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Fast Analysis System for Bubble Chamber Data*

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Within the past decade the bubble chambers and spark chambers together with the large accelerators have conspired to generate a new experimental problem. It has become possible to acquire interesting and information-rich photographs of the production, interaction and decay of elementary particles in quantities 1 to 2 orders of magnitude beyond our capacity to analyze them. And the statistical limitations in strange-particle physics are sufficiently famous that I need only suggest that the extra data, if it can be made available, will find immediate honorable work in choosing between alternative theories or in framing quantitatively new postulates for a theory.

This rather tantalizing situation of unanalyzed data has called forth very much experimental-physics and engineering-development effort. The cloud-chamber days of circular templates to measure track curvature have been succeeded by an elaborate and successful development of the two-dimensional coordinate comparator familiar from classical astronomy. The automated coordinate comparator finds its highest expression in the Franckenstein measuring projector of the Lawrence Radiation Laboratory in Berkeley. Until the last month or two virtually all the bubble chamber film in the world had been measured on two-dimensional coordinate comparators, either of the measuring-projector

*Work performed under the auspices of the United States Atomic Energy Commission.

or measuring-microscope type. By now, however, about 60 bubble chamber events have been measured on a new type of precision measuring instrument called a flying spot digitizer (FSD). The FSD is the principal instrumental component of the new system I want to describe this morning. In the talk by Professor Pless which follows you will hear about a system which may well be the next generation in our steady search for transfer of recognition and measurement functions from humans to digital computers.

The mechanical flying spot digitizer, or FSD, or HPD, was imagined, together with a system permitting human scanning to guide it, about 3 years ago by B. Powell and myself at CERN. A prototype FSD was tested successfully at CERN about a year and a half ago, and at about the same time CERN, Berkeley and Brookhaven began construction of production machines. All three production FSD's were working last summer as machines and since then all have been put under control of their IBM 7090 or 709 computers. They are just now beginning to operate with their computer programs. The master architect of the programming system is H. White, head of the Data handling Group at Berkeley. Playing a leading role in the system development have been B. Powell and G. Moorhead at CERN, D. Lord and J. Burren at Harwell, H. White, J. Franck and J.A.G. Russell at Berkeley, and R.B. Palmer, M.J. Rosenblum, N.W. Webre, P.L. Connolly and myself at Brookhaven. Mark II machines of an advanced design due largely to R.B. Palmer are under construction at Brookhaven and Harwell and planned for the University of Pennsylvania, Columbia University, Imperial College (London), CERN, and several other laboratories in the United States and abroad.

The basic idea of the HPD is extremely simple, as shown by Fig. 1. A mechanical aperture ~20μ or 0.8 mil square is formed by a means familiar to early workers in television. Approximately radial slits, 8 in number and each 20μ wide, are carried by the rotating disk. Downstream of the light beam by 8 mils is a fixed slit at right angles to the moving radial slits. For strictly radial slits the perpendicularity obtain for only one disk angle but, as Professor Mc Millan of Berkeley has shown, appropriate curving of the moving slits leads to perpendicularity for all disk angles and moreover the linear speed of the 20μ square aperture becomes constant. The overall length of the fixed slit is illuminated by the high pressure mercury arc shown at the left and as the disk rotates a fine spot of light traverses a line (fixed and straight to a fraction of a micron) 480 times/sec. The flying spot is imaged at 2.1 reduction both on a bubble chamber or spark chamber negative and on a precision grating consisting of alternate opaque and clear strips each 16μ wide. By counting grating lines and interpolating between them the coordinate on film of the flying spot in its direction of motion is known at any time to within a few microns. The film is clamped to a precision stage and driven in the coordinate perpendicular to the flying spot coordinate at a rate of 1-1/2-3 cm/sec, yielding line separations of 30-60μ. Since the flying spot diameter on the film (with aberrations) is 15-20μ in diameter, and since bubble image diameters are typically 25-30μ, the 30μ line spacing mentioned insures that every bubble image on the negative is traversed by the flying spot. This is how we have been running the Mark I FSD at Brookhaven.

When the flying spot encounters a bubble image it is attenuated typically 25-75% depending on the directness of hit and the bubble chamber photographic and operating parameters. The width of the bell-shaped attenuation curve is roughly the sum of the spot and bubble image diameters, or 40-50μ. The high precision of the FSD derives from the fact that it is possible to find the center of area of the attenuation curve to a standard deviation of 3-4μ out the much larger full-width at the base. Each flying spot coordinate is then of a precision about equal to that given by a measuring projector, but typically 16 flying spot points are obtained to one measuring-projector, point, so the effective error can be 4 times less. Substantially less than one-micron standard deviations have been obtained, but in the presence of other pressing system problems the three production digitizers are showing 1-2μ standard errors so far.

The digital electronics problem associated with a flying spot digitizer is basically the trapping of the grating count at the time a bubble image center is found, the storage of the number temporarily until the IBM 7090 computer is free, and then the transmission of the coordinate to the computer. At the end of each scan line the perpendicular stage coordinate is also transmitted, so that the information flow consists of a string of flying spot coordinates of bubble centers encountered along one scan line, then the coordinate of the scan line itself, then the sequence repeated for the next scan line, etc. until perhaps 2000 scan lines have been traced and 15,000-40,000 coordinates have been transmitted.

Fig. 2 shows the Brookhaven Mark I FSD as far as mechanics and optics are concerned. Inside the circular box is the spinning disk, and the flying spot is imaged both on the grating at the left and on the film at a point not very visible in this picture. Fig. 3 shows the type and incidentally about the quantity of electronics required for the information flow. With this amount of hardware entire pictures can be encoded and transmitted to the computer and then repainted by the computer on its display CRT so one can judge the adequacy of the digitizing. Fig. 4 shows a BNL 20" chamber photograph, in the original, and Fig. 5 a playback from the computer's display CRT. The display has been stretched arbitrarily in the vertical direction by about a factor 4/3. To overcome the limited resolution of the display CRT we have had the 7090 plot the data in sections and have then pasted the sections together by hand to get an entire picture. In Fig. 4 may be noted the coded picture number, and in both figures the external or "road" fiducial X's, and the internal or "precision" fiducial X's. Apart from the CRT display, the detailed computer printout is analyzed, e.g. for the precision of the data which we have quoted. The downstream two-prong, incidentally, is the first event processed by the new system at Brookhaven and the only event we have processed completely.

At this stage two jobs remained to be accomplished in practice. The first was computer control of the FSD. It does no good to measure a bubble chamber frame in a few seconds unless you can get to another one that needs measuring in a comparable time. The quantity of electronics required for computer control is about equal to that for the information flow and several of the problems are non-trivial. As a kind of slide-with-time-dimension we have made a small film strip of our Mark I under computer control.

(Begin Film Commentary)

Here is one of our senior technicians initializing the machine at the beginning of a run. In starting a run we set the Moire-fringe counters for the stage to standard values and run in a few frames of film so the FSD knows what picture number it has currently in its platen.

Through open double doors from the last scene is the 7090 computer. The second of these small consoles in the foreground shepherds orders from 7090 to the FSD and coordinate flow in the reverse direction.

Here we see the indicator lights showing orders received from the computer. When all these left-hand lights are on, a measurement pass is being made. Of the two left-hand lights, the extreme-left shows film-advance complete and the next stage-retrace complete. We are in real time for the slowest measurement speed of our Mark I, giving the close-spaced scan lines which catch every bubble.

Here are the mechanical motions. The next two film advances are of 62 frames and 101 frames respectively. (This) is stage retrace, and (This) the measurement pass.

We run the Mark I at twice this cycling rate for the pattern recognition programs.

(End Film Commentary)

Now let's consider how the 7090 can make use of the mass of coordinate data to obtain Franckenstein-like points for particular events.

It may be that the 7090 or its immediate descendent will be able to make sense directly of the 15,000-40,000 coordinates transmitted to it by the HPD. In fact R. Marr and G. Rabinowitz at Brookhaven, with colleagues at Brookhaven, Illinois and Berkeley, have made rather deep inroads into the problem and hope to give us an experimental computer program with which to start trying out machine scanning in a month or two.

However, in advance of successful computer pattern recognition we are relying on human scanning of photographs and on a scheme for directing the computer's attention to the events found by the humans. The scheme is this: at the scan table, as shown in Fig. 6, the scanner uses a simple measuring rig to record three low-precision points for each track on punched cards. The cards also receive the picture number, and an event-type number which says that the event is 2-prong, stop plus single V a double-Vee, etc. The punched cards for a triad of 400 ft. rolls of film, containing typically 100-1000 events, are converted at a 1401 computer into "scan tapes", one for each view. With view 1 scan type mounted, e.g., and the view 1 reel of film mounted on the flying spot digitizer, the computer reads the scan tape, winds film to the frame-number requested, and makes a measurement pass. In the measurement phase it uses the rough coordinates taken at the scan table. It constructs a circle through the three rough points with an error band on either side of the circle. The region of the two error bands we call a road. Now as data flows in through the FSD, the 7090 accepts only coordinates lying in the roads and throws away the rest. Since the roads are reasonably narrow, ~300μ wide on film or 3mm wide on the scan table projected image, one might expect the pattern recognition problem to be reduced to a triviality. In favorable circumstances this is the case, as shown by the next few slides. Fig. 7 shows all the points in the road for two successive 20-pt bites of clean track. The computer program for road-gating the new coordinates and for screening out bad points due to crossing tracks and electron spirals is called HAZE, with an important inner core called FILTER. HAZE has a final output "master points" or "Franckenstein-equivalent points" shown as X's in the figure. Fig. 8 shows FILTER working a bit harder, in one case with 2 tracks in the road and in the other with a crossing track. In the second case it refused to generate a master point, but this was just because it had plenty of master points already for this track. In Fig. 9 I show a plot of the master points of the scattered proton for our initial event, which is $\pi^+ + p \rightarrow \pi^+ + p + \pi^0$ with 1 Bev/c π^+ incident. A linear test function has been subtracted and the lateral scale expanded. In Fig. 10 for the same track a quadratic test function is subtracted and the scale expanded further to show the scatter in the points. The residual slope and curvature are not significant because the test functions were not least-squares fits. The master-point standard deviation of 1.8μ is the one which very likely can be made 1μ or less.

The master-point data for the three tracks in three views of our first event were transformed by hand into a format suitable for input to the standard geometry and kinematics programs FOG-CLOUDY-FAIR of H. White. We also had to do considerable hand measurement of fiducials. Finally about December 1 we fitted our first event to π^+ scattering with π^0 production, with a satisfactory χ^2 (about 3) and atisfactory agreement between measuring-projector and FSD determination of all geometrical and kinematical variables.

It was then necessary to arrange, first, that the 7090 find its own fiducials. Second, since we had up to this time run events in two steps, first storing coordinates on tape and then running the tape as input to HAZE, it was necessary to learn to run HAZE in real time. Finally it was necessary to make the HAZE Franckenstein-equivalent output directly acceptable to FOG-CLOUDY-FAIR, which demanded a slightly revised FOG.

These basic chores we finished about two weeks ago at which time we put the HPD on line to HAZE. H. White at Berkeley has been in this desirable situation since about mid-December. The system in this condition we have both found to be like an uncaged and largely untrained beast. H. White has recovered to the extent that he is now beginning seriously to analyze the performance of HAZE and especially its basic ingredient FILTER. He has carried 55 events successfully through HAZE-FOG-CLOUDY-FAIR.

We have obtained HAZE output, i.e. Franckenstein-like data, for only 5 more events. And we are just getting the HAZE-adapted version of FOG to work on our 7090 so we have not yet run these 5 events through reconstruction and fitting. In general, with programming the final problem in the system, we have a phase lag behind Berkeley by the time to put new programs in service. H. White has studied the filtering of $\sim$1000 tracks and reports that at the moment $\sim$15% of all tracks are being rejected but that the removal of obvious bugs should drop this $\sim$5%. We have filtered $\sim$100 tracks but actually have not really accomplished the reduction to practice of on-line high-speed operation of HAZE.

At the rough digitizing scan table our first Brookhaven run of 1000 events showed a production rate in agreement with or a bit above our early estimates. So if FILTER in particular and HAZE in general will fall into line we should be able to process 600-1000 simple events per day with the 3 rough-digitizing scan tables now working, and double these numbers with the additional scan tables to be ready later this spring.

Berkeley has some experience with strange particle events and states that HAZE finds no marked increase in difficulty over the 2-prongs to which we have so far restricted ourselves.

At Brookhaven R.C. Strand has analyzed the filtered output data from HAZE to obtain the bubble density and he finds good agreement with the most careful hand measurements and only slightly higher standard errors. It is planned to obtain and use bubble density information for all tracks. Fig. 11 shows the FSD hit-miss sequence with which he works. There remains the determination of the systematic effects of track angle and track location in the chamber on the measured bubble density.

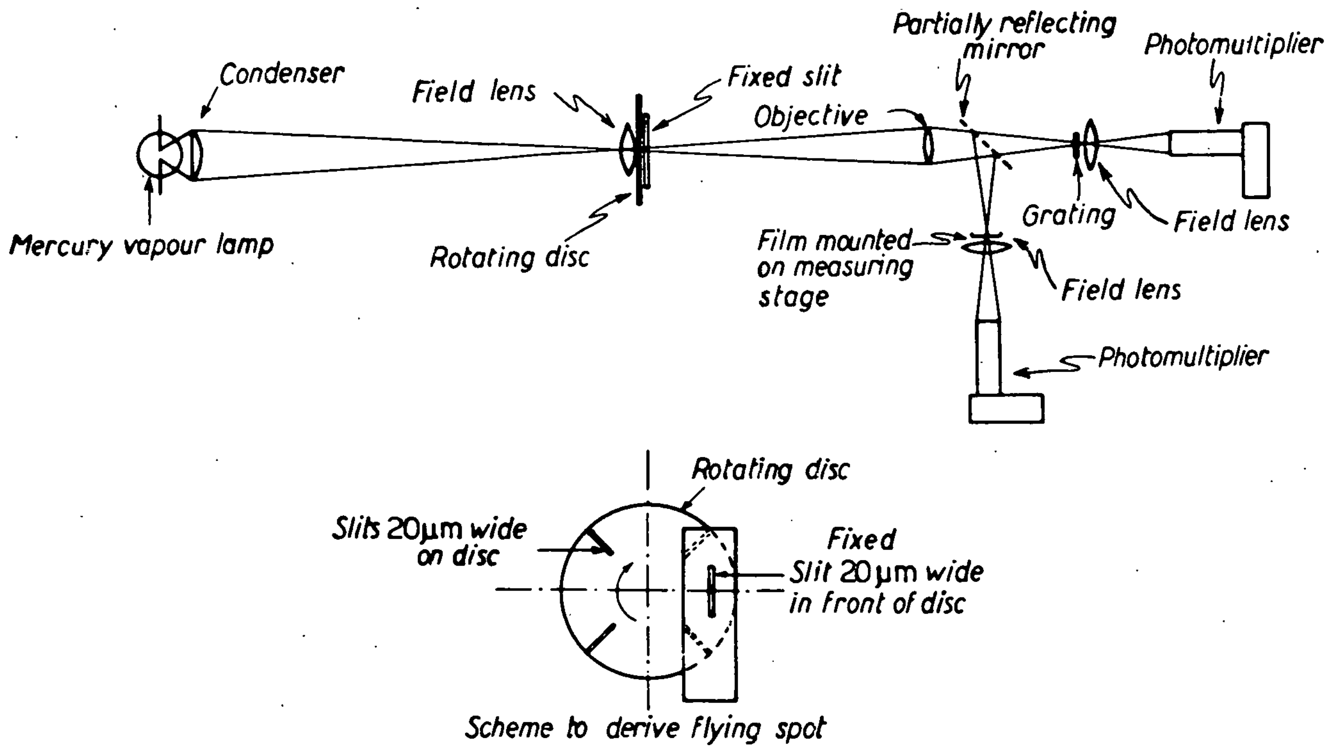
Finally, just a few pattern recognition results. An early program divided the picture of Fig. 12 into a recognized part (Fig. 13) and a residue (Fig. 14). It was rather slow. The newer programs (operating at ~15,000 coordinates/sec on the 7090) have been used so far only for beam-track recognition. Fig. 15 shows the program "initiating" over the first 32 scan lanes and then using rather sophisticated look-ahead with roads only 1/5 the width of the HAZE roads. Fig. 16 shows a beam track interacting. The search for continuation is poignant.

The "experimental computer program" I mentioned will initiate over the entire picture, not just at the top, and both initiate and track follow for all angles of tracks, not just beam tracks. A strong argument for digital pattern recognition, using the high precision coordinates directly, is the following: if the programs begin to work, then the steady increase in speed of digital computers applies automatically. And an order of magnitude increase in computing speed is due just next year with the CDC 6600.

To summarize our current situation, our Mark I hardware is operating quite satisfactorily, but our software is still sputtering in several places. We will be working closely with H. White on making the programs first secure and then increasingly versatile and powerful in the direction of pattern recognition. Concurrently our Mark II hardware for 80" chamber film is being assembled under the direction of R.B. Palmer.

Figure Captions

1. The basic scheme for generating the flying spot.
2. The mechanics and optics of the Brookhaven Mark I FSD.
3. Showing the type of electronics construction used in the Mark I.
4. An original BNL 20" chamber negative.
5. A computer re-display of the negative of Fig. 4.
6. The rough-digitizing scan table.
7. Road-gated and filtered points for two successive 20-pt. bites of clean track.
8. Two more difficult cases for FILTER.
9. Master points for the scattered proton track of the downstream two-prong in Figs. 4 and 5. A linear test function has been subtracted and the vertical scale expanded.
10. The master points of Fig. 9 with a quadratic test function subtracted and the vertical scale further expanded.
11. The hit-miss sequence obtained from the FSD for use in determining bubble density.
12. A computer display of input data for the early pattern recognition programs.
13. The recognized part of the data of Fig. 12.
14. The unrecognized residue from the data of Fig. 12.
15. Showing the new Marr-Rabinowitz program "initiating" over the first 32 scan line.
16. Showing look-ahead for a beam track which has interacted.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Photomultiplier
Condenser
Field lens
Fixed slit
Objective
Mercury vapour lamp
Rotating disc
Grating
Field lens
Film mounted on measuring stage
Field lens
Photomultiplier
Rotating disc
Slits 20µm wide on disc
Fixed Slit 20µm wide in front of disc
Scheme to derive flying spot

FIGURE 1

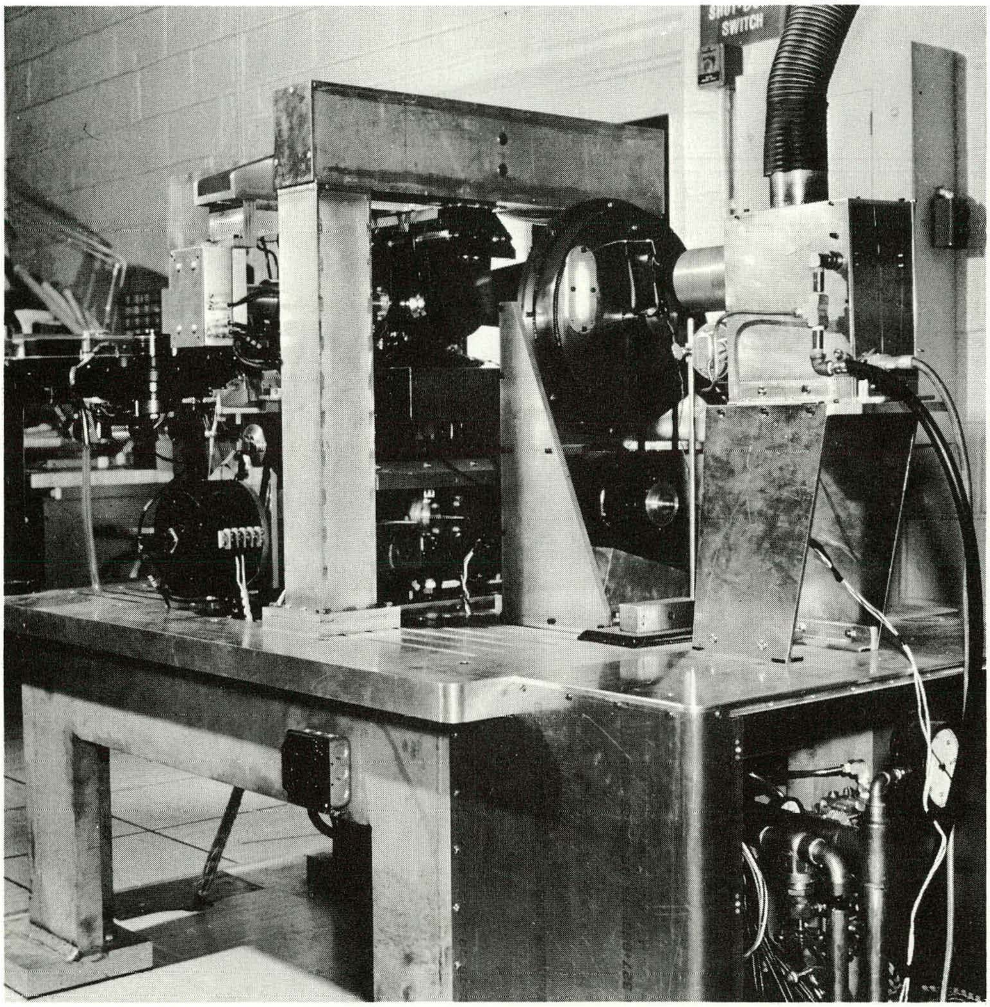


FIGURE 2

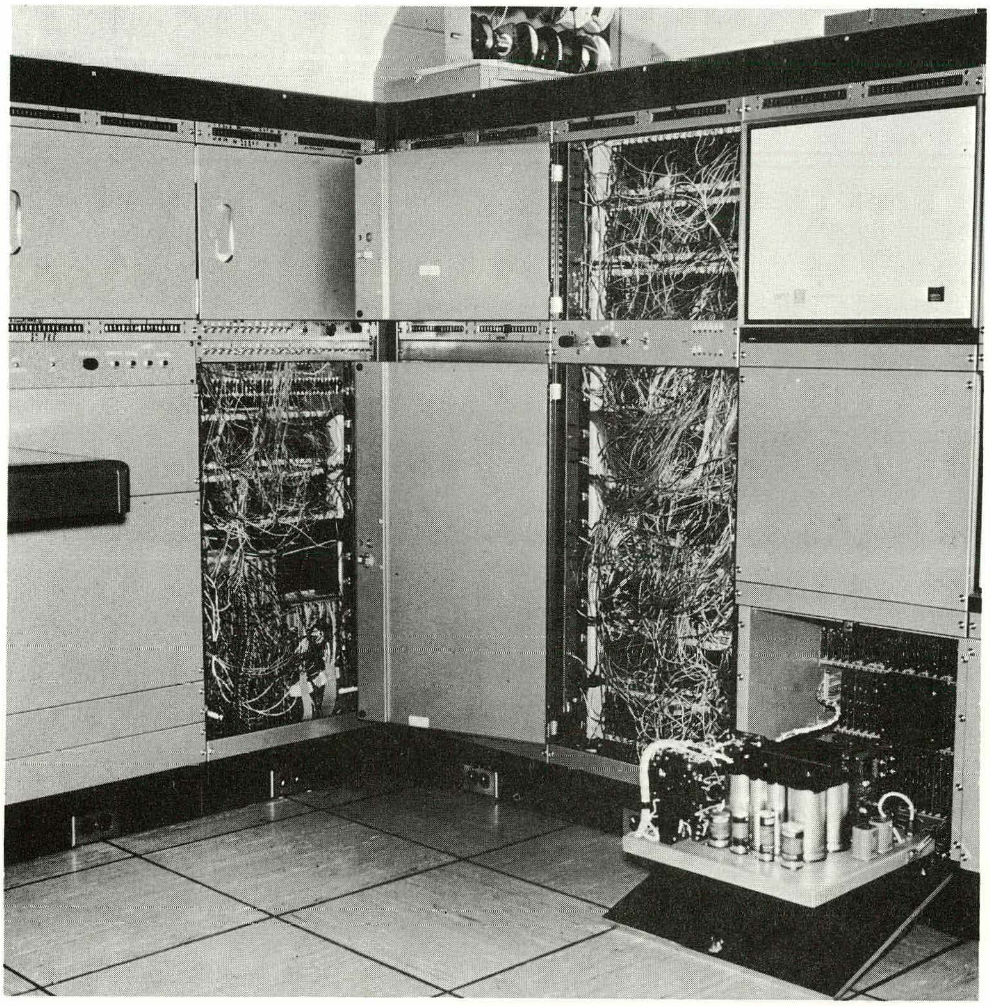


FIGURE 3

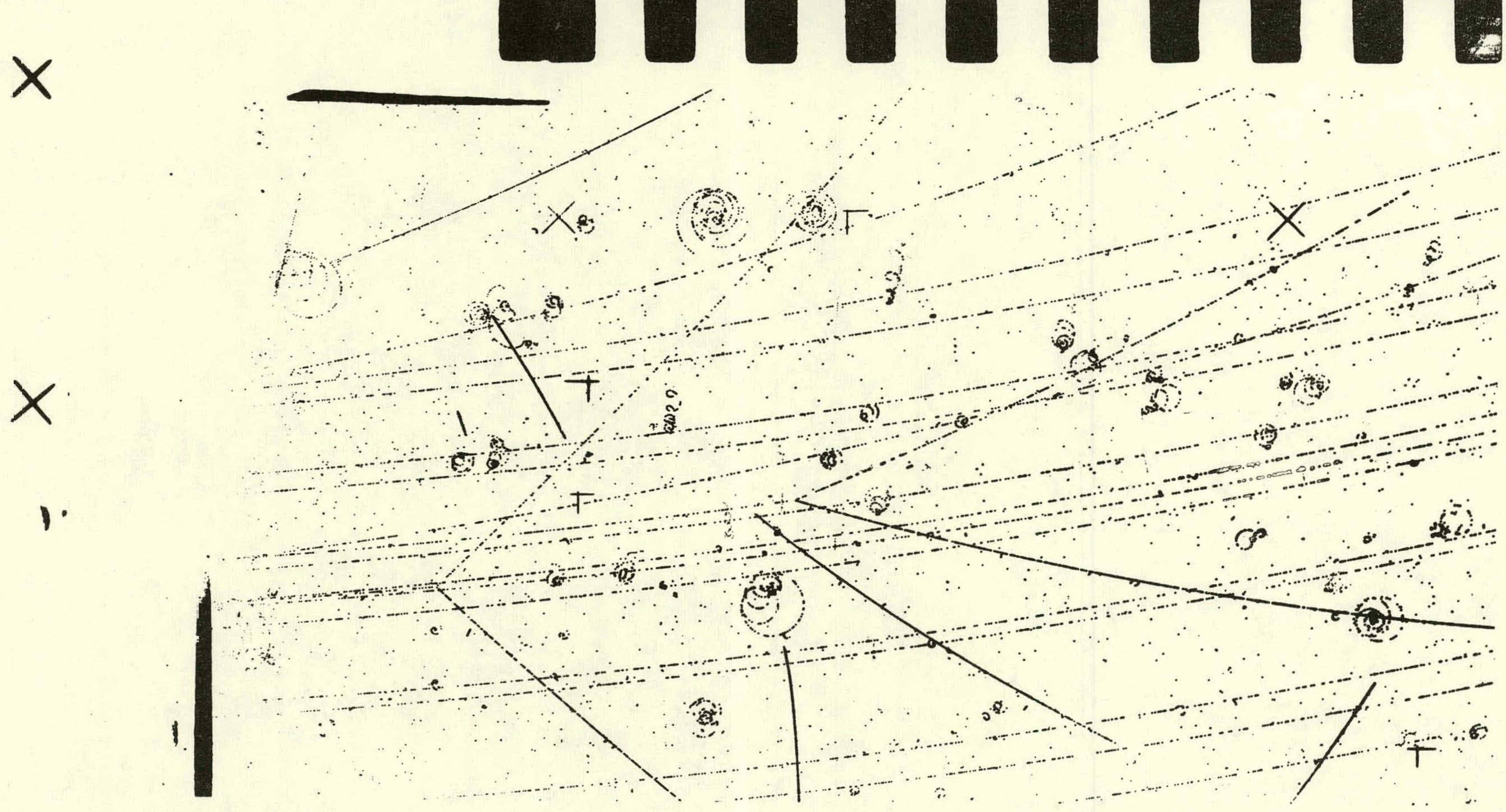


FIGURE 4

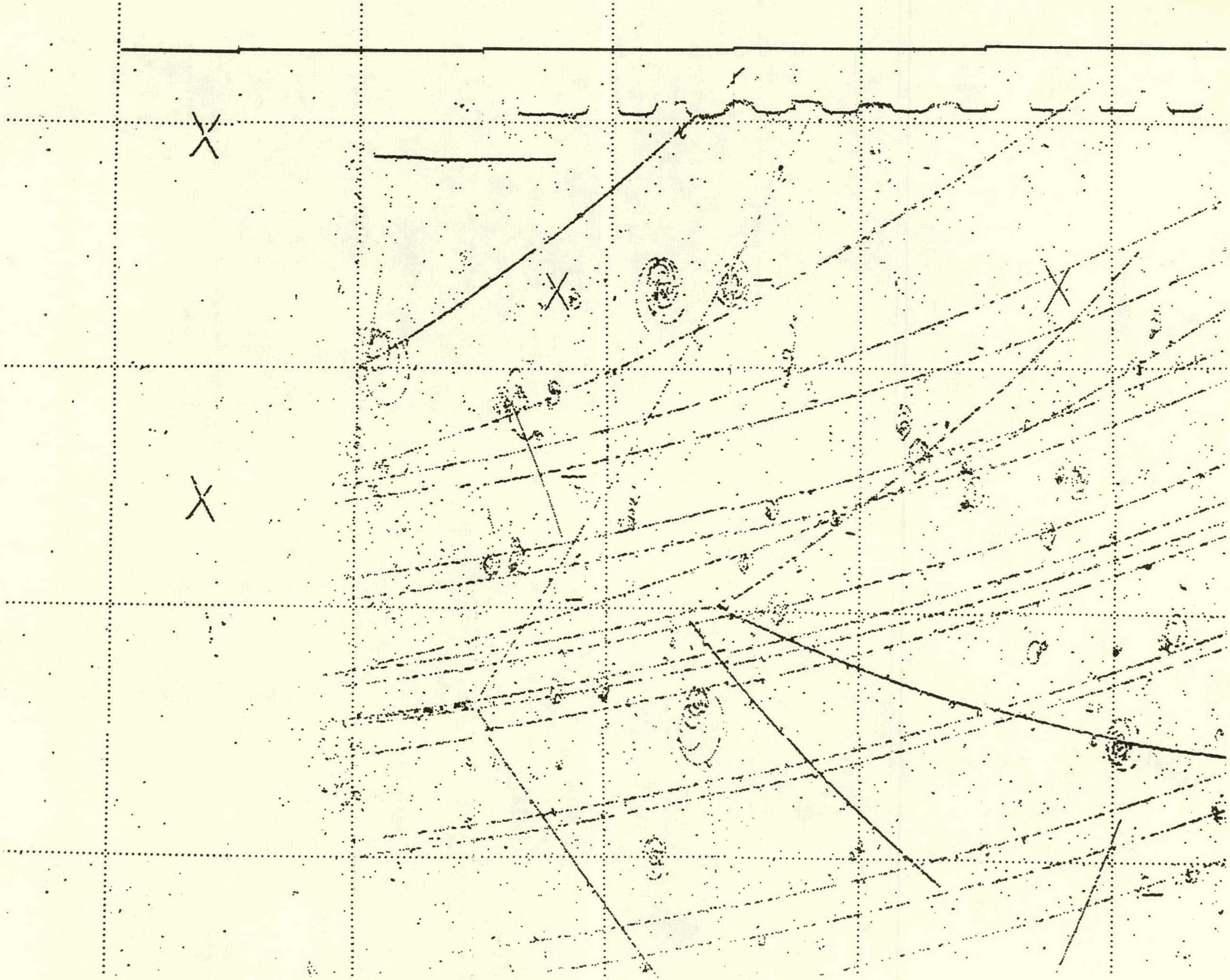


FIGURE 5

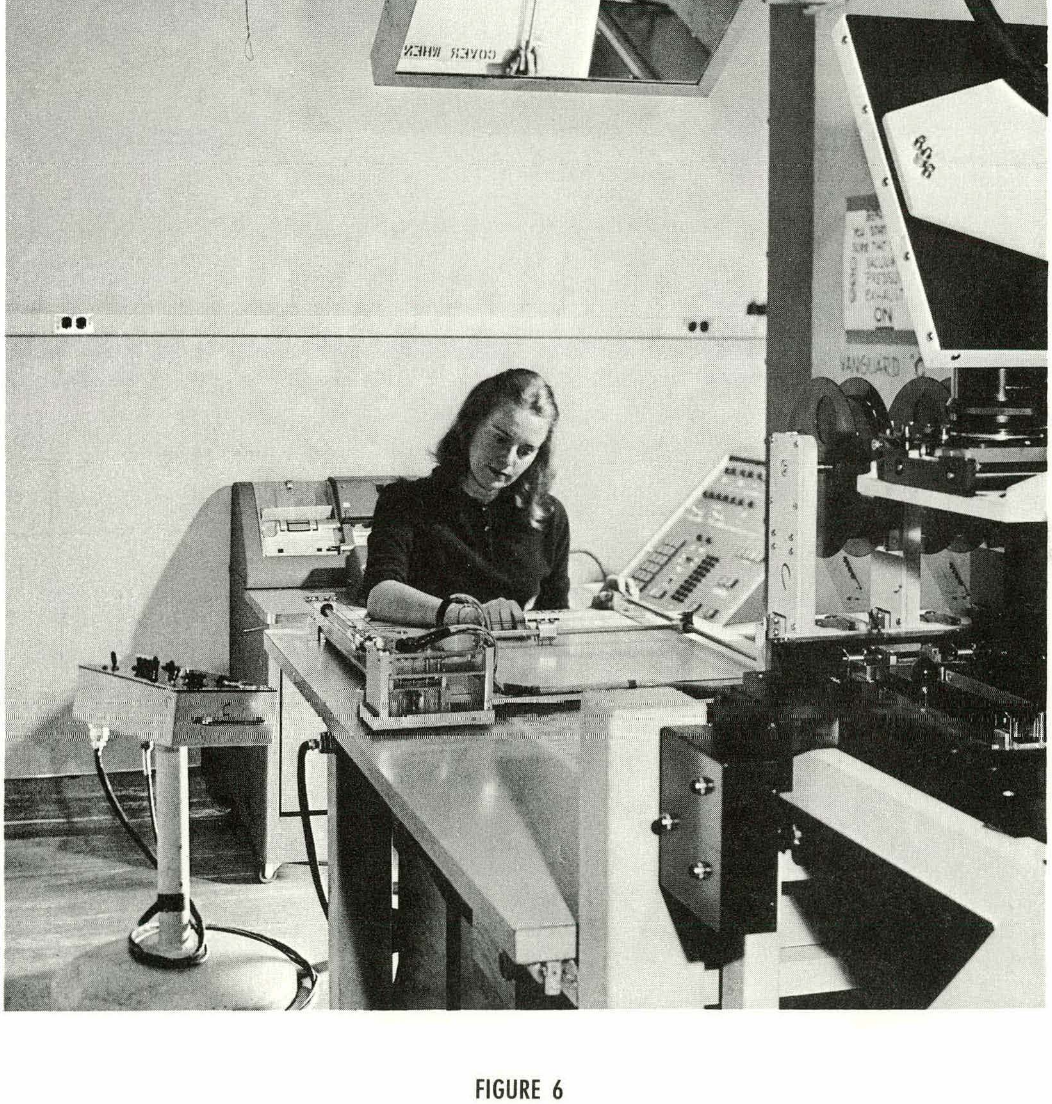


FIGURE 6

HPD FILTERED TRACKS

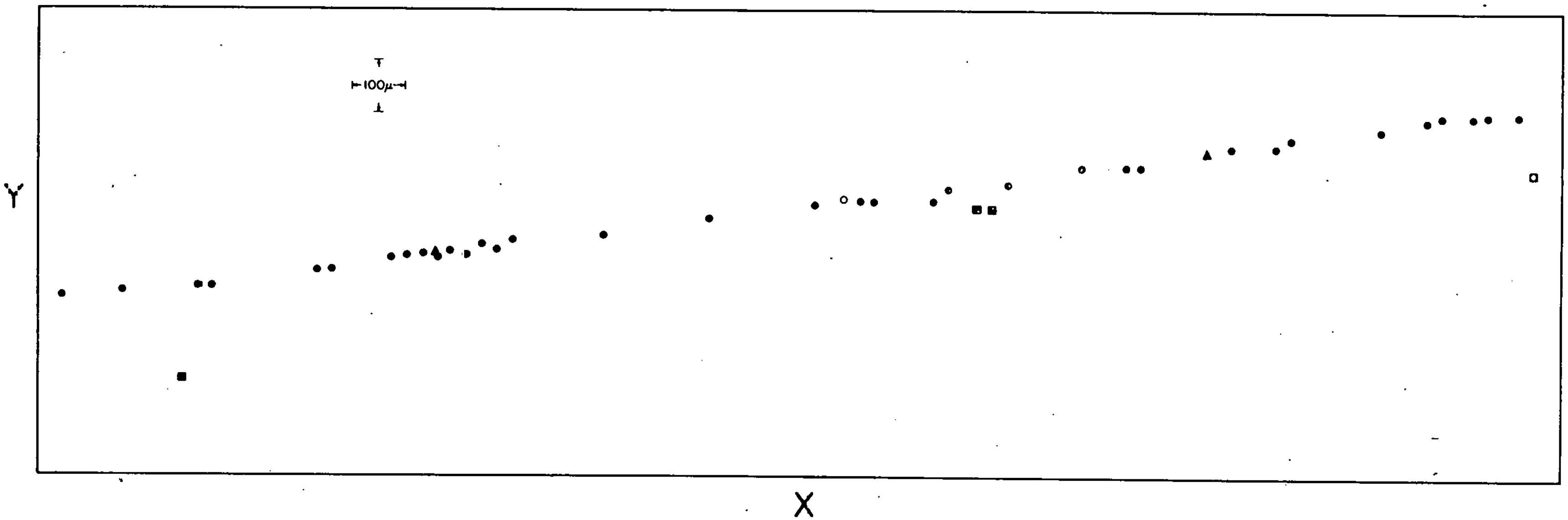


FIGURE 7

HPD FILTERED TRACKS

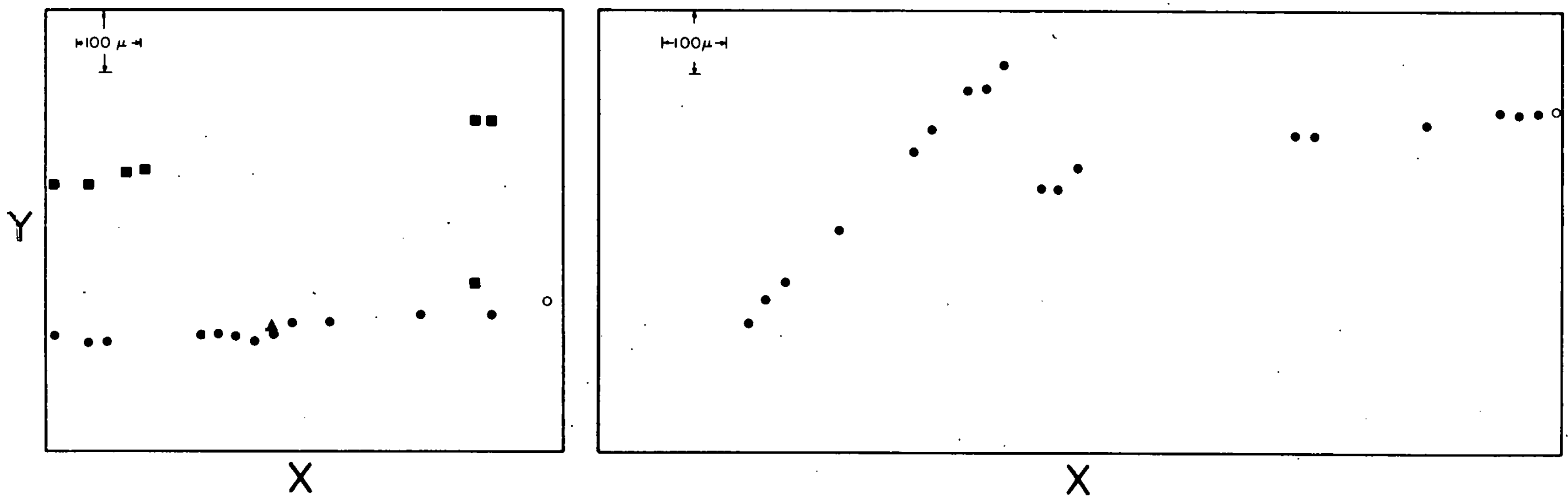


FIGURE 8

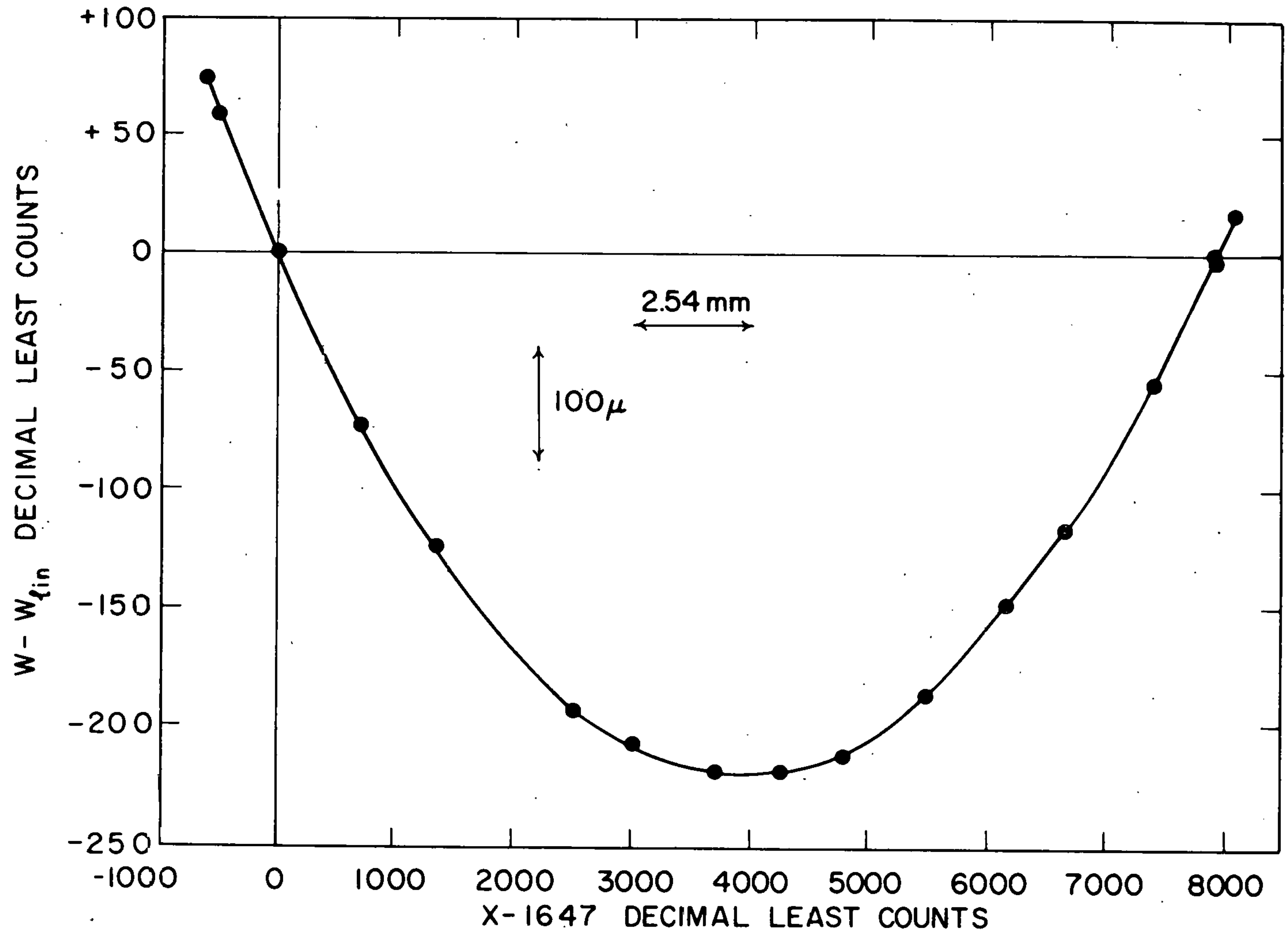
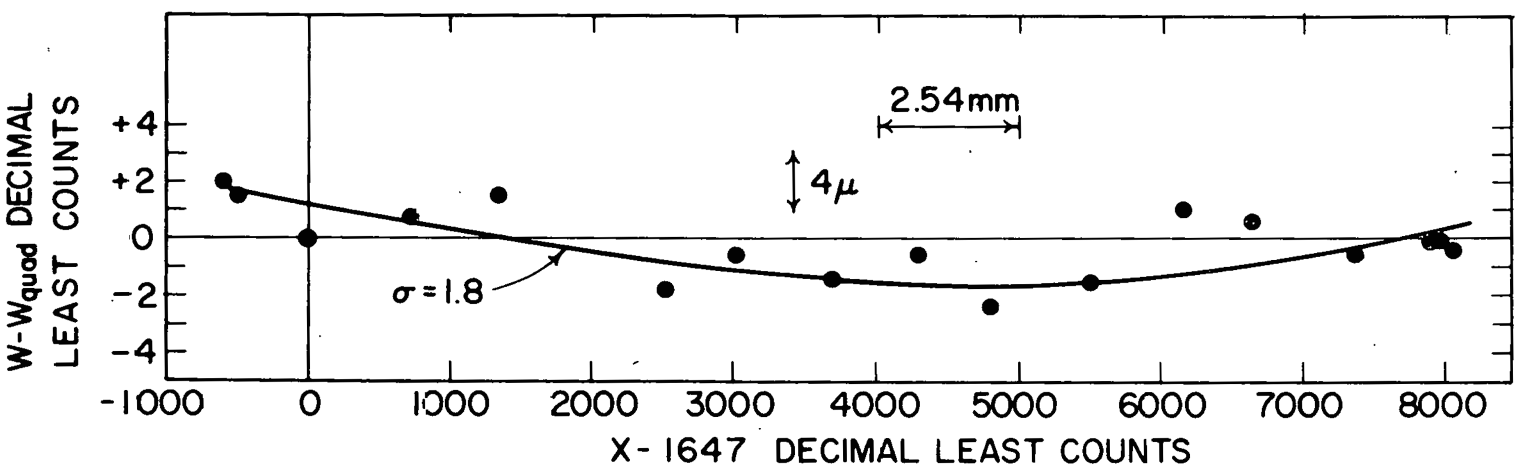

+100
+50
0
-50
-100
-150
-200
-250
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
X-1647 DECIMAL LEAST COUNTS
W- W$_{\ell in}$ DECIMAL LEAST COUNTS
2.54 mm
100μ

FIGURE 9



W-W$_{quad}$ DECIMAL LEAST COUNTS
+4
+2
0
-2
-4
2.54mm
4μ
σ=1.8
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
X- 1647 DECIMAL LEAST COUNTS

FIGURE 10

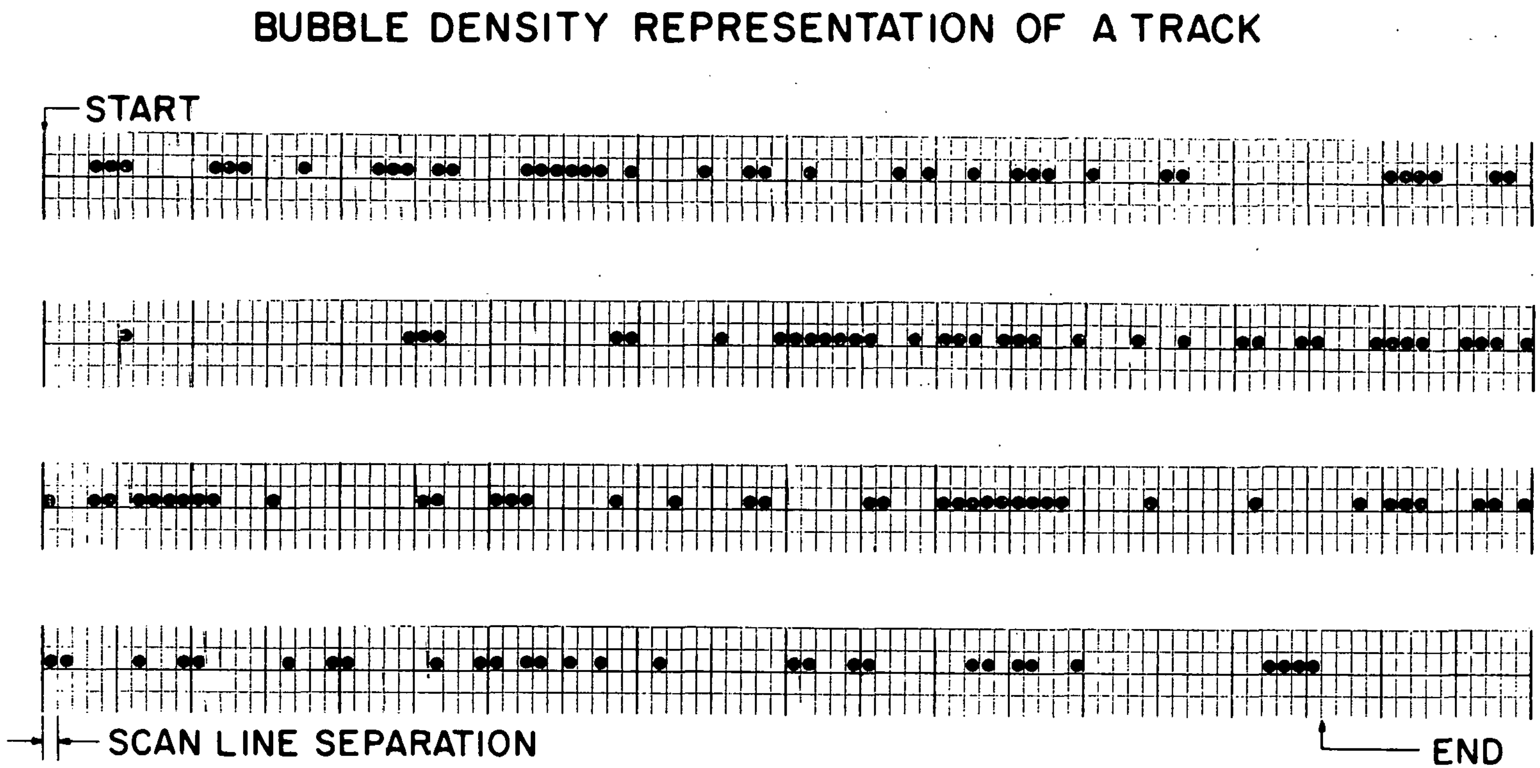

BUBBLE DENSITY REPRESENTATION OF A TRACK
START
SCAN LINE SEPARATION
END

FIGURE 11

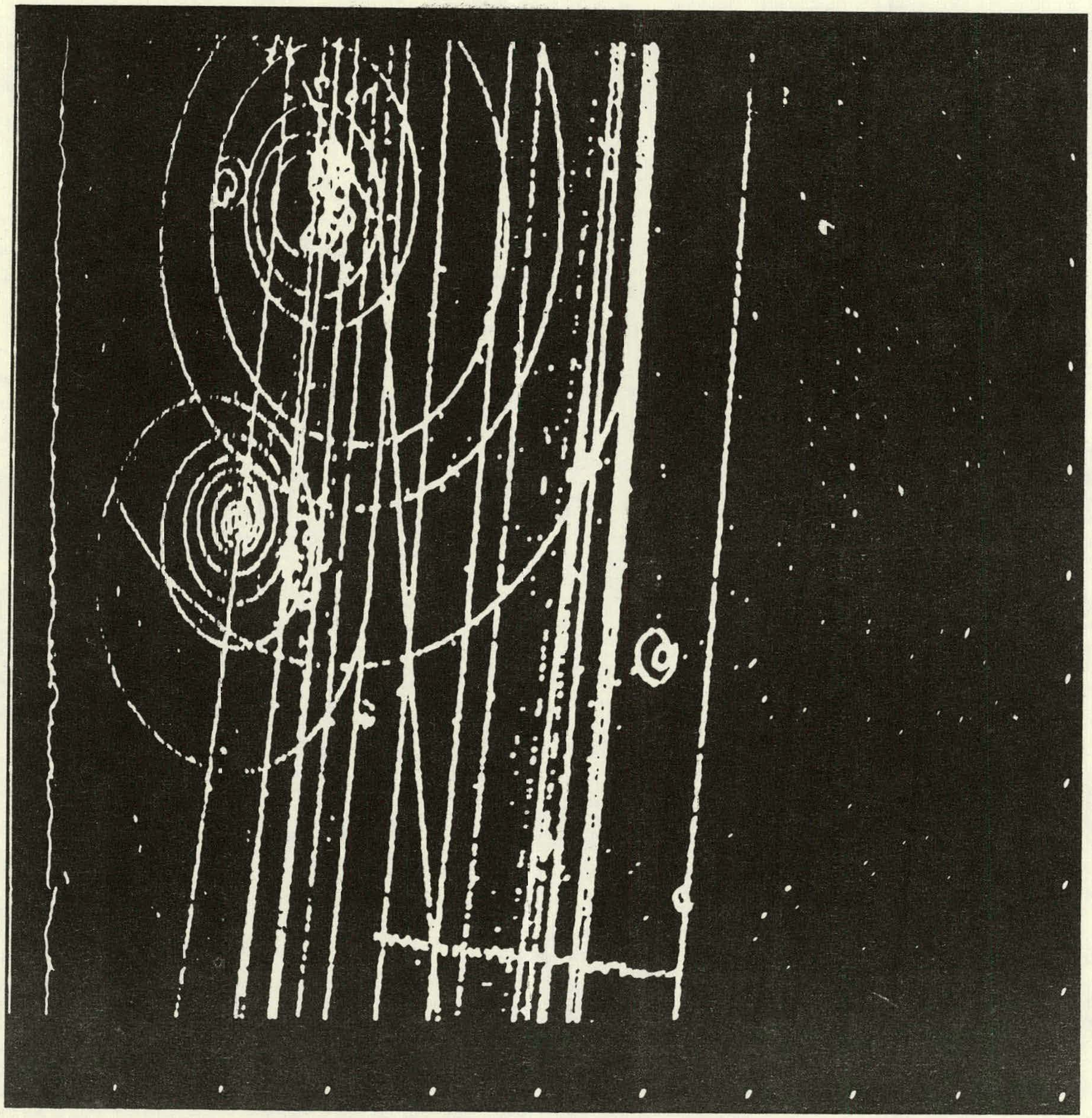


FIGURE 12

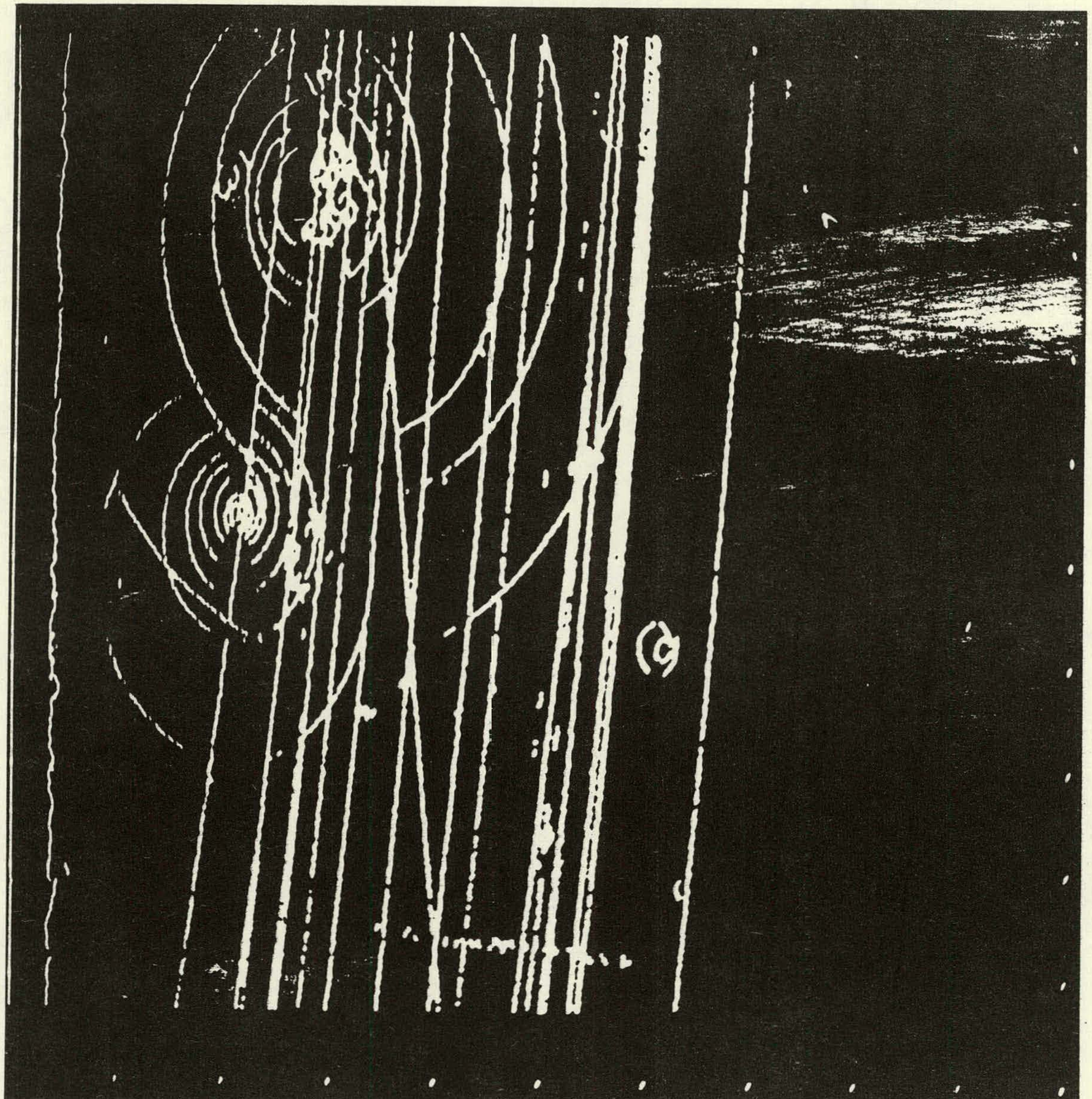


FIGURE 13

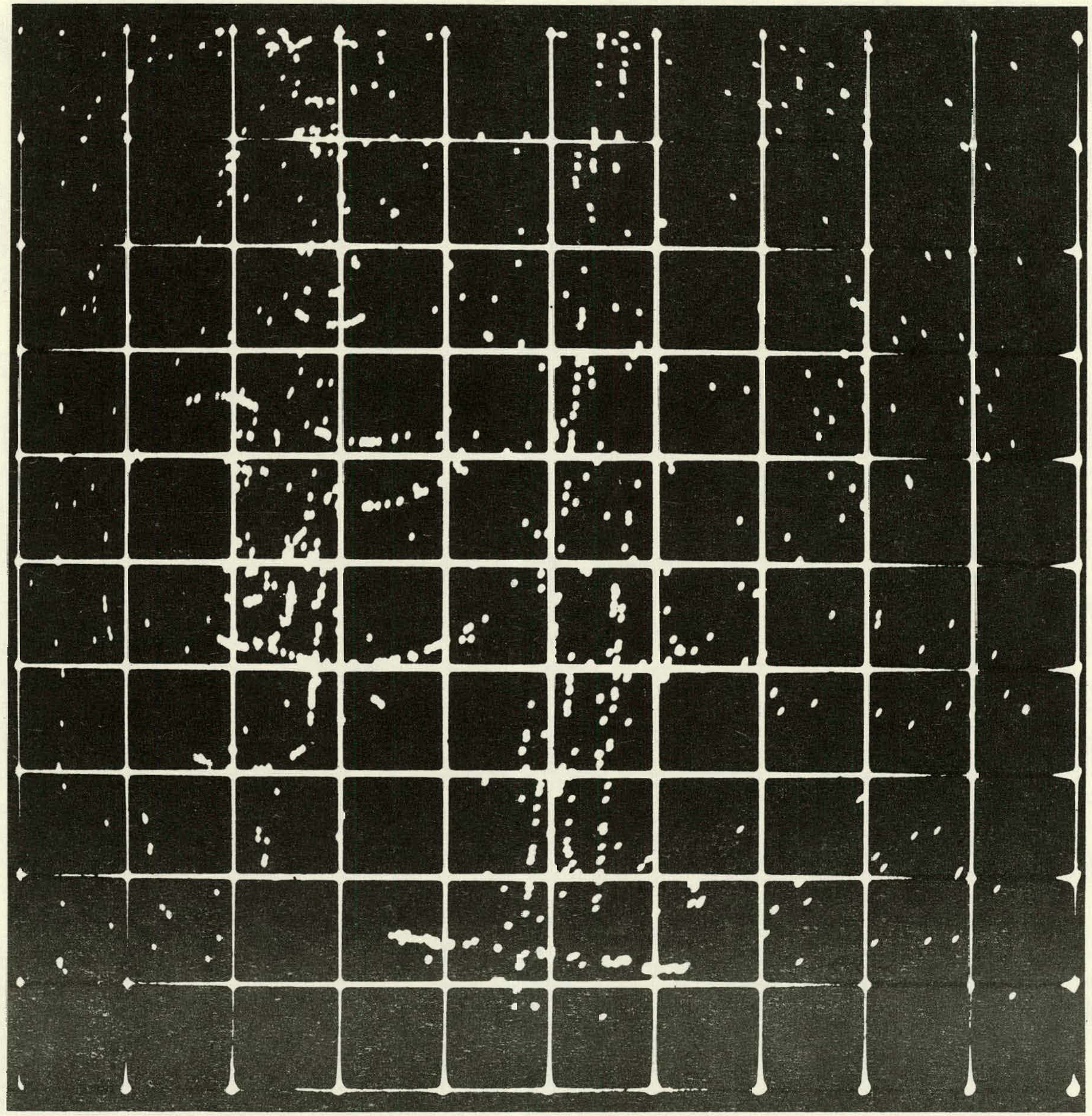


FIGURE 14

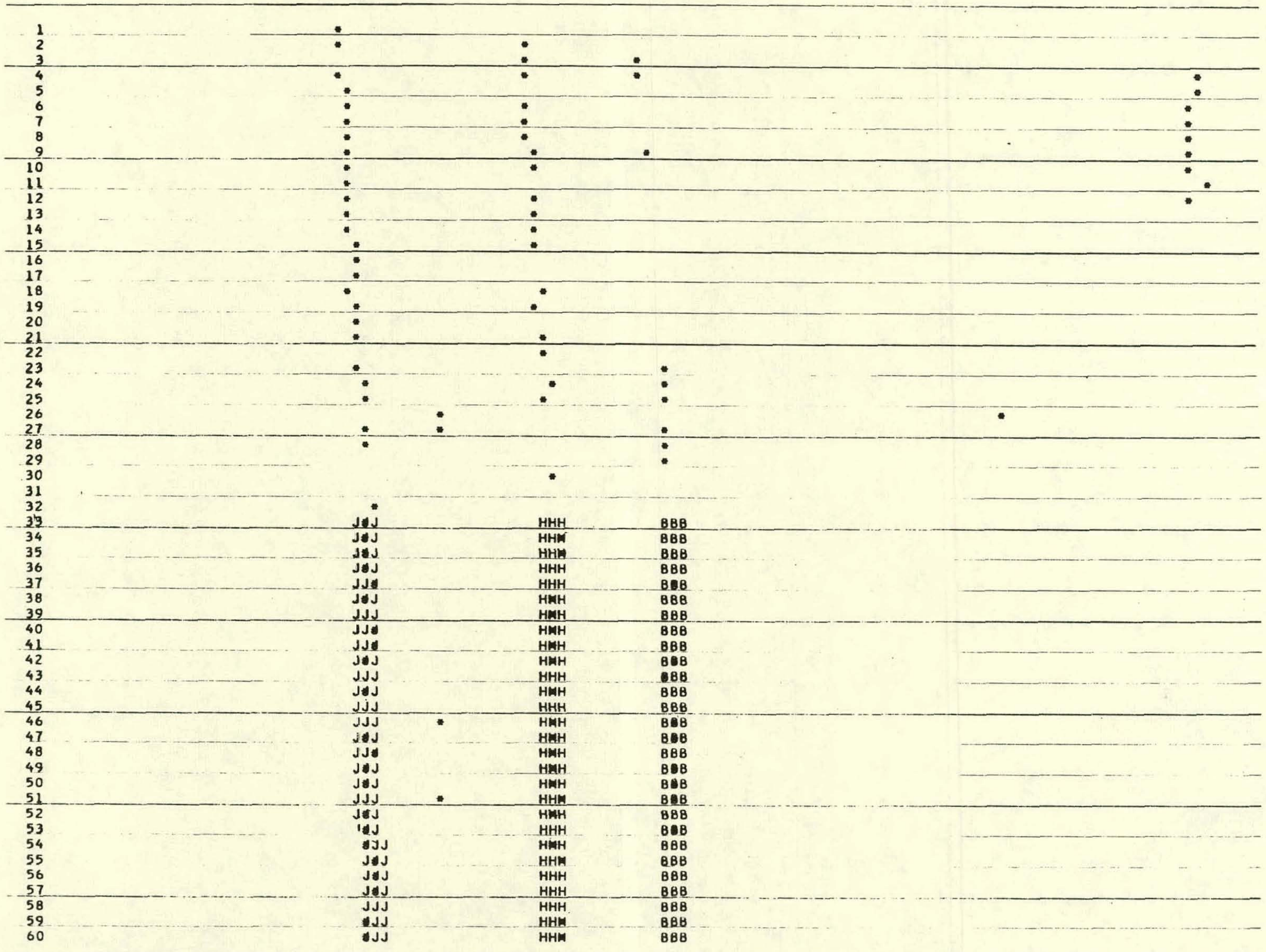


FIGURE 15

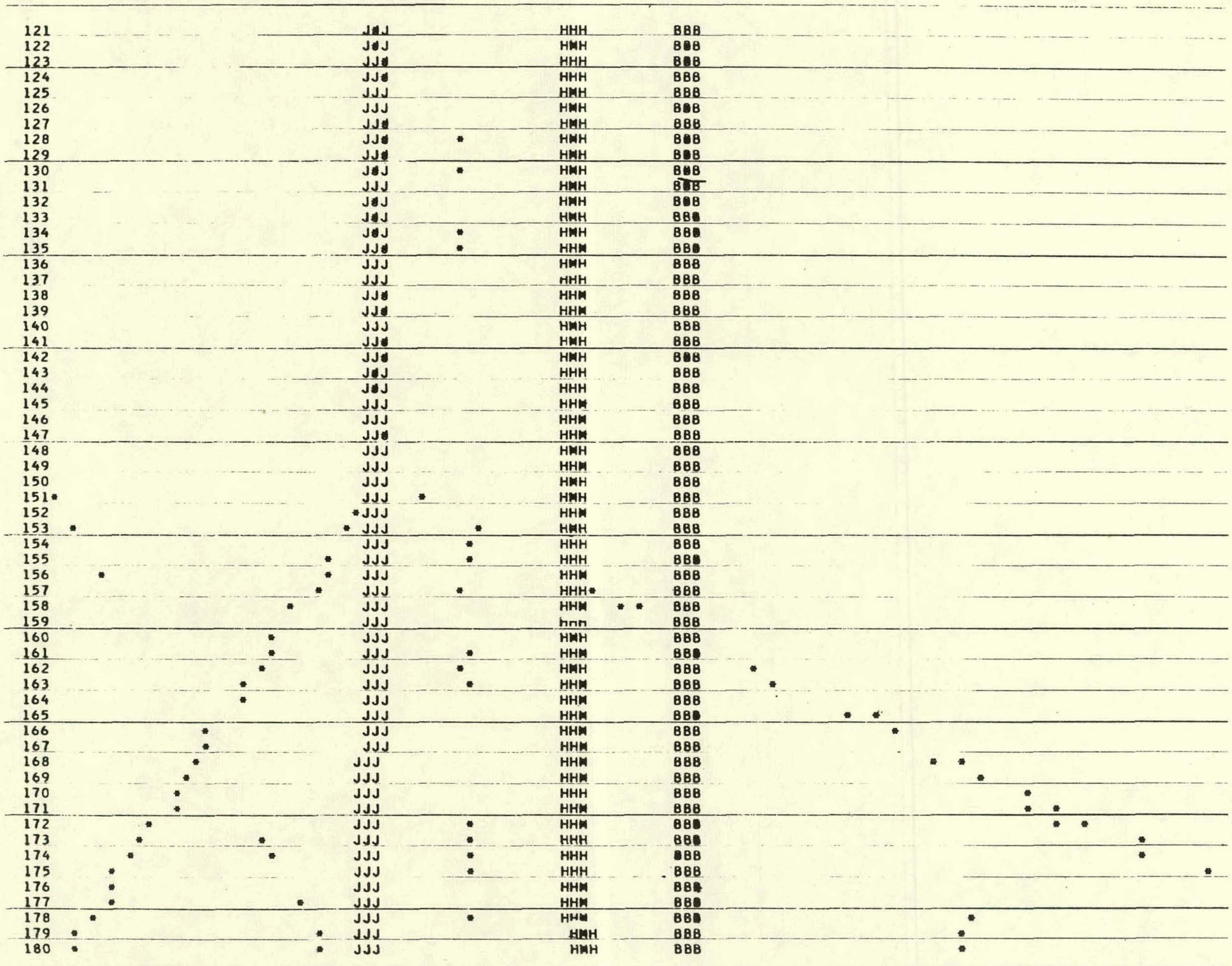


FIGURE 16