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P. Allen, L. Barone, I. Laakso, F. Marcelja, G. Piredda, V. Rossi, G. Susinno, L. Votano and L. Zanello: A SET OF ON-LINE ROUTINES TO GUIDE PEPR IN MEASURING BUBBLE CHAMBER FILM.

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A SET OF ON-LINE ROUTINES TO GUIDE PEPR IN MEASURING BUBBLE CHAMBER FILM.

ABSTRACT.

A description is given of a set of routines which have been written for a DEC PDP 11/45 computer to guide PEPR, in the digitization of tracks of low energy particles, recorded on bubble chamber film. There is no pre-scanning. The starting points of the primary tracks are located automatically in one view. There are extensive facilities for an operator to assist the following of the tracks in difficult cases.

1. - INTRODUCTION.

In this section we give a brief description of the PEPR hardware, the computer configuration, the principal aims of the present experiments, an outline of the procedure of measuring, the facilities for operator intervention, and a summary of the philosophy of the software.

1.1. - PEPR Hardware.

PEPR (Precision Encoding and Pattern Recognition) is a Cathode Ray Tube scanning device. This has been described previously(1, 2). It is sufficient to note that PEPR is based on a 9 inch Ferranti CRT. This produces a spot of light which may be deformed into a line element of various lengths, by the use of diquadrupoles. The spot/line is imaged by an optical system and falls on a piece of film clamped in a holder (see Fig. 1). A deflection of the spot/line is produced in two steps : i) A main deflection, in which it is sent to one of $2^{16} \times 2^{16}$ addressable points on the face of the CRT. The main deflection unit (MDU) is about 2.5 μ. ii) By sweeping in either the x or y direction about the addressed point in units of an Interpolation Count (IC). This unit may be either 1.5 μ or 6 μ or 24 μ or 96 μ as selected by the user. Each scan-cell requires 64 μsec sweeping time and covers a distance of ± 64 ICs about its centre. The user may gate the scan-cell, to cover a smaller distance.

When the spot/line crosses an object on the film the light received by a photomultiplier (PM) behind the film varies in intensity. The resulting signal is divided in an analog divider by the averaged signal of four reference PMs which monitor the light output of the CRT. This circuitry is regulated to give a signal proportional to the image density. Then, a variable background (pedestal) is subtracted, using the technique of a dummy sweep with a defocussed spot(3).

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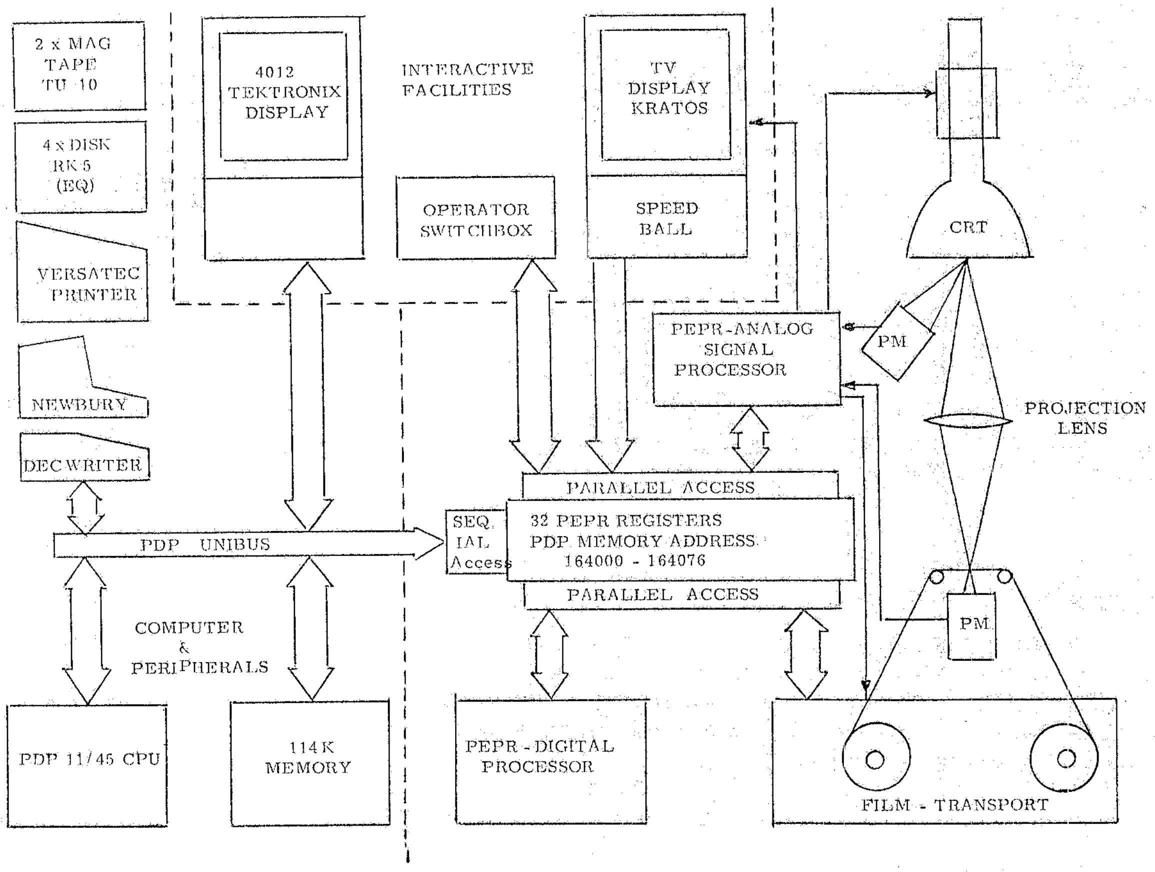


FIG. 1 - Schematic diagram of PEPR, the PDP 11/45 and Peripherals.

The digital sampling is performed at 128 points along the sweep, and is stored into a 128 x 8 bit random access memory. During the following measurement sweep in the same scan-cell, the pedestal values are reconverted to analog form and subtracted from the signal. Finally the difference signal is converted to digital form, for treatment by the Signal Processor. Here we use a pre-set digital threshold, with a fixed hysteresis to determine the centre and width of the hit. The hardware is also able to find the peak value of the signal. The threshold logic tests that the width (at threshold) of the signal is within a given limit, and is completely contained within the gates. We record the number of accepted hits in the cell, and for each of these, the centre, the width, the angle at which it was obtained, and the peak value of the signal.

1. 2. - Computer configuration.

The Computer has a CPU of 16 general purpose, 16-bit registers, as well as 6 additional 64-bit floating point registers. The memory (core) has 114K, 16-bit locations. The peripherals are:

- 4 Moving Head Disk Units, each of capacity 2. 2 MBytes. Two are DEC RK 05, and two are Plessey PM-DD 11/B ;
- 2 Magnetic Tape Units (DEC TU 10, 9 Track, 800 bpi) ;
- 1 Versatec Electrostatic Printer Plotter (M-1100 A) ;
- 1 Teletype ;
- 1 Tektronix 4012 Display (graphics or terminal) ;
- 1 Newbury alpha numeric display (Model 7002).

The computer 'sees' PEPR as a Digital Controller of 32, 16-bit registers. Each of these has an address in the computer's "external page", and may be read or written, almost as if they were locations of the memory. Physically the connection is made by means of an M 1710 Unibus Interface Foundation Module.

1. 3. - Aims of the Experiment.

The film being measured in this experiment is of $\bar{p}p$ interactions in the CERN 2 metre HBC. The bubble chamber groups of Frascati, Padova, Rome and Trieste are collaborating in a high statistics study of $\bar{p}p$ interactions at low energy. We want to obtain the total, elastic, and topological cross sections, with resolution in energy of about 2 MeV, in the region of the S-Meson ($M = 1935$ MeV, $\Gamma \simeq 9$ MeV). We plan to determine the mass, width, cross section, and decay modes of this object. Later, it is hoped to determine its isotopic spin, from a similar exposure which we have made in deuterium$^{(4)}$. The anti-protons enter the visible volume of the chamber with momentum $p = 600$ MeV/c, and a residual range of 157 cms, all of which is visible. The momentum spread is ± 5 MeV/c (HWHM). The basic idea of the experiment is that the momentum of each interacting particle is known from the position of the vertex, with an error much smaller than that which would be obtained from measuring the curvature ($\pm$ 40 MeV/c). We have about 1.6 million anti-proton tracks.

1. 4. - Process of Measuring ; Operator Interaction.

There is no pre-scanning or measurement. Two views, 1 and 3, are measured, separately. We locate the antiprotons by making a search near the entrance of the chamber, and follow the track till it exits or comes to a vertex. We define a true vertex as an inelastic interaction of 0, 2, 4, 6 or 8 prongs, or an elastic scatter with a recoil proton longer than 300 μ (on film) or a backward elastic scatter (secondary $\bar{p}$ not visible). In addition we recognize a kink topology as an event in which the recoiling proton is shorter than 300 μ. The operator must intervene in order to measure the coordinates of the vertex or kink, record the topology, and initiate the measurement of secondary tracks (elastic events only) or the segment after a kink. In View 3 the operator sees a TV image in the region of the vertex whose approximate coordinates are known by transformation from View 1. The measurement of the anti-proton track is initiated manually at this point. The facilities available to the operator are (see area enclosed by dashed lines, Fig. 1) :

a) A TV display of the film : The operator may choose to view an area of film 10×10 mm^2 or 0.6×0.6 mm^2. Also available is an asymmetric (1 : 4) display of either 5×20 mm^2 or 0.3×1.2 mm^2.

b) A Speed Ball : This enables the operator to view any part of the frame on the TV. The motion of the speed ball directly modifies two of the PEPR registers allowing manual measurements to be made.

c) A set of 16 buttons, with which the operator may give commands to the program, or record his choices. These buttons are arranged around the borders of the graphic display. During any interaction of the operator, a certain number of them are enabled. A label for each validated button appears on the display.

d) The Graphics Display. This presents a display of a trajectory through the points which have been measured. The blinker indicates the current position of the TV image.

The method of measurement is heavily dependent on operator interaction, which accounts for 70-80 per cent of the total time. Thus the speed and attentiveness of the operator are, essentially, the rate determining factors.

1. 5. - Philosophy of Software.

An overall block diagram for the programs which guide the measurement is shown in Fig. 2. There are five stages in this process, which will be described in following sections in order of decreasing generality. In Section 2 we discuss the overall control, with initialization and finalization. In Section 3 we describe the routines which concern the entire frame, that is the measurement of the data box and fiducials, and the beam search. In Section 4 we discuss the overall event strategy. Section 5 is devoted to those routines which control the following of a given track. In Section 6 we describe the basic data acquisitive routines, which measure the coordinates of a given point.

The programs have been written with a view to separating as far as possible the parts which are experiment dependent (e. g. the event strategy) from those which can be used with little change in future work (e. g. the data acquisitive routines). The routines described in this note constitute one task which runs in parallel with two tasks which service interrupts, and one which writes the final output. We make efficient use of the multi-task facilities of the RSX 11-D Operating System, leaving nearly 70% of the CPU time for other tasks.

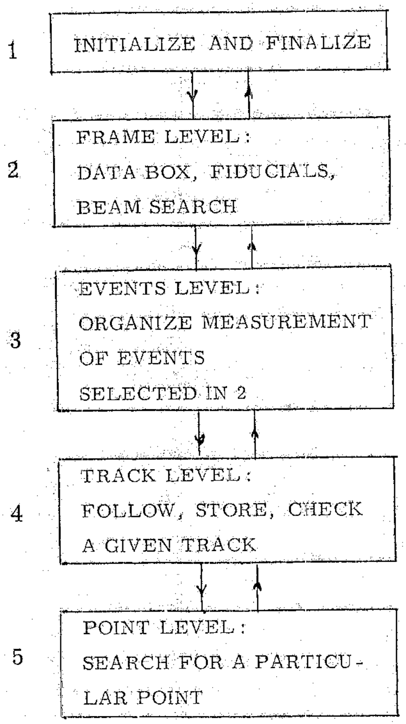


FIG. 2 - Block Diagram for the set of programs.

2. - OVERALL CONTROL, INITIALIZATION AND FINALIZATION.

The Main Program immediately calls Subroutine INITR to perform a number of operations which are required only once in each measuring session.

Subroutine INITR initiates the graphics routines, and reads from a disk file made at the end of the previous session, the roll, frame, and view numbers of the last measured event. If the operator does not want to continue immediately from this point, he types in other starting values. Another disk file is opened to read in a set of forty two calibration coefficients which are needed to make a fifth order transformation between the distorted space of PEPR measurements (A, B in units of MDU) and real film space (x, y)

$$x = C_1 + C_2A + C_3B + C_4A^2 + C_5AB + C_6B^2 + \cdots + C_{21}A^5 ,$$

$$y = D_1 + D_2A + D_3B + D_4A^2 + D_5AB + D_6B^2 + \cdots + D_{21}A^5 .$$

A similar set of forty two coefficients to perform the reverse transformation (x, y) to (A, B) is also read in. These values have been obtained by fitting the measurements of a diamond grid (168 points), using standard polynomial fitting techniques(2).

If we are in View 1, the operator is asked if he wants to update the existing output data file. He may elect, instead, to open a new one. We read in a map (in film space) of the positions of the fiducials for the current view, and also the position of the film, at which the map was made.

Upon return from INITR, we call Subroutine LOG to record the starting time and frame number. The operator then identifies himself to the program. The film positioning routine FLM is then called. This may move the film backwards or forwards by an integral number of frames, by counting the passage of the Brenner marks. It may also move the film, within a frame, in steps of about 100 μ. It reports how many frames it has moved and the stopping position beyond the current Brenner mark.

We then call Subroutine DATBX (Sect. 3.1) to read the roll and frame number, which are displayed to the operator. If these are incorrect he must dismount the film or command the film transport to move to the desired frame.

Next, we call Subroutine FIDS to locate and measure a minimum of five fiducials, which must include a certain "prime fiducial" (Sect. 3.2). If there is an error return, the operator is given the choice to retry the measurement, or skip to the next frame.

We now pass to the selection of primary anti-protons. In View 1, we call Subroutine FNDBM to search for tracks of about twice minimum ionization, near the entrance to the chamber (Sect. 3.5). There is a relatively heavy background of minimum ionizing pions and muons, which we try to filter out by considerations of pulse height angle and position. If no primary anti-protons are found we skip to the next frame. Likewise if more than five primaries are found, the frame is skipped in order to avoid probable difficulty in following close and crossing tracks. In View 3 we transform the coordinates of each vertex as measured in View 1 (Sect. 3.6).

We then pass the coordinates of the starting points (View 1) or the vertices (View 3) to the Subroutine EVENTS (Section 4) which organizes the measurement of each primary, with its associate kinks, vertices, and secondary tracks. This routine in turn calls the track level routines, to follow individual tracks, with some operator intervention (Sect. 5). The Track Follower (TKF) calls the ultimate point level routine MSCAN to find the individual points (Sect. 6. 3).

Upon return from the events and lower levels the program may read the data box, and remeasure the frame beginning from the fiducial measurement, if the operator has requested. If we are in View 1, an output record is written on the open disk file. This consists of the labels and coordinates of the fiducials; the topologies of the tracks, and the coordinates of the vertices and track points. In View 3, the current output record is merged with the corresponding record from the disk file of View 1, and written on tape for off-line use. We then repeat the process for each succeeding frame, except that we only read the data box once every fifty frames. At the end of the session the operator signals to the program to go to Entry FINER of Subroutine INITR to write on a disk file the roll frame and view numbers of the last measured frame, and to call LOG to calculate and print the number of frames, events and tracks measured, and their hourly rate.

3. - FRAME LEVEL.

In this section we describe the routines which concern the frame as whole, without reference to individual events. These routines are those which read the data box, measure the fiducials, and search for beam tracks.

3. 1. - Reading of the Data Box (Subroutine DATBX).

The Data Box comprises two rows of encoded numbers. Row 1, nearer the Brenner Mark, shows the frame number and the expansion, while Row 2 displays the roll number and view. The numbers are represented in natural BCD form, and each digit is followed by a check number, which is either its complement or its equal. In this way each number is represented by a unique combination of four on bits and four off bits as described in Ref.(5).

Firstly we locate one of the data box fiducials, in a manner analogous to that of finding the prime fiducial (Sect. 3. 2). Then, the data search routine MSCAN (Sect. 6. 3), looks for each bit in turn of the roll and frame numbers, or of the frame only. The search is made in Stop Mode, scanning in 10 steps of 0. 7° from a base angle of 0°, with an open scan-cell, 770 μ in size. Each bit (no bit) corresponds to a bit set (not set) in a 32 bit integer word. Each byte (8 bits) of this word is checked against the representation of the various digits. The number can still be recognized if its bit pattern differs by only one bit from the correct form.

3. 2. - Fiducial Search (Subroutine FIDS and Associates).

We enter the search with a map in (x, y) space on film of the centres of eight chamber based fiducials. The first of these (25) is designated the "prime fiducial" which must be found on each frame, and for which an extended search will be made if necessary.

In Subroutine ALLFID we begin looping over the eight fiducials (Fig. 3). The map position of the first is translated by the difference in x between the stopping position of the film, and that at which the map was made, and then transformed into PEPR's coordinate system. We set up a scan-cell at the expected position (Subroutine FDSER) inclined at the angle of the first arm of the fiducial (45°), using an empirical threshold. We call the data acquisition routine MSCAN (Sect. 6. 3), operating in Stop Mode, and a scan-cell of size 770 μ(IC = 6 μ) employing the 1 mm line element, to search for a point on the arm. As needed we set up a maximum of 25 scan-cells. The base angle is 45° with up to 4 steps of 0. 7°. The first scan-cell is at the expected position of the fiducial. The centres of the others are shifted in A(x) in units of ± 50 MDU (125 μ), keeping B(y) fixed, and then varying B(y) in units of ± 50 MDU about the expected position. We commence the search for a point on the second arm in like manner, beginning in the scan-cell in which the first arm was found. The base orientation of the scan-cells is now 135° (Fig. 4a).

Then, we obtain our first value for the centre of the cross, knowing the coordinates of one point on each arm, and the inclination of the arms. This should be within 120 MDU (300 μ) in both

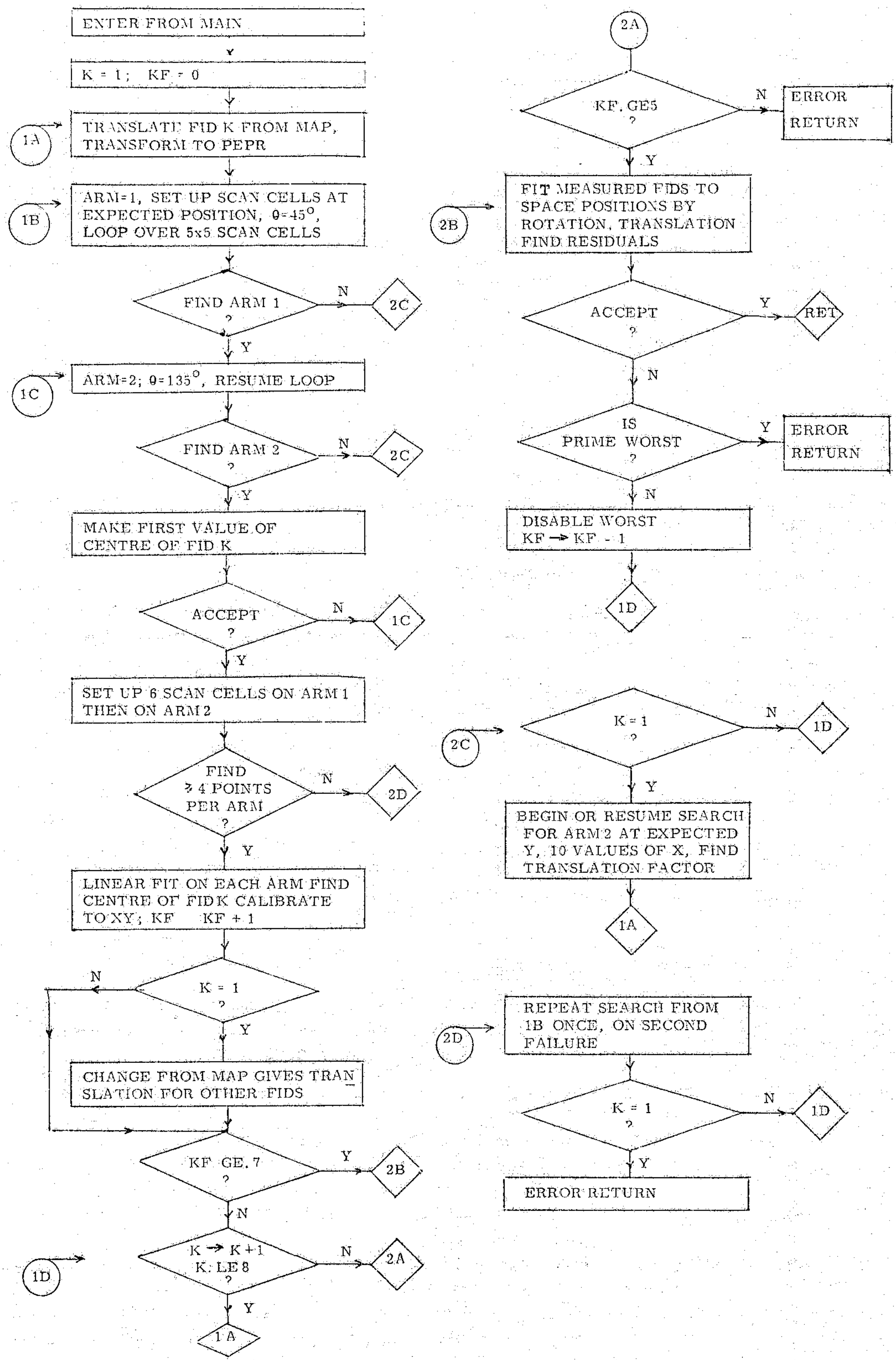


FIG. 3 - Flow chart for fiducial search (Subroutine FIDS and associates).

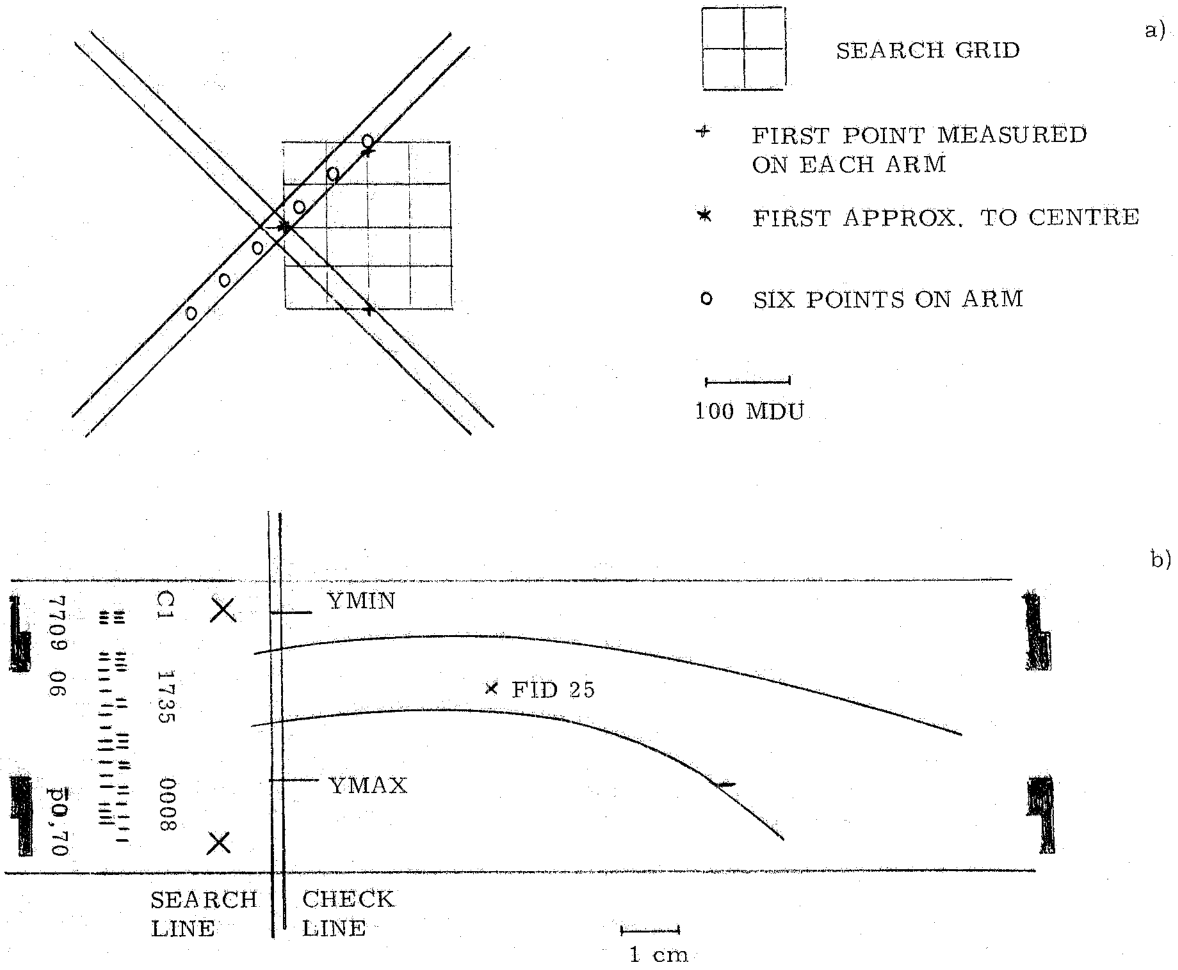


FIG. 4 - a) Fiducial searching and measuring strategy; b) Geometry of beam search.

coordinates of the expected value. We now attempt to improve this measurement. We set up a scan-cell (Subroutine ONEFID) along the first arm 140 MDU (350 μ) distant from the center of the cross and search for a point. Then the scan-cell is moved along the arm in five steps of 60 MDU (150 μ), to search for three points on either side of the centre of the cross, and the process is repeated for the second arm. We require to find at least four points on each arm in this search. We make a linear least squares fit to the coordinates of the points of each arm, and thus derive a second value for the centre of the cross. The difference between the found and expected values of the coordinates of the first fiducial are used as translation factors for the other fiducials. These are searched for in an analogous manner, each with its own threshold. The search is concluded when we find a total of seven, or when the map is exhausted.

3. 3. - Difficulties in the search for Individual Fiducials

1) Failure to find either arm in one of the 25 scan cells. If this happens with the prime fiducial an extended search is made in the A(x) direction as this is the coordinate most effected by variations in the positioning of the film. We make the search at the expected position in y and in five steps of ± 100 MDU (250 μ) in A(x) about the expected position. When we find a hit, its coordinates are used to recalculate the map translation factors, and the normal search process is begun again. In the event of continued failure we resume the extended search from the point from which it was discontinued, or finally make an error return. If this trouble arises in the search for any fiducial other than the prime, we simply pass to the next fiducial.

2) If the first value for the centre of the cross fails the tolerance test, we resume the search for the second arm from the point from which it was discontinued. When all 25 scan cells have been exhausted we treat the case as 1).

3) If we fail to find four points on either arm we repeat the search for the fiducial. If this problem recurs on the prime fiducial, we make an error return; otherwise we skip to the next fiducial

3.4. - Fitting of the Fiducial Set.

Having found the required minimum set of five fiducials we call Subroutine CKFID, to check the measured fiducials against their positions as seen from the cameras. We obtain a least squares fit for the rotation and translation and apply these to the measured set. If the residual of the worst fiducial is greater than 75 μ we disable the worst fiducial. If we have less than the required minimum number we search for any fiducials which remain in the map and refit. We make an error return if we do not have the required minimum, or if the prime fiducial has been rejected.

3.5. - Beam Search in View 1.

In Subroutine FNDBM we define a search line 3.7 cms (on film) up stream of the prime fiducial (Fig. 4b). This corresponds to $x \approx -75$ cms, in the standard 2 m HBC coordinate system. We place upper and lower limits on the search line of 1.65 cms and -1.2 cms on film with respect to the prime fiducial. We set up a series of ungated scan cells (Fig. 5) of size 770 μ (IC = 6 μ) using the 1 mm line element. The base angle is 2°, and this is augmented in 18 steps of 0.7° up to a maximum of 14.7°. We set a threshold which in principle allows a reasonable discrimination between the antiprotons and the copious background of minimum ionizing tracks. The area search routine, SCAN is called to explore the cell (Sect. 6.2). This routine may return for up to four accepted hits, the A (x) and B (y) coordinates and an angle. We then increment the B (y) coordinate of the scan cell by 280 MDU (700 μ) and repeat the search until the upper limit in B (y) has been reached. We compare the first hit of each cell with the last hit of the previous cell, and reject it if it is within 20 MDU (50 μ) in B (y).

Each hit is checked against the previous hit and both are rejected if they are within 150 MDU (375 μ) of one another as close tracks are difficult to follow. When the search has been completed we call Subroutine DID to perform a pulse height analysis (Sect. 3.7). This sets up a scan cell at each of the accepted hits, and orientes it through the range of angles mentioned above. It returns the maximum value of the pulse height, and the angle at which this was observed. Empirical cuts are made on the pulse height between the antiprotons and the background. We now repeat the calls to SCAN at a check line 800 MDU (2 mms) downstream of the scan line, using the initial threshold. The accepted track elements at the scan line are extrapolated to the check line, and compared with the hits accepted there. They are paired off and finally accepted if they are within 50 MDU (125 μ) of each other. The output from the routine gives the number of useful hits, i.e. those which satisfy the empirical cuts on the pulse height at the scan line, and which are observed again at the check line, in both cases free from close neighbours. For each useful element we have A(x) and B(y) coordinates at the scan line, the angle at which it gives the clearest signal, and the threshold. The routine gives a selection of candidate antiproton primaries, with a minimum of about 30 mms (in space) of track length. The operator will have the opportunity to reject any background tracks which filter through.

3.6. - View Association.

A reliable view association could not be made by repeating the beam search in View 3. Instead, during the measurement of each event of View 1 an entry is made in a guidance file written on disk (Sect. 4.3). For each vertex we record its calibrated coordinate with respect to the prime fiducial, the inclination of the tracks, and its topology. (We do not use kinks for the purpose, as they are not always clearly visible in both views). In View 3, the beam search is substituted by the reading of the guidance file. The coordinates are transformed to View 3, using the method of corresponding triangles. The uncertainty in the resulting x coordinate is about 100 μ, while that in y is about 2000 μ, due to the spread in depth of the vertices.

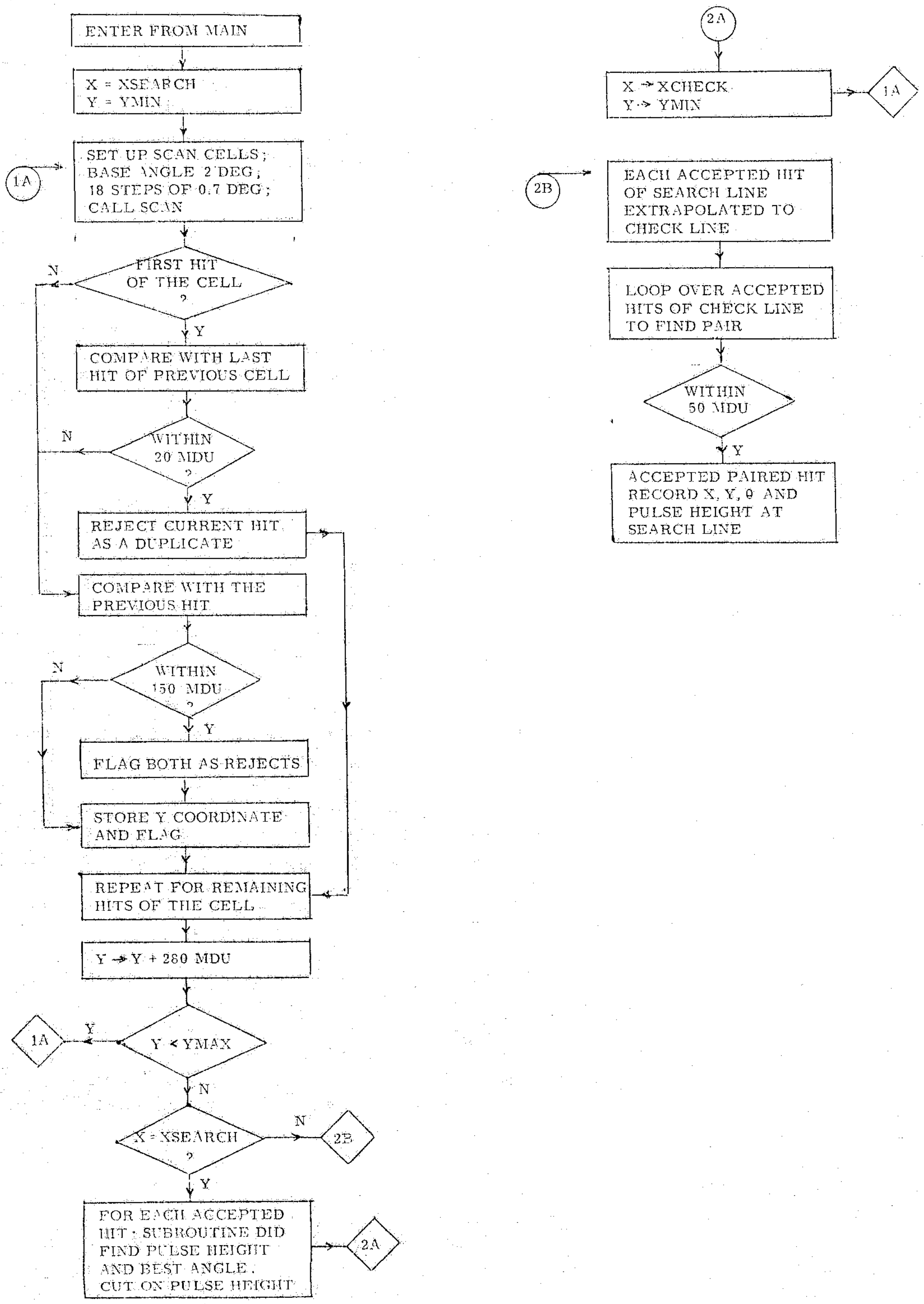


FIG. 5 - Flow chart for beam search (Subroutine FNDBM).

3.7. - Pulse Height and Threshold Analysis.

Subroutine DID, may be called to find the best threshold at which to begin following a track, or subsequently to change this threshold in case of difficulty in the following. The calling program specifies the coordinates of the centre of each sweep, and the orientations of the scan cells. We set narrow gates $\pm$ 20 IC ($\pm$ 120 μ). The hardware cycle begins at a very high threshold, which is decremented in small steps. The cycle ends when a signal is observed. This appearing threshold is essentially the pulse height. The process is repeated at each of the indicated angles, starting from the same initial threshold. We obtain the highest appearing threshold, corresponding to the clearest signal, and note the angle at which it was obtained. The working threshold for the track is set at 15% below the peak.

4. - EVENTS LEVEL.

We enter this level knowing which primary tracks of the frame have been admitted to our sample. We must organize the measurement of the primary tracks, and their associated kinks, vertices and secondary tracks. We will describe separately the event strategies used in Views 1 and 3.

4.1. - Event Strategy for View 1.

We have already obtained in FNDBM, the coordinates and inclination of the selected primary tracks at the search line. We have no information on the behaviour of any of these tracks, nor do we know what happens at their end points. We loop over each primary in turn (Fig. 6) and pass it to the next level of the process, the track level which follows it until it exits, or comes to a vertex or kink. The operator manually measures the vertex or kink and gives the topology. We then pass the track to SAVCHK and KINK where it is calibrated and placed in the output bank and post-mortem kink detection performed. If the track left the chamber, or ended in an inelastic interaction, we pass immediately to the next primary. If a kink has been detected by the Track Follower (TKF), the TV lights up at the point of the kink, and the operator is presented with a display of what has been measured so far of this primary. A message on the display reminds him to "measure after the kink". He manually measures the coordinates of one point just beyond the kink, and we derive the inclination of the segment from these coordinates and those of the kink. Thus we have the necessary input to begin the automatic measurement of this new segment of the primary in TKF where it is followed until it comes to its main vertex or a kink, or leaves the chamber. The track segment is stored and checked as above. If an elastic scatter has been found, the operator sees a TV display centered on the vertex, and a graphics display of what has been measured so far. He is presented with the message "measure the antiproton". He does this as in the "after kink" case. The track is stored in SAVCHK, but no kink detection is attempted. We check that the sign of the curvature is negative. If it is not, we delete the track and begin it again. We pass to the measurement of the recoil proton with the message "measure the proton". Upon return from SAVCHK we check to see that the curvature is positive. If not, we delete the track and begin it again. The measurement of the back-scatter is performed in like manner, except that there is only one secondary, the proton, to be measured. We may add that at the point of initiating the measurement of the secondary track, the operator may measure it manually and give the topology, without going through procedure of the track level routines. This possibility is particularly useful in the case of recoil protons, many of which require the measurement of only two points.

4.2. - Event Strategy for View 3.

We enter the events level, knowing the approximate coordinates of the vertices and the inclination of the tracks as obtained by transformation from View 1. The errors on the transformation are far too large to permit an automatic start on the track (Sect. 3.6). The operator is presented with a TV display of the predicted region of the vertex. On the graphics unit, he sees a display of the positions of all vertices of the frame. Those events which have been measured already, are marked by a + sign. The event which he is about to measure is signalled by the graphics blinker, and the remaining events are indicated with an asterisk. The topologies obtained in View 1, are displayed beside the vertex positions. The object of this display is to help the operator locate the correct vertex with the TV and speed ball. He measures the vertex and topology. He is called upon to confirm or correct his choice if there is a discrepancy of more then 140 MDU

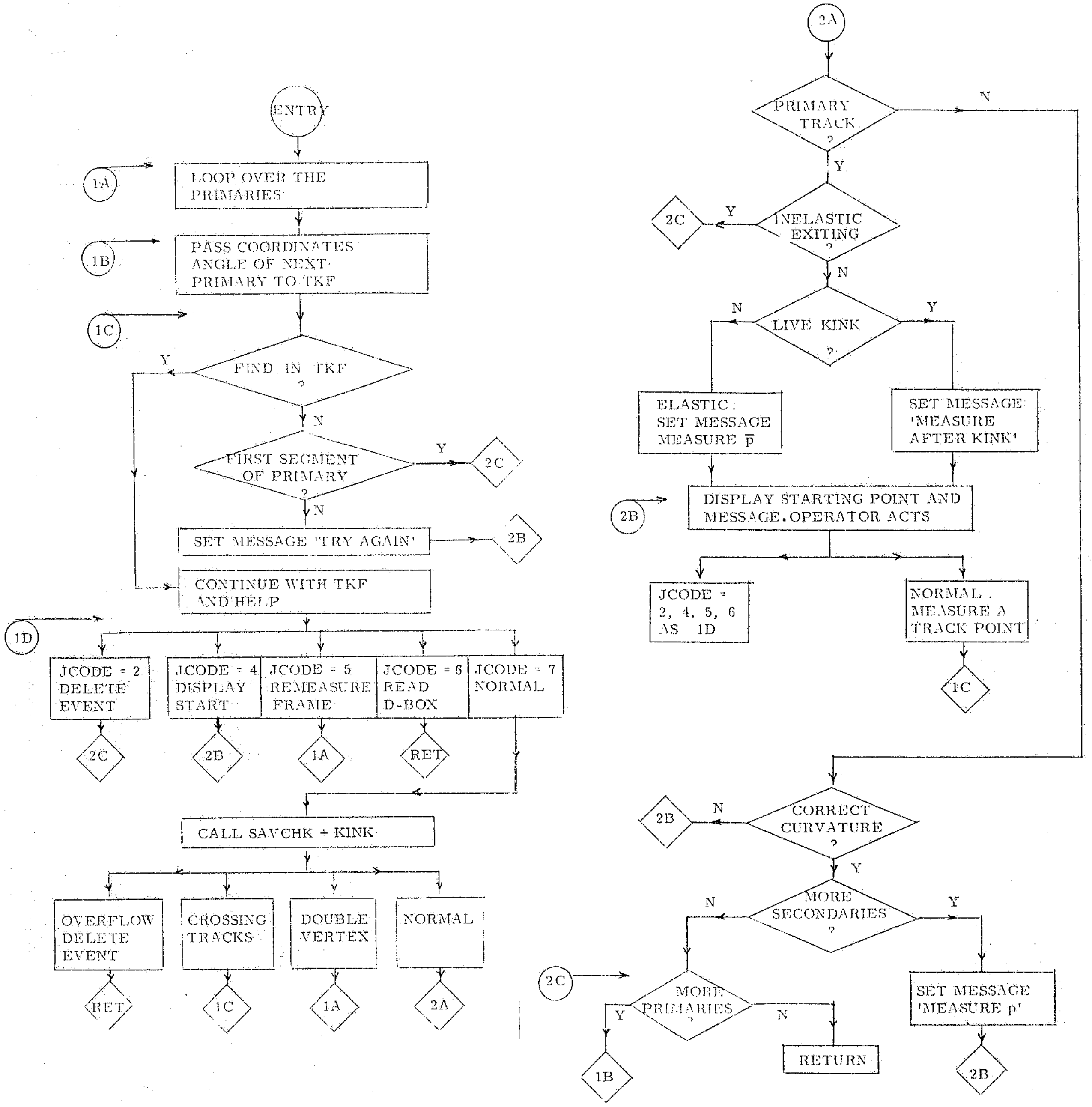


FIG. 6 - Flow chart for event strategy in View 1 (Subroutine EVENTS).

(350 μ) between the predicted and measured A(x) coordinates. We calculate the coordinates of a point, 250 MDU (625 μ) back along the track, and go to track level to have it followed backwards. The track is stored and checked as in the case of View 1. If any live kinks are detected, the operator measures the point of the kink, and restarts the next segment manually as in the case of the other view. The following of the various segments proceeds until the track reaches at least as far as a set limit in A (x). The process of measuring the secondaries emanating from the main vertex is then commenced, as in the case of View 1.

4. 3. - Error Conditions at Events Level.

There are numerous error conditions which may be detected and corrected. We have to consider failure (at track level) to find the given starting point. In the case of a primary of View 1, this failure is extremely rare, as the point has already been found in FNDBM; we pass to the next primary. In other cases, the segment after a kink, a secondary track, or a primary of View 3, this error is slightly more probable, as the relevant point has been found manually. Here, we make a display of the starting point of the track, with the message "try again". As before, we measure a starting point, and we go to track level again.

More generally, the operator has the possibility of signalling certain error conditions, when he is about to initiate a track. We must also take account of errors more serious than those related to finding the next point on a particular track, which have been seen at track level. The signals are: i) Cancel Event (JCODE = 2). All tracks of the current event are deleted. If we are in View 1 we pass to the next primary; if we are in View 3 a one point track is stored. This situation would arise for example if the operator sees that the primary is not really a beam track. ii) Re-examine the current track (JCODE = 4). The operator sees a TV display of the starting point of the track. He may reinitialize it, or start another track. This facility could be used for example if the operator finds he has just measured the wrong secondary. iii) Rescan the frame (JCODE = 5). The operator would give this error in the case of a confused picture, or if he had measured several wrong events. iv) Read the Data Box (JCODE = 6). We return to frame level to have the data box read.

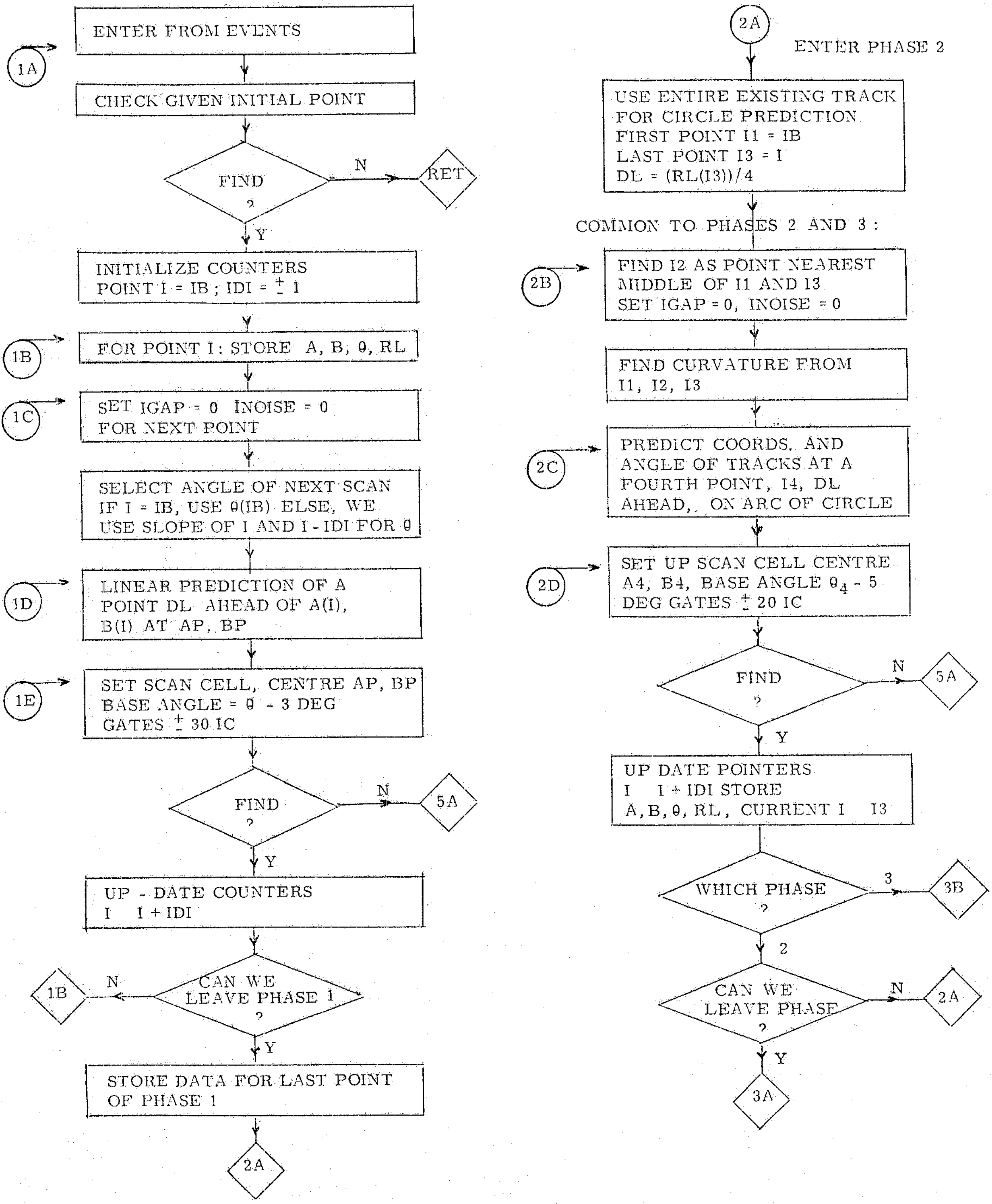
Finally, there are some errors in the storage and checking of tracks which must be dealt with. v) There are too many track segments and/or too many coordinate pairs. All tracks of the event on which the overflow occurred are deleted. The remaining events are skipped and we pass to the next frame. vi) An error has been detected during the post-mortem checking. The track is remeasured and the operator warned to examine it with care. vii) A suspected duplication of an event has been seen. Here we remeasure the frame.

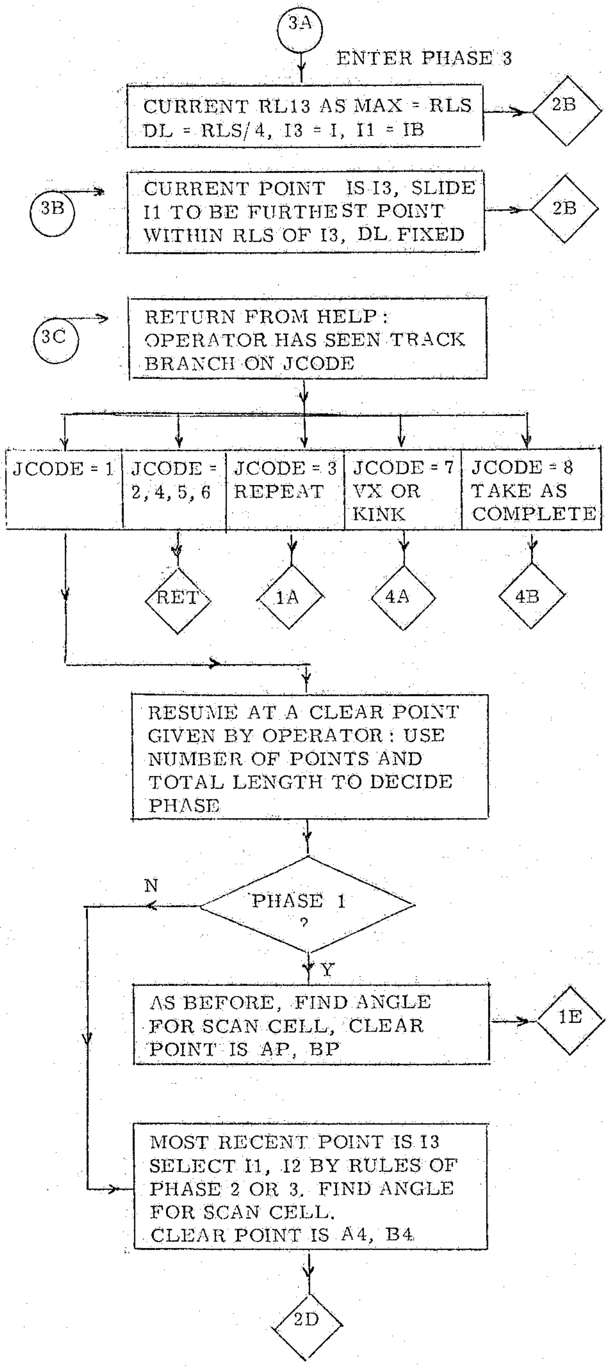
5. - TRACK LEVEL.

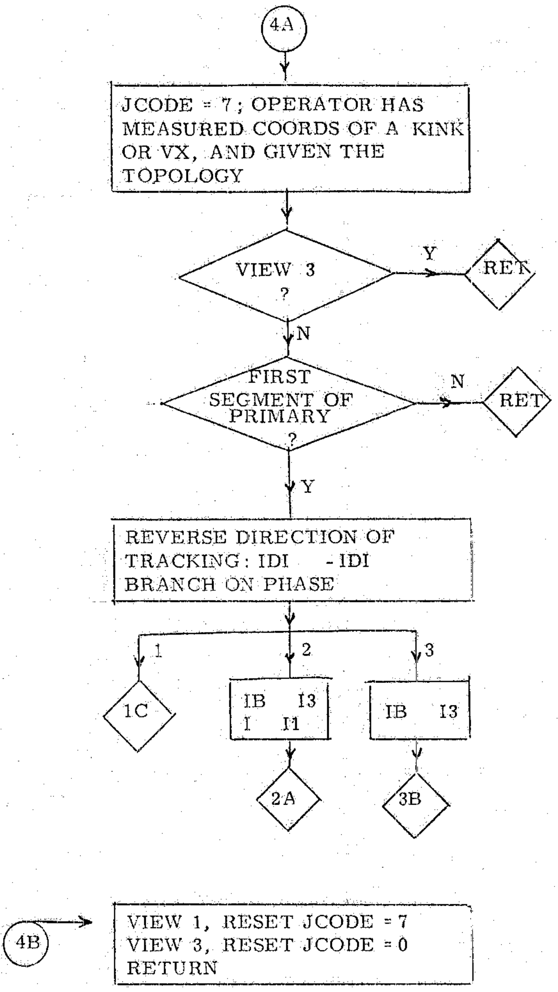
We enter this level in order to follow, store, and check a particular track. The routines in question are the Track Follower (TKF) with Subroutine HELP, Subroutine SAVCHK, and Subroutine KINK.

5. 1. - The Track Follower (TKF).

Our knowledge of the track upon entry, consists of the coordinates of one point, and the angle of inclination of the track. In the case of the primary of View 1, this information comes from Subroutine FNDBM, while for the primary of View 3, or the secondaries of either view this has been derived manually by the operator. For the primaries of View 1, we know the threshold at which the track is to be viewed. In other cases we take a reasonable "average" threshold. We specify the direction of following - along the motion of the particle (IDI = -1) for all tracks except the primaries of View 3, which we follow in the opposite sense (IDI = +1). We give the location IB in the output bank where we will commence storing track coordinates, thus allowing for the possibility of a later reversal in the direction of tracking (see Fig. 7). TKF works entirely in uncalibrated PEPR coordinates as discussed by Harris(6). We employ the 1 mm line element and a scan cell of size 770 μ (IC = 6 μ) with the data acquisitive routine MSCAN, operating in Stop Mode (Sect. 6. 3).


ENTER FROM EVENTS
1A
CHECK GIVEN INITIAL POINT
FIND ?
N
RET
Y
INITIALIZE COUNTERS
POINT I = IB ; IDI = ± 1
1B
FOR POINT I : STORE A, B, θ, RL
1C
SET IGAP = 0 INOISE = 0
FOR NEXT POINT
SELECT ANGLE OF NEXT SCAN
IF I = IB, USE θ(IB) ELSE, WE
USE SLOPE OF I AND I - IDI FOR θ
1D
LINEAR PREDICTION OF A
POINT DL AHEAD OF A(I),
B(I) AT AP, BP
1E
SET SCAN CELL, CENTRE AP, BP
BASE ANGLE = θ - 3 DEG
GATES ± 30 IC
FIND ?
N
5A
Y
UP - DATE COUNTERS
I I + IDI
CAN WE LEAVE PHASE 1 ?
N
1B
Y
STORE DATA FOR LAST POINT
OF PHASE 1
2A
2A
ENTER PHASE 2
USE ENTIRE EXISTING TRACK
FOR CIRCLE PREDICTION
FIRST POINT I1 = IB
LAST POINT I3 = I
DL = (RL(I3))/4
COMMON TO PHASES 2 AND 3 :
2B
FIND I2 AS POINT NEAREST
MIDDLE OF I1 AND I3
SET IGAP = 0, INOISE = 0
FIND CURVATURE FROM
I1, I2, I3
2C
PREDICT COORDS. AND
ANGLE OF TRACKS AT A
FOURTH POINT, I4, DL
AHEAD, ON ARC OF CIRCLE
2D
SET UP SCAN CELL CENTRE
A4, B4, BASE ANGLE θ4 - 5
DEG GATES ± 20 IC
FIND ?
N
5A
Y
UP DATE POINTERS
I I + IDI STORE
A, B, θ, RL, CURRENT I I3
WHICH PHASE ?
3
3B
2
CAN WE LEAVE PHASE ?
N
2A
Y
3A


3A
ENTER PHASE 3
CURRENT RL13 AS MAX = RLS
DL = RLS/4, I3 = I, I1 = IB
2B
3B
CURRENT POINT IS I3, SLIDE
I1 TO BE FURTHEST POINT
WITHIN RLS OF I3, DL FIXED
2B
3C
RETURN FROM HELP:
OPERATOR HAS SEEN TRACK
BRANCH ON JCODE
JCODE = 1
JCODE = 2, 4, 5, 6
JCODE = 3 REPEAT
JCODE = 7 VX OR KINK
JCODE = 8 TAKE AS COMPLETE
RET
1A
4A
4B
RESUME AT A CLEAR POINT
GIVEN BY OPERATOR: USE
NUMBER OF POINTS AND
TOTAL LENGTH TO DECIDE
PHASE
PHASE 1
?
N
Y
AS BEFORE, FIND ANGLE
FOR SCAN CELL, CLEAR
POINT IS AP, BP
1E
MOST RECENT POINT IS I3
SELECT I1, I2 BY RULES OF
PHASE 2 OR 3. FIND ANGLE
FOR SCAN CELL.
CLEAR POINT IS A4, B4
2D


4A
JCODE = 7; OPERATOR HAS
MEASURED COORDS OF A KINK
OR VX, AND GIVEN THE
TOPOLOGY
VIEW 3
?
Y
RET
N
FIRST
SEGMENT OF
PRIMARY
?
N
RET
Y
REVERSE DIRECTION OF
TRACKING: IDI -IDI
BRANCH ON PHASE
1
2
3
1C
IB I3
I I1
IB I3
2A
3B
4B
VIEW 1, RESET JCODE = 7
VIEW 3, RESET JCODE = 0
RETURN

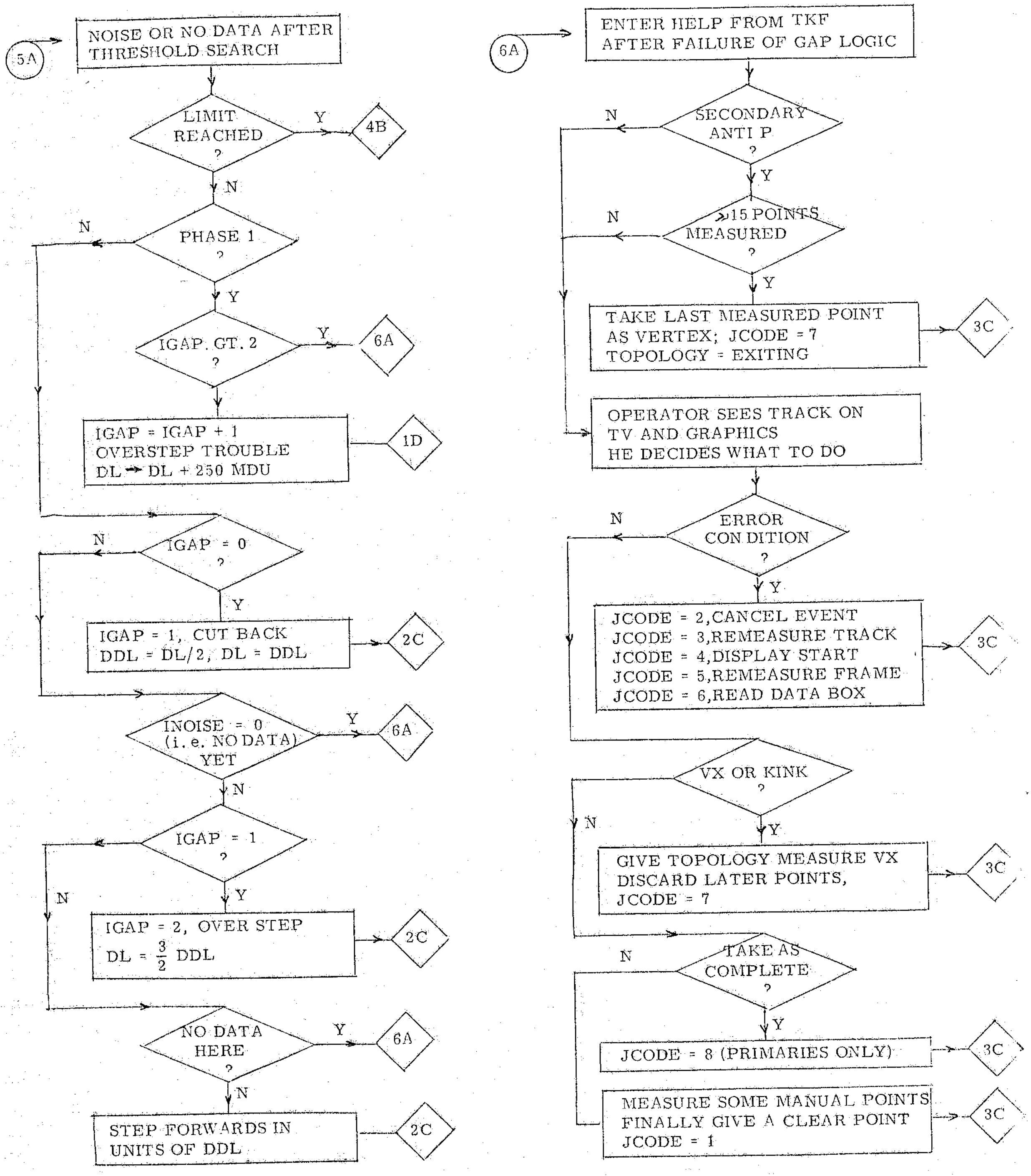


FIG. 7 - Flow chart for track-following (Subroutines TKF and HELP).

There are three phases in the operation of TKF - firstly a brief linear phase, secondly a circular phase with an increasing prediction step, and thirdly a circular phase with a constant prediction step. We commence the linear phase by verifying the input point, sweeping from a base angle of $(\theta-3)^\circ$ in 10 steps of 0.7°. The gates are $\pm$ 30 IC ($\pm$ 180 μ).

We make a linear prediction for the centre of a second scan cell distant DL = 250 MDU (625 μ) from the input point, offset by 3° from the measured angle of the track at the input point. The remaining predictions are generated in like manner except that for the third and subsequent points we set up the cell at a base angle given by the measured coordinates of the two previous points, offset by 3°. The data stored per point in this and the other phases are the returned coordinates A, B the track angles θ and the cumulative step length RL. We exit from Phase 1 when we have measured at least three points and the sum of the step lengths exceeds 1000 MDU (2.5 mm). We enter the second phase (circle prediction with increasing step), equating the sum of the step lengths, RL 13, to the chord, and arc of a circle. We assume that the circle passes through the first I1 (A_1, B_1) and last points I3 (A_3, B_3) measured in Phase 1, and the point nearest to their middle I2 (A_2, B_2).

We predict the coordinates and inclination of the track at a fourth point I4 (A_4, B_4, θ_4) distant DL = RL 13/4 along the arc of the presumed circle, using the formulae given in Ref. (6). We set up a scan cell to search for the predicted point, with the base at $(\theta_4 - 5)^\circ$ and with gates of $\pm$ 20 IC ($\pm$ 120 μ). The most recently found point now becomes I3 for the next prediction, while I1 remains the original point. Thus the prediction arc RL 13 is continually extended, and with it, the prediction step DL which is RL 13/4. We continue in this way until we exceed a limit of 4000 MDU (1 cm) on the followed arc or of 10° on its subtended angle. Thus the maximum step is $<$ 1000 MDU (2.5 mm) and the corresponding turning angle $<$ 2.5 degrees. A limit is placed on the maximum step size in order to obtain a sufficient number of points. With the value chosen here the uncertainty in the prediction due to multiple scattering dominates those arising from the use of uncalibrated coordinates or the inadequacies of the circle model.

We pass to Phase 3 setting the maximum prediction arc length RLS to be that with which we exited from Phase 2. DL remains fixed at RLS/4. We take the most recent point to be I3 ; I1 is the point furthest back, whose distance from I3 does not exceed RLS. We use the same formulae as before to predict I4.

TKF continues until trouble arises at the vertex or end point of the primary (View 1) or secondary, when HELP is called to determine the vertex and topology (Section 5.2). A secondary track is over at this point. However, for the primary of View 1, we reverse the direction of tracking and follow it backwards as far as possible towards the entrance of the chamber. This helps us to filter out tracks which have entered through the walls of the chamber. For the primaries of View 3 we track in the backwards direction and continue to do so at least until a set limit in A (x) is reached. Having completed the track, we return to Subroutine EVENTS. For a full-length primary track TKF collects about sixty points - 4 or 5 in Phase 1, 10 or 12 in Phase 2 and the rest in Phase 3. In spite of this seemingly large number of points, the average tracking time is only about 1/10 th of a second, per track.

5.2. - Difficulties in TKF.

All tracks fall into difficulties at least once. This always happens at the vertex, when we are going forwards or near the chamber entrance going backward. In general, trouble manifests itself in one of two ways : a) NO DATA. This is the condition which appears at the end of a track. It could also arise if our prediction falls far off the track due to an error in following or a large kink, or if we encounter a section of weakly ionized or poorly contrasted track. b) NOISE. This is probably due to the presence of a near parallel track within the gates of the scan-cell. There are three stages in the solution of the difficulty. The first two are internal correcting mechanisms, while the third is to call the operator.

5.2.1. - Threshold Adjustment.

We make one attempt to find the track at the predicted point by calling Subroutine DID (Sect. 3.7), sweeping at this point, from the current base angle in 10 steps of 0.7°. If we succeed in finding the track, the normal flow of TKF is resumed, and the new threshold is retained. If the threshold search fails, and we are at the input point of the track, we return to Subroutine EVENTS.

If we have already reached the limit, the track is now complete. Otherwise, we pass to the Gap Logic, using the previous threshold.

5. 2. 2. - Gap Logic.

If we are in Phase 1 we increase the value of DL by 250 MDU (625 μ) once, or twice as needed, in order to overstep the troublesome region. If we succeed, we reset DL to 250 MDU (625 μ) and resume the main flow of TKF. If we fail we call the operator. If we are in Phase 2 or 3, we firstly cut back the from the main-flow prediction point by defining a new step length DDL = current DL/2 (points I1, I2, I3 are not redefined), and resume the main flow of TKF if we find the track. If we don't find the track we overstep the main flow prediction point by DDL and advance in units of DDL from there. At each point a threshold search may be made. The gap logic is abandonned and the operator is called on reaching either of two conditions : a) we have obtained no data twice, or b) we have obtained no data beyond the mainflow prediction point. These are prima facie indications that we have reached the end of the track.

5. 2. 3. - Operator Interaction (Subroutine HELP).

Most tracks will call for operator help at least once - certainly at the end point, and possibly also in some very confused situations. The only exception is a kink-free primary of View 3, which reaches its limiting point without problems. When Subroutine HELP is called the operator sees a TV image of the film at the last measured point, and a display of the track segments stored by TKF. If the track has kinked or interacted the operator measures manually the coordinates of the kink or vertex, and presses a topology key (JCODE = 7). The track is cleaned of all downstream points, in case we have wandered beyond the vertex. If the track has reached a satisfactory point going backwards (not necessarily its limit) the operator signals that the track is complete (JCODE = 8, only applies to primaries).

A relatively common error is where TKF has progressed some distance along a close crossing track, and maybe even returned to the original. This by mixing points from two tracks would cause the predicted point to fall clear of both. Here the operator measures several points on either side of the cross-over. These points are inserted in the usual coordinate bank, cancelling the existing downstream points. When the two tracks are sufficiently well separated the operator gives a "clear point", which upon return to TKF (with JCODE = 1) is treated as if it were an internally generated prediction point. The main flow of TKF is then resumed, with a change of phase (to lower or higher) if this is implied by the new value of RL. The operator may also command deletion of the current event (EVENTS, JCODE = 2) or the refollowing of the current track (TKF, JCODE = 3) from its initial point. He may ask to return to the point of initialization of the current track (EVENTS, JCODE = 4), and recommence this or another . He may order rescanning of the frame, or reading of the data box (EVENTS, DATBX; JCODE = 5, 6).

To assist in viewing the entire track subroutine HELP has the facility to pass successively to each of the measured points, delaying 0.2 seconds before passing to the next, or reversing the direction of viewing.

5. 3. - Storage and Checking of Tracks.

Assuming that we have made an error free return from TKF to EVENTS, SAVCHK is called to organize the placement of the current track into the output banks for the events of this frame. We ensure that adding one further track would not exceed the space available in the track bank (16 tracks) or in the coordinate bank (300 points). All the measured points are calibrated to Cartesian coordinates. We want to store at most 40 calibrated points per track. We define a separation parameter corresponding to 1/40th of the track length, and test the distance of each point from the previous one, against this. If the point is too close to the previous one, we discard it, and test the next point against the previous. We always return the vertex point, the two points closest to it, and the point furthest from it, without regard to the separation parameter. The output information for each track is a set of coordinate pairs, the topology, and the sign of the curvature. For segments of primaries of View 1 nearest to the principal vertex, we record the coordinates of the vertex with respect to the prime fiducial, the inclination near the vertex, and the topology. This information is used to write the guidance file for the subsequent measurement of View 3 (Sect. 4. 6). The coordinates of the vertex are checked against those of all other vertices for possible duplication. The frame is flagged for remeasurement if any vertices are within 4 μ of one another. All primary tracks are subjected to a track checking procedure with the object of detecting very small kinks and track cross-overs, which would escape notice in TKF. We select points from the calibrated coordinate bank corresponding to momenta $>$ 400 MeV/c. Another separation check is performed. We don't use the point in kink analysis if its separation from the previous point is less than half the average separation parameter, or its absolute separation is less than 750 μ.

Assuming we have a least 8 points we call subroutine KINK (see below). There are three possible outcomes : a) nothing wrong - return to EVENTS, b) a crossing error in TKF confirmed by the operator. The track is deleted, and we return to EVENTS to organize its remeasurement. c) a kink confirmed by the operator. The track is separated into two segments at the point of the kink as measured by the operator. We go back to the beginning of SAVCHK, treating each of these segments in turn; that nearest the main vertex retains the original topology, while the other is given the topology of a "post-mortem kink". It is possible to have more than forty points on the sum of the two segments, as would be the case if the kink had been detected "live" in TKF and HELP. The Kink Detection (KINK) is based on the method of Hanton et al.$^{(7)}$. We obtain the tangents between successive points as a function of the distance along the track (Plot A). For purposes of smoothing we make a sliding linear fit along Plot A, using successive (not independent) groups of four points, and obtain a set of slopes. A kink if present will cause points before and after to be "mixed" in three of the combinations, giving rise to exceptional slopes.

In Plot B we plot the slopes as a function of the distance of the mid point along the track. We make a linear fit to Plot B, and then refit it excluding the worst residual and those close to it. Two tests are then made for kink candidates, before provoking operator interaction. The preliminary test is on the value of the worst residual of Plot B ; if this less than 3.0, in units of the standard deviation of the fit the track is not considered further. Otherwise, we return to Plot A, and extrapolate the unmixed fits on either side to the centre of the kink region.

If the difference between the intercepts is greater than 20 mrad, the operator is called. He is presented with a TV display of the film in the suspect region, a display of the track as seen by TKF and a display of Plot B in which a kink should stand out as three points distant from the trend of the others. The operator may decide that nothing is wrong, or that there was an error in following the track or that there is a kink, at a point whose coordinates he measures manually. The use of the asymmetric magnification is especially helpful in this operation.

With the provoking parameters mentioned above, about 5 % of all primaries result in the making of the operator display.

6. - DATA ACQUISITIVE ROUTINES.

Here we describe the lowest level of the software, that is those routines which interact directly with the PEPR controller registers. They give parameters and commands to the hardware, and in turn receive the results of the sweep. There are two such routines : SCAN and MSCAN. The former is typically used to make a general search of a large area whose contents are unknown, e.g. in FNDBM. MSCAN is used where we already have a reasonable prediction of where to find what we are looking for as in FIDS or TKF. The routines allow the user to operate in many different modes. However in this present note we will only describe the options, which are used in the routines we have described. Technically both SCAN and MSCAN appear as entry points in the same subroutine, together with several other entry points which initialize the registers for both.

6.1. - Common Initialization Routines.

There are four routines which receive the values of parameters specified by the user and transfer them to the PEPR registers :

MSAB - The user specifies the centre of the scan cell in units of MDU. The geometry of the scan cell is illustrated in Fig. 8a.

MSIAFA - The user specifies the base angle of orientation of the cell ($0 < \theta < 180$) degrees. The PEPR controller uses one byte to represent the angle, so that degrees are converted into units of $180/256 = 0.7^{\circ}$. The user also specifies the number of steps of orientation of the scan cell and the size of the step in units of 0.7°. If the angular range is contained within the same

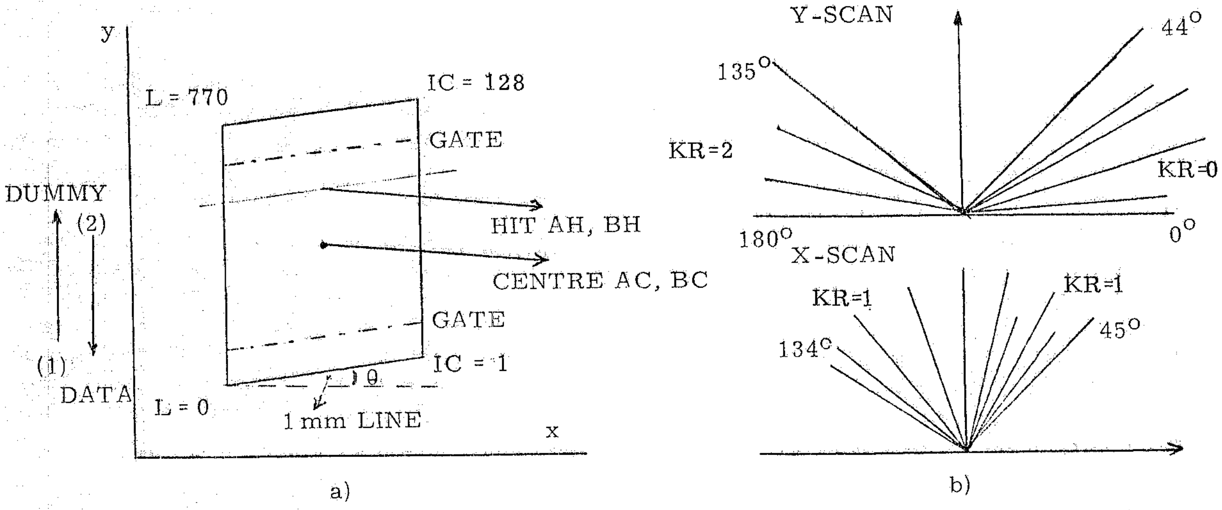


FIG. - a) Geometry of a typical scan cell ; b) Range of angles for x and y sweeps.

quadrant the locus of the centre of the line element is as indicated in Fig. 8b. The boundaries of the quadrants may be stretched by 15° if the angular range is not contained within the same quadrant. If this is insufficient we make an error return.

MSMODE - The user states if he wants to sweep with the spot or the line. In the latter case he select one of five available lengths between 0.5 and 2.5 mms. In practice we generally use the 1 mm line element. The user also specifies the size of the scan cell in the direction of the sweep. There are four available sizes $192\,\mu$ (IC = $1.5\,\mu$), $770\,\mu$ (IC = $6\,\mu$), 3.1 mm (IC = $24\,\mu$), and 12.3 mm (IC = $96\,\mu$). Only the second of these has been used in the present work.

MSREG - The user states the threshold and its hysteresis, and the maximum acceptable track width ; the upper and lower gates , whether the histogramming facility is to be used or not (see next Section).

6. 2. - Subroutine SCAN.

This subroutine always uses the histogramming mode. It commands the hardware to commence scanning at the position, and through the range of angles already loaded. In the histogramming mode the hardware writes in a 128 x 8 bit memory, at the location corresponding to the IC of the hit, the angle at which the hit was observed. In general a hit will be observed over a range of a few degrees. In this case we overwrite the previous angle. If the IC of the hit also changes with angle we have a multiplet of contiguous locations corresponding to the same real hit. The information is transferred to the PEPR registers. If there are more than four multiplets, or any of them is broader than 5 ICs we make an error return. Otherwise we extract the centre of the multiplet and the average angle, combining multiplets whose centres differ by less than 4 ICs. We return the centre of the multiplet in MDU, and the angle in degrees.

6. 3. - MSCAN.

The hardware commences sweeping at the position and through the range of angles already loaded. In the Stop Mode used in this present work, control is returned to the software as soon as one acceptable hit is found in the scan-cell. We then have the centre of the hit, and its angle available directly in the PEPR registers.

The user may optionally proceed to make a precise measurement of the angle of the track as the average of the range of angles over which it is visible.

7. - SUMMARY OF PEPR PERFORMANCE.

The PEPR of the Laboratori Nazionali di Frascati has been routinely measuring data for about eight months. During that time over 50000 events have been measured and about 15000 events per month are being added to this number. The average measuring rate is about 80 events (both views) per hour. With more experienced operators and perhaps some improvement in the interactive facilities, we should be able to reach a measuring rate of 120 events per hour.

The root mean square residual after a fifth order fit of 168 measured points of a diamond grid is $< 2\ \mu$ in both coordinates. So far, about 16000 events have been passed through the HYDRA Geometry Program. The pass rate is about 95% (However we must point out that the technique of measurement is peculiar to this experiment. This number cannot be translated into a more normal context). The failures are due to events being outside the fiducial volume,(3%) difficulties in reconstructing a vertex (2%). Failure to reconstruct fiducials is very rare. The residuals of the mass fit peak at about 60 μ(in space). The residuals on the coordinates of the measured vertices are 250 μ, 100 μ and 1 mm, in x, y and z respectively.

ACKNOWLEDGMENT.

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