THE UNIVERSITY OF MICHIGAN

COLLEGE OF LITERATURE, SCIENCE, AND THE ARTS
Department of Physics

Progress Report

MACHINE-SCANNING OF NUCLEAR EMULSIONS AND BUBBLE-CHAMBER PICTURES

Paul V. C. Hough
Associate Professor of Physics

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ABSTRACT

This report is divided into three parts. The first part gives a brief summary of research activity during the period January-August 1959. The second part is in the form of a paper which has been submitted for publication in *Nuclear Instruments*: the paper is a critical review of the performance of the nuclear emulsion scanner in reading cyclotron plates. The third part is in the form of a report to be given at the International Conference on High Energy Accelerators and Instrumentation, at CERN in September, 1959: the report describes a program for machine analysis of bubble chamber pictures.

PERSONNEL

Paul V. C. Hough, Principal Investigator

J. A. Koenig, Assistant in Research

D. E. Damouth and M. J. Smit, Graduate Students

G. R. Spray and D. S. Sattinger, Undergraduate Scanner Operators

I. SUMMARY OF RESEARCH ACTIVITY, JANUARY-AUGUST 1959

About 3/4 of our research effort has been devoted to work with and improvements in the nuclear emulsion scanner. The results of this work are given in detail in Sec. II. The most important new development has been the introduction of a "continuous strip" search pattern. Preliminary scanning results are displayed in Sec. II, Fig. 7, and are fairly satisfactory, but it is too early to decide whether the absolute counting problem is really solved. If so, the "continuous strip" counting will be used as a supplement to the faster "isolated-field" counting to give absolute counts of the individual proton group which occur.

Most scanning work has been devoted to energy spectra and angular distributions for Mg^{24} (d,p) Mg^{25} and Mg^{25}(d,p) Mg^{26}; in addition much of the survey work for W. Williams' thesis experiment on O^{19} was done with the scanner.

A good deal of effort has gone into trying to insure successful scanning during the absence of the writer, September 1959 to September 1960 (on sabbatic leave and a Guggenheim Fellowship at CERN in Geneva). A complete set of drawings of waveforms, for normal circuit operation, has been prepared. D. E. Damouth has developed considerable skill at diagnosis of circuit failures and will be on call for maintainance. Undergraduate scanner operators are trained for second-shift operations. J. A. Koenig has complete knowledge of normal scanner operation. The use of the scanner will be under the direction of Professor W. C. Parkinson.

About 1/4 of our research time has been devoted to the problem of machine analysis of complex patterns such as bubble chamber photographs. The results of this work are given in Sec. III.

When our proposal to the AEC was written in July 1958, most emphasis was given to the detection of minimum ionizing tracks in emulsion, since it was felt that this was the next problem in a natural porder of increasing complexity. Since then, however, a definite scheme has been found for providing information on a bubble chamber photograph to an IBM 704 computer, so that the computer may recognize a complex event in a time of a few seconds. The ultimate value of this scheme, if successful, seemed much greater than that of a device for recognizing minimum tracks in emulsions, so our development effort has shifted entirely to the problem of complex pattern analysis.

The recognition scheme assumes that line segments which make up the overall pattern are detected (by some means) and that the computer is furnished with (1) rough slopes of the line segments and (2) precision intercepts of the segments with a predetermined grid of lines in the picture. We have found then by actually writing a code that the 704 can link together the line segments into tracks and provide tables of track coordinates in a satisfactorily short time.

Two large questions remain to be answered. The first is whether the required line segment information can be obtained instrumentally with sufficient accuracy and reliability (see Sec. III). The second is whether recognition of complex events can be managed in practice from a knowledge of track coordinates. The coding problem at this stage seems much easier, but we know from experience with the nuclear emulsion scanner that until many sample pictures have been analyzed by machine, almost no idea of mistake rate or detection efficiency can be had.

One of the most promising means for obtaining line segment information is the "plane transform", described in our proposal and in Sec. III of this report. Initial experiments have showed that a Vidicon Television camera could not be used to read the plane transform as originally planned because of excessive retention of image. Therefore an Image Orthicon camera has been purchased and put in service. This camera is the major equipment purchase made for the development program.

Some consideration has been given to the possibility of patenting the plane transform. Correspondence with the Chicago Operations Office showed that it was not possible to release the commercial patent rights for the plane transform to the writer. At present the patent group at Chicago has the plane transform under consideration for patentability by the Commission.

Next year the writer will cooperate fully with the bubble chamber data processing group at CERN to help them make use of any of our developments which are of interest to them. However, it would not be in the spirit of the Guggenheim or the sabbatic leave to take major responsibility for development of an analysis machine there.

On return to Ann Arbor, the writer plans to continue the bubble chamber analysis work, or whatever modification of it is indicated by wider experience in high energy physics. The overall program will be aimed at active exploitation of the excellent facilities under development at Argonne.

II. THE PERFORMANCE OF THE NUCLEAR EMULSION SCANNER*

(A paper submitted for publication in Nuclear Instruments)

*This work was supported by the Michigan Memorial-Phoenix Project and by the United States Atomic Energy Commission.

ABSTRACT

A machine has been constructed which meets many of the needs for scanning of nuclear emulsions as emulsions are used in charged particle nuclear spectroscopy. Methods developed for track detection are reviewed briefly. In more detail an account is given of the performance of the machine in scanning plates exposed at the Michigan 42" cyclotron over a seven months period. Finally, some special techniques which may have other applications are described.

I. REQUIREMENTS FOR A SCANNER TO BE USED IN CHARGED PARTICLE NUCLEAR SPECTROSCOPY

In typical experiments in charged-particle nuclear spectroscopy a well collimated, monoenergetic beam of protons, deuterons, or alpha particles falls on a thin target and reaction particles at arbitrary angle relative to the incident beam are analyzed in momentum by a high-resolution magnet. Usually several hundred momentum channels are available at the image plane of the magnet and nuclear emulsions have often been used[1,2] to record in all these channels simultaneously.

The particular geometry at the image plane of the Michigan analyzer magnet is shown in Fig. 1. The useful region of image plane extends from x =

[1] Buechner, Browne, Enge, Mazari, and Buntschuh, Phys. Rev. 95, 609 (1954)
[2] Bach, Childs, Hockney, Hough, and Parkinson, Rev. Sci. Instr., 27, 516 (1956)

+100 to x = -120 mm (in the coordinate system of the figure) and corresponds to an energy variation equal to 15% of the central energy. The overall system resolution is about 20 kev for (d,p) reactions and is limited primarily by a 15 kev spread in energy of the 7.8 kev deuteron beam on target. With this resolution, a 10 Mev proton group will have a width $\Delta x \sim 4\text{-}5$ mm at the emulsion.

With this background, we can give a reasonable set of requirements for an emulsion scanner to read plates exposed at the magnet image plane:

(1) Track detection efficiency. A scanner need not have high absolute efficiency and probably any efficiency greater than about one-half would be quite satisfactory. However, the efficiency should be reproducible and constant for all emulsions used in a given experiment. Probably a fluctuation of 5% in efficiency would be tolerable for all nuclear structure experiments because of uncertainties in nuclear reaction theory.

(2) Spurious counting. In exposures at the cyclotron for high energy proton groups (corresponding to low excitation of the residual nucleus) even long exposures will still yield regions on the emulsion where no tracks at all are found. This observation leads to the difficult conclusion that a scanner should introduce no spurious counts. More realistically, 10-20 tracks are certainly required to establish the presence of a proton group and therefore a spurious count of 3-4 over a 4-5 mm width of emulsion is probably satisfactory.

(3) Scanning speed. It has proved possible at the Michigan cyclotron to expose five to ten 1" x 10" nuclear emulsions per day for a number of days. Since an accelerator will normally be used for other experiments, this is probably an upper limit to the production rate for a single magnet image plane.

On the other hand, a multi-gap magnet[3] will increase this rate by an order of magnitude. It appears then that a scanner should be able to read 25-100 1" x 10" nuclear emulsions per day under the rather extreme demands placed on it by a multi-gap magnet installation.

II. TRACK DETECTION METHODS

Details of electronic and optical methods developed to detect slow proton tracks are given elsewhere.[4] Here we only want to review the logic of the scheme so as to make clear the reasons for the performance characteristics listed in the next section.

1. Pattern of search over the emulsion. A motor driven stage (Fig. 2) moves the 1" x 10" emulsion under a microscope in a series of traverses of the short dimension, each traverse followed by an advance of the plate. During a traverse the stage moves continuously, but by means of a pulsed light source 140 separate fields of view are presented to a television camera and associated computer for analysis. Each field of view is 0.12-mm x 0.18-mm; corresponding points in successive fields are separated by 0.15-mm; and successive traverses are separated by 0.25-mm. Normally the track count for four traverses is recorded as a single datum and so points are available for each mm along the emulsions. However, because of the gaps between fields and between traverses, each point corresponds to a search area only 0.56-mm wide (extending across the plate). The emulsion is examined at only one depth, midway between top and bottom of emulsion, so scanning is effective only for tracks

[3] W. W. Buechner, private communication
[4] Hough, Koenig, and Williams, Electronics, March 27, 1959 (McGraw-Hill)

which penetrate the emulsion completely.

2. The detection of emulsion grains, especially the grains making up tracks. A standard Leitz 22x oil immersion objective and 10x eyepiece are used to project an image of the emulsion scene onto an Image Orthicon television camera tube. Figure 3 shows a typical emulsion scene photographed from a television receiver wired to the camera. (The white dots to the right of the tracks are explained in paragraph 3 below, and the white splashes at the bottom in paragraph 4.) Two alterations have been made in the microscope optics:

It is found that the contrast is considerably enhanced by blocking off a band of light entering the microscope condenser in a plane containing the tracks and the optic axis; this leaves two "crossfire" beams illuminating the emulsion.

Also it is found helpful to introduce a cylindrical lens of radius of curvature 15-cm adjacent to the eyepiece so that the image of each grain becomes a short line roughly parallel to most tracks. This track tends to patch gaps in tracks without seriously patching together background grains into false tracks.

Kodak NTB2 or Ilford G-special emulsion are used to provide strong tracks with tolerable background grain density.

The portions of the scene detected by a special screening circuit are shown in Fig. 4. A narrowness criterion is incorporated in the screening circuit so that any large-area opacities which may occur are ignored.

3. The recognition of a track by its continuity. Delay and coincidence units are used to establish the existence of a grain just one scan line after a previous grain. A continuous track will of course give the required coinci-

dence. The coincidence resolving time is chosen so that tracks at angles up to ±45° to the vertical will still give a coincidence. An actual counting operation is performed along a track by this (delay + coincidence) technique; in fact a continual testing of background grains for the possibility that they are linked to form tracks proceeds at all lateral positions in the field of view. An output pulse which we name "track segment pulse" is produced when the count along any track reaches 16, and for each 8 counts thereafter. Since the number of television scan lines used per field is about 180, the number of track segment pulses for a track crossing the entire field is 23. A more typical number of track segment pulses for a track is 8-10 as shown in a display of these pulses as white dots to the right of each track in Fig. 3. (The doubling of pulses for the left track occurs because the exposure extends over several television scanning periods and the count along the track has begun at two different points in the different periods.)

4. Generation of a single output pulse per track. Owing to different quality of development for different tracks and to more or less favorable location of a track in the field, the number of track segment pulses obtained per track varies widely. In order to obtain one count for each track the following technique is used: an oscilloscope beam is swept along a fixed line in synchromism with the horizontal deflection of the television scanning beam. Whenever a track segment pulse occurs the oscilloscope beam is intensified and a flash of light is produced. For vertical tracks all flashes for one track occur in one spot. The oscilloscope screen is projected back into the television camera at the bottom of the field of view. The camera tube integrates

the light from the flashes originating in any one spot, i.e., from one track. Finally, a single television scan line through the spots is devoted to reading out the number of spots and therefore the number of tracks. (The two spots for the two tracks of Fig. 3 appear dimly at the bottom of the figure. The brightness distribution is distorted badly by the television receiver; as actually used, the spots have a uniform intensity over a vertical distance equal to that of the black band of the figure. The read-out line is centered in the black band.) It is possible to set a discriminator level on the final spot readout to select only tracks with more than a specified number of track segment pulses, usually 5 or 6.

5. Final output. The number of spots detected is accumulated in a scalar until four traverses across the plate width are completed. Then this number is printed on paper tape and plotted on a chart recorder as shown in Fig. 5. The error bars are obtained via a square-root potentiometer mounted on the shaft of the chart recorder. A recorder scale change from 200 tracks to 2000 tracks full scale can be seen for three intense groups in Fig. 5.

III. SCANNER PERFORMANCE

A. TRACK DETECTION: ABSOLUTE EFFICIENCY AND REPRODUCIBILITY

On comparing the scanner with a human observer for a series of proton groups and a series of plates, the scanner count may be found anywhere between 80% and 120% of the human count, for equal search areas.* The machine-human ratio changes only slowly with position on the plate so that peak positions and peak

*A smaller fluctuation of ±5% is quoted in Ref. 4, but this is incorrect.

contours are reproduced fairly accurately, but the failure of the machine to maintain constant efficiency is a major defect.

The difficulty has been traced to the use of isolated fields of view as the search pattern for the scanner. Referring to Fig. 6, we define w = width of field of view, h = height of field of view, L = length of track in good focus (as judged by the electronics), ℓ = length of track within the field of view required for the track to count. Evidently if the upper end of a track falls within the area $w \times [h + (L - \ell) - \ell]$ the track will count, and therefore the effective search area is increased over the geometrical area wxh by the factor $\frac{h + (L - \ell) - \ell}{h}$. The parameter ℓ is easily held constant, usually at the value $\ell = h/4$, but L is subject to fairly wide variation with quality of emulsion development and especially with slight changes in the optical and television systems. This variation in L and the corresponding variation in search area is responsible for the major part of the observed variation in machine detection efficiency.

Simply considering the scanner as a counter, this problem of searching in isolated fields shows up clearly. Because tracks can have any fraction of their length inside the field of view the pulse height distribution from tracks observed in a collection of isolated fields necessarily extends down to zero. Now since the scanner uses a simple level discriminator to record all track pulses above a certain arbitrary height, if the mean pulse height changes (i.e., the mean track length as judged by the electronics changes), the fraction of pulses above a fixed level will in first order respond linearly. The scanner, regarded as a counter, is a counter without a plateau.

The scanner is still quite useful in searching for new particle groups and for identification of the mass of the target nucleus responsible for new groups by reading spectra at a number of reaction angles. However, human scanning is needed for absolute counts over the peaks.

Recently, an alternate scanner research pattern of continuous strips has been provided at a factor 4 reduction in speed. The results of two such machine scans are compared with a hand scan in Fig. 7, showing a much more constant detection efficiency. It seems that it may be possible to carry out also by machine the absolute counting required.

B. SPURIOUS COUNTS

The background count introduced by the machine averages about one per plotted point, i.e., per geometrical search area equal to a strip 0.56-mm wide extending across the 1-inch dimension of the plate. Most of this machine background arises from neutron recoil tracks which are easily rejected by a human observer.

At first, emulsion surface marks often introduced whole blocks of spurious counts. Fortunately it was found that surface marks are easily removed by rubbing off the top few microns of processed emulsion with paper tissue soaked in methyl alchohol. This cleaning process is now followed routinely and is necessary for low background.

The scanner background is low enough so that it is not a limitation in nuclear spectroscopic applications.

C. SHORT-TERM AND TIME-AVERAGED SCANNING RATES

We have noted that a "point" plotted for each mm of the analyzer magnet image actually corresponds to the geometrical search area of a strip 0.56-mm wide. So about half the plate area is normally scanned.

The scanner plots four points per minute and therefore reads the 220-mm useful range of an image plane in 55 minutes. Normal cleaning, recording, and checking operations between plates occupy another 20 minutes, so that in steady, trouble-free scanning plates are read at the rate of one every hour and 15 minutes.

Averaged over an eight hour day it is possible to read five image planes (1" x 10" plates) and fairly easy to read four. For the past few months, it has proved useful to employ undergraduate assistants to run a second shift from 5 to 11 P.M. in which case another three or four plates are normally read. In sum, 7-9 image planes can be read per day, or about 1800 plotted points. By comparison, a human scanner will produce between 100 and 150 plotted points per day.

Because of operator fatigue, the machine rate could probably not be maintained for months. It has not been necessary to try, because on the one hand large scale cyclotron exposures are ordinarily interspersed with exploratory runs or experiments with counters, and on the other, it has unfortunately been easy for the machine to saturate the three available human scanners with absolute counting jobs.

D. PROBLEMS OF OPERATION AND MACHINE MAINTAINANCE

The whole system uses 635 tubes: 128 in locally designed and built circuits, 154 in the television system, 132 in broad band amplifiers, 103 in various other commercial units, and 118 in power supplies. In view of this complexity, arrangement is made to check the performance of any part of the scanner by switching in a synthetic signal which imitates a straight, vertical, continuous track. As a final integral check, at the beginning and end of each scanning period a standard proton group is counted and the machine required to produce a count within ±10% of the correct value.

During scanning runs, the track segment pulses defined in Sec. II, paragraph 3, are displayed continuously on a television screen. The resulting pattern changes at a 60 cps rate, but it is still possible to detect tracks by eye and for low track densities to verify the performance of the machine track by track. At higher track densities visual checking becomes impossible, but a gross failure of any part of the machine is usually obvious.

The failure rate of the circuitry built in our laboratory is about the same as the failure rate of the television, and for about the same number of tubes. Tube failure has been the most frequent but not the most annoying cause of circuit failure. More troublesome have been the development of bad contacts at solder joints and the development of high frequency oscillations in portions of the circuit which had been free of difficulty since construction, often a year or two earlier. The effort and especially the quantity of highly skilled effort which can go into uncovering the cause of failures has encouraged the development of very complete records of normal circuit performance, especially a comprehensive collection of oscilloscope drawings.

E. RESULTS OBTAINED OVER A SEVEN MONTHS PERIOD

Over the first seven months of 1959 the scanner read 206 1" x 10" plates exposed at the cyclotron. About 30 plates were not read, 4 because of a development failure and the rest because similar exposures had been read by machine and the existence and rough intensities of the various proton groups had been established. At the beginning of the period scanning requests were met with great difficulty and often several days would elapse while operational difficulties were traced down. A shift from Kodak NTB to Kodak NTB2 (or Ilford G-special) emulsion, the development of a really reliable focus control for the microscope, and a number of small engineering improvements have made scanning much easier so that by the end of the period relatively untrained personnal could read plates on demand within the performance specifications we have quoted.

Figure 8 shows a chart of a machine scan, with hand counts over several peaks also plotted. The lateral shift of hand and machine data is due to a different convention in reading the left end of the plate.

Finally, as a general indication of the kind of work done by the scanner, we show in Fig. 9 a photograph of part of an analysis board used to keep track of an investigation of the level structure of Mg^{25}. The board is divided into halves, the left half devoted to proton groups of energy between 4 and 8 Mev, the right half to groups between 8 and 14 Mev. In each half, channels are established for mounting spectra of reaction protons observed at angles 10°, 20°, 30°, 40°, 50°, 70°, and 90°. (About twice as many angles are run for an angular distribution.) In each channel the same energy scale is established: the scale is non-uniform, with a rate of change of energy with position at any energy approximately equal to that of a scanner chart run at that energy. Therefore overlapping charts fit together to give continuous spectra. The analysis board is mainly a bookkeeping aid, useful for planning exposures and deciding what work is completed. By looking at the forward-angle charts the qualitative stripping angular distribution of a particular group is clear, and by inspection of the large-angle charts, the change in proton energy with angle is evident and therefore even by inspection one can make a close estimate of the mass of the target nucleus responsible for the group. The energies of the usual contaminant groups from carbon, oxygen, and hydrogen can be plotted on the board once for all.

IV. SOME SPECIAL TECHNIQUES

A. AUTOMATIC FOCUS CONTROL FOR A MICROSCOPE

In scanner operation it is necessary to control the position of the microscope objective relative to the top surface of the emulsion to within ±10 microns. This particular number follows from the need to keep a focal region about 20 microns deep entirely within a thickness of processed emulsion equal to 40 microns. Without focus control, reasonable care in leveling the microscope stage will reduce variations in objective-emulsion separation to about 50 microns. This residual variation is of two types: (1) the focus changes abruptly by 15-20 microns according to the direction of traverse; (2) the focus changes slowly with the lateral posotion due to a non-zero angle between the plane of the top surface of the emulsion and the plane of the stage motion.

A very simple mechanical control reduces focus variations to about ±5 microns. In Fig. 10, spring A is used to load the lower part of the objective against the emulsion. The tungsten carbide ball B is rigidly attached to the loaded objective by the heavy steel piece C and constitutes the bearing point against the emulsion. The bearing point is displaced from the optic axis of the objective by about 4-mm, perpendicular to the plane of the paper. The screw D is turned with a small removable wrench to distort piece C by a mil or two, moving the ball B up or down relative to the objective and thereby adjusting the depth at which the focus is controlled. In making the initial adjustment of the control the objective is lifted via the tungsten carbide bearing about 6 mils from its equilibrium position by raising the microscope stage. Then a restraining cam (not shown) is installed to catch the objective after a drop of 2 mils. This allows the objective to slide smoothly onto the emulsion again after leaving it at the end of scanning traverse.

B. ELECTRONIC CONTRAST ENHANCEMENT FOR FASTER HUMAN SCANNING

Given a television system to look at emulsions, the various types of electronic analysis used in wholly automatic scanning can be presented also on a television receiver for easier human scanning. Without going into detail, Fig. 11 shows a normal scene with two possible forms of electronic enhancement. A defect in some application would be the discrimination likely to occur against tracks which are parallel to the television scan lines.

V. ACKNOWLEDGMENTS

It is a pleasure to thank G. R. Garrison, Director, and F. M. Remley, Technical Director, of The University of Michigan Television station for generous assistance. The excellent technical development work of J. A. Koenig was essential at every stage of the investigation. D. E. Damouth has been responsible for the development of continuous-strip scanning which shows such promise for reproducible efficiency. The contribution of R. O. Winder, W. Williams, and B. Cosby in the creation of certain component parts of the scanner is greatfully acknowledged.

FIGURE CAPTIONS

Figure

1 The geometry of the image plane of the Michigan analyzer magnet.

2 The scanner microscope, showing the motor driven stage.

3 A typical emulsion scene photographed from a television receiver wired to the Image Orthicon television camera. For an explanation of the white marks beside the tracks and at the bottom of the field, see Secs. II-3 and II-4.

4 The portions of the scene of Fig. 3 which are detected by a special screening circuit.

5 Track counts accumulated for four traverses are printed on paper tape, and also plotted with appropriate error bars on a chart recorder. The strong groups are plotted with a factor 10 scale change.

6 Two tracks of length L shown in extreme positions for detection. The minimum length within the field required for detection is ℓ.

7 Preliminary results for continuous strip scanning. Two machine scans are compared with a hand scan of the same region.

8 A typical machine scan. Hand counts over the peak are also shown. The lateral shift of hand and machine data is due to a different convention in reading the left end of the plate.

9 An analysis board used to keep track of an investigation of the level structure of Mg^{25}. For details, see the text.

10 A simple mechanical focus control which maintains the plane of best focus a fixed distance below the emulsion surface with an accuracy of about ± 5 microns.

11 A normal scene with two possible forms of electronic contrast enhancement.

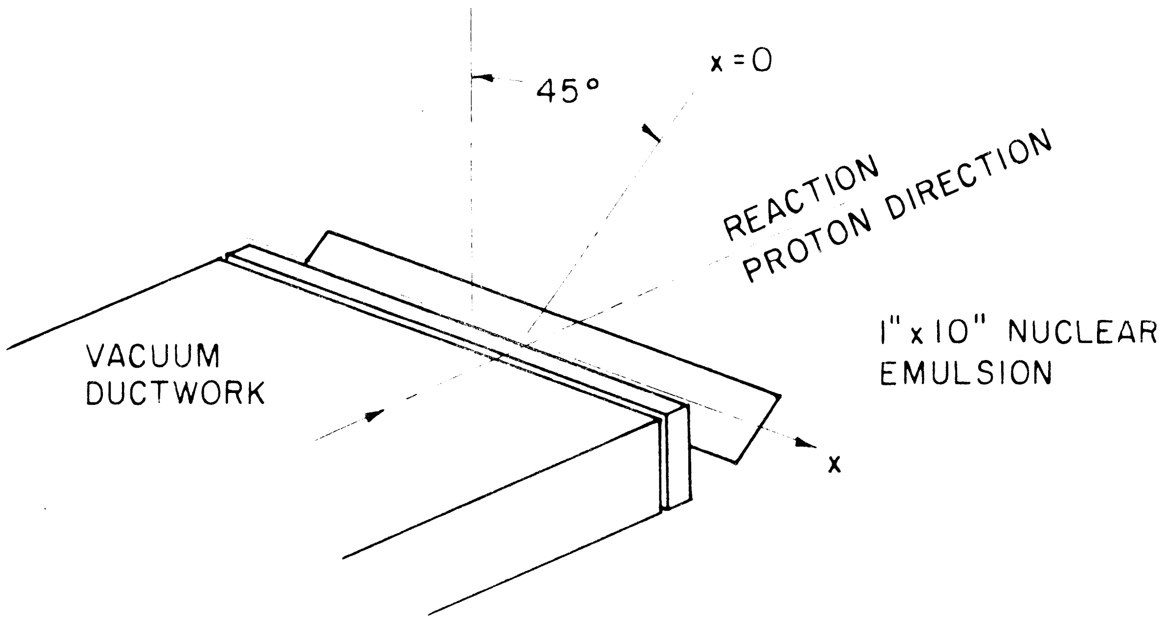

45°
x = 0
REACTION
PROTON DIRECTION
VACUUM
DUCTWORK
1" x 10" NUCLEAR
EMULSION
x

Fig. 1

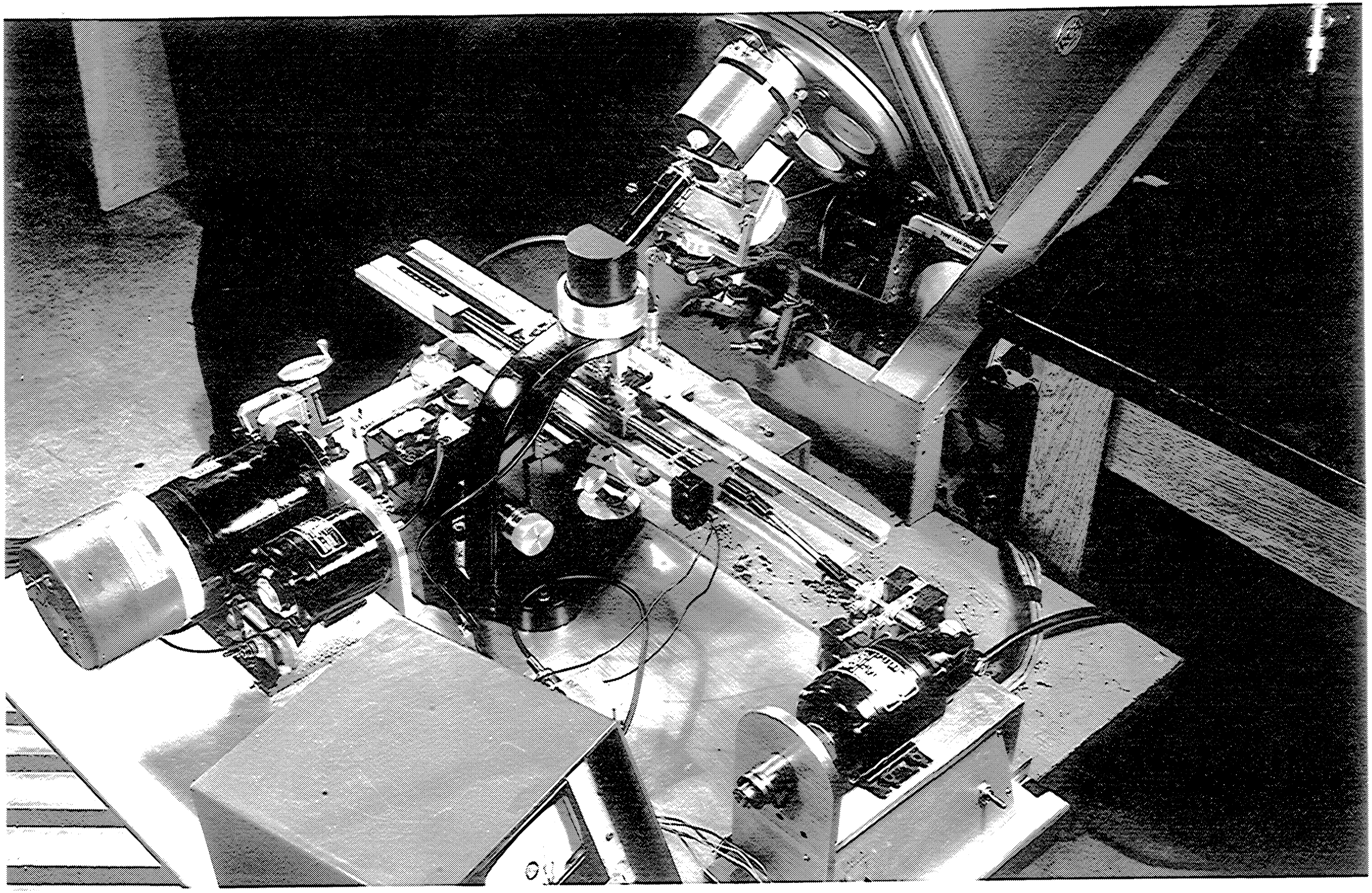


Fig. 2

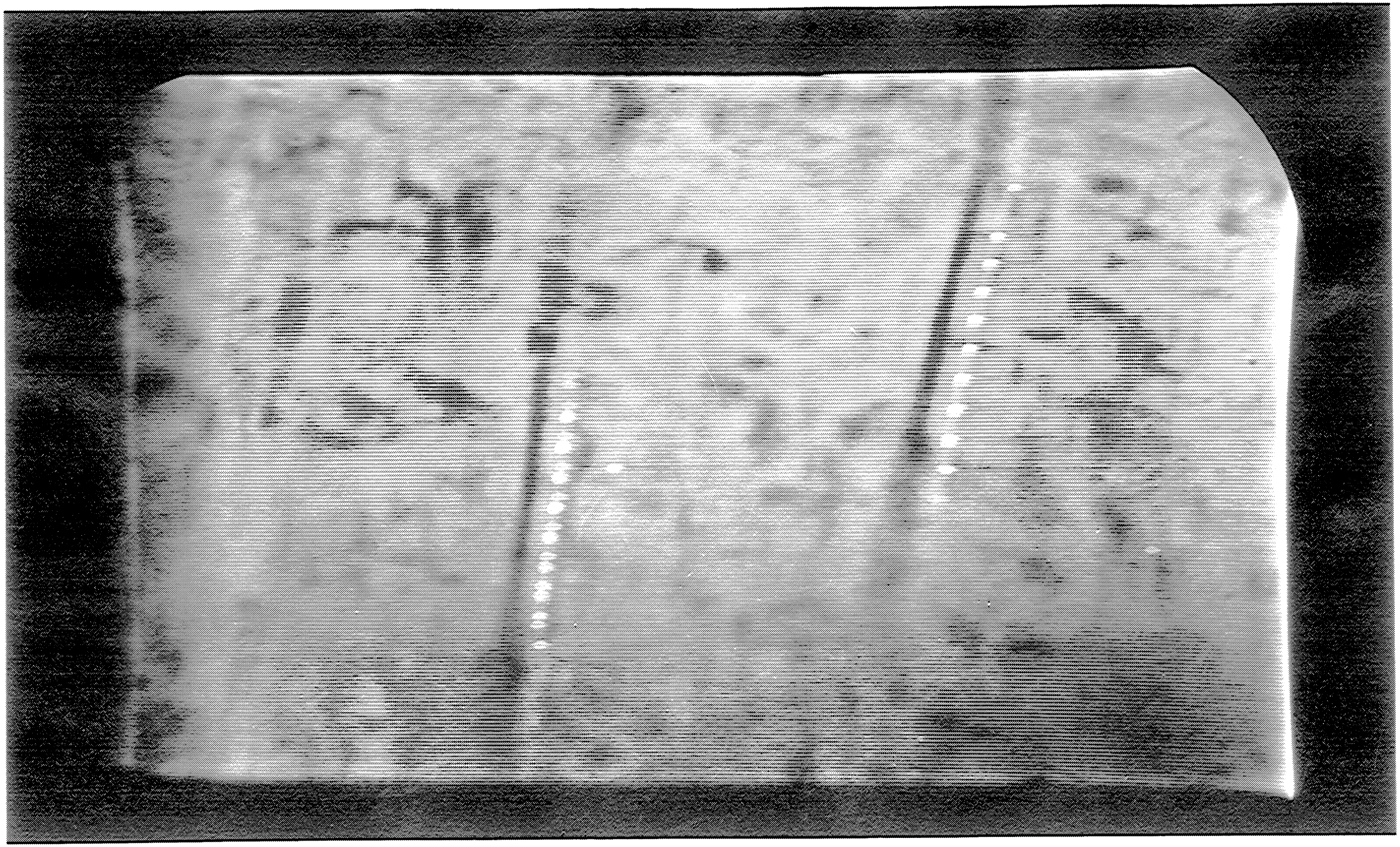


Fig. 3

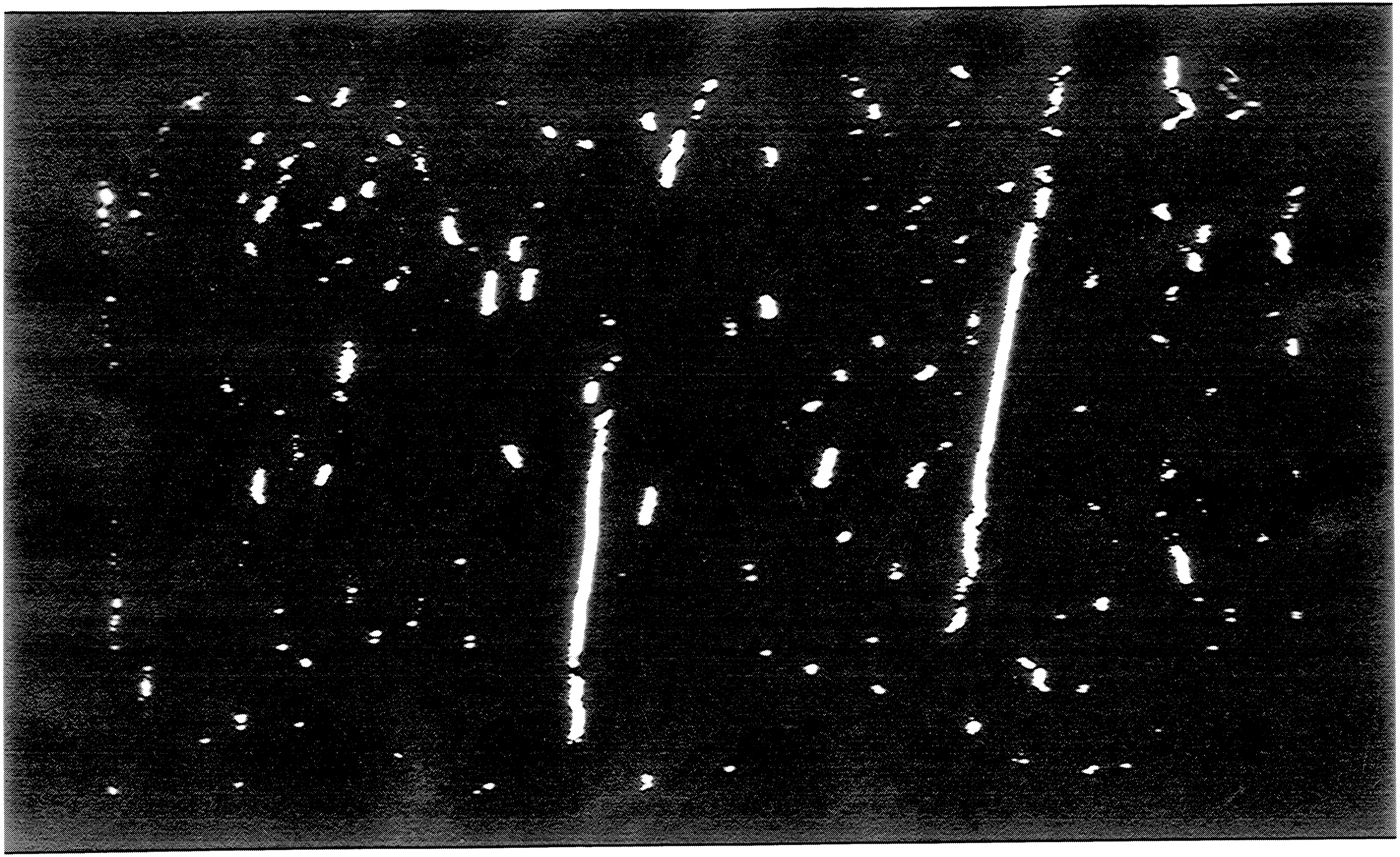


Fig. 4

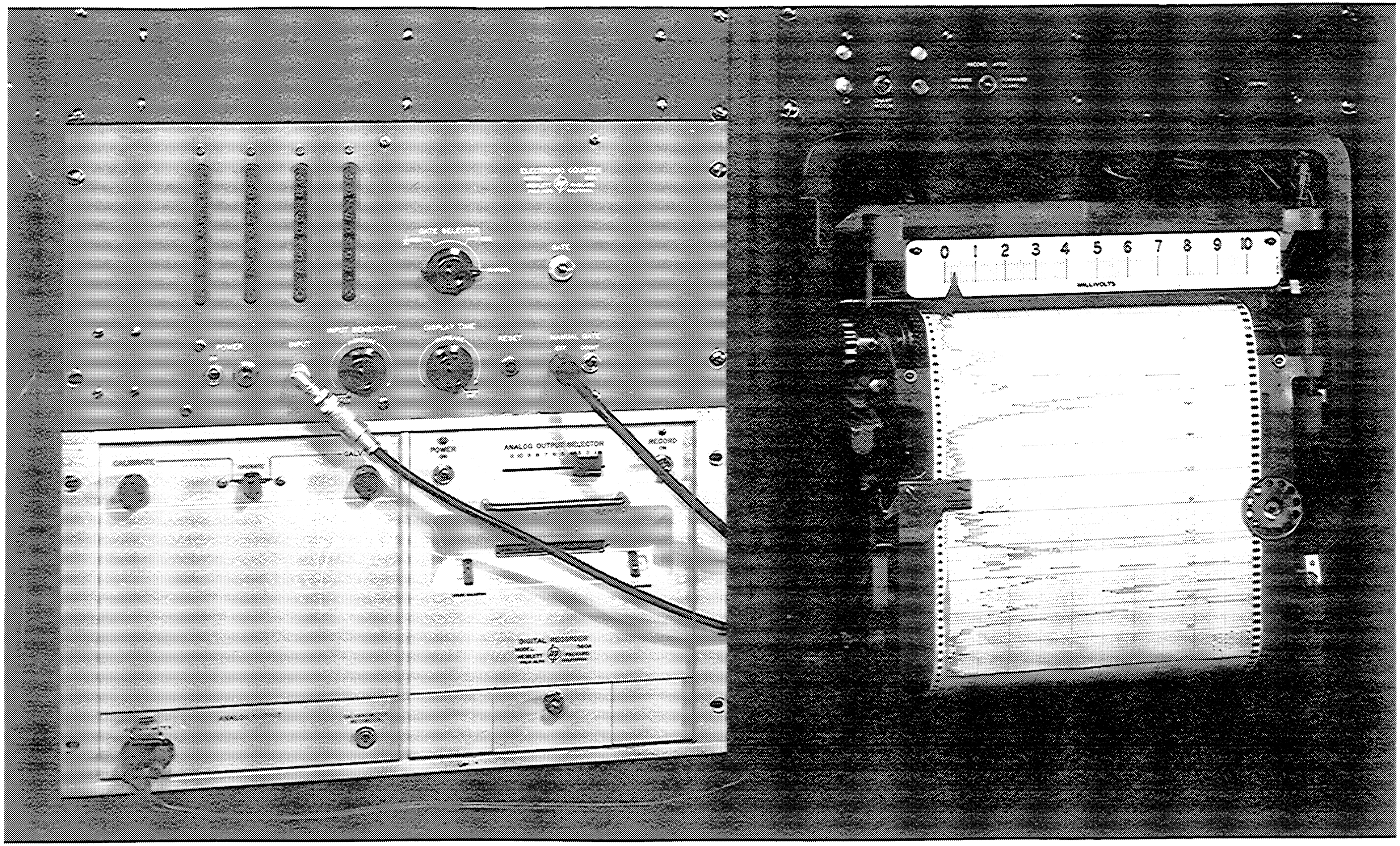

ELECTRONIC COUNTER
GATE SELECTOR
GATE
POWER
INPUT
INPUT SENSITIVITY
DISPLAY TIME
RESET
MANUAL GATE
CALIBRATE
OPERATE
ANALOG OUTPUT
POWER
ANALOG OUTPUT SELECTOR
RECORD
DIGITAL RECORDER
HEWLETT PACKARD
0 1 2 3 4 5 6 7 8 9 10
MILLIVOLTS

Fig. 5

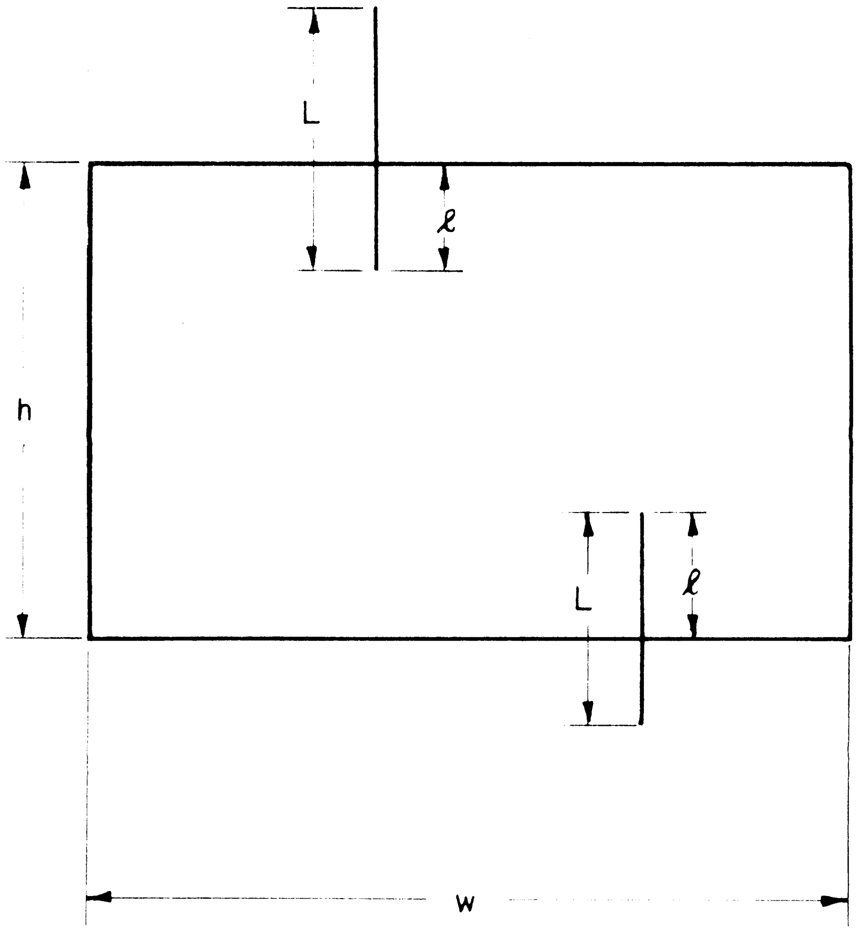
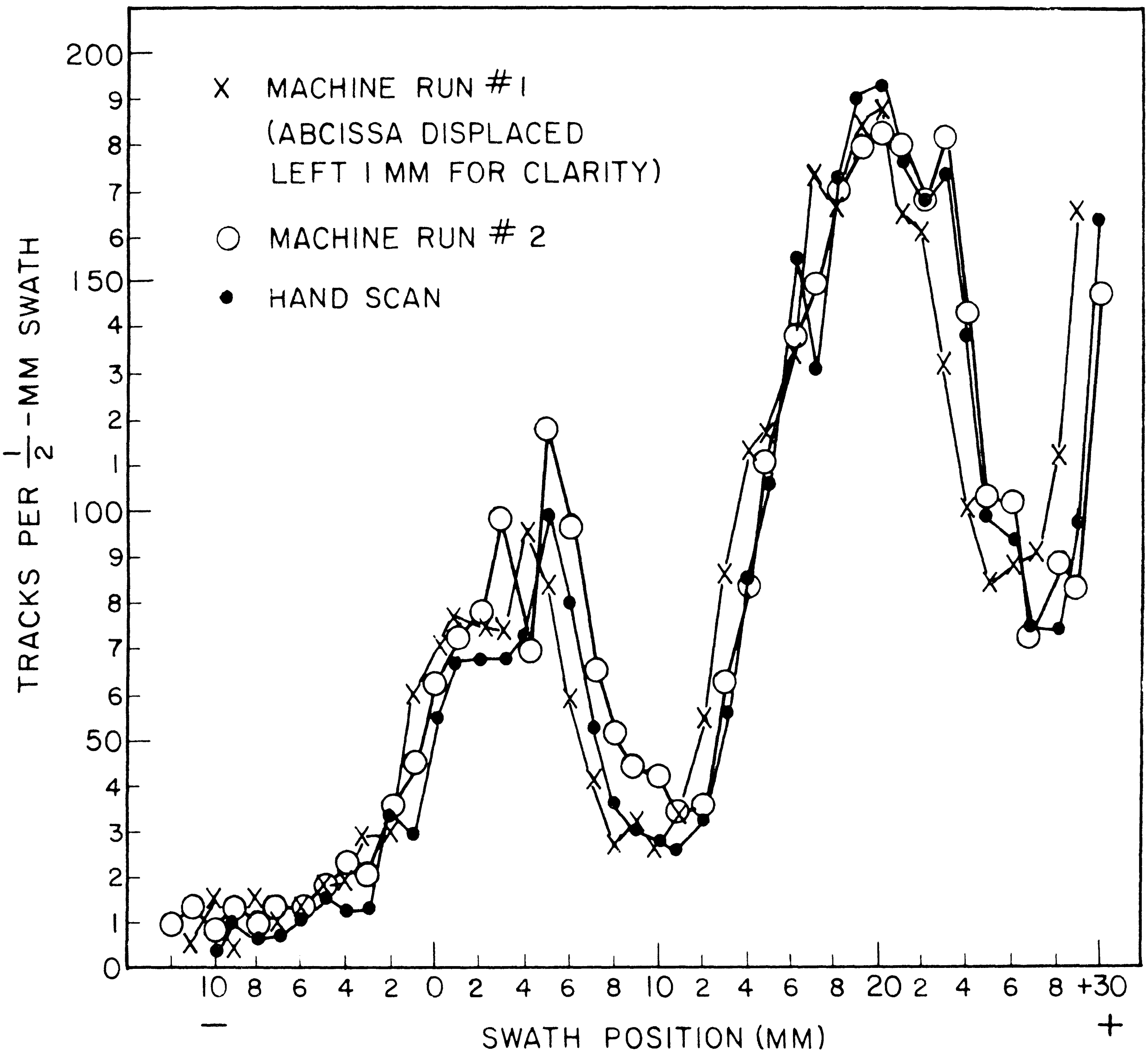


Fig. 6



X MACHINE RUN #1
(ABCISSA DISPLACED
LEFT 1 MM FOR CLARITY)
MACHINE RUN # 2
HAND SCAN
TRACKS PER 1/2 -MM SWATH
200
9
8
7
6
150
4
3
2
1
100
9
8
7
6
50
4
3
2
1
0
10 8 6 4 2 0 2 4 6 8 10 2 4 6 8 20 2 4 6 8 +30
—
+
SWATH POSITION (MM)

Fig. 7

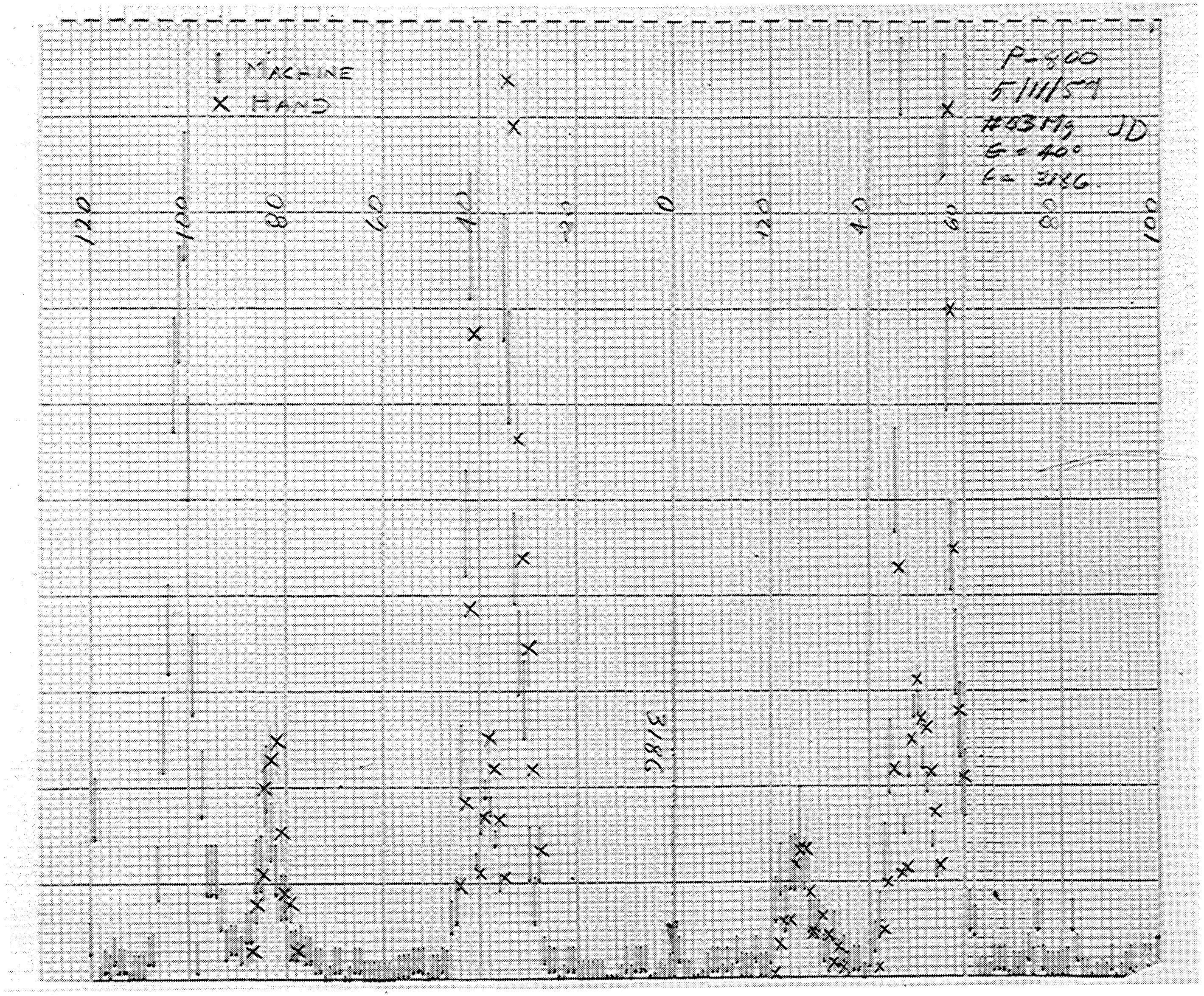

| MACHINE
X HAND
P-400
5/11/59
#03 Mg JD
θ = 40°
ℓ = 3186
120
100
80
60
40
20
0
20
40
60
80
100
3186

Fig. 8

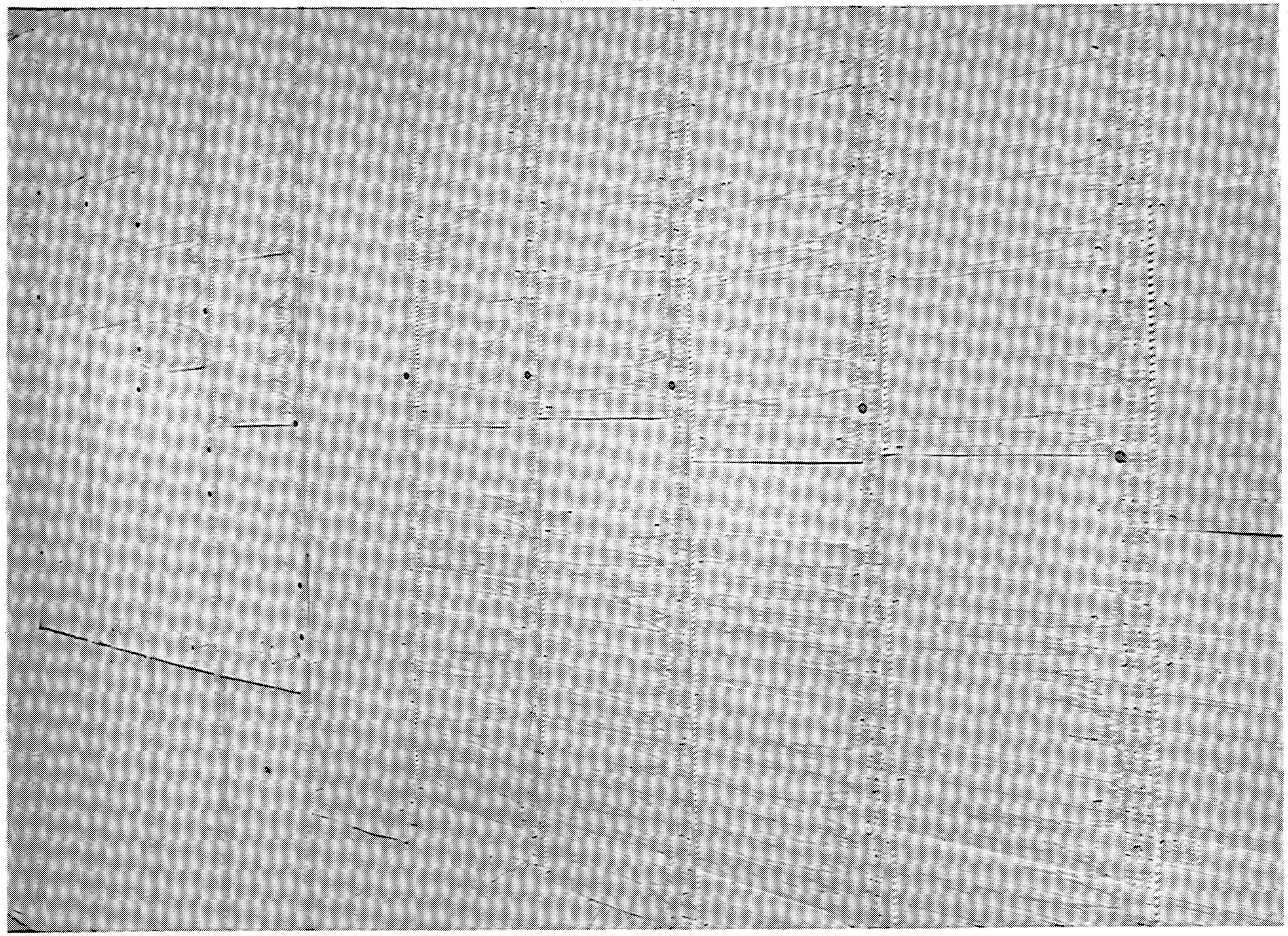


Fig. 9

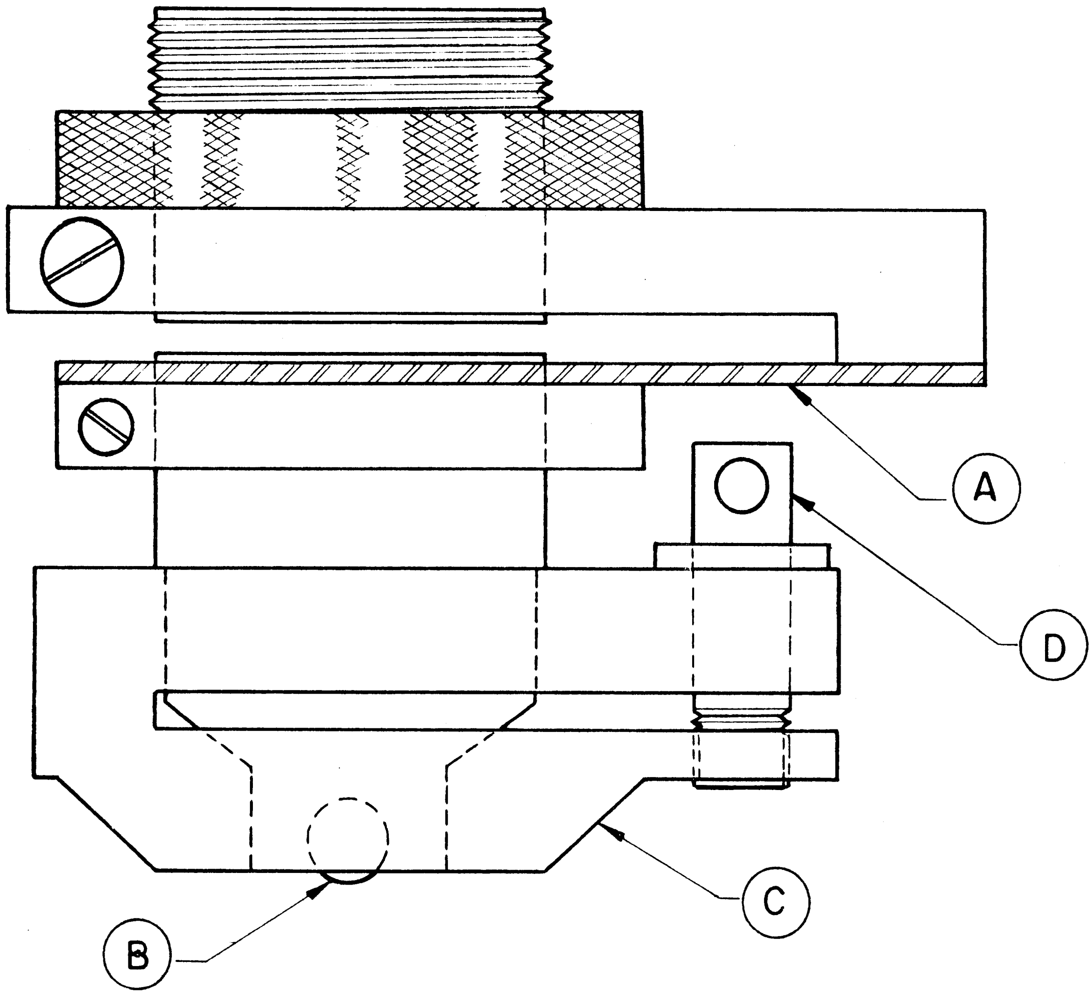


Fig. 10

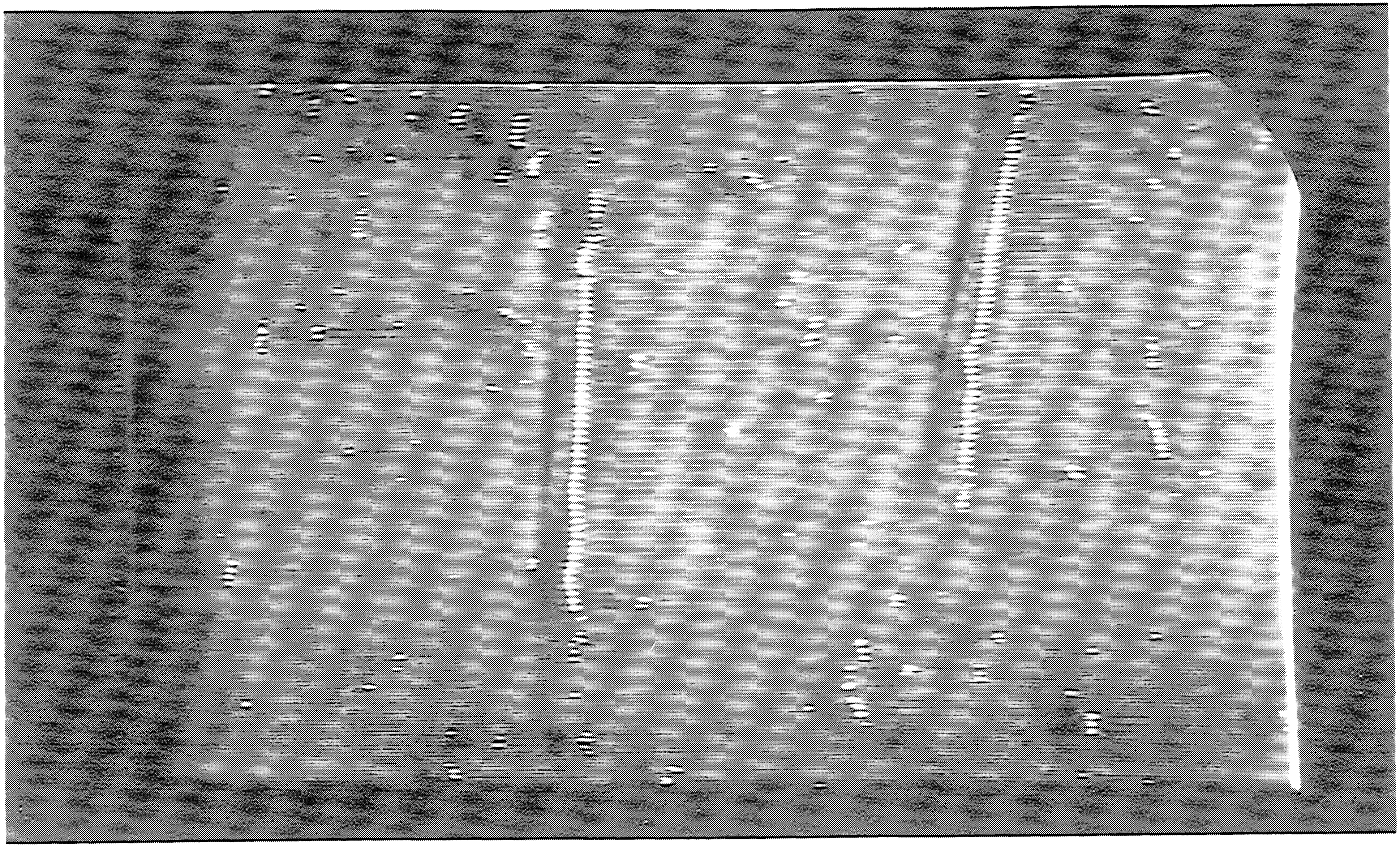


Fig. 11a

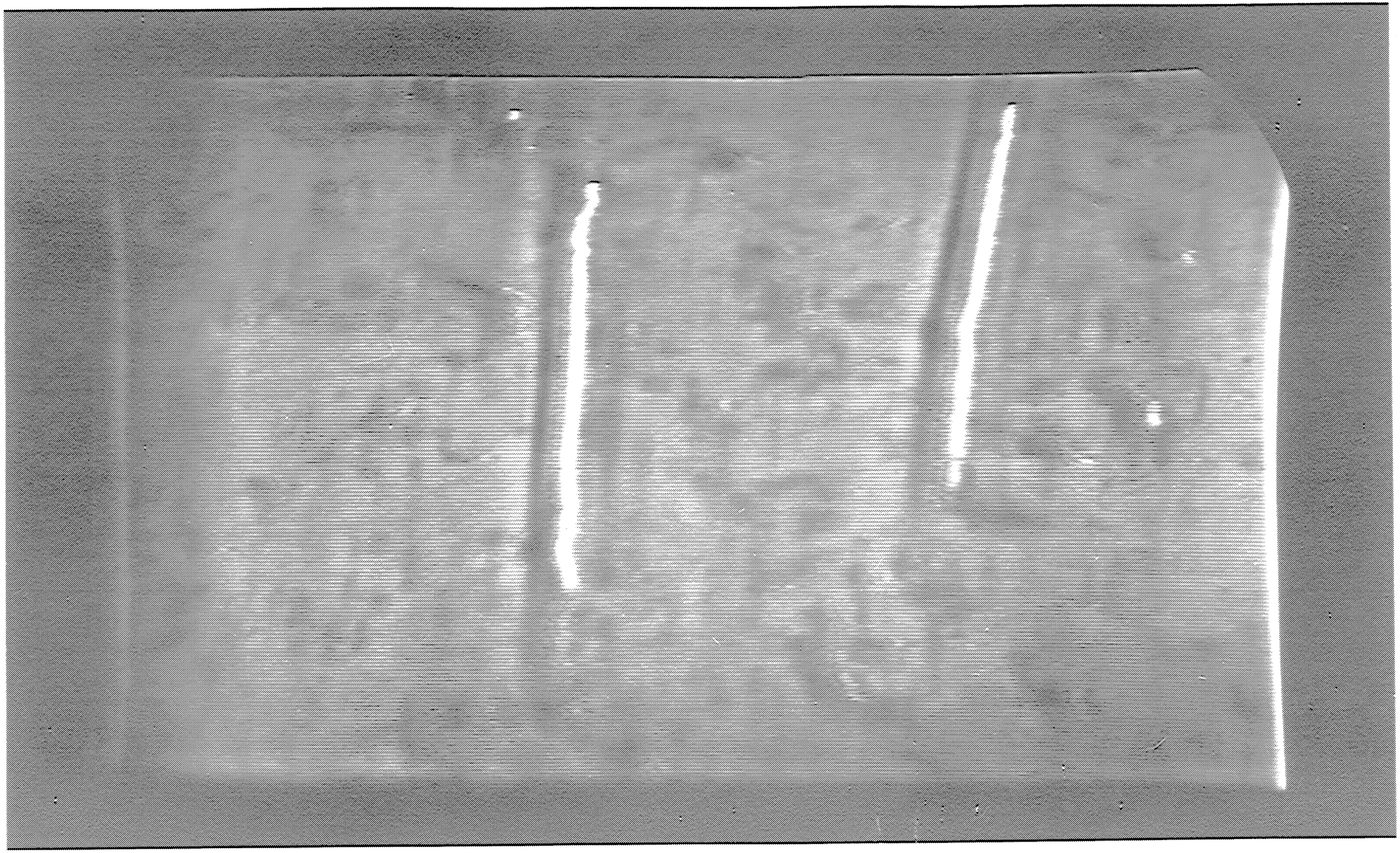


Fig. 11b

III. MACHINE ANALYSIS OF BUBBLE CHAMBER PICTURES

(A report to be given at the CERN Conference, September, 1959)

ABSTRACT

A method is proposed for going over from television inspection of a bubble chamber picture to geometrical and kinematic analysis of strange particle events without human intervention. The innovation which makes this possible (at least in principle) is the direct detection of line segments which make up the tracks in the picture. Two methods are proposed for recognition of line segments. Either furnishes positions and slopes of track line segments in the picture to an IBM 704 computer which can then in a time of 1-2 seconds link the line segments into tracks and provide tables of track coordinates. A computer program for recognition of complex events has not been carried further but may well be less difficult from this stage on.

An analysis machine using these ideas is under construction. The results of experiments with parts of the machine are described in context.

1. AREA ELEMENTS VS LINE SEGMENTS IN PICTURE ANALYSIS

Many people have suggested that a modern digital computer should be able to recognize a fairly complex pattern of tracks in a bubble chamber photograph such as that shown in Fig. 1a.*

Concrete schemes for such recognition generally assume that information is available about the presence or absence of bubbles in area elements covering the pictures and of a size appropriate to the resolution of the chamber. However, rough investigation of the time to read such information into a computer and to conduct a search for linear correlations among bubbles has so far led to computing times of hours or days for the recognition of tracks in a

*We are indebted to the hydrogen bubble chamber group at Berkley for the provision of this print and the negatives mentioned in Sec. 6.

single picture.

The situation is changed if a computer can be provided with numbers describing the positions and slopes of line elements making up the tracks. For one reason, the quantity of information which must be handled by the computer is reduced by at least an order of magnitude. For a second and more important reason, the slope of each line segment provides the computer with a good prediction of the location of the adjoining line segment and so reduces enormously the search time in recognizing a track.

It will be shown below that the tracks in one picture may be recognized in a time of the order of 1-2 seconds, and therefore a stereo pair of pictures may be analyzed in less than 5 seconds. It seems that an analysis time of this order of magnitude is a reasonable goal since it matches the cycle time of large accelerators.

2. DIVISION OF A PICTURE INTO "FRAMELETS"

In our proposed analysis scheme a picture such as that of Fig. 1a is subdivided into several hundred rectangular areas which we name "framelets."

The height of a framelet is chosen small enough so that the portions of tracks within each framelet are essentially straight lines and large enough so that line segments can be distinguished reliably from the random bubble background.

A reasonable framelet subdivision of the picture of Fig. 1a is shown in Fig. 1b.

The width of a framelet is selected according to the accuracy needed in the measurement of the lateral position of the segments in the framelet. If the lateral position of the television scanning beam can be known via calibration to within 1% of its total span, then the framelet subdivision of Fig. 1b leads to an accuracy of lateral position determination of 0.1% of the width of the bubble chamber. A chamber of 20-cm lateral extent would therefore have track segment positions determined to within about 1/5-mm (in the chamber).

3. THE "PLANE TRANSFORM"

A block of four framelets is presented to a television camera each 1/60th second. Each framelet is then treated separately in a way best explained with reference to Fig. 2a. The upper portion of 2a is a projection drawing of the bubble pattern appearing in one of the framelets of Fig. 1b. The lower portion is a "transform" of the framelet, made as follows: for each bubble in the framelet a line is drawn in the transform. The line is made to have an <u>intercept</u> with the horizontal midline in the lower rectangle equal to the horizontal coordinate of the bubble in the framelet. The line is drawn with a <u>slope</u> relative to the vertical which is proportional to the vertical displacement of the bubble from a horizontal midline in the framelet.

Now it is an exact theorem, easy to prove, that if a set of bubbles in a framelet lie on a straight line, the corresponding lines in the transform intersect in a point. This intersection point we call a "knot."

The rectangular coordinates of a knot in the transform plane turn out to have this significance: the horizontal coordinate equals the horizontal coordinate in the framelet plane at which the line of bubbles intercepts the horizontal midline of the framelet. The vertical coordinate of the knot (relative to a horizontal midline) is proportional to the slope of the line of bubbles relative to the vertical. So the positions of knots in the transform plane give the slopes and intercepts of line segments in the original framelet.

In the recognition machine, transforms are drawn by a simple circuit on an oscilloscope screen. Examples of the results are shown in Figs. 2b and 2c.

The knots may be detected by a second television camera which observes the transform plane.

4. AN ALTERNATIVE MTHOD FOR LINE SEGMENT RECOGNITION

The plane transform was a natural extension of certain methods developed in our laboratory for detection of low energy protons in nuclear emulsions, for charged particle nuclear spectroscopy. From the transform followed naturally the method of computation described in the next section for recognition of a complex pattern by use of line segment coordinates. However it now appears that the second of these two developments, i.e., the computation method, is the more fundamental to the overall scheme. For line segment detection and classification the following method may prove to be simpler than the plane transform:

(a) By means of a rotating mirror sweep the image of an entire row of framelets (Fig. 1b) past a slit of fixed orientation—this detects track segments at that orientation.

(b) Duplicate the slit to provide an array of orientations which cover a fan from (say) -45° to +45° relative to the vertical; duplicate the image by an array of fixed mirrors so that corresponding lateral positions of each image reach the slit for that image at the same time. Now track segments are detected at all orientations. About 30 slits and 30 images are required.

In this method as well as in the plane transform method each picture must be scanned twice at right angles.

Of course there are many difficulties, but the track segments have been shown to be readily detected by a slit. Also the scanning time for a picture is reduced over the plane-transform scanning time so that the computing operation of the next section constitutes the entire limitation in speed of analysis.

5. "ZIPPERING"—THE LINKING OF LINE SEGMENTS INTO TRACKS

We now suppose that by one of the methods of the two preceding sections the line segments in a picture are detected, and that numbers representing slope and intercept for the segments are recorded on magnetic tape. The time required for taping the whole picture is about 1 second by the plane transform method and less than 1/2 second by the multiple slit method. An equal time is required for a second scan of the same picture at right angles to the first, leading to a total taping time of 1-2 seconds for each stereo view.

A small buffer storage is to be provided to group together on the magnetic tape the numbers from each framelet (or row of framelets). It has been found then (by actually writing a code) that an IBM 704 computer can be made to "zipper" together the track segments into tracks and provide at specified locations in its memory tables of track coordinates. The search operations which accomplish the zippering are carried out, while the input magnetic tape is running, between transmissions into memory of the groups of numbers which specify the track segment information.

One feature of the code should perhaps be mentioned. Track segment numbers are stored in the machine at addresses in the fast memory which have one-to-one correspondence with geometrical position in the original bubble chamber photographs. An instruction to search for a continuation of a track is then easily given as an instruction to examine the contents of the fast memory in the neighborhood of a certain address.

6. CURRENT EXPERIMENTAL PROGRAM

Attempts to realize the instrument described above are proceeding at the beginning and end of the data-handling chain.

For the work at the end of the chain, slope and intercept numbers are measured by hand from a picture such as that of Fig. 1a. The zipper code can then be checked out using these numbers, and this checkout is in process. If the 704 zippers correctly and provides correct tables of track coordinates, the code will be extended in an effort to obtain recognition of complex events (such as the associated production event of Fig. 1a) as well as to measure particle moments and production or scattering angles.

For the work at the beginning of the data chain, individual framelets from hydrogen bubble chamber negatives are being projected onto a television camera tube, the corresponding plane transforms are being constructed electronically, and the knot detection problem is under study. In a parallel operation, the detection of line segments by a multiple slit system is under investigation.

7. ACKNOWLEDGMENTS

The zipper code has been constructed with skill and ingenuity by M. J. Smit. The cooperation of IBM and the General Motors Corporation in the computer work is gratefully acknowledged. D. E. Damouth and J. A. Koenig have found solutions to many problems of electronic, optical, and mechanical design. The Michigan Memorial Phoenix Project and the U. S. Atomic Energy Commission have provided essential support.

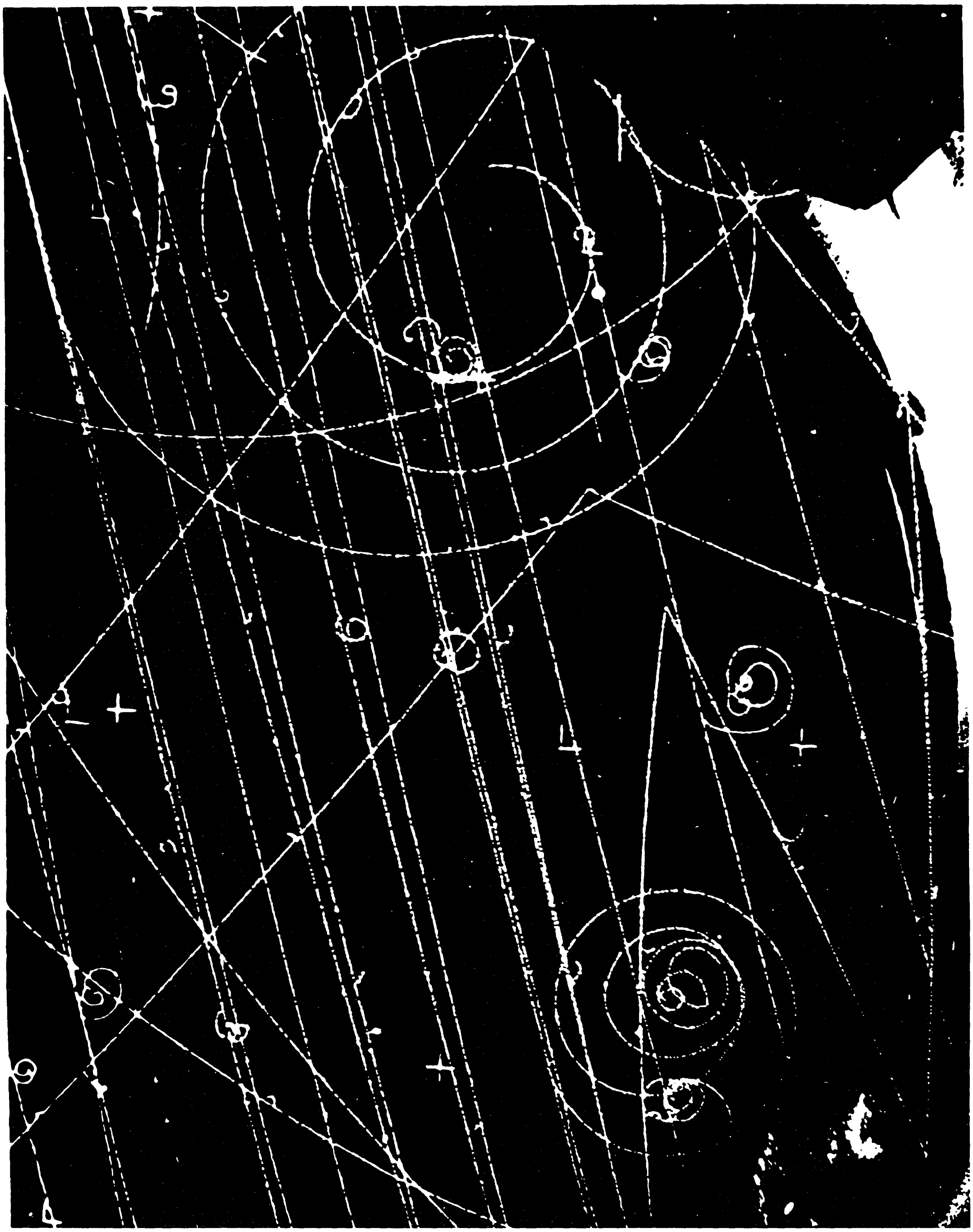


Fig. 1a

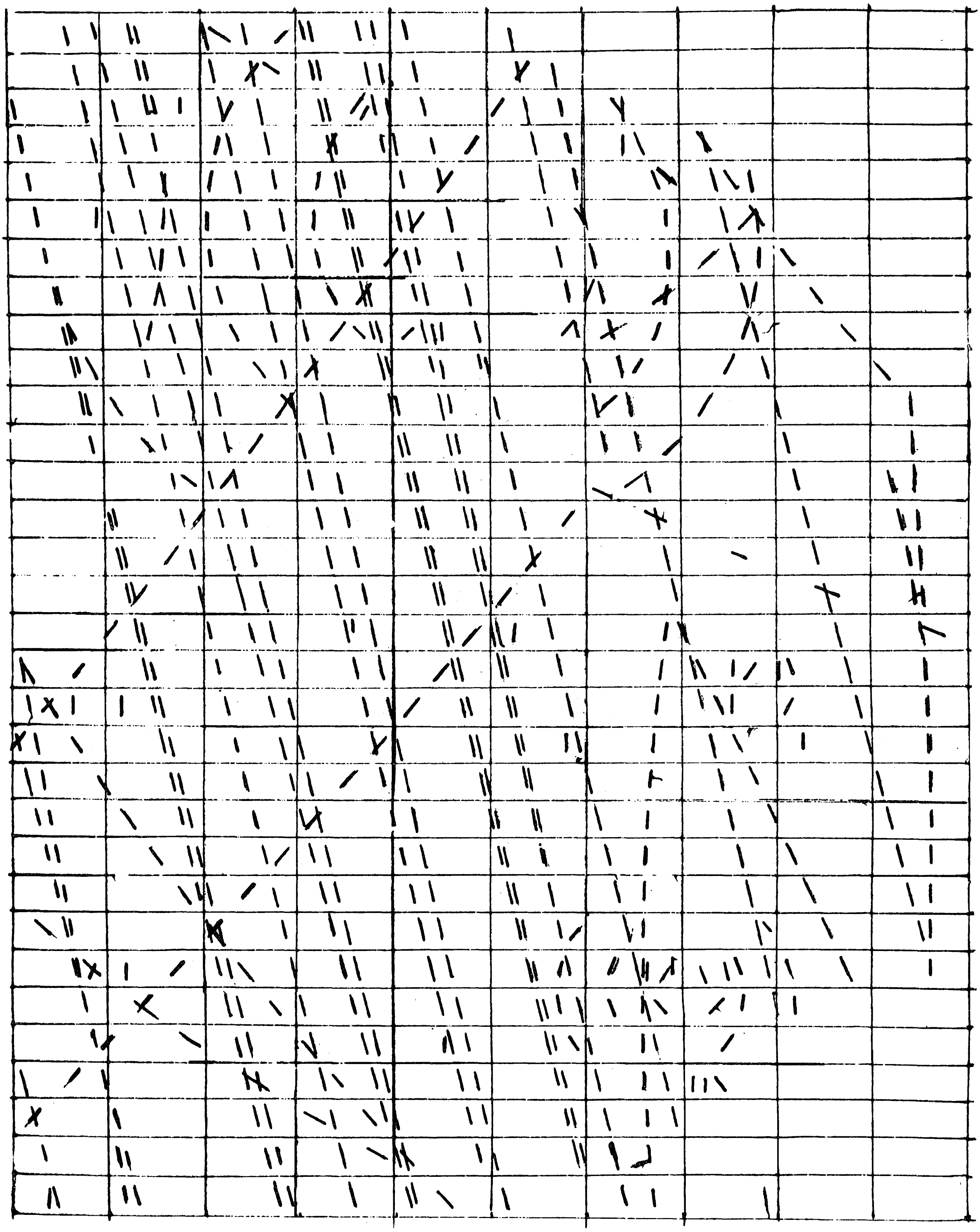


Fig. 1b

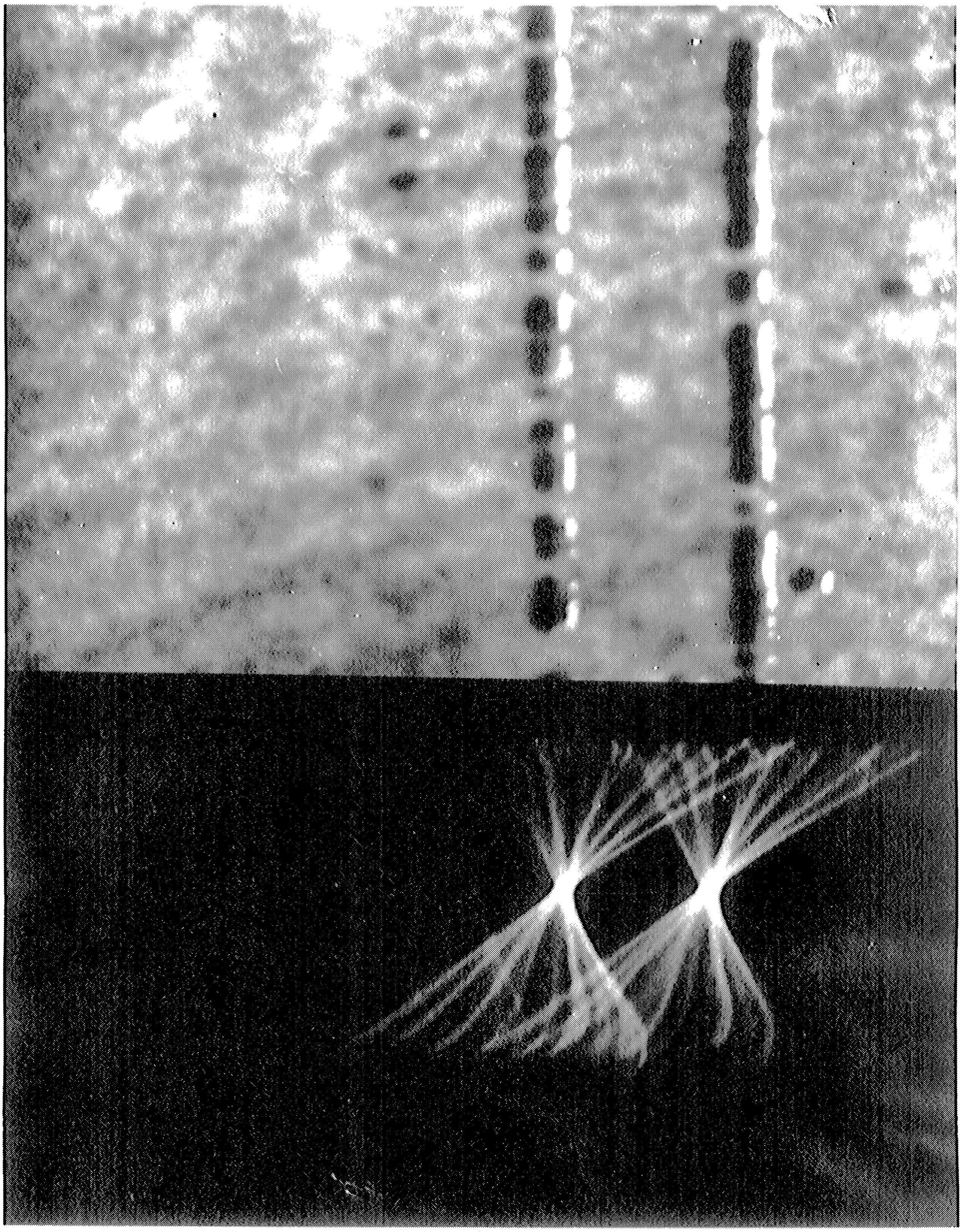


Fig. 2b

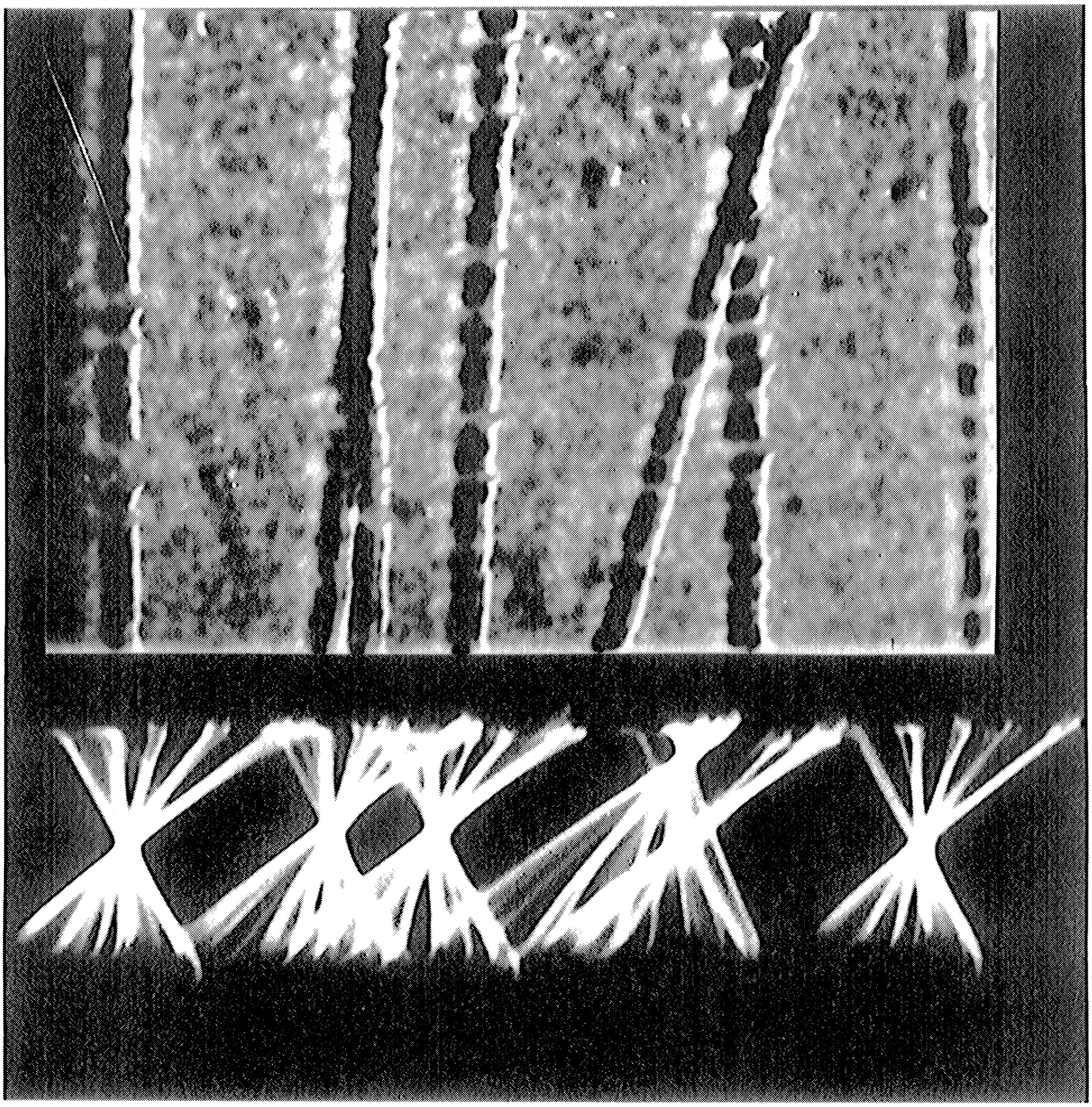


Fig. 2c

APPENDIX

A SEMI-POPULAR ACCOUNT OF THE SCANNER

(Reprinted from _Electronics_, McGraw-Hill Book Company)

Scanner Recognizes Atomic Particle Tracks

By PAUL V. C. HOUGH, J. A. KOENIG and W. WILLIAMS,
Michigan Memorial Phoenix Project and Randall Laboratory of Physics, U. of Michigan, Ann Arbor, Mich.

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Recognition system scans nuclear emulsion strips coated on glass, using image orthicon tube sighting through microscope. Tracks in emulsion caused by nuclear particles are recognized and counted by electronic circuits. Device greatly reduces labor, increases volume of data available from cyclotron

By PAUL V. C. HOUGH, J. A. KOENIG and W. WILLIAMS,
Michigan Memorial Phoenix Project and Randall Laboratory of Physics, U. of Michigan, Ann Arbor, Mich.

Scanner Recognizes

SPECIAL SILVER-BROMIDE-rich photographic emulsions are widely used as particle detectors. Nuclear emulsions are simple, record continuously in many energy channels simultaneously and have low background. But these advantages have been nearly vitiated by the need for slow and expensive microscopic scanning by human observers. This scanning problem is met by a recognition machine, equivalent to 15 human observers, which has been developed to read emulsions.

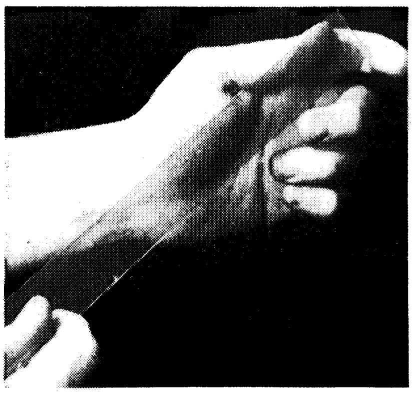
Protons from nuclear reactions are deflected by an analyzer magnet and brought to a focus on 1-in. by 10-in. by 0.004-in. emulsion strips. The relative position of a proton track from one end of the emulsion measures the proton's energy. If the number of proton tracks in 0.5-mm swaths across the 1-in. dimension of the emulsion is counted, an energy spectrum is obtained. The position and intensity of each peak gives information about a particular state of motion of neutrons and protons produced under bombardment by the cyclotron.

The machine recognition problem is complex because real tracks enter the emulsion over a range of angles and are often curved. Also, a great variety of background patterns in the emulsion must be rejected.

Detection of the faint tracks of high-energy particles and machine recognition of events such as nuclear explosions occurring in the emulsion are not yet possible but are the objectives of research.

Recognition System

In the recognition system, a standard microscope is arranged to project an image of an emulsion scene onto the photo surface of a 5820 image orthicon camera tube used as pickup in a television system. The nuclear emulsion, coated on glass, rests in a channel under the microscope objective. Figure 1A shows an emulsion scene photographed from a television receiver wired to the camera. The diagonal stripe is introduced by the motion of the focal plane shutter of the camera taking the photograph. The scene shows the background grains present in all nuclear emulsion and a proton track. The microscopic



Typical strip of nuclear emulsion on glass backing used in cyclotron

Nuclear particle tracks are clearly visible on tv screen at left as emulsion scene is scanned by tv camera through microscope at right

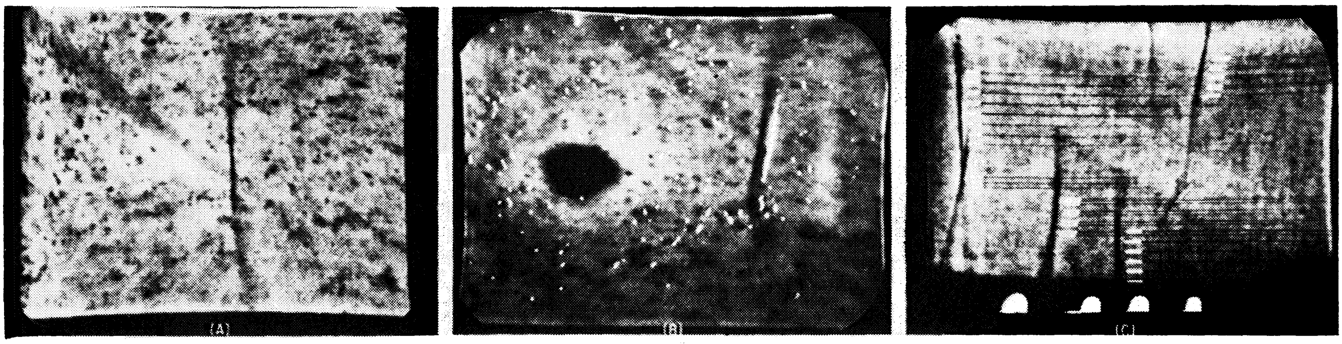
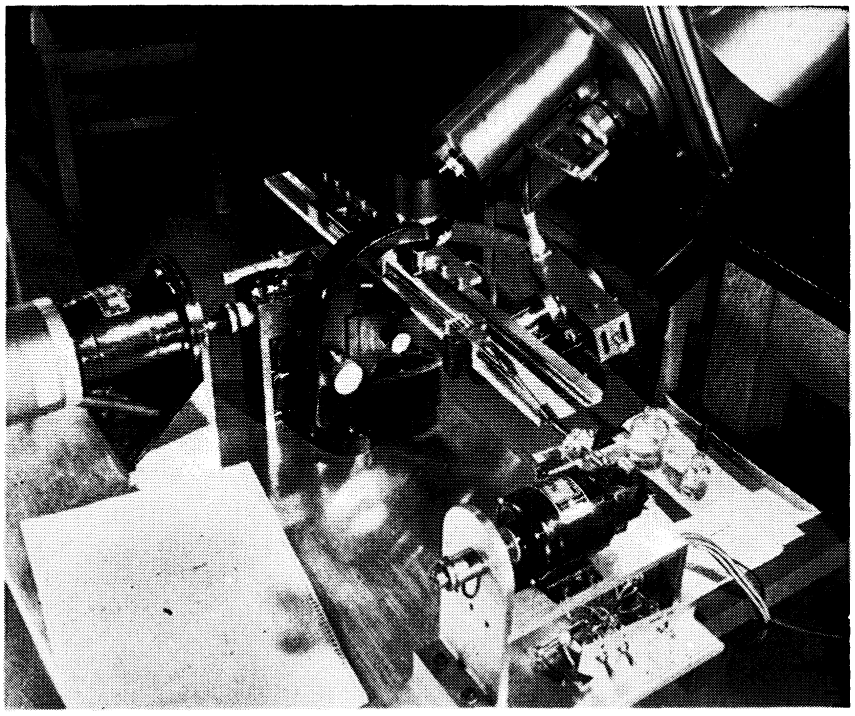


FIG. 1—Emulsion scenes photographed from tv receiver. (A) shows typical scene with background grains and proton track in center. In (B) pulses obtained from screening circuit are mixed with video. In (C) four tracks are clearly delineated by marks obtained from counters

Atomic Particle Tracks

depth of field is less than the thickness of the emulsion and the track can be seen to come into and go out of focus. The television scan lines are horizontal in the picture.

Track recognition proceeds in three steps: first, a unit pulse is generated when the television scanning spot crosses an opacity narrow enough to be part of a track. Large-area opacities are ignored. The result of the screening process is shown in Fig. 1B. In the background is an emulsion scene with background grains, a track, and a blob of silver—a common background element in emulsions. Mixed with the video signal are the unit pulses just mentioned which show white in Fig. 1B. The track and background grains are clearly marked but the blob is screened out.



Microscope projects image of emulsion scene enlarged 200 times onto photosurface of image orthicon

Binary Scaler

Second, a combination of a fast binary scaler and four ultrasonic delay lines is used to count up successive passes across a track. The circuit performs the count at all lateral positions in the field of view, counts up several tracks in the field simultaneously and tests clumps of background grains continually for track possibilities.

Third, only one count is obtained for each track. The situation is illustrated in Fig. 1C. A scene is shown with four tracks (dark vertical lines), the maximum number normally encountered per field. The white marks to the right of each track are obtained from the counting circuits at the 32nd, 40th, 48th, etc., successful pass across each track. Because of fluctuations in dip angle and quality of development, the various tracks show different total counts. What is needed is a summing of whatever number of white marks may occur for a given track; however, summing is complicated by the fact that pulses from different tracks occur interleaved in time.

The solution to the summing problem can be seen at the bottom of Fig. 1C. An auxiliary oscilloscope is swept in synchronism with the horizontal scanning beam of the television camera. The oscilloscope trace is brightened when each of the counting markers of Fig. 1C occurs; therefore one spot per track appears on the oscilloscope. To make use of the excellent light-integrating properties of the image orthicon tube, the spots are projected onto the bottom of the television camera field of view. Finally a single television scan line through the spots is selected for

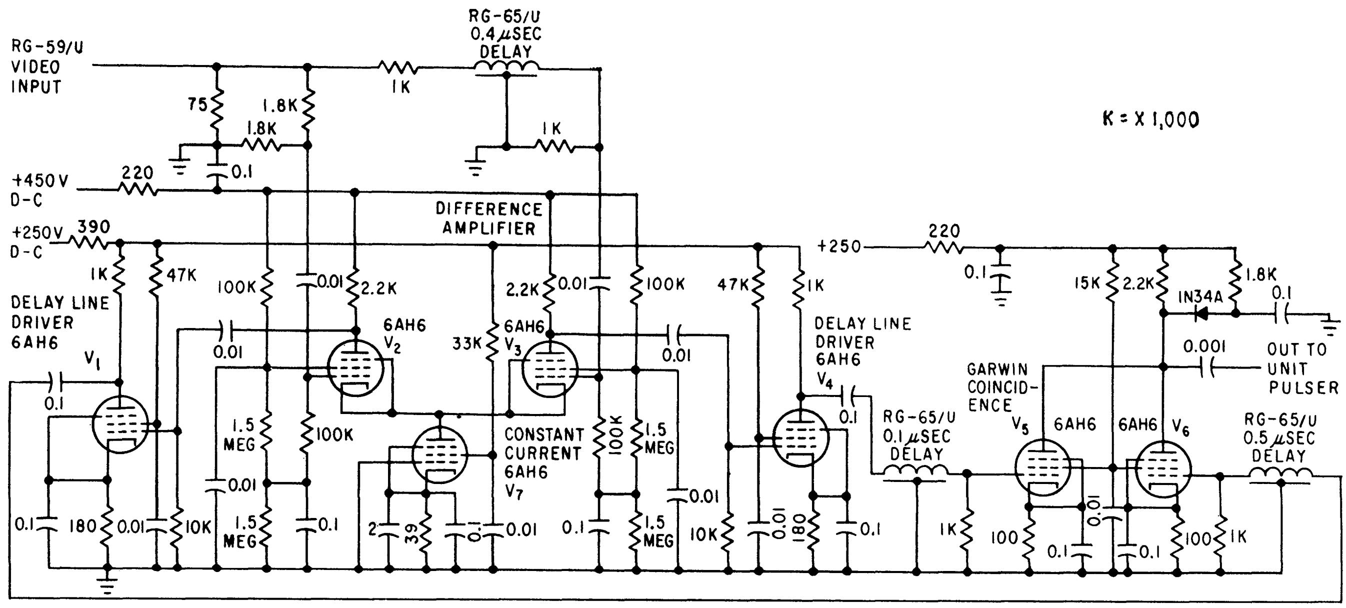


FIG. 2—Schematic diagram of the video screening circuit. Opaque regions on emulsion which meet narrowness criteria trigger monostable multivibrator (not shown)

readout and the number of spots is recorded by a counter.

The summing technique just described is limited to tracks deviating by less than about ±20 deg from the vertical. Steps 1 and 2 operate successfully for tracks inclined at angles up to about 45 deg.

Video Screening

Initial screening for narrowness is accomplished in the circuit of Fig. 2. The video signal from the television camera is presented directly to the grid of one stage of a difference amplifier V_2 and after a 0.4-μsec delay, to the grid of the other stage V_3. The output of the difference amplifier represents the difference in light level at two points along a scan line separated by half the width of a track.

The negative output of delay line driver V_1, which occurs as the television scanning spot enters the track, is delayed 0.5-μsec to coincide with the negative output from delay line driver V_4 as the scanning spot leaves the track. The two coincident negative pulses are applied to the grids of a Garwin coincidence circuit[1], V_5 and V_6, whose output drives a 0.5-μsec monostable multivibrator which generates the white unit pulses of Fig. 1B. Any opacity greater than twice the width of a track fails to trigger the Garwin circuit and is therefore ignored.

The unit pulses resulting from the video screening are inserted in a quartz ultrasonic delay line[2] as damped 40-mc oscillations each about 0.1 μsec long. The damped oscillation generator of Fig. 3 has proved to be satisfactory.

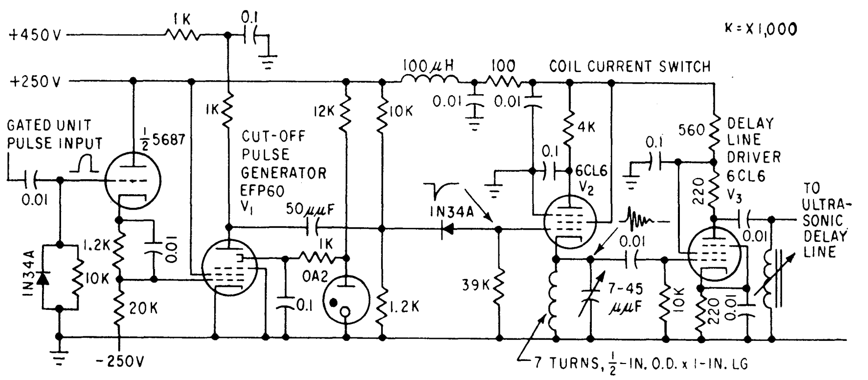


FIG. 3—Circuit diagram of the 40-mc damped oscillation generator

The EFP60 secondary emission pentode V_1 drives pentode V_2 to cutoff in a few milliμsecs. Cutoff time must be a quarter period or less to get a large-amplitude damped oscillation in the tuned circuit in the cathode. On extraction from the delay line the damped oscillations are amplified by two commercial broadband amplifiers and detected at a level of about 1 v.

The overall ultrasonic delay time is 63 μsec as compared with a time between successive television scan lines of 63.5 μsec. Extracted pulses are used to close a gate on the first delay line and open a gate on a second line, both for 1 μsec. If a second pass across a track occurs within the 1-μsec period a pulse is inserted in the second line. Figure 4 is a block diagram of the system.

Delay Lines

A total of 4 delay lines is used. At any stage of the counting, the number of track passes N is inserted in the 4 lines as a binary number ($N \leq 15$). At the next count, $N + 1$ is formed in a fast binary scaler, gating the four lines in binary representation of $N + 1$. The gate time of 1 μsec allowed for receipt of the $(N + 1)$th successful track pass permits tracks at angles up to ±45 deg to be counted.

Moderately curved tracks are counted as well as straight tracks. Ordinarily, counting goes on at several lateral positions in the field at once, since clumps of background grains are continually tested for track qualification.

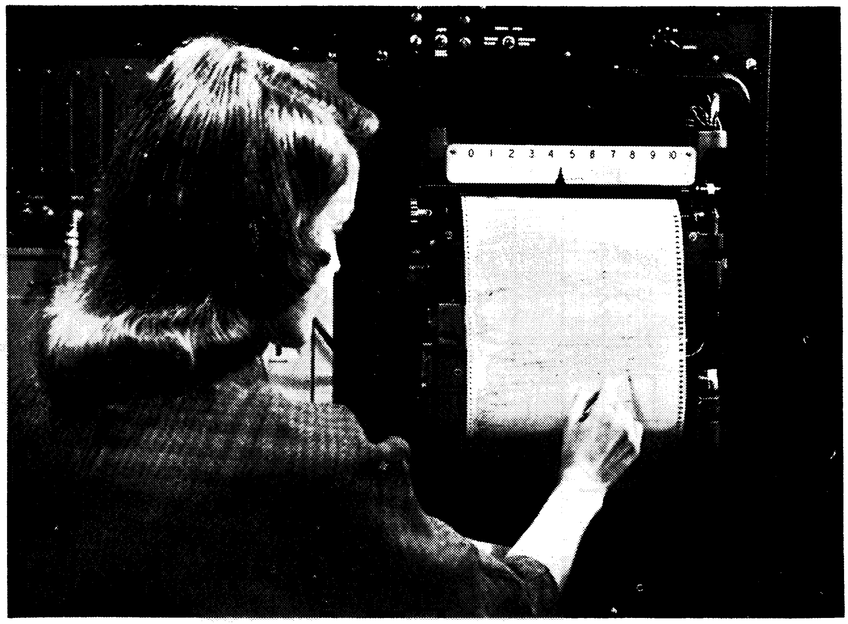
Readout Line

A commercial synchronizing generator provides the master timing for the television system. In this circuit the field repetition rate is obtained by a binary countdown from the line repetition rate. Associated with each line of the television raster is a particular pattern of on and off for the countdown binaries. A standard multidiode coincidence gate[3] senses any desired pattern and selects any line of the raster. A cathode follower direct-connected to the proper plate on each binary drives each diode of the gate without loading the binary.

Pulsed Light Source

New fields of view are presented by the microscope stage drive each 1/60th sec. Under steady illumination the picture blurs, so illumination is provided in short bursts at the end of each television field. A 0.3-μf capacitor charged to 3,000 v is discharged through a xenon flash-tube by a 5C22 hydrogen thyratron on command of the television vertical drive pulse. The light pulse lasts about 10 μsec.

The total number of tracks encountered in a 0.5-mm by 1-in. swath representing four passes across the emulsion is printed on a tape and plotted on a chart recorder. Scales of 0-100 and 0-1,000 tracks are provided. The number of tracks n is plotted with its standard error $\pm\sqrt{n}$. The error magnitude is derived from a square root potentiometer mounted on the same shaft as



Final readout of recognition system is energy spectrum chart shown being examined by analyst.

the balancing potentiometer of the recorder.

Performance

Over a recent three-week period the scanner read 52 emulsions corresponding to 35 man-weeks of human scanning, and was therefore equivalent to a crew of about 12. With more experience this equivalence figure may reach 20. One highly trained technician is required to run the machine and close collaboration with the physicist responsible for the experiment is essential.

Spurious counts produced by the machine arise almost entirely from real tracks which fail to satisfy criteria easily applied by human observers. For example, in long exposures at the cyclotron, neutrons produced elsewhere in the room collide with hydrogen atoms in the emulsion, producing tracks with one end wholly within the emulsion. Such tracks are rejected by humans but not always by the machine. At its lowest, the spurious count by the machine is 2 or 3 per 0.5 mm by 1-in. swath; hence about a dozen tracks are required in a real proton group for reliable detection.

The machine saturates at about 2,500 tracks per 0.5-mm by 1-in. swath. Over its useful intensity range of say 10 to 1,500, it is accurate to within ±5 percent which is sufficient for most nuclear reaction studies.

Development of the scanner has been supported by the U. S. Atomic Energy Commission and the Michigan Memorial Phoenix Project. G. R. Garrison, Director, and F. M. Remley, Jr., Technical Director of the University television station provided support and technical assistance at critical stages of the research. The work of B. Cosby on the recording system and R. O. Winder on problems of logical design is gratefully acknowledged.

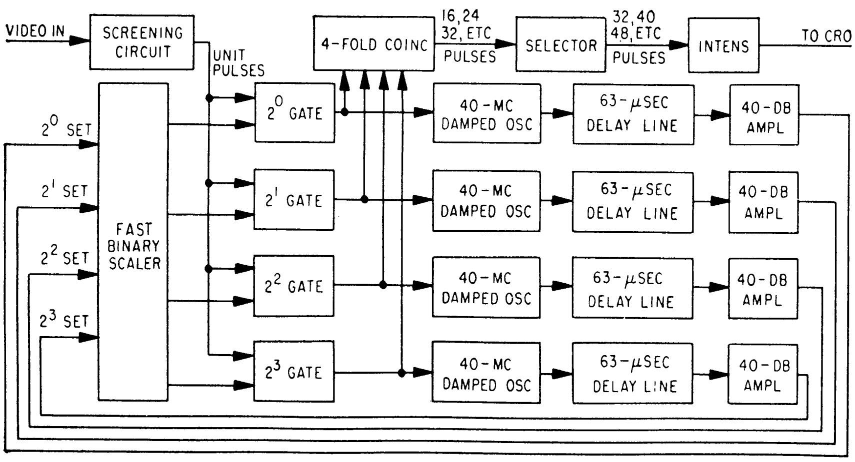


FIG. 4—Block diagram of counting circuits which convert number of track passes to binary number inserted into four delay lines

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