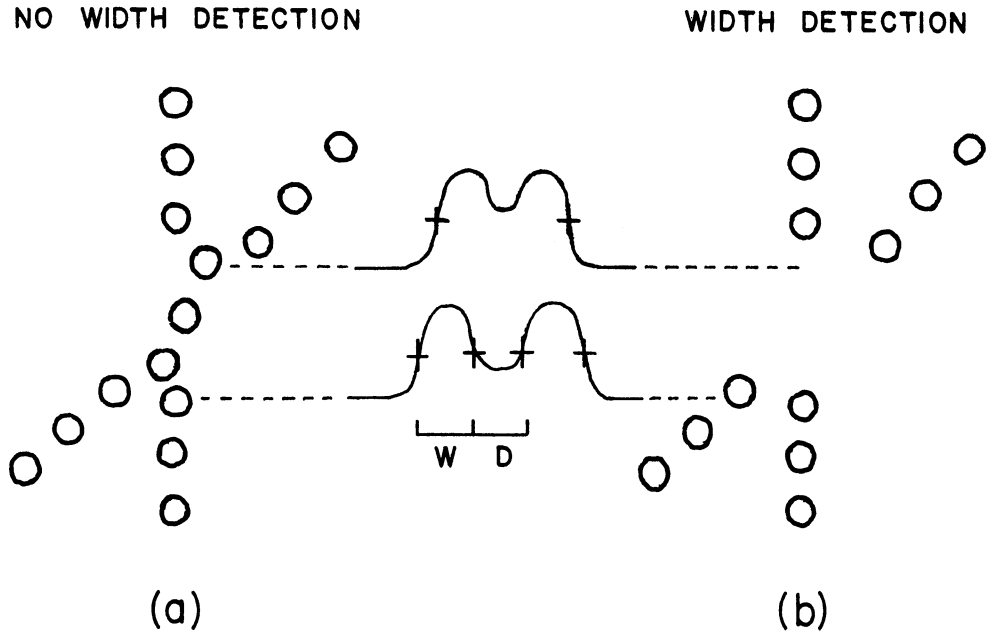

Fig. 8

Representative sketch of hits from two crossing tracks showing the removal of erroneous hits when hit width restriction is imposed. This is one of the major advantages possible with the flying spot sweep.

A very important consequence of this feature is sketched in Figure 8. In the region of crossing, or close parallel tracks, two bubbles can merge to generate a wide PM pulse. Without the width circuit, the logic described here may digitize midway between the two bubbles as shown in Figure 8a. It is much better if the width circuit blocks the digitization to yield the result shown in Figure 8b.

Another desirable consequence of this width circuit is shown in Figure 7a and 7b. In this event, also shown in Figure 6, the second track counter clockwise from the top is in fact doubled. In 7a the hit width is set very wide and this track digitizes much more often than the track just under it. With the width set more normally in 7b, many of the hits on the double track are eliminated, but the next lower track is unaffected. Note the loss of hits on some other tracks due to the scan lines not crossing the tracks at 90°. For multiprong events at high energies this width information can prove to be very useful indeed.

At high energies, it is particularly important that the hardware be able to successfully digitize and transmit hits on closely spaced forward tracks. To match the fast hardware times to the relatively slow computer channel times, a feature common in the SATR system has been included. A hardware hit queue composed of seven 20 bit registers accepts hits within 200 ns of each other and transfers them to the computer whenever the channel is available. This system effectively eliminates one source of "dead time" between hits.

5. SOFTWARE CONSIDERATIONS

Two main features of the polar sweep require somewhat special software treatment. First, the circular sweep covers a lot of area, most of it useful only occasionally. Because of this the time for a sweep pattern is relatively long, typically 5 ms. This time makes it important that we take advantage of the Sigma-5 computer's I/O channel possibilities and overlap calculations with the sweep. A software development is in progress which will permit the RIPPLE to switch from one track to another rapidly thereby overlapping calculation for one track with

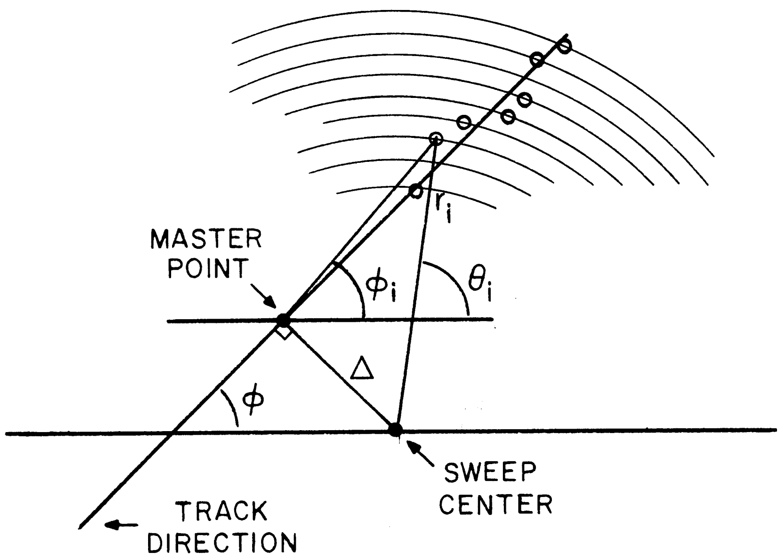

Fig. 9

Coordinate system used to determine a master point near the sweep center.

sweeping for another. The scheme will also allow the RIPPLE to exhaust the automatic jobs it can perform while awaiting the results of a request for operator intervention. Details of this software will be reported at a later date.

Second, the hits are returned in a polar coordinate system r, θ, centered at a main deflection X, Y. Assume for the present that it is unnecessary to correct each hit individually, rather that the hits can first be used to determine a master point and the master point can then be corrected. Since it is then desirable to remain in the polar system, simply to avoid the time consuming conversion to X, Y coordinates, a scheme has been developed to obtain a master point from hits expressed in polar coordinates.

Referring to the sketch in Figure 9, we define $\bar{\phi}$ as the estimator of the track angle and Δ as the perpendicular distance from the sweep center to the track. For each hit we write the approximate expression

$$\phi_i = \theta_i - \frac{\Delta}{r_i} \qquad (1)$$

where r_i and θ_i are the hit coordinates. The expression for the average track angle $\bar{\phi}$ based on n hits is

$$\bar{\phi} = \bar{\theta} - \frac{\Delta}{n} \sum_{i=1} \frac{1}{r_i} \quad , \qquad (2)$$

where $\bar{\theta}$ is given by

$$\bar{\theta} = \frac{1}{n} \sum_{i=1} \theta_i \ .$$

A simple chi squared for the angle ϕ would be

$$\chi^2 = \sum_{i=1} (\phi_i - \bar{\phi})^2 \ . \qquad (3)$$

Substituting in (1) and (2) and minimizing this quantity with respect to Δ yields

$$\Delta = \frac{\Sigma_i(\theta_i - \bar{\theta})(I_i - \bar{I})}{\Sigma_i(I_i - I)^2} \quad , \qquad (4)$$

where $I_i = \frac{1}{r}$ and $\overline{I} = \frac{1}{n} \sum_{i=1} \frac{1}{r_i}$.

This technique finds the point from which the track hits occupy the smallest angular spread. The point thus determined should require little additional correction for sweep distortion since it is quite near the center of the sweep. The main X, Y deflection must of course be corrected prior to locating the sweep center, but this is one correction per sweep rather than one per hit.

6. CONCLUSION

The above discussion has described features of the RIPPLE system which are currently operational. We have not, as yet, tried track following, fiducial finding, vertex finding, or secondary track finding in an automatic and routine way. We do feel, however, that the RIPPLE system is well matched to these problems and will soon be in automatic operation.

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DISCUSSION

H. GRIMM *(Heidelberg):* How many circles can you do with your controller?

L. FORTNEY: They are done automatically, and we have complete control over the number. We can go from a 1500 μ radius to a 400 μ radius, with three different spacings -- typically they are 12 μ, and 24 μ, and 48 μ. So you can get as many as 60 consecutive circles, though normally we run with 30-40.

H. WHITE *(UCRL):* The SLAC 82" has many features, due to the illumination system, which cause wide local regions in tracks. With inhibition of digitizing due to track width discrimination, what corrections do you need to measure ionization?

L. FORTNEY: This will ruin our ionization completely, unless we map these regions, which should be possible. We have trouble digitizing in the region of the coathanger lines, because of increased background.

A. WERBROUCK *(Torino):* What type of guidance do you plan for this device?

L. FORTNEY: We intend to zone-predigitize the vertex or a point on the beam track, and then to proceed from the beam track to the vertex, like POLLY.

H. GRIMM *(Heidelberg):* How much did your controller cost, and is it possible to combine it with the one provided by Astrodata, Inc.?

L. FORTNEY: We purchased the Astrodata package for $80,000, and we built our own controller for $30,000. We have made only very minor changes to the part of the Astrodata package that we purchased.

D. WISKOTT *(CERN):* Do you make a two-step evaluation of your scan, using the histograms for guiding you through the stored digitizings?

L. FORTNEY: We do not preserve all the digitizings, only the digitizings within the gates, whereas the histogram feature covers the full 360°. The question is, other tracks which cross over a little ahead, or have crossed a little behind the part of the track being measured (we do not want to do ionization in these regions) or when we are coming along a beam track and searching for a vertex -- the histogram is particularly useful then, since the gate may be too narrow for one to "see" them.

A. WERBROUCK *(Torino):* How long does it take to follow a track with this device?

L. FORTNEY: Each circle takes 200 μsec -- this is slow compared to FEPR, but not so slow compared to POLLY. A typical series of concentric circles is expected to take 5-10 msec, depending on how many you do, and how close they are. Each circle corresponds to about 3 mm on the film, and so one would expect to need 10-20 times that 5 msec. However, this is the limit set by the hardware, and in fact the software will probably be the determining factor. I might add that an area scan is one of the biggest problems with this device. If you have to convert from R-θ to X-Y, that is time-consuming.