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RESULTS FROM PROTOTYPE DAPR PROGRAMS

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Publication Date

1965-10-01

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For Conference on Programming for
Flying Spot Devices, Columbia
University, New York, N. Y.

UCRL-16509

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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Charles Dickens, Mary Downton, Joan Pinchak, and Howard S. White

October 1965

Results from Prototype DAPR Programs

Charles Dickens, Mary Downton, Joan Pinchak, and Howard S. White

Several prototype programs relating to Digital Automatic Pattern Recognition (DAPR) have been developed at Berkeley working in close contact with the Brookhaven efforts. The Brookhaven programs were developed under the direction of Marr, Pasta, and Rabinowitz. The work on the prototype programs at Berkeley was done by Mary Downton and Charles Dickens. These programs have produced very promising results and we now deem it feasible to organize a production system. The purpose of this paper is to show the results of the Berkeley prototype DAPR programs. There are several problems which remain to be worked out, but in general, the results show that we can successfully recognize bubble chamber events.

The problem of recognizing bubble chamber events has been broken into several phases. The first phase which is track following, constitutes a single 7094 program which operates in real time, satisfying the data demands of the FSD. The subsequent phases of track joining, linking, and vertex recognition constitute another 7094 program, which has a magnetic tape interface with the track following program. Cal comp plotter pictures have been made showing the results of these programs.

The Flying Spot Digitizer (FSD) which generates the data for the track following phase produces approximately 60,000 digitizings per view of the 72 inch Hydrogen Bubble Chamber. These digitizings are produced and transmitted to the computer within approximately four seconds. Therefore, the track following program must process about 15,000 digitizings per second which it does in real time.

The FSD has a mechanical stage which moves along the length of the film, while a mechanically generated spot of light sweeps across the film. The flying spot moves across the film in a manner similar to a TV scan, except that digitizings are produced when the spot is moving in the forward direction only. Each time the spot comes back to the initial point, a new scan line is started. Here, the position of the stage is read out and is the X-coordinate; the spot produces the W-coordinate. This we call the normal mode sweep. Beam tracks and all other tracks with slopes up to about 50 degrees from the sides of the film can be digitized in the normal mode.

Tracks which are parallel to the motion of the sweep will not digitize in the normal mode. An orthogonal mode sweep in which the stage moves across the film, and the flying spot moves along the length of the film is necessary. In this mode, the stage position produces a Y-coordinate, and the spot produces a W-coordinate.

Track Following

A major portion of the digitizings from a bubble chamber picture are of beam tracks. Since the paths of these beam tracks can be predicted, it is worthwhile in terms of speed and accuracy to devise a fast method of following these tracks alone. A simple transformation can be applied to beam tracks to project them into straight lines parallel to the sides of the film. A table is calculated which gives the shear necessary at each scan line to map the points of an ideal beam track into a straight line. This shear table need be computed only once for each experiment since it is a function of chamber parameters.

The program begins by searching the first few scan lines for beam track pulses. This is done by mapping the sheared W-coordinates into a histogram

whose bins are 40 octal microns (1 track width) wide. After a number of scan lines has been processed, the histogram is searched for pulses which will open track following blocks. Each canonical block contains instructions for following one track.

For Brookhaven 80 Hydrogen Chamber film with 4 BEV/C K^+ beam, 48 scan lines have been used for beam track initialization; 40 scan lines were used for Berkeley 72 inch Hydrogen Chamber film with 3.9 BEV/C π^- beam since the tracks are more heavily ionized. Here, we expect that the number of bubbles and their diameter will be such as to produce a digitizing density of 50 per cent. In searching for pulses, only histogram bins with more than four hits are examined. First, single bins with more than six hits are accepted as pulses. After these pulses have been found, they are eliminated from the next step which searches for pulses which are two bins wide with a total hit count greater than seven.

Thus, the beam tracks are initialized and the program enters the track following stage. Here beam tracks are followed and the program begins to follow non beam tracks. In track following, the W-coordinate is first sheared and checked to see if it lies on a beam track. If it does, the point is stored in the canonical block of the track on which it lies. After four such points have been collected, an average point is entered into the track's average point storage bank.

The track blocks are checked every fourth scan line, and those which have accumulated no hits within the last 32 or more scan lines are closed out. The 32 scan line allowance is made so that nearly crossing beam tracks, whose digitizings are depleted, will not be closed out before the tracks get a chance to separate. When beam tracks cross, only one pulse is produced and the program

holds the roads of the two tracks together until two pulses appear and the roads are separated.

Beam tracks are followed in sheared space throughout the picture; non-beam tracks are followed in unsheared space, using the actual W-coordinate. Points which are not on beam tracks are examined to see if they lie on established non-beam tracks. If not, the point is saved until there are four such points within a small interval, at which time a canonical block is started.

In collecting these four points, there may not be a gap of more than three scan lines between them. If four scan lines occur without a digitizing, all points thus far collected for this track are disregarded. After a non-beam track following block has been opened, the track enters the initialization stage.

So far, four track points have been found, enough to form one average point. The first pair and last pair of these four points are averaged to obtain two points from which a slope is calculated. The next four points are gathered using this slope, the last of the first set of points as a window, and a road width of 300 octal microns. It is required that these four points occur within the next 16 scan lines.

After the second set of four points is obtained, a second average point can be computed which will be the window center for finding the next four points. The slope will now be computed from the first and second average points. The new road width will depend upon the slope of the track. Here it is convenient to separate tracks into three categories: those with low, medium, or high slopes. Tracks with slopes less than 15 degrees from the direction of the FSD stage motion are considered to be in the low category. Those whose slopes are between 14 and 40 degrees are classified as medium; the remainder have

high slopes. For low tracks, the road width is reduced to 200 octal microns; for medium and high tracks it is set at 240 octal microns. Thus, the four points which form the third average point can be found. The requirements are that these be found within 20 scan lines for low and medium tracks, and within 16 scan lines for highly sloped tracks.

When three average points have accumulated, the track is initialized and it is assigned an average point storage bank. Here, the track enters the intermediate straight line extrapolation stage.

In obtaining the four points which will constitute the fourth average point, the density requirements and road width are the same as for the third average point except that medium tracks have road width 200 microns. The slope is derived from the second and third average points and the third average point is taken as the window center. The road width is not changed for finding the fifth average point, but the density requirements are relaxed slightly. For low slope tracks, the four points must be found within 24 scan lines, 22 scan lines for medium tracks, and 17 scan lines for highly sloped tracks. The window center is the fourth average point, and the slope is computed from the third and fourth average points.

At this point, the road width is reset to 120, 160, or 220 octal microns for tracks of low, medium, or high slope. The density requirements remain fixed. Here, a second order calculation which uses the change of slope per scan line is used for predicting the slope. This change of slope per scan line is computed from three average points which are uniformly distributed (i. e., points 1, 3, 5 or 8, 13, 18). The slope used in each case is that of the central average point (i. e., 3rd, 13th). Each time an average point is computed the road center is extrapolated from this point.

The average point storage bank for each track is limited by storage requirements to 18 points. For tracks with more than 18 average points, an algorithm is used for dynamically editing these points. This algorithm assures a fairly reasonable distribution along the full length of

the track. At the end of track following, these 18 average points are reduced to 10 evenly distributed points.

There are 60 track following blocks (58 words each) and 150 average point storage banks (24 words each). Track blocks are added or removed as necessary, however the average point banks are preserved. As track blocks are opened, they are inserted into a list of tracks ordered by increasing W-coordinate to facilitate rapid processing.

Since there will most likely be tracks which are parallel to the normal scan, there must be an orthogonal sweep to pick them up. The beam track following is eliminated in the orthogonal sweep; the non-beam following proceeds exactly as in the normal mode. The current program has provision for one orthogonal sweep somewhere in the middle of the picture. This will have to be revised to allow for as many orthogonal scans as is necessary to cover the entire picture. Another program which will be discussed later links the normal and orthogonal track segments to form one set of average points for each track.

When crossing tracks occur, there will be only one digitizing on the scan line in which they intersect. A highly probable occurrence would be a non-beam track crossing a beam track. Since a point is first checked to see if it lies on a beam track, it would be lost to the non-beam track. This could contribute to losing a track during following, and could be detrimental to the ionization calculations. It is impossible, due to real time demands, to check each point on a beam track for non-beam following. This is not a serious problem, however, since the separate track segments are later joined together.

In track following, average points are computed using all of the points which lie inside the road. It sometimes happens that a point lies within a

road, but is not actually on the track. At this stage of development, there is no way of ruling out these points; they are included in the average point calculations. This is highly undesirable and an efficient method must be found which will eliminate these extraneous points.

Track Segment Joining and Linking

During track following, it is possible that a track is lost and later reinitialized. It is therefore necessary to examine all of the track segments to see if they are portions of a longer track. Fiducial arms should be isolated and the normal and orthogonal track segments must be linked. The program which performs these functions is separate from the track following program. It first joins track segments in the normal scan, then does the same in the orthogonal scan. When this is done, the two sweeps are examined for track linkages. This same program then searches for vertices.

The term "joining" will be used to denote the connecting of track segments within one scan (normal or orthogonal mode). "Linking" will be used when connecting between the normal and orthogonal scans is discussed. Once two track segments are joined or linked, their average point lists are merged and the process is irreversable. Therefore, the track segments must meet rather stringent requirements before they are joined or linked.

Within a single normal or orthogonal scan, track joining is done in two passes. The first pass uses the slope, rate of change of slope, and the last point of one segment to predict the slope and first point of the other segment. This method is used where one track segment starts near the end point of the other and where both segments have the same direction of curvature. It is faster than circle fitting and is very efficient where gaps between track segments are small or where the segments form a fairly straight track.

The second pass fits a circle to the longer of the two segments being considered. From this circle, W-coordinates are predicted for the first, middle, and last points on the shorter segment. If the predictions are within an acceptable tolerance of the actual W-coordinates, the two segments have passed the test for joining, and their points are combined into a single list.

In order to determine if two track segments are near enough for joining, the program sets up a box around the end point of one track. It then looks to see if any other track segments have end points within this box. A distinction is made between short and long tracks because the program is willing to extrapolate over a longer length on longer tracks; it has more confidence in connecting these.

The first pass attempts to join tracks whose end points are less than 2000 octal microns apart in W (one millimeter on film). The maximum separation allowed in X (or Y for orthogonal) is 96 scan lines for short tracks (tracks with less than 6 average points). The scan line threshold is increased to 128 for tracks with 6 or more average points. The box size for the second pass is $1 \frac{1}{2}$ times that just described for the first pass.

When track segments are joined, the total number of average points is reduced to the standard saved for each track (10 points). After both passes for joining, the program attempts to find fiducials. Short, straight tracks at an angle near 45 degrees are candidates for fiducial arms. When a pair of these tracks cross, their intersection is computed to obtain a fiducial center. The fiducial centers and the track average points are converted from FSD least counts to microns.

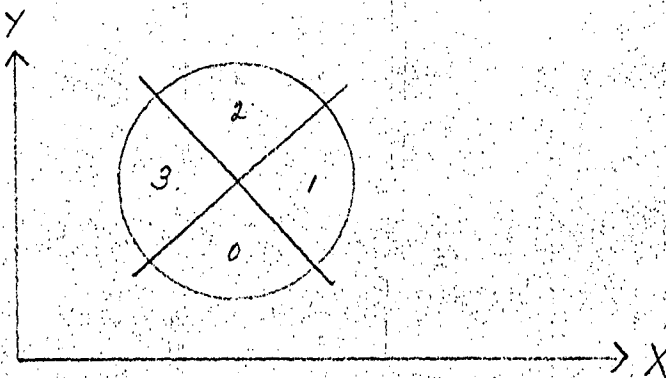
Track joining, fiducial finding and conversion to microns is done first for the normal scan. The same procedure is then followed for the orthogonal

sweep; further linking is still necessary for tracks with both normal and orthogonal segments.

All tracks whose slope and curvature indicate that they could continue into the other mode are considered for normal to orthogonal linking. If a segment is very long or has a high slope, two circles are fit, one to the first half of the segment, and one to the last half. Otherwise, one three-point circle or a two-point straight line is used.

The maximum gap allowed between segments considered for linking is 20K μ microns which is about one centimeter on film, or 1/15th the length of the 72 inch chamber. If the tracks are 40,000 octal microns or longer, two circles are fit; one using the first, third and fifth average point, the other on the fifth, seventh, and tenth average points. Tracks shorter than 14,000 octal microns have circles fit to their first, fifth, and tenth average points. Intermediate length tracks are fit to straight lines.

Tracks are sorted among five lists: four for the quadrants of a circle, one for all straight tracks. The quadrants are as indicated in Figure 1. Normal tracks are sorted among quadrants 0, 2, or straight, orthogonal tracks among quadrants 1, 3, or straight. The program begins to link segments in a counter clockwise direction: quadrant 0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 0.



Direction of beam \rightarrow

Figure 1

In checking two curved segments for linking, three points from the shorter segment are tested against the appropriate circle from the longer segment. If each point lies within an acceptable tolerance of the circle, the two segments are linked. If one segment is completely superimposed over the other, the shorter one is simply deleted, otherwise, the two segments are linked. Their average points are merged into one list and 10 points are selected to be as evenly spaced as possible.

Vertex Search

At this point, we have found fiducials and abstracted tracks in one frame of bubble chamber film. A search must now be made for vertices so that events can be identified. The present program attempts to find vertices only at the ends of tracks. It looks first at the end of beam tracks and unrelated non-beam tracks. If an interaction is found, the search is continued at the free ends of all the tracks in the event.

A large box is set up around the end point of a track (track A for purposes of discussion), and all other tracks which end in this box are examined. For each of these tracks, the point of intersection with track A is computed by means of a subroutine which calculates the intersection of two circles, a circle and a line, or two lines. If the tracks do not intersect, but are close together, the point halfway between their end points is computed. The tracks with intersection points nearest the end of track A are selected. A track is rejected if its intersection with track A lies outside the fiducial area or if the intersection is too far from its own end point. The allowance for distance from intersection point to end point is small if the intersection point is internal to the track, but is fairly large if the point is external to the track. This distinction is made because an internal intersection is less likely to be a vertex than an external intersection.

The dimensions of the box in which the program searches for vertices is 23,400 octal microns in both the X and Y directions. This roughly corresponds

to a one centimeter square on film. In cases where the intersection point is internal to the track, the maximum acceptable distance from the end point of the track to the intersection point is 2000 octal microns for non-beam tracks. For beam tracks, this threshold is increased to 6000 octal microns, or about 3 millimeters on film. The maximum gap allowed for intersection points which are external to the track is 6000 octal microns for all tracks.

Tracks accepted thus far are recorded in a list. Each intersection point is then tested against circles fit to all of the other tracks in the list. The intersection point which fits the most tracks is chosen as a rough vertex point and the tracks that it fits are listed as prongs of the event. Each vertex is recorded in a "vertex list" with pointers to other related vertices in the event.

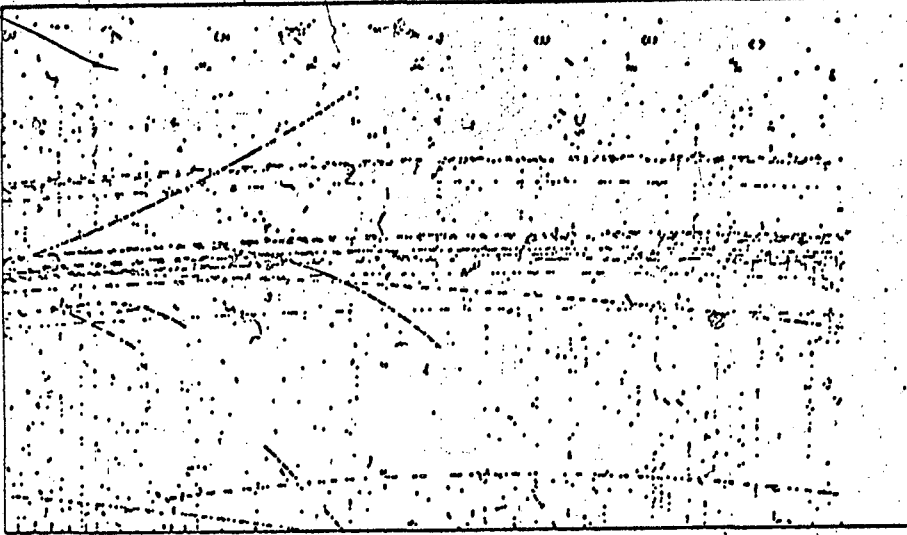
Very short non-beam tracks are not allowed to initiate events. However, once the first vertex of an event is found, all tracks in that vertex are used to search for subsequent vertices.

This vertex search method is primarily geometrical and does not apply any physics to tracks being considered. It is highly probable that false vertices will be found, however the procedure of event identification should eliminate these extraneous vertices. Event identification has not yet been attempted at Berkeley; however, the task should not be too difficult providing all of the vertices are found.

References

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2. C. R. Dickens, M. W. Downton, H. S. White: "Software Developments Toward Automatic Scanning of Bubble Chamber Photographs"
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3. R. Marr, J. Pasta, G. Rabinowitz: "A Preliminary Report on Digital Pattern Recognition at BNL"
February 28, 1963
ENL #6866

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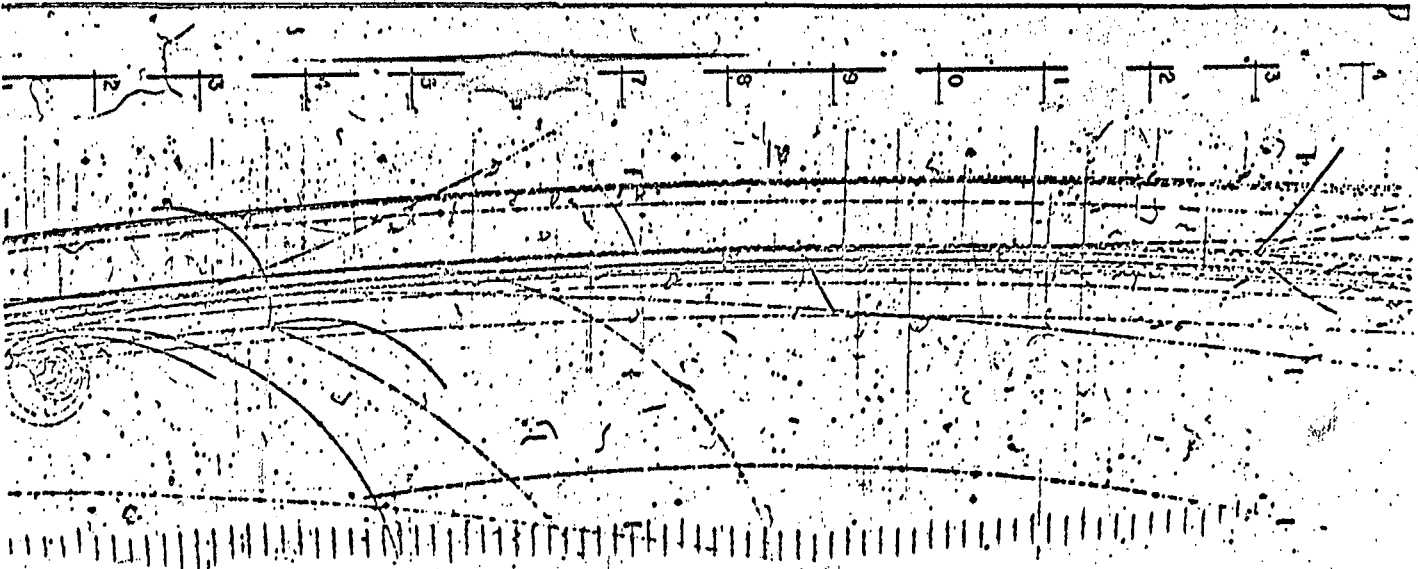
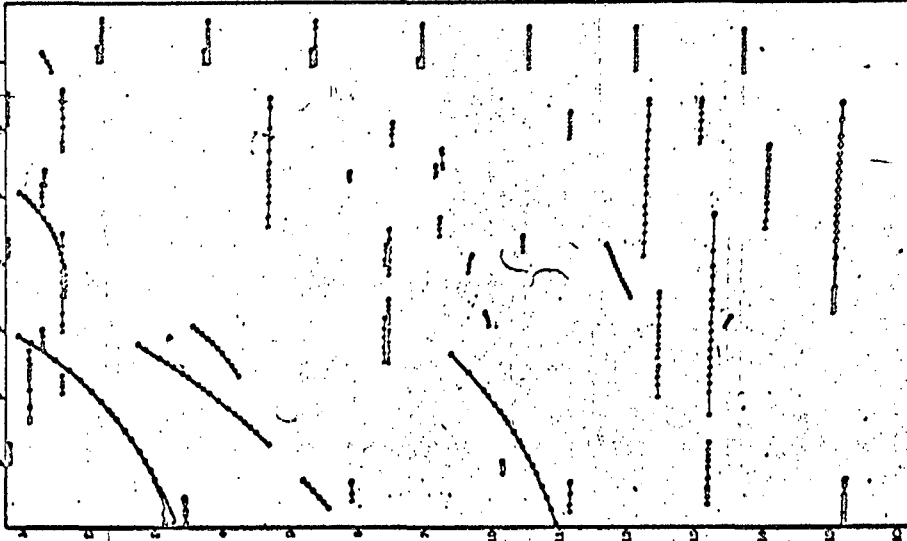


Figure 3. Results of orthogonal mode track following

Berkeley 74 inch HBC

BERKELEY 72 INCH CHAMBER

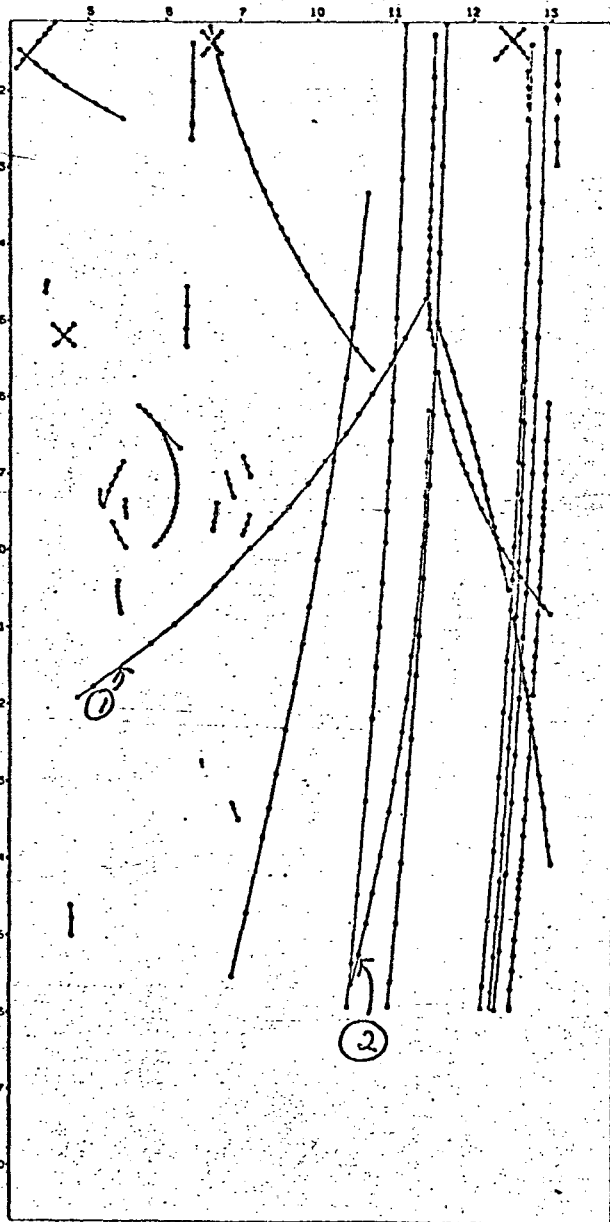
DATE 650311 EXPERIMENT 000030 ROLL 006341
 FRAME 000332 VIEW 000002 NORMAL SCAN
 PROCESSING TIME IN SECONDS
 TOTAL ELAPSED 3.08 ACTIVE FOLLOWING 1.13
 DATA COUNT
 FSD WORDS 27,551 W-POINTS 17,039
 TRACK COUNT
 TOTAL 192 BEAM 15 NON-BEAM 61
 NUMBER OF W-POINTS ON TRACKS
 TOTAL 9,236 BEAM 5,465 NON-BEAM 3,771
 AVERAGE POINT COUNT
 TOTAL 751 BEAM 221 NON-BEAM 530
 NUMBER OF W-POINTS PROCESSED PER SECOND 15,000
 RATIO OF W-POINTS TO AVERAGE POINTS 22
 NUMBER OF TRACKS WITH LESS THAN 12 HITS 116

BERKELEY 72 INCH CHAMBER

DATE 650311 EXPERIMENT 000030 ROLL 006341
 FRAME 000332 VIEW 000002 ORTHOGONAL SCAN
 PROCESSING TIME IN SECONDS
 TOTAL ELAPSED 1.39 ACTIVE FOLLOWING .56
 DATA COUNT
 FSD WORDS 13,430 W-POINTS 7,814
 TRACK COUNT
 TOTAL 214 BEAM 00 NON-BEAM 61
 NUMBER OF W-POINTS ON TRACKS
 TOTAL 2,251 BEAM , 00 NON-BEAM 2,251
 AVERAGE POINT COUNT
 TOTAL 446 BEAM 00 NON-BEAM 446
 NUMBER OF W-POINTS PROCESSED PER SECOND 13,900
 RATIO OF W-POINTS TO AVERAGE POINTS 17
 NUMBER OF TRACKS WITH LESS THAN 12 HITS 153

Figure 4. Track following diagnostics

ROLL 0107, FRAME 5423, VIEW 1, MED 000
XD = 34158, YD = 40000



ROLL 0107, FRAME 5423, VIEW 1, MED 000
XD = 34158, YD = 40000

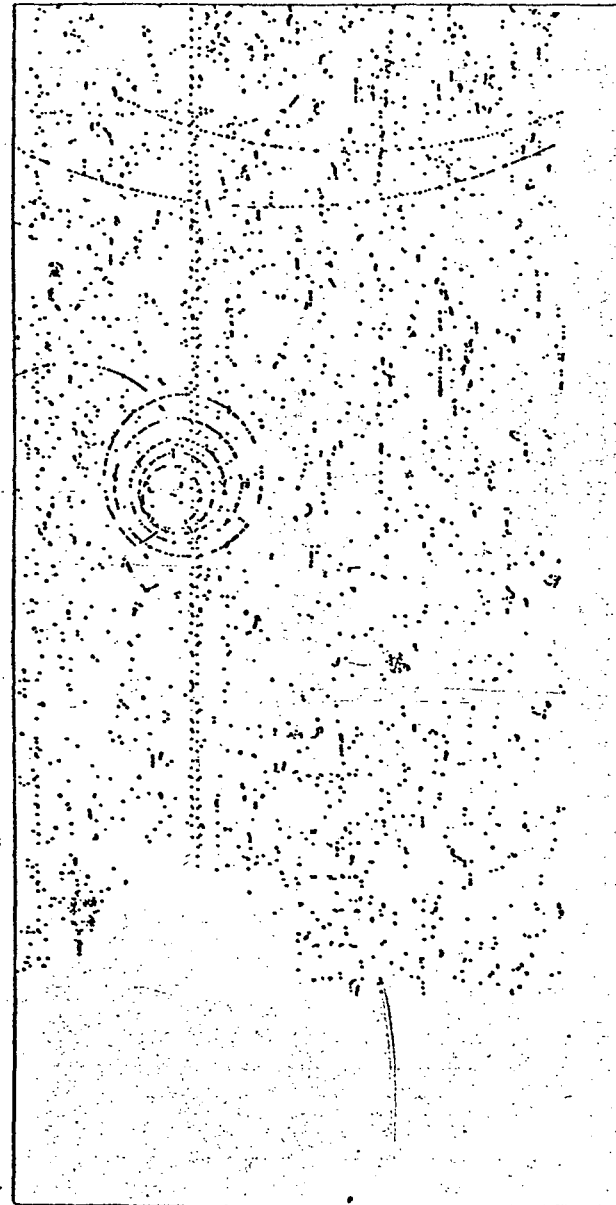


Figure 5. Results of normal mode track following

Brookhaven 30 inch HBC

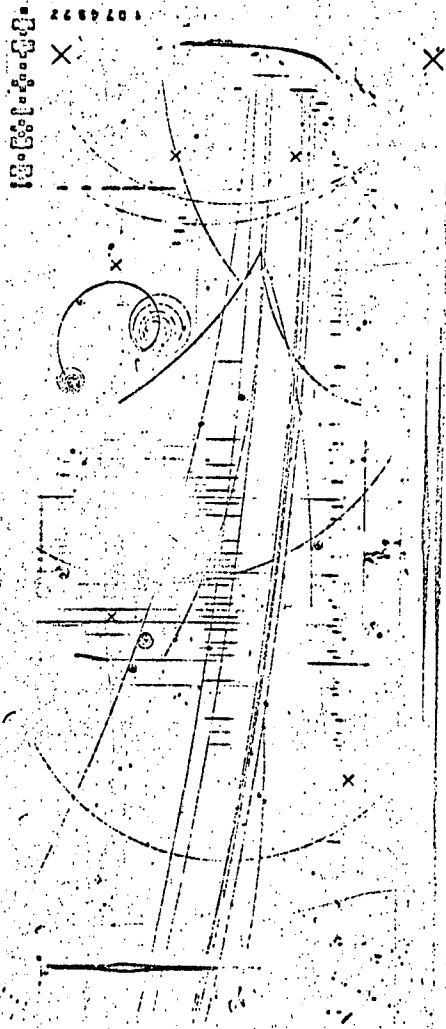
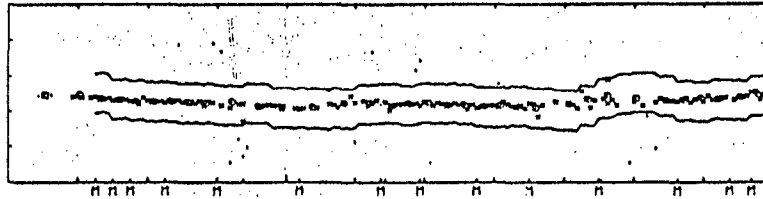


Figure 5a. Print of film from Brookhaven 80 inch
Hydrogen Bubble Chamber with 4 BEV/C K⁺ beam.

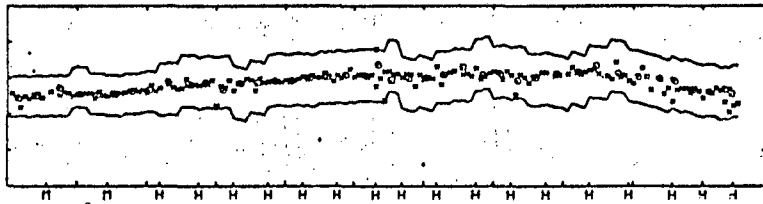
(applies to fig. 5,7,11)

TRACK 4.8,11.5 11.7, 4.8

LINEO = 444

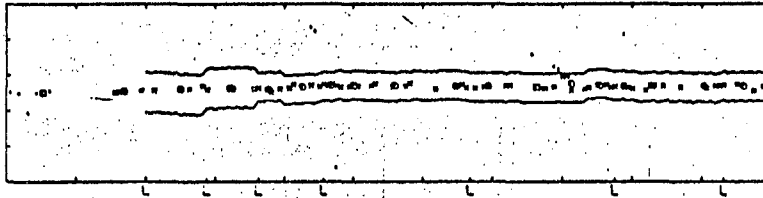


LINEO = 724

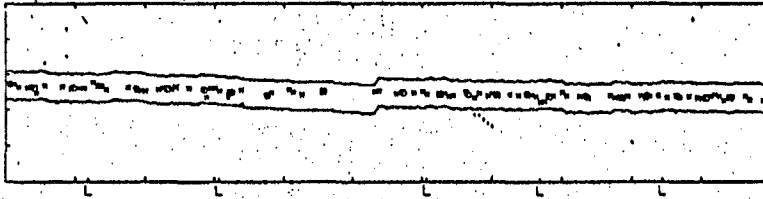


TRACK 8.1,11.5 15.8,10.5

LINEO = 002



LINEO = 1082



LINEO = 1542

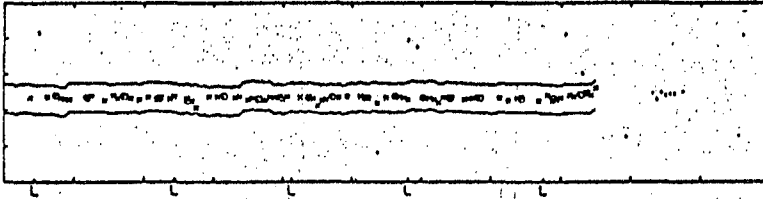


Figure 6. Detailed plot of non-beam tracks from normal mode track following

Brookhaven 80 inch HBC

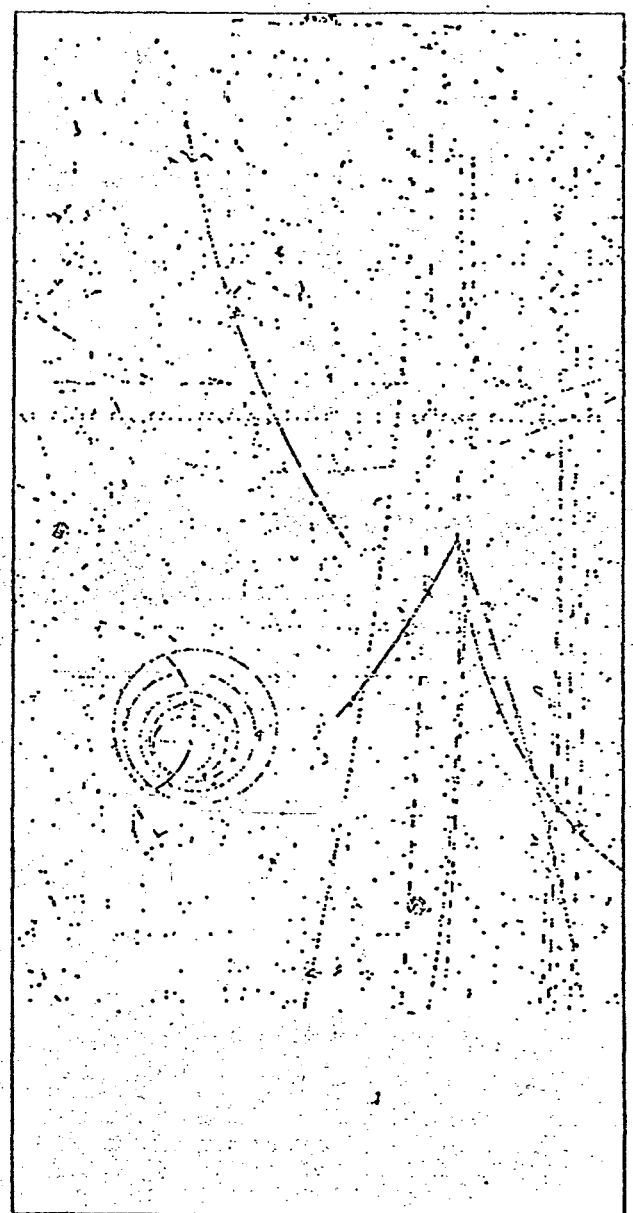
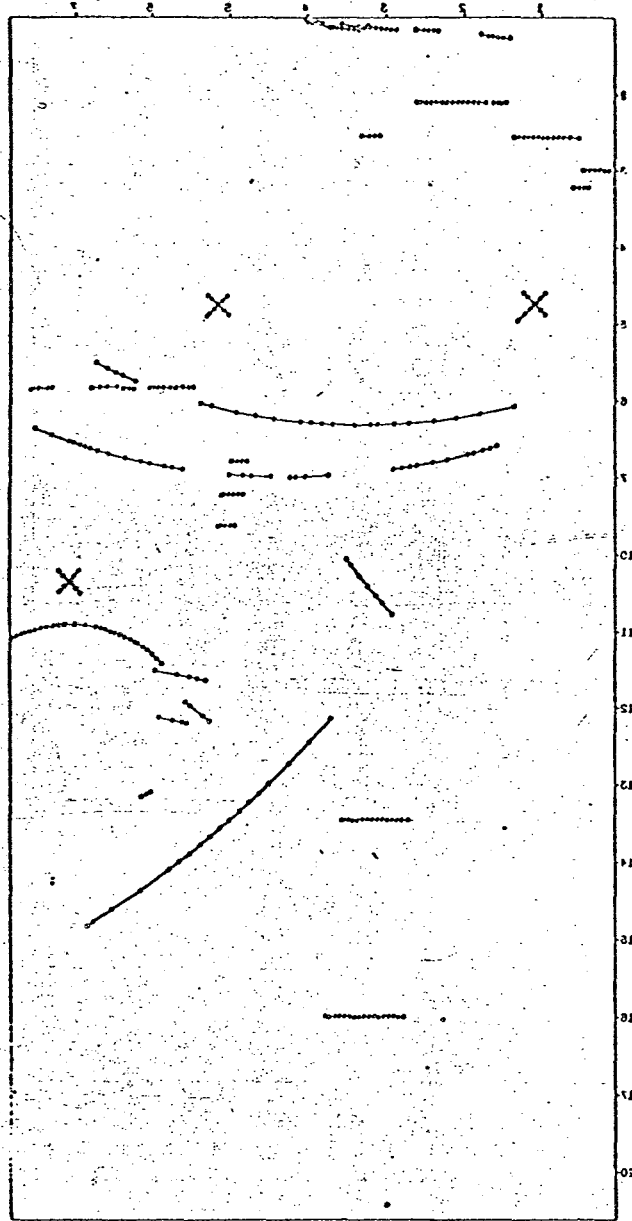


Figure 7. Results of orthogonal mode track following
 Brookhaven 80 inch HBC

010 007 11 1214 7542 3744 7010 J.09
02114 - 04 2014E - 04

POLL 0107, FRAME 8423, VIEW 1, MAG 100
X0 = 10000, Y0 = 54403

TRACK ABSTRACTION, POLL 0107, FRAME 423, VIEW 1.
X0 = 102000, Y0 = 160000.

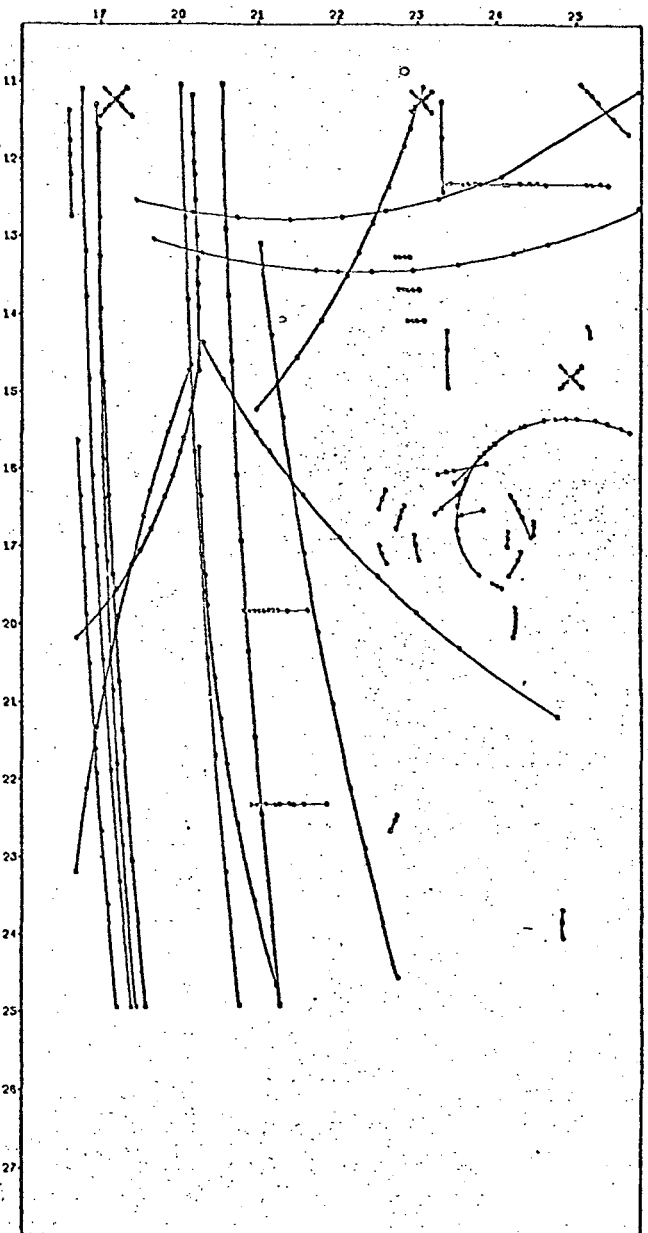
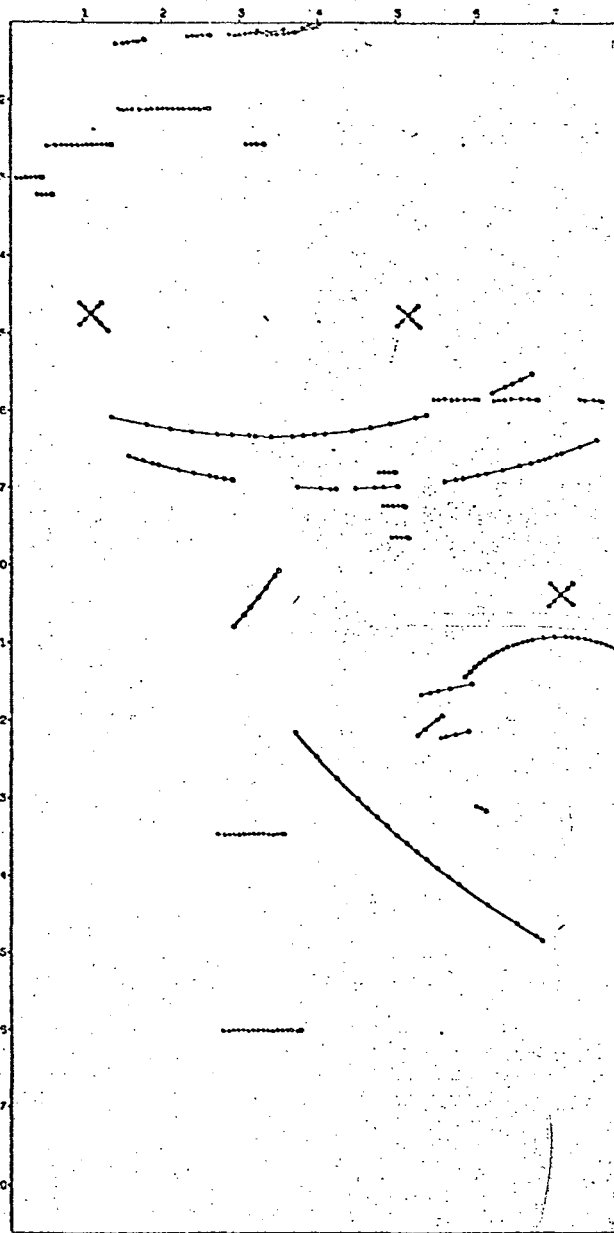
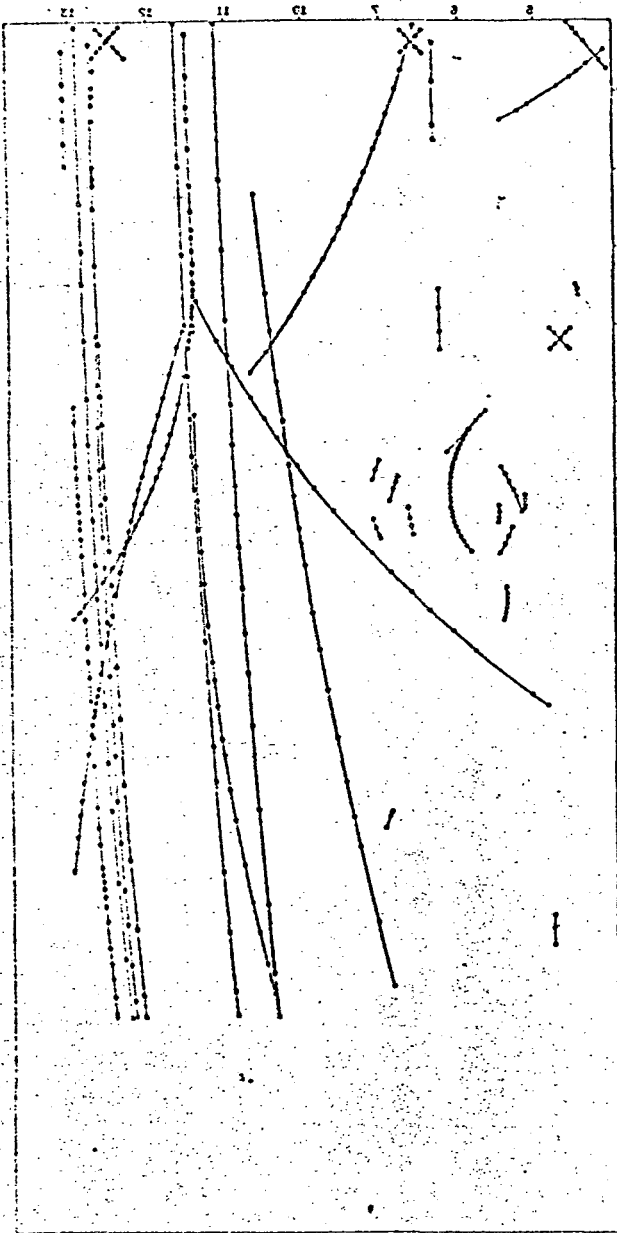
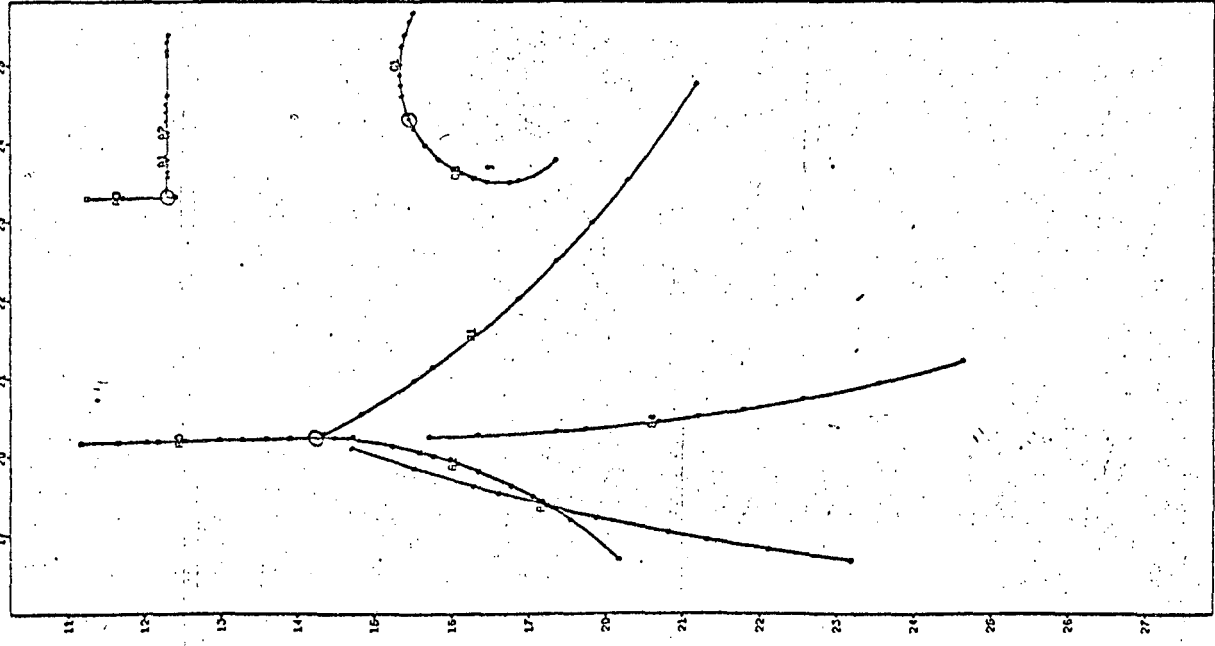


Figure 9. Results of track joining and linking

Brookhaven 30 inch HEC

VERTICES. ROL 0107, FREQ 423, VIEW 1.
10 = 107000, 10 = 180000.



BACK PROJECTION. ROL 0107, FREQ 423, VIEW 1.
10 = 107000, 10 = 180000.

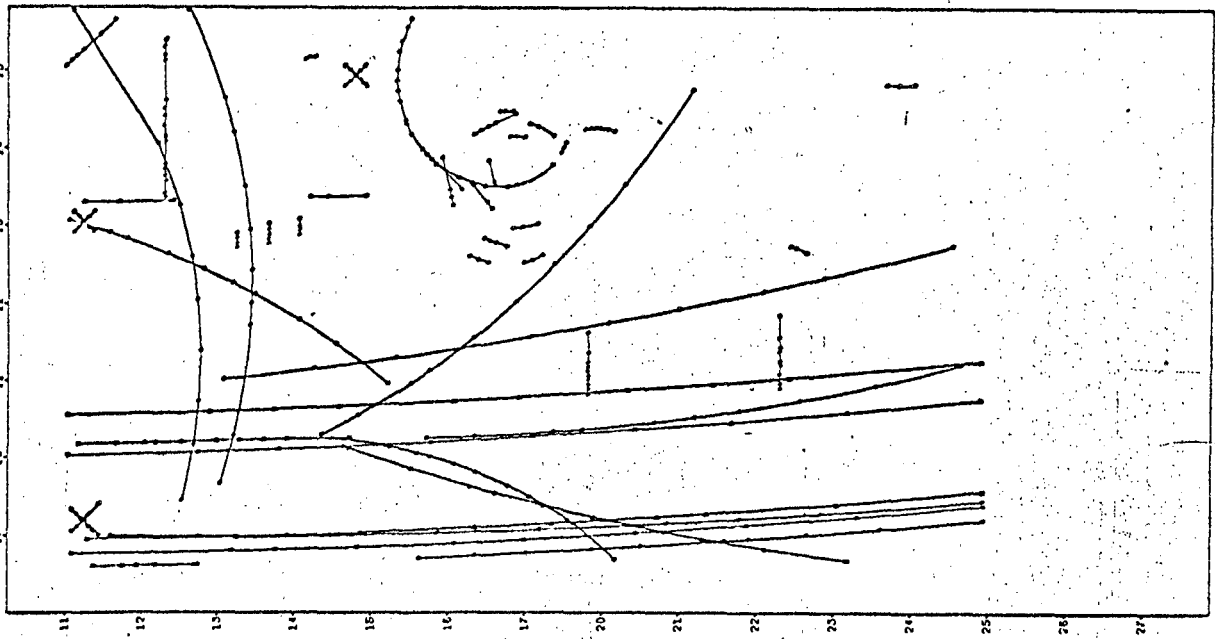


Figure 11. Results of vertex search
Brookhaven 80 inch HEC

A P P E N D I X 2

Figure 2: Results of normal mode track following (Berkeley 72" HBC).

On the left is a print of film from the Berkeley 72 inch Hydrogen bubble chamber with 3.9 BEV/C π^- beam. The other portions are Cal Comp plots showing the results of track following. In the center is a display of the average points found in all the tracks. On the right is a plot of the residue points (those points which the program found not to be on tracks).

A separate diagnostic program is used to make these Cal Comp plots. The average points on beam tracks are indicated by squares; those on non-beam tracks by circles. The lines connecting the average points are generated by the display prog. for ease in reading the output.

The horizontal scale shows W-coordinates; the tick marks are 10,000 octal microns apart. The vertical scale is the scan line count; tick marks are 100 octal scan lines apart. The scale and coordinate values on the residue plot are identical to those on the average point display.

The upper left corner of the film was somehow masked out in the printing process, so the fiducials do not show. There is a scratch on the film which was not present at the time the abstraction was made so it does not show on the Cal Comp plots.

The fiducials were followed, and can be seen in the average point display. We hope to have several such X-shaped fiducials well distributed throughout the picture in film which we process. A close examination shows that the program has found all of the tracks within the normal sweep. The residue buffer shows some track portions which will be followed in the orthogonal mode.

Figure 3: Results of orthogonal mode track following (Berkeley 72" HBC).

On the left again, is a print of the 72 inch Berkeley hydrogen chamber film. In the center is a display of the average points found during orthogonal mode track following. On the right is the residue buffer.

The horizontal scale on the track following plot has tick marks every 100 octal scan lines. The vertical scale shows the W-coordinates with tick marks 10,000 octal microns apart.

The residue buffer shows a great many tracks in the direction of the beam. Tracks in this direction are not followed in the orthogonal sweep.

Figure 4: Track following diagnostics.

This is printed output generated by the track following program for diagnostic purposes. The production program will not have output in this form, although there will most likely be some form of output for monitoring purposes.

Figure 5: Results of normal mode track following Brookhaven 80 inch HEC.

The Cal Comp plots are as those described for fig 2. In the residue buffer, vertical lines in the direction of the beam can be seen about 1/3 of the way from the left edge of the plot. These lines are scratches on the film which did not qualify as tracks.

Figure 6: Detailed plot of non-beam tracks from normal mode track following in Brookhaven 80 inch HEC.

The horizontal scale shows the line count, with tick marks every 16 scan lines. On the vertical scale are tick marks 100 octal microns apart in W.

A circle is fit to the track and all points and road edges in the graph are sheared from this circle to a straight line for easier displaying. Thus, the points should make a straight horizontal path through the center of the graph. Road edges are computed from the road center and slope of the track, and are shown by lines on the graph. Rate of change of slope are not taken into account in these plots.

Whenever the slope of the track has been recomputed, a letter indicating the magnitude of the slope is plotted just below the graph. The magnitude is represented by:

- L: slope less than 15 degrees
- M: slope between 15 and 40 degrees
- H: slope greater than 40 degrees

Points are represented as follows:

- average point that was saved
- average point that was not saved
- × actual point on track
- residue point

The first four points of the track appear as residue points because it was not possible to write them out as track points this early in track following. Similarly, the second average point and the four points associated with it do not appear at all. All other points on the track are included in the plot.

Figure 7: Results of orthogonal mode track following in Brookhaven 80" HBC.

The Cal Comp plots are as those described for Figure 3. Fiducials were followed and can be seen in the average point display. Coathangers were also followed.

Figure 8: Results of track joining and linking in Berkeley 72" HBC.

On the left is a Cal Comp plot of the track average points from the normal mode sweep (same display as middle portion of Figure 2). In the center is a display of the orthogonal mode track average points (same as middle portion of Figure 3). On the right is a Cal Comp display of the results of track joining and linking. This plot has tick marks every 10,000 octal microns apart in both the X (vertical) and Y (horizontal) coordinate axes.

Track joining in the normal mode can be seen at ①; in the orthogonal mode at ②. Linkages between normal and orthogonal modes are shown in ③, ④, ⑤, ⑥ and ⑦. In most cases, there is an overlap where a portion of the track is followed in both modes. The linking program removes this overlap section when it merges average point lists.

Figure 9: Results of track joining and linking in Brookhaven 80" HBC.

On the left is a display of the average points from the normal mode sweep; in the center is the orthogonal mode average point display. The plot on the right shows the results of track joining and linking. Both the horizontal (Y) and vertical (X) axes have tick marks every 10,000 octal microns apart.

Note the beam track on the side of the picture with the tick marks. This track was not joined due to the large gap between the segments.

Figure 10: Results of vertex search in Berkeley 72" HBC.

On the left is a print of the film from the Berkeley 72 inch HBC with 3.9 BEV/C π^- beam. In the center, is the final track avstraction: the results of track following, joining, and linking. On the right is a display of all the vertices with their associated tracks. The remainder of the tracks do not show on this plot because they are not associated with an event; however, they have not been thrown out.

On both plots, the horizontal is the Y axis; the vertical is the X axis. The tick marks are 10,000 octal microns apart on both axes. The circles on the vertex display have as their centers, the vertex point.

The letter A denotes the vertex of the two-prong event; B shows the four-prong vertex. The others are false vertices.

Figure 11: Results of vertex search in Brookhaven 80 inch HBC.

Both plots have tick marks 10,000 octal microns apart on the X (vertical) and Y (horizontal) axes.

The four-prong event was found. Close examination of this vertex will show that it is internal to the beam track. Since one of the outgoing tracks was very straight at the vertex, the track following program followed it in beam track following as a continuation of the beam track. The end of the beam track should be trimmed back to the vertex point in a subsequent phase of the system.

Part of the electron spiral was followed as two separate tracks. These segments were not linked probably due to their difference of curvature, causing a false vertex to be found. The upper right of the plot shows another false vertex. This will happen quite frequently since the search is for geometrical vertices of tracks which radiate from the same point.

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