Submitted to the Optical Society of America, March 30, 1963

APR 22 1963

C-37

BNL 6878

A Flying Spot Film Measuring Machine

Employing Crossed Glass Fibers*

R. B. Palmer

Brookhaven National Laboratory, Upton, L.I., N.Y.

MASTER

Flying spot measuring machines for use on bubble chamber film were first proposed by P.V.C. Hough and B.W. Powell in 1960. A new machine nearing completion at Brookhaven National Laboratory employs a fixed and moving fiber to generate a 15 μ m spot that will scan over an area 53 x 160mm in 10 seconds. Centers of marks on the film will be digitized to an accuracy of $\pm 5 \mu$ m and the coordinates fed on line into a computer for analysis.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Facsimile Price \$ 4.60
Microfilm Price \$ 1.55
Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

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

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

I. INTRODUCTION

Since the measuring machine to be described will measure bubble chamber film, it is appropriate first to say what a bubble chamber is and what sort of film it produces. The principle of operation of a bubble chamber was first proposed by D.A. Glaser¹. A liquid is heated under pressure to a temperature above its normal boiling point. A sudden reduction of pressure brings the liquid into a superheated condition. If a charged particle, say a proton, passes rapidly through the liquid in this superheated condition, then the liquid begins to boil along the track of that particle. Stereo photographs are taken about one millisecond after the particle has passed, and the boiling appears then as a row, or track, of tiny bubbles. Fig. 1 shows such a photograph, where many particles have passed through the chamber and thus many tracks are seen. Each track consists of a row of dots, and each dot is the image of a tiny bubble. The tracks are curved because there is a magnetic field in the chamber which deflects the particles as they move. The higher the momentum of the particles the less they are deflected, and the less the curvature. Measurement of the curvature of a track thus gives a determination of the particle's momentum. The particle's velocity can also, though less accurately, be determined by observing the density (the number of bubbles per cm) of a track. By comparing these two determinations the particle's mass can often be found. In Fig. 1 most of the tracks are seen to pass right through the chamber. These might be tracks of beam protons

accelerated by the Synchrocyclotron and deliberately brought into the chamber. In general, such beam tracks are uninteresting unless they represent a proton that interacted with the material of the liquid. In Fig. 1 one such event did occur and one of the beam tracks is seen to fork into two tracks at different angles. The three tracks of this particular fork might be of a proton that struck a stationary proton of the liquid and bounced off it "like a billiard ball", sending the stationary proton away at a different angle. Many "events" are far more complicated than this but the principles are the same. By measuring the angles, lengths, curvatures and densities of the tracks information is found on the properties of the particles involved. Note that the many beam tracks which pass right through the picture have no connection with the event and need not be measured.

The accuracy required in the determination of curvatures and angles is equivalent to an accuracy of coordinate determination of about $\pm 5\mu\text{m}$ and advantages would be gained if the accuracy could be improved to $\pm 1\mu\text{m}$. This is formidable in itself but made more so by the number of pictures to be measured. The Brookhaven National Laboratory 80 inch liquid hydrogen bubble chamber is expected to produce several million $53 \times 160\text{mm}$ pictures per year. Admittedly not all of these pictures require measuring. Many pictures have no events in them, only having beam tracks. The pictures are, therefore, first projected one by one onto a table and there viewed by girls who pick out those containing events. From amongst the several million pictures, up to one million events per year might

be found, and all these will require measurement to the accuracies mentioned.

It has already been noted that in the pictures containing events there are many beam tracks which can give no information. In fact useful information, is only contained in strips along the tracks of the event. When designing a measuring machine it is tempting to make use of this fact and conceive of some device that drives along the tracks of interest, measuring them as it goes, leaving unmeasured all the unwanted tracks. In the past this approach² has usually been followed. The steering of the device along the road is performed by a human operator, and the need for this human operator usually limits the speed of measurement. A typical "Frankenstein" measuring machine, which is of this type, takes about 5 minutes to measure each picture (15 minutes to measure a stereo triad).

Hough and Powell in 1960³ proposed an entirely different scheme. They proposed that a spot of light should be made to scan over the entire film area with a television type raster. Behind the film a photomultiplier would detect whenever the spot passed over a bubble image, and the coordinates of each bubble would then be digitized electronically and sent on line into a large electronic computer. There, in the computer the selection would be made between useful information (on the event) and useless information (on beam tracks). The selection could in principle be made in two ways:

a) If programs could be developed, the patterns on the pictures would be "recognized" and only coordinates of interesting

patterns, such as the fork in our picture (Fig. 1), would be passed on to the programs that compute the required data on the event.

b) Until such programs did exist the computer would select the useful information on the basis of what it had been "told" should be there. When the picture is viewed by a girl to determine if an event is present at all, the girl can also take rough measurements of the event. These rough measurements can be digitized using a simple measuring device lying on the table on which the picture is projected (Fig. 2). The digitized rough coordinates of each event can then be punched onto cards and these cards could be fed into the computer before the flying spot measuring machine (HPD) measures an event. Then when the measured coordinates start flowing from the measuring machine the computer would "know" approximately where to "look" for the event and could with relative ease find the coordinates of interest.

It may seem at first that this system would be slower than the more conventional type of machine that measures only the parts of the film of interest. It was shown, however, that with reasonably high speed electronics track centers could be located to within a few microns even when the spot of light was traveling 25 μm every microsecond. At this speed it would be possible to scan the entire 53 x 160mm picture with 30 μ spaced scan lines in only 10 seconds. It was also shown to be easily possible to feed all the coordinates obtained, and there might be over 100,000 of them, into an IBM 7090 or similar computer within the same 10 seconds. This speed was a considerable advance on the 5 minutes needed by the conventional

measuring machines and made practical the measurement of the million pictures per year that are expected to come available.

The first step in demonstrating the practicability of these proposals was taken at the European Organization for Nuclear Research (CERN) with the collaboration of Brookhaven National Laboratory and Lawrence Radiation Laboratory. There, in June 1961 a prototype measuring machine (Hough Powell Device) was operated and 30,000 coordinates of tracks on a small picture were digitized and fed into an IBM 709 computer⁴. At that time the three laboratories involved in the collaboration all started to build complete systems with the hope of measuring film usefully as soon as possible. At the time of writing all three of these systems are working mechanically and electronically, although program difficulties are still delaying the production use of the machines. At the same time that these Mark I machines were being built, the author started thinking of possible improvements in design that could be incorporated in Mark II machines. It is to one of these Mark II machines that the rest of this paper is devoted. This machine has been designed to measure film from the BNL 80" bubble chamber, and at the time of writing the machine is nearing completion, most of the critical parts having been run and tested. To the authors knowledge at least 5 other machines are to be built which will incorporate most of the basic ideas described here.

II. THE CROSSED FIBER FLYING SPOT GENERATOR

In the previous section we have introduced Hough and Powell's idea of scanning bubble chamber film with a fine raster, but we have said little as to how this raster is to be produced. It will be remembered that measurements are required to an accuracy of a few microns over an area 53 x 160mm. A raster of this size is therefore required, in which the spot's position is always known to a few microns; also since the finest bubbles may be as small as 15 μ m diameter the spot should be of this order of size. Although high resolution cathode ray tubes are rapidly improving it is fair to say that it is not yet practicable to obtain a 15 μ m spot over 53 x 160mm. Hough and Powell in their prototype used a mechanical system in which a spot was moved repetitively across the film while the film was slowly moved at right angles to that line, so generating a raster. The present machine also uses this principle. In the prototype a rotating disc with radial slits was placed very near to a long straight fixed slit (Fig. 3). Where a radial slit intersects the fixed slit a small "pin hole" was formed. As the disc rotated so this pin hole moved in a straight line. When illuminated from one side the moving pin hole became a moving spot which was projected down onto the film. In order to know where the spot on the film was at any time, the beam was split and an identical spot projected on to a high precision grating. Behind both the film and the grating there were photomultipliers, the first of which detected when the spot passes over a bubble image, and the second of which provided a scale against which the position of the spot was determined. It is this crossed slit system that provided the

basis for the crossed fiber system to be described.

In either system one of the main requirements is a high flux of light in the spot on the film. In order to observe the track and grating signals from the photomultipliers the band width of the circuits has to be large. At these large band widths the noise due to the corpuscular nature of light is far from negligible, and the ratio of signal to this noise can only be reduced by having more light flux. Before considering the crossed fiber system it will be convenient to consider the limitations on the light flux in the slit system. A similar consideration will be given later for the fiber system.

The light flux F in the spot on the film is given by

$$F = A \Omega B \quad (1)$$

where A is the geometrical area of the spot on the film (assuming no lens aberration), Ω is the solid angle subtended by the projection lens stop at the film, and B is the luminance of the source. A can obviously not be increased since we require a small spot. Ω can only be increased if larger aperture lenses with the required resolution can be found. B , the luminance of the source, is of course limited by the lamps that are available. The Mark I machine at Brookhaven which uses the slit system, employs a Westinghouse BH 6 (1 kilowatt) high pressure mercury capillary arc which has a luminance of 40,000 lumens per mm^2 per steradian, over an area of 20mm x 1mm. Higher continuous luminance is, to the author's knowledge, only available from smaller mercury arc lamps. It is of

interest, therefore to calculate the minimum size of arc lamp that can be used. Referring to Fig. 4, letting the scan length on the film be η , and letting the solid angle subtended by the objective on the film be Ω ; it can be seen that the fixed slit length is $\frac{\eta}{M}$ and the arc length $\frac{\eta}{MM_1}$, where M and M_1 are the magnifications of the objective and condenser respectively. Similarly it is seen that the solid angle at the slit is ΩM^2 and the solid angle at the arc lamp is $\Omega M^2 M_1^2$. In practice there is a limit to the aperture of condenser that can be used; Ω_1 will thus have some maximum value $\Omega_1 \text{ max}$:

$$\begin{aligned} \text{thus} \quad \frac{\Omega (M M_1)^2}{M M_1} &\leq \frac{\Omega_1 \text{ Max}}{\sqrt{\frac{\Omega_1 \text{ Max}}{\Omega}}} \end{aligned}$$

and the length of the arc

$$L = \frac{\eta}{MM_1} \leq \eta \sqrt{\frac{\Omega}{\Omega_1 \text{ Max}}} \quad (2)$$

the arc length is thus limited by the scan length η , the solid angle subtended by the objective on the film Ω and the maximum practical condenser aperture.

For a scan length $\eta = 50\text{mm.}$, and objective aperture $f/4$ and an $f/2$ condenser we get

$$\begin{aligned} \Omega &= 2.2 \cdot 10^{-2} \\ \Omega_1 \text{ Max} &= 19.5 \cdot 10^{-2} \\ L &= 50 \sqrt{\frac{2.2}{19.5}} = 17\text{mm.} \end{aligned}$$

the 20mm BH6 lamp is thus only just adequate, and smaller higher intensity arc lamps cannot be considered.

The fundamental change made to the system just described was to replace the fixed and moving slits by fixed and moving glass fibers, each about 1mm in diameter. Although this may seem a simple change it does in fact generate a moving spot by a fundamentally different process which, as far as the author knows, has not been used before. As in the slit system there is a rotating disc but where there were radial slits there are now radial 1mm diameter glass fibers held in jaws such that light is stopped from passing through the disc anywhere except through the fibers. Near the disc is placed a straight tangential fiber, also with jaws to stop light passing anywhere except through the fiber. The geometry of fixed and moving fibers are exactly the same as that of the slits shown in the lower part of Fig. 3. As in the slit case, a source is placed behind the disc such that, if the disc were removed, the full length of the fixed fiber would be illuminated. Where before the intersection of a radial with the fixed slit defined a pin hole, now the intersection of a radial fiber with the fixed fiber defines an aperture in which there are two crossed glass fibers, each of which acts as a cylindrical lens. Together the two cylindrical lenses act as one spherical lens which forms an image of the source. Since the fibers are small in diameter, their focal length is also small and the image of the source they form becomes a tiny spot of light. As the disc is rotated so this spot of light moves with the point of intersection of the fixed and moving fibers and can be focussed on to the film in just the same way that the illuminated pin hole was in the slit system.

There is one complication. Whereas the fixed and moving slits could be brought into nearly the same plane, the fixed and moving fibers, with their finite diameter, cannot possibly be brought into the same plane. The images of the source produced by each fiber are, in fact, lines just behind each fiber (Fig. 5). These two line images together, when viewed from the side opposite the source, form a single astigmatic image of the source. Only if this astigmatic image is projected with a lens to which a weak cylindrical element is added will a single corrected image of the source be formed on the film (Fig. 5). When the disc is rotated it is this tiny image of the source that moves across the film; in contrast to the slit system in which it is an image of a rectangular hole that moves across the film.

The limitations on the light flux in this fiber system may now be considered. As before the flux F in the spot is given by

$$F = A \Omega B \quad (4)$$

and once again the flux can only be increased if a lamp with higher luminance B can be employed. In order to see if a higher luminance lamp can be used, the minimum size of the lamp must be calculated. Consider Fig. 6. As for the slit system if the scan length is η , the fixed fiber length is $\frac{\eta}{M}$, and the arc length is given by

$$L = \frac{\eta}{MM_1} \quad (5)$$

where M is the objective magnification and M_1 is the condenser magnification. The calculation of the

solid angle at the lamp Ω_1 is different from the slit case. For a spot source image on the film of radius r the source image just behind the fibers must be

$$r_1 = \frac{r}{M}$$

where M is again the objective magnification. The solid angle of light Ω_2 leaving the fibers is then given by

$$\Omega_2 = \frac{\pi r_1^2}{\ell^2}$$

where ℓ is the conjugate distance from the fiber to the source image. Since this conjugate is very small compared to the long conjugate ℓ' , ℓ is approximately equal to the fiber focal length f .

Thus

$$\Omega_2 \approx \frac{\pi r_1^2}{f^2} = \frac{\pi r^2}{M^2 f^2}$$

and the solid angle at the source Ω_1 is

$$\Omega_1 = \frac{M_1^2}{M^2} \frac{\pi r^2}{f^2}$$

Setting an upper limit on this condenser aperture, $\Omega_1 \text{ max.}$,

$$M_1 = \frac{Mf}{r} \sqrt{\frac{\Omega_1 \text{ max.}}{\pi}}$$

Using expression (5) the arc length can be expressed by

$$L = \frac{1}{M^2 f} \eta r \sqrt{\frac{\pi}{\Omega_1 \text{ max.}}} \quad (6)$$

This expression is seen to differ considerably from that derived for the slit system (equation 2). In the slit system the arc length is a function only of Ω , $\Omega_1 \text{ max.}$, and η , none of which could

be varied to reduce the arc length. In the fiber case (equation 6) the arc length is seen to be a function of both f , the focal length of the fibers, and of M the magnification of the objective. With reasonable choices of f and M the value of L could be reduced to as little as 1.5mm, which is to be compared with 17mm for the slit case (equation 3). In fact it was desired to use a 0.3mm diameter source for which the gain due to the use of the fibers was not sufficient, and a "following" illumination was developed. Before describing this system, however, some of the other advantages of the fiber system will be considered.

1. Since the spot on the film is a real image of the source it is clearly easy to vary the size of the spot by placing an iris in front of the source. To change the spot size in the slit system the fixed slit and all the moving slits would have to be changed. In the fiber system it would even be possible to scan with a short line element, or other shape, simply by placing a suitable stop in front of the source.
2. Unlike the case in the slit system, a large cone of light leaves the crossed fibers, and this cone of light is not a function of the illumination system. Objectives of very large aperture could be used without changing the arc lamp, or several objectives may be set up to take light from the fiber at different angles. This was in fact done with two objectives, as will be described in Section III. There is, of course, a limit to the useful cone of light due to

aberrations in the fibers at the wider apertures involved in large cones. Such aberrations can, however, always be made negligible by reducing the fiber diameters.

3. Because of the astigmatism no single point near the fibers is conjugate with the spot image on the film. Thus no single particle of dirt near the fibers can block out the spot. This should result in much greater constancy in the intensity of the flying spot compared with the slit case in which a single piece of dirt in one of the slits can completely cut off the light. There is similarly no problem with ragged edges and non constancy of width of a fine slit. It is relatively easy to obtain fibers whose diameters are constant to a fraction of a %, whereas the problem of making a 20 μ m slit with such constancy of width would be almost insurmountable. In principle it is felt that the fiber system could be used in photometric applications where slits are inapplicable. It should be noted, however, that certain dust problems due to the presence of electrostatic charge on the fibers would have first to be overcome.

4. Unlike a 20 μ m slit the moving fibers can be curved without affecting their constancy of diameter or focusing properties. Why is it desirable to curve the slits of fibers? If straight radial slits or fibers are used the spot of light generated does not move with a constant velocity. Although in view of the use of the grating scale, this may not seem of consequence; yet if interpolation is to be done between the lines of the grating scale fairly constant velocity is desirable. If the slits or fibers are curved into suitable involutes and the fixed fiber is offset (see Fig. 7) then

not only is constant velocity of spot achieved but it is seen that at the intersection the fixed and moving fibers are always perpendicular; a condition necessary if full correction of the astigmatism is required. The fibers can easily be curved by allowing them to sag in an oven into a machined former of the required shape. Any fine irregularities in the former are not imparted to the fiber.

5. It is very easy to obtain a very straight fixed fiber, much easier than it is to obtain a very straight slit. When a 1mm diameter hand drawn fiber is held under a tension of 2 K gm it is found to be straight within a fraction of a micron. With time it is expected that the fiber will flow enough that it will become even straighter, although the measurement of the effect will become difficult.

This basic moving spot generator consisting of a disc with radial or curved fibers moving near a fixed fiber held under tension should find application in other fields besides our own. The latter part of this paper will be devoted to other details of the present design which may be of interest but which should not be considered necessary parts of a crossed fiber spot generator.

III. DETAILS OF THE MARK II FLYING SPOT DIGITIZER

In the last section the principle of a crossed fiber flying spot generator has been described. Details will now be given of one particular measuring machine which uses this idea. At the time of writing some parts of the machine have not been completed, but

the flying spot generator itself has been successfully tested.

The specification for the machine has been given in earlier sections of the paper and may be summarized as follows:

Spot size	15 μ m
Spot intensity	As high as possible
Least count on position of spot	1.6 μ m
Length of scan	53mm
Speed of scan	Approx. 25 μ m/ μ sec.

Perhaps the most critical component in the machine is the objective that projects the generated flying spot onto the film. No suitable commercial objective was found⁶ that was capable of producing the required 15 μ m spot over a 53mm field and it was necessary to have a special lens designed for the purpose. Consider what magnification should be chosen. For maximum spot intensity the numerical aperture on the exit side of the objective Ω should be as large as possible. For a given aperture of the objective the larger the demagnification, the larger is this numerical aperture on the exit side, although little is gained by a demagnification greater than 2. The entrance field (length of fixed fiber) was in fact chosen to be 100mm, giving a demagnification of 1.89. The design of a special lens was undertaken by Dr. Wynn, of Imperial College, London. After an initial design of a six element lens using third order theory, the parameters were optimized using a powerful computer program⁶. The lens has a focal length of 91.5mm

an aperture of $f/4$ and is corrected for two of the strongest lines of the mercury spectrum: 436 and 546 nm. The lens was designed for use with 6mm of glass in the long conjugate and a large block of glass (83.3mm) in the short conjugate. The original reason for the large block was to increase the physical path length between the lens and film, in fact it also made possible a higher lens performance. A cross section of the lens is shown in Fig. 8. A typical lens gives a modulation of 0.65 of a 40 line per mm sinusoidal grating over the entire field. This is roughly equivalent to an image less than $8\mu\text{m}$ diameter at half height. The lens is clearly well capable of providing the $15\mu\text{m}$ spot required.

Consider now the disc and fixed fiber which will generate the flying spot. For a scan length of 53mm and a demagnification of 1.89 the fixed fiber is 100mm long. Eight moving fibers were used in the disc in order that the involute curves of the fibers be not too strong. This fixed the diameter of the disc at approximately 40 cm. A spot speed of $25\ \mu\text{m}/\mu\text{sec}$. required one scan in 2 milliseconds, one revolution of 8 fibers in 16 milliseconds, or approximately 3600 rpm. 3600* rpm was chosen as being a convenient speed to obtain with a synchronous motor. The moving fibers were mounted near to the lower face of the disc, clamped between two curved jaws. One of the curved moving fibers is shown in Fig. 9. In Fig. 10 is shown the disc, on the upper face of which can be seen the eight plugs in which the moving fibers are mounted. The disc is seen mounted in its bearing with a Synchronous motor above.

*It is also possible to spin the disc at 7200 rpm doubling the rate of measurement.

Also in Fig. 10, round the periphery of the disc will be seen eight 45° mirrored surfaces. These surfaces form part of the illumination system that will bring light down onto the crossed fibers from above. In a straight forward system the source lamp would be placed above the disc with a condenser immediately in front of it. It will be remembered that one of the advantages given of the crossed fiber system was that it enabled a smaller, and in general brighter, source to be used. In practice, however, the only lamp available with higher luminance than the 20mm Westinghouse BH6 lamp ($40,000$ lumens per mm^2) is the Osram HBO 100W ($140,000$ lumens per mm^2) mercury arc*. This Osram lamp has an arc only 0.3mm long and the crossed fiber system alone did not allow its use. However, the gain of light flux of 3.5 was considered of sufficient importance to consider some other way to enable the use of the Osram lamp. A system was therefore designed that instead of illuminating the whole fixed fiber at any one time, would illuminate a small region that followed the point of intersection of the fixed and moving fibers. The method is illustrated in Fig. 11. The light from the source is focussed into a parallel beam which falls on to 45° mirrored faces on a disc. The angle of the parallel light reflected off the disc moves with the angle of the disc. The parallel light leaving the disc is focussed by a fixed lens to a point on the fixed fiber and as the disc rotates so this point moves along the fixed fiber. Field lenses are inserted before the fiber performing two functions. Firstly, they focus the light so

*Similar lamps are also available from Pek Labs Inc., Palo Alto, California

that it is heading for the projection lens. In this way the fibers are used "on axis". Secondly, these field lenses are designed to provide a constant velocity of movement of the spot given constant angular velocity of the disc. Since the intersection of the fixed and involute moving fibers also moves with constant velocity it only remains to synchronize the rotation of the mirrored disc with that holding the moving fibers. A simple way of obtaining this synchronization is to make the two discs into one and the same disc. This was in fact done and thus it is that these mirror faces were seen on the disc in Fig. 10. After the light is reflected from the 45° mirrored faces it is bent round by reflection in a number of prisms and brought down again onto the disc in the correct position to follow the fiber intersections. Fig. 12 shows these prisms together with the arc lamp and condenser system. It is seen here that there are two identical following illumination systems placed one either side of the disc, each taking light from opposite sides of the same arc lamp. The reason for this will be given later. The arc lamp is placed some distance from the disc to keep its heat away. Light is brought through a chain of lenses and finally brought down onto the disc as a parallel beam. After reflection from the mirror faces it enters the complex of prisms and lenses that bring the light round and down onto the fibers. Fig. 13 shows the prisms and lenses used in the following illumination. They are seen in this photograph as though viewed from below.

Using the 0.3mm diameter Osram arc and an $f/0.7$ condenser, an area 2mm in diameter is illuminated around the intersection of the

fibers. At the present time this illuminated area follows the intersection of the fibers to within 0.5mm and provides a spot of light whose intensity remains constant to within $\pm 15\%$. It is hoped that this will be improved. Some difficulty was experienced using the f/0.7 condenser due to aberration introduced by the bulb of the Osram lamp. This aberration turned out to be primarily astigmatism and was corrected by a simple cylindrical element. Another difficulty could arise in production use due to a tendency, after prolonged burning, for the arc to jump about inside the lamp. It is not yet known how serious this problem will be. If it were serious it would be necessary to revert to use of the Westinghouse BH6 lamp and dispense with the following illumination. A trial using this lamp has been made and gave a highly uniform intensity spot.

Fig. 14 shows the disc mounted in its vacuum tank together with the fixed fiber and following optics. Light enters the port holes to the left and right of the synchronous motor. Underneath the tank there are, of course, two more windows through which the flying spot may be viewed.

It is now necessary to explain the reason for there being two complete illumination systems. Consider the sort of picture that is to be measured (Fig. 1). In the main it contains tracks that lie along the longer dimension of the picture. A spot flying across the short dimension of the picture will usually intersect each track at a reasonably large angle so that little difficulty should be experienced in sorting out the information. Occasionally,

however, there is in a picture a "steep" track nearly perpendicular to the long dimension and thus nearly parallel with the flying spot. As the spot runs down such a steep track, a confusing signal will be received on the photomultiplier and it will be difficult to obtain useful information on the track. For this reason an abnormal mode of operation of the machine is provided. In this abnormal mode a spot is used which flies along the long dimension of the film, while the stage moves the film slowly along its short dimension. In this mode the spot intersects the steep track at a large angle and no trouble is experienced. In practice the normal and abnormal mode flying spots are brought down onto the film at all times and are viewed by two different photomultipliers, the signal from either of which may be used as required. The two illumination systems and spot generators are used to provide these normal and abnormal flying spots. Fig. 15 shows how the light from the two parallel flying spot generators are reflected in mirrors and brought down through two objectives to form the two scans on the film. The arrangement is complicated by the film being on edge to ease certain film transport problems. Just before the film is a large prism which reflects the light from above onto the film surface. After the film are field lenses and finally the two photomultipliers.

In the upper part of Fig. 15 are also seen the grating channels where spots identical to those in the normal and abnormal scans are projected onto two precision gratings. From the signals on the photomultipliers placed behind these gratings the positions

of the spots on the film are known. In the Mark I machines the identical scan on the grating was obtained by splitting the light beam on its way between the spot generator and the film. When crossed fibers are used it is no longer necessary to split the beam and lose half the light. As was stated above, the cone of light leaving the fibers is large and more than one objective can be placed in the cone. In the Mark II design two objectives are placed with their axes perpendicular to the fixed fiber (Fig. 16). Each objective projects an identical moving spot onto the film and grating, and no light splitter is used. The two objectives are not, of course, physically placed one beside the other as in Fig. 16, mirrors are used to place the image positions of the two lenses, one straight in front of the fibers, and the other at 7.5° to one side.

The grating used* has one thousand black lines per inch printed photographically on it. The widths of the black lines and the spaces between them are approximately equal and the edges between them are very sharp. The precision is of the order of $1\mu\text{m}$. A signal seen on a grating photomultiplier is shown in the lower half of Fig. 17 with a track signal above. (These signals were obtained with a mock up of the final system). The grating signal is used to generate a grating pulse at every cycle, corresponding to every $25.4\mu\text{m}$. In order to obtain the specified least count of $1.6\mu\text{m}$ 15 interpolation pulses are, in effect, inserted between each grating pulse, using a clock.⁷ Since the spot speed is certainly constant

*Provided by the National Physical Lab., England

to $\pm 1\%$ the use of a clock introduces negligible error. A track center pulse is obtained using an integration method⁷ and is then compared with a count of the interpolated grating pulses. This count is then transmitted to the computer via a buffer memory and represents the coordinate of the bubble along the scan line. The coordinate of the scan line in the orthogonal direction is obtained by reading the position of the stage using Moiré fringes. This coordinate is only transmitted to the computer every scan line.

In the course of scanning an entire picture about 100,000 coordinates of bubbles may be transmitted to the computer. As a demonstration all these coordinates may be plotted on a cathode ray tube and the resultant "picture" of the original photograph viewed. Since the Mark II machine is not yet running and since the 80" hydrogen bubble chamber, for which it is made, has not yet taken a photograph, it is not possible to show such a picture. It may still be of interest, however, to include a photograph of the plotted points measured with the Mark I flying spot digitizer (HPD). Fig. 18 shows this plot and it will be seen to be of the same photograph shown in Fig. 1. With care it will be found that even the specs of dust are faithfully digitized, fed to the computer, and plotted on the cathode ray tube in their correct positions.

One last feature of the final machine needs to be mentioned. It will only take 10 seconds to measure one bubble chamber picture, but this speed is of no use unless the time to wind the film into place and stop it, is short compared with the 10 seconds. In order

to ensure that this is the case, an automatic picture number readout and a fast film transport is used. A digital representation of the picture number, such as that seen at the top of Fig. 1, is projected from the film onto a pattern of photo transistors which read the number serially as the film moves. The projection system used will have been noticed in Fig. 15. The film transport* will move film at 6 meters per second and stop it in 20 cm. Since it is not possible to stop the 1000 ft. reels of film fast enough to allow such a rapid deceleration, loops of film are formed between the drive capstans and the reels. These loops are held in vacuum boxes and the length of film in the boxes is used to servo drive the reels. One half of this system (similar to an IBM tape transport) is illustrated in Fig. 19. The splicer is inserted to avoid having to re-thread film through the machine every time a new reel is put on.

It should be stressed in closing that a project of this magnitude involves the participation of many people. The original ideas for this flying spot digitizer are due to Paul Hough and Brian Powell in CERN, Geneva. The design and construction of the Mark II has involved the work of P.V.C. Hough, J. Rosenblum, C.L. Goodzeit and S.C. Mo; while the computer programs are being written by a collaboration involving CERN; Lawrence Radiation Laboratory, California; and Brookhaven. The authors peculiar contribution lies in the concept of the crossed fiber spot generator.

*Based on a design by the Bureau of Census, Washington, D.C.

References

1. D.A. Glaser, Phys. Rev. 87, 665 (1952).
2. Y. Goldschmidt-Clermont, Int. Conference on High Energy Accelerators (CERN, 1959).
3. P.V.C. Hough and B.W. Powell, Nuovo Cimento X, 18, 1184 (1960).
4. M. Benot et al, An Analysis of Results From The Prototype H.P.D. (CERN Yellow Report 61-31, 1961).
5. C. Wynn, Proc. Phys. Soc. (London), 74, 316 (1959).
6. R.B. Palmer, Lenses for Flying Spot Measuring Devices, (CERN Internal Report DD/IEP/61/33, 1961).
7. T. Lingjaerde, The H.P.D. Logic, (CERN Yellow Report 62-10, 1962)

Figure Captions

- Fig. 1. Tracks in BNL 20" Liquid Hydrogen Bubble Chamber.
- Fig. 2. The Rough Digitizer.
- Fig. 3. The Original Slit System.
- Fig. 4. Calculation of Arc Length For The Original Slit System.
- Fig. 5. The Principle of the Fiber System.
- Fig. 6. Calculation of Arc Length For The Fiber System.
- Fig. 7. Involute Fiber to Give Constant Spot Velocity.
- Fig. 8. The Objective Designed by Dr. C. Wynn.
- Fig. 9. A Curved Moving Fiber.
- Fig. 10. The Disc and Fixed Fiber Mount.
- Fig. 11. The Principle of the Following Illumination.
- Fig. 12. The Illumination System.
- Fig. 13. The Following Optics.
- Fig. 14. The Vacuum Tank Containing the Disc and Following Optics.
- Fig. 15. The Optical System Below the Disc.
- Fig. 16. Elimination of Light Splitter.
- Fig. 17. Track and Grating Photomultiplier Signals.
- Fig. 18. Plot of All Individual Measurements Made on a 20" Bubble Chamber Photograph Using the Mark I Flying Spot Measuring Machine (HPD)
- Fig. 19. One Half of the Film Transport.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13

FIGURE 14

FIGURE 15

FIGURE 16

FIGURE 17

FIGURE 18

FIGURE 19